Efficient estimation of conditional covariance matrices for dimension reduction
Jean-Michel Loubes, Clément Marteau, Michael Solis, Sébastien da Veiga

To cite this version:
Jean-Michel Loubes, Clément Marteau, Michael Solis, Sébastien da Veiga. Efficient estimation of conditional covariance matrices for dimension reduction. 2011. hal-00632576

HAL Id: hal-00632576
https://hal.archives-ouvertes.fr/hal-00632576
Preprint submitted on 14 Oct 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Efficient estimation of conditional covariance matrices for dimension reduction

JEAN-MICHEL LOUBES
Institut de Mathématiques de Toulouse
loubes@math.univ-toulouse.fr

CLÉMENT MARTEAU
Institut de Mathématiques de Toulouse
clement.marteau@insa-toulouse.fr

MICHAEL SOLÍS CHACÓN
Institut de Mathématiques de Toulouse
msolisch@math.univ-toulouse.fr

SEBASTIEN DA VEIGA
Institut Français du Pétrole
sebastien.da-veiga@ifp.fr

Abstract

We consider the problem of estimating a conditional covariance matrix in an inverse regression setting. We show that this estimation can be achieved by estimating a quadratic functional extending the results of Da Veiga & Gamboa (2008). We prove that this method provides a new efficient estimator whose asymptotic properties are studied.

1 Introduction

Consider the nonparametric regression

\[ Y = \varphi(X) + \epsilon, \]

where \( X \in \mathbb{R}^p, Y \in \mathbb{R} \) and \( \mathbb{E}[\epsilon] = 0 \). The main difficulty with any regression method is that, as the dimension of \( X \) becomes larger, the number of observations needed for a good estimator increases exponentially. This phenomena is usually called the curse of dimensionality. All the “classical” methods could break down, as the dimension \( p \) increases, unless we have at hand a very huge sample.
For this reason, there have been along the past decades a very large number of methods to cope with this issue. Their aim is to reduce the dimensionality of the problem, using just to name a few, the generalized linear model in Brillinger (1983), the additive models in Hastie & Tibshirani (1990), sparsity constraint models as Li (2007) and references therein.

Alternatively, Li (1991a) proposed the procedure of Sliced Inverse Regression (SIR) considering the following semiparametric model,

$$Y = \phi(v_1^\top X, \ldots, v_K^\top X, \epsilon)$$

where the \(v\)'s are unknown vectors in \(\mathbb{R}^p\), \(\epsilon\) is independent of \(X\) and \(\phi\) is an arbitrary function in \(\mathbb{R}^{K+1}\). This model can gather all the relevant information about the variable \(Y\), with only the projection of \(X\) onto the \(K \ll p\) dimensional subspace \((v_1^\top X, \ldots, v_K^\top X)\). In the case when \(K\) is small, it is possible to reduce the dimension by estimating the \(v\)'s efficiently. This method is also used to search nonlinear structures in data and to estimate the projection directions \(v\)'s. For a review on SIR methods, we refer to Li (1991a,b); Duan & Li (1991); Hardle & Tsybakov (1991) and references therein. The \(v\)'s define the effective dimension reduction (e.d.r) direction and the eigenvectors of \(\mathbb{E}[\text{Cov}(X|Y)]\) are the e.d.r. directions. Many estimators have been proposed in order to study the e.d.r directions in many different cases. For example, Zhu & Fang (1996) and Ferré & Yao (2005, 2003) use kernel estimators, Hsing (1999) combines nearest neighbor and SIR, Bura & Cook (2001) assume that \(\mathbb{E}[X|Y]\) has some parametric form, Setodji & Cook (2004) use k-means and Cook & Ni (2005) transform SIR to least square form.

In this paper, we propose an alternate estimation of the matrix

$$\text{Cov}(\mathbb{E}[X|Y]) = \mathbb{E}[\mathbb{E}[X|Y] \mathbb{E}[X|Y]^\top] - \mathbb{E}[X] \mathbb{E}[X]^\top,$$

using ideas developed by Da Veiga & Gamboa (2008), inspired by the prior work of Laurent (1996). More precisely since \(\mathbb{E}[X] \mathbb{E}[X]^\top\) can be easily estimated with many usual methods, we will focus on finding an estimator of \(\mathbb{E}[\mathbb{E}[X|Y] \mathbb{E}[X|Y]^\top]\). For this we will show that this estimation implies an estimation of a quadratic functional rather than plugging non parametric estimate into this form as commonly used. This method has the advantage of getting an efficient estimator in a semi-parametric framework.

This paper is organized as follows. Section 2 is intended to motivate our investigation of \(\text{Cov}(\mathbb{E}[X|Y])\) using a Taylor approximation. In Section 3.1 we set up notation and hypothesis. Section 3.2 is devoted to demonstrate that each coordinate of \(\text{Cov}(\mathbb{E}[X|Y])\) converge efficiently. Also we find the normality asymptotic for the whole matrix. An asymptotic bound of the variance for the quadratic part for the Taylor’s expansion of \(\text{Cov}(\mathbb{E}[X|Y])\) is found in Section 4. All technical Lemmas and their proofs are postponed to Sections 6 and 5 respectively.
2 Methodology

Our aim is to estimate \( \text{Cov}(\mathbb{E}[X|Y]) \) efficiently when observing \( X \in \mathbb{R}^p \), for \( p \geq 1 \), and \( Y \in \mathbb{R} \). For this, write the matrix

\[
\text{Cov}(\mathbb{E}[X|Y]) = \mathbb{E}[\mathbb{E}[X|Y] \mathbb{E}[X|Y]^\top] - \mathbb{E}[X] \mathbb{E}[X]^\top,
\]

where \( A^\top \) means the transpose of \( A \). If \( \mathbb{E}[X] \) can be easily estimated by classical methods, the remainder term

\[
\mathbb{E}[\mathbb{E}[X|Y] \mathbb{E}[X|Y]^\top] = (T^*_i)_{ij} \quad i, j = 1, \ldots, p;
\]

is a non linear term whose estimation is the main topic of this paper. Each term of this matrix can be written as

\[
T^*_i = \frac{\int x_i f(x_i, x_j, y)dx_i dx_j}{\int f(x_i, x_j, y)dx_i dx_j} \left( \frac{\int x_j f(x_i, x_j, y)dx_i dx_j}{\int f(x_i, x_j, y)dx_i dx_j} \right) f(x_i, x_j, y)dx_i dx_j dy,
\]

where \( f(x_i, x_j, y) \) for \( i \) and \( j \) fixed, is the joint density of \((X_i, X_j, Y)\) \( i, j = 1, \ldots, p \).

Hence, we focus on the efficient estimation of the corresponding non linear functional for \( f \in \mathbb{L}(dx_i, dx_j, dy) \)

\[
f \mapsto T_{ij}(f) = \int \left( \frac{\int x_i f(x_i, x_j, y)dx_i dx_j}{\int f(x_i, x_j, y)dx_i dx_j} \right) \left( \frac{\int x_j f(x_i, x_j, y)dx_i dx_j}{\int f(x_i, x_j, y)dx_i dx_j} \right) f(x_i, x_j, y)dx_i dx_j dy.
\]

In the case \( i = j \), this estimation has been considered in \cite{DaVeigaGamboa2008, Laurent1996}. Here we extend their methodology to this case. Assume we have at hand an i.i.d sample \( (X_i^{(k)}, X_j^{(k)}, Y^{(k)}) \), \( k = 1, \ldots, n \) such that it is possible to build a preliminary estimator \( \hat{f} \) of \( f \) with a subsample of size \( n_1 < n \). Now, the main idea is to make a Taylor’s expansion of \( T_{ij}(f) \) in a neighborhood of \( \hat{f} \) which will play the role of a suitable approximation of \( f \). More precisely, define an auxiliar function \( F : [0, 1] \to \mathbb{R} \);

\[
F(u) = T_{ij}(uf + (1 - u)\hat{f})
\]

with \( u \in [0, 1] \). The Taylor’s expansion of \( F \) between 0 and 1 up to the third order is

\[
F(1) = F(0) + F'(0) + \frac{1}{2} F''(0) + \frac{1}{6} F'''(\xi)(1 - \xi)^3
\]

for some \( \xi \in [0, 1] \). Moreover, we have

\[
F(1) = T_{ij}(f)
\]

\[
F(0) = T_{ij}(\hat{f}) = \int \left( \frac{\int x_i \hat{f}(x_i, x_j, y)dx_i dx_j}{\int \hat{f}(x_i, x_j, y)dx_i dx_j} \right) \left( \frac{\int x_j \hat{f}(x_i, x_j, y)dx_i dx_j}{\int \hat{f}(x_i, x_j, y)dx_i dx_j} \right) \hat{f}(x_i, x_j, y)dx_i dx_j dy.
\]

To simplify the notations, let

\[
m_i(f_u, y) = \frac{\int x_i f_u(x_i, x_j, y)dx_i dx_j}{\int f_u(x_i, x_j, y)dx_i dx_j}
\]

\[
m_i(f_0, y) = m_i(\hat{f}, y) = \frac{\int x_i \hat{f}(x_i, x_j, y)dx_i dx_j}{\int \hat{f}(x_i, x_j, y)dx_i dx_j},
\]

3
where \( f_u = uf + (1 - u)\hat{f} \), \( \forall u \in [0, 1] \). Then, we can rewrite \( F(u) \) as

\[
F(u) = \int m_i(f_u, y)m_j(f_u, y)f_u(x_i, x_j, y)dx_idx_jdy.
\]

The Taylor’s expansion of \( T_{ij}(f) \) is given in the next Proposition.

**Proposition 1** (Linearization of the operator \( T \)). For the functional \( T_{ij}(f) \) defined in (2), the following decomposition holds

\[
T_{ij}(f) = \int H_1(\hat{f}, x_i, x_j, y)f(x_i, x_j, y)dx_idx_jdy
+ \int H_2(\hat{f}, x_{i1}, x_{j2}, y)f(x_{i1}, x_{j1}, y)f(x_{i2}, x_{j2}, y)dx_{i1}dx_{j1}dx_{i2}dx_{j2}dy + \Gamma_n
\]

where

\[
H_1(\hat{f}, x_i, x_j, y) = x_im_j(\hat{f}, y) + x_jm_i(\hat{f}, y) - m_i(\hat{f}, y)m_j(\hat{f}, y)
\]

\[
H_2(\hat{f}, x_{i1}, x_{j2}, y) = \frac{1}{\int \hat{f}(x_i, x_j, y)dx_idx_j}(x_{i1} - m_i(\hat{f}, y))(x_{j2} - m_j(\hat{f}, y))
\]

\[
\Gamma_n = \frac{1}{6}F'''(\xi)(1 - \xi)^3,
\]

for some \( \xi \in ]0, 1[ \).

This decomposition has the main advantage of separating the terms to be estimated into a linear functional of \( f \), which can be easily estimated and a second part which is a quadratic functional of \( f \). In this case, Section 4 will be dedicated to estimate this kind of functionals and specifically to control its variance. This will enable to provide an efficient estimator of \( T_{ij}(f) \) using the decomposition of Proposition 1.

### 3 Main Results

In this section we build a procedure to estimate \( T_{ij}(f) \) efficiently. Since we used \( n_1 < n \) to build a preliminary approximation \( \hat{f} \), we will use a sample of size \( n_2 = n - n_1 \) to estimate (5) and (6). Since (5) is a linear functional of the density \( f \), it can be estimated by its empirical counterpart

\[
\frac{1}{n_2} \sum_{k=1}^{n_2} H_1(\hat{f}, X_i^{(k)}, X_j^{(k)}, Y^{(k)}).
\]

Since (6) is a nonlinear functional of \( f \), the estimation is harder. Its estimation will be a direct consequence of the technical results presented in Section 4, where we build an estimator for the general functional

\[
\theta(f) = \int \eta(x_{i1}, x_{j2}, y)f(x_{i1}, x_{j1}, y)f(x_{i2}, x_{j2}, y)dx_{i1}dx_{j1}dx_{i2}dx_{j2}dy
\]

where \( \eta: \mathbb{R}^3 \to \mathbb{R} \) is a bounded function. The estimator \( \hat{\theta}_n \) of \( \theta(f) \) is an extension of the method developed in Da Veiga & Gamboa (2008).
3.1 Hypothesis and Assumptions

The following notations will be used throughout the paper. Let $d_s$ and $b_s$ for $s = 1, 2, 3$ be real numbers where $d_s < b_s$. Let, for $i$ and $j$ fixed, $\mathbb{L}^2(dx, dy, dz)$ be the squared integrable functions in the cube $[d_1, b_1] \times [d_2, b_2] \times [d_3, b_3]$. Moreover, let $(p_i(x, y, z))_{i \in D}$ be an orthonormal basis of $\mathbb{L}^2(dx, dy, dz)$, where $D$ is a countable set. Let $a_i = \int p_i f$ denote the scalar product of $f$ with $p_i$.

Furthermore, denote by $\mathbb{L}^2(dx, dy, dz)$ (resp. $\mathbb{L}^2(dy)$) the set of squared integrable functions in $[d_1, b_1] \times [d_2, b_2]$ (resp. $[d_3, b_3]$). If $(\alpha_{i\alpha}(x, y)_{i\alpha \in D_1})$ (resp. $(\beta_{i\beta}(y)_{i\beta \in D_2})$) is an orthonormal basis of $\mathbb{L}^2(dx, dy, dz)$ (resp. $\mathbb{L}^2(dy)$) then $p_l(x, y, z) = \alpha_{i\alpha}(x, y)\beta_{i\beta}(y)$ with $l = (l_{\alpha}, l_{\beta}) \in D_1 \times D_2$.

We also use the following subset of $\mathbb{L}^2(dx, dy, dz)$

$$\mathcal{E} = \left\{ \sum_{i \in D} e_i p_i : (e_i)_{i \in D} \text{ is such that } \sum_{i \in D} \left| \frac{e_i}{c_i} \right|^2 < 1 \right\}$$

where $(c_i)_{i \in D}$ is a given fixed sequence.

Moreover assume that $(X_i, X_j, Y)$ have a bounded joint density $f$ on $[d_1, b_1] \times [d_2, b_2] \times [d_3, b_3]$ which lies in the ellipsoid $\mathcal{E}$.

In what follows, $X_n \xrightarrow{D} X$ (resp. $X_n \xrightarrow{P} X$) denotes the convergence in distribution or weak convergence (resp. convergence in probability) of $X_n$ to $X$.

Moreover assume that $(X_i, X_j, Y)$ have a bounded joint density $f$ on $[d_1, b_1] \times [d_2, b_2] \times [d_3, b_3]$ which lies in the ellipsoid $\mathcal{E}$.

Assumption 1. For all $n \geq 1$ there is a subset $M_n \subset D$ such that $(\sup_{l \in M_n} |c_l|^2)^2 \leq |M_n|/n^2$ ($A_n \approx B$ means $\lambda_1 \leq A_n/B \leq \lambda_2$ for some positives constants $\lambda_1$ and $\lambda_2$). Moreover, $\forall f \in L^2(dx, dy, dz)$, $\int (S_{M_n} f - f)^2 dx dy dz \to 0$ when $n \to 0$, where $S_{M_n} f = \sum_{l \in M_n} a_l p_l$

Assumption 2. $\supp f \subset [d_1, b_1] \times [d_2, b_2] \times [d_3, b_3]$ and $\forall (x, y, z) \in \supp f, 0 < \alpha \leq f(x, y, z) \leq \beta$ with $\alpha, \beta \in \mathbb{R}$.

Assumption 3. It is possible to find an estimator $\hat{f}$ of $f$ built with $n_1 \approx n/\log(n)$ observations, such that for $\epsilon > 0$,

$$\forall (x, y, z) \in \supp f, 0 < \alpha - \epsilon \leq \hat{f}(x, y, z) \leq \beta + \epsilon$$

and,

$$\forall 2 \leq q \leq +\infty, \forall l \in \mathbb{N}^n, |E_f| \| \hat{f} - f \|^q \leq C(q, l)n^{-\lambda}$$

for some $\lambda > 1/6$ and some constant $C(q, l)$ not depending on $f$ belonging to the ellipsoid $\mathcal{E}$.

Assumption 1 is necessary to bound the bias and variance of $\hat{\theta}_n$. Assumption 2 and 3 allow to establish that the remainder term in the Taylor expansion is negligible, i.e $\Gamma_n = O(1/n)$. Assumption 3 depends on the regularity of the density function. For instance for $x \in \mathbb{R}^p$, $s > 0$ and $L > 0$, consider the class
\[ H_q(s, L) \] of Nikol’skii of functions \( f \in \mathbb{L}^r(dx) \) with partials derivatives up to order \( r = \lfloor s \rfloor \) inclusive, and for each of these derivatives \( g^{(r)} \)

\[
\| f^{(r)}(\cdot + h) - f^{(r)}(\cdot) \|_q \leq L |h|^{s-r} \quad \forall h \in \mathbb{R}.
\]

Then, Assumption 3 is satisfied for \( f \in H_q(s, L) \) with \( s > \frac{p}{q} \).

### 3.2 Efficient Estimation of \( T_{ij}(f) \)

As seen in Section 2, \( T_{ij}(f) \) can be decomposed as (4). Hence, using (8) and (14) we consider the following estimate

\[
\hat{T}_{ij}^{(n)} = \frac{1}{n^2} \sum_{k=1}^{n_2} H_1(\hat{f}, X_i^{(k)}, X_j^{(k)}, Y^{(k)}) \\
+ \frac{1}{n_2(n_2 - 1)} \sum_{l \in M} \sum_{k \neq k'}^{n_2} p_l(X_i^{(k)}, X_j^{(k)}, Y^{(k)}) \int p_l(x_i, x_j, Y^{(k')}) H_3(\hat{f}, x_i, x_j, X_i^{(k')}, X_j^{(k')}, Y^{(k')}) dx_i dx_j \\
- \frac{1}{n_2(n_2 - 1)} \sum_{l \in M} \sum_{k \neq k'}^{n_2} p_l(X_i^{(k)}, X_j^{(k)}, Y^{(k)}) p_{l'}(X_i^{(k')}, X_j^{(k')}, Y^{(k')}) \\
\int p_l(x_i, x_j, y) p_{l'}(x_i, x_j, y) H_2(\hat{f}, x_i, x_j, y) dx_i dx_j dx_i dx_j dy.
\]

where \( H_3(f, x_i, x_j, x_k, x_l, y) = H_2(f, x_i, x_j, y) + H_2(f, x_k, x_l, y) \) and \( n_2 = n - n_1 \). The remainder \( \Gamma_n \) does not appear because we will prove that it is negligible when compared to the other error terms.

The asymptotic behavior of \( \hat{T}_{ij}^{(n)} \) for \( i \) and \( j \) fixed is given in the next Theorem.

**Theorem 1.** Let Assumptions 1-3 hold and \( |M_n|/n \to 0 \) when \( n \to \infty \). Then:

\[
\sqrt{n}(\hat{T}_{ij}^{(n)} - T_{ij}(f)) \xrightarrow{D} \mathcal{N}(0, C_{ij}(f)),
\]

and

\[
\lim_{n \to \infty} n \mathbb{E} \left[ (\hat{T}_{ij}^{(n)} - T_{ij}(f))^2 \right] = C_{ij}(f),
\]

where

\[
C_{ij}(f) = \text{Var}(H_1(f, X_i, X_j, Y)).
\]

Note that, in Theorem 1 it appears that the asymptotic variance of \( T_{ij}(f) \) depends only on \( H_1(f, X_i, X_j, Y) \). Hence the asymptotic variance of \( \hat{T}_{ij}^{(n)} \) is explained only by the linear part of (4). This will entail that the estimator is naturally efficient as proved in the following.

Indeed, the semi-parametric Cramér-Rao bound is given in the next theorem.

**Theorem 2** (Semi-parametric Cramér-Rao bound.). Consider the estimation of

\[
T_{ij}(f) = \int \left( \frac{\int x_i f(x_i, x_j, y) dx_i dx_j}{\int f(x_i, x_j, y) dx_i dx_j} \right) \left( \frac{\int x_j f(x_i, x_j, y) dx_i dx_j}{\int f(x_i, x_j, y) dx_i dx_j} \right) f(x_i, x_j, y) dx_i dx_j dy
\]

6
for a random vector \((X_i, X_j, Y)\) with joint density \(f \in \mathcal{E}\). Let \(f_0 \in \mathcal{E}\) be a density verifying the assumptions of Theorem 1. Then, for all estimator \(\hat{T}_{ij}^{(n)}(f)\) of \(T_{ij}(f)\) and every family \(\{\mathcal{V}_r(f_0)\}_{r > 0}\) of neighborhoods of \(f_0\) we have

\[
\inf_{\{\mathcal{V}_r(f_0)\}_{r > 0}} \liminf_{n \to \infty} \sup_{f \in \mathcal{V}_r(f_0)} n \mathbb{E} \left[ \hat{T}_{ij}^{(n)}(f) - T_{ij}(f_0) \right]^2 \geq C_{ij}(f_0)
\]

where \(\mathcal{V}_r(f_0) = \{ f : \|f - f_0\|_2 < r \}\) for \(r > 0\).

Consequently, the estimator \(\hat{T}_{ij}^{(n)}\) is efficient.

In the case of our estimate, its variance is \(C_{ij}(f)\), which proves its asymptotically efficiency.

Remark that Theorem 1 proves asymptotic normality entry by entry of the matrix \(T(f) = (T_{ij}(f))_{p \times p}\). To extend the result for the whole matrix it is necessary to introduce the half-vectorization operator \(\text{vech}\). This operator, stacks only the columns from the principal diagonal of a square matrix downwards in a column vector, that is, for an \(p \times p\) matrix \(A = (a_{ij})\),

\[
\text{vech}(A) = [a_{11}, \ldots, a_{p1}, a_{22}, \ldots, a_{p2}, \ldots, a_{33}, \ldots, a_{pp}]^\top.
\]

Let define the estimator matrix \(\hat{T}^{(n)} = (\hat{T}_{ij}^{(n)})\) and \(H_1(f)\) denote the matrix with entries \((H_1(f, x_i, x_j, y))_{i,j}\). Now we are able to state the following

**Corollary 1.** Let Assumptions 1-3 hold and \(|M_n|/n \to 0\) when \(n \to \infty\). Then \(\hat{T}^{(n)}\) has the following properties:

\[
\sqrt{n} \text{vech}(\hat{T}^{(n)} - T(f)) \xrightarrow{D} \mathcal{N}(0, C(f)),
\]

\[
\lim_{n \to \infty} n \mathbb{E} \left[ \text{vech}(\hat{T}^{(n)} - T(f)) \text{vech}(\hat{T}^{(n)} - T(f))^\top \right] = C(f)
\]

where

\[
C(f) = \text{Cov}(\text{vech}(H_1(f)))
\]

Previous results depend on the accurate estimation of the quadratic part of the estimator of \(T_{ij}^{(n)}\), which is the issue of the following section.

## 4 Estimation of quadratic functionals

As pointed out in Section 2 the decomposition (4) has a quadratic part (6) that we want to estimate. To achieve this we will construct a general estimator of the form:

\[
\theta = \int \eta(x_{i1}, x_{j2}, y)f(x_{i1}, x_{j1}, y)f(x_{i2}, x_{j2}, y)dx_{i1}dx_{j1}dx_{i2}dx_{j2}dy,
\]

for \(f \in \mathcal{E}\) and \(\eta : \mathbb{R}^3 \to \mathbb{R}\) a bounded function.
Given $M$, a subset of $D$, consider the estimator

$$\hat{\theta}_n = \frac{1}{n(n-1)} \sum_{l,M} \sum_{k,k'=1}^n p_l(X_i^{(k)}, X_j^{(k)}, Y^{(k)})$$

$$\int p_l(x_i, x_j, Y^{(k)}) \left( \eta(x_i, X_j^{(k')}), Y^{(k')} \right) dx_i dx_j$$

$$- \frac{1}{n(n-1)} \sum_{l,M} \sum_{k,k'=1}^n p_l(X_i^{(k)}, X_j^{(k)}, Y^{(k)} p_l(X_i^{(k)}, X_j^{(k)}, Y^{(k)}))$$

$$\int p_l(x_i, x_j, y) p_l(x, x, y) \eta(x, x, y) dx_i dx_j dx_j dy. \quad (13)$$

In order to simplify the presentation of the main Theorem, let $\psi(x_i, x_j, x_j, y) = \eta(x_i, x_j, y) + \eta(x_i, x_j, y)$ verifying

$$\int \psi(x_i, x_j, x_j, x_j, y) dx_i dx_j dx_j dx_j dy = \int \psi(x_i, x_j, x_i, x_j, y) dx_i dx_j dx_j dx_j dy.$$ 

With this notation we can simplify (13) in

$$\hat{\theta}_n = \frac{1}{n(n-1)} \sum_{l,M} \sum_{k,k'=1}^n p_l(X_i^{(k)}, X_j^{(k)}, Y^{(k)}) \int p_l(x_i, x_j, Y^{(k)}) \psi(x_i, x_j, X_i^{(k)}, X_j^{(k)}, Y^{(k)}) dx_i dx_j$$

$$- \frac{1}{n(n-1)} \sum_{l,M} \sum_{k,k'=1}^n p_l(X_i^{(k)}, X_j^{(k)}, Y^{(k)} p_l(X_i^{(k)}, X_j^{(k)}, Y^{(k)}))$$

$$\int p_l(x_i, x_j, y) p_l(x, x, y) \eta(x, x, y) dx_i dx_j dx_j dx_j dy. \quad (14)$$

Using simple algebra, it is possible to prove that this estimator has bias equal to

$$- \int (S_{M}f(x_i, x_j, y) - f(x_i, x_j, y))(S_{M}f(x_i, x_j, y) - f(x_i, x_j, y)) \eta(x, x, y) dx_i dx_j dx_j dx_j dy \quad (15)$$

The following Theorem gives an explicit bound for the variance of $\hat{\theta}_n$.

**Theorem 3.** Let Assumption 1 hold. Then if $|M_n|/n \rightarrow 0$ when $n \rightarrow 0$, then $\hat{\theta}_n$ has the following property

$$|nE[(\hat{\theta}_n - \theta)^2] - \Lambda(f, \eta)| \leq \gamma \left[ \frac{|M_n|}{n} + \|S_{M_n}f - f\|_2 + \|S_{M_n}g - g\|_2 \right], \quad (16)$$

where $g(x_i, x_j, y) = \int f(x_i, x_j, y) \psi(x_i, x_j, x_i, x_j, y) dx_i dx_j$ and

$$\Lambda(f, \eta) = \int g(x_i, x_j, y) f(x_i, x_j, y) dx_i dx_j dy - \left( \int g(x_i, x_j, y) f(x_i, x_j, y) dx_i dx_j dy \right)^2,$$

where $\gamma$ is constant depending only on $\|f\|_\infty$, $\|\eta\|_\infty$, and $\Delta_{x,x_j} = (b_1 - a_1) \times (b_2 - a_2)$. Moreover, this constant is an increasing function of these quantities.
Now, using (17) we first compute $F$ which has the form of the quadratic functional $\theta$ with the particular choice $\eta(x_{i1}, x_{j2}, y) = H_2(\hat{f}, x_{i1}, x_{j2}, y)$. We point out that we also show that in this particular frame, we get $\Lambda(f, \eta) = 0$. This is the reason why the asymptotic variance of the estimate $\hat{F}^{(n)}_{ij}$ built in the previous section, is only governed by its linear part, yielding asymptotic efficiency.

5 Proofs

Proof of Proposition 1

We need to calculate the three first derivatives of $F(u)$. In order to facilitate the calculation, we are going to differentiate $m_i(f_u, y)$:

$$\frac{d}{du}(m_i(f_u, y)) = \frac{d}{du}\left(\frac{\int x_i f_u(x_i, x_j, y)dx_idx_j}{\int f_u(x_i, x_j, y)dx_idx_j}\right)$$

$$= \frac{\int x_i(f(x_i, x_j, y) - \hat{f}(x_i, x_j, y))dx_idx_j}{\int f_u(x_i, x_j, y)dx_idx_j}$$

$$- \frac{\int x_i f_u(x_i, x_j, y)dx_idx_j \int f(x_i, x_j, y) - \hat{f}(x_i, x_j, y)dx_idx_j}{\left(\int f_u(x_i, x_j, y)dx_idx_j\right)^2}$$

$$= \frac{x_i(f(x_i, x_j, y) - \hat{f}(x_i, x_j, y))dx_idx_j}{\int f_u(x_i, x_j, y)dx_idx_j}$$

$$- \frac{m_i(f_u, y) \int f(x_i, x_j, y) - \hat{f}(x_i, x_j, y)dx_idx_j}{\int f_u(x_i, x_j, y)dx_idx_j}$$

$$= \frac{\int (x_i - m_i(f_u, y))(f(x_i, x_j, y) - \hat{f}(x_i, x_j, y))dx_idx_j}{\int f_u(x_i, x_j, y)dx_idx_j}.$$ (17)

Now, using (17) we first compute $F'(u)$,

$$\int \frac{d}{du}(m_i(f_u, y)) m_j(f_u, y) f_u(x_i, x_j, y) + m_i(f_u, y) \frac{d}{du}(m_j(f_u, y)) f_u(x_i, x_j, y)$$

$$+ m_i(f_u, y) m_j(f_u, y) \frac{d}{du}(f_u(x_i, x_j, y)) dx_idx_j dy,$$

$$= \int [x_i m_j(f_u, y) + x_j m_i(f_u, y) - m_i(f_u, y) m_j(f_u, y)] \left(f(x_i, x_j, y) - \hat{f}(x_i, x_j, y)\right) dx_idx_j dy.$$

Taking $u = 0$ we have

$$F'(0) = \int [x_i m_j(f, y) + x_j m_i(f, y) - m_i(f, y) m_j(f, y)] \left(f(x_i, x_j, y) - \hat{f}(x_i, x_j, y)\right) dx_idx_j dy.$$ (18)
We derive now $m_i(f_u, y)m_j(f_u, y)$ to obtain
\[
\frac{d}{du} (m_i(f_u, y)m_j(f_u, y)) = \frac{d}{du} (m_i(f_u, y))m_j(f_u, y) + m_i(f_u, y) \frac{d}{du} (m_j(f_u, y))
\]
\[
= m_j(f_u, y) \int (x_i - m_i(f_u, y)) (f(x_i, x_j, y) - \hat{f}(x_i, x_j, y)) dx_i dx_j
\]
\[
+ m_i(f_u, y) \int (x_j - m_j(f_u, y)) (f(x_i, x_j, y) - \hat{f}(x_i, x_j, y)) dx_i dx_j
\]
\[
\int f_u(x_i, x_j, y) dx_i dx_j
\]
(19)

Following with $F''(u)$ and using (17) and (19) we get,
\[
F''(u) = \int \left[ x_{i1} \int (x_{j2} - m_j(f_u, y)) (f(x_{i1}, x_{j2}, y) - \hat{f}(x_{i1}, x_{j2}, y)) dx_{i1} dx_{j2}
\]
\[
+ x_{j1} \int (x_{i2} - m_i(f_u, y)) (f(x_{i2}, x_{j1}, y) - \hat{f}(x_{i2}, x_{j1}, y)) dx_{i2} dx_{j1}
\]
\[
- m_j(f_u, y) \int f(x_{i2}, x_{j2}, y) (f(x_{i1}, x_{j2}, y) - \hat{f}(x_{i1}, x_{j2}, y)) dx_{i2} dx_{j2}
\]
\[
= m_i(f_u, y) \int f(x_{i1}, x_{j1}, y) (f(x_{i2}, x_{j2}, y) - \hat{f}(x_{i2}, x_{j2}, y)) dx_{i1} dx_{j1} dy.
\]

Simplifying the last expression we obtain
\[
F''(u) = \int \frac{1}{f_u(x_i, x_j, y) dx_i dx_j} \left\{ (x_{i1} - m_i(f_u, y)) (x_{j2} - m_j(f_u, y)) + (x_{i2} - m_i(f_u, y)) (x_{j1} - m_j(f_u, y)) \right\}
\]
\[
(f(x_{i1}, x_{j1}, y) - \hat{f}(x_{i1}, x_{j1}, y)) (f(x_{i2}, x_{j2}, y) - \hat{f}(x_{i2}, x_{j2}, y)) dx_{i1} dx_{j1} dx_{i2} dx_{j2} dy.
\]

Besides, when $u = 0$
\[
F''(0) = \int \frac{1}{f(x_i, x_j, y) dx_i dx_j} \left\{ (x_{i1} - m_i(f, y)) (x_{j2} - m_j(f, y)) + (x_{i2} - m_i(f, y)) (x_{j1} - m_j(f, y)) \right\}
\]
\[
(f(x_{i1}, x_{j1}, y) - \hat{f}(x_{i1}, x_{j1}, y)) (f(x_{i2}, x_{j2}, y) - \hat{f}(x_{i2}, x_{j2}, y)) dx_{i1} dx_{j1} dx_{i2} dx_{j2} dy.
\]
\[
= \int \frac{2}{f(x_i, x_j, y) dx_i dx_j} (x_{i1} - m_i(f, y)) (x_{j2} - m_j(f, y))
\]
\[
(f(x_{i1}, x_{j1}, y) - \hat{f}(x_{i1}, x_{j1}, y)) (f(x_{i2}, x_{j2}, y) - \hat{f}(x_{i2}, x_{j2}, y)) dx_{i1} dx_{j1} dx_{i2} dx_{j2} dy.
\]
(21)
Using the previous arguments we can finally find $F'''(u)$:

$$F'''(u) = -6 \int \frac{1}{f_u(x_1, x_2, x_3, y) dx_1 dx_2 dx_3} \left( x_1^3 - m_1(f_u, y) \right) \left( x_2^3 - m_2(f_u, y) \right) \left( x_3^3 - m_3(f_u, y) \right)$$

Replacing (18), (21) and (22) into (3) we get the desired decomposition. 

**Proof of Theorem 1**

We will first control the remaining term (7),

$$\Gamma_n = \frac{1}{6} F'''(\xi)(1 - \xi)^3.$$ 

Remember that

$$F'''(\xi) = -6 \int \frac{1}{f_u(x_1, x_2, x_3, y) dx_1 dx_2 dx_3} \left( x_1^3 - m_1(f_u, y) \right) \left( x_2^3 - m_2(f_u, y) \right) \left( x_3^3 - m_3(f_u, y) \right)$$

$$\left( f(x_{ij}, x_{ij}, y) - \hat{f}(x_{ij}, x_{ij}, y) \right) \left( f(x_{ij}, x_{ij}, y) - \hat{f}(x_{ij}, x_{ij}, y) \right) dx_1 dx_2 dx_3 dx_4 dy.$$ 

Assumptions 1 and 2 ensure that the first part of the integrand is bounded by a constant $\mu$. Furthermore,

$$|\Gamma_n| \leq \mu \int \left| f(x_{ij}, x_{ij}, y) - \hat{f}(x_{ij}, x_{ij}, y) \right| \left| f(x_{ij}, x_{ij}, y) - \hat{f}(x_{ij}, x_{ij}, y) \right| dx_1 dx_2 dx_3 dx_4 dy$$

$$\leq \mu \Delta^3_{x,y} \int \left| f(x_{ij}, x_{ij}, y) - \hat{f}(x_{ij}, x_{ij}, y) \right|^3 dx_1 dx_2 dx_3 dy$$

by the Hölder inequality. Then $E[\Gamma_n^2] = O(E(\int |f - \hat{f}|^3)^2) = O(\|f - \hat{f}\|_{\delta}^3)$. Since $\hat{f}$ verifies Assumption 3, this quantity is of order $O(n_1^{-6\lambda})$. Since we also assume $n_1 \approx n/ \log(n)$ and $\lambda > 1/6$, then $n_1^{-6\lambda} = o(1/n)$. Therefore, we get $E[\Gamma_n^2] = o(1/n)$ which implies that the remaining term $\Gamma_n$ is negligible.

To prove the asymptotic normality of $\hat{T}_{ij}^{(n)}$, we shall show that $\sqrt{n} \left( \hat{T}_{ij}^{(n)} - T_{ij}(f) \right)$ and define

$$Z_{ij}^{(n)} = \frac{1}{n_2} \sum_{k=1}^{n_2} \left[ H_1(f, X_{ij}^{(k)}, X_{ij}^{(k)}, Y^{(k)}) - \int H_1(f, x_i, x_j, y) f(x_i, x_j, y) dx_i dx_j dy \right]$$

have the same asymptotic behavior. We can get for $Z_{ij}^{(n)}$ a classic central limit theorem with variance

$$C_{ij}(f) = \text{Var}(H_1(f, x_i, x_j, y))$$

$$= \int H_1(f, x_i, x_j, y)^2 f(x_i, x_j, y) dx_i dx_j dy - \left( \int H_1(f, x_i, x_j, y) f(x_i, x_j, y) dx_i dx_j dy \right)^2$$
which implies (9) and (10). In order to establish our claim, we will show that
\[
P_{ij}^{(n)} = \sqrt{n} \left[ \hat{T}_{ij}^{(n)} - T_{ij}(f) - Z_{ij}^{(n)} \right]
\]
has second-order moment converging to 0.

Define \(\hat{Z}_{ij}^{(n)}\) as \(Z_{ij}^{(n)}\) with \(f\) replaced by \(\hat{f}\). Let us note that \(P_{ij}^{(n)} = R_1 + R_2\) where
\[
R_1 = \sqrt{n} \left[ \hat{T}_{ij}^{(n)} - T_{ij}(f) - \hat{Z}_{ij}^{(n)} \right]
\]
\[
R_2 = \sqrt{n} \left[ \hat{Z}_{ij}^{(n)} - Z_{ij}^{(n)} \right].
\]

It only remains to state that \(\mathbb{E}[R_1^2]\) and \(\mathbb{E}[R_2^2]\) converges to 0. We can rewrite \(R_1\) as
\[
R_1 = -\sqrt{n} \left[ \hat{Q} - Q + \Gamma_n \right]
\]
where we note that
\[
Q = \int H_2(\hat{f}, x_{i1}, x_{j2}, y) f(x_{i1}, x_{j1}, y) f(x_{i2}, x_{j2}, y) dx_{i1}dx_{j1}dx_{i2}dx_{j2}dy
\]
\[
H_2(\hat{f}, x_{i1}, x_{j2}, y) = \frac{1}{\int \hat{f}(x_i, x_j, y)dx_i dx_j} \left( x_{i1} - m_1(\hat{f}, y) \right) \left( x_{j2} - m_2(\hat{f}, y) \right)
\]
has the form of a quadratic functional studied in Section 4 with \(\eta(x_{i1}, x_{j2}, y) = H_2(\hat{f}, x_{i1}, x_{j2}, y)\). Hence such functional can be estimated as done in Section 4 and let \(\hat{Q}\) be its corresponding estimator. Since \(\mathbb{E}[\Gamma_n^2] = o(1/n)\), we only have to control the term \(\sqrt{n}(\hat{Q} - Q)\) which is such that \(\lim_{n \to \infty} n \mathbb{E}[(\hat{Q} - Q)^2] = 0\) by Lemma 7. This Lemma implies that \(\mathbb{E}[R_1^2] \to 0\) as \(n \to \infty\). For \(R_2\) we have
\[
\mathbb{E}[R_2^2] = \frac{n}{n^2} \left[ \int \left( H_1(f, x_i, x_j, y) - H_1(\hat{f}, x_i, x_j, y) \right)^2 f(x_i, x_j, y) dx_i dx_j dy \right]
\]
\[
-\frac{n}{n^2} \left[ \int H_1(f, x_i, x_j, y) f(x_i, x_j, y) dx_i dx_j dy - \int H_1(\hat{f}, x_i, x_j, y)^2 f(x_i, x_j, y) dx_i dx_j dy \right]^2.
\]
The same arguments as the ones of Lemma 7 (mean value and Assumptions 2 and 3) show that \(\mathbb{E}[R_2^2] \to 0\).

**Proof of Theorem 2.** To prove the inequality we will use the usual framework described in [Ibragimov & Khas’minskii (1991)](IbragimovKhasminskii1991). The first step is to calculate the Fréchet derivative of \(T_{ij}(f)\) at some point \(f_0 \in \mathcal{E}\). Assumptions 2 and 3 and equation (4), imply that
\[
T_{ij}(f) - T_{ij}(f_0) = \int \left( x_i m_j(f_0, y) + x_j m_i(f_0, y) - m_i(f_0, y)m_j(f_0, y) \right) \left( f(x_i, x_j, y) - f_0(x_i, x_j, y) \right) dx_i dx_j dy + O \left( \int (f - f_0)^2 \right)
\]

12
where \( m_i(f_0, y) = \int x_i f_0(x, y) dx dy \). Therefore, the Fréchet derivative of \( T_{ij}(f) \) at \( f_0 \) is \( T_{ij}'(f_0) \cdot h = \langle H_1(f_0, \cdot), h \rangle \) with

\[
H_1(f_0, x, x, y) = x_i m_j(f_0, y) + x_j m_i(f_0, y) - m_i(f_0, y) m_j(f_0, y).
\]

Using the results of Ibragimov & Khas’minskii (1991), denote \( H(f_0) = \{ u \in L^2(dx, dy) : \int u(x, y) \sqrt{f_0(x, y)} dx dy = 0 \} \) the set of functions in \( L^2(dx, dy) \) orthogonal to \( \sqrt{f_0} \), \( \Pr_{H(f_0)} \) the projection onto \( H(f_0) \), \( A_n(t) = (\sqrt{f_0}) t / \sqrt{n} \) and \( P^{(n)}_f \) the joint distribution of \( (X^{(k)}_i, X^{(k)}_j) \) for \( k = 1, \ldots, n \) under \( f_0 \). Since \( (X^{(k)}_i, X^{(k)}_j) \) are i.i.d., the family \( \{ P^{(n)}_f, f \in E \} \) is differentiable in quadratic mean at \( f_0 \) and therefore locally asymptotically normal at all points \( f_0 \in E \) in the direction \( H(f_0) \) with normalizing factor \( A_n(f_0) \) (see the details in Van der Vaart (2000)). Then, by the results of Ibragimov & Khas’minskii (1991) say that under these conditions, denoting \( K_n = B_n \theta'(f_0) A_n \Pr_{H(f_0)} \) with \( B_n = \sqrt{n} u \), if \( K_n \xrightarrow{D} K \) and if \( K(u) = \langle t, u \rangle \), then for every estimator \( \hat{T}^{(n)}_{ij} \) of \( T_{ij}(f) \) and every family \( \mathcal{V}(f_0) \) of vicinities of \( f_0 \), we have

\[
\inf_{\{\mathcal{V}(f_0)\}} \liminf_{n \to \infty} \sup_{f \in \mathcal{V}(f_0)} n \mathbb{E} \left[ \| \hat{T}^{(n)}_{ij} - T_{ij}(f_0) \|^2 \right] \geq \| t \|^2_{L^2(dx, dy)}.
\]

Here,

\[
K_n(u) = \sqrt{n} T'(f_0) \cdot \frac{\sqrt{f_0}}{\sqrt{n}} \Pr_{H(f_0)}(u) = T'(f_0) \left( \sqrt{f_0} u - \sqrt{f_0} \int u \sqrt{f_0} \right),
\]

since for any \( u \in L^2(dx, dy) \) we can write it as \( u = \sqrt{f_0} \left( \sqrt{f_0}, u \right) + \Pr_{H(f_0)}(u) \). In this case \( K_n(u) \) does not depend on \( n \) and

\[
K(h) = T'(f_0) \cdot \left( \sqrt{f_0} \left( u - \sqrt{f_0} \int h \sqrt{f_0} \right) \right) = \int H_1(f_0, \cdot) \sqrt{f_0} u - \int H_1(f_0, \cdot) \sqrt{f_0} \int u \sqrt{f_0} = \langle t, u \rangle
\]

with

\[
t(x, x, y) = H_1(f_0, x, x, y) \sqrt{f_0} - \left( \int H_1(f_0, x, x, y) f_0 \right) \sqrt{f_0}.
\]

The semi-parametric Cramér-Rao bound for this problem is thus

\[
\| t \|^2_{L^2(dx, dy)} = \int H_1(f_0, x, x, y)^2 f_0 dx dy - \left( \int H_1(f_0, x, x, y) f_0 dx dy \right)^2 = C_{ij}(f_0)
\]

and we recognize the expression \( C_{ij}(f_0) \) found in Theorem I

\[\square\]

**Proof of Corollary I** The proof is based in the following observation. Employing equation (24) we have

\[
\hat{T}^{(n)} - T(f) = Z^{(n)}(f) + \frac{R^{(n)}}{\sqrt{n}}
\]

13
where \( Z^{(n)}(f) \) and \( R^{(n)} \) are matrices with elements \( Z_{ij}^{(n)} \) and \( R_{ij}^{(n)} \), defined in (23) and (24), respectively.

Hence we have,

\[
n\mathbb{E}[\| \text{vech} \left( \hat{T}^{(n)} - T(f) - Z^{(n)}(f) \right) \|^2] = \mathbb{E}[\| \text{vech} \left( R^{(n)} \right) \|^2] = \sum_{i \leq j} \mathbb{E}[\left( R_{ij}^{(n)} \right)^2].
\]

We see by Lemma [7] that \( \mathbb{E}[R_{ij}^2] \to 0 \) as \( n \to 0 \). It follows that

\[
n\mathbb{E}[\| \text{vech} \left( \hat{T}^{(n)} - T(f) - Z^{(n)}(f) \right) \|^2] \to 0 \quad \text{as} \quad n \to 0.
\]

We know that if \( X_n, X \) and \( Y_n \) are random variables, then if \( X_n \xrightarrow{D} X \) and \( (X_n - Y_n) \xrightarrow{D} 0 \), follows that \( Y_n \xrightarrow{D} X \).

Remember also that convergence in \( L^2 \) implies convergence in probability, therefore

\[
\sqrt{n} \text{vech} \left( \hat{T}^{(n)} - T(f) - Z^{(n)}(f) \right) \xrightarrow{P} 0.
\]

By the multivariate central limit theorem we have that \( \sqrt{n} \text{vech} \left( Z^{(n)}(f) \right) \xrightarrow{D} \mathcal{N}(0, C(f)) \). Therefore, \( \sqrt{n} \text{vech} \left( \hat{T}^{(n)} - T(f) \right) \xrightarrow{P} \mathcal{N}(0, C(f)) \).

**Proof of Theorem 3**

For abbreviation, we write \( M \) instead of \( M_n \) and set \( m = |M_n| \). We first compute the mean squared squared error of \( \hat{\theta}_n \) as

\[
\mathbb{E}[\hat{\theta}_n - \theta]^2 = \text{Bias}^2(\hat{\theta}_n) + \text{Var}(\hat{\theta}_n)
\]

where \( \text{Bias} (\hat{\theta}_n) = \mathbb{E}[\hat{\theta}_n] - \theta \).

We begin the proof by bounding \( \text{Var}(\hat{\theta}_n) \). Let \( A \) and \( B \) be \( m \times 1 \) vectors with components

\[
a_l = \int p_l(x_1, x_j, y) f(x_i, x_j, y) dx_i dx_j dy \quad l = 1, \ldots, m,
\]

\[
b_l = \int p_l(x_1, x_j, y) f(x_1, x_j, y) \psi(x_1, x_j, y) dx_1 dx_j dy
= \int p_l(x_i, x_j, y) g(x_i, x_j, y) dx_i dx_j dy \quad l = 1, \ldots, m
\]

where \( g(x, x, y) = \int f(x_1, x_j, y) \psi(x_1, x_j, y) dx_1 dx_j dy \). Let \( Q \) and \( R \) be \( m \times 1 \) vectors of centered functions

\[
q_l(x_i, x_j, y) = p_l(x_i, x_j, y) - a_l
\]

\[
r_l(x_i, x_j, y) = \int p_l(x_1, x_j, y) \psi(x, x_j, y) dx_1 dx_j dy - b_l
\]

for \( l = 1, \ldots, m \). Let \( C \) a \( m \times m \) matrix of constants

\[
c_{ll'} = \int p_l(x_1, x_j, y) p_{l'}(x_2, x_j, y) \eta(x_1, x_j, y) dx_1 dx_j dy \quad l, l' = 1, \ldots, m.
\]
Let us denote by $U_n$ the process

$$U_nh = \frac{1}{n(n-1)} \sum_{k \neq k'}^n h(X_i^{(k)}, X_j^{(k)}, Y^{(k)}, X_i^{(k')}, X_j^{(k')})$$

and $P_n$ the empirical measure

$$P_nh = \frac{1}{n} \sum_{k=1}^n h(X_i^{(k)}, X_j^{(k)}, Y^{(k)})$$

for some $h$ in $\mathbb{L}^2(dx_i, dx_j, dy)$. With these notations, $\hat{\theta}_n$ has the Hoeffding’s decomposition

$$\hat{\theta}_n = \frac{1}{n(n-1)} \sum_{l \in M, k \neq k'}^n (q_l(X_i^{(k)}, X_j^{(k)}, Y^{(k)}) + a_l)(r_l(X_i^{(k)}, X_j^{(k')}, Y^{(k')}) + b_l)
- \frac{1}{n(n-1)} \sum_{l,l' \in M, k \neq k'}^n (q_l(X_i^{(k)}, X_j^{(k)}, Y^{(k)}) + a_l)(q_{l'}(X_i^{(k')}, X_j^{(k')}, Y^{(k')}) + a_{l'})c_{ll'}$$

$$= U_nK + P_nL + A^\top B - A^\top CA$$

where

$$K(x_1, x_2, x_3, y_1, y_2, x_4, x_5, y_3) = Q^\top(x_1, x_2, y_1)R(x_2, x_3, y_2) - Q^\top(x_3, x_4, y_3)CQ(x_4, x_5, y_3)$$

$$L(x_1, x_2, y) = A^\top R(x_1, x_2, y) + BQ(x_3, x_4, y) - 2A^\top CQ(x_3, x_4, y).$$

Therefore $\text{Var}(\hat{\theta}_n) = \text{Var}(U_nK) + \text{Var}(P_nL) - 2\text{Cov}(U_nK, P_nL)$. These three terms are bounded in Lemmas 2-4 which gives

$$\text{Var}(\hat{\theta}_n) \leq \frac{20}{n(n-1)} \left\| \eta \right\|_\infty^2 \left\| f \right\|_\infty^2 \Delta_{x_i,x_j}^2(m + 1) + \frac{12}{n} \left\| \eta \right\|_\infty^2 \left\| f \right\|_\infty^2 \Delta_{x_i,x_j}^2.$$

For $n$ enough large and a constant $\gamma \in \mathbb{R}$,

$$\text{Var}(\hat{\theta}_n) \leq \gamma \left\| \eta \right\|_\infty^2 \left\| f \right\|_\infty^2 \Delta_{x_i,x_j}^2 \left( \frac{m}{n^2} + \frac{1}{n} \right).$$

The term $\text{Bias}(\hat{\theta}_n)$ is easily computed, as proven in Lemma 5, is equal to

$$- \int (S_Mf(x_1, x_2, y) - f(x_1, x_2, y)) \cdot (S_Mf(x_2, x_3, y) - f(x_2, x_3, y)) \cdot \eta(x_1, x_2, x_3, x_4, x_5, y)dx_1dx_2dx_3dx_4dx_5dy.$$

From Lemma 5 the bias of $\hat{\theta}_n$ is bounded by

$$\left| \text{Bias}(\hat{\theta}_n) \right| \leq \Delta_{x_i,x_j} \left\| \eta \right\|_\infty \sup_{l \in M} \left| c_l \right|^2.$$

The assumption of $\left( \sup_{l \in M} \left| c_l \right|^2 \right)^2 \approx m/n^2$ and since $m/n \to 0$, we deduce that $\mathbb{E}[\hat{\theta}_n - \theta]^2$ has a parametric rate of convergence $O(1/n)$. 

15
Finally to prove (16), note that
\[ n \mathbb{E} [\hat{\theta}_n - \theta]^2 = n \text{Bias}^2 (\hat{\theta}_n) + n \text{Var}(\hat{\theta}_n) \]
\[ = n \text{Bias}^2 (\hat{\theta}_n) + n \text{Var}(U_n K) + n \text{Var}(P_n L). \]

We previously proved that for some \( \lambda_1, \lambda_2 \in \mathbb{R} \)
\[
 n \text{Bias}^2 (\hat{\theta}_n) \leq \lambda_1 \Delta^2_x \| \eta \|_\infty^2 \frac{m}{n},
\]
\[
 n \text{Var}(U_n K) \leq \lambda_2 \Delta^2_x \| \eta \|_\infty^2 \frac{m}{n}.
\]

Thus, Lemma 5 implies
\[
 |n \text{Var}(P_n L) - \Lambda (f, \eta)| \leq \lambda \left[ \| S_M f - f \|_2 + \| S_M g - g \|_2 \right],
\]
where \( \lambda \) is an increasing function of \( \| f \|_\infty^2 \| \eta \|_\infty^2 \) and \( \Delta_x \). From all this we deduce (16) which ends the proof of Theorem 3.

\[ \Box \]

### 6 Technical Results

**Lemma 1 (Bias of \( \hat{\theta}_n \)).** The estimator \( \hat{\theta}_n \) defined in (14) estimates \( \theta \) with bias equal to
\[
- \int (S_M f(x_{i1}, x_{j1}, y) - f(x_{i1}, x_{j1}, y)) (S_M f(x_{i2}, x_{j2}, y) - f(x_{i2}, x_{j2}, y)) \eta(x_{i1}, x_{j2}, y) dx_{i1} dx_{j1} dx_{i2} dx_{j2} dy.
\]

**Proof.** Let \( \hat{\theta}_n = \hat{\theta}_n^1 - \hat{\theta}_n^2 \) where
\[
\hat{\theta}_n^1 = \frac{1}{n(n-1)} \sum_{l \in M} \sum_{k \neq k'} \int p_l(x_i, x_j, Y^{(k)}) \psi_l(x_{i1}, x_{j1}, Y^{(k)}) dx_{i1} dx_{j1} dx_{i2} dx_{j2} \]
\[
\hat{\theta}_n^2 = \frac{1}{n(n-1)} \sum_{l \in M} \sum_{k \neq k'} \int p_l(x_i, x_j, Y^{(k)}) \psi_l(x_{i1}, x_{j1}, Y^{(k)}) dx_{i1} dx_{j1} dx_{i2} dx_{j2}.
\]
Let us first compute $\mathbb{E}[\hat{\theta}_n^1]$.

$$
\mathbb{E}[\hat{\theta}_n^1] = \sum_{l \in M} \int p_l(x_{i_1}, y) f(x_{i_1}, y) dx_{i_1} dy \\
= \sum_{l \in M} \int p_l(x_{i_1}) \psi(x_{i_1}, x_{i_2}) f(x_{i_1}, y) dx_{i_1} dy \\
= \sum_{l \in M} \int \left( \sum_{r \in M} a_r p_r(x_{j_2}, y) \right) \psi(x_{i_1}, x_{i_2}) f(x_{i_1}, y) dx_{i_1} dy \\
= \int S_M f(x_{i_1}, y) \psi(x_{i_1}, x_{i_2}) f(x_{i_1}, y) dx_{i_1} dy \\
\quad + \int S_M f(x_{i_1}, x_{j_2}) f(x_{i_1}, y) \psi(x_{i_1}, x_{i_2}) f(x_{i_1}, y) dx_{i_1} dy.
$$

Now for $\hat{\theta}_n^2$, we get

$$
\mathbb{E}[\hat{\theta}_n^2] = \sum_{l, p \in M} \int p_l(x_{i_1}, y) f(x_{i_1}, y) dx_{i_1} dy \\
\quad \int p_p(x_{j_1}, y) f(x_{j_1}, y) dx_{j_1} dy \\
= \sum_{l, p \in M} \int \left( \sum_{r \in M} a_r p_r(x_{j_2}, y) \right) \left( \sum_{r \in M} a_r p_r(x_{j_2}, y) \right) \psi(x_{i_1}, x_{i_2}) f(x_{i_1}, y) dx_{i_1} dy \\
= \int S_M f(x_{i_1}, y) S_M f(x_{j_1}, y) \psi(x_{i_1}, x_{i_2}) f(x_{i_1}, y) dx_{i_1} dy.
$$

Arranging these terms and using

$$
\text{Bias } (\hat{\theta}_n) = \mathbb{E}[\hat{\theta}_n] - \theta = \mathbb{E}[\hat{\theta}_n^1] - \mathbb{E}[\hat{\theta}_n^2] - \theta
$$

we obtain the desire bias. \(\square\)

**Lemma 2** (Bound of $\text{Var}(U_n K)$). Under the assumptions of Theorem 3 we have

$$
\text{Var}(U_n K) \leq \frac{20}{n(n-1)} \| \eta \|_\infty^2 \| f \|_\infty^2 \Delta_x^2 (m + 1)
$$

**Proof.** Note that $U_n K$ is centered because $Q$ and $R$ are centered and $(X^{(k)}_i, X^{(k)}_j, Y^{(k)})$, $k = \ldots$
By the Cauchy-Schwarz inequality, we get

\[
\mathbb{E} [U_nK]^2 = \mathbb{E} \left( \frac{1}{n(n-1)} \sum_{k_1 \neq k_1'} \sum_{k_2 \neq k_2'} K(X_i^{(k_1)}, X_j^{(k_1')}, Y^{(k_1)}, X_i^{(k_1')}, X_j^{(k_1)}), Y^{(k_1')}) \right)
\]

\[
= \frac{1}{n(n-1)} \mathbb{E} \left( K^2(X_i^{(1)}, X_j^{(1)}, Y^{(1)}, X_i^{(2)}, X_j^{(2)}, Y^{(2)}) \right)
\]

\[
+ K(X_i^{(1)}, X_j^{(1)}, Y^{(1)}, X_i^{(2)}, X_j^{(2)}, Y^{(2)}) K(X_i^{(2)}, X_j^{(2)}, Y^{(2)}, X_i^{(1)}, X_j^{(1)}, Y^{(1)}) \right)
\]

By the Cauchy-Schwarz inequality, we get

\[
\text{Var}(U_nK) \leq \frac{2}{n(n-1)} \mathbb{E}[K^2 \left( X_i^{(1)}, X_j^{(1)}, Y^{(1)}, X_i^{(2)}, X_j^{(2)}, Y^{(2)} \right)].
\]

Moreover, using the fact that \(2 \mathbb{E}[XY] \leq \mathbb{E}[X^2] + \mathbb{E}[Y^2] \), we obtain

\[
\mathbb{E}[K^2 \left( X_i^{(1)}, X_j^{(1)}, Y^{(1)}, X_i^{(2)}, X_j^{(2)}, Y^{(2)} \right)] \leq 2 \left[ \mathbb{E}[(Q^\top(X_i^{(1)}, X_j^{(1)}, Y^{(1)})R(X_i^{(2)}, X_j^{(2)}, Y^{(2)})]^2 \right]
\]

\[
+ \mathbb{E}[(Q^\top(X_i^{(1)}, X_j^{(1)}, Y^{(1)})CQ(X_i^{(2)}, X_j^{(2)}, Y^{(2)})]^2] \right)
\]

We will bound these two terms. The first one is

\[
\mathbb{E}[(Q^\top(X_i^{(1)}, X_j^{(1)}, Y^{(1)})R(X_i^{(2)}, X_j^{(2)}, Y^{(2)})]^2]
\]

\[
= \sum_{l,l' \in \mathcal{M}} \left( \int p_l(x_i, x_j, y)p_{l'}(x_i, x_j, y)f(x_i, x_j, y)dx_idx_jdy - a_l a_{l'} \right)
\]

\[
\left( \int p_l(x_{i2}, x_{j2}, y)p_{l'}(x_{i3}, x_{j3}, y)\psi(x_{i1}, x_{i1}, x_{i2}, x_{j2}, y)\psi(x_{i1}, x_{j1}, x_{i3}, x_{j3}, y)\right)\psi(x_{i1}, x_{j1}, x_{i3}, x_{j3}, y)f(x_{i1}, x_{j1}, y)dx_{i1}dx_{j1}dx_{i2}dx_{j2}dx_{i3}dx_{j3}dy - b_{l} b_{l'} \right)
\]

\[
= W_1 - W_2 - W_3 + W_4
\]
where

\[
W_1 = \int \sum_{l,l' \in M} p_l(x_{i1}, x_{j1}, y)p_{l'}(x_{i1}, x_{j1}, y)p_l(x_{i2}, x_{j2}, y')p_{l'}(x_{i3}, x_{j3}, y')\psi(x_{i4}, x_{j4}, x_{i2}, x_{j2}, y') dx_1 dx_2 dx_{j3} dx_{i4} dy dy'
\]

\[
W_2 = \int \sum_{l,l' \in M} b_l b_{l'} p_l(x_{i1}, x_{j1}, y)p_{l'}(x_{i1}, x_{j1}, y)f(x_{i1}, x_{j1}, y) dx_1 dx_1 dy
\]

\[
W_3 = \int \sum_{l,l' \in M} a_l a_{l'} p_l(x_{i2}, x_{j2}, y')p_{l'}(x_{i3}, x_{j3}, y')\psi(x_{i4}, x_{j4}, x_{i2}, x_{j2}, y') dx_2 dx_2 dx_{j3} dx_{i4} dy dy'
\]

\[
W_4 = \sum_{l,l' \in M} a_l a_{l'} b_l b_{l'}.
\]

\(W_2\) and \(W_3\) are positive, hence

\[
\mathbb{E}\left[\left(2Q^\top(X^{(1)}_i, X^{(1)}_j, Y^{(1)})R(X^{(2)}_i, X^{(2)}_j, Y^{(2)})\right)^2\right] \leq W_1 + W_4.
\]

\[
W_1 = \int \sum_{l,l' \in M} p_l(x_{i1}, x_{j1}, y)p_{l'}(x_{i1}, x_{j1}, y)\left(\int p_l(x_{i2}, x_{j2}, y')\psi(x_{i4}, x_{j4}, x_{i2}, x_{j2}, y') dx_2 dx_{j2}\right) dx_1 dx_1 dx_{j3} dx_{i4} dy dy'
\]

\[
\leq \|f\|^2 \sum_{l,l' \in M} \int p_l(x_{i1}, x_{j1}, y)p_{l'}(x_{i1}, x_{j1}, y) dx_1 dx_1 dy
\]

\[
\int \left(\int p_l(x_{i2}, x_{j2}, y')\psi(x_{i4}, x_{j4}, x_{i2}, x_{j2}, y') dx_{i2} dx_{j2}\right)
\]

\[
\int p_{l'}(x_{i3}, x_{j3}, y')\psi(x_{i4}, x_{j4}, x_{i3}, x_{j3}, y') dx_{i3} dx_{j3} dx_{i4} dx_{j4} dy'
\]

Since \(p_l\)'s are orthonormal we have

\[
W_1 \leq \|f\|^2 \sum_{l \in M} \int \left(\int p_l(x_{i2}, x_{j2}, y')\psi(x_{i4}, x_{j4}, x_{i2}, x_{j2}, y') dx_{i2} dx_{j2}\right)^2 dx_{i4} dx_{j4} dy'.
\]

Moreover by the Cauchy-Schwarz inequality and \(\|\psi\|_\infty \leq 2\|\eta\|_\infty\)

\[
\left(\int p_l(x_{i2}, x_{j2}, y')\psi(x_{i4}, x_{j4}, x_{i2}, x_{j2}, y') dx_{i2} dx_{j2}\right)^2 \leq \int p_l(x_{i2}, x_{j2}, y')^2 dx_{i2} dx_{j2}
\]

\[
\int \psi(x_{i4}, x_{j4}, x_{i2}, x_{j2}, y')^2 dx_{i2} dx_{j2}
\]

\[
\leq \|\psi\|_\infty^2 \Delta_{x,x} \int p_l(x_{i2}, x_{j2}, y')^2 dx_{i2} dx_{j2}
\]

\[
\leq 4\|\eta\|_\infty^2 \Delta_{x,x} \int p_l(x_{i2}, x_{j2}, y')^2 dx_{i2} dx_{j2},
\]

19
and then
\[
\int \left( \int p_l(x_{i2}, x_{j2}, y') \psi(x_{i4}, x_{j4}, x_{i2}, x_{j2}, y') \, dx_{i2} dx_{j2} \right)^2 \, dx_{i4} dx_{j4} dy' \leq 4 \| \eta \|_\infty^2 \Delta^2_{x,x_j} \int p_l(x_{i2}, x_{j2}, y')^2 \, dx_{i2} dx_{j2} dy' = 4 \| \eta \|_\infty^2 \Delta^2_{x,x_j}.
\]

Finally,
\[
W_1 \leq 4 \| \eta \|_\infty^2 \| f \|_\infty^2 \Delta^2_{x,x_j}, m.
\]

For the term \(W_4\) using the facts that \(S_M f\) and \(S_M g\) are projection and that \(\int f = 1\), we have
\[
W_4 = \left( \sum_{l \in M} a_l b_l \right)^2 \leq \sum_{l \in M} a_l^2 \sum_{l \in M} b_l^2 \leq \| f \|_2^2 \| g \|_2^2 \leq \| f \|_\infty \| g \|_2^2.
\]
By the Cauchy-Schwartz inequality we have \(\| g \|_2^2 \leq 4 \| \eta \|_\infty^2 \| f \|_\infty \Delta^2_{x,x_j}\), and then
\[
W_4 \leq 4 \| \eta \|_\infty^2 \| f \|_\infty^2 \Delta^2_{x,x_j}
\]
which leads to
\[
\mathbb{E} \left[ \left( Q^T (X^{(1)}, X^{(1)}, Y^{(1)}) R (X^{(2)}, X^{(2)}, Y^{(2)}) \right)^2 \right] \leq 4 \| \eta \|_\infty^2 \| f \|_\infty^2 \Delta^2_{x,x_j} (m + 1). \quad (25)
\]
The second term \(\mathbb{E} \left[ \left( Q^T (X^{(1)}, X^{(1)}, Y^{(1)}) C Q (X^{(2)}, X^{(2)}, Y^{(2)}) \right) \right] = W_5 - 2W_6 + W_7\) where
\[
W_5 = \int \sum_{l_1,l'_1} \sum_{l_2,l'_2} c_{l_1,l'_1} c_{l_2,l'_2} p_{l_1}(x_{i1}, x_{j1}, y) p_{l_2}(x_{i1}, x_{j1}, y) p_{l'_1}(x_{i2}, x_{j2}, y') p_{l'_2}(x_{i2}, x_{j2}, y') f(x_{i1}, x_{j1}, y) f(x_{i2}, x_{j2}, y') \, dx_{i1} dx_{j1} dx_{i2} dx_{j2} dy' \, dy.
\]
\[
W_6 = \int \sum_{l_1,l'_1} \sum_{l_2,l'_2} c_{l_1,l'_1} c_{l_2,l'_2} a_{l_1} a_{l'_1} p_{l_1}(x_{i1}, x_{j1}, y) p_{l_2}(x_{i1}, x_{j1}, y) p_{l'_1}(x_{i2}, x_{j2}, y') p_{l'_2}(x_{i2}, x_{j2}, y') \, dx_{i1} dx_{j1} dx_{i2} dx_{j2} dy dy' \, dy.
\]
\[
W_7 = \sum_{l_1,l'_1} \sum_{l_2,l'_2} c_{l_1,l'_1} c_{l_2,l'_2} a_{l_1} a_{l'_1} a_{l_2} a_{l'_2}.
\]

Using the previous manipulation, we show that \(W_6 \geq 0\). Thus
\[
\mathbb{E} \left[ \left( Q^T (X^{(1)}, X^{(1)}, Y^{(1)}) C Q (X^{(2)}, X^{(2)}, Y^{(2)}) \right) \right] \leq W_5 + W_7.
\]
First, observe that

\[ W_5 = \sum_{l_1,l_1',l_2,l_2'} c_{l_1 l_1'} c_{l_2 l_2'} \left( \int p_{l_1} (x_i, x_j, y) p_{l_2} (x_i, x_j, y) f (x_i, x_j, y) dx_i dx_j dy \right) \]
\[ \leq \| f \|_\infty^2 \sum_{l_1,l_1',l_2,l_2'} c_{l_1 l_1'} c_{l_2 l_2'} \left( \int p_{l_1} (x_i, x_j, y) p_{l_2} (x_i, x_j, y) dx_i dx_j dy \right) \]
\[ = \| f \|_\infty^2 \sum_{l,l'} c_{ll'}^2 \]

again using the orthonormality of the the \( p_l \)'s. Besides given the decomposition
\( p_l (x_i, x_j, y) = \alpha_{l_n} (x_i, x_j) \beta_{l_y} (y), \)

\[ \sum_{l,l'} c_{ll'}^2 = \sum_{l_1,l_1',l_2,l_2'} (\int \alpha_{l_n} (x_i, x_j) \alpha_{l_n'} (x_i, x_j) \beta_{l_y} (y) \beta_{l_y'} (y') dx_i dx_j dy) \]
\[ \sum_{l_1,l_1',l_2,l_2'} \left( \int \alpha_{l_n} (x_i, x_j) \alpha_{l_n'} (x_i, x_j) \beta_{l_y} (y) \beta_{l_y'} (y') dx_i dx_j dy \right) \]
\[ = \sum_{l_1,l_1',l_2,l_2'} \left( \int \alpha_{l_n} (x_i, x_j) \alpha_{l_n'} (x_i, x_j) \beta_{l_y} (y) \beta_{l_y'} (y') dx_i dx_j dy \right) \]
\[ \sum_{l_1,l_1'} \sum_{l_2,l_2'} \left( \int \alpha_{l_n} (x_i, x_j) \alpha_{l_n'} (x_i, x_j) \beta_{l_y} (y) \beta_{l_y'} (y') dx_i dx_j dy \right) \]
\[ = \sum_{l_1,l_1'} \left( \int \alpha_{l_n} (x_i, x_j) \alpha_{l_n'} (x_i, x_j) \beta_{l_y} (y) \beta_{l_y'} (y') dx_i dx_j dy \right) \]
\[ \sum_{l_1,l_1'} \left( \int \alpha_{l_n} (x_i, x_j) \alpha_{l_n'} (x_i, x_j) \beta_{l_y} (y) \beta_{l_y'} (y') dx_i dx_j dy \right) \]
\[ \leq \Delta_{x_i,x_j} \| \eta \|_\infty^2 \]
using the orthonormality of the basis $\alpha_i$. Then we get

$$
\sum_{l,l'} c_{l,l'}^2 \leq \Delta_{x,x_j}^2 \| \eta \|_\infty^2 \left( \int \sum_{l,l'} \beta_{l,l}(y) \beta_{l',l}(y')dydy' \right)
$$

$$
= \Delta_{x,x_j}^2 \| \eta \|_\infty^2 \sum_{l,l'} \left( \int \beta_{l,l}(y)dy \right)^2
$$

$$
\leq \Delta_{x,x_j}^2 \| \eta \|_\infty^2 m
$$

since the $\beta_{l,l}$ are orthonormal. Finally

$$
W_5 \leq \| f \|_\infty^2 \| \eta \|_\infty^2 \Delta_{x,x_j}^2 m.
$$

Now for $W_7$ we first will bound,

$$
\left| \sum_{l,l'} c_{l,l'} a_{l,l'} \right| = \left| \int \sum_{l,l'} a_{l,l'} p_{l,l}(x_{i1}, x_{j1}, y)p_{l,l}(x_{i2}, x_{j2}, y)\eta(x_{i1}, x_{j2}, y)d_{x_{i1}}d_{x_{i2}}d_{x_{j1}}d_{x_{j2}}dy \right|
$$

$$
\leq \left| \int S_M(x_{i1}, x_{j1}, y)S_M(x_{i2}, x_{j2}, y)\eta(x_{i1}, x_{j2}, y)d_{x_{i1}}d_{x_{i2}}d_{x_{j1}}d_{x_{j2}}dy \right|
$$

Taking squares in both sides and using the Cauchy-Schwartz inequality twice, we get

$$
\left( \sum_{l,l'} c_{l,l'} a_{l,l'} \right)^2 = \| \eta \|_\infty^2 \left( \int \left( \int S_M(x_{i1}, x_{j1}, y)S_M(x_{i2}, x_{j2}, y)dy \right)d_{x_{i1}}d_{x_{i2}}d_{x_{j1}}d_{x_{j2}} \right)^2
$$

$$
\leq \| \eta \|_\infty^2 \Delta_{x,x_j}^2 \left( \int \left( \int S_M(x_{i1}, x_{j1}, y)S_M(x_{i2}, x_{j2}, y)dy \right)d_{x_{i1}}d_{x_{i2}}d_{x_{j1}}d_{x_{j2}} \right)^2
$$

$$
\leq \| \eta \|_\infty^2 \Delta_{x,x_j}^2 \left( \int S_M(x_{i1}, x_{j1}, y)^2S_M(x_{i2}, x_{j2}, y')dydy' \right)d_{x_{i1}}d_{x_{i2}}d_{x_{j1}}d_{x_{j2}}
$$

$$
= \| \eta \|_\infty^2 \Delta_{x,x_j}^2 \left( \int S_M(x_{i1}, x_{j1}, y)^2dx_{i1}dx_{j1} \right)
$$

Finally,

$$
\mathbb{E}[\left( Q^T(X^{(1)}_i, X^{(1)}_j, Y^{(1)})CQ(X^{(2)}_i, X^{(2)}_j, Y^{(2)}) \right)^2] \leq \| \eta \|_\infty^2 \| f \|_\infty^2 \Delta_{x,x_j}^2 (m + 1). \quad (26)
$$
Collecting (25) and (26), we obtain

\[ \text{Var}(U_n K) \leq \frac{20}{n(n-1)} \| \eta \|_\infty^2 \| f \|_\infty^2 \Delta_x^2 \text{Var}_G, \]

which concludes the proof of Lemma 2.

**Lemma 3** (Bound for \( \text{Var}(P_n L) \)). Under the assumptions of Theorem 3 we have

\[ \text{Var}(P_n L) \leq \frac{12}{n} \| \eta \|_\infty^2 \| f \|_\infty^2 \Delta_x^2. \]

**Proof.** First note that given the independence of \((X_i^{(k)}, X_j^{(k)}, Y^{(k)}) \) \( k = 1, \ldots, n \) we have

\[ \text{Var}(P_n L) = \frac{1}{n} \text{Var}(L(X_i^{(1)}, X_j^{(1)}, Y^{(1)})) \]

we can write \( L(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) \) as

\[ A^T R \left( X_i^{(1)}, X_j^{(1)}, Y^{(1)} \right) + B^T Q \left( X_i^{(1)}, X_j^{(1)}, Y^{(1)} \right) - 2 A^T C Q \left( X_i^{(1)}, X_j^{(1)}, Y^{(1)} \right) \]

\[ = \sum_{l \in M} a_l \left( \int p_l(x_i, x_j, Y^{(1)}) \psi(x_i, x_j, X_i^{(1)}, X_j^{(1)}, Y^{(1)}) dx_i dx_j - b_l \right) \]

\[ + \sum_{l \in M} b_l \left( p_l(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) - a_l \right) - 2 \sum_{l, l' \in M} c_{ll'} a_{ll'} \left( p_l(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) - \psi \right) \]

\[ = \sum_{l \in M} \int a_l p_l(x_i, x_j, Y^{(1)}) \psi(x_i, x_j, X_i^{(1)}, X_j^{(1)}, Y^{(1)}) dx_i dx_j \]

\[ + \sum_{l \in M} b_l p_l(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) - 2 \sum_{l, l' \in M} c_{ll'} a_{ll'} p_l(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) - 2 A^T B - 2 A^T CA. \]

\[ = \sum_{l \in M} \int S_M f(x_i, x_j, Y^{(1)}) \psi(x_i, x_j, X_i^{(1)}, X_j^{(1)}, Y^{(1)}) dx_i dx_j + S_M g(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) \]

\[ - 2 \sum_{l, l' \in M} c_{ll'} a_{ll'} p_l(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) - 2 A^T B - 2 A^T CA. \]

Let \( h(x_i, x_j, y) = \int S_M f(x_i, x_j, y) \psi(x_i, x_j, x_{i2}, x_{j2}, y) dx_{i2} dx_{j2} \), we have

\[ S_M h(x_i, x_j, y) \]

\[ = \sum_{l \in M} \left( \int h(x_{i2}, x_{j2}, y) p_l(x_{i2}, x_{j2}, y) dx_{i2} dx_{j2} dy \right) p_l(x_i, x_j, y) \]

\[ = \sum_{l \in M} \left( \int S_M f(x_{i3}, x_{j3}, y) \psi(x_{i2}, x_{j2}, x_{i3}, x_{j3}, y) p_l(x_{i2}, x_{j2}, y) dx_{i2} dx_{j2} dx_{i3} dx_{j3} dy \right) p_l(x_i, x_j, y) \]

\[ = \sum_{l, l' \in M} \left( \int a_{ll'} p_{ll'}(x_{i3}, x_{j3}, y) \psi(x_{i2}, x_{j2}, x_{i3}, x_{j3}, y) p_l(x_{i2}, x_{j2}, y) dx_{i2} dx_{j2} dx_{i3} dx_{j3} dy \right) p_l(x_i, x_j, y) \]

\[ = 2 \sum_{l, l' \in M} \left( \int a_{ll'} p_{ll'}(x_{i3}, x_{j3}, y) \psi(x_{i2}, x_{j2}, x_{i3}, x_{j3}, y) p_l(x_{i2}, x_{j2}, y) dx_{i2} dx_{j2} dx_{i3} dx_{j3} dy \right) p_l(x_i, x_j, y) \]

\[ = 2 \sum_{l, l' \in M} a_{ll'} c_{ll'} p_l(x_i, x_j, y) \]
and we can write
\[
L(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) = h(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) + S_M g(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) - S_M h(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) - 2A^\top B - 2A^\top CA.
\]
Thus,
\[
\text{Var}(L(X_i^{(1)}, X_j^{(1)}, Y^{(1)})) = \text{Var}(h(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) + S_M g(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) + S_M h(X_i^{(1)}, X_j^{(1)}, Y^{(1)}))
\leq \mathbb{E}[(h(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) + S_M g(X_i^{(1)}, X_j^{(1)}, Y^{(1)}) + S_M h(X_i^{(1)}, X_j^{(1)}, Y^{(1)}))^2]
\leq \mathbb{E}[(h(X_i^{(1)}, X_j^{(1)}, Y^{(1)}))^2 + (S_M g(X_i^{(1)}, X_j^{(1)}, Y^{(1)}))^2 + (S_M h(X_i^{(1)}, X_j^{(1)}, Y^{(1)}))^2].
\]
Each of these terms can be bounded
\[
\mathbb{E}[(h(X_i^{(1)}, X_j^{(1)}, Y^{(1)}))^2] = \int \left( \int S_M f(x_{i1}, x_{j2}, y)\psi(x_{i1}, x_{j2}, x_{i1}, x_{j2}, y)dx_{i2}dx_{j2} \right)^2 f(x_{i1}, x_{j1}, y)dx_{i1}dx_{j1}dy
\leq \Delta_{x_{i1}x_{j1}} \int S_M f(x_{i1}, x_{j1}, y)^2\psi(x_{i1}, x_{j1}, x_{i1}, x_{j1}, x_{i1}, x_{j1}, y)^2f(x_{i1}, x_{j1}, y)dx_{i1}dx_{j1}dx_{i2}dx_{j2}dy
\leq 4\Delta_{x_{i1}x_{j1}}^2 \|f\|_\infty^2 \|\psi\|_\infty^2 \int S_M f(x_{i1}, x_{j1}, y)^2dx_{i1}dx_{j1}dy
= 4\Delta_{x_{i1}x_{j1}}^2 \|f\|_\infty^2 \|\psi\|_\infty^2 \|S_M f\|_2^2
\leq 4\Delta_{x_{i1}x_{j1}}^2 \|f\|_\infty^2 \|\psi\|_\infty^2 \|f\|_2^2
\leq 4\Delta_{x_{i1}x_{j1}}^2 \|f\|_\infty^2 \|\psi\|_\infty^2
\]
and similar calculations are valid for the others two terms,
\[
\mathbb{E}[(S_M g(X_i^{(1)}, X_j^{(1)}, Y^{(1)}))^2] \leq \|f\|_\infty^2 \|S_M g\|_2^2 \leq \|f\|_\infty^2 \|g\|_2^2 \leq 4\Delta_{x_{i1}x_{j1}}^2 \|f\|_\infty^2 \|\psi\|_\infty^2^2
\mathbb{E}[(S_M h(X_i^{(1)}, X_j^{(1)}, Y^{(1)}))^2] \leq \|f\|_\infty^2 \|S_M h\|_2^2 \leq \|f\|_\infty^2 \|h\|_2^2 \leq 4\Delta_{x_{i1}x_{j1}}^2 \|f\|_\infty^2 \|\psi\|_\infty^2^2.
\]
Finally we get,
\[
\text{Var}(P_n L) \leq \frac{12}{n} \|\eta\|_\infty^2 \|f\|_\infty^2 \Delta_{x_{i1}x_{j1}}^2.
\]
\[\square\]

**Lemma 4** (Computation of Cov$(U_n, K, P_n L)$). Under the assumptions of Theorem 3 we have
\[
\text{Cov}(U_n K, P_n L) = 0.
\]
Proof of Lemma 4. Since $U_n K$ and $P_n L$ are centered, we have
\[
\text{Cov}(U_n K, P_n L) = \mathbb{E}[U_n K P_n L]
\]
\[
= \mathbb{E} \left[ \frac{1}{n^2(n-1)} \sum_{k \neq k' = 1}^n K(X_k^{(k)}, X_j^{(k)}, Y_k^{(k)}, X_j^{(k')}, Y_j^{(k')}) \sum_{k=1}^n L(X_k^{(k)}, X_j^{(k), Y_k^{(k)}}) \right]
\]
\[
= \frac{1}{n} \mathbb{E} \left[ K(X_1^{(1)}, X_j^{(1)}, Y_1^{(1)}, X_j^{(2)}, Y_1^{(2)}) \left( L(X_1^{(1)}, X_j^{(1), Y_1^{(1)})} + L(X_1^{(2)}, X_j^{(2)}, Y_1^{(2)}) \right) \right]
\]
\[
= \frac{1}{n} \mathbb{E} \left[ \left( Q^T(X_1^{(1)}, X_j^{(1)}, Y_1^{(1)}) R(X_1^{(2)}, X_j^{(2)}, Y_1^{(2)}) - Q^T(X_1^{(1)}, X_j^{(1)}, Y_1^{(1)}) C Q(X_1^{(2)}, X_j^{(2)}, Y_1^{(2)}) \right) \right]
\]
\[
= 0.
\]
Since $K, L, Q$ and $R$ are centered.

Lemma 5 (Bound of Bias $(\hat{\theta}_n)$). Under the assumptions of Theorem 3, we have
\[
\left| \text{Bias}(\hat{\theta}_n) \right| \leq \Delta_{x,x_j} \| \eta \|_\infty \sup_{l \in M} |c_l|^2.
\]

Proof.
\[
\left| \text{Bias}(\hat{\theta}_n) \right| \leq \| \eta \|_\infty \int \left( \int |S_M f(x_{i1}, x_{j1}, y) - f(x_{i1}, x_{j1}, y)| \, dx_{i1} \, dx_{j1} \right)
\]
\[
\left( \int |S_M f(x_{i2}, x_{j2}, y) - f(x_{i2}, x_{j2}, y)| \, dx_{i2} \, dx_{j2} \right) \, dy
\]
\[
= \| \eta \|_\infty \int \left( \int |S_M f(x, x, y) - f(x, x, y)| \, dx \, dx_j \right)^2 \, dy
\]
\[
\leq \Delta_{x,x_j} \| \eta \|_\infty \int (S_M f(x, x, y) - f(x, x, y))^2 \, dx \, dx_j \, dy
\]
\[
= \Delta_{x,x_j} \| \eta \|_\infty \sum_{l \neq l' \in M} \alpha_l \alpha_{l'} \int p_l(x_i, x_j, y) p_{l'}(x_i, x_j, y) \, dx_i \, dx_j \, dy
\]
\[
= \Delta_{x,x_j} \| \eta \|_\infty \sum_{l \in M} |a_l|^2 \leq \Delta_{x,x_j} \| \eta \|_\infty \sup_{l \in M} |c_l|^2.
\]

We use the H"older’s inequality and the fact that $f \in \mathcal{E}$ then $\sum_{l \notin M} |a_l|^2 \leq \sup_{l \notin M} |c_l|^2$.

Lemma 6 (Asymptotic variance of $\sqrt{n}(P_n L)$). Under the assumptions of Theorem 3, we have
\[
n \text{Var}(P_n L) \rightarrow \Lambda(f, \eta)
\]
where
\[
\Lambda(f, \eta) = \int g(x_i, x_j, y)^2 f(x_i, x_j, y) \, dx_i \, dx_j \, dy - \left( \int g(x_i, x_j, y) f(x_i, x_j, y) \, dx_i \, dx_j \, dy \right)^2.
\]

25
Proof. We proved in Lemma 3 that
\[
\begin{align*}
\Var(L(X_{i}^{(1)}, X_{j}^{(1)}, Y^{(1)})) &= \Var(h(X_{i}^{(1)}, X_{j}^{(1)}, Y^{(1)}) + S_{M} g(X_{i}^{(1)}, X_{j}^{(1)}, Y^{(1)}) + S_{M} h(X_{i}^{(1)}, X_{j}^{(1)}, Y^{(1)})) \\
&= \Var(A_{1} + A_{2} + A_{3}) \\
&= \sum_{k,l=1}^{3} \Cov(A_{k}, A_{l}).
\end{align*}
\]

We claim that \( \forall k, l \in \{1, 2, 3\}^{2} \), we have
\[
\left| \Cov(A_{k}, A_{l}) - \epsilon_{kl} \left( \int g(x_{i}, x_{j}, y)^{2} f(x_{i}, x_{j}, y) dx_{i} dx_{j} dy - \left( \int g(x_{i}, x_{j}, y) f(x_{i}, x_{j}, y) dx_{i} dx_{j} dy \right)^{2} \right) \right| \\
\leq \lambda \left[ \| S_{M} f - f \|_{2} + \| S_{M} g - g \|_{2} \right]
\] (27)

where
\[
\epsilon_{kl} = \begin{cases} 
-1 & \text{if } k = 3 \text{ or } l = 3 \text{ and } k \neq l \\
1 & \text{otherwise}
\end{cases}
\]

and where \( \lambda \) depends only on \( \| f \|_{\infty}, \| g \|_{\infty} \) and \( \Delta_{x_{i}x_{j}} \). We will do the details only for the case \( k = l = 3 \) since the calculations are similar for others configurations.

\[
\Var(A_{3}) = \int S_{M}^{2} h(x_{i}, x_{j}, y) f(x_{i}, x_{j}, y) dx_{i} dx_{j} dy - \left( \int S_{M} h(x_{i}, x_{j}, y) f(x_{i}, x_{j}, y) dx_{i} dx_{j} dy \right)^{2}.
\]

The computation will be done in two steps. We first bound the quantity by the Cauchy-Schwarz inequality
\[
\left| \int S_{M}^{2} h(x_{i}, x_{j}, y) f(x_{i}, x_{j}, y) dx_{i} dx_{j} dy - \int g(x_{i}, x_{j}, y)^{2} f(x_{i}, x_{j}, y) dx_{i} dx_{j} dy \right| \\
\leq \int \left| S_{M}^{2} h(x_{i}, x_{j}, y) f(x_{i}, x_{j}, y) - S_{M}^{2} g(x_{i}, x_{j}, y) f(x_{i}, x_{j}, y) \right| dx_{i} dx_{j} dy \\
+ \int \left| S_{M}^{2} g(x_{i}, x_{j}, y) f(x_{i}, x_{j}, y) - g(x_{i}, x_{j}, y)^{2} f(x_{i}, x_{j}, y) \right| dx_{i} dx_{j} dy \\
\leq \| f \|_{\infty} \| S_{M} h - S_{M} g \|_{2} \| S_{M} h \|_{2} + \| f \|_{\infty} \| S_{M} g + g \|_{2} \| S_{M} g - g \|_{2}.
\]

Using several times the fact that since \( S_{M} \) is a projection, \( \| S_{M} g \|_{2} \leq \| g \|_{2} \), the sum is bounded by
\[
\| f \|_{\infty} \| h + g \|_{2} \| h - g \|_{2} + 2 \| f \|_{\infty} \| g \|_{2} \| S_{M} g - g \|_{2} \\
\leq \| f \|_{\infty} \left( \| h \|_{2} + \| g \|_{2} \right) \| h - g \|_{2} + 2 \| f \|_{\infty} \| g \|_{2} \| S_{M} g - g \|_{2}.
\]

We saw previously that \( \| g \|_{2} \leq 2 \Delta_{x_{i}x_{j}} \| f \|_{\infty}^{1/2} \| \eta \|_{\infty} \) and \( \| h \|_{2} \leq 2 \Delta_{x_{i}x_{j}} \| f \|_{\infty}^{1/2} \| \eta \|_{\infty} \). The sum is then bound by
\[
4 \Delta_{x_{i}x_{j}} \| f \|_{\infty}^{3/2} \| \eta \|_{\infty} \| h - g \|_{2} + 4 \Delta_{x_{i}x_{j}} \| f \|_{\infty}^{3/2} \| \eta \|_{\infty} \| S_{M} g - g \|_{2}.
\]
We now have to deal with \( \| h - g \|_2^2 \):

\[
\| h - g \|_2^2 = \int \left( \int (S_M f(x, y) - f(x, y)) \psi(x, y) dx \right)^2 dx dy
\]

\[
\leq \int \left( \int (S_M f(x, y) - f(x, y))^2 dx dy \right) \left( \int \psi^2(x, y) dx dy \right) dx dy
\]

\[
\leq 4\Delta^2_{x,y} \| \eta \|_\infty^2 \| S_M f - f \|_2^2.
\]

Finally this first part is bounded by

\[
\left| \int S_M^2 h(x, y) f(x, y) dx dy - \int g(x, y) f(x, y) dx dy \right|
\]

\[
\leq 4\Delta_{x,y} \| f \|_\infty^{3/2} \| \eta \|_\infty \left( 2\Delta_{x,y} \| \eta \|_\infty \| S_M f - f \|_2 + \| S_M g - g \|_2 \right).
\]

Following with the second quantity

\[
\left| \left( \int S_M h(x, y) f(x, y) dx dy \right)^2 - \left( \int g(x, y) f(x, y) dx dy \right)^2 \right|
\]

\[
= \left| \left( \int (S_M h(x, y) - g(x, y)) f(x, y) dx dy \right) \right|
\]

By using the Cauchy-Schwartz inequality, it is bounded by

\[
\| f \|_2 \| S_M h - g \|_2 \| f \|_2 \| S_M h + g \|_2
\]

\[
\leq \| f \|_2 \left( \| h \|_2 + \| g \|_2 \right) \left( \| S_M h - S_M g \|_2 + \| S_M g - g \|_2 \right)
\]

\[
\leq 4\Delta_{x,y} \| f \|_\infty^{3/2} \| \eta \|_\infty \left( \| h - g \|_2 + \| S_M g - g \|_2 \right)
\]

\[
\leq 4\Delta_{x,y} \| f \|_\infty^{3/2} \| \eta \|_\infty \left( 2\Delta_{x,y} \| \eta \|_\infty \| S_M f - f \|_2 + \| S_M g - g \|_2 \right)
\]

using the previous calculations. Collecting the two inequalities gives (27) for \( k = l = 3 \). Finally, since by assumption \( \forall t \in \mathbb{R}^2(d\mu), \| S_M t - t \|_2 \to 0 \) when \( n \to \infty \) a direct consequence of (27) is

\[
\lim_{n \to \infty} \text{Var}(L(X_i^{(1)}, X_j^{(1)}, Y^{(1)})) = \Lambda(f, \eta).
\]

We conclude by noting that \( \text{Var}(\sqrt{n}(P_n L)) = \text{Var}(L(X_i^{(1)}, X_j^{(1)}, Y^{(1)})). \)
Lemma 7 (Asymptotics for $\sqrt{n}(\hat{Q} - Q)$). Under the assumptions of Theorem 1 we have
\[
\lim_{n \to \infty} n \mathbb{E} [\hat{Q} - Q]^2 = 0.
\]

Proof. The bound given in (16) states that if $|M_n|/n \to 0$ we have
\[
\left| n \mathbb{E} [\hat{Q} - Q]^2 \right| - \left| \int \hat{g}(x, x, y)^2 f(x, x, y) dx, dx, dy \right| \leq \gamma \left( \|f\|_\infty, \|\eta\|_\infty, \Delta x, x \right) \left[ \frac{|M_n|}{n} + \|S_M f - f\|_2 + \mathbb{E} [\|S_M \hat{g} - \hat{g}\|_2] \right]
\]
where $\hat{g}(x, x, y) = \int H_3(f, x, i, x, j, x) f(x, x, x) dx, dx, dy$ where we recall that $H_3(f, x, i, x, j, x, y) = H_2(f, x, x, j, x, y) + H_2(f, x, x, j, x, y)$ with $H_3(f, x, i, x, j, x, y) = \frac{1}{f(x, x, x, y, x, x)} (x_{i} - m_i(f, y)) (x_{j} - m_j(f, y))$. By deconditioning we get
\[
\left| n \mathbb{E} [\hat{Q} - Q]^2 \right| - \mathbb{E} \left[ \int \hat{g}(x, x, y)^2 f(x, x, y) dx, dx, dy \right] \leq \gamma \left( \|f\|_\infty, \|\eta\|_\infty, \Delta x, x \right) \left[ \frac{|M_n|}{n} + \|S_M f - f\|_2 + \mathbb{E} [\|S_M \hat{g} - \hat{g}\|_2] \right]
\]
Note that
\[
\mathbb{E} [\|S_M \hat{g} - \hat{g}\|_2^2] \leq \mathbb{E} [\|S_M \hat{g} - S_M g\|_2^2] + \mathbb{E} [\|\hat{g} - g\|_2^2] + \mathbb{E} [\|S_M g - g\|_2^2] \leq 2\mathbb{E} [\|\hat{g} - g\|_2^2] + \mathbb{E} [\|S_M g - g\|_2^2]
\]
where $g(x, x, y) = \int H_3(f, x, i, x, j, x, y) f(x, x, x, y, x, x) dx, dx, dy$. The second term converges to 0 since $g \in L^2(dx, dy, dz)$ and $\forall t \in L^2(dx, dy, dz)$, $\int (S_M t - t)^2 dx, dy, dz \to 0$. Moreover
\[
\|\hat{g} - g\|_2^2 = \int [\hat{g}(x, x, y) - g(x, x, y)]^2 dx, dx, dy
\]
\[
= \int \left[ \int (H_3(f, x, i, x, j, x, y) - H_3(f, x, x, i, x, j, y)) f(x, x, x, y, x, x) dx, dx, dy \right]^2 dx, dx, dy
\]
\[
\leq \int \left[ \int (H_3(f, x, i, x, j, x, y) - H_3(f, x, x, j, x, y))^2 dx, dx, dy \right] dx, dx, dy
\]
\[
\leq \Delta x, x, y \|f\|_\infty^2 \int (H_3(f, x, i, x, j, x, y) - H_2(f, x, x, j, x, y))^2 dx, dx, dy
\]
\[
\leq \delta \Delta x, x, y \|f\|_\infty^2 \int (\hat{f}(x, x, y) - f(x, x, y))^2 dx, dx, dy
\]
for some constant $\delta$ that comes out of applying the mean value theorem to $H_3(f, x, i, x, j, x, y) - H_3(f, x, x, i, x, j, y)$. The constant $\delta$ was taken under Assumptions 1-3. Since $\mathbb{E} [\|f - \hat{f}\|_2] \to 0$ then $\mathbb{E} [\|\hat{g} - \hat{g}\|_2] \to 0$. Now show that the expectation of
\[
\int \hat{g}(x, x, y)^2 f(x, x, y) dx, dx, dy - \left( \int \hat{g}(x, x, y) f(x, x, y) dx, dx, dy \right)^2
\]

28
converges to 0. We develop the proof for only the first term. We get
\[
\left| \int \hat{g}(x_i, x_j, y)^2 f(x_i, x_j, y) dx_i dx_j dy - \int g(x_i, x_j, y)^2 f(x_i, x_j, y) dx_i dx_j dy \right|
\leq \int |\hat{g}(x_i, x_j, y)^2 - g(x_i, x_j, y)^2| f(x_i, x_j, y) dx_i dx_j dy
\leq \lambda \int (\hat{g}(x_i, x_j, y) - g(x_i, x_j, y))^2 dx_i dx_j dy
= \lambda \|\hat{g} - g\|_2^2
\]
for some constant \( \lambda \). By taking the expectation of both sides, we see it is enough to show that \( \mathbb{E}[\|\hat{g} - g\|_2^2] \to 0 \). Besides, we can verify
\[
g(x_i, x_j, y) = \int H_3(f, x_i, x_j, x_{i2}, x_{j2}, y) f(x_{i2}, x_{j2}, y) dx_{i2} dx_{j2}
= \frac{2}{\int f(x_i, x_j, y) dx_i dx_j} (x_i - \hat{m}_i(y))
\left( \int x_{j2} f(x_{i2}, x_{j2}, y) dx_{i2} dx_{j2} - \hat{m}_j(y) \int f(x_{i2}, x_{j2}, y) dx_{i2} dx_{j2} \right)
= 0
\]
which proves that the expectation of \( \int \hat{g}(x_i, x_j, y)^2 f(x_i, x_j, y) dx_i dx_j \) converges to 0. Similar computations shows that the expectation of \( (\int \hat{g}(x_i, x_j, y) f(x_i, x_j, y) dx_i dx_j)^2 \) also converges to 0. Finally we have
\[
\lim_{n \to \infty} n \mathbb{E}[\hat{Q} - Q]^2 = 0.
\]

References


