Quantitative Economics 12 (2021), 405–442 1759-7331/20210405

Linear regression with many controls of limited explanatory power

Chenchuan (Mark) Li
Department of Economics, Princeton University

Ulrich K. Müller
Department of Economics, Princeton University

We consider inference about a scalar coefficient in a linear regression model. One previously considered approach to dealing with many controls imposes sparsity, that is, it is assumed known that nearly all control coefficients are (very nearly) zero. We instead impose a bound on the quadratic mean of the controls' effect on the dependent variable, which also has an interpretation as an R^2-type bound on the explanatory power of the controls. We develop a simple inference procedure that exploits this additional information in general heteroskedastic models. We study its asymptotic efficiency properties and compare it to a sparsity-based approach in a Monte Carlo study. The method is illustrated in three empirical applications.

Keywords. High dimensional linear regression, L2 bound, invariance to linear reparameterizations.

JEL classification. C12, C21.

1. Introduction

A classic issue that arises frequently in applied econometrics is how to deal with a potentially large number of control variables in a linear regression. In observational studies, the plausibility of an unconfoundedness assumption often hinges on having correctly controlled for the value of predetermined variables, which might require including higher order interactions, leading to many control variables. As is well understood, excluding controls that have nonzero coefficients in general yields estimators with omitted variable bias, and corresponding confidence intervals with less than nominal coverage. In empirical practice, this issue is often addressed by reporting results from several specifications that vary in the number and identity of included control variables.

A seemingly more systematic approach is to use a pretest to identify which controls have nonzero coefficients, such as testing down procedures, or information criteria, and then proceed with standard inference using only the selected controls. As stressed by

Chenchuan (Mark) Li: chenchuanli@gmail.com
Ulrich K. Müller: umueller@princeton.edu

We thank Michal Kolesar, two anonymous referees, and participants at various workshops for useful comments and advice, and Guido Imbens for providing us with the data of Section 6.2. Müller gratefully acknowledges financial support from the National Science Foundation through grant SES-1627660.

 https://doi.org/10.3982/QE1577

Leeb and Pötscher (2005) (also see Leeb and Pötscher (2008a, 2008b) and the references therein), however, this does not yield uniformly valid inference: If a control coefficient is of order $O(n^{-1/2})$ in a sample of size n, then it is not selected with probability one, yet it induces an omitted variable bias that is still large enough to yield oversized confidence intervals. This speaks to a broader theoretical result that in the regression model with Gaussian errors, a hypothesis test either overrejects for some value of the control coefficients, or its power is uniformly dominated by the "long regression" that simply includes all potential controls. Hence, an assumption on the control coefficients is necessary to make progress.

In that context, the empirical practice of reporting several specifications amounts to two extremes: A specification that does not include a set of potential control variables is justified under the assumption that all coefficients are zero, while the specification with the control variables leaves them entirely unconstrained. A potentially more attractive middle ground is an assumption that the control coefficients are, in some sense, of limited magnitude.

One formalization of this idea that has spawned a burgeoning literature is the assumption of sparsity (Tibshirani (1996), Fan and Li (2001), etc.). Most of the control coefficients are known to be zero (or very close to zero), but it is not known which ones. A standard Lasso implementation does not lead to valid inference about the coefficient of interest. But by combining a sparsity assumption on the control coefficients with a sparsity assumption on the correlations between the regressor of interest and the control variables, recent work by Belloni, Chernozhukov, and Hansen (2014) shows how a novel Lasso based "double selection procedure" does yield uniformly valid large-sample inference (also see Zhang and Zhang (2014) and van de Geer, Bühlmann, Ritov, and Dezeure (2014) for related approaches).

While this work is important progress, a sparsity assumption might not always be a compelling starting point: In social science applications, it is usually not obvious why the large majority of control coefficients should be very nearly zero. In addition, the sparsity restriction does not remain invariant to linear reparameterizations of the controls. For instance, in the context of technical controls that are functions of an underlying continuous variable, sparsity drives a distinction between specifying the controls as powers or Chebyshev polynomials, and when including a set of fixed effects, in general it matters which one is dropped to avoid perfect multicollinearity. Finally, in a Lasso implementation, the imposed degree of sparsity is implicitly controlled by a penalty parameter, which makes the small sample interpretation of the resulting inference less than straightforward.

This paper develops an alternative approach that considers a priori upper bounds on the weighted average of squared control coefficients, rather than on the number of nonzero control coefficients. To be precise, consider constructing a confidence interval for the scalar parameter β from the observations $\{y_i, x_i, \mathbf{q}_i, \mathbf{z}_i\}_{i=1}^n$, where

$$y_i = \beta x_i + \mathbf{q}_i'\boldsymbol{\delta} + \mathbf{z}_i'\boldsymbol{\gamma} + \varepsilon_i, \tag{1}$$

the $m \times 1$ control variables $\mathbf{q}_i$ are the baseline specification, the $p \times 1$ additional variables $\mathbf{z}_i$ are potential additional control variables, and ε_i is a conditionally mean zero

error term. To ease notation, assume that $\mathbf{z}_i$ has been projected off $\mathbf{q}_i$, so that $\mathbf{z}_i'\boldsymbol{\gamma}$ is the contribution of $\mathbf{z}_i$ to the conditional mean of y_i after having controlled for the baseline controls $\mathbf{q}_i$. We impose the bound

$$\kappa^2 = n^{-1}\sum_{i=1}^{n}\left(\mathbf{z}_i'\boldsymbol{\gamma}\right)^2 \leq \bar{\kappa}^2. \tag{2}$$

The parameter κ^2 is the average of the squared mean effects $\mathbf{z}_i'\boldsymbol{\gamma}$ on y_i induced by $\mathbf{z}_i$, that is, κ is the quadratic mean of the mean effects of $\mathbf{z}_i$ on y_i, after controlling for the baseline controls $\mathbf{q}_i$. Small values of $\bar{\kappa}$ thus embed the a priori assumption that the explanatory power of the controls is small.

Let $\hat{\beta}_{\text{short}}$ and $\hat{\beta}_{\text{long}}$ be the coefficients on x_i from a linear regression of y_i on $(x_i, \mathbf{q}_i)$, and from a linear regression of y_i on $(x_i, \mathbf{q}_i, \mathbf{z}_i)$, respectively. We combine the information in $(\hat{\beta}_{\text{short}}, \hat{\beta}_{\text{long}})$ and the bound (2) to develop a likelihood ratio (LR) procedure that is more informative than the usual confidence interval centered at $\hat{\beta}_{\text{long}}$. Since $(\hat{\beta}_{\text{short}}, \hat{\beta}_{\text{long}})$ and the bound (2) are invariant to linear transformations of the additional controls, so is the new confidence interval. The new interval essentially reduces to the usual intervals centered at $\hat{\beta}_{\text{short}}$ and $\hat{\beta}_{\text{long}}$ for $\bar{\kappa} = 0$ and $\bar{\kappa} \to \infty$, respectively.[1] The intervals thus provide a continuous bridge between omitting the additional controls and including them with unconstrained coefficients.

Choosing $\bar{\kappa}$ in practice is difficult. At the same time, it is arguably no more difficult than choosing the a priori degree of sparsity of $\boldsymbol{\gamma}$, say. Typical implementations of sparsity-based inference use penalty-based implicit choices for the level of sparsity, which makes it even harder to relate to the effective constraint that is imposed.[2] And, as noted above, it is impossible to sharpen long regression based inference without additional constraints on $\boldsymbol{\gamma}$, so the implicit assumption embedded in the choice of penalty terms is *the* substantive constraint that drives the validity of sparsity-based inference.

In contrast, the interpretation of $\bar{\kappa}$ as the quadratic mean of the effect of $\mathbf{z}_i$ on y_i makes it more explicitly interpretable. It might also be useful to consider the ratio of $n\bar{\kappa}^2$ and the sum of squared residuals of a regression of y_i on $\mathbf{q}_i$; this R^2-type ratio is the upper bound on the fraction of the variability of y_i that is explained by the effect of $\mathbf{z}_i$ on y_i under the null hypothesis of $\beta = 0$, after controlling for the baseline controls $\mathbf{q}_i$. Thus, beliefs about plausible upper bounds on the explanatory power of $\mathbf{z}_i$ in terms of R^2 values directly translate into plausible values of $\bar{\kappa}$, and vice versa.

Still, we expect that empirical researchers will typically not argue for a particular $\bar{\kappa}$, but report results for a range of values. In this way, readers learn about the sensitivity of the results to the additional controls in a more comprehensive manner compared to the $\bar{\kappa} = 0$ short regression and $\bar{\kappa} \to \infty$ long regression extremes. It turns out that when the short regression rejects, and the long regression does not, then there is a unique $\bar{\kappa}^*_{\text{LR}}$ such that for all $\bar{\kappa} < \bar{\kappa}^*_{\text{LR}}$, the LR based test rejects, and for $\bar{\kappa} > \bar{\kappa}^*_{\text{LR}}$, it does not. The resulting threshold value $\bar{\kappa}^*_{\text{LR}}$, and the associated R^2-type ratio, thus form interpretable

[1] See Section 3 for details.

[2] Indeed, recent work by Wüthrich and Zhu (2020) documents severe small sample size distortions of the LASSO-based post-double-selection method even in some very sparse designs.

summaries about the robustness of the statistical significance of β to allowing for additional controls. Whether the value $\bar{\kappa}^*_{\text{LR}}$ is substantively large or small depends on the particular situation at hand; see Section 6 below for three empirical examples and discussion.

Our suggested test and confidence interval is based on the Likelihood Ratio (LR) test statistic obtained from the large sample normality of $(\hat{\beta}_{\text{short}}, \hat{\beta}_{\text{long}})$ and the bound on the omitted variable bias of $\hat{\beta}_{\text{short}}$ implied by (2). From an econometric theory perspective, it is interesting to investigate whether this simple "bivariate" approach comes close to efficiently exploiting the information contained in (2). To this end, we consider the Gaussian homoskedastic version of the regression model (1) and consider asymptotics where the number of additional controls p is of the same order of magnitude as the sample size n. Our main theoretical finding is that in this model, tests that depend on the data only through $(\hat{\beta}_{\text{short}}, \hat{\beta}_{\text{long}})$ are asymptotically efficient in a well-defined sense as long as $\kappa = o(n^{-1/4})$. This rate corresponds to a ratio of $n\kappa^2$ to the sum of squared residuals of a regression of y_i on $\mathbf{q}_i$ of order $o(n^{-1/2})$. While converging to zero, this rate allows for finitely many nonzero coefficients of order $o(n^{-1/4})$, which would lead to corresponding individual t-statistics that diverge at the rate $o(n^{1/4})$. It also allows for a fraction $o(n^{1/4})$ of control coefficients of the already problematic order $O(n^{-1/2})$. Since we expect that our procedure is most valuable in cases where the additional control coefficients are not obviously relevant a priori, this limited efficiency result is thus still useful. The validity of the suggested inference does not depend on any assumptions about κ or $\bar{\kappa}$.

L_2 penalties of the form (2) play a key role in ridge regression (Hoerl and Kennard (1970)), but our set-up uses (2) as a constraint on the nuisance parameter $\boldsymbol{\gamma}$ only. Furthermore, our focus is on hypothesis testing and confidence intervals, and ridge regression estimators do not automatically lead to shorter confidence intervals (see, for instance, Obenchain (1977)). Armstrong and Kolesár (2018) derive small sample minimax optimal confidence intervals in a class of Gaussian regression models with the regression function an element of a known convex set. As they point out in Section 4.1.2 of the corresponding working paper Armstrong and Kolesár (2016), their generic results could be applied to (1) under the bound (2), and we provide some comparison with the LR confidence interval in our Section 2.2 below. Our approach of exploiting an a priori bound on the value of a nuisance parameter is also related in spirit to the analysis of Conley, Hansen, and Rossi (2012), who consider instrumental variable estimation with an imperfect instrument that has a direct effect on the outcome of bounded magnitude.

The rest of the paper is organized as follows. Section 2 contains the analysis of the Gaussian linear regression model (1). In this model, bivariate LR inference is exact, and we analyze and compare its properties. Section 2.3 derives the asymptotic efficiency result for bivariate inference. Section 3 discusses the implementation of feasible inference for non-normal, possibly heteroskedastic and clustered linear regressions. Section 4 contains two extensions: First, we discuss instrumental variable regression with a scalar instrument and a scalar endogenous variable, and second, how to further sharpen inference under an additional bound on the explanatory power in the population regression

of x_i on the potential controls $\mathbf{z}_i$. Section 5 provides a small sample Monte Carlo analysis of our procedure and compares it to the double selection Lasso procedure proposed by Belloni, Chernozhukov, and Hansen (2014). Section 6 provides a self-contained description of the suggested methodology, and applies it in three empirical illustrations. Section 7 concludes. All proofs are collected in the Appendix.

2. Gaussian linear model

2.1 *Set-up*

Write model (1) in vector form as

$$\mathbf{y} = \mathbf{x}\beta + \mathbf{Q}\boldsymbol{\delta} + \mathbf{Z}\boldsymbol{\gamma} + \boldsymbol{\varepsilon} \tag{3}$$

in obvious notation. To ease notation, assume that $\mathbf{x}$ and the additional controls $\mathbf{Z}$ have been projected off the baseline controls $\mathbf{Q}$ (so that $\mathbf{Q}'\mathbf{x} = \mathbf{0}$ and $\mathbf{Z}'\mathbf{Q} = \mathbf{0}$), and that $\mathbf{x}$ and $\mathbf{Z}$ are normalized to satisfy $\mathbf{x}'\mathbf{x} = n$ and $\mathbf{Z}'\mathbf{Z} = n\mathbf{I}_p$. Our efficiency results focus on the simplest model where the regressors $(\mathbf{x}, \mathbf{Q}, \mathbf{Z})$ are nonstochastic and $\boldsymbol{\varepsilon} \sim \mathcal{N}(\mathbf{0}, \mathbf{I}_n)$.

We assume throughout that $(\mathbf{x}, \mathbf{Q}, \mathbf{Z})$ is of full column rank. The $(1 + m + p)$ vector of OLS estimators

$$\begin{pmatrix} \hat{\beta}_{\text{long}} \\ \hat{\boldsymbol{\delta}} \\ \hat{\boldsymbol{\gamma}} \end{pmatrix} = \begin{pmatrix} n & \mathbf{0} & \mathbf{x}'\mathbf{Z} \\ \mathbf{0} & \mathbf{Q}'\mathbf{Q} & \mathbf{0} \\ \mathbf{Z}'\mathbf{x} & \mathbf{0} & n\mathbf{I}_p \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{x}'\mathbf{y} \\ \mathbf{Q}'\mathbf{y} \\ \mathbf{Z}'\mathbf{y} \end{pmatrix} \sim \mathcal{N}\left(\begin{pmatrix} \beta \\ \boldsymbol{\delta} \\ \boldsymbol{\gamma} \end{pmatrix}, \begin{pmatrix} 1 & \mathbf{0} & \mathbf{x}'\mathbf{Z} \\ \mathbf{0} & \mathbf{Q}'\mathbf{Q} & \mathbf{0} \\ \mathbf{Z}'\mathbf{x} & \mathbf{0} & n\mathbf{I}_p \end{pmatrix}^{-1} \right) \tag{4}$$

form a sufficient statistic. Inference about β thus becomes inference about one element of the mean of a $p + m + 1$ dimensional multivariate normal with known covariance matrix.

Let $\mathbf{Y} = (\mathbf{y}, \mathbf{x}, \mathbf{Q}, \mathbf{Z}) \in \mathbb{R}^{(2+m+p)n}$ be the observed data, let $\boldsymbol{\vartheta} = (\beta, \boldsymbol{\delta}', \boldsymbol{\gamma}') \in \mathbb{R}^{1+m+p}$, and let $\varphi_{\beta_0}(\mathbf{Y}) \in \{0, 1\}$ be nonrandomized level α tests of the null hypothesis $H_0 : \beta = \beta_0$, where $\varphi_{\beta_0}(\mathbf{Y}) = 1$ indicates rejection. A confidence set of level $1 - \alpha$ is obtained by "inverting" the family of tests φ_{β_0}, that is, by collecting the values of β_0 for which the test does not reject, $\text{CS}(\mathbf{Y}) = \{\beta_0 : \varphi_{\beta_0}(\mathbf{y}) = 0\}$. By Proposition 15.2 of van der Vaart (1998), for one-sided hypothesis tests about β, the uniformly most powerful test is simply based on the statistic $\hat{\beta}_{\text{long}}$, and the uniformly most powerful unbiased test is based on the statistic $|\hat{\beta}_{\text{long}}|$. By Pratt (1961), the inversion of these uniformly most powerful tests yield confidence sets of minimal expected length: Let $(-\infty, U(\mathbf{Y}))$ be a confidence interval obtained from inverting one-sided tests of the form $H_0 : \beta \geq \beta_0$ against $H_a : \beta < \beta_0$. For a given realization $\mathbf{Y}$ and true value β, the excess length of this interval is $\max(U(\mathbf{Y}) - \beta, 0) = \int_\beta^\infty (1 - \varphi_{\beta_0}(\mathbf{Y}))\, d\beta_0$. By Tonelli's theorem, $E_{\boldsymbol{\vartheta}}[\int_\beta^\infty (1 - \varphi_{\beta_0}(\mathbf{Y}))\, d\beta_0] = \int_\beta^\infty E_{\boldsymbol{\vartheta}}[1 - \varphi_{\beta_0}(\mathbf{Y})]\, d\beta_0$, and the integrand on the right-hand side is minimized by a family of uniformly most powerful tests, indexed by β_0. Similarly, for a two-sided test, the length of the resulting confidence set can be written as $\int (1 - \varphi_{\beta_0}(\mathbf{Y}))\, d\beta_0$, so we obtain $E_{\boldsymbol{\vartheta}}[\int (1 - \varphi_{\beta_0}(\mathbf{Y}))\, d\beta_0] = \int (1 - E_{\boldsymbol{\vartheta}}[\varphi_{\beta_0}(\mathbf{Y})])\, d\beta_0$ and the inversion of uniformly most powerful unbiased tests thus yield the confidence interval of shortest expected length

among all unbiased confidence intervals. In the Gaussian model, no procedure whatsoever can therefore do better than simply running the "long regression" that includes all controls in a well-defined sense.

2.2 *Bivariate inference problem*

In order to exploit the bound (2) for more informative inference, consider the coefficient estimator $\hat{\beta}_{\text{short}}$ from the regression of $\mathbf{y}$ on $(\mathbf{x}, \mathbf{Q})$ that excludes the additional controls $\mathbf{Z}$. Since $\mathbf{Q}'\mathbf{x} = 0$, $\hat{\beta}_{\text{short}} = \mathbf{x}'\mathbf{y}/n$. Let $\rho^2 = \mathbf{x}'\mathbf{Z}\mathbf{Z}'\mathbf{x}/n^2$, the observed R^2 of a regression of $\mathbf{x}$ on $\mathbf{Z}$. To avoid trivial complications in notation, assume $0 < \rho$ in the following. Straightforward algebra yields

$$\begin{pmatrix} \hat{\beta}_{\text{long}} \\ \hat{\beta}_{\text{short}} \end{pmatrix} \sim \mathcal{N}\left(\begin{pmatrix} \beta \\ \beta + \Delta \end{pmatrix}, n^{-1}\boldsymbol{\Sigma}(\rho) \right), \qquad \boldsymbol{\Sigma}(\rho) = \begin{pmatrix} \dfrac{1}{1-\rho^2} & 1 \\ 1 & 1 \end{pmatrix}, \tag{5}$$

where $\Delta = \mathbf{x}'\mathbf{Z}\boldsymbol{\gamma}/n$ is the unknown omitted variable bias. Equation (5) is intuitive: the long regression provides an unbiased signal $\hat{\beta}_{\text{long}}$ about β, but with a variance that is larger than the (typically biased) signal $\hat{\beta}_{\text{short}}$ from the short regression.[3] If $\rho \to 0$, then $\mathbf{Z}$ is orthogonal to $\mathbf{x}$, there is no bias from the short regression, and the two signals are identical, $\hat{\beta}_{\text{long}} = \hat{\beta}_{\text{short}}$.

Notice that $\kappa^2 = \boldsymbol{\gamma}'\boldsymbol{\gamma}$ in (2) may be rewritten as

$$\begin{aligned} \kappa^2 &= \boldsymbol{\gamma}'\mathbf{Z}'\mathbf{x}\left(\mathbf{x}'\mathbf{Z}\mathbf{Z}'\mathbf{x}\right)^{-1}\mathbf{x}'\mathbf{Z}\boldsymbol{\gamma} + \boldsymbol{\gamma}'\mathbf{M}_\rho\boldsymbol{\gamma} \\ &= \rho^{-2}\Delta^2 + \boldsymbol{\gamma}'\mathbf{M}_\rho\boldsymbol{\gamma}, \end{aligned} \tag{6}$$

where $\mathbf{M}_\rho = \mathbf{I}_n - \mathbf{Z}'\mathbf{x}(\mathbf{x}'\mathbf{Z}\mathbf{Z}'\mathbf{x})^{-1}\mathbf{x}'\mathbf{Z}$. The bound $\kappa^2 \le \bar{\kappa}^2$ in (2) thus implies an upper bound on the omitted variable bias,

$$|\Delta| \le \rho\bar{\kappa} \tag{7}$$

and this bound is sharp. This limit on the magnitude of the omitted variable bias in (5) makes $\hat{\beta}_{\text{short}}$ potentially valuable for inference about β, especially if ρ is close to one (so that $\hat{\beta}_{\text{short}}$ is much less variable than $\hat{\beta}_{\text{long}}$).

We focus in the following on tests of $H_0 : \beta = 0$, since the general case $H_0 : \beta = \beta_0$ may be reduced to this case by subtracting β_0 from $\hat{\beta}_{\text{long}}$ and $\hat{\beta}_{\text{short}}$. In terms of the localized parameters $b = \sqrt{n}\beta$, $d = \sqrt{n}\rho^{-1}\Delta$, and $\bar{k} = \sqrt{n}\bar{\kappa}$, the inference problem then becomes testing $H_0 : b = 0$ from observing the bivariate normal vector $\hat{\mathbf{b}} = (\hat{b}_{\text{long}}, \hat{b}_{\text{short}})' \sim (\sqrt{n}\hat{\beta}_{\text{long}}, \sqrt{n}\hat{\beta}_{\text{short}})'$,

$$\begin{pmatrix} \hat{b}_{\text{long}} \\ \hat{b}_{\text{short}} \end{pmatrix} \sim \mathcal{N}\left(\begin{pmatrix} b \\ b + \rho d \end{pmatrix}, \boldsymbol{\Sigma}(\rho) \right), \quad |d| \le \bar{k}. \tag{8}$$

[3] This strict ranking of the variance of the short and long regression estimators holds because we consider fixed regressors; see Section 4.2 for discussion.

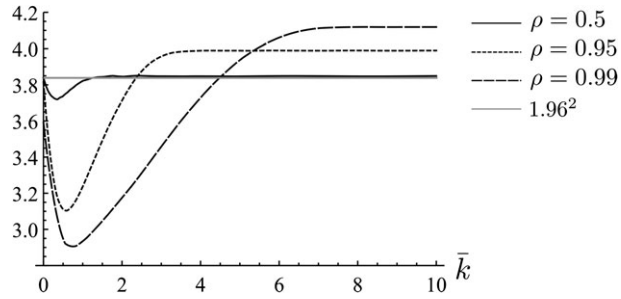

FIGURE 1. Five percent critical value of $\mathrm{LR}(\bar{k})$ as a function of $\bar{k}$..

The inference problem (8) is a fairly transparent small sample problem indexed by two known parameters $(\rho, \bar{k}) \in (0,1) \times [0,\infty)$, and involves a one-dimensional unknown nuisance parameter $d \in \mathbb{R}$. The second observation $\hat{b}_{\text{short}}$ augments the usual Gaussian shift experiment, and there are a variety of potential approaches to exploiting this additional information. We found that a simple but effective test of $H_0 : b = 0$ is generated by the generalized likelihood ratio statistic

$$\begin{aligned}\mathrm{LR}(\bar{k}) = &\min_{|\tilde{d}|\le\bar{k}} \begin{pmatrix} \hat{b}_{\text{long}} \\ \hat{b}_{\text{short}} - \rho\tilde{d} \end{pmatrix}' \boldsymbol{\Sigma}(\rho)^{-1} \begin{pmatrix} \hat{b}_{\text{long}} \\ \hat{b}_{\text{short}} - \rho\tilde{d} \end{pmatrix} \\ &- \min_{\tilde{b},|\tilde{d}|\le\bar{k}} \begin{pmatrix} \hat{b}_{\text{long}} - \tilde{b} \\ \hat{b}_{\text{short}} - \tilde{b} - \rho\tilde{d} \end{pmatrix}' \boldsymbol{\Sigma}(\rho)^{-1} \begin{pmatrix} \hat{b}_{\text{long}} - \tilde{b} \\ \hat{b}_{\text{short}} - \tilde{b} - \rho\tilde{d} \end{pmatrix}. \end{aligned} \tag{9}$$

The level α critical value $\mathrm{cv}_\rho(\bar{k})$ is the largest $1-\alpha$ quantile under (8) with $b = 0$, maximized over $|d| \le \bar{k}$. Figure 1 plots $\mathrm{cv}_\rho(\bar{k})$ for $\rho \in \{0.5, 0.95, 0.99\}$, and Figure 2 plots the rejection region of the resulting 5% level test for $\rho = 0.95$ and $\bar{k} \in \{0, 1, 3, 10\}$. For

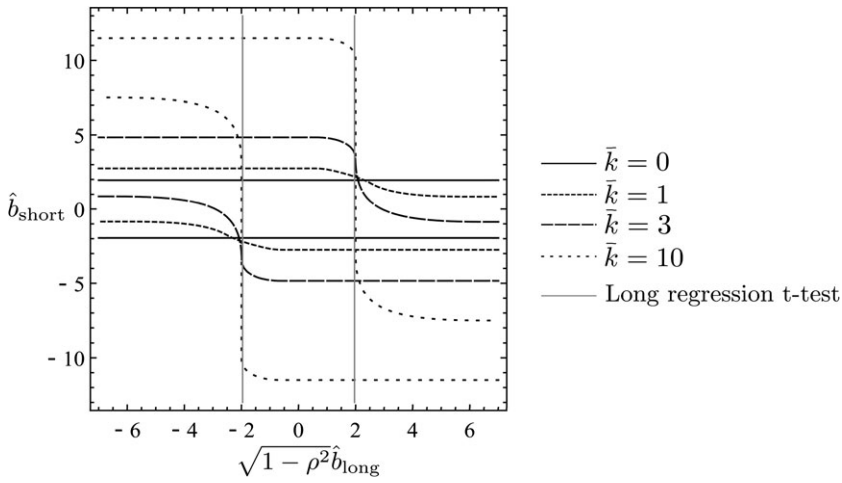

FIGURE 2. Acceptance regions of $\mathrm{LR}(\bar{k})$ for $\rho = 0.95$. Notes: The lines are the boundaries of the acceptance region. For all values of $\bar{k}$, $(0,0)$ is in the acceptance region.

$\bar{k} = 0$, the LR test reduces to rejecting for large values of $(\hat{b}_{\text{short}})^2 > \text{cv}_\rho(0) = 1.96^2$, that is, it reduces to the usual t-test based on the short regression. More generally, whenever $|\hat{b}^{\text{short}}| \gg \rho\bar{k}$, that is the short regression coefficient is much larger than $\rho\bar{k}$ in absolute value, then the LR test rejects. On the other hand, for $|\hat{b}_{\text{short}}| \ll \rho\bar{k}$ and $\bar{k}$ large, the LR test rejects when $(1-\rho^2)(\hat{b}_{\text{long}})^2 > \text{cv}_\rho(\bar{k})$, that is, whenever the long regression coefficient is too large in absolute value, with a critical value that is slightly larger than 1.96^2. Once $\bar{k}$ is moderately large (say, larger than 8), the critical value $\text{cv}_\rho(\bar{k})$ stabilizes at $\text{cv}_\rho(\infty)$, and further increases of $\bar{k}$ simply amount to an additional elongation of the acceptance region along the $\hat{b}_{\text{short}}$-axis.

To formally characterize the limit of the acceptance region for values of $|\hat{b}^{\text{short}}| \approx \rho\bar{k}$ under larger and larger bounds $\bar{k} \to \infty$, consider the observation $\hat{\mathbf{b}}^o = (\hat{b}_{\text{long}}, \hat{b}^o_{\text{short}})' \sim (\hat{b}_{\text{long}}, \hat{b}_{\text{short}} - \rho s)'$ with $\hat{b}_{\text{short}}$, that is, $\hat{b}^o_{\text{short}}$ is shifted by ρs relative to $\hat{b}_{\text{short}}$. Under a corresponding reparameterization $a = d - s$, we obtain

$$\hat{\mathbf{b}}^o \sim \mathcal{N}\left(\begin{pmatrix} b \\ b + \rho a \end{pmatrix}, \boldsymbol{\Sigma}(\rho)\right), \quad a \in A \tag{10}$$

and the constraint $a \in A$ resulting from $|d| \le \bar{k}$ depends on the relationship between s and $\bar{k}$. In particular, with $s = \bar{k}$, $a \in A_1 = (-\infty, 0]$, and this corresponds to the case where the bound $\bar{k}$ is very large and $\hat{b}_{\text{short}}$ is close to the bound $\rho\bar{k}$. Similarly, with $s = -\bar{k}$, $\hat{b}_{\text{short}}$ is close to $-\rho\bar{k}$, and the corresponding constraint in (10) becomes $a \in A_{-1} = [0, \infty)$. Finally, if $\bar{k} \to \infty$ and $\bar{k} - |s| \to \infty$, so that the bound $\bar{k}$ is much larger than $|\hat{b}_{\text{short}}|$, then $a \in A_0 = \mathbb{R}$ is unrestricted in (10). For each of these three cases $i \in \{1, -1, 0\}$, the $\text{LR}(\bar{k})$ statistic converges to

$$\begin{aligned} \text{LR}^o_i = &\min_{\tilde{a} \in A_i} \begin{pmatrix} \hat{b}_{\text{long}} \\ \hat{b}^o_{\text{short}} - \rho\tilde{a} \end{pmatrix}' \boldsymbol{\Sigma}(\rho)^{-1} \begin{pmatrix} \hat{b}_{\text{long}} \\ \hat{b}^o_{\text{short}} - \rho\tilde{a} \end{pmatrix} \\ &- \min_{\tilde{b}, \tilde{a} \in A_i} \begin{pmatrix} \hat{b}_{\text{long}} - \tilde{b} \\ \hat{b}^o_{\text{short}} - \rho\tilde{a} - \tilde{b} \end{pmatrix}' \boldsymbol{\Sigma}(\rho)^{-1} \begin{pmatrix} \hat{b}_{\text{long}} - \tilde{b} \\ \hat{b}^o_{\text{short}} - \rho\tilde{a} - \tilde{b} \end{pmatrix}. \end{aligned}$$

We consider this LR approach attractive for a number of reasons. First, it is easy to implement (we discuss implementation issues in more detail in Section 3 below). Second, inversion of the LR statistic for general null hypotheses $H_0 : b = b_0$ yields a confidence interval for b that is translation equivariant, that is, the interval obtained from the observation $(\hat{b}_{\text{long}} + c, \hat{b}_{\text{short}} + c)$ simply shifts the interval from $(\hat{b}_{\text{long}}, \hat{b}_{\text{short}})$ by c, for any $c \in \mathbb{R}$. Third, it yields confidence intervals that are close to minimal weighted expected length under a weighting function where d is uniform between $[-\bar{k}, \bar{k}]$, among all translation equivariant confidence intervals. This is shown in panel A of Table 1, which reports a lower bound on this weighted expected length for selected values of $(\rho, \bar{k})$, along with the weighted expected length of the LR interval. Given the tight link between the power of tests and their expected length discussed in Section 2.1 above, this implies that the LR tests are also close to maximizing the corresponding weighted average power. Fourth, as shown in panel B, it is reasonably close to being maximin in terms of

expected length among all equivariant confidence intervals. Fifth, its expected length is nearly uniformly shorter over all $|d| \leq \bar{k}$ than the standard long regression interval; panel C provides corresponding numerical evidence. And finally, the LR approach has the potentially attractive feature that if $|\hat{b}_{\text{short}}| > 1.96$ and $\sqrt{1-\rho^2}|\hat{b}_{\text{long}}| < 1.96$ (i.e., the short regression rejects, but the long regression does not), then there is a unique threshold value $\bar{k}^*_{\text{LR}} > 0$ such that the LR test rejects only when $\bar{k} < \bar{k}^*_{\text{LR}}$, so in this sense, imposing a smaller value of $\bar{k}$ always leads to more informative inference.

A family of level α tests of $H_0 : b = b_0$ given a value of $\bar{k}$ in (8) can be inverted to obtain a level $1-\alpha$ confidence set $\text{S}(\hat{\mathbf{b}}) \subset \mathbb{R}^2$, which collect pairs of $(b_0, \bar{k})$ for which the test does not reject. The informativeness of a procedure is usefully measured by the size of this set. The discussion so far concerned the length of the interval for b for a given $\bar{k}$, which are slices of $\text{S}(\hat{\mathbf{b}})$ in one direction. Now consider the length along the other direction: Let $\phi(\bar{k}, \hat{\mathbf{b}}) \in \{0, 1\}$ be the tests of $H_0 : b = 0$ for given $\bar{k}$. Then the threshold value $\bar{k}^*_\phi : \mathbb{R}^2 \mapsto [0, \infty) \cup \{+\infty\}$ is the lower endpoint of $\text{S}(\hat{\mathbf{b}})$ along the $b = 0$ axis,

$$\bar{k}^*_\phi(\hat{\mathbf{b}}) = \inf_{\bar{k}} \{\bar{k} : \phi(\bar{k}, \hat{\mathbf{b}}) = 0\}$$

that is, $\bar{k}^*_\phi(\hat{\mathbf{b}})$ is the smallest value of $\bar{k}$ for which the test $\phi(\bar{k}, \hat{\mathbf{b}})$ does not reject. From this alternative perspective, one might prefer tests ϕ that generate large $\bar{k}^*_\phi(\hat{\mathbf{b}})$. As $\bar{k}^*_\phi(\hat{\mathbf{b}})$ can be equal to $+\infty$, it is not sensible to maximize the expectation of $\bar{k}^*_\phi(\hat{\mathbf{b}})$. Instead, consider a quantile of $\bar{k}^*_\phi(\hat{\mathbf{b}})$, such as its median. Since $\phi(\bar{k}, \hat{\mathbf{b}})$ is a level α test of $H_0 : b = 0$, $|d| \leq \bar{k}$, the $1-\alpha$ quantile of $\bar{k}^*_\phi(\hat{\mathbf{b}})$ must be smaller than $|d|$ under $b = 0$, and $[\bar{k}^*_\phi(\hat{\mathbf{b}}), \infty)$ is thus a $1-\alpha$ confidence interval for $|d|$ under $b = 0$. This constrains the possibility of making the median of $\bar{k}^*_\phi(\hat{\mathbf{b}})$ arbitrarily large. In panel D of Table 1, we report the median of $\bar{k}^*_{\text{LR}}$ of the LR tests under $b = 0$ and $P(d = d_0) = P(d = -d_0) = 1/2$ for various d_0, along with an upper bound that holds for all $\bar{k}^*_\phi(\hat{\mathbf{b}})$.[4] We find that unless $|d|$ is very small, the median of $\bar{k}^*_{\text{LR}}$ is only slightly smaller than the upper bound, and unreported results show this to hold also for other quantiles and assumptions about the distribution of b. The LR approach thus also performs well in the sense that it is nearly as informative as possible about values of $\bar{k}$ that are empirically incompatible with $b = 0$, $|d| \leq \bar{k}$.

Finally, consider the problem of improving the estimation of b under the constraint (2). Our suggested estimator is $\hat{b}_{\text{LR}}(\bar{k})$, the center of the 95% confidence interval constructed by inverting the $\text{LR}(\bar{k})$ statistic. As shown in panel E of Table 1, this estimator comes close to minimizing the weighted average mean square error among all translation equivariant estimators of b, with a weighting function on d that is uniform on $[-\bar{k}, \bar{k}]$. (Unreported results show that the center of the 95% interval does particularly

[4]Note that existence of an estimator $\bar{k}^*_\phi(\hat{\mathbf{b}})$ with median larger than M under some distribution F for (b, d) is equivalent to the existence of a test $\phi_M(\hat{\mathbf{b}}) \in \{0, 1\}$ such that $E[\phi_M(\hat{\mathbf{b}})] \leq \alpha$ for all $b = 0$, $|d| \leq M$ and $E[\phi_M(\hat{\mathbf{b}})] \geq 1/2$ with $(b, d) \sim F$, since we can always set $\phi_M(\hat{\mathbf{b}}) = \mathbf{1}[\bar{k}^*_\phi(\hat{\mathbf{b}}) \geq M]$ or $\bar{k}^*_\phi(\hat{\mathbf{b}}) = M\phi_M(\hat{\mathbf{b}})$, respectively. The upper bound can therefore be obtained from the upper bound of the power of tests in Elliott, Müller, and Watson (2015).

TABLE 1. Properties of 95% bivariate LR inference.

Panel A: Weighted expected length of CI for b under $d \sim U[-\bar{k}, \bar{k}]$

	LR($\bar{k}$) Interval					Lower Bound				
$\rho\backslash\bar{k}$	0	1	3	10	30	0	1	3	10	30
0.50	3.9	4.2	4.4	4.5	4.5	3.9	4.2	4.4	4.5	4.5
0.90	3.9	5.0	7.1	8.5	8.9	3.9	5.0	6.9	8.2	8.7
0.99	3.9	5.3	9.1	18.7	25.3	3.9	5.2	8.9	17.4	23.9

Panel B: Expected length of CI for b, maximized over $|d| \leq \bar{k}$

	LR($\bar{k}$) Interval					Lower Bound				
$\rho\backslash\bar{k}$	0	1	3	10	30	0	1	3	10	30
0.50	3.9	4.3	4.5	4.5	4.6	3.9	4.2	4.4	4.5	4.5
0.90	3.9	5.0	7.4	9.1	9.1	3.9	5.0	7.1	8.4	8.9
0.99	3.9	5.3	9.1	20.0	28.7	3.9	5.2	8.9	18.4	25.1

Panel C: Ratio of expected length of LR CI for b relative to long regression interval

	Minimized over $\|d\| \leq \bar{k}$					Maximized over $\|d\| \leq \bar{k}$				
$\rho\backslash\bar{k}$	0	1	3	10	30	0	1	3	10	30
0.50	0.87	0.92	0.93	0.92	0.94	0.87	0.94	1.00	1.01	1.03
0.90	0.43	0.55	0.72	0.73	0.73	0.43	0.56	0.82	1.01	1.02
0.99	0.14	0.19	0.33	0.59	0.61	0.14	0.19	0.33	0.72	1.03

Panel D: Median of $\bar{k}^*_\phi$ under $b = 0$, $P(d = d_0) = P(d = -d_0) = 1/2$

	$\bar{k}^*_{\mathrm{LR}}$					Upper Bound				
$\rho\backslash d_0$	0	1	3	10	30	0	1	3	10	30
0.50	0.0	0.0	0.0	3.1	13.2	0.0	0.0	0.7	4.2	14.3
0.90	0.0	0.0	0.9	7.1	25.3	0.0	0.0	1.2	7.6	25.8
0.99	0.0	0.0	1.3	8.0	28.0	0.0	0.0	1.4	8.4	28.4

Panel E: Weighted average MSE of equivariant estimators of b under $d \sim U[-\bar{k}, \bar{k}]$

	$\hat{b}_{\mathrm{LR}}$					Lower Bound				
$\rho\backslash\bar{k}$	0	1	3	10	30	0	1	3	10	30
0.50	1.00	1.11	1.25	1.31	1.32	1.00	1.07	1.22	1.30	1.32
0.90	1.00	1.29	2.62	4.42	4.98	1.00	1.25	2.53	4.38	4.97
0.99	1.00	1.33	3.79	21.1	39.9	1.00	1.32	3.77	20.4	39.7

Note: Bounds in Panels A, B, D, and E are numerically determined using the algorithm in Elliott, Müller, and Watson (2015) and Müller and Wang (2019), and impose translation equivariance in Panels A, B, and E (cf. Müller and Norets (2016)). Based on 500,000 importance sampling draws.

well compared to other levels.) One might think that the maximum likelihood estimator of b in (8) under $|d| \leq \bar{k}$ is a more natural estimator; but unreported results show that the MLE is much more variable, resulting in a substantially larger mean squared error compared to $\hat{b}_{\mathrm{LR}}(\bar{k})$.

As mentioned in the Introduction, the problem (8) falls into the general class considered by Armstrong and Kolesár (2016). They construct fixed-length confidence intervals for b that are minimax among all fixed length confidence intervals centered at a linear estimator of b. Table S.1 in the supplemental Appendix (Li and Müller (2021)) is the analogue of Table 1 for their confidence interval, and implied estimators $\bar{k}^*_\phi(\hat{\mathbf{b}})$ and midpoint $\hat{b}_\phi(\bar{k})$. Comparing the tables reveals that the LR approach never does substantially worse, but in some dimensions does substantially better: The LR approach can yield much shorter intervals, it leads to much larger $\bar{k}^*_\phi$, and it has lower weighted average MSE, especially for large $\bar{k}$.

2.3 *Asymptotic efficiency of bivariate inference*

Regardless how exactly they are constructed, confidence intervals about β obtained from the bivariate observation $(\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}})'$ will in general be shorter than those based on $\hat{\beta}_{\mathrm{long}}$ alone. But this does not mean that they necessarily fully exploit the information in the bound (2). After all, the reduction to the bivariate problem (5) was not based on any sufficiency argument. So the question arises whether one can do systematically better than what can be achieved in the bivariate problem (8).

In general, the distribution of tests and confidence intervals about β that are a function of the entire set of observations $\mathbf{Y}$ not only depends on β, the bias $\Delta = \mathbf{x}'\mathbf{Z}\boldsymbol{\gamma}/n$ of the short regression and the slackness in the inequality (7) $\tau^2 = \kappa^2 - \rho^{-2}\Delta^2 = \boldsymbol{\gamma}'\mathbf{M}_\rho\boldsymbol{\gamma}$, but also of the direction of $\boldsymbol{\gamma}$ that leads to identical values of Δ and τ. Let $\mathbf{P}_{xZ}$ be a $p \times (p-1)$ matrix such that $\mathbf{P}'_{xZ}\mathbf{Z}'\mathbf{x} = \mathbf{0}$ and $\mathbf{P}'_{xZ}\mathbf{P}_{xZ} = \mathbf{I}_{p-1}$. Then with $\hat{\boldsymbol{\phi}} = \mathbf{P}'_{xZ}\hat{\boldsymbol{\gamma}}$, it follows from (4) that

$$\hat{\boldsymbol{\xi}} = \begin{pmatrix} \hat{\beta}_{\mathrm{long}} \\ \hat{\beta}_{\mathrm{short}} \\ \hat{\boldsymbol{\delta}} \\ \hat{\boldsymbol{\phi}} \end{pmatrix} \sim \mathcal{N}\left(\begin{pmatrix} \beta \\ \beta + \Delta \\ \boldsymbol{\delta} \\ \tau\boldsymbol{\omega} \end{pmatrix}, \begin{pmatrix} n^{-1}\boldsymbol{\Sigma}(\rho) & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & (\mathbf{Q}'\mathbf{Q})^{-1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & n^{-1}\mathbf{I}_{p-1} \end{pmatrix} \right), \tag{11}$$

where $\boldsymbol{\omega} = \mathbf{P}'_{xZ}\boldsymbol{\gamma}/\|\mathbf{P}'_{xZ}\boldsymbol{\gamma}\| = \mathbf{P}'_{xZ}\boldsymbol{\gamma}/\tau$. The parameter $\boldsymbol{\omega}$ is an element of the surface of the $p-1$ dimensional unit hypersphere and indicates the direction of $\boldsymbol{\gamma}$ in the $p-1$ dimensional subspace orthogonal to $\mathbf{Z}'\mathbf{x}$.

As noted before, by sufficiency, it suffices to consider functions of $\hat{\boldsymbol{\xi}}$. Given the decomposition of κ^2 in (6), it would clearly be beneficial to know the value of τ^2 for inference about β, as it would allow the strengthening of the bound on Δ under (2) to

$$|\Delta| \leq \rho\sqrt{\bar{\kappa}^2 - \tau^2}. \tag{12}$$

Since $\hat{\boldsymbol{\phi}}$ contains information about τ, it thus seems that one can do better than restricting attention to tests that are a solely a function of $(\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}})'$.

We initially discuss a result concerning maximin length properties, which follows from the logic in Donoho (1994). To make the claim precise, let $\mathrm{CS}(\mathbf{Y}) \subset \mathbb{R}$ be a generic level $1-\alpha$ confidence set for β, as introduced in Section 2.1, and let $\ell(\boldsymbol{\xi}, \mathrm{CS}) = E_{\boldsymbol{\xi}}[\int_{\mathrm{CS}(\mathbf{Y})} d\beta_0]$ its expected length under parameter $\boldsymbol{\xi} = (\beta, \Delta, \boldsymbol{\delta}, \tau, \boldsymbol{\omega}) \in \Xi(\bar{\kappa}) = \{\boldsymbol{\xi} : |\Delta| \leq \rho\sqrt{\bar{\kappa}^2 - \tau^2}\}$. Also, let $\mathrm{CS}^{\mathrm{biv}}(\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}}) \subset \mathbb{R}$ be a level $1-\alpha$ confidence set of β that depends on the data $\mathbf{Y}$ only through $(\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}})$.

PROPOSITION 1. *Under* (11), $\min_{\mathrm{CS}} \max_{\boldsymbol{\xi} \in \Xi(\bar{\kappa})} \ell(\boldsymbol{\xi}, \mathrm{CS}) = \min_{\mathrm{CS}^{\mathrm{biv}}} \max_{\boldsymbol{\xi} \in \Xi(\bar{\kappa})} \ell(\boldsymbol{\xi}, \mathrm{CS}^{\mathrm{biv}})$.

In words, the proposition states that for the purpose of obtaining maximin expected length confidence sets, one may restrict attention to bivariate confidence sets that are functions of $(\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}})$. So to the extent that the bivariate LR confidence set is numerically close to being maximin in terms of expected length (cf. Panel B of Table 1), it is therefore also approximately maximin among all confidence sets that are functions of $\mathbf{Y}$. The proof of Proposition 1 follows from the arguments in Donoho (1994): If $(\boldsymbol{\delta}, \tau\boldsymbol{\omega})$ was known, the maximal expected length can only decrease. The maximal expected length of confidence sets that treat $(\boldsymbol{\delta}, \tau\boldsymbol{\omega})$ as known is thus a lower bound for the maximal expected length in the original problem, for any $(\boldsymbol{\delta}, \tau\boldsymbol{\omega})$. Furthermore, with $(\boldsymbol{\delta}, \tau\boldsymbol{\omega})$ known, it is evident from (11) that we may ignore $(\hat{\boldsymbol{\delta}}, \hat{\boldsymbol{\phi}})$, that is, the maximin confidence set in the resulting problem can be written as a function of $(\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}})$ alone. In particular, this holds for $(\boldsymbol{\delta}, \tau\boldsymbol{\omega}) = \mathbf{0}$. Thus, the maximal expected length of the bivariate confidence set that is optimal for $(\boldsymbol{\delta}, \tau\boldsymbol{\omega}) = \mathbf{0}$ known is a lower bound on the overall expected length. But it is also an upper bound on the overall maximal expected length, since for $(\boldsymbol{\delta}, \tau\boldsymbol{\omega}) \neq \mathbf{0}$, the expected length of the bivariate procedure can only decrease, since it can only lead to a lower bound (12) if $\tau > 0$.

This is a noteworthy result, but there is the usual concern that the maximin criterion is inherently too pessimistic: One might well be willing to give up a little bit of worst-case expected length in return for much expected length in other parts of the parameter space. We now establish a further result about the asymptotic efficiency of bivariate inference based on $(\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}})$, although this additional result only holds for small values of τ and large p.

We focus on tests $\varphi(\bar{\kappa}, \mathbf{Y}) \in [0, 1]$ of $H_0 : \beta = 0$, where values between zero and one indicate the probability of rejection, so that a nonrandomized test has range $\{0, 1\}$. In absence of any information about the controls $(\mathbf{Q}, \mathbf{Z})$ beyond (2), it seems natural to consider tests whose rejection probability does not depend on the baseline coefficients $\boldsymbol{\delta}$, or the direction $\boldsymbol{\omega}$. Otherwise, the ability of the test to reject would necessarily be higher for some values of $(\boldsymbol{\delta}, \boldsymbol{\omega})$ compared to others, which only makes substantive sense in the presence of some a priori information about $(\boldsymbol{\delta}, \boldsymbol{\omega})$.

The following lemma shows that for any such test, there exists another test with the same rejection probability that is a function of the three-dimensional statistic $\mathbf{T} = (\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}}, \hat{\tau})'$, where

$$\hat{\tau}^2 = \hat{\boldsymbol{\gamma}}' \mathbf{M}_\rho \hat{\boldsymbol{\gamma}} = \hat{\boldsymbol{\phi}}' \hat{\boldsymbol{\phi}}.$$

Note that the distribution of $\mathbf{T}$ only depends on (β, Δ, τ). Thus, to the extent that one is willing to restrict attention to tests whose power function is symmetric in this sense, one might focus on tests that are functions of $\mathbf{T}$, with an effective parameter space equal to $\theta = (\beta, \Delta, \tau) \in \mathbb{R}^2 \times [0, \infty)$.

LEMMA 1. *For given $\bar{\kappa}$ and any $n > p + m$, if $E_{\boldsymbol{\xi}}[\varphi(\bar{\kappa}, \mathbf{Y})]$ does not vary in $(\boldsymbol{\delta}, \boldsymbol{\omega})$ for any (β, Δ, τ), then there exists a test $\tilde{\varphi} : \mathbb{R}^3 \mapsto [0, 1]$ such that $E_{\boldsymbol{\xi}}[\tilde{\varphi}(\mathbf{T})] = E_{\boldsymbol{\xi}}[\varphi(\bar{\kappa}, \mathbf{Y})]$ for all $\boldsymbol{\xi}$.*

For the observation $\hat{\tau}^2$ to be useful to obtain a sharper bound (12), the estimation error in $\hat{\tau}^2$ must not be too large relative to $\bar{\kappa}^2$. The following lemma shows that in large samples, $\hat{\tau}$ does not contain useful information about τ as long as τ is small. From now on, we use subscripts to denote the value of quantities and functions that depend on the sample size n.

LEMMA 2. *Let $L_n(\tau)$ be the likelihood of τ based on the observation $\hat{\tau}_n$ in the regression model (1) with n observations and $\varepsilon_i \sim iid\, \mathcal{N}(0, 1)$. If $p_n/n \to c \in (0, 1)$, $\tau_n = o(n^{-1/4})$ and $t_n = o(n^{-1/4})$, then $L_n(t_n)/L_n(0) \xrightarrow{p} 1$.*

The lemma shows that even the likelihood ratio statistic for the observation $\hat{\tau}_n$ does not drive an asymptotic wedge between the values $\tau_n = 0$ and $\tau_n = o(n^{-1/4})$, suggesting that $\mathbf{T}_n$ does not help to determine the value of τ_n of order $o(n^{-1/4})$.

As discussed in the Introduction, $\tau_n = o(n^{-1/4})$ allows for a fixed number of nonzero coefficients in $\boldsymbol{\phi} = \tau\boldsymbol{\omega}$ (and thus $\boldsymbol{\gamma}$) of order $o(n^{-1/4})$, with associated t-statistics diverging at a corresponding rate $o(n^{1/4})$, or a fraction of $o(n^{1/4})$ nonzero coefficients of order $O(n^{-1/2})$, with associated t-statistics that indicate a statistically significant nonzero value with probability close to one. The condition $\tau_n = o(n^{-1/4})$ thus captures statistically meaningful departures from a baseline assumption that the control coefficients $\boldsymbol{\gamma}$ are entirely irrelevant. Intuitively, the high-dimensional nature of $\hat{\boldsymbol{\phi}}$ makes it impossible to know "where to look" for such departures, leading to Lemma 2.

Combining the observations in Lemmas 1 and 2 with limit of experiments arguments leads to the following result.

THEOREM 2. *Consider a sequence of observations from the linear regression model with $\varepsilon_i \sim iid\, \mathcal{N}(0, 1)$ where $p_n/n \to (0, 1)$ and $\rho_n^2 \to \rho^2 \in [0, 1)$, and let $\varphi_n(\bar{\kappa}_n, \mathbf{Y}_n)$ be a sequence of tests that, for all sufficiently large n, satisfy the assumption of Lemma 1. If for some sequence s_n and all $(b, a) \in \mathbb{R}^2$, $E_{\theta_n}[\varphi_n(\bar{\kappa}_n, \mathbf{Y}_n)]$ converges along a sequence θ_n with $(\sqrt{n}\beta_n, \sqrt{n}\Delta_n - s_n) = (b, a)$ and $\tau_n = o(n^{-1/4})$ (where τ_n may depend on (b, a)), then there exists a function $\phi : \mathbb{R}^2 \mapsto [0, 1]$ such that $\lim_{n\to\infty} E_{\theta_n}[\varphi_n(\bar{\kappa}_n, \mathbf{Y}_n)] = E_{b,a}[\phi(\hat{\mathbf{b}}^o)]$, with $\hat{\mathbf{b}}^o$ distributed as in (10). Furthermore, $\lim_{n\to\infty} E_{\theta_n}[\varphi_n(\bar{\kappa}_n, \mathbf{Y}_n)] = E_{b,a}[\phi(\hat{\mathbf{b}}^o)]$ then holds under* all *sequences θ_n with $(\sqrt{n}\beta_n, \sqrt{n}\Delta_n - s_n) = (b, a)$ and $\tau_n = o(n^{-1/4})$.*

The theorem allows for $\sqrt{n}\bar{\kappa}_n \to k_0$ and $s_n = 0$, so the localized problem (8) initially considered in Section 2.2 is covered as a special case with $a = d$, and the case with $|s_n| \to \infty$ and $\sqrt{n}\bar{\kappa}_n - |s_n| \to 0$ or $\sqrt{n}\bar{\kappa}_n - |s_n| \to \infty$ correspond to the $|\bar{k}| \to \infty$

cases discussed below (10). The theorem thus demonstrates that under $\tau_n = o(n^{-1/4})$ the asymptotic power function of any test satisfying the condition of Lemma 1 can always be matched by the power function of a bivariate test that depends on the data only through the short and long regression coefficient estimators. The determination of inference procedures with attractive asymptotic power properties is hence reduced to the problem of identifying good bivariate inference, as discussed in the last subsection.

The implementation of asymptotically valid bivariate tests is straightforward in the Gaussian homoskedastic model. In particular, the test

$$\varphi_{\mathrm{LR},n}(\bar\kappa_n, \mathbf{Y}_n) = \mathbf{1}\big[\mathrm{LR}_n(\sqrt{n}\bar\kappa_n) > \mathrm{cv}_{\rho_n}(\sqrt{n}\bar\kappa_n)\big] \tag{13}$$

with $\mathrm{LR}_n(\bar k)$ equal to (9) and $\hat{\mathbf{b}} = (\sqrt{n}\hat\beta_{\mathrm{long}}, \sqrt{n}\hat\beta_{\mathrm{short}})'$ and $\mathrm{cv}_\rho(\bar k)$ as defined in Section 2.2 has asymptotic rejection probability equal to the small sample rejection probability of the LR test discussed there. The attractive properties of the LR approach among all bivariate tests thus translate via Theorem 2 into attractive asymptotic properties in the Gaussian homoskedastic model among the larger class of tests that are only required to satisfy Lemma 1.

Note that Theorem 2 does not require τ_n to be smaller than $\bar\kappa_n$; for instance, $\sqrt{n}\bar\kappa_n$ may converge, while $\sqrt{n}\tau_n$ diverges. This corresponds to a situation where the bound $\bar\kappa_n$ is much smaller than the actual value κ_n. This is most easily interpreted along the lines discussed at the end of Section 2.2 above: The limited information in the data may make it impossible to correctly conclude that such small values of $\bar\kappa_n$ are incompatible with $\beta = 0$, but one would still prefer a procedure that comes to this conclusion for as many $\bar\kappa_n$ as possible. Specifically, assuming that $\varphi_n(\bar\kappa, \mathbf{Y}_n)$ is not randomized, one would prefer the threshold value $\bar\kappa_n^*(\mathbf{Y}_n) \in [0, \infty) \cup \{+\infty\}$ defined via

$$\bar\kappa_n^*(\mathbf{Y}_n) = \inf_{\bar\kappa}\big\{\bar\kappa : \varphi_n(\bar\kappa, \mathbf{Y}_n) = 0\big\} \tag{14}$$

to be as large as possible, as discussed in Section 2.2, under the constraint that $[0, \bar\kappa_n^*(\mathbf{Y}_n)]$ forms a $1-\alpha$ confidence set for $|\Delta_n|$ under $\beta = 0$. We formulate a corresponding result in terms of a generic scalar estimator $\psi_n(\mathbf{Y}_n)$, which allows for potential recentering, $\psi_n(\mathbf{Y}_n) = \bar\kappa_n^*(\mathbf{Y}_n) - c_n$.

Corollary 1. *In addition to the assumptions of Theorem 2, suppose $\psi_n(\mathbf{Y}_n)$ has a distribution that depends on $\boldsymbol{\xi}$ only through (β, Δ, τ) for all large enough n. If for some sequence s_n, and all $(b, a) \in \mathbb{R}^2$, $\psi_n(\mathbf{Y}_n)$ converges in distribution along a sequence θ_n with $(\sqrt{n}\beta_n, \sqrt{n}\Delta_n - s_n) = (b, a)$ and $\tau_n = o(n^{-1/4})$ (where τ_n may depend on (b, a)), then the limit distribution is of the form $\psi^o(\hat{\mathbf{b}}^o, U)$ for some function $\psi^o : \mathbb{R}^3 \mapsto \mathbb{R} \cup \{+\infty\}$, with $\hat{\mathbf{b}}^o$ distributed as in (10), and U a uniform random variable on $[0, 1]$ independent of $\hat{\mathbf{b}}^o$. Furthermore, $\psi_n(\mathbf{Y}_n)$ then converges in distribution to $\psi^o(\hat{\mathbf{b}}^o, U)$ under* all *sequences θ_n with $(\sqrt{n}\beta_n, \sqrt{n}\Delta_n - s_n) = (b, a)$ and $\tau_n = o(n^{-1/4})$.*

The corollary shows that the problem of constructing asymptotically attractive threshold estimators $\bar\kappa_n^*(\mathbf{Y}_n)$ is effectively reduced to considering functions of $\hat\beta_{\mathrm{long}}$,

$\hat{\beta}_{\text{short}}$, and potentially an independent randomization device, as long as one restricts attention to $\bar{\kappa}_n^*(\mathbf{Y}_n)$ whose distribution does not depend on the nuisance parameters $(\boldsymbol{\delta}, \boldsymbol{\omega})$. The local asymptotic properties of the threshold estimator (14) implied by the LR test (13) corresponds to the small sample properties of $\bar{k}_{\text{LR}}^*(\hat{\mathbf{b}})$ discussed at the end of Section 2.2, so similar to Theorem 2, its attractive features again extend to this larger class. And by setting $\psi_n(\mathbf{Y}_n)$ in Corollary 1 equal to a potentially recentered and rescaled estimator of β that exploits the bound (2), the same holds for our suggested midpoint estimator $\hat{\beta}_{\text{LR}}(\bar{\kappa})$.

In summary, under $p_n \to \infty$ asymptotics, as long as $\tau_n = o(n^{-1/4})$, the quality of asymptotic inference in the Gaussian homoskedastic model is limited from above by the performance of bivariate procedures. The attractive small sample features of the LR approach discussed in Section 2.2 thus translate into attractive large sample inference.

3. Implementation in non-Gaussian and potentially heteroskedastic models

In the Gaussian linear regression model, the bivariate tests introduced in Section 2.2 have exact small sample properties. But for applied use, it is important to have a valid implementation in non-Gaussian and potentially heteroskedastic models. With the regressors nonstochastic (or after conditioning on the regressors with a conditionally mean zero error term), the general model is still of the form (1), where now $\varepsilon_i \sim (0, \sigma_i^2)$ independent across i. Under weak technical conditions on the tails of the distribution of ε_i, on the sequence $\{\sigma_i^2\}_{i=1}^n$ and on the regressors $\{x_i, \mathbf{q}_i, \mathbf{z}_i\}_{i=1}^n$, a central limit theorem yields

$$\boldsymbol{\Omega}_n^{-1/2} \begin{pmatrix} \hat{\beta}_{\text{long},n} - \beta_n \\ \hat{\beta}_{\text{short},n} - \beta_n - \Delta_n \end{pmatrix} \Rightarrow \mathcal{N}(\mathbf{0}, \mathbf{I}_2) \tag{15}$$

for some suitably defined $\boldsymbol{\Omega}_n$, since $(\hat{\beta}_{\text{long},n} - \beta_n, \hat{\beta}_{\text{short}} - \beta_n - \Delta_n)$ are linear combinations of the heterogeneous but mean zero and independent random variables $\{\varepsilon_i\}_{i=1}^n$. We provide a corresponding result in the supplemental Appendix that allows for dependence among the ε_i due to clustering.

Suppose $\hat{\boldsymbol{\Omega}}_n$ is a consistent estimator of $\boldsymbol{\Omega}_n$ in the sense that $\boldsymbol{\Omega}_n^{-1}\hat{\boldsymbol{\Omega}}_n \xrightarrow{p} \mathbf{I}_2$. The natural LR statistic of $H_0 : \beta_n = 0$ under the bound (2) then becomes

$$\begin{aligned} \widehat{\text{LR}}_n(\bar{\kappa}_n) = & \min_{|\tilde{\Delta}| \le \rho_n \bar{\kappa}_n / \sqrt{\mathbf{x}_n' \mathbf{x}_n / n}} \begin{pmatrix} \hat{\beta}_{\text{long},n} \\ \hat{\beta}_{\text{short},n} - \tilde{\Delta} \end{pmatrix}' \hat{\boldsymbol{\Omega}}_n^{-1} \begin{pmatrix} \hat{\beta}_{\text{long},n} \\ \hat{\beta}_{\text{short},n} - \tilde{\Delta} \end{pmatrix} \\ & - \min_{\tilde{\beta}, |\tilde{\Delta}| \le \rho_n \bar{\kappa}_n / \sqrt{\mathbf{x}_n' \mathbf{x}_n / n}} \begin{pmatrix} \hat{\beta}_{\text{long},n} - \tilde{\beta} \\ \hat{\beta}_{\text{short},n} - \tilde{\beta} - \tilde{\Delta} \end{pmatrix}' \hat{\boldsymbol{\Omega}}_n^{-1} \begin{pmatrix} \hat{\beta}_{\text{long},n} - \tilde{\beta} \\ \hat{\beta}_{\text{short},n} - \tilde{\beta} - \tilde{\Delta} \end{pmatrix}, \end{aligned}$$

where ρ_n^2 is the R^2 of a regression of x_i on $\mathbf{z}_i$. Exploiting the invariance of the LR statistic to reparameterizations, the distribution of $\widehat{\text{LR}}_n(\bar{\kappa}_n)$ under the approximations (15) and

$\hat{\boldsymbol{\Omega}}_n = \boldsymbol{\Omega}_n$ is effectively indexed by $\boldsymbol{\chi} = (\chi_1, \chi_2)$ with

$$\chi_1 = \frac{|\Omega_{11} - \Omega_{12}|}{\sqrt{\Omega_{11}\Omega_{22} - \Omega_{12}^2}}, \tag{16}$$

$$\chi_2 = \frac{\sqrt{\Omega_{11}}}{\sqrt{\Omega_{11}\Omega_{22} - \Omega_{12}^2}} \frac{\rho_n \bar{\kappa}_n}{\sqrt{\mathbf{x}_n'\mathbf{x}_n/n}}, \tag{17}$$

where Ω_{ij} is the i, jth element of $\boldsymbol{\Omega}_n$, and under the null hypothesis of $\beta_n = 0$ and $\sqrt{\Omega_{11}}\Delta_n/\sqrt{\Omega_{11}\Omega_{22} - \Omega_{12}^2} \to g$, the asymptotic distribution of $\widehat{\mathrm{LR}}_n(\bar{\kappa}_n)$ is equal to

$$\begin{aligned} &\min_{|\tilde{g}| \le \chi_2} \begin{pmatrix} Z_1 \\ Z_2 + g - \tilde{g} \end{pmatrix}' \begin{pmatrix} Z_1 \\ Z_2 + g - \tilde{g} \end{pmatrix} \\ &\quad - \min_{\tilde{h}, |\tilde{g}| \le \chi_2} \begin{pmatrix} Z_1 - \tilde{h} \\ Z_2 + g - \chi_1 \tilde{h} - \tilde{g} \end{pmatrix}' \begin{pmatrix} Z_1 - \tilde{h} \\ Z_2 + g - \chi_1 \tilde{h} - \tilde{g} \end{pmatrix}, \end{aligned} \tag{18}$$

where $(Z_1, Z_2)' \sim \mathcal{N}(\mathbf{0}, \mathbf{I}_2)$. This limit distribution depends on the nuisance parameter $|g| \le \chi_2$, but a numerical calculation shows that its $1-\alpha$ quantile is maximized at $g = \chi_2$ for $\alpha \in \{0.01, 0.05, 0.1\}$ and all χ_1. It is hence straightforward to obtain the appropriated critical value $\mathrm{cv}(\boldsymbol{\chi})$ via simulation, and we provide a corresponding look-up table in the replication files. Alternatively, a linear interpolation of the values in Table 2 that only depend on χ_1 generate (slightly conservative) critical values or all χ_2 (cf. Figure 1). Either way, a subsequence argument then yields asymptotic validity of this feasible LR test $\hat{\varphi}_{\mathrm{LR},n}(\bar{\kappa}_n, \mathbf{Y}_n) = \mathbf{1}[\widehat{\mathrm{LR}}_n(\bar{\kappa}_n) > \mathrm{cv}(\hat{\boldsymbol{\chi}}_n)]$, where $\hat{\boldsymbol{\chi}}_n = (\hat{\chi}_{n,1}, \hat{\chi}_{n,2})$ are as in (16) and (17), with the elements of $\boldsymbol{\Omega}_n$ replaced by those of $\hat{\boldsymbol{\Omega}}_n$.

LEMMA 3. (a) *If* $\boldsymbol{\Omega}_n^{-1}\hat{\boldsymbol{\Omega}}_n \xrightarrow{p} \mathbf{I}_2$ *and* (15) *holds, then* $\limsup_{n\to\infty} E_{\theta_n}[\hat{\varphi}_{\mathrm{LR},n}(\bar{\kappa}_n, \mathbf{Y}_n)] \le \alpha$ *for all sequences* θ_n *with* $\beta_n = 0$ *and* $|\Delta_n| \le \rho_n \bar{\kappa}_n/\sqrt{\mathbf{x}_n'\mathbf{x}_n/n}$.

(b) *Under the assumptions of Theorem 2,* $E_{\theta_n}[\hat{\varphi}_{\mathrm{LR},n}(\bar{\kappa}_n, \mathbf{Y}_n)] - E_{\theta_n}[\varphi_{\mathrm{LR},n}(\bar{\kappa}_n, \mathbf{Y}_n)] \to 0$.

Note that the asymptotic validity in part (a) holds without any assumptions about the sequences p_n or $\bar{\kappa}_n$. In particular, it is not required that $p_n/n \to c \in (0,1)$ or $\bar{\kappa}_n = o(n^{-1/4})$. In the Gaussian homoskedastic model, $\boldsymbol{\Omega}_n$ is equal to $(\mathbf{x}_n'\mathbf{x}_n)^{-1}\boldsymbol{\Sigma}(\rho_n)$, and in large samples, $\hat{\varphi}_{\mathrm{LR},n}$ reduces to the bivariate LR test introduced in Section 2.2. Formally,

TABLE 2. Interpolation table for upper bound on $\mathrm{cv}(\boldsymbol{\chi})$.

$\alpha\backslash\chi_1$	0	2	5	8	12	25	∞
0.01	6.663	6.931	7.170	7.218	7.251	7.287	7.306
0.05	3.845	3.959	4.081	4.142	4.174	4.203	4.219
0.10	2.711	2.750	2.810	2.870	2.898	2.926	2.941

Note: Linear interpolation within each row yields slightly conservative asymptotic critical values for $\widehat{\mathrm{LR}}_n(\bar{\kappa}_n)$.

part (b) of the Lemma shows that the large sample power properties of $\hat{\varphi}_{\mathrm{LR},n}$ in the Gaussian homoskedastic model are equal to the small sample power properties of the LR test as introduced in Section 2.2. Thus, $\hat{\varphi}_{\mathrm{LR},n}(\bar{\kappa}_n, \mathbf{Y}_n)$ has the same asymptotic efficiency properties as $\varphi_{\mathrm{LR},n}(\bar{\kappa}_n, \mathbf{Y}_n)$ discussed below Theorem 2, even among tests that depend on the data beyond the short and long regression coefficient.

Given Lemma 3, the only obstacle to a straightforward implementation of the LR test in a more general model is the estimation of the asymptotic variance $\boldsymbol{\Omega}_n$. If the number of controls p is fixed, or only slowly increasing with n, the usual heteroskedasticity robust White (1980) estimator for $\boldsymbol{\Omega}_n$ is consistent under reasonably weak assumptions. However, under asymptotics where $p_n/n \to c \in (0,1)$, as employed for the asymptotic efficiency argument in Theorem 2, Cattaneo, Jansson, and Newey (2018a) show that the White (1980) estimator is no longer consistent, and Cattaneo, Jansson, and Newey (2018b) provide an alternative estimator that remains consistent. Alternatively, if the explanatory power of the additional controls is limited in the sense that $\kappa_n = o(1)$, one may also consistently estimate $\hat{\boldsymbol{\Omega}}_n$ from the usual White formula based on the residuals from the short regression that only includes the baseline controls. This has the advantage of being readily implementable also with clustering. We provide a corresponding result in the supplemental Appendix.

Given any value of $\bar{\kappa} \geq 0$, a confidence set for β is obtained by collecting the values for β_0 such that the test $H_0 : \beta = \beta_0$ based on the LR statistic does not reject (in the following, we drop n subscripts again to ease notation). For $\bar{\kappa} = 0$, and under homoskedasticity, this yields the same interval as obtained from standard short regression inference using the 2, 2 element of $\hat{\boldsymbol{\Omega}}$ as the variance estimator. In small samples, when $\hat{\boldsymbol{\Omega}}$ does not impose homoskedasticity, the confidence interval for $\bar{\kappa} = 0$ is centered at a slightly different value, since under heteroskedasticity, it is in general more efficient to estimate β by a linear combination of $\hat{\beta}_{\mathrm{long}}$ and $\hat{\beta}_{\mathrm{short}}$ that puts nonzero weight on $\hat{\beta}_{\mathrm{long}}$. For $\bar{\kappa} \to \infty$, the interval is exactly centered at $\hat{\beta}_{\mathrm{long}}$, but the LR test uses a slightly larger critical value, as discussed in Section 2.2 above.

4. Extensions

4.1 *Instrumental variable regression*

Suppose the scalar regressor x_i of interest in the linear regression (1) is endogenous, but we have access to a scalar instrument w_i (w_i could be a linear combination of a vector of instruments, such as in two stage least squares). As in the baseline model, we treat $\{w_i, \mathbf{q}_i, \mathbf{z}_i\}_{i=1}^n$ as nonstochastic, or equivalently, we condition on their realization in the following. To simplify notation, let w_i be orthogonal to the baseline controls $\mathbf{q}_i$. Assume that the data is generated via

$$x_i = \eta w_i + \mathbf{q}_i' \boldsymbol{\delta}_x + \mathbf{z}_i' \boldsymbol{\gamma}_x + \varepsilon_{xi}, \tag{19}$$

$$y_i = \beta x_i + \mathbf{q}_i' \boldsymbol{\delta} + \mathbf{z}_i' \boldsymbol{\gamma} + \varepsilon_i, \tag{20}$$

where $(\varepsilon_{xi}, \varepsilon_i)$ is mean-zero independent across i, but potentially heteroskedastic, and if ε_{xi} is correlated with ε_i, the regressor x_i in (20) is endogenous.

Let $(\hat{\beta}^{\mathrm{IV}}_{\mathrm{long}}, \hat{\beta}^{\mathrm{IV}}_{\mathrm{short}})$ be the IV estimators of β that include or exclude the additional controls $\mathbf{z}_i$. These estimators involve the term $\sum_{i=1}^n w_i x_i$, which under (19) is stochastic and depends on the realization of ε_{xi}, complicating the description of their bias. In order to avoid these difficulties, we focus on their moment condition instead, as in Anderson and Rubin (1949). Let $\hat{w}_i^z$ be the residuals of a regression of w_i on $\mathbf{z}_i$. The estimators $\hat{\beta}^{\mathrm{IV}}_{\mathrm{long}}$ and $\hat{\beta}^{\mathrm{IV}}_{\mathrm{short}}$ are identified from the two moment conditions $E[n^{-1}\sum_{i=1}^n \hat{w}_i^z \varepsilon_i] = 0$ and $E[n^{-1}\sum_{i=1}^n w_i \varepsilon_i] = 0$, respectively. Consider testing $H_0 : \beta = 0$ (nonzero values can be reduced to this case by subtracting $\beta_0 x_i$ from y_i). Similar to (15), under H_0, the empirical moment conditions then satisfy

$$\left(\boldsymbol{\Omega}^{\mathrm{IV}}\right)^{-1/2} \begin{pmatrix} n^{-1}\sum_{i=1}^n \hat{w}_i^z y_i \\ n^{-1}\sum_{i=1}^n w_i y_i - \Delta^{\mathrm{IV}} \end{pmatrix} \Rightarrow \mathcal{N}(\mathbf{0}, \mathbf{I}_2) \tag{21}$$

for some suitably defined $\boldsymbol{\Omega}^{\mathrm{IV}}$, which can be consistently estimated by $\hat{\boldsymbol{\Omega}}^{\mathrm{IV}}$. The "bias" Δ^{IV} in (21) is given by $\Delta^{\mathrm{IV}} = n^{-1}\sum_{i=1}^n w_i \mathbf{z}_i'\boldsymbol{\gamma}$, and a straightforward calculation shows that under (2), we have the sharp bound

$$\left|\Delta^{\mathrm{IV}}\right| \leq \bar{\kappa}\sqrt{\mathbf{w}'\mathbf{Z}\left(\mathbf{Z}'\mathbf{Z}\right)^{-1}\mathbf{Z}'\mathbf{w}/n}$$

with $\mathbf{w} = (w_1, \ldots, w_n)'$. Thus, under the null hypothesis of $H_0 : \beta = 0$, the observations (21) have the identical structure as (15) of the previous section, and one can apply the LR test in entirely analogous fashion to obtain a valid large sample test that exploits the bound (2) to sharpen inference in instrumental variable regression. Our focus on the moments (21), rather than the estimators $(\hat{\beta}^{\mathrm{IV}}_{\mathrm{long}}, \hat{\beta}^{\mathrm{IV}}_{\mathrm{short}})$, has the additional appeal that no assumptions about the strength of the instrument are required.

4.2 *Double bounds*

In Sections 2 and 3, we have treated the regressors $\{x_i, \mathbf{q}_i, \mathbf{z}_i\}_{i=1}^n$ as either nonstochastic, or the analysis conditioned on their value. In the simple Gaussian model of Section 2 with random regressors, the Gram matrix forms an ancillary statistic. It is textbook advice to condition inference on ancillary statistics in general and on the Gram matrix in particular (see, for instance, Chapter 2.2 in Cox and Hinkley (1974)), providing a rationale for our analysis. Furthermore, our approach does not require or depend on a model for the potentially stochastic properties of the regressors. This is attractive in so far as it relieves applied researchers from having to defend a particular data generating mechanism, and avoids a source of potential misspecification.

We now discuss how one could exploit additional assumptions on the generation of the regressor of interest x_i to potentially further sharpen inference about β. In particular, assume that $\tilde{x}_i$ is generated by the linear model

$$\tilde{x}_i = \mathbf{q}_i'\boldsymbol{\delta}_x + \mathbf{z}_i'\boldsymbol{\gamma}_x + \varepsilon_{xi}, \tag{22}$$

where ε_{xi} is conditionally mean zero given $\{\mathbf{q}_i, \mathbf{z}_i\}_{i=1}^n$. The regressor x_i is simply defined as the residuals of a least squares regression of $\tilde{x}_i$ on $\mathbf{q}_i$, so that consistent with our notation above $\mathbf{Q}'\mathbf{x} = \mathbf{0}$. We maintain, as in Sections 2 and 3, that ε_i in (1) is conditionally mean zero (so $\tilde{x}_i$ is not endogenous, and no instrument is required). Assume further that we are willing to assume that in addition to (2), also

$$\kappa_x^2 = n^{-1}\sum_{i=1}^n \left(\mathbf{z}_i'\boldsymbol{\gamma}_x\right)^2 \leq \bar{\kappa}_x^2, \tag{23}$$

so that $\bar{\kappa}_x$ has the interpretation of an upper bound on the quadratic mean of the effect of $\mathbf{z}_i$ on x_i, after controlling for $\mathbf{q}_i$. This "double bounds" structure of limiting the population coefficients in both the regression of interest (1), and the auxiliary regression (22), parallels the assumptions validating the double Lasso procedure by Belloni, Chernozhukov, and Hansen (2014).

As in the previous subsection, it is convenient to focus on the moment conditions defining the OLS estimators $(\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}})$: Under weak regularity conditions, (2), (22), and (23) imply that under $H_0 : \beta = 0$

$$\left(\boldsymbol{\Omega}^{\text{Dbl}}\right)^{-1/2}\begin{pmatrix} n^{-1}\sum_{i=1}^n \hat{x}_i^z y_i \\ n^{-1}\sum_{i=1}^n x_i y_i - \Delta^{\text{Dbl}} \end{pmatrix} \Rightarrow \mathcal{N}(\mathbf{0}, \mathbf{I}_2), \tag{24}$$

where $\hat{x}_i^z$ are the residuals of a regression of x_i on $\mathbf{z}_i$, and Δ^{Dbl} satisfies the sharp bound $|\Delta^{\text{Dbl}}| \leq \bar{\kappa} \cdot \bar{\kappa}_x$ (see the supplemental Appendix for details). With an appropriate estimator $\hat{\boldsymbol{\Omega}}^{\text{Dbl}}$, this again has the same structure as the problem discussed in Section 3, so the LR test defined there can be used to exploit the additional information contained in (22) and (23).

5. Small sample simulations

In this section, we use Monte Carlo simulations to evaluate the finite-sample properties of confidence intervals based on $\hat{\varphi}_{\text{LR}}$, and we compare it to the performance of the Lasso-based post-double-selection technique of Belloni, Chernozhukov, and Hansen (2014) (abbreviated BCH in the following two sections).

As in BCH's Monte Carlo, we set the total number of observations to $n = 500$, let $p = 200$, and generate data from a model where the baseline control is simply a constant,

$$y_i = \tilde{\delta}_1 + \tilde{x}_i\beta + \tilde{\mathbf{z}}_i'\boldsymbol{\gamma} + \varepsilon_i, \quad i = 1, \ldots, n \tag{25}$$

with $\varepsilon_i \sim iid\ \mathcal{N}(0,1)$ independent of $\{\tilde{x}_i, \tilde{\mathbf{z}}_i\}$, and $\tilde{\mathbf{z}}_i$ is generated by the linear model

$$\tilde{x}_i = \tilde{\mathbf{z}}_i'\boldsymbol{\mu} + \varepsilon_i^x \tag{26}$$

with $\varepsilon_i^x \sim iid\ \mathcal{N}(0,1)$ independent of $\{\tilde{\mathbf{z}}_i\}$. To be consistent with our previous notation, we orthogonalize the regressors in (25) off the baseline control, that is, $x_i =$

$\tilde{x}_i - n^{-1}\sum_{l=1}^n \tilde{x}_l$ and $\mathbf{z}_i = (z_{i1}, \ldots, z_{ip})'$ with $z_{ij} = \tilde{z}_{ij} - n^{-1}\sum_{l=1}^n \tilde{z}_{lj}$, so that (25) implies the linear model (1) with an appropriate definition of δ_1. We set $\beta = 0$ throughout. Our designs vary according to the value of four parameters: the previously introduced $\rho^2 \in \{0.6, 0.95\}$ and $\kappa \in \{0.2, 0.5\}$; the scalar $\eta \in \{0.1, 0.3\}$ determines the degree of sparsity of $\boldsymbol{\gamma} = (\gamma_1, \ldots, \gamma_p)'$ and $\boldsymbol{\mu} = (\mu_1, \ldots, \mu_p)'$; and $\nu \in \{0, 0.5, 1\}$ determines the overlap between the nonzero indices of $\boldsymbol{\gamma}$ and $\boldsymbol{\mu}$. Specifically, $\gamma_j = c_\gamma \mathbf{1}[j \leq \lfloor \eta p \rfloor]$, where the scalar c_γ is chosen such that the implied value of κ^2 is equal to the specified value, and $\mu_j = c_\mu \mathbf{1}[\lfloor \eta(1-\nu)p \rfloor + 1 \leq j \leq \lfloor \eta(2-\nu)p \rfloor]$, $j = 1, \ldots, p$, where $c_\mu \in \mathbb{R}$ is chosen such that the sample R^2 of a regression of x_i on $\mathbf{z}_i$ is equal to ρ^2.

The parameter η plays a crucial role for the BCH method, since the method requires that the number of nonzero values in $\boldsymbol{\gamma}$ and $\boldsymbol{\mu}$ is not too large. In contrast, the test $\hat{\varphi}_{\mathrm{LR}}$ remains numerically invariant to any linear reparameterizations of the regressors. Finally, the parameter ν determines the omitted variable bias in the short regression coefficient $\hat{\beta}_{\mathrm{short}}$ (which is the coefficient on x_i in the regression of y_i on $(1, x_i)$). Under $\nu = 0$, there is no overlap, and the variables z_{ij} with nonzero coefficient γ_j are uncorrelated with the regressor of interest x_i, so there is no omitted variable bias, at least over repeated samples with random regressors. In the other extreme, with $\nu = 1$, every variable z_{ij} with nonzero coefficient γ_j is correlated with x_i, leading to a large omitted variable bias.

We consider four types of confidence intervals for β. First, the usual confidence interval based on $\hat{\beta}_{\mathrm{short}}$. Second, the usual confidence interval based on $\hat{\beta}_{\mathrm{long}}$. Third, the confidence interval obtained by inverting the feasible test $\hat{\varphi}_{\mathrm{LR}}$ introduced in Section 3, where we set $\bar{\kappa}$ equal to the actual value of κ. Fourth, the Lasso-based post-double-selection method "LPDS" from BCH, as specified in their Monte Carlo Section 4.2. For the first three types of methods, we estimate standard errors of $(\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}})'$ with the heteroskedasticity-robust estimator of Cattaneo, Jansson, and Newey (2018b). In addition, we report quartiles of the threshold value $\bar{\kappa}^*_{\mathrm{LR}} \in [0, \infty) \cup \{+\infty\}$ computed from the family of tests $\hat{\varphi}_{\mathrm{LR}}$ for each draw, defined to be zero if $\bar{\kappa} = 0$ does not lead to rejection, and $+\infty$ if none of the $\bar{\kappa}$ values lead to rejection.

Table 3 contains the results. The confidence interval based on $\hat{\beta}_{\mathrm{short}}$ has coverage substantially below the nominal level whenever the overlap parameter ν is positive. This shows that the considered values of κ are large enough to severely distort inference that simply sets the control coefficients to zero. In contrast, the interval associated with $\hat{\beta}_{\mathrm{long}}$ has size very close to the nominal level throughout, but at the cost of being fairly long. The LPDS method sometimes substantially undercovers even in the relatively sparse design with $\eta = 0.1$. Apparently, the relatively small values of γ_j make it difficult for the method to correctly pick up the $\eta \cdot p = 20$ nonzero coefficients, leading to a remaining omitted variable bias that is large enough to induce nonnegligible overrejections. When $\kappa = 0.5$ and $\rho^2 = 0.95$, so that both γ_j and μ_j are relatively larger, the LPDS method reliably controls size in the $\eta = 0.1$ sparse design, but yields somewhat longer intervals compared to $\hat{\beta}_{\mathrm{long}}$. The new tests $\hat{\varphi}_{\mathrm{LR}}(\kappa, \mathbf{Y})$ control size throughout as they should, given that $\bar{\kappa} = \kappa$ trivially implies $\kappa \leq \bar{\kappa}$, and yield intervals that are shorter than the $\hat{\beta}_{\mathrm{long}}$-interval when $\nu > 0$, with larger gains for larger values of ρ and ν.

Of course, with κ unknown in practice, one cannot apply $\hat{\varphi}_{\mathrm{LR}}(\bar{\kappa}, \mathbf{Y})$ with $\kappa = \bar{\kappa}$. We expect that in practice, researchers will consider a range of values of $\bar{\kappa}$ to gauge the sensitivity of the results about β. Then, by construction, researchers will also consider $\bar{\kappa} = \kappa$,

TABLE 3. Small sample properties for $n = 500$ and $p = 200$.

			$\hat{\beta}_{\text{short}}$		$\hat{\beta}_{\text{long}}$		LPDS		$\hat{\varphi}_{\text{LR}}(\kappa, \mathbf{Y})$		$\bar{\kappa}^*_{\text{LR}}$		
η	ρ^2	ν	Cov	Lgth	Cov	Lgth	Cov	Lgth	Cov	Lgth	Q1	Q2	Q3
						$\kappa = 0.20$							
0.10	0.60	0.00	0.94	0.14	0.94	0.22	0.95	0.23	0.94	0.22	0.00	0.00	0.00
0.10	0.60	0.50	0.74	0.14	0.95	0.22	0.92	0.23	0.95	0.22	0.00	0.00	0.00
0.10	0.60	1.00	0.27	0.14	0.94	0.22	0.82	0.23	0.95	0.20	0.00	0.04	0.08
0.10	0.95	0.00	0.94	0.05	0.94	0.22	0.95	0.26	0.98	0.14	0.00	0.00	0.00
0.10	0.95	0.50	0.42	0.05	0.95	0.22	0.95	0.26	0.98	0.14	0.00	0.02	0.05
0.10	0.95	1.00	0.01	0.05	0.95	0.22	0.95	0.25	0.95	0.13	0.08	0.11	0.15
0.30	0.60	0.00	0.94	0.14	0.95	0.22	0.95	0.21	0.95	0.22	0.00	0.00	0.00
0.30	0.60	0.50	0.74	0.14	0.94	0.22	0.87	0.21	0.94	0.22	0.00	0.00	0.00
0.30	0.60	1.00	0.27	0.14	0.94	0.22	0.62	0.21	0.95	0.20	0.00	0.04	0.08
0.30	0.95	0.00	0.94	0.05	0.95	0.22	0.95	0.18	0.98	0.14	0.00	0.00	0.00
0.30	0.95	0.50	0.43	0.05	0.95	0.22	0.91	0.17	0.98	0.14	0.00	0.02	0.05
0.30	0.95	1.00	0.01	0.05	0.95	0.22	0.81	0.17	0.95	0.13	0.08	0.11	0.15
						$\kappa = 0.50$							
0.10	0.60	0.00	0.92	0.14	0.94	0.22	0.95	0.24	0.94	0.22	0.00	0.00	0.00
0.10	0.60	0.50	0.13	0.14	0.94	0.22	0.77	0.24	0.94	0.22	0.03	0.08	0.12
0.10	0.60	1.00	0.00	0.14	0.94	0.22	0.38	0.24	0.95	0.22	0.22	0.26	0.31
0.10	0.95	0.00	0.91	0.05	0.95	0.22	0.95	0.27	0.95	0.22	0.00	0.00	0.00
0.10	0.95	0.50	0.00	0.05	0.94	0.22	0.95	0.26	0.96	0.19	0.13	0.16	0.20
0.10	0.95	1.00	0.00	0.05	0.94	0.22	0.95	0.25	0.95	0.15	0.37	0.41	0.44
0.30	0.60	0.00	0.91	0.14	0.94	0.22	0.95	0.22	0.94	0.22	0.00	0.00	0.00
0.30	0.60	0.50	0.12	0.14	0.94	0.22	0.50	0.22	0.94	0.22	0.04	0.08	0.12
0.30	0.60	1.00	0.00	0.14	0.94	0.22	0.03	0.22	0.95	0.22	0.22	0.27	0.31
0.30	0.95	0.00	0.92	0.05	0.94	0.22	0.95	0.18	0.95	0.22	0.00	0.00	0.00
0.30	0.95	0.50	0.00	0.05	0.94	0.22	0.74	0.18	0.96	0.19	0.13	0.16	0.20
0.30	0.95	1.00	0.00	0.05	0.94	0.22	0.42	0.17	0.95	0.15	0.37	0.41	0.44

Note: Entries are coverage and average length of 95% confidence intervals for β, and the quartiles of the distribution of $\bar{\kappa}^*_{\text{LR}}$. Rows correspond to different DGPs, with η measuring the sparsity of the design, ν the overlap between the nonzero indices on $\mathbf{z}_i$ in the regressions of y_i on $\mathbf{z}_i$ and of x_i on $\mathbf{z}_i$, and ρ^2 is R^2 of a regression of x_i on $\mathbf{z}_i$. The columns are different confidence intervals, with $\hat{\beta}_{\text{short}}$ and $\hat{\beta}_{\text{long}}$ the confidence interval based on short and long regression coefficients, $\hat{\varphi}_{\text{LR}}(\bar{\kappa}, \mathbf{Y})$ the LR based confidence interval developed in this paper that imposes the bound $\kappa \leq \bar{\kappa}$, and LPDS is BCH's Lasso-based post-double-selection procedure. Based on 20,000 Monte Carlo simulations.

and the length of $\hat{\varphi}_{\text{LR}}(\kappa, \mathbf{Y})$ in Table 3 indicates that at that point, the interval exploiting the bound (2) is often considerably more informative than the interval based on $\hat{\beta}_{\text{long}}$. In addition, researchers might compute the threshold value $\bar{\kappa}^*_{\text{LR}}$, defined such that $\hat{\varphi}_{\text{LR}}(\bar{\kappa}, \mathbf{Y})$ rejects for all $\bar{\kappa} \leq \bar{\kappa}^*_{\text{LR}}$. The last three columns in Table 3 report the quartiles of the distribution of $\bar{\kappa}^*_{\text{LR}}$. For $\nu = 1$, as well as for $(\kappa, \nu) = (0.5, 0.5)$, its median is always positive. Thus, in the majority of draws, researchers would have been able to conclude that small upper bounds for $\bar{\kappa}$ are empirically incompatible with $\beta = 0$. Unreported results show that if the true value of β is nonzero, these medians become larger. Thus, the LR approach helps sharpen inference about β in a meaningful way.

Still, looking over the table, it is tempting to conclude that one should use $\hat{\beta}_{\text{short}}$ whenever there is no overlap, $\nu = 0$, as this leads to the shortest intervals by far, and only slight size distortions. Similarly, if $\nu < 1$ the quartiles of $\bar{\kappa}^*_{\text{LR}}$ are much smaller than κ. However, it is not possible to consistently determine the value of ν from the observations. This is the result of the asymptotic efficiency derivations in Section 2.3: For small values of $\bar{\kappa}$, it is impossible to do better than to construct inference based on the bivariate statistics $(\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}})'$ at least in large samples, and as demonstrated there, the LR approach comes close to exploiting the information contained in this pair of statistics.

6. Empirical applications

6.1 *Overview*

We illustrate the suggested method in three empirical examples based on studies by Macchiavello and Morjaria (2015), Donohue and Levitt (2001), and Imbens, Rubin, and Sacerdote (2001). Our examples serve to highlight the mechanics of the bivariate LR test and illustrate its empirical content. In particular, for each of the studies, we calculate the LR statistic $\widehat{\text{LR}}(\bar{\kappa})$ over a grid of values for $\bar{\kappa}$, resulting in a family of confidence intervals in β indexed by $\bar{\kappa} \geq 0$. This family provides an explicit correspondence between assumptions on the control coefficients $\boldsymbol{\gamma}$ and empirical conclusions about the parameter of interest β. As a by-product, we obtain the threshold value $\bar{\kappa}^*_{\text{LR}}$, so that the intervals exclude the zero-effect value $\beta = 0$ for $\bar{\kappa} < \bar{\kappa}^*_{\text{LR}}$, and contain it otherwise.

The intervals are computed in the following steps:

1. Let $\mathbf{y}$ be the $n \times 1$ vector of outcome variables, $\tilde{\mathbf{x}}$ the scalar regressor of interest, $\mathbf{Q}$ the matrix of baseline controls, and $\tilde{\mathbf{Z}}$ the matrix of additional controls of questionable relevance. Run the long regression of $\mathbf{y}$ on $(\tilde{\mathbf{x}}, \tilde{\mathbf{Z}}, \mathbf{Q})$ to find the long coefficient $\hat{\beta}_{\text{long}}$, and run the short regression of $\mathbf{y}$ on $(\tilde{\mathbf{x}}, \mathbf{Q})$ to find the short coefficient $\hat{\beta}_{\text{short}}$.

2. Let $\mathbf{x}$ and $\mathbf{Z}$ denote the residuals of $\tilde{\mathbf{x}}$, $\tilde{\mathbf{Z}}$ in a regression on $\mathbf{Q}$. Define $\mathbf{v}_i = ((\mathbf{x}'\mathbf{x})^{-1}x_i, (\check{\mathbf{x}}'\check{\mathbf{x}})^{-1}\check{x}_i)'$, $i = 1, \ldots, n$ with $\check{\mathbf{x}}$ the vector of residuals of a linear regression of $\mathbf{x}$ on $\mathbf{Z}$.

3. Obtain an estimate $\hat{\boldsymbol{\Omega}}_n$ of the 2×2 covariance matrix of $(\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}})'$:

   (a) If the total number of controls (the number of elements in $\boldsymbol{\delta}$ and $\boldsymbol{\gamma}$) is small compared to the sample size, a standard heteroskedasticity robust estimator may be used

   $$\hat{\boldsymbol{\Omega}}_n = \sum_j \Big(\sum_{i \in G_j} \mathbf{v}_i e_i \Big) \Big(\sum_{i \in G_j} \mathbf{v}_i e_i \Big)', \tag{27}$$

   where the sets C_j partition the indices $i = 1, \ldots, n$ into clusters (so that for independent samples, $C_j = \{j\}$), and e_i are the residuals of the long regression.

   (b) If the total number of controls is of the same order as the sample size (say, 5% or more), then without clustering, apply the Cattaneo, Jansson, and Newey

(2018b) estimator

$$\hat{\boldsymbol{\Omega}}_n = \sum_{i=1}^{n}\sum_{j=1}^{n} \kappa_{ij} e_i^2 \mathbf{v}_i \mathbf{v}_i',$$

where κ_{ij} are the elements of the $n \times n$ matrix $(\mathbf{M} \odot \mathbf{M})^{-1}$ with $\mathbf{M} = \mathbf{I}_n - \mathbf{W}(\mathbf{W}'\mathbf{W})^{-1}\mathbf{W}'$ and $\mathbf{W} = (\mathbf{Q}, \mathbf{Z})$, $\odot$ denotes the element-by-element product, and e_i are the residuals of the long regression.

(c) If the number of baseline controls is small, and the number of additional controls is of the same order as the sample size (say, 5% or more), then under clustering, use (27) with e_i equal to residuals of the short regression.

4. Compute $\rho^2 = \mathbf{x}'\mathbf{Z}(\mathbf{Z}'\mathbf{Z})^{-1}\mathbf{Z}'\mathbf{x}/(\mathbf{x}'\mathbf{x})$, the R^2 of a regression of $\mathbf{x}$ on $\mathbf{Z}$, and for given $\bar{\kappa}$, χ_1 and χ_2 from equations (16) and (17) with Ω_{ij} the elements of $\hat{\boldsymbol{\Omega}}_n$. Define the function $h : \mathbb{R}^2 \mapsto \mathbb{R}$ via $h(Y_1, Y_2) = h_0(Y_1, Y_2) - h_1(Y_1, Y_2)$, where

$$h_0(Y_1, Y_2) = Y_1^2 + \mathbf{1}\big[|Y_2| > \chi_2\big]\big(|Y_2| - \chi_2\big)^2,$$

$$h_1(Y_1, Y_2) = \begin{cases} \dfrac{(\chi_2 + \chi_1 Y_1 - Y_2)^2}{1 + \chi_1^2} & \text{if } \chi_2 + \chi_1 Y_1 < Y_2, \\ \dfrac{(\chi_2 - \chi_1 Y_1 + Y_2)^2}{1 + \chi_1^2} & \text{if } \chi_2 - \chi_1 Y_1 < -Y_2, \\ 0 & \text{otherwise.} \end{cases}$$

5. Compute the level α critical value cv as the $1 - \alpha$ quantile of $h(Z_1, Z_2 + \chi_2)$, where (Z_1, Z_2) are independent standard normals via simulation (or rely on the look-up table in the replication files, or on the slightly conservative interpolation from Table 2).

6. The level $1 - \alpha$ confidence interval for β is formed by the values of β_0 that satisfy

$$h\left(\operatorname{sign}(\Omega_{11} - \Omega_{12})\frac{\hat{\beta}_{\text{long}} - \beta_0}{\sqrt{\Omega_{11}}}, \frac{\Omega_{11}(\hat{\beta}_{\text{short}} - \beta_0) - \Omega_{12}(\hat{\beta}_{\text{long}} - \beta_0)}{\sqrt{\Omega_{11}}\sqrt{\Omega_{11}\Omega_{22} - \Omega_{12}^2}}\right) \leq \text{cv}$$

and the estimator $\hat{\beta}_{\text{LR}}(\bar{\kappa})$ is the midpoint of this interval.

6.2 *Macchiavello and Morjaria (2015)*

Macchiavello and Morjaria (2015) use data on African rose exports to identify reputational effects in markets without contract enforcement. The authors construct a model with the feature that binding incentive constraints yield observable proxies for the buyer–seller relationship value during periods of maximum temptation for sellers and buyers to undercut each other. They find, empirically, that this value proxy is correlated with relationship age but not outside prices, evidence that reputation constrains trade in the absence of enforcement. We apply our approach to determine the extent to which

the correlation between relationship value and age is sensitive to Macchiavello and Morjaria's (2015) choice of control variables.

We treat the panel regression from Table 5, Column 8 of Macchiavello and Morjaria (2015) as the short regression, where relationships are the unit of observation and the time dimension corresponds to four growing seasons (years), for a total of $n = 372$ observations. This regression has the log of the relationship value as the dependent variable, the regressor of interest is the log of relationship age, and the baseline controls are the maximum of the previous observed log auction value as well as relationship and season fixed-effects. This is a difference-in-differences model in which the main effect is identified by variation in sales across seasons for buyer–seller relationships of different ages. Macchiavello and Morjaria (2015) find that β, the coefficient on relationship age, is statistically significant at standard confidence levels.

We investigate the sensitivity of these results to $p = 123$ additional buyer $\times$ season fixed effects. This specification is an extension of the baseline season controls that allows flexibility over buyers. One might imagine that because sellers are located in Kenya, but buyers are located globally, time trends might be more plausibly heterogeneous for buyers. Hence, to the extent that purchase patterns over seasons differed between buyers with relationships of various lengths for reasons unrelated to learning about seller quality, omitting these additional fixed effects could lead to bias in β. However, absent constraints on the coefficient of these additional controls, only variation from seller differences across seasons can identify the main effect β, so including these additional fixed effects in an unconstrained fashion leads to much less informative inference.

Figure 3 plots 90%, 95%, and 99% confidence intervals for β from our new procedure as a function of $\bar{\kappa}$, along with the point estimates $\hat{\beta}_{\mathrm{LR}}(\bar{\kappa})$. The standard errors are clustered by seller and are computed as described in Step 3c of Section 6.1. We see that the short regression strongly rejects, but the long regression does not. The largest value of $\bar{\kappa}$ that still leads to rejection, $\bar{\kappa}^*_{\mathrm{LR}}$, of the 5% level test is indicated by a vertical line and equals $\bar{\kappa}^*_{\mathrm{LR}} = 0.203$. Thus, since the outcome is measured in logs, as long as one believes that season-specific idiosyncratic buyer preferences not already captured by Macchiavello and Morjaria's (2015) baseline controls induce on average changes in the

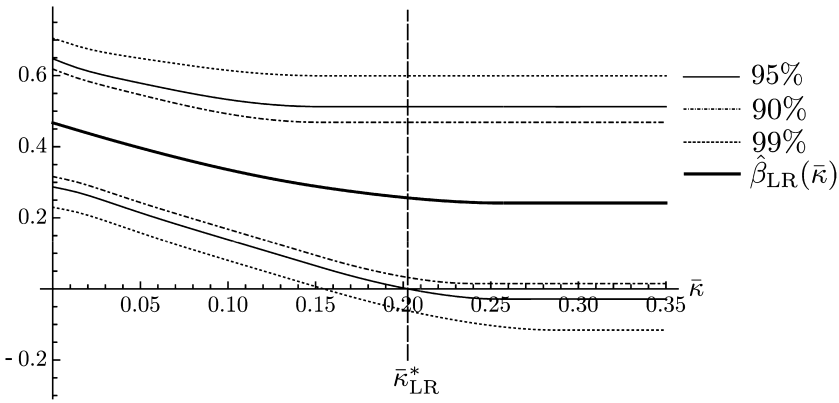

FIGURE 3. LR Confidence intervals for β in Macchiavello and Morjaria (2015).

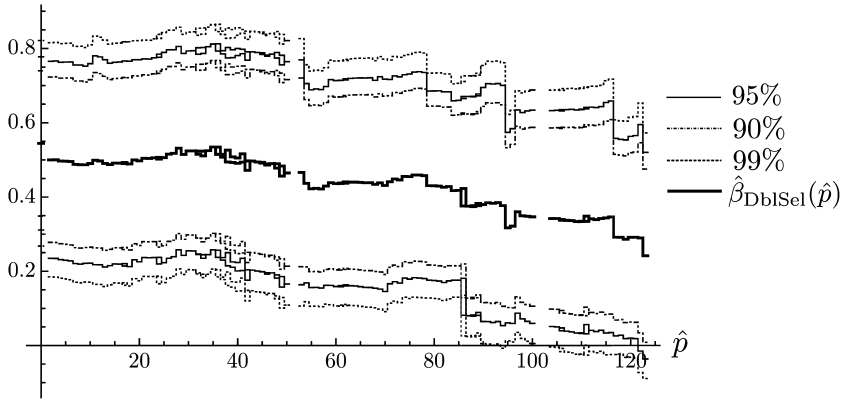

FIGURE 4. Sparsity based confidence intervals for β in Macchiavello and Morjaria (2015).

relationship value of no more than 20.2%, the conclusion of a statistically significant effect of the age of the relationship is upheld. The corresponding R^2-type ratio of $n(\bar{\kappa}^*_{\text{LR}})^2$ and the sum of squared residuals of a regression of y_i on $\mathbf{q}_i$ equals 18.8% in this example. In other words, significance of β at the 5% level prevails as long as the direct effect of season-specific idiosyncratic buyer preferences is assumed to be responsible for less than 18.8% of residual variation in the log-relationship value.

It might be useful to contrast these results to what is obtained from an analysis imposing sparsity. Figure 4 provides post-double Lasso point estimates and confidence intervals for β, where the penalty terms suggested by Belloni, Chernozhukov, and Hansen (2014) are multiplied by a common factor that induces the sparsity index $0 \leq \hat{p} \leq p$ in the post-double Lasso regression.[5] The confidence interval on the very left and very right are again standard short and long regression inference. But in between, the bounds on the confidence intervals are not a monotone function of the sparsity index, complicating the interpretation of a higher index as a "weaker" assumption on the control coefficients. What is more, there is no justification for the confidence intervals reported in Figure 4: The asymptotic justification for double selection Lasso inference is not for a specific sparsity index, but rather, it is shown to be valid under certain asymptotic sequences of penalty terms if the model satisfies some asymptotic sparsity constraint. The default penalty choice suggested by Belloni, Chernozhukov, and Hansen (2014) applied to the example selects $\hat{p} = 2$ controls and leads to a significant β at all conventional levels.

6.3 *Abortion and crime*

In an influential paper, Donohue and Levitt (2001) found a significant effect of lagged abortion rates on crime, using a panel data of U.S. states from 1985 to 1997, but these results were disputed in follow-up studies (see, for instance, Foote and Goetz (2008), and

[5]The gaps in the figure arise because it seems numerically impossible to induce all values of $0 \leq \hat{p} \leq p$ by varying the penalty term factor. When there is more than one post selection regression at a given sparsity level $\hat{p}$ (which is possible, since Lasso is based on an L_1 penalty, rather than directly penalizing sparsity), we report the lower and upper envelopes.

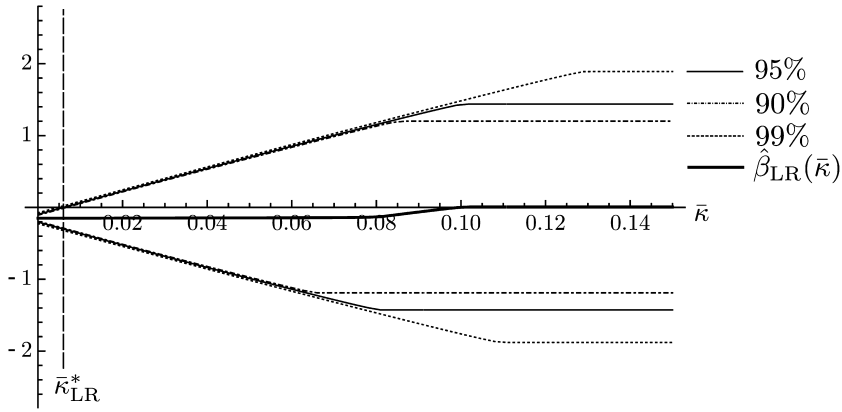

FIGURE 5. LR confidence intervals for β in Donohue and Levitt (2001).

Joyce (2004, 2009)). BCH also consider this example as an illustration of their methodology.

We apply the same specification as in BCH, and focus on violent crimes (results are similar for property and murder crime rates). The regression models panel data from 48 states over 12 years, with all variables expressed in first differences to account for state fixed-effects, for a total of $n = 576$ observations. The explanatory variable is the violent crime rate, the regressor of interest with coefficient β is a measure of lagged abortion rates, the "short" specification includes a set of 20 controls (including 12 time dummies) present in Donohue and Levitt's original specification, and the potential additional controls are a set of $p = 284$ regressors proposed by BCH, including higher-order terms, initial conditions, and interactions of variables with state-specific observables. Using standard errors clustered at the state level, as described in Step 3c of Section 6.1, the t-tests based on $\hat{\beta}_{\mathrm{short}}$ rejects at the 5% level, but the t-test using the estimator $\hat{\beta}_{\mathrm{long}}$ from the long regression does not.

Figure 5 plots the LR confidence intervals for β as a function of the bound $\bar{\kappa}$. It is apparent from the figure that trying to control for the 284 additional controls is very ambitious, as it leads to a dramatically increased standard error compared to the short regression. Correspondingly, the cut-off value $\bar{\kappa}^*_{\mathrm{LR}}$ is rather small at 0.6%: As soon as one allows for a quadratic mean effect of the additional controls on the crime rate to be larger than 0.6%, one loses significance of lagged abortion rates on violent crime rates. The corresponding threshold of the ratio of $n(\bar{\kappa}^*_{\mathrm{LR}})^2$ to the sum of squared residuals in a regression of y_i on $\mathbf{q}_i$ is a mere 0.7%. This conclusion of extreme fragility of the empirical results to inclusion of this large set of additional controls accords qualitatively with the analysis of BCH, who find that post double Lasso inference about β is not significant.

6.4 *Earnings, lottery winnings and treatment heterogeneity*

It is well understood that inference on average treatment effects is sensitive to the accommodation of treatment heterogeneity (Imbens and Wooldridge (2009)). In particular, procedures that ignore heterogeneity of treatment effects may misappropriate explanatory power from the treatment to the confounding factors in a way that biases the

average treatment effect. However, allowing too much heterogeneity can lead to noisy inference. Our approach can be used to illuminate how assumptions on treatment heterogeneity shape inference on the average treatment effect. We illustrate this in this section using data from a study by Imbens, Rubin, and Sacerdote (2001).[6]

Using data on a cross-section of $n = 496$ individuals participating in the Massachusetts lottery from 1984 to 1988, these authors study the effects of unearned income on the marginal propensity to earn (MPE). In their main empirical exercise, the authors regress post-lottery earnings on lottery winnings, and they interpret the coefficient on lottery winnings as the effect of income on MPE. Although winning the lottery is plausibly exogenous conditional on purchasing a lottery ticket, the frequency of lottery ticket purchases may be correlated with factors that also affect labor and wages. Hence, the authors include observable individual characteristics as control variables. For illustration, we focus on the specification from Row 1, Column 2 of their Table 4,

$$y_i = \beta x_i + \sum_{j=1}^{7} q_{ij}\delta_j + \varepsilon_i. \tag{28}$$

In this specification, the outcome y_i denotes the average of social security earnings in the 6 years after the lottery measured in multiples of \$1000, the main regressor x_i denotes lottery winnings in multiples of \$1000, and the baseline covariates q_{ij} include years of education, age, an intercept term, and dummies for gender, some college, age greater than 55, and age greater than 65. In Row 1, Column 2 of their Table 4, the authors estimate β, the coefficient on winnings, to be -0.052 and statistically significant at standard levels.

Following their baseline specification, Imbens, Rubin, and Sacerdote (2001) explore heterogeneity in the main effect. In particular, in their Table 5, the authors explore how β differs by gender, prior earnings, age, education, and years since winning. Despite this heterogeneity, the coefficients in (28) may still be unbiased for the conditional average effect in the sample of 496 individuals, if one assumes that potential heterogeneity in β is uncorrelated with the observed regressors. However, without this assumption, inference based on the short regression (28) may be invalid. We apply our approach to assess the extent to which allowing heterogeneity in β over different subgroups of the data changes inference on the conditional average effect.

In particular, we consider potential controls in the form of subgroup dummies and interactions with the regressor of interest in order to allow for heterogeneity in the coefficient of interest. Formally, we identify subgroups of the data generated by the cross-products of dummies for gender, full college, age greater than 45, age greater than 55, and age greater than 65. This results in 16 potential subgroups $G_1, \ldots, G_{16}$ that partition the full set of observables $i \in \{1, \ldots, 496\}$, with each individual i belonging to one subgroup G_j. A linear model allowing for arbitrary heterogeneity of the treatment effect

[6]Also see Imbens and Rubin (2015) for further exploration of this data set from a causal inference perspective.

across these groups is given by

$$y_i = \sum_{j=1}^{16} \mathbf{1}[i \in G_j] x_i \beta_j + \sum_{j=1}^{7} q_{ij} \delta_j + \sum_{j=1}^{16} \mathbf{1}[i \in G_j] \gamma_j + \varepsilon_i$$

with β_j the conditional treatment effect in subgroup j.

Suppose that under treatment heterogeneity, the parameter of interest is the average $\beta = n^{-1} \sum_{i=1}^{n} \sum_{j=1}^{16} \mathbf{1}[i \in G_j] \beta_j$. Following Section 5.2 of Imbens and Wooldridge (2009), inference about β can conveniently be performed by augmenting the short regression (28) by controls z_{ik} consisting of dummies $\mathbf{1}[i \in G_j]$ and interaction terms $(\mathbf{1}[i \in G_j] - n^{-1} \sum_{l=1}^{n} \mathbf{1}[l \in G_j]) x_i$. Dropping collinear terms, this results in the "long regression" with 25 additional controls z_{ik},

$$y_i = \beta x_i + \sum_{j=1}^{7} q_{ij} \delta_j + \sum_{k=1}^{25} z_{ik} \gamma_k + \varepsilon_i.$$

We use our approach to study the sensitivity of inference about β to varying assumptions about population group heterogeneity, that is, the coefficients γ_k. Figure 6 plots confidence intervals for β as a function of the bound $\bar{\kappa}$, using Cattaneo, Jansson, and Newey (2018b) standard errors. We find that for the 95% level, $\bar{\kappa}^*_{\mathrm{LR}} = \$1.79\text{k}$, so under the assumption that the quadratic mean of heterogeneity across groups is smaller than \$1.79k, we still reject the null hypothesis that the conditional average treatment effect of lottery winnings on post-lottery earnings is zero at the 5% significance level. This translates into a ratio of 1.8% of $n(\bar{\kappa}^*_{\mathrm{LR}})^2$ to the sum of squared residuals in a regression of y_i on $\mathbf{q}_i$. As such, we conclude that the significance of the homogeneous baseline (28) are somewhat sensitive, but not extremely sensitive to the assumption of treatment homogeneity.

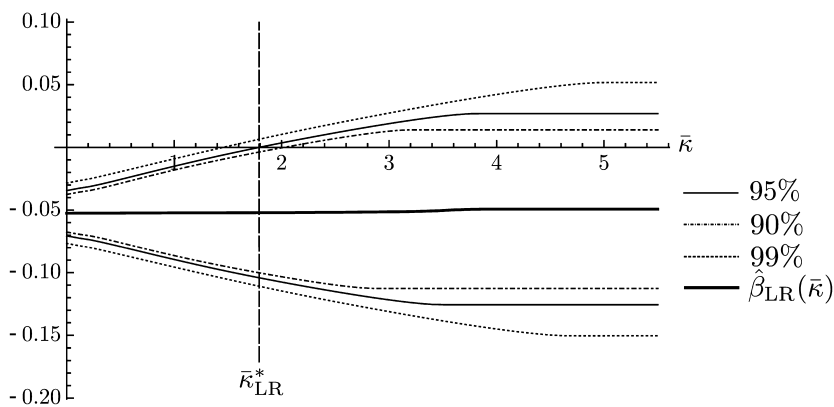

FIGURE 6. LR confidence intervals for β in Imbens, Rubin, and Sacerdote (2001).

7. Conclusion

Improving inference over including all potential controls in a "long regression" requires some a priori knowledge about the control coefficients. In this paper, we develop a simple inference procedure that exploits a bound on the overall explanatory power of questionable additional controls. This yields a continuous bridge between excluding these controls and including them with unconstrained coefficients, as a function of the bound. The approach enables applied researchers to explore the robustness of an empirical result relative to set of additional controls, beyond the dichotomous conclusion that significance is, or is not lost with their inclusion.

In particular, we suggest computing $\bar{\kappa}^*_{\mathrm{LR}}$, the threshold value for the explanatory power of the additional controls for which the parameter of interest is still significant. We offer a purely statistical and a more substantive approach to judging the magnitude of $\bar{\kappa}^*_{\mathrm{LR}}$ in practice: On the one hand, one can translate $\bar{\kappa}^*_{\mathrm{LR}}$ into a fraction of the variation of the outcome that is explained by the additional controls. In the three illustrations we considered, the threshold values for this fraction were 18.8%, 0.7%, and 1.8%, respectively. Since we expect that this approach would typically be applied to additional controls that are a priori plausibly irrelevant, a fraction of 5% is quite large, and even 1% is arguably not an entirely trivial fraction. On the other hand, $\bar{\kappa}^*_{\mathrm{LR}}$ is directly interpretable in terms of the quadratic mean of the effects of the additional controls. This number has the same units as the outcome variable, and its magnitude must necessarily be judged in the context of the application at hand. From that perspective, we deem $\bar{\kappa}^*_{\mathrm{LR}}$ quite large in Macchiavello and Morjaria (2015), but very small in Donohue and Levitt (2001) and of moderate magnitude in Imbens and Wooldridge (2009), although one might reasonably disagree with this assessment. Ultimately, these judgements might best be left to consumers of the empirical study, with $\bar{\kappa}^*_{\mathrm{LR}}$ delineating what one must be willing to assume to sustain the finding of a significant effect.

Appendix: Proofs

A.1 *Proof of Lemma* 1

Let $\varphi_0(\hat{\boldsymbol{\xi}}) = E_{\boldsymbol{\xi}}[\varphi(\bar{\kappa}, \mathbf{Y})|\hat{\boldsymbol{\xi}}]$, so that by sufficiency of $\hat{\boldsymbol{\xi}}$, and the law of iterated expectations, $E_{\boldsymbol{\xi}}[\varphi(\bar{\kappa}, \mathbf{Y})] = E_{\boldsymbol{\xi}}[\varphi_0(\hat{\boldsymbol{\xi}})]$. Since by assumption, $E_{\boldsymbol{\xi}}[\varphi(\bar{\kappa}, \mathbf{Y})]$ does not depend on $\boldsymbol{\delta}$, $E_{\boldsymbol{\xi}}[\varphi_0(\hat{\boldsymbol{\xi}})] = E_{\boldsymbol{\xi}_0}[\varphi_0(\hat{\boldsymbol{\xi}})]$, where $\boldsymbol{\xi}_0 = (\beta, \Delta, \mathbf{0}, \tau, \boldsymbol{\omega})$. Define $\varphi_S(\hat{\boldsymbol{\zeta}}) = E_{\boldsymbol{\xi}_0}[\varphi_0(\hat{\boldsymbol{\xi}})|\hat{\boldsymbol{\zeta}}]$ with $\hat{\boldsymbol{\zeta}} = (\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}}, \hat{\boldsymbol{\phi}}')$. Then by the law of iterated expectations, $E_{\boldsymbol{\xi}_0}[\varphi_S(\hat{\boldsymbol{\zeta}})] = E_{\boldsymbol{\xi}_0}[\varphi_0(\hat{\boldsymbol{\xi}})] = E_{\boldsymbol{\xi}}[\varphi(\bar{\kappa}, \mathbf{Y})]$ for all $\boldsymbol{\xi}$.

Furthermore, with $\mathbf{O}$ a $(p-1) \times (p-1)$ rotation matrix

$$
\begin{aligned}
E_{\beta,\Delta,\tau,\boldsymbol{\omega}}\big[\varphi_S(\hat{\boldsymbol{\zeta}})\big] &= E_{\beta,\Delta,\tau}\big[\varphi_S(\hat{\boldsymbol{\zeta}})\big] \\
&= E_{\beta,\Delta,\tau}\big[\varphi_S\big((\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}}, (\tau\boldsymbol{\omega} + \mathbf{e})')\big)\big] \\
&= E_{\beta,\Delta,\tau}\big[\varphi_S\big((\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}}, (\tau\boldsymbol{\omega} + \mathbf{O}\mathbf{e})')\big)\big] \\
&= E_{\beta,\Delta,\tau}\big[\varphi_S\big((\hat{\beta}_{\mathrm{long}}, \hat{\beta}_{\mathrm{short}}, (\tau\mathbf{O}\boldsymbol{\omega} + \mathbf{O}\mathbf{e})')\big)\big],
\end{aligned}
$$

where $\mathbf{e} \sim \mathcal{N}(\mathbf{0}, n^{-1}\mathbf{I}_{p-1})$ is independent of $(\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}})$, the first and last equality follow from assumption about the rejection probability of $\varphi(\bar{\kappa}, \mathbf{Y})$, and the before last equality follows from the spherical symmetry of the distribution of $\mathbf{e}$. Since $\mathbf{O}$ was arbitrary, we also have

$$E_{\boldsymbol{\xi}}\big[\varphi(\bar{\kappa}, \mathbf{Y})\big] = \int E_{\beta,\Delta,\tau}\big[\varphi_S\big(\big(\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}}, (\mathbf{O}\tau\boldsymbol{\omega} + \mathbf{O}\mathbf{e})'\big)\big)\big]\, dH_{p-1}(\mathbf{O}),$$

where H_{p-1} is the Haar measure on the $p-1$ rotation matrices. Now set $\tilde{\varphi}(\mathbf{T}) = \int \varphi_S((\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}}, \hat{\tau}\boldsymbol{\iota}'\mathbf{O}))\, dH_{p-1}(\mathbf{O}) = \int \varphi_S((\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}}, \hat{\boldsymbol{\phi}}'\mathbf{O}))\, dH_{p-1}(\mathbf{O})$ with $\boldsymbol{\iota} = (1, 0, \ldots, 0)' \in \mathbb{R}^{p-1}$. Then

$$\begin{aligned} E_{\beta,\Delta,\tau}\big[\tilde{\varphi}(\mathbf{T})\big] &= E_{\beta,\Delta,\tau}\left[\int \varphi_S\big(\big(\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}}, \hat{\boldsymbol{\phi}}'\mathbf{O}'\big)\big)\, dH_{p-1}(\mathbf{O})\right] \\ &= \int E_{\beta,\Delta,\tau}\big[\varphi_S\big(\big(\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}}, (\tau\mathbf{O}\boldsymbol{\omega} + \mathbf{O}\mathbf{e})'\big)\big)\big]\, dH_{p-1}(\mathbf{O}) \end{aligned}$$

and the result follows.

A.2 *Proof of Lemma 2*

We will make use of the following lemma.

LEMMA 4. *Let $\mathcal{I}_m$ denote the modified Bessel function of the first kind of degree $m > 0$. Then for any positive sequence $s_m = o(m^{1/2})$,*

$$\lim_{m\to\infty} \mathcal{I}_m(s_m) \frac{\Gamma(m+1)}{\left(\frac{1}{2}s_m\right)^m} = 1,$$

where Γ is the Gamma function.

PROOF. From the definition of $\mathcal{I}_m$, for any $s > 0$,

$$\begin{aligned} \mathcal{I}_m(s) &= \left(\frac{1}{2}s\right)^m \sum_{j=0}^{\infty} \frac{\left(\frac{1}{4}s^2\right)^j}{j!\Gamma(m+j+1)} \\ &= \frac{\left(\frac{1}{2}s\right)^m}{\Gamma(m+1)} \left(1 + \sum_{j=1}^{\infty} \frac{\left(\frac{1}{4}s^2\right)^j}{j!} \frac{\Gamma(m+1)}{\Gamma(m+j+1)}\right). \end{aligned}$$

Now

$$\sum_{j=1}^{\infty} \frac{\left(\frac{1}{4}s^2\right)^j}{j!} \frac{\Gamma(m+1)}{\Gamma(m+j+1)} \le \sum_{j=1}^{\infty} \frac{s^{2j}}{j!} \frac{\Gamma(m+1)}{\Gamma(m+j+1)}$$
$$\le \sum_{j=1}^{\infty} \frac{\left(s^2/m\right)^j}{j!} = \exp\left[s^2/m\right] - 1$$

where the second inequality uses the elementary inequality $\Gamma(m+1)m^j/\Gamma(m+j+1) \le 1$ obtained from repeatedly applying $\Gamma(m+i+1) = (m+i)\Gamma(m+i) \le m\Gamma(m+i)$ for all $i \ge 0$ and $m > 0$. The result now follows from $s_m^2/m \to 0$ under $s_m = o(m^{1/2})$. □

For ease of notation, we omit the dependence on n (and $p = p_n$), except for t_n. From (11), it follows that $n\hat{\tau}^2 = n\hat{\boldsymbol{\phi}}'\hat{\boldsymbol{\phi}}$ with $\hat{\boldsymbol{\phi}} \sim \mathcal{N}(\tau\boldsymbol{\omega}, n^{-1}\mathbf{I}_{p-1})$ is distributed noncentral χ^2 with $p-1$ degrees of freedom and noncentrality parameter $n\tau^2$. Without loss of generality, assume $\boldsymbol{\omega} = \boldsymbol{\iota} = (1, 0, \ldots, 0)'$. Then, with $\hat{\boldsymbol{\omega}} = \hat{\boldsymbol{\phi}}/\|\hat{\boldsymbol{\phi}}\|$, from the density of $\hat{\boldsymbol{\phi}}$ and using the notation of the proof of Lemma 1,

$$L_n(t_n) = C \int \exp\left[-\frac{1}{2}n\|\hat{\tau}\mathbf{O}\hat{\boldsymbol{\omega}} - \boldsymbol{\iota}t_n\|^2\right] dH_{p-1}(\mathbf{O})$$

for some constant C that does not depend on t_n (and note that $L_n(t_n)$ does not depend on the realization of $\hat{\boldsymbol{\omega}}$). Thus

$$L_n(t_n)/L_n(0) = \int \exp\left[nt_n\hat{\tau}\hat{\boldsymbol{\omega}}'\mathbf{O}\boldsymbol{\iota} - \frac{1}{2}nt_n^2\right] dH_{p-1}(\mathbf{O}).$$

We initially show the convergence under $\tau = 0$. It then suffices to show that $E[(L_n(t_n)/L_n(0) - 1)^2] \to 1$ under $\hat{\boldsymbol{\phi}} \sim \mathcal{N}(\mathbf{0}, n^{-1}\mathbf{I}_{p-1})$ and an arbitrary sequence $t_n = o(n^{-1/4})$. Observe that

$$\begin{aligned}
&E\left[\left(L_n(t_n)/L_n(0) - 1\right)^2\right] \\
&\quad = E\left[\left(\int \exp\left[t_n\hat{\boldsymbol{\phi}}'\mathbf{O}\boldsymbol{\iota} - \frac{1}{2}nt_n^2\right] dH_{p-1}(\mathbf{O}) - 1\right)^2\right] \\
&\quad = E\left[\left(\int \exp\left[t_n\hat{\boldsymbol{\phi}}'\mathbf{O}\boldsymbol{\iota} - \frac{1}{2}nt_n^2\right] dH_{p-1}(\mathbf{O}) - 1\right)\right. \\
&\qquad \left.\times \left(\int \exp\left[t_n\hat{\boldsymbol{\phi}}'\tilde{\mathbf{O}}\boldsymbol{\iota} - \frac{1}{2}nt_n^2\right] dH_{p-1}(\tilde{\mathbf{O}}) - 1\right)\right] \\
&\quad = E\left[\left(\int \exp\left[t_n\hat{\boldsymbol{\phi}}'\mathbf{O}\boldsymbol{\iota} - \frac{1}{2}nt_n^2\right] dH_{p-1}(\mathbf{O})\right)\left(\int \exp\left[t_n\hat{\boldsymbol{\phi}}'\tilde{\mathbf{O}}\boldsymbol{\iota} - \frac{1}{2}nt_n^2\right] dH_{p-1}(\tilde{\mathbf{O}})\right)\right] \\
&\qquad - 2 \cdot E\left[\int \exp\left[t_n\hat{\boldsymbol{\phi}}'\mathbf{O}\boldsymbol{\iota} - \frac{1}{2}nt_n^2\right] dH_{p-1}(\mathbf{O})\right] + 1 \\
&\quad = h_n(t_n) - 2\tilde{h}_n(t_n) + 1.
\end{aligned}$$

In what follows, we show that $h_n(t_n) \to 1$. The convergence $\tilde{h}_n(t_n) \to 1$ follows from the same arguments and is omitted for brevity.

Tonelli's theorem and $\hat{\boldsymbol{\phi}} \sim \mathcal{N}(\mathbf{0}, n^{-1}\boldsymbol{I}_{p-1})$ imply

$$\begin{aligned} h_n(t_n) &= E\Big[\int\int \exp\big[t_n\hat{\boldsymbol{\phi}}'(\mathbf{O}\boldsymbol{\iota}+\tilde{\mathbf{O}}\boldsymbol{\iota}) - nt_n^2\big]\, dH_{p-1}(\mathbf{O})\, dH_{p-1}(\tilde{\mathbf{O}})\Big] \\ &= \int\int E\big[\exp\big[t_n\hat{\boldsymbol{\phi}}'(\mathbf{O}\boldsymbol{\iota}+\tilde{\mathbf{O}}\boldsymbol{\iota}) - nt_n^2\big]\big]\, dH_{p-1}(\mathbf{O})\, dH_{p-1}(\tilde{\mathbf{O}}) \\ &= \int\int \exp\Big[\frac{1}{2}nt_n^2\|\mathbf{O}\boldsymbol{\iota}+\tilde{\mathbf{O}}\boldsymbol{\iota}\|^2 - nt_n^2\Big]\, dH_{p-1}(\mathbf{O})\, dH_{p-1}(\tilde{\mathbf{O}}) \\ &= \int\int \exp\big[nt_n^2(\mathbf{O}\boldsymbol{\iota})'\tilde{\mathbf{O}}\boldsymbol{\iota}\big]\, dH_{p-1}(\mathbf{O})\, dH_{p-1}(\tilde{\mathbf{O}}) \\ &= \int \exp\big[nt_n^2\boldsymbol{\iota}'\mathbf{O}\boldsymbol{\iota}\big]\, dH_{p-1}(\mathbf{O}). \end{aligned}$$

Using the notation of Lemma 4, the formula for the normalizing constant of the von Mises–Fisher distribution (see, for instance, equation (9.3.4) of Mardia and Jupp (2000)) implies $h_n(t_n) = 2^{\tilde{p}/2-1}\cdot\mathcal{I}_{\tilde{p}/2-1}(nt_n^2)\cdot\Gamma(\tilde{p}/2)/(nt_n^2)^{\tilde{p}/2-1}$ where $\tilde{p} = p-1$. Application of Lemma 4 with $s_n = nt_n^2$ now yields $h_n(t_n) \to 1$, since under $t_n = o(n^{-1/4})$ and $p/n \to c \in (0,1)$, $s_n^2 = n^2t_n^4 = o(p/2-1)$.

This concludes the proof under $\tau_n = 0$. Now apply this very result to another sequence t_n, $t_n = t_n'$. Then $L_n(t_n')/L_n(0) \xrightarrow{p} 1$ implies via LeCam's first lemma (see, for instance, Lemma 6.4 in van der Vaart (1998)) that in the experiment of observing $\hat{\tau}_n^2$, the sequence $\tau_n = t_n'$ is contiguous to $\tau_n = 0$. Thus, $L_n(t_n)/L_n(0) \xrightarrow{p} 1$ also holds under $\tau_n = t_n' = o(n^{-1/4})$ by definition of contiguity, which was to be shown.

A.3 *Proof of Theorem 2*

Let $\ell_n(\mathbf{T}_n)$ be the log-likelihood ratio statistic based on $\mathbf{T}_n$ of testing $H_0 : (b, a, \tau_n) = (b_0, a_0, \tau_{n,0})$ against $H_1 : (b, a, \tau_n) = (b_1, a_1, \tau_{n,1})$. Let $h_{j,n} = (b_j, b_j + \rho_n a_j)'$ and $h_j = (b_j, b_j + \rho a_j)$, $j = 0, 1$. From (11),

$$\begin{aligned} \ell_n(\mathbf{T}_n) = \sqrt{\mathbf{x}_n'\mathbf{x}_n}\begin{pmatrix}\hat{\beta}_{\text{long},n} \\ \hat{\beta}_{\text{short},n} - s_n\end{pmatrix}' \boldsymbol{\Sigma}(\rho_n)^{-1}(h_{1,n} - h_{0,n}) - \frac{1}{2}h_{1,n}'\boldsymbol{\Sigma}(\rho_n)^{-1}h_{1,n} \\ + \frac{1}{2}h_{0,n}'\boldsymbol{\Sigma}(\rho_n)^{-1}h_{0,n} + \log\Big(\frac{L_n(\tau_{n,1})}{L_n(\tau_{n,0})}\Big) \end{aligned}$$

and with $\ell_0(\hat{\mathbf{b}}^o)$ the log-likelihood ratio statistic based on $\hat{\mathbf{b}}^o$ of of testing $H_0 : (b, a) = (a_0, b_0)$ against $H_1 : (b, a) = (b_1, a_1)$,

$$\ell_0(\hat{\mathbf{b}}^o) = \begin{pmatrix}\hat{b}_{\text{long}} \\ b^o_{\text{short}}\end{pmatrix}' \boldsymbol{\Sigma}(\rho)^{-1}(h_1 - h_0) - \frac{1}{2}h_1'\boldsymbol{\Sigma}(\rho)^{-1}h_1 + \frac{1}{2}h_0'\boldsymbol{\Sigma}(\rho)^{-1}h_0.$$

By Lemma 2,

$$\frac{L_n(\tau_{n,1})}{L_n(\tau_{n,0})} = \frac{L_n(\tau_{n,1})}{L_n(0)} \frac{L_n(0)}{L_n(\tau_{n,0})} \xrightarrow{p} 1$$

and from $\rho_n \to \rho$, $\sqrt{\mathbf{x}_n'\mathbf{x}_n}(\hat{\beta}_{\text{long},n}, \hat{\beta}_{\text{short},n})' \Rightarrow \hat{\mathbf{b}}^o$ and $h_{j,n} \to h_j$ for $j = 0, 1$. Thus, under H_0, $\ell_n(\mathbf{T}_n) \Rightarrow \ell_0(\hat{\mathbf{b}}^o)$. This straightforwardly extends more generally to $\{\ell_n(\mathbf{T}_n)\}_{(b,a)\in H} \Rightarrow \{\ell_0(\hat{\mathbf{b}}^o)\}_{(b,a)\in H}$ for any finite $H \subset \mathbb{R}^2$. Thus, by Definition 9.1 in van der Vaart (1991), under the assumptions of the lemma, the sequence of experiments of observing $\mathbf{T}_n$ with local parameter space $(b, a) \in \mathbb{R}^2$ converges to the experiment of observing $\hat{\mathbf{b}}^o$. The first claim now follows from Theorem 15.1 in van der Vaart (1991).

For the second claim, for given (b, a), suppose $E_{\theta_n}[\varphi_n(\bar{\kappa}_n, \mathbf{Y}_n)] \to E_{b,a}[\phi(\hat{\mathbf{b}}^o)]$ along $\theta_n = \theta_{n,1}$ with $\tau_n = \tau_{n,1} = o(n^{-1/4})$. Let $\tau_{n,2} = o(n^{-1/4})$ be another sequence, and denote $\theta_{n,2}$ the corresponding sequence of θ. Suppose $E_{\theta_{n,2}}[\varphi_n(\bar{\kappa}_n, \mathbf{Y}_n)]$ does not converge to $E_{b,a}[\phi(\hat{\mathbf{b}}^o)]$. By Prohorov's theorem (see, for instance, Theorem 2.4 in van der Vaart (1998)) and $0 \le \varphi_n(\bar{\kappa}_n, \mathbf{Y}_n) \le 1$, there exists a subsequence of n such that $\varphi_n(\bar{\kappa}_n, \mathbf{Y}_n)$ converges in distribution along that subsequence. Furthermore, by Lemma 2, the likelihood ratio statistic between the corresponding sequences $\theta_{n,1}$ and $\theta_{n,2}$ with identical values of (b, a) converges in probability to one, and this convergence automatically holds jointly with $\varphi_n(\bar{\kappa}_n, \mathbf{Y}_n)$ along the subsequence. Thus, a trivial application of LeCam's third lemma (see, for instance, Theorem 6.6 in van der Vaart (1998)) yields that under $\theta_{n,2}$, $\varphi_n(\bar{\kappa}_n, \mathbf{Y}_n)$ converges to the same weak limit as under $\theta_{n,1}$ under the subsequence. But convergence in distribution implies convergence of expectations given that $0 \le \varphi_n \le 1$, and the desired contradiction follows.

A.4 *Proof of Corollary 1*

We use the same notation as the proof of Lemma 1, and momentarily drop the index n to ease notation. By assumption, the distribution of $\psi(\mathbf{Y})$ only depends on $\boldsymbol{\xi}$ through (β, Δ, τ), so $\psi(\mathbf{Y})$ has the same distribution under $\boldsymbol{\xi}$ and $\boldsymbol{\xi}_0$. By sufficiency, the conditional distribution of $\psi(\mathbf{Y})$ given $\hat{\boldsymbol{\zeta}}$ under $\boldsymbol{\xi}_0$ does not depend on $\boldsymbol{\xi}_0$, so by inverting the probability integral transform conditional on $\hat{\boldsymbol{\zeta}}$, we can write $\psi(\mathbf{Y}) \sim \psi_S(\hat{\boldsymbol{\zeta}}, U_S)$ for some function $\psi_S : \mathbb{R}^{p+2} \mapsto \mathbb{R}$ with $U_S \sim [0, 1]$ independent of $\hat{\boldsymbol{\zeta}}$.

Let $\hat{\mathbf{O}}$ be a random rotation matrix drawn from the Haar measure H_{p-1}, independent of $(\hat{\boldsymbol{\zeta}}, U_S)$. Since by assumption, the distribution of $\psi(\mathbf{Y})$ does not depend on $\boldsymbol{\omega}$, we have

$$\begin{aligned}
\psi_S(\hat{\boldsymbol{\zeta}}, U_S) &\sim \psi_S\big((\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}}, (\tau\hat{\mathbf{O}}\boldsymbol{\iota} + \mathbf{e})'\big), U_S\big) \\
&\sim \psi_S\big((\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}}, (\tau\boldsymbol{\iota} + \mathbf{e})'\hat{\mathbf{O}}'\big), U_S\big) \\
&\sim \psi_S\big((\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}}, \hat{\tau}\boldsymbol{\iota}'\hat{\mathbf{O}}'\big), U_S\big),
\end{aligned}$$

where the second equality follows from the spherical symmetry of the distribution of $\mathbf{e}$. Since $(\hat{\beta}_{\text{long}}, \hat{\beta}_{\text{short}}, \hat{\tau}\boldsymbol{\iota}'\hat{\mathbf{O}}')$ is a one-to-one function of $\mathbf{T}$, so we can hence write $\psi(\mathbf{Y}) \sim \tilde{\psi}(\mathbf{T}, U_S)$ for some function $\tilde{\psi} : \mathbb{R}^4 \mapsto \mathbb{R}$.

Now reintroducing n subscripts, consider the sequence of experiments of observing $(\mathbf{T}_n', U_S)$. Recalling that U_S is independent of $\mathbf{T}_n$, these experiments converge to the

limit experiment of observing $(\hat{\mathbf{b}}^{o\prime}, U_S) \in \mathbb{R}^3$ under the assumptions of the corollary, by the same arguments employed in the proof of Theorem 2. Thus, by the asymptotic representation theorem (Theorem 9.3 in van der Vaart (1998)), there exists a function $\tilde{\psi}^o : \mathbb{R}^4 \mapsto \mathbb{R} \cup \{+\infty\}$ and uniform random variable U independent of $(\hat{\mathbf{b}}^{o\prime}, U_S)$ such that the limit distribution of $\tilde{\psi}_n(\mathbf{T}_n, U_S)$ can be written as $\tilde{\psi}^o(\hat{\mathbf{b}}^o, U_S, U)$, for all (a, b). Since the distribution of $\tilde{\psi}^o(\hat{\mathbf{b}}^o, U_S, U)$ conditional on $\hat{\mathbf{b}}^o$ does not depend (a, b), there exists a function $\psi^o : \mathbb{R}^3 \mapsto \mathbb{R} \cup \{+\infty\}$ so that $\tilde{\psi}^o(\hat{\mathbf{b}}^o, U_S, U) \sim \psi^o(\hat{\mathbf{b}}^o, U)$ for all (a, b), as was to be shown.

A.5 *Proof of Lemma 3*

We will make use of the following lemma.

LEMMA 5. *Let* $\mathbf{H}_n$ *and* $\hat{\mathbf{H}}_n$ *be the Choleski decompositions of* $\boldsymbol{\Omega}_n = \mathbf{H}_n\mathbf{H}_n'$ *and* $\hat{\boldsymbol{\Omega}}_n = \hat{\mathbf{H}}_n\hat{\mathbf{H}}_n'$*, respectively, and let* $\mathbf{w}_n = (\hat{\beta}_{\text{long},n} - \beta_n, \hat{\beta}_{\text{short},n} - \beta_n - \Delta_n)'$*. Then under* (15) *and* $\boldsymbol{\Omega}_n^{-1}\hat{\boldsymbol{\Omega}}_n \xrightarrow{p} \mathbf{I}_2$*:*

(a) $\hat{\mathbf{H}}_n^{-1}\mathbf{H}_n \xrightarrow{p} \mathbf{I}_2$

(b) $\hat{\mathbf{H}}_n^{-1}\mathbf{w}_n \Rightarrow \mathcal{N}(\mathbf{0}, \mathbf{I}_2)$.

PROOF. (a) Note that $\hat{\mathbf{H}}_n^{-1}\mathbf{H}_n\mathbf{H}_n'\hat{\mathbf{H}}_n'^{-1}$, by similarity, has the same eigenvalues as $\hat{\mathbf{H}}_n'^{-1}\hat{\mathbf{H}}_n^{-1}\mathbf{H}_n\mathbf{H}_n' = \hat{\boldsymbol{\Omega}}_n^{-1}\boldsymbol{\Omega}_n \xrightarrow{p} \mathbf{I}_2$, so they both converge to one in probability. But $\hat{\mathbf{H}}_n^{-1}\mathbf{H}_n\mathbf{H}_n'\hat{\mathbf{H}}_n'^{-1}$ is symmetric, and all symmetric matrices with eigenvalues converging to one converge to the identity matrix. Thus $\hat{\mathbf{H}}_n^{-1}\mathbf{H}_n\mathbf{H}_n'\hat{\mathbf{H}}_n'^{-1} \xrightarrow{p} \mathbf{I}_2$, and since $\hat{\mathbf{H}}_n^{-1}\mathbf{H}_n$ is lower triangular, this further implies $\hat{\mathbf{H}}_n^{-1}\mathbf{H}_n \xrightarrow{p} \mathbf{I}_2$.

(b) Note that $\mathbf{H}_n$ is related to $\boldsymbol{\Omega}_n^{1/2}$ via $\mathbf{H}_n = \boldsymbol{\Omega}_n^{1/2}\mathbf{O}_n$ for some rotation matrix $\mathbf{O}_n$. Thus, also $\mathbf{H}_n^{-1}\mathbf{w}_n = \mathbf{O}_n'\boldsymbol{\Omega}^{-1/2}\mathbf{w}_n \Rightarrow \mathcal{N}(\mathbf{0}, \mathbf{I}_2)$. (Suppose otherwise. Then, by the Cramér–Wold device, for some 2×1 vector $\boldsymbol{v}$ and $c \in \mathbb{R}$, $\liminf_{n\to\infty} |P(\boldsymbol{v}'\mathbf{O}_n'\boldsymbol{\Omega}^{-1/2}\mathbf{w}_n > c) - P(\mathcal{N}(\mathbf{0}, \boldsymbol{v}'\boldsymbol{v}) > c)| > 0$. Pick a subsequence along which the liminf is attained, and $\mathbf{O}_n$ converges. Then we have a contradiction, because the continuous mapping theorem implies the convergence $P(\boldsymbol{v}'\mathbf{O}_n'\boldsymbol{\Omega}^{-1/2}\mathbf{w}_n > c) - P(\mathcal{N}(\mathbf{0}, \boldsymbol{v}'\boldsymbol{v}) > c) \to 0$ along that subsequence.) Invoking Lemma 5(a), also $\hat{\mathbf{H}}_n^{-1}\mathbf{w}_n = (\hat{\mathbf{H}}_n^{-1}\mathbf{H}_n)\mathbf{H}_n^{-1}\mathbf{w}_n \Rightarrow \mathcal{N}(\mathbf{0}, \mathbf{I}_2)$ by the continuous mapping theorem. □

(a) Write $L(Z_1, Z_2 + g, \chi_1, \chi_2)$ for the expression in equation (18). Reparametrize $\boldsymbol{\chi}$ and g in (18) in terms of $(r, \phi, u) \in [0, \infty) \times [0, \pi/2) \times [0, 1]$ via $\chi_1 = r\cos(\phi)$, $\chi_2 = r\sin(\phi)$ and $u = g/\chi_2$ (with $u = 0$ if $\chi_2 = 0$). By a direct calculation, the limit of $L(Z_1, Z_2 + ur\sin(\phi), r\cos(\phi), r\sin(\phi))$ as $r \to \infty$ exists for almost all Z_1, Z_2 and all $(u, \phi) \in [0, 1] \times [0, \pi/2)$ and is equal to

$$L^\infty(Z_1, Z_2, u, \phi) = \begin{cases} \big(Z_1 - (1+u)\tan\phi\big)^2 & \text{if } Z_1 > (1+u)\tan\phi, \\ \big(Z_1 + (1-u)\tan\phi\big)^2 & \text{if } Z_1 < -(1-u)\tan\phi, \\ 0 & \text{otherwise.} \end{cases}$$

Correspondingly, $\lim_{r\to\infty} \mathrm{cv}((r\cos(\phi), r\sin(\phi)) = \mathrm{cv}^\infty(\phi)$ exists, too, and satisfies $\sup_{0\le u\le 1} P(L^\infty(Z_1, Z_2, u, \phi) \ge \mathrm{cv}^\infty(\phi)) \le \alpha$. (In general, this inequality is not sharp, since the definition of $\mathrm{cv}^\infty(\phi)$ also requires $P(L(Z_1, Z_2 + ur\sin(\phi), r\cos(\phi), r\sin(\phi)) \ge \mathrm{cv}^\infty(\phi)) \le \alpha$ for all finite r.) If $r \to \infty$ and $\phi \to \pi/2$, then the limit still exists and is equal to $L^\infty(Z_1, Z_2, u, \pi/2) = 0$.

Suppose the assertion of the lemma is false. Then there exists a subsequence of n such that along that subsequence,

$$\lim_{n\to\infty} E_{\theta_n}\big[\hat\varphi_{\mathrm{LR},n}(\bar\kappa_n, \mathbf{Y}_n)\big] = \lim \sup_{n\to\infty} E_{\theta_n}\big[\hat\varphi_{\mathrm{LR},n}(\bar\kappa_n, \mathbf{Y}_n)\big] > \alpha.$$

Pick a sub-subsequence, such that with (r_n, ϕ_n, u_n) the parameters computed from $\boldsymbol{\Omega} = \boldsymbol{\Omega}_n$ and $g_n = \sqrt{\Omega_{n,11}}\Delta_n/\sqrt{\Omega_{n,11}\Omega_{n,22} - \Omega_{n,12}^2}$, (r_n, ϕ_n, u_n) converge along that sub-subsequence to some value $(r_0, \phi_0, u_0) \in [0,\infty] \times [0, \pi/2] \times [0, 1]$. Correspondingly, let cv_0 be the limit of $\mathrm{cv}((r_n\cos(\phi_n), r_n\sin(\phi_n))$ along that sub-subsequence (which exists by the above observations also when $r_n \to \infty$, even when $\phi_0 = \pi/2$).

By Lemma 5(a), $(\hat Z_{n,1}, \hat Z_{n,2})' = \hat{\mathbf{H}}_n^{-1}\mathbf{w}_n \Rightarrow (Z_1, Z_2)' \sim \mathcal{N}(\mathbf{0}, \mathbf{I}_2)$ by the continuous mapping theorem. Since

$$\hat{\mathbf{H}}_n^{-1} = \begin{pmatrix} 1/\sqrt{\hat\Omega_{n,11}} & 0 \\ -\dfrac{\hat\Omega_{n,12}}{\sqrt{\hat\Omega_{n,11}}\sqrt{\hat\Omega_{n,11}\hat\Omega_{n,22} - \hat\Omega_{n,12}^2}} & \dfrac{\sqrt{\hat\Omega_{n,11}}}{\sqrt{\hat\Omega_{n,11}\hat\Omega_{n,22} - \hat\Omega_{n,12}^2}} \end{pmatrix}$$

the definitions of $\hat\chi_{1,n} = \hat\chi_1$ and $\hat\chi_{2,n} = \hat\chi_2$ yield

$$\widehat{\mathrm{LR}}_n(\bar\kappa_n) = \min_{|\tilde g|\le\hat\chi_{2,n}} \left\| \begin{pmatrix} \hat Z_{n,1} \\ \hat Z_{n,2} + \hat g_n - \tilde g \end{pmatrix} \right\|^2 - \min_{\tilde h, |\tilde g|\le\hat\chi_{2,n}} \left\| \begin{pmatrix} \hat Z_{n,1} - \tilde h \\ \hat Z_{n,2} + \hat g_n - \tilde g - \hat\chi_{1,n}\tilde h \end{pmatrix} \right\|^2,$$

where $\hat g_n = \sqrt{\hat\Omega_{n,11}}\Delta_n/\sqrt{\hat\Omega_{n,11}\hat\Omega_{n,22} - \hat\Omega_{n,12}^2}$. Let $(\hat r_n, \hat\phi_n, \hat u_n) \in [0,\infty) \times [0, \pi/2) \times [0, 1]$ be such that $\hat\chi_{1,n} = \hat r_n\cos(\hat\phi_n)$, $\hat\chi_{2,n} = \hat r_n\sin(\hat\phi_n)$ and $\hat u_n = \hat g_n/\hat\chi_{2,n}$ (with $\hat u_n = 0$ if $\hat\chi_{2,n} = 0$). Write $\hat{\mathbf{H}}_n^{-1}\mathbf{H}_n \xrightarrow{p} \mathbf{I}_2$ from Lemma 5(b) element-by-element to conclude that $\hat\Omega_{11,n}/\Omega_{11,n} \xrightarrow{p} 1$, $(\hat\Omega_{11,n}\hat\Omega_{22,n} - \hat\Omega_{12,n}^2)/(\Omega_{11,n}\Omega_{22,n} - \Omega_{12,n}^2) \xrightarrow{p} 1$ and $(\hat\Omega_{12,n} - \Omega_{12,n})/(\Omega_{11,n}\Omega_{22,n} - \Omega_{12,n}^2) \xrightarrow{p} 0$. Therefore, also $(\hat r_n - r_n)/\max(r_n, 1) \xrightarrow{p} 0$, $\hat u_n - u_n \xrightarrow{p} 0$ and $\hat\phi_n - \phi_n \xrightarrow{p} 0$. Thus, along the sub-subsequence defined above, by the continuous mapping theorem,

$$\widehat{\mathrm{LR}}_n(\bar\kappa_n) \Rightarrow L_0 = \begin{cases} L\big(Z_1, u_0 r_0\cos(\phi_0) + Z_2, r_0\cos(\phi), r_0\sin(\phi_0)\big) & \text{if } r_0 < \infty, \\ L^\infty(Z_1, Z_2, u_0, \phi_0) & \text{otherwise} \end{cases}$$

and $E_{\theta_n}[\hat\varphi_{\mathrm{LR},n}(\bar\kappa_n, \mathbf{Y}_n)] \to P(L_0 > \mathrm{cv}_0)$. But by the definition of cv_0, $P(L_0 > \mathrm{cv}_0) \le \alpha$, yielding the desired contradiction.

References

Anderson, T. W. and H. Rubin (1949), "Estimators of the parameters of a single equation in a complete set of stochastic equations." *The Annals of Mathematical Statistics*, 21, 570–582. [422]

Armstrong, T. B. and M. Kolesár (2016), "Optimal inference in a class of regression models." arXiv:1511.06028v2. [408, 415]

Armstrong, T. B. and M. Kolesár (2018), "Optimal inference in a class of regression models." *Econometrica*, 86. [408]

Belloni, A., V. Chernozhukov, and C. Hansen (2014), "Inference on treatment effects after selection among high-dimensional controls." *The Review of Economic Studies*, 81 (2), 608–650. [406, 409, 423, 429]

Cattaneo, M. D., M. Jansson, and W. K. Newey (2018a), "Alternative asymptotics and the partially linear model with many regressors." *Econometric Theory*, 34 (2), 277–301. [421]

Cattaneo, M. D., M. Jansson, and W. K. Newey (2018b), "Inference in linear regression models with many covariates and heteroscedasticity." *Journal of the American Statistical Association*, 113 (523), 1350–1361. [421, 424, 426, 427, 432]

Conley, T. G., C. B. Hansen, and P. E. Rossi (2012), "Plausibly exogenous." *Review of Economics and Statistics*, 94 (1), 260–272. [408]

Cox, D. R. and D. V. Hinkley (1974), *Theoretical Statistics*. Chapman&Hall/CRC, New York, NY. [422]

Donoho, D. L. (1994), "Statistical estimation and optimal recovery." *The Annals of Statistics*, 22 (1), 238–270. [416]

Donohue, J. J. and S. D. Levitt (2001), "The impact of legalized abortion on crime." *Quarterly Journal of Economics*, CXVI, 379–420. [426, 429, 430, 433]

Elliott, G., U. K. Müller, and M. W. Watson (2015), "Nearly optimal tests when a nuisance parameter is present under the null hypothesis." *Econometrica*, 83, 771–811. [413, 414]

Fan, J. and R. Li (2001), "Variable selection via nonconcave penalized likelihood and its oracle properties." *Journal of the American Statistical Association*, 96 (456), 1348–1360. [406]

Foote, C. L. and C. F. Goetz (2008), "The impact of legalized abortion on crime: Comment." *The Quarterly Journal of Economics*, 123, 407–423. [429]

Hoerl, A. E. and R. W. Kennard (1970), "Ridge regression: Biased estimation for nonorthogonal problems." *Technometrics*, 12 (1), 55–67. [408]

Imbens, G. W., D. B. Rubin, and B. I. Sacerdote (2001), "Estimating the effect of unearned income on labor earnings, savings, and consumption: Evidence from a survey of lottery players." *American Economic Review*, 91, 778–794. [426, 431, 432]

Imbens, G. W. and D. B. Rubin (2015), *Causal Inference for Statistics, Social, and Biomedical Sciences*. Cambridge University Press, New York, NY. [431]

Imbens, G. W. and J. M. Wooldridge (2009), "Recent developments in the econometrics of program evaluation." *Journal of Economic Literature*, 47, 5–86. [430, 432, 433]

Joyce, T. (2004), "Did legalized abortion lower crime?" *Journal of Human Resources*, 39 (1), 1–28. [430]

Joyce, T. (2009), "A simple test of abortion and crime." *The Review of Economics and Statistics*, 91 (1), 112–123. [430]

Leeb, H. and B. M. Pötscher (2005), "Model selection and inference: Facts and fiction." *Econometric Theory*, 21, 21–59. [406]

Leeb, H. and B. M. Pötscher (2008a), "Can one estimate the unconditional distribution of post-model-selection estimators?" *Econometric Theory*, 24 (2), 338–376. [406]

Leeb, H. and B. M. Pötscher (2008b), "Recent developments in model selection and related areas." *Econometric Theory*, 24 (2), 319–322. [406]

Li, C. (M.) and U. K. Müller (2021), "Supplement to 'Linear regression with many controls of limited explanatory power'." *Quantitative Economics Supplemental Material*, 12, https://doi.org/10.3982/QE1577. [415]

Macchiavello, R. and A. Morjaria (2015), "The value of relationships: Evidence from a supply shock to Kenyan rose exports." *American Economic Review*, 105, 2911–2945. [426, 427, 428, 429, 433]

Mardia, K. V. and P. E. Jupp (2000), *Directional Statistics*. Wiley Series in Probability and Statistics. John Wiley & Sons, Chichester. [436]

Müller, U. K. and A. Norets (2016), "Credibility of confidence sets in nonstandard econometric problems." *Econometrica*, 84, 2183–2213. [414]

Müller, U. K. and Y. Wang (2019), "Nearly weighted risk minimal unbiased estimation." *Journal of Econometrics*, 209, 18–34. [414]

Obenchain, R. L. (1977), "Classical F-tests and confidence regions for ridge regression." *Technometrics*, 19, 429–439. [408]

Pratt, J. W. (1961), "Length of confidence intervals." *Journal of the American Statistical Association*, 56, 549–567. [409]

Tibshirani, R. (1996), "Regression shrinkage and selection via the lasso." *Journal of the Royal Statistical Society. Series B (Methodological)*, 58, 267–288. [406]

van de Geer, S., P. Bühlmann, Y. Ritov, and R. Dezeure (2014), "On asymptotically optimal confidence regions and tests for high-dimensional models." *Annals of Statistics*, 42, 1166–1202. [406]

van der Vaart, A. W. (1991), "An asymptotic representation theorem." *International Statistical Review*, 259, 97–121. [437]

van der Vaart, A. W. (1998), *Asymptotic Statistics*. Cambridge University Press, Cambridge, UK. [409, 436, 437, 438]

White, H. (1980), "A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity." *Econometrica*, 48, 817–830. [421]

Wüthrich, K. and Y. Zhu (2020), "Omitted variable bias of lasso-based inference methods: A finite sample analysis." arXiv:1903.08704. [407]

Zhang, C.-H. and S. S. Zhang (2014), "Confidence intervals for low dimensional parameters in high dimensional linear models." *Journal of the Royal StatisticalSociety: Series B (Statistical Methodology)*, 76, 217–242. [406]

Co-editor Andres Santos handled this manuscript.

Manuscript received 15 March, 2020; final version accepted 19 November, 2020; available online 21 December, 2020.