Empirical Bayes When Estimation Precision Predicts Parameters

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Abstract. Empirical Bayes shrinkage methods usually maintain a prior independence assumption: The unknown parameters of interest are independent from the known standard errors of the estimates. This assumption is often theoretically questionable and empirically rejected. For one, the sample sizes associated with each estimate may select on or may influence the underlying parameters of interest, thereby making standard errors predictive of the unknown parameters. This paper instead models the conditional distribution of the parameter given the standard errors as a flexibly parametrized family of distributions, leading to a family of methods that we call close. This paper establishes that (i) close is rate-optimal for squared error Bayes regret, (ii) squared error regret control is sufficient for an important class of economic decision problems, and (iii) close is worst-case robust when our location-scale assumption is misspecified. Empirically, using close leads to sizable gains for selecting high-mobility Census tracts targeting a variety of economic mobility measures. Census tracts selected by close are substantially more mobile on average than those selected by the standard shrinkage method. This additional improvement is often multiple times the improvement of the standard shrinkage method over selection without shrinkage.

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1. Introduction

Applied economists often use empirical Bayes methods to shrink noisy parameter estimates, in hopes of accounting for the imprecision in the estimates and improving subsequent policy decisions.\footnote{Empirical Bayes methods are appropriate whenever many parameters for heterogeneous populations are estimated in tandem. For instance, value-added modeling, where the parameters are latent qualities for different service providers (e.g. teachers, schools, colleges, insurance providers, etc.), is a common thread in several literatures (Angrist et al., 2017; Mountjoy and Hickman, 2021; Chandra et al., 2016; Doyle et al., 2017; Hull, 2018; Einav et al., 2022; Abaluck et al., 2021; Dimick et al., 2010). Our application (Bergman et al., 2023) is in a literature on place-based effects, where the unknown parameters are latent features of places (Chyn and Katz, 2021; Finkelstein et al., 2021; Chetty et al., 2020; Chetty and Hendren, 2018; Diamond and Moretti, 2021; Baum-Snow and Han, 2019). Empirical Bayes methods are also applicable in studies of discrimination (Kline et al., 2022, 2023; Rambachan, 2021; Egan et al., 2022; Arnold et al., 2022; Montiel Olea et al., 2021), meta-analysis (Azevedo et al., 2020; Meager, 2022; Andrews and Kasy, 2019; Elliott et al., 2022; Wernerfelt et al., 2022; DellaVigna and Linos, 2022; Abadie et al., 2023), and correlated random effects in panel data (Chamberlain, 1984; Arellano and Bonhomme, 2009; Bonhomme et al., 2020; Bonhomme and Manresa, 2015; Liu et al., 2020; Giacomini et al., 2023). In terms of policy decisions driven by empirical Bayes posterior means, Gilraine et al. (2020) report that by the end of 2017, 39 states require that teacher value-added measures—typically, empirical Bayes posterior means of teacher performance—be incorporated into the teacher evaluation process.\footnote{To see this, take value-added modeling as an example. The precision of value-added estimates is usually a function of the number of customers associated with a service provider (e.g. number of students for a teacher). It is possible that customers select into higher quality providers. It is also possible that congestion effects render more popular service providers worse. These channels predict that the sample sizes for a provider are associated with latent value-added, and the direction of association depends on the interplay of the selection and congestion effects. Appendix A.5 outlines a formal discrete choice model to illustrate these effects. Potential failure of prior independence is noted by, among others, Bruhn et al. (2022), Kline et al. (2023), George et al. (2017), and Mehta (2019).} Throughout this paper, measures of economic mobility are defined as certain average outcomes of children from low-income households. There are various definitions of economic mobility provided by Chetty et al. (2020), discussed later in the paper. They are all measures of economic outcomes for children from low-income households (households at the 25\textsuperscript{th} percentile of the national income distribution). One example is the probability that a Black person have incomes in the top 20 percentiles, whose parents have household incomes at the 25\textsuperscript{th} percentile. As another example, Bergman et al. (2023) measure economic mobility as the mean income rank of children growing up in households at the 25\textsuperscript{th} income percentile.} The textbook empirical Bayes method assumes *prior independence*—that the precisions of the noisy estimates do not predict the underlying unknown parameters. However, prior independence is economically questionable and empirically rejected in many contexts. This is frequently because sample sizes associated with the estimates either *select on* or *affect* the underlying parameters, rendering the resulting standard errors highly predictive of the parameters.\footnote{Throughout this paper, measures of economic mobility are defined as certain average outcomes of children from low-income households. There are various definitions of economic mobility provided by Chetty et al. (2020), discussed later in the paper. They are all measures of economic outcomes for children from low-income households (households at the 25\textsuperscript{th} percentile of the national income distribution). One example is the probability that a Black person have incomes in the top 20 percentiles, whose parents have household incomes at the 25\textsuperscript{th} percentile. As another example, Bergman et al. (2023) measure economic mobility as the mean income rank of children growing up in households at the 25\textsuperscript{th} income percentile.} Inappropriately imposing prior independence can harm empirical Bayes decisions, possibly even making them underperform decisions without using shrinkage. Motivated by these concerns, this paper introduces empirical Bayes methods that relax prior independence.

To be concrete, our primary empirical example (Bergman et al., 2023) computes empirical Bayes posterior means for economic mobility estimates of low-income children\footnote{Throughout this paper, measures of economic mobility are defined as certain average outcomes of children from low-income households. There are various definitions of economic mobility provided by Chetty et al. (2020), discussed later in the paper. They are all measures of economic outcomes for children from low-income households (households at the 25\textsuperscript{th} percentile of the national income distribution). One example is the probability that a Black person have incomes in the top 20 percentiles, whose parents have household incomes at the 25\textsuperscript{th} percentile. As another example, Bergman et al. (2023) measure economic mobility as the mean income rank of children growing up in households at the 25\textsuperscript{th} income percentile.} published in the Opportunity Atlas (Chetty et al., 2020). Here, prior independence assumes that the...
standard errors of these noisy mobility estimates do not predict true economic mobility. However, more upwardly mobile Census tracts tend to have fewer low-income children and hence noisier estimates of economic mobility. Consequently, the standard errors of the estimates and true economic mobility are positively correlated, violating prior independence.

Bergman et al. (2023) use empirical Bayes posterior means to select high-mobility Census tracts, choosing those with high estimated posterior means. Using a validation procedure that we develop, for a few measures of economic mobility where prior independence is severely violated, we find that screening on conventional empirical Bayes posterior means selects less economically mobile tracts, on average, than screening on the unshrunk estimates.\(^4\) In contrast, screening on empirical Bayes posterior means computed by our method selects substantially more mobile tracts.

To describe our method, let \( Y_i \) be some noisy estimates for some parameters \( \theta_i \), with standard errors \( \sigma_i \), over heterogeneous populations \( i = 1, \ldots, n \). In our empirical application, \((Y_i, \sigma_i)\) are published in the Opportunity Atlas for each Census tract \( i \) and are designed to measure true economic mobility \( \theta_i \). Motivated by the central limit theorem applied to the underlying micro-data, \( Y_i \) is approximately Gaussian:

\[
Y_i \mid \theta_i, \sigma_i \sim \mathcal{N}(\theta_i, \sigma_i^2) \quad i = 1, \ldots, n. \tag{1.1}
\]

If we knew the distribution of \((\theta_i, \sigma_i)\), then we can do no better than oracle Bayes decisions, based on the posterior distribution \( \theta_i \mid \sigma_i, Y_i \). Empirical Bayes emulates such optimal decisions by estimating the oracle prior distribution of \((\theta_i, \sigma_i)\). Prior independence \( \theta_i \perp \sigma_i \) simplifies this estimation problem. However, empirical Bayes methods based on this assumption can have poor performance when it fails to hold.

We relax prior independence by modeling the prior distribution \( \theta_i \mid \sigma_i \) flexibly, detailed in Section 2. We model \( \theta_i \mid \sigma_i \) as a conditional location-scale family, controlled by \( \sigma_i \)-dependent location and scale hyperparameters and a \( \sigma_i \)-independent shape hyperparameter. Under this assumption, different values of the standard errors \( \sigma_i \) translate, compress, or dilate the distribution of the parameters \( \theta_i \mid \sigma_i \), but the underlying shape of \( \theta_i \mid \sigma_i \) does not vary. This model subsumes prior independence as the special case where the unknown location and scale parameters are constant functions of \( \sigma_i \).

This conditional location-scale assumption leads naturally to a family of empirical Bayes methods that we call CLOSE. Since the unknown prior distribution \( \theta_i \mid \sigma_i \) is fully described by its location, scale, and shape hyperparameters, CLOSE estimates these parameters flexibly.

\(^4\)Fortunately, for the measure of economic mobility (mean income rank pooling over all demographic groups whose parents are at the 25\(^{th}\) percentile of household income) used in Bergman et al. (2023), the violation of prior independence is sufficiently mild, so that screening on these empirical Bayes posterior means still outperforms screening on the raw estimates.
and plugs the estimated parameters into downstream decision rules. Among different estimation strategies for the hyperparameters, our preferred specification of close uses nonparametric maximum likelihood (NPML, Kiefer and Wolfowitz, 1956; Koenker and Mizera, 2014) to estimate the unknown shape of the prior distribution \( \theta_i | \sigma_i \). We find that close-NPML inherits the favorable computational and theoretical properties of NPML documented in the literature (Soloff et al., 2021; Jiang, 2020; Polyanskiy and Wu, 2020).

Section 3 provides three statistical guarantees for close-NPML. First and foremost, close-NPML emulates the oracle as well as possible, at least in terms of squared error loss. Specifically, Corollary 1 and Theorem 2 establish that close-NPML is minimax rate-optimal—up to logarithmic factors and under the conditional location-scale assumptions—for Bayes regret in squared error, a standard performance metric (Jiang and Zhang, 2009). Bayes regret is the performance gap between close-NPML and oracle Bayes decisions made with knowledge of the distribution of \( (\theta_i, \sigma_i) \).

Second, our guarantee for squared error regret also controls the Bayes regret for two ranking-related decision problems, including the problem of selecting high-mobility tracts encountered by Bergman et al. (2023). Theorem 3 shows that the Bayes regret in squared error dominates the Bayes regret for these decision problems. Thus, these ranking-related problems are easier than squared error estimation, and our squared error regret result implies upper bounds for the regrets of these problems.

Third, to assess robustness of close to the location-scale modeling assumption, Theorem 4 establishes that close-NPML is worst-case robust. Without imposing the location-scale assumptions, for a population version of close-NPML, we show that its worst-case mean-squared error is a bounded multiple of that of the minimax procedure. Since the minimax procedure optimizes its worst-case risk, this result shows that close-NPML does not perform exceedingly poorly even when the location-scale model is misspecified.

Since practitioners may want to assess how and whether close-NPML provides improvements in specific applications, Section 4.3 produces an out-of-sample validation procedure by extending the coupled bootstrap in Oliveira et al. (2021). If one had access to the micro-data, one could split the data into training and testing samples, use one to compute decisions, and use the other to evaluate them. Our validation procedure emulates this sample-splitting without needing access to the underlying micro-data. It provides unbiased loss estimates for any decision rules. In particular, this procedure allows practitioners to evaluate whether close provides improvements for their setting by comparing loss estimates for close and those for the standard shrinkage procedure.

To illustrate our method, Section 5 applies close to two empirical exercises, building on Chetty et al. (2020) and Bergman et al. (2023). The first exercise is a calibrated Monte Carlo
simulation, in which we have access to the true distribution of \( (\theta_i, \sigma_i) \). We find that close-npmle has mean-squared error (MSE) performance close to that of the oracle posterior, uniformly across the 15 measures of economic mobility that we include. For all 15 measures, close-npmle captures over 90% of possible MSE gains relative to no shrinkage, whereas conventional shrinkage captures only 70% on average and as little as 40% for some measures.

The second exercise evaluates the out-of-sample performance of various procedures for an economic policy problem. Bergman et al. (2023) use empirical Bayes procedures to select high-mobility Census tracts in Seattle. We consider a version of their exercise with different mobility measures, scaled up to the largest Commuting Zones in the United States. We find that close-npmle selects more economically mobile tracts than the conventional shrinkage method. These improvements are large relative to two benchmarks. First, they are on median 3.2 times the value of basic empirical Bayes—that is, the improvements the standard method delivers over screening on the raw estimates \( Y_i \) directly. Therefore, if one finds using the standard empirical Bayes method a worthwhile methodological investment, then the additional gain of using close is likewise meaningful. Second, for 6 out of 15 measures of mobility, close even improves over the standard method by a larger amount than the value of data—that is, the amount by which the standard method improves over selecting Census tracts completely at random. These improvements are substantial, since the value of data is likely economically significant if the mobility estimates are at all useful for the policy problem.

### 2. Model and proposed method

We observe estimates \( Y_i \) and their standard errors \( \sigma_i \) for parameters \( \theta_i \), over populations \( i \in \{1, \ldots, n\} \). We maintain throughout that the estimates are conditionally Gaussian and independent across \( i \):

\[
Y_i \mid \theta_i, \sigma_i^2 \sim \mathcal{N}(\theta_i, \sigma_i^2) \quad i = 1, \ldots, n.
\]  

The Normality in (2.1) is motivated by the central limit theorem applied to the underlying micro-data that generate the estimates \( Y_i \). That is, let \( n_i \) denote the underlying sample size in the micro-data which generate \( (Y_i, \sigma_i) \). Standard large-sample approximation implies

\[
\frac{Y_i - \theta_i}{\sigma_i} \overset{d}{\to} \mathcal{N}(0, 1)
\]  

as \( n_i \to \infty \).

We also assume that the population parameters \( (\theta_i, \sigma_i) \) are sampled from some joint distribution. Throughout this paper, we condition on \( \sigma_{1:n} = (\sigma_1, \ldots, \sigma_n) \) and treat them as

\[\text{Note that, under standard assumptions, the approximation (2.2) holds regardless of whether } \sigma_i \text{ is an estimated standard error or its unknown population counterpart. This is because the estimation error in } \sigma_i \text{ is typically of order } 1/n_i, \text{ which is smaller than that in } Y_i, \text{ which is of order } 1/\sqrt{n_i}.\]
fixed. We assume that \((\theta_i, \sigma_i)\) are independently and identically drawn,\(^6\) but the conditional distribution \(\theta_i \mid \sigma_i\) may be different across \(\sigma_i\):

\[
\theta_i \mid \sigma_i \overset{\text{i.i.d.}}{\sim} G_{(i)}. \quad (2.3)
\]

We use \(G_{(i)}\) to denote the distribution of \(\theta_i \mid \sigma_i\). We use \(P_0\) to denote the distribution of \(\theta_{1:n} \mid \sigma_{1:n}\), which is fully described by \((G_{(1)}, \ldots, G_{(n)})\). We refer to \(P_0\) as the oracle Bayes prior.

These assumptions imply that the Bayes decision rule with respect to the oracle Bayes prior \(P_0\) is optimal (Lehmann and Casella, 2006). Consider a loss function \(L(\delta, \theta_{1:n})\), which evaluates an action \(\delta\) at a vector of parameters \(\theta_{1:n}\). For instance, in our empirical application, the loss function may measure how well we estimate true mobility \(\theta_{1:n}\) or how well we select high mobility Census tracts.\(^7\) At any realization of the data \((Y_{1:n}, \sigma_{1:n})\), the oracle Bayes decision rule \(\delta^\star\) picks an action that minimizes the posterior expected loss:

\[
\delta^\star(Y_{1:n}, \sigma_{1:n}; P_0) \in \arg\min_\delta \mathbb{E}_{P_0}[L(\delta, \theta_{1:n}) \mid Y_{1:n}, \sigma_{1:n}]. \quad (2.4)
\]

Empirical Bayesians seek to approximate the oracle Bayes rule \(\delta^\star\) (Efron, 2014). With an estimate \(\hat{P}\) for \(P_0\), it is natural to plug \(\hat{P}\) into (2.4):\(^8\)

\[
\delta_{\text{EB}}(Y_{1:n}, \sigma_{1:n}; \hat{P}) \in \arg\min_\delta \mathbb{E}_{\hat{P}}[L(\delta, \theta_{1:n}) \mid Y_{1:n}, \sigma_{1:n}]. \quad (2.5)
\]

Popular empirical Bayes methods impose more structure than (2.3) in order to simplify estimating \(P_0\).\(^9\) The standard parametric empirical Bayes method additionally models \(G_{(i)}\) as identical across \(i\) and Gaussian: i.e., for all \(i\), \(G_{(i)} \overset{\text{i.i.d.}}{\sim} \mathcal{N}(m_0, s_0^2)\) (Morris, 1983). Following the recipe (2.5), this approach estimates the prior parameters \((m_0, s_0^2)\). Henceforth, we shall refer to this method as INDEPENDENT-GAUSS. On the other hand, state-of-the-art empirical

\(^6\)Combined with the independence assumption of \(Y_i\) across \(i\), we assume that \((\theta_i, \sigma_i, Y_i)\) are independently drawn unconditionally. The independence assumption for the estimates \(Y_i\) conditional on \((\theta_i, \sigma_i)\) holds when the underlying micro-data for different estimates \(Y_i\) are sampled independently. This assumption does not precisely hold for the Opportunity Atlas, but the correlation between \(Y_i\) and \(Y_j\), which arises from individuals who move between tracts, is likely small. Papers imposing this assumption include Mogstad et al. (2020) and Andrews et al. (2023). Moreover, we discuss an interpretation of the procedure when we erroneously assume that \(Y_i\) and/or \(\theta_i\) are independent across \(i\) in Appendix A.6.

\(^7\)To emphasize the distinction between the true expectation with respect to the data-generating process (2.3) and a posterior mean taken with respect to some possibly estimated measure \(\hat{P}\), we shall use \(\mathbb{E}\) to refer to the former and \(\mathbb{E}\) to refer to the latter. Subscripts typically make the distinction clear as well. Specifically,

\[
\mathbb{E}_{\hat{P}}[L(\delta, \theta_{1:n}) \mid Y_{1:n}, \sigma_{1:n}] = \frac{\int L(\delta(Y_{1:n}, \sigma_{1:n}), \theta_{1:n}) \prod_{i=1}^n \varphi \left( \frac{\theta_i - m_0}{\sigma_i} \right) \hat{P}(d\theta_{1:n} \mid \sigma_{1:n})}{\int \prod_{i=1}^n \varphi \left( \frac{\theta_i - m_0}{\sigma_i} \right) \hat{P}(d\theta_{1:n} \mid \sigma_{1:n})},
\]

where \(\varphi(\cdot)\) is the probability density function of a standard Gaussian.

\(^8\)The literature on empirical Bayes methods is vast. For theoretical and applied results of particular interest to economists, see the recent lecture by Gu and Walters (2022) and references therein. Efron (2019) and accompanying discussions are excellent introductions to the statistics literature.
Bayes methods (Jiang, 2020; Soloff et al., 2021; Jiang and Zhang, 2009; Koenker and Gu, 2019; Gilraine et al., 2020) assume that the marginal distributions are equal to some common, unknown distribution \( G_{(0)} \), not necessarily Gaussian: i.e., for all \( i \), \( G_{(i)} \overset{\text{i.i.d.}}{\sim} G_{(0)} \). They estimate \( G_{(0)} \) with nonparametric maximum likelihood and form decision rules according to (2.5). We refer to this method as \textsc{independent-npmle}. The “\textsc{independent}” here emphasizes that these methods assume prior independence: \( \theta_i \perp \sigma_i \) under the prior \( P_0 \).

We relax prior independence by instead modeling \( \theta_i \mid \sigma_i \) as a location-scale family,\(^{10}\) indexed by unknown hyperparameters \( (m_0(\cdot), s_0(\cdot), G_0(\cdot)) \): Specifically, we assume

\[
P(\theta_i \leq t \mid \sigma_i) = G_0\left( \frac{t - m_0(\sigma_i)}{s_0(\sigma_i)} \right),
\]

where the distribution \( G_0 \) is normalized to have zero mean and unit variance. Under (2.6), different values of \( \sigma \) may translate, compress, or dilate the conditional distribution of \( \theta \mid \sigma \) via the location parameter \( m_0(\cdot) \) and the scale parameter \( s_0(\cdot) \), but the conditional distributions can be normalized to take the same shape \( G_0(\cdot) \). Under this model, the oracle prior distribution \( P_0 \) is fully described by the hyperparameters \( (m_0(\cdot), s_0(\cdot), G_0(\cdot)) \). Our method, \textsc{close}, proposes to estimate \( P_0 \) with an estimate \( \hat{P} \) derived from estimated hyperparameters \( (\hat{m}(\cdot), \hat{s}(\cdot), \hat{G}_n) \). \textsc{close} then produces empirical Bayes decision rules with respect to the estimated prior \( \hat{P} \), following the recipe (2.5).

Before specifying our procedure in detail in Section 2.2, we illustrate with an example where prior independence fails and show what happens to empirical Bayes decision rules that inappropriately impose prior independence.

2.1. \textbf{Plausibility of prior independence.} As a running example, let us define economic mobility \( \theta_i \) as the probability of family income ranking in the top 20 percentiles of the national income distribution, for a Black individual growing up in tract \( i \) whose parents are at the 25\textsuperscript{th} national income percentile. Note that the standard error \( \sigma_i \) for an estimate of \( \theta_i \) is then related to the implicit sample size—the number of Black households at the 25\textsuperscript{th} income percentile in tract \( i \).

Prior independence is readily rejected for this measure of economic mobility. Figure 1 plots \( Y_i \) against \( \log_{10}(\sigma_i) \) and imposes a nonparametric regression estimate of the conditional mean function \( m_0(\sigma_i) \equiv \mathbb{E}[\theta_i \mid \sigma_i] = \mathbb{E}[Y_i \mid \sigma_i] \). If \( \theta_i \) were independent of \( \sigma_i \), then the true

\(^{10}\)We explore alternatives to the location-scale model in Appendix A.7. We find that no alternative provides a free-lunch improvement over our assumptions. More restrictive forms of this assumption also appear in the past and concurrent literature. For instance, Kline et al. (2023) model the dependence as a pure scale model \( \theta \mid \sigma \sim s(\sigma) \cdot \tau \) for some \( \tau \mid \sigma \overset{\text{i.i.d.}}{\sim} G \) (with additional parametric restrictions on \( s(\cdot) \)) and George et al. (2017) impose the location scale model (2.6) with \( G_0 \sim \mathcal{N}(0, 1) \) (as well as additional parametric restrictions on \( s_0(\cdot), m_0(\cdot) \)).
Notes. All tracts within the largest 20 Commuting Zones (CZs) are shown. Due to the regression specification in Chetty et al. (2020), point estimates of $\theta_i \in [0, 1]$ do not always lie within $[0, 1]$. The orange line plots nonparametric regression estimates of the conditional mean $\mathbb{E}[Y \mid \sigma] = \mathbb{E}[\theta \mid \sigma] \equiv m_0(\sigma)$, estimated via local linear regression with automatic bandwidth selection implemented in Calonico et al. (2019). The orange shading shows a 95% uniform confidence band, constructed by the max-$t$ confidence set over 50 equally spaced evaluation points. The confidence band excludes any constant function. See Appendix G for details on estimating conditional moments of $\theta_i$ given $\sigma_i$.

Figure 1. Scatter plot of $Y_i$ against $\log_{10}(\sigma_i)$ in the Opportunity Atlas conditional mean function $m_0(\sigma_i)$ should be constant. Figure 1 shows the contrary—tracts with more imprecisely estimated $Y_i$ tend to have higher economic mobility.\footnote{Moreover, $\log \sigma_i$ remains predictive of $Y_i$ even if we residualize $Y_i$ against a vector of tract-level covariates (Figure B.9).}

This correlation is in part through the following channel. Since $\theta_i$ is an average outcome for children from poor Black families, tracts with more poor Black families tend to have more precise estimates of $\theta_i$.\footnote{Prior independence is also readily rejected for the mobility measure used in Bergman et al. (2023), but its violation is not as severe once adjusted for tract-level covariates (see Section 5 and Figure B.8).} However, these tracts also tend to have lower economic mobility $\theta_i$ due to the pernicious effects of residential segregation.

What happens if we apply empirical Bayes methods that assume prior independence here? Figure 2 overlays empirical Bayes posterior means on the $Y_i$-against-$\log \sigma_i$ scatterplot. In the top panel, INDEPENDENT-GAUSS shrinks estimates $Y_i$ towards a common estimated mean $\hat{m}_0$, depicted as the black line. INDEPENDENT-GAUSS shrinks noisier estimates more aggressively.\footnote{Since $\theta_i$ is also the mean of a binary outcome, the asymptotic variance of its estimators also depend on mechanically on $\theta_i$.}
Notes. The top panel shows posterior mean estimates with INDEPENDENT-GAUSS shrinkage. The middle panel shows the same with INDEPENDENT-NPMLE shrinkage. The bottom panel displays posterior mean estimates from our preferred procedure, CLOSE-NPMLE. In the top panel, the estimates for \( m_0, s_0^2 \) are weighted by the precision \( 1/\sigma_i^2 \) (as in Bergman et al., 2023). Under \( \theta_i \perp \sigma_i \), this weighting scheme improves efficiency of the \((m_0, s_0^2)\)-estimates by underweighting noisier \( Y_i \).

\[ \square \]

Figure 2. Posterior mean estimates under prior independence
When \( \sigma_i \) and \( \theta_i \) are positively correlated—as is the case here—estimated posterior means under INDEPENDENT-GAUSS systematically undershoot \( \theta_i \) for populations with imprecise estimates. Similarly, the middle panel of Figure 2 shows that INDEPENDENT-NPMLE suffers from the same undershooting, though less so. In contrast, the bottom panel of Figure 2 previews our preferred procedure, CLOSE-NPMLE, which shrinks towards the conditional mean \( \mathbb{E}[\theta_i | \sigma_i] \), thus avoiding the undershooting.

This undershooting is particularly problematic if one would like to select high-mobility Census tracts. These high-mobility tracts are exactly those with high imprecision \( \sigma_i \), owing to the positive correlation between \( \theta_i \) and \( \sigma_i \). By shrinking these tracts severely towards the estimated common mean, empirical Bayes under prior independence makes suboptimal selections that may even underperform screening directly based on \( Y_i \).

For a given empirical context, prior independence can always be checked empirically by plotting à la Figure 1. Nevertheless, we discuss the general plausibility of prior independence in the following remark.

**Remark 1 (Plausibility of prior independence).** To describe the general channels underlying the potential failure of prior independence, let us write (2.2) in a different form

\[
\sqrt{n_i}(Y_i - \theta_i) \xrightarrow{d} N(0, \sigma_0^2) \quad \text{where} \quad \sigma_i \approx \frac{\sigma_{0i}}{\sqrt{n_i}}. \tag{2.7}
\]

Expression (2.7) decomposes the (estimated) standard error into the underlying sample size \( n_i \) in the micro-data and the asymptotic variance \( \sigma_0^2 \) of the (properly scaled) estimator. Both \( n_i \) and \( \sigma_{0i} \) may predict \( \theta_i \) in a variety of empirical contexts.

Let us start with the implicit sample sizes \( n_i \). It is possible that \( n_i \) is in part determined by \( \theta_i \), which we loosely term selection. In value-added modeling, \( n_i \) is the number of observations associated with a provider. It is possible that \( n_i \) selects on the latent quality \( \theta_i \) of that provider. For instance, Chandra et al. (2016) find “higher quality hospitals have higher market shares and grow more over time.” If market share and hospital size relate to the underlying sample size \( n_i \) (e.g. number of patient observations) for estimating hospital value-added, then this suggests non-independence between \( \theta_i \) and \( \sigma_i \) (see George et al. (2017) for some empirical evidence). As another example, in meta-analysis, suppose \( \theta_i \) represents the treatment effect of some intervention \( i \). If researchers power studies based on informative priors for \( \theta_i \), then we should observe that interventions with larger conjectured effect sizes have smaller sample sizes \( n_i \).

Another channel driving the correlation between \( n_i \) and \( \theta_i \) can be loosely termed congestion, where \( n_i \) affects the latent feature \( \theta_i \). For our primary application, \( n_i \) represents the number of poor and minority households in a Census tract, and \( \theta_i \) represents underlying economic or social mobility. Places with more poor and minority households experience white

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\[\text{This latter point is similarly made in Mehta (2019), though for different loss functions.}\]
flight and residential segregation (Cutler et al., 1999; Agan and Starr, 2020; Kain, 1968),
develop oppressive institutions (Derenoncourt, 2022; Alesina et al., 2001), and provide worse
public goods (Laliberté, 2021; Jackson and Mackevicius, 2021; Colmer et al., 2020). These
factors contribute to lower economic mobility $\theta_i$. Appendix A.5 contains more examples
of violation of prior independence and outlines a model in which selection and congestion
effects drive correlation between $n_i$ and $\theta_i$.

There are also channels for the asymptotic variance $\sigma_0^2$ to correlate with $\theta_i$. In the context
of intergenerational mobility, a parallel literature on the Great Gatsby curve (Durlauf et
al., 2022) seeks to explain a negative relationship between inequality—which contributes to
$\sigma_0^2$—and intergenerational mobility. For instance, Becker et al. (2018) posit that parental
investment and parental human capital are complements for forming the skills of a child. As
a result, parents with higher human capital—and more wealth—invest disproportionately
more in their children’s education than parents with lower human capital. This process then
produces both inequality and low economic mobility. In other words, places that are more
unequal (which may result in higher $\sigma_0^2$) have lower mobility $\theta_i$.

2.2. Conditional location-scale relaxation of prior independence. Having argued
that (i) prior independence is theoretically suspect and empirically rejected and that (ii)
inappropriately imposing it can harm empirical Bayes decision rules, we propose the con-
ditional location-scale model (2.6) as a relaxation. Here, we state the location-scale as-
sumption (2.6) equivalently as the following representation with transformed parameters
$\tau_i = \frac{\theta_i - m_0(\sigma_i)}{s_0(\sigma_i)}$:

$$\theta_i = m_0(\sigma_i) + s_0(\sigma_i)\tau_i \quad \tau_i \mid \sigma_i \overset{i.i.d.}{\sim} G_0 \quad \mathbb{E}_{G_0}[\tau_i] = 0 \quad \text{Var}_{G_0}(\tau_i) = 1.$$ (2.8)

To estimate $P_0$ under (2.8), it suffices to estimate the unknown hyperparameters $(m_0, s_0, G_0)$. Expression (2.8) makes clear that, under the location-scale model, the transformed parameter $\tau_i \sim G_0$ is independent from $\sigma_i$. Analogously, let $Z_i = \frac{Y_i - m_0(\sigma_i)}{s_0(\sigma_i)}$ be the transformed estimates and $\nu_i = \frac{\sigma_i}{s_0(\sigma_i)}$ be their standard errors.

Crucially, $(Z_i, \tau_i, \nu_i)$ obey an analogue of the Gaussian location model (2.1) in which prior
independence holds:

$$Z_i \mid \nu_i, \tau_i \sim \mathcal{N}(\tau_i, \nu_i^2), \text{ independently across } i \text{ and } \tau_i \mid \sigma_i \overset{i.i.d.}{\sim} G_0.$$ 

Therefore, it is a natural to first transform $(Y_i, \sigma_i)$ into $(Z_i, \nu_i)$ and then use empirical Bayes
methods that assume prior independence on these transformed quantities to estimate $G_0$.

This strategy is still infeasible, since the transformation depends on unknown location and
scale parameters $\eta_0 = (m_0, s_0)$. Fortunately, $m_0(\cdot)$ and $s_0(\cdot)$ are readily estimable from the

\(^{14}\)In the presence of covariates $X_i$—which do not predict the noise in $Y_i$, $Y_i \perp X_i \mid \theta_i, \sigma_i$—the assumption
(2.6) can be modified to accommodate additional covariates as well. We provide additional discussion of
covariates in Appendix A.6.2.
data \((Y_i, \sigma_i)\), as they only require conditional expectations and variances of \(Y\) given \(\sigma\):

\[
m_0(\sigma) = \mathbb{E}[\theta | \sigma] = \mathbb{E}[Y | \sigma] \quad \text{and} \quad s_0^2(\sigma) = \text{Var}(\theta | \sigma) = \mathbb{E}[(Y - m_0(\sigma))^2 | \sigma] - \sigma^2. \quad (2.9)
\]

Given estimates \(\hat{m}\) and \(\hat{s}\) of \(m_0(\cdot)\) and \(s_0(\cdot)\), we then form the estimated transformed data \(\hat{Z}_i, \hat{\nu}_i\) as

\[
\hat{Z}_i = \frac{Y_i - \hat{m}(\sigma_i)}{\hat{s}(\sigma_i)} \quad \text{and} \quad \hat{\nu}_i = \frac{\sigma_i}{s(\sigma_i)}. \quad (2.10)
\]

We then apply empirical Bayes methods assuming prior independence on \((\hat{Z}_i, \hat{\nu}_i)\). This leads to a family of empirical Bayes strategies that we refer to as conditional location-scale empirical Bayes, or \textit{CLOSE}:\textsuperscript{15}

\begin{itemize}
  \item **CLOSE–STEP 1** Nonparametrically estimate \(m_0(\sigma), s_0^2(\sigma)\) according to (2.9).
  \item **CLOSE–STEP 2** With the estimates \(\hat{\eta} = (\hat{m}, \hat{s})\), transform the data according to (2.10). Apply empirical Bayes methods with prior independence to estimate \(G_0\) with some \(\hat{G}_n\) on the transformed data \((\hat{Z}_i, \hat{\nu}_i)\).
  \item **CLOSE–STEP 3** Having estimated \((\hat{\eta}, \hat{G}_n)\), which implies an estimate \(\hat{P}\) of \(P_0\), we then form empirical Bayes decision rules following (2.5).
\end{itemize}

This framework produces a family of empirical Bayes strategies, since \textit{CLOSE–STEP 2} can take different forms. To leverage theoretical and computational advances, we will focus on—and recommend—using nonparametric maximum likelihood (\textit{npMLE}) to estimate \(G_0\). That is, we maximize the log-likelihood of (an estimated version of) the transformed data \(Z_i\), whose marginal distribution is the convolution \(G_0 \ast \mathcal{N}(0, \nu_i^2)\):\textsuperscript{16}

\[
\hat{G}_n \in \arg \max_{G \in \mathcal{P}(\mathbb{R})} \frac{1}{n} \sum_{i=1}^{n} \log \int_{-\infty}^{\infty} \varphi \left( \frac{\hat{Z}_i - \tau}{\hat{\nu}_i} \right) \frac{1}{\hat{\nu}_i} G(d\tau). \quad (2.11)
\]

When the estimated moments \(\hat{m}, \hat{s}\) are constant functions of \(\sigma\), \textit{CLOSE-\textit{npMLE}} estimates the same prior as \textit{INDEPENDENT-\textit{npMLE}}. In the theoretical literature, under prior independence, \textit{INDEPENDENT-\textit{npMLE}} is state-of-the-art in terms of computational ease and regret

\textsuperscript{15}We give a more detailed walkthrough of these steps in Section 4. We also detail a local linear regression estimator in Appendix G for \textit{CLOSE–STEP 1}.

\textsuperscript{16}We use \((f \ast g)(t) = \int_{-\infty}^{\infty} f(x)g(t-x) \, dx\) to denote convolution and \(\varphi(t) = \frac{1}{\sqrt{2\pi}} e^{-t^2/2}\) to denote the Gaussian probability density function. The maximization is over the set of all probability measures on \(\mathbb{R}, \mathcal{P}(\mathbb{R})\).
properties. Our subsequent results in Section 3 extend some of these favorable properties to CLOSE-NPMLE under the conditional location-scale model.

A simple alternative, which we call CLOSE-GAUSS and think of as a "lite" version of CLOSE-NPMLE, additionally models the shape $G_0$ as standard Gaussian. We briefly discuss its properties in the following remark.

**Remark 2 (CLOSE-GAUSS).** Under $G_0 \sim \mathcal{N}(0,1)$, the oracle Bayes posterior means are simply

$$
\hat{\theta}_n^{* \mathcal{N}(0,1):\eta_0} = \frac{\sigma_i^2}{s_0^2(\sigma_i) + \sigma_i^2 m_0(\sigma_i)} + \frac{s_0^2(\sigma_i)}{s_0^2(\sigma_i) + \sigma_i^2} Y_i.
$$

Equation (2.12) is the analogue of posterior means estimated by INDEPENDENT-GAUSS, where the unconditional mean $m_0$ and variance $s_0^2$ are replaced with their conditional counterparts $(m_0(\cdot), s_0^2(\cdot))$. As an empirical Bayes strategy, CLOSE-GAUSS then replaces the unknown conditional moments with their estimated counterparts. Its properties depend on those of the oracle (2.12) it mimics, which we turn to now.

Despite being rationalized under the assumption $\theta_i | \sigma_i \sim \mathcal{N}(m_0(\sigma_i), s_0^2(\sigma_i))$, (2.12) enjoys strong robustness properties: It is optimal over a restricted class of decision rules and minimax over all decision rules—without imposing the location-scale assumption (2.6). First, (2.12) is the optimal decision rule for estimating $\theta_i$ when we restrict to the class of decision rules that are linear in $Y_i$ (Weinstein et al., 2018). Second, (2.12) is minimax in the sense that it minimizes the worst-case mean squared error, where an adversary chooses $G_{(1)}, \ldots, G_{(n)}$, subjected to the constraint that $G_{(j)}$’s first two moments are $(m_0(\sigma_i), s_0^2(\sigma_i))$.\(^{18}\)

\(^{17}\)The nonparametric maximum likelihood has a long history in econometrics and statistics (Kiefer and Wolfowitz, 1956; Lindsay, 1995; Heckman and Singer, 1984). There is recent renewed interest. See, among others, Koenker and Gu (2019); Koenker and Mizera (2014); Jiang and Zhang (2009); Jiang (2020); Soloff et al. (2021); Saha and Guntuboyina (2020); Polanskiy and Wu (2020); Shen and Wu (2022); Polanskiy and Wu (2021). Empirical Bayes methods via NPMLE have computational and theoretical advantages, though much of the favorable theoretical results are proven in a homoskedastic setting. Its computational ease (Koenker and Mizera, 2014; Koenker and Gu, 2017) and lack of tuning parameters are advocated in Koenker and Gu (2019). Polanskiy and Wu (2020) find that, with high probability, NPMLE recovers a distribution $\hat{G}_n$ with only $O(\log n)$ support points despite searching over the set of all distributions; they refer to this property as self-regularization. For regret control in the homoskedastic Gaussian model, Jiang and Zhang (2009)'s result is the best known and matches a lower bound up to log factors (Polanskiy and Wu, 2021). \(^{18}\) (2.12) is first proposed by Weinstein et al. (2018). Weinstein et al. (2018) propose estimating $m_0(\cdot), s_0(\cdot)$ in a particular manner to ensure the resulting empirical Bayes posterior means dominate the naive estimates $Y_i$ uniformly over $\theta_{1:n}, \sigma_{1:n}$, which are conditioned upon.

\(^{19}\) Formally,

$$
\theta_n^{* \mathcal{N}(0,1):\eta_0} = \arg \min_{\theta_{1:n}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} \mathbb{E}_{G_{(i)}} \left[ (\delta_i(Y_{1:n}, \sigma_{1:n}) - \theta_i)^2 \right] \right],
$$

where the supremum is taken over $G_{(i)}$ having moments $\eta_0(\sigma_i)$. To wit, note that the Bayes risk of (2.12) is the same regardless of choices of $G_{(1)}, \ldots, G_{(n)}$ under the moment constraint, and it is equal to the optimal Bayes risk when $G_{(i)} \sim \mathcal{N}(m_0(\sigma_i), s_0^2(\sigma_i))$. We therefore conclude that (2.12) is minimax by observing that the minimax Bayes risk is at least the risk of (2.12).
However, the Normality assumption does imply that (2.12), unlike close-NPMLE, fails to approximate the optimal decision (2.4) when the location-scale assumption (2.6) holds but \( \theta_i \mid \sigma_i \) may not be Gaussian. Since we also show that close-NPMLE is worst-case robust—though with higher worst-case risk than close-GAUSS, we recommend close-NPMLE over close-GAUSS, unless the researcher is extremely concerned about the misspecification of the location-scale model.

2.3. Decision problems. To prepare for our theoretical results in the next section, we close this one by introducing decision theory notation and formalizing a few decision problems. Let \( \mathbf{\delta}(Y_{1:n}, \sigma_{1:n}) \) be a decision rule mapping the data \((Y_{1:n}, \sigma_{1:n})\) to actions. Let \( L(\mathbf{\delta}, \theta_{1:n}) \) denote a loss function mapping actions and parameters to a scalar. Let \( R_F(\mathbf{\delta}, \theta_{1:n}) = \mathbb{E}[L(\mathbf{\delta}, \theta_{1:n}) \mid \theta_{1:n}, \sigma_{1:n}] \) denote the frequentist risk associated with the loss function \( L \), which integrates over the randomness in \( Y_{1:n} \), keeping \( \theta_{1:n}, \sigma_{1:n} \) fixed. Finally, let \( R_B(\mathbf{\delta}; P_0) = \mathbb{E}_{P_0}[R_F(\mathbf{\delta}, \theta_{1:n}) \mid \sigma_{1:n}] \) be the Bayes risk of \( \mathbf{\delta} \) under \( P_0 \), which additionally integrates over the conditional distribution \( \theta_{1:n} \mid \sigma_{1:n} \).

The oracle Bayes decision rule \( \mathbf{\delta}^* \) (2.4) is optimal in the sense that it minimizes \( R_B \). A natural metric of success for the empirical Bayesian (2.5) is thus the gap between the Bayes risks of \( \mathbf{\delta}_{EB} \) and \( \mathbf{\delta}^* \). We refer to this quantity as Bayes regret:

\[
\text{BayesRegret}_n(\mathbf{\delta}_{EB}) = R_B(\mathbf{\delta}_{EB}; P_0) - R_B(\mathbf{\delta}^*; P_0) = \mathbb{E}[L(\mathbf{\delta}_{EB}, \theta_{1:n}) - L(\mathbf{\delta}^*, \theta_{1:n}) \mid \sigma_{1:n}] \tag{2.13}
\]

where the right-hand side integrates over the randomness in \( \theta_{1:n}, Y_{1:n} \), and, by extension, \( \hat{P} \). If an empirical Bayes method achieves low Bayes regret, then it successfully imitates the decisions of the oracle Bayesian, and its decisions are thus approximately optimal. Our theoretical results focus on bounding Bayes regret for close.

We introduce a few concrete decision problems by specifying the actions \( \mathbf{\delta} \) and loss functions \( L \) and state the corresponding oracle Bayes and empirical Bayes decision rules.

**Decision Problem 1** (Squared-error estimation of \( \theta_{1:n} \)). The canonical statistical problem (Robbins, 1956) is estimating the parameters \( \theta_{1:n} \) under mean-squared error (MSE). That is, the action \( \mathbf{\delta} = (\delta_1, \ldots, \delta_n) \) collects estimates \( \hat{\theta}_i \) for parameters \( \theta_i \), evaluated with MSE:

\[
L(\mathbf{\delta}, \theta_{1:n}) = \frac{1}{n} \sum_{i=1}^{n} (\delta_i - \theta_i)^2.
\]

---

20Since \( \sigma_{1:n} \) is kept fixed throughout, we suppress their appearances in \( R_B(\cdot), R_F(\cdot) \).

21Bayes regret is likewise the focus of the literature in empirical Bayes that we build on (Jiang, 2020; Soloff et al., 2021). On the other hand, other optimality criteria are also considered. For instance, Kwon (2021), Xie et al. (2012), Abadie and Kasy (2019), and Jing et al. (2016) propose methods that use Stein’s Unbiased Risk Estimate (SURE) to select hyperparameters for a class of shrinkage procedures. A common thread of these approaches is that they seek optimality in terms of the frequentist risk \( R_F \)—which is stronger than controlling the Bayes risk \( R_B \)—but limit attention to squared error and to a restricted class of methods.
The oracle Bayes decision rule \( \delta^* = (\delta_1^*, \ldots, \delta_n^*) \) here is the posterior mean under \( P_0 \), denoted by \( \theta_i^* = \theta_{i,P_0}^* \):

\[
\delta_i^* = \theta_{i,P_0}^* \equiv \mathbb{E}_{P_0}[\theta_i | Y_i, \sigma_i]
\]

with empirical Bayesian counterpart \( \hat{\theta}_{i, \hat{P}} = \mathbb{E}_{\hat{P}}[\theta_i | Y_i, \sigma_i] \).

Next, we describe two problems that are likely more relevant for policy-making, such as replacing low value-added teachers and recommending high economic mobility tracts (Gilraine et al., 2020; Bergman et al., 2023).\(^{22}\)

**Decision Problem 2** (utility maximization by selection). Suppose \( \delta = (\delta_1, \ldots, \delta_n) \), where \( \delta_i \in \{0, 1\} \) is a selection decision for population \( i \). For each population, selecting that population has benefit \( \theta_i \) and known cost \( c_i \). The decision maker wishes to maximize utility (i.e., negative loss):

\[
-L(\delta, \theta_{1:n}) = \frac{1}{n} \sum_{i=1}^{n} \delta_i (\theta_i - c_i).
\]

The oracle Bayes rule selects all populations whose posterior mean benefit \( \theta_{i,P_0}^* \) exceeds the selection cost \( c_i \):

\[
\delta_i^* = 1 \left( \theta_{i,P_0}^* \geq c_i \right).
\]

One natural empirical Bayes decision rule replaces \( \theta_{i,P_0}^* \) with \( \theta_{i,\hat{P}}^* \), following (2.5).

In a context where the parameters are conditional average treatment effects for a particular covariate cell, \( \theta_i = \text{CATE}(i) \equiv \mathbb{E}[Y(1) - Y(0) | X = i] \), and \( \delta_i \) are treatment decisions, this problem is an instance of welfare maximization by treatment choice (Manski, 2004; Stoye, 2009; Kitagawa and Tetenov, 2018; Athey and Wager, 2021). In this setting, \( \delta_i \) is a decision to treat individuals with covariate values in the \( i \)th cell. The average benefit of treating these individuals is their conditional average treatment effect \( \theta_i \), and the cost of treatment is \( c_i \).\(^{23}\)

**Decision Problem 3** (top-\( m \) selection). Similar to utility maximization by selection, suppose \( \delta \) consists of binary selection decisions, with the additional constraint that exactly \( m \) populations are chosen: \( \sum_i \delta_i = m \). The decision maker’s utility is the average \( \theta_i \) of the selected set:

\[
-L(\delta, \theta_{1:n}) = \frac{1}{m} \sum_{i=1}^{n} \delta_i \theta_i.
\]  

\(^{22}\)We analyze these problems from a decision-theoretic perspective, under the sampling assumption (2.3). For a different and complementary perspective in terms of conditional-on-\( \theta \) frequentist inference on ranks, see Mogstad et al. (2020, 2023). For additional ranking-related decision problems, see Gu and Koenker (2023).\(^{23}\)The literature on treatment choice uses a different notion of regret compared to this paper (based on \( R_F \) rather than \( R_B \)).
Oracle Bayes selects the populations corresponding to the \( m \) largest posterior means \( \theta_{i,P_0}^* \) (breaking ties arbitrarily):
\[
\delta_i^* = \mathbb{1} \left( \theta_{i,P_0}^* \text{ is among the top-} m \text{ of } \theta_{1:n,P_0}^* \right).
\]
Again, the empirical Bayes recipe (2.5) suggests replacing \( P_0 \) with the estimate \( \hat{P} \).

The utility function (2.14) rationalizes the widespread practice of screening based on empirical Bayes posterior means. For instance, this objective may be reasonable for rewarding the top 5% of teachers or replacing the bottom 5%, according to value-added (Gilraine et al., 2020; Chetty et al., 2014; Kane and Staiger, 2008; Hanushek, 2011). In Bergman et al. (2023), where housing voucher holders are incentivized to move to Census tracts selected according to economic mobility, (2.14) represents the expected economic mobility of a mover if they move randomly to one of the selected tracts.\(^{24}\)

### 3. Regret results for close-npmle

We observe \((Y_i, \sigma_i)_{i=1}^n\), where \((\theta_i, \sigma_i)\) satisfies the location-scale assumption (2.6) and \((Y_i, \theta_i, \sigma_i)\) obeys the Gaussian location model (2.1). Our recommended procedure, close-npmle, transforms the data \((Y_i, \sigma_i)\) into \((\hat{Z}_i, \hat{\nu}_i)\), with estimated nuisance parameters \(\hat{\eta} = (\hat{m}, \hat{s})\) for \(\eta_0 = (m_0, s_0)\) in [CLOSE–STEP 1]. It then estimates the unknown shape parameter \(G_0\) via npmle (2.11) on \((\hat{Z}_i, \hat{\nu}_i)_{i=1}^n\).

Our leading result shows that close-npmle mimics the oracle Bayesian as well as possible, for the problem of estimation under squared error loss, in the sense that its Bayes regret vanishes at the minimax optimal rate. Our second result connects squared error estimation to Decision Problems 2 and 3, by showing that if an empirical Bayesian has low regret in squared error loss, then they likewise have low regret for Decision Problems 2 and 3.

Since our main result assumes the location-scale model, one may be concerned about its potential misspecification. The last result in this section, Theorem 4, bounds the worst-case Bayes risk of an idealized version of close-npmle (i.e. with known \(\eta_0\) and fixed but misspecified \(\hat{G}_n\)) as a multiple of a notion of minimax risk, without assuming (2.6). Thus, even under misspecification, close-npmle does not perform arbitrarily badly relative to the minimax procedure.

The rest of this section states and discusses these results formally. Practitioners who are less interested in the theoretical details are free to skip to Section 4, where we discuss a number of practical considerations.

**Remark 3 (Notation).** In what follows, we use the symbol \(C\) to denote a generic positive and finite constant which does not depend on \(n\). We use the symbol \(C_x\) to denote a generic positive

---

\(^{24}\)Our theoretical results in Section 3.2 can accommodate a slightly more general decision problem, which allows for an expected mobility interpretation for movers who do not move uniformly randomly. See Remark 5.
and finite constant that depends only on \( x \), some parameter(s) that describe the problem. Occurrences of the same symbol \( C, C_x \) may not refer to the same constants. Similarly, for \( A_n, B_n \geq 0 \), generally functions of \( n \), we use \( A_n \lesssim B_n \) to mean that some universal \( C \) exists such that \( A_n \leq CB_n \) for all \( n \), and we use \( A \lesssim x \) to mean that some universal \( C_x \) exists such that \( A_n \leq C_x B_n \) for all \( n \). In logical statements, appearances of \( \lesssim \) implicitly preprend “there exists a universal constant” to the statement. Since all expectation or probability statements are with respect to the conditional distribution \( P_0 \) of \( \theta_{1:n} \mid \sigma_{1:n} \), going forward, we treat \( \sigma_{1:n} \) as fixed and simply write \( E[\cdot], P(\cdot) \) to denote the expectation and probability over \( \theta_{1:n} \mid \sigma_{1:n} \sim P_0 \). We omit the \( P_0 \) subscript and the conditioning on \( \sigma_{1:n} \). □

3.1. **Regret rate in squared error.** Since we consider close-npmle in mean-squared error, we define

\[
\text{MSERegret}_n(G, \eta) \equiv \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_{i,G,\eta} - \theta_i)^2 - \frac{1}{n} \sum_{i=1}^{n} (\theta^*_i - \theta_i)^2
\]

\[
\theta^*_i \equiv \theta^*_i, P_0 = E_{P_0}[\theta_i \mid Y_i, \sigma_i] \quad \hat{\theta}_{i,G,\eta} \equiv E_{G,\eta}[\theta_i \mid Y_i, \sigma_i] \equiv \frac{\int \theta \varphi \left( \frac{Y_i - \theta}{\sigma_i} \right) \frac{1}{\sigma_i} dG \left( \frac{\theta - m(\sigma_i)}{s(\sigma_i)} \right)}{\int \varphi \left( \frac{Y_i - \theta}{\sigma_i} \right) \frac{1}{\sigma_i} dG \left( \frac{\theta - m(\sigma_i)}{s(\sigma_i)} \right)}
\]

as the excess loss of the empirical Bayes posterior means—obtained by prior \( G \) and nuisance parameter estimate \( \eta \) for \( \eta_0 \)—relative to that of the oracle Bayes posterior means. The Bayes regret for close-npmle in squared error is then the \( P_0 \)-expectation of \( \text{MSERegret}_n \):

\[
\text{BayesRegret}_n = E \left[ \text{MSERegret}_n(\hat{G}_n, \hat{\eta}) \right] = E \left[ \frac{1}{n} \sum_{i=1}^{n} (\theta^*_i - \hat{\theta}_{i,\hat{G}_n,\hat{\eta}})^2 \right].
\] (3.1)

Equation (3.1) additionally notes that expected \( \text{MSERegret}_n \) is equal to the expected mean-squared difference between the empirical Bayesian posterior means \( \hat{\theta}_{i,\hat{G}_n,\hat{\eta}} \) and the oracle Bayes posterior means.

We assume that \( P_0 \in \mathcal{P}_0 \) belongs to some restricted class. Informally speaking, our first main result shows that for some constants \( C, \beta > 0 \) that depend solely on \( \mathcal{P}_0 \), the Bayes regret in squared error decays at the same rate as the maximum estimation error for \( \eta_0 \) squared:

\[
\text{BayesRegret}_n \leq C(\log n)^\beta \max \left( E \| \hat{\eta} - \eta_0 \|_\infty^2, \frac{1}{n} \right),
\]

where we define \( \| \eta \|_\infty = \max(\| m \|_\infty, \| s \|_\infty) \) for \( \eta = (m, s) \). This result continues a recent statistics literature on empirical Bayes methods via npmle by characterizing the effect of an estimated nuisance parameter \( \hat{\eta} \) in a first step.\(^{26}\)

\(^{25}\)For instance, statements like “under certain assumptions, \( P(A_n \lesssim B_n) \geq c_0 \)” should be read as “under certain assumptions, there exists a constant \( C > 0 \) such that for all \( n \), \( P(A_n \leq C B_n) \geq c_0 \).”

\(^{26}\)Our theory hews closely to—and extends—the results in Jiang (2020) and Soloff et al. (2021), which themselves are extensions of earlier results in the homoskedastic setting (Jiang and Zhang, 2009; Saha
Moreover, we show that controlling the Bayes regret is no easier than estimating $m$ in $\| \cdot \|_2$, which is a corresponding lower bound on regret. There exists $c$ such that for any estimator of $\theta$, its worst-case regret is bounded below:

$$\sup_{P_0 \in \mathcal{P}_0} \text{BayesRegret}_n \geq c \inf_m \sup_{m_0} \mathbb{E} \| \hat{m} - m_0 \|_2^2.$$  

Since the minimax estimation rates of $\| \hat{\eta} - \eta_0 \|_\infty$ and of $\| \hat{\eta} - \eta_0 \|_2$ are the same up to logarithmic factors, we conclude that our regret upper bound is rate-optimal up to logarithmic factors. We now introduce the assumptions on $P_0 \in \mathcal{P}_0$ needed for these results, state the upper and lower bounds, and provide a technical discussion.

3.1.1. Assumptions for regret upper bound. We first assume that $\hat{G}_n$ is an approximate maximizer of the log-likelihood on the transformed data $\hat{Z}_i$ and $\hat{\nu}_i$ satisfying some support restrictions. This is not a restrictive assumption, as the actual maximizers of the log-likelihood function satisfy it.

**Assumption 1.** Let $\psi_i(Z_i, \hat{\eta}, G) \equiv \log \left( \int_{-\infty}^{\infty} \varphi \left( \frac{\hat{Z}_i - \tau}{\hat{\nu}_i} \right) G(d\tau) \right)$ be the objective function in (2.11), ignoring a constant factor $1/\hat{\nu}_i$. We assume that $\hat{G}_n$ satisfies

$$\frac{1}{n} \sum_{i=1}^{n} \psi_i(Z_i, \hat{\eta}, \hat{G}_n) \geq \sup_{H \in \mathcal{P}(\mathbb{R})} \frac{1}{n} \sum_{i=1}^{n} \psi_i(Z_i, \hat{\eta}, H) - \kappa_n$$  

for tolerance $\kappa_n$

$$\kappa_n = \frac{2}{n} \log \left( \frac{n}{\sqrt{2\pi e}} \right).$$

Moreover, we require that $\hat{G}_n$ has support points within $[\min_i \hat{Z}_i, \max_i \hat{Z}_i]$. To ensure that $\kappa_n$ is positive, we assume that $n \geq 7 = [\sqrt{2\pi e}]$.

We now state further assumptions on the data-generating processes $P_0$ beyond (2.6). First, we assume that $G_0$ is exponential-tailed with parameter $\alpha$ that controls the thickness of its tails. We state the restriction in an equivalent form of simultaneous moment control.

These results, under either homoskedasticity or prior independence, show that empirical Bayes derived from estimating the prior via npmle achieves fast regret rates. In particular, Soloff et al. (2021) show that the regret rate is of the form $C(\log n)^{\beta} 1/n$ under prior independence and assumptions similar to ours.

27Our proof only exploits a lower bound for the performance of $\hat{m}$; doing so is without loss if $m_0$ and $s_0$ belong to the same smoothness class.

28In particular, the support restriction for $\hat{G}_n$ in Assumption 1 is satisfied by all maximizers of the likelihood function (see Corollary 3 in Soloff et al., 2021).

29The constants $\kappa_n$ also feature in Jiang (2020) to ensure that the fitted likelihood is bounded away from zero. The particular constants in $\kappa_n$ are chosen to simplify expressions and are not material to the result.

30An equivalent statement to Assumption 2 is that there exists $a_1, a_2 > 0$ such that $P_{G_0}(|\tau| > t) \leq a_1 \exp(-a_2 t^\alpha)$ for all $t > 0$. Note that when $\alpha = 2$, $G_0$ is subgaussian, and when $\alpha = 1$, $G_0$ is subexponential (see the definitions in Vershynin, 2018), as commonly assumed in high-dimensional statistics. Assumption 2 is slightly stronger than requiring that all moments exist for $G_0$, and weaker than requiring...
**Assumption 2.** The distribution $G_0$ is has zero mean, unit variance, and admits simultaneous moment control with parameter $\alpha \in (0, 2)$: There exists a constant $A_0 > 0$ such that for all $p > 0$,

$$
(\mathbb{E}_{\tau \sim G_0}[|\tau|^p])^{1/p} \leq A_0 p^{1/\alpha}.
$$

Next, Assumption 3 imposes that members of $\mathcal{P}_0$ have various variance parameters uniformly bounded away from zero and infinity. This is a standard assumption in the literature, maintained likewise by Jiang (2020) and Soloff et al. (2021).

**Assumption 3.** The variances $(\sigma_{1:n}, s_0)$ admit lower and upper bounds:

$$
\sigma_\ell < \sigma_i < \sigma_u \text{ and } s_\ell < s_0(\cdot) < s_u,
$$

where $0 < \sigma_\ell, \sigma_u, s_\ell, s_{0u} < \infty$. This implies that $0 < \nu_\ell \leq \nu_i = \frac{\sigma_i}{s_0(\sigma_i)} \leq \nu_u < \infty$ for some $\nu_\ell, \nu_u$.

Lastly, we require that $m_0, s_0$ satisfies some smoothness restrictions. We also require that $\hat{m}, \hat{s}$ satisfy some corresponding regularity conditions.

**Assumption 4.** Let $C_{A_1}^p([\sigma_\ell, \sigma_u])$ be the Hölder class of order $p \geq 1$ with maximal Hölder norm $A_1 > 0$ supported on $[\sigma_\ell, \sigma_u]$.

1. The true conditional moments are Hölder-smooth: $m_0, s_0 \in C_{A_1}^p([\sigma_\ell, \sigma_u])$.

Additionally, let $\beta_0 > 0$ be a constant. Let $\mathcal{V}$ be a set of bounded functions supported on $[\sigma_\ell, \sigma_u]$ that (i) admits the uniform bound $\sup_{f \in \mathcal{V}} \|f\|_\infty \leq C_{A_1}$ and (ii) admits the metric entropy bound

$$
\log N(\epsilon, \mathcal{V}, \|\cdot\|_\infty) \leq C_{A_1,p,\sigma_\ell,\sigma_u}(1/\epsilon)^{1/p}.
$$

We assume that the estimators for $m_0$ and $s_0$, $\hat{m} = (\hat{m}, \hat{s})$, satisfy the following assumptions.

2. For any $\epsilon > 0$, there exists a sufficiently large $C = C(\epsilon)$, independently of $n$, such that for all $n$,

$$
P\left(\max (\|\hat{m} - m_0\|_\infty, \|\hat{s} - s_0\|_\infty) > C(\epsilon)n^{-\frac{p}{p+\alpha}}(\log n)^{\beta_0}\right) < \epsilon.
$$

$G_0$ to have a moment-generating function. Similar tail assumptions feature in the theoretical literature on empirical Bayes (Soloff et al., 2021; Jiang and Zhang, 2009; Jiang, 2020).

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31We recall the definition of a Hölder class from van der Vaart and Wellner (1996), Section 2.7.1. We specialize its definition to functions of one real variable. For an integer $p$, Hölder-$p$ functions are $(p - 1)$-times differentiable, with a Lipschitz continuous $(p - 1)^{st}$ derivative.

**Definition 1.** For some set $\mathcal{X} \subset \mathbb{R}$ and constant $A > 0$, $p > 0$, let $C_{A}^p(\mathcal{X})$ be the set of continuous functions $f : \mathcal{X} \to \mathbb{R}$ with $\|f\|_p \leq A$. The norm $\|\cdot\|_p$ is defined as follows. Let $p$ be the greatest integer strictly smaller than $p$. Define

$$
\|f\|_p = \max_{k \leq p} \sup_{x \in \mathcal{X}} |f^{(k)}(x)| + \sup_{x, y \in \mathcal{X}} \frac{|f^{(k)}(x) - f^{(k)}(y)|}{|x - y|^{p-k}}.
$$

We refer to $C_{A}^p(\mathcal{X})$ as a Hölder class of order $p$ and $\|f\|_p$ as the Hölder norm.
(3) The nuisance estimators take values in \( V \) almost surely: \( \mathbb{P} (\hat{m} \in V, \hat{s} \in V) = 1. \)

(4) The conditional variance estimator respects the conditional variance bounds in Assumption 3: \( \mathbb{P} \left( \frac{m_0}{2} < \hat{s} < 2s_{0u} \right) = 1. \)

Assumption 4 is a Hölder smoothness assumption on the nuisance parameters \( m_0 \) and \( s_0 \), which is a standard regularity condition in nonparametric regression; our subsequent minimax rate optimality statements are relative to this class. Moreover, it is also a high-level assumption on the quality of the estimation procedure for \((\hat{m}, \hat{s})\). Specifically, Assumption 4 expects that the nuisance parameter estimates \( \hat{m} \) and \( \hat{s} \) are rate-optimal up to logarithmic factors (Stone, 1980). Assumption 4 also expects that the nuisance parameter estimates belong to a class \( V \) with the same metric entropy behavior as the Hölder class \( C^p_{A_1}([\sigma_\ell, \sigma_u]). \)

Assumptions 2 to 4 specify a class of distributions \( \mathcal{P}_0 \) and nuisance estimators \( \hat{\eta} \) indexed by a set of hyperparameters \( \mathcal{H} = (\sigma_\ell, \sigma_u, s_\ell, s_u, A_0, A_1, \alpha, \beta_0, p) \). Our subsequent theoretical results are finite sample, with implicit constants dependent on these hyperparameters \( \mathcal{H} \). To review, \((\sigma_\ell, \sigma_u, s_\ell, s_u)\) are bounds on the variances \((\sigma^2_\ell, s^2(\sigma_\ell)); (A_0, \alpha)\) control the tails of \( G_0; \) and \((A_1, p)\) control the smoothness of \( \eta_0 \); and \( \beta_0 \) is the power of the log factor in the \( \| \cdot \|_\infty \) estimation rate for \( \eta_0 \).

3.1.2. Regret results. Consider the following “good event,” indexed by \( C > 0 \),

\[
A_n(C) \equiv \left\{ \| \hat{\eta} - \eta_0 \|_\infty \leq C n^{-\frac{p}{2p+1}} (\log n)^{\beta_0} \right\}.
\] (3.5)

\( A_n(C) \) indicates that the nuisance parameter estimates satisfy some rate in \( \| \cdot \|_\infty \). Our main result derives a convergence rate for the expected MSE regret conditional on this good event \( A_n(C) \).

**Theorem 1.** Assume Assumptions 1 to 4 hold. Then, for any \( \delta \in (0, \frac{1}{2}) \), there exists universal constants \( C_{1,\mathcal{H},\delta} > 0 \) and \( C_{0,\mathcal{H},\delta} > 0 \) such that (i) \( \mathbb{P}(A_n(C_{1,\mathcal{H},\delta})) \geq 1 - \delta \) and that (ii) the expected regret conditional on \( A_n(C_{1,\mathcal{H},\delta}) \) is dominated by the rate function

\[
\mathbb{E} \left[ \text{MSERegret}_n(\hat{G}_n, \hat{\eta}) \mid A_n(C_{1,\mathcal{H},\delta}) \right] \leq C_{0,\mathcal{H},\delta} n^{-\frac{2p}{2p+1}} (\log n)^{\frac{24\alpha}{\sigma} + 3 + 2\beta_0}.
\] (3.6)

If the event \( A_n(C) \) is sufficiently likely, we can control expected regret on the bad event \( A_n^C \) as well. In Appendix G, we verify that local linear regression satisfies a weakening of these assumptions that are also sufficient for the conclusion of Corollary 1.

---

\(^{32}\)Regarding Assumption 4(2), we note that kernel smoothing estimators attain the rates required for Hölder smooth functions \( m_0, s_0 \) (see Tsybakov (2008) and Appendix G). Regarding Assumption 4(3), if the nuisance parameters are \( p \)-Hölder smooth almost surely, we can simply take \( \mathcal{V} = C^p_{A'_1}([\sigma_\ell, \sigma_u]) \) for some potentially different \( A'_1 \). This can be achieved in practice by, say, projecting estimated nuisance parameters \( \hat{\eta} \) to \( C_{A_1}([\sigma_\ell, \sigma_u]) \) in \( \| \cdot \|_\infty \). Finally, Assumption 4(4) also expects the nuisance parameter estimates to respect the boundedness constraints for \( s_0 \). This is mainly so that our results are easier to state; we discuss this assumption in Remark C.1.
Corollary 1. Assume the same setting as Theorem 1. Suppose, additionally, for all sufficiently large $C_{1,H} > 0$, $P(A_n(C_{1,H})) \geq 1 - n^{-2}$. Then, there exists a constant $C_{0,H} > 0$ such that the expected regret is dominated by the rate function

$$\text{BayesRegret}_n = \mathbb{E} \left[ \text{MSERegret}_n(\hat{G}_n, \hat{\eta}) \right] \leq C_{0,H} n^{-\frac{2p}{2p+1}} (\log n)^{\frac{2\alpha_0}{n} + 3 + 2\beta_0}.$$

We can show a corresponding lower bound on the Bayes regret—i.e., a lower bound on the worst-case Bayes regret when an adversary picks $G_0, \eta_0$—by showing that any good posterior mean estimate $\hat{\theta}_i$ implies a good estimate $\hat{m}(\sigma_i)$ for $m_0$. Minimax lower bounds for estimation of $m_0$ then imply lower bounds for estimation of the oracle posterior means $\theta_i^*$.\footnote{A similar argument is considered in Ignatiadis and Wager (2019) for a related but distinct setting. See, also, Appendix A.6.2.}

Theorem 2. Fix a set of valid hyperparameters $\mathcal{H} = (\sigma_0, \sigma_u, s_0, s_u, A_0, A_1, \alpha, \beta_0, p)$ for Assumptions 2 to 4. Let $P(\mathcal{H}, \sigma_{1:n})$ be the set of distributions $P_0$ on support points $\sigma_{1:n}$ which satisfy (2.6) and Assumptions 2 to 4 corresponding to $\mathcal{H}$. For a given $P_0$, let $\theta_i^* = \mathbb{E}_{P_0}[\theta_i | Y_i, \sigma_i]$ denote the oracle posterior means. Then there exists a constant $c_H > 0$ such that the worst-case Bayes regret of any estimator exceeds $c_H n^{-\frac{2p}{2p+1}}$:

$$\inf_{\theta_{1:n}} \sup_{\sigma_{1:n} \in (\sigma_0, \sigma_u)} \mathbb{E}_{P_0} \left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta_i)^2 - (\theta_i^* - \theta_i)^2 \right] \geq c_H n^{-\frac{2p}{2p+1}},$$

where the infimum is taken over all (possibly randomized) estimators of $\theta_{1:n}$.

As a result, the rate (3.6) is optimal up to logarithmic factors. The additional logarithmic factors are partly the price of having to estimate $G_0$ via npmle and partly deficiencies in the proof of Theorem 1. In any case, this cost is not substantial.

The regret upper bounds Theorem 1 and Corollary 1 are finite-sample statements. As a result, they hold uniformly over all distributions $P_0$ delineated by the problem parameters $\mathcal{H}$. However, the usefulness of Theorem 1 and Corollary 1 still lies in the convergence rate, as the constants implied by the proofs are not sharp.

These regret upper bounds readily extend to the case where covariates are present and the location-scale assumption is with respect to the additional covariates $X_i$:

$$\theta_i \mid \sigma_i, X_i \sim G_0 \left( \frac{\theta_i - m_0(X_i, \sigma_i)}{s_0(X_i, \sigma_i)} \right),$$

under assumption on $m_0, s_0, \hat{m}, \hat{s}$ analogous to Assumption 4. Of course, the resulting convergence rate would suffer from the curse of dimensionality, and the term $n^{-\frac{2p}{2p+1}}$ would be replaced with $n^{-\frac{2p}{2p+1+d}}$, where $d$ is the dimension of $X$.

Taken together, Corollary 1 and Theorem 2 are strong statistical optimality guarantees for close-npmle in the canonical problem of estimation with squared error loss. That is,
the worst-case performance gap of CLOSE-NPMLE relative to the oracle contracts at the best possible rate, meaning that CLOSE-NPMLE mimics the oracle as well as possible.

For interested readers, we provide an overview of the proof of our main result Theorem 1 in the following remark. A more detailed walkthrough is in Appendix C.3.

**Remark 4** (Informal discussion of the proof for Theorem 1). Regret results assuming prior independence are established by Soloff et al. (2021) and Jiang (2020), and we build on these results for Theorem 1. Applied to \((Z_i, \nu_i, \tau_i)\), these results state that (i) approximate maximizers \(\tilde{G}_n\) of the (infeasible) log-likelihood \(\Psi_n(\eta_0, G) \equiv \frac{1}{n} \sum_i \psi_i(Z_i, \eta_0, G)\) are close to \(G_0\) in terms of the average Hellinger distance of the induced densities of \(Z_i\)

\[
\bar{h}^2(f_{\tilde{G}_n}, f_{G_0}) \equiv \frac{1}{n} \sum_{i=1}^n h^2 \left( \mathcal{N}(0, \nu_i^2) \ast \tilde{G}_n, \mathcal{N}(0, \nu_i^2) \ast G_0 \right), \quad h^2(f, g) \equiv 1 - \int_{-\infty}^{\infty} \sqrt{f(x)g(x)} \, dx
\]

and (ii) if \(\bar{h}^2(f_{\tilde{G}_n}, f_{G_0})\) is small, then posterior means for \(\tau_i\) under \(\tilde{G}_n\) are close to posterior means under \(G_0\) in squared error.

Our results extend this argument by accommodating the fact that \(\eta_0\) is unknown and must be estimated with \(\hat{\eta}\).\(^{34}\) To apply (ii) in the literature, we would like to show that (i') \(\hat{G}_n\)—an approximate maximizer of the feasible log-likelihood \(\Psi_n(\hat{\eta}, G) = \frac{1}{n} \sum_i \psi_i(Z_i, \hat{\eta}, G)\)—is close to \(G_0\) in terms of \(\bar{h}^2(\cdot, \cdot)\). This is not a straightforward task and is the most intricate part of our argument. To show (i'), we prove a lower bound for the likelihood \(\Psi_n(\eta_0, \hat{G}_n)\) (Theorem D.1) and adapt the argument for (i) to accommodate our likelihood lower bound (Theorem E.1).

To lower bound \(\Psi_n(\eta_0, \hat{G}_n)\), we relate the two likelihoods by linearization (formally, see (D.4)):

\[
\Psi_n(\hat{\eta}, \hat{G}_n) - \Psi_n(\eta_0, \hat{G}_n) \approx \frac{1}{n} \sum_{i=1}^n \frac{\partial \psi_i(Z_i, \eta_0, \hat{G}_n)}{\partial \eta} (\hat{\eta}(\sigma_i) - \eta_0(\sigma_i)) \leq \|\hat{\eta} - \eta_0\|_{\infty}.
\]

Since \(\hat{G}_n\) approximately maximizes the feasible likelihood \(\Psi_n(\hat{\eta}, \cdot)\), \(\Psi_n(\hat{\eta}, \hat{G}_n)\) is large by construction. Thus, if we can show that the right-hand side is small, then the infeasible likelihood \(\Psi_n(\eta_0, \hat{G}_n)\) would be close to \(\Psi_n(\hat{\eta}, \hat{G}_n)\) and hence would also be large. To obtain the rate (3.6), it is important to show that the right-hand side vanishes strictly faster than \(\|\hat{\eta} - \eta_0\|_{\infty}\). To do so, we additionally need to show that the derivatives \(\frac{1}{n} \sum_i \partial \psi_i(Z_i, \eta_0, \hat{G}_n) / \partial \eta\) are small. Without it, we would obtain a worse squared error regret rate of the form \(n^{-\frac{\beta}{2\beta+1}} (\log n)^{\beta}\).

\(^{34}\)We also translate the resulting regret guarantee on estimating \(\tau_i\) to regret guarantees on estimating \(\theta_i\). In doing so, we identify an apparent gap in the arguments of Jiang (2020) and Soloff et al. (2021). We show a modified argument avoids the gap in our setting, which applies to the setting in Soloff et al. (2021) as well. See Remark F.1 for details.
In particular, we manage to relate the average derivative to the average Hellinger distance (see Lemmas D.1 and D.2)

\[
\frac{1}{n} \sum_{i=1}^{n} \frac{\partial \psi_i(Z_i, \eta_0, \hat{G}_n)}{\partial \eta}(\hat{\eta}(\sigma_i) - \eta_0(\sigma_i)) \leq (\log n)^\gamma \bar{h}(f_{\hat{G}_n}, \cdots, f_{G_0}) \| \hat{\eta} - \eta_0 \|_\infty, \text{ for some } \gamma > 0.
\]

Loosely, this is because the population score in \( \eta \) is mean-zero, \( \mathbb{E}[\partial \psi_i(Z, \eta_0, G_0)/\partial \eta] = 0 \). Thus if \( \hat{G}_n \) is close to \( G_0 \), then the sample score evaluated at \( \hat{G}_n \) should also be approximately zero. This is a key step in Appendix D.

This bound for \( \Psi_n(\eta_0, \hat{G}_n) \) creates an additional complication when attempting to apply the claim (i). The claim (i) upper bounds the Hellinger distance \( \bar{h}(f_{\hat{G}_n}, \cdots, f_{G_0}) \) using a lower bound for \( \Psi_n(\eta_0, \hat{G}_n) \). However, now our lower bound for the likelihood \( \Psi_n(\eta_0, \hat{G}_n) \) itself depends on \( \bar{h}(f_{\hat{G}_n}, \cdots, f_{G_0}) \), and so we cannot apply (i) directly. The proof for (i') additionally modifies the argument for (i) to accommodate our likelihood bound (Appendix E).

So far, our regret guarantees are only about estimation in squared error (Decision Problem 1). In the next subsection, we analyze regret for empirical Bayes decision rules targeted to the ranking-related problems (Decision Problems 2 and 3), and relate their performances to those for Decision Problem 1.

### 3.2. Other decision objectives and relation to squared-error loss.

Notably, the oracle Bayes decision rules \( \delta^* \) in Decision Problems 2 and 3 depend solely on the vector of oracle Bayes posterior means \( \theta^*_1, \cdots, \theta^*_m \).\(^{35}\) Therefore, for these problems, the natural empirical Bayes decision rules simply replace oracle Bayes posterior means (\( \hat{\theta}^*_i \)) with empirical Bayes ones (\( \hat{\theta}_i \)) in the oracle decision rules.\(^{36}\) For instance, if one is comfortable with the prior estimated by close-npmle, then the corresponding decision rules for Decision Problems 2 and 3 threshold based on estimated posterior means under close-npmle.

In these problems, BayesRegret\(_n\) (2.13) is equal to the expected risk gap between using the feasible decision rules \( \hat{\delta} \) and the oracle decision rules \( \delta^* \). To specialize, we let UMRegret\(_n\)

\(^{35}\)In principle, one could consider many other policy problems with a ranking flavor (Koenker and Gu, 2019; Kline et al., 2023). Among these problems, utility maximization by selection and top-\( m \) selection are special in that optimal decisions are simple functions of the posterior means. We caution that the worst-case regret rate for ranking-type problems without this property can be unfavorable—as Gu and Koenker (2023) put it, “inherently futile”—since their optimal decisions depend on functionals that are known to be difficult to estimate (i.e., they have logarithmic minimax rates of estimation, Pensky, 2017; Dedecker and Michel, 2013; Cai and Low, 2011), without stronger assumptions on the prior.

In general, the minimax squared error rate of estimating \( \mathbb{E}[f(\theta)] \) is logarithmic, unless \( f \) is an analytic function, by an extension of the argument in Cai and Low (2011). Ranking-type problems often involve \( f \) of the form \( f(\theta) = 1(\theta > c) \) or \( f(\theta) = \max(\theta, c) \), which are not smooth. This observation suggests that these ranking-type problems may also suffer from logarithmic regret rates—though, this observation alone does not rigorously prove this, as difficulties in estimating \( \mathbb{E}[f(\theta)] \) in squared error might not preclude a polynomial regret rate for these ranking-type problems.

\(^{36}\)Theorem 3 applies to any estimators of the oracle Bayes posterior means—not necessarily derived through an empirical Bayes procedure—and does not impose the location-scale assumption. As a result, it may be of independent interest.
denote BayesRegret for Decision Problem 2 and we let TopRegret\(^{(m)}\) denote BayesRegret\(_n\) for Decision Problem 3. The following result relates UMRegret\(_n\) and TopRegret\(^{(m)}\) to MSERegret\(_n\).

**Theorem 3.** Suppose (2.3) holds, but (2.6) may or may not hold. Let \(\hat{\delta}_i\) be the plug-in decisions with any vector of estimates \(\hat{\theta}_i\), not necessarily from close-npmle. We have the following inequalities on the expected regret corresponding to the decision rules \(\hat{\delta}_i\):

1. For utility maximization by selection,
   \[
   \mathbb{E}[\text{UMRegret}_n] \leq \left( \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta^*_i)^2 \right] \right)^{1/2}.
   \] (3.7)

2. For top-\(m\) selection,
   \[
   \mathbb{E}[\text{TopRegret}^{(m)}_n] \leq 2 \sqrt{\frac{n}{m}} \left( \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta^*_i)^2 \right] \right)^{1/2}.
   \] (3.8)

Theorem 3 shows that the two decision problems utility maximization by selection and top-\(m\) selection are easier than estimating the oracle Bayesian posterior means. As a result, our convergence rates from Theorem 1 and Corollary 1 also upper bound regret rates for these two decision problems, rendering the regret rates more immediately useful for policy problems. In particular, for \(m/n \approx 1\), both regret rates (3.7) and (3.8) are of the form \(n^{-p/(2p+1)}(\log n)^c = o(1)\) under Corollary 1. Thus, the performance of the empirical Bayes decision rule approximates that of the oracle with at least the rate \(O(n^{-p/(2p+1)})\) up to log factors.

**Remark 5** (Mover interpretation of Theorem 3). Recall that we can think of top-\(m\) selection as the decision problem in Bergman et al. (2023). The utility function represents the expected mobility of a mover, assuming that the mover moves randomly into one of the high mobility Census tracts. Our proof of Theorem 3 in Appendix A.2 allows for a slightly more general decision problem. Suppose the decision now is to provide a full ranking of Census tracts for potential movers and maximize the expected mobility for a mover. Suppose that the probability that a mover moves to a tract depends decreasingly and solely on the tract’s rank. To be more concrete, suppose the mover has probability \(\pi_1\) of moving to the highest-ranked tract, \(\pi_2\) to the second-highest, and so forth. Then, with the same argument, the corresponding regret is dominated by

\[
2\sqrt{n \sum_{i=1}^{n} \pi_i^2 \cdot \left( \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta^*_i)^2 \right] \right)^{1/2}},
\]

which generalizes (3.8).

**Remark 6** (Tightness of Theorem 3). We suspect that the actual performance of close-npmle for Decision Problems 2 and 3 may be better than predicted by Theorem 3. Take the bound for UMRegret\(_n\), for instance. As would be clear from the proof, the bound (3.7)
holds even when the $c_i$’s are adversarially chosen\textsuperscript{37} such that the empirical Bayesian makes every mistake: $\hat{\delta}_i \neq \delta_i^\star$ for every $i$. However, for a fixed vector $c$, we expect that $\hat{\delta}_i \neq \delta_i^\star$ only for a vanishing fraction of populations, and thus the actual performance of $\hat{\delta}_i$ may be better than the rate in Appendix A.2 implies.\textsuperscript{38}

Though we conjecture that the rate in Theorem 3 does not match a lower bound, Theorem 3 is competitive with recent results. Top-$m$ selection is recently studied by Coey and Hung (2022), who show that under prior independence, if $\hat{\theta}_{1:n}$ are posterior means for some estimate $\hat{G}$ of the prior $G_0(0)$, then

$$
\mathbb{E}[\text{TopRegret}^m_n] = O\left(W_1^2(G_0, \hat{G})\right)
$$

where $W_1(P, Q)$ is the Wasserstein-1 distance between $P, Q$. Theorem 3 attains a worse rate in parametric settings, when the prior $G_0(0)$ can be estimated at fast rates. However, in nonparametric settings, $G_0(0)$ is often only estimable at logarithmic rates (Dedecker and Michel, 2013), and thus the rate in Theorem 3 is much more favorable in those settings. ■

3.3. Robustness to the location-scale assumption (2.6). We prove our regret upper and lower bounds imposing the location-scale model (2.6). This is an optimistic assessment of the performance of close-npmle. While (2.6) nests prior independence, it may still be misspecified. We now consider the worst-case behavior of close-npmle without the location-scale assumption. Since without the location-scale assumption, close-npmle can no longer hope to emulate the oracle Bayes decisions, we focus on worst-case Bayes risk here, instead of on regret.

We will do so by considering an idealized version of the procedure. So long as $\theta_i \mid \sigma_i$ has two moments, $\eta_0(\cdot) = (m_0(\cdot), s_0(\cdot))$ are well-defined as conditional moments of $\theta_i \mid \sigma_i$ without imposing the location-scale assumption. We will assume that $m_0, s_0$ are known. Without the location-scale model, $G_0$ is ill-defined, but we will assume that we obtain some pseudo-true value $G_0^\star$ that has zero mean and unit variance. This is a reasonable condition to impose,

\footnote{That said, if the $c_i$’s are indeed adversarially chosen given knowledge of $(Y_{1:n}, \sigma_{1:n}, P_0)$, then Theorem 3 does match a corresponding lower bound, derived by choosing $c_i = (\hat{\theta}_i + \theta_i^\star) / 2$.}

\footnote{Upper and lower bounds are derived in related but distinct settings by Audibert and Tsybakov (2007); Bonvini et al. (2023); Liang (2000); some upper bounds, under possibly stronger assumptions, appear better than implied by Appendix A.2.}

For utility maximization by selection, suppose we impose a margin condition of the form

$$
\text{For all } i, \ P(|\theta_i^\star - c_i| \leq t) \lesssim t^\xi \quad \xi \in (0, \infty), t \in (0, c_0]
$$

where if $\theta_i^\star$ has (uniform-in-$i$) bounded density around $c_i$, then $\xi$ can be taken to be 1. Proposition 2 in Bonvini et al. (2023) then yields the sharper result that

$$
\text{UMRegret}_n \lesssim \frac{1}{n} \sum_{i=1}^n \mathbb{E}[(\hat{\theta}_i - \theta_i)^2] \leq \left( \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n (\hat{\theta}_i - \theta_i)^2 \right] \right)^{\frac{1}{2} + \frac{\xi}{2}} + \frac{\xi}{2}.
$$

Further applications of Audibert and Tsybakov (2007) and Bonvini et al. (2023) to the Gaussian sequence setting remain open.

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since every conditional prior distribution $\tau_i \mid \sigma_i$ obeys this moment constraint. Thus, for estimating $\tau_i = \frac{\theta_i - m_0(\sigma_i)}{s_0(\sigma_i)}$, whose true prior is $\tau_i \mid \sigma_i \sim G_i$, this idealized procedure uses some misspecified prior $G_0^* \neq G_i$, which does have the correct first two moments.

Using results we develop in a related note (Chen, 2023), we show that this idealized procedure has maximum risk within a constant factor of the minimax risk, uniformly over $\eta_0$. The minimax risk here is defined with respect to a game where the analyst knows $m_0, s_0$ and an adversary chooses the shape of the distribution $\tau_i \mid \sigma_i$ for every $i$.

**Theorem 4.** Under (2.3) but not (2.6), assume the conditional distribution $\theta_i \mid \sigma_i$ has mean $m_0(\sigma_i)$ and variance $s_0^2(\sigma_i)$. Denote the set of distributions of $\theta_{1:n} \mid \sigma_{1:n}$ which obey these restrictions as $\mathcal{P}(m_0, s_0)$. Let $\hat{\theta}_{i,G_0^*,\eta_0}$ denote the posterior mean estimates with some prior $P^*$ under the location-scale model $P^*(\theta_i \leq t \mid \sigma_i) = G_0^* \left( \frac{t - m_0(\sigma_i)}{s_0(\sigma_i)} \right)$, for some fixed $G_0^*$ with zero mean and unit variance. Suppose additionally that $\sigma_\ell = \min_i \sigma_i > 0$ and $s_u = \max_i s(\sigma_i) < \infty$. Then, for some $C_{\sigma_\ell,s_u} < \infty$ that solely depends on $\sigma_\ell, s_u$,

$$
\sup_{P_0 \in \mathcal{P}(m_0, s_0)} \mathbb{E}_{P_0} \left[ \frac{1}{n} \sum_{i=1}^{n}(\hat{\theta}_{i,G_0^*,\eta_0} - \theta_i)^2 \right] \leq C_{\sigma_\ell,s_u} \inf_{\hat{\theta}_{1:n} \in \mathcal{P}(m_0, s_0)} \sup_{P_0 \in \mathcal{P}(m_0, s_0)} \mathbb{E}_{P_0} \left[ \frac{1}{n} \sum_{i=1}^{n}(\hat{\theta}_i - \theta_i)^2 \right].
$$

(3.9)

where the infimum on the right-hand side is over all (possibly randomized) estimators of $\theta_i$ given $(Y_i, \sigma_i)_{i=1}^n$ and $\eta_0(\cdot)$.

Theorem 4 shows that the worst-case behavior of an idealized version of CLOSE-NPMLE must come within a factor of the minimax risk and hence is not arbitrarily unreasonable, even under misspecification. We note that (3.9) does not hold for the idealized version of INDEPENDENT-GAUSS, plugging in known unconditional moments $m_0 = \frac{1}{n} \sum_{i=1}^{n} m_0(\sigma_i)$ and $s_0^2 = \frac{1}{n} \sum_{i=1}^{n} (m_0(\sigma_i) - m_0)^2 + s_0^2(\sigma_i)$. To provide additional reassurance for CLOSE-NPMLE under misspecification, Appendix A.7.3 discusses an interpretation of CLOSE-NPMLE under misspecification of (2.6), and the validation procedure developed in Section 4.3 provides unbiased evaluation without relying on the location-scale model.

4. **Practical considerations**

4.1. **A detailed recipe.** We now describe the implementation of CLOSE-NPMLE in more detail, following our previous outline in **CLOSE–STEP 1** to **CLOSE–STEP 3**.

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39 We do not know if the maximizer $G$ of the population analogue to (2.11) respects the moment constraints. In any case, imposing these moment constraints computationally in NPMLE is feasible, as they are simply linear constraints over the optimizing variables. Projecting the estimated $\hat{G}_n$ to these moment constraints makes little difference in our empirical exercise (Appendix B.2).

40 To wit, take $s_0(\sigma_i) \approx 0$. Then, the minimax risk as a function of $(s_0(\cdot), m_0(\cdot))$ is approximately zero, but $m_0(\cdot)$ can be chosen such that the risk of INDEPENDENT-GAUSS is bounded away from zero.
The first step [CLOSE–STEP 1] estimates the conditional moments \( \eta_0 = (m_0, s_0) \) nonparametrically. Since the two conditional moments can be written as conditional expectations

\[
m_0(\sigma) = \mathbb{E}[\theta \mid \sigma] = \mathbb{E}[Y \mid \sigma]
\]

\[
s_0^2(\sigma) = \text{Var}(\theta \mid \sigma) = \mathbb{E}[(Y - m_0(\sigma))^2 \mid \sigma] - \sigma^2,
\]

we can estimate them accordingly with off-the-shelf methods (e.g., local polynomial kernel smoothing methods implemented by Calonico et al., 2019). Specifically, estimating \( m_0 \) with \( \hat{m} \) is directly a nonparametric regression of \( Y_i \) on \( \sigma_i \).

Estimating \( s_0^2(\cdot) \) can be operationalized by first nonparametrically regressing \((Y_i - \hat{m}(\sigma_i))^2\) on \( \sigma_i \), and then subtracting off \( \sigma_i^2 \). This is a plug-in estimator for \( s_0^2 \), as it replaces quantities in (4.1) with their empirical counterparts.

A wrinkle is that the plug-in estimate \( \hat{s} \) may be negative. Truncating \( \hat{s} \) at zero results in observations whose estimated prior variances \( \hat{s}^2(\sigma_i) = 0 \). These observations also have implied \( \hat{\nu}_i = \infty \). For these observations, an empirical Bayesian taking \( \hat{s}^2(\sigma_i) = 0 \) at face value has degenerate priors at \( \hat{m}(\sigma_i) \). Since observations with \( \nu_i = \infty \) do not contribute to the likelihood objective for NPMLE, excluding them from the NPMLE computation does not alter the estimated \( \hat{G}_n \). Thus, we can continue to use \((\hat{m}, \hat{s}, \hat{G}_n)\) as the estimated posterior—an observation with \( \hat{s}^2(\sigma_i) = 0 \) would have a point mass at \( \hat{m}(\sigma_i) \) as its estimated posterior. In our experience, this simple approach does not appear to affect performance. Nevertheless, in Appendix G, we propose a heuristic but data-driven truncation rule, borrowing from a statistics literature on estimating non-centrality parameters for non-central \( \chi^2 \) distributions (Kubokawa et al., 1993). Appendix G also discusses tuning parameter selection for estimating \((m_0, s_0)\) and verifies that our local linear regression estimators satisfy the regularity conditions in Section 3.

Next, in the second step [CLOSE–STEP 2], we form the transformed estimates \( \hat{Z}_i = \frac{Y_i - \hat{m}(\sigma_i)}{\hat{s}(\sigma_i)} \) and the transformed standard errors \( \hat{\nu}_i = \sigma_i / \hat{s}(\sigma_i) \). We then estimate the NPMLE on the data \((\hat{Z}_i, \hat{\nu}_i)\) by maximizing (2.11). In practice, the infinite-dimensional optimization problem (2.11) is approximated with a finite-dimensional one by discretizing distributions on a grid. To be precise, let \( \min_i \hat{Z}_i = \tau_{(1)} \leq \cdots \leq \tau_{(J)} = \max_i \hat{Z}_i \) be a pre-specified grid of points, not

\[41\]We take \( \log(\sigma_i) \) in our empirical implementation since the distribution of \( \sigma_i \) tends to be right-skewed, and thus we suspect regressing on \( \log(\sigma_i) \) has a better fit.

\[42\]Since (4.1) can be written in different forms, there are other reasonable plug-in estimators for \( s_0 \). We investigate one such alternative estimator in Appendix B.2 and find very similar performance in our empirical exercise.

\[43\]The negative estimated variance phenomenon similarly may occur with estimating the prior variance with independent-gauss and with conditional variance estimation in Armstrong et al. (2022). This is in part caused by estimation noise in \( \text{Var}(Y_i \mid \sigma_i) \). However, there is some evidence that observations with large estimated \( \sigma_i \)'s are underdispersed for the measures of economic mobility in the Opportunity Atlas (see Appendix B.1.)
necessarily equally spaced, and denote it by \( \tau \). The feasible version of (2.11) maximizes the concave program \( \pi^* \equiv \max_{\pi \in \mathbb{R}^J, \pi^*} \sum_{i=1}^{n} \log \left( \sum_{j=1}^{J} \pi_j \varphi \left( \frac{\hat{Z}_i - \tau(j)}{\nu_i} \right) \right) \). The estimated NPMLE \( \hat{G}_n \) is a discrete distribution with support points \( \tau(j) \) and corresponding masses \( \pi_j^* \).

Finally, given the estimate \( \hat{G}_n = (\tau, \pi^*) \), we can compute empirical Bayes decision rules and implement \( \text{CLOSE-STEP 3} \) by minimizing posterior expected loss. Since \( \hat{G}_n \) is a discrete distribution, the posterior for \( \tau_i \) is given by the probability mass function

\[
P_{\hat{G}_n}(\tau_i = \tau(j) \mid \hat{Z}_i = z, \hat{\nu}_i = \nu) \propto \pi_j^* \exp \left( -\frac{1}{2\nu^2} (z - \tau(j))^2 \right),
\]

normalized so that the probabilities sum to 1. This probability mass function can be plugged into (2.5) to compute the empirical Bayes decision rule for any loss function \( L \).

4.2. **When does relaxing prior independence matter?** When prior independence holds, CLOSE-NPMLE is the same as INDEPENDENT-NPMLE, up to the estimation of the constant conditional moments \((m_0(\cdot), s_0(\cdot))\). Since CLOSE-NPMLE has to estimate the conditional moments, we expect it to underperform INDEPENDENT-NPMLE, though not by much in large samples.

When prior independence does not hold, but when the conditional location-scale model (2.6) approximately holds, we expect CLOSE to outperform methods that assume prior independence. Qualitatively speaking, we expect the improvement of CLOSE-methods to be large when the conditional expectation accounts for large portions of the unconditional signal variance \( \text{Var}(\theta_i) \). Since we can decompose \( \text{Var}(\theta_i) = \mathbb{E}[s_0^2(\sigma_i)] + \text{Var}(m_0(\sigma_i)) \), we expect the improvement of CLOSE-methods to be large when the variance of the conditional expectation \( \text{Var}(m_0(\sigma_i)) \) is large compared to \( \mathbb{E}[s_0^2(\sigma_i)] \). Intuitively, this is the case when \( \sigma_i \) is highly predictive of \( \theta_i \). Whether this is the case can be easily checked by plotting \( Y_i \) against \( \sigma_i \), as in Figure 1, and inspecting the estimated conditional moments.

Finally, when the conditional distributions \( \theta_i \mid \sigma_i \) are non-Gaussian, and in particular when they are discrete, skewed, or thick-tailed, we expect CLOSE-NPMLE to additionally outperform INDEPENDENT-GAUSS due to not assuming Normality of \( \theta_i \). When the conditional priors are Gaussian, estimating it via the NPMLE pays a modest statistical price. Admittedly, it is often difficult to diagnose whether the underlying conditional distributions \( \theta_i \mid \sigma_i \) have these

---

\(^{44}\)Since the gridding is a computational approximation to the infinite dimensional optimization problem, the sole downside of a finer grid is computational burden (cf. bias-variance tradeoffs in typical tuning parameter selection problems). Ideally, adjacent grid points should have a sufficiently small and economically insignificant gap between them. Since the true prior \( G_0 \) for \( \tau_i \) have zero mean and unit variance, we find that a fine grid within \([-6, 6]\) (e.g., 400 equally spaced grid points), with a coarse grid on \([\min \hat{Z}, \max \hat{Z}] \backslash [-6, 6] \) (e.g., 100 equally spaced grid points), performs well. Also see recommendations in Koenker and Gu (2017) and Koenker and Mizera (2014).

\(^{45}\)In the leading use-case, the posterior means for \( \theta_i \) are simply \( \hat{m}(\sigma_i) + \hat{s}(\sigma_i) \mathbb{E}_{\hat{G}_n, \hat{\nu}_i}[\tau_i \mid \hat{Z}_i, \hat{\nu}_i] \). In practice, \( \text{REBayes::GLmix} \) (Koenker and Gu, 2017) in R implements estimation of the NPMLE and computation of the posterior means \( \mathbb{E}_{\hat{G}_n, \hat{\nu}_i}[\tau_i \mid \hat{Z}_i, \hat{\nu}_i] \).
properties, since we only observe \((Y_i, \sigma_i)\). Likewise, so far the discussion in this subsection is heuristic. To be more certain of the extent of improvement of CLOSE-NPMLE over other methods, it is helpful to have out-of-sample validation. The next subsection proposes a minor extension of Oliveira et al. (2021), which allows for an unbiased estimate of loss and serves as a validation procedure.

4.3. A formal validation procedure via coupled bootstrap. Consider \((Y_i, \sigma_i, \theta_i)\) where \(Y_i \mid \sigma_i, \theta_i \sim \mathcal{N}(\theta_i, \sigma_i^2)\). For some \(\omega > 0\) and an independent Gaussian noise \(W_i \sim \mathcal{N}(0, 1)\), consider adding to \(Y_i\) and subtracting from \(Y_i\) some scaled version of \(W_i\):

\[
Y_i^{(1)} = Y_i + \sqrt{\omega} \sigma_i W_i \quad Y_i^{(2)} = Y_i - \frac{1}{\sqrt{\omega}} \sigma_i W_i.
\]

Oliveira et al. (2021) call \((Y_i^{(1)}, Y_i^{(2)})\) the coupled bootstrap draws. Observe that the two draws are conditionally independent:

\[
\begin{bmatrix}
Y_i^{(1)} \\
Y_i^{(2)}
\end{bmatrix} \mid \theta_i, \sigma_i^2 \sim \mathcal{N}
\begin{bmatrix}
\theta_i \\
\theta_i
\end{bmatrix},
\begin{bmatrix}
(1 + \omega) \sigma_i^2 & 0 \\
0 & (1 + \omega^{-1}) \sigma_i^2
\end{bmatrix}.
\]

(4.2)

The conditional independence allows us to use \(Y_i^{(2)}\) as an out-of-sample validation for decision rules computed based on \(Y_i^{(1)}\). We denote their variances by \(\sigma_i^2, (1)\) and \(\sigma_i^2, (2)\).

It is helpful to think of \(Y_i^{(1)}\) as training data and \(Y_i^{(2)}\) as testing data. In fact, the coupled bootstrap precisely emulates sample-splitting on the micro-data. To see that, suppose \(Y_i = \frac{1}{n_i} \sum_{j=1}^{n_i} Y_{ij}\) is a sample mean of i.i.d. micro-data \(\{Y_{ij} : j = 1, \ldots, n_i\}\). Suppose we split the micro-data \(\{Y_{ij} : j = 1, \ldots, n_i\}\) into a training set and a testing set, with proportions \(\frac{1}{\omega+1}\) and \(\frac{\omega}{\omega+1}\), respectively. Let \(Y_i^{(1)}\) and \(Y_i^{(2)}\) be the training and testing set sample means, respectively. Then the central limit theorem implies that, approximately,

\[
Y_i^{(1)} \mid \theta_i, \sigma_i^2 \sim \mathcal{N}(\theta_i, (1 + \omega) \sigma_i^2) \quad Y_i^{(2)} \mid \theta_i, \sigma_i^2 \sim \mathcal{N}(\theta_i, (1 + \omega^{-1}) \sigma_i^2)
\]

independently. Note that the two representations (4.2) and (4.3) are equivalent, and hence coupled bootstrap emulates sample-splitting. For instance, coupled bootstrap with a value of \(\omega = 1/9\) is statistically equivalent to splitting the micro-data with a 90-10 train-test split.

Just as we can perform out-of-sample validation with sample-splitting on the micro-data, we can also do so with the coupled bootstrap emulation of sample-splitting. The following proposition formalizes this and states unbiased estimators for the loss of these decision rules, as well as their accompanying standard errors.\(^{46}\)

\(^{46}\)Oliveira et al. (2021) state the unbiased estimation result for the mean-squared error estimation problem. They develop the result further by connecting the coupled bootstrap estimator to Stein’s unbiased risk estimate. Our analogous calculation for other loss functions and for the standard errors is a minor extension of their results. Proposition 1 can also be easily generalized to other loss functions that admit unbiased estimators (Effectively, the loss is a function of a Gaussian location \(\theta_i\). For unbiased estimation of functions of Gaussian parameters, see Table A1 in Voinov and Nikulin, 2012).
Table 1. Unbiased estimators for loss of decision rules and associated conditional variance expressions (Proposition 1)

<table>
<thead>
<tr>
<th>Problem</th>
<th>Unbiased estimator of loss, $T \left(Y_{1:n}^{(2)}, \delta\right)$</th>
<th>$\text{Var} \left[T\left(Y_{1:n}^{(2)}, \delta\right) \mid \mathcal{F}\right]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision Problem 1</td>
<td>$\frac{1}{n} \sum_{i=1}^{n} \left(Y_i^{(2)} - \delta_i(Y_{1:n}^{(1)})\right)^2 - \sigma_{i,1}^2$</td>
<td>$\frac{1}{n^2} \sum_{i=1}^{n} \text{Var} \left(\left(Y_i^{(2)} - \delta_i(Y_{1:n}^{(1)})\right)^2 \mid \mathcal{F}\right)$</td>
</tr>
<tr>
<td>Decision Problem 2</td>
<td>$-\frac{1}{n} \sum_{i=1}^{n} \delta_i(Y_{1:n}^{(1)})(Y_i^{(2)} - c_i)$</td>
<td>$\frac{1}{n^2} \sum_{i=1}^{n} \delta_i(Y_{1:n}^{(1)})\sigma_{i,2}^2$</td>
</tr>
<tr>
<td>Decision Problem 3</td>
<td>$-\frac{1}{n^2} \sum_{i=1}^{n} \delta_i(Y_{1:n}^{(1)})Y_i^{(2)}$</td>
<td>$\frac{1}{n^2} \sum_{i=1}^{n} \delta_i(Y_{1:n}^{(1)})\sigma_{i,2}^2$</td>
</tr>
</tbody>
</table>

Proposition 1. Suppose $(Y_i, \sigma_i)$ obey the Gaussian heteroskedastic location model, assumed to be independent across $i$ (2.3). Fix some $\omega > 0$ and let $Y_{1:n}^{(1)}, Y_{1:n}^{(2)}$ be the coupled bootstrap draws. For some decision problem, let $\delta(Y_{1:n}^{(1)})$ be some decision rule using only data $(Y_i^{(1)}, \sigma_i^{(1)})_{i=1}^{n}$. Let $\mathcal{F} = \left(\theta_{1:n}, Y_{1:n}^{(1)}, \sigma_{1:n,(1)}, \sigma_{1:n,(2)}\right)$, for Decision Problems 1 to 3, the estimators $T(Y_{1:n}^{(2)}, \delta)$ displayed in Table 1 are unbiased for the corresponding loss:

$$
E \left[T(Y_{1:n}^{(2)}, \delta(Y_{1:n}^{(1)})) \mid \mathcal{F}\right] = L \left(\delta(Y_{1:n}^{(1)}), \theta_{1:n}\right).
$$

Moreover, their conditional variances are equal to those expressions displayed in the third column of Table 1.

Proposition 1 allows for an out-of-sample evaluation of decision rules, as well as uncertainty quantification around the estimate of loss, solely imposing the heteroskedastic Gaussian model. This is a useful property in practice for comparing different empirical Bayes methods. The alternative is to take some estimated prior—say the one learned by close-npmle—as the true prior, and evaluate performance of competing methods. Doing so likely tips the scale in favor of a particular method, and we advocate for the coupled bootstrap instead.

5. Empirical illustration

How does close-npmle perform in the field? We now consider two empirical exercises related to the Opportunity Atlas (Chetty et al., 2020) and Creating Moves to Opportunity (Bergman et al., 2023). We first summarize these papers.

5.1. The Opportunity Atlas and Creating Moves to Opportunity. Chetty et al. (2020) and Bergman et al. (2023) are motivated by a growing literature in neighborhood effects on upward mobility. There is a large body of quasiexperimental evidence that the neighborhood a child grows up in has substantial causal effects on upward mobility (Chetty and Hendren, 2018; Chetty et al., 2016; Laliberté, 2021; Chyn and Katz, 2021). Consequently, social programs that encourage low-income families to move to better neighborhoods can potentially benefit upward mobility.

Such programs hinge on two economic questions and one econometric question. First, how do we measure neighborhood mobility? Second, are low-income families currently living in
low-opportunity neighborhoods because they prefer some unobserved quality of these neighborhoods, or is it due to certain economic and informational barriers? Third, econometrically, given noisy measures of mobility, how do we identify high-mobility neighborhoods?

Motivated by the first question, Chetty et al. (2020) provide Census tract-level estimates of poor children’s outcomes in adulthood and argue that these observational measures of mobility predict neighborhoods’ causal effects. Motivated by the second question, Bergman et al. (2023) show that financial assistance and informational support do induce low-income families to move to neighborhoods that researchers recommend, indicating that these families indeed face barriers to moving to opportunity. The third question is naturally answered by empirical Bayes methods.

Specifically, using longitudinal Census micro-data, Chetty et al. (2020) estimate tract-level children’s outcomes in adulthood and publish the estimates in a collection of datasets called the Opportunity Atlas. Each dataset contains estimates and standard errors for some particular definition of the economic parameter of interest, at the Census tract level. Taking these estimates from the Opportunity Atlas, Bergman et al. (2023) conducted a program in Seattle called Creating Moves to Opportunity. They provided assistance to treated low-income individuals\(^47\) to move to “Opportunity Areas”—Census tracts with empirical Bayes posterior means in the top third.\(^48\) We view Bergman et al.’s (2023) objectives as top-\(m\) selection (Decision Problem 3), for \(m\) equal to one third of the number of tracts in King County, Washington (Seattle).

The Opportunity Atlas also includes tract-level covariates, a complication that we have so far abstracted away from. In the ensuing empirical exercises—as well as in Bergman et al. (2023)—the estimates and parameters are residualized against the covariates as a preprocessing step. We now let \(\tilde{Y}_i\) denote the raw Opportunity Atlas estimates for a pre-residualized parameter \(\vartheta_i\) and let \((Y_i, \theta_i)\) be their residualized counterparts against a vector of tract-level covariates \(X_i\), with regression coefficient \(\beta\).\(^49\) We can apply the empirical Bayes procedures in this paper to \((Y_i, \sigma_i^2)\) and obtain an estimated posterior for \(\theta_i\). This estimated posterior for the residualized parameter \(\theta_i\) then implies an estimated posterior for

\(^47\)They are families with a child below age 15 who are issued Section 8 vouchers between April 2018 and April 2019, with median household income of $19,000. About half of the sampled households are Black and about a quarter are white (Table 1, Bergman et al., 2023).

\(^48\)There are also adjustments to make the selected tracts geographically contiguous. See Bergman et al. (2023) for details.

\(^49\)Precisely speaking, let \(X_i\) be a vector of tract-level covariates. Let \(\tilde{Y}_i\) be the raw Opportunity Atlas estimates of a parameter \(\vartheta_i\), with accompanying standard errors \(\sigma_i\). Let \(\beta\) be some vector of coefficients, typically estimated by weighted least-squares of \(Y_i\) on \(X_i\). Let \(Y_i = \tilde{Y}_i - X_i'\beta\) and \(\theta_i = \vartheta_i - X_i'\beta\) be the residuals. We assume that the tract-level covariates do not predict the estimation noise in \(\tilde{Y}_i\): i.e., \(X_i \perp \tilde{Y}_i | \theta_i, \sigma_i^2\). Since \(\beta\) is precisely estimated, we ignore its estimation noise. Then, the residualized objects \((Y_i, \theta_i)\) obey the Gaussian location model \(Y_i | \theta_i, \sigma_i^2 \sim N(\theta_i, \sigma_i^2)\). See additional discussion on covariates in Appendix A.6.2. Figure B.6 contains empirical results without residualizing against covariates.
the original parameter \( \vartheta_i = \theta_i + X_i' \beta \) (Fay and Herriot, 1979). When there are no covariates, \( \vartheta_i = \theta_i \) and \( Y_i = \tilde{Y}_i \).

We consider several measures of economic mobility \( \vartheta_i \). For our purposes, these definitions of \( \vartheta_i \) take the following form: \( \vartheta_i \) is the population mean of some outcome for individuals of some demographic subgroup growing up in tract \( i \), whose parents are at the 25\textsuperscript{th} income percentile. We will consider three types of outcomes:

1. Percentile rank of adult income
2. An indicator for whether the individual has incomes in the top 20 percentiles
3. An indicator for whether the individual is incarcerated

for the following demographic subgroups:\(^{50}\) (1) all individuals (POOLED), (2) white individuals, (3) white men, (4) Black individuals, and (5) Black men. As shorthands, we refer to the three types of outcomes as MEAN RANK, TOP-20 PROBABILITY, and INCARCERATION, respectively. The outcome we use in Section 2 corresponds to TOP-20 PROBABILITY for Black individuals, while Bergman et al. (2023) consider MEAN RANK POOLED.\(^{51}\)

The remainder of this section compares several empirical Bayes approaches on two exercises. The first exercise is a calibrated simulation. In the simulation, we compare MSE performance of various methods to the that of the oracle posterior. We find that CLOSE-NPMLE has near-oracle performance in terms of MSE, and substantially outperforms INDEPENDENT-GAUSS. The second exercise is an empirical application to a scale-up of the exercise in Bergman et al. (2023). It uses the coupled bootstrap to evaluate whether CLOSE-NPMLE selects more economically mobile tracts than INDEPENDENT-GAUSS. We find that it does, and the magnitude of improvement is substantial compared to two benchmarks, which we refer to as the value of basic empirical Bayes methods and the value of data.

5.2. **Calibrated simulation.** Our first empirical exercise is a calibrated simulation. To devise a data-generating process that does not impose the location-scale assumption, we partition \( \sigma \) into vingtiles, fit a location-scale model within each vingtile, and draw from the estimated model (see Appendix B.3 for details). Since the location-scale model is only imposed within each vingtile, this data-generating process does not impose (2.6) on the entire dataset. Figure 3 shows an overlay of real and simulated data for one of the variables we consider. Visually, at least, the simulated data resemble the real estimates.

\(^{50}\)We focus on men as a subgroup since incarceration rates for women are extremely low.

\(^{51}\)In each Opportunity Atlas dataset, the estimates \( \tilde{Y}_i, \sigma_i \) are computed from the fitted value of a semiparametric regression procedure on the Census micro-data. The regression procedure implicitly pools observation with similar parent income ranks and is not fully nonparametric. As a result of this extrapolation, the estimates \( Y_i \) need not respect support conditions for Bernoulli means. For instance, some estimates for TOP-20 PROBABILITY and for INCARCERATION are negative. Similarly, the standard errors for estimates for binarized \( \vartheta_i \) are typically not precisely of the form \( \sqrt{\vartheta_i(1 - \vartheta_i)/n_i} \). We refer interested readers to Chetty et al. (2020) for details of their regression specification.
Figure 3. A draw of real vs. simulated data for estimates of top-20 probability for Black individuals

On the simulated data, we then put various empirical Bayes strategies to test. We consider the feasible procedures naive, independent-gauss, independent-npmle, close-gauss, and close-npmle, where naive sets $\hat{\theta}_i = Y_i$. Because we have the ground truth data-generating process, we additionally have two infeasible benchmarks:

- **ORACLE**: A Bayesian who has access to the distribution of $(\theta_i, \sigma_i)$ and uses the true posterior means for $\theta_i$.

- **ORACLE-GAUSS**: A Bayesian who knows $(m_0, s_0)$ and uses (2.12).

For this exercise, we focus on estimating the parameters $\vartheta_i$ in MSE (Decision Problem 1).

Figure 4 plots the main results from this calibrated simulation. For each method and each target variable, we display a relative measure of gain in terms of mean-squared error. For each method, we calculate its squared error gain over naive, as a percentage of the squared error gain of oracle over naive. If we think of the ORACLE–NAIVE difference as the total size of the “statistical pie,” then Figure 4 shows how much of this pie each method captures.

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We note that none of the feasible procedures (naive, independent-gauss, independent-npmle, close-gauss, and close-npmle) have access to the true projection coefficient $\beta$ of $\tilde{Y}_i$ onto $X_i$, which they must estimate by residualizing against covariates on the data. Additionally, we weight the estimation of $m_0$ and $s_0$ in independent-gauss by the precision $1/\sigma_i^2$, following Bergman et al. (2023).

These posterior means are computed by approximating the true prior with the empirical distribution of a large sample drawn from the true prior.
| Notes. Each column is an empirical Bayes strategy that we consider, and each row is a different definition of \( \theta_i \). The table shows relative performance, defined as the squared error improvement over NAIVE, normalized as a percentage of the improvement of ORACLE over NAIVE. That is, if we think of going to ORACLE from NAIVE as the total extent of risk gains via empirical Bayes methods, this relative performance denotes how much of those gains each method captures. The last row shows the column median. Since we rely on Monte Carlo approximations of ORACLE, the resulting Monte Carlo error causes CLOSE-NPMLE to outperform ORACLE in the top right. Results are averaged over 1,000 Monte Carlo draws.

For absolute, un-normalized performance of INDEPENDENT-GAUSS, INDEPENDENT-NPMLE, CLOSE-NPMLE, and ORACLE, see Figure B.10.

Figure 4. Table of relative squared error Bayes risk for various empirical Bayes approaches

A value of 70 in Figure 4, for instance, indicates that a particular method captures 70% of the possible extent of risk gains for a particular parameter definition.

The first four columns show the relative mean-squared error performance \textit{without} residualizing against covariates, applying empirical Bayes methods directly on \((\tilde{Y}_i, \sigma_i)\). We see that methods which assume prior independence—INDEPENDENT-GAUSS and INDEPENDENT-NPMLE—perform worse than methods based on CLOSE.\(^{54}\) Across the 15 variables, the median

\(^{54}\)It may be surprising that INDEPENDENT-GAUSS can perform worse than NAIVE on MSE, since Gaussian empirical Bayes typically has a connection to the James–Stein estimator, which dominates the MLE. We note that, as in Bergman et al. (2023), when we estimate the prior mean and prior variance, we weight the data with precision weights proportional to \(1/\sigma_i^2\). When the independence between \(\theta\) and \(\sigma\) holds, these
proportion of possible gains captured by INDEPENDENT-GAUSS is only 30%. This value is 51% for INDEPENDENT-NPMLE, and 87% for CLOSE-NPMLE. Individually for each variable, among the first four columns, CLOSE-NPMLE uniformly dominates all three other methods. This is because the standard error $\sigma_i$ contains much of the predictive power of the covariates, and using that information can be very helpful when the researcher does not have rich covariate information.

The next five columns show performance when the methods do have access to covariate information. Compared to their no-covariates counterparts, the methods that assume prior independence do substantially better, since the covariates absorb some dependence between $\vartheta_i$ and $\sigma_i$. For MEAN RANK, after covariate residualization, there appears to be little dependence between $\theta_i$ and $\sigma_i$. INDEPENDENT-NPMLE and CLOSE-NPMLE perform similarly, capturing almost all of the available gains. Both methods slightly outperform the Gaussian methods for MEAN RANK.\footnote{Appendix B.4 contains an alternative data-generating process in which the true prior is Weibull, which has thicker tails and higher skewness. Under such a scenario, NPMLE-based methods substantially outperform methods assuming Gaussian priors.}

For the other two outcome variables, TOP-20 PROBABILITY and INCARCERATION, the dependence between $\theta_i$ and $\sigma_i$ is stronger, and CLOSE-based methods display substantial improvements over INDEPENDENT-GAUSS and INDEPENDENT-NPMLE. CLOSE-NPMLE achieves near-oracle performance across the different definitions of $\theta_i$ (capturing a median of 95% of the ORACLE-NAIVE gap), and uniformly dominates all other feasible methods.

So far, we have tested the methods in a synthetic environment set up to imitate the real data. Next, we turn to an empirical application that uses the coupled bootstrap (Section 4.3) estimator of performance.

5.3. Validation exercise via coupled bootstrap. Our second empirical exercise uses the coupled bootstrap described in Section 4.3 for the ranking policy problem in Bergman et al. (2023). Throughout, we choose $\omega$ to emulate a 90-10 train-test split on the micro-data.

Bergman et al. (2023) use empirical Bayes methods to select the top third Census tracts in Seattle, based on economic mobility—which we view as a TOP-$m$ SELECTION problem (Decision Problem 3). Can CLOSE-NPMLE make better selections—can it select tracts with higher $\vartheta_i$ on average? Specifically, we imagine scaling up Bergman et al. (2023)’s exercise and perform INDEPENDENT-GAUSS and CLOSE-NPMLE for all Census tracts in the largest twenty Commuting Zones. We then select the top third of tracts within each Commuting Zone, according to empirical Bayesian posterior means for $\vartheta_i$. Additionally, to faithfully mimic precision weights typically improve efficiency. However, the weighting does break the connection between Gaussian empirical Bayes and James–Stein, and the resulting posterior mean does not always dominate the MLE (i.e., naive). To take an extreme example, if a particular observation has $\sigma_i \approx 0$, then that observation is highly influential for the prior mean estimate. If $\mathbb{E}[\theta_i \mid \sigma_i]$ is very different for that observation than the other observations, then the estimated prior mean is a bad target to shrink towards. \footnote{Appendix B.4 contains an alternative data-generating process in which the true prior is Weibull, which has thicker tails and higher skewness. Under such a scenario, NPMLE-based methods substantially outperform methods assuming Gaussian priors.}
Bergman et al. (2023), here we perform all empirical Bayes procedures within Commuting Zone. That is, for each of the twenty Commuting Zones that we consider, we execute all empirical Bayes methods—including the residualization by covariates—with only $\tilde{Y}_i, \sigma_i$ of tracts within the Commuting Zone.\footnote{Appendix B.6 contains results where we perform empirical Bayes pooling over all Commuting Zones and select the top third within each Commuting Zone. We obtain very similar results. Appendix B.6 also contains results without residualizing against covariates, and INDEPENDENT-GAUSS performs very poorly in that setting. Appendix B.5 contains results on estimating $\vartheta_i$ in MSE (Decision Problem 1) in this context.}

Figure 5(a) shows the estimated performance gap between a given empirical Bayes method and NAIVE as the $x$-position of the dots. The estimated performance of each method,\footnote{By virtue of Proposition 1, these estimated performances are unbiased for the true (negative) Bayes risk. Despite being averaged over 1,000 coupled bootstrap draws, these estimates are not free of sampling error, since, for one, the stochastic components in $Y_i$ are not redrawn.} defined as the average $\vartheta_i$ among those selected (2.14), is shown in the annotated figures. According to these estimates, CLOSE-NPMLE generally improves over INDEPENDENT-GAUSS.\footnote{For MEAN RANK POOLED, CLOSE-NPMLE is worse by 0.012 percentile ranks, and CLOSE-NPMLE is worse by 0.058 percentile ranks for MEAN RANK for white males. In either case, the estimated disimprovement is small.}

For the MEAN RANK variables, using CLOSE-NPMLE generates substantial gains for mobility measures for Black individuals (0.8 percentile ranks for Black men and 0.5 percentile ranks for Black individuals). To put these gains in dollar terms, the Housing Choice Voucher holders in Bergman et al. (2023) have incomes around $19,000, and for these individuals, an incremental percentile rank amounts to about $1,000. Thus, the estimated gain in terms of mean income rank is roughly $500–800. For the other two outcomes, TOP-20 PROBABILITY and INCARCERATION,\footnote{For incarceration, we consider a policy objective of encouraging people to move out of high-incarceration areas.} the gains are even more sizable, especially for Black individuals. These gains are as high as 2–3 percentage points on average in terms of these two variables.

Bergman et al. (2023) select tracts based on MEAN RANK POOLED. For this measure, there is little additional gain from using CLOSE-NPMLE, at least when residualized against sufficiently rich covariates. Nevertheless, since about half of the trial participants are Black in Bergman et al.’s (2023) setting, one might consider providing more personalized recommendations by targeting measures of economic mobility for finer demographic subgroups. If we select tracts based on these demographic-specific measures of economic mobility, CLOSE-NPMLE then provides economically significant improvements.\footnote{Appendix B.7 shows that screening with mobility measures for Black individuals outperforms screening mobility for Black individuals with the POOLED estimate.}

We can think of the performance gap between INDEPENDENT-GAUSS and NAIVE as the value of basic empirical Bayes. If practitioners find using the standard empirical Bayes method to be a worthwhile investment over screening on the raw estimates directly, perhaps they reveal that the value of basic empirical Bayes is economically significant. Across the
Notes. These figures show the estimated performance of various decision rules over 1,000 draws of coupled bootstrap. Empirical Bayes methods, including residualization with respect to the covariates, are applied within each Commuting Zone. Performance is measured as the mean $\vartheta_i$ among selected Census tracts. All decision rules select the top third of Census tracts within each Commuting Zone. Figure (a) plots the estimated performance gap relative to NAIVE, where we annotate with the estimated performance for close-npmle and independent-gauss. Figure (b) plots the estimated performance gap relative to picking uniformly at random; we continue to annotate with the estimated performance. The shaded regions in Figure (b) have lengths equal to the unconditional standard deviation of the underlying parameter $\vartheta$.

Figure 5. Performance of decision rules in top-$m$ selection exercise

15 measures, the improvement of close-npmle over independent-gauss is on median 320% of the value of basic empirical Bayes, where the median is attained by mean rank for Black individuals. Thus, the additional gain of close-npmle over independent-gauss is substantial compared to the value of basic empirical Bayes. If the latter is economically significant, then it is similarly worthwhile to use close-npmle instead.
For 3 of the 15 measures, including our running example, INDEPENDENT-GAUSS in fact underperforms NAIVE, rendering the estimated value of basic empirical Bayes negative. As a result, we consider a different normalization in Figure 5(b). Figure 5(b) plots the difference between a given method’s performance and the estimated mean $\vartheta_i$ for a given measure. Analogous to the value of basic empirical Bayes, we think of the difference between INDEPENDENT-GAUSS’s performance and the estimated mean $\vartheta_i$ as the value of data, since choosing the tracts randomly in the absence of data has expected performance equal to mean $\vartheta_i$. If the mobility estimates are at all useful for decision-making, the value of data must be economically significant.

Across the 15 measures considered, the gain of CLOSE-NPMLE is on median 25% of the value of data. For six of the 15 measures, the gain of CLOSE-NPMLE exceeds the value of data. For MEAN RANK for Black individuals, the incremental value of CLOSE-NPMLE over INDEPENDENT-GAUSS is about 15% of the value of data, which is already sizable. These relative gains are more substantial for the binarized outcome variables TOP-20 PROBABILITY and INCARCERATION. For our running example (TOP-20 PROBABILITY for Black individuals), this incremental gain of CLOSE-NPMLE is 210% the value of data. That is, relative to choosing randomly, CLOSE-NPMLE delivers gains 3.1 times that of INDEPENDENT-GAUSS.

6. Conclusion

This paper studies empirical Bayes methods in the heteroskedastic Gaussian location model. We argue that prior independence—the assumption that the precision of estimates does not predict the true parameter—is theoretically questionable and often empirically rejected. Empirical Bayes shrinkage methods that rely on prior independence can generate worse posterior mean estimates, and screening decisions based on these estimates can suffer as a result. They may even be worse than the selection decisions made with the unshrunk estimates directly.

Instead of treating $\theta_i$ as independent from $\sigma_i$, we model its conditional distribution as a location-scale family. This assumption leads naturally to a family of empirical Bayes strategies that we call CLOSE. We prove that CLOSE-NPMLE attains minimax-optimal rates in Bayes regret, extending previous theoretical results. That is, it approximates infeasible oracle Bayes posterior means as competently as statistically possible. Our main theoretical results are in terms of squared error, which we further connect to ranking-type decision problems in Bergman et al. (2023). Additionally, we show that an idealized version of CLOSE-NPMLE is robust, with finite worst-case Bayes risk. Lastly, we introduce a simple validation procedure based on coupled bootstrap (Oliveira et al., 2021) and highlight its utility for practitioners choosing among empirical Bayes shrinkage methods.
Simulation and validation exercises demonstrate that CLOSE-NPMLE generates sizable gains relative to the standard parametric empirical Bayes shrinkage method. Across calibrated simulations, CLOSE-NPMLE attains close-to-oracle mean-squared error performance. In a hypothetical, scaled-up version of Bergman et al. (2023), across a wide range of economic mobility measures, CLOSE-NPMLE consistently selects more mobile tracts than does the standard empirical Bayes method. The gains in the average economic mobility among selected tracts, relative to the standard empirical Bayes procedure, are often comparable to—or even multiples of—the value of basic empirical Bayes. These gains are even comparable to the benefit of using standard empirical Bayes procedures over ignoring the data.

We close by highlighting some future directions. In Section 5, we use kernel smoothing methods to estimate the unknown conditional moments $\eta_0 = (m_0, s_0)$. These methods presume a given level of smoothness and do not adapt to the true smoothness of $\eta_0$. We can imagine replacing the conditional moment estimation with adaptive methods (e.g., van der Vaart and van Zanten, 2009). With cross-fitting, the regret result should similarly adapt to the $\|\cdot\|_\infty$ rate of the estimators. Additionally, for the purpose of frequentist inference, the procedure of Armstrong et al. (2022) apply in our setting as well and provide confidence sets for the vector of parameters $\theta_{1:n}$ with average coverage guarantees. For frequentist inference on the oracle posterior mean $\mathbb{E}_{\phi_0}[\theta_i \mid Y_i, \sigma_i]$, we conjecture that a version of Ignatiadis and Wager’s (2022) procedure—which so far only applies in the homoskedastic Gaussian case—is valid under the location-scale model (2.6).
References


Alesina, Alberto F, Edward L Glaeser, and Bruce Sacerdote, “Why doesn’t the US have a European-style welfare system?,” 2001. 11


Andrews, Isaiah and Maximilian Kasy, “Inference on Winners,” 2023. 6


Arellano, Manuel and Stéphane Bonhomme, “Robust priors in nonlinear panel data models,” Econometrica, 2009, 77 (2), 489–536. 2

Armstrong, Timothy B, Michal Kolesár, and Mikkel Plagborg-Møller, “Robust empirical bayes confidence intervals,” Econometrica, 2022, 90 (6), 2567–2602. 27, 39


Chamberlain, Gary, “Panel data,” Handbook of econometrics, 1984, 2, 1247–1318. 2

Chandra, Amitabh, Amy Finkelstein, AdamSacarny, and Chad Syverson, “Health care exceptionalism? 40
DellaVigna, Stefano and Elizabeth Linos, “RCTs to scale: Comprehensive evidence from two nudge units,” *Econometrica*, 2022, 90 (1), 81–116. 2


____ and ______, “Invidious comparisons: Ranking and selection as compound decisions,” Econometrica, 2023, 91 (1), 1–41. 15, 23


Hull, Peter, “Estimating hospital quality with quasi-experimental data,” Available at SSRN 3118358, 2018, 2


____ and ______, “Confidence intervals for nonparametric empirical Bayes analysis,” Journal of the American Statistical Association, 2022, 117 (539), 1149–1166. 39


Kain, John F, “Housing segregation, negro employment, and metropolitan decentralization,” The quarterly journal of economics, 1968, 82 (2), 175–197. 11


____ and ______, “Comment: Minimalist g-modeling,” 2019, 7, 13, 23


Lindsay, Bruce G, “Mixture models: theory, geometry, and applications,” in “in” Ims 1995. 13


Müller, Ulrich K and Mark W Watson, “Spatial Unit Roots,” *manuscript, Princeton University*, 2022. 55

Olea, José Luis Montiel, Brendan O’Flaherty, and Rajiv Sethi, “Empirical Bayes Counterfactuals in Poisson Regression with an Application to Police Use of Deadly Force,” *Available at SSRN 3837213*, 2021. 2


Pensky, Marianna, “Minimax theory of estimation of linear functionals of the deconvolution density with or without sparsity,” 2017. 23


Rambachan, Ashesh, “Identifying prediction mistakes in observational data,” 2021. 2


Stoye, Jörg, “Minimax regret treatment choice with finite samples,” *Journal of Econometrics*, 2009, 151 (1), 70–81. 15


van der Vaart, Aad W and J Harry van Zanten, “Adaptive Bayesian estimation using a Gaussian random field with inverse gamma bandwidth,” 2009. 39


Weinstein, Asaf, Zhuang Ma, Lawrence D Brown, and Cun-Hui Zhang, “Group-linear empirical Bayes...
estimates for a heteroscedastic normal mean,” *Journal of the American Statistical Association*, 2018, **113** (522), 698–710. 13


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Part 1. Proofs and discussions of results except the regret upper bound

Appendix A. Proofs and discussions of results except the regret upper bound

A.1. A simple regret rate lower bound: proof of Theorem 2. In this section, we prove Theorem 2, restated below.

**Theorem 2.** Fix a set of valid hyperparameters $\mathcal{H} = (\sigma_\ell, \sigma_u, s_\ell, s_u, A_0, A_1, \alpha, \beta_0, p)$ for Assumptions 2 to 4. Let $\mathcal{P}(\mathcal{H}, \sigma_{1:n})$ be the set of distributions $P_0$ on support points $\sigma_{1:n}$ which satisfy (2.6) and Assumptions 2 to 4 corresponding to $\mathcal{H}$. For a given $P_0$, let $\theta^*_i = \mathbb{E}_{P_0}[\theta_i \mid Y_i, \sigma_i]$ denote the oracle posterior means. Then there exists a constant $c_\mathcal{H} > 0$ such that the worst-case Bayes regret of any estimator exceeds $c_\mathcal{H} n^{-2p+p_{\text{oracle}}}$:

$$\inf_{\tilde{\theta}_{1:n}} \sup_{\sigma_{1:n} \in (\sigma_{\ell}, \sigma_u)} \mathbb{E}_{P_0} \left[ \frac{1}{n} \sum_{i=1}^{n} (\tilde{\theta}_i - \theta_i)^2 - (\theta^*_i - \theta_i)^2 \right] \geq c_\mathcal{H} n^{-2p+p_{\text{oracle}}} ,$$

where the infimum is taken over all (possibly randomized) estimators of $\theta_{1:n}$.

**Proof.** We consider a specific choice of $G_0, \sigma_{1:n}$, and $s_0$. Namely, suppose $G_0 \sim \mathcal{N}(0,1)$, $\sigma_{1:n}$ are equally spaced in $[\sigma_\ell, \sigma_u]$, and $s_0(\sigma) = (s_\ell + s_u)/2 \equiv s_0$ is constant. Note that we can represent

$$Y_i = \theta_i + \sigma_\ell W_i + (\sigma_i^2 - \sigma_\ell^2)^{1/2} U_i,$$

for independent Gaussians $W_i, U_i \sim \mathcal{N}(0,1)$. Suppose we are additionally given $V_i, \sigma_\ell$. The expanded class of estimators $\tilde{\theta}_{1:n}$ that may depend on $V_i, \sigma_\ell$ is larger than the estimators $\hat{\theta}_{1:n}$. Moreover, since $((V_i, \sigma_i)_{i=1}^{n})_{i=1}^{n}$ is sufficient for $\theta_{1:n}$, we may restrict attention to $\tilde{\theta}_{1:n}$ that depend solely on $V_{1:n}, \sigma_{1:n}, \sigma_\ell$.

Under our assumptions, the oracle posterior means $\theta^*_i$ are equal to

$$\theta^*_i = \frac{s_0^2}{s_0^2 + \sigma_i^2} Y_i + \frac{\sigma_i^2}{s_0^2 + \sigma_i^2} m_0(\sigma_i).$$

For a given vector of estimates $\tilde{\theta}_{1:n}$, we can form

$$\tilde{m}(\sigma_i) = \frac{s_0^2 + \sigma_i^2}{\sigma_i^2} \left( \tilde{\theta}_i - \frac{s_0^2}{s_0^2 + \sigma_i^2} Y_i \right).$$

Then

$$\mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} (\tilde{\theta}_i - \theta^*_i)^2 \right] = \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} \left( \frac{\sigma_i^2}{s_0^2 + \sigma_i^2} \right)^2 (\tilde{m}(\sigma_i) - m_0(\sigma_i))^2 \right] \geq \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} (\tilde{m}(\sigma_i) - m_0(\sigma_i))^2 \right].$$

We have just shown that

$$\inf_{\tilde{\theta}_{1:n}, \sigma_{1:n}, P_0} \sup \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} (\tilde{\theta}_i - \theta^*_i)^2 - (\theta^*_i - \theta_i)^2 \right] \geq \inf_{\tilde{m}} \sup \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} (\tilde{m}(\sigma_i) - m_0(\sigma_i))^2 \right]$$

where the supremum is over $m_0$ satisfying Assumption 4, and the infimum is over all randomized estimators of $m_0(\sigma_1), \ldots, m_0(\sigma_n)$ with data $(V_i, \sigma_i)$. Note that the squared error loss on the right-hand side takes expectation over the fixed design points $\sigma_1, \ldots, \sigma_n$. 

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Lastly, we connect the squared loss on the design points to the \( L_2 \) loss of estimating \( m_0(\cdot) \) with homoskedastic data \( V_i \sim \mathcal{N}(m_0(\sigma_i), \sigma_i^2 + s_i^2) \). Since we are simply confronted with a nonparametric regression problem, note that we may translate and rescale so that the design points \( \sigma_{1:n} \) are equally spaced in \([0, 1]\) and the variance of \( V_i \) is \( 1 \)—potentially changing the constant \( A_1 \) for the Hölder smoothness condition. The remaining task is to connect the average \( \ell \) loss regression problem, note that we may translate and rescale so that the design points \( \sigma_{1:n} \) are equally spaced grid points to the \( L_2 \) loss over the interval.

Observe that for any \( \hat{m}(\sigma_1), \ldots, \hat{m}(\sigma_n) \), there is a function \( \hat{m} : [0, 1] \to \mathbb{R} \) such that its average value on \([1 + (i - 1)/n, 1 + i/n]\) is \( \hat{m}(\sigma_i) \):

\[
n \int_{[1+(i-1)/n,1+i/n]} \hat{m}(\sigma) \, d\sigma = \hat{m}(\sigma_i).
\]

Now, note that

\[
\begin{align*}
\int_0^1 (\hat{m}(x) - m_0(x))^2 \, dx &= \sum_{i=1}^n \int_{[i-1/n,i/n]} (\hat{m}(x) - m_0(x))^2 \, dx \\
&\leq 2 \sum_{i=1}^n \int_{[i-1/n,i/n]} (\hat{m}(x) - m_0(\sigma_i))^2 + (m_0(\sigma_i) - m_0(x))^2 \, dx \\
&\leq 2 \sum_{i=1}^n \left[ \frac{1}{n} (\hat{m}_i - m_0(\sigma_i))^2 + \frac{L^2}{n^3} \right] \\
&= \frac{2}{n} \sum_{i=1}^n (\hat{m}_i - m_0(\sigma_i))^2 + \frac{2L^2}{n^2}.
\end{align*}
\]

The third line follows by observing (i) \( \int_0^1 (\hat{m}(x) - m_0(\sigma_i))^2 \, dx = (n \int_0^1 \hat{m}(x) \, dx - m_0(\sigma_i))^2 \frac{1}{n} \) and (ii) \( m_0(\cdot) \) is Lipschitz for some constant \( L \) since \( p \geq 1 \) in Assumption 4.

Therefore,

\[
\inf \sup \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n (\hat{m}(\sigma_i) - m_0(\sigma_i))^2 \right] \geq \frac{1}{2} \inf \sup m_o \left\{ \mathbb{E} \left[ \int_0^1 (\hat{m}(x) - m_0(x))^2 \, dx \right] - \frac{2L^2}{n^2} \right\} \geq H n^{-\frac{2p}{2p+1}},
\]

where the last inequality follows from the well-known result of \( L_2 \) minimax regression rate for Hölder classes. See, for instance, Corollary 2.3 in Tsybakov (2008).

\[\square\]

**Remark A.1.** For ease of interpretation, Theorem 2 is stated in the expected regret version, which is slightly disconnected from the upper bound Theorem 1, which conditions on a high-probability event. Observe that Theorem 1 immediately implies the in-probability upper bound on \( \text{MSERegret}_n \):

\[
\text{MSERegret}_n(G_n, \bar{y}) = \mathcal{O}_p \left( n^{-\frac{2p}{2p+1}} (\log n)^{\frac{2\alpha}{\alpha} + 3 + 2/\alpha} \right).
\]

Using the in-probability version of the minimax lower bound for nonparametric regression in Theorem 2 then implies an analogous lower bound (See, for instance, Theorems 2.4 and 2.5 in Tsybakov, 2008).

\[\blacksquare\]

**A.2. Relating other decision objects to squared-error loss.**
Theorem 3. Suppose (2.3) holds, but (2.6) may or may not hold. Let \( \hat{\delta}_i \) be the plug-in decisions with any vector of estimates \( \hat{\theta}_i \), not necessarily from close-npmle. We have the following inequalities on the expected regret corresponding to the decision rules \( \hat{\delta}_i \):

1) For utility maximization by selection,

\[
E[\text{UMRegret}_n] \leq \left( E\left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta^*_i)^2 \right] \right)^{1/2}.
\]  

(3.7)

2) For top-\( m \) selection,

\[
E[\text{TopRegret}^{(m)}_n] \leq 2 \sqrt{\frac{n}{m}} \left( E\left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta^*_i)^2 \right] \right)^{1/2}.
\]  

(3.8)

Proof. (1) We compute

\[
\text{UMRegret}_n = \frac{1}{n} \sum_{i=1}^{n} \mathbb{1}(\theta^*_i \geq c_i)(\theta_i - c_i) - \frac{1}{n} \sum_{i=1}^{n} \mathbb{1}(\hat{\theta}_i \geq c_i)(\theta_i - c_i)
\]

\[
= \frac{1}{n} \sum_{i=1}^{n} \left\{ \mathbb{1}(\theta^*_i \geq c_i) - \mathbb{1}(\hat{\theta}_i \geq c_i) \right\} (\theta_i - c_i)
\]

By law of iterated expectations, since \( \hat{\theta}_i, \theta^*_i \) are both measurable with respect to the data,\(^{61}\)

\[
E[\text{UMRegret}_n] = E\left[ \frac{1}{n} \sum_{i=1}^{n} \left\{ \mathbb{1}(\theta^*_i \geq c_i) - \mathbb{1}(\hat{\theta}_i \geq c_i) \right\} (\theta^*_i - c_i) \right]
\]

Note that, for \( \mathbb{1}(\theta^*_i \geq c_i) - \mathbb{1}(\hat{\theta}_i \geq c_i) \) to be nonzero, \( c_i \) is between \( \hat{\theta}_i \) and \( \theta^*_i \). Hence, \( |\theta^*_i - c_i| \leq |\theta^*_i - \theta_i| \) and thus

\[
E[\text{UMRegret}_n] \leq E\left[ \frac{1}{n} \sum_{i=1}^{n} |\theta^*_i - \theta_i| \right] \leq E\left[ \frac{1}{n} \sum_{i=1}^{n} (\theta^*_i - \theta_i)^2 \right]^{1/2}.
\]  

(Jensen’s inequality)

(2) Let \( J^* \) collect the indices of the top-\( m \) entries of \( \theta^*_i \) and let \( \hat{J} \) collect the indices of the top-\( m \) entries of \( \hat{\theta}_i \). Then,

\[
\frac{m}{n} \text{TopRegret}^{(m)}_n = \frac{1}{n} \sum_{i=1}^{n} \left\{ \mathbb{1}(i \in J^*) - \mathbb{1}(i \in \hat{J}) \right\} \theta_i
\]

and hence, by law of iterated expectations,

\[
\frac{m}{n} E[\text{TopRegret}^{(m)}_n] = \frac{1}{n} \sum_{i=1}^{n} E \left[ \left\{ \mathbb{1}(i \in J^*) - \mathbb{1}(i \in \hat{J}) \right\} \theta^*_i \right].
\]

\(^{61}\)For a randomized decision rule \( \hat{\theta}_i \) that is additionally measurable with respect to some \( U \) independent of \( (\theta_i, Y_i, \sigma_i)_{i=1}^{n} \), this step continues to hold since \( E[\theta_i | U, Y_i, \sigma_i] = \theta^*_i \).
Observe that this can be controlled by applying Proposition A.1, where \( w_i = 0 \) for all \( i \leq n - m \) and \( w_i = 1 \) for all \( i > n - m \). In this case, \( \|w\| = \sqrt{m} \). Hence,

\[
\frac{m}{n} E[\text{TopRegret}^{(m)}_n] \leq 2 \sqrt{\frac{m}{n}} \left[ \left( \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta_i^*)^2 \right)^{1/2} \right] \leq 2 \sqrt{\frac{m}{n}} \left( \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta_i^*)^2 \right)^{1/2}.
\]

Divide through by \( m/n \) to obtain the result.

\[\square\]

**Proposition A.1.** Suppose \( \sigma(\cdot) \) is a permutation such that \( \hat{\theta}_{\sigma(n)} \geq \cdots \geq \hat{\theta}_{\sigma(1)} \). Then

\[
\frac{1}{n} \sum_{i=1}^{n} w_i \theta^*_i - \frac{1}{n} \sum_{i=1}^{n} w_i \theta^*_{\sigma(i)} \leq \frac{2\|w\|}{\sqrt{n}} \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta^*_i)^2},
\]

where \( \|w\| = \sqrt{\sum_i w_i^2} \).

**Proof.** We compute

\[
\frac{1}{n} \sum_{i=1}^{n} w_i \theta^*_i - \frac{1}{n} \sum_{i=1}^{n} w_i \theta^*_{\sigma(i)} \leq \left| \frac{1}{n} \sum_{i=1}^{n} w_i \theta^*_i - \frac{1}{n} \sum_{i=1}^{n} w_i \hat{\theta}_{\sigma(i)} \right| + \left| \frac{1}{n} \sum_{i=1}^{n} w_i (\hat{\theta}_{\sigma(i)} - \theta^*_i) \right|
\leq \frac{\|w\|_2}{\sqrt{n}} \left( \frac{1}{n} \sum_{i=1}^{n} (\theta^*_i - \hat{\theta}_{\sigma(i)})^2 \right)^{1/2} + \frac{\|w\|_2}{\sqrt{n}} \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta^*_i)^2}
\leq 2 \frac{\|w\|_2}{\sqrt{n}} \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta^*_i)^2}.
\]

The last step follows from the observation that

\[
\sum_{i=1}^{n} (\theta^*_i - \hat{\theta}_{\sigma(i)})^2 \leq \sum_{i=1}^{n} (\hat{\theta}_i - \theta^*_i)^2.
\]

The left-hand side is the sorted difference between \( \theta^*_i \) and \( \hat{\theta}_i \). This is smaller than the unsorted difference by an application of the rearrangement inequality.\(^{62}\)

\[\square\]

**A.3. Worst-case risk.**

**Theorem 4.** Under (2.3) but not (2.6), assume the conditional distribution \( \theta_i \mid \sigma_i \) has mean \( m_0(\sigma_i) \) and variance \( s^2_0(\sigma_i) \). Denote the set of distributions of \( \theta_{1:n} \mid \sigma_{1:n} \) which obey these restrictions as \( \mathcal{P}(m_0, s_0) \). Let \( \hat{\theta}_{i,G,s_0} \) denote the posterior mean estimates with some prior \( P^* \) under the location-scale model \( P^* (\theta_i \mid \sigma_i) = G_0 \left( \frac{t-m_0(\sigma_i)}{s_0(\sigma_i)} \right) \), for some fixed \( G_0 \) with zero mean and unit variance. Suppose additionally that \( \sigma_e = \min \sigma_i > 0 \) and \( s_u = \max \sigma_i < \infty \). Then, for some \( C_{\sigma_e,s_u} < \infty \) that solely depends on \( \sigma_e, s_u \),

\[
\sup_{F_0 \in \mathcal{P}(m_0, s_0)} \mathbb{E}_{F_0} \left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta^*_i)^2 \right] \leq C_{\sigma_e,s_u} \cdot \inf_{\theta_{1:n}} \sup_{F_0 \in \mathcal{P}(m_0, s_0)} \mathbb{E}_{F_0} \left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta_i)^2 \right].
\]

\(^{62}\)That is, for all real numbers \( x_1 \leq \cdots \leq x_n, y_1 \leq \cdots \leq y_n, \sum_i x_i y_{\pi(i)} \leq \sum_i x_i y_i \) for any permutation \( \pi(\cdot) \).
Thus, and risk the Bayes risk (achieved by (2.12)). Hence, the Bayes risk under this
Proof. Note that 
\[ \hat{\theta}_i, G^*_0 \equiv s_0(\sigma_i) \bar{\tau}_i, G^*_0 \equiv m_0(\sigma_i) \]
and 
\[ \theta_i = s_0(\sigma_i) \tau_i + m_0(\sigma_i). \]
Thus,
\[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta_i)^2 = \frac{1}{n} \sum_{i=1}^{n} s_0^2(\sigma_i)(\bar{\tau}_i, G^*_0 \equiv m_0(\sigma_i), \tau_i)^2. \]
Chen (2023) shows that
\[ \mathcal{R}_B \equiv \sup \left\{ \mathbb{E}_{\tau_i \sim G(i), Z_i \sim N(\tau_i, \nu_i^2)}[(\hat{\tau}_i, G^*_0 \equiv m_0(\sigma_i), \tau_i)^2] : \nu_i > 0, G(i), G^*_0 \text{ has zero mean and unit variance} \right\} \]
is finite. Taking the expected value with respect to \( P_0 \in \mathcal{P}(m_0, s_0) \) and apply the bound \( \mathcal{R}_B \), we have that
\[ \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta_i)^2 \right] \leq \mathcal{R}_B \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} s_0^2(\sigma_i) \right]. \]
Note that when \( P_0 \) is such that \( \hat{\theta}_i, \sigma_i \sim N(m_0(\sigma_i), s_0^2(\sigma_i)) \), the risk of any procedure exceeds the Bayes risk (achieved by (2.12)). Hence, the Bayes risk under this \( P_0 \) lower bounds the minimax risk
\[ \frac{1}{n} \sum_{i=1}^{n} \sigma_i^2 \left( \frac{\sigma_i^2}{s_0^2(\sigma_i)} \right) s_0^2(\sigma_i) \leq \inf_{\hat{\theta}_1, n} \sup_{P_0 \in \mathcal{P}(m_0, s_0)} \mathbb{E}_{P_0} \left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta_i)^2 \right]. \]
Note that, for some \( c_{\sigma_i, s_0} > 0 \),
\[ \frac{1}{n} \sum_{i=1}^{n} \frac{s_0^2(\sigma_i)}{\sigma_i^2 + s_0^2(\sigma_i)} s_0^2(\sigma_i) \geq c_{\sigma_i, s_0} \frac{1}{n} \sum_{i=1}^{n} s_0^2(\sigma_i). \]
Hence
\[ \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta_i)^2 \right] \leq \frac{\mathcal{R}_B}{c_{\sigma_i, s_0}} \frac{1}{n} \sum_{i=1}^{n} \frac{\sigma_i^2}{\sigma_i^2 + s_0^2(\sigma_i)} s_0^2(\sigma_i) \leq C_{\sigma_i, s_0} \inf_{\hat{\theta}_1, n} \sup_{P_0 \in \mathcal{P}(m_0, s_0)} \mathbb{E}_{P_0} \left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \theta_i)^2 \right]. \]
\[ \Box \]


Proposition 1. Suppose \((Y_i, \sigma_i)\) obey the Gaussian heteroskedastic location model, assumed to be independent across \( i \) (2.3). Fix some \( \omega > 0 \) and let \( Y_{1:n}^{(1)}, Y_{1:n}^{(2)} \) be the coupled bootstrap draws. For some decision problem, let \( \delta(Y_{1:n}^{(1)}) \) be some decision rule using only data \( \left(Y_i^{(1)}, \sigma_i^{2(1)}\right)_{i=1}^{n} \). Let \( F = \left(\theta_{1:n}, Y_{1:n}^{(1)}, \sigma_{1:n(1)}, \sigma_{1:n(2)}\right) \), for Decision Problems 1 to 3, the estimators \( T(Y_{1:n}, \delta) \) displayed in Table 1 are unbiased for the corresponding loss:
\[ \mathbb{E} \left[ T(Y_{1:n}, \delta(Y_{1:n}^{(1)})) | F \right] = L \left( \delta(Y_{1:n}^{(1)}), \theta_{1:n} \right). \]
Moreover, their conditional variances are equal to those expressions displayed in the third column of Table 1.
Proof. These are straightforward calculations of the expectation. Since every expectation and variance is conditional on \( \theta_{1:n}, Y_{1:n}^{(1)}, \sigma_{1:n,(1)}, \sigma_{1:n,(2)} \), we write \( \mathbb{E}[\cdot \mid \mathcal{F}] \) and \( \text{Var}(\cdot \mid \mathcal{F}) \) without ambiguity.

1. (Decision Problem 1) The unbiased estimation follows directly from the calculation

\[
\mathbb{E} \left[ (Y_i^{(2)} - \delta_i(Y_{1:n}^{(1)}))^2 \mid \mathcal{F} \right] = (\theta_i^{(2)} - \delta_i(Y_{1:n}^{(1)}))^2 + \sigma_{i,(2)}^2
\]

The conditional variance statement holds by definition.

2. (Decision Problem 2) The unbiased estimation follows directly from the calculation

\[
\mathbb{E} \left[ \delta_i(Y_{1:n}^{(1)})(Y_i^{(2)} - c_i) \mid \mathcal{F} \right] = \delta_i(Y_{1:n}^{(1)})(\theta_i - c_i).
\]

The conditional variance statement follows from

\[
\text{Var} \left[ \delta_i(Y_{1:n}^{(1)})(Y_i^{(2)} - c_i) \mid \mathcal{F} \right] = \delta_i(Y_{1:n}^{(1)})\sigma_{1:n,(2)}^2.
\]

3. (Decision Problem 3) The loss function for Decision Problem 3 is the same as that for Decision Problem 2 with \( c_i = 0 \). Since we condition on \( Y_{1:n}^{(1)} \), the argument is thus analogous.

\( \square \)

A.5. A discrete choice model. There are \( n \) options facing \( N \) consumers, where each consumer chooses one option. Each option is characterized by idiosyncratic quality \( \beta_j \) and inherent quality \( \alpha_j \). The latent quality of an option is \( \theta_j = \alpha_j + \rho \frac{N_j}{\mathbb{E}[N]} \), where \( N_j \leq N \) is the number of consumers using option \( j \), generated in equilibrium from a discrete choice model. The term \( \rho N_j \) reflects externalities generated by the users of an option (congestion). We assume that \( \alpha_j, \beta_j \sim i.i.d. F \) where \( \mu \) denotes \( \mathbb{E}[\alpha_j + \beta_j] \) and \( \sigma_\alpha^2, \sigma_\beta^2, \sigma_{\alpha\beta} \) denotes the variances and covariance of \( \alpha \) and \( \beta \).

To connect this model to our setting, we can imagine that the data analyst has estimates \( Y_j \) for \( \theta_j \), whose standard errors are a function of \( N_j \). The discrete choice model specifies how \( N_j \) selects on the quality component \( \alpha_j \), and \( \rho \) determines how \( \theta_j \) is affected by \( N_j \). We characterize \( \text{Cov}(\theta_j, N_j) \) as a function of the primitives \( \rho, \mu, \sigma_\alpha, \sigma_\beta, \sigma_{\alpha\beta} \).

Each individual \( i \) is endowed with a private type \( \epsilon_i = (\epsilon_{i1}, \ldots, \epsilon_{ij}) \) of i.i.d Type-1 extreme value random utilities. This prior for \( \epsilon_i \) is common knowledge and well-specified. \( \alpha_{1:n}, \beta_{1:n}, N \) are common knowledge as well. Each individual \( i \) is an expected utility maximizer, where the utility of item \( j \) is

\[
V_j = \left( \alpha_j + \beta_j + \rho \frac{N_{j,-i}}{N - 1} \right) \exp(\epsilon_{ij})
\]

where \( N_{j,-i} \) is the number of other individuals choosing item \( j \). Since individuals other than \( i \) are symmetric to \( i \), the expected utility (conditional on what \( i \) observes) is

\[
\mathbb{E}_i V_j = (\alpha_j + \beta_j + \rho \pi_{-ij}) \exp(\epsilon_{ij}),
\]

\( \text{Note that the externality that enters the utility is different from the externality in } \theta. \text{ This is for analytical tractability purposes.} \)

To prevent the utility component from becoming negative, we additionally assume that \( \alpha_j + \beta_j > -\rho \) almost surely, which imposes that \( \rho > -\mu. \)
where $\pi_{-ij}$ is $i$’s prior expectation of $N_{j,-i}/(N - 1)$. A Bayes-Nash equilibrium is one in which individual $i$ chooses the option with the highest $E_i V_j$ and his beliefs about other individuals, $\pi_{-ij}$, are correct.

Since individuals are ex-ante symmetric, we assume that

$$\pi_{-ij} = \pi_j = P(E_i V_j \geq E_i V_k \quad \forall k).$$

In such a symmetric equilibrium, $\pi$ solves the system of equations

$$\frac{\alpha_j + \beta_j + \rho \pi_j (N - 1)}{\sum_j \alpha_j + \beta_j + \rho \pi_j (N - 1)} = \pi_j \implies \pi_j = \frac{\alpha_j + \beta_j}{\sum_j \alpha_j + \beta_j}.$$

Finally, we assume that the total number of consumers is ex ante random

$$N \mid (\alpha_{1:n}, \beta_{1:n}) \sim \text{Pois} \left( \lambda \cdot \left( \sum_{j=1}^{n} \alpha_j + \beta_j \right) \right).$$

Assume that the data-generating process draws $\alpha, \beta, N$, and individuals play the Bayes–Nash equilibrium under symmetric beliefs $\pi$. By the thinning property of Poisson processes, we have that

**Lemma A.1.** $N_j \mid (\alpha_{1:n}, \beta_{1:n}) \sim \text{Pois} \left( \lambda (\alpha_j + \beta_j) \right)$ independently across $j$.

Now, under this process, we can compute the covariance between the latent quality $\theta_j$ and the sample size $N_j$ in closed form:

$$\text{Cov} (\theta_j, N_j) = \underbrace{\text{Cov}(\alpha_j, N_j)}_{\text{selection}} + \underbrace{\frac{\rho}{\lambda n \mu} \text{Var}(N_j)}_{\text{congestion}}$$

$$= \frac{\lambda (\sigma^2_\alpha + \sigma_{\alpha\beta}) + \frac{\rho}{\lambda n \mu} [\lambda \mu + \lambda^2 (\sigma^2_\alpha + \sigma^2_\beta + 2 \sigma_{\alpha\beta})]}{\lambda n \mu + \lambda^2 (\sigma^2_\alpha + \sigma^2_\beta + 2 \sigma_{\alpha\beta})}.$$  

This is positive—meaning that the latent quality is positively associated with precision—iff

$$\frac{\rho}{\lambda n \mu} > - \frac{\text{Cov}(\alpha_j, N_j)}{\text{Var}(N_j)} = - \frac{\sigma^2_\alpha + \sigma_{\alpha\beta}}{\mu + \lambda (\sigma^2_\alpha + \sigma^2_\beta + 2 \sigma_{\alpha\beta})}.$$

When the selection effect is positive ($\text{Cov}(\alpha_j, N_j)$), the above display requires the externality $\rho$ to not be too negative so as to dominate the selection effect. Note that the sign of the selection contribution depends on the covariance between $\alpha$ and $\beta$, and thus could be negative. Moreover, if $\alpha$ instead were an undesirable trait to consumers, then the selection effect may also be negative. The congestion effect similarly does not have to be negative. We allow for positive spillovers by $\rho > 0$.

We can interpret various empirical observations through this model:

- For hospital value-added (Chandra et al., 2016), $N_j$ positively selects on hospital quality $\alpha_j$. This is likely true for most value-added settings.
- For teacher value-added, it is possible (Lazear, 2001; Barrett and Toma, 2013; Mehta, 2019) that teachers may prefer smaller classes, and school administrators may reward good
teachers by letting them teach smaller classes. In the lens of this model, \( N_j \) negatively selects on quality.\(^64\)

- In integenerational mobility, \( N_j \) is the number of poor minority households. Higher \( N_j \) leads to oppressive institutions and residential segregation. We can interpret these pernicious effects as a negative \( \rho \).

However, this model does not capture all channels through which \( \theta_j \) can be correlated with \( \sigma_j \). For instance, the following is difficult to map to the discrete choice model.

- In unbalanced panel data settings, the length of the observed period for a unit—which relates to the precision of the unit’s estimated fixed effect—may be correlated with the underlying fixed effect. This observation dates at least to Olley and Pakes (1996), who note that in a firm panel, those firms with shorter observed period are probably less productive and have to shut down sooner. For value-added modeling of nursing homes, Einav et al. (2022) note that patients with shorter stays at nursing homes typically experience an adverse health event, including death. Such events are presumably more likely for worse nursing homes, again inducing a correlation between nursing home qualities and the sample sizes used to estimate them. Similarly, for teacher value-added, Bruhn et al. (2022) find that teachers who have shorter observed spells in administrative datasets tend to be worse and have noisier value added estimates.

A.6. **Interpretation of empirical Bayes sampling model.** When the empirical Bayes sampling model fails to hold, empirical Bayes methods do not precisely mimic an oracle Bayesian’s decision. However, in many cases, we can still interpret the empirical Bayes decision rules. In most such cases, the interpretation is in terms of emulating an oracle Bayesian who is constrained. The oracles are constrained either by removing its access to certain information or by restricting its decisions to a particular class. We will consider two scenarios when such an interpretation is natural.

A.6.1. **Interpretation when independence of units fails.** We consider the interpretation of the sampling model (2.3) when it is misspecified. Recall that we assume \((Y_i, \theta_i, \sigma_i)\) are sampled independently across \(i\), with \(Y_i \mid \theta_i, \sigma_i \sim N(\theta_i, \sigma_i)\). This sampling model can fail in two ways. First, it is possible that \(Y_{1:n} \mid \theta_{1:n}, \sigma_{1:n}\) are correlated but still multivariate Gaussian. Second, it is possible that \((\theta_i, \sigma_i)\) are correlated across \(i\). Here, we limit our discussion to Decision Problem 1.

Let \(Y = (Y_1, \ldots, Y_n)\) and \(\theta = (\theta_1, \ldots, \theta_n)'\). Let us assume instead that

\[
Y \mid \theta, \Sigma \sim N(\theta, \Sigma)
\]

where \(\text{diag}(\Sigma) = [\sigma_1^2, \ldots, \sigma_n^2]\) and the variance-covariance matrix \(\Sigma\) is known. Let \(Q_0\) be the joint distribution of \(\theta \mid \Sigma\). Now, the oracle Bayesian—who knows \(Q_0\)—would use \(\mathbb{E}_{Q_0}[\theta_i \mid Y, \Sigma]\) as their decision rule. The empirical Bayesian can similarly emulate that oracle Bayes decision rule by estimating \(Q_0\). If the empirical Bayesian is willing to assume that the location-scale assumption

\(^{64}\)Though the channel is not through student-level discrete choice of teachers.
(2.6) describes $Q_0$:

\[
(\theta_i \mid \Sigma) \sim (\theta_i \mid \sigma_{1:n}) \sim G_0 \left( \frac{\cdot - m_0(\sigma_i)}{s_0(\sigma_i)} \right),
\]

then the empirical Bayesian can similarly implement close, and output estimates of $E_{Q_0}[\theta_i \mid Y, \Sigma]$. We should caveat that the npmle step no longer maximizes the full likelihood of $Y$ with respect to $G_0$, but a quasi-likelihood that averages over the log-likelihood of each $Y_i$ separately, ignoring their joint distribution.

Now, let us consider what interpretation our method has when we erroneously assume either the independence of $Y_i$ across $i$ or that $\theta_i \mid \Sigma$ are independent across $i$. The latter independence may fail, for instance, when the populations index places, and the $\theta_i$’s are thought to be spatially correlated (e.g., in Müller and Watson, 2022). Consider the class of separable decision rules, where the forecast for $\theta_i$ can depend solely on $Y_i, \sigma_i$:

\[
\delta_i(Y, \sigma_{1:n}) = \delta_i(Y_i, \sigma_i).
\]

Consider a constrained oracle Bayesian who is forced to use a separable decision rule. They would use $E_{Q_0}[\theta_i \mid Y_i, \sigma_i]$. Note that this constrained decision rule depends on $Q_0$ only through the distribution $\theta_i \mid \sigma_i$ (and not $\theta_i \mid \Sigma$). Thus, under the location-scale assumption

\[
(\theta_i \mid \sigma_{1:n}) \sim G_0 \left( \frac{\cdot - m_0(\sigma_i)}{s_0(\sigma_i)} \right),
\]

CLOSE-based methods emulate this oracle Bayesian constrained to separable decision rules. Of course, the resulting empirical Bayesian decision rule is not separable (since $\hat{G}_n$ presumably depends on all the data), but it seeks to emulate the best possible separable rule. This interpretation in terms of emulating a constrained oracle Bayesian holds regardless of the joint distribution of $Y$ or of $\theta$, so long as our specification of the marginal distribution holds. Of course, our regret results do not immediately carry over to this setting.

### A.6.2. Interpretation with additional covariates $X_i$.

Additionally, we may also have population-level covariates $X_i$. Let us maintain that $X_i$ does not predict the noise in $Y_i$:

\[
Y_i \perp X_i \mid \theta_i, \sigma_i.
\]

Here, we will discuss two questions. First, how do we handle covariates? Second, what is the difference between using $X_i$ and $\sigma_i$—is the standard error simply a covariate?\(^{65}\)

On the first question, there are two ways of incorporating covariates, under similar but distinct assumptions. First, close-methods can be extended to incorporate covariates by augmenting (2.6)\(^{65}\)

\(^{65}\)Covariates are considered in Ignatiadis and Wager (2019). They assume a homoskedastic setting where the prior depends on some covariates $X_i$; i.e., in our notation, $\theta_i \mid X_i \sim \mathcal{N}(m(X_i), s^2_X)$ and $Y_i \mid \theta_i \sim \mathcal{N}(\theta_i, \sigma^2)$. Starting from our setting (2.6), to obtain theirs, one would (i) restrict to homoskedasticity $\sigma_i = \sigma$, (ii) consider some covariates $X_i$ that predict $\theta_i$, and model $\theta_i \mid X_i$ as a conditional location—but not scale—familly, and (iii) restrict $G_0 \sim \mathcal{N}(0, 1)$. Their minimax lower bound on the regret uses essentially the same argument as we do in Theorem 2.
to incorporate covariates. That is, we can instead assume that
\[ P_0(\theta_i \leq t \mid X_i, \sigma_i) \sim G_0 \left( t - m_0(\sigma_i, X_i) \right) \frac{s_0(\sigma_i, X_i)}{s_0(\sigma_i, X_i)} \]  
(A.1)
and estimate \( m_0, s_0 \) nonparametrically. Instead of being one-dimensional nonparametric regression problems, they are now \((d + 1)\)-dimensional nonparametric problems. Under the same Hölder-type smoothness conditions, the corresponding regret rate replaces \( n^{-\frac{2p}{2p+1}} \) with \( n^{-\frac{2p}{2p+1+d}} \). Second, as we do in the empirical exercises, one could consider a strategy of residualizing against \( X_i \) in some arbitrary way, performing empirical Bayes, and undoing the residualization. This strategy dates back to Fay and Herriot (1979). That is, with raw data \( \tilde{Y}_i \) for parameter \( \tilde{\vartheta}_i \), we can consider forming the residuals \( Y_i = \tilde{Y}_i - b(X_i) \) and \( \theta_i = Y_i - b(X_i) \), and perform empirical Bayes methods on \((Y_i, \theta_i, \sigma_i)\). At a high level, we can rationalize this strategy as mimicking a constrained oracle Bayesian who solely has access to \( Y_i, \sigma_i \), who knows the joint distribution of \((\theta_i, \sigma_i)\), but who does not have access to \( X_i \). Note that this interpretation is coherent regardless of the transformation \( b(X_i) \), allowing us to be more blasé about modeling \( X_i \) than the previous approach. In particular, choosing \( b(X_i) = 0 \) ignores the covariate entirely; the resulting empirical Bayes procedure mimics an oracle that does not have access to \( X_i \). Of course, when we impose the location-scale assumption (2.6) on \((\theta_i, \sigma_i)\), different \( b(X_i) \) gives rise to different—and possibly mutually exclusive—underlying models on \((\vartheta_i, \sigma_i, X_i)\).

On the second question, in an operational sense, \( \sigma_i \) is simply another covariate. \( \sigma_i \) is not particularly special in the assumption (A.1), and one interpretation of \( \text{CLOSE} \) is treating \( \sigma_i \) precisely as a covariate to be regressed out. However, \( \ sigma_i \) does occupy a special place in the statistical structure of the problem. The likelihood of the data, \( Y_i \mid \theta_i, \sigma_i \), depends on \( \sigma_i \) but not \( X_i \). This special role of \( \sigma_i \) means that we must treat it with more care so that the resulting procedure has a coherent interpretation. If we wanted to ignore covariates \( X_i \), we can imagine an oracle Bayesian who does not have access to \( X_i \), and the resulting empirical procedure simply mimics that constrained oracle. This line of reasoning does not work with \( \sigma_i \), since any oracle Bayesian—constrained or otherwise—must have access to \( \sigma_i \). As a result, we cannot avoid the problem of modeling \( \theta_i \mid \sigma_i \) as easily as we could have avoided modeling \( \theta_i \mid X_i, \sigma_i \) by changing the goalpost.

A.7. Alternatives to \text{CLOSE}.

A.7.1. Alternative methods. Let us turn to a few specific alternative methods that consider failure of prior independence. We argue that they do not provide a free-lunch improvement over our assumptions. At a glance, these alternative methods have properties summarized in Table 2.

**Alternative 1** (Working with \( t \)-ratios). We may consider normalizing \( \sigma_i \) away by working with \( t \)-ratios \( T_i \equiv \frac{Y_i}{\sigma_i} \mid (\sigma_i, \theta_i) \sim \mathcal{N}(\theta_i/\sigma_i, 1) \). The resulting problem is homoskedastic by construction. It is natural to consider performing empirical Bayes shrinkage assuming that \( \frac{\theta_i}{\sigma_i} \mid T_i, H_{0_1} \) and use, say, \( \sigma_i E_{H_{0_1}} \left[ \frac{\theta_i}{\sigma_i} \mid T_i \right] \) as an estimator for the posterior mean of \( \theta_i \) (Jiang and Zhang, 2010). However, such an approach approximates the optimal decision rule within a restricted class on a different objective.
Table 2. Properties of alternative methods

<table>
<thead>
<tr>
<th></th>
<th>t-ratios</th>
<th>Var. stab. transforms</th>
<th>Random ( \hat{\sigma}_i )</th>
<th>SURE</th>
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</thead>
<tbody>
<tr>
<td>Restrict to a class of procedures</td>
<td>✗</td>
<td></td>
<td></td>
<td>✗</td>
</tr>
<tr>
<td>Change the loss function</td>
<td>✗</td>
<td>✗</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Require access to micro-data</td>
<td>✗</td>
<td></td>
<td></td>
<td>✗</td>
</tr>
<tr>
<td>Assume ( \theta_i ) is independent from some other known nuisance parameter, e.g. ( n_i )</td>
<td>✗</td>
<td>✗</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parametric restrictions on the micro-data</td>
<td>✗</td>
<td>✗</td>
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</tbody>
</table>

Let us restrict decision rules to those of the form \( \delta_{i,t \text{-stat}}(Y_i, \sigma_i) = \sigma_i h(Y_i/\sigma_i) \). The oracle Bayes choice of \( h \) is \( h^*(T_i) = \frac{E[\theta_i/T_i]}{E[\sigma_i^2/T_i]} \). However, \( h^* \) is not the posterior mean of \( \theta_i/\sigma_i \) given the t-ratio \( T_i \), unless \( \sigma_i^2 = \theta_i/\sigma_i \). On the other hand, the loss function that does rationalize the posterior mean \( h(T_i) = E[\theta_i/\sigma_i \mid \sigma_i] \) is the precision-weighted compound loss \( L(\delta, \theta_1:n) = \frac{1}{n} \sum_{i=1}^{n} \sigma_i^{-2}(\delta_i - \delta)^2 \).

Thus, rescaling posterior means on t-ratios achieves optimality for a weighted objective among a restricted class of decision rules \( \delta_{i,t \text{-stat}} \).

**Alternative 2** (Variance-stabilizing transforms). Second, we may consider a variance-stabilizing transform when the underlying micro-data are Bernoulli and \( \theta_i \) is a Bernoulli mean (Efron and Morris, 1975; Brown, 2008). Specifically, we rely on the asymptotic approximation

\[
\sqrt{n_i}(Y_i - \theta_i) \xrightarrow{d} \mathcal{N}(0, \theta_i(1 - \theta_i)).
\]

A variance-stabilizing transform can disentangle the dependence: Let \( W_i = 2 \arcsin(\sqrt{Y_i}) \) and \( \omega_i = 2 \arcsin(\sqrt{\theta_i}) \), and, by the delta method,

\[
\sqrt{n_i}(W_i - \omega_i) \xrightarrow{d} \mathcal{N}(0, 1). \quad \text{Thus, approximately, } W_i \mid \omega_i, n_i \sim \mathcal{N} \left( \omega_i, \frac{1}{n_i} \right).
\]

One might consider an empirical Bayes approach on the resulting \( W_i \). Note that \( W_i \) may still violate prior independence, since \( \omega_i \) may not be independent of \( n_i \). Moreover, squared error loss on estimating \( \omega_i = 2 \arcsin(\sqrt{\theta_i}) \) is different from squared error loss on estimating \( \theta_i \). We do not know of any guarantees for the loss function on \( \theta_i, \frac{1}{n} \sum_{i=1}^{n} (\delta_i - \sin^2(\omega_i/2))^2 \), when we perform empirical Bayes analysis on \( \omega_i \).

**Alternative 3** (Treating the standard error as estimated). Lastly, if the researcher has access to micro-data, Gu and Koenker (2017) and Fu et al. (2020) propose empirical Bayes strategies that treat \( \sigma_i \) as noisy as well, in which we know the likelihood of \( (Y_i, \sigma_i) \). This approach allows for dependence between \( \theta_i \) and \( \sigma_i \) but assumes independence between \( (\theta_i, \sigma_i) \) and some other known nuisance parameter. To describe their model, we introduce more notation. Let \( Y_{ij}, j = 1, \ldots, n_i \), denote the micro-data for population \( i \), where, for each \( i \), we are interested in the mean of \( Y_{ij} \). Let \( Y_i \) denote their sample mean and \( S_i^2 \) denote their sample variance, where \( \sigma_i^2 = S_i^2/n_i \). Let \( \sigma_{i0}^2 \) denote the true variance of observations from population \( i \).
Both papers work under Gaussian assumptions on the micro-data. This parametric assumption on the micro-data—which is stronger than we require—implies that $Y_i \equiv S_i^2 | (\sigma_{i0}, \theta_i, n_i)$ with marginal distributions:

$$Y_i | \sigma_{i0}, \theta_i, n_i \sim \mathcal{N} \left( \theta_i, \frac{\sigma_{i0}^2}{n_i} \right) \quad \text{and} \quad S_i^2 | \sigma_{i0}, \theta_i, n_i \sim \text{Gamma} \left( \frac{n_i - 1}{2}, \frac{1}{2\sigma_{i0}^2} \right).$$

They then propose empirical Bayes methods treating $Y_i \equiv (Y_i, S_i^2)$ as noisy estimates for parameters $\theta_i \equiv (\theta_i, \sigma_{i0}^2)$. This formulation allows $\theta_i$ to have a flexible distribution, and thus allows for dependence between $\theta_i$ and $\sigma_{i0}^2$. However, since the known sample size $n_i$ enters the likelihood of $Y_i$, this approach still assumes that $n_i \equiv \theta_i$.

This discussion is not to say that close is necessarily preferable to these alternatives. It highlights that the possible dependence between $\theta_i$ and $\sigma_i$ cannot be easily resolved. As summarized in Table 2, existing alternatives compromise on optimality, use a different loss function, or implicitly assume $\theta_i$ is independent from components of $\sigma_i^2$ (e.g., $n_i$). Of course, depending on the empirical context, these may well be reasonable features.

In contrast, our approach models $\theta_i | \sigma_i$ directly via the location-scale assumption (2.6). A natural question is whether other types of modeling may be superior—which we turn to next. We argue that the location-scale model uniquely capitalizes on the appealing properties of the NPMLE-based empirical Bayes approaches.

### A.7.2. Alternative models for $\theta_i | \sigma_i$

One alternative is simply treating the joint distribution of $(\theta_i, \sigma_i)$ fully nonparametrically. For instance, an $f$-modeling approach with Tweedie’s formula implies that an estimate of the conditional distribution $Y_i | \sigma_i$ is all one needs for computing the posterior means (Brown and Greenshtein, 2009; Liu et al., 2020; Luo et al., 2023). However, conditional density estimation is a challenging problem, and most available methods do not exploit the restriction that $Y_i | \sigma_i$ is a Gaussian convolution. Similarly, one could consider flexible parametric

---

66 The parametric restriction on the micro-data $Y_{ij}$ can be relaxed by appealing to the asymptotic distribution of $(Y_i, S_i^2)$—resulting in the Gaussian likelihood $(Y_i, S_i^2) | \theta_i, \Sigma_i \sim \mathcal{N}(\theta_i, \Sigma_i)$. In general, however, $\Sigma_i$ also depends on $n_i$ and higher moments of $Y_{ij}$, which again may not be independent of $\theta_i$.

67 That is, the posterior mean can be written as a functional of the density of $Y$:

$$\mathbb{E}[\theta_i | Y_i, \sigma_i] = Y_i + \sigma_i^2 \frac{d}{dy} \log f(y | \sigma_i) \bigg|_{y = Y_i},$$

where $f(y | \sigma)$ is the conditional density of $Y | \sigma$. Empirical Bayes approaches exploiting this formula is known as $f$-modeling (Efron, 2014), since $f$ usually denotes the marginal distribution of $Y$. This is in contrast to $g$-modeling, which seeks to estimate the prior distribution of $\theta_i$.

Brown and Greenshtein (2009) develop an $f$-modeling approach with a kernel smoothing density estimator in the homoskedastic setting. Liu et al. (2020) extend this approach to a homoskedastic, balanced dynamic panel setting, where the initial outcome for each unit acts as a known nuisance parameter, much like $\sigma_i$ in our case. Brown and Greenshtein (2009) and Liu et al. (2020) show that the squared error Bayes regret converges to zero faster than the oracle Bayes risk. These guarantees do not imply regret rate characterizations similar to those that we obtain. See Jiang and Zhang (2009) for additional discussion about the strengths of the theoretical results in Brown and Greenshtein (2009) compared to NPMLE-based $g$-modeling approaches.
g-modeling of $\theta_i \mid \sigma_i$ in the vein of the log-spline sieve of Efron (2016). This has the advantage of estimating a smooth prior at the cost of having tuning parameters. We are not aware of regret results for this approach.

If we commit to making some substantive restriction on the joint distribution of $(\theta_i, \sigma_i)$, it is fair to ask why the conditional location-scale restriction (2.6) is necessarily preferable. However, if we wish to capitalize on the theoretical and computational advantages of NPMLE, it is natural to consider a class of procedures that transform the data in some way and use the NPMLE on the resulting transformed data to estimate the prior distribution (Appendix A.7.3 gives a heuristic justification for this strategy). If we wish to preserve the Gaussian location model structure on the transformed data, then effectively we can only consider affine transformations (i.e., $Z = a(\sigma) + b(\sigma)Y$) (shown in Lemma A.2 below). If we further wish that $Z$ obeys a Gaussian location model in which prior independence holds (i.e., $\tau \equiv a(\sigma) + b(\sigma)\theta$ is independent from $\nu \equiv b(\sigma)\sigma$)—so that we can apply NPMLE-based approaches assuming prior independence—then we have no other choice but to assume (2.6). Thus, the conditional location-scale assumption is uniquely well-suited to capitalize on the favorable properties of NPMLE already established in the literature, which we extend via Theorem 1.

**Lemma A.2.** Let $Y \sim \mathcal{N}(\theta, \sigma^2)$ with known $\sigma^2$. Consider a strictly increasing and differentiable function $g(\cdot)$. Let $Z = h(Y)$. Then the corresponding family of distributions of $Z$ is a natural exponential family if and only if $h(Y) = a + bY$.

**Proof.** The “if” part ($\Rightarrow$) is immediate. We focus on the “only if” ($\Leftarrow$) part. Writing the distribution of $Y$ as an exponential family,

$$p_Y(y) \propto \exp\left(\frac{\theta}{\sigma^2} + g(y, \sigma) + A(\theta, \sigma)\right)$$

for some $g(y, \sigma)$ and $A(\theta, \sigma)$. Note that we have

$$p_Z(z) = p_Y(y)\left|\frac{dy}{dz}\right| = p_Y(h^{-1}(z))\left|\frac{dh^{-1}(z)}{dz}\right|$$

Thus, writing in exponential family form, for some $\tilde{g}$, we have that

$$p_Z(z) \propto \exp\left(h^{-1}(z)\frac{\theta}{\sigma^2} + \tilde{g}(z, \sigma) + A(\theta, \sigma)\right)$$

Suppose $Z$ follows a natural exponential family with natural parameter $q(\theta; \sigma)$. Then we can write

$$h^{-1}(z)\frac{\theta}{\sigma^2} = zq(\theta; \sigma) + v(\theta, \sigma) + w(z).$$

Since $h$ is strictly monotone and differentiable, so is $h^{-1}$. Taking the $z$-derivative of both sides:

$$\frac{dh^{-1}}{dz} = \sigma^2 q(\theta; \sigma) + w'(z)\frac{\sigma^2}{\theta}.$$
Since the left-hand side does not depend on $\theta$, it follows that
\[ \frac{q(\theta; \sigma) + w'(z)}{\theta} \]
is free of $\theta$ for all $z$. Suppose $w'(z)$ is not constant, then for $z_1 \neq z_2$ and $w'(z_1) \neq w'(z_2)$, the difference is $\theta$-dependent
\[ \frac{q(\theta; \sigma) + w'(z_1)}{\theta} - \frac{q(\theta; \sigma) + w'(z_2)}{\theta} = \frac{w'(z_1) - w'(z_2)}{\theta}. \]
Hence $w'(z)$ is a constant. As a result, $\frac{dh}{dz}$ does not depend on $z$, and hence $h(z) = a + bz$. □

A.7.3. Model-free interpretation of close-npmle. When the location-scale model fails to hold, it remains sensible to consider estimating the npmle on an affine transformation of the data, as in close-npmle.

Let us first consider a given affine transformation of the data—not necessarily $\tau = Z - m_0(\sigma)s_0(\sigma)$—into $(Z_i, \tau_i, \nu_i)$ for which $\tau_i | \nu_i \sim H(i)$, and ask why npmle is reasonable. In population, npmle seeks to minimize the average Kullback–Leibler (KL) divergence between the distribution of the estimates $Z_i$ and the distribution implied by the convolution $H \ast \mathcal{N}(0, \nu_i^2)$:
\[
\max_H \frac{1}{n} \sum_{i=1}^{n} \mathbb{E}_{Z_i \sim f_{H(i), \nu_i}} \left[ \log f_{H, \nu_i}(Z_i) \right], \quad \text{equivalent to} \quad \min_H \frac{1}{n} \sum_{i=1}^{n} \text{KL} \left( f_{H(i), \nu_i} \| f_{H, \nu_i} \right),
\]
where $f_{H, \nu}$ is the density of the convolution $H \ast \mathcal{N}(0, \nu^2)$. As shown by Jiang and Zhang (2009) and Jiang (2020) (see Appendix C.3), the regret in mean-squared error under a misspecified prior $\tau_i \sim H$ is upper bounded by the average squared Hellinger distance between the distribution of the data and the distribution implied by $H$. The average Hellinger distance is further upper bounded by the average KL divergence:
\[
\frac{1}{n} \sum_{i=1}^{n} \text{KL} \left( f_{H(i), \nu_i} \| f_{H, \nu_i} \right) \leq \frac{1}{n} \sum_{i=1}^{n} \text{KL} \left( f_{H(i), \nu_i} \| f_{H, \nu_i} \right).
\]
In this sense, even under misspecification ($H(i) \neq H(j)$), npmle chooses a common distribution $H$ that minimizes an upper bound of regret.

Now that we have a justification for the npmle, let us consider the transformation we would like to choose. It is reasonable, then, to choose the affine transform $(a(\sigma), b(\sigma))$ so that the resulting conditional distributions $H(i)$ of the transformed parameter $\tau_i | \sigma_i$ are similar—under some distance measure. Doing so does not recover prior independence on the transformed data but limits the extent of non-independence. Choosing $a(\sigma), b(\sigma)$ to ensure that $\tau_i | \sigma_i$ has the same first two moments is intuitively reasonable, and actually has a formal interpretation in terms of information-theoretic divergences and optimal transport metrics, at least in a large-$\sigma$ regime (Chen and Niles-Weed, 2022).
Part 2. Additional empirical results

Appendix B. Additional empirical exercises

Figure B.1. Estimated conditional variance $s_0^2(\sigma)$, binned into deciles, with 95% uniform confidence intervals shown.

B.1. Positivity of $s_0(\cdot)$ in the Opportunity Atlas data. In the Opportunity Atlas data, we often observe that the estimated conditional variance is negative: $s_0^2 < 0$. To test if this is due to sampling variation or underdispersion of the Opportunity Atlas estimates relative to the estimated standard error, we consider the following upward-biased estimator of $s_0^2(\sigma_i)$. Without loss, let us sort the $Y_i, \sigma_i$ by $\sigma_i$, where $\sigma_1 \leq \cdots \leq \sigma_n$. Let $S_i = \frac{1}{2}[(Y_{i+1} - Y_i)^2 - (\sigma_i^2 + \sigma_{i+1}^2)]$. Note that

$$E[S_i \mid \sigma_{1:n}] = \frac{1}{2}E[(\theta_{i+1} - \theta_i)^2 \mid \sigma_{1:n}] = \frac{s_0^2(\sigma_{i+1}) + s_0^2(\sigma_i)}{2} + \frac{1}{2}(m_0(\sigma_{i+1}) - m_0(\sigma_i))^2 \geq \frac{s_0^2(\sigma_{i+1}) + s_0^2(\sigma_i)}{2}.$$

Hence $S_i$ is an overestimate of the successive averages of $s_0(\sigma)$. Figure B.1 plot the estimated conditional expectation of $S_i$ given $\sigma_i$, using a sample of $(S_1, S_3, S_5, \ldots)$ so that the $S_i$’s used are mutually independent. We see that for many measures of economic mobility, we can reject $E[S_i \mid \sigma_i] \geq 0$, indicating some overdispersion in the data.
### Figure B.2. Additional close-npmle variants for the calibrated simulation in Section 5. Here the results average over 100 replications.

#### B.2. Robustness checks for the calibration exercise in Section 5. In Figure B.2, we evaluate two variants of close-npmle. The first variant (column 4) uses an estimator for $s_0(\cdot)$ that smooths the difference $(Y - \hat{m}(\sigma))^2 - \sigma^2$, rather than smoothing $(Y - \hat{m}(\sigma))^2$ and then subtracting $\sigma^2$. Since local linear regression suffers from bias coming from the convexity of the underlying unknown function, smoothing the difference can perform better, as the convexity bias differences out. The second variant (column 6) projects the estimated npmle $\hat{G}_n$ to the space of mean zero and variance one distributions, by normalizing by its estimated first and second moments. Neither variant performs appreciably differently from the main version of close-npmle (column 5) that we demonstrate in the main text.

#### B.3. Simulation exercise setup. This section describes the details of the simulation exercise in Section 5. We restrict to the 10,109 tracts within the twenty largest Commuting Zones. Tracts with missing information are dropped for each measure of mobility. Specifically, the simulated data-generating process is as follows:

(Sim-1) Residualize $\tilde{Y}_i$ against some covariates $X_i$ to obtain $\beta$ and residuals $Y_i$. Estimate the conditional moments $m_0, s_0$ on $(Y_i, \sigma_i)$ via local linear regression, described in Appendix G.
(Sim-2) Partition $\sigma$ into vintiles. Within each vintile $j$, estimate an NPMLE $G_j$ over the data \( \left( \frac{Y_i - m_0(\sigma_i)}{s_0(\sigma_i)}, \frac{\sigma_i}{s_0(\sigma_i)} \right) \) and normalize $G_j$ to have zero mean and unit variance. Sample $\tau^*_i | \sigma_i \sim G_j$ if observation $i$ falls within vintile $j$.

(Sim-3) Let $\vartheta^*_i = s_0(\sigma_i) \tau^*_i + m_0(\sigma_i) + \beta' X_i$ and let $\tilde{Y}_i^* | \theta^*_i, \sigma_i \sim \mathcal{N}(\theta^*_i, \sigma^2_i)$.

The estimated $\beta, m_0, s_0$ will serve as the basis for the true data-generating process in the simulation, and as a result we do not denote it with hats.

The covariates used are poverty rate in 2010, share of Black individuals in 2010, mean household income in 2000, log wage growth for high school graduates, mean family income rank of parents, mean family income rank of Black parents, the fraction with college or post-graduate degrees in 2010, and the number of children—and the number of Black children—under 18 living in the given tract with parents whose household income was below the national median. These covariates are included in Chetty et al.'s (2020) publicly available data, and these descriptions are from their codebook. This set of covariates is not precisely the same as what is used in Bergman et al. (2023). Bergman et al. (2023) additionally use economic mobility estimates for a later birth cohort, which are not included in the publicly released version of the Opportunity Atlas. The “number of children” variables are used by (Chetty et al., 2020) as a population weighting variable; they contain some information on the implicit micro-data sample sizes $n_i$.

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**Figure B.3.** Analogue of Figure 4 for the data-generating process in Appendix B.4. Here the results average over 100 replications.
B.4. Different Monte Carlo setup. We have also conducted a Monte Carlo exercise where we replace (Sim-2) with the following step:

- For each $\sigma_i$, let
  \[ \alpha_i = \frac{1}{2} + \frac{1}{2} \frac{m_0(\sigma_i) - \min_i m_0(\sigma_i)}{\max_i m_0(\sigma_i) - \min_i m_0(\sigma_i)} \in [1/2, 1] \]

We sample $\tau^*_i \mid \sigma_i$ as a scaled and shifted Weibull distribution with shape $\alpha_i$. The scaling and translation ensures that $\tau_i \mid \sigma_i$ has mean zero and variance one. Because we choose the Weibull distribution, the shape parameter $\alpha_i$ corresponds exactly to $\alpha$ in Assumption 2. Our choices of $\alpha_i$ implies that $\tau_i \mid \sigma_i$ has thicker tails than exponential and does not have a moment-generating function.

The Weibull distribution has thicker tails and is skewed, and as a result, NPMLE-based methods tend to greatly outperform methods based on assuming Gaussian priors. Figure B.3 show the analogue of Figure 4 for this data-generating process. Indeed, we see that INDEPENDENT-NPMLE improves over INDEPENDENT-GAUSS considerably, and similarly for CLOSE-NPMLE and ORACLE-GAUSS.

B.5. MSE in validation exercise with coupled bootstrap. We compare empirical Bayes procedures for the squared error estimation problem (Decision Problem 1), in the setting of the validation exercise in Section 5. Since this is an empirical application on real, rather than synthetic, data, we no longer have access to oracle estimators. As a result, for the relative MSE performance, we normalize by a different benchmark. We can think of the performance gain of INDEPENDENT-GAUSS over NAIVE as the value of doing basic, standard empirical Bayes shrinkage. We normalize each method’s estimated MSE improvement against NAIVE as a multiple of this “value of basic empirical Bayes.” Figure B.4(a) shows the resulting relative performance. Since our notion of relative performance has changed, we use a different color scheme. A value of 1 means that a method does exactly as well as INDEPENDENT-GAUSS, and a value of 2 means that, relative to NAIVE, a method doubles the gain of basic empirical Bayes. Performance on a non-relative scale is shown in Figure B.4(b).

We find that our empirical patterns from the calibrated simulation Figure 4 mostly persists on real data. In particular, INDEPENDENT-NPMLE offers small improvements over INDEPENDENT-GAUSS. Nevertheless, CLOSE-NPMLE continues to dominate other methods. Across the definitions of $\vartheta_i$, CLOSE-NPMLE generates a median of 180% the value of basic empirical Bayes. That is, on mean-squared error, moving from INDEPENDENT-GAUSS to CLOSE-NPMLE is about half as valuable as moving from NAIVE to INDEPENDENT-GAUSS. For our running example (TOP-20 PROBABILITY for Black individuals), moving from INDEPENDENT-GAUSS to CLOSE-NPMLE is more valuable than moving from NAIVE to INDEPENDENT-GAUSS. If practitioners find using the standard empirical Bayes method to be a worthwhile investment over using the raw estimates directly, then they may find using CLOSE-NPMLE over INDEPENDENT-GAUSS to be a similarly worthwhile investment.

B.6. Empirical Bayes pooling over all Commuting Zones in validation exercise. Here, we repeat the exercise in Figure 5, but we now estimate empirical Bayes methods pooling over all
Notes. In panel (a), each column is an empirical Bayes strategy that we consider, and each row is a different definition of $\theta_i$. The table shows relative performance, defined as the squared error improvement over NAIVE, normalized as a multiple of the improvement of INDEPENDENT-GAUSS over NAIVE. By definition, such a measure is zero for NAIVE and one for INDEPENDENT-GAUSS. The last row shows the column median. The mean-squared error estimates average over 100 coupled bootstrap draws. For the variable INCARCERATION for white individuals, the strategy INDEPENDENT-GAUSS underperform NAIVE, and the resulting ratio is thus undefined.

Panel (b) shows the difference in MSE against NAIVE.

Figure B.4. Estimated MSE Bayes risk for various empirical Bayes strategies in the validation exercise.

Commuting Zones. We still pick the top third of every Commuting Zone. Our first exercise repeats Figure 5 in this setting, shown in Figure B.5. The results are extremely similar.
Notes. These figures show the estimated performance of various decision rules over 100 coupled bootstrap draws. Performance is measured as the mean $\vartheta_i$ among selected Census tracts. All decision rules select the top third of Census tracts within each Commuting Zone. Figure (a) plots the estimated performance, averaged over 100 coupled bootstrap draws, with the estimated unconditional mean and standard deviation shown as the grey interval. Figure (b) plots the estimated performance gap relative to NAIVE, where we annotate with the estimated performance for CLOSE-NPMLE and INDEPENDENT-GAUS. Figure (c) plots the estimated performance gap relative to picking uniformly at random; we continue to annotate with the estimated performance. The shaded regions in Figure (c) have lengths equal to the unconditional standard deviation of the underlying parameter $\vartheta$.

Figure B.5. Performance of decision rules in top-$m$ selection exercise
Separately, we consider the version of this exercise without covariates in Figure B.6. We see that covariates are extremely important for the performance of independent-gauss, as it frequently underperforms naive without covariates. By comparison, they are less important for the performance of close-npmle, as $\sigma_i$ contains a lot of the signal in the tract-level covariates.

B.7. The tradeoff between accurate targeting and estimation precision. In this section, we investigate the tradeoff between accurate targeting and estimation precision. That is, suppose $\theta_i, Y_i, \sigma_i$ and $\vartheta_i, \Upsilon_i, \varsigma_i$ are two sets variables corresponding to two measures of economic mobility. For instance, perhaps $\theta_i$ is mean rank for Black individuals and $\vartheta_i$ is mean rank pooling over all individuals. Suppose the decision maker would like to select populations with high $\theta_i$, but the estimates $Y_i$ are noisier than the estimates $\Upsilon_i$. It is plausible that screening on posterior means for $\vartheta_i$ might outperform screening on posterior means for $\theta_i$.

We investigate this question via coupled bootstrap in the Bergman et al. (2023) exercise. In particular, we let the subscript $b$ (resp. $w$) denote quantities for Black (resp. white) individuals. We assume that $Y_{ib} \perp Y_{iw} \mid \theta_{ib}, \theta_{iw}$. For each tract, we construct $\pi_i = n_{ib}/n_i$, where $n_i$ (resp. $n_b$) is the number of (resp. Black) children under 18 living in the given tract with parents whose household income was below the national median. Let $\theta_i = \pi_i \theta_{ib} + (1 - \pi_i) \theta_{iw}$ be a pooled measure, where

$$Y_i = \pi_i Y_{ib} + (1 - \pi_i) Y_{iw} \mid \theta_i \sim \mathcal{N}(0, \pi_i^2 \sigma_{ib}^2 + (1 - \pi_i)^2 \sigma_{iw}^2).$$

Each coupled bootstrap draw adds and subtracts noise $Z_{ib}, Z_{iw}$ to $Y_{ib}$ and $Y_{iw}$, where $Z_{ib} \perp Z_{iw}$. Bootstrap draws for $Y_i$ are constructed by taking the $\pi$-combination of bootstrap draws for $Y_{ib}, Y_{iw}$.

Here, we investigate whether screening tracts based on posterior mean estimates for $\theta_{iw}$ or $\theta_i$ generates better decisions in terms of $\theta_{ib}$, owing to the precision in $Y_{iw}$ and $Y_i$. Figure B.7 shows estimated performances of different empirical Bayes methods by different proxy variables that the screening targets. For each measure of economic mobility for Black individuals, dots on the thick black dashed line correspond to screening on the corresponding $\theta_{ib}$. Dots on the red (resp. blue) dashed line correspond to screening on $\theta_{iw}$ (resp. $\theta_i$). We see that for all three measures of economic mobility, using close-npmle to screen on the original parameter $\theta_{ib}$ performs best. In other words, the benefits of higher precision are insufficient to offset inaccurate targeting.

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69 This is in part since our implementation of independent-gauss uses weighted means for estimating the prior parameters, worsening the misspecification. See Footnote 54.

70 This is the demographic weighting variable used in Chetty et al. (2020). We use this weighting to construct a pooled variable, rather than use the pooled variable in the Opportunity Atlas directly for the following reasons. The pooled estimates of Chetty et al. (2020) unfortunately frequently lies outside the convex hull of the white and Black estimates, making it difficult to infer the relative weights for Black individuals in a tract.
Notes. These figures show the estimated performance of various decision rules over 100 coupled bootstrap draws. There are no covariates to residualize against. Performance is measured as the mean $\vartheta_i$ among selected Census tracts. All decision rules select the top third of Census tracts within each Commuting Zone. Figure (a) plots the estimated performance, averaged over 100 coupled bootstrap draws, with the estimated unconditional mean and standard deviation shown as the grey interval. Figure (b) plots the estimated performance gap relative to **naive**, where we annotate with the estimated performance for **close-npmle** and **independent-gauss**. Figure (c) plots the estimated performance gap relative to picking uniformly at random; we continue to annotate with the estimated performance. The shaded regions in Figure (c) have lengths equal to the unconditional standard deviation of the underlying parameter $\vartheta$.

**Figure B.6.** Performance of decision rules in top-$m$ selection exercise (No covariates)
Notes. Estimated performance for different empirical Bayes methods by different proxy parameters. The performance of screening based on the raw $Y_{ib}$ is normalized to zero. All results are over 100 coupled bootstrap draws.

Figure B.7. Performances of strategies that screen on posterior means for more precisely estimated parameters

Part 3. Regret control proofs

Appendix C. Setup, assumptions, and notation

We recall some notation in the main text, and introduce additional notation. Recall that we assume $n \geq 7$. We observe $(Y_i, \sigma_i)_{i=1}^n, (Y_i, \sigma_i) \in \mathbb{R} \times \mathbb{R}_{>0}$ such that

$$Y_i \mid (\theta_i, \sigma_i) \sim \mathcal{N}(\theta_i, \sigma_i^2)$$

and $(Y_i, \theta_i, \sigma_i)$ are mutually independent. Assume that the joint distribution for $(\theta_i, \sigma_i)$ takes the location-scale form (2.6)

$$\theta_i \mid (\sigma_1, \ldots, \sigma_n) \sim G_0\left(\frac{\theta_i - m_0(\sigma_i)}{s_0(\sigma_i)}\right)$$

Define shorthands $m_{0i} = m_0(\sigma_i)$ and $s_{0i} = s_0(\sigma_i)$. Define the transformed parameter $\tau_i = \frac{\theta_i - m_{0i}}{s_{0i}}$, the transformed data $Z_i = \frac{Y_i - m_{0i}}{s_{0i}}$, and the transformed variance $\nu_i^2 = \frac{\sigma_i^2}{s_{0i}^2}$. By assumption,

$$Z_i \mid (\tau_i, \nu_i) \sim \mathcal{N}(\tau_i, \nu_i^2) \quad \tau_i \mid \nu_1, \ldots, \nu_n \text{ i.i.d. } G_0.$$

Let $\hat{\eta} = (\hat{m}, \hat{s})$ denote estimates of $m_0$ and $s_0$. Likewise, let $\hat{\eta}_i = (\hat{m}_i, \hat{s}_i) = (m(\sigma_i), s(\sigma_i))$. For a given $\hat{\eta}$, define

$$\hat{Z}_i = \hat{Z}_i(\hat{\eta}) = \hat{Z}_i(Z_i, \hat{\eta}) = \frac{Y_i - \hat{m}_i}{\hat{s}_i} = \frac{s_{0i}Z_i + m_{0i} - \hat{m}_i}{\hat{s}_i} = \frac{\nu_i^2}{\hat{s}_i^2}. $$

We will condition on $\sigma_{1:n}$ throughout, and hence we treat them as fixed.
Notes. This figure shows the estimated $E[\theta | \sigma]$ for mean income rank, pooling over all demographic groups. This is the measure of economic mobility used by Bergman et al. (2023). The estimation and the confidence band procedures are the same as those in Figure 1. In panel (a), $\theta_i, Y_i$ are defined as unresidualized measures of mean income rank. In panel (b), we treat $\theta_i, Y_i$ as residualized against a vector of tract-level covariates as specified in Appendix B.3.

Figure B.8. Estimated $E[\theta | \sigma]$ for mean income rank among those with parents at the 25th percentile

For generic $G$ and $\nu > 0$, define

$$f_{G, \nu}(z) = \int_{-\infty}^{\infty} \varphi \left( \frac{z - \tau}{\nu} \right) \frac{1}{\nu} G(d\tau).$$
Figure B.9. The analogue of Figure 1 where $Y_i, \theta_i$ are treated as residualized against a vector of covariates as specified in Appendix B.3.

Figure B.10. Absolute mean-squared error risk of key methods for the calibrated simulation in Figure 4.

to be the marginal density of some mixed normal deviate $Z \mid \tau \sim \mathcal{N}(\tau, \nu^2)$ with mixing distribution $\tau \sim G$. As a shorthand, we write

$$f_{i,G} = f_{G,\nu_i}(Z_i) \quad f'_{i,G} = f'_{G,\nu_i}(Z_i)$$

Let the average squared Hellinger distance be

$$\bar{h}^2(f_{G_1,:}, f_{G_2,:}) = \frac{1}{n} \sum_{i=1}^{n} h^2(f_{G_1,\nu_i}, f_{G_2,\nu_i}).$$
For generic values $\eta = (m, s)$ and distribution $G$, define the log-likelihood function

$$
\psi_i(z, \eta, G) = \psi_i(z, (m, s), G) = \log \int_{-\infty}^{\infty} \varphi \left( \frac{\hat{Z}_i(\eta) - \tau}{\hat{\nu}_i(\eta)} \right) G(d\tau) = \log \left( \hat{\nu}_i(\eta) \cdot f_{G, \hat{\nu}_i(\eta)}(\hat{Z}_i(\eta)) \right)
$$

Define

$$
\text{Sub}_n(G) = \left( \frac{1}{n} \sum_{i=1}^{n} \psi_i(Z_i, \eta_0, G) - \frac{1}{n} \sum_{i=1}^{n} \psi_i(Z_i, \eta_0, G_0) \right) + \text{C.1.}
$$

as the log-likelihood suboptimality of $G$ against the true distribution $G_0$, evaluated on the true, but unobserved, transformed data $Z_i, \nu_i$.

Fix some generic $G$ and $\eta = (m, s)$. The empirical Bayes posterior mean ignores the fact that $G, \eta$ are potentially estimated. The posterior mean for $\theta_i = s_i \tau + m_i$ is

$$
\hat{\theta}_{i,G,\eta} = m_i + s_i \mathbf{E}_{G,\hat{\nu}_i(\eta)}[\tau | \hat{Z}_i(\eta)].
$$

Here, we define $\mathbf{E}_{G,\nu}[h(\tau, Z) | z]$ as the function of $z$ that equals the posterior mean for $h(\tau, Z)$ under the data-generating model $\tau \sim G$ and $Z \sim \mathcal{N}(\tau, \nu)$. Explicitly,

$$
\mathbf{E}_{G,\nu}[h(\tau, Z) | z] = \frac{1}{f_{G,\nu}(z)} \int h(\tau, z) \varphi \left( \frac{z - \tau}{\nu} \right) \frac{1}{\nu} G(d\tau).
$$

Explicitly, by Tweedie’s formula,

$$
\mathbf{E}_{G,\hat{\nu}_i(\eta)}[\tau_i | \hat{Z}_i(\eta)] = \hat{Z}_i(\eta) + \hat{\nu}_i^2(\eta) \frac{f'_{G,\hat{\nu}_i(\eta)}(\hat{Z}_i(\eta))}{f_{G,\hat{\nu}_i(\eta)}(\hat{Z}_i(\eta))}.
$$

Hence, since $\hat{Z}_i(\eta) = \frac{Y_i - m_i}{s_i}$,

$$
\hat{\theta}_{i,G,\eta} = Y_i + s_i \hat{\nu}_i^2(\eta) \frac{f'_{G,\hat{\nu}_i(\eta)}(\hat{Z}_i(\eta))}{f_{G,\hat{\nu}_i(\eta)}(\hat{Z}_i(\eta))}.
$$

Define $\theta_i^* = \hat{\theta}_{i,G_0,\eta_0}$ to be the oracle Bayesian’s posterior mean. Fix some positive number $\rho > 0$, define a regularized posterior mean as

$$
\hat{\theta}_{i,G,\eta,\rho} = Y_i + s_i \hat{\nu}_i^2(\eta) \frac{f'_{G,\hat{\nu}_i(\eta)}(\hat{Z}_i(\eta))}{f_{G,\hat{\nu}_i(\eta)}(\hat{Z}_i(\eta))} \vee \frac{\rho}{\hat{\nu}_i(\eta)} \quad \text{C.2}
$$

and define $\theta_i^* = \hat{\theta}_{i,G_0,\eta_0,\rho}$ correspondingly.

Lastly, we will also define

$$
\varphi_+ (\rho) = \varphi^{-1}(\rho) = \sqrt{\frac{1}{2\pi \rho^2}} \quad \rho \in (0, (2\pi)^{-1/2}) \quad \text{C.3}
$$

so that $\varphi(\varphi_+(\rho)) = \rho$. Observe that $\varphi_+(\rho) \lesssim \sqrt{\log(1/\rho)}$.

**C.1. Assumptions.** Recall the assumptions we stated in the main text.
Assumption 1. Let \( \psi_i(Z_i, \hat{\eta}, G) \equiv \log \left( \int_{-\infty}^{\infty} \varphi \left( \frac{Z_i - \tau}{\nu_i} \right) G(d\tau) \right) \) be the objective function in (2.11), ignoring a constant factor \( 1/\nu_i \). We assume that \( \hat{G}_n \) satisfies
\[
\frac{1}{n} \sum_{i=1}^{n} \psi_i(Z_i, \hat{\eta}, \hat{G}_n) \geq \sup_{H \in P(\mathbb{R})} \frac{1}{n} \sum_{i=1}^{n} \psi_i(Z_i, \hat{\eta}, H) - \kappa_n
\]
for tolerance \( \kappa_n \)
\[
\kappa_n = \frac{2}{n} \log \left( \frac{n}{\sqrt{2\pi} \epsilon} \right). \tag{3.2}
\]
Moreover, we require that \( \hat{G}_n \) has support points within \( [\min \hat{Z}_i, \max \hat{Z}_i] \). To ensure that \( \kappa_n \) is positive, we assume that \( n \geq 7 = \lceil \sqrt{2\pi} \epsilon \rceil \).\(^7\)

Assumption 2. The distribution \( G_0 \) has zero mean, unit variance, and admits simultaneous moment control with parameter \( \alpha \in (0, 2] \): There exists a constant \( A_0 > 0 \) such that for all \( p > 0 \),
\[
(\mathbb{E}_{\tau \sim G_0} |\tau|^p)^{1/p} \leq A_0 p^{1/\alpha}. \tag{3.4}
\]

Assumption 3. The variances \( (\sigma_1, s_0) \) admit lower and upper bounds:
\[
0 < \sigma_{\ell} < \sigma_i < \sigma_u \quad \text{and} \quad s_{\ell} < s_0(\cdot) < s_u,
\]
where \( 0 < \sigma_{\ell}, \sigma_u, s_{0\ell}, s_{0u} < \infty \). This implies that \( 0 < \nu_{\ell} \leq \nu_i = \frac{\sigma_{\ell}}{s_0(\sigma_{\ell})} \leq \nu_u < \infty \) for some \( \nu_{\ell}, \nu_u \).

Assumption 4. Let \( C^p_A([\sigma_{\ell}, \sigma_u]) \) be the Hölder class of order \( p \geq 1 \) with maximal Hölder norm \( A_1 > 0 \) supported on \( [\sigma_{\ell}, \sigma_u] \).\(^7\) We assume that
\(1\) The true conditional moments are Hölder-smooth: \( m_0, s_0 \in C^p_A([\sigma_{\ell}, \sigma_u]) \).

Additionally, let \( \beta_0 > 0 \) be a constant. Let \( V \) be a set of bounded functions supported on \( [\sigma_{\ell}, \sigma_u] \) that (i) admits the uniform bound \( \sup_{f \in V} \|f\|_\infty \leq C A_1 \) and (ii) admits the metric entropy bound
\[
\log N(\epsilon, V, \|\cdot\|_\infty) \leq C A_1, p, \sigma_{\ell}, \sigma_u (1/\epsilon)^{1/p}.
\]
We assume that the estimators for \( m_0 \) and \( s_0 \), \( \hat{\eta} = (\hat{m}, \hat{s}) \), satisfy the following assumptions.
\(2\) For any \( \epsilon > 0 \), there exists a sufficiently large \( C = C(\epsilon) \), independently of \( n \), such that for all \( n \),
\[
\mathbb{P} \left( \max \left( \|\hat{m} - m_0\|_\infty, \|\hat{s} - s_0\|_\infty \right) > C(\epsilon) n^{-\frac{p}{2(p+1)}} (\log n)^{\beta_0} \right) < \epsilon.
\]
\(^7\)The constants \( \kappa_n \) also feature in Jiang (2020) to ensure that the fitted likelihood is bounded away from zero. The particular constants in \( \kappa_n \) are chosen to simplify expressions and are not material to the result.
\(^7\)We recall the definition of a Hölder class from van der Vaart and Wellner (1996), Section 2.7.1. We specialize its definition to functions of one real variable. For an integer \( p \), Hölder-\( p \) functions are \((p-1)\)-times differentiable, with a Lipschitz continuous \((p-1)^{th} \) derivative.

Definition 2. For some set \( \mathcal{X} \subset \mathbb{R} \) and constant \( A > 0, p > 0 \), let \( C^p_A(\mathcal{X}) \) be the set of continuous functions \( f : \mathcal{X} \to \mathbb{R} \) with \( \|f\|_{(p)} \leq A \). The norm \( \|\cdot\|_{(p)} \) is defined as follows. Let \( \overline{p} \) be the greatest integer strictly smaller than \( p \). Define
\[
\|f\|_{(p)} = \max_{k \leq \overline{p}} \sup_{x \in \mathcal{X}} \left| f^{(k)}(x) \right| + \sup_{x,y \in \mathcal{X}} \frac{\left| f^{(p)}(x) - f^{(p)}(y) \right|}{|x - y|^{p - \overline{p}}}. \]
We refer to \( C^p_A(\mathcal{X}) \) as a Hölder class of order \( p \) and \( \|f\|_{(p)} \) as the Hölder norm.
(3) The nuisance estimators take values in $\mathcal{V}$ almost surely: $P(\hat{m} \in \mathcal{V}, \hat{s} \in \mathcal{V}) = 1$.

(4) The conditional variance estimator respects the conditional variance bounds in Assumption 3: $P\left(\frac{2\pi}{2} < \hat{s} < 2s_0\right) = 1$.

C.2. Regret control: result statement. Define the regret as the difference between the mean-squared error of some feasible posterior means $\hat{\theta}_{i,G,\eta}$ against the mean-squared error of the oracle posterior means

$$
\text{MSERegret}_n(G, \eta) = \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_{i,G,\eta} - \theta_i)^2 - \frac{1}{n} \sum_{i=1}^{n} (\theta^*_{i} - \theta_i)^2
$$

$$
= \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_{i,G,\eta} - \theta^*_{i})^2 + \frac{2}{n} \sum_{i=1}^{n} (\theta^*_{i} - \theta_i)(\hat{\theta}_{i,G,\eta} - \theta^*_{i})
$$

(C.4)

(C.4) decomposes the MSE regret into a mean term that equals the mean-squared distance between the feasible posterior means and the oracle posterior means, as well as a term that is mean zero conditional on the data $Y_1, \ldots, Y_n$, since $\theta^*_{i} - \theta_i$ represents irreducible noise.

Fix sequences $\Delta_n > 0$ and $M_n > 0$. Define the following “good” event which we use in Theorem F.1:

$$
A_n = \left\{ \|\hat{\eta} - \eta\|_\infty \equiv \max(||\hat{m} - m_0||_\infty, ||\hat{s} - s_0||_\infty) \leq \Delta_n, \left\| \theta \right\| \leq \Delta_n \right\}. \quad (C.5)
$$

On the event $A_n$, the nuisance estimates $\hat{\eta}$ are good, and the data $Z_i$ are not too large. Note that, with $\Delta_n = C_1 n^{-2p/(p+1)}(\log n)^{\beta_0}$,

$$
A_n = A_n(C_1) \cap \{ \left\| Z \right\| \leq M_n \}
$$

where $A_n$ is the event in (3.5).

Here, we prove the version of our result stated in the main text.

**Theorem 1.** Assume Assumptions 1 to 4 hold. Then, for any $\delta \in (0, \frac{1}{2})$, there exists universal constants $C_{1,H,\delta} > 0$ and $C_{0,H,\delta} > 0$ such that (i) $P(A_n(C_{1,H,\delta})) \geq 1 - \delta$ and that (ii) the expected regret conditional on $A_n(C_{1,H,\delta})$ is dominated by the rate function

$$
\mathbb{E} \left[ \text{MSERegret}_n(\hat{G}_n, \hat{\eta}) \mid A_n(C_{1,H,\delta}) \right] \leq C_{0,H,\delta} n^{-2p/(p+1)}(\log n)^{2+3+2\beta_0}. \quad (3.6)
$$

**Proof.** Immediately by Assumption 4(2–3), we can choose $C_{1,H}$ so that $P(A_n(C_{1,H})) \geq 1 - \delta$. Let $\Delta_n = C_{1,H} n^{-2p/(p+1)}(\log n)^{\beta_0}$ and $M_n = C(\log n)^{1/\alpha}$ for some $C$ to be chosen. Both $C_{1,H}$ and $C$ may depend on $\delta$. Moreover, we can decompose

$$
\mathbb{E} \left[ \text{MSERegret}_n(\hat{G}_n, \hat{\eta}) \mid A_n(C_{1,H}) \right]
$$

$$
\leq \frac{1}{1 - \delta} \left\{ \mathbb{E} \left[ \text{MSERegret}_n(\hat{G}_n, \hat{\eta}) 1(A_n) \right] + \mathbb{E} \left[ \text{MSERegret}_n(\hat{G}_n, \hat{\eta}) 1(A_n, \left\| \theta \right\| > M_n) \right] \right\}
$$

$$
\lesssim_{\mathcal{H}} n^{-2p/(p+1)}(\log n)^{2+3+2\beta_0} + \frac{1}{n}(\log n)^{2/\alpha}
$$

(Theorem F.1 and Lemma F.1)
Note that the application of Theorem F.1 and Lemma F.1 implicitly picks some constant for $M_n = C(\log n)^{1/\alpha}$. This concludes the proof.

**Corollary 1.** Assume the same setting as Theorem 1. Suppose, additionally, for all sufficiently large $C_{1,H} > 0$, $P(A_n(C_{1,H})) \geq 1 - n^{-2}$. Then, there exists a constant $C_{0,H} > 0$ such that the expected regret is dominated by the rate function

$$
\text{BayesRegret}_n = E\left[\text{MSERegret}_n(\hat{G}_n, \hat{\eta})\right] \leq C_{0,H} n^{-\frac{2p}{p+1}} (\log n)^{\frac{2+\alpha}{\alpha} + 3 + 2\beta_0}.
$$

**Proof.** Let $\Delta_n, M_n$ as in the proof of Theorem 1. Decompose

$$
E[\text{MSERegret}_n(\hat{G}_n, \hat{\eta})] = E[\text{MSERegret}_n(\hat{G}_n, \hat{\eta}) 1(A_n)] + E[\text{MSERegret}_n(\hat{G}_n, \hat{\eta}) 1(A_n^c)]
$$

$$
= E[\text{MSERegret}_n(\hat{G}_n, \hat{\eta}) 1(A_n)] + E[\text{MSERegret}_n(\hat{G}_n, \hat{\eta}) 1(A_n^c \cup \{Z_n > M_n\})] 
$$

$$
\leq E[\text{MSERegret}_n(\hat{G}_n, \hat{\eta}) 1(A_n)] + E[\text{MSERegret}_n(\hat{G}_n, \hat{\eta}) 1(A_n^c)] 
$$

$$
+ E[\text{MSERegret}_n(\hat{G}_n, \hat{\eta}) 1(Z_n > M_n)] 
$$

$$
\lesssim H n^{-\frac{2p}{p+1}} (\log n)^{\frac{2+\alpha}{\alpha} + 3 + 2\beta_0} + \frac{2}{n} (\log n)^{2/\alpha} \tag{Theorem F.1 and Lemma F.1}
$$

where our application of Lemma F.1 uses the assumption that $P(A_n(C_{1,H})^C) = \mathbb{1}(\|\hat{\eta} - \eta\|_\infty > \Delta_n) \leq \frac{1}{n^2}$.

**Remark C.1** (Relaxing Assumption 4(4)). Note that the event $A_n(C)$ implies $s_0/2 \leq \hat{s} \leq 2s_0$. Since we condition on $A_n(C)$ in Theorem 1, we can drop Assumption 4(3) by only requiring (3.6) to hold for all sufficiently large $n$. This is a minor modification since Theorem 1 is an upper bound on the convergence rate. On the other hand, dropping Assumption 4(4) does affect regret control on the event $A_n^C(C_1)$ below. Our truncation rule for $\hat{s}(\cdot)$ in Appendix G ensures that $\hat{s}(\cdot) \geq \frac{\hat{s}}{n}$. We show in Appendix G that this is sufficient for the conclusion of Corollary 1.

**C.3. Regret control: proof ideas.** We now discuss the main ideas and the structure of our argument. Existing work (Soloff et al., 2021) controls the following quantity, in our notation,

$$
E\left[\text{MSERegret}_n(\hat{G}_n, \hat{\eta})\right] = E\left[\frac{1}{n} \sum_{i=1}^{n} (\hat{\tau}_{i, \hat{G}_n, \hat{\eta}} - \tau^*_n)^2\right] \tag{C.6}
$$

where $\hat{\tau}_{i, \hat{G}_n, \hat{\eta}} = E_{G_n, \eta_1} [\tau | Z_i]$ and $\hat{G}_n$ is an approximate NPMLE on the data $(Z_i, \nu_i)_{i=1}^{n}$ (Theorem 8 in Soloff et al. (2021)).

They do so by showing that, loosely speaking,

\[\text{This lower bound on } \hat{s} \text{ also adds enough regularity to avoid writing “sufficiently large } n \text{” for the statement analogous to Theorem 1 as well. See Appendix G for details.}\]
(i) For some constant $C$ and rate function $\delta_n$, with high probability, the NPMLE achieves low average squared Hellinger distance:

$$P\left(\tilde{H}^2(\hat{f}_{G_n^*}, f_{G_0}) > C\delta^2_n\right) < \frac{1}{n}.$$  

This is because distributions $G$ that achieve high likelihood—which $G^*_n$ does by construction—tend to have low average squared Hellinger distance with respect to $G_0$ (Theorem 6 in Soloff et al. (2021)). Roughly speaking, the rate function is linked to likelihood suboptimality (C.1):

$$\delta^2_n \propto \max\left(\text{Sub}_n(\hat{G}_n), \frac{1}{n}(\log n)^{\frac{2p}{2p+1}}+1\right). \quad \text{(C.7)}$$

(ii) For a fixed distribution $G$, the deviation from oracle between the regularized posterior means (C.2) is bounded by the average squared Hellinger distance:

$$\mathbb{E}[(\hat{\tau}_{i,G,\eta_0,\rho_n} - \tau^*_{i,\rho_n})^2] \lesssim (\log(1/\rho_n))^{3\tilde{H}^2(\hat{f}_{G^*}, f_{G_0})}.$$ \quad \text{(C.8)}

Therefore, we should expect that the rate attained is $\log(1/\rho_n)^3\delta^2_n$, subjected to resolving the following two issues.

(iii) Additional arguments can handle the difference between (C.8) and (C.6).

(iv) Additional empirical process arguments can handle the fact that $\hat{G}_n^*$ is estimated.

Our proof adapts this argument, where the key challenge is that we only observe $(\hat{Z}_i, \hat{\nu}_i)$ instead of $(Z_i, \nu_i)$. As an outline,

- Appendix D (Theorem D.1 and Corollary D.1) establishes that $\hat{G}_n$, estimated off $(\hat{Z}_i, \hat{\nu}_i)$, achieves high likelihood (i.e., low $\text{Sub}_n(\hat{G}_n)$) on the data $(Z_i, \nu_i)$, with high probability. This is an oracle inequality in the sense that it bounds the performance degredation of $\hat{G}_n$ relative to a setting where $\eta_0$ is known.

- Appendix E (Theorem E.1 and Corollary E.2) establishes that $\hat{G}_n$, with high probability, achieves low Hellinger distance. This is a result of independent interest, as it characterizes the quality of $f_{\hat{G}_n,\nu_i}$ as an estimate of the true density $f_{G_0,\nu_i}$.

- Appendix F (Theorem F.1) establishes that the regret of $\hat{\theta}_{i,G_n,\hat{\eta}}$ is low, using the argument controlling (C.6).

C.3.1. Intuition for Appendix D. The argument in Appendix D is our most novel theoretical contribution. Note that, by (C.7), to obtain a rate of the form $\delta^2_n = n^{-\frac{2p}{2p+1}}(\log n)\gamma$, \footnote{We let $(\log n)^\gamma$ denote a generic logarithmic factor, and we will not keep track of $\gamma$ throughout this heuristic discussion.} we would require that $\text{Sub}_n(\hat{G}_n) \lesssim n^{-\frac{2p}{2p+1}}(\log n)^\gamma$. However, such a rate is not immediately attainable. To see this, note that a direct Taylor expansion in $\eta$ of the log-likelihood yields

$$\frac{1}{n} \sum_i \psi_i(Z_i, \hat{\eta}, \hat{G}_n) - \frac{1}{n} \sum_i \psi_i(Z_i, \eta_0, \hat{G}_n) \approx \frac{1}{n} \sum_i \left(\frac{\partial \psi_i}{\partial \eta_i}\right)'(\hat{\eta}_i - \eta_0) + \frac{1}{2n} \sum_i (\hat{\eta}_i - \eta_0)\frac{\partial^2 \psi_i}{\partial \eta_i^2}(\hat{\eta}_i - \eta_0). \quad \text{(C.9)}$$
an upper bound for using standard arguments in the literature. This is now feasible since the event \((C.10)\) comes with \(\gamma\) for some rates \(\lambda\).

Thus, without somehow showing that the first-order term \(\frac{\partial \psi_i}{\partial \eta_i}\) converges to zero, we would only be able to obtain \(\text{Sub}_n(\hat{G}_n) \lesssim n^{-\frac{p}{2r+1}}(\log n)^\gamma\), which is insufficient.

Fortunately, it is easy to compute that the expected first derivative, evaluated at \(G_0\), is zero:

\[
\mathbb{E}\left[\frac{\partial \psi_i(Z, G_0, \eta)}{\partial \eta_i}\right] = 0.
\]

As a result, we expect that if \(\hat{G}_n\) is close to \(G_0\), then the corresponding first-order terms for \(\hat{G}_n\) will also be small. More precisely, it is possible to bound the first-order term in terms of the average squared Hellinger distance, yielding

\[
\left|\frac{1}{n} \sum_i \left(\left.\frac{\partial \psi_i}{\partial \eta_i}\right|_{\eta_i - \eta_{0i}}\right)\right| \lesssim n^{-\frac{p}{2r+1}}(\log n)^\gamma \bar{h}(f_{\hat{G}_n}, f_{G_0}^\cdot).
\]

To summarize, through our calculation, the rate we obtain (Corollary D.1, (D.3)) for \(\text{Sub}_n(\hat{G}_n)\) is

\[
\varepsilon_n = (\log n)^\gamma \left\{n^{-\frac{p}{2r+1}} \bar{h}(f_{\hat{G}_n}, f_{G_0}^\cdot) + n^{-\frac{2p}{2r+1}}\right\}.
\]

A more detailed breakdown is presented in Appendix D.2.4.

C.3.2. Intuition for Appendix E. Since the rate for \(\text{Sub}_n(\hat{G}_n)\) from Appendix D itself includes \(\bar{h}\), it is necessary to adapt the argument in the literature on Hellinger rate control (See, e.g., Theorem 4 in Jiang, 2020).

Our argument proceeds by observing that, with high probability,

\[
\text{Sub}_n(\hat{G}_n) \lesssim \gamma_n^2 + \bar{h}(f_{\hat{G}_n}, f_{G_0})\lambda_n.
\]

for some rates \(\gamma_n, \lambda_n\). Then, we separately bound, for \(k = 1, \ldots, K\),

\[
P\left[C\lambda_n^{1-2-k} \leq \bar{h}(f_{\hat{G}_n}, f_{G_0}) \leq C\lambda_n^{1-2-k+1}, \text{Sub}_n(\hat{G}_n) \lesssim \gamma_n^2 + \bar{h}(f_{\hat{G}_n}, f_{G_0})\lambda_n\right]
\]

\[
\leq P\left[C\lambda_n^{1-2-k} \leq \bar{h}(f_{\hat{G}_n}, f_{G_0}) \leq C\lambda_n^{1-2-k+1}, \text{Sub}_n(\hat{G}_n) \lesssim \gamma_n^2 + \lambda_n^{1-2-k+1}\lambda_n\right]
\]

using standard arguments in the literature. This is now feasible since the event \((C.10)\) comes with an upper bound for \(\bar{h}\). Thus, by a union bound,

\[
P\left(\bar{h}(f_{\hat{G}_n}, f_{G_0}) > C\lambda_n \cdot \lambda_n^{2-2-k}\right) \approx \frac{K}{n}.
\]

We can choose \(K \to \infty\) appropriately slowly so as to obtain \(\bar{h}^2 \lesssim \delta_n^2\) with high probability.

C.3.3. Intuition for Appendix F. All that is remaining before we can use the bound \((C.6)\) directly is dealing with the difference between \(\hat{\theta}_{i, \hat{G}_n, \hat{\eta}}\) and \(\tau_{i, \hat{G}_n, \eta}\). In Appendix F.3, we can use a Taylor expansion to control the distance

\[
\left|\hat{\theta}_{i, \hat{G}_n, \hat{\eta}} - \hat{\theta}_{i, \hat{G}_n, \eta}\right| = \sigma_i^2 \left|\frac{f'_{\hat{G}_n, \hat{\eta}}(\hat{Z}_i)}{s_{i, \hat{G}_n, \hat{\eta}}(\hat{Z}_i)} - \frac{f'_{\hat{G}_n, \eta}(Z_i)}{s_{0, \hat{G}_n, \eta}(Z_i)}\right| = \sigma_i \left|\frac{\partial \psi_i}{\partial m} \hat{G}_n, \hat{\eta} - \frac{\partial \psi_i}{\partial m} \hat{G}_n, \eta\right|.
\]
Doing so requires bounding the second derivatives of \( \psi_i \), which are posterior moments under \( \hat{G}_n \) (Appendix D.10), and hence bounded due to assuming that \( \hat{G}_n \) has supported bounded within the range of the data \( \hat{Z}_i \) (Lemma D.14). We then immediately find that
\[
\left| \hat{\theta}_{i, \hat{G}_n, \eta_0} - \hat{\theta}_{i, G_0, \eta_0} \right|
\]
is proportional to the difference in \( \tau \)-space. Therefore, the existing argument for (C.6) controls the regret.

**Appendix D. An oracle inequality for the likelihood**

Recall that for some fixed \( \Delta_n, M_n \), we define \( A_n = \{ \| \hat{\eta} - \eta \|_\infty \leq \Delta_n, \bar{Z}_n \leq M_n \} \). In this section, we bound
\[
P \left[ A_n, \text{Sub}_n(\hat{G}_n) \geq_H \epsilon_n \right]
\]
for some rate function \( \epsilon_n \). It is convenient to state a set of high-level assumptions on the rates \( \Delta_n, M_n \). These are satisfied for \( \Delta_n \asymp n^{-p/(2p+1)}(\log n)^\beta, M_n \asymp (\log n)^{1/\alpha} \).

**Assumption D.1.** Assume that

1. \( \frac{1}{\sqrt{n}} \preceq_H \Delta_n \preceq_H \frac{1}{M_n} \preceq_H 1 \)
2. \( \log n \preceq_H M_n \)

Note that there exists \( \rho_n \) by Lemma D.9 that lower bounds the density \( f_{\hat{G}_n, \nu_i}(z) \) for all \( Z_i \). Then our main result is an oracle inequality.

**Theorem D.1.** Let \( \| \hat{\eta} - \eta \|_\infty = \max(\| \hat{\eta} - \eta \|_\infty, \| \hat{\eta} - \eta \|_\infty) \) and \( \bar{Z}_n = \max_{i \in [n]} |Z_i| \vee 1 \). Suppose \( \hat{G}_n \) satisfies Assumption 1. Under Assumptions 2 to 4 and D.1, there exists constants \( C_{1, \mathcal{H}, C_2, \mathcal{H}} > 0 \) such that the following tail bound holds: Let
\[
\epsilon_n = M_n \sqrt{\log n \Delta_n} \frac{1}{n} \sum_{i=1}^{n} h \left( f_{\hat{G}_n, \nu_i}, f_{\hat{G}_0, \nu_i} \right) + \Delta_n M_n \sqrt{\log n} e^{-C_{2, \mathcal{H}} M_n} + \Delta_n^2 M_n^2 \log n + M_n^2 \Delta_n^{1 - \frac{1}{p}} \sqrt{n}.
\]

Then,
\[
P \left[ \bar{Z}_n \leq M_n, \| \hat{\eta} - \eta \|_\infty \leq \Delta_n, \text{Sub}_n(\hat{G}_n) > C_{1, \mathcal{H}} \epsilon_n \right] \leq \frac{9}{n}.
\]

The following corollary plugs in some concrete rates for \( \Delta_n, M_n \) and verifies that they satisfy Assumption D.1.

**Corollary D.1.** For \( \beta \geq 0 \), suppose
\[
\Delta_n = C_{\mathcal{H}} n^{-\frac{p}{2p+1}}(\log n)^\beta \text{ and } M_n = (C_{\mathcal{H}} + 1)(C_{2, \mathcal{H}}^{-1} \log n)^{1/\alpha}.
\]

Then there exists a \( C_{\mathcal{H}}^* \) such that the following tail bound holds. Suppose \( \hat{G}_n \) satisfies Assumption 1. Under Assumptions 2 to 4, define \( \epsilon_n \) as:
\[
\epsilon_n = n^{-\frac{p}{2p+1}}(\log n)^{\frac{2\alpha}{\alpha} + \beta} \left( f_{\hat{G}_n, \nu}, f_{\hat{G}_0, \nu} \right) + n^{-\frac{2\alpha}{2p+1}}(\log n)^{\frac{2\alpha}{\alpha} + 2\beta},
\]
we have that,
\[
P \left[ \bar{Z}_n \leq M_n, \| \hat{\eta} - \eta \|_\infty \leq \Delta_n, \text{Sub}_n(\hat{G}_n) > C_{\mathcal{H}}^* \epsilon_n \right] \leq \frac{9}{n}.
\]
The constant $C_H$ in $\Delta_n, M_n$ affects the conclusion of the statement only through affecting the constant $C_H^*$. 

D.1. Proof of Corollary D.1. We first show that the specification of $\Delta_n$ and $M_n$ means that the requirements of Assumption D.1 are satisfied. Among the requirements of Assumption D.1:

(1) is satisfied since the polynomial part of $\Delta_n$ converges to zero slower than $n^{-1/2}$, but converges to zero faster than any logarithmic rate. $M_n$ is a logarithmic rate.

(2) is satisfied since $\alpha \leq 2$.

We also observe that by Jensen’s inequality,

$$\frac{1}{n} \sum_{i=1}^{n} h(f_{\hat{G}_n, i}, f_{G_0, i}) \leq h(f_{\hat{G}_n}, f_{G_0}),$$

and so we can replace the corresponding factor in $\epsilon_n$ by $h$. Now, we plug the rates $\Delta_n, M_n$ into $\epsilon_n$. We find that the term

$$\Delta_n M_n e^{-C_H M_n^2} = \Delta_n M_n^2 e^{-(C_H+1)^2 n} \leq \Delta_n M_n^2 n^{-1} \leq \frac{1}{n} \Delta_n M_n^2 \lesssim_H \Delta_n^2 M_n^2 \log n$$

since $\log n > 1$ as $n > \sqrt{2\pi e}$ by Assumption 1. Plugging in the rates for the other terms, we find that

$$\epsilon_n \lesssim_H \epsilon_n.$$ 

Therefore, Corollary D.1 follows from Theorem D.1.


D.2.1. Decomposition of $\text{Sub}_n(\hat{G}_n)$. Observe that, by definition of $\hat{G}_n$ in (3.2),

$$\frac{1}{n} \sum_{i=1}^{n} \psi(Z_i, \hat{\eta}, \hat{G}_n) - \frac{1}{n} \sum_{i=1}^{n} \psi(Z_i, \eta_0, \hat{G}_n) \geq \kappa_n$$

For random variables $a_n, b_n$ such that almost surely

$$\left| \frac{1}{n} \sum_{i=1}^{n} \psi(Z_i, \hat{\eta}, \hat{G}_n) - \psi(Z_i, \eta_0, \hat{G}_n) \right| \leq a_n$$

$$\left| \frac{1}{n} \sum_{i=1}^{n} \psi(Z_i, \hat{\eta}, G_0) - \psi(Z_i, \eta_0, G_0) \right| \leq b_n$$

we have

$$\frac{1}{n} \sum_{i=1}^{n} \psi(Z_i, \eta_0, \hat{G}_n) - \frac{1}{n} \sum_{i=1}^{n} \psi(Z_i, \eta_0, G_0) \geq -a_n - b_n - \kappa_n$$

and

$$\text{Sub}_n(\hat{G}_n) \leq a_n + b_n + \kappa_n.$$ 

Therefore, it suffices to show large deviation results for $a_n$ and $b_n$.

D.2.2. Taylor expansion of $\psi(Z_i, \hat{\eta}, \hat{G}_n) - \psi(Z_i, \eta_0, \hat{G}_n)$. Define $\Delta_m = \hat{m}_i - m_0$, $\Delta_s = \hat{s}_i - s_0$, and $\Delta = [\Delta_m, \Delta_s]'$. Recall $\|\hat{\eta} - \eta\|_\infty = \max(\|s - s_0\|_\infty, \|m - m_0\|_\infty)$ as in (C.5). Since $\psi(Z_i, \eta, G)$
is smooth in \((m_i, s_i) \in \mathbb{R} \times \mathbb{R}_{>0}\), we can take a second-order Taylor expansion:

\[
\psi_i(Z_i, \hat{\eta}, \hat{G}_n) - \psi_i(Z_i, \eta_0, \hat{G}_n) = \frac{\partial \psi_i}{\partial m_i} \bigg|_{\eta_0, \hat{G}_n} \Delta_{mi} + \frac{\partial \psi_i}{\partial s_i} \bigg|_{\eta_0, \hat{G}_n} \Delta_{si} + \frac{1}{2} \Delta_i H_i(\hat{\eta}_i, \hat{G}_n) \Delta_i
\]  

(D.4)

where \(H_i(\hat{\eta}_i, \hat{G}_n)\) is the Hessian matrix \(\frac{\partial^2 \psi_i}{\partial m_i \partial \eta_i}\) evaluated at some intermediate value \(\hat{\eta}_i\) lying on the line segment between \(\hat{\eta}_i\) and \(\eta_0\).

We further decompose the first-order terms into an empirical process term and a mean-component term. By Lemma D.9, (D.26), and (D.28), for

\[
\rho_n = \frac{1}{n^3} e^{-C_n M_n^2} \Delta_n \wedge \frac{1}{e \sqrt{2\pi}},
\]  

(D.5)

we have that the numerators to the first derivatives can be truncated at \(\rho_n\), as the truncation does not bind:

\[
\frac{\partial \psi_i}{\partial m_i} \bigg|_{\eta_0, \hat{G}_n} = -\frac{1}{s_i} \frac{f_i': \hat{G}_n}{\hat{f}_i: \hat{G}_n} \equiv D_{m,i}(Z_i, \hat{G}_n, \eta_0, \rho_n)
\]

\[
\frac{\partial \psi_i}{\partial s_i} \bigg|_{\eta_0, \hat{G}_n} = \frac{s_i}{\sigma_i^2} \frac{Q_i(\eta_i, \eta_0, \hat{G}_n)}{\hat{f}_i: \hat{G}_n \vee 2U_i} \equiv D_{s,i}(Z_i, \hat{G}_n, \eta_0, \rho_n).
\]

Let

\[
D_{k,i}(\hat{G}_n, \eta_0, \rho_n) = \int D_{k,i}(Z, \hat{G}_n, \eta_0, \rho_n) f_{G_0, \nu_i}(z) dz \quad \text{for } k \in \{m, s\}
\]

be the mean of \(D_{k,i}\). Then, for \(k \in \{m, s\}\),

\[
\frac{\partial \psi_i}{\partial k_i} \bigg|_{\eta_0, \hat{G}_n} \Delta_{ki} = \left[D_{k,i}(Z_i, \hat{G}_n, \eta_0, \rho_n) - D_{k,i}(\hat{G}_n, \eta_0, \rho_n)\right] \Delta_{ki} + D_{k,i}(\hat{G}_n, \eta_0, \rho_n) \Delta_{ki}
\]

Hence, we can decompose the first-order terms in \(a_n\) as

\[
\frac{1}{n} \sum_{i=1}^{n} \frac{\partial \psi_i}{\partial k_i} \bigg|_{\eta_0, \hat{G}_n} \Delta_{ki} = \frac{1}{n} \sum_{i=1}^{n} D_{k,i}(\hat{G}_n, \eta_0, \rho_n) \Delta_{ki} + \frac{1}{n} \sum_{i=1}^{n} \left[D_{k,i}(Z_i, \hat{G}_n, \eta_0, \rho_n) - D_{k,i}(\hat{G}_n, \eta_0, \rho_n)\right] \Delta_{ki}
\]

\[
\equiv U_{1k} + U_{2k}
\]

Let the second order term be \(R_1 = \frac{1}{n} \sum_i R_{1i}\). We let \(a_n = |R_1| + \sum_{k \in \{m, s\}} |U_{1k}| + |U_{2k}|\)

D.2.3. **Taylor expansion of \(\psi_i(Z_i, \hat{\eta}, G_0) - \psi_i(Z_i, \eta_0, G_0)\).** Like (D.4), we similarly decompose

\[
\psi_i(Z_i, \hat{\eta}, G_0) - \psi_i(Z_i, \eta_0, G_0) = \frac{\partial \psi_i}{\partial m_i} \bigg|_{\eta_0, G_0} \Delta_{mi} + \frac{\partial \psi_i}{\partial s_i} \bigg|_{\eta_0, G_0} \Delta_{si} + \frac{1}{2} \Delta_i H_i(\hat{\eta}_i, G_0) \Delta_i
\]

(D.6)

\[
= \sum_{k \in \{m, s\}} D_{k,i}(Z_i, G_0, \eta_0, 0) \Delta_{ki} + R_{2i}
\]

\[
\equiv U_{3mi} + U_{3si} + R_{2i},
\]

(D.7)

Let \(U_{3k} = \frac{1}{n} \sum_i U_{3ki}\) for \(k \in \{m, s\}\) and let \(R_2 = \frac{1}{n} \sum_i R_{2i}\). We let \(b_n = |R_2| + \sum_{k \in \{m, s\}} |U_{3k}| + |U_{3k}|\)

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D.2.4. Bounding each term individually. By our decomposition, we can write

\[ a_n + b_n + \kappa_n \leq \kappa_n + |R_1| + |R_2| + \sum_{k \in \{m,s\}} |U_{1k}| + |U_{2k}| + |U_{3k}| \]

The ensuing subsections bound each term individually. Here we give an overview of the main ideas:

1. We bound \( \mathbb{1}(A_n)|U_{1m}| \) in almost sure terms in Lemma D.1 by observing that \( |\mathcal{D}_{mi}| \) is small when \( \hat{G}_n \) is close to \( G_0 \), since \( \mathcal{D}_{mi}(G_0, \eta_0, 0) = 0 \). To do so, we need to control the differences

\[ \mathcal{D}_{mi}(\hat{G}_n, \eta_0, \rho_n) - \mathcal{D}_{mi}(G_0, \eta_0, \rho_n) \]

and

\[ \mathcal{D}_{mi}(G_0, \eta_0, \rho_n) - \mathcal{D}_{mi}(G_0, \eta_0, 0) = \mathcal{D}_{mi}(G_0, \eta_0, \rho_n). \]

Controlling the first difference features the Hellinger distance, while controlling the second relies on the fact that \( P_{X \sim f(X)}(f(X) \leq \rho) \) cannot be too large, by a Chebyshev’s inequality argument in Lemma D.12. Similarly, we bound \( \mathbb{1}(A_n)|U_{1s}| \) in Lemma D.2.

2. The empirical process terms \( U_{2m}, U_{2s} \) are bounded probabilistically in Lemmas D.3 and D.4 with statements of the form

\[ P(A_n, |U_{2k}| > c_1) \leq c_2. \]

To do so, we upper bound \( \mathbb{1}(A_n)U_{2k} \leq U_{2k} \) in almost sure terms. The upper bound is obtained by projecting \( \hat{G}_n \) onto a \( \omega \)-net of \( \mathcal{P}(\mathbb{R}) \) in terms of some pseudo-metric \( d_{k, \infty, M_n} \) induced by \( \overline{D}_{k,i} \). The upper bound \( U_{2k} \) then takes the form

\[ \omega \Delta_n + \max_{j \in \mathbb{N}} \sup_{\eta \in S} \left| \frac{1}{n} \sum_i (D_{ki} - \overline{D}_{ki})(\eta_i - \eta_0) \right| \leq N(\omega, \mathcal{P}(\mathbb{R}), d_{k, \infty, M_n}). \]

Large deviation of \( U_{2k} \) is further controlled by applying Dudley’s chaining argument (Vershynin, 2018), since the entropy integral over Hölder spaces is well-behaved. The covering number \( N \) is controlled via Proposition D.1 and Proposition D.2, which are minor extensions to Lemma 4 and Theorem 7 in Jiang (2020). The covering number is of a manageable size since the induced distributions \( f_{G,\nu_1} \) are very smooth.

3. Since \( \overline{D}_{k,i}(G_0, \eta_0, 0) = 0 \), \( U_{3m}, U_{3s} \) are effectively also empirical process terms, without the additional randomness in \( \hat{G}_n \). Thus the \( \omega \)-net argument above is unnecessary for \( U_{3m}, U_{3s} \), whereas the bounding follows from the same Dudley’s chaining argument. Lemma D.6 bounds \( U_{3k} \).

4. For the second derivative terms \( R_1, R_2, \) we observe that the second derivatives take the form of functions of posterior moments. The posterior moments under prior \( \hat{G}_n \) is bounded within constant factors of \( M_n^\alpha \) since the support of \( G_n \) is restricted. The posterior moments under prior \( G_0 \) is bounded by \( |Z_r|^\beta \lesssim H M_n^\alpha \) as we show in Lemma D.18, thanks to the simultaneous moment control for \( G_0 \). Hence \( \mathbb{1}(A_n)R_1 \) can be bounded in almost sure terms. We bound \( \mathbb{1}(A_n)R_2 \) probabilistically. The second derivatives are bounded in Lemmas D.5 and D.7.

(1) and (4) above bounds \( U_{1k}, R_1, R_2 \) almost surely under \( A_n \). (2) and (3) bounds \( U_{2k}, U_{3k} \) probabilistically. By a union bound in Lemma D.17, we can simply add the rates. Doing so, we find that the first term in \( \epsilon_n \) (D.1) comes from \( U_{1s} \), which dominates \( U_{1m} \). The second term comes
from $U_{2s}$, which dominates $U_{2m}$. The third term comes from $R_1$, which dominates $R_2$. The fourth term comes from $U_{3s}$. The leading terms in $\epsilon_n$ dominate $\kappa_n$, recalling (3.3). This completes the proof.

Before we proceed to the individual lemmas, we highlight a few convenient facts:

- The support of $\hat{G}_n$ is within $[-M_n, M_n]$, where $M_n = \max_i |\tilde{Z}_i(\hat{\eta})| \lor 1$. Under Assumption D.1, 1($A_n$)$M_n \lesssim \mathcal{H} M_n$ by Lemma D.11(3).
- As a result, moments of $\hat{G}_n$ and $f_{\hat{G}_n, \nu_1}$ is bounded by appropriate moments of $M_n$, up to constants, under $A_n$.

### D.3. Bounding $U_{1m}$.

**Lemma D.1.** Under Assumptions 1 to 4, assume additionally that $\|\hat{\eta} - \eta\|_\infty \leq \Delta_n$, $Z_n \leq M_n$. Assume that the rates satisfy Assumption D.1. Then

$$|U_{1m}| \equiv \left| \frac{1}{n} \sum_{i=1}^{n} D_{mi}(\hat{G}_n, \eta_0, \rho_n) \Delta_{mi} \right| \lesssim_{\mathcal{H}} \Delta_n \left[ \frac{\log n}{n} \sum_{i=1}^{n} h(f_{G_0, \nu_1}, f_{\hat{G}_n, \nu_1}) + \frac{M_n^{1/3}}{n} \right]. \quad (D.8)$$

**Proof.** Note that

$$|D_{mi}(\hat{G}_n, \eta_0, \rho_n)| \lesssim_{\mathcal{H}} \left| \int \frac{f'_{\hat{G}_n, \nu_1}(z)}{f_{\hat{G}_n, \nu_1}(z) \lor \frac{\rho_n}{\nu_1}} f_{G_0, \nu_1}(z) dz \right|$$

$$= \left| \int \frac{f'_{\hat{G}_n, \nu_1}(z)}{f_{\hat{G}_n, \nu_1}(z) \lor \frac{\rho_n}{\nu_1}} [f_{G_0, \nu_1}(z) - f_{\hat{G}_n, \nu_1}(z) + f_{\hat{G}_n, \nu_1}(z)] dz \right|$$

$$\leq \left| \int \frac{f'_{\hat{G}_n, \nu_1}(z)}{f_{\hat{G}_n, \nu_1}(z) \lor \frac{\rho_n}{\nu_1}} [f_{G_0, \nu_1}(z) - f_{\hat{G}_n, \nu_1}(z)] dz \right| \quad (D.9)$$

$$+ \left| \int \frac{f'_{\hat{G}_n, \nu_1}(z)}{f_{\hat{G}_n, \nu_1}(z) \lor \frac{\rho_n}{\nu_1}} f_{\hat{G}_n, \nu_1}(z) dz \right| \quad (D.10)$$

By the bounds for (D.9) and (D.10) below, we have that

$$|U_{1m}| \lesssim_{\mathcal{H}} \Delta_n \left\{ \frac{\sqrt{\log n}}{n} \sum_{i=1}^{n} h(f_{G_0, \nu_1}, f_{\hat{G}_n, \nu_1}) + \frac{M_n^{1/3}}{n} \right\}$$

by Assumption D.1. \qed

**D.3.1. Bounding (D.9).** Consider the first term (D.9):

$$\left| \int \frac{f'_{\hat{G}_n, \nu_1}(z)}{f_{\hat{G}_n, \nu_1}(z) \lor \frac{\rho_n}{\nu_1}} \left( f_{G_0, \nu_1}(z) - f_{\hat{G}_n, \nu_1}(z) \right) dz \right|$$

$$= \left| \int \frac{f'_{\hat{G}_n, \nu_1}(z)}{f_{\hat{G}_n, \nu_1}(z) \lor \frac{\rho_n}{\nu_1}} \left( \sqrt{f_{G_0, \nu_1}(z)} - \sqrt{f_{\hat{G}_n, \nu_1}(z)} \right) \left( \sqrt{f_{G_0, \nu_1}(z)} + \sqrt{f_{\hat{G}_n, \nu_1}(z)} \right) dz \right|$$
Lemma D.2. Bounding (D.10). The second term (D.10) is

\[
\left| \int \frac{f'_{\hat{G}_n, \nu_i}(z)}{f'_{\hat{G}_n, \nu_i}(z) \vee \frac{p_n}{\nu_i}} f_{\hat{G}_n, \nu_i}(z) \, dz \right|
\]

\[
= \int \frac{f'_{\hat{G}_n, \nu_i}(z)}{f'_{\hat{G}_n, \nu_i}(z) \vee \frac{p_n}{\nu_i}} \left( \frac{f_{\hat{G}_n, \nu_i}(z) - 1}{f_{\hat{G}_n, \nu_i}(z) \vee \frac{p_n}{\nu_i}} \right) f_{\hat{G}_n, \nu_i}(z) \, dz
\]

\[
\leq \int \frac{f'_{\hat{G}_n, \nu_i}(z)}{f'_{\hat{G}_n, \nu_i}(z) \vee \frac{p_n}{\nu_i}} \mathbb{1} \left( \frac{f_{\hat{G}_n, \nu_i}(z) - \rho_n/\nu_i}{f_{\hat{G}_n, \nu_i}(z)} \leq \rho_n/\nu_i \right) f_{\hat{G}_n, \nu_i}(z) \, dz
\]

\[
\leq \left( \mathbb{E}_{z \sim f_{\hat{G}_n, \nu_i}} \left[ \mathbb{E}_{\hat{G}_n, \nu_i} \left[ \left( \frac{\tau - Z}{\nu_i^2} \right)^2 \right] \cdot \frac{p_n}{\nu_i} \left[ f_{\hat{G}_n, \nu_i}(Z) \leq \rho_n/\nu_i \right] \right] \right)^{1/2}
\]

\[
\leq \mathbb{E}_{\tau \sim f_{\hat{G}_n, \nu_i}} \left[ \left( \frac{\tau - Z}{\nu_i^2} \right)^2 \right]^{1/2} \cdot \frac{p_n}{\nu_i} \left[ f_{\hat{G}_n, \nu_i}(Z) \leq \rho_n/\nu_i \right].
\]

(Cauchy–Schwarz and (D.33))

By Jensen’s inequality and law of iterated expectations, the first term is bounded by \( \frac{1}{\nu_i} \). By Lemma D.12, the second term is bounded by \( \rho_n^{1/3} \text{Var}_{Z \sim f_{\hat{G}_n, \nu_i}}(Z)^{1/6} \). Now,

\[
\text{Var}_{Z \sim f_{\hat{G}_n, \nu_i}}(Z) \leq \nu_i^2 + \mu_2^2(\hat{G}_n) \lesssim \Delta_n^2
\]

Hence,

\[
\left| \int \frac{f'_{\hat{G}_n, \nu_i}(z)}{f'_{\hat{G}_n, \nu_i}(z) \vee \frac{p_n}{\nu_i}} f_{\hat{G}_n, \nu_i}(z) \, dz \right| \lesssim \Delta_n M_n^{1/3} \rho_n^{1/3} \lesssim M_n^{1/3} n^{-1}.
\]

(Lemma D.9)

D.4. Bounding \( U_{18} \).

Lemma D.2. Under Assumptions 1 to 4 and D.1, if \( \| \hat{\eta} - \eta \|_{\infty} \leq \Delta_n, \bar{Z}_n \leq M_n \), then

\[
|U_{18}| \lesssim \Delta_n \left[ \frac{M_n \sqrt{\log n}}{n} \sum_{i=1}^{n} h(f_{\hat{G}_n, \nu_i}, f_{G_0, \nu_i}) + M_n^{4/3} \right].
\]

(D.12)
Proof. Similar to our computation with \( \mathcal{D}_{m,i} \), we decompose
\[
\left| \mathcal{D}_{s,i}(\hat{G}_{n}, \eta_0, \rho_n) \right| \lesssim_{\sigma, \sigma_u, \theta, \phi_u} \left| \int \frac{Q_i(z, \eta_0, \hat{G}_{n})}{f_{\hat{G}_{n}, \nu_i}(z) \vee (\rho_n / \nu_i)} \left( f_{\hat{G}_{n}, \nu_i}(z) - f_{\hat{G}_n, \nu_i}(z) \right) dz \right| \quad (D.13)
\]
\[
+ \left| \int \frac{Q_i(z, \eta_0, \hat{G}_{n})}{f_{\hat{G}_n, \nu_i}(z) \vee (\rho_n / \nu_i)} f_{\hat{G}_n, \nu_i}(z) dz \right| . \quad (D.14)
\]
We conclude the proof by plugging in our subsequent calculations.

D.4.1. **Bounding (D.13).** The first term (D.13) is bounded by
\[
\left( \int \frac{Q_i(z, \eta_0, \hat{G}_{n})}{f_{\hat{G}_n, \nu_i}(z) \vee (\rho_n / \nu_i)} \left( f_{\hat{G}_n, \nu_i}(z) - f_{\hat{G}_n, \nu_i}(z) \right) dz \right)^2
\]
\[
\lesssim k^2 (f_{\hat{G}_n, \nu_i}, f_{\hat{G}_n, \nu_i}) \int \left( \int \frac{Q_i(z, \eta_0, \hat{G}_{n})}{f_{\hat{G}_n, \nu_i}(z) \vee (\rho_n / \nu_i)} \right)^2 \left[ f_{\hat{G}_n, \nu_i}(z) + f_{\hat{G}_n, \nu_i}(z) \right] dz,
\]
similar to the computation in (D.11).

By Lemmas D.9 and D.13,
\[
\left( \int \frac{Q_i(z, \eta_0, \hat{G}_{n})}{f_{\hat{G}_n, \nu_i}(z) \vee (\rho_n / \nu_i)} \right)^2 \lesssim_{\sigma, \sigma_u, \theta, \phi_u} (\sqrt{\log n} M_n + \log n)^2 \lesssim_M M_n^2 \log n
\]
Hence
\[
\int \left( \int \frac{Q(z, \nu_i)}{f_{\hat{G}_n, \nu_i}(z) \vee (\rho_n / \nu_i)} \right)^2 \left[ f_{\hat{G}_n, \nu_i}(z) + f_{\hat{G}_n, \nu_i}(z) \right] dz \lesssim_M M_n^2 \log n.
\]
Hence
\[
(D.13) \lesssim_{\sigma, \sigma_u, \theta, \phi_u} M_n \sqrt{\log nh(f_{\hat{G}_n, \nu_i}, f_{\hat{G}_n, \nu_i})}. \quad (D.15)
\]

D.4.2. **Bounding (D.14).** Observe that
\[
(D.14) = \left| \int \frac{Q_i(z, \eta_0, \hat{G}_{n})}{f_{\hat{G}_n, \nu_i}(z) \vee (\rho_n / \nu_i)} \left( \frac{f_{\hat{G}_n, \nu_i}(z)}{f_{\hat{G}_n, \nu_i}(z) \vee (\rho_n / \nu_i)} - 1 \right) f_{\hat{G}_n, \nu_i}(z) dz \right|
\]
Similar to our argument for (D.10), by Cauchy–Schwarz,
\[
(D.14) \leq \left( \mathbf{E}_{f_{\hat{G}_n, \nu_i}}(z) \left[ \left( \mathbf{E}_{f_{\hat{G}_n, \nu_i}} \left[ (\tau - Z)^2 | Z \right] \right)^2 \right] \right)^{1/2} \sqrt{\mathbf{P}(f_{\hat{G}_n, \nu_i}(z) \leq \rho_n / \nu_i)}
\]
\[
\lesssim_M M_n \rho_n^{1/3} M_n^{1/3} \lesssim_M \frac{M_n^{4/3}}{n}.
\]

D.5. **Bounding \( U_{2m} \).**

**Lemma D.3.** Under Assumptions 1 to 4 and D.1,
\[
P \left[ \| \hat{\eta} - \eta \|_\infty \leq \Delta_n, Z_n \leq M_n, |U_{2m}| \lesssim_M \sqrt{\log n \Delta_n} \left\{ e^{-M_n \alpha n^2} + \frac{\log n}{\sqrt{n}} + \frac{1}{(n \Delta_n^{1/p})^{1/2}} \right\} \right] \leq \frac{2}{n}
\]
Proof. We prove this claim by first showing that if \( \| \hat{\eta} - \eta \|_\infty \leq \Delta_n \) and \( Z_n \leq M_n \), we can upper bound \( |U_{2m}| \) by some stochastic quantity \( U_{2m} \). Now, observe that

\[
P [ \| \hat{\eta} - \eta \|_\infty \leq \Delta_n, Z_n \leq M_n, |U_{2m}| > t ] \leq P [ \| \hat{\eta} - \eta \|_\infty \leq \Delta_n, Z_n \leq M_n, U_{2m} > t ] \leq P[U_{2m} > t].
\]

Hence, a stochastic upper bound on \( U_{2m} \) would verify the claim.

We now construct \( U_{2m} \) assuming \( \| \hat{\eta} - \eta \|_\infty \leq \Delta_n \) and \( Z_n \leq M_n \). Let

\[
D_{m,i,M_n}(Z_i, \hat{G}_n, \hat{\eta}, \rho_n) = D_{m,i}(Z_i, \hat{G}_n, \hat{\eta}, \rho_n)1(\{|z| \leq M_n\})
\]

and let

\[
D_{m,i,M_n}(\hat{G}_n, \hat{\eta}, \rho_n) = \int D_{m,i}(z, \hat{G}_n, \hat{\eta}, \rho_n)1(\{|z| \leq M_n\}) f_{\hat{G}_n, \nu_i}(z) \, dz.
\]

On the event \( Z_n \leq M_n, D_{m,i,M_n} = D_{m,i} \). We recall that

\[
|U_{2m}| = \left| \frac{1}{n} \sum_{i=1}^{n} (D_{m,i} - D_{m,i}) \Delta_{mi} \right|
\]

\[
\leq \left| \frac{1}{n} \sum_{i=1}^{n} (D_{m,i,M_n} - D_{m,i,M_n}) \Delta_{mi} \right| + \left| \frac{1}{n} \sum_{i=1}^{n} (D_{m,i} - D_{m,i,M_n}) \Delta_{mi} \right|
\]

Note that

\[
|D_{m,i,M_n} - D_{m,i,M_n}| \lesssim_{\sigma_f, \sigma_u, s_0, s_0} \int_{|z| > M_n} \frac{f'_{\mu, \nu_i}(z)}{f_{\mu, \nu_i}(z) \vee (\rho_n/\nu_i)} f_{\mu, \nu_i}(z) \, dz
\]

\[\lesssim_{H} \sqrt{\log n} P_{G_0, \nu_i}(\{|z| > M_n\})\]

By Lemma D.16, \( P_{G_0, \nu_i}(\{|Z_i| > M_n\}) \leq \exp(-C_{G_0, \nu_i} M_n^a) \). Hence, the second term \( \frac{1}{n} \sum_{i=1}^{n} (D_{m,i} - D_{m,i,M_n}) \Delta_{mi} \) is bounded above by \( e^{-C_H M_n^a} \sqrt{\log n} \Delta_n \), up to constants.

Note that under our assumptions, \( \max_i |\hat{Z}_i| \leq 1 \leq C_H M_n \). Let \( \mathcal{L} = [-C_H M_n, C_H M_n] \equiv [-\overline{M}, \overline{M}] \).

Define

\[
S = \left\{ (m, s) : \| m - m_0 \| \leq \Delta_n, \| s - s_0 \| \leq \Delta_n, (m, s) \in C^p_{A_1}(\sigma_f, \sigma_u) \right\}.
\]

For two distributions \( G_1, G_2 \), define the following pseudo-metric

\[
d_{m, \infty, M_n}(G_1, G_2) = \max_{i \in [n]} \sup_{|z| \leq M_n} |D_{m,i}(z, G_1, \eta_0, \rho_n) - D_{m,i}(z, G_2, \eta_0, \rho_n)|
\]

Let \( G_1, \ldots, G_N \) be an \( \omega \)-net of \( \mathcal{P}(\mathcal{L}) \) in terms of \( d_{m, \infty, M_n}(G_1, G_2) \), where \( N \) is taken to be the covering number

\[
N = N(\omega, \mathcal{P}(\mathcal{L}), d_{m, \infty, M_n}(\cdot, \cdot)).
\]

Let \( G_j^* \) be a \( G_j \) where \( d_{m, \infty, M_n}(\hat{G}_n, G_j^*) \leq \omega \).

By construction, \( |D_{m,i,M_n}(\hat{G}_n, \hat{\eta}, \rho_n) - D_{m,i,M_n}(G_j^*, \hat{\eta}, \rho_n)| \leq \omega \) as well, since the integrand is bounded uniformly. Hence, by projecting \( \hat{G}_n \) to \( G_j^* \), we obtain

\[
\left| \frac{1}{n} \sum_{i=1}^{n} (D_{m,i,M_n}(Z_i, \hat{G}_n, \eta_0, \rho_n) - D_{m,i,M_n}(\hat{G}_n, \eta_0, \rho_n)(\hat{m}(\sigma_i) - m_0(\sigma_i))\right|
\]

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Recall that \( \| \cdot \|_\infty \) and D.10, so that, when

\[
\omega \Delta_n \lesssim \omega \Delta_n + \max_{j \in [N]} |V_{n,j}(\eta)|.
\]

This concludes the proof. \( \square \)

Next, consider the process

\[
\eta \mapsto \frac{1}{n} \sum_{i=1}^{n} \left( D_{m,i,M_n}(Z_i, G_j, \eta_0, \rho_n) - D_{m,i,M_n}(G_j, \eta_0, \rho_n) \right) (m(\sigma_i) - m_0(\sigma_i))
\]

so that, when \( \| \eta - \hat{\eta} \|_\infty \leq \Delta_n, \mathbb{Z}_n \leq M_n, \)

\[
(D.18) \lesssim \omega \Delta_n + \max_{j \in [N]} |V_{n,j}(\eta)|.
\]

Thus, we can take

\[
\mathcal{U}_{2m} = C_\mathcal{H} \left\{ e^{-C_\mathcal{H} M_n^\alpha} \sqrt{\log n} \Delta_n + \omega \Delta_n + \max_{j \in [N]} \sup_{\eta \in S} |V_{n,j}(\eta)| \right\}
\]

where we shall prove a stochastic upper bound and optimize \( \omega \) shortly.

By the results in Appendix D.5.1 via Dudley’s chaining argument, with probability at least \( 1 - 2/n \),

\[
\max_{j \in [N]} \sup_{\eta \in S} |V_{n,j}(\eta)| \lesssim_{\mathcal{H}} \Delta_n \sqrt{\log n} + \frac{\Delta_n^{-1/2}}{\sqrt{n}} + \sqrt{\log n} + \sqrt{\log n}
\]

By Appendix D.5.2, we can pick \( \omega \) such that

\[
\omega \Delta_n + \max_{j \in [N]} \sup_{\eta \in S} |V_{n,j}(\eta)| \lesssim_{\mathcal{H}} \Delta_n \sqrt{\log n} \left( \frac{\log n}{\sqrt{n}} + \frac{1}{\sqrt{n \Delta_n^{1/p}}} \right)
\]

with probability at least \( 1 - 2/n \). Putting these observations together, we have that

\[
P \left[ \mathcal{U}_{2m} \lesssim_{\mathcal{H}} \sqrt{\log n} \Delta_n \left( e^{-C_\mathcal{H} M_n^\alpha} \frac{\log n}{\sqrt{n}} + \frac{1}{(n \Delta_n^{1/p})^{1/2}} \right) \right] \leq \frac{2}{n}.
\]

This concludes the proof. \( \square \)

D.5.1. Bounding \( \max_{j \in [N]} \sup_{\eta \in S} |V_{n,j}(\eta)| \). Note that \( \mathbb{E}v_{ij}(\eta) = 0 \). Moreover, by Lemmas D.9 and D.10,

\[
\max \left( D_{m,i,M_n}(Z_i, G_j, \eta_0, \rho_n), D_{m,i,M_n}(G_j, \eta_0, \rho_n) \right) \lesssim_{\mathcal{H}} \sqrt{\log(1/\rho_n)} \lesssim_{\mathcal{H}} \sqrt{\log n}
\]

Recall that \( \| \eta_1 - \eta_2 \|_\infty = \max (\| m_1 - m_2 \|_\infty, \| s_1 - s_2 \|_\infty) \). Then,

\[
|v_{ij}(\eta_1) - v_{ij}(\eta_2)| \lesssim_{\mathcal{H}} \sqrt{\log n} \| \eta_1 - \eta_2 \|_\infty
\]

As a result,\(^{75}\)

\[
\| V_{n,j}(\eta_1) - V_{n,j}(\eta_2) \|_{\psi_2} \lesssim_{\mathcal{H}} \frac{\sqrt{\log n}}{\sqrt{n}} \| \eta_1 - \eta_2 \|_\infty.
\]

\(^{75}\)See Definition 2.5.6 in Vershynin (2018) for a definition of the \( \psi_2 \)-norm (subgaussian norm).
Hence $V_{n,j}(\eta)$ is a mean-zero process with subgaussian increments\textsuperscript{76} with respect to $\|\eta_1 - \eta_2\|_{\infty}$. Note that the diameter of $S$ under $\|\eta_1 - \eta_2\|_{\infty}$ is at most $2\Delta_n$. Hence, by an application of Dudley’s tail bound (Theorem 8.1.6 in Vershynin (2018)), for all $u > 0$,

$$P \left[ \sup_{\eta \in S} |V_{n,j}(\eta)| \gtrsim_{\mathcal{H}} \frac{\sqrt{\log n}}{\sqrt{n}} \left\{ \int_0^{2\Delta_n} \sqrt{\log N(\epsilon, S, \|\cdot\|_{\infty})} \, d\epsilon + u \Delta_n \right\} \right] \leq 2e^{-u^2}.$$ 

Note that

$$\sqrt{\log N(\epsilon, S, \|\cdot\|_{\infty})} \leq \sqrt{2 \log N(\epsilon, C_{A_1}(\pm \sigma_{\ell}, \sigma_u), \|\cdot\|_{\infty})} \leq \sqrt{2 \log N(\epsilon/A_1, C_{A_1}^p(\pm \sigma_{\ell}, \sigma_u), \|\cdot\|_{\infty})}$$ 

By Theorem 2.7.1 in van der Vaart and Wellner (1996),

$$\log N(\epsilon/A_1, C_{A_1}^p(\pm \sigma_{\ell}, \sigma_u), \|\cdot\|_{\infty}) \lesssim_{p, \sigma_{\ell}, \sigma_u} A_1 \epsilon^{1/p} \lesssim_{p, \sigma_{\ell}, \sigma_u} A_1 \epsilon^{1/p}.$$ 

Hence, plugging in these calculations, we obtain

$$P \left[ \sup_{\eta \in S} |V_{n,j}(\eta)| \gtrsim_{\mathcal{H}} \frac{\sqrt{\log n}}{\sqrt{n}} \left\{ \Delta_n^{1 - \frac{1}{2p}} + u \Delta_n \right\} \right] \leq 2e^{-u^2}.$$ 

This implies that

$$\sup_{\eta \in S} |V_{n,j}(\eta)| \lesssim_{\mathcal{H}} \frac{\sqrt{\log n}}{\sqrt{n}} \Delta_n^{1 - \frac{1}{2p}} + \tilde{V}_{n,j},$$ 

for some random variable $\tilde{V}_{n,j} \geq 0$ and $\|\tilde{V}_{n,j}\|_{\psi^2} \lesssim_{\mathcal{H}} \frac{\Delta_n}{\sqrt{n}} \sqrt{\log n}$.\textsuperscript{77} Thus,

\begin{equation}
\tag{D.18}
\lesssim_{\mathcal{H}} \Delta_n \left[ \omega + \frac{\sqrt{\log n}}{\sqrt{n} \Delta_n^{1/p}} \right] + \max_{j \in [N]} \tilde{V}_{n,j}.
\end{equation}

Finally, note that by Lemma D.15 with the choice $t = \sqrt{\log n}$,

$$P \left[ \max_{j \in [N]} \tilde{V}_{n,j} \gtrsim_{\mathcal{H}} \frac{\Delta_n}{\sqrt{n}} \sqrt{\log n} \left[ \sqrt{\log N} + \sqrt{\log n} \right] \right] \leq \frac{2}{n}.$$ 

D.5.2. Selecting $\omega$. The rate function that involves $\omega$ and $\log N$ is of the form

$$\omega + \sqrt{\frac{\log N}{n}} \sqrt{\log n}$$ 

Reparametrizing $\omega = \delta \log(1/\delta) \frac{\sqrt{\log(1/\rho_n)}}{\rho_n}$, by Proposition D.2, shows that

$$\log N \leq \log N \left( \delta \log(1/\delta) \frac{\sqrt{\log(1/\rho_n)}}{\rho_n} ; \mathcal{P}(\mathbb{R}), d_{m,\infty,M} \right) \lesssim_{\mathcal{H}} \log(1/\delta^2) \max \left( 1, \frac{M_n}{\sqrt{\log(1/\delta)}} \right)$$

\textsuperscript{76}See Definition 8.1.1 in Vershynin (2018).

\textsuperscript{77}We can take

$$\tilde{V}_{n,j} = \left\{ \sup_{\eta \in S} |V_{n,j}(\eta)| - C_{A_1} \frac{M_n}{\sqrt{n}} \Delta_n^{1 - \frac{1}{2p}} \right\}_+.$$ 

The tail bound $P(\tilde{V}_{n,j} \gtrsim_{\mathcal{H}} \frac{\Delta_n}{\sqrt{n}} M_n) \leq 2e^{-u^2}$ implies the $\psi_2$-norm bound by expression (2.14) in Vershynin (2018).
Consider picking \( \delta = \rho_n \frac{1}{\sqrt{n}} \leq 1/e \) so that \( \log(1/\delta) = \log(1/\rho_n) + \frac{1}{2} \log n \lesssim_H \log n \). Since \( \log(1/\rho_n) \gtrsim M_n^2 \), we conclude that \( \max \left( 1, \frac{M_n}{\sqrt{\log(1/\delta)}} \right) \lesssim_H 1 \). Hence,

\[
\log N \lesssim_H \log^2 n.
\]

Note too that \( \omega \lesssim_H \frac{(\log n)^{3/2}}{\sqrt{n}} \). Thus, under Assumption D.1,

\[
\omega + \sqrt{\log N} \frac{1}{\sqrt{n}} \sqrt{\log n} \lesssim_H \frac{(\log n)^{3/2}}{\sqrt{n}}.
\]

D.6. Bounding \( U_{2s} \).

Lemma D.4. Under Assumptions 1 to 4 and D.1,

\[
P \left[ \|\hat{\eta} - \eta\|_\infty \leq \Delta_n, Z_n \leq M_n, |U_{2s}| \lesssim_H \Delta_n M_n \sqrt{\log n} \left\{ e^{-C_H M_n^a} + \frac{\log n}{\sqrt{n}} + \frac{1}{\sqrt{n^{\Delta_n/p}}} \right\} \right] \leq \frac{2}{n}
\]

Proof. This proof operates much like the proof of Lemma D.3. We observe that we can come up with an upper bound \( \bar{U}_{2s} \) of \( U_{2s} \) under the event \( \|\hat{\eta} - \eta\|_\infty \leq \Delta_n \) and \( Z_n \leq M_n \). A stochastic upper bound on \( U_{2s} \) then implies the lemma.

Let us first assume \( \|\hat{\eta} - \eta\|_\infty \leq \Delta_n \) and \( Z_n \leq M_n \). Define \( D_{s,i,M_n} \) and \( \bar{D}_{s,i,M_n} \) analogously to \( D_{m,i,M_n} \) and \( \bar{D}_{m,i,M_n} \). A similar decomposition shows

\[
|U_{2s}| \leq \left| \frac{1}{n} \sum_{i=1}^{n} (D_{s,i,M_n} - \bar{D}_{s,i,M_n}) \Delta_{si} \right| + \left| \frac{1}{n} \sum_{i=1}^{n} (\bar{D}_{s,i} - \bar{D}_{s,i,M_n}) \Delta_{si} \right|
\]

Lemma D.13 is a uniform bound on the integrand in the second term. Hence, the second term is bounded by

\[
\left| \frac{1}{n} \sum_{i=1}^{n} (\bar{D}_{s,i} - \bar{D}_{s,i,M_n}) \Delta_{si} \right| \
\lesssim_H \Delta_n \sqrt{\log(1/\rho_n)} \frac{1}{n} \sum_{i=1}^{n} \left( \int_{|Z_i| > M_n} |z| f_{G_0,\nu_i}(z) \, dz + \sqrt{\log(1/\rho_n)} \int_{|Z_i| > M_n} f_{G_0,\nu_i}(z) \, dz \right) \
\lesssim_H \Delta_n \sqrt{\log n} \left\{ e^{-C_H M_n^a} \max_{i \in [n]} \mu_2(f_{G_0,\nu_i}) + \sqrt{\log n} e^{-C_H M_n^a} \right\}
\]

(Cauchy–Schwarz for the first term and apply Lemmas D.9 and D.16)

\[
\lesssim_H \Delta_n (\log n) e^{-C_H M_n^a}.
\]

Note that under our assumptions, \( \max_i |\hat{Z}_i| \vee 1 \leq C_H M_n \). Let \( \mathcal{L} = [-C_H M_n, C_H M_n] \equiv [-\bar{M}, \bar{M}] \).

Define \( S = \left\{ (m, s) : \|m - m_0\| \leq \Delta_n, \|s - s_0\| \leq \Delta_n, (m, s) \in C_{A_1}^p(\sigma_\ell, \sigma_u) \right\} \). For two distributions \( G_1, G_2 \), define the following pseudo-metric

\[
d_{s,\infty,M_n}(G_1, G_2) = \max_{i \in [n]} \sup_{|z| \leq M_n} |D_{s,i}(z, G_1, \eta_0, \rho_n) - D_{s,i}(z, G_2, \eta_0, \rho_n)|
\]

(D.20)

Let \( G_1, \ldots, G_N \) be an \( \omega \)-net of \( \mathcal{P}(\mathcal{L}) \) in terms of \( d_{s,\infty,M_n}(G_1, G_2) \), where

\[
N = N(\omega, \mathcal{P}(\mathcal{L}), d_{s,\infty,M_n}(\cdot, \cdot)).
\]
Let $G_j^*$ be a $G_j$ where $d_{s,\infty,M_n}(G_j, G_j^*) \leq \omega$. By construction, $|\mathcal{D}_{s,i,M_n}(\hat{G}_n, \eta_0, \rho_n) - \mathcal{D}_{s,i,M_n}(G_j^*, \eta_0, \rho_n)| \leq \omega$ as well, since the integrand is bounded uniformly.

Hence

$$\left| \frac{1}{n} \sum_{i=1}^{n} (D_{s,i,M_n}(Z_i, \hat{G}_n, \eta_0, \rho_n) - \mathcal{D}_{s,i,M_n}(\hat{G}_n, \eta_0, \rho_n)) \left( \hat{s}(\sigma_i) - s_0(\sigma_i) \right) \right|$$

$$\leq 2\omega \Delta_n + \max_{j \in [N]} \left| \frac{1}{n} \sum_{i=1}^{n} (D_{s,i,M_n}(Z_i, G_j, \eta_0, \rho_n) - \mathcal{D}_{s,i,M_n}(G_j, \eta_0, \rho_n)) \left( s(\sigma_i) - s_0(\sigma_i) \right) \right|$$

(D.21)

Next, consider the process

$$\eta \mapsto \frac{1}{n} \sum_{i=1}^{n} (D_{s,i,M_n}(Z_i, G_j, \eta_0, 0) - \mathcal{D}_{s,i,M_n}(G_j, \eta_0, 0)) (s(\sigma_i) - s_0(\sigma_i)) \equiv \frac{1}{n} \sum_{i=1}^{n} v_{i,j}(\eta) \equiv V_{n,j}(\eta)$$

so that (D.21) $\leq \omega \Delta_n + \max_{j \in [N]} \sup_{\eta \in \mathbb{S}} |V_{n,j}(\eta)|$. This again upper bounds $|U_{is}|$ with some $\overline{U}_{is}$ that does not depend on the event $\|\hat{\eta} - \eta\|_\infty \leq \Delta_n, Z_n \leq M_n$, on the event $\|\hat{\eta} - \eta\|_\infty \leq \Delta_n, Z_n \leq M_n$. Hence, we can choose

$$\overline{U}_{2s} = C_{\mathcal{H}} \left\{ \omega \Delta_n + \max_{j \in [N]} \sup_{\eta \in \mathbb{S}} |V_{n,j}(\eta)| + \Delta_n (\log n) e^{-C_{\mathcal{H}} M_n^a} \right\}.$$

It remains to show a tail bound with an appropriate choice of $\omega$ for $\overline{U}_{2s}$.

By Lemma D.13, the process $V_{n,j}$ has the subgaussian increment property

$$|V_{n,j}(\eta_1) - V_{n,j}(\eta_2)| \lesssim_{\mathcal{H}} \frac{M_n \sqrt{\log n}}{\sqrt{n}} \|\eta_1 - \eta_2\|_\infty$$

as in Appendix D.5.1, with a different constant for the subgaussianity. Hence, by the same argument as in Appendix D.5.1, with probability at least $1 - 2/n$,

$$\max_{j \in [N]} \sup_{\eta \in \mathbb{S}} |V_{n,j}(\eta)| \lesssim_{\mathcal{H}} \frac{\Delta_n M_n \sqrt{\log n}}{\sqrt{n}} \left[ \Delta_n^{1/(2p)} + \sqrt{\log N} + \sqrt{\log n} \right]$$

We turn to selecting $\omega$. The relevant term for selecting $\omega$ is $\omega + \frac{M_n \sqrt{\log n}}{\sqrt{n}} \sqrt{\log N}$. Reparametrize $\omega = M_n \sqrt{\log(1/\rho_n)} \delta (1/\delta)/\rho_n$. Pick $\delta = \rho_n / \sqrt{n} < 1/e$. The same argument as in Appendix D.5.2 with Proposition D.2 shows that

$$\omega + \frac{M_n \sqrt{\log n}}{\sqrt{n}} \sqrt{\log N} \lesssim_{\mathcal{H}} \frac{M_n (\log n)^{3/2}}{\sqrt{n}}.$$

Therefore, we can select $\omega$ such that, overall, with probability at least $1 - 2/n$, under Assumption D.1,

$$\overline{U}_{2s} \lesssim_{\mathcal{H}} \Delta_n \left\{ M_n \sqrt{\log n} \exp \left(-C_{\alpha,A_0,\rho_n} M_n^a\right) + \frac{M_n (\log n)^{3/2}}{\sqrt{n}} + \frac{M_n \sqrt{\log n}}{\sqrt{n} \Delta_n^{1/p}} + \frac{\sqrt{\log n}}{\sqrt{n} \Delta_n^{1/p}} \right\} M_n \sqrt{\log n} \right\}$$

$$\lesssim_{\mathcal{H}} \Delta_n M_n \sqrt{\log n} \left\{ e^{-C_{\alpha,A_0,\rho_n} M_n^a} + \frac{\log n}{\sqrt{n}} + \frac{1}{\sqrt{n} \Delta_n^{1/p}} \right\}.$$
This concludes the proof. □

D.7. Bounding \( R_1 \).

Lemma D.5. Recall \( R_{1i} \) from (D.4). Then, under Assumptions 1 to 4 and D.1, if \( \|\hat{\eta} - \eta\|_{\infty} \leq \Delta_n \) and \( \overline{Z}_n \leq M_n \), then \( R_{1i} \lesssim_{\mathcal{H}} \Delta_n^3 M_n^2 \log n \).

Proof. Observe that \( R_{1i} \lesssim_{\sigma, \sigma_u, \sigma_{su}, \sigma_{su}} \max (\Delta_{m_i}^2, \Delta_{s_i}^2) \cdot \|H_i(\hat{\eta}_i, \hat{G}_n)\|_{\infty} \), where \( \|\cdot\|_{\infty} \) takes the largest element from a matrix by magnitude. By assumption, the first term is bounded by \( \Delta_n^2 \). By Lemma D.14, the second derivatives are bounded by \( M_n^2 \log n \). Hence \( \|H_i(\hat{\eta}_i, \hat{G}_n)\|_{\infty} \lesssim_{\mathcal{H}} M_n^2 \log n \). This concludes the proof. □

D.8. Bounding \( U_{3m}, U_{3s} \).

Lemma D.6. Under Assumptions 2 to 4 and D.1,

\[
P \left[ \|\hat{\eta} - \eta\|_{\infty} \leq \Delta_n, \overline{Z}_n \leq M_n, |U_{3m}| \lesssim_{\mathcal{H}} \Delta_n \left\{ e^{-C_h M_n^a} + \frac{M_n}{\sqrt{n}} \left( \Delta_n^{-1/2p} + \log n \right) \right\} \right] \leq \frac{2}{n} \]

\[
P \left[ \|\hat{\eta} - \eta\|_{\infty} \leq \Delta_n, \overline{Z}_n \leq M_n, |U_{3s}| \lesssim_{\mathcal{H}} \Delta_n \left\{ e^{-C_h M_n^a} + \frac{M_n^2}{\sqrt{n}} \left( \Delta_n^{-1/2p} + \log n \right) \right\} \right] \leq \frac{2}{n} \]

Proof. The proof structure follows that of Lemmas D.3 and D.4.

Recall that

\[
U_{3m} = \frac{1}{n} \sum_{i=1}^{n} D_{m,i}(Z_i, G_0, \eta_0, 0)(\hat{m}_i - m_0).
\]

\[
= \frac{1}{n} \sum_{i=1}^{n} (D_{m,i,M_n} - \overline{D}_{m,i,M_n})(\hat{m}_i - m_0) + \overline{D}_{m,i,M_n}(\hat{m}_i - m_0)
\]

Note that

\[
|\overline{D}_{m,i,M_n}| = \left| \int_{|z| \leq M_n} f'_{G_0,\nu_1}(z) f_{G_0,\nu_1}(z) \, dz \right|
\]

\[
= \left| \int_{1 (|z| > M_n)} f'_{G_0,\nu_1}(z) f_{G_0,\nu_1}(z) \, dz \right|
\]

\[
\lesssim_{\sigma, \sigma_u, \sigma_{su}, \sigma_{su}} P(|z| > M_n)^{1/2}
\]

(Cauchy–Schwarz, Jensen, and law of iterated expectations via (D.33))

\[
\lesssim_{\mathcal{H}} e^{-C_h M_n^a} \quad (D.22)
\]

Recall \( S \) in (D.16). Define the process \( V_n(\eta) = \frac{1}{n} \sum_i v_{n,i}(\eta) = \frac{1}{n} \sum_{i=1}^{n} (D_{m,i,M_n} - \overline{D}_{m,i,M_n})(\hat{m}_i - m_0) \). Therefore, if \( \|\hat{\eta} - \eta\|_{\infty} \leq \Delta_n, \overline{Z}_n \leq M_n \),

\[
|U_{3m}| \lesssim_{\mathcal{H}} \Delta_n e^{-C_h M_n^a} + \sup_{\eta \in S} |V_n(\eta)| \equiv U_{3m}.
\]

Therefore, to bound \( U_{3m} \) it suffices to show a tail bound for \( \sup_{\eta \in S} |V_n(\eta)| \). Observe that

\[
V_n(\eta_1) - V_n(\eta_2) = \frac{1}{n} \sum_i (D_{m,i,M_n} - \overline{D}_{m,i,M_n})(\eta_1 - \eta_2)
\]

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Now, by Lemma 2.6.8 in Vershynin (2018), since $|D_{m,i,M_n}| \lesssim_{\mathcal{H}} M_n$ by Lemma D.18,
\[\|v_{ni}(\eta_1) - v_{ni}(\eta_2)\|_{\psi_2} \lesssim \|D_{m,i,M_n}(\eta_i - \eta_2)\|_{\psi_2} \lesssim_{\mathcal{H}} M_n\|\eta_1 - \eta_2\|_{\infty}.
\] Since $v_{ni}(\eta_1) - v_{ni}(\eta_2)$ is mean zero, we have that
\[\|V_n(\eta_1) - V_n(\eta_2)\|_{\psi_2} \lesssim_{\mathcal{H}} \frac{M_n}{\sqrt{n}}\|\eta_1 - \eta_2\|_{\infty} \tag{D.23}
\]
Hence, by the same Dudley’s chaining calculation in Appendix D.5.1, with probability at least $1 - 2/n$,
\[U_{3m} \lesssim_{\mathcal{H}} \Delta_n \left\{ e^{-C_{\mathcal{H}}M_n^a} + \frac{M_n}{\sqrt{n}} (\Delta_n^{-1/(2p)} + \log n) \right\}.
\]
This concludes the proof for $U_{3m}$.

The proof for $U_{3s}$ is similar. We need to establish the analogue of (D.22) and (D.23). For the tail bound (analogue of (D.22)), we have the same bound
\[|\overline{D}_{s,i,M_n}| \lesssim P \left( |z| > M_n \right)^{1/2} \left( \mathbb{E}_{f_{G_0,v_i}} \left[ (\mathbb{E}_{G_0,v_i} [(Z - \tau)\tau | Z])^2 \right] \right)^{1/2} \lesssim_{\mathcal{H}} e^{-C_{\mathcal{H}}M_n^a}.
\]
For the analogue of (D.23), since Lemma D.18 implies that $|D_{s,i,M_n}| \lesssim_{\mathcal{H}} Z_i^2 1(Z_i \leq M_n) \leq M_n^2$,
\[\|V_n(\eta_1) - V_n(\eta_2)\|_{\psi_2} \lesssim_{\mathcal{H}} M_n^2 \frac{2}{\sqrt{n}}\|\eta_1 - \eta_2\|_{\infty}.
\]
Hence, with probability at most $2/n$
\[\overline{U}_{3s} \gtrsim_{\mathcal{H}} \Delta_n \left\{ e^{-C_{\mathcal{H}}M_n^a} + \frac{M_n^2}{\sqrt{n}} (\Delta_n^{-1/(2p)} + \log n) \right\}.
\]
\[\square
\]

**Lemma D.7.** Under Assumptions 2 to 4 and D.1, then $P \left( \|\hat{\eta} - \eta\|_{\infty} \leq \Delta_n, Z_n \leq M_n, |R_2| \gtrsim_{\mathcal{H}} \Delta_n^2 \right) \leq \frac{1}{n}$.

**Proof.** Recall that $1(A_n) = 1(\|\hat{\eta} - \eta\|_{\infty} \leq \Delta_n, Z_n \leq M_n)$. Note that
\[1(A_n)|R_2| \lesssim_{\mathcal{H}} \Delta_n^2 \frac{1}{n} \sum_{i=1}^{n} 1(A_n)\|H_i\|_{\infty},
\]
by $(1,\infty)$-Hölder inequality. Moreover, note that the second derivatives that occur in entries of $H_i$ are functions of posterior moments. By Lemma D.18, under $G_0$, these posterior moments are bounded by above by corresponding moments of $\hat{Z}_i(\hat{\eta}_i)$. By Lemma D.18, under $G_0$, these posterior moments are bounded by above by corresponding moments of $\hat{Z}_i(\hat{\eta}_i)$. Hence,
\[1(A_n)\|H_i\|_{\infty} \lesssim_{\mathcal{H}} 1(A_n) \left( \hat{Z}_i(\hat{\eta}_i) \vee 1 \right)^4 \lesssim_{\mathcal{H}} (Z_i \vee 1)^4 \tag{D.24}
\]
Hence,
\[1(A_n)|R_2| \lesssim_{\mathcal{H}} \Delta_n^2 \frac{1}{n} \sum_{i=1}^{n} (Z_i \vee 1)^4.
\]
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By Chebyshev’s inequality,
\[ P \left( \frac{1}{n} \sum_{i=1}^{n} (Z_i \vee 1)^4 > \mathbb{E}[(Z_i \vee 1)^4] + t \right) \leq \frac{1}{t^2} \text{Var} \left( \frac{1}{n} \sum_{i=1}^{n} (Z_i \vee 1)^4 \right) = \frac{\text{Var}(Z_i^4 \vee 1)}{nt^2}. \]

Picking \( t^2 = \text{Var}(Z_i^4 \vee 1) \) yields that
\[ P \left( \frac{1}{n} \sum_{i=1}^{n} (Z_i \vee 1)^4 \geq \mathcal{H} 1 \right) \leq \frac{1}{n}. \]

Hence,
\[ P \left( \|\eta - \eta\|_{\infty} \leq \Delta_n, Z_n \leq M_n, |R_2| \geq \mathcal{H}^2 \Delta_n^2 \right) \leq \frac{1}{n}. \]

\[ \square \]

D.10. Derivative computations. It is sometimes useful to relate the derivatives of \( \psi_i \) to \( \mathbb{E}_{G,\eta} \).

We compute the following derivatives. Since they are all evaluated at \( G, \eta \), we let \( \hat{\nu} = \hat{\nu}_i(\eta) \) and \( \hat{z} = \hat{Z}_i(\eta) \) as a shorthand.

\[ \frac{\partial \psi_i}{\partial m_i} \bigg|_{\eta,G} = -\frac{1}{s_i} \frac{f_{G,\hat{\nu}}(\hat{z})}{f_{G,\hat{\nu}}(\hat{z})} = \frac{s_i}{\sigma_i^2} \mathbb{E}_{G,\hat{\nu}}[Z - \tau \mid \hat{z}] \] (D.25)

\[ \frac{\partial \psi_i}{\partial s_i} \bigg|_{\eta,G} = \frac{1}{\sigma_i \hat{\nu}} \mathbb{E}_{G,\hat{\nu}}(\hat{z} - \tau) \frac{1}{\left[ \mathbb{E}_{G,\hat{\nu}}((\hat{Z}_i(\eta) - \tau) \tau \varphi \left( \frac{\hat{Z}_i(\eta) - \tau}{\hat{\nu}_i(\eta)} \right) \right]} \] (D.27)

\[ \frac{\partial^2 \psi_i}{\partial m_i^2} \bigg|_{\eta,G} = \frac{1}{2} \left[ \frac{f_{G,\hat{\nu}}''(\hat{z})}{f_{G,\hat{\nu}}(\hat{z})} - \left( \frac{f_{G,\hat{\nu}}'(\hat{z})}{f_{G,\hat{\nu}}(\hat{z})} \right)^2 \right] \] (D.29)

\[ \frac{\partial^2 \psi_i}{\partial m_i \partial s_i} \bigg|_{\eta,G} = \left( \frac{1}{\sigma_i^2} \mathbb{E}_{G,\hat{\nu}}[(Z - \tau)^2 \mid \hat{z}] - \frac{1}{s_i^2} \mathbb{E}_{G,\hat{\nu}}[(\tau - Z)^2 \mid \hat{z}] \right) + \frac{1}{\nu^2} \mathbb{E}_{G,\hat{\nu}}[(\tau - Z)^2 \mid \hat{z}] \] (D.31)

\[ \frac{\partial^2 \psi_i}{\partial s^2} \bigg|_{\eta,G} = \frac{1}{\sigma_i^2} \left\{ \mathbb{E}_{G,\hat{\nu}} \left[ \left( \frac{s_i^2}{\sigma_i} (Z - \tau)^2 \right)^2 \right] - \frac{1}{\nu^2} \left( \mathbb{E}_{G,\hat{\nu}}[(Z - \tau)^2 \mid \hat{z}] \right)^2 \right\} \] (D.32)

It is useful to note that
\[ \frac{f_{G,\hat{\nu}}'(z)}{f_{G,\hat{\nu}}(z)} = \frac{1}{\nu^2} \mathbb{E}_{G,\hat{\nu}}[(\tau - Z) \mid z] \] (D.33)

\[ \frac{f_{G,\hat{\nu}}''(z)}{f_{G,\hat{\nu}}(z)} = \frac{1}{\nu^4} \mathbb{E}_{G,\hat{\nu}}[(\tau - Z)^2 \mid z] - \frac{1}{\nu^2} \] (D.34)

D.11. Metric entropy of \( \mathcal{P}(\mathbb{R}) \) under moment-based distance. The following is a minor generalization of Lemma 4 and Theorem 7 in Jiang (2020). In particular, Jiang (2020)’s Lemma
4 reduces to the case \( q = 0 \) below, and Jiang (2020)'s Theorem 7 relies on the results below for \( q = 0, 1 \). The proof largely follows the proofs of these two results of Jiang (2020).

We first state the following fact readily verified by differentiation.

**Lemma D.8.** For all integer \( m \geq 0 \):

\[
\sup_{t \in \mathbb{R}} |t^m \varphi(t)| = m^{m/2} \varphi(\sqrt{m}).
\]

As a corollary, there exists absolute \( C_m > 0 \) such that \( t \mapsto t^m \varphi(t) \) is \( C_m \)-Lipschitz.

**Proposition D.1.** Fix some \( q \in \mathbb{N} \cup \{0\} \) and \( M > 1 \). Consider the pseudometric

\[
d_{q,M}^{(q)}(G_1, G_2) = \max_{i \in [n]} \max_{0 \leq v \leq q} \sup_{|x| \leq M} \left| \int_{(u-x)\nu_i} (x-u) \varphi \left( \frac{x-u}{\nu_i} \right) (G_1 - G_2)(du) \right|.
\]

Let \( \nu_l, \nu_u \) be the lower and upper bounds of \( \nu_i \). Then, for all \( 0 < \delta < \exp(-q/2) \wedge e^{-1} \),

\[
\log N(\delta \log^{q/2}(1/\delta), \mathcal{P}(\mathbb{R}), d_{q,M}^{(q)}) \lesssim_{q,\nu_l,\nu_u} \log^2(1/\delta) \max \left( \frac{M}{\sqrt{\log(1/\delta)}}, 1 \right).
\]

**Proof.** The proof strategy is as follows. First, we discretize \(-M, M\) into a union of small intervals \( I_j \). Fix \( G \). There exists a finitely supported distribution \( G_m \) that matches moments of \( G \) on every \( I_j \). It turns out that such a \( G_m \) is close to \( G \) in terms of \( \| \cdot \|_{q,\infty,M} \). Next, we discipline \( G_m \) by approximating \( G_m \) with \( G_m, \omega \), a finitely supported distribution supported on the fixed grid \( \{ k\omega : k \in \mathbb{Z} \} \cap [-M, M] \). Finally, the set of all \( G_m, \omega \)'s may be approximated by a finite set of distributions, and we count the size of this finite set.

D.11.1. Approximating \( G \) with \( G_m \). First, let us fix some \( \omega < \varphi(\sqrt{q}) \wedge \varphi(1) \).

Let \( a = \frac{\nu_l}{\nu_u} \varphi_+(\omega) \geq 1 \). Let \( I_j = [-M + (j-2) a \nu_l, -M + (j-1) a \nu_l] \) be such that

\[
I = [-M - a \nu_l, +M + a \nu_l] \subset \bigcup_j I_j
\]

where \( I_j \) is a width \( a \nu_l \) interval. Let \( j^* = \lceil \frac{2M}{a \nu_l} + 2 \rceil \) be the number of such intervals.

There exists by Carathéodory’s theorem a distribution \( G_m \) with support on \( I \) and no more than

\[
m = (2k^* + q + 1) j^* + 1
\]

support points s.t. the moments match

\[
\int_{I_j} u^k dG(u) = \int_{I_j} u^k dG_m(u) \quad \text{for all } k = 0, \ldots, 2k^* + q \text{ and } j = 1, \ldots, j^*.
\]

for some \( k^* \) to be chosen later.

Then, for some \( x \in I_j \cap [-M, M] \), we have

\[
d_{q,M}^{(q)}(G_m, G_m) \leq \max_{0 \leq v \leq q} \left| \int_{(I_j-1) \cup I_j \cup I_{j+1})^c} (u-x) \varphi \left( \frac{x-u}{\nu_i} \right) (G_m(du) - G_m(du)) \right| \tag{D.35}
\]
Thus the second term (D.36) can be written as the maximum-over-$k$

\[ (D.35) \leq 2 \max_{0 \leq v \leq q} \varphi(\omega) v = 2 \varphi(\omega)^q \omega. \]

Note that

\[ \varphi(t) = \sum_{k=0}^{\infty} \frac{(-t^2/2)^k}{\sqrt{2\pi k!}} = \sum_{k=0}^{k^*} \frac{(-t^2/2)^k}{\sqrt{2\pi k!}} + R(t) \]

Thus the second term (D.36) can be written as the maximum-over-$v$ of the absolute value of

\[ \sum_{k=0}^{k^*} \int_{I_{j-1} \cup I_j \cup I_{j+1}} \frac{(x-u)/v_i}{\sqrt{2\pi k!}} [G(du) - G_m(du)] + \int R \left( \frac{x-u}{v_i} \right) [G(du) - G_m(du)]. \]

The first term in the line above is zero since the moments match up to $2k^* + q$. Therefore (D.36) is equal to

\[ (D.36) = \max_{0 \leq v \leq q} \left| \int_{(I_{j-1} \cup I_j \cup I_{j+1})} \left( \frac{u-x}{v_i} \right)^v R \left( \frac{x-u}{v_i} \right) [G(du) - G_m(du)] \right|. \]

We know that since $\varphi(t)$ has alternating-signed Taylor expansion,

\[ |R(t)| \leq \frac{(\sqrt{2}/2)^{k^*+1}}{2\pi (k^* + 1)!}. \]

We can bound $|u-x|/v_i \leq 2a\upsilon_i/v_i \leq 2a$. Hence the integral is upper bounded by

\[ (D.36) \leq 2 \cdot (2a)^q \cdot \frac{(2a)^2/2}{\sqrt{2\pi (k^* + 1)!}} \]

\[ \leq \frac{2(2a)^q}{(2\pi)^{k^*+1}} \frac{2a^2}{k^*+1} e^{k^*+1}. \]

(Recall Stirling’s formula $(k^* + 1)! \geq \sqrt{2\pi (k^* + 1)} \left( \frac{k^*+1}{e} \right)^{k^*+1}$.)

\[ \leq \frac{(2a)^q}{\pi \sqrt{k^*+1}} \left( \frac{e}{3} \right)^{k^*+1} \]

(Choosing $k^* + 1 \geq 6a^2 \geq 6$)

\[ \leq \frac{(2a)^q}{\pi \sqrt{k^*+1}} \exp \left( -\frac{1}{2} \frac{k^* + 1}{6} \right) \]

\[ \leq \frac{(2a)^q}{\pi \sqrt{k^*+1} \sqrt{\pi/2}} \varphi(a\upsilon_i/v_i) \]

\[ \varphi(\varphi(\omega)) \]

\[ \leq \frac{(2a)^q}{\pi \sqrt{k^*+1} \sqrt{\pi/2}} \omega \]

\[ \leq \frac{2^q}{\sqrt{3\pi}} \left( \frac{\nu_\ell}{\upsilon_i} \right)^{q-1} \varphi^{q-1}(\omega) \omega \]

\[ (k^* + 1 \geq 6a^2). \]
This bounds (D.35) + (D.36) uniformly over \(|x| \leq M\). Therefore,

\[
d_{q,i,M}(G, G_m) \leq \left(2 + \frac{2q}{\sqrt{3\pi}} (\nu_u/\nu_t)^{q-1}\right) \cdot \varphi^q_+(\omega) \omega \lesssim_{q,\nu_u,\nu_t} q^{q/2}(1/\omega) \omega.
\]

D.11.2. Disciplining \(G_m\) onto a fixed grid. Now, consider a gridding of \(G_m\) via \(G_{m,\omega}\). We construct \(G_{m,\omega}\) to be the following distribution. For a draw \(\xi \sim G_m\), let \(\tilde{\xi} = \omega \text{sgn}(\xi) \lfloor |\xi|/\omega \rfloor\). We let \(G_{m,\omega}\) be the distribution of \(\tilde{\xi}\). \(G_{m,\omega}\) has at most \(m = (2k^* + q + 1)j^* + 1\) support points by construction, and all its support points are multiples of \(\omega\).

Since

\[
\int g(x,u)G_{m,\omega}(du) = \int g(x,\omega \text{sgn}(u)[|u|/\omega]) G_m(du)
\]

we have that

\[
\left| \int g(x,u)G_{m,\omega}(du) - \int g(x,u)G_m(du) \right| \leq \int |g(x,\omega \text{sgn}(u)[|u|/\omega]) - g(x,u)| G_m(du)
\]

In the case of \(g(x,u) = ((x-u)/\nu_t)^q \varphi((x-u)/\nu_t)\), this function is Lipschitz by Lemma D.8, we thus have that,

\[
d_{q,i,M}(G_m, G_{m,\omega}) \lesssim_{q,\nu_u,\nu_t} \omega
\]

in \(d_{q,\infty,M}(\cdot,\cdot)\).

D.11.3. Covering the set of \(G_{m,\omega}\). Let \(\Delta^{m-1}\) be the \((m-1)\)-simplex of probability vectors in \(m\) dimensions. Consider discrete distributions supported on the support points of \(G_{m,\omega}\), which can be identified with a subset of \(\Delta^{m-1}\). Thus, there are at most \(N(\omega, \Delta^{m-1}, ||\cdot||_1)\) such distributions that form an \(\omega\)-net in \(||\cdot||_1\). Now, consider a distribution \(G'_{m,\omega}\) where

\[
\|G'_{m,\omega} - G_{m,\omega}\|_1 \leq \omega.
\]

Since \(t^q \varphi(t)\) is bounded, we have that

\[
\|G'_{m,\omega} - G_{m,\omega}\|_{q,i,M} \leq \omega \max_{0 \leq v \leq q} v^{q/2} \varphi(\sqrt{v}) \lesssim_q \omega
\]

by Lemma D.8.

There are at most

\[
\left(1 + 2\left\lfloor (M + a\nu_t)/\omega \right\rfloor \right)^m
\]

configurations of \(m\) support points. Hence there are a collection of at most

\[
\left(1 + 2\left\lfloor (M + a\nu_t)/\omega \right\rfloor \right)^m N(\omega, \Delta^{m-1}, ||\cdot||_1)
\]

distributions \(\mathcal{G}\) where

\[
\min_{H \in \mathcal{G}} \|G - H\|_{q,\infty,M} \leq C_{q,\nu_u,\nu_t} \omega \log(1/\omega)^{q/2} \omega.
\]

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D.11.4. Putting things together. In other words,

$$N(\omega^*, \mathcal{P}(\mathbb{R}), \|\cdot\|_{q,\infty,M}) \leq \left( \frac{1 + 2[(M + \alpha \nu)]}{m} \right) N(\omega, \Delta^{m-1}, \|\cdot\|_1)$$

$$\leq \left( \frac{\omega + 2(\omega + 2(M + \alpha \nu))c}{m} \right)^m \omega^{-2m(2\pi m)^{-1/2}}$$

$$(6.24) \text{ in Jiang (2020)}$$

Since $\omega < 1$ and $m \geq 2 \frac{12a^2 + 3 + q}{\alpha \nu} (M + \alpha \nu)$, the first term is of the form $C^m$:

$$\frac{(\omega + 2)(\omega + 2(M + \alpha \nu))c}{m} \leq \frac{3c}{m} (1 + 2(M + \alpha \nu)) \lesssim \frac{\alpha \nu}{12a^2 + 3 + q} \lesssim \nu.$$ 

Therefore

$$\log N(\omega^*, \mathcal{P}(\mathbb{R}), \|\cdot\|_{q,\infty,M}) \lesssim m \cdot |\log(1/\omega)| + m \log \nu \lesssim \nu_{\nu,\nu, q} m \log(1/\omega).$$

Finally, since $m = (2k^* + q + 1)j^* + 1$. Recall that we have required $k^* + 1 \geq 6a^2$, and it suffices to pick $k^* = \lceil 6a^2 \rceil$. Then

$$m \lesssim q, \nu, \nu \log(1/\omega) \max \left( \frac{M}{\sqrt{\log(1/\omega)}}, 1 \right).$$

Hence

$$\log N(\omega^*, \mathcal{P}(\mathbb{R}), \|\cdot\|_{q,\infty,M}) \lesssim q, \nu, \nu \log(1/\omega) \max \left( \frac{M}{\sqrt{\log(1/\omega)}}, 1 \right).$$

Lastly, let $K$ equal the constant in $\omega^* = K \log(1/\omega)^{9/2} \omega$. Note that we can take $K \geq 1$. For some $c > 1$ such that $\log(cK)^{9/2} < c$, we plug in $\omega = \frac{\delta}{cK}$ such that whenever $\delta < cK(\varphi(1) \wedge \varphi(\sqrt{q})) \wedge e^{-q/2}$, the covering number bound holds for

$$\omega^* = \frac{\delta}{c} \log(cK/\delta)^{9/2} \leq \delta \log(1/\delta)^{9/2}.$$ 

In this case,

$$N \left( \delta \log(1/\delta)^{9/2}, \mathcal{P}(\mathbb{R}), \|\cdot\|_{q,\infty,M} \right) \leq N \left( \omega^* \log(1/\delta)^{9/2}, \mathcal{P}(\mathbb{R}), \|\cdot\|_{q,\infty,M} \right)$$

$$\lesssim q, \nu, \nu \log(1/\omega) \max \left( \frac{M}{\sqrt{\log(1/\omega)}}, 1 \right)$$

This bound holds for all sufficiently small $\delta$. Since $\delta \log(1/\delta)^{9/2}$ is increasing over $(0, e^{-q/2} \wedge e^{-1})$ and the right-hand side does not vanish over the interval, we can absorb larger $\delta$’s into the constant.

As a consequence, we can control the covering number in terms of $d_{k,\infty,M}$ for $k \in \{m, s\}$
Proposition D.2. Consider $d_{\infty,M}^{(q)}$ in Proposition D.1, $d_{s,\infty,M}$ in (D.20), and $d_{m,\infty,M}$ in (D.17) for some $M > 1$. Then

$$d_{\infty,M}^{(2)}(H_1, H_2) \leq \delta \implies d_{s,\infty,M}(H_1, H_2) \lesssim_{H} M \frac{\log(1/\rho_n) + \log(1/\rho_n)}{\rho_n} \delta,$$

and

$$d_{\infty,M}^{(2)}(H_1, H_2) \leq \delta \implies d_{m,\infty,M}(H_1, H_2) \lesssim_{H} \frac{\sqrt{\log(1/\rho_n)}}{\rho_n} \delta.$$

As a corollary, for all $\delta \in (0, 1/e)$,

$$\log N \left( \frac{\delta \log(1/\delta)}{\rho_n} \sqrt{\log(1/\rho_n)}, (P(\mathbb{R}), d_{s,\infty,M}) \right) \lesssim_{H} \log(1/\delta)^2 \max \left( 1, \frac{M}{\sqrt{\log(1/\delta)}} \right).$$

Proof. Recall that

$$D_{s,i}(z_i, G, \eta_0, \rho_n) = \frac{s_i}{\sigma_i^2} \frac{Q_i(z_i, \eta_0, G)}{f_i,G \vee \frac{\rho_n}{\nu_i}}.$$

Hence

$$|D_{s,i}(z, G_1, \eta_0, \rho_n) - D_{s,i}(z, G_2, \eta_0, \rho_n)| \lesssim_{H} \frac{1}{f_i,G_1 \vee \frac{\rho_n}{\nu_i}} |Q_i(z, \eta_0, G_1) - Q_i(z, \eta_0, G_2)| + |Q_i(z, \eta_0, G_2)| \left| \frac{1}{f_i,G_1 \vee \frac{\rho_n}{\nu_i}} - \frac{1}{f_i,G_2 \vee \frac{\rho_n}{\nu_i}} \right|$$

$$\lesssim_{H} \frac{1}{\rho_n} |f_{i,G_1} E_{G_1,\nu}[((Z - \tau) \mid z) - f_{i,G_2} E_{G_2,\nu}[((Z - \tau) \mid z)]|$$

$$+ \frac{M \sqrt{\log(1/\rho_n) + \log(1/\rho_n)}}{\rho_n} |f_{i,G_1} - f_{i,G_2}|$$

where the last inequality follows from the definition of $Q_i$ and Lemma D.13.

Note that

$$f_{i,G_1} E_{G_1,\nu}[((Z - \tau) \mid z) = f_{i,G_1} E_{G_1,\nu}[((Z - \tau)^2 \mid z) - z f_{i,G_1} E_{G_1,\nu}[(Z - \tau) \mid z]].$$

Thus we can further upper bound, by the bound on $d_{\infty,M}^{(2)}$,

$$|E_{G_1,\nu}[(Z - \tau) \mid z] - E_{G_2,\nu}[(Z - \tau) \mid z]| \lesssim_{H} \delta (1 + M) \lesssim M \delta.$$

Similarly, $|f_{i,G_1} - f_{i,G_2}| \lesssim_{H} \delta$. Hence,

$$|D_{s,i}(z, G_1, \eta_0, \rho_n) - D_{s,i}(z, G_2, \eta_0, \rho_n)| \lesssim_{H} \left\{ \frac{M}{\rho_n} + \rho_n^{-1} \left( M \sqrt{\log(1/\rho_n) + \log(1/\rho_n)} \right) \right\} \delta$$

$$\lesssim_{H} \frac{M \sqrt{\log(1/\rho_n) + \log(1/\rho_n)}}{\rho_n} \delta.$$

Similarly,

$$D_{m,i}(z, G, \eta_0) = \frac{s_i}{\sigma_i^2} \frac{f_{i,G} E_{G,\nu_1}[(Z - \tau) \mid z]}{f_{i,G} \vee \rho_n / \nu_i}.$$
Therefore
\[ |D_{m,i}(z, G_1, \eta_0) - D_{m,i}(z, G_2, \eta_0)| \lesssim_{\mathcal{H}} \frac{1}{\rho_n} \delta + \frac{1}{\rho_n} \sqrt{\log(1/\rho_n)} \delta \lesssim \frac{1}{\rho_n} \sqrt{\log(1/\rho_n)} \]
by a similar calculation, involving Lemma D.10.

Thus, for the “corollary” part, note that, letting \( C_{\mathcal{H}} \) be the constant in the bound, taken to be at least 1:
\[
N \left( \frac{\delta \log(1/\delta)}{\rho_n} \sqrt{\log(1/\rho_n)}, \mathcal{P}(\mathbb{R}), d_{m,\infty,M} \right) \leq N \left( \frac{\delta}{C_{\mathcal{H}} \log(1/(\delta/(C_{\mathcal{H}}))), \mathcal{P}(\mathbb{R}), d_{s,\infty,M}^{(2)}} \right)
\]
\[
\lesssim_{\mathcal{H}} (1/\delta)^2 \max \left( 1, \frac{M}{\sqrt{\log(1/\delta)}} \right).
\]
for all \( 0 < \delta < 1/e \). Similarly for the covering number in \( d_{s,\infty,M} \).

\[ \square \]


**Lemma D.9.** Suppose \( |\hat{Z}_n| = \max_{i \in [n]} |Z_i| \lor 1 \leq M_n \), \( \|\hat{s} - s_0\|_{\infty} \leq \Delta_n \), and \( \|\hat{m} - m_0\|_{\infty} \leq \Delta_n \).

Let \( \hat{G}_n \) satisfy Assumption 1. Then, under Assumption D.1,

1. \( |\hat{Z}_i \lor 1| \lesssim_{\mathcal{H}} M_n \)
2. There exists \( C_{\mathcal{H}} \) such that with \( \rho_n = \frac{1}{n^3} \exp (-C_{\mathcal{H}}M_n^2\Delta_n) \wedge \frac{1}{e\sqrt{2\pi}}, \)

\[ f_{\hat{G}_n,\nu_i}(Z_i) \geq \frac{\rho_n}{\nu_i}. \]

3. The choice of \( \rho_n \) satisfies \( \log(1/\rho_n) \asymp_{\mathcal{H}} \log n \), \( \varphi_+(\rho_n) \asymp_{\mathcal{H}} \sqrt{\log n} \), and \( \rho_n \lesssim_{\mathcal{H}} n^{-3}. \)

**Proof.** Observe that \( |\hat{Z}_i| \lor 1 \lesssim_{\sigma_\ell,\sigma_u,s_\ell,s_u} (1 + \Delta_n)M_n + \Delta_n \lesssim (1 + \Delta_n)M_n \) by Lemma D.11(3). Hence by Assumption D.1, \( |\hat{Z}_i| \lor 1 \lesssim_{\mathcal{H}} M_n \).

For (2), we note by Theorem 5 in Jiang (2020),
\[ f_{\hat{G}_n,\nu_i}(\hat{Z}_i) \geq \frac{1}{n^3 \nu_i} \]
thanks to \( \kappa_n \) in (3.3). That is,
\[ \int \varphi \left( \frac{\hat{Z}_i - \tau}{\nu_i} \right) \hat{G}_n(d\tau) \geq \frac{1}{n^3}. \]

Now, note that
\[ \frac{\hat{Z}_i - \tau}{\nu_i} = \frac{Z_i + m_{0i} - \hat{m}_i}{s_{0i}} \frac{(1 - \frac{\hat{s}_i}{s_{0i}})\tau - \tau}{\nu_i} = \frac{Z_i - \tau}{\nu_i} + \frac{m_{0i} - \hat{m}_i}{\sigma_i} + \frac{1}{\sigma_i}(s_i - s_{0i})\tau = \frac{Z_i - \tau}{\nu_i} + \xi(\tau) \]
where \( |\xi(\tau)| \lesssim_{\mathcal{H}} \Delta_n M_n \) over the support of \( \tau \) under \( \hat{G}_n \), under our assumptions.

Then, for all \( Z_i \), since \( |Z_i| \leq M_n \) by assumption,
\[ \varphi \left( \frac{\hat{Z}_i - \tau}{\nu_i} \right) = \varphi \left( \frac{Z_i - \tau}{\nu_i} \right) \exp \left( -\frac{1}{2} \xi^2(\tau) - \xi(\tau) \frac{Z_i - \tau}{\nu_i} \right) \]
\[ \leq \varphi \left( \frac{Z_i - \tau}{\nu_i} \right) \exp \left( C_{\mathcal{H}}\Delta_n M_n \left| Z_i - \tau \right| \nu_i \right) \]

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\[
\leq \varphi \left( \frac{Z_i - \tau}{\nu_i} \right) \exp \left( C_H \Delta_n M_n^2 \right). \\
\left( \frac{Z_i - \tau}{\nu_i} \right) \lesssim_H M_n
\]

Therefore,
\[
\int \varphi \left( \frac{Z_i - \tau}{\nu_i} \right) \hat{G}_n(d\tau) \geq \frac{1}{n^3} e^{-C_H \Delta_n M_n^2}.
\]

Dividing by \( \nu_i \) on both sides finishes the proof of (2). Claim (3) is immediate by calculating \( \log(1/\rho_n) = (3 \log n - C_H M_n^2 \Delta_n^2) \vee \log(e \sqrt{2\pi}) \lesssim_H \log n \) and apply Assumption D.1(1) to obtain that \( \Delta_n M_n^2 \lesssim_H 1. \)

\[\square\]

**Lemma D.10** (Lemma 2 Jiang (2020)). For all \( x \in \mathbb{R} \) and all \( \rho \in (0, 1/\sqrt{2\pi e}) \),
\[
\left| \frac{\nu^2 f'_{H,\nu}(x)}{(\rho/\nu) \vee f_{H,\nu}(x)} \right| \leq \nu \varphi_+(\rho).
\]

Moreover, for all \( x \in \mathbb{R} \) and all \( \rho \in (0, e^{-1}/\sqrt{2\pi}) \),
\[
\left| \left( \frac{\nu^2 f''_{H,\nu}(x)}{f_{H,\nu}(z)} + 1 \right) \left( \frac{\nu f_{H,\nu}(x)}{(\nu f_G(x)) \vee \rho} \right) \right| \leq \varphi_+^2(\rho),
\]

where we recall \( \varphi_+ \) from (C.3).

**Proof.** The first claim is immediate from Lemma 2 in Jiang (2020). The second claim follows from parts of the proof. Lemma 1 in Jiang (2020) shows that
\[
0 \leq \frac{\nu^2 f''_{H,\nu}(x)}{f_{H,\nu}(z)} + 1 \leq \log \frac{1}{2\pi \nu^2 f_{H,\nu}(z)^2} \cdot \varphi_+^2(\nu f_{H,\nu}(z)).
\]

Case 1 (\( \nu f_{H,\nu}(x) \leq \rho < e^{-1}/\sqrt{2\pi} \)): Observe that \( t \log \frac{1}{2\pi t^3} \) is increasing over \( t \in (0, e^{-1}(2\pi)^{-1/2}) \). Hence,
\[
\left( \frac{\nu^2 f''_{H,\nu}(x)}{f_{H,\nu}(z)} + 1 \right) \nu f_{H,\nu}(x) \leq \nu f_{H,\nu} \log \frac{1}{2\pi \nu^2 f_{H,\nu}(z)^2} \leq \rho \log \frac{1}{2\pi \rho^2}.
\]

Dividing by \( (\nu f) \vee \rho = \rho \) confirms the bound for \( \nu f < \rho \).

Case 2 (\( \nu f > \rho \)): Since \( \log \frac{1}{2\pi t^3} \) is decreasing in \( t \), we have that
\[
\left| \left( \frac{\nu^2 f''_{H,\nu}(x)}{f_{H,\nu}(z)} + 1 \right) \left( \frac{\nu f_{H,\nu}(x)}{(\nu f_G(x)) \vee \rho} \right) \right| = \frac{\nu^2 f''_{H,\nu}(x)}{f_{H,\nu}(z)} + 1 \leq \varphi_+^2(\nu f_{H,\nu}) \leq \log \frac{1}{2\pi \rho^2}.
\]

\[\square\]

**Lemma D.11.** The following statements are true:

1. Under Assumption 4, \( 1/\hat{\nu}_i \lesssim_{s_0, \sigma} 1 \) and \( \hat{\nu}_i \lesssim_{s_0, \sigma} 1 \)
2. Under Assumption 4, \( |1 - \frac{2\hat{m}}{\hat{n}}| \lesssim_{s_0} \| \hat{s} - s_0 \|_\infty \)
3. Under Assumption 4,
\[
\max_i |\hat{Z}_i| \lesssim_{\sigma, \sigma, s_0, s_0} (1 + \| \hat{s} - s_0 \|_\infty) \mathcal{Z}_n + \| \hat{m} - m_0 \|_\infty
\]

where \( \mathcal{Z}_n \) is defined in (C.5).
Proof.  (1) Immediate by $1/\hat{\nu}_i = \hat{s}_i/\sigma_i$ and $P[s_{0\ell} < \hat{s}_i < s_{0u}] = 1.$

(2) Immediate by observing that $|1 - \frac{s_{0u}}{\hat{s}_i}| = |\frac{\hat{s}_i - s_{0u}}{\hat{s}_i}|$ and $P[s_{0\ell} < \hat{s}_i < s_{0u}] = 1.$

(3) Immediate by $\hat{Z}_i = \frac{\hat{s}_i}{\hat{\nu}_i} Z_i + [m_{0i} - \hat{m}_i]$

\[\square\]

**Lemma D.12** (Zhang (1997), p.186). Let $f$ be a density and let $\sigma(f)$ be its standard deviation. Then, for any $M, t > 0,$

$$\int_{-\infty}^{\infty} \mathbb{1}(f(z) \leq t) f(z) \, dz \leq \frac{\sigma(f)^2}{M^2} + 2Mt.$$

In particular, choosing $M = t^{-1/3}\sigma(f)^2/3$ gives

$$\int_{-\infty}^{\infty} \mathbb{1}(f(z) \leq t) f(z) \, dz \leq 3t^{2/3}\sigma^{2/3}.$$

Proof. Since the value of the integral does not change if we shift $f(z)$ to $f(z - c),$ it is without loss of generality to assume that $E_f[Z] = 0.$

$$\int_{-\infty}^{\infty} \mathbb{1}(f(z) \leq t) f(z) \, dz \leq \int_{-\infty}^{\infty} \mathbb{1}(f(z) \leq t, |z| < M) f(z) \, dz + \int_{-\infty}^{\infty} \mathbb{1}(f(z) \leq t, |z| > M) f(z) \, dz$$

$$\leq \int_{-M}^{M} t \, dz + P(|Z| > M)$$

$$\leq 2Mt + \frac{\sigma^2(f)}{M^2}. \quad \text{(Chebyshev’s inequality)}$$

\[\square\]

**Lemma D.13.** Recall that $Q_i(z, \eta, G) = \int (z - \tau) \varphi \left( \frac{z - \tau}{\nu (\eta)} \right) \frac{1}{\nu (\eta)} G(d\tau).$ Then, for any $G, z$ and $\rho_n \in (0, e^{-1}/\sqrt{2\pi}),$

$$\left| \frac{Q_i(z, \eta_0, G)}{f_{G, \nu_i}(z) \vee (\rho_n/\nu_i)} \right| \leq \varphi_+ (\rho_n) (\nu_i |z| + \nu_i \varphi_+ (\rho_n)). \quad \text{(D.38)}$$

Proof. We can write

$$Q_i(z, \eta_0, G) = f_{G, \nu_i}(z) \left\{ z \mathbb{E}_{G, \nu_i}[(z - \tau) \mid |z| - \mathbb{E}_{G, \nu_i}[(z - \tau)^2 \mid |z]] \right\}.$$ 

From Lemma D.10,

$$\frac{f_{G, \nu_i}(z)}{f_{G, \nu_i}(z) \vee (\rho_n/\nu_i)} \mathbb{E}_{G, \nu_i}[(z - \tau) \mid |z| \leq \nu_i \varphi_+ (\rho_n)$$

and

$$\frac{f_{G, \nu_i}(z)}{f_{G, \nu_i}(z) \vee (\rho_n/\nu_i)} \mathbb{E}_{G, \nu_i}[(z - \tau)^2 \mid |z| = \nu_i \varphi_+ (\rho_n).$$

Therefore,

$$\left| \frac{Q_i(z, \eta_0, G)}{f_{G, \nu_i}(z) \vee (\rho_n/\nu_i)} \right| \leq \varphi_+ (\rho_n) \nu_i (|z| + \varphi_+ (\rho_n)).$$

\[\square\]

**Lemma D.14.** Under the assumptions in Lemma D.9, suppose $\tilde{\eta}_i$ lies on the line segment between $\eta_0$ and $\tilde{\eta}_i$ and define $\tilde{\nu}_i, \tilde{m}_i, \tilde{s}_i, \tilde{Z}_i$ accordingly. Then, the second derivatives (D.29), (D.31), (D.32),
evaluated at $\tilde{\eta}, \hat{G}_n, \tilde{Z}_i$, satisfy

$|\text{(D.29)}| \lesssim \mathcal{H} \log n$

$|\text{(D.31)}| \lesssim \mathcal{H} M_n \log n$

$|\text{(D.32)}| \lesssim \mathcal{H} M_n^2 \log n$.

Proof. First, we show that

$|\log(f_{\hat{G}_n, i}(\tilde{Z}_i)\tilde{\nu}_i)| \lesssim \mathcal{H} \log n$. \hfill (D.39)

Observe that we can write

$\hat{Z}_i = \frac{s_i \tilde{Z}_i + \tilde{m}_i - \hat{m}_i}{s_i}$,

where $\|\tilde{s} - s\|_\infty \leq \Delta_n$ and $\|\tilde{m} - m\|_\infty \leq \Delta_n$. This also shows that $|\tilde{Z}_i| \lesssim \mathcal{H} M_n$ under the assumptions.

Note that by the same argument in (D.37) in Lemma D.9, we have that

$\varphi \left( \frac{\tilde{Z}_i - \tau}{\tilde{\nu}_i} \right) \leq \varphi \left( \frac{\tilde{Z}_i - \tau}{\nu_i} \right) e^{-C_{\mathcal{H}} \Delta_n M_n^2}.$

Hence,

$\tilde{\nu}_i f_{\hat{G}(i), \tilde{\nu}_i}(\tilde{Z}_i) \geq \frac{1}{n^3} e^{-C_{\mathcal{H}} \Delta_n M_n^2}$.

This shows (D.39).

Now, observe that

$E_{\hat{G}_n, \tilde{\nu}_i}[\tau Z | \tilde{Z}_i] \lesssim \mathcal{H} \log \left( \frac{1}{\tilde{\nu}_i f_{\hat{G}(i), \tilde{\nu}_i}(\tilde{Z}_i)} \right) \lesssim \mathcal{H} \log n$

and

$E_{\hat{G}_n, \tilde{\nu}_i}[\tau | \tilde{Z}_i] \lesssim \mathcal{H} \sqrt{\log n}$

by Lemma D.10, since we can always choose $\rho = \tilde{\nu}_i f_{\hat{G}(i), \tilde{\nu}_i}(\tilde{Z}_i) \wedge \frac{1}{\sqrt{2\pi e}}$. Similarly, by Lemma D.13, and plugging in $\rho = \tilde{\nu}_i f_{\hat{G}(i), \tilde{\nu}_i}(\tilde{Z}_i) \wedge \frac{1}{\sqrt{2\pi e}}$,

$E_{\hat{G}_n, \tilde{\nu}_i}[\tau Z | \tilde{Z}_i] \lesssim \mathcal{H} \sqrt{\log n} |\tilde{Z}_i| + \log n \lesssim \mathcal{H} \sqrt{\log n} M_n$.

Observe that

$E_{\hat{G}_n, \tilde{\nu}_i}[\tau Z \tau | \tilde{Z}_i] \lesssim \mathcal{H} M_n E_{\hat{G}_n, \tilde{\nu}_i}[\tau | \tilde{Z}_i] \lesssim \mathcal{H} M_n \log n$.

since $|\tau| \lesssim \mathcal{H} M_n$ under $\hat{G}_n$. Similarly,

$E_{\hat{G}_n, \tilde{\nu}_i}[\tau Z \tau | \tilde{Z}_i] \lesssim \mathcal{H} M_n^2 \log n$.

$E_{\hat{G}_n, \tilde{\nu}_i}[\tau \tau | \tilde{Z}_i] \lesssim \mathcal{H} M_n^2$.

Plugging these intermediate results into (D.29), (D.31), (D.32) proves the claim. \hfill \Box
Lemma D.15. Let $X_1, \ldots, X_J$ be subgaussian random variables with $K = \max_i \|X_i\|_{\psi_2}$, not necessarily independent. Then for some universal $C$, for all $t \geq 0$,

$$P \left[ \max_i |X_i| \geq CK \sqrt{\log J} + CKt \right] \leq 2e^{-t^2}.$$ 

Proof. By (2.14) in Vershynin (2018), $P(|X_i| > t) \leq 2e^{-ct^2/\|X_i\|_{\psi_2}^2} \leq 2e^{-ct^2/K}$ for some universal $c$. By a union bound,

$$P \left[ \max_i |X_i| \geq Ku \right] \leq 2 \exp \left( -cu^2 + \log J \right) \leq 2 \exp \left( -cu^2 + \log J \right) \leq 2e^{-t^2}.$$ 

Implicitly, $C = 1/\sqrt{c}$.

Lemma D.16. Suppose $Z$ has simultaneous moment control $E[|Z|^p]^{1/p} \leq Ap^{1/a}$. Then

$$P(|Z| > M) \leq \exp (-C_{A,a}M^a).$$

As a corollary, suppose $Z \sim f_{G_0, \nu}(\cdot)$ and $G_0$ obeys Assumption 2, then

$$P(|Z| > M) \leq \exp (-C_{A_0,a,\nu,M}^a).$$

Proof. Observe that

$$P(|Z| > M) = P(|Z|^p > M^p) \leq \left( \frac{Ap^{1/a}}{M} \right)^p. \quad \text{(Markov)}$$

Choose $p = (M/(eA))^a$ such that

$$\left( \frac{Ap^{1/a}}{M} \right)^p = \exp (-p) = \exp \left( -\left( \frac{1}{eA} \right)^a M^a \right).$$

Lemma D.17. Let $E$ be some event and assume that

$$P(E, A > a) \leq p_1 \quad P(E, B > b) \leq p_2$$

Then $P(E, A + B > a + b) \leq p_1 + p_2$

Proof. Note that $A + B > a + b$ implies that one of $A > a$ and $B > b$ occurs. Hence

$$P(E, A + B > a + b) \leq P(E, A > a) \cup E, B > b) \leq p_1 + p_2$$

by union bound.

Lemma D.18. Let $\tau \sim G_0$ where $G_0$ satisfies Assumption 2. Let $Z | \tau \sim N(\tau, \nu^2)$. Then the posterior moment is bounded by a power of $|z|:

$$E[|\tau|^p | Z = z] \lesssim_p (|z| \vee 1)^p$$

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Proof. Let \( M \geq |z| \vee 2 \). We write
\[
\mathbb{E}[|\tau|^p \mid Z = z] = \frac{1}{f_{G_0, \nu}(z)} \int |\tau|^p \varphi \left( \frac{z - \tau}{\nu} \right) \frac{1}{\nu} G_0(d\tau).
\]
Note that
\[
\int |\tau|^p \varphi \left( \frac{z - \tau}{\nu} \right) \frac{1}{\nu} G_0(d\tau) \leq (3M)^p f_{G_0, \nu}(z) + \int 1(|\tau| > 3M) |\tau|^p \varphi \left( \frac{z - \tau}{\nu} \right) \frac{1}{\nu} G_0(d\tau)
\]
\[
\leq (3M)^p f_{G_0, \nu}(z) + \int_{|\tau| > 3M} |\tau|^p G_0(d\tau) \cdot \frac{1}{\nu} \varphi (|2M|/\nu)
\]
\[
(|z - \tau| \geq 2M \text{ when } |\tau| > 3M)
\]
Also note that
\[
f_{G_0, \nu}(z) = \int \varphi \left( \frac{z - \tau}{\nu} \right) \frac{1}{\nu} G_0(d\tau) \geq \frac{1}{\nu} \varphi (|2M|/\nu) G_0([-M, M]) \quad (|z - \tau| \leq 2M \text{ if } \tau \in [-M, M])
\]
Hence,
\[
\mathbb{E}[|\tau|^p \mid Z = z] \leq (3M)^p + \int \frac{|\tau|^p G_0(d\tau)}{G_0([-M, M])}
\]
Since \( G_0 \) is mean zero and variance 1, by Chebyshev’s inequality, \( G_0([-M, M]) \geq G_0([-2, 2]) \geq 3/4 \). Hence
\[
\mathbb{E}[|\tau|^p \mid Z = z] \lesssim_p M^p \lesssim_p (|z| \vee 1)^p,
\]
since we have simultaneous moment control by Assumption 2. \( \square \)

Appendix E. A large-deviation inequality for the average Hellinger distance

Theorem E.1. For some \( n > \sqrt{2\pi} \epsilon \), let \( \tau_1, \ldots, \tau_n \mid (\nu_1^2, \ldots, \nu_n^2) \sim \text{ i.i.d. } G_0 \) where \( G_0 \) satisfies Assumption 2. Let \( \nu_u = \max_i \nu_i \) and \( \nu_t = \min_i \nu_i \). Assume \( Z_i \mid \tau_i, \nu_i^2 \sim N(\tau_i, \nu_i^2) \). Fix positive sequences \( \gamma_n, \lambda_n \rightarrow 0 \) with \( \gamma_n, \lambda_n \leq 1 \) and constant \( \epsilon > 0 \). Fix some positive constant \( C^* \). Consider the set of distributions that approximately maximize the likelihood
\[
A(\gamma_n, \lambda_n) = \{ H : \text{Sub}_n(H) \leq C^*(\gamma_n^2 + \text{d}(f_{H}, f_{G_0})\lambda_n) \}.
\]
Also consider the set of distributions that are far from \( G_0 \) in \( \text{d}_h \):
\[
B(t, \lambda_n, \epsilon) = \{ H : \text{d}(f_{H}, f_{G_0}) \geq tB\lambda_n^{1-\epsilon} \}
\]
with some constant \( B \) to be chosen. Assume that for some \( C_\lambda \),
\[
\lambda_n^2 \geq \left( \frac{C_\lambda}{n} (\log n)^{1 + \frac{\alpha^2}{2\alpha}} \right) \vee \gamma_n^2.
\]
Then the probability that \( A \cap B \) is nonempty is bounded for \( t > 1 \): There exists a choice of \( B \) that depends only on \( \nu_t, \nu_u, C^*, C_\lambda \) such that
\[
\mathbb{P}[A(\gamma_n, \lambda_n) \cap B(t, \lambda_n, \epsilon) \neq \emptyset] \leq (\log (1/\epsilon) + 1)n^{-t^2}.
\] (E.1)

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Corollary E.1. Let \( \lambda_n = n^{-\frac{p}{2p+1}}(\log n)^{\gamma_1} \wedge 1 \) and \( \gamma_n = n^{-\frac{p}{2p+1}}(\log n)^{\gamma_2} \wedge 1 \) where \( \gamma_1 \geq \gamma_2 > 0 \). Fix some \( C_H^* \). Fix \( \epsilon > 0 \). Then there exists \( B_H \) that depends solely on \( C_H^*, p, \gamma_1, \gamma_2, \nu_\ell, \nu_u \) such that

\[
P \left[ \text{There exists } H: \text{Sub}_n(H) \leq C_H^* (\gamma_n^2 + \Theta(f_H, \ldots, f_{G_0, \cdot}) \lambda_n) \text{ and } \Theta(f_H, \ldots, f_{G_0, \cdot}) \geq tB_H n^{-\frac{p}{2p+1}}(\log n)^{\gamma_1} \right] \leq \left( \frac{\log \log n}{\log 2} + 1 \right) n^{-\epsilon}
\]

Proof. First, note that \( \lambda_n^2 \geq \gamma_n^2 \) and \( \lambda_n^2 \gtrsim \frac{(\log \log n)^{\alpha + 2}}{n} \).

Note that \( tB \lambda_n^{1-\epsilon} \leq tB_H n^{-\frac{p}{2p+1}+\epsilon} \frac{p}{2p+1} \) \( (\log n)^{\gamma_1} \leq tB_H n^{-\frac{p}{2p+1}+\epsilon} \) \( (\log n)^{\gamma_1} \). Therefore,

\[
\{ H: \Theta(f_H, \ldots, f_{G_0, \cdot}) \geq tB_H n^{-\frac{p}{2p+1}+\epsilon} \} \subset \{ H: \Theta(f_H, \ldots, f_{G_0, \cdot}) \geq tB \lambda_n^{1-\epsilon} \}.
\]

As a result, the probability

\[
P \left[ \text{There exists } H: \text{Sub}_n(H) \leq C_H^* (\gamma_n^2 + \Theta(f_H, \ldots, f_{G_0, \cdot}) \lambda_n) \text{ and } \Theta(f_H, \ldots, f_{G_0, \cdot}) \geq tB_H n^{-\frac{p}{2p+1}+\epsilon} \right] \leq (\log_2(1/\epsilon) + 1) n^{-\epsilon}
\]

via an application of Theorem E.1.

Finally, set \( \epsilon = \frac{1}{\log n} \). Note that \( n^\epsilon = n^{\frac{1}{\log n}} = \exp(\log n/\log n) = e \). Hence

\[
tB_H n^{-\frac{p}{2p+1}+\epsilon} \leq tB_H e n^{-\frac{p}{2p+1}}(\log n)^{\gamma_1}.
\]

\( \square \)

Corollary E.2. Assume the conditions in Corollary D.1. That is,

1. The estimate \( \hat{G}_n \) satisfies Assumption 1.
2. For \( \beta \geq 0 \), and suppose that \( \Delta_n, M_n \) take the form (D.2).
3. Suppose Assumptions 2 to 4 hold.

Define the rate function

\[
\delta_n = n^{-p/(2p+1)}(\log n)^{\frac{2\gamma_\alpha}{2\alpha} + \beta}.
\]

(E.2)

Then, there exists some constant \( B_H \), depending solely on \( C_H^* \) in Corollary D.1, \( \beta \), and \( p, \nu_\ell, \nu_u \) such that

\[
P \left[ \mathcal{Z}_n \leq M_n, \| \hat{\eta} - \eta \|_\infty \leq \Delta_n, h(f_{\hat{G}_n, \cdot}, f_{G_0, \cdot}) > B_H \delta_n \right] \leq \left( \frac{\log \log n}{\log 2} + 10 \right) \frac{1}{n}.
\]

Proof. Let \( \gamma = \frac{2\gamma_\alpha}{2\alpha} + \beta \). We first verify that, for \( \epsilon_n \) in (D.3), we make the choices

\[
\lambda_n = n^{-p/(2p+1)}(\log n)^{\frac{2\gamma_\alpha}{2\alpha} + \beta} \wedge 1 \quad \gamma_n = n^{-p/(2p+1)}(\log n)^{\frac{2\gamma_\alpha}{2\alpha} + \beta} \wedge 1
\]

does satisfy \( \lambda_n^2 \geq \gamma_n^2 \), as required by Corollary D.1. Since \( \epsilon_n \lesssim \lambda_n \hat{H} + \frac{1}{2}\hat{\eta} \), the truncation by 1 only affects our subsequent results by constant factors.

The event in question is a subset of the union of

\[
\left\{ \mathcal{Z}_n \leq M_n, \| \hat{\eta} - \eta \|_\infty \leq \Delta_n, \text{Sub}_n(\hat{G}_n) > C_H^* \epsilon_n \right\}
\]
and
\[ \{ Z_n \leq M_n, \| \tilde{\eta} - \eta \|_\infty \leq \Delta_n, {\text{Sub}}_n(\tilde{G}_n) \leq C_{\eta'} \varepsilon_n, \tilde{R}(f_{\tilde{G}_n}, f_{G_0}) > B_\mathcal{H} n^{-p/(2p+1)} (\log n)^\gamma \} . \]

The first event has measure at most $9/n$ by Corollary D.1, and there exists a choice of $B_\mathcal{H}$ such that the second has measure at most $n^{-1} \left( \frac{\log \log n}{\log 2} + 1 \right)$ by Corollary E.1. We conclude the proof by applying a union bound. \hfill \Box

**E.1. Proof of Theorem E.1.**

E.1.1. *Decompose $B(t, \lambda_n, \varepsilon)$.* We decompose $B(t, \lambda_n, \varepsilon) \subset \bigcup_{k=1}^K B_k(t, \lambda_n)$ where, for some constant $B$ to be chosen,
\[ B_k = \left\{ H : \tilde{R}(f_{H_t}, f_{G_0}) \in \left( tB \lambda_n^{1-2-k}, tB \lambda_n^{1-2-k+1} \right) \right\} . \]
The relation $B(t, \lambda_n, \varepsilon) \subset \bigcup_k B_k$ holds if we take $K = \lceil \log_2(1/\varepsilon) \rceil$, since, in that case, $K \geq \log_3(1/\varepsilon) \implies 2^{-K} \leq \varepsilon \implies \lambda_n^{1-2K} \leq \lambda_n^{1-\varepsilon}$.

We will bound $\text{P}(A(\gamma_n, \lambda_n) \cap B_k(t, \lambda_n) \neq \emptyset) \leq n^{-t^2}$ which becomes the bound (E.1) by a union bound. For $k \in [K]$, define $\mu_{n,k} = B \lambda_n^{1-2-k+1}$ such that $B_k = \left\{ H : \tilde{R}(f_{H_t}, f_{G_0}) \in (t\mu_{n,k+1}, t\mu_{n,k}) \right\}$. To that end, fix some $k$.

E.1.2. *Construct a net for the set of densities $f_G$.* Fix a positive constant $M$ and define the seminorm
\[ \| G \|_{\infty, M} = \max_{\mathbb{Z} \in [n]} \sup_{y \in [-M, M]} f_{G,\nu_i}(y) . \]
Note that $\| G \|_{\infty, M}$ is proportional to $\| G \|_{0,\infty, M}$ defined in Proposition D.1. Fix $\omega = \frac{1}{n^2} > 0$ and consider an $\omega$-net for the distribution $\mathcal{P}(\mathbb{R})$ under $\| \cdot \|_{\infty, M}$. Let $N = N(\omega, \mathcal{P}(\mathbb{R}), \| \cdot \|_{\infty, M})$ and the $\omega$-net is the distributions $H_1, \ldots, H_N$. For each $j$, let $H_{k,j}$ be the distribution with
\[ \tilde{R}(f_{H_{k,j}}, f_{G_0}) \geq \mu_{n,k+1} \]
if it exists, and let $J_k$ collect the indices for which $H_{k,j}$ exists.

E.1.3. *Project to the net and upper bound the likelihood.* Fix a distribution $H \in \mathcal{B}_k(t, \lambda_n)$. There exists some $H_j$ where $\| H - H_j \|_{\infty, M} \leq \omega$. Moreover, $H$ serves as a witness that $H_{k,j}$ exists, with $\| H - H_{k,j} \|_{\infty, M} \leq 2\omega$.

We can construct an upper bound for $f_{H,\nu_i}(z)$ via
\[ f_{H,\nu_i}(z) \leq \begin{cases} f_{H_{k,j},\nu_i}(z) + 2\omega & |z| < M \\ \frac{1}{\sqrt{2\pi \nu_i}} & |z| \geq M \end{cases} . \]

Define
\[ v(z) = \omega 1(|z| < M) + \frac{\omega M^2}{2} 1(|z| \geq M) . \]
Observe that
\[ f_{H,\nu_i}(z) \leq \frac{f_{H_{k,j},\nu_i}(z) + 2v(z)}{\sqrt{2\pi \nu_iv(z)}} \text{ if } |z| > M \]

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If $E \in A(t, \gamma_n, \lambda_n)$, then the likelihood ratio is lower bounded:

$$\prod_{i=1}^{n} \frac{f_{H, \nu_i}(Z_i)}{f_{G_0, \nu_i}(Z_i)} \geq \exp\left(-ntC^*\left(\gamma_n^2 + f_{H, \nu_i}(Z_i) + 2v(Z_i)\right) \right) \geq \exp\left(-ntC^*\left(\gamma_n^2 + \mu_{n,k}\lambda_n\right)\right).$$

Hence,

$$P[A(t, \gamma_n, \lambda_n) \cap B_k(t, \lambda_n) \neq \emptyset] \leq \prod_{i=1}^{n} \frac{f_{H, \nu_i}(Z_i)}{f_{G_0, \nu_i}(Z_i)} \geq \exp\left(-ntC^*\left(\gamma_n^2 + \mu_{n,k}\lambda_n\right)\right).$$

The first inequality follows from plugging in $\bar{v} \leq t\mu_{n,k}$. The second inequality follows from choosing some $a > 1$ and applying union bound.

**E.1.4. Bounding (E.3).** We consider bounding the first term (E.3) now:

$$(E.3) \leq \sum_{j \in J_k} \prod_{i=1}^{n} \frac{f_{H_{k, j, \nu_i}}(Z_i) + 2v(Z_i)}{f_{G_0, \nu_i}(Z_i)} \geq e^{-nt^2C^*(\gamma_n^2 + \mu_{n,k}\lambda_n)}$$

(Union bound)

$$\leq \sum_{j \in J_k} \mathbb{E}\left[\prod_{i=1}^{n} \frac{f_{H_{k, j, \nu_i}}(Z_i) + 2v(Z_i)}{f_{G_0, \nu_i}(Z_i)} \right] e^{nt^2C^*(\gamma_n^2 + \mu_{n,k}\lambda_n)/2}$$

(Take square root of both sides, then apply Markov’s inequality)

$$= \sum_{j \in J_k} e^{nt^2C^*(\gamma_n^2 + \mu_{n,k}\lambda_n)/2} \prod_{i=1}^{n} \mathbb{E}\left[\sqrt{\frac{f_{H_{k, j, \nu_i}}(Z_i) + 2v(Z_i)}{f_{G_0, \nu_i}(Z_i)}}\right]$$

(E.5)

where the last step (E.5) is by independence over $i$. Note that

$$\mathbb{E}\left[\sqrt{\frac{f_{H_{k, j, \nu_i}}(Z_i) + 2v(Z_i)}{f_{G_0, \nu_i}(Y_i)}}\right] = \int_{-\infty}^{\infty} \sqrt{f_{H_{k, j, \nu_i}}(x) + 2v(x)} \sqrt{f_{G_0, \nu_i}(x)} \, dx$$
and thus

\[ \leq 1 - h^2(f_{H_k,j,v_1}, f_{G_0,v_1}) + \int_{-\infty}^{\infty} \sqrt{2v(x)f_{G_0,v_1}(x)} \, dx \]

(\( \sqrt{a + b} \leq \sqrt{a} + \sqrt{b} \))

\[ \leq 1 - h^2(f_{H_k,j,v_1}, f_{G_0,v_1}) + \left( 2 \int_{-\infty}^{\infty} v(x) \, dx \right)^{1/2} \] (Jensen's inequality)

\[ = 1 - h^2(f_{H_k,j,v_1}, f_{G_0,v_1}) + \sqrt{8M\eta} \] (Direct integration)

Also note that, for \( t_i > 0 \), we have

\[ \prod_i t_i = \exp \left( \sum_i \log t_i \right) \leq \exp \left( \sum_i (t_i - 1) \right). \]

and thus

\[ \prod_{i=1}^{n} \mathbb{E} \left[ \sqrt{\frac{f_{H_k,j,v_1} + 2v(Z_i)}{f_{G_0,v_1}(Z_i)}} \right] \leq \exp \left[ -nh^2(f_{H_k,j}, f_{G_0,v}) + n\sqrt{8M\omega} \right]. \]

Thus, we can further bound (E.5):

\[ \text{(E.3)} \leq (E.5) = \sum_{j \in J_k} e^{\text{nat}(\gamma_n^2 + \mu_{n,k}\lambda_n)/2} \prod_{i=1}^{n} \mathbb{E} \left[ \sqrt{\frac{f_{H_k,j,v_1} + 2v(Z_i)}{f_{G_0,v_1}(Z_i)}} \right] \]

\[ \leq \sum_{j \in J_k} \exp \left\{ \frac{\text{nat}^2 C^*}{2} (\gamma_n^2 + \mu_{n,k}\lambda_n) - nh^2(f_{H_k,j}, f_{G_0,v}) + n\sqrt{8M\omega} \right\} \]

\[ \leq \sum_{j \in J_k} \exp \left\{ \frac{\text{nat}^2 C^*}{2} (\gamma_n^2 + \mu_{n,k}\lambda_n) - nh^2(f_{H_k,j}, f_{G_0,v}) + n\sqrt{8M\omega} \right\} \]

\[ \leq \exp \left\{ \frac{\text{nat}^2 C^*}{2} (\gamma_n^2 + \mu_{n,k}\lambda_n) - nh^2(f_{H_k,j}, f_{G_0,v}) + n\sqrt{8M\omega} + \log N \right\} \]

(\(|J_k| \leq N\))

\[ \leq \exp \left\{ \frac{\text{nat}^2 C^*}{2} (\gamma_n^2 + \mu_{n,k}\lambda_n) - nh^2(f_{H_k,j}, f_{G_0,v}) + n\sqrt{8M\omega} + C|\log \omega|^2 \max \left( \frac{M}{\sqrt{\log \omega}}, 1 \right) \right\} \]

(Proposition D.1, \( q = 0 \))

\[ = \exp \left\{ \frac{\text{nat}^2 C^*}{2} (\gamma_n^2 + \mu_{n,k}\lambda_n) - nh^2(f_{H_k,j}, f_{G_0,v}) + n\sqrt{8M\omega} + C|\log n|^2 \max \left( \frac{M}{\log n}, 1 \right) \right\}. \]

(Recall that \( \omega = \frac{1}{n^2} \))

E.1.5. Bounding (E.4). We now consider bounding the second term (E.4). By Markov’s inequality again (taking \( x \mapsto x^{1/(2\log n)} \) on both sides, we can choose to bound

\[ \text{(E.4)} \leq \mathbb{E} \left[ \prod_{i=1}^{n} \left( \frac{Z_i}{(2\pi\nu_i^2)^{1/4} M \sqrt{\omega}} \right)^{\frac{1}{2} \log n (\log_2 |Z_i| > M)} \right] \exp \left( -\frac{n(a - 1)\nu^2 C^* (\gamma_n^2 + \mu_{n,k}\lambda_n)}{2\log n} \right) \]

instead. Define

\[ a_i = \frac{1}{(2\pi\nu_i^2)^{1/4} M \sqrt{\omega}} \leq \frac{C_{\nu_i} n}{M} \quad \lambda = \frac{1}{\log n} \]

Apply Lemma E.1 to obtain the following. Note that to do so, we require

\[ M \geq \nu_a \sqrt{8\log n} \quad p \geq \frac{1}{\log n} \]

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Hence the first term in (E.6) is less than 2

As a result,

\[
\log E \left[ \prod_{i=1}^{n} \left( \frac{1}{(2\pi i^2)^{1/4}} M/\sqrt{2} \right) \right] = \log E \left[ \prod_{i} (a_i Z_i)^{\lambda_1(|Z_i| \geq M)} \right] \\
\leq \sum_{i=1}^{n} (a_i M)^{\lambda} \left( \frac{1}{M} + \frac{2p \mu_p^p(G_0)}{M^p} \right) \\
\leq \sum_{i=1}^{n} (C_{\nu} n)^{\log \alpha} \left( \frac{1}{M} + \frac{2p \mu_p^p(G_0)}{M^p} \right) \\
\leq \nu \left( \frac{1}{M} + \frac{2p \mu_p^p(G_0)}{M^p} \right)
\]

As a result,

\[
\log[(E.4)] \leq C_{\nu} \left( \frac{1}{M} + \frac{2p n \mu_p^p(G_0)}{M^p} \right) - \frac{n(a - 1)}{2} t^2 C^* \left( \gamma_n^2 + B \lambda_n^{2(1-2^{-k})} \right). \quad (E.6)
\]

E.1.6. Choosing \( p, M, a \) and verifying conditions. By Assumption 2, \( \mu_p^p(G_0) \leq A_0^p \mu_p^p/\alpha \). Let \( M = 2eA_0(c_m \log n)^{1/\alpha} \) and \( p = (M/(2eA_0))^{1/\alpha} \) so that

\[
2p \mu_p^p(G_0)/M^p \leq \exp(-c_m \log n)
\]

We choose \( c_m \geq 2 \) sufficiently large such that \( M = 2eA_0(c_m \log n)^{1/\alpha} > \nu \sqrt{8 \log n} \) and \( p \geq 1 \) for all \( n > 2 \) to ensure that our application of Lemma E.1 is correct. Since \( \alpha \leq 2 \), such a choice is available. Hence,

\[
\frac{2p n \mu_p^p(G_0)}{M^p} \leq \frac{1}{n}.
\]

Hence the first term in (E.6) is less than \( 2C_{\nu} \).

Choose \( a = 1.5 \) to obtain that

\[
\log[(E.4)] \leq 2C_{\nu} - \frac{n}{4 \log n} t^2 C^* \left( \gamma_n^2 + B \lambda_n^{2(1-2^{-k})} \right)
\]

\[
\leq t^2 \left[ 2C_{\nu} - \frac{n}{4 \log n} C^* B \lambda_n^2 \right] \quad (t \geq 1, \gamma_n > 0, \lambda_n < 1)
\]

\[
\leq t^2 \left[ 2C_{\nu} - \frac{C^* B \lambda_n^2}{4} (\log n) \right] \quad (\lambda_n^2 \geq C_\lambda (\log n)^{1+2^{-k}}/n \geq C_\lambda (\log n)^2/n)
\]

There exists a sufficiently large \( B \) dependent only on \( C^*, C_\lambda, C_{\nu} \) where \( 2C_{\nu} - \frac{C^* BC_\lambda}{4} (\log n) \leq -\log n \) for all \( n \geq 2 \). Hence, for all sufficiently large \( B \),

\[
\log[(E.4)] \leq -t^2 \log n.
\]

Similarly, under these choices,

\[
\log[(E.3)] \leq -nt^2 \left[ -\frac{3}{4} C^* (\gamma_n^2 + B \lambda_n^{2(1-2^{-k})}) + B^2 \lambda_n^{2(1-2^{-k+1})} \right] + C(\log n)^{1+2^{-k}/\alpha}
\]

\[
\leq -nt^2 \left[ -\frac{3}{4} C^* (\lambda_n^2 + B \lambda_n^{2(1-2^{-k})}) + B^2 \lambda_n^{2(1-2^{-k+1})} \right] + C(\log n)^{1+2^{-k}/\alpha} t^2 \quad (\gamma_n \leq \lambda_n, t \geq 1)
\]
\[
\begin{align*}
&\leq -t^2 \left[ n\lambda_n^2 \left( -\frac{3}{4}C^* - \frac{3}{4}C^*B \left( \frac{1}{\lambda_n} \right)^{2^{-k+1}} + B^2 \left( \frac{1}{\lambda_n} \right)^{2^{-k+2}} \right) - C (\log n)^{1+\frac{2+\alpha}{2\alpha}} \right] \\
&\leq -t^2 \left[ n\lambda_n^2 \left( \frac{1}{\lambda_n} \right)^{2^{-k+2}} \left( -\frac{3}{4}C^* - \frac{3}{4}C^*B + B^2 \right) - C (\log n)^{1+\frac{2+\alpha}{2\alpha}} \right] \\
&\leq -t^2 \left[ n\lambda_n^2 (\frac{1}{\lambda_n} \lambda_n)^{2^{-k+2}} \left( -\frac{3}{4}C^* - \frac{3}{4}C^*B + B^2 \right) - C (\log n)^{1+\frac{2+\alpha}{2\alpha}} \right] \\
&\leq -t^2 (\log n)^{1+\frac{2+\alpha}{2\alpha}} \left[ C_\lambda \left( -\frac{3}{4}C^* - \frac{3}{4}C^*B + B^2 \right) - C \right]
\end{align*}
\]

There exists choices of \( B, \) depending solely on \( C^*, C, C_\lambda, C_{\nu_\alpha,\nu_\ell} \) where \[ C_\lambda \left( -\frac{3}{4}C^* - \frac{3}{4}C^*B + B^2 \right) - C \] > 1 so that the above is at most \(-t^2 \log n \rightarrow \log 2\).

Putting the union bound together, we obtain that
\[
(E.3) + (E.4) \leq n^{-t^2}.
\]

This concludes the proof.

E.2. Auxiliary lemmas.

**Lemma E.1** (Lemma 5 in Jiang (2020)). Suppose \( Z_i | \tau_i \sim \mathcal{N}(\tau_i, \nu_i^2) \) where \( \tau_i | \nu_i^2 \sim G_0 \) independently across \( i \). Let \( 0 < \nu_{\alpha}, \nu_\ell < \infty \) be the upper and lower bounds for \( \nu_i \). Then, for all constants \( M > 0, \lambda > 0, a_i > 0, p \in \mathbb{N} \) such that \( M \geq \nu_\alpha \sqrt{\log n}, \lambda \in (0, p \land 1), \) and \( a_1, \ldots, a_n > 0 \):
\[
\mathbb{E} \left( \prod_i |a_i Z_i|^{\lambda_1(|Z_i|\geq M)} \right) \leq \exp \left( \sum_{i=1}^n (a_i M)^{\lambda} \left( \frac{4\nu_\alpha}{M \pi^{1/2} + \left( \frac{2\mu_p(G_0) \lambda}{M} \right)^p} \right) \right).
\]

Appendix F. An oracle inequality for the Bayes squared-error risk

Recall the definition of \( \text{MSERegret}_n \) in (C.4) and the event \( A_n \) in (C.5).

F.1. Controlling \( \text{MSERegret}_n \) on \( A_n^C \). The first term is the regret when a bad event occurs, on which either the nuisance estimates are bad or the data has large values. The probability of this bad event is
\[
P(A_n^C) \leq P(\|\hat{\eta} - \eta\|_\infty > \Delta_n) + P(\overline{Z}_n > M_n) \leq P(\|\hat{\eta} - \eta\|_\infty > \Delta_n) + n^{-2}.
\]

There exist choices of the constant in (D.2) for \( M_n \) such that \( P(\overline{Z}_n > M_n) \leq n^{-2} \), by Lemma F.6. Thus, at a minimum, the first term is \( o(1) \) for appropriate choices of \( \Delta_n, M_n \) such that \( P(A_n^C) \rightarrow 0 \).

We can also control the expected value of \( \text{MSERegret}_n \) on the bad event \( A_n^C \).

**Lemma F.1.** Under Assumptions 1 to 4. For \( \beta \geq 0 \), suppose \( n > 3 \) and suppose \( \Delta_n, M_n \) satisfies (D.2) such that \( P(\overline{Z}_n > M_n) \leq n^{-2} \), we can decompose
\[
\mathbb{E}[\text{MSERegret}_n(\hat{G}_n, \eta) 1(\|\hat{\eta} - \eta\|_\infty > \Delta_n)] \lesssim_{\mathcal{H}} P(\|\hat{\eta} - \eta\|_\infty > \Delta_n)^{1/2}(\log n)^{2/\alpha}
\]
\[
\mathbb{E}[\text{MSERegret}_n(\hat{G}_n, \eta) 1(\overline{Z}_n > M_n)] \lesssim_{\mathcal{H}} \frac{1}{n} (\log n)^{2/\alpha}
\]
Proof. Observe that, for an event $A$ on the data $Z_{1:n}$,

$$
\mathbb{E} \left[ \text{MSERegret}_n(\hat{G}_n, \hat{\eta}) \mathbbm{1}(A) \right] = \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_{i,\hat{G},\hat{\eta}} - \theta_i^*)^2 \mathbbm{1}(A) \right]
$$

$$
\leq \mathbb{E} \left[ \left( \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_{i,\hat{G},\hat{\eta}} - \theta_i^*)^2 \right) \right]^{1/2} \text{P}(A)^{1/2}
$$

by Cauchy–Schwarz.

A crude bound (Lemma F.5) shows that, almost surely,

$$
\left\{ \frac{1}{n} \sum_{i=1}^{n} (\hat{\theta}_{i,\hat{G},\hat{\eta}} - \theta_i^*)^2 \right\} \lesssim_{\mathcal{H}} Z_n^4.
$$

Apply Lemma F.6 to find that

$$
\mathbb{E}[Z_n^4] \lesssim_{\mathcal{H}} n^{-2/3+1} (\log n)^{2+n/3+2\beta}.
$$

This proves both claims.

F.2. Controlling $\text{MSERegret}_n$ on $A_n$.

**Theorem F.1.** Assume the conditions in Corollary E.2. That is,

1. Suppose $\hat{G}_n$ satisfies Assumption 1.
2. For $\beta \geq 0$, suppose $\Delta_n, M_n$ satisfies (D.2).
3. Suppose Assumptions 2 to 4 hold.

Then,

$$
\mathbb{E} \left[ \text{MSERegret}_n(\hat{G}_n, \hat{\eta}) \mathbbm{1}(A_n) \right] \lesssim_{\mathcal{H}} n^{-2/3+1} (\log n)^{2+n/3+2\beta}.
$$

**Proof.** Let $C^*_\mathcal{H}$ be the constant in Corollary D.1 and $B_\mathcal{H}$ be the constant in Corollary E.2. Recall the Hellinger rate $\delta_n$ in (E.2).

Recall the decomposition (C.4) for $\text{MSERegret}_n$. Note that the term corresponding to the second term in the decomposition (C.4),

$$
\mathbb{E} \left[ \mathbbm{1}(A_n) \frac{2}{n} \sum_{i=1}^{n} (\theta_i^* - \theta_i)(\hat{\theta}_{i,\hat{G}_n,\hat{\eta}} - \theta_i^*) \right] = 0,
$$

is mean zero, since $\mathbb{E}[((\theta_i^* - \theta_i) | Y_1, \ldots, Y_n] = 0$. Thus, we can focus on

$$
\mathbb{E} \left[ \mathbbm{1}(A_n) \frac{2}{n} \sum_{i=1}^{n} (\hat{\theta}_{i,\hat{G}_n,\hat{\eta}} - \theta_i^*)^2 \right] \equiv \frac{1}{n} \mathbb{E}[\mathbbm{1}(A_n) ||\hat{\theta}_{\hat{G}_n,\hat{\eta}} - \theta^*||^2],
$$

where we let $\hat{\theta}_{\hat{G}_n,\hat{\eta}}$ denote the vector of estimated posterior means and let $\theta^*$ denote the corresponding vector of oracle posterior means. Let the subscript $\rho_n$ denote a vector of regularized posterior means as in (C.2).

Thus, we may further decompose,

$$
||\hat{\theta}_{\hat{G}_n,\hat{\eta}} - \theta^*|| \leq ||\hat{\theta}_{\hat{G}_n,\hat{\eta}} - \hat{\theta}_{\hat{G}_n,\hat{\eta}_0}|| + ||\hat{\theta}_{\hat{G}_n,\hat{\eta}_0} - \hat{\theta}_{\hat{G}_n,\hat{\eta}_0,\rho_n}|| + ||\hat{\theta}_{\hat{G}_n,\hat{\eta}_0,\rho_n} - \theta^*_\rho_n\|| + ||\theta^*_\rho_n - \theta^*||.
$$

Let

$$
\xi_1 = \frac{1}{n} \mathbb{E}[\mathbbm{1}(A_n) ||\hat{\theta}_{\hat{G}_n,\hat{\eta}} - \hat{\theta}_{\hat{G}_n,\hat{\eta}_0}||^2]
$$

(F.2)
Hence, squaring both sides, we obtain

\[
\xi_2 = \frac{1}{n} \| \hat{\theta}_{G_n,\eta_0} - \hat{\theta}_{G_n,\eta_0,\rho_n} \|^2 \tag{F.3}
\]

\[
\xi_3 = \frac{1}{n} \| \hat{\theta}_{G_n,\eta_0,\rho_n} - \theta^* \|^2 \tag{F.4}
\]

\[
\xi_4 = \frac{1}{n} \| \theta^* - \theta^* \|^2 \tag{F.5}
\]
corresponding to the square of each of the terms, such that

\[
(F.1) \leq 4(\mathbb{E}\xi_1 + \mathbb{E}\xi_2 + \mathbb{E}\xi_3 + \mathbb{E}\xi_4) = 4(\mathbb{E}\xi_1 + \mathbb{E}\xi_3 + \mathbb{E}\xi_4).
\]

Observe that \(\xi_2 = 0\) by Lemma D.9, since the truncation by \(\rho_n\) does not bind when \(A_n\) occurs.

The ensuing subsections control \(\mathbb{E}\xi_1, \mathbb{E}\xi_3, \mathbb{E}\xi_4\) individually. Putting together the rates we obtain, we find that

\[
\xi_1 \lesssim_{\mathcal{H}} M_n^6 \Delta_n^2 \implies \mathbb{E}\xi_1 \lesssim_{\mathcal{H}} M_n^2 (\log n)^2 \Delta_n^2
\]

\[
\mathbb{E}\xi_3 \lesssim_{\mathcal{H}} (\log n)^3 \delta_n^2
\]

\[
\mathbb{E}\xi_4 \lesssim_{\mathcal{H}} \frac{1}{n}
\]

Now, observe that \(\delta_n \gg_{\mathcal{H}} \Delta_n M_n^2 \gg_{\mathcal{H}} \Delta_n M_n \log n\) and \(\frac{1}{n} \lesssim_{\mathcal{H}} (\log n)^3 \delta_n^2\). Hence, the dominating rate is \((\log n)^3 \delta_n^2\). Plugging in \(\delta_n^2\) in (E.2) to obtain the rate

\[
(F.1) \lesssim_{\mathcal{H}} n^{-\frac{2\nu}{2\nu+1}} (\log n)^{\frac{2\nu}{2\nu+1}+3+2\beta_1}.
\]

\(\square\)

F.3. Controlling \(\xi_1\).

**Lemma F.2.** Under the assumptions of Theorem F.1, in the proof of Theorem F.1, \(\xi_1 \lesssim_{\mathcal{H}} M_n^2 (\log n)^2 \Delta_n^2\).

**Proof.** Note that, by an application of Taylor’s theorem,

\[
\left| \hat{\theta}_{i,\bar{G}_n,\bar{\eta}} - \hat{\theta}_{i,\bar{G}_n,\eta_0} \right| = \sigma_i^2 \left| \frac{f'_{G_n,\bar{\eta}}(\tilde{Z}_i)}{s_i f_{G_n,\bar{\eta}}(\tilde{Z}_i)} - \frac{f'_{G_n,\eta_0}(\tilde{Z}_i)}{s_0 i f_{G_n,\eta_0}(\tilde{Z}_i)} \right|
\]

\[
= \sigma_i^2 \left| \left. \frac{\partial \psi_i}{\partial m_i} \right|_{\bar{G}_n,\bar{\eta}} - \left. \frac{\partial \psi_i}{\partial m_i} \right|_{\bar{G}_n,\eta_0} \right|
\]

\[
= \sigma_i^2 \left| \left. \frac{\partial^2 \psi_i}{\partial m_i \partial s_i} \right|_{\bar{G}_n,\bar{\eta}} (\tilde{s}_i - s_{0i}) + \left. \frac{\partial^2 \psi_i}{\partial m_i^2} \right|_{\bar{G}_n,\bar{\eta}} (\tilde{m}_i - m_{0i}) \right|
\]

where we use \(\bar{\eta}_i\) to denote some intermediate value lying on the line segment between \(\bar{\eta}_i\) and \(\eta_0\).

By Lemma D.14,

\[
\mathbb{P}(A_n) \left| \hat{\theta}_{i,\bar{G}_n,\bar{\eta}} - \hat{\theta}_{i,\bar{G}_n,\eta_0} \right| \lesssim_{\mathcal{H}} M_n \log n \Delta_n.
\]

Hence, squaring both sides, we obtain \(\xi_1 \lesssim_{\mathcal{H}} M_n^2 (\log n)^2 \Delta_n^2\).

\(\square\)

F.4. Controlling \(\xi_3\).

**Lemma F.3.** Under the assumptions of Theorem F.1, in the proof of Theorem F.1, \(\mathbb{E}\xi_3 \lesssim_{\mathcal{H}} (\log n)^3 \delta_n^2\).
Proof. Observe that
\[
\left| \hat{\theta}_{i,G_n,\eta_0,\rho_n} - \theta_{i,\rho_n}^* \right| = s_0 \left| \tilde{\tau}_{i,G_n,\eta_0,\rho_n} - \tau_{i,\rho_n}^* \right|
\]
where \( \tilde{\tau}_{i,G_n,\eta_0,\rho_n} \) is the regularized posterior with prior \( G_n \) at nuisance parameter \( \eta_0 \) and \( \tau_{i,\rho_n}^* = \hat{\tau}_{i,G_0,\eta_0,\rho_n} \).

We shall focus on controlling
\[
1(A_n) \| \hat{\tau}_{G_n,\eta_0,\rho_n} - \tau_{\rho_n}^* \|^2
\]
Fix the rate function \( \delta_n \) in (E.2) and the constant \( B_H \) in Corollary E.2 (which in turn depends on \( G_n^* \) in Corollary D.1). Let \( B_n = \{ \hat{F}(f,\hat{G}_n) < B_H \delta_n \} \) be the event of a small average squared Hellinger distance. Let \( G_1, \ldots, G_N \) be a finite set of prior distributions (chosen to be a net of \( \mathcal{P}(\mathbb{R}) \) in some distance), and let \( \tau_{\rho_n}^{(j)} \) be the posterior mean vector corresponding to prior \( G_j \) with nuisance parameter \( \eta_0 \) and regularization \( \rho_n \).

Then
\[
\frac{1(A_n)}{n} \| \hat{\tau}_{G_n,\eta_0,\rho_n} - \tau_{\rho_n}^* \|^2 \leq \frac{4}{n} \left( \zeta_1^2 + \zeta_2^2 + \zeta_3^2 + \zeta_4^2 \right)
\]
where
\[
\zeta_1^2 = \| \hat{\tau}_{G_n,\eta_0,\rho_n} - \tau_{\rho_n}^* \|^2 \mathbb{1}(A_n \cap B_n^C)
\]
\[
\zeta_2^2 = \left( \| \hat{\tau}_{G_n,\eta_0,\rho_n} - \tau_{\rho_n}^* \| - \max_{j \in [N]} \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \right)^2 \mathbb{1}(A_n \cap B_n)
\]
\[
\zeta_3^2 = \max_{j \in [N]} \left( \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| - \mathbb{E} \left[ \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \right] \right)^2
\]
\[
\zeta_4^2 = \max_{j \in [N]} \left( \mathbb{E} \left[ \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \right] \right)^2
\]
The decomposition \( \zeta_1 \) through \( \zeta_4 \) is exactly analogous to Section C.3 in Soloff et al. (2021) and to the proof of Theorem 1 in Jiang (2020). In particular, \( \zeta_1 \) is the gap on the “bad event” where the average squared Hellinger distance is large, which is manageable since \( 1(A_n \cap B_n^C) \) has small probability by Corollary E.2. \( \zeta_2 \) is the distance from the posterior means at \( \hat{G}_n \) to the closest posterior mean generated from the net \( G_1, \ldots, G_N \); \( \zeta_2 \) is small if we make the net very fine. \( \zeta_3 \) measures the density between \( \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \) and its expectation; \( \zeta_3 \) can be controlled by (i) a large-deviation inequality and (ii) controlling the metric entropy of the net (Proposition D.2). Lastly, \( \zeta_4 \) measures the expected distance between \( \tau_{\rho_n}^{(j)} \) and \( \tau_{\rho_n}^* \); it is small since \( G_j \) are fixed priors with small average squared Hellinger distance.

However, our argument for \( \zeta_3 \) is slightly different and avoids an argument in Jiang and Zhang (2009) which appears to not apply in the heteroskedastic setting. See Remark F.1.

The subsequent subsections control \( \zeta_1 \) through \( \zeta_4 \), and find that \( \zeta_4 \lesssim_{\mathcal{H}} (\log n)^3 \delta_n^2 \) is the dominating term.

F.4.1. Controlling \( \zeta_1 \). First, we note that
\[
\left( \hat{\tau}_{i,G_n,\eta_0,\rho_n} - \tau_{\rho_n}^* \right)^2 \mathbb{1}(A_n \cap B_n^C) \lesssim_{\mathcal{H}} \log(1/\rho_n) \mathbb{1}(A_n \cap B_n^C) = \log n \mathbb{1}(A_n \cap B_n^C)
\]

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By Corollary E.2, \( P(A_n \cap B_n^C) \leq \left( \frac{\log \log n}{\log 2} + 9 \right) \frac{1}{n} \), and hence
\[
\frac{1}{n} \mathbb{E}_{\xi} 2 \lesssim \frac{\log n \log \log n}{n}.
\]

F.4.2. Controlling \( \zeta_2 \). Choose \( G_1, \ldots, G_N \) to be a minimal \( \omega \)-covering of \( \{ G : \overline{h}(f_{G' \cdot}, f_{G_0 \cdot}) \leq \delta_n \} \) under the pseudometric

\[
d_{M_n, \rho_n}(H_1, H_2) = \max_{i \in [n]} \sup_{z : |z| \leq M_n} \left| \frac{\nu_i}{\nu_i} f'_{H_1, \nu_i}(z) - \frac{\nu_i}{\nu_i} f'_{H_2, \nu_i}(z) \right| \quad (F.10)
\]

where \( N \leq N(\omega, \mathcal{P}(\mathbb{R}), d_{M_n, \rho_n}) \). We note that (F.10) and (D.17) are different only by constant factors. Therefore, Proposition D.2 implies that

\[
\log N \left( \frac{\delta \log (1/\delta)}{\rho_n} \sqrt{\log (1/\rho_n)} \right) \lesssim \mathcal{H} \log (1/\delta)^2 \max \left( 1, \frac{M_n}{\sqrt{\log (1/\delta)}} \right) \quad (F.11)
\]

for all sufficiently small \( \delta > 0 \).

Then
\[
\frac{1}{n} \zeta_2^2 \leq \mathbb{E} \left( A_n \cap B_n \right) \max_{j \in [N]} \left( \left| \hat{r}_{G_j, \nu_0, \rho_0} - \tau^{(j)} \right| \right)^2 \quad \text{(Triangle inequality: } \|a - b\| - \|b - c\| \leq \|a - c\|) \]
\[
= \mathbb{E} \left( A_n \cap B_n \right) \max_{j \in [N]} \sum_{i=1}^n \mathbb{I} \left( |Z_i| \leq M_n \right) \left( \frac{\nu_i^2}{\nu_i} f'_{G_j, \nu_i}(Z_i) \left( \frac{\rho_i}{\nu_i} \right) - \frac{\nu_i^2}{\nu_i} f'_{G_j, \nu_i}(Z_i) \left( \frac{\rho_i}{\nu_i} \right) \right)^2 
\]
\[
\leq \omega^2 \frac{\delta^2 \log (1/\delta)^2}{\rho_n} \log (1/\rho_n). \quad \text{(Reparametrize } \omega = \delta \log (1/\delta) \rho^{-1} \sqrt{\log (1/\rho_n)})
\]

F.4.3. Controlling \( \zeta_3 \). We first observe that \( V_{ij} = |\hat{r}_{i, \rho_n}^{(j)} - \tau^*_i| \lesssim \mathcal{H} \sqrt{\log n} \), by Lemma D.10. Let \( V_j = (V_{ij} : i \in [n]) \), we have that
\[
\zeta_3 = \max_j (\|V_j\| - \mathbb{E}[\|V_j\|]) +
\]
Let \( K_n = C_n \log n \geq \max \{ |V_{ij}| \} \). Since \( G_j, G_0 \) are both fixed, \( V_{ij}, \ldots, V_{nj} \) are mutually independent.

Observe that
\[
P \left( \|V_j\| > \mathbb{E}[\|V_j\|] + u \right) = P \left( \frac{\|V_j\|}{K_n} > \mathbb{E} \left( \frac{V_j}{K_n} \right) + \frac{u}{K_n} \right) \leq \exp \left( -\frac{u^2}{2K_n^2} \right).
\]
by Lemma F.7. By a union bound,
\[
P (\zeta_3^2 > x) \leq N \exp \left( -\frac{x}{2K_n^2} \right).
\]
Therefore
\[
\mathbb{E}[\zeta_3^2] = \int_0^\infty P(\zeta_3^2 > x) \, dx
\]
\[ \begin{align*}
&= \int_0^\infty \min \left( 1, N \exp \left( -\frac{x}{2K_n^2} \right) \right) \, dx \\
&= 2K_n^2 \log N + \int_0^\infty N \exp \left( -\frac{x}{2K_n^2} \right) \, dx \\
&\lesssim \mathcal{H} \log n \log N.
\end{align*} \]

Now, if we take \( \delta = \rho_n/n \), then
\[
\frac{1}{n}E[\zeta_2^2 + \zeta_3^2] \lesssim \mathcal{H} \frac{(\log n)^3}{n}.
\]

**Remark F.1.** For the analogous term in the homoskedastic setting, Jiang and Zhang (2009) (and, later on, Saha and Guntuboyina (2020)) observe that \( \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \) is a Lipschitz function of the noise component \( Z_i - \tau_i \). As a result, a Gaussian isoperimetric inequality (Theorem 5.6 in Boucheron et al. (2013)) establishes that
\[
P \left( \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \geq \mathbb{E} \left[ \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \mid \tau_1, \ldots, \tau_n \right] + x \right)
\]
is small, independently of \( n \)—a fact used in Proposition 4 of Jiang and Zhang (2009). Note that the concentration of \( \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \) is towards its conditional mean \( \mathbb{E} \left[ \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \mid \tau_1, \ldots, \tau_n \right] \). In the homoskedastic setting where \( \nu_i = \nu \),
\[
\mathbb{E} \left[ \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \mid \tau_1, \ldots, \tau_n \right] = \mathbb{E}_{\mathcal{G}_{0,n}} \left[ \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \right]
\]
where \( \mathcal{G}_{0,n} = \frac{1}{n} \sum \delta_{\tau_i} \) is the empirical distribution of the \( \tau \)'s. However, (F.12) no longer holds in the heteroskedastic setting, and to adapt this argument, we need to additionally control the difference between \( \mathbb{E} \left[ \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \mid \tau_1, \ldots, \tau_n \right] \) and \( \mathbb{E} \left[ \| \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \| \right] \). The arguments of Jiang (2020) (p.2289) and Soloff et al. (2021) (Section C.3.3, arXiv:2109.03466v1) appear to use the Gaussian concentration of Lipschitz functions argument without the additional step.

Instead, we establish control of \( \zeta_3 \) by observing that entries of \( \tau_{\rho_n}^{(j)} - \tau_{\rho_n}^* \) are bounded and applying the convex Lipschitz concentration inequality. Since, like Soloff et al. (2021), we seek regret control in terms of mean-squared error, this argument applies to their setting as well. Jiang (2020), on the other hand, seeks regret control in terms of root-mean-squared error, and it is unclear if similar fixes apply.

\[ \blacksquare \]

**F.4.4. Controlling \( \zeta_4 \).** Consider a change of variables where we let \( w_i = z/\nu_i \) and \( \lambda_i = \tau/\nu_i \). Let \( G_{(i)} \) be the distribution of \( \lambda_i \) under \( G \), where
\[
G_{(i)}(d\lambda) = G(d\tau)
\]
Then
\[
f_{G_{\nu_i}}(z) = \int \frac{1}{\nu_i} \varphi(w_i - \lambda_i) G(d\tau) = \frac{1}{\nu_i} \int \varphi(w_i - \lambda_i) G_{(i)}(d\lambda_i) = \frac{1}{\nu_i} f_{G_{(i)},1}(w_i)
\]
and
\[
f'_{G_{\nu_i}}(z) = \frac{1}{\nu_i} f'_{G_{(i)},1}(w_i).
\]

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Hence,
\[
\mathbb{E}(r_{\rho_n}^{(j)} - r_{\rho_n}^{*})^2 = \nu_i^2 \mathbb{E} \left( \frac{f'_{G_{j1}}(w_i)}{f_{G_{j1}}(w_i) \vee \rho_n} - \frac{f'_{G_{01}}(w_i)}{f_{G_{01}}(w_i) \vee \rho_n} \right)^2 \\
\lesssim_{\mathcal{H}} \max \left( \left( \log \frac{1}{\rho_n} \right)^3, |\log h(f_{G_{j1}}, f_{G_{01}})| \right) h^2(f_{G_{j1}}, f_{G_{01}}) \\
\leq \max \left( \left( \log \frac{1}{\rho_n} \right)^3, |\log h(f_{G_{j1}}, g_{G_{01}})| \right) h^2(f_{G_{j1}}, g_{G_{01}})
\]
\[(\text{Lemmas D.9 and F.8})\]

Let \( h_i = h(f_{G_{j1}}, g_{G_{01}}) \).

Hence,
\[
\frac{1}{n} \mathbb{E}[\xi_4^2] \lesssim_{\mathcal{H}} \frac{(\log n)^3}{n} \left( \sum_{i: |\log h_i| < (\log 1/\rho_n)^3} h_i^2 + \frac{1}{n} \sum_{i: |\log h_i| > (\log 1/\rho_n)^3} |\log h_i| h_i^2 \right) \\
\leq (\log n)^3 h^2(f_{G_{j1}}, g_{G_{01}}) + \frac{1}{n} \sum_{i: |\log h_i| > (\log 1/\rho_n)^3} \frac{1}{n} h_i e^{(x|\log x| \leq e^{-1})}
\]

Note that
\[
|\log h_i| > (\log 1/\rho_n)^3 \implies h_i < \exp(-\log(1/\rho_n)^3) < \rho_n^{(\log 1/\rho_n)^2} \lesssim_{\mathcal{H}} \rho_n^{3} \lesssim_{\mathcal{H}} n^{-1}.
\]

Therefore the first term dominates, and
\[
\frac{1}{n} \mathbb{E}[\xi_4^2] \lesssim_{\mathcal{H}} (\log n)^3 \delta_n^2.
\]

F.5. Controlling \( \xi_4 \).

Lemma F.4. Under the assumptions of Theorem F.1, in the proof of Theorem F.1, \( \mathbb{E}[\xi_4] \lesssim_{\mathcal{H}} \frac{1}{n} \).

Proof. Note that
\[
\mathbb{E}[(\theta_{i, \rho_n}^* - \theta_i^*)^2] = \int \left( \nu_i^2 f'_{G_{01}, \nu_i}(z) \right)^2 \left( 1 - \frac{f_{G_{01}, \nu_i}}{f_{G_{01}, \nu_i} \vee \rho_n} \right)^2 f_{G_{01}, \nu_i}(z) \, dz \\
\leq \mathbb{E} \left( \nu_i^2 f'_{G_{01}, \nu_i}(z) \left/ f_{G_{01}, \nu_i}(z) \right\right)^{1/2} \mathbb{P} \left( f_{G_{01}, \nu_i}(Z) < \rho_n / \nu_i \right)^{1/2} \quad \text{(Cauchy–Schwarz)} \\
\lesssim_{\mathcal{H}} \rho_n^{1/3} \mathbb{V}(Z)^{1/6} \quad \text{(Lemma D.12)} \\
\lesssim_{\mathcal{H}} \frac{1}{n}.
\]

Therefore, \( \mathbb{E}[\xi_4] \lesssim_{\mathcal{H}} \frac{1}{n} \). \( \square \)

F.6. Auxiliary lemmas.

Lemma F.5. Let \( \hat{\theta}_{i, \hat{G}, \hat{\rho}} \) be the posterior mean at prior \( \hat{G} \) and nuisance parameter estimate at \( \hat{\rho} \). Let \( \theta_i^* = \hat{\theta}_{i, G_{01}, \rho_0} \) be the true posterior mean. Assume that \( \hat{G} \) is supported within \([-\overline{M}_n, \overline{M}_n]\) where \( \overline{M}_n = \max_i \left| \hat{Z}_i(\hat{\eta}) \right| \vee 1 \). Let \( \|\hat{\eta} - \eta\|_{\infty} = \max(\|\hat{m} - m_0\|_{\infty}, \|\hat{s} - s_0\|_{\infty}) \).

Then, suppose

\[\]
(1) \( \| \hat{\eta} - \eta \|_{\infty} \lesssim_{\mathcal{H}} 1 \).
(2) Assumptions 2 and 3 holds.
(3) \( \hat{s} \gtrsim_{\mathcal{H}} s_{t_n} \) for some fixed sequence \( s_{t_n} > 0 \).

Then
\[
\left\| \hat{\theta}_{i, \hat{G}, \hat{\eta}} - \hat{\theta}_i \right\|_{\infty} \lesssim_{\mathcal{H}} s_{t_n}^2 \mathcal{Z}_n.
\]
Moreover, the assumptions are satisfied by Assumptions 1 to 4 with \( s_{t_n} = s_{0t} \approx 1 \).

**Proof.** Observe that
\[
\left\| \hat{\theta}_{i, \hat{G}, \hat{\eta}} - \hat{\theta}_i \right\|_{\infty} = \left| \frac{1}{\hat{s}_i} \frac{\hat{v}_i^2 f'_{\hat{\nu}_i}(\hat{Z}_i)}{f_{\hat{\nu}_i}(\hat{Z}_i)} - \frac{1}{s_{0i}} \frac{v_i^2 f'_{\nu_i}(Z_i)}{f_{\nu_i}(Z_i)} \right|
\lesssim_{\mathcal{H}} s_{t_n}^{-1} M_n + \mathcal{Z}_n.
\]
by the boundedness of \( \hat{G}_n \) and Lemma D.18. Note that
\[
|\hat{Z}_i(\hat{\eta})| = \left| \frac{s_{0i}}{\hat{s}_i} Z_i + \frac{m_{0i} - \hat{m}_i}{\hat{s}_i} \right| \lesssim_{\mathcal{H}} s_{t_n}^{-1} |Z_i|.
\]
Therefore,
\[
\left\| \hat{\theta}_{i, \hat{G}, \hat{\eta}} - \hat{\theta}_i \right\|_{\infty} \lesssim_{\mathcal{H}} s_{t_n}^{-2} \mathcal{Z}_n.
\]

**Lemma F.6.** Let \( \mathcal{Z}_n = \max_i |Z_i| \vee 1 \). Under Assumption 2, for \( t > 1 \)
\[
P(\mathcal{Z}_n > t) \leq n \exp \left( -C_{A_0, \alpha, \nu} t^{\alpha} \right).
\]
and
\[
\mathbb{E}[\mathcal{Z}_n^p] \lesssim_{p, \mathcal{H}} (\log n)^{p/\alpha}.
\]
Moreover, if \( M_n = (C_{\mathcal{H}} + 1)(C_{2, \mathcal{H}}^{-1} \log n)^{1/\alpha} \) as in (D.2), then for all sufficiently large choices of \( C_{\mathcal{H}} \), \( P(\mathcal{Z}_n > M_n) \leq n^{-2} \).

**Proof.** The first claim is immediate under Lemma D.16 and a union bound.

The second claim follows from the observation that
\[
\mathbb{E}[\max_i (|Z_i| \vee 1)^p] \leq \left( \sum_i \mathbb{E}[(|Z_i| \vee 1)^p] \right)^{1/c} \leq n^{1/c} C^p_{\mathcal{H}} (pc)^{p/\alpha}.
\]
where the last inequality follows from simultaneous moment control. Choose \( c = \log n \) with \( n^{1/\log n} = e \) to finish the proof.

For the “moreover” part, we have that
\[
P(\mathcal{Z}_n > M_n) \leq \exp \left( \log n - C_{A_0, \alpha, \nu} (C_{\mathcal{H}} + 1)^\alpha C_{2, \mathcal{H}}^{-1} \log n \right)
\]
and it suffices to choose \( C_{\mathcal{H}} \) such that \( (C_{\mathcal{H}} + 1)^\alpha > \frac{3C_{2, \mathcal{H}}}{C_{A_0, \alpha, \nu}} \) so that \( P(\mathcal{Z}_n > M_n) \leq e^{-2 \log n} = n^{-2} \).
Lemma F.7. Let $W = (W_1, \ldots, W_n)$ be a vector containing independent entries, where $W_i \in [0, 1]$. Let $\|\cdot\|$ be the Euclidean norm. Then, for all $t > 0$
\[
\Pr[\|W\| > \mathbb{E}[\|W\|] + t] \leq e^{-t^2/2}.
\]

**Proof.** We wish to use Theorem 6.10 of Boucheron et al. (2013), which is a dimension-free concentration inequality for convex Lipschitz functions of bounded random variables. To do so, we observe that $w \mapsto \|w\|$ is Lipschitz with respect to $\|\cdot\|$, since
\[
\|w + a\| \leq \|w\| + \|a\| \implies \|w + a\| - \|w\| \leq \|a\|.
\]
Moreover, trivially $\|\lambda w + (1 - \lambda)v\| \leq \lambda\|w\| + (1 - \lambda)\|v\|$ for $\lambda \in [0, 1]$, and hence $w \mapsto \|w\|$ is convex. Convexity implies separate convexity required in Theorem 6.10 of Boucheron et al. (2013). This checks all conditions and the claim follows by applying Theorem 6.10 of Boucheron et al. (2013). \hfill \Box

Lemma F.8. Let $f_H = f_{H,1}$. Then, for $0 < \rho_n \leq \frac{1}{\sqrt{2\pi e^2}}$
\[
\int \left( \frac{f'_{H_1}(x)}{f_{H_1}(x) \vee \rho_n} - \frac{f'_{H_0}(x)}{f_{H_0}(x) \vee \rho_n} \right)^2 f_{H_0}(x) \, dx 
\leq \max \left( (\log 1/\rho_n)^2, \log h(f_{H_1}, f_{H_0}) \right) \log h(f_{H_1}, f_{H_0})
\]
where we define the right-hand side to be zero if $H_1 = H_0$.

**Proof.** This claim is an intermediate step of Theorem 3 of Jiang and Zhang (2009). In (3.10) in Jiang and Zhang (2009), the left-hand side of this claim is defined as $r(f_{H_1}, \rho_n)$. Their subsequent calculation, which involves Lemma 1 of Jiang and Zhang (2009), proceeds to bound
\[
r(f_{H_1}, \rho_n) \leq 4e^2 h^2(f_{H_1}, f_{H_0}) \max \left( \varphi^0_+(\rho_n), 2a^2 \right) + 2 \varphi_+(\rho_n) \sqrt{h(f_{H_1}, f_{H_0})},
\]
for $a^2 = \max \left( \varphi^2_+(\rho_n) + 1, \log h(f_{H_1}, f_{H_0}) \right)$. Collecting the powers on $h$, $\log h$ and using $\varphi_+(\rho_n) \lesssim \sqrt{\log(1/\rho_n)}$ proves the claim. \hfill \Box

**Appendix G. Estimating $\eta_0$ by local linear regression**

In this section, we verify that estimating $\eta_0$ by local linear regression satisfies the conditions we require for the nuisance estimators, when the true nuisance parameters belong to a Hölder class of order $p = 2$: $m_0(\sigma), s_0(\sigma) \in C^2_{A_1}([\sigma_L, \sigma_U])$.

In our empirical application, we estimate $m_0, s_0$ by nonparametrically regressing $Y_i$ on $x_i \equiv \log_{10}(\sigma_i)$. Since $\log(\cdot)$ is a smooth transformation on strictly positive compact sets, Hölder smoothness conditions for $(m_0, s_0)$ translate to the same conditions on $(\mathbb{E}[Y \mid x], \text{Var}(Y \mid x) - \sigma^2(x))$, with potentially different constants. Moreover, scaling and translating $x_i$ linearly do not affect our technical results. As a result, we assume, without essential loss of generality, $x_i \in [0, 1]$. We abuse and recycle notation to write $m_0(x) = \mathbb{E}[Y_i \mid x_i = x], s_0(x) = \text{Var}(\theta_i \mid x_i = x)$. We also note that $m_0(x), s_0(x) \in C^2_{A_3}([0,1])$ for some $A_3 \lesssim_H A_1$.

\[\text{Correspondingly, let } \sigma(x) = 10^x.\]
We will consider the following local linear regression of \( Y_i \) on \( x_i \). There are many steps imposed for ease of theoretical analysis, but we conjecture are unnecessary in practice. In our empirical exercises, omitting these steps do not affect performance.

(LLR-1) Fix some kernel \( K(\cdot) \). Use the direct plug-in procedure of Calonico et al. (2019) to estimate a bandwidth \( \hat{h}_{n,m} \).

(LLR-2) For some \( C_h > 1 \), project \( \hat{h}_{n,m} \) to some interval \([C_h^{-1} n^{-1/5}, C_h n^{-1/5}]\) so as to enforce that it converges at the optimal rate:

\[
\hat{h}_{n,m} \leftarrow (\hat{h}_{n,m} \lor C_h^{-1} n^{-1/5}) \land C_h n^{-1/5}.
\]

(LLR-3) Using \( \hat{h}_{n,m} \), estimate \( m_0 \) with the local linear regression estimator \( \hat{m}_{\text{raw}} \) under kernel \( K(\cdot) \) and bandwidth \( \hat{h}_{n,m} \).

(LLR-4) Project the resulting estimator \( \hat{m} \) to the Hölder class \( C^2_{A_1}([0,1]) \):

\[
\hat{m} \in \arg\min_{m \in C^2_{A_1}([0,1])} \|m - \hat{m}_{\text{raw}}\|_\infty.
\]

We obtain \( \hat{m} \) through this procedure.

(LLR-5) Form estimated squared residuals \( \hat{R}^2_i = (Y_i - \hat{m}(x_i))^2 \).

(LLR-6) Repeat (LLR-1) on data \((\hat{R}^2_i, x_i)\) to obtain a bandwidth \( \hat{h}_{n,s} \).

(LLR-7) Repeat (LLR-2) to project \( \hat{h}_{n,s} \).

(LLR-8) Using \( \hat{h}_{n,s} \), estimate \( v(x) = \mathbb{E}[R^2_i \mid X = x] \) with the local linear regression estimator \( \hat{v} \) under kernel \( K(\cdot) \).

(LLR-9) Since \( \hat{v} \) is a local linear regression estimator, it can be written as a linear smoother \( \hat{v}(x) = \sum_{i=1}^n \ell_i(x; \hat{h}_{n,s}) \hat{R}^2_i \). Let an estimate of the effective sample size be

\[
p_n = \frac{1}{n} \sum_{i=1}^n \frac{1}{\sum_{j=1}^n \ell^2_i(x_j, \hat{h}_{n,s})}.
\]  

(G.1)

(LLR-10) Truncate the estimated conditional standard deviation:

\[
\hat{s}_{\text{raw}}(x) = \sqrt{\hat{v}(x) - \sigma^2(x)} \lor \sqrt{\frac{2}{p_n + 2} \hat{v}(x)}.
\]

(G.2)

(LLR-11) Finally, project the resulting estimate to the Hölder class as in (LLR-4):

\[
\hat{s}(x) \in \arg\min_{s \in C^2_{A_1}([0,1])} \|s - \hat{s}_{\text{raw}}\|_\infty.
\]

In practice, we expect the projection steps (LLR-3), (LLR-4), (LLR-7), and (LLR-11) to be unnecessary, at least with exceedingly high probability, since (i) Calonico et al. (2019)’s procedure is consistent for the optimal bandwidth, which contracts at \( n^{-1/5} \), and (ii) local linear regression estimated functions are likely sufficiently smooth to obey Assumption 4(3). Hence, in our empirical implementation, we do not enforce these steps and simply set \( \hat{m} = \hat{m}_{\text{raw}}, \hat{s} = \hat{s}_{\text{raw}} \). Omitting the projection steps does not appear to affect performance.

\(^{79}\)We use the \( \leftarrow \) notation to reassign a variable so that we can reduce notation clutter.
To ensure we always have a positive estimate of \( s_0 \), we truncate at a particular point (G.2). This truncation rule is a heuristic (and improper) application of results from the literature on estimating non-centrality parameters. We digress and discuss the truncation rule in the next remark.

Remark G.1 (The truncation rule in (G.2)). The truncation rule in (G.2) is an ad hoc adjustment without affecting asymptotic performance.\(^8^0\) It is based on a literature on the estimation of non-central \( \chi^2 \) parameters (Kubokawa et al., 1993). Specifically, let \( U_i \overset{i.i.d.}{\sim} \mathcal{N}(\lambda, 1) \) and let \( V = \sum_{i=1}^p U_i^2 \) be a noncentral \( \chi^2 \) random variable with \( p \) degrees of freedom and noncentrality parameter \( \lambda = \sum_{i=1}^p \lambda_i^2 \). The UMVUE for \( \lambda \) is \( V - p \), which is dominated by its positive part \((V - p)_+\).

Kubokawa et al. (1993) derive a class of estimators of the form
\[
\hat{\lambda} = \lambda P
\]
\( p \) achieve a smaller constant in the rate expression, despite not mattering asymptotically.

Our following argument assumes that the truncation of order \( O(n^{4/5}) \). Doing so is likely to achieve a smaller constant in the rate expression, despite not mattering asymptotically.

Remark G.1 (The truncation rule in (G.2)). The truncation rule in (G.2) is an ad hoc adjustment without affecting asymptotic performance.\(^8^0\) It is based on a literature on the estimation of non-central \( \chi^2 \) parameters (Kubokawa et al., 1993). Specifically, let \( U_i \overset{i.i.d.}{\sim} \mathcal{N}(\lambda, 1) \) and let \( V = \sum_{i=1}^p U_i^2 \) be a noncentral \( \chi^2 \) random variable with \( p \) degrees of freedom and noncentrality parameter \( \lambda = \sum_{i=1}^p \lambda_i^2 \). The UMVUE for \( \lambda \) is \( V - p \), which is dominated by its positive part \((V - p)_+\).

Kubokawa et al. (1993) derive a class of estimators of the form \( \hat{\lambda} = \lambda P \) that dominate \((V - p)_+\) in squared error risk. An estimator in this class is \((V - p) \lor \frac{2}{p+2} V\).\(^8^1\)

This setting is loosely connected to ours. Suppose \( m_0 \) is known, and we were using a Nadaraya–Watson estimator with uniform kernel. Then, for a given evaluation point \( x_0 \), we would be averaging nearby \( R^2_i \)’s. Each \( R_i \) is conditionally Gaussian, \( R_i \mid (\theta_i, \sigma_i) \sim \mathcal{N}(\theta_i - m_0(\sigma_i), \sigma_i^2) \) with approximately equal variance \( \sigma^2 \approx \sigma(x_0)^2 \). If there happens to be \( p_0 \) \( R^2_i \)’s that we are averaging, the Nadaraya–Watson estimator is of the form
\[
\hat{v}(x_0) = \frac{\sigma(x_0)^2}{p_0} \sum_{i=1}^{p_0} \left( \frac{R_i}{\sigma(x_0)} \right)^2
\]

Conditional on \( \sigma^2, \theta_i \), the quantity \( \sum_{i=1}^{p_0} \left( \frac{R_i}{\sigma(x_0)} \right)^2 \) is (approximately) noncentral \( \chi^2 \) with \( p \) degrees of freedom and noncentrality parameter
\[
\lambda = \sum_{i=1}^{p_0} \left( \frac{\theta_i - m_0(x_i)}{\sigma(x_0)} \right)^2
\]

Therefore, correspondingly, applying the truncation rule from Kubokawa et al. (1993), an estimator for the sample variance of \( \theta_i \)
\[
\frac{1}{p_0} \sum_{i=1}^{p_0} (\theta_i - m_0(x_i))^2,
\]
is
\[
\left( \hat{v}(x_0) - \sigma^2(x_0) \right) \lor \frac{2}{p_0 + 2} \hat{v}(x_0).
\]

Here, we apply this truncation rule (improperly) to the case where \( \hat{v}(x_0) \) is a weighted average of the squared residuals, with potentially negative weights due to higher-order polynomials (equiv. higher-order kernels). To do so, we would need to plug in an analogue of \( p_0 \). We note that when independent random variables \( V_i \) have unit variance, the weighted average has variance equal to the squared length of the weights
\[
\text{Var} \left( \sum_i \ell_i(x) V_i \right) = \sum_{i=1}^n \ell_i^2(x).
\]

\(^8^0\)Indeed, since we already assumed that the true conditional variance \( s_0(x) > s_\ell \), we can truncate by any vanishing sequence. Given any vanishing sequence, eventually it is lower than \( s_\ell \), and eventually \( |\hat{s} - s_0| \) is small enough for the truncation to not bind. This is, in some sense, silly, since finite sample performance is likely affected if we truncate by, say, \( \frac{1}{\log \log n} \), reflected in a large constant in the corresponding rate expression. Our following argument assumes that the truncation of order \( O(n^{-4/5}) \). Doing so is likely to achieve a smaller constant in the rate expression, despite not mattering asymptotically.

\(^8^1\)Though, since neither \((V - p)_+ \) and \((V - p) \lor \frac{2}{p+2} V\) is differentiable in \( V \), they are not admissible.
Since a simple average has variance equal to $1/n$, we can take $(\sum_{i=1}^{n} \ell_i^2(x))^{-1}$ to be an effective sample size. Our rule simply takes the average effective sample size over evaluation points in (G.1) and use it as a candidate for $p$.

The goal in this section is to control the following probability as a function of $t > 0$

$$
P\left(\|\hat{\eta} - \eta_0\|_\infty > C_H t n^{-2/5} (\log n)^\beta \right)
$$

for some constants $\beta, C_H$ to be chosen. Since we treat $x_1, \ldots, x_n$ as fixed (fixed design), we shall do so placing some assumptions on sequences of the design points $x_{1:n}$ as a function of $n$. These assumptions are mild and satisfied when the design points are equally spaced. They are also satisfied with high probability when the design points are drawn from a well-behaved density $f(\cdot)$.

Before doing so, we introduce some notation on the local linear regression estimator. Note that, by translating and scaling if necessary, it is without essential loss of generality to assume $x_i$ take values in $[0, 1]$. Let $h_n$ denote some (possibly data-driven) choice of bandwidth. Let $u(x) = [1, x]'$ and let $B_{nx} = B_{nx}(h_n) = \frac{1}{nh_n} \sum_{i=1}^{n} K\left(\frac{x_i - x}{h_n}\right) u\left(\frac{x_i - x}{h_n}\right) u\left(\frac{x_i - x}{h_n}\right)'$. Then, it is easy to see that the local linear regression weights can be written in terms of $B_{nx}$ and $u(\cdot)$:

$$
s_n \equiv nh_n \ell_i(x) = \ell_i(x, h_n) \equiv \frac{1}{s_n} u(0)' B_{nx}^{-1} u\left(\frac{x_i - x}{h_n}\right) K\left(\frac{x_i - x}{h_n}\right).
$$

We shall maintain the following assumptions on the design points. The following assumptions introduce constants $(C_h, n_0, \lambda_0, a_0, K_0, K(\cdot), c, C, C_K, V_K)$ which we shall take as primitives like those in $\mathcal{H}$. The symbols $\lesssim, \gtrsim, \asymp$ are relative to these constants, and we will not keep track of exact dependencies through subscripts.

**Assumption G.1.** For some constant $C_h > 1$, the data-driven bandwidth $h_n$ is almost surely contained in the set $H_n \equiv \left[ C_h^{-1} n^{-1/5} \vee \frac{1}{2n}, C_h n^{-1/5} \right]$. Assumption G.1 is automatically satisfied by the projection steps (LLR-3) and (LLR-7).

**Assumption G.2.** The sequence of design points $(x_i : i = 1, \ldots, n)$ satisfy:

1. There exists a real number $\lambda_0 > 0$ and integer $n_0 > 0$ such that, for all $n \geq n_0$, any $x \in [0, 1]$, and any $\hat{h} \in \left[ C_h^{-1} n^{-1/5} \vee \frac{1}{2n}, C_h n^{-1/5} \right]$, the smallest eigenvalue $\lambda_{\min}(B_{nx}(\hat{h})) \geq \lambda_0$.

2. There exists a real number $a_0 > 0$ such that for any interval $I \subset [0, 1]$ and all $n \geq 1$,

$$
\frac{1}{n} \sum_{i=1}^{n} \mathbb{1}(x_i \in I) \leq a_0 \left( \lambda(I) \vee \frac{1}{n} \right)
$$

where $\lambda(I)$ is the Lebesgue measure of $I$.

3. The kernel $K$ is supported on $[-1, 1]$ and uniformly bounded by some positive constant $K_0$.

4. There exists $c, C > 0$ such that for all $n \geq n_0$, the choice of $p_n$ in (G.1) satisfies $cn^{4/5} \leq p_n(\hat{h}) \leq C n^{4/5}$ for all $\hat{h} \in \left[ C_h^{-1} n^{-1/5} \vee \frac{1}{2n}, C_h n^{-1/5} \right]$.

Assumption G.2(1-3) is nearly the same as Assumption (LP) in Tsybakov (2008). The only difference is that Assumption G.2(1) requires the lower bound $\lambda_0$ to hold uniformly over a range of bandwidth choices, relative to LP-1 in Tsybakov (2008), which requires $\lambda_0$ to hold for some deterministic sequence $h_n$. This is a mild strengthening of LP-1: Note that if $x_i$ are drawn from a
Assume that the kernel $x$ heuristically, if $\succ$ Lipschitz-continuous, everywhere-positive density $f(x)$, then for $h \to 0, nh \to \infty$,

$$B_{nx}(h) \approx \int K(t)u(t)u(t)'f(x)dt \gtrsim \int K(t)u(t)u(t)'dt \left( \min_{x \in [0,1]} f(x) \right)$$

where $\succ$ denotes the positive-definite matrix order. Thus the minimum eigenvalue of $B_{nx}(h)$ should be positive irrespective of $x$ and $h$. See, also, Lemma 1.5 in Tsybakov (2008).

Assumption G.2(2)–(3) are the same as (LP-2)–(LP-3) in Tsybakov (2008). (2) expects that the design points are sufficiently spread out, and (3) is satisfied by, say, the Epanechnikov kernel.

Lastly, (4) expects that the average effective sample size is about $s_n = nh_n \asymp n^{-4/5}$. Again, heuristically, if $x_i$ are drawn from a Lipschitz and everywhere-positive density $f(x)$, then

$$\sum_{i=1}^{n} \ell_i^2(x_j) \approx n \frac{1}{s_n^2} h_n \cdot \int (u(0)'B^{-1}_{nx,j}u(t)K(t))^2f(x_j)dt = \frac{1}{s_n} \int (u(0)'B^{-1}_{nx,j}u(t)K(t))^2f(x_j)dt.$$

Hence the mean reciprocal $p_{n}$ is of order $s_{n}$. We also remark that Assumption G.2 is satisfied by regular design points $x_i = i/n$.

**Assumption G.3.** The kernel satisfies the following VC subgraph-type conditions. Let

$$\mathcal{F}_k = \left\{ y \mapsto \left( \frac{y-x}{h} \right)^{k-1} K\left( \frac{y-x}{h} \right) : x \in [0,1], h \in H_n \right\}$$

for $k = 1, 2$. For any finitely supported measure $Q$,

$$N(\epsilon, \mathcal{F}_k, L_2(Q)) \leq C_K(1/\epsilon)^{V_K}$$

for $C_{K}, V_{K}$ that do not depend on $Q$.

Assumption G.3 is satisfied for a wide range of kernels, e.g. the Epanechnikov kernel. By Lemma 7.22 in Sen (2018), reproduced as Lemma G.2 below, so long as the function $t \mapsto t^{k-1}K(t)$ is bounded (assumed in Assumption G.2(3)) and of bounded variation (satisfied by any absolutely continuous kernel function), the covering number conditions hold by exploiting the finite VC dimension of subgraphs of these functions.

We now state and prove the main results in this section. The key to these arguments is Proposition G.1 on the bias and variance of local linear regression estimators. Proposition G.1 is uniform in both the evaluation point $x$ and the bandwidth $h$, as long as the latter converges at the optimal rate.

**Theorem G.1.** Suppose the conditional distribution $\theta_i \mid \sigma_i$ and the design points $\sigma_{1:n}$ satisfy Assumptions 2, 3, and G.2. Moreover, suppose $m_0, s_0$ satisfies Assumption 4(1) with $p = 2$.

Suppose the kernel $K(\cdot)$ satisfies Assumption G.3. Let $\hat{m}, \hat{s}$ denote the estimators computed by (LLR-1) through (LLR-11). Then:

1. $P\left( \hat{m}, \hat{s} \in C_{A_3}([0,1]) \right) = 1$

2. For some $C$ depending only on the parameters in the assumptions, for all $n \geq 7$ and $t > 1$,

$$P \left( \max (\| \hat{m} - m_0 \|_\infty, \| \hat{s} - s_0 \|) \geq C t n^{-2} (\log n)^{1+2/\alpha} \right) \leq \frac{1}{n^{10} t^2}.$$  (G.3)
(3) For some \( c \) depending only on the parameters in the assumptions, for all \( n \geq 7 \),

\[
P \left( \frac{c}{n} \leq \hat{s} \right) = 1.
\]

Proof. The first claim is true automatically by the projection to the Hölder space. The third claim is true automatically by (LLR-11), since \( p_n \asymp n^{1/5} \) and \( n^{-4/5} \gtrsim n^{-1} \).

Now, we show the second claim. Since we assume that \( m_0, s_0 \) lies in the Hölder space with \( s_0 > s_0 \), then projection to the Hölder space (and truncation by \( 2/(2 + p_n) \min_i \sigma_i^2 \)) worsens performance by at most a factor of two for all sufficiently large \( n \). The projection to the Hölder space ensures that \( \| \hat{\eta} - \eta_0 \|_\infty \) is bounded a.s. for all \( n \), so that we can remove “for all sufficiently large \( n \)” at the cost of enlarging a constant so as to accommodate the first finitely many values of \( n \). As a result, it suffices to show that

\[
P \left( \max (\| \hat{m}_{\text{raw}} - m_0 \|_\infty, \| \hat{s}_{\text{raw}} - s_0 \|_\infty) > C n^{2/5} (\log n)^3 \right) \leq \frac{1}{n^{10} t^2}
\]

for some \( C \) and \( \beta = 1 + 2/\alpha \).

Let \( Y_i = m_0(x_i) + \xi_i \) where \( \xi_i = \theta_i - m_0(x_i) + (Y_i - \theta_i) \). Note that we have simultaneous moment control for \( \xi_i \):

\[
\max_i \mathbb{E}[|\xi_i|^p]^{1/p} \lesssim p^{1/\alpha}
\]

where \( \alpha \) is the constant in Assumption 2. Therefore, we can apply Proposition G.1 to obtain

\[
P \left( \| \hat{m}_{\text{raw}} - m_0 \|_\infty > C n^{2/5} (\log n)^{1 + 1/\alpha} \right) \leq \frac{1}{2 n^{10} t^2}
\]

for the local linear regression estimator \( \hat{m}_{\text{raw}} \).

The same argument to control \( \| \hat{s}_{\text{raw}} - s_0 \|_\infty \) is more involved. First observe that

\[
|s_{\text{raw}}^2 - s_0^2| = |\hat{s}_{\text{raw}} - s_0| (\hat{s}_{\text{raw}} + s_0) \geq s_0 |\hat{s}_{\text{raw}} - s_0|.
\]

Also observe that for a positive \( f_0 \),

\[
|\hat{f} \vee g - f_0| \leq |\hat{f} - f_0| \vee |g|.
\]

As a result, it suffices to control the upper bound in

\[
\| \hat{s}_{\text{raw}} - s_0 \|_\infty \leq \frac{1}{s_0} (\| \hat{v} - v_0 \|_\infty \vee \left( \frac{2}{2 + p_n} \hat{v} \right)) \quad (v_0(x) \equiv \text{Var}(Y_i \mid x_i = x))
\]

\[
\lesssim \| \hat{v} - v_0 \|_\infty \vee \frac{\| \hat{v} - v_0 \|_\infty + \| v_0 \|_\infty}{2 n^{1/5}}
\]

\[
\lesssim \| \hat{v} - v_0 \|_\infty
\]

(Assumption G.2)

Now, observe that \( \hat{R}_i^2 = R_i^2 + (m_0 - \hat{m})^2 - 2(m_0 - \hat{m}) \xi_i \). Hence,

\[
|\hat{v}(x) - v_0(x)| \leq \sum_{i=1}^n \ell_i(x, \hat{h}_{n,s},) R_i^2 - v_0(x) + \left\{ \| m_0 - \hat{m} \|_\infty^2 + 2 \| m_0 - \hat{m} \|_\infty \left( \max_{i \in [n]} |\xi_i| \right) \right\} \sum_{i=1}^n |\ell_i(x, \hat{h}_{n,s})|
\]

\[
\leq \sum_{i=1}^n \ell_i(x, \hat{h}_{n,s},) R_i^2 - v_0(x) + C \left\{ \| m_0 - \hat{m} \|_\infty^2 + 2 \| m_0 - \hat{m} \|_\infty \left( \max_{i \in [n]} |\xi_i| \right) \right\}.
\]

(G.5)
By Lemma 1.3 in Tsybakov (2008), the term $\sum_{i=1}^{n} |\xi_i(x, \hat{h}_{n,s})|$ is bounded uniformly in $h$ and $x$ by a constant. Note that

$$\tilde{\xi}_i \equiv R_i^2 - v_0(x_i)$$

has simultaneous moment control with a different parameter ($\tilde{\alpha} = \alpha/2$):

$$\max_{i} (E|\tilde{\xi}_i|^p)^{1/p} \lesssim p^{2/\alpha}.$$

Thus, applying Proposition G.1 and taking care to plug in $\tilde{\xi}, \tilde{\alpha}$, we can bound the first term in (G.5)

$$P \left( \left\| \sum_{i=1}^{n} \ell_i(x, \hat{h}_{n,s}) R_i^2 - v_0(x) \right\|_{\infty} \geq C t n^{-2/5} (\log n)^{1+2/\alpha} \right) \leq \frac{1}{4n^{10} t^2}.$$

Note that by an application of Lemma F.6, for any $a, b > 0$, we have that

$$P \left( \max_{i} |\xi_i| > C(a,b)t(\log n)^{1/\alpha} \right) \leq a^{-b} e^{-t^2}.$$

As a result, the second term in (G.5) admits

$$P \left( \|m_0 - \hat{m}\|_{\infty}^2 + 2 \|m_0 - \hat{m}\|_{\infty} \left( \max_{i \in [n]} |\xi_i| \right) > C t n^{-2/5} (\log n)^{1+2/\alpha} \right) \leq \frac{1}{4n^{10} t^2}.$$

Finally, putting these bounds together, we have that

$$P \left( \|\hat{v} - v_0\|_{\infty} > C t n^{-2/5} (\log n)^{1+2/\alpha} \right) \leq \frac{1}{2n^{10} t^2},$$

where the same bound (with a different constant) holds for $s_{\text{raw}}$ by (G.4).

Combining the bounds for $\hat{m}$ and $\hat{s}$, we obtain (G.3). This concludes the proof. \qed

**Theorem G.2.** Under the assumptions of Theorem G.1, let $\hat{n} = (\hat{m}, \hat{s})$ denote estimators computed by (LLR-1) through (LLR-11). Then,

$$E \left[ \text{MSERegret}_n(\hat{G}_n, \hat{n}) \right] \lesssim n^{-2/5} (\log n)^{1+2/\alpha}.$$

**Proof.** Recall the event $A_n$ in (C.5) for $\Delta_n = C_1 n^{-2/5} (\log n)\beta$ and $M_n = C_2 (\log n)^{1/\alpha}$, where $C_1, C_2$ are to be chosen and $\beta = 1 + 2/\alpha$. Define $\tilde{A}_n = A_n \cap \{ s_{\ell}/2 \leq \tilde{s} \leq 2s_{\ell} \}$. Decompose

$$E \left[ \text{MSERegret}_n(\hat{G}_n, \hat{n}) \right] = E \left[ \text{MSERegret}_n(\hat{G}_n, \hat{n}) 1(\tilde{A}_n) \right] + E \left[ \text{MSERegret}_n(\hat{G}_n, \hat{n}) 1(\tilde{A}_n^C) \right].$$

Note that, for all sufficiently large $n > N$, such that $N$ depends only on $C_1, \beta, s_{\ell}, s_u$, the event $A_n$ implies $\{ s_{\ell}/2 \leq \tilde{s} \leq 2s_{\ell} \}$ and hence $A_n = \tilde{A}_n$. Thus, by Theorem G.1, for all sufficiently large $n$, on the event $A_n$, statements analogous to Assumption 4(2-4) hold for the estimator $\hat{n}$. As a result, we may apply Theorem F.1, *mutatis mutandis*, to obtain that

$$E \left[ \text{MSERegret}_n(\hat{G}_n, \hat{n}) 1(\tilde{A}_n) \right] \lesssim n^{-4/5} (\log n)^{2+\alpha+3+2\beta}$$

for all sufficiently large choices of $C_1, C_2$.

To control $E \left[ \text{MSERegret}_n(\hat{G}_n, \hat{n}) 1(\tilde{A}_n^C) \right]$, we observe that under Lemma F.5 and Theorem G.1(1 and 3), we have that almost surely,

$$\text{MSERegret}_n(\hat{G}_n, \hat{n}) \lesssim n^4 Z_n^2.$$
Hence, by Cauchy–Schwarz as in Lemma F.1,
\[
E \left[ \text{MSERegret}_n(\hat{G}_n, \hat{n}) \mathbb{I}(\hat{A}_n^C) \right] \lesssim P(\hat{A}_n^C)^{1/2} n^4 (\log n)^{2/\alpha},
\]
where we apply Lemma F.6 to bound \( E[Z_n^4] \).

For all sufficiently large \( n > N \),
\[
P(\hat{A}_n^C) = P(\hat{C}_n^C) \leq P(\mathbb{Z}_n > M_n) + P(\|\hat{n} - n_0\|_\infty > \Delta_n).
\]
Sufficiently large \( C_1, C_2 \) can be chosen such that the right-hand side is bounded by \( n^{-10} \). To wit, we can apply Theorem G.1 to bound \( \|\hat{n} - n_0\|_\infty \). We can apply Lemma F.6 to bound \( P(\mathbb{Z}_n > M_n) \).

As a result, we would obtain
\[
E \left[ \text{MSERegret}_n(\hat{G}_n, \hat{n}) \mathbb{I}(\hat{A}_n^C) \right] \lesssim \frac{1}{n} (\log n)^{2/\alpha}
\]
for all sufficiently large \( n \).

Since \( E[\text{MSERegret}_n(\hat{G}_n, \hat{n})] \lesssim n^4 (\log n)^{2/\alpha} \) is finite for all \( n \), at the cost of enlarging the implicit constant, we have the result of the theorem holding for all \( n \).

\[\square\]

G.1. Auxiliary lemmas.

**Proposition G.1.** Consider the local linear regression of data \( Y_i = f_0(x_i) + \xi_i \) on the design points \( x_i \), for \( i = 1, \ldots, n \). Suppose \( f_0 \) belongs to a Hölder class of order two: \( f_0 \in C^2_\gamma([0, 1]) \) for some \( L > 0 \). Suppose that the design points satisfy Assumption G.2 and the (possibly data-driven) bandwidths \( h_n \) satisfy Assumption G.3. Assume the kernel additionally satisfies Assumption G.3.

Assume that the residuals \( \xi_i \) are mean zero, and there exists a constant \( A_\xi > 0, \alpha > 0 \) such that
\[
\max_{i = 1, \ldots, n} \left( E[|\xi_i|^p]\right)^{1/p} \leq A_\xi p^{1/\alpha}
\]
for all \( p \geq 2 \). Let \( \ell_i(x, h) \) be the weights corresponding to local linear regression, and define the bias part \( b(x, h_n) = (\sum_{i=1}^n \ell_i(x, h_n)f_0(x_i)) - f_0(x) \) and the stochastic part \( v(x, h) = \sum_{i=1}^n \ell_i(x, h)\xi_i \).

Recall that \( H_n \) is the interval for \( h_n \) in Assumption G.1. Then:

1. The bias term is of order \( n^{-2/5} \):
   \[
   \sup_{x \in [0, 1], h \in H_n} |b(x, h)| \lesssim n^{-2/5}.
   \]
2. The variance term admits the following large-deviation inequality: For any \( a, b > 0 \), there exists a constant \( C(a, b) \), which may additionally depend on the constants in the assumptions, such that for all \( n > 1 \) and \( t \geq 1 \)
   \[
P \left( \sup_{x \in [0, 1], h \in H_n} |v(x, h)| > C(a, b) \cdot t \cdot (\log n)^{1+1/\alpha} n^{-2/5} \right) \leq an^{-b} \frac{1}{t^2}.
   \]
3. As a result, let \( \hat{f}(\cdot) = b(\cdot, h_n) + v(\cdot, h_n) + f_0(\cdot) \), we have that for any \( a, b > 0 \), there exists a constant \( C(a, b) \) such that for all \( n > 1 \) and \( t \geq 1 \),
   \[
P \left( \|\hat{f} - f_0\|_\infty > C(a, b) t (\log n)^{1+1/\alpha} n^{-2/5} \right) \leq an^{-b} \frac{1}{t^2}.
   \]
Proof. Note that (3) follows immediately from (1) and (2) since the bounds in (1) and (2) are uniform over all \( h \in H_n \). We now verify (1) and (2).

(1) This claim follows immediately from the bound for \( b(x_0) \) in Proposition 1.13 in Tsybakov (2008). The argument in Tsybakov (2008) shows that

\[
\sup_{x \in [0,1]} |b(x, h_n)| \leq Ch_n^2,
\]

which is uniformly bounded by \( Cn^{-2/5} \) by Assumption G.1. Hence

\[
\sup_{x \in [0,1], h \in H_n} |b(x, h)| \lesssim n^{-2/5}.
\]

(2) Let \( M \) be a truncation point to be defined. Let

\[
\xi_{i,<M} = \xi_i \mathbb{1}(|\xi_i| \leq M) - \mathbb{E}[\xi_i \mathbb{1}(|\xi_i| \leq M)]
\]

\[
\xi_{i,>M} = \xi_i \mathbb{1}(|\xi_i| > M) - \mathbb{E}[\xi_i \mathbb{1}(|\xi_i| > M)]
\]

be truncated and demeaned variables. Note that

\[
\xi_i = \xi_{i,<M} + \xi_{i,>M}.
\]

First, let \( V_{1n}(x, h_n) = \sum_{i=1}^n \ell_i(x, h_n)\xi_{i,>M} \). Note that by Cauchy–Schwarz, uniformly over \( x, h_n \),

\[
V_{1n}^2 \leq \sum_{i=1}^n \ell_i(x, h_n)^2 \sum_{i=1}^n \xi_{i,>M}^2
\]

\[
\lesssim \frac{1}{h_n^2} \frac{1}{n} \sum_{i=1}^n \xi_{i,>M}^2 \quad \text{(Lemma 1.3(i) in Tsybakov (2008) shows that} |\ell_i(x, h_n)| \leq \frac{C}{nh_n})
\]

\[
\lesssim n^{2/5} \frac{1}{n} \sum_{i=1}^n \xi_{i,>M}^2
\]

Now, for some \( C \) related to the implicit constant in the above display,

\[
P \left( \sup_{x \in [0,1], h_n \in H_n} V_{1n}(x, h_n) > Ct^2 \right) \leq P \left( \frac{1}{n} \sum_{i=1}^n \xi_{i,>M}^2 > t^2 n^{-2/5} \right) \leq \frac{\max_i \mathbb{E}\xi_{i,>M}^2}{t^2} n^{2/5}.
\]

\text{(Markov’s inequality)}

We note that by Cauchy–Schwarz,

\[
\mathbb{E}[\xi_{i,>M}^2] \leq \sqrt{\mathbb{E}[\xi_i^4]} \mathbb{P}(|\xi_i| > M) \lesssim \sqrt{\mathbb{P}(|\xi_i| > M)} \leq \exp(-cM^\alpha)
\]

\text{(Lemma D.16)}

where \( c \) depends on \( A_\xi \). Hence, for a potentially different constant \( C \),

\[
P \left( \sup_{x \in [0,1], h_n \in H_n} |V_{1n}(x, h_n)| > Ct \right) \leq \exp \left( -cM^\alpha - 2 \log t + \frac{2}{5} \log n \right).
\]

\text{(G.6)}

Next, consider the process

\[
V_{2n}(x, h_n) = \sum_{i=1}^n \ell_i(x, h_n)\xi_{i,<M}
\]
\[ \begin{align*}
  &= \frac{1}{nh_n} \sum_{i=1}^{n} u(0)^t B^{-1}_{nx} \begin{bmatrix} 1 \\ 0 \end{bmatrix} K \left( \frac{x_i - x}{h_n} \right) \xi_i, < M \\
  &\quad + \frac{1}{nh_n} \sum_{i=1}^{n} u(0)^t B^{-1}_{nx} \begin{bmatrix} 0 \\ 1 \end{bmatrix} K \left( \frac{x_i - x}{h_n} \right) \left( \frac{x_i - x}{h_n} \right) \xi_i, < M \\
  &\equiv A_1(x, h_n) \frac{1}{n} \sum_{i=1}^{n} K \left( \frac{x_i - x}{h_n} \right) \xi_i, M + A_2(x, h_n) \frac{1}{n} \sum_{i=1}^{n} K \left( \frac{x_i - x}{h_n} \right) \left( \frac{x_i - x}{h_n} \right) \xi_i, < M.
\end{align*} \]

Note that, by Assumption G.2(1), uniformly over \( x \in [0, 1] \) and \( h_n \in H_n \),

\[ |A_k(x, h_n)| \leq \|u(0)^t B^{-1}_{nx}\| \leq \frac{1}{\lambda_0}. \]

By triangle inequality,

\[ V_{2n}(x, h_n) \lesssim \frac{1}{h_n} \left| \frac{1}{n} \sum_{i=1}^{n} K \left( \frac{x_i - x}{h_n} \right) \xi_i, < M \right| + \frac{1}{h_n} \left| \frac{1}{n} \sum_{i=1}^{n} K \left( \frac{x_i - x}{h_n} \right) \left( \frac{x_i - x}{h_n} \right) \xi_i, < M \right| \]

\[ \equiv \frac{1}{\sqrt{nh_n}} V_{2n,1}(x, h_n) + \frac{1}{\sqrt{nh_n}} V_{2n,2}(x, h_n). \]

We will aim to control the \( \psi_2 \)-norm of the left-hand side. Note that it suffices to control the \( \psi_2 \)-norm of both terms on the right-hand side:

\[ \left\| \sup_{x \in [0, 1], h_n \in H_n} |V_{2n}(x, h_n)| \right\|_{\psi_2} \lesssim \frac{1}{\sqrt{nh_n}} \max_{k=1, 2} \left( \left\| \sup_{x \in [0, 1], h_n \in H_n} |V_{2n,k}(x, h_n)| \right\|_{\psi_2} \right). \]

The above display follows from replacing the sum with two times the maximum and Lemma 2.2.2 in van der Vaart and Wellner (1996).

We will do so by applying Lemma G.1. The analogue of \( f \) in Lemma G.1 is

\[ t \mapsto f(t; x, h) = \left( \frac{t - x}{h} \right)^{k-1} K \left( \frac{t - x}{h} \right) \]

for \( V_{2n,k}, k = 1, 2 \). Naturally, the analogues of \( F \) is

\[ F_k = \{ t \mapsto f(t; x, h) : x \in [0, 1], h \in H_n \} \cup \{ t \mapsto 0 \}. \]

Note that

\[ f(t; x, h) \leq \mathds{1}(|t - x| \leq h) K_0 \]

and thus the diameter of \( F_k \) is at most

\[ \sup_{A \subset [0, 1], \mathds{1}(A) \leq 4C h n^{-1/5}} K_0 \sqrt{\frac{1}{n} \sum_{i=1}^{n} \mathds{1}(x_i \in A)} \lesssim n^{-1/10} \]

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by Assumption G.2(2). Therefore, by Assumption G.3, we apply Lemma G.1 and obtain that for $k = 1, 2$
\[ \left\| \sup_{x \in [0,1], h \in H_n} |V_{2n,k}(x, h)| \right\|_{\psi_2} \lesssim M n^{-1/10} \sqrt{\log n}. \]

Finally, this argument shows that
\[ \left\| \sup_{x \in [0,1], h \in H_n} |V_{2n}(x, h)| \right\|_{\psi_2} \lesssim \frac{1}{\sqrt{nh} n^{1/10}} M \sqrt{\log n} \lesssim n^{-2/5} M \sqrt{\log n}. \]  \hspace{1cm} (G.7)

Putting things together, we can choose $M = (c_m \log n)^{1/\alpha}$ for sufficiently large $c_m$ so that by (G.6),
\[ \Pr \left( \sup_{x \in [0,1], h \in H_n} |V_{1n}(x, h)| > C n^{-2/5} \right) \leq \frac{a}{2} n^{-b} \frac{1}{t^2}, \]
where $c_m$ depends on $a, b$. The bound (G.7) in turns shows that
\[ \Pr \left( \sup_{x \in [0,1], h \in H_n} |V_{2n}(x, h_n)| > C(a, b)s \log n)^{1+1/\alpha} n^{-2/5} \right) \leq 2 e^{-t^2} \]

Taking $t = \sqrt{b \log n + \log(a/4)} s$ gives
\[ \Pr \left( \sup_{x \in [0,1], h \in H_n} |V_{2n}(x, h_n)| > C(a, b)s \log n)^{1+1/\alpha} n^{-2/5} e^{-s^2} \right) \leq \frac{a}{2} n^{-b} e^{-s^2} < \frac{a}{2} n^{-b} \frac{1}{s^2} \]
for all $s > 1$.

Therefore, combining the two bounds,
\[ \Pr \left( \sup_{x \in [0,1], h \in H_n} |v(x, h_x)| > C(a, b)s \log n)^{1+1/\alpha} n^{-2/5} \right) \leq \frac{b}{2} \frac{1}{t^2}. \]

\[ \square \]

**Lemma G.1.** Suppose $\xi_i$ are bounded by $M \geq 1$ and mean zero. Consider the process
\[ V_n(f) = \frac{1}{\sqrt{n}} \sum_{i=1}^{n} f(x_i) \xi_i \]

over a class of real-valued functions $f \in \mathcal{F}$ and evaluation points $x_1, \ldots, x_n \in [0,1]$. Define the seminorm $\|\cdot\|_n$ relative to $x_1, \ldots, x_n$ by
\[ \|f\|_n = \left( \frac{1}{n} \sum_{i=1}^{n} f(x_i)^2 \right)^{1/2}. \]

Suppose $0 \in \mathcal{F}$ and $\mathcal{F}$ has polynomial covering numbers:
\[ N(\epsilon, \mathcal{F}, \|\cdot\|_n) \leq C(1/\epsilon)^V \quad \epsilon \in [0,1] \]
where $C, V > 0$ depend solely on $F$. Then
\[
\left\| \sup_{f \in F} |V_n(f)| \right\|_{\psi_2} \lesssim M \text{diam}(F) \sqrt{\log(1/\text{diam}(F))},
\]
where $\text{diam}(F) = \sup_{f_1, f_2 \in F} \| f_1 - f_2 \|_n$.

Proof. The process $V_n(f)$ has subgaussian increments with respect to $\| \cdot \|_n$:
\[
\| V_n(f_1) - V_n(f_2) \|_{\psi_2} \lesssim M \| f_1 - f_2 \|_n.
\]
Hence, by Dudley’s chaining argument (e.g. Corollary 2.2.5 in van der Vaart and Wellner (1996)), for some fixed $f_0 \in F$,
\[
\left\| \sup_{f} V_n(f) \right\|_{\psi_2} \leq \| V_n(f_0) \|_{\psi_2} + CM \int_{0}^{\text{diam}(F)} \sqrt{\log N(\delta, F, \| \cdot \|_n)} \, d\delta.
\]
Note that (i) the metric entropy integral is bounded by $C \text{diam}(F) \sqrt{\log(1/\text{diam}(F))}$, and (ii) for a fixed $f_0$, $\| V_n(f_0) \|_{\psi_2} \lesssim \| f_0 \|_n M \leq \text{diam}(F) M$ since $0 \in F$. Therefore,
\[
\left\| \sup_{f} V_n(f) \right\|_{\psi_2} \lesssim M \text{diam}(F) \sqrt{\log(1/\text{diam}(F))}.
\]

\[\Box\]

Lemma G.2 (Lemma 7.22(ii) in Sen (2018)). Let $q(\cdot)$ be a real-valued function of bounded variation on $\mathbb{R}$. The covering number of $F = \{ x \mapsto q(ax + b) : (a, b) \in \mathbb{R} \}$ satisfies
\[
N(\epsilon, F, L_2(Q)) \leq K_1 \epsilon^{-V_1}
\]
for some $K_1$ and $V_1$ and for a constant envelope.