

Bridging Dense and Sparse Models in High-Dimensional Quantile Regression

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High-Dimensional Quantile Regression

- Research on risk in economics and finance has exploded recently
- Quantile Regression

$$Y_t = q_{Y_t|\mathbf{X}_t}(\tau) + \varepsilon_t, \quad t = 1, \dots, T, \quad \mathbf{X}_t \in \mathbb{R}^p, \quad \tau \in \mathcal{T} \subset (0, 1)$$
$$\tau = \mathbb{P}(\varepsilon_t \leq 0 \mid \mathbf{X}_t)$$

- ▷ Allows a heterogeneous relationship between the target and predictors across the entire target distribution
- ▷ Robust to *outliers and heavy-tailed distributions*
- High-dimensional Quantile Regression
 - ▷ The number of predictors p grows with sample size T , and potentially $p \gg T$.

Existing methods

- **Dense modeling:** All predictors might be important although their individual contribution might be small
 - ▷ Ridge-type: Hard to interpret
 - ▷ Factor: Ignores idiosyncratic signals
- **Sparse modeling:** Selects a small number of relevant predictors: θ_T has only $s_T \ll p$ nonzero entries.
 - ▷ Assume predictors are cross-sectionally weakly correlated
 - ▷ Unstable under strong co-movements among predictors
- **But is the real world purely dense or sparse?**

This Paper

- Bridge sparse and dense models through a *factor-augmented sparse quantile regression* for serially dependent data
 - ▷ The conditional quantile depends densely on factors and sparsely on idiosyncratic components
- Propose a two-step estimation strategy that is easy to implement
- Establish the convergence rate for the coefficient estimator, even under *weak factor signals*
- Demonstrates the method in forecasting housing activity in the U.S. Northeast

Literature Review

1 Sparse quantile regression:

- ▷ Belloni and Chernozhukov, 2011; Tan et al., 2021; L. Wang et al., 2012; Yan et al., 2023; Zheng et al., 2018

2 Factor-augmented sparse regression:

- ▷ Fan et al., 2020; Fan, Lou, et al., 2023; Fan, Masini, et al., 2023; Kneip and Sarda, 2011

3 Weak factors:

- ▷ Bai and Ng, 2023; Onatski, 2012; Uematsu and Yamagata, 2021, 2022; W. Wang and Fan, 2017

4 Quantile regression with generated regressors:

- ▷ Bhattacharya, 2020; L. Chen, Galvao, et al., 2021; X. Chen et al., 2003; Galvao et al., 2020

Model

Model

- We observe $\{(Y_t, \mathbf{X}_t)\}_{t=1}^T$ taking values in $\mathcal{Y} \times \mathcal{X} \subset \mathbb{R} \times \mathbb{R}^p$, satisfying

$$\mathbf{X}_t = \mathbf{B} \mathbf{f}_t + \mathbf{u}_t \quad (1)$$

and $q_{Y_t | \mathcal{I}_t}(\tau) = \mu_0(\tau) + \underbrace{\mathbf{u}'_t \boldsymbol{\theta}_0(\tau)}_{\text{sparse}} + \underbrace{\mathbf{f}'_t \boldsymbol{\gamma}_0(\tau)}_{\text{dense}}, \quad t = 1, \dots, T \quad (2)$

where

- ▷ $\mathbf{f}_t \in \mathbb{R}^r$ are latent common factors, $\mathbf{B} \in \mathbb{R}^{p \times r}$ are factor loadings, $\mathbf{u}_t \in \mathbb{R}^p$ are idiosyncratic components.
- ▷ $\mathcal{I}_t := \sigma(\mathbf{X}_t, \mathbf{f}_t)$, the σ -algebra generated by \mathbf{X}_t and \mathbf{f}_t ,
- ▷ $\boldsymbol{\theta}_0(\tau)$ has only $s_\tau \ll p$ nonzero entries
- ▷ $\boldsymbol{\theta}_0(\tau) \in \mathbb{R}^p$ and $\boldsymbol{\gamma}_0(\tau) \in \mathbb{R}^r$ are **quantile-specific** coefficient vectors

Two Extremes (i)

The model:

$$\mathbf{X}_t = \mathbf{B} \mathbf{f}_t + \mathbf{u}_t$$

and $q_{Y_t|\mathcal{I}_t}(\tau) = \mu_0(\tau) + \underbrace{\mathbf{u}'_t \boldsymbol{\theta}_0(\tau)}_{\text{sparse}} + \underbrace{\mathbf{f}'_t \boldsymbol{\gamma}_0(\tau)}_{\text{dense}}, \quad t = 1, \dots, T$

- $\boldsymbol{\theta}_0(\tau) = \mathbf{0}$: factor only quantile regression

▷ Relying only on \mathbf{f}_t ignores the sparse contribution of \mathbf{u}_t . While factors often capture comovements in \mathbf{X}_t , they rarely explain the full variation in the response Y_t - especially when factor strength is weak (low signal-to-noise).

Two Extremes (ii)

The model:

$$q_{Y_t|\mathcal{I}_t}(\tau) = \mu_0(\tau) + \underbrace{\mathbf{u}'_t \boldsymbol{\theta}_0(\tau)}_{\text{sparse}} + \underbrace{\mathbf{f}'_t \boldsymbol{\gamma}_0(\tau)}_{\text{dense}} \quad (3)$$

By substituting $\mathbf{X}_t = \mathbf{B}\mathbf{f}_t + \mathbf{u}_t$ into (3), we equivalently obtain:

$$q_{Y_t|\mathcal{I}_t}(\tau) = \mu_0(\tau) + \underbrace{\mathbf{X}'_t \boldsymbol{\theta}_0(\tau)}_{\text{sparse}} + \underbrace{\mathbf{f}'_t \varphi_0(\tau)}_{\text{dense}}, \quad \text{where } \varphi_0(\tau) := \boldsymbol{\gamma}_0(\tau) - \mathbf{B}' \boldsymbol{\theta}_0(\tau)$$

- $\varphi_0(\tau) = \mathbf{0}$: sparse high-dimensional quantile regression
 - ▷ \mathbf{f}_t may have additional contributions to the response, beyond the observed predictors \mathbf{X}_t
 - ▷ \mathbf{f}_t can be viewed as unobserved confounding variables (Y. Wang and Shah, 2025)

Estimation

Estimation Overview

A natural formulation for the estimation of $(\mu_0(\tau), \boldsymbol{\theta}_0(\tau), \boldsymbol{\gamma}_0(\tau))'$ is

$$\arg \min_{\mu, \boldsymbol{\theta}, \boldsymbol{\gamma}} \frac{1}{T} \sum_{t=1}^T \rho_\tau(Y_t - \mu_0(\tau) - \mathbf{u}'_t \boldsymbol{\theta}(\tau) - \mathbf{f}'_t \boldsymbol{\gamma}(\tau)) \quad \text{s.t.} \quad \|\boldsymbol{\theta}(\tau)\|_0 \leq s_\tau$$

where

$$\rho_\tau(z) = z(\tau - \mathbf{1}\{z \leq 0\})$$

is the check loss function

- Both \mathbf{f}_t and \mathbf{u}_t are unobserved latent components.
- The objective is nonconvex due to the ℓ_0 -constraint and latent inputs.
 - a two-step plug-in approach

Step 1: Factor Estimation via PCA

Let $\mathbf{X} = (\mathbf{X}_1, \dots, \mathbf{X}_T)' \in \mathbb{R}^{T \times p}$ denote the data matrix constructed from $\{\mathbf{X}_t\}_{t=1}^T$.

- 1 Estimate factor scores and loadings

$$\hat{\mathbf{F}} = \sqrt{T} \cdot \text{First } r \text{ eigenvectors of } \mathbf{X}\mathbf{X}' \in \mathbb{R}^{T \times r}, \quad \hat{\mathbf{B}} = \frac{1}{T} \mathbf{X}' \hat{\mathbf{F}} \in \mathbb{R}^{p \times r}$$

- 2 Estimate idiosyncratic component

$$\hat{\mathbf{u}}_t = \mathbf{X}_t - \hat{\mathbf{B}} \hat{\mathbf{f}}_t, \quad \text{with } \hat{\mathbf{f}}_t \text{ being the } t\text{-th row of } \hat{\mathbf{F}}$$

- The latent factors \mathbf{f}_t are only identified up to a rotation matrix \mathbf{H} : we estimate the space spanned by $\{\mathbf{f}_t\}$, i.e. $\hat{\mathbf{f}}_t \approx \mathbf{H}' \mathbf{f}_t$.
- As a result, only the linear combination $\mathbf{f}_t' \gamma_0(\tau)$ can be recovered.

Step 2: ℓ_1 -Penalized Quantile Regression

Given the estimated components $\hat{\mathbf{u}}_t$ and $\hat{\mathbf{f}}_t$, we estimate $(\mu_0(\tau), \boldsymbol{\theta}_0(\tau), \gamma_0(\tau))'$ by solving:

$$\min_{\mu, \boldsymbol{\theta}, \gamma} \frac{1}{T} \sum_{t=1}^T \rho_\tau \left(Y_t - \mu(\tau) - \hat{\mathbf{u}}_t' \boldsymbol{\theta}(\tau) - \hat{\mathbf{f}}_t' \gamma(\tau) \right) + \lambda \sum_{j=1}^p |\theta_j(\tau)|$$

where $\rho_\tau(z) = z(\tau - \mathbf{1}\{z \leq 0\})$ is the check loss for quantile τ and $\lambda > 0$ is a regularization parameter.

- We penalize only $\boldsymbol{\theta}(\tau)$.
- A plug-in solution to tightest convex relaxation of the combinatorial ℓ_0 -minimization problem

Theory

Theory

- Establish non-asymptotic estimation error bounds under general dependence
- Convergence of

$$\hat{\phi}(\tau) = (\hat{\mu}(\tau), \hat{\theta}(\tau)', \hat{\gamma}(\tau)')' \quad \text{to} \quad \tilde{\phi}(\tau) = (\mu_0(\tau), \theta_0(\tau)', (\mathbf{H}\gamma_0(\tau))')'$$

- **Latent variables:** Estimated variables $\hat{\mathbf{f}}_t$ and $\hat{\mathbf{u}}_t$, introducing rotation and estimation error propagation.
- **Non-smooth Loss:** Quantile loss prevents classical second-order expansion
- **Temporal Dependence:** High-dimensional time series with strong mixing

Assumptions

- Data Generating Process
 - 1 Orthogonality: $\mathbb{E}[f_{jt}] = \mathbb{E}[u_{it}] = \mathbb{E}[f_{jt}u_{it}] = 0$; process $(\mathbf{f}'_t, \mathbf{u}'_t)'$ is stationary.
 - 2 Sub-Gaussian tails: both \mathbf{f}_t and \mathbf{u}_t are sub-Gaussian.
 - 3 α -mixing (r_α): the process $\{(Y_t, \mathbf{f}_t, \mathbf{u}'_t)'\}$ exhibits strong mixing with exponentially decaying coefficients: $\alpha(l) \leq \exp(-C_\alpha l^{r_\alpha})$.
- Factors and Idiosyncratic Components
 - 1 Factor strength (α): eigenvalues of $\mathbf{B}'\mathbf{B}$ diverge at rate $\lambda_i = c_i p^\alpha$, where $\alpha \in (0, 1]$ controls factor signal strength (weak/strong regimes). Loadings are uniformly bounded.
 - 2 Well-conditioned $\Sigma_u = \mathbb{E}(\mathbf{u}_t \mathbf{u}'_t)$: $\|\Sigma_u\|_2 \leq c_{r+1}$.
 - 3 Number of predictors: $p = O(T^{r_p})$ where $r_p < \{r_\alpha \wedge \frac{1}{\frac{r_\alpha+1}{r_\alpha} - \alpha}\}$.

Assumptions

- Quantile Model
 - 1 The error ε_t satisfies the quantile restriction: $\mathbb{P}(\varepsilon_t \leq 0 | \mathcal{I}_t) = \tau$, and has a conditional density $f_{\varepsilon_t | \mathcal{I}_t}(0) \in [f_{\min}, f_{\max}]$ and its derivative $f'_{\varepsilon_t | \mathcal{I}_t}(0) \in [f'_{\min}, f'_{\max}]$
 - 2 Restricted nonlinearity: ensures identifiability through a local curvature condition on the loss function.

Why We Do Not Assume REC on \mathbf{X}_t

What is the Restricted Eigenvalue Condition (REC)?

- REC ensures that \mathbf{X}_t cannot be “nearly collinear”
- Mathematically: there exists a $\kappa > 0$ such that

$$\frac{1}{T} \sum_{t=1}^T (\mathbf{X}'_t \boldsymbol{\delta})^2 \geq \kappa \|\boldsymbol{\delta}\|_2^2, \quad \text{for all sparse } \boldsymbol{\delta}$$

Why REC Fails with \mathbf{X}_t ?

- All regressors share the same common component $\mathbf{f}_t \rightarrow$ near-collinearity of \mathbf{X}_t .
- We avoid REC on \mathbf{X}_t , and instead:
 - ▷ Explicitly isolate $\mathbf{X}_t = \mathbf{B}\mathbf{f}_t + \mathbf{u}_t$ and using $[\mathbf{f}'_t, \mathbf{u}'_t]'$: the space expands
 - ▷ Impose eigenvalue conditions on \mathbf{u}_t only (the sparse part); the penalized block U now satisfies a REC.

Convergence Rate

Under the above assumptions: for each $\tau \in \mathcal{T}$,

$$\|\hat{\phi}(\tau) - \tilde{\phi}(\tau)\|_2 = O_{\mathbb{P}}\left(\frac{\sqrt{1+s_\tau+r}}{\kappa^2} \left[\sqrt{\frac{\log T}{T}} + \frac{(p+\log T)^{(r_\alpha+1)/r_\alpha}}{p^\alpha T} + \frac{1}{p^\alpha} \right]\right).$$

- Strong signals ($\alpha = 1$), i.i.d. ($r_\alpha = \infty$): $\frac{\sqrt{1+s_\tau+r}}{\kappa^2} \left(\sqrt{\frac{\log T}{T}} + \frac{1}{p} \right)$
- Weak signals ($0 < \alpha < 1$): Robust to weak factors with large T

r_α : decay rate of α -mixing coefficient

α : factor strength

Monte Carlo Design

- **High-dimensional predictors:** \mathbf{X}_t follows an *approximate factor model* with $r = 3$ latent factors
- **Factor dynamics:** Latent factors follow a stable VAR(1) with moderate persistence ($\phi_f = 0.5$), normalized so that $\mathbb{E}(\mathbf{f}_t \mathbf{f}'_t) = \mathbf{I}_r$.
- **Factor strength:** Loadings are scaled so that eigenvalues of $\mathbf{B}'\mathbf{B}$ grow as p^α .
 - ▷ *DGP1: Strong factors* ($\alpha = 1$)
 - ▷ *DGP2: Weak factors* ($\alpha = 0.4$)
- **Idiosyncratic component:** \mathbf{u}_t follows a VAR(1) with temporal dependence ($\phi_u = 0.3$) and cross-sectional correlation (Toeplitz covariance).
- **Quantile function:** The conditional median ($\tau = 0.5$) depends on *both* a dense factor channel and a *sparse* idiosyncratic channel ($s = 10$ active predictors).
- **Heavy-tailed errors:** Errors follow a symmetric Student- $t(3)$ distribution

Monte Carlo Performance

- **FA-QR:** $\min_{\mu, \gamma, \theta} \frac{1}{T} \sum_{t=1}^T \rho_{0.5} \left(Y_t - \mu - \hat{\mathbf{f}}_t^\top \gamma - \hat{\mathbf{u}}_t^\top \theta \right) + \lambda \|\theta\|_1.$
- **SO-QR:** $\min_{\mu, \theta} \frac{1}{T} \sum_{t=1}^T \rho_{0.5} (Y_t - \mu - \mathbf{X}_t^\top \theta) + \lambda \|\theta\|_1.$
- **FA-LS:** $\min_{\mu, \gamma, \theta} \frac{1}{T} \sum_{t=1}^T \left(Y_t - \mu - \hat{\mathbf{f}}_t^\top \gamma - \hat{\mathbf{u}}_t^\top \theta \right)^2 + \lambda \|\theta\|_1.$

(A) Estimation error for sparse coefficients $\|\hat{\theta} - \theta_0\|_2 \times 10^2$.

(p, T)	Strong factors ($\alpha = 1$)			Weak factors ($\alpha = 0.4$)		
	FA-QR	SO-QR	FA-LS	FA-QR	SO-QR	FA-LS
(100,100)	0.72	0.94	1.08	0.80	0.85	1.12
(150,100)	0.75	1.10	1.22	0.86	0.93	1.25
(200,100)	0.77	1.28	1.40	0.92	1.01	1.43
(150,150)	0.63	0.86	0.98	0.70	0.74	1.02
(200,150)	0.64	0.98	1.12	0.76	0.82	1.16
(200,200)	0.58	0.82	0.95	0.66	0.70	0.99

Monte Carlo Performance

- **Quantile error:** the mean squared error for the conditional median function,

$$\text{QE} = \frac{1}{T} \sum_{t=1}^T (q_t - \hat{q}_t)^2, \quad q_t := \mathbf{f}_t^\top \boldsymbol{\gamma}_0 + \mathbf{u}_t^\top \boldsymbol{\theta}_0,$$

where \hat{q}_t is the fitted conditional median implied by each method.

(B) QE for the conditional median ($\times 10^2$).

(p, T)	Strong factors ($\alpha = 1$)			Weak factors ($\alpha = 0.4$)		
	FA-QR	SO-QR	FA-LS	FA-QR	SO-QR	FA-LS
(100,100)	4.6	6.1	7.3	5.4	5.8	7.6
(150,100)	4.9	6.9	8.1	5.7	6.2	8.4
(200,100)	5.2	7.8	9.0	6.0	6.6	9.3
(150,150)	3.6	5.1	6.3	4.2	4.5	6.7
(200,150)	3.9	5.7	7.0	4.6	4.9	7.4
(200,200)	3.2	4.8	5.9	3.8	4.0	6.2

Empirical Studies

Prediction of Housing Activity in the U.S. Northeast

- Target variable: HOUSTNE
- The predictor dimension is $p = 128$, corresponding to the number of macroeconomic variables in FRED-MD, covering monthly observations from 1980 to 2012.
- We perform the prediction by using the moving window approach with window size 120 months (i.e. the sample size is $T = 120$)
- We measure the prediction accuracy by using the out-of-sample pinball loss

$$\text{PL}_{\tau,h} = \frac{1}{|\mathcal{T}_h|} \sum_{t \in \mathcal{T}_h} \rho_\tau(Y_{t+h} - \hat{q}_{\tau,h}(t)), \quad \rho_\tau(u) := u\{\tau - \mathbf{1}(u < 0)\},$$

where $\hat{q}_{\tau,h}(t)$ denotes the τ -quantile forecast for y_{t+h} formed at t

Table 1: Out-of-Sample Pinball Loss (HOUSTNE)

Model	Quantile τ						
	0.05	0.10	0.25	0.50	0.75	0.90	0.95
<i>Horizon $h = 6$</i>							
FO-QR	0.77	0.67	0.64	0.54	0.59	0.71	0.86
SO-QR	0.79	0.73	0.67	0.57	0.62	0.74	0.89
FA-QR	0.69	0.64	0.61	0.53	0.57	0.67	0.71

Notes: Entries report the out-of-sample pinball loss (lower is better). Bold numbers indicate the lowest loss for each quantile τ .

Table 2: Sparse predictors for HOUSTNE across quantiles after factor adjustment

Quantile	Variable	Sign	Select. Prob.
$\tau = 0.10$	MORTG (Mortgage cost)	—	0.88
	PERMITNE (Building Permits)	+	0.81
	BAAFFM (Credit Spread)	—	0.74
$\tau = 0.50$	PERMITNE (Building Permits)	+	0.92
	GS10–FEDFUNDS (Term Spread)	+	0.78
	CES2000000008 (Construction Employment)	+	0.67
$\tau = 0.90$	PPICMM (Construction cost)	—	0.75
	MORTG (Mortgage cost)	—	0.69
	PERMITNE (Building Permits)	+	0.65

Notes: Selection probabilities are computed across all windows.

Concluding Remarks

- Existing high-dimensional quantile regression methods often suffer from instability and limited interpretability.
- This paper introduces a new framework that integrates **dense** and **sparse** channels, offering both theoretical and practical advantages:
 - ▷ Consistency under weak factors, provided sufficient T ;
 - ▷ Simple implementation through a two-step procedure: PCA + ℓ_1 -QR.
- Empirical results on forecasting housing activity reveal distinct **heterogeneous patterns across quantiles** that mean-based approaches fail to capture.

Thank you!

Model Comparison I

- A factor-augmented quantile model considered in Ando and Tsay, 2011:

$$\mathbf{X}_t = \mathbf{B} \mathbf{f}_t + \mathbf{u}_t$$

$$\text{and } q_{Y_t|\mathcal{I}_t}(\tau) = \mathbf{W}'_t \boldsymbol{\theta}(\tau) + \mathbf{f}'_t \boldsymbol{\varphi}(\tau)$$

where $\mathbf{W}_t \in \mathbb{R}^d$, and $d \ll T$.

- 1 Low-dimensional setting
- 2 Factor-augmented model in the classical sense

Model Comparison II

- A panel quantile model considered in Ando and Bai, 2020:

$$q_{Y_{i,t}|\mathcal{I}_t}(\tau) = \mathbf{W}'_{i,t} \boldsymbol{\theta}_i(\tau) + \mathbf{b}_i(\tau)' \mathbf{f}_t(\tau)$$

- 1 Panel setting: $i \in [n]$ where n is the number of cross-sectional units
 - 2 The unobservable factor structure in panel data is known as the *interactive fixed effects*
 - 3 Factors are quantile specific
 - 4 If $\mathbf{W}'_{i,t} \boldsymbol{\theta}_i(\tau) = 0$, it reduces to L. Chen, Dolado, et al., 2021's quantile factor model
-
- Belloni et al., 2023 extend this to a high-dimensional setting:

$$q_{Y_{i,t}|\mathcal{I}_t}(\tau) = \mathbf{X}'_{i,t} \boldsymbol{\theta}(\tau) + \mathbf{b}_i(\tau)' \mathbf{f}_t(\tau), \quad \text{s.t.} \quad \|\boldsymbol{\theta}\|_0 \leq s_\tau$$

Choice of \hat{r}

1 Eigenvalue Ratio

$$\hat{r} = \arg \max_{r \leq \mathcal{R}} \frac{\lambda_r(\mathbf{XX}')}{\lambda_{r+1}(\mathbf{XX}')}$$

where $1 \leq \mathcal{R} \leq p$ is a prescribed upper bound for r .

2 Grid search (r, λ)

- ▷ Instead of fixing r for PCA, treat r as a hyperparameter. Jointly select the best pair (r, λ) by minimizing cross-validated quantile loss in the second-stage regression
- ▷ Task-oriented: aligns factor selection with predictive performance.

Proof Sketch: High-Level Structure

Recall that

$$\hat{\phi}(\tau) = (\hat{\mu}(\tau), \hat{\theta}(\tau)', \hat{\gamma}(\tau)')' \quad \text{and} \quad \tilde{\phi}(\tau) = (\mu_0(\tau), \theta_0(\tau)', (\mathbf{H}\gamma_0(\tau))')'$$

$$\hat{\phi}(\tau) = \arg \min_{\phi} \left(\hat{Q}_{\tau}(\phi) + \lambda \|\theta(\tau)\|_1 \right), \quad \text{where} \quad \hat{Q}_{\tau}(\phi) = \frac{1}{T} \sum_{t=1}^T \rho_{\tau} \left(Y_t - \mu - \hat{\mathbf{u}}_t' \theta - \hat{\mathbf{f}}_t' \gamma \right),$$

$$\tilde{\phi}(\tau) = \arg \min_{\phi} Q_{\tau}(\phi), \quad \text{where} \quad Q_{\tau}(\phi) = \mathbb{E} \left(\frac{1}{T} \sum_{t=1}^T \rho_{\tau} \left(Y_t - \mu - \mathbf{u}_t' \theta - \mathbf{f}_t' \mathbf{H}' \mathbf{H} \gamma \right) \right).$$

Key Insight: Error decomposition

$$\hat{\phi}(\tau) - \tilde{\phi}(\tau) = \underbrace{\text{empirical process fluctuation}}_{\text{stochastic}} + \underbrace{\ell_1\text{-penalization error}}_{\text{regularization bias}} + \underbrace{\text{PCA misalignment}}_{\text{regressor estimation error}}$$

Proof Sketch: Technical Core

Restricted Set (Cone): Define

$$\mathcal{A} = \left\{ \delta \in \mathbb{R}^{p+r+1} : \|\delta_{\mathcal{S}_\xi}\|_1 \leq C_0 \|\delta_{\mathcal{S}_\diamond}\|_1 \right\}, \quad \text{where } \mathcal{S}_\diamond = \text{supp}(\tilde{\phi})$$

1 Identification: Population Curvature Bound

- ▷ Use Knight's identity to expand the population quantile loss over \mathcal{A} :

$$Q(\tilde{\phi} + \delta) - Q(\tilde{\phi}) \geq \underbrace{\delta^\top \Sigma \delta}_{\text{quadratic curvature}} - \underbrace{\mathbb{E}[\|\nu_t^\top \delta\|^3]}_{\text{negligible under A.8}}$$

2 Cone Condition: Estimator Structure

- ▷ Using the subgradient conditions from ℓ_1 -penalized optimization to show that estimation error $\hat{\delta} = \hat{\phi} - \tilde{\phi}$ lies in $\mathcal{A} \rightarrow$ **upper bound** on $\|\hat{\delta}\|_2^2$
- ▷ Optimality of $\hat{\phi}$ in empirical loss $\hat{Q}(\cdot) \rightarrow$ **lower bound** on $\|\hat{\delta}\|_2$

Proof Sketch: Technical Core

Restricted Set (Cone): Define

$$\mathcal{A} = \left\{ \boldsymbol{\delta} \in \mathbb{R}^{p+r} : \|\boldsymbol{\delta}_{\mathcal{S}_\diamond^c}\|_1 \leq C_0 \|\boldsymbol{\delta}_{\mathcal{S}_\diamond}\|_1 \right\}, \quad \text{where } \mathcal{S}_\diamond = \text{supp}(\tilde{\phi})$$

3 Empirical Process Bound

- ▷ Control the stochastic deviation between empirical and population losses for all $\boldsymbol{\delta} \in \mathcal{A}$:

$$\sup_{\boldsymbol{\delta} \in \mathcal{A}} \left| \widehat{Q}(\tilde{\phi} + \boldsymbol{\delta}) - \widehat{Q}(\tilde{\phi}) - \left(Q(\tilde{\phi} + \boldsymbol{\delta}) - Q(\tilde{\phi}) \right) \right| \lesssim \text{Error}_{\text{EP}}$$

Where Error_{EP} is controlled under mixing and Lipschitz assumptions.

4 Plug-in Error: PCA Factor Estimation

- ▷ Analyze additional error from plug-in estimates:

$$\widehat{\mathbf{f}}_t \approx \mathbf{H}' \mathbf{f}_t, \quad \widehat{\mathbf{u}}_t \approx \mathbf{u}_t$$

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