Least Favorable Direction Test for Multivariate Analysis of Variance in High Dimension

Beijing Institute of Technology

Supplementary Material

This supplement contains the proofs of Propositions and Theorems given in the main text.

S1 Technical lemmas

Lemma 1. *Suppose* $\mathbf{A}$ *is a* $p \times r$ *matrix with rank* r *and* $\mathbf{B}$ *is a* $p \times p$ *non-zero positive semi-definite matrix. Denote by* $\mathbf{A} = \mathbf{U}_{\mathbf{A}}\mathbf{D}_{\mathbf{A}}\mathbf{V}_{\mathbf{A}}^\top$ *the singular value decomposition of* $\mathbf{A}$*, where* $\mathbf{U}_{\mathbf{A}}$ *and* $\mathbf{V}_{\mathbf{A}}$ *are* $p \times r$ *and* $r \times r$ *column orthogonal matrices, respectively, and* $\mathbf{D}_{\mathbf{A}}$ *is a* $r \times r$ *diagonal matrix. Let* $\mathbf{P}_{\mathbf{A}} = \mathbf{U}_{\mathbf{A}}\mathbf{U}_{\mathbf{A}}^\top$ *be the projection matrix onto the column space of* $\mathbf{A}$*. Then*

$$\max_{a^\top a=1, a^\top \mathbf{A}\mathbf{A}^\top a=0} a^\top \mathbf{B} a = \lambda_1\big(\mathbf{B}(\mathbf{I}_p - \mathbf{P}_{\mathbf{A}})\big).$$

Proof. It can be seen that $a^\top \mathbf{A}\mathbf{A}^\top a = 0$ if and only if $a = (\mathbf{I}_p - \mathbf{P}_{\mathbf{A}})a$.

Then

$$\max_{a^\top a=1, a^\top \mathbf{A}\mathbf{A}^\top a=0} a^\top \mathbf{B} a = \max_{a^\top a=1, \mathbf{P_A} a=0} a^\top (\mathbf{I}_p - \mathbf{P_A})\mathbf{B}(\mathbf{I}_p - \mathbf{P_A})a, \tag{S1.1}$$

which is obviously no greater than $\lambda_1\big((\mathbf{I}-\mathbf{P_A})\mathbf{B}(\mathbf{I}-\mathbf{P_A})\big)$. To prove that they are equal, without loss of generality, we can assume $\lambda_1\big((\mathbf{I}-\mathbf{P_A})\mathbf{B}(\mathbf{I}-\mathbf{P_A})\big) > 0$. Let α_1 be one eigenvector corresponding to the largest eigenvalue of $(\mathbf{I}-\mathbf{P_A})\mathbf{B}(\mathbf{I}-\mathbf{P_A})$. Since $(\mathbf{I}-\mathbf{P_A})\mathbf{B}(\mathbf{I}-\mathbf{P_A})\mathbf{P_A} = (\mathbf{I}-\mathbf{P_A})\mathbf{B}(\mathbf{P_A}-\mathbf{P_A}) = \mathbf{O}_{p\times p}$ and $\mathbf{P_A}$ is symmetric, the rows of $\mathbf{P_A}$ are eigenvetors of $(\mathbf{I}-\mathbf{P_A})\mathbf{B}(\mathbf{I}-\mathbf{P_A})$ corresponding to eigenvalue 0. It follows that $\mathbf{P_A}\alpha_1 = 0$. Therefore, α_1 satisfies the constraint of (S1.1) and thus (S1.1) is no less than $\lambda_1\big((\mathbf{I}-\mathbf{P_A})\mathbf{B}(\mathbf{I}-\mathbf{P_A})\big)$. The conclusion now follows by noting that $\lambda_1\big((\mathbf{I}-\mathbf{P_A})\mathbf{B}(\mathbf{I}-\mathbf{P_A})\big) = \lambda_1\big(\mathbf{B}(\mathbf{I}-\mathbf{P_A})\big)$.

□

Lemma 2. *Let $\xi_{n,i}$, $i=1,\ldots,n$, $n=1,2,\ldots$, be iid s-dimensional random vectors with mean zero, covariance matrix $\mathbf{M}$ and finite fourth moment. For $n=1,2,\ldots$, let $\{a_{n,i}\}_{i=1}^n$ be real random variables which are independent of $\{\xi_{n,i}\}_{i=1}^n$ and satisfy*

$$\frac{\max_{1\le i\le n} a_{n,i}^2}{\sum_{i=1}^n a_{n,i}^2} \xrightarrow{P} 0. \tag{S1.2}$$

Then

$$\Big(\sum_{i=1}^n a_{n,i}^2\Big)^{-1/2} \sum_{i=1}^n a_{n,i}\xi_{n,i} \xrightarrow{\mathcal{L}} \mathcal{N}_s(\mathbf{0}_s, \mathbf{M}).$$

Proof. First we observe that if $\{a_{n,i}\}_{i=1}^n$ are fixed numbers satisfying (S1.2), then Lyapunov central limit theorem and continuity theorem imply that for any $t \in \mathbb{R}^s$,

$$\mathrm{E}\left[\exp\left((\sum_{i=1}^n a_{n,i}^2)^{-1/2}\sum_{i=1}^n a_{n,i} i t^\top \xi_{n,i}\right)\right] \to \exp\left(-\frac{1}{2}t^\top \mathbf{M} t\right).$$

We only need to prove that for every subsequence of $\{n\}$, there is a further subsequence along which the conclusion holds. Let $\{m(n)\}$ be a subsequence of $\{n\}$. We can find a further subsequence of $\{m(n)\}$ along which (S1.2) holds almost surely. Then along this subsequence, our previous argument implies that for any $t \in \mathbb{R}^s$,

$$\mathrm{E}\left[\exp\left((\sum_{i=1}^n a_{n,i}^2)^{-1/2}\sum_{i=1}^n a_{n,i} i t^\top \xi_{n,i}\right)\Bigg| a_{n,1},\ldots,a_{n,n}\right] \to \exp\left(-\frac{1}{2}t^\top \mathbf{M} t\right)$$

almost surely. Then by dominated convergence theorem, we have

$$\mathrm{E}\left[\exp\left((\sum_{i=1}^n a_{n,i}^2)^{-1/2}\sum_{i=1}^n a_{n,i} i t^\top \xi_{n,i}\right)\right] \to \exp\left(-\frac{1}{2}t^\top \mathbf{M} t\right)$$

along this further subsequence. This implies the conclusion holds along this further subsequence, which completes the proof.

$\square$

Lemma 3 (Weyl's inequality)**.** *Let* $\mathbf{A}$ *and* $\mathbf{B}$ *be two symmetric* $n \times n$ *ma-*

trices. If $r+s-1 \leq i \leq j+k-n$*, we have*

$$\lambda_j(\mathbf{A}) + \lambda_k(\mathbf{B}) \leq \lambda_i(\mathbf{A}+\mathbf{B}) \leq \lambda_r(\mathbf{A}) + \lambda_s(\mathbf{B}).$$

See, for example, Horn and Johnson (2012) Theorem 4.3.1.

Lemma 4 (von Neumann's trace theorem)**.** *Let* $\mathbf{A}$ *and* $\mathbf{B}$ *be two* $m \times n$ *matrices. Let* $\sigma_1(\mathbf{A}) \geq \ldots \geq \sigma_q(\mathbf{A})$ *and* $\sigma_1(\mathbf{B}) \geq \cdots \geq \sigma_q(\mathbf{B})$ *denote the non-increasingly ordered singular values of* $\mathbf{A}$ *and* $\mathbf{B}$*, respectively. Then*

$$\operatorname{tr}(\mathbf{A}\mathbf{B}^\top) \leq \sum_{i=1}^{\min(m,n)} \sigma_i(\mathbf{A})\sigma_i(\mathbf{B}).$$

See, for example, Horn and Johnson (2012) Theorem 7.4.1.1.

Lemma 5. *Let* $\{Z_i\}_{i=1}^n$ *be iid* m*-dimensional random vectors with common distribution* $\mathcal{N}_m(\mathbf{0}_m, \mathbf{I}_m)$*. Then for any* n*-dimensional vector* $\omega = (\omega_1, \ldots, \omega_n)^\top$*, we have*

$$\left\| \sum_{i=1}^n \omega_i (Z_i Z_i^\top - \mathbf{I}_m) \right\| = O_P(|\omega|_2 \sqrt{m} + |\omega|_\infty m),$$

where $|\omega|_2 = \sqrt{\sum_{i=1}^n \omega_i^2}$ *and* $|\omega|_\infty = \max_{1 \leq i \leq n} |\omega_i|$*.*

Remark 1. Our proof implies that the conclusion is still valid if ω is random and is independent of $\{Z_i\}_{i=1}^n$.

Proof. Our proof is adapted from the proof of Theorem 5.39 in Vershynin (2010). By Lemma 5.2 and Lemma 5.4 of Vershynin (2010), there exists a set $\mathcal{C} \subset \{x \in \mathbb{R}^m : |x|_2 = 1\}$ satisfying $\mathrm{Card}(\mathcal{C}) \leq 9^m$ such that for any $m \times m$ symmetric matrix $\mathbf{A}$,

$$\|A\| \leq 2 \max_{x \in \mathcal{C}} \left| x^\top \mathbf{A} x \right|. \tag{S1.3}$$

Then for $t > 4$,

$$\begin{aligned}
&\Pr\left(\left\| \sum_{i=1}^n \omega_i (Z_i Z_i^\top - \mathbf{I}_m) \right\| > t(|\omega|_2 \sqrt{m} + |\omega|_\infty m) \right) \\
\leq &\Pr\left(2 \max_{x \in \mathcal{C}} \left| \sum_{i=1}^n \omega_i (x^\top Z_i Z_i^\top x - 1) \right| > t(|\omega|_2 \sqrt{m} + |\omega|_\infty m) \right) \\
\leq &\sum_{x \in \mathcal{C}} \Pr\left(\left| \sum_{i=1}^n \omega_i (x^\top Z_i Z_i^\top x - 1) \right| > 2|\omega|_2 \sqrt{\frac{mt}{4}} + 2|\omega|_\infty \frac{mt}{4} \right) \\
\leq &2 \cdot 9^m \exp\left(-\frac{mt}{4} \right) = 2 \exp\left((2\log 3 - t/4) m \right),
\end{aligned}$$

where the first inequality follows from (S1.3), the second inequality follows from the union bound and the third inequality follows Lemma 1 of Laurent and Massart (2000). The upper bound $2\exp\left((2\log 3 - t/4)m\right)$ can be arbitrarily small as long as t is large enough. This completes the proof. □

S2 Proofs of Propositions 1-4

Proof of Proposition 1. We only need to deal with the matrix $n^{-1}\mathbf{Z}^\top \mathbf{\Lambda} \mathbf{Z}$ since it shares the same non-zero eigenvalues as $\hat{\mathbf{\Sigma}}$. Write

$$\begin{aligned}
n^{-1}\mathbf{Z}^\top \mathbf{\Lambda} \mathbf{Z} =& n^{-1}\mathbf{Z}_1^\top \mathbf{\Lambda}_1 \mathbf{Z}_1 + n^{-1}\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 \\
=& n^{-1}\mathbf{Z}_1^\top \mathbf{\Lambda}_1 \mathbf{Z}_1 + n^{-1}\mathrm{tr}(\mathbf{\Lambda}_2)\mathbf{I}_n + n^{-1}\left(\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 - \mathrm{tr}(\mathbf{\Lambda}_2)\mathbf{I}_n \right).
\end{aligned}$$

Then Weyl's inequality implies that for $i = 1, \ldots, r$,

$$
\begin{aligned}
&\left|\lambda_i\left(n^{-1}\mathbf{Z}^\top\mathbf{\Lambda}\mathbf{Z}\right) - \lambda_i(n^{-1}\mathbf{Z}_1^\top\mathbf{\Lambda}_1\mathbf{Z}_1) - n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)\right| \\
\leq & n^{-1}\left\|\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2 - \operatorname{tr}(\mathbf{\Lambda}_2)\mathbf{I}_n\right\|.
\end{aligned}
\tag{S2.1}
$$

Using Weyl's inequality, we can derive the following lower bound for $\lambda_i(\mathbf{Z}_1^\top\mathbf{\Lambda}_1\mathbf{Z}_1)$, $i = 1, \ldots, r$.

$$
\begin{aligned}
\lambda_i(\mathbf{Z}_1^\top\mathbf{\Lambda}_1\mathbf{Z}_1) \geq & \lambda_i(\mathbf{Z}_1^\top \operatorname{diag}(\boldsymbol{\lambda}_i\mathbf{I}_i, \mathbf{O}_{(r-i)\times(r-i)})\mathbf{Z}_1) \\
= & \lambda_i\Big(\boldsymbol{\lambda}_i\mathbf{Z}_1^\top\mathbf{Z}_1 - \boldsymbol{\lambda}_i\mathbf{Z}_1^\top \operatorname{diag}(\mathbf{O}_{i\times i}, \mathbf{I}_{r-i})\mathbf{Z}_1\Big) \\
\geq & \lambda_r\Big(\boldsymbol{\lambda}_i\mathbf{Z}_1^\top\mathbf{Z}_1\Big) + \lambda_{n+i-r}\Big(- \boldsymbol{\lambda}_i\mathbf{Z}_1^\top \operatorname{diag}(\mathbf{O}_{i\times i}, \mathbf{I}_{r-i})\mathbf{Z}_1\Big) \\
= & \boldsymbol{\lambda}_i\lambda_r(\mathbf{Z}_1\mathbf{Z}_1^\top).
\end{aligned}
$$

Similarly, we can derive the following upper bound for $\lambda_i(\mathbf{Z}_1^\top\mathbf{\Lambda}_1\mathbf{Z}_1)$, $i = 1, \ldots, r$.

$$
\begin{aligned}
& \lambda_i(\mathbf{Z}_1^\top\mathbf{\Lambda}_1\mathbf{Z}_1) \\
= & \lambda_i\Big(\mathbf{Z}_1^\top \operatorname{diag}(\boldsymbol{\lambda}_1, \ldots, \boldsymbol{\lambda}_{i-1}, \mathbf{O}_{(r-i+1)\times(r-i+1)})\mathbf{Z}_1 \\
& \quad + \mathbf{Z}_1^\top \operatorname{diag}(\mathbf{O}_{(i-1)\times(i-1)}, \boldsymbol{\lambda}_i, \ldots, \boldsymbol{\lambda}_r)\mathbf{Z}_1\Big) \\
\leq & \lambda_i\Big(\mathbf{Z}_1^\top \operatorname{diag}(\boldsymbol{\lambda}_1, \ldots, \boldsymbol{\lambda}_{i-1}, \mathbf{O}_{(r-i+1)\times(r-i+1)})\mathbf{Z}_1\Big) \\
& \quad + \lambda_1\Big(\mathbf{Z}_1^\top \operatorname{diag}(\mathbf{O}_{(i-1)\times(i-1)}, \boldsymbol{\lambda}_i, \ldots, \boldsymbol{\lambda}_r)\mathbf{Z}_1\Big) \\
\leq & \lambda_1(\mathbf{Z}_1^\top \operatorname{diag}(\mathbf{O}_{(i-1)\times(i-1)}, \boldsymbol{\lambda}_i\mathbf{I}_{r-i+1})\mathbf{Z}_1) \\
\leq & \boldsymbol{\lambda}_i\lambda_1(\mathbf{Z}_1\mathbf{Z}_1^\top).
\end{aligned}
$$

The above lower bound and upper bound imply

$$\begin{aligned}
&\left|\lambda_i(n^{-1}\mathbf{Z}_1^\top \mathbf{\Lambda}_1 \mathbf{Z}_1) - \boldsymbol{\lambda}_i\right| \\
\leq& \boldsymbol{\lambda}_i \max\left(|\lambda_1(n^{-1}\mathbf{Z}_1\mathbf{Z}_1^\top) - 1|, |\lambda_r(n^{-1}\mathbf{Z}_1\mathbf{Z}_1^\top) - 1|\right) \qquad \text{(S2.2)} \\
=& \boldsymbol{\lambda}_i \|n^{-1}\mathbf{Z}_1\mathbf{Z}_1^\top - \mathbf{I}_r\|.
\end{aligned}$$

Combining the bounds (S2.1) and (S2.2) gives that for $i = 1, \ldots, r$,

$$\begin{aligned}
&\left|\lambda_i\left(n^{-1}\mathbf{Z}^\top \mathbf{\Lambda}\mathbf{Z}\right) - \boldsymbol{\lambda}_i - n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)\right| \\
\leq& n^{-1}\left\|\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 - \operatorname{tr}(\mathbf{\Lambda}_2)\mathbf{I}_n\right\| + \boldsymbol{\lambda}_i \|n^{-1}\mathbf{Z}_1\mathbf{Z}_1^\top - \mathbf{I}_r\|.
\end{aligned}$$

From Lemma 5, we have

$$\|n^{-1}\mathbf{Z}_1\mathbf{Z}_1^\top - \mathbf{I}_r\| = O_P\left(\sqrt{\frac{r}{n}}\right), \qquad \text{(S2.3)}$$

$$n^{-1}\left\|\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 - \operatorname{tr}(\mathbf{\Lambda}_2)\mathbf{I}_n\right\| = O_P\left(\sqrt{\frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{n}} + \boldsymbol{\lambda}_{r+1}\right). \qquad \text{(S2.4)}$$

This proves the first statement.

Next we prove the second statement. Note that

$$\begin{aligned}
\sum_{i=r+1}^n \lambda_i(\hat{\mathbf{\Sigma}}) =& \sum_{i=r+1}^n \lambda_i(n^{-1}\ \mathbf{Z}^\top \mathbf{\Lambda}\mathbf{Z}) \\
=& \operatorname{tr}(n^{-1}\mathbf{Z}^\top \mathbf{\Lambda}\mathbf{Z}) - \sum_{i=1}^r \lambda_i(n^{-1}\ \mathbf{Z}^\top \mathbf{\Lambda}\mathbf{Z}) \\
=& \operatorname{tr}(n^{-1}\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2) - \frac{r}{n}\operatorname{tr}(\mathbf{\Lambda}_2) \\
&- \left(\sum_{i=1}^r \lambda_i(n^{-1}\ \mathbf{Z}^\top \mathbf{\Lambda}\mathbf{Z}) - \operatorname{tr}(n^{-1}\mathbf{Z}_1^\top \mathbf{\Lambda}_1 \mathbf{Z}_1) - \frac{r}{n}\operatorname{tr}(\mathbf{\Lambda}_2)\right).
\end{aligned}$$

It follows from inequalities (S2.1) and (S2.4) that

$$\begin{aligned}&\left|\sum_{i=1}^{r}\lambda_i(n^{-1}\ \mathbf{Z}^\top\boldsymbol{\Lambda}\mathbf{Z})-\mathrm{tr}(n^{-1}\mathbf{Z}_1^\top\boldsymbol{\Lambda}_1\mathbf{Z}_1)-\frac{r}{n}\,\mathrm{tr}(\boldsymbol{\Lambda}_2)\right|\\ \leq&\frac{r}{n}\left\|\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2-\mathrm{tr}(\boldsymbol{\Lambda}_2)\mathbf{I}_n\right\|=O_P\left(r\sqrt{\frac{\mathrm{tr}(\boldsymbol{\Lambda}_2^2)}{n}}+r\boldsymbol{\lambda}_{r+1}\right).\end{aligned}$$

Thus,

$$\sum_{i=r+1}^{n}\lambda_i(\hat{\boldsymbol{\Sigma}})=\mathrm{tr}(n^{-1}\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2)-\frac{r}{n}\,\mathrm{tr}(\boldsymbol{\Lambda}_2)+O_P\left(r\sqrt{\frac{\mathrm{tr}(\boldsymbol{\Lambda}_2^2)}{n}}+r\boldsymbol{\lambda}_{r+1}\right).$$

It is straightforward to show that

$$\mathrm{E}\,\mathrm{tr}(n^{-1}\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2)=\mathrm{tr}(\boldsymbol{\Lambda}_2),\quad \mathrm{Var}\left(\mathrm{tr}(n^{-1}\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2)\right)=\frac{2}{n}\,\mathrm{tr}(\boldsymbol{\Lambda}_2^2).$$

Hence

$$\begin{aligned}&\sum_{i=r+1}^{n}\lambda_i(\hat{\boldsymbol{\Sigma}})\\ =&\mathrm{tr}(\boldsymbol{\Lambda}_2)+O_P\left(\sqrt{\frac{\mathrm{tr}(\boldsymbol{\Lambda}_2^2)}{n}}\right)-\frac{r}{n}\,\mathrm{tr}(\boldsymbol{\Lambda}_2)+O_P\left(r\sqrt{\frac{\mathrm{tr}(\boldsymbol{\Lambda}_2^2)}{n}}+r\boldsymbol{\lambda}_{r+1}\right)\\ =&\mathrm{tr}(\boldsymbol{\Lambda}_2)-\frac{r}{n}\,\mathrm{tr}(\boldsymbol{\Lambda}_2)+O_P\left(r\sqrt{\frac{\mathrm{tr}(\boldsymbol{\Lambda}_2^2)}{n}}+r\boldsymbol{\lambda}_{r+1}\right).\end{aligned}$$

This completes the proof of the second statement. □

Proof of Proposition 2. The first two statements are direct consequences of Proposition 1 and the condition $r=o(n)$. Next we prove the third statement. We have $\widehat{\mathrm{tr}(\boldsymbol{\Lambda}_2^2)}=n^{-2}\sum_{i=r+1}^{n}\lambda_i^2(\mathbf{Y}^\top\mathbf{Y}-\widehat{\mathrm{tr}(\boldsymbol{\Lambda}_2)}\mathbf{I}_n)$. Note that Weyl's inequality implies that for $i=r+1,\ldots,n$,

$$\lambda_i(\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2-\widehat{\mathrm{tr}(\boldsymbol{\Lambda}_2)}\mathbf{I}_n)\leq\lambda_i(\mathbf{Y}^\top\mathbf{Y}-\widehat{\mathrm{tr}(\boldsymbol{\Lambda}_2)}\mathbf{I}_n)\leq\lambda_{i-r}(\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2-\widehat{\mathrm{tr}(\boldsymbol{\Lambda}_2)}\mathbf{I}_n).$$

Define

$$\mathcal{C}_1 = \left\{i : 1 \leq i \leq n,\, \lambda_i \left(\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n\right) > 0\right\},$$
$$\mathcal{C}_2 = \left\{i : r+1 \leq i \leq n,\, \lambda_{i-r} \left(\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n\right) \leq 0\right\}.$$

It can be seen that $\mathcal{C}_1 \cap \mathcal{C}_2 = \emptyset$ and $\mathrm{Card}(\mathcal{C}_1 \cup \mathcal{C}_2) \geq n - r$. For $i \geq r+1$ and $i \in \mathcal{C}_1$,

$$\lambda_i^2(\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n) \leq \lambda_i^2(\mathbf{Y}^\top \mathbf{Y} - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n) \leq \lambda_{i-r}^2(\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n);$$

for $i \in \mathcal{C}_2$,

$$\lambda_{i-r}^2(\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n) \leq \lambda_i^2(\mathbf{Y}^\top \mathbf{Y} - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n) \leq \lambda_i^2(\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n);$$

for $i \geq r+1$ and $i \notin \mathcal{C}_1 \cup \mathcal{C}_2$,

$$\begin{aligned}
&\lambda_i^2(\mathbf{Y}^\top \mathbf{Y} - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n) \\
\leq &\max\left(\lambda_{i-r}^2(\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n), \lambda_i^2(\mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n)\right).
\end{aligned}$$

Therefore,

$$
\begin{aligned}
&\left|\sum_{i=r+1}^{n} \lambda_i^2 \left(\mathbf{Y}^\top\mathbf{Y} - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n\right) - \operatorname{tr}(\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2 - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n)^2\right| \\
\leq & \left|\sum_{i>r,\, i\in\mathcal{C}_1} \lambda_i^2 \left(\mathbf{Y}^\top\mathbf{Y} - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n\right) - \sum_{i\in\mathcal{C}_1} \lambda_i^2 \left(\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2 - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n\right)\right| \\
& + \left|\sum_{i>r,\, i\in\mathcal{C}_2} \lambda_i^2 \left(\mathbf{Y}^\top\mathbf{Y} - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n\right) - \sum_{i\notin\mathcal{C}_1} \lambda_i^2 \left(\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2 - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n\right)\right| \\
& + \left|\sum_{i>r,\, i\notin\mathcal{C}_1\cup\mathcal{C}_2} \lambda_i^2 \left(\mathbf{Y}^\top\mathbf{Y} - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n\right)\right| \\
\leq & 3r\|\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2 - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n\|^2 \\
\leq & 3r\left(\|\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2 - \operatorname{tr}(\mathbf{\Lambda}_2)\mathbf{I}_n\| + \left|\operatorname{tr}(\mathbf{\Lambda}_2) - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\right|\right)^2 \\
= & O_P\left(rn\operatorname{tr}(\mathbf{\Lambda}_2^2) + rn^2\boldsymbol{\lambda}_{r+1}^2\right).
\end{aligned}
\tag{S2.5}
$$

where the last equality follows from (S2.4) and the second statement of the proposition.

Now we deal with $\operatorname{tr}(\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2 - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n)^2$. Let $Z_{2,i}$ be the ith column of $\mathbf{Z}_2$, $i = 1, \ldots, n$. Then

$$
\operatorname{tr}(\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2 - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n)^2 = \sum_{i=1}^{n}(Z_{2,i}^\top\mathbf{\Lambda}_2 Z_{2,i} - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)})^2 + 2\sum_{1\leq i<j\leq n}(Z_{2,i}^\top\mathbf{\Lambda}_2 Z_{2,j})^2.
$$

For the first term, we have

$$
\sum_{i=1}^{n}(Z_{2,i}^\top\mathbf{\Lambda}_2 Z_{2,i} - \widehat{\operatorname{tr}(\mathbf{\Lambda}_2)})^2 \leq 2\sum_{i=1}^{n}(Z_{2,i}^\top\mathbf{\Lambda}_2 Z_{2,i} - \operatorname{tr}(\mathbf{\Lambda}_2))^2 + 2n(\widehat{\operatorname{tr}(\mathbf{\Lambda}_2)} - \operatorname{tr}(\mathbf{\Lambda}_2))^2.
$$

Then it follows from the second statement of the proposition and the fact

$\mathrm{E}\sum_{i=1}^{n}(Z_{2,i}^{\top}\mathbf{\Lambda}_2 Z_{2,i} - \mathrm{tr}(\mathbf{\Lambda}_2))^2 = 2n\,\mathrm{tr}(\mathbf{\Lambda}_2^2)$ that

$$\sum_{i=1}^{n}(Z_{2,i}^{\top}\mathbf{\Lambda}_2 Z_{2,i} - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)})^2 = O_P\left((n+r^2)\,\mathrm{tr}(\mathbf{\Lambda}_2^2) + r^2 n \boldsymbol{\lambda}_{r+1}^2\right). \tag{S2.6}$$

For the second term, it is straightforward to show that $\mathrm{E}\,2\sum_{1\le i<j\le n}(Z_{2,i}^{\top}\mathbf{\Lambda}_2 Z_{2,j})^2 = n(n-1)\,\mathrm{tr}(\mathbf{\Lambda}_2^2)$. Furthermore, Chen et al. (2010), Proposition A.2 implies that

$$\begin{aligned}
\mathrm{Var}\left(2\sum_{1\le i<j\le n}(Z_{2,i}^{\top}\mathbf{\Lambda}_2 Z_{2,j})^2\right) =& O\left(n^2\,\mathrm{tr}^2(\mathbf{\Lambda}_2^2) + n^3\,\mathrm{tr}(\mathbf{\Lambda}_2^4)\right) \\
=& O\left(n^2\,\mathrm{tr}^2(\mathbf{\Lambda}_2^2) + n\,\mathrm{tr}(\mathbf{\Lambda}_2^2) n^2 \boldsymbol{\lambda}_{r+1}^2\right) \\
=& O\left(n^2\,\mathrm{tr}^2(\mathbf{\Lambda}_2^2) + n^4 \boldsymbol{\lambda}_{r+1}^4\right).
\end{aligned}$$

Thus,

$$2\sum_{1\le i<j\le n}(Z_{2,i}^{\top}\mathbf{\Lambda}_2 Z_{2,j})^2 = n^2\,\mathrm{tr}(\mathbf{\Lambda}_2^2) + O_P\left(n\,\mathrm{tr}(\mathbf{\Lambda}_2^2) + n^2\boldsymbol{\lambda}_{r+1}^2\right).$$

Combining the last display and (S2.6) yields

$$\mathrm{tr}(\mathbf{Z}_2^{\top}\mathbf{\Lambda}_2\mathbf{Z}_2 - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n)^2 = n^2\,\mathrm{tr}(\mathbf{\Lambda}_2^2) + O_P\left((n+r^2)\,\mathrm{tr}(\mathbf{\Lambda}_2^2) + (n+r^2)n\boldsymbol{\lambda}_{r+1}^2\right).$$

Combine the last display and (S2.5), we have

$$\sum_{i=r+1}^{n}\lambda_i^2\left(\mathbf{Y}^{\top}\mathbf{Y} - \widehat{\mathrm{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_n\right) = O_P\left(rn\,\mathrm{tr}(\mathbf{\Lambda}_2^2) + rn^2\boldsymbol{\lambda}_{r+1}^2\right).$$

This completes the proof.

□

Proposition 6. *Suppose that* $r = o(n)$ *and* $r\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\boldsymbol{\Lambda}_2) \to 0$. *Then*

$$\|\mathbf{P}_{\mathbf{Y},1} - \mathbf{P}^*_{\mathbf{Y},1}\| = O_P\left(\frac{\boldsymbol{\lambda}_{r+1} + n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2)}{\boldsymbol{\lambda}_r + n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2)}\right),$$

where

$$\mathbf{P}^*_{\mathbf{Y},1} = \mathbf{U}\begin{pmatrix}\mathbf{I}_r \\ \mathbf{Q}\end{pmatrix}\left(\mathbf{I}_r + \mathbf{Q}^\top\mathbf{Q}\right)^{-1}\begin{pmatrix}\mathbf{I}_r & \mathbf{Q}^\top\end{pmatrix}\mathbf{U}^\top.$$

Proof. The following intermediate matrix

$$\begin{aligned}\hat{\boldsymbol{\Sigma}}_0 =& n^{-1}\mathbf{U}_1\boldsymbol{\Lambda}_1^{1/2}\mathbf{Z}_1\mathbf{Z}_1^\top\boldsymbol{\Lambda}_1^{1/2}\mathbf{U}_1^\top + n^{-1}\mathbf{U}_1\boldsymbol{\Lambda}_1^{1/2}\mathbf{Z}_1\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top \\ &+ n^{-1}\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{Z}_1^\top\boldsymbol{\Lambda}_1^{1/2}\mathbf{U}_1^\top + n^{-1}\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top\end{aligned}$$

plays a key role in the proof. It can be seen that

$$\hat{\boldsymbol{\Sigma}}_0 = n^{-1}\mathbf{U}\begin{pmatrix}\mathbf{I}_r \\ \mathbf{Q}\end{pmatrix}\boldsymbol{\Lambda}_1^{1/2}\mathbf{Z}_1\mathbf{Z}_1^\top\boldsymbol{\Lambda}_1^{1/2}\begin{pmatrix}\mathbf{I}_r & \mathbf{Q}^\top\end{pmatrix}\mathbf{U}^\top.$$

Consequently, $\hat{\boldsymbol{\Sigma}}_0$ is a positive semi-definite matrix with rank r, and $\mathbf{P}^*_{\mathbf{Y},1}$ is the projection matrix onto the rank r principal subspace of $\hat{\boldsymbol{\Sigma}}_0$.

From Cai et al. (2015), Proposition 1, we have

$$\|\mathbf{P}_{\mathbf{Y},1} - \mathbf{P}^*_{\mathbf{Y},1}\| \leq \frac{2\|\hat{\boldsymbol{\Sigma}} - \hat{\boldsymbol{\Sigma}}_0\|}{\lambda_r(\hat{\boldsymbol{\Sigma}}_0)}. \tag{S2.7}$$

We have the following upper bound for $\|\hat{\boldsymbol{\Sigma}} - \hat{\boldsymbol{\Sigma}}_0\|$.

$$
\begin{aligned}
&\|\hat{\boldsymbol{\Sigma}} - \hat{\boldsymbol{\Sigma}}_0\| \\
=&n^{-1}\left\|\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top - \mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top\right\| \\
=&n^{-1}\left\|\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2(\mathbf{I}_n - \mathbf{V}_{\mathbf{Z}_1}\mathbf{V}_{\mathbf{Z}_1}^\top)\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\right\| \\
\leq&n^{-1}\left\|\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\right\| \qquad\qquad (S2.8)\\
\leq&n^{-1}\left\|\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2 - \operatorname{tr}(\boldsymbol{\Lambda}_2)\mathbf{I}_n\right\| + n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2) \\
=&O_P\left(\sqrt{\frac{\operatorname{tr}\left(\boldsymbol{\Lambda}_2^2\right)}{n}} + \boldsymbol{\lambda}_{r+1} + n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2)\right) \\
=&O_P\left(\boldsymbol{\lambda}_{r+1} + n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2)\right),
\end{aligned}
$$

where the second last equality follows from (S2.4) and the last equality follows from

$$
\sqrt{\frac{\operatorname{tr}\left(\boldsymbol{\Lambda}_2^2\right)}{n}} \leq \sqrt{\frac{\boldsymbol{\lambda}_{r+1}\operatorname{tr}\left(\boldsymbol{\Lambda}_2\right)}{n}} \leq \frac{1}{2}\left(\boldsymbol{\lambda}_{r+1} + n^{-1}\operatorname{tr}\left(\boldsymbol{\Lambda}_2\right)\right).
$$

Now we deal with $\lambda_r(\hat{\boldsymbol{\Sigma}}_0)$. We have

$$
\begin{aligned}
\lambda_r(\hat{\boldsymbol{\Sigma}}_0) =&\lambda_r\left(n^{-1}(\mathbf{Z}_1\mathbf{Z}_1^\top)^{1/2}\boldsymbol{\Lambda}_1^{1/2}(\mathbf{I}_r + \mathbf{Q}^\top\mathbf{Q})\boldsymbol{\Lambda}_1^{1/2}(\mathbf{Z}_1\mathbf{Z}_1^\top)^{1/2}\right) \\
=&\lambda_r\left(n^{-1}(\mathbf{Z}_1\mathbf{Z}_1^\top)^{1/2}\boldsymbol{\Lambda}_1(\mathbf{Z}_1\mathbf{Z}_1^\top)^{1/2} + n^{-1}\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\right).
\end{aligned}
$$

It can be seen that $\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}$ is a $(p-r)\times r$ random matrix with iid $\mathcal{N}(0,1)$

entries. Then Lemma 5 implies that

$$
\begin{aligned}
&\left\|n^{-1}\mathbf{V}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 \mathbf{V}_{\mathbf{Z}_1} - n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)\mathbf{I}_r\right\| \\
=&O_P\left(n^{-1}\sqrt{r\operatorname{tr}\left(\mathbf{\Lambda}_2^2\right)} + rn^{-1}\boldsymbol{\lambda}_{r+1}\right) \\
=&O_P\left(n^{-1}\sqrt{r\boldsymbol{\lambda}_{r+1}\operatorname{tr}\left(\mathbf{\Lambda}_2\right)} + rn^{-1}\boldsymbol{\lambda}_{r+1}\right) \\
=&o_P\left(n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)\right),
\end{aligned}
\tag{S2.9}
$$

where the last equality follows from the condition $r\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\mathbf{\Lambda}_2) \to 0$. Then it follows from Weyl's inequality that

$$
\begin{aligned}
&\left|\lambda_r(\hat{\mathbf{\Sigma}}_0) - \lambda_r\left(n^{-1}(\mathbf{Z}_1\mathbf{Z}_1^\top)^{1/2}\mathbf{\Lambda}_1(\mathbf{Z}_1\mathbf{Z}_1^\top)^{1/2} + n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)\mathbf{I}_r\right)\right| \\
\le&\left\|n^{-1}\mathbf{V}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 \mathbf{V}_{\mathbf{Z}_1} - n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)\mathbf{I}_r\right\| \\
=&o_P\left(n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)\right).
\end{aligned}
$$

On the other hand, (S2.2) and (S2.3) imply that

$$
\begin{aligned}
&\lambda_r\left(n^{-1}(\mathbf{Z}_1\mathbf{Z}_1^\top)^{1/2}\mathbf{\Lambda}_1(\mathbf{Z}_1\mathbf{Z}_1^\top)^{1/2} + n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)\mathbf{I}_r\right) \\
=&\lambda_r\left(n^{-1}\mathbf{Z}_1^\top\mathbf{\Lambda}_1\mathbf{Z}_1\right) + n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2) \\
=&\boldsymbol{\lambda}_r + o_P(\boldsymbol{\lambda}_r) + n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2).
\end{aligned}
$$

Hence we have

$$
\lambda_r(\hat{\mathbf{\Sigma}}_0) = (1 + o_P(1))(\boldsymbol{\lambda}_r + n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)). \tag{S2.10}
$$

Then the conclusion follows from (S2.7), (S2.8) and (S2.10). □

Proof of Proposition 3. Note that

$$
\left\|\mathbf{P}_{\mathbf{Y},1} - \mathbf{P}_{\mathbf{Y},1}^\dagger\right\| \le \left\|\mathbf{P}_{\mathbf{Y},1} - \mathbf{P}_{\mathbf{Y},1}^*\right\| + \left\|\mathbf{P}_{\mathbf{Y},1}^* - \mathbf{P}_{\mathbf{Y},1}^\dagger\right\|.
$$

Under the condition $\mathrm{tr}(\mathbf{\Lambda}_2)/(n\boldsymbol{\lambda}_r) \to 0$, Proposition 6 implies that

$$\left\|\mathbf{P}_{\mathbf{Y},1} - \mathbf{P}^*_{\mathbf{Y},1}\right\| = O_P\left(\frac{\boldsymbol{\lambda}_{r+1}}{\boldsymbol{\lambda}_r} + \frac{\mathrm{tr}(\mathbf{\Lambda}_2)}{n\boldsymbol{\lambda}_r}\right).$$

So we only need to deal with $\|\mathbf{P}^*_{\mathbf{Y},1} - \mathbf{P}^\dagger_{\mathbf{Y},1}\|$. We have

$$\begin{aligned}
&\left\|\mathbf{P}^*_{\mathbf{Y},1} - \mathbf{P}^\dagger_{\mathbf{Y},1}\right\| \\
\leq&\left\|\mathbf{P}^*_{\mathbf{Y},1} - \mathbf{U}\begin{pmatrix}\mathbf{I}_r\\ \mathbf{Q}\end{pmatrix}\begin{pmatrix}\mathbf{I}_r & \mathbf{Q}^\top\end{pmatrix}\mathbf{U}^\top\right\| + \left\|\mathbf{U}\begin{pmatrix}\mathbf{I}_r\\ \mathbf{Q}\end{pmatrix}\begin{pmatrix}\mathbf{I}_r & \mathbf{Q}^\top\end{pmatrix}\mathbf{U}^\top - \mathbf{P}^\dagger_{\mathbf{Y},1}\right\| \\
=&\left\|\begin{pmatrix}\mathbf{I}_r\\ \mathbf{Q}\end{pmatrix}\left(\left(\mathbf{I}_r + \mathbf{Q}^\top\mathbf{Q}\right)^{-1} - \mathbf{I}_r\right)\begin{pmatrix}\mathbf{I}_r & \mathbf{Q}^\top\end{pmatrix}\right\| + \left\|\mathbf{U}_2\mathbf{Q}\mathbf{Q}^\top\mathbf{U}_2^\top\right\| \\
=&\left\|\left(\left(\mathbf{I}_r + \mathbf{Q}^\top\mathbf{Q}\right)^{-1} - \mathbf{I}_r\right)\left(\mathbf{I}_r + \mathbf{Q}^\top\mathbf{Q}\right)\right\| + \left\|\mathbf{U}_2\mathbf{Q}\mathbf{Q}^\top\mathbf{U}_2^\top\right\| \\
=&2\left\|\mathbf{Q}^\top\mathbf{Q}\right\|.
\end{aligned}$$

Note that

$$\begin{aligned}
\|\mathbf{Q}^\top\mathbf{Q}\| =& \left\|\mathbf{\Lambda}_1^{-1/2}(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1/2}\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1/2}\mathbf{\Lambda}_1^{-1/2}\right\| \\
\leq&\boldsymbol{\lambda}_r^{-1}\left\|(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1}\right\|\left\|\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\right\| \qquad \text{(S2.11)} \\
=&O_P\left(\frac{\mathrm{tr}(\mathbf{\Lambda}_2)}{n\boldsymbol{\lambda}_r}\right),
\end{aligned}$$

where the second last equality follows from the fact $\|(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1}\| = \lambda_r(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1}$, (S2.3), (S2.9) and Weyl's inequality. Therefore, we have

$$\left\|\mathbf{P}^*_{\mathbf{Y},1} - \mathbf{P}^\dagger_{\mathbf{Y},1}\right\| = O_P\left(\frac{\mathrm{tr}(\mathbf{\Lambda}_2)}{n\boldsymbol{\lambda}_r}\right).$$

This completes the proof.

□

Proposition 7. *Suppose that* $r = o(n)$ *and* $n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\boldsymbol{\Lambda}_2) \to 0$. *Then*

$$\left\|\mathbf{P}_{\mathbf{Y},2} - \mathbf{P}^*_{\mathbf{Y},2}\right\| = O_P\left(\min\left(\sqrt{\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}}, 1\right)\right).$$

where $\mathbf{P}^*_{\mathbf{Y},2} = \mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\left(\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\right)^{-1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top$.

Proof. We only need to prove that for any subsequence of $\{n\}$, there is a further subsequence along which the conclusion holds. Thus, without loss of generality, we assume $\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1/(n\boldsymbol{\lambda}_r^2) \to c \in [0, +\infty]$. Since $\mathbf{P}_{\mathbf{Y},2}$ and $\mathbf{P}^*_{\mathbf{Y},2}$ are both projection matrices, we have $\left\|\mathbf{P}_{\mathbf{Y},2} - \mathbf{P}^*_{\mathbf{Y},2}\right\| \le 2$. Therefore, the conclusion holds if $c > 0$. In the rest of the proof, we assume $c = 0$, that is $\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1/(n\boldsymbol{\lambda}_r^2) \to 0$.

Note that $\mathbf{U}_{\mathbf{Y},2}$ is in fact the leading $n-r$ eigenvectors of $(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1})\hat{\boldsymbol{\Sigma}}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1})$. Under the condition $n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\boldsymbol{\Lambda}_2) \to 0$, Proposition 3 implies that

$$\left\|\mathbf{P}_{\mathbf{Y},1} - \mathbf{P}^\dagger_{\mathbf{Y},1}\right\| = O_P\left(\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)}{n\boldsymbol{\lambda}_r}\right).$$

It can be seen that

$$\begin{aligned}
&\left\|(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1})\hat{\boldsymbol{\Sigma}}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}) - (\mathbf{I}_p - \mathbf{P}^\dagger_{\mathbf{Y},1})\hat{\boldsymbol{\Sigma}}(\mathbf{I}_p - \mathbf{P}^\dagger_{\mathbf{Y},1})\right\| \\
\le &\left\|(\mathbf{P}^\dagger_{\mathbf{Y},1} - \mathbf{P}_{\mathbf{Y},1})\hat{\boldsymbol{\Sigma}}(\mathbf{P}^\dagger_{\mathbf{Y},1} - \mathbf{P}_{\mathbf{Y},1})\right\| + 2\left\|(\mathbf{P}^\dagger_{\mathbf{Y},1} - \mathbf{P}_{\mathbf{Y},1})\hat{\boldsymbol{\Sigma}}(\mathbf{I}_p - \mathbf{P}^\dagger_{\mathbf{Y},1})\right\|.
\end{aligned}$$

Under the condition $n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\boldsymbol{\Lambda}_2)\to 0$, Proposition 1 implies that

$$
\begin{aligned}
\|\hat{\boldsymbol{\Sigma}}\| =&\boldsymbol{\lambda}_1\left(1+\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)}{n\boldsymbol{\lambda}_1}+O_P\left(\sqrt{\frac{r}{n}}+\sqrt{\frac{\boldsymbol{\lambda}_{r+1}}{\boldsymbol{\lambda}_1}\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)}{n\boldsymbol{\lambda}_1}}+\frac{\boldsymbol{\lambda}_{r+1}}{\boldsymbol{\lambda}_1}\right)\right)\\
=&\boldsymbol{\lambda}_1(1+o_P(1)).
\end{aligned}
$$

Then

$$
\begin{aligned}
\left\|(\mathbf{P}^\dagger_{\mathbf{Y},1}-\mathbf{P}_{\mathbf{Y},1})\hat{\boldsymbol{\Sigma}}(\mathbf{P}^\dagger_{\mathbf{Y},1}-\mathbf{P}_{\mathbf{Y},1})\right\| \le&\|\hat{\boldsymbol{\Sigma}}\|\left\|\mathbf{P}^\dagger_{\mathbf{Y},1}-\mathbf{P}_{\mathbf{Y},1}\right\|^2\\
=&O_P\left(\frac{\operatorname{tr}^2(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1}{n^2\boldsymbol{\lambda}_r^2}\right).
\end{aligned}
\tag{S2.12}
$$

On the other hand, we have

$$
\begin{aligned}
&\left\|(\mathbf{P}^\dagger_{\mathbf{Y},1}-\mathbf{P}_{\mathbf{Y},1})\hat{\boldsymbol{\Sigma}}(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\right\|\\
\le&\left\|\mathbf{P}^\dagger_{\mathbf{Y},1}-\mathbf{P}_{\mathbf{Y},1}\right\|\left\|n^{-1}\mathbf{U}\boldsymbol{\Lambda}^{1/2}\mathbf{Z}\right\|\left\|\mathbf{Z}^\top\boldsymbol{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\right\|\\
=&n^{-1/2}\left\|\mathbf{P}^\dagger_{\mathbf{Y},1}-\mathbf{P}_{\mathbf{Y},1}\right\|\left\|\hat{\boldsymbol{\Sigma}}\right\|^{1/2}\left\|\mathbf{Z}^\top\boldsymbol{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\right\|\\
=&O_P\left(\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1^{1/2}}{n^{3/2}\boldsymbol{\lambda}_r}\right)\left\|\mathbf{Z}^\top\boldsymbol{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\right\|.
\end{aligned}
$$

It is straightforward to show that

$$
\begin{aligned}
&\mathbf{Z}^\top\boldsymbol{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\\
=&\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top-\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\mathbf{Z}_1^\top(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1}\boldsymbol{\Lambda}_1^{-1/2}\mathbf{U}_1^\top.
\end{aligned}
\tag{S2.13}
$$

Then

$$
\begin{aligned}
&\left\|\mathbf{Z}^\top\boldsymbol{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\right\|\\
\le&\left\|\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\right\|^{1/2}+\boldsymbol{\lambda}_r^{-1/2}\left\|\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\right\|\left\|(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1}\right\|^{1/2}.
\end{aligned}
$$

It follows from (S2.4) and the condition $n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\boldsymbol{\Lambda}_2)\to 0$ that

$$
\|\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\| = (1+o_P(1))\operatorname{tr}(\boldsymbol{\Lambda}_2). \tag{S2.14}
$$

Consequently,

$$\begin{aligned}\left\|\mathbf{Z}^\top\mathbf{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\right\| =&O_P\left(\mathrm{tr}^{1/2}(\mathbf{\Lambda}_2)\right)+O_P\left(\frac{\mathrm{tr}(\mathbf{\Lambda}_2)}{\sqrt{n\boldsymbol{\lambda}_r}}\right)\\ =&O_P\left(\mathrm{tr}^{1/2}(\mathbf{\Lambda}_2)\right).\end{aligned}$$

Thus,

$$\left\|(\mathbf{P}^\dagger_{\mathbf{Y},1}-\mathbf{P}_{\mathbf{Y},1})\hat{\mathbf{\Sigma}}(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\right\|=O_P\left(\frac{\mathrm{tr}^{3/2}(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1^{1/2}}{n^{3/2}\boldsymbol{\lambda}_r}\right). \tag{S2.15}$$

Combine (S2.12) and (S2.15), we obtain

$$\begin{aligned}&\left\|(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1})\hat{\mathbf{\Sigma}}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1})-(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\hat{\mathbf{\Sigma}}(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\right\|\\ =&O_P\left(\frac{\mathrm{tr}^2(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1}{n^2\boldsymbol{\lambda}_r^2}+\frac{\mathrm{tr}^{3/2}(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1^{1/2}}{n^{3/2}\boldsymbol{\lambda}_r}\right).\end{aligned}$$

Now we deal with $(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\hat{\mathbf{\Sigma}}(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})$. In view of (S2.13), we have

$$\begin{aligned}&(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\hat{\mathbf{\Sigma}}(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\\ =&n^{-1}\mathbf{U}_2\mathbf{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2^{1/2}\mathbf{U}_2^\top-n^{-1}\mathbf{U}_2\mathbf{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2^{1/2}\mathbf{Q}\mathbf{U}_1^\top\\ &-n^{-1}\mathbf{U}_1\mathbf{Q}^\top\mathbf{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2^{1/2}\mathbf{U}_2^\top+n^{-1}\mathbf{U}_1\mathbf{Q}^\top\mathbf{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{Z}_2^\top\mathbf{\Lambda}_2^{1/2}\mathbf{Q}\mathbf{U}_1^\top.\end{aligned}$$

Then

$$\begin{aligned}&\left\|(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})\hat{\mathbf{\Sigma}}(\mathbf{I}_p-\mathbf{P}^\dagger_{\mathbf{Y},1})-n^{-1}\mathbf{U}_2\mathbf{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2^{1/2}\mathbf{U}_2^\top\right\|\\ \le&n^{-1}\left\|\mathbf{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2^{1/2}\mathbf{Q}\right\|+n^{-1}\left\|\mathbf{Q}^\top\mathbf{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{Z}_2^\top\mathbf{\Lambda}_2^{1/2}\mathbf{Q}\right\|\\ \le&n^{-1}\|\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\|\|\mathbf{Q}^\top\mathbf{Q}\|^{1/2}+n^{-1}\|\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\|\|\mathbf{Q}^\top\mathbf{Q}\|\\ =&O_P\left(\frac{\mathrm{tr}^{3/2}(\mathbf{\Lambda}_2)}{n^{3/2}\boldsymbol{\lambda}_r^{1/2}}\right),\end{aligned}$$

where the last equality follows from (S2.11) and (S2.14).

Combine the above bounds, we obtain

$$\begin{aligned}&\left\|(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1})\hat{\boldsymbol{\Sigma}}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}) - n^{-1}\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top\right\| \\ =&O_P\left(\frac{\operatorname{tr}^2(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1}{n^2\boldsymbol{\lambda}_r^2} + \frac{\operatorname{tr}^{3/2}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1^{1/2}}{n^{3/2}\boldsymbol{\lambda}_r}\right).\end{aligned} \tag{S2.16}$$

The matrix $n^{-1}\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top$ shares the same non-zero eigenvalues as $n^{-1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}$. Note that $\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}$ is a $p\times(n-r)$ random matrix with iid $\mathcal{N}(0,1)$ entries. Then it follows from Lemma 5 and the condition $n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\boldsymbol{\Lambda}_2)\to 0$ that

$$\begin{aligned}&\left\|n^{-1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1} - n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2)\mathbf{I}_{n-r}\right\| \\ =&O_P\left(n^{-1/2}\sqrt{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)} + \boldsymbol{\lambda}_{r+1}\right) \\ =&O_P\left(n^{-1/2}\sqrt{\boldsymbol{\lambda}_{r+1}\operatorname{tr}(\boldsymbol{\Lambda}_2)} + \boldsymbol{\lambda}_{r+1}\right) \\ =&o_P\left(n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2)\right).\end{aligned} \tag{S2.17}$$

This bound, combined with Weyl's inequality, leads to

$$\lambda_{n-r}\left(n^{-1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\right) = (1+o_P(1))n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_1). \tag{S2.18}$$

It can be seen that the matrix $\mathbf{P}_{\mathbf{Y},2}^*$ is the projection matrix onto the rank $n-r$ principal subspace of $n^{-1}\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top$. Therefore, Cai et al. (2015), Proposition 1 implies that

$$\begin{aligned}
&\left\|\mathbf{P}_{\mathbf{Y},2}-\mathbf{P}^{*}_{\mathbf{Y},2}\right\| \\
\leq&\frac{2\left\|(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1})\hat{\boldsymbol{\Sigma}}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1})-n^{-1}\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top\right\|}{\lambda_{n-r}\left(n^{-1}\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top\right)} \\
=&O_P\left(\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}+\sqrt{\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}}\right) \\
=&O_P\left(\sqrt{\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}}\right),
\end{aligned}$$

where the second last equality follows from (S2.16) and (S2.18). This completes the proof. □

Proof of Proposition 4. By some algebra, it can be seen that

$$\begin{aligned}
\left\|\mathbf{P}^{*}_{\mathbf{Y},2}-\mathbf{P}^{\dagger}_{\mathbf{Y},2}\right\|=&(\operatorname{tr}(\boldsymbol{\Lambda}_2))^{-1}\left\|\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}-\operatorname{tr}(\boldsymbol{\Lambda}_2)\mathbf{I}_{n-r}\right\| \\
=&O_P\left(\frac{\sqrt{n\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}+\frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}\right) \\
=&O_P\left(\sqrt{\frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}}\right),
\end{aligned}$$

where the second last equality follows from (S2.17) and the last equality follows from the fact $\sqrt{n\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}/\operatorname{tr}(\boldsymbol{\Lambda}_2)\leq\sqrt{n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\boldsymbol{\Lambda}_2)}$ and the condition $\sqrt{n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\boldsymbol{\Lambda}_2)}\to 0$. Then the conclusion follows from the last display and Proposition 7.

□

S3 Proofs of Theorems 1 and 2

It can be seen that $\mathbf{XJC}$ is independent of $\mathbf{Y}$. We write $\mathbf{XJC} = \mathbf{\Theta C} + \mathbf{U\Lambda}^{1/2}\mathbf{Z}^{\dagger}$, where $\mathbf{Z}^{\dagger}$ is a $p \times (k-1)$ matrix with iid $\mathcal{N}(0,1)$ entries and is independent of $\mathbf{Z}$. Then

$$\begin{aligned}
&\mathbf{C}^{\top}\mathbf{J}^{\top}\mathbf{X}^{\top}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{XJC} \\
=&\mathbf{Z}^{\dagger\top}\mathbf{\Lambda}^{1/2}\mathbf{U}^{\top}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U\Lambda}^{1/2}\mathbf{Z}^{\dagger} + \mathbf{C}^{\top}\mathbf{\Theta}^{\top}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{\Theta C} \\
&+ \mathbf{C}^{\top}\mathbf{\Theta}^{\top}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U\Lambda}^{1/2}\mathbf{Z}^{\dagger} + \mathbf{Z}^{\dagger\top}\mathbf{\Lambda}^{1/2}\mathbf{U}^{\top}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{\Theta C}.
\end{aligned} \tag{S3.1}$$

It can be seen that the first term of (S3.1) can be written as

$$\mathbf{Z}^{\dagger\top}\mathbf{\Lambda}^{1/2}\mathbf{U}^{\top}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U\Lambda}^{1/2}\mathbf{Z}^{\dagger} = \sum_{i=1}^{p} \lambda_i((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}))\eta_i\eta_i^{\top},$$

where $\eta_1, \ldots, \eta_p$ are independent $\mathcal{N}_{k-1}(\mathbf{0}_{k-1}, \mathbf{I}_{k-1})$ random vectors and are independent of $\mathbf{P}_{\mathbf{Y}}$.

Lemma 6. *Suppose that $n\boldsymbol{\lambda}_1/\operatorname{tr}(\mathbf{\Sigma}) \to 0$. Then*

$$\operatorname{tr}\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) = \operatorname{tr}(\mathbf{\Sigma}) - \frac{n\operatorname{tr}(\mathbf{\Sigma}^2)}{\operatorname{tr}(\mathbf{\Sigma})} + O_P\left(n(\boldsymbol{\lambda}_1 - \boldsymbol{\lambda}_p)\sqrt{\frac{n\boldsymbol{\lambda}_1}{\operatorname{tr}(\mathbf{\Sigma})}}\right),$$

$$\operatorname{tr}\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)^2 = \operatorname{tr}(\mathbf{\Sigma}^2) - \frac{n\operatorname{tr}^2(\mathbf{\Sigma}^2)}{\operatorname{tr}^2(\mathbf{\Sigma})} + O_P(n\boldsymbol{\lambda}_1(\boldsymbol{\lambda}_1 - \boldsymbol{\lambda}_p)).$$

Proof. First we approximate $\mathbf{P}_{\mathbf{Y}}$ by a simple expression. We have

$$\begin{aligned}
\left\|\mathbf{P}_{\mathbf{Y}} - (\operatorname{tr}(\mathbf{\Sigma}))^{-1}\mathbf{YY}^{\top}\right\| =& \left\|\mathbf{Y}(\mathbf{Y}^{\top}\mathbf{Y})^{-1}\mathbf{Y}^{\top} - (\operatorname{tr}(\mathbf{\Sigma}))^{-1}\mathbf{YY}^{\top}\right\| \\
=&(\operatorname{tr}(\mathbf{\Sigma}))^{-1}\left\|\mathbf{Y}^{\top}\mathbf{Y} - \operatorname{tr}(\mathbf{\Sigma})\mathbf{I}_n\right\|.
\end{aligned}$$

Then from Lemma 5, we have

$$
\begin{aligned}
\left\|\mathbf{P}_{\mathbf{Y}}-(\operatorname{tr}(\boldsymbol{\Sigma}))^{-1}\mathbf{Y}\mathbf{Y}^{\top}\right\| =&(\operatorname{tr}(\boldsymbol{\Sigma}))^{-1}\left\|\mathbf{Z}^{\top}\boldsymbol{\Sigma}\mathbf{Z}-\operatorname{tr}(\boldsymbol{\Sigma})\mathbf{I}_n\right\| \\
=&O_P\left(\frac{\sqrt{n\operatorname{tr}(\boldsymbol{\Sigma}^2)}}{\operatorname{tr}(\boldsymbol{\Sigma})}+\frac{n\boldsymbol{\lambda}_1}{\operatorname{tr}(\boldsymbol{\Sigma})}\right) \\
=&O_P\left(\frac{\sqrt{n\boldsymbol{\lambda}_1\operatorname{tr}(\boldsymbol{\Sigma})}}{\operatorname{tr}(\boldsymbol{\Sigma})}+\frac{n\boldsymbol{\lambda}_1}{\operatorname{tr}(\boldsymbol{\Sigma})}\right) \\
=&O_P\left(\sqrt{\frac{n\boldsymbol{\lambda}_1}{\operatorname{tr}(\boldsymbol{\Sigma})}}\right).
\end{aligned}
\tag{S3.2}
$$

Now we deal with $\operatorname{tr}\left((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\right)$. It can be seen that

$$
\begin{aligned}
&\operatorname{tr}\left((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\right) \\
=&\operatorname{tr}(\boldsymbol{\Sigma})-\operatorname{tr}(\boldsymbol{\Sigma}\mathbf{P}_{\mathbf{Y}}) \\
=&\operatorname{tr}(\boldsymbol{\Sigma})-\operatorname{tr}\left(\left(\boldsymbol{\Sigma}-\frac{\operatorname{tr}(\boldsymbol{\Sigma}^2)}{\operatorname{tr}(\boldsymbol{\Sigma})}\mathbf{I}_p\right)\mathbf{P}_{\mathbf{Y}}\right)-\frac{n\operatorname{tr}(\boldsymbol{\Sigma}^2)}{\operatorname{tr}(\boldsymbol{\Sigma})}.
\end{aligned}
\tag{S3.3}
$$

For the second term, we have

$$
\begin{aligned}
&\left|\operatorname{tr}\left(\left(\boldsymbol{\Sigma}-\frac{\operatorname{tr}(\boldsymbol{\Sigma}^2)}{\operatorname{tr}(\boldsymbol{\Sigma})}\mathbf{I}_p\right)\mathbf{P}_{\mathbf{Y}}\right)-(\operatorname{tr}(\boldsymbol{\Sigma}))^{-1}\operatorname{tr}\left(\left(\boldsymbol{\Sigma}-\frac{\operatorname{tr}(\boldsymbol{\Sigma}^2)}{\operatorname{tr}(\boldsymbol{\Sigma})}\mathbf{I}_p\right)\mathbf{Y}\mathbf{Y}^{\top}\right)\right| \\
=&\left|\operatorname{tr}\left(\left(\boldsymbol{\Sigma}-\frac{\operatorname{tr}(\boldsymbol{\Sigma}^2)}{\operatorname{tr}(\boldsymbol{\Sigma})}\mathbf{I}_p\right)\left(\mathbf{P}_{\mathbf{Y}}-(\operatorname{tr}(\boldsymbol{\Sigma}))^{-1}\mathbf{Y}\mathbf{Y}^{\top}\right)\right)\right| \\
\leq&2n\left\|\boldsymbol{\Sigma}-\frac{\operatorname{tr}(\boldsymbol{\Sigma}^2)}{\operatorname{tr}(\boldsymbol{\Sigma})}\mathbf{I}_p\right\|\left\|\mathbf{P}_{\mathbf{Y}}-(\operatorname{tr}(\boldsymbol{\Sigma}))^{-1}\mathbf{Y}\mathbf{Y}^{\top}\right\| \\
=&O_P\left(n(\boldsymbol{\lambda}_1-\boldsymbol{\lambda}_p)\sqrt{\frac{n\boldsymbol{\lambda}_1}{\operatorname{tr}(\boldsymbol{\Sigma})}}\right),
\end{aligned}
$$

where the last inequality follows from von Neumann's trace theorem and the fact $\operatorname{Rank}\left(\mathbf{P}_{\mathbf{Y}}-(\operatorname{tr}(\boldsymbol{\Sigma}))^{-1}\mathbf{Y}\mathbf{Y}^{\top}\right)\leq 2n$, and the last equality follows from (S3.2) and the fact $\operatorname{tr}(\boldsymbol{\Sigma}^2)/\operatorname{tr}(\boldsymbol{\Sigma})\in[\boldsymbol{\lambda}_p,\boldsymbol{\lambda}_1]$. On the other hand, it is straightforward to show that

$$\mathrm{E}\left((\mathrm{tr}(\boldsymbol{\Sigma}))^{-1}\,\mathrm{tr}\left(\left(\boldsymbol{\Sigma}-\frac{\mathrm{tr}(\boldsymbol{\Sigma}^2)}{\mathrm{tr}(\boldsymbol{\Sigma})}\mathbf{I}_p\right)\mathbf{Y}\mathbf{Y}^\top\right)\right)=0,$$

and

$$\begin{aligned}&\mathrm{Var}\left((\mathrm{tr}(\boldsymbol{\Sigma}))^{-1}\,\mathrm{tr}\left(\left(\boldsymbol{\Sigma}-\frac{\mathrm{tr}(\boldsymbol{\Sigma}^2)}{\mathrm{tr}(\boldsymbol{\Sigma})}\mathbf{I}_p\right)\mathbf{Y}\mathbf{Y}^\top\right)\right)\\ =&\frac{2n}{\mathrm{tr}^2(\boldsymbol{\Sigma})}\,\mathrm{tr}\left(\boldsymbol{\Sigma}^2-\frac{\mathrm{tr}(\boldsymbol{\Sigma}^2)}{\mathrm{tr}(\boldsymbol{\Sigma})}\boldsymbol{\Sigma}\right)^2\\ =&\frac{2n}{\mathrm{tr}^2(\boldsymbol{\Sigma})}\sum_{i=1}^p\boldsymbol{\lambda}_i^2\left(\boldsymbol{\lambda}_i-\frac{\mathrm{tr}(\boldsymbol{\Sigma}^2)}{\mathrm{tr}(\boldsymbol{\Sigma})}\right)^2\\ \le&\frac{2n\boldsymbol{\lambda}_1(\boldsymbol{\lambda}_1-\boldsymbol{\lambda}_p)^2}{\mathrm{tr}(\boldsymbol{\Sigma})}.\end{aligned}$$

Thus,

$$\mathrm{tr}\left(\left(\boldsymbol{\Sigma}-\frac{\mathrm{tr}(\boldsymbol{\Sigma}^2)}{\mathrm{tr}(\boldsymbol{\Sigma})}\mathbf{I}_p\right)\mathbf{P}_{\mathbf{Y}}\right)=O_P\left(n(\boldsymbol{\lambda}_1-\boldsymbol{\lambda}_p)\sqrt{\frac{n\boldsymbol{\lambda}_1}{\mathrm{tr}(\boldsymbol{\Sigma})}}\right).$$

Then the first statement follows from the last display and (S3.3).

Next we deal with $\mathrm{tr}\left((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\right)^2$. We have

$$\mathrm{tr}\left((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\right)^2=\mathrm{tr}(\boldsymbol{\Sigma}^2)-2\,\mathrm{tr}(\boldsymbol{\Sigma}^2\mathbf{P}_{\mathbf{Y}})+\mathrm{tr}((\boldsymbol{\Sigma}\mathbf{P}_{\mathbf{Y}})^2).$$

From von Neumann's trace theorem, the second term satisfies

$$\left|\mathrm{tr}(\boldsymbol{\Sigma}^2\mathbf{P}_{\mathbf{Y}})-\frac{n\,\mathrm{tr}^2(\boldsymbol{\Sigma}^2)}{\mathrm{tr}^2(\boldsymbol{\Sigma})}\right|=\left|\mathrm{tr}\left(\left(\boldsymbol{\Sigma}^2-\frac{\mathrm{tr}^2(\boldsymbol{\Sigma}^2)}{\mathrm{tr}^2(\boldsymbol{\Sigma})}\mathbf{I}_p\right)\mathbf{P}_{\mathbf{Y}}\right)\right|\le n\boldsymbol{\lambda}_1(\boldsymbol{\lambda}_1-\boldsymbol{\lambda}_p),$$

and the third term satisfies

$$\begin{aligned}
&\left|\operatorname{tr}((\boldsymbol{\Sigma}\mathbf{P}_{\mathbf{Y}})^2) - \frac{n\operatorname{tr}^2(\boldsymbol{\Sigma}^2)}{\operatorname{tr}^2(\boldsymbol{\Sigma})}\right| \\
=&\left|\operatorname{tr}\left(\left(\boldsymbol{\Sigma} + \frac{\operatorname{tr}(\boldsymbol{\Sigma}^2)}{\operatorname{tr}(\boldsymbol{\Sigma})}\mathbf{I}_p\right)\mathbf{P}_{\mathbf{Y}}\left(\boldsymbol{\Sigma} - \frac{\operatorname{tr}(\boldsymbol{\Sigma}^2)}{\operatorname{tr}(\boldsymbol{\Sigma})}\mathbf{I}_p\right)\mathbf{P}_{\mathbf{Y}}\right)\right| \\
\leq& 2n\boldsymbol{\lambda}_1(\boldsymbol{\lambda}_1 - \boldsymbol{\lambda}_p).
\end{aligned}$$

This completes the proof of the second statement. □

Proof of Theorem 1. In the current context, Lemma 6 implies that

$$\operatorname{tr}\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) = \operatorname{tr}(\boldsymbol{\Sigma}) - \frac{n\operatorname{tr}(\boldsymbol{\Sigma}^2)}{\operatorname{tr}(\boldsymbol{\Sigma})} + o_P(\sqrt{\operatorname{tr}(\boldsymbol{\Sigma}^2)}), \tag{S3.4}$$

$$\operatorname{tr}\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)^2 = (1 + o_P(1))\operatorname{tr}(\boldsymbol{\Sigma}^2). \tag{S3.5}$$

The fact $\lambda_1\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) \leq \boldsymbol{\lambda}_1$ and (S3.5) imply that the first term of (S3.1) satisfies the Lyapunov condition

$$\frac{\lambda_1\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)}{\sqrt{\operatorname{tr}\left(((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}))^2\right)}} \leq \frac{\boldsymbol{\lambda}_1}{\sqrt{(1 + o_P(1))\operatorname{tr}^2(\boldsymbol{\Sigma})}} \xrightarrow{P} 0.$$

From Lemma 2, we have

$$\frac{\mathbf{Z}^{\dagger\top}\boldsymbol{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}\boldsymbol{\Lambda}^{1/2}\mathbf{Z}^\dagger - \operatorname{tr}\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)\mathbf{I}_{k-1}}{\sqrt{\operatorname{tr}\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)^2}} \xrightarrow{\mathcal{L}} \mathbf{W}_{k-1}.$$

Then it follows from (S3.4), (S3.5) and Slutsky's theorem that

$$\frac{\mathbf{Z}^{\dagger\top}\boldsymbol{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}\boldsymbol{\Lambda}^{1/2}\mathbf{Z}^\dagger - \left(\operatorname{tr}(\boldsymbol{\Sigma}) - n\operatorname{tr}(\boldsymbol{\Sigma}^2)/\operatorname{tr}(\boldsymbol{\Sigma})\right)\mathbf{I}_{k-1}}{\sqrt{\operatorname{tr}(\boldsymbol{\Sigma}^2)}} \xrightarrow{\mathcal{L}} \mathbf{W}_{k-1}. \tag{S3.6}$$

Next we consider the second term of (S3.1). Note that

$$\left\|\mathbf{C}^\top\mathbf{\Theta}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{\Theta}\mathbf{C}-\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}\right\|=\left\|\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{Y}(\mathbf{Y}^\top\mathbf{Y})^{-1}\mathbf{Y}^\top\mathbf{\Theta}\mathbf{C}\right\|.$$

We have

$$\begin{aligned}
&\left\|\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{Y}(\mathbf{Y}^\top\mathbf{Y})^{-1}\mathbf{Y}^\top\mathbf{\Theta}\mathbf{C}-\operatorname{tr}(\mathbf{\Sigma})^{-1}\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{Y}\mathbf{Y}^\top\mathbf{\Theta}\mathbf{C}\right\|\\
\le&\left\|\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{Y}\mathbf{Y}^\top\mathbf{\Theta}\mathbf{C}\right\|\left\|(\mathbf{Y}^\top\mathbf{Y})^{-1}-\operatorname{tr}(\mathbf{\Sigma})^{-1}\mathbf{I}_n\right\|\\
\le&\left\|\operatorname{tr}(\mathbf{\Sigma})^{-1}\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{Y}\mathbf{Y}^\top\mathbf{\Theta}\mathbf{C}\right\|\left\|(\mathbf{Y}^\top\mathbf{Y})^{-1}\right\|\left\|\mathbf{Y}^\top\mathbf{Y}-\operatorname{tr}(\mathbf{\Sigma})\mathbf{I}_n\right\|.
\end{aligned}$$

From Lemma 5, we have

$$\begin{aligned}
\left\|\mathbf{Y}^\top\mathbf{Y}-\operatorname{tr}(\mathbf{\Sigma})\mathbf{I}_n\right\|=&\left\|\mathbf{Z}^\top\mathbf{\Lambda}\mathbf{Z}-\operatorname{tr}(\mathbf{\Sigma})\mathbf{I}_n\right\|\\
=&O_P(\sqrt{n\operatorname{tr}(\mathbf{\Sigma}^2)}+n\boldsymbol{\lambda}_1)\\
=&o_P(\operatorname{tr}(\mathbf{\Sigma})).
\end{aligned}$$

Then $\left\|(\mathbf{Y}^\top\mathbf{Y})^{-1}\right\|=\lambda_n^{-1}(\mathbf{Z}^\top\mathbf{\Lambda}\mathbf{Z})=(1+o_P(1))\operatorname{tr}(\mathbf{\Sigma})$. Therefore,

$$\begin{aligned}
&\left\|\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{Y}(\mathbf{Y}^\top\mathbf{Y})^{-1}\mathbf{Y}^\top\mathbf{\Theta}\mathbf{C}-\operatorname{tr}(\mathbf{\Sigma})^{-1}\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{Y}\mathbf{Y}^\top\mathbf{\Theta}\mathbf{C}\right\|\\
=&o_P\left(\left\|\operatorname{tr}(\mathbf{\Sigma})^{-1}\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{Y}\mathbf{Y}^\top\mathbf{\Theta}\mathbf{C}\right\|\right).
\end{aligned}$$

Note that the columns of $\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{Y}=\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{U}\mathbf{\Lambda}^{1/2}\mathbf{Z}$ are iid $\mathcal{N}_{k-1}(\mathbf{0}_{k-1},\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Sigma}\mathbf{\Theta}\mathbf{C})$ random vectors. Hence we can write $\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{Y}=(\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Sigma}\mathbf{\Theta}\mathbf{C})^{1/2}\mathbf{Z}^*$, where $\mathbf{Z}^*$ is a $(k-1)\times n$ random matrix with iid $\mathcal{N}(0,1)$ entries. Then

$$\begin{aligned}
&\left\|\operatorname{tr}(\mathbf{\Sigma})^{-1}\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{Y}\mathbf{Y}^\top\mathbf{\Theta}\mathbf{C}-\frac{n}{\operatorname{tr}(\mathbf{\Sigma})}\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Sigma}\mathbf{\Theta}\mathbf{C}\right\|\\
\le&\frac{n}{\operatorname{tr}(\mathbf{\Sigma})}\left\|\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Sigma}\mathbf{\Theta}\mathbf{C}\right\|\left\|n^{-1}\mathbf{Z}^*\mathbf{Z}^{*\top}-\mathbf{I}_{k-1}\right\|\\
=&o_P\left(\frac{n}{\operatorname{tr}(\mathbf{\Sigma})}\left\|\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Sigma}\mathbf{\Theta}\mathbf{C}\right\|\right),
\end{aligned}$$

where the last equality follows from the law of large numbers. Combine the above arguments, we have

$$\begin{aligned}\left\|\mathbf{C}^\top\mathbf{\Theta}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{\Theta}\mathbf{C}-\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}\right\| =& (1+o_P(1))\frac{n}{\operatorname{tr}(\mathbf{\Sigma})}\left\|\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Sigma}\mathbf{\Theta}\mathbf{C}\right\| \\ \leq& (1+o_P(1))\frac{n\boldsymbol{\lambda}_1}{\operatorname{tr}(\mathbf{\Sigma})}\left\|\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}\right\| \\ =& o_P\left(\sqrt{\operatorname{tr}(\mathbf{\Sigma}^2)}\right).\end{aligned} \tag{S3.7}$$

Now we deal with the cross term of (S3.1). Note that

$$\begin{aligned}&\mathrm{E}[\|\mathbf{C}^\top\mathbf{\Theta}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{U}\mathbf{\Lambda}^{1/2}\mathbf{Z}^\dagger\|_F^2|\mathbf{Y}] \\ =&(k-1)\operatorname{tr}\left(\mathbf{C}^\top\mathbf{\Theta}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{\Sigma}(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{\Theta}\mathbf{C}\right) \\ \leq&(k-1)\boldsymbol{\lambda}_1\operatorname{tr}\left(\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}\right).\end{aligned}$$

Therefore,

$$\begin{aligned}\|\mathbf{C}^\top\mathbf{\Theta}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{U}\mathbf{\Lambda}^{1/2}\mathbf{Z}^\dagger\| =& O_P\left(\sqrt{\boldsymbol{\lambda}_1\operatorname{tr}\left(\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}\right)}\right) \\ =& o_P\left(\sqrt{\operatorname{tr}(\mathbf{\Sigma}^2)}\right),\end{aligned} \tag{S3.8}$$

where the last equality follows from the conditions $\boldsymbol{\lambda}_1/\sqrt{\operatorname{tr}(\mathbf{\Sigma}^2)}\to 0$ and $\operatorname{tr}\left(\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}\right)\leq(k-1)\left\|\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}\right\| = O(\sqrt{\operatorname{tr}(\mathbf{\Sigma}^2)})$.

It follows from (S3.7), (S3.8) and Weyl's inequality that

$$
\begin{aligned}
&\left|T(\mathbf{X})-\left(\lambda_1\left(\mathbf{Z}^{\dagger\top}\mathbf{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{U}\mathbf{\Lambda}^{1/2}\mathbf{Z}^\dagger+\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}\right)\right)\right|\\
\leq&\left\|\mathbf{C}^\top\mathbf{\Theta}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{\Theta}\mathbf{C}-\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}\right.\\
&\quad\left.+\mathbf{C}^\top\mathbf{\Theta}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{U}\mathbf{\Lambda}^{1/2}\mathbf{Z}^\dagger+\mathbf{Z}^{\dagger\top}\mathbf{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{\Theta}\mathbf{C}\right\|\\
\leq&\left\|\mathbf{C}^\top\mathbf{\Theta}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{\Theta}\mathbf{C}-\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}\right\|+2\left\|\mathbf{C}^\top\mathbf{\Theta}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{U}\mathbf{\Lambda}^{1/2}\mathbf{Z}^\dagger\right\|\\
=&o_P\left(\sqrt{\operatorname{tr}(\mathbf{\Sigma}^2)}\right).
\end{aligned}
$$

But (S3.6) implies that

$$
\begin{aligned}
&\frac{1}{\sqrt{\operatorname{tr}(\mathbf{\Sigma}^2)}}\left(\lambda_1\left(\mathbf{Z}^{\dagger\top}\mathbf{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{U}\mathbf{\Lambda}^{1/2}\mathbf{Z}^\dagger+\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}\right)\right.\\
&\qquad\qquad\left.-\left(\operatorname{tr}(\mathbf{\Sigma})-n\operatorname{tr}(\mathbf{\Sigma}^2)/\operatorname{tr}(\mathbf{\Sigma})\right)\right)\\
=&\lambda_1\left(\frac{\mathbf{Z}^{\dagger\top}\mathbf{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{U}\mathbf{\Lambda}^{1/2}\mathbf{Z}^\dagger-\left(\operatorname{tr}(\mathbf{\Sigma})-n\operatorname{tr}(\mathbf{\Sigma}^2)/\operatorname{tr}(\mathbf{\Sigma})\right)\mathbf{I}_{k-1}}{\sqrt{\operatorname{tr}(\mathbf{\Sigma}^2)}}\right.\\
&\qquad\left.+\frac{\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}}{\sqrt{\operatorname{tr}(\mathbf{\Sigma}^2)}}\right)\\
\sim&\lambda_1\left(\mathbf{W}_{k-1}+\frac{\mathbf{C}^\top\mathbf{\Theta}^\top\mathbf{\Theta}\mathbf{C}}{\sqrt{\operatorname{tr}(\mathbf{\Sigma}^2)}}\right)+o_P(1).
\end{aligned}
$$

This completes the proof.

$\square$

Proof of Corollary 1. It is straightforward to show that $\operatorname{E}\widehat{\operatorname{tr}(\mathbf{\Sigma})}=\operatorname{tr}(\mathbf{\Sigma})$ and $\operatorname{Var}\left(\widehat{\operatorname{tr}(\mathbf{\Sigma})}\right)=2n^{-1}\operatorname{tr}(\mathbf{\Sigma}^2)$. Then $\widehat{\operatorname{tr}(\mathbf{\Sigma})}=\operatorname{tr}(\mathbf{\Sigma})+O_P(\sqrt{n^{-1}\operatorname{tr}(\mathbf{\Sigma}^2)})$.

Let $Z_1, \ldots, Z_n$ be the columns of $\mathbf{Z}$. Then we have

$$\begin{aligned}\widehat{\operatorname{tr}(\mathbf{\Sigma}^2)} =& n^{-2} \operatorname{tr}(\mathbf{Z}^\top \mathbf{\Lambda} \mathbf{Z} - n^{-1} \operatorname{tr}(\mathbf{Z}^\top \mathbf{\Lambda} \mathbf{Z}) \mathbf{I}_n)^2 \\ =& n^{-2} \sum_{i=1}^n (Z_i^\top \mathbf{\Lambda} Z_i - n^{-1} \sum_{i=1}^n Z_i^\top \mathbf{\Lambda} Z_i)^2 + 2n^{-2} \sum_{1 \le i < j \le n} (Z_i^\top \mathbf{\Lambda} Z_i)^2.\end{aligned}$$

It can be seen that $n^{-2} \sum_{i=1}^n (Z_i^\top \mathbf{\Lambda} Z_i - n^{-1} \sum_{i=1}^n Z_i^\top \mathbf{\Lambda} Z_i)^2 = O_P(n^{-1} \operatorname{tr}(\mathbf{\Sigma}^2))$. On the other hand, we have $\operatorname{E} 2 \sum_{1 \le i < j \le n} (Z_i^\top \mathbf{\Lambda} Z_i)^2 = n(n-1) \operatorname{tr}(\mathbf{\Sigma}^2)$. Furthermore, Chen et al. (2010), Proposition A.2 implies that

$$\operatorname{Var}\left(2 \sum_{1 \le i < j \le n} (Z_i^\top \mathbf{\Lambda} Z_j)^2\right) = O\left(n^2 \operatorname{tr}^2(\mathbf{\Sigma}^2) + n^3 \operatorname{tr}(\mathbf{\Sigma}^4)\right) = O\left(n^3 \operatorname{tr}^2(\mathbf{\Sigma}^2)\right).$$

Hence $\widehat{\operatorname{tr}(\mathbf{\Sigma}^2)} = (1 + O_P(n^{-1/2})) \operatorname{tr}(\mathbf{\Sigma}^2)$.

Thus, we have

$$\begin{aligned}&\widehat{\operatorname{tr}(\mathbf{\Sigma})} - n\widehat{\operatorname{tr}(\mathbf{\Sigma}^2)}/\widehat{\operatorname{tr}(\mathbf{\Sigma})} \\ =& \operatorname{tr}(\mathbf{\Sigma}) + O_P(\sqrt{n^{-1} \operatorname{tr}(\mathbf{\Sigma}^2)}) - \frac{n \operatorname{tr}(\mathbf{\Sigma}^2)(1 + O_P(n^{-1/2}))}{\operatorname{tr}(\mathbf{\Sigma})(1 + O_P(\sqrt{n^{-1} \operatorname{tr}(\mathbf{\Sigma}^2)/\operatorname{tr}^2(\mathbf{\Sigma})}))} \\ =& \operatorname{tr}(\mathbf{\Sigma}) + O_P(\sqrt{n^{-1} \operatorname{tr}(\mathbf{\Sigma}^2)}) - \frac{n \operatorname{tr}(\mathbf{\Sigma}^2)}{\operatorname{tr}(\mathbf{\Sigma})} \left(1 + O_P\left(\frac{1}{\sqrt{n}} + \sqrt{\frac{\operatorname{tr}(\mathbf{\Sigma}^2)}{n \operatorname{tr}^2(\mathbf{\Sigma})}}\right)\right) \\ =& \operatorname{tr}(\mathbf{\Sigma}) - \frac{n \operatorname{tr}(\mathbf{\Sigma}^2)}{\operatorname{tr}(\mathbf{\Sigma})} + o_P(\sqrt{\operatorname{tr}(\mathbf{\Sigma}^2)}).\end{aligned}$$

Therefore,

$$Q_1 = \frac{T(\mathbf{X}) - (\operatorname{tr}(\mathbf{\Sigma}) - n \operatorname{tr}(\mathbf{\Sigma}^2)/\operatorname{tr}(\mathbf{\Sigma}))}{\sqrt{\operatorname{tr}(\mathbf{\Sigma}^2)}} + o_P(1).$$

Then the conclusion follows from Theorem 1. □

Lemma 7. *Suppose that* $r = o(n)$, $\operatorname{tr}(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1/(n\boldsymbol{\lambda}_r^2) \to 0$, $n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\mathbf{\Lambda}_2) \to 0$. *Then uniformly for* $i = 1, \ldots, r$,

$$
\begin{aligned}
&\lambda_i\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) \\
=&n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)\left(1 + O_P\left(\sqrt{\frac{\operatorname{tr}(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}} + \sqrt{\frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\mathbf{\Lambda}_2)}} + \sqrt{\frac{r}{n}}\right)\right).
\end{aligned}
$$

Proof. Note that

$$
(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}) = (\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},2})(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1})(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},2}). \quad \text{(S3.9)}
$$

We first deal with $(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1})$. Under the condition $n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\mathbf{\Lambda}_2) \to 0$, Proposition 3 implies that

$$
\|\mathbf{U}_{\mathbf{Y},1}\mathbf{U}_{\mathbf{Y},1}^\top - \mathbf{P}_{\mathbf{Y},1}^\dagger\| = O_P\left(\frac{\operatorname{tr}(\mathbf{\Lambda}_2)}{n\boldsymbol{\lambda}_r}\right).
$$

From the decomposition

$$
\begin{aligned}
&(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}) \\
=&(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}^\dagger)\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}^\dagger) + (\mathbf{P}_{\mathbf{Y},1}^\dagger - \mathbf{P}_{\mathbf{Y},1})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}^\dagger) \\
&+ (\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}^\dagger)\mathbf{\Sigma}(\mathbf{P}_{\mathbf{Y},1}^\dagger - \mathbf{P}_{\mathbf{Y},1}) + (\mathbf{P}_{\mathbf{Y},1}^\dagger - \mathbf{P}_{\mathbf{Y},1})\mathbf{\Sigma}(\mathbf{P}_{\mathbf{Y},1}^\dagger - \mathbf{P}_{\mathbf{Y},1}),
\end{aligned}
$$

we have

$$
\begin{aligned}
&\left\|(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}) - (\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}^\dagger)\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}^\dagger)\right\| \\
\le&2\left\|\mathbf{P}_{\mathbf{Y},1}^\dagger - \mathbf{P}_{\mathbf{Y},1}\right\|\left\|\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}^\dagger)\right\| + \boldsymbol{\lambda}_1\|\mathbf{P}_{\mathbf{Y},1}^\dagger - \mathbf{P}_{\mathbf{Y},1}\|^2. \\
=&O_P\left(\frac{\operatorname{tr}(\mathbf{\Lambda}_2)}{n\boldsymbol{\lambda}_r}\right)\left\|\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},1}^\dagger)\right\| + O_P\left(\frac{\operatorname{tr}^2(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1}{n^2\boldsymbol{\lambda}_r^2}\right).
\end{aligned}
$$

Note that

$$
\begin{aligned}
&\left\|\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1}^{\dagger})\right\|\\
=&\left\|\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top-\mathbf{U}_1\boldsymbol{\Lambda}_1\mathbf{Q}^\top\mathbf{U}_2^\top-\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{Q}\mathbf{U}_1^\top\right\|\\
\leq&\boldsymbol{\lambda}_{r+1}+\left\|\boldsymbol{\Lambda}_1\mathbf{Q}^\top\right\|+\boldsymbol{\lambda}_{r+1}\left\|\mathbf{Q}\right\|\\
=&\boldsymbol{\lambda}_{r+1}+\left\|\boldsymbol{\Lambda}_1^{1/2}(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1/2}\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\right\|+\boldsymbol{\lambda}_{r+1}\|\mathbf{Q}^\top\mathbf{Q}\|^{1/2}\\
\leq&\boldsymbol{\lambda}_{r+1}+\boldsymbol{\lambda}_1^{1/2}\left\|(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1/2}\right\|\left\|\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\right\|^{1/2}+\boldsymbol{\lambda}_{r+1}\|\mathbf{Q}^\top\mathbf{Q}\|^{1/2}\\
=&O_P\left(\sqrt{\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1}{n}}\right),
\end{aligned}
$$

where the last equality follows from (S2.9), (S2.11) and the condition $n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\boldsymbol{\Lambda}_2)\to 0$. Thus,

$$
\begin{aligned}
&\left\|(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1})-(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1}^{\dagger})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1}^{\dagger})\right\|\\
=&O_P\left(\frac{\operatorname{tr}^{3/2}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1^{1/2}}{n^{3/2}\boldsymbol{\lambda}_r}\right).
\end{aligned}
\tag{S3.10}
$$

From the decomposition

$$
\begin{aligned}
&(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1}^{\dagger})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1}^{\dagger})\\
=&\mathbf{U}_2\mathbf{Q}\boldsymbol{\Lambda}_1\mathbf{Q}^\top\mathbf{U}_2^\top+\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top-\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{Q}\mathbf{U}_1^\top-\mathbf{U}_1\mathbf{Q}^\top\boldsymbol{\Lambda}_2\mathbf{U}_2^\top+\mathbf{U}_1\mathbf{Q}^\top\boldsymbol{\Lambda}_2\mathbf{Q}\mathbf{U}_1^\top,
\end{aligned}
$$

we have

$$
\begin{aligned}
&\left\|(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1}^{\dagger})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y},1}^{\dagger})-\mathbf{U}_2\mathbf{Q}\boldsymbol{\Lambda}_1\mathbf{Q}^\top\mathbf{U}_2^\top\right\|\\
\leq&\boldsymbol{\lambda}_{r+1}(1+2\|\mathbf{Q}^\top\mathbf{Q}\|^{1/2}+\|\mathbf{Q}^\top\mathbf{Q}\|)\\
=&O_P\left(\boldsymbol{\lambda}_{r+1}\right),
\end{aligned}
\tag{S3.11}
$$

where the last equality follows from (S2.11). Note that $\mathbf{U}_2\mathbf{Q}\boldsymbol{\Lambda}_1\mathbf{Q}^\top\mathbf{U}_2^\top = \mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1}\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top$. We have

$$\begin{aligned}
&\left\|\mathbf{U}_2\mathbf{Q}\boldsymbol{\Lambda}_1\mathbf{Q}^\top\mathbf{U}_2^\top - n^{-1}\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top\right\| \\
\le&\left\|\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top\right\|\left\|(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1} - n^{-1}\mathbf{I}_r\right\| \\
\le&\left\|\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\right\|\left\|(\mathbf{Z}_1\mathbf{Z}_1^\top)^{-1}\right\|\left\|n^{-1}\mathbf{Z}_1\mathbf{Z}_1^\top - \mathbf{I}_r\right\| \\
=&O_P\left(\frac{r^{1/2}\operatorname{tr}(\boldsymbol{\Lambda}_2)}{n^{3/2}}\right),
\end{aligned} \tag{S3.12}$$

where the last equality follows from (S2.3) and (S2.9). From (S3.9), (S3.10), (S3.11) and (S3.12), we obtain that

$$\begin{aligned}
&\|(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}) \\
&\quad - n^{-1}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},2})\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y},2})\Big\| \\
=&O_P\left(\left(\sqrt{\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}} + \frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\boldsymbol{\Lambda}_2)} + \sqrt{\frac{r}{n}}\right)\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)}{n}\right).
\end{aligned}$$

Thus, the last display, together with Weyl's inequality, implies that uniformly for $i = 1, \ldots, r$,

$$\begin{aligned}
&\lambda_i\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) \\
=&n^{-1}\lambda_i\left(\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top(\mathbf{I} - \mathbf{P}_{\mathbf{Y},2})\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\right) \\
&+ O_P\left(\left(\sqrt{\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}} + \frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\boldsymbol{\Lambda}_2)} + \sqrt{\frac{r}{n}}\right)\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)}{n}\right).
\end{aligned}$$

Note that

$$
\begin{aligned}
&\Big\| n^{-1}\mathbf{V}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2^{1/2}\mathbf{U}_2^\top(\mathbf{I}-\mathbf{P}_{\mathbf{Y},2})\mathbf{U}_2\mathbf{\Lambda}_2^{1/2}\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1} \\
&-\Big(n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)\mathbf{I}_r-(n\operatorname{tr}(\mathbf{\Lambda}_2))^{-1}\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\Big)\Big\| \\
\le&\left\| n^{-1}\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}-n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2)\mathbf{I}_r\right\| \\
&+n^{-1}\left\|\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\right\|\left\|\mathbf{P}_{\mathbf{Y},2}-(\operatorname{tr}(\mathbf{\Lambda}_2))^{-1}\mathbf{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2^{1/2}\right\| \\
=&O_P\left(\left(\sqrt{\frac{\operatorname{tr}(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}}+\sqrt{\frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\mathbf{\Lambda}_2)}}\right)\frac{\operatorname{tr}(\mathbf{\Lambda}_2)}{n}\right),
\end{aligned}
$$

where the last equality follows from (S2.9) and Proposition 4. Then it follows from Weyl's inequality that uniformly for $i=1,\ldots,r$,

$$
\begin{aligned}
&\lambda_i\left((\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{\Sigma}(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\right) \\
=&n^{-1}\operatorname{tr}(\mathbf{\Lambda}_2) \\
&-(n\operatorname{tr}(\mathbf{\Lambda}_2))^{-1}\lambda_{r+1-i}\left(\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}\right) \\
&+O_P\left(\left(\sqrt{\frac{\operatorname{tr}(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}}+\sqrt{\frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\mathbf{\Lambda}_2)}}+\sqrt{\frac{r}{n}}\right)\frac{\operatorname{tr}(\mathbf{\Lambda}_2)}{n}\right).
\end{aligned}
\tag{S3.13}
$$

Now we deal with the matrix $\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}$. Note that $\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}$ and $\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}$ both have iid $\mathcal{N}(0,1)$ entries and they are mutually independent. Then Lemma 5 implies that

$$
\begin{aligned}
&\left\|\mathbf{V}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2\mathbf{V}_{\mathbf{Z}_1}-\operatorname{tr}(\mathbf{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2)\mathbf{I}_r\right\| \\
=&O_P\left(\sqrt{r\operatorname{tr}(\mathbf{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2)^2}+r\left\|\mathbf{\Lambda}_2\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\mathbf{\Lambda}_2\right\|\right).
\end{aligned}
$$

By some algebra, we have

$$
\begin{aligned}
&\left\|\mathbf{V}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 \tilde{\mathbf{V}}_{\mathbf{Z}_1} \tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 \mathbf{V}_{\mathbf{Z}_1} - \operatorname{tr}(\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2^2 \mathbf{Z}_2 \tilde{\mathbf{V}}_{\mathbf{Z}_1}) \mathbf{I}_r\right\| \\
=&O_P\left(\sqrt{r\left\|\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2^2 \mathbf{Z}_2 \tilde{\mathbf{V}}_{\mathbf{Z}_1}\right\| \operatorname{tr}(\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2^2 \mathbf{Z}_2 \tilde{\mathbf{V}}_{\mathbf{Z}_1})}\right. \\
&\qquad \left. + r\left\|\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2^2 \mathbf{Z}_2 \tilde{\mathbf{V}}_{\mathbf{Z}_1}\right\|\right).
\end{aligned}
$$

Since $\mathrm{E} \operatorname{tr}(\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2^2 \mathbf{Z}_2 \tilde{\mathbf{V}}_{\mathbf{Z}_1}) = (n-r)\operatorname{tr}(\mathbf{\Lambda}_2^2)$, we have

$$
\operatorname{tr}(\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2^2 \mathbf{Z}_2 \tilde{\mathbf{V}}_{\mathbf{Z}_1}) = O_P\left(n \operatorname{tr}(\mathbf{\Lambda}_2^2)\right) = O_P\left(n \boldsymbol{\lambda}_{r+1} \operatorname{tr}(\mathbf{\Lambda}_2)\right).
$$

On the other hand, Lemma 5 implies that

$$
\|\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2^2 \mathbf{Z}_2 \tilde{\mathbf{V}}_{\mathbf{Z}_1}\| = O_P\left(\operatorname{tr}(\mathbf{\Lambda}_2^2) + n\boldsymbol{\lambda}_{r+1}^2\right) = O_P\left(\boldsymbol{\lambda}_{r+1} \operatorname{tr}(\mathbf{\Lambda}_2)\right).
$$

Combine these bounds, we have

$$
\left\|\mathbf{V}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 \tilde{\mathbf{V}}_{\mathbf{Z}_1} \tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 \mathbf{V}_{\mathbf{Z}_1} - n \operatorname{tr}(\mathbf{\Lambda}_2^2) \mathbf{I}_r\right\| = O_P\left(\sqrt{rn}\boldsymbol{\lambda}_{r+1} \operatorname{tr}(\mathbf{\Lambda}_2)\right).
$$

The last display, combined with Weyl's inequality, implies that uniformly for $i = 1, \ldots, r$,

$$
(n \operatorname{tr}(\mathbf{\Lambda}_2))^{-1} \lambda_i\left(\mathbf{V}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 \tilde{\mathbf{V}}_{\mathbf{Z}_1} \tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top \mathbf{Z}_2^\top \mathbf{\Lambda}_2 \mathbf{Z}_2 \mathbf{V}_{\mathbf{Z}_1}\right) = O_P(\boldsymbol{\lambda}_{r+1}).
$$

Then (S3.13) and the last display implies that uniformly for $i = 1, \ldots, r$,

$$
\begin{aligned}
&\lambda_i\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) \\
=&n^{-1} \operatorname{tr}(\mathbf{\Lambda}_2) + O_P\left(\left(\sqrt{\frac{\operatorname{tr}(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}} + \sqrt{\frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\mathbf{\Lambda}_2)}} + \sqrt{\frac{r}{n}}\right)\frac{\operatorname{tr}(\mathbf{\Lambda}_2)}{n}\right).
\end{aligned}
$$

This completes the proof.

□

Lemma 8. *Suppose that* $r = o(n)$, $\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1/(n\boldsymbol{\lambda}_r^2) \to 0$, $n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\boldsymbol{\Lambda}_2) \to 0$. *Then*

$$\begin{aligned}
&\sum_{i=r+1}^{p} \lambda_i\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) \\
=&\operatorname{tr}(\boldsymbol{\Lambda}_2) - \frac{n\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}(\boldsymbol{\Lambda}_2)} \\
&+ O_P\left(n(\boldsymbol{\lambda}_{r+1} - \boldsymbol{\lambda}_p)\left(\sqrt{\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}} + \sqrt{\frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}}\right) + r\boldsymbol{\lambda}_{r+1}\right).
\end{aligned}$$

Proof. Write $\boldsymbol{\Sigma} = \mathbf{U}_1\boldsymbol{\Lambda}_1\mathbf{U}_1^\top + \mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top$. Note that $\mathbf{U}_1\boldsymbol{\Lambda}_1\mathbf{U}_1^\top$ is of rank r. Then Weyl's inequality implies that for $i = r+1, \ldots, p$,

$$\lambda_i\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) \geq \lambda_i\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right), \quad \text{(S3.14)}$$

$$\lambda_i\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) \leq \lambda_{i-r}\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right). \quad \text{(S3.15)}$$

Hence we have

$$\begin{aligned}
&\left|\sum_{i=r+1}^{p} \lambda_i\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) - \operatorname{tr}\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)\right| \\
\leq& r\lambda_1\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) \\
\leq& r\boldsymbol{\lambda}_{r+1}.
\end{aligned} \quad \text{(S3.16)}$$

Write

$$\begin{aligned}
&\operatorname{tr}\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)\\
=&\operatorname{tr}\left(\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\right)\\
=&\operatorname{tr}(\boldsymbol{\Lambda}_2) - \operatorname{tr}\left(\left(\boldsymbol{\Lambda}_2 - \frac{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2\right) - \frac{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}\operatorname{tr}\left(\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2\right).
\end{aligned} \tag{S3.17}$$

For the third term, note that $\operatorname{tr}\left(\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2\right) = \operatorname{tr}(\mathbf{P}_{\mathbf{Y}}) - \operatorname{tr}\left(\mathbf{P}_{\mathbf{Y}}\mathbf{U}_1\mathbf{U}_1^\top\right)$. Since $\mathbf{P}_{\mathbf{Y}}$ is of rank n and $\mathbf{U}_1$ is of rank r, we have

$$|\operatorname{tr}\left(\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2\right) - n| \le r. \tag{S3.18}$$

Next we deal with the second term. We have

$$\begin{aligned}
&\left|\operatorname{tr}\left(\left(\boldsymbol{\Lambda}_2 - \frac{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2\right)\right.\\
&\left.- \operatorname{tr}\left(\left(\boldsymbol{\Lambda}_2 - \frac{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\left(\mathbf{P}_{\mathbf{Y},1}^\dagger + \mathbf{P}_{\mathbf{Y},2}^\dagger\right)\mathbf{U}_2\right)\right|\\
=&\left|\operatorname{tr}\left(\left(\boldsymbol{\Lambda}_2 - \frac{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\left(\mathbf{P}_{\mathbf{Y}} - \mathbf{P}_{\mathbf{Y},1}^\dagger - \mathbf{P}_{\mathbf{Y},2}^\dagger\right)\mathbf{U}_2\right)\right|.
\end{aligned}$$

Since $\operatorname{tr}(\boldsymbol{\Lambda}_2^2)/\operatorname{tr}(\boldsymbol{\Lambda}_2) \in [\boldsymbol{\lambda}_p, \boldsymbol{\lambda}_{r+1}]$, we have $\|\boldsymbol{\Lambda}_2 - (\operatorname{tr}(\boldsymbol{\Lambda}_2^2)/\operatorname{tr}(\boldsymbol{\Lambda}_2))\mathbf{I}_{p-r}\| \le \boldsymbol{\lambda}_{r+1} - \boldsymbol{\lambda}_p$. Also note that the rank of the matrix $\mathbf{P}_{\mathbf{Y}} - \mathbf{P}_{\mathbf{Y},1}^\dagger - \mathbf{P}_{\mathbf{Y},2}^\dagger$ is at most $2n$. Therefore, von Neumann's trace theorem implies that

$$\begin{aligned}
&\left|\operatorname{tr}\left(\left(\mathbf{\Lambda}_2 - \frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\left(\mathbf{P}_{\mathbf{Y}} - \mathbf{P}_{\mathbf{Y},1}^\dagger - \mathbf{P}_{\mathbf{Y},2}^\dagger\right)\mathbf{U}_2\right)\right| \\
\le& 2n(\boldsymbol{\lambda}_{r+1} - \boldsymbol{\lambda}_p)\left\|\mathbf{P}_{\mathbf{Y}} - \mathbf{P}_{\mathbf{Y},1}^\dagger - \mathbf{P}_{\mathbf{Y},2}^\dagger\right\| \\
\le& 2n(\boldsymbol{\lambda}_{r+1} - \boldsymbol{\lambda}_p)\left(\left\|\mathbf{P}_{\mathbf{Y},1} - \mathbf{P}_{\mathbf{Y},1}^\dagger\right\| + \left\|\mathbf{P}_{\mathbf{Y},2} - \mathbf{P}_{\mathbf{Y},2}^\dagger\right\|\right) \\
=& O_P\left(n(\boldsymbol{\lambda}_{r+1} - \boldsymbol{\lambda}_p)\left(\sqrt{\frac{\operatorname{tr}(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}} + \sqrt{\frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\mathbf{\Lambda}_2)}}\right)\right),
\end{aligned} \tag{S3.19}$$

where the last equality follows from Proposition 3 and Proposition 4. Note that

$$\begin{aligned}
&\operatorname{tr}\left(\left(\mathbf{\Lambda}_2 - \frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\left(\mathbf{P}_{\mathbf{Y},1}^\dagger + \mathbf{P}_{\mathbf{Y},2}^\dagger\right)\mathbf{U}_2\right) \\
=& \operatorname{tr}\left(\left(\mathbf{\Lambda}_2 - \frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y},2}^\dagger\mathbf{U}_2\right) \\
=& \frac{1}{\operatorname{tr}(\mathbf{\Lambda}_2)}\operatorname{tr}\left(\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\left(\mathbf{\Lambda}_2^2 - \frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{\Lambda}_2\right)\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\right)
\end{aligned}$$

It is straightforward to show that

$$\operatorname{E}\operatorname{tr}\left(\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\left(\mathbf{\Lambda}_2^2 - \frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{\Lambda}_2\right)\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\right) = 0,$$

and

$$\begin{aligned}
&\operatorname{Var}\left(\operatorname{tr}\left(\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\left(\mathbf{\Lambda}_2^2 - \frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{\Lambda}_2\right)\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\right)\right) \\
=& 2(n-r)\operatorname{tr}\left(\mathbf{\Lambda}_2^2 - \frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{\Lambda}_2\right)^2 \\
\le& 2n\operatorname{tr}(\mathbf{\Lambda}_2^2)(\boldsymbol{\lambda}_{r+1} - \boldsymbol{\lambda}_p)^2 \\
\le& 2n\boldsymbol{\lambda}_{r+1}\operatorname{tr}(\mathbf{\Lambda}_2)(\boldsymbol{\lambda}_{r+1} - \boldsymbol{\lambda}_p)^2.
\end{aligned}$$

Thus,

$$\begin{aligned}
&\operatorname{tr}\left(\left(\mathbf{\Lambda}_2 - \frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\left(\mathbf{P}_{\mathbf{Y},1}^\dagger + \mathbf{P}_{\mathbf{Y},2}^\dagger\right)\mathbf{U}_2\right) \\
=&O_P\left((\boldsymbol{\lambda}_{r+1} - \boldsymbol{\lambda}_p)\sqrt{\frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\mathbf{\Lambda}_2)}}\right).
\end{aligned}$$

The last display, combined with (S3.19), leads to

$$\begin{aligned}
&\operatorname{tr}\left(\left(\mathbf{\Lambda}_2 - \frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2\right) \\
=&O_P\left(n(\boldsymbol{\lambda}_{r+1} - \boldsymbol{\lambda}_p)\left(\sqrt{\frac{\operatorname{tr}(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}} + \sqrt{\frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\mathbf{\Lambda}_2)}}\right)\right).
\end{aligned}$$

It then follows from (S3.17), (S3.18) and the last display that

$$\begin{aligned}
&\operatorname{tr}\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\mathbf{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) \\
=&\operatorname{tr}(\mathbf{\Lambda}_2) - \frac{n\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)} \\
&+ O_P\left(n(\boldsymbol{\lambda}_{r+1} - \boldsymbol{\lambda}_p)\left(\sqrt{\frac{\operatorname{tr}(\mathbf{\Lambda}_2)\boldsymbol{\lambda}_1}{n\boldsymbol{\lambda}_r^2}} + \sqrt{\frac{n\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\mathbf{\Lambda}_2)}}\right) + r\boldsymbol{\lambda}_{r+1}\right).
\end{aligned}$$

Then the conclusion follows from (S3.16) and the last display. □

Lemma 9. *Suppose $p > n$, we have*

$$\begin{aligned}
&\sum_{i=r+1}^{p}\lambda_i^2\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) \\
=&\operatorname{tr}(\mathbf{\Lambda}_2^2) - \frac{n\operatorname{tr}^2(\mathbf{\Lambda}_2^2)}{\operatorname{tr}^2(\mathbf{\Lambda}_2)} + O_P\left(n\boldsymbol{\lambda}_{r+1}(\boldsymbol{\lambda}_{r+1} - \boldsymbol{\lambda}_p) + r\boldsymbol{\lambda}_{r+1}^2\right).
\end{aligned}$$

Proof. From (S3.14) and (S3.15), we have

$$\begin{aligned}
&\left|\sum_{i=r+1}^{p}\lambda_i^2\left((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\right)-\operatorname{tr}\left((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\right)^2\right|\\
\leq& r\lambda_1^2\left((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\right)\\
\leq& r\boldsymbol{\lambda}_{r+1}^2.
\end{aligned} \tag{S3.20}$$

It is straightforward to show that

$$\begin{aligned}
&\operatorname{tr}\left((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\right)^2\\
=&\operatorname{tr}(\boldsymbol{\Lambda}_2^2)-2\operatorname{tr}(\boldsymbol{\Lambda}_2^2\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2)+\operatorname{tr}(\boldsymbol{\Lambda}_2\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2)^2.
\end{aligned}$$

For the second term, we have

$$\begin{aligned}
&\left|\operatorname{tr}(\boldsymbol{\Lambda}_2^2\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2)-\frac{\operatorname{tr}^2(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}^2(\boldsymbol{\Lambda}_2)}\operatorname{tr}(\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2)\right|\\
=&\left|\operatorname{tr}\left(\left(\boldsymbol{\Lambda}_2^2-\frac{\operatorname{tr}^2(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}^2(\boldsymbol{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2\right)\right|\\
\leq& n\boldsymbol{\lambda}_{r+1}(\boldsymbol{\lambda}_{r+1}-\boldsymbol{\lambda}_p),
\end{aligned}$$

where the last equality follows from von Neumann's trace theorem. The last display, combined with (S3.18), implies that

$$\operatorname{tr}(\boldsymbol{\Lambda}_2^2\mathbf{U}_2^\top\mathbf{P}_{\mathbf{Y}}\mathbf{U}_2)=\frac{n\operatorname{tr}^2(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}^2(\boldsymbol{\Lambda}_2)}+O_P\left(n\boldsymbol{\lambda}_{r+1}(\boldsymbol{\lambda}_{r+1}-\boldsymbol{\lambda}_p)+r\boldsymbol{\lambda}_{r+1}^2\right).$$

For the third term, von Neumann's trace theorem implies that

$$\begin{aligned}
&\left|\operatorname{tr}(\boldsymbol{\Lambda}_2\mathbf{U}_2^\top\mathbf{P}_\mathbf{Y}\mathbf{U}_2)^2-\frac{\operatorname{tr}^2(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}^2(\boldsymbol{\Lambda}_2)}\operatorname{tr}(\mathbf{U}_2^\top\mathbf{P}_\mathbf{Y}\mathbf{U}_2)^2\right|\\
=&\left|\operatorname{tr}\left(\left(\boldsymbol{\Lambda}_2-\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\mathbf{P}_\mathbf{Y}\mathbf{U}_2\left(\boldsymbol{\Lambda}_2+\frac{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}\mathbf{I}_{p-r}\right)\mathbf{U}_2^\top\mathbf{P}_\mathbf{Y}\mathbf{U}_2\right)\right|\\
\le&2n\boldsymbol{\lambda}_{r+1}(\boldsymbol{\lambda}_{r+1}-\boldsymbol{\lambda}_p).
\end{aligned}$$

Note that

$$\begin{aligned}
\operatorname{tr}(\mathbf{U}_2^\top\mathbf{P}_\mathbf{Y}\mathbf{U}_2)^2=&\operatorname{tr}\left(\mathbf{P}_\mathbf{Y}-\mathbf{P}_\mathbf{Y}\mathbf{U}_1\mathbf{U}_1^\top\right)^2\\
=&n-2\operatorname{tr}(\mathbf{P}_\mathbf{Y}\mathbf{U}_1\mathbf{U}_1^\top)+\operatorname{tr}(\mathbf{P}_\mathbf{Y}\mathbf{U}_1\mathbf{U}_1^\top)^2\\
=&n+O_P(r).
\end{aligned}$$

Therefore, the third term satisfies

$$\operatorname{tr}(\boldsymbol{\Lambda}_2\mathbf{U}_2^\top\mathbf{P}_\mathbf{Y}\mathbf{U}_2)^2=\frac{n\operatorname{tr}^2(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}^2(\boldsymbol{\Lambda}_2)}+O_P\left(n\boldsymbol{\lambda}_{r+1}(\boldsymbol{\lambda}_{r+1}-\boldsymbol{\lambda}_p)+r\boldsymbol{\lambda}_{r+1}^2\right).$$

Thus,

$$\begin{aligned}
&\operatorname{tr}\left((\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\right)^2\\
=&\operatorname{tr}(\boldsymbol{\Lambda}_2^2)-\frac{n\operatorname{tr}^2(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}^2(\boldsymbol{\Lambda}_2)}+O_P\left(n\boldsymbol{\lambda}_{r+1}(\boldsymbol{\lambda}_{r+1}-\boldsymbol{\lambda}_p)+r\boldsymbol{\lambda}_{r+1}^2\right).
\end{aligned}$$

Then the conclusion follows from the last display and (S3.20). □

Proof of Theorem 2. We have

$$\begin{aligned}
&\mathbf{Z}^{\dagger\top}\boldsymbol{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\mathbf{U}\boldsymbol{\Lambda}^{1/2}\mathbf{Z}^\dagger\\
=&\sum_{i=1}^r\lambda_i((\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_\mathbf{Y}))\eta_i\eta_i^\top+\sum_{i=r+1}^p\lambda_i((\mathbf{I}_p-\mathbf{P}_\mathbf{Y})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_\mathbf{Y}))\eta_i\eta_i^\top.
\end{aligned}$$

From Lemma 7, the first term satisfies

$$\sum_{i=1}^{r} \lambda_i((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}))\eta_i\eta_i^\top = (1 + o_P(r^{-1/2}))n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2)\sum_{i=1}^{r}\eta_i\eta_i^\top.$$

Then

$$\begin{aligned}&\frac{\sum_{i=1}^{r} \lambda_i((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}))\eta_i\eta_i^\top - rn^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2)\mathbf{I}_{k-1}}{\sqrt{r}n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2)}\\ =&\frac{\sum_{i=1}^{r}\eta_i\eta_i^\top - r\mathbf{I}_{k-1}}{\sqrt{r}} + o_P(1).\end{aligned} \tag{S3.21}$$

Next we deal with the term $\sum_{i=r+1}^{p} \lambda_i((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}))\eta_i\eta_i^\top$. In the current context, Lemma 8 and Lemma 9 imply that

$$\sum_{i=r+1}^{p} \lambda_i\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) = \operatorname{tr}(\boldsymbol{\Lambda}_2) - \frac{n\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}{\operatorname{tr}(\boldsymbol{\Lambda}_2)} + o_P\left(\sqrt{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}\right), \tag{S3.22}$$

$$\sum_{i=r+1}^{p} \lambda_i^2\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right) = (1 + o_P(1))\operatorname{tr}(\boldsymbol{\Lambda}_2^2). \tag{S3.23}$$

By Weyl's inequality, we have

$$\begin{aligned}&\lambda_{r+1}((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}))\\ =&\lambda_{r+1}\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_1\boldsymbol{\Lambda}_1\mathbf{U}_1^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}) + (\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)\\ \le&\lambda_1\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)\\ \le&\boldsymbol{\lambda}_{r+1}.\end{aligned}$$

The last display and (S3.22) imply that

$$\frac{\lambda_{r+1}^2\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)}{\sum_{i=r+1}^{p}\lambda_i^2\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top(\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)} \le \frac{\boldsymbol{\lambda}_{r+1}^2}{(1 + o_P(1))\operatorname{tr}(\boldsymbol{\Lambda}_2^2)} \xrightarrow{P} 0.$$

Then Lemma 2 implies that

$$\frac{1}{\sqrt{\sum_{i=r+1}^{p}\lambda_i^2((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}}))}}\left(\sum_{i=r+1}^{p}\lambda_i((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}}))\eta_i\eta_i^\top \right.$$
$$\left. -\sum_{i=r+1}^{p}\lambda_i((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}}))\mathbf{I}_{k-1}\right)\xrightarrow{\mathcal{L}}\mathbf{W}_{k-1}.$$

The last display, combined with (S3.22) and (S3.23), leads to

$$\begin{aligned}\frac{1}{\sqrt{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}}\Bigg(&\sum_{i=r+1}^{p}\lambda_i((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}}))\eta_i\eta_i^\top \\ &-\big(\operatorname{tr}(\boldsymbol{\Lambda}_2)-n\operatorname{tr}(\boldsymbol{\Lambda}_2^2)/\operatorname{tr}(\boldsymbol{\Lambda}_2)\big)\,\mathbf{I}_{k-1}\Bigg)\xrightarrow{\mathcal{L}}\mathbf{W}_{k-1}.\end{aligned}\tag{S3.24}$$

Note that $\sum_{i=1}^{r}\eta_i\eta_i^\top$ is independent of $\sum_{i=r+1}^{p}\lambda_i((\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\boldsymbol{\Sigma}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}}))\eta_i\eta_i^\top$.

Then(S3.21) and (S3.24) implies that

$$\begin{aligned}&\frac{\mathbf{Z}^{\dagger\top}\boldsymbol{\Lambda}^{1/2}\mathbf{U}^\top(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\mathbf{U}\boldsymbol{\Lambda}^{1/2}\mathbf{Z}^{\dagger}-((1+r/n)\operatorname{tr}(\boldsymbol{\Lambda}_2)-n\operatorname{tr}(\boldsymbol{\Lambda}_2^2)/\operatorname{tr}(\boldsymbol{\Lambda}_2))\,\mathbf{I}_{k-1}}{\sqrt{rn^{-2}\operatorname{tr}^2(\boldsymbol{\Lambda}_2)+\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}}\\ \sim&\frac{n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2)}{\sqrt{rn^{-2}\operatorname{tr}^2(\boldsymbol{\Lambda}_2)+\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}}(\mathbf{W}_{k-1}^*-r\mathbf{I}_{k-1})+\frac{\sqrt{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}}{\sqrt{rn^{-2}\operatorname{tr}^2(\boldsymbol{\Lambda}_2)+\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}}\mathbf{W}_{k-1}\\ &+o_P(1).\end{aligned}\tag{S3.25}$$

This completes the proof of the first statement.

Now we prove the second statement. For the second term of (S3.1), we have $\mathbf{C}^\top\boldsymbol{\Theta}^\top(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\boldsymbol{\Theta}\mathbf{C}=\mathbf{C}^\top\boldsymbol{\Theta}^\top\boldsymbol{\Theta}\mathbf{C}-\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{P}_{\mathbf{Y}}\boldsymbol{\Theta}\mathbf{C}$. We need to deal with $\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{P}_{\mathbf{Y}}\boldsymbol{\Theta}\mathbf{C}$. Note that Proposition 3 implies that

$$\left\|\mathbf{P}_{\mathbf{Y},1}-\mathbf{U}_1\mathbf{U}_1^\top\right\|\leq\left\|\mathbf{P}_{\mathbf{Y},1}-\mathbf{P}_{\mathbf{Y},1}^{\dagger}\right\|+2\left\|\mathbf{Q}\right\|=o_P(1).$$

It follows from the last display and Proposition 4 that

$$
\begin{aligned}
&\left\|\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{P}_{\mathbf{Y}}\boldsymbol{\Theta}\mathbf{C}-\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{U}_1\mathbf{U}_1^\top\boldsymbol{\Theta}\mathbf{C}-\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{P}_{\mathbf{Y},2}^\dagger\boldsymbol{\Theta}\mathbf{C}\right\|\\
\le&\left\|\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{P}_{\mathbf{Y},1}\boldsymbol{\Theta}\mathbf{C}-\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{U}_1\mathbf{U}_1^\top\boldsymbol{\Theta}\mathbf{C}\right\|\\
&+\left\|\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{P}_{\mathbf{Y},2}\boldsymbol{\Theta}\mathbf{C}-\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{P}_{\mathbf{Y},2}^\dagger\boldsymbol{\Theta}\mathbf{C}\right\|\\
\le&\left\|\mathbf{C}^\top\boldsymbol{\Theta}^\top\boldsymbol{\Theta}\mathbf{C}\right\|\left(\left\|\mathbf{P}_{\mathbf{Y},1}-\mathbf{U}_1\mathbf{U}_1^\top\right\|+\left\|\mathbf{P}_{\mathbf{Y},2}-\mathbf{P}_{\mathbf{Y},2}^\dagger\right\|\right)\\
=&o_P\left(\sqrt{rn^{-2}\operatorname{tr}^2(\boldsymbol{\Lambda}_2)+\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}\right).
\end{aligned}
$$

We have

$$
\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{P}_{\mathbf{Y},2}^\dagger\boldsymbol{\Theta}\mathbf{C}=\left(\operatorname{tr}(\boldsymbol{\Lambda}_2)\right)^{-1}\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}\tilde{\mathbf{V}}_{\mathbf{Z}_1}^\top\mathbf{Z}_2^\top\boldsymbol{\Lambda}_2^{1/2}\mathbf{U}_2^\top\boldsymbol{\Theta}\mathbf{C}.
$$

Note that $\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}$ is a $(p-r)\times(n-r)$ matrix with iid $\mathcal{N}(0,1)$ entries. Then the columns of $\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}$ are iid $\mathcal{N}_{k-1}(\mathbf{0}_{k-1},\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top\boldsymbol{\Theta}\mathbf{C})$ random vectors. Write $\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{U}_2\boldsymbol{\Lambda}_2^{1/2}\mathbf{Z}_2\tilde{\mathbf{V}}_{\mathbf{Z}_1}=(\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top\boldsymbol{\Theta}\mathbf{C})^{1/2}\mathbf{Z}^*$, where $\mathbf{Z}^*$ is a $(k-1)\times(n-r)$ random matrix with iid $\mathcal{N}(0,1)$ entries. Then

$$
\begin{aligned}
&\left\|\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{P}_{\mathbf{Y},2}^\dagger\boldsymbol{\Theta}\mathbf{C}-\frac{n}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top\boldsymbol{\Theta}\mathbf{C}\right\|\\
\le&\frac{n}{\operatorname{tr}(\boldsymbol{\Lambda}_2)}\left\|\mathbf{C}^\top\boldsymbol{\Theta}^\top\mathbf{U}_2\boldsymbol{\Lambda}_2\mathbf{U}_2^\top\boldsymbol{\Theta}\mathbf{C}\right\|\left\|n^{-1}\mathbf{Z}^*\mathbf{Z}^{*\top}-\mathbf{I}_{k-1}\right\|\\
=&o_P\left(\sqrt{rn^{-2}\operatorname{tr}^2(\boldsymbol{\Lambda}_2)+\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}\right),
\end{aligned}
$$

where the last equality follows from the law of large numbers, the local alternative condition and the condition $n\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\boldsymbol{\Lambda}_2) \to 0$. But

$$\begin{aligned}\frac{n}{\operatorname{tr}(\boldsymbol{\Lambda}_2)} \left\|\mathbf{C}^\top \boldsymbol{\Theta}^\top \mathbf{U}_2 \boldsymbol{\Lambda}_2 \mathbf{U}_2^\top \boldsymbol{\Theta}\mathbf{C}\right\| \leq & \frac{n\boldsymbol{\lambda}_2}{\operatorname{tr}(\boldsymbol{\Lambda}_2)} \left\|\mathbf{C}^\top \boldsymbol{\Theta}^\top \boldsymbol{\Theta}\mathbf{C}\right\| \\ = & o_P\left(\sqrt{rn^{-2}\operatorname{tr}^2(\boldsymbol{\Lambda}_2) + \operatorname{tr}(\boldsymbol{\Lambda}_2^2)}\right).\end{aligned}$$

Hence $\left\|\mathbf{C}^\top \boldsymbol{\Theta}^\top \mathbf{P}_{\mathbf{Y},2}^\dagger \boldsymbol{\Theta}\mathbf{C}\right\| = o_P\left(\sqrt{rn^{-2}\operatorname{tr}^2(\boldsymbol{\Lambda}_2) + \operatorname{tr}(\boldsymbol{\Lambda}_2^2)}\right)$. Consequently, $\left\|\mathbf{C}^\top \boldsymbol{\Theta}^\top \mathbf{P}_{\mathbf{Y}} \boldsymbol{\Theta}\mathbf{C} - \mathbf{C}^\top \boldsymbol{\Theta}^\top \mathbf{U}_1 \mathbf{U}_1^\top \boldsymbol{\Theta}\mathbf{C}\right\| = o_P\left(\sqrt{rn^{-2}\operatorname{tr}^2(\boldsymbol{\Lambda}_2) + \operatorname{tr}(\boldsymbol{\Lambda}_2^2)}\right)$. Thus, the second term of (S3.1) satisfies

$$\begin{aligned}& \left\|\mathbf{C}^\top \boldsymbol{\Theta}^\top (\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}) \boldsymbol{\Theta}\mathbf{C} - \mathbf{C}^\top \boldsymbol{\Theta}^\top \mathbf{U}_2 \mathbf{U}_2^\top \boldsymbol{\Theta}\mathbf{C}\right\| \\ = & o_P\left(\sqrt{rn^{-2}\operatorname{tr}^2(\boldsymbol{\Lambda}_2) + \operatorname{tr}(\boldsymbol{\Lambda}_2^2)}\right).\end{aligned} \tag{S3.26}$$

Next we consider the cross term of (S3.1). Note that

$$\begin{aligned}& \mathrm{E}[\|\mathbf{C}^\top \boldsymbol{\Theta}^\top (\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}) \mathbf{U}\boldsymbol{\Lambda}^{1/2}\mathbf{Z}^\dagger\|_F^2 | \mathbf{Y}] \\ = & (k-1)\operatorname{tr}(\mathbf{C}^\top \boldsymbol{\Theta}^\top (\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}) \boldsymbol{\Sigma} (\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}) \boldsymbol{\Theta}\mathbf{C}) \\ \leq & (k-1)\lambda_1\left((\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}) \boldsymbol{\Sigma} (\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}})\right)\operatorname{tr}(\mathbf{C}^\top \boldsymbol{\Theta}^\top \boldsymbol{\Theta}\mathbf{C}) \\ = & O_P\left(n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2)\left\|\mathbf{C}^\top \boldsymbol{\Theta}^\top \boldsymbol{\Theta}\mathbf{C}\right\|\right),\end{aligned}$$

where the last equality follows from Lemma 7. Under the condition $r \to \infty$ or $\operatorname{tr}(\boldsymbol{\Lambda}_2)/(n\sqrt{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}) \to 0$, we have $n^{-1}\operatorname{tr}(\boldsymbol{\Lambda}_2) = o_P\left(\sqrt{rn^{-2}\operatorname{tr}^2(\boldsymbol{\Lambda}_2) + \operatorname{tr}(\boldsymbol{\Lambda}_2^2)}\right)$. Therefore,

$$\|\mathbf{C}^\top \boldsymbol{\Theta}^\top (\mathbf{I}_p - \mathbf{P}_{\mathbf{Y}}) \mathbf{U}\boldsymbol{\Lambda}^{1/2}\mathbf{Z}^\dagger\| = o_P\left(\sqrt{rn^{-2}\operatorname{tr}^2(\boldsymbol{\Lambda}_2) + \operatorname{tr}(\boldsymbol{\Lambda}_2^2)}\right).$$

It follows from the last display, (S3.26) and Weyl's inequality that

$$
\begin{aligned}
&\left|T(\mathbf{X})-\lambda_1\left(\mathbf{Z}^{\dagger\top}\mathbf{\Lambda}^{1/2}\mathbf{U}^{\dagger}(\mathbf{I}_p-\mathbf{P}_{\mathbf{Y}})\mathbf{U}\mathbf{\Lambda}^{1/2}\mathbf{Z}^{\dagger}+\mathbf{C}^{\top}\mathbf{\Theta}^{\top}\mathbf{U}_2\mathbf{U}_2^{\top}\mathbf{\Theta}\mathbf{C}\right)\right|\\
=&o_P\left(\sqrt{rn^{-2}\operatorname{tr}^2(\mathbf{\Lambda}_2)+\operatorname{tr}(\mathbf{\Lambda}_2^2)}\right).
\end{aligned}
$$

Then the second statement follows from the last display and (S3.25).

□

Proof of Corollary 2. From Proposition 2, we have

$$
rn^{-2}(\widehat{\operatorname{tr}(\mathbf{\Lambda}_2)})^2+\widehat{\operatorname{tr}(\mathbf{\Lambda}_2^2)}=(1+o_P(1))(rn^{-2}\operatorname{tr}^2(\mathbf{\Lambda}_2)+\operatorname{tr}(\mathbf{\Lambda}_2^2)),
$$

and

$$
\begin{aligned}
&(1+r/n)\widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}-n\widehat{\operatorname{tr}(\mathbf{\Lambda}_2^2)}/\widehat{\operatorname{tr}(\mathbf{\Lambda}_2)}\\
=&(1+r/n)\operatorname{tr}(\mathbf{\Lambda}_2)+O_P\left(r\sqrt{\frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{n}}+r\boldsymbol{\lambda}_{r+1}\right)\\
&-\frac{n\operatorname{tr}(\mathbf{\Lambda}_2^2)\left(1+O_P\left(r/n+r\boldsymbol{\lambda}_{r+1}^2/\operatorname{tr}(\mathbf{\Lambda}_2^2)\right)\right)}{\operatorname{tr}(\mathbf{\Lambda}_2)\left(1+O_P\left(r\sqrt{\operatorname{tr}(\mathbf{\Lambda}_2^2)/n\operatorname{tr}^2(\mathbf{\Lambda}_2)}+r\boldsymbol{\lambda}_{r+1}/\operatorname{tr}(\mathbf{\Lambda}_2)\right)\right)}\\
=&(1+r/n)\operatorname{tr}(\mathbf{\Lambda}_2)+O_P\left(r\sqrt{\frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{n}}+r\boldsymbol{\lambda}_{r+1}\right)\\
&-\frac{n\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)}\left(1+O_P\left(\frac{r}{n}+\frac{r\boldsymbol{\lambda}_{r+1}^2}{\operatorname{tr}(\mathbf{\Lambda}_2^2)}+r\sqrt{\frac{\operatorname{tr}(\mathbf{\Lambda}_2^2)}{n\operatorname{tr}^2(\mathbf{\Lambda}_2)}}+\frac{r\boldsymbol{\lambda}_{r+1}}{\operatorname{tr}(\mathbf{\Lambda}_2)}\right)\right)\\
=&(1+r/n)\operatorname{tr}(\mathbf{\Lambda}_2)-\frac{n\operatorname{tr}(\mathbf{\Lambda}_2^2)}{\operatorname{tr}(\mathbf{\Lambda}_2)}+o_P\left(\sqrt{\operatorname{tr}(\mathbf{\Lambda}_2^2)}\right).
\end{aligned}
$$

Therefore,

$$
Q_2=\frac{T(\mathbf{X})-((1+r/n)\operatorname{tr}(\mathbf{\Lambda}_2)-n\operatorname{tr}(\mathbf{\Lambda}_2^2)/\operatorname{tr}(\mathbf{\Lambda}_2))}{\sqrt{rn^{-2}\operatorname{tr}^2(\mathbf{\Lambda}_2)+\operatorname{tr}(\mathbf{\Lambda}_2^2)}}+o_P(1).
$$

On the other hand, it is not hard to see that the ratio consistency of $\widehat{\operatorname{tr}(\boldsymbol{\lambda}_2)}$ and $\widehat{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}$ imply $F_2^{-1}(1-\alpha; \widehat{\operatorname{tr}(\boldsymbol{\Lambda}_2)}, \widehat{\operatorname{tr}(\boldsymbol{\Lambda}_2^2)}) = F_2^{-1}(1-\alpha; \operatorname{tr}(\boldsymbol{\Lambda}_2), \operatorname{tr}(\boldsymbol{\Lambda}_2^2)) + o_P(1)$. Then the conclusion follows from Theorem 2 and Slutsky's theorem.

□

Proof of Proposition 5. Under the conditions of Theorem 1, we have $n\boldsymbol{\lambda}_1/\operatorname{tr}(\boldsymbol{\Sigma}) \to 0$. From Lemma 5 and Weyl's inequality, we have

$$\begin{aligned}
\lambda_1(\hat{\boldsymbol{\Sigma}}) =& n^{-1}\lambda_1(\mathbf{Z}^\top \boldsymbol{\Lambda}\mathbf{Z}) \\
=& n^{-1}\operatorname{tr}(\boldsymbol{\Sigma}) + O_P\left(\sqrt{\frac{\operatorname{tr}(\boldsymbol{\Sigma}^2)}{n}} + \boldsymbol{\lambda}_1\right) \\
=& (1+o_P(1))n^{-1}\operatorname{tr}(\boldsymbol{\Sigma}).
\end{aligned}$$

From the proof of Corollary 1, we have $\operatorname{tr}(\hat{\boldsymbol{\Sigma}}) = (1+o_P(1))\operatorname{tr}(\boldsymbol{\Sigma})$. Therefore,

$$\frac{n\lambda_1(\hat{\boldsymbol{\Sigma}})}{\operatorname{tr}(\hat{\boldsymbol{\Sigma}})} \xrightarrow{P} 1.$$

This completes the proof of (i).

Now we prove (ii). Under the conditions of Theorem 2, Proposition 1 implies that

$$\begin{aligned}
\frac{n\lambda_1(\hat{\boldsymbol{\Sigma}})}{\operatorname{tr}(\hat{\boldsymbol{\Sigma}})} =& \frac{n\lambda_1(\hat{\boldsymbol{\Sigma}})}{\sum_{i=1}^r \lambda_i(\hat{\boldsymbol{\Sigma}}) + \sum_{i=r+1}^n \lambda_i(\hat{\boldsymbol{\Sigma}})} \\
=& (1+o_P(1))\frac{n\boldsymbol{\lambda}_1 + \operatorname{tr}(\boldsymbol{\Lambda}_2)}{\sum_{i=1}^r \boldsymbol{\lambda}_i + \operatorname{tr}(\boldsymbol{\Lambda}_2)} \\
\geq& (1+o_P(1))\frac{n\boldsymbol{\lambda}_1}{r\boldsymbol{\lambda}_1 + \operatorname{tr}(\boldsymbol{\Lambda}_2)} \xrightarrow{P} \infty.
\end{aligned}$$

It follows that

$$\Pr\left(\frac{n\lambda_1(\hat{\mathbf{\Sigma}})}{\operatorname{tr}(\hat{\mathbf{\Sigma}})} < \tau\right) \to 0.$$

Next we consider the consistency of $\hat{r}$. Note that

$$\{\hat{r} = r\} = \left\{\frac{n\lambda_{i+1}(\hat{\mathbf{\Sigma}})}{\sum_{j=i+1}^{n}\lambda_j(\hat{\mathbf{\Sigma}})} \geq \tau, i = 1, \ldots, r-1\right\} \cap \left\{\frac{n\lambda_{r+1}(\hat{\mathbf{\Sigma}})}{\sum_{j=r+1}^{n}\lambda_j(\hat{\mathbf{\Sigma}})} < \tau\right\}.$$

But Proposition 1 implies that uniformly for $i = 1, \ldots, r-1$,

$$\begin{aligned}\frac{n\lambda_{i+1}(\hat{\mathbf{\Sigma}})}{\sum_{j=i+1}^{n}\lambda_j(\hat{\mathbf{\Sigma}})} \geq& \frac{n\lambda_{i+1}(\hat{\mathbf{\Sigma}})}{(r-i)\lambda_{i+1}(\hat{\mathbf{\Sigma}}) + \sum_{j=r+1}^{n}\lambda_j(\hat{\mathbf{\Sigma}})} \\ =&(1 + o_P(1))\frac{n\boldsymbol{\lambda}_{i+1} + \operatorname{tr}(\mathbf{\Lambda}_2)}{(r-i)\boldsymbol{\lambda}_{i+1} + (1 - i/n)\operatorname{tr}(\mathbf{\Lambda}_2)} \xrightarrow{P} \infty.\end{aligned}$$

Thus, we only need to prove that

$$\Pr\left(\frac{n\lambda_{r+1}(\hat{\mathbf{\Sigma}})}{\sum_{j=r+1}^{n}\lambda_j(\hat{\mathbf{\Sigma}})} < \tau\right) \to 1.$$

Weyl' inequality implies that $n\lambda_{r+1}(\hat{\mathbf{\Sigma}}) = \lambda_{r+1}(\mathbf{Z}_1^\top\mathbf{\Lambda}_1\mathbf{Z}_1 + \mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2) \leq \lambda_1(\mathbf{Z}_2^\top\mathbf{\Lambda}_2\mathbf{Z}_2)$. Then using Lemma 5, we have $n\lambda_{r+1}(\hat{\mathbf{\Sigma}}) \leq (1+o_P(1))\operatorname{tr}(\mathbf{\Lambda}_2)$. Thus,

$$\frac{n\lambda_{r+1}(\hat{\mathbf{\Sigma}})}{\sum_{j=r+1}^{n}\lambda_j(\hat{\mathbf{\Sigma}})} \leq (1 + o_P(1)).$$

This completes the proof.

□

References

Cai, T., Z. Ma, and Y. Wu (2015). Optimal estimation and rank detection for sparse spiked covariance matrices. *Probability Theory & Related*

Fields 161(3-4), 781–815.

Chen, S. X., L. Zhang, and P. Zhong (2010). Tests for high-dimensional covariance matrices. *Journal of the American Statistical Association 105*(490), 810–819.

Horn, R. A. and C. R. Johnson (2012). *Matrix Analysis* (2nd ed.). New York: Cambridge University Press.

Laurent, B. and P. Massart (2000). Adaptive estimation of a quadratic functional by model selection. *The Annals of Statistics 28*(5), 1302–1338.

Vershynin, R. (2010). Introduction to the non-asymptotic analysis of random matrices. *arXiv preprint arXiv:1011.3027*.