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# ON THE NADARAYA-WATSON KERNEL REGRESSION ESTIMATOR FOR IRREGULARLY SPACED SPATIAL DATA

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## Abstract

We investigate the asymptotic normality of the Nadaraya-Watson kernel regression estimator for irregularly spaced data collected on a finite region of the lattice  $\mathbb{Z}^d$  where  $d$  is a positive integer. The results are stated for strongly mixing random fields in the sense of Rosenblatt (1956) and for weakly dependent random fields in the sense of Wu (2005). Only minimal conditions on the bandwidth parameter and simple conditions on the dependence structure of the data are assumed.

*AMS Subject Classifications (2000):* 62G05, 60J25, 62G07.

*Key words and phrases:* Nonparametric estimation, Nadaraya-Watson estimator, irregularly spaced spatial data, strong mixing,  $m$ -dependence, physical dependence measure, random fields, asymptotic normality.

## 1 Introduction

In many situations, practitioners want to know the relationship between some predictors and a response. If the form of the functional relation is unknown then a nonparametric approach is necessary. This is a natural question and a very important task in statistics. A very popular tool to handle this problem is the Nadaraya-Watson estimator (NWE) introduced by Nadaraya [21] and Watson [29]. In this work, we investigate the asymptotic normality of the NWE in the context of dependent irregularly spaced spatial data. Let  $d$ ,  $n$  and  $N$  be positive integers. Let also  $(Y_i, X_i)_{i \in \mathbb{Z}^d}$  be a strictly stationary  $\mathbb{R} \times \mathbb{R}^N$ -valued random field defined on a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$ . We assume that the common law  $\mu$  of the random variables  $(X_i)_{i \in \mathbb{Z}^d}$  is absolutely continuous with respect to the Lebesgue measure on  $\mathbb{R}^N$ . We denote by  $f$  the unknown probability density function of  $\mu$ . Let  $\Lambda_n$  be a finite region of  $\mathbb{Z}^d$  and let  $(\eta_i)_{i \in \mathbb{Z}^d}$  be iid  $\mathbb{R}^N$ -valued random

variables with zero mean and finite variance and independent of  $(X_i)_{i \in \mathbb{Z}^d}$ . The regression model is characterized by the relation  $Y_i = R(X_i, \eta_i)$  for  $i$  in  $\Lambda_n$  where  $R$  is an unknown functional. In our setting, it is important to note that no regularity condition is imposed on  $\Lambda_n$  which can be very general (irregularly spaced data). The regression function  $r$  is defined for any  $x$  in  $\mathbb{R}^N$  by

$$r(x) = \begin{cases} \mathbb{E}[R(x, \eta_0)] & \text{if } f(x) \neq 0 \\ \mathbb{E}[Y_0] & \text{else,} \end{cases}$$

and the NWE  $r_n$  of  $r$  is defined for any  $x$  in  $\mathbb{R}^N$  by

$$r_n(x) = \begin{cases} \frac{\sum_{i \in \Lambda_n} Y_i K\left(\frac{x-X_i}{b_n}\right)}{\sum_{i \in \Lambda_n} K\left(\frac{x-X_i}{b_n}\right)} & \text{if } \sum_{i \in \Lambda_n} K\left(\frac{x-X_i}{b_n}\right) \neq 0 \\ \frac{1}{|\Lambda_n|} \sum_{i \in \Lambda_n} Y_i & \text{else,} \end{cases}$$

where  $|\Lambda_n|$  is the number of elements in the region  $\Lambda_n$ , the function  $K : \mathbb{R}^N \rightarrow \mathbb{R}$  is a probability kernel (that is  $\int_{\mathbb{R}^N} K(t) dt = 1$ ) and the bandwidth parameter  $b_n$  is a positive constant going to zero as  $n$  goes to infinity. For time series (i.e. for  $d = 1$ ), the problem which we are concerned has been extensively studied. One can refer, e.g., to Lu and Cheng [18], Masry and Fan [19], Robinson [24], Roussas [27] and many references therein. In the spatial case (i.e. for  $d \geq 2$ ), some contributions for strongly mixing random fields were made by Biau and Cadre [1], Carbon et al. [2], Dabo-Niang and Rachdi [3], Dabo-Niang and Yao [4], El Machkouri [7], El Machkouri and Stoica [10], Hallin et al. [12] and Lu and Chen [16, 17]. The main motivation of this work is to provide sufficient simple conditions for the NWE to be asymptotically normal in the context of mixing but also non-mixing random fields. More precisely, we consider strongly mixing random fields in the sense of Rosenblatt [25] and weakly dependent random fields in the sense of Wu [30] (see also [11]). To the best of our knowledge, our work provides the first central limit theorem (Theorem 2) for the NWE under minimal conditions on the bandwidth parameter and irregularly spaced dependent spatial data (i.e.  $b_n \rightarrow 0$  and  $|\Lambda_n| b_n^N \rightarrow \infty$  as  $n \rightarrow \infty$ ). In particular, our result improves in several directions a previous central limit theorem for the NWE for spatial data established by [1] (see the comments after Corollary 1 below).

The paper is organized as follows. Our main results are stated and discussed in Section 2 whereas proofs of the main results and its preliminary lemmas are deferred to Sections 4 and 5. Finally, Section 3 is devoted to a numerical illustration of the central limit theorem obtained in Section 2.

## 2 Main results

Given two  $\sigma$ -algebras  $\mathcal{U}$  and  $\mathcal{V}$ , the  $\alpha$ -mixing coefficient introduced by Rosenblatt [25] is

$$\alpha(\mathcal{U}, \mathcal{V}) = \sup\{|\mathbb{P}(A \cap B) - \mathbb{P}(A)\mathbb{P}(B)|, A \in \mathcal{U}, B \in \mathcal{V}\}.$$

Let  $p$  be fixed in  $[1, +\infty]$ . The strong mixing coefficients  $(\alpha_{1,p}(n))_{n \geq 0}$  associated to  $(X_i)_{i \in \mathbb{Z}^d}$  are defined by

$$\alpha_{1,p}(n) = \sup\{\alpha(\sigma(X_k), \mathcal{F}_\Gamma), k \in \mathbb{Z}^d, \Gamma \subset \mathbb{Z}^d, |\Gamma| \leq p, \rho(\Gamma, \{k\}) \geq n\},$$

where  $\mathcal{F}_\Gamma = \sigma(X_i; i \in \Gamma)$ ,  $|\Gamma|$  is the number of element in  $\Gamma$  and the distance  $\rho$  is defined for any subsets  $\Gamma_1$  and  $\Gamma_2$  of  $\mathbb{Z}^d$  by  $\rho(\Gamma_1, \Gamma_2) = \min\{|i - j|, i \in \Gamma_1, j \in \Gamma_2\}$  with  $|i - j| = \max_{1 \leq s \leq d} |i_s - j_s|$  for any  $i = (i_1, \dots, i_d)$  and  $j = (j_1, \dots, j_d)$  in  $\mathbb{Z}^d$ . We say that the random field  $(X_i)_{i \in \mathbb{Z}^d}$  is strongly mixing if  $\lim_{n \rightarrow \infty} \alpha_{1,p}(n) = 0$ . Let  $m$  be a positive integer. We are also going to establish our results for Bernoulli fields of the form

$$X_i = G(\varepsilon_{i-s}; s \in \mathbb{Z}^d), \quad i \in \mathbb{Z}^d, \quad (1)$$

where  $G : (\mathbb{R}^m)^{\mathbb{Z}^d} \rightarrow \mathbb{R}^N$  is some function and  $(\varepsilon_i)_{i \in \mathbb{Z}^d}$  are iid  $\mathbb{R}^m$ -valued random variables. Let  $(\varepsilon'_j)_{j \in \mathbb{Z}^d}$  be an iid copy of  $(\varepsilon_j)_{j \in \mathbb{Z}^d}$  and let  $X_i^*$  be the coupled version of  $X_i$  defined by

$$X_i^* = G(\varepsilon_{i-s}^*; s \in \mathbb{Z}^d),$$

where  $\varepsilon_j^* = \varepsilon_j$  if  $j \neq 0$  and  $\varepsilon_0^* = \varepsilon'_0$ . Note that  $X_i^*$  is obtained from  $X_i$  by replacing  $\varepsilon_0$  by its copy  $\varepsilon'_0$ . For any positive integer  $\ell$  and any  $\mathbb{R}^\ell$ -valued random variable  $Z \in \mathbb{L}^p(\Omega, \mathcal{F}, \mathbb{P})$  with  $p > 0$ , we denote  $\|Z\|_p := \mathbb{E}[\|Z\|^p]^{1/p}$  where  $\|\cdot\|$  is the Euclidian norm of  $\mathbb{R}^\ell$ . Following Wu [30] and El Machkouri et al. [11], we define the physical dependence measure

$$\delta_{i,p} := \|X_i - X_i^*\|_p$$

as soon as  $X_i$  is  $p$ -integrable for  $p \geq 2$ . We say that  $X$  is  $p$ -stable if  $\sum_{i \in \mathbb{Z}^d} \delta_{i,p} < \infty$ . Physical dependence measure should be seen as a measure of the dependence of the function  $G$  (defined in (1)) in the coordinate zero. In some sense, it quantifies the degree of dependence of outputs on inputs in physical systems and provide a natural framework for a limit theory for stationary random fields (see [11]). In particular, it gives mild and easily verifiable conditions (see condition (A3)(ii) below) because it is directly related to the data-generating mechanism. In mathematical physics, various versions of similar ideas (local perturbation of a configuration) appear. One can refer for example to Liggett [14] or Stroock and Zegarlinski [28]. As an illustration, the reader should keep in mind the following two examples:

- Linear random fields: Let  $(\varepsilon_i)_{i \in \mathbb{Z}^d}$  be i.i.d  $\mathbb{R}^m$ -valued random variables such that  $\varepsilon_i$  belongs to  $\mathbb{L}^p(\Omega, \mathcal{F}, \mathbb{P})$ ,  $p \geq 2$ . The linear random field  $X$  defined for all  $i$  in  $\mathbb{Z}^d$  by

$$X_i = \sum_{s \in \mathbb{Z}^d} A_s \varepsilon_{i-s}$$

where  $A_s = (a_{s,k_1,k_2})_{\substack{1 \leq k_1 \leq N \\ 1 \leq k_2 \leq m}}$  is a  $N \times m$  matrix such that  $\sum_{s \in \mathbb{Z}^d} \sum_{k_1=1}^N \sum_{k_2=1}^m a_{s,k_1,k_2}^2 < \infty$  is of the form (1) with a linear functional  $G$ . For all  $i$  in  $\mathbb{Z}^d$ ,

$$\delta_{i,p} \leq \|\varepsilon_0 - \varepsilon'_0\|_p \times \sqrt{\sum_{k_1=1}^N \sum_{k_2=1}^m a_{i,k_1,k_2}^2}.$$

So,  $X$  is  $p$ -stable as soon as  $\sum_{i \in \mathbb{Z}^d} \sqrt{\sum_{k_1=1}^N \sum_{k_2=1}^m a_{i,k_1,k_2}^2} < \infty$ . Clearly, if  $H$  is a Lipschitz continuous function, under the above condition, the subordinated process  $Y_i = H(X_i)$  is also  $p$ -stable.

- Volterra field: Another class of nonlinear random field is the Volterra process which plays an important role in the nonlinear system theory. Let  $i \in \mathbb{Z}^d$  and

$$X_i = \sum_{s_1, s_2 \in \mathbb{Z}^d} a_{s_1, s_2} \varepsilon_{i-s_1} \varepsilon_{i-s_2},$$

where  $a_{s_1, s_2}$  are real coefficients with  $a_{s_1, s_2} = 0$  if  $s_1 = s_2$  and  $(\varepsilon_i)_{i \in \mathbb{Z}^d}$  are i.i.d. real random variables with  $\varepsilon_i$  in  $\mathbb{L}^p(\Omega, \mathcal{F}, \mathbb{P})$ ,  $p \geq 2$ . By the Burkholder inequality, there exists a constant  $C_p > 0$  such that

$$\delta_{i,p} \leq C_p \|\varepsilon_0 - \varepsilon'_0\|_p \|\varepsilon_0\|_p \times \sqrt{\sum_{s \in \mathbb{Z}^d} (a_{s,i} + a_{i,s})^2}$$

So,  $X$  is  $p$ -stable as soon as  $\sum_{i \in \mathbb{Z}^d} \sqrt{\sum_{s \in \mathbb{Z}^d} (a_{s,i} + a_{i,s})^2} < \infty$ .

Let  $(b_n)_{n \geq 1}$  be a sequence of positive real numbers going to zero as  $n$  goes to infinity. Denote  $K_n(x, v) = K\left(\frac{x-v}{b_n}\right)$  for any  $(x, v) \in \mathbb{R}^N \times \mathbb{R}^N$  and any integer  $n \geq 1$ . If  $x \in \mathbb{R}^N$  and  $f_n(x) \neq 0$  then  $r_n(x) = \varphi_n(x)/f_n(x)$ , where

$$\varphi_n(x) = \frac{\sum_{i \in \Lambda_n} Y_i K_n(x, X_i)}{|\Lambda_n| b_n^N} \quad \text{and} \quad f_n(x) = \frac{\sum_{i \in \Lambda_n} K_n(x, X_i)}{|\Lambda_n| b_n^N}.$$

Recall that  $f_n$  is the classical Parzen-Rosenblatt estimator of the marginal density  $f$  of  $X_0$  (see [8, 9, 22, 26]). Similarly, if  $\varphi$  is the function defined for any  $x \in \mathbb{R}^N$  by  $\varphi(x) = r(x)f(x)$  then  $\varphi_n$  is an estimator of  $\varphi$ . In the sequel, we consider the following assumptions:

(A1) Assume  $b_n \rightarrow 0$  such that  $|\Lambda_n| b_n^N \rightarrow \infty$  and that  $K$  is symmetric, Lipschitz and satisfies  $\|K\|_\infty := \sup_{t \in \mathbb{R}^N} |K(t)| < \infty$ ,  $\lim_{\|t\| \rightarrow \infty} \|t\| |K(t)| = 0$ ,  $\int_{\mathbb{R}^N} |K(t)| dt < \infty$  and  $\int_{\mathbb{R}^N} \|t\|^2 |K(t)| dt < \infty$  where  $\|\cdot\|$  is the Euclidian norm on  $\mathbb{R}^N$ .

(A2) There exists  $\kappa > 0$  such that  $|f_{0,i}(x, y) - f(x)f(y)| \leq \kappa$  for any  $(x, y)$  in  $\mathbb{R}^N \times \mathbb{R}^N$  and any  $i$  in  $\mathbb{Z}^d \setminus \{0\}$ , where  $f_{0,i}$  is the joint density of  $(X_0, X_i)$ .

(A3) There exists  $\theta > 0$  such that  $\mathbb{E}[|Y_0|^{2+\theta}] < \infty$  and one of the following condition holds:

(i)  $(X_i)_{i \in \mathbb{Z}^d}$  is strongly mixing and  $\sum_{n=1}^{\infty} n^{\frac{(2d-1)\theta+6d-2}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(n) < \infty$ ;

(ii)  $(X_i)_{i \in \mathbb{Z}^d}$  is of the form (1) and  $\sum_{i \in \mathbb{Z}^d} |i|^{\frac{d((3N+2)\theta^2+(10N+8)\theta+8N)}{2\theta(\theta+2)N}} \delta_{i,2}^{\frac{\theta}{2+\theta}} < \infty$ .

(A4) There exists  $\theta > 0$  such that  $\mathbb{E}[|Y_0|^{2+\theta}] < \infty$  and the function  $x \mapsto \mathbb{E}[\Psi_p(|Y_0|) | X_0 = x]$  is continuous for  $p \in \{1, 2, 2 + \theta\}$  where  $\Psi_p(t) = t^p$  for any real  $t$ . Moreover, the functions  $f$  and  $\varphi$  are twice differentiable with bounded second partial derivatives.

Assumptions (A1), (A2) and (A4) are classical conditions in nonparametric statistics (see [2], [16]). Moreover, one can notice that if  $\theta = \infty$  then (A3)(i) and (A3)(ii) reduce to the conditions obtained in [8] and [9] respectively where the asymptotic normality of the Parzen-Rosenblatt estimator is established.

First, we show that  $\varphi_n$  and  $f_n$  are asymptotically unbiased estimators of  $\varphi$  and  $f$  respectively.

**Theorem 1** Assume that  $f$  and  $\varphi$  are twice differentiable with bounded second partial derivatives and  $\int_{\mathbb{R}^N} \|t\|^2 |\mathbb{K}(t)| dt < \infty$ . Then

$$\sup_{x \in \mathbb{R}^N} |\mathbb{E}[f_n(x)] - f(x)| = O(b_n^2) \quad \text{and} \quad \sup_{x \in \mathbb{R}^N} |\mathbb{E}[\varphi_n(x)] - \varphi(x)| = O(b_n^2).$$

Consequently, if  $|\Lambda_n| b_n^{N+4} \rightarrow 0$  as  $n \rightarrow \infty$ , then

$$\lim_{n \rightarrow \infty} \sqrt{|\Lambda_n| b_n^N} \sup_{x \in \mathbb{R}^N} |\mathbb{E}[f_n(x)] - f(x)| = \lim_{n \rightarrow \infty} \sqrt{|\Lambda_n| b_n^N} \sup_{x \in \mathbb{R}^N} |\mathbb{E}[\varphi_n(x)] - \varphi(x)| = 0.$$

Our main result is the following central limit theorem for the NWE.

**Theorem 2** If (A1), (A2), (A3) and (A4) hold, then for any  $x \in \mathbb{R}^N$  such that  $f(x) > 0$ ,

$$\sqrt{|\Lambda_n| b_n^N} \left( r_n(x) - \frac{\mathbb{E}[\varphi_n(x)]}{\mathbb{E}[f_n(x)]} \right) \xrightarrow[n \rightarrow \infty]{Law} \mathcal{N}(0, \sigma^2(x)),$$

where  $\sigma^2(x) = \frac{V(x)}{f(x)} \int_{\mathbb{R}^N} \mathbb{K}^2(t) dt$  and  $V(x) = \mathbb{E}[Y_0^2 | X_0 = x] - r^2(x)$ .

Using Theorem 1, the condition  $|\Lambda_n| b_n^{N+4} \rightarrow 0$  can be imposed for the control of the bias of the estimator and leads immediately to the following corollary (its proof is left to the reader).

**Corollary 1** If (A1), (A2), (A3) and (A4) hold and  $|\Lambda_n| b_n^{N+4} \rightarrow 0$ , then for any  $x \in \mathbb{R}^N$  such that  $f(x) > 0$ ,

$$\sqrt{|\Lambda_n| b_n^N} (r_n(x) - r(x)) \xrightarrow[n \rightarrow \infty]{Law} \mathcal{N}(0, \sigma^2(x)),$$

where  $\sigma^2(x)$  is defined in Theorem 2.

The asymptotic normality of  $r_n$  given by Theorem 2 holds under mild conditions on the regions  $\Lambda_n$  and the bandwidth  $b_n$ , that is  $b_n \rightarrow 0$  and  $|\Lambda_n| b_n^N \rightarrow \infty$ . These conditions on the bandwidth parameter are sometimes called *minimal conditions* since these are required for the asymptotic normality of the Parzen-Rosenblatt estimator  $f_n$  when the observations are assumed to be independent (see [22]). To the best of our knowledge, Theorem 2 is the first central limit theorem for the NWE under minimal conditions on the bandwidth and irregularly spaced dependent spatial data. In particular, we improve in several directions Theorem 2.2 in [1] for strongly mixing random fields where the authors considered a set of conditions on the bandwidth parameter and the mixing coefficients interlaced in a complicated way. More precisely, using our notations, Theorem 2.2 in [1] gives the asymptotic normality of the NWE as soon as  $\mathbb{E}[\exp(|Y_0|^\tau)] < \infty$  for some positive real  $\tau$ , the regions  $\Lambda_n$  are rectangular subsets of  $\mathbb{Z}^d$  such that  $|\Lambda_n| b_n^{N+2} \rightarrow 0$  and  $|\Lambda_n| b_n^{N(1+2\delta d)} \log(|\Lambda_n|)^{-8d/\tau} \rightarrow \infty$  for some  $0 < \delta < 1/2$ , there exists  $q_n \rightarrow \infty$  such that  $q_n^{2d} = o(b_n^{N(1+2\delta d)} \log(|\Lambda_n|)^{-8d/\tau})$  and  $|\Lambda_n| \sum_{n \geq 1} n^{d-1} \alpha_{1,\infty}(n q_n) \rightarrow 0$  and  $b_n^{-N\delta} (\log(|\Lambda_n|))^{2/\tau} \sum_{n \geq q_n} n^{d-1} \alpha_{1,\infty}^\delta(n) \rightarrow 0$ . In particular, it is assumed that  $\sum_{n=1}^\infty n^{d-1} \alpha_{1,\infty}^\delta(n) < \infty$ . In order to compare with our results, one can notice that if  $\delta = \theta/(2+\theta) \in ]0, 1/2[$  and  $\mathbb{E}[|Y_0|^{2+\theta}] < \infty$  with  $0 < \theta < 2$  then (A3)(i) reduces to  $\sum_{n \geq 1} n^{d(3-\delta)-1} \alpha_{1,\infty}^\delta(n) < \infty$ . However, our main result holds even if  $Y_0$  does not have finite exponential moments and also for general regions  $\Lambda_n$  (irregularly spaced spatial data) and under only minimal conditions on the bandwidth ( $b_n \rightarrow 0$  and  $|\Lambda_n| b_n^N \rightarrow \infty$ ).

### 3 Numerical illustration

In order to illustrate the asymptotic normality of the NWE provided by Theorem (1), we are going to consider two regression models where the predictors are given by an autoregressive random field  $(X_{i,j}^{(AR)})_{(i,j) \in \mathbb{Z}^2}$  and a Volterra random field  $(X_{i,j}^{(Vol)})_{(i,j) \in \mathbb{Z}^2}$  respectively (see Model 1 and Model 2 below). In Model 1, the autoregressive random field  $(X_{i,j}^{(AR)})_{(i,j) \in \mathbb{Z}^2}$  is defined by

$$X_{i,j}^{(AR)} = 0.7X_{i-1,j}^{(AR)} + 0.15X_{i,j-1}^{(AR)} + \varepsilon_{i,j}, \quad (2)$$

where  $(\varepsilon_{i,j})_{(i,j) \in \mathbb{Z}^2}$  are iid real random variables ( $N = 1$ ) with standard normal law. From [13], we know that the stationary solution of (2) is the linear random field given by

$$X_{i,j}^{(AR)} = \sum_{s_1 \geq 0} \sum_{s_2 \geq 0} \binom{s_1 + s_2}{s_1} (0.7)^{s_1} (0.15)^{s_2} \varepsilon_{i-s_1, j-s_2}. \quad (3)$$

So, we fix a positive integer  $n_1$  and we simulate the  $\varepsilon_{i,j}$ 's over the grid  $[0, 2n_1]^2 \cap \mathbb{Z}^2$  in order to get the data  $X_{i,j}^{(AR)}$  for  $(i, j)$  in  $[n_1 + 1, 2n_1]^2 \cap \mathbb{Z}^2$  following (2) and (3). In Model 2, in order to consider nonlinearity, we define

$$X_{i,j}^{(Vol)} = \sum_{s_1 \geq 0} \sum_{s_2 \geq 0} \sum_{t_1 > s_1} \sum_{t_2 > s_2} \binom{s_1 + s_2}{s_1} \binom{t_1 - s_1 + t_2 - s_2}{t_1 - s_1} (0.7)^{s_1 + t_1} (0.15)^{s_2 + t_2} \varepsilon_{i-s_1, j-s_2} \varepsilon_{i-t_1, j-t_2}.$$

Since

$$X_{i,j}^{(Vol)} = \sum_{s_1 \geq 0} \sum_{s_2 \geq 0} \binom{s_1 + s_2}{s_1} (0.7)^{2s_1} (0.15)^{2s_2} \varepsilon_{i-s_1, j-s_2} \beta_{i-s_1, j-s_2} \quad (4)$$

where

$$\beta_{i,j} = \sum_{t_1 > 0} \sum_{t_2 > 0} \binom{t_1 + t_2}{t_1} (0.7)^{t_1} (0.15)^{t_2} \varepsilon_{i-t_1, j-t_2}, \quad (5)$$

we fix a positive integer  $n_2$  and we simulate the  $\varepsilon_{i,j}$ 's over the grid  $[0, 4n_2]^2 \cap \mathbb{Z}^2$  and we get the data  $\beta_{i,j}$  for  $(i, j)$  in  $[2n_2 + 1, 4n_2]^2 \cap \mathbb{Z}^2$  using (5) and following the previous implementation of  $(X_{i,j}^{(AR)})_{(i,j) \in \mathbb{Z}^2}$ . Starting from the data  $\varepsilon_{i,j} \beta_{i,j}$  for  $(i, j)$  in  $[2n_2 + 1, 4n_2]^2$ , we simulate in the same way the data  $X_{i,j}^{(Vol)}$  for  $(i, j)$  in  $[3n_2 + 1, 4n_2]^2$  using (4). From the two data sets

$$Y_{i,j}^{(AR)} = \sin(X_{i,j}^{(AR)}) + \varepsilon_{i,j}, \quad (i, j) \in [n_1 + 1, 2n_1]^2 \quad (\text{Model 1})$$

and

$$Y_{i,j}^{(Vol)} = \sin(X_{i,j}^{(Vol)}) + \varepsilon_{i,j}, \quad (i, j) \in [3n_2 + 1, 4n_2]^2 \quad (\text{Model 2}),$$

we consider 500 replications of  $\sqrt{2\sqrt{\pi} \hat{f}_{n_1}^{(AR)}(0)} n_1^2 b_{n_1} r_{n_1}^{(AR)}(0)$  and  $\sqrt{2\sqrt{\pi} \hat{f}_{n_2}^{(Vol)}(0)} n_2^2 b_{n_2} r_{n_2}^{(Vol)}(0)$  where

$$\hat{f}_{n_1}^{(AR)}(0) = \frac{1}{n_1^2 b_{n_1}} \sum_{(i,j) \in [n_1+1, 2n_1]^2} K\left(\frac{X_{i,j}^{(AR)}}{b_{n_1}}\right), \quad \hat{f}_{n_2}^{(Vol)}(0) = \frac{1}{n_2^2 b_{n_2}} \sum_{(i,j) \in [3n_2+1, 4n_2]^2} K\left(\frac{X_{i,j}^{(Vol)}}{b_{n_2}}\right),$$

$$r_{n_1}^{(AR)}(0) = \frac{\sum_{(i,j) \in [n_1+1, 2n_1]^2} Y_{i,j}^{(AR)} K\left(\frac{X_{i,j}^{(AR)}}{b_{n_1}}\right)}{n_1^2 b_{n_1} \hat{f}_{n_1}^{(AR)}(0)}, \quad r_{n_2}^{(Vol)}(0) = \frac{\sum_{(i,j) \in [3n_2+1, 4n_2]^2} Y_{i,j}^{(Vol)} K\left(\frac{X_{i,j}^{(Vol)}}{b_{n_2}}\right)}{n_2^2 b_{n_2} \hat{f}_{n_2}^{(Vol)}(0)},$$

the kernel  $K$  is Gaussian and the bandwidth parameters  $b_{n_1}$  and  $b_{n_2}$  are selected by cross validation. So, in Figure 1 below, we obtain the histograms for

$$\sqrt{2\sqrt{\pi}\hat{f}_{n_1}^{(AR)}(0)}n_1^2 b_{n_1} r_{n_1}^{(AR)}(0) \quad \text{and} \quad \sqrt{2\sqrt{\pi}\hat{f}_{n_2}^{(Vol)}(0)}n_2^2 b_{n_2} r_{n_2}^{(Vol)}(0)$$

with  $n_1, n_2 \in \{10, 30\}$  along with the standard normal law.

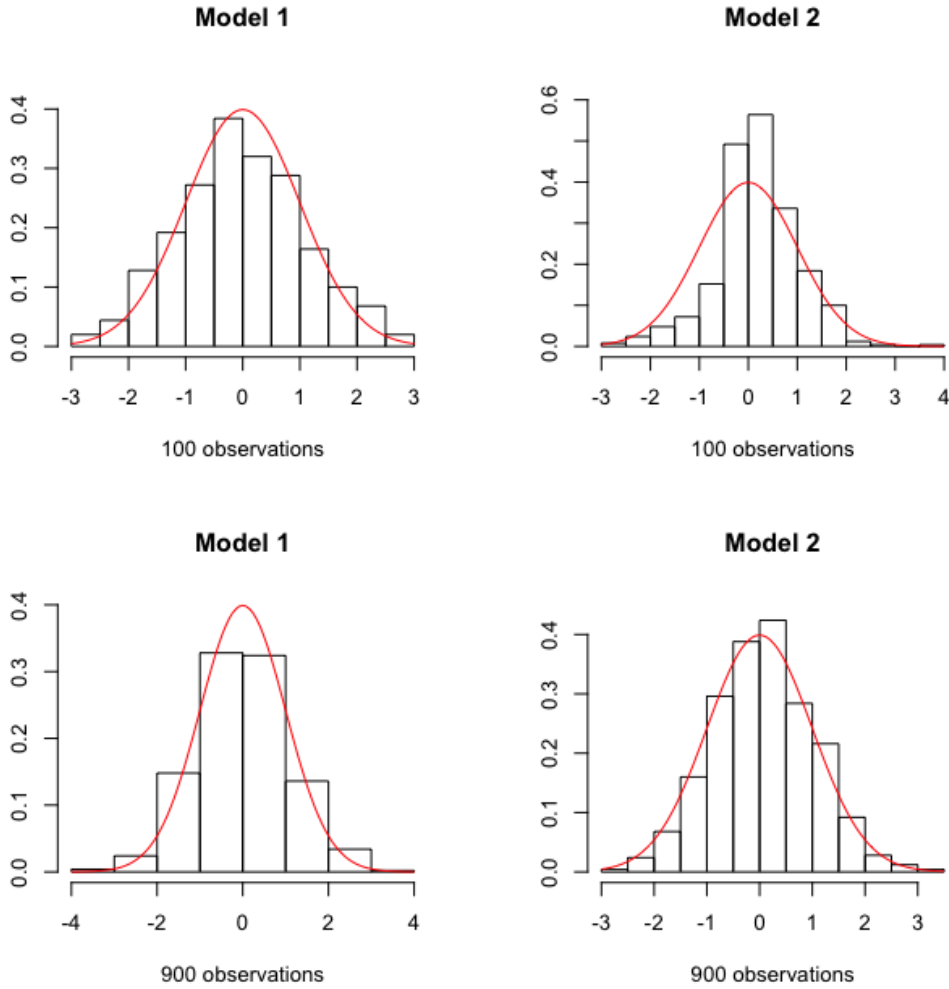


Figure 1: Histograms for  $\sqrt{2\sqrt{\pi}\hat{f}_{n_1}^{(AR)}(0)}n_1^2 b_{n_1} r_{n_1}^{(AR)}(0)$  (Model 1) and  $\sqrt{2\sqrt{\pi}\hat{f}_{n_2}^{(Vol)}(0)}n_2^2 b_{n_2} r_{n_2}^{(Vol)}(0)$  (Model 2) along with the standard normal density.



## 4 Preliminary lemmas

In the sequel, for any sequences  $(a_n)_{n \geq 1}$  and  $(b_n)_{n \geq 1}$  of real positive numbers, we denote  $a_n \asymp b_n$  if and only if there exists  $\kappa > 0$  (not depending on  $n$ ) such that  $a_n \leq \kappa b_n$ . For any real  $x$ , we define also  $\lceil x \rceil = \lfloor x \rfloor + 1$ , where  $\lfloor x \rfloor$  is the largest integer less than  $x$ . We shall need the following technical lemmas.

**Lemma 1** *Assume (A1), (A2) and (A4) and let  $x \in \mathbb{R}^N$ . If  $\Phi_1 : \mathbb{R} \rightarrow \mathbb{R}$  and  $\Phi_2 : \mathbb{R} \rightarrow \mathbb{R}$  are two functions such that  $x \mapsto \mathbb{E}[\Phi_1(Y_0)|X_0 = x]$  is continuous and the conditions  $\sup_{t \in \mathbb{R}^N} |\Phi_2(K(t))| < \infty$ ,  $\lim_{\|t\| \rightarrow \infty} \|t\| |\Phi_2(K(t))| = 0$  and  $\int_{\mathbb{R}^N} |\Phi_2(K(t))| dt < \infty$  are satisfied then*

$$\lim_{n \rightarrow \infty} \frac{\mathbb{E}[\Phi_1(Y_0)\Phi_2(K_n(x, X_0))]}{b_n^N} = \mathbb{E}[\Phi_1(Y_0)|X_0 = x] f(x) \int_{\mathbb{R}^N} \Phi_2(K(v)) dv.$$

Moreover, we have also  $\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E}[|K_n(x, X_0)K_n(x, X_j)|] \asymp b_n^{2N}$ .

*Proof.* Let  $x \in \mathbb{R}^N$  and let  $n$  be a positive integer. It is obvious that

$$\mathbb{E}[\Phi_1(Y_0)\Phi_2(K_n(x, X_0))] = b_n^N \int_{\mathbb{R}^N} \mathbb{E}[\Phi_1(Y_0) | X_0 = x - vb_n] \Phi_2(K(v)) f(x - vb_n) dv.$$

By Theorem 1A in [22], we have

$$\begin{aligned} \lim_{n \rightarrow \infty} \int_{\mathbb{R}^N} \mathbb{E}[\Phi_1(Y_0) | X_0 = x - vb_n] \Phi_2(K(v)) f(x - vb_n) dv \\ = \mathbb{E}[\Phi_1(Y_0) | X_0 = x] f(x) \int_{\mathbb{R}^N} \Phi_2(K(v)) dv. \end{aligned}$$

Consequently,

$$\lim_{n \rightarrow \infty} \frac{\mathbb{E}[\Phi_1(Y_0)\Phi_2(K_n(x, X_0))]}{b_n^N} = \mathbb{E}[\Phi_1(Y_0) | X_0 = x] f(x) \int_{\mathbb{R}^N} \Phi_2(K(v)) dv. \quad (6)$$

In the other part, keeping in mind assumptions (A1) and (A2) and using (6), we derive

$$\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E}[|K_n(x, X_0)K_n(x, X_j)|] \leq \kappa \left( \int_{\mathbb{R}^N} |K_n(x, u)| du \right)^2 + (\mathbb{E}[|K_n(x, X_0)|])^2 \asymp b_n^{2N}.$$

The proof of Lemma 1 is complete.  $\square$

**Lemma 2** *If (A3) holds, then there exists a sequence  $(m_n)_{n \geq 1}$  of positive integers satisfying*

$$\lim_{n \rightarrow \infty} m_n = +\infty, \quad \lim_{n \rightarrow \infty} m_n^d b_n^{\frac{\theta N}{4+\theta}} = 0 \quad \text{and} \quad \begin{cases} \lim_{n \rightarrow \infty} b_n^{-\frac{\theta N}{2+\theta}} \sum_{|i| > m_n} \alpha_{1, \infty}^{\frac{\theta}{2+\theta}}(|i|) = 0 & \text{if (A3)(i) holds} \\ \lim_{n \rightarrow \infty} b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|i| > m_n} |i|^d \delta_{i,2}^{\frac{\theta}{2+\theta}} = 0 & \text{if (A3)(ii) holds.} \end{cases}$$

Notice that when  $|\Lambda_n| b_n^N \rightarrow \infty$ , we have  $m_n^d = o(|\Lambda_n|)$ .

*Proof.* First, we assume (A3)(i). So, we have  $\mathbb{E}[|Y_0|^{2+\theta}] < \infty$  and  $\sum_{i \in \mathbb{Z}^d} |i|^{\frac{d(4+\theta)}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(|i|) < \infty$  for some  $\theta > 0$ . Let  $\gamma > (4 + \theta)/(2 + \theta)$  be fixed and let  $(m_n)_{n \geq 1}$  be defined by

$$m_n = \max \left\{ v_n, \left\lceil b_n^{-\frac{\theta N}{d(4+\theta)}} \left( \sum_{|i| > v_n} |i|^{\frac{d(4+\theta)}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(|i|) \right)^{\frac{1}{d\gamma}} \right\rceil \right\} \quad \text{and} \quad v_n = \lfloor b_n^{-\frac{\theta N}{2d(4+\theta)}} \rfloor.$$

Since  $v_n \rightarrow \infty$ , we have  $m_n \rightarrow \infty$  as  $n$  goes to infinity. Moreover,

$$m_n^d b_n^{\frac{\theta N}{4+\theta}} \leq \max \left\{ b_n^{\frac{\theta N}{2(4+\theta)}}, \left( \sum_{|i| > v_n} |i|^{\frac{d(4+\theta)}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(|i|) \right)^{\frac{1}{\gamma}} + b_n^{\frac{\theta N}{4+\theta}} \right\} \xrightarrow{n \rightarrow \infty} 0.$$

Since  $v_n \leq m_n$ , we have

$$m_n^d b_n^{\frac{\theta N}{4+\theta}} \geq \left( \sum_{|i| > m_n} |i|^{\frac{d(4+\theta)}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(|i|) \right)^{\frac{1}{\gamma}}.$$

Consequently,

$$b_n^{-\frac{\theta N}{2+\theta}} \sum_{|i| > m_n} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(|i|) \leq \left( m_n^d b_n^{\frac{\theta N}{4+\theta}} \right)^{-\frac{4+\theta}{2+\theta}} \sum_{|i| > m_n} |i|^{\frac{d(4+\theta)}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(|i|) \leq \left( \sum_{|i| > m_n} |i|^{\frac{d(4+\theta)}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(|i|) \right)^{\frac{\gamma(2+\theta)-4-\theta}{\gamma(2+\theta)}}.$$

Since  $\gamma > (4 + \theta)/(2 + \theta)$ , we derive  $\lim_{n \rightarrow \infty} b_n^{-\frac{\theta N}{2+\theta}} \sum_{|i| > m_n} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(|i|) = 0$ .

Similarly, assume (A3)(ii) holds and define

$$\tilde{m}_n = \max \left\{ v_n, \left\lceil b_n^{-\frac{\theta N}{d(4+\theta)}} \left( \sum_{|i| > v_n} |i|^{\frac{d(3N+2)\theta^2 + (10N+8)\theta + 8N}{2\theta(2+\theta)N}} \delta_{i,2}^{\frac{\theta}{2+\theta}} \right)^{\frac{1}{d\gamma}} \right\rceil \right\} \quad \text{with} \quad \gamma > \frac{((N+2)\theta + 2N)(\theta + 4)}{2\theta(\theta + 2)N}.$$

Then, arguing as before, we derive

$$\lim_{n \rightarrow \infty} \tilde{m}_n^d b_n^{\frac{\theta N}{4+\theta}} = 0 \quad \text{and} \quad \lim_{n \rightarrow \infty} b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|i| > \tilde{m}_n} |i|^d \delta_{i,2}^{\frac{\theta}{2+\theta}} = 0.$$

The details of the proof are left to the reader. The proof of Lemma 2 is complete.  $\square$

For any  $i$  in  $\mathbb{Z}^d$ , any positive integer  $n$  and any  $x \in \mathbb{R}^N$ , we denote

$$\Delta_i = \frac{K_n(x, X_i) - \mathbb{E}[K_n(x, X_0)]}{\sqrt{b_n^N}} \quad \text{and} \quad \Theta_i = \frac{Y_i K_n(x, X_i) - \mathbb{E}[Y_0 K_n(x, X_0)]}{\sqrt{b_n^N}}. \quad (7)$$

**Lemma 3** Assume (A1), (A2) and (A4). If there exists  $\theta > 0$  such that  $\mathbb{E}[|Y_0|^{2+\theta}] < \infty$ , then  $\max\{\|\Delta_0\|_{2+\theta}^2, \|\Theta_0\|_{2+\theta}^2\} \leq b_n^{-\frac{\theta N}{2+\theta}}$ .

*Proof.* Let  $\theta > 0$  such that  $\mathbb{E} [|Y_0|^{2+\theta}] < \infty$ , we have

$$\|\Delta_0\|_{2+\theta}^2 \leq \frac{2 \|\mathbb{K}_n(x, X_0)\|_{2+\theta}^2}{b_n^N} + \frac{2 (\mathbb{E} [\mathbb{K}_n(x, X_0)])^2}{b_n^N}$$

and

$$\|\Theta_0\|_{2+\theta}^2 \leq \frac{2 \|Y_0 \mathbb{K}_n(x, X_0)\|_{2+\theta}^2}{b_n^N} + \frac{2 (\mathbb{E} [Y_0 \mathbb{K}_n(x, X_0)])^2}{b_n^N}.$$

Keeping in mind that  $\|\mathbb{K}\|_\infty := \sup_{t \in \mathbb{R}^N} |\mathbb{K}(t)| < \infty$  and using Lemma 1, we derive

$$\begin{aligned} \mathbb{E} [|\mathbb{K}_n(x, X_0)|^{2+\theta}] &\leq b_n^N, & \left| \mathbb{E} [\mathbb{K}_n(x, X_0)] \right| &\leq b_n^N, \\ \mathbb{E} [Y_0 \mathbb{K}_n(x, X_0)^{2+\theta}] &\leq b_n^N & \text{and} & \left| \mathbb{E} [Y_0 \mathbb{K}_n(x, X_0)] \right| &\leq b_n^N. \end{aligned}$$

Consequently, we obtain  $\max\{\|\Delta_0\|_{2+\theta}^2, \|\Theta_0\|_{2+\theta}^2\} \leq b_n^{-\frac{\theta N}{2+\theta}}$ . The proof of Lemma 3 is complete.  $\square$

**Lemma 4** *Assume (A1), (A2) and (A4). Then,  $\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|\Delta_0 \Delta_j|] \leq b_n^N$ . Moreover, if  $\mathbb{E} [|Y_0|^{2+\theta}] < \infty$  for some  $\theta > 0$  then*

$$\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|\Theta_0 \Theta_j|] \leq b_n^{\frac{\theta N}{4+\theta}} \quad \text{and} \quad \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|\Theta_0 \Delta_j|] \leq b_n^{\frac{\theta N}{2+\theta}}.$$

*Proof.* Let  $j \neq 0$  in  $\mathbb{Z}^d$ , then

$$\mathbb{E} [|\Delta_0 \Delta_j|] \leq \frac{\mathbb{E} [|\mathbb{K}_n(x, X_0) \mathbb{K}_n(x, X_j)|] + 3 (\mathbb{E} [|\mathbb{K}_n(x, X_0)|])^2}{b_n^N}.$$

Applying Lemma 1, we get

$$\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|\Delta_0 \Delta_j|] \leq b_n^N.$$

Let  $L \geq 1$ . We have

$$\mathbb{E} [|\Theta_0 \Theta_j|] \leq \frac{\mathbb{E} [Y_0 Y_j \mathbb{K}_n(x, X_0) \mathbb{K}_n(x, X_j)] + 3 (\mathbb{E} [Y_0 \mathbb{K}_n(x, X_0)])^2}{b_n^N} \quad (8)$$

and

$$\begin{aligned} \mathbb{E} [Y_0 Y_j \mathbb{K}_n(x, X_0) \mathbb{K}_n(x, X_j)] &= \mathbb{E} [Y_0 Y_j \mathbf{1}_{|Y_0| \leq L} \mathbf{1}_{|Y_j| \leq L} \mathbb{K}_n(x, X_0) \mathbb{K}_n(x, X_j)] \\ &\quad + \mathbb{E} [Y_0 Y_j \mathbf{1}_{|Y_0| \leq L} \mathbf{1}_{|Y_j| > L} \mathbb{K}_n(x, X_0) \mathbb{K}_n(x, X_j)] \\ &\quad + \mathbb{E} [Y_0 Y_j \mathbf{1}_{|Y_0| > L} \mathbf{1}_{|Y_j| \leq L} \mathbb{K}_n(x, X_0) \mathbb{K}_n(x, X_j)] \\ &\quad + \mathbb{E} [Y_0 Y_j \mathbf{1}_{|Y_0| > L} \mathbf{1}_{|Y_j| > L} \mathbb{K}_n(x, X_0) \mathbb{K}_n(x, X_j)]. \end{aligned}$$

By Cauchy-Schwarz's inequality, we derive

$$\begin{aligned} \mathbb{E} [ |Y_0 Y_j K_n(x, X_0) K_n(x, X_j)| ] &\leq L^2 \mathbb{E} [ |K_n(x, X_0) K_n(x, X_j)| ] \\ &\quad + \sqrt{\mathbb{E} [ Y_0^2 K_n^2(x, X_0) ]} \sqrt{\mathbb{E} [ Y_0^2 \mathbf{1}_{|Y_0|>L} K_n^2(x, X_0) ]} \\ &\quad + \sqrt{\mathbb{E} [ Y_0^2 \mathbf{1}_{|Y_0|>L} K_n^2(x, X_0) ]} \sqrt{\mathbb{E} [ Y_0^2 K_n^2(x, X_0) ]} \\ &\quad + \mathbb{E} [ Y_0^2 \mathbf{1}_{|Y_0|>L} K_n^2(x, X_0) ]. \end{aligned}$$

Let  $\theta > 0$  such that  $\mathbb{E} [ |Y_0|^{2+\theta} ] < \infty$ . Applying Lemma 1, we get

$$\frac{\mathbb{E} [ |Y_0 Y_j K_n(x, X_0) K_n(x, X_j)| ]}{b_n^N} \leq L^2 b_n^N + L^{-\theta/2} + L^{-\theta} \leq L^2 b_n^N + L^{-\theta/2}. \quad (9)$$

Making the choice  $L = b_n^{-\frac{2N}{4+\theta}}$  and combining (8), (9) and Lemma 1, we obtain

$$\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [ |\Theta_0 \Theta_j| ] \leq b_n^{\frac{\theta N}{4+\theta}}.$$

Now,

$$\mathbb{E} [ |\Theta_0 \Delta_j| ] \leq \frac{\mathbb{E} [ |Y_0 K_n(x, X_0) K_n(x, X_j)| ] + 3 \mathbb{E} [ |Y_0 K_n(x, X_0)| ] \mathbb{E} [ |K_n(x, X_0)| ]}{b_n^N}.$$

So, if  $L' \geq 1$  is fixed then

$$\begin{aligned} \mathbb{E} [ |\Theta_0 \Delta_j| ] &\leq \frac{L' \mathbb{E} [ |K_n(x, X_0) K_n(x, X_j)| ]}{b_n^N} + \frac{\mathbb{E} [ |Y_0| \mathbf{1}_{|Y_0|>L'} |K_n(x, X_0) K_n(x, X_j)| ]}{b_n^N} \\ &\quad + \frac{3 \mathbb{E} [ |Y_0 K_n(x, X_0)| ] \mathbb{E} [ |K_n(x, X_0)| ]}{b_n^N}. \end{aligned}$$

By Cauchy-Schwarz's inequality, we get

$$\mathbb{E} [ |Y_0| \mathbf{1}_{|Y_0|>L'} |K_n(x, X_0) K_n(x, X_j)| ] \leq L'^{-\theta/2} \sqrt{\mathbb{E} [ |Y_0|^{2+\theta} K_n^2(x, X_0) ]} \sqrt{\mathbb{E} [ K_n^2(x, X_0) ]}.$$

Applying Lemma 1 and making the choice  $L' = b_n^{-\frac{2N}{2+\theta}}$ , we obtain

$$\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [ |\Theta_0 \Delta_j| ] \leq L' b_n^N + L'^{-\theta/2} + b_n^N \leq b_n^{\frac{\theta N}{2+\theta}}.$$

The proof of Lemma 4 is complete. □

The following proposition is a crucial tool in the proof of the asymptotic normality for the NWE (Theorem 2) when the random field  $(X_i)_{i \in \mathbb{Z}^d}$  is of the form (1).

**Proposition 1** Let  $n$  and  $M$  be two positive integers and let  $x \in \mathbb{R}^N$ . If  $\Lambda$  is a finite subset of  $\mathbb{Z}^d$  and  $\Phi : \mathbb{R} \rightarrow \mathbb{R}$  is a measurable function such that  $\|\Phi(Y_0)\|_{2+\theta} < \infty$  for some  $\theta \in ]0, +\infty]$  then for any family  $(c_i)_{i \in \Lambda}$  of real numbers and any  $(p, q) \in [2, +\infty[ \times ]0, +\infty]$  such that  $p + q \leq 2 + \theta$ , we have

$$\left\| \sum_{i \in \Lambda} c_i W_{i,n} \right\|_p \leq 8pM^d |\mathbb{K}|^{\frac{p}{p+q}} C(p, q) \sqrt{\sum_{i \in \Lambda} c_i^2 b_n^{-\frac{q}{p+q}} \sum_{|i| > M} \delta_{i,p}^{\frac{q}{p+q}}},$$

where

$$W_{i,n} := \Phi(Y_i) \mathbb{K}_n(x, X_i) - \mathbb{E} [\Phi(Y_i) \mathbb{K}_n(x, X_i) | \mathcal{H}_{i,M}], \quad (10)$$

$$C(p, q) = 2^{\frac{2p+q}{p+q}} \|\Phi(Y_0)\|_{p+q} \|\mathbb{K}\|_{\text{Lip}}^{\frac{q}{p+q}} + |\mathbb{K}|^{\frac{q}{p+q}} \left\| \sup_{\substack{(x,y) \in \mathbb{R}^N \times \mathbb{R}^N \\ x \neq y}} \frac{|\Phi(R(x, \eta_0)) - \Phi(R(y, \eta_0))|}{\|x - y\|} \right\|_p.$$

and

$$\mathcal{H}_{i,M} = \sigma(\eta_i, \varepsilon_{i-s}; |s| \leq M) \quad \text{and} \quad \|\mathbb{K}\|_{\text{Lip}} = \sup_{\substack{(x,y) \in \mathbb{R}^N \times \mathbb{R}^N \\ x \neq y}} \frac{|\mathbb{K}(x) - \mathbb{K}(y)|}{\|x - y\|}.$$

*Proof.* Let  $M$  and  $n$  be two positive integers and let  $x$  in  $\mathbb{R}^N$  and  $i$  in  $\mathbb{Z}^d$  be fixed. Recall that  $Y_i = R(X_i, \eta_i)$ . We follow the same lines as in the proof of Proposition 1 in [11]. Let  $2 \leq p < 2 + \theta$  and denote by  $H_n$  the measurable function such that  $W_{i,n} = H_n(\mathcal{H}_{i,\infty})$  with  $\mathcal{H}_{i,\infty} = \sigma(\eta_i, \varepsilon_{i-s}; s \in \mathbb{Z}^d)$ . Then, we define the physical dependence measure coefficient  $\delta_{i,p}^{(n)}$  associated to  $W_{i,n}$  by  $\delta_{i,p}^{(n)} = \|W_{i,n} - W_{i,n}^*\|_p$ , where  $W_{i,n}^* = H_n(\mathcal{H}_{i,\infty}^*)$  and  $\mathcal{H}_{i,\infty}^* = \sigma(\eta_i, \varepsilon_{i-s}^*; s \in \mathbb{Z}^d)$  keeping in mind that  $\varepsilon_j^* = \varepsilon_j$  if  $j \neq 0$  and  $\varepsilon_0^* = \varepsilon_0'$ . In other words, we obtain  $W_{i,n}^*$  from  $W_{i,n}$  by just replacing  $\varepsilon_0$  by its copy  $\varepsilon_0'$  (see [30]). Let  $\tau$  be a bijection from  $\mathbb{Z}$  to  $\mathbb{Z}^d$  and  $\ell$  in  $\mathbb{Z}$  be fixed. We define the projection operator  $P_\ell$  by  $P_\ell f = \mathbb{E}[f | \mathcal{F}_\ell] - \mathbb{E}[f | \mathcal{F}_{\ell-1}]$  for any integrable function  $f$ , where  $\mathcal{F}_\ell = \sigma(\varepsilon_{\tau(s)}; s \leq \ell)$ . Consequently, by stationarity, we have

$$\|P_\ell W_{i,n}\|_p = \left\| \mathbb{E}[W_{0,n} | T^i \mathcal{F}_\ell] - \mathbb{E}[W_{0,n} | T^i \mathcal{F}_{\ell-1}] \right\|_p,$$

where  $T^i \mathcal{F}_\ell = \sigma(\varepsilon_{\tau(s)-i}; s \leq \ell)$ . Keeping in mind that  $W_{0,n} = H_n(\mathcal{H}_{0,\infty})$ , we derive

$$\|P_\ell W_{i,n}\|_p = \left\| \mathbb{E}[H_n(\mathcal{H}_{0,\infty}) | T^i \mathcal{F}_\ell] - \mathbb{E}[H_n(\mathcal{H}_{0,\infty}^{(i,\ell)}) | T^i \mathcal{F}_\ell] \right\|_p \leq \left\| H_n(\mathcal{H}_{0,\infty}) - H_n(\mathcal{H}_{0,\infty}^{(i,\ell)}) \right\|_p,$$

where  $\mathcal{H}_{0,\infty}^{(i,\ell)} = \sigma(\eta, \varepsilon_{\tau(\ell)-i}^', \varepsilon_{-s}; s \in \mathbb{Z}^d \setminus \{i - \tau(\ell)\})$ . It means that  $\mathcal{H}_{0,\infty}^{(i,\ell)}$  is obtained from  $\mathcal{H}_{0,\infty}$  by replacing  $\varepsilon_{\tau(\ell)-i}$  by its copy  $\varepsilon_{\tau(\ell)-i}^'$ . Consequently, using again the stationarity of the random field and noting that

$$\begin{aligned} T^{\tau(\ell)-i} \mathcal{H}_{0,\infty} &= \sigma(\eta_{i-\tau(\ell)}, \varepsilon_{i-\tau(\ell)-s}; s \in \mathbb{Z}^d) = \mathcal{H}_{i-\tau(\ell),\infty}, \\ T^{\tau(\ell)-i} \mathcal{H}_{0,\infty}^{(i,\ell)} &= \sigma(\eta_{i-\tau(\ell)}, \varepsilon_0', \varepsilon_{i-\tau(\ell)-s}; s \in \mathbb{Z}^d \setminus \{i - \tau(\ell)\}) = \mathcal{H}_{i-\tau(\ell),\infty}^*, \end{aligned}$$

we obtain

$$\|P_\ell W_{i,n}\|_p \leq \left\| H_n(T^{\tau(\ell)-i} \mathcal{H}_{0,\infty}) - H_n(T^{\tau(\ell)-i} \mathcal{H}_{0,\infty}^{(i,\ell)}) \right\|_p = \left\| W_{i-\tau(\ell),n} - W_{i-\tau(\ell),n}^* \right\|_p = \delta_{i-\tau(\ell),p}^{(n)}. \quad (11)$$

Moreover, since  $W_{i,n} = \sum_{\ell \in \mathbb{Z}} P_\ell W_{i,n}$ , we have

$$\left\| \sum_{j \in \Lambda} c_j W_{j,n} \right\|_p = \left\| \sum_{\ell \in \mathbb{Z}} \sum_{j \in \Lambda} c_j P_\ell W_{j,n} \right\|_p.$$

Since  $(\sum_{j \in \Lambda} c_j P_\ell W_{j,n})_{\ell \in \mathbb{Z}}$  is a martingale difference sequence with respect to the filtration  $(\mathcal{F}_\ell)_{\ell \in \mathbb{Z}}$ , the Burkholder inequality (see [6], remark 6, page 85) implies

$$\left\| \sum_{j \in \Lambda} c_j W_{j,n} \right\|_p \leq \left( 2p \sum_{\ell \in \mathbb{Z}} \left\| \sum_{j \in \Lambda} c_j P_\ell W_{j,n} \right\|_p^2 \right)^{\frac{1}{2}} \leq \left( 2p \sum_{\ell \in \mathbb{Z}} \left( \sum_{j \in \Lambda} |c_j| \|P_\ell W_{j,n}\|_p \right)^2 \right)^{\frac{1}{2}}. \quad (12)$$

Moreover, by the Cauchy-Schwarz inequality, we have

$$\left( \sum_{j \in \Lambda} |c_j| \|P_\ell W_{j,n}\|_p \right)^2 \leq \sum_{i \in \Lambda} c_i^2 \|P_\ell W_{i,n}\|_p \times \sum_{j \in \Lambda} \|P_\ell W_{j,n}\|_p. \quad (13)$$

Using (11), we have  $\sup_{\ell \in \mathbb{Z}} \sum_{j \in \mathbb{Z}^d} \|P_\ell W_{j,n}\|_p \leq \sum_{j \in \mathbb{Z}^d} \delta_{j,p}^{(n)}$ . So, combining (12) and (13), we obtain

$$\left\| \sum_{j \in \Lambda} c_j W_{j,n} \right\|_p \leq \left( 2p \sum_{j \in \mathbb{Z}^d} \delta_{j,p}^{(n)} \sum_{i \in \Lambda} c_i^2 \sum_{\ell \in \mathbb{Z}} \|P_\ell W_{i,n}\|_p \right)^{\frac{1}{2}}.$$

Using (11) and keeping in mind that  $\tau$  is a bijection, we have  $\sup_{i \in \mathbb{Z}^d} \sum_{\ell \in \mathbb{Z}} \|P_\ell W_{i,n}\|_p \leq \sum_{j \in \mathbb{Z}^d} \delta_{j,p}^{(n)}$ . Hence, we derive

$$\left\| \sum_{j \in \Lambda} c_j W_{j,n} \right\|_p \leq \left( 2p \sum_{j \in \Lambda} c_j^2 \right)^{\frac{1}{2}} \sum_{j \in \mathbb{Z}^d} \delta_{j,p}^{(n)}. \quad (14)$$

Now, since

$$\mathbb{E} [\Phi(Y_i) K_n(x, X_i) | \mathcal{H}_{i,M}^*] = \mathbb{E} [\Phi(R(X_i^*, \eta_i)) K_n(x, X_i^*) | \mathcal{H}_{i,M}^*],$$

where  $\mathcal{H}_{i,M}^* = \sigma(\eta_i, \varepsilon_{i-s}^*; |s| \leq M)$ , we have

$$W_{i,n}^* = \Phi(R(X_i^*, \eta_i)) K_n(x, X_i^*) - \mathbb{E} [\Phi(R(X_i^*, \eta_i)) K_n(x, X_i^*) | \mathcal{H}_{i,M}^*].$$

Moreover,

$$\mathbb{E} [\Phi(Y_i) K_n(x, X_i) | \mathcal{H}_{i,M}] = \mathbb{E} [\Phi(Y_i) K_n(x, X_i) | \mathcal{H}_{i,M} \vee \mathcal{H}_{i,M}^*]$$

and

$$\mathbb{E} [\Phi(R(X_i^*, \eta_i)) K_n(x, X_i^*) | \mathcal{H}_{i,M}^*] = \mathbb{E} [\Phi(R(X_i^*, \eta_i)) K_n(x, X_i^*) | \mathcal{H}_{i,M} \vee \mathcal{H}_{i,M}^*].$$

Consequently,

$$\delta_{i,p}^{(n)} = \|W_{i,n} - W_{i,n}^*\|_p \leq 2 \|\Phi(R(X_i, \eta_i)) K_n(x, X_i) - \Phi(R(X_i^*, \eta_i)) K_n(x, X_i^*)\|_p. \quad (15)$$

Let  $L > 0$  be fixed. From (15), we derive

$$\begin{aligned} \delta_{i,p}^{(n)} &\leq 2 \left\| \Phi(R(X_i, \eta_i)) (K_n(x, X_i) - K_n(x, X_i^*)) - (\Phi(R(X_i^*, \eta_i)) - \Phi(R(X_i, \eta_i))) K_n(x, X_i^*) \right\|_p \\ &\leq 2L \|K\|_{\text{Lip}} \frac{\delta_{i,p}}{b_n} + 4|K|_{\infty} L^{-q/p} \|\Phi(Y_0)\|_{p+q}^{\frac{p+q}{p}} + 2|K|_{\infty} \left\| \sup_{\substack{(x,y) \in \mathbb{R}^N \times \mathbb{R}^N \\ x \neq y}} \frac{|\Phi(R(x, \eta_0)) - \Phi(R(y, \eta_0))|}{\|x - y\|} \right\|_p \delta_{i,p}. \end{aligned}$$

Optimizing this last inequality in  $L$ , we get

$$\delta_{i,p}^{(n)} \leq 2|K|_{\infty}^{\frac{p}{p+q}} C(p, q) b_n^{-\frac{q}{p+q}} \delta_{i,p}^{\frac{q}{p+q}}, \quad (16)$$

where

$$C(p, q) = 2^{\frac{2p+q}{p+q}} \|\Phi(Y_0)\|_{p+q} \|K\|_{\text{Lip}}^{\frac{q}{p+q}} + |K|_{\infty}^{\frac{q}{p+q}} \left\| \sup_{\substack{(x,y) \in \mathbb{R}^N \times \mathbb{R}^N \\ x \neq y}} \frac{|\Phi(R(x, \eta_0)) - \Phi(R(y, \eta_0))|}{\|x - y\|} \right\|_p.$$

Now, by stationarity, we have  $\delta_{i,p}^{(n)} = \|W_{i,n} - W_{i,n}^*\|_p \leq 2 \|W_{0,n}\|_p$ . Let  $\ell \geq 0$  be a fixed integer. We denote by  $\Gamma_{\ell}$  the set of all  $j$  in  $\mathbb{Z}^d$  such that  $|j| = \ell$  and we define

$$a_{\ell} := \sum_{j=0}^{\ell} |\Gamma_j| = 1 + 2d \sum_{j=1}^{\ell} (2j+1)^{d-1}.$$

If  $u = (u_1, \dots, u_d)$  and  $v = (v_1, \dots, v_d)$  are distinct elements of  $\mathbb{Z}^d$ , the notation  $u <_{\text{lex}} v$  means that either  $u_1 < v_1$  or for some  $k$  in  $\{2, \dots, d\}$ ,  $u_k < v_k$  and  $u_s = v_s$  for  $1 \leq s < k$  (lexicographic order). Let  $\tau_0 : ]0, +\infty[ \cap \mathbb{Z} \rightarrow \mathbb{Z}^d$  be the bijection defined by

- $\tau_0(1) = 0$ ,
- $\tau_0(s) \in \Gamma_{\ell}$  if  $a_{\ell-1} < s \leq a_{\ell}$  and  $\ell > 0$ ,
- $\tau_0(s) <_{\text{lex}} \tau_0(t)$  if  $a_{\ell-1} < s < t \leq a_{\ell}$  and  $\ell > 0$ .

Let  $\mathcal{G}_M = \sigma(\eta_0, \varepsilon_{\tau_0(s)}; 1 \leq s \leq M)$  and recall that  $\mathcal{H}_{0,M} = \sigma(\eta_0, \varepsilon_{-s}; |s| \leq M)$ . Since  $1 \leq s \leq a_M$  if and only if  $|\tau_0(s)| \leq M$ , we have  $\mathcal{G}_{a_M} = \mathcal{H}_{0,M}$ . Consequently,

$$W_{0,n} = \sum_{\ell > a_M} D_{\ell} \quad \text{where} \quad D_{\ell} = \mathbb{E}[\Phi(R(X_0, \eta_0)) K_n(x, X_0) | \mathcal{G}_{\ell}] - \mathbb{E}[\Phi(R(X_0, \eta_0)) K_n(x, X_0) | \mathcal{G}_{\ell-1}].$$

Since  $(D_{\ell})_{\ell \geq 1}$  is a martingale difference sequence with respect to the filtration  $(\mathcal{G}_{\ell})_{\ell \geq 1}$ , we apply Burkholder's inequality ([6], remark 6, page 85) and we obtain

$$\|W_{0,n}\|_p \leq \left( 2p \sum_{\ell > a_M} \|D_{\ell}\|_p^2 \right)^{1/2}. \quad (17)$$

Let  $L > 0$  be fixed. Denoting  $X'_{0,\ell} = G(\eta_0, \varepsilon'_{\tau_0(\ell)}, \varepsilon_{-s}; s \in \mathbb{Z}^d \setminus \{-\tau_0(\ell)\})$ , we have

$$\mathbb{E}[\Phi(R(X_0, \eta_0)) K_n(x, X_0) | \mathcal{G}_{\ell-1}] = \mathbb{E}[\Phi(R(X'_{0,\ell}, \eta_0)) K_n(x, X'_{0,\ell}) | \mathcal{G}_{\ell}].$$

Then

$$\begin{aligned}
\|D_\ell\|_p &\leq \left\| \Phi(R(X_0, \eta_0))K_n(x, X_0) - \Phi(R(X'_{0,\ell}, \eta_0))K_n(x, X'_{0,\ell}) \right\|_p \\
&= \left\| \Phi(R(X_0, \eta_0)) (K_n(x, X_0) - K_n(x, X'_{0,\ell})) - (\Phi(R(X'_{0,\ell}, \eta_0)) - \Phi(R(X_0, \eta_0))) K_n(x, X'_{0,\ell}) \right\|_p \\
&\leq \frac{L \|K\|_{\text{Lip}}}{b_n} \|X_0 - X'_{0,\ell}\|_p + 2|K|_\infty L^{-q/p} \|\Phi(Y_0)\|_{p+q}^{\frac{p+q}{p}} + |K|_\infty \left\| \sup_{\substack{(x,y) \in \mathbb{R}^N \times \mathbb{R}^N \\ x \neq y}} \frac{|\Phi(R(x, \eta_0)) - \Phi(R(y, \eta_0))|}{\|x - y\|} \right\|_p \|X_0 - X'_{0,\ell}\|_p.
\end{aligned}$$

Optimizing in  $L$ , we obtain

$$\|D_\ell\|_p \leq |K|_\infty^{\frac{p}{p+q}} C(p, q) b_n^{-\frac{q}{p+q}} \|X_0 - X'_{0,\ell}\|_p^{\frac{q}{p+q}}.$$

Moreover, by stationarity, we have

$$\begin{aligned}
\|X_0 - X'_{0,\ell}\|_p &= \left\| G(\varepsilon_{-s}; s \in \mathbb{Z}^d) - G(\varepsilon'_{\tau_0(\ell)}, \varepsilon_{-s}; s \in \mathbb{Z}^d \setminus \{-\tau_0(\ell)\}) \right\|_p \\
&= \left\| G(\varepsilon_{-\tau_0(\ell)-s}; s \in \mathbb{Z}^d) - G(\varepsilon'_0, \varepsilon_{-\tau_0(\ell)-s}; s \in \mathbb{Z}^d \setminus \{-\tau_0(\ell)\}) \right\|_p \\
&= \|X_{-\tau_0(\ell)} - X_{-\tau_0(\ell)}^*\|_p \\
&= \delta_{-\tau_0(\ell), p}.
\end{aligned}$$

So, we derive

$$\|D_\ell\|_p \leq |K|_\infty^{\frac{p}{p+q}} C(p, q) b_n^{-\frac{q}{p+q}} \delta_{-\tau_0(\ell), p}^{\frac{q}{p+q}}. \quad (18)$$

Combining (17) and (18), we obtain

$$\|W_{0,n}\|_p \leq |K|_\infty^{\frac{p}{p+q}} \sqrt{2p} C(p, q) b_n^{-\frac{q}{p+q}} \sum_{\ell > a_M} \delta_{-\tau_0(\ell), p}^{\frac{q}{p+q}} \leq |K|_\infty^{\frac{p}{p+q}} \sqrt{2p} C(p, q) b_n^{-\frac{q}{p+q}} \sum_{|j| > M} \delta_{j,p}^{\frac{q}{p+q}} \quad (19)$$

and

$$\sup_{i \in \mathbb{Z}^d} \delta_{i,p}^{(n)} \leq 2 \|W_{0,n}\|_p \leq 2\sqrt{2p} |K|_\infty^{\frac{p}{p+q}} C(p, q) b_n^{-\frac{q}{p+q}} \sum_{|j| > M} \delta_{j,p}^{\frac{q}{p+q}}. \quad (20)$$

So, from (16) and (20), we get

$$\sum_{i \in \mathbb{Z}^d} \delta_{i,p}^{(n)} \leq 2\sqrt{2p} |K|_\infty^{\frac{p}{p+q}} C(p, q) b_n^{-\frac{q}{p+q}} (M^d + 1) \sum_{|j| > M} \delta_{j,p}^{\frac{q}{p+q}}. \quad (21)$$

Finally, combining (14) and (21), we derive

$$\left\| \sum_{i \in \Lambda} c_i W_{i,n} \right\|_p \leq 8pM^d |K|_\infty^{\frac{p}{p+q}} C(p, q) \left( \sum_{i \in \Lambda} c_i^2 \right)^{\frac{1}{2}} b_n^{-\frac{q}{p+q}} \sum_{|j| > M} \delta_{j,p}^{\frac{q}{p+q}}.$$

The proof of Proposition 1 is complete.  $\square$

Now, we denote by  $\mathbb{V}(Z)$  the variance of any square-integrable  $\mathbb{R}$ -valued random variable  $Z$ .



**Lemma 5** Assume (A1) – (A4). For any  $x \in \mathbb{R}^N$  such that  $f(x) > 0$ , we have

$$\begin{aligned}\lim_{n \rightarrow \infty} |\Lambda_n| b_n^N \nabla [f_n(x)] &= f(x) \int_{\mathbb{R}^N} K^2(t) dt, \\ \lim_{n \rightarrow \infty} |\Lambda_n| b_n^N \nabla [\varphi_n(x)] &= \mathbb{E} [Y_0^2 | X_0 = x] f(x) \int_{\mathbb{R}^N} K^2(t) dt, \\ \lim_{n \rightarrow \infty} |\Lambda_n| b_n^N \text{Cov}[\varphi_n(x), f_n(x)] &= r(x) f(x) \int_{\mathbb{R}^N} K^2(t) dt.\end{aligned}$$

*Proof.* Let  $n \geq 1$  and  $x \in \mathbb{R}^N$  such that  $f(x) > 0$  be fixed. Then,

$$|\Lambda_n| b_n^N \nabla [f_n(x)] = \mathbb{E} \left[ \left( \frac{\sum_{i \in \Lambda_n} \Delta_i}{\sqrt{|\Lambda_n|}} \right)^2 \right] = \mathbb{E} [\Delta_0^2] + \frac{1}{|\Lambda_n|} \sum_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} |\Lambda_n \cap (\Lambda_n - j)| \mathbb{E} [\Delta_0 \Delta_j].$$

Consequently,

$$\left| |\Lambda_n| b_n^N \nabla [f_n(x)] - \mathbb{E} [\Delta_0^2] \right| \leq \sum_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\Delta_0 \Delta_j] \right|, \quad (22)$$

where

$$\mathbb{E} [\Delta_0^2] = \frac{\mathbb{E} [K_n^2(x, X_0)] - (\mathbb{E} [K_n(x, X_0)])^2}{b_n^N}.$$

Applying Lemmas 1 and 4, we get

$$\lim_{n \rightarrow \infty} \mathbb{E} [\Delta_0^2] = f(x) \int_{\mathbb{R}^N} K^2(v) dv \quad (23)$$

and

$$\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\Delta_0 \Delta_j] \right| \leq b_n^N \leq b_n^{\frac{\theta N}{4+\theta}}, \quad (24)$$

where  $\theta > 0$  is given by (A3). Similarly, we have

$$|\Lambda_n| b_n^N \nabla [\varphi_n(x)] = \mathbb{E} \left[ \left( \frac{\sum_{i \in \Lambda_n} \Theta_i}{\sqrt{|\Lambda_n|}} \right)^2 \right] = \mathbb{E} [\Theta_0^2] + \frac{1}{|\Lambda_n|} \sum_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} |\Lambda_n \cap (\Lambda_n - j)| \mathbb{E} [\Theta_0 \Theta_j].$$

So, we derive

$$\left| |\Lambda_n| b_n^N \nabla [\varphi_n(x)] - \mathbb{E} [\Theta_0^2] \right| \leq \sum_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\Theta_0 \Theta_j] \right|, \quad (25)$$

where

$$\mathbb{E} [\Theta_0^2] = \frac{\mathbb{E} [Y_0^2 K_n^2(x, X_0)] - (\mathbb{E} [Y_0 K_n(x, X_0)])^2}{b_n^N}.$$

Applying again Lemma 1, we obtain

$$\lim_{n \rightarrow \infty} \mathbb{E} [\Theta_0^2] = \mathbb{E} [Y_0^2 | X_0 = x] f(x) \int_{\mathbb{R}^N} K^2(v) dv. \quad (26)$$

By Lemma 4, we have also

$$\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\Theta_0 \Theta_j] \right| \leq b_n^{\frac{\theta N}{4+\theta}}. \quad (27)$$

Arguing as before, we write

$$|\Lambda_n| b_n^N \text{Cov}(\varphi_n(x), f_n(x)) = \mathbb{E} [\Theta_0 \Delta_0] + \frac{1}{|\Lambda_n|} \sum_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} |\Lambda_n \cap (\Lambda_n - j)| \mathbb{E} [\Theta_0 \Delta_j].$$

Consequently,

$$\left| |\Lambda_n| b_n^N \text{Cov}(\varphi_n(x), f_n(x)) - \mathbb{E} [\Theta_0 \Delta_0] \right| \leq \sum_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\Theta_0 \Delta_j] \right|, \quad (28)$$

where, using Lemma 1, we have

$$\mathbb{E} [\Theta_0 \Delta_0] = \frac{\mathbb{E} [Y_0 K_n^2(x, X_0)] - \mathbb{E} [Y_0 K_n(x, X_0)] \mathbb{E} [K_n(x, X_0)]}{b_n^N} \xrightarrow{n \rightarrow \infty} r(x) f(x) \int_{\mathbb{R}^N} K^2(v) dv. \quad (29)$$

By Lemma 4, we have also

$$\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\Theta_0 \Delta_j] \right| \leq b_n^{\frac{\theta N}{2+\theta}} \leq b_n^{\frac{\theta N}{4+\theta}}. \quad (30)$$

Now, we assume that (A3)(i) holds and we introduce the letter  $\Xi$  which can be replaced in the sequel by either  $\Delta$  or  $\Theta$ . By Rio's inequality (see [23]), for  $j \neq 0$ , we have

$$\left| \mathbb{E} [\Xi_0 \Xi_j] \right| \leq 2 \int_0^{2\alpha_{1,\infty}(|j|)} Q_{\Xi_0}^2(u) du \quad \text{where } Q_{\Xi_0}(u) = \inf \left\{ t \geq 0 \mid \mathbb{P}(|\Xi_0| > t) \leq u \right\}.$$

Using Lemma 3 and noting that  $Q_{\Xi_0}(u) \leq u^{-\frac{1}{2+\theta}} \|\Xi_0\|_{2+\theta}$ , we derive

$$\left| \mathbb{E} [\Xi_0 \Xi_j] \right| \leq \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(|j|) \|\Xi_0\|_{2+\theta}^2 \leq b_n^{-\frac{\theta N}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(|j|). \quad (31)$$

Combining (24), (27) and (31) and using Lemma 2, we obtain

$$\sum_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\Xi_0 \Xi_j] \right| \leq m_n^d b_n^{\frac{\theta N}{4+\theta}} + b_n^{-\frac{\theta N}{2+\theta}} \sum_{|j| > m_n} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(|j|) \xrightarrow{n \rightarrow \infty} 0, \quad (32)$$

where  $m_n$  is given by Lemma 2. Combining (22), (23), (25), (26) and (32), we get

$$\lim_{n \rightarrow \infty} |\Lambda_n| b_n^N \mathbb{V} [f_n(x)] = f(x) \int_{\mathbb{R}^N} K^2(t) dt \quad \text{and} \quad \lim_{n \rightarrow \infty} |\Lambda_n| b_n^N \mathbb{V} [\varphi_n(x)] = \mathbb{E} [Y_0^2 | X_0 = x] f(x) \int_{\mathbb{R}^N} K^2(t) dt.$$

Applying again Rio's inequality, we have

$$\left| \mathbb{E} [\Theta_0 \Delta_j] \right| \leq 2 \int_0^{2\alpha_{1,\infty}(|j|)} Q_{\Theta_0}(u) Q_{\Delta_j}(u) du$$

and by Lemma 3, we derive

$$Q_{\Theta_0}(u) \leq u^{-\frac{1}{2+\theta}} \|\Theta_0\|_{2+\theta} \leq u^{-\frac{1}{2+\theta}} b_n^{-\frac{\theta N}{2(2+\theta)}} \quad \text{and} \quad Q_{\Delta_j}(u) \leq u^{-\frac{1}{2+\theta}} \|\Delta_0\|_{2+\theta} \leq u^{-\frac{1}{2+\theta}} b_n^{-\frac{\theta N}{2(2+\theta)}}$$

for any  $u \in ]0, 1[$ . Consequently, we obtain

$$\left| \mathbb{E} [\Theta_0 \Delta_j] \right| \leq b_n^{-\frac{\theta N}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}} (|j|). \quad (33)$$

Combining (30) and (33), we derive

$$\sum_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\Theta_0 \Delta_j] \right| \leq m_n^d b_n^{\frac{\theta N}{4+\theta}} + b_n^{-\frac{\theta N}{2+\theta}} \sum_{|j| > m_n} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}} (|j|) \xrightarrow{n \rightarrow \infty} 0, \quad (34)$$

where  $m_n$  is given by Lemma 2. Finally, combining (28), (29) and (34), we obtain

$$\lim_{n \rightarrow \infty} |\Lambda_n| b_n^N \text{Cov} [\varphi_n(x), f_n(x)] = r(x) f(x) \int_{\mathbb{R}^N} K^2(t) dt.$$

From now on, we assume (A3)(ii) holds. Keeping in mind that  $\Xi$  stands for either  $\Delta$  or  $\Theta$ , we define  $\bar{\Xi}_i = \mathbb{E} [\Xi_i | \mathcal{H}_{i, m_n}]$  for any  $i$  in  $\mathbb{Z}^d$ . Note that  $(\bar{\Xi}_i)_{i \in \mathbb{Z}^d}$  is a  $2m_n$ -dependent random field (it means that if  $|i - j| > 2m_n$  then  $\bar{\Xi}_i$  and  $\bar{\Xi}_j$  are independent) and

$$\left| \mathbb{E} \left[ \left( \sum_{i \in \Lambda_n} \Xi_i \right)^2 \right] - \mathbb{E} \left[ \left( \sum_{i \in \Lambda_n} \bar{\Xi}_i \right)^2 \right] \right| \leq \left\| \sum_{i \in \Lambda_n} (\Xi_i - \bar{\Xi}_i) \right\|_2^2 + 2 \left\| \sum_{i \in \Lambda_n} \bar{\Xi}_i \right\|_2 \left\| \sum_{i \in \Lambda_n} (\Xi_i - \bar{\Xi}_i) \right\|_2. \quad (35)$$

Using Proposition 1 and Lemma 2, we obtain

$$|\Lambda_n|^{-1/2} \left\| \sum_{i \in \Lambda_n} (\Xi_i - \bar{\Xi}_i) \right\|_2 \leq b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|j| > m_n} |j|^d \delta_{j,2}^{\frac{\theta}{2+\theta}} \xrightarrow{n \rightarrow \infty} 0. \quad (36)$$

In the other part, since  $(\bar{\Xi}_i)_{i \in \mathbb{Z}^d}$  is  $2m_n$ -dependent, we have

$$\frac{1}{|\Lambda_n|} \mathbb{E} \left[ \left( \sum_{i \in \Lambda_n} \bar{\Xi}_i \right)^2 \right] = \mathbb{E} [\bar{\Xi}_0^2] + \frac{1}{|\Lambda_n|} \sum_{\substack{j \in \mathbb{Z}^d \setminus \{0\} \\ |j| \leq 2m_n}} |\Lambda_n \cap (\Lambda_n - j)| \mathbb{E} [\bar{\Xi}_0 \bar{\Xi}_j]$$

and consequently

$$\left| \frac{1}{|\Lambda_n|} \mathbb{E} \left[ \left( \sum_{i \in \Lambda_n} \bar{\Xi}_i \right)^2 \right] - \mathbb{E} [\bar{\Xi}_0^2] \right| \leq (2m_n + 1)^d \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\bar{\Xi}_0 \bar{\Xi}_j] \right|. \quad (37)$$

Moreover, using (19) and Lemma 2 and noting that  $\|\Xi_0\|_2 \leq 1$ , we have also

$$\left| \mathbb{E} [\bar{\Xi}_0^2] - \mathbb{E} [\Xi_0^2] \right| \leq 2 \|\Xi_0\|_2 \|\bar{\Xi}_0 - \Xi_0\|_2 \leq b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|j| > m_n} \delta_{j,2}^{\frac{\theta}{2+\theta}} \xrightarrow{n \rightarrow \infty} 0.$$

So, using (23) and (26), we derive

$$\lim_{n \rightarrow \infty} \mathbb{E} \left[ \overline{\Xi}_0^2 \right] = \xi(x) f(x) \int_{\mathbb{R}^N} K^2(t) dt, \quad (38)$$

where  $\xi(x) = 1$  if  $\Xi = \Delta$  and  $\xi(x) = \mathbb{E} [Y_0^2 | X_0 = x]$  if  $\Xi = \Theta$ . Similarly, using (19), we obtain

$$m_n^d \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \left| \mathbb{E} [\overline{\Xi}_0 \overline{\Xi}_j] \right| - \left| \mathbb{E} [\Xi_0 \Xi_j] \right| \right| \leq 2m_n^d \|\Xi_0\|_2 \|\overline{\Xi}_0 - \Xi_0\|_2 \leq b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|j| > m_n} |j|^d \delta_{j,2}^{\frac{\theta}{2+\theta}} \xrightarrow{n \rightarrow \infty} 0.$$

Using Lemma 4, we have  $\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} |\mathbb{E} [\Xi_0 \Xi_j]| \leq b_n^{\frac{\theta N}{4+\theta}}$  and consequently, by Lemma 2, we get

$$m_n^d \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\overline{\Xi}_0 \overline{\Xi}_j] \right| \leq m_n^d b_n^{\frac{\theta N}{4+\theta}} + b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|j| > m_n} |j|^d \delta_{j,2}^{\frac{\theta}{2+\theta}} \xrightarrow{n \rightarrow \infty} 0. \quad (39)$$

Combining (37), (38) and (39), we obtain

$$\lim_{n \rightarrow \infty} \frac{1}{|\Lambda_n|} \mathbb{E} \left[ \left( \sum_{i \in \Lambda_n} \overline{\Xi}_i \right)^2 \right] = \xi(x) f(x) \int_{\mathbb{R}^N} K^2(t) dt. \quad (40)$$

Combining (35), (36) and (40), we get

$$\lim_{n \rightarrow \infty} \frac{1}{|\Lambda_n|} \mathbb{E} \left[ \left( \sum_{i \in \Lambda_n} \Xi_i \right)^2 \right] = \xi(x) f(x) \int_{\mathbb{R}^N} K^2(t) dt.$$

So, we have shown

$$\lim_{n \rightarrow \infty} |\Lambda_n| b_n^N \mathbb{V} [f_n(x)] = f(x) \int_{\mathbb{R}^N} K^2(t) dt \quad \text{and} \quad \lim_{n \rightarrow \infty} |\Lambda_n| b_n^N \mathbb{V} [\varphi_n(x)] = \mathbb{E} [Y_0^2 | X_0 = x] f(x) \int_{\mathbb{R}^N} K^2(t) dt.$$

Now, it suffices to prove

$$\lim_{n \rightarrow \infty} |\Lambda_n| b_n^N \text{Cov} [\varphi_n(x), f_n(x)] = r(x) f(x) \int_{\mathbb{R}^N} K^2(t) dt$$

when (A3)(ii) holds. If we define

$$\bar{f}_n(x) = \frac{1}{|\Lambda_n| b_n^N} \sum_{i \in \Lambda_n} \mathbb{E} [K_n(x, X_i) | \mathcal{H}_{i, m_n}] \quad \text{and} \quad \bar{\varphi}_n(x) = \frac{1}{|\Lambda_n| b_n^N} \sum_{i \in \Lambda_n} \mathbb{E} [Y_i K_n(x, X_i) | \mathcal{H}_{i, m_n}]$$

then

$$|\Lambda_n| b_n^N \text{Cov} [\varphi_n(x), f_n(x)] = C_1 + C_2 + C_3 + C_4,$$

where

$$\begin{aligned}
C_1 &= |\Lambda_n| b_n^N \mathbb{E} \left[ (\varphi_n(x) - \bar{\varphi}_n(x)) (f_n(x) - \bar{f}_n(x)) \right] \\
C_2 &= |\Lambda_n| b_n^N \mathbb{E} \left[ (\varphi_n(x) - \bar{\varphi}_n(x)) (\bar{f}_n(x) - \mathbb{E} [\bar{f}_n(x)]) \right] \\
C_3 &= |\Lambda_n| b_n^N \mathbb{E} \left[ (\bar{\varphi}_n(x) - \mathbb{E} [\bar{\varphi}_n(x)]) (f_n(x) - \bar{f}_n(x)) \right] \\
C_4 &= |\Lambda_n| b_n^N \mathbb{E} \left[ (\bar{\varphi}_n(x) - \mathbb{E} [\bar{\varphi}_n(x)]) (\bar{f}_n(x) - \mathbb{E} [\bar{f}_n(x)]) \right].
\end{aligned}$$

Using Proposition 1, we have

$$|C_1| \leq \frac{1}{\sqrt{|\Lambda_n|}} \left\| \sum_{i \in \Lambda_n} (\Theta_i - \bar{\Theta}_i) \right\|_2 \times \frac{1}{\sqrt{|\Lambda_n|}} \left\| \sum_{i \in \Lambda_n} (\Delta_i - \bar{\Delta}_i) \right\|_2 \leq \left( b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|i| > m_n} |i|^d \delta_{i,2}^{\frac{\theta}{2+\theta}} \right)^2 = o(1).$$

From (40), we have  $|\Lambda_n|^{-1/2} \left\| \sum_{j \in \Lambda_n} \bar{\Delta}_j \right\|_2 \leq 1$  and  $|\Lambda_n|^{-1/2} \left\| \sum_{j \in \Lambda_n} \bar{\Theta}_j \right\|_2 \leq 1$ . So,

$$|C_2| \leq \frac{1}{\sqrt{|\Lambda_n|}} \left\| \sum_{i \in \Lambda_n} (\Theta_i - \bar{\Theta}_i) \right\|_2 \times \frac{1}{\sqrt{|\Lambda_n|}} \left\| \sum_{j \in \Lambda_n} \bar{\Delta}_j \right\|_2 \leq b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|i| > m_n} |i|^d \delta_{i,2}^{\frac{\theta}{2+\theta}} = o(1)$$

and

$$|C_3| \leq \frac{1}{\sqrt{|\Lambda_n|}} \left\| \sum_{i \in \Lambda_n} (\Delta_i - \bar{\Delta}_i) \right\|_2 \times \frac{1}{\sqrt{|\Lambda_n|}} \left\| \sum_{j \in \Lambda_n} \bar{\Theta}_j \right\|_2 \leq b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|i| > m_n} |i|^d \delta_{i,2}^{\frac{\theta}{2+\theta}} = o(1).$$

Finally, since

$$C_4 = \mathbb{E} [\bar{\Theta}_0 \bar{\Delta}_0] + \frac{1}{|\Lambda_n|} \sum_{\substack{j \in \mathbb{Z}^d \setminus \{0\} \\ |j| \leq 2m_n}} |\Lambda_n \cap (\Lambda_n - j)| \mathbb{E} [\bar{\Theta}_0 \bar{\Delta}_j],$$

we obtain

$$\left| C_4 - \mathbb{E} [\bar{\Theta}_0 \bar{\Delta}_0] \right| \leq (2m_n + 1)^d \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\bar{\Theta}_0 \bar{\Delta}_j] \right|. \quad (41)$$

Using (19) and keeping in mind that  $\|\Delta_0\|_2 \leq 1$  and  $\|\Theta_0\|_2 \leq 1$ , we have also

$$\left| \mathbb{E} [\bar{\Theta}_0 \bar{\Delta}_0] - \mathbb{E} [\Theta_0 \Delta_0] \right| \leq \|\Theta_0\|_2 \|\bar{\Delta}_0 - \Delta_0\|_2 + \|\Delta_0\|_2 \|\bar{\Theta}_0 - \Theta_0\|_2 \leq b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|i| > m_n} \delta_{i,2}^{\frac{\theta}{2+\theta}} = o(1).$$

Moreover, using Lemma 1, we have

$$\mathbb{E} [\Theta_0 \Delta_0] = \frac{1}{b_n^N} \left( \mathbb{E} [Y_0 K_n^2(x, X_0)] - \mathbb{E} [K_n(x, X_0)] \mathbb{E} [Y_0 K_n(x, X_0)] \right) \xrightarrow{n \rightarrow \infty} r(x) f(x) \int_{\mathbb{R}^N} K^2(t) dt$$

and consequently, we obtain

$$\lim_{n \rightarrow \infty} \mathbb{E} [\bar{\Theta}_0 \bar{\Delta}_0] = r(x) f(x) \int_{\mathbb{R}^N} K^2(t) dt. \quad (42)$$

Now, using (19) and Lemma 2, we have

$$m_n^d \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\bar{\Theta}_0 \bar{\Delta}_j] \right| - \left| \mathbb{E} [\Theta_0 \Delta_j] \right| \leq m_n^d \left( \|\Theta_0\|_2 \|\bar{\Delta}_0 - \Delta_0\|_2 + \|\Delta_0\|_2 \|\bar{\Theta}_0 - \Theta_0\|_2 \right) \leq b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|j| > m_n} |j|^d \delta_{j,2}^{\frac{\theta}{2+\theta}} = o(1).$$

Using Lemma 4, we have  $\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\Theta_0 \Delta_j] \right| \leq b_n^{\frac{\theta N}{2+\theta}} \leq b_n^{\frac{\theta N}{4+\theta}}$  and consequently, by Lemma 2, we get

$$m_n^d \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [\overline{\Theta}_0 \overline{\Delta}_j] \right| \leq m_n^d b_n^{\frac{\theta N}{4+\theta}} + b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|j| > m_n} |j|^d \delta_{j,2}^{\frac{\theta}{2+\theta}} \xrightarrow{n \rightarrow \infty} 0. \quad (43)$$

Combining (41), (42) and (43), we obtain

$$C_4 \xrightarrow{n \rightarrow \infty} r(x) f(x) \int_{\mathbb{R}^N} K^2(t) dt.$$

The proof of Lemma 5 is complete.  $\square$

## 5 Proofs of Theorems

In this section, we present the proofs of Theorems 1 and 2.

*Proof of Theorem 1.* Let  $n \geq 1$  be fixed. Since  $K$  is symmetric such that  $\int_{\mathbb{R}^N} \|v\|^2 |K(v)| dv < \infty$  and  $f$  and  $\varphi$  are twice differentiable with bounded second partial derivatives, by Taylor's formula, we get

$$\sup_{x \in \mathbb{R}^N} \left| \mathbb{E} [f_n(x)] - f(x) \right| = \sup_{x \in \mathbb{R}^N} \left| \int_{\mathbb{R}^N} (f(x - vb_n) - f(x)) K(v) dv \right| \leq b_n^2 \int_{\mathbb{R}^N} \|v\|^2 |K(v)| dv$$

and

$$\sup_{x \in \mathbb{R}^N} \left| \mathbb{E} [\varphi_n(x)] - \varphi(x) \right| = \sup_{x \in \mathbb{R}^N} \left| \int_{\mathbb{R}^N} (\varphi(x - vb_n) - \varphi(x)) K(v) dv \right| \leq b_n^2 \int_{\mathbb{R}^N} \|v\|^2 |K(v)| dv.$$

The proof of Theorem 1 is complete.  $\square$

*Proof of Theorem 2.* Let  $n \geq 1$  and  $x \in \mathbb{R}^N$  such that  $f(x) > 0$  be fixed. Then

$$r_n(x) - \frac{\mathbb{E} [\varphi_n(x)]}{\mathbb{E} [f_n(x)]} = \frac{(\varphi_n(x) - \mathbb{E} [\varphi_n(x)]) \mathbb{E} [f_n(x)] - (f_n(x) - \mathbb{E} [f_n(x)]) \mathbb{E} [\varphi_n(x)]}{f_n(x) \mathbb{E} [f_n(x)]}.$$

Combining Lemma 5 and Theorem 1, we obtain that  $f_n(x)$  converges in probability to  $f(x)$  as  $n \rightarrow \infty$ . Moreover, we have also  $\lim_{n \rightarrow \infty} \frac{\mathbb{E} [\varphi_n(x)]}{\mathbb{E} [f_n(x)]} = r(x)$ . So, using Slutsky's lemma and assumptions (A1) – (A4), it is sufficient to prove that

$$\lambda_1 \sqrt{|\Lambda_n| b_n^N} (\varphi_n(x) - \mathbb{E} [\varphi_n(x)]) + \lambda_2 \sqrt{|\Lambda_n| b_n^N} (f_n(x) - \mathbb{E} [f_n(x)]) \xrightarrow[n \rightarrow \infty]{\text{Law}} \mathcal{N} (0, \rho^2(x)),$$

where  $\rho^2(x) = (\lambda_1^2 \mathbb{E} [Y_0^2 | X_0 = x] + 2\lambda_1 \lambda_2 r(x) + \lambda_2^2) \times f(x) \int_{\mathbb{R}^N} K^2(t) dt$  for any  $(\lambda_1, \lambda_2) \in \mathbb{R}^2$ .

Let  $(\lambda_1, \lambda_2) \in \mathbb{R}^2$  be fixed. Then

$$\lambda_1 \sqrt{|\Lambda_n| b_n^N} (\varphi_n(x) - \mathbb{E} [\varphi_n(x)]) + \lambda_2 \sqrt{|\Lambda_n| b_n^N} (f_n(x) - \mathbb{E} [f_n(x)]) = |\Lambda_n|^{-1/2} \sum_{i \in \Lambda_n} U_i,$$

where

$$U_i = \lambda_1 \Theta_i + \lambda_2 \Delta_i = \frac{(\lambda_1 Y_i + \lambda_2) K_n(x, X_i) - \mathbb{E}[(\lambda_1 Y_0 + \lambda_2) K_n(x, X_0)]}{\sqrt{b_n^N}}$$

with  $\Theta_i$  and  $\Delta_i$  defined by (7). For the asymptotic normality of  $r_n$  when  $(X_i)_{i \in \mathbb{Z}^d}$  is of the form (1), we are going to use an approximation by  $2m_n$ -dependent random fields. So, recall that  $\mathcal{H}_{i, m_n} = \sigma(\eta_i, \varepsilon_{i-s}; |s| \leq m_n)$  and define

$$\bar{\Delta}_i = \mathbb{E}[\Delta_i | \mathcal{H}_{i, m_n}], \quad \bar{\Theta}_i = \mathbb{E}[\Theta_i | \mathcal{H}_{i, m_n}] \quad \text{and} \quad \bar{U}_i = \lambda_1 \bar{\Theta}_i + \lambda_2 \bar{\Delta}_i = \mathbb{E}[U_i | \mathcal{H}_{i, m_n}].$$

By construction,  $(\bar{U}_i)_{i \in \mathbb{Z}^d}$  is  $2m_n$ -dependent (it means that if  $|i - j| > 2m_n$  then  $\bar{U}_i$  and  $\bar{U}_j$  are independent). So, if (A3)(ii) holds, applying Proposition 1 with  $\Phi(t) = \lambda_1 t + \lambda_2$  for any  $t \in \mathbb{R}$ , then

$$|\Lambda_n|^{-1/2} \left\| \sum_{i \in \Lambda_n} (U_i - \bar{U}_i) \right\|_2 \leq b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|i| > m_n} |i|^d \delta_{i,2}^{\frac{\theta}{2+\theta}} \xrightarrow[n \rightarrow \infty]{} 0 \quad (\text{by Lemma 2}).$$

Consequently, when  $(X_i)_{i \in \mathbb{Z}^d}$  is of the form (1) it suffices to establish the asymptotic normality of  $|\Lambda_n|^{-1/2} \sum_{i \in \Lambda_n} \bar{U}_i$ . From now on, we denote

$$Z_i = \begin{cases} U_i & \text{if } (X_i)_{i \in \mathbb{Z}^d} \text{ is strongly mixing} \\ \bar{U}_i & \text{if } (X_i)_{i \in \mathbb{Z}^d} \text{ is of the form (1)} \end{cases}$$

and

$$M_n = \begin{cases} m_n & \text{if } (X_i)_{i \in \mathbb{Z}^d} \text{ is strongly mixing} \\ 2m_n & \text{if } (X_i)_{i \in \mathbb{Z}^d} \text{ is of the form (1)}. \end{cases}$$

**Lemma 6**  $\lim_{n \rightarrow \infty} \mathbb{E}[Z_0^2] = \rho^2(x)$ .

*Proof.* We have

$$\mathbb{E}[U_0^2] = \frac{\mathbb{E}[(\lambda_1 Y_0 + \lambda_2)^2 K_n^2(x, X_0)] - (\mathbb{E}[(\lambda_1 Y_0 + \lambda_2) K_n(x, X_0)])^2}{b_n^N}.$$

Applying Lemma 1, we get

$$\lim_{n \rightarrow \infty} \mathbb{E}[U_0^2] = \mathbb{E}[(\lambda_1 Y_0 + \lambda_2)^2 | X_0 = x] f(x) \int_{\mathbb{R}^N} K^2(t) dt = \rho^2(x).$$

Moreover, by Proposition 1 and Lemma 2 and using  $\|U_0\|_2 \leq 1$ , we derive

$$\left| \mathbb{E}[\bar{U}_0^2] - \mathbb{E}[U_0^2] \right| \leq 2 \|U_0\|_2 \|U_0 - \bar{U}_0\|_2 \leq b_n^{-\frac{\theta(N+2)+2N}{2(2+\theta)}} \sum_{|i| > M_n} |i|^d \delta_{i,2}^{\frac{\theta}{2+\theta}} \xrightarrow[n \rightarrow \infty]{} 0.$$

So,  $\lim_{n \rightarrow \infty} \mathbb{E}[\bar{U}_0^2] = \rho^2(x)$ . The proof of Lemma 6 is complete.  $\square$

Let  $(\xi_i)_{i \in \mathbb{Z}^d}$  be i.i.d. normal random variables independent of  $(X_i)_{i \in \mathbb{Z}^d}$  and  $(\eta_i)_{i \in \mathbb{Z}^d}$ . Assume that  $\mathbb{E}[\xi_0] = 0$  and  $\mathbb{E}[\xi_0^2] = \mathbb{E}[Z_0^2]$ . For any  $i \in \mathbb{Z}^d$ , we define

$$T_i = \frac{Z_i}{\sqrt{|\Lambda_n|}} \quad \text{and} \quad \gamma_i = \frac{\xi_i}{\sqrt{|\Lambda_n|}}.$$

Let  $g$  be the unique function from  $[1, |\Lambda_n|] \cap \mathbb{Z}$  to  $\Lambda_n$  such that  $g(k) <_{\text{lex}} g(\ell)$  for  $1 \leq k < \ell \leq |\Lambda_n|$ , where  $<_{\text{lex}}$  is the lexicographic order on  $\mathbb{Z}^d$ . For all integer  $1 \leq k \leq |\Lambda_n|$ , we put

$$S_{g(k)}(T) = \sum_{s=1}^k T_{g(s)} \quad \text{and} \quad S_{g(k)}^c(\gamma) = \sum_{s=k}^{|\Lambda_n|} \gamma_{g(s)}$$

with the convention  $S_{g(0)}(T) = S_{g(|\Lambda_n|+1)}^c(\gamma) = 0$ . Let  $\psi$  be any measurable function from  $\mathbb{R}$  to  $\mathbb{R}$ . For any  $1 \leq k \leq \ell \leq |\Lambda_n|$ , we introduce the notation  $\psi_{k,\ell} = \psi(S_{g(k)}(T) + S_{g(\ell)}^c(\gamma))$ . Let  $h : \mathbb{R} \rightarrow \mathbb{R}$  be a four times continuously differentiable function such that  $\max_{0 \leq i \leq 4} \|h^{(i)}\|_\infty \leq 1$ . It suffices to prove  $\lim_{n \rightarrow \infty} |L_n| = 0$ , where

$$L_n := \mathbb{E} \left[ h \left( \sum_{i \in \Lambda_n} \frac{Z_i}{\sqrt{|\Lambda_n|}} \right) \right] - \mathbb{E} \left[ h \left( \sum_{i \in \Lambda_n} \frac{\xi_i}{\sqrt{|\Lambda_n|}} \right) \right].$$

Using Lindeberg's idea [15] (see also [5]), we have

$$\begin{aligned} L_n &= \mathbb{E} [h_{|\Lambda_n|, |\Lambda_n|+1} - h_{0,1}] = \sum_{k=1}^{|\Lambda_n|} \mathbb{E} [h_{k,k+1} - h_{k-1,k}] \\ &= \sum_{k=1}^{|\Lambda_n|} \left( \mathbb{E} [h_{k,k+1} - h_{k-1,k+1}] - \mathbb{E} [h_{k-1,k} - h_{k-1,k+1}] \right). \end{aligned}$$

Applying Taylor's formula, we get

$$L_n = \sum_{k=1}^{|\Lambda_n|} \left( \mathbb{E} \left[ T_{g(k)} h'_{k-1,k+1} + \frac{1}{2} T_{g(k)}^2 h''_{k-1,k+1} + v_k \right] - \mathbb{E} \left[ \gamma_{g(k)} h'_{k-1,k+1} + \frac{1}{2} \gamma_{g(k)}^2 h''_{k-1,k+1} + w_k \right] \right),$$

where  $|v_k| \leq T_{g(k)}^2 (1 \wedge |T_{g(k)}|)$  and  $|w_k| \leq \gamma_{g(k)}^2 (1 \wedge |\gamma_{g(k)}|)$ . Since  $\gamma_{g(k)}^2$  and  $h''_{k-1,k+1}$  are independent,  $\mathbb{E}[\gamma_{g(k)} h'_{k-1,k+1}] = 0$  and  $\mathbb{E}[\gamma_{g(k)}^2] = \frac{\mathbb{E}[Z_0^2]}{|\Lambda_n|}$ , we obtain

$$L_n = \sum_{k=1}^{|\Lambda_n|} \left( \mathbb{E} [T_{g(k)} h'_{k-1,k+1}] + \frac{1}{2} \mathbb{E} \left[ \left( T_{g(k)}^2 - \frac{\mathbb{E}[Z_0^2]}{|\Lambda_n|} \right) h''_{k-1,k+1} \right] + \mathbb{E} [v_k - w_k] \right).$$

Since  $\xi_0$  is a gaussian random variable with zero mean and variance  $\mathbb{E}[Z_0^2]$  and  $\mathbb{E}[Z_0^2] \leq \mathbb{E}[U_0^2]$ , we have

$$\sum_{k=1}^{|\Lambda_n|} \mathbb{E} [|w_k|] \leq \frac{\mathbb{E}[|\xi_0|^3]}{\sqrt{|\Lambda_n|}} \leq \frac{(\mathbb{E}[U_0^2])^{3/2}}{\sqrt{|\Lambda_n|}}.$$



By Lemma 1, we have  $\mathbb{E} [U_0^2] \asymp 1$  and consequently, we obtain  $\lim_{n \rightarrow \infty} \sum_{k=1}^{|\Lambda_n|} \mathbb{E} [|w_k|] = 0$ . Let  $d_n := (|\Lambda_n| b_n^N)^{\frac{-\theta}{2(\theta+1)}}$ . Then,

$$\sum_{k=1}^{|\Lambda_n|} \mathbb{E} [|v_k|] \leq d_n \mathbb{E} [Z_0^2] + \mathbb{E} \left[ Z_0^2 \mathbf{1}_{|Z_0| > d_n \sqrt{|\Lambda_n|}} \right] \leq d_n \mathbb{E} [U_0^2] + \frac{\mathbb{E} [|U_0|^{2+\theta}]}{d_n^\theta |\Lambda_n|^{\theta/2}}.$$

Using Lemma 3, we get

$$\sum_{k=1}^{|\Lambda_n|} \mathbb{E} [|v_k|] \asymp d_n + \frac{1}{d_n^\theta (|\Lambda_n| b_n^N)^{\theta/2}} = 2d_n \xrightarrow{n \rightarrow \infty} 0.$$

Now, we have to prove that

$$\lim_{n \rightarrow \infty} \sum_{k=1}^{|\Lambda_n|} \left( \mathbb{E} [T_{g(k)} h'_{k-1, k+1}] + \mathbb{E} \left[ \left( \frac{Z_{g(k)}^2 - \mathbb{E} [Z_0^2]}{2|\Lambda_n|} \right) h''_{k-1, k+1} \right] \right) = 0. \quad (44)$$

For any integers  $n \geq 1$  and  $1 \leq k \leq |\Lambda_n|$ , we define

$$\mathbb{E}_k^{(n)} = \left\{ j \in \Lambda_n \mid j <_{\text{lex}} g(k) \text{ and } |j - g(k)| > M_n \right\} \quad \text{and} \quad S_{g(k)}^{(M_n)}(T) = \sum_{i \in \mathbb{E}_k^{(n)}} T_i.$$

For any  $1 \leq k < \ell \leq |\Lambda_n|$  and any function  $\psi$  from  $\mathbb{R}$  to  $\mathbb{R}$ , we define also  $\psi_{k-1, \ell}^{(M_n)} = \psi (S_{g(k)}^{(M_n)}(T) + S_{g(\ell)}^c(\gamma))$ . Using Taylor's formula, we have

$$T_{g(k)} h'_{k-1, k+1} = T_{g(k)} h'_{k-1, k+1}^{(M_n)} + T_{g(k)} (S_{g(k-1)}(T) - S_{g(k)}^{(M_n)}(T)) h''_{k-1, k+1}^{(M_n)} + v'_k$$

with

$$|v'_k| \leq 2 \left| T_{g(k)} (S_{g(k-1)}(T) - S_{g(k)}^{(M_n)}(T)) (1 \wedge |S_{g(k-1)}(T) - S_{g(k)}^{(M_n)}(T)|) \right|.$$

In order to obtain (44), we have to prove

$$\lim_{n \rightarrow \infty} \sum_{k=1}^{|\Lambda_n|} \mathbb{E} [T_{g(k)} h'_{k-1, k+1}^{(M_n)}] = 0, \quad (45)$$

$$\lim_{n \rightarrow \infty} \sum_{k=1}^{|\Lambda_n|} \mathbb{E} [T_{g(k)} (S_{g(k-1)}(T) - S_{g(k)}^{(M_n)}(T)) h''_{k-1, k+1}^{(M_n)}] = 0 \quad (46)$$

$$\lim_{n \rightarrow \infty} \sum_{k=1}^{|\Lambda_n|} \mathbb{E} [|v'_k|] = 0, \quad (47)$$

and

$$\lim_{n \rightarrow \infty} \frac{1}{|\Lambda_n|} \sum_{k=1}^{|\Lambda_n|} \mathbb{E} [(Z_{g(k)}^2 - \mathbb{E} [Z_0^2]) h''_{k-1, k+1}] = 0. \quad (48)$$

First, we are going to prove (45). Since  $\gamma$  is independent of  $T$ , then  $\mathbb{E} [T_{g(k)} h' (S_{g(k+1)}^c(\gamma))] = 0$ . Consequently, if  $\pi$  is a one to one map from  $[1, |\mathbb{E}_k^{(n)}|] \cap \mathbb{Z}$  to  $\mathbb{E}_k^{(n)}$  such that  $|\pi(i) - g(k)| \leq |\pi(i-1) - g(k)|$  then

$$\mathbb{E} [T_{g(k)} h'_{k-1, k+1}^{(M_n)}] = \mathbb{E} [T_{g(k)} (h'_{k-1, k+1}^{(M_n)} - h' (S_{g(k+1)}^c(\gamma)))] = \sum_{i=1}^{|\mathbb{E}_k^{(n)}|} \text{Cov} (T_{g(k)}, \beta_i - \beta_{i-1}),$$

where  $\beta_i = h' (S_{\pi(i)}(T) + S_{g(k+1)}^c(\gamma))$  and  $S_{\pi(0)}(T) = 0$ . If  $(X_i)_{i \in \mathbb{Z}^d}$  is strongly mixing then, using Rio's inequality ([23], Theorem 1.1) and keeping in mind that  $|\pi(i) - g(k)| \leq |\pi(i-1) - g(k)|$ , we get

$$\left| \mathbb{E} [T_{g(k)} h'_{k-1, k+1}^{(M_n)}] \right| \leq 2 \sum_{i=1}^{|\mathbb{E}_k^{(n)}|} \int_0^{2\alpha_{1,\infty}(|\pi(i)-g(k)|)} Q_{T_{g(k)}}(u) Q_{\beta_i - \beta_{i-1}}(u) du.$$

For any  $u \in ]0, 1[$ , noting that  $h'$  is Lipschitz, we have

$$Q_{T_{g(k)}}(u) \leq \frac{u^{-\frac{1}{2+\theta}} \|Z_0\|_{2+\theta}}{\sqrt{|\Lambda_n|}} \quad \text{and} \quad Q_{\beta_i - \beta_{i-1}}(u) \leq \frac{u^{-\frac{1}{2+\theta}} \|Z_0\|_{2+\theta}}{\sqrt{|\Lambda_n|}}.$$

Moreover, by Lemma 3, we have  $\|Z_0\|_{2+\theta}^2 \leq \|U_0\|_{2+\theta}^2 \leq b_n^{-\frac{\theta N}{2+\theta}}$  and consequently, we obtain

$$\sum_{k=1}^{|\Lambda_n|} \left| \mathbb{E} [T_{g(k)} h'_{k-1, k+1}^{(M_n)}] \right| \leq \frac{b_n^{-\frac{\theta N}{2+\theta}}}{|\Lambda_n|} \sum_{k=1}^{|\Lambda_n|} \sum_{i=1}^{|\mathbb{E}_k^{(n)}|} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}} (|\pi(i) - g(k)|) \leq b_n^{-\frac{\theta N}{2+\theta}} \sum_{|i| > M_n} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}} (|i|).$$

Using Lemma 2, we get (45).

The following lemma is a simple consequence of Lemma 4 (its proof is left to the reader).

**Lemma 7**  $\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|U_0 U_j|] \leq b_n^{\frac{\theta N}{4+\theta}}.$

Since  $(X_i)_{i \in \mathbb{Z}^d}$  is assumed to be strongly mixing, we have  $Z_i = U_i$  for any  $i \in \mathbb{Z}^d$ . Using Lemma 2 and Lemma 4, we have

$$\sum_{k=1}^{|\Lambda_n|} \mathbb{E} [|v'_k|] \leq 2 \mathbb{E} \left[ |Z_0| \left( \sum_{\substack{|i| \leq M_n \\ i \neq 0}} |Z_i| \right) \left( 1 \wedge \sum_{\substack{|i| \leq M_n \\ i \neq 0}} \frac{|Z_i|}{\sqrt{|\Lambda_n|}} \right) \right] \leq 2 \sum_{\substack{|i| \leq M_n \\ i \neq 0}} \mathbb{E} [|U_0 U_i|] \leq M_n^d b_n^{\frac{\theta N}{4+\theta}} \xrightarrow{n \rightarrow \infty} 0$$

and

$$\sum_{k=1}^{|\Lambda_n|} \left| \mathbb{E} [T_{g(k)} (S_{g(k-1)}(T) - S_{g(k)}^{(M_n)}(T)) h''_{k-1, k+1}^{(M_n)}] \right| \leq \sum_{\substack{|i| \leq M_n \\ i \neq 0}} \mathbb{E} [|U_0 U_i|] \leq M_n^d b_n^{\frac{\theta N}{4+\theta}} \xrightarrow{n \rightarrow \infty} 0.$$

So, we obtain (46) and (47).

Now, it suffices to prove (48). Let  $\beta \geq 1$  be a positive integer. In the sequel, for any  $j \in \mathbb{Z}^d$ , the notation  $\mathbb{E}_\beta[Z_j]$  stands for the conditional expectation of  $Z_j$  with respect to the  $\sigma$ -algebra  $\sigma(Z_i; i <_{\text{lex}} j \text{ and } |i - j| \geq \beta)$ . Then,

$$\frac{1}{|\Lambda_n|} \sum_{k=1}^{|\Lambda_n|} \left| \mathbb{E} [(Z_{g(k)}^2 - \mathbb{E}[Z_0^2]) h''_{k-1, k+1}] \right| \leq I_1 + I_2,$$

where

$$I_1 = \frac{1}{|\Lambda_n|} \sum_{k=1}^{|\Lambda_n|} \left| \mathbb{E} [(Z_{g(k)}^2 - \mathbb{E}_\beta[Z_{g(k)}^2]) h''_{k-1, k+1}] \right| \quad \text{and} \quad I_2 = \frac{1}{|\Lambda_n|} \sum_{k=1}^{|\Lambda_n|} \left| \mathbb{E} [(\mathbb{E}_\beta[Z_{g(k)}^2] - \mathbb{E}[Z_0^2]) h''_{k-1, k+1}] \right|.$$

The next result can be found in [20].

**Lemma 8** Let  $\mathcal{U}$  and  $\mathcal{V}$  be two  $\sigma$ -algebras and let  $X$  be a random variable which is measurable with respect to  $\mathcal{U}$ . If  $1 \leq p \leq r \leq \infty$ , then

$$\|\mathbb{E}[X|\mathcal{V}] - \mathbb{E}[X]\|_p \leq 2(2^{1/p} + 1)(\alpha(\mathcal{U}, \mathcal{V}))^{\frac{1}{p} - \frac{1}{r}} \|X\|_r.$$

Assume that  $(X_i)_{i \in \mathbb{Z}^d}$  is strongly mixing. Using Lemma 8 with  $p = 1$  and  $r = (2 + \theta)/2$  and keeping in mind that  $\|Z_0\|_{2+\theta}^2 = \|U_0\|_{2+\theta}^2 \leq b_n^{-\frac{\theta N}{2+\theta}}$ , we have

$$I_2 \leq \left\| \mathbb{E}_\beta[Z_0^2] - \mathbb{E}[Z_0^2] \right\|_1 \leq 6\alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(\beta) \|Z_0\|_{2+\theta}^2 \leq 6b_n^{-\frac{\theta N}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(\beta).$$

Now, we make the choice

$$\beta = \left[ b_n^{-\frac{\theta N}{(2d-1)\theta+6d-2}} \right]. \quad (49)$$

Consequently, using (A3)(i), we obtain

$$I_2 \leq \beta^{\frac{(2d-1)\theta+6d-2}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(\beta) \xrightarrow{n \rightarrow \infty} 0.$$

In the other part, noting that  $\mathbb{E} \left[ (Z_{g(k)}^2 - \mathbb{E}_\beta[Z_{g(k)}^2]) h''_{k-1,k+1}(\beta) \right] = 0$ , we have

$$\mathbb{E} \left[ (Z_{g(k)}^2 - \mathbb{E}_\beta[Z_{g(k)}^2]) h''_{k-1,k+1} \right] = \mathbb{E} \left[ (Z_{g(k)}^2 - \mathbb{E}_\beta[Z_{g(k)}^2]) (h''_{k-1,k+1} - h''_{k-1,k+1}(\beta)) \right].$$

So, we obtain

$$I_1 \leq \mathbb{E} \left[ \left( 2 \wedge \sum_{\substack{|i| \leq \beta \\ i < \text{lex } 0}} \frac{Z_i}{\sqrt{|\Lambda_n|}} \right) (Z_0^2 + \mathbb{E}_\beta[Z_0^2]) \right].$$

If  $L > 0$ , then

$$I_1 \leq \frac{L}{\sqrt{|\Lambda_n|}} \sum_{\substack{|i| \leq \beta \\ i \neq 0}} \mathbb{E}[|Z_0 Z_i|] + 2\mathbb{E}[Z_0^2 \mathbf{1}_{|Z_0| > L}] + 2 \left\| \mathbb{E}_\beta[Z_0^2] - \mathbb{E}[Z_0^2] \right\|_1 + \left\| \sum_{\substack{|i| \leq \beta \\ i < \text{lex } 0}} \frac{Z_i}{\sqrt{|\Lambda_n|}} \right\|_2 \mathbb{E}[Z_0^2].$$

Recall that  $Z_i = U_i$  for any  $i$  in  $\mathbb{Z}^d$ . Since  $\mathbb{E}[U_0^2] \leq 1$  and  $\|U_0\|_{2+\theta}^2 \leq b_n^{-\frac{\theta N}{2+\theta}}$ , we derive from Lemma 7 that

$$I_1 \leq \frac{\beta^d L b_n^{\frac{\theta N}{4+\theta}}}{\sqrt{|\Lambda_n|}} + L^{-\theta} b_n^{-\frac{\theta N}{2}} + \beta^{\frac{(2d-1)\theta+6d-2}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(\beta) + \left\| \sum_{\substack{|i| \leq \beta \\ i < \text{lex } 0}} \frac{Z_i}{\sqrt{|\Lambda_n|}} \right\|_2.$$

Now, we make the choice

$$L = \frac{|\Lambda_n|^{\frac{1}{2(1+\theta)}}}{\beta^{\frac{d}{1+\theta}} b_n^{\frac{\theta(4+\theta)(2d-1)\theta+6d-2}{2(1+\theta)(4+\theta)}}} \quad (50)$$

and we obtain

$$I_1 \leq (|\Lambda_n| b_n^N)^{\frac{-\theta}{2(1+\theta)}} \times b_n^{\frac{\theta^2(2+\theta)(d-1)N}{(1+\theta)(4+\theta)((2d-1)\theta+6d-2)}} + \beta^{\frac{(2d-1)\theta+6d-2}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(\beta) + \left\| \sum_{\substack{|i| \leq \beta \\ i < \text{lex } 0}} \frac{U_i}{\sqrt{|\Lambda_n|}} \right\|_2.$$

Moreover,

$$\begin{aligned} \left\| \sum_{\substack{|i| \leq \beta \\ i <_{\text{lex}} 0}} \frac{U_i}{\sqrt{|\Lambda_n|}} \right\|_2^2 &\leq \frac{(2\beta + 1)^d \mathbb{E} [U_0^2]}{|\Lambda_n|} + \frac{1}{|\Lambda_n|} \sum_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} |[-\beta, \beta]^d \cap ([-\beta, \beta]^d - j)| \left| \mathbb{E} [U_0 U_j] \right| \\ &\leq \frac{\beta^d}{|\Lambda_n|} \left( \mathbb{E} [U_0^2] + \sum_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [U_0 U_j] \right| \right). \end{aligned}$$

Using (32) and (34), we have  $\sum_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [U_0 U_j] \right| = o(1)$ . Consequently, we get

$$\left\| \sum_{\substack{|i| \leq \beta \\ i <_{\text{lex}} 0}} \frac{U_i}{\sqrt{|\Lambda_n|}} \right\|_2^2 \leq \frac{\beta^d}{|\Lambda_n|} \leq \frac{1}{|\Lambda_n| b_n^{\frac{d\theta N}{(2d-1)\theta+6d-2}}} \leq \frac{1}{|\Lambda_n| b_n^N}.$$

So, we obtain

$$I_1 \leq (|\Lambda_n| b_n^N)^{\frac{-\theta}{2(1+\theta)}} \times b_n^{\frac{\theta^2(2+\theta)(d-1)N}{(1+\theta)(4+\theta)((2d-1)\theta+6d-2)}} + \beta^{\frac{(2d-1)\theta+6d-2}{2+\theta}} \alpha_{1,\infty}^{\frac{\theta}{2+\theta}}(\beta) + \frac{1}{\sqrt{|\Lambda_n| b_n^N}} \xrightarrow{n \rightarrow \infty} 0.$$

Finally, if  $(X_i)_{i \in \mathbb{Z}^d}$  is strongly mixing, then (48) holds. In order to complete the proof of Theorem 2, we only need to prove (45), (46), (47) and (48) when  $(X_i)_{i \in \mathbb{Z}^d}$  is of the form (1). So, assume that  $(X_i)_{i \in \mathbb{Z}^d}$  is of the form (1) and (A3)(ii) holds. Then  $(Z_i)_{i \in \mathbb{Z}^d} = (\bar{U}_i)_{i \in \mathbb{Z}^d}$  is  $M_n$ -dependent. Consequently,  $\mathbb{E} [T_{g(k)} h'_{k-1, k+1}^{(M_n)}] = 0$  and (45) follows.

**Lemma 9**  $\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|\bar{U}_0 \bar{U}_j|] = o(M_n^{-d})$ .

*Proof.* We have

$$\sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \left| \mathbb{E} [|\bar{U}_0 \bar{U}_j|] - \mathbb{E} [U_0 U_j] \right| \leq 2 \|U_0\|_2 \|U_0 - \bar{U}_0\|_2.$$

Combining (19), Lemma 2 and Lemma 7 and keeping in mind  $\|U_0\|_2 \leq 1$ , we obtain

$$M_n^d \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|\bar{U}_0 \bar{U}_j|] \leq M_n^d b_n^{\frac{\theta N}{4+\theta}} + b_n^{\frac{-\theta(N+2)+2N}{2(2+\theta)}} \sum_{|j| > M_n} |j|^d \delta_{j,2}^{\frac{\theta}{2+\theta}} \xrightarrow{n \rightarrow \infty} 0.$$

The proof of Lemma 9 is complete. □

Applying Lemma 9, we have

$$\sum_{k=1}^{|\Lambda_n|} \mathbb{E} [|\mathcal{V}_k'|] \leq 2\mathbb{E} \left[ |Z_0| \left( \sum_{\substack{|i| \leq M_n \\ i \neq 0}} |Z_i| \right) \left( 1 \wedge \sum_{\substack{|i| \leq M_n \\ i \neq 0}} \frac{|Z_i|}{\sqrt{|\Lambda_n|}} \right) \right] \leq 2 \sum_{\substack{|i| \leq M_n \\ i \neq 0}} \mathbb{E} [|\bar{U}_0 \bar{U}_i|] \xrightarrow{n \rightarrow \infty} 0$$

and

$$\sum_{k=1}^{|\Lambda_n|} \left| \mathbb{E} \left[ T_{g(k)} \left( S_{g(k-1)}(T) - S_{g(k)}^{(M_n)}(T) \right) h''_{k-1,k+1} \right] \right| \leq \sum_{\substack{|i| \leq M_n \\ i \neq 0}} \mathbb{E} \left[ |\bar{U}_0 \bar{U}_i| \right] \xrightarrow{n \rightarrow \infty} 0.$$

So, we obtain (46) and (47). Moreover, we have

$$\mathbb{E} \left[ \left( Z_{g(k)}^2 - \mathbb{E} [Z_0^2] \right) h''_{k-1,k+1} \right] = \mathbb{E} \left[ \left( \bar{U}_{g(k)}^2 - \mathbb{E} [\bar{U}_0^2] \right) h''_{k-1,k+1} \right] = 0.$$

Consequently,

$$\begin{aligned} \frac{1}{|\Lambda_n|} \sum_{k=1}^{|\Lambda_n|} \left| \mathbb{E} \left[ \left( Z_{g(k)}^2 - \mathbb{E} [Z_0^2] \right) h''_{k-1,k+1} \right] \right| &= \frac{1}{|\Lambda_n|} \sum_{k=1}^{|\Lambda_n|} \left| \mathbb{E} \left[ \left( \bar{U}_{g(k)}^2 - \mathbb{E} [\bar{U}_0^2] \right) \left( h''_{k-1,k+1} - h''_{k-1,k+1}^{(M_n)} \right) \right] \right| \\ &\leq \mathbb{E} \left[ \left( 2 \wedge \sum_{\substack{|i| \leq M_n \\ i < \text{lex } 0}} \frac{\bar{U}_i}{\sqrt{|\Lambda_n|}} \right) \left( \bar{U}_0^2 + \mathbb{E} [\bar{U}_0^2] \right) \right]. \end{aligned}$$

As before, if  $L' > 0$ , then using  $\|\bar{U}_0\|_{2+\theta}^2 \leq \|U_0\|_{2+\theta}^2 \leq b_n^{-\frac{\theta N}{2+\theta}}$ , we get

$$\frac{1}{|\Lambda_n|} \sum_{k=1}^{|\Lambda_n|} \left| \mathbb{E} \left[ \left( Z_{g(k)}^2 - \mathbb{E} [Z_0^2] \right) h''_{k-1,k+1} \right] \right| \leq \frac{M_n^d L' \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|\bar{U}_0 \bar{U}_j|]}{\sqrt{|\Lambda_n|}} + L'^{-\theta} b_n^{-\frac{\theta N}{2}} + \mathbb{E} [U_0^2] \left\| \sum_{\substack{|i| \leq M_n \\ i < \text{lex } 0}} \frac{\bar{U}_i}{\sqrt{|\Lambda_n|}} \right\|_2.$$

Applying Lemma 9 and keeping in mind that  $\mathbb{E} [U_0^2] \leq 1$  then

$$\begin{aligned} \left\| \sum_{\substack{|i| \leq M_n \\ i < \text{lex } 0}} \frac{\bar{U}_i}{\sqrt{|\Lambda_n|}} \right\|_2^2 &\leq \frac{(2M_n + 1)^d \mathbb{E} [\bar{U}_0^2]}{|\Lambda_n|} + \frac{1}{|\Lambda_n|} \sum_{\substack{|j| \leq M_n \\ j \neq 0}} \left| [-M_n, M_n]^d \cap ([-M_n, M_n]^d - j) \right| \left| \mathbb{E} [\bar{U}_0 \bar{U}_j] \right| \\ &\leq \frac{M_n^d}{|\Lambda_n|} \left( \mathbb{E} [U_0^2] + M_n^d \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|\bar{U}_0 \bar{U}_j|] \right) \leq \frac{M_n^d}{|\Lambda_n|}. \end{aligned}$$

Then,

$$\frac{1}{|\Lambda_n|} \sum_{k=1}^{|\Lambda_n|} \left| \mathbb{E} \left[ \left( Z_{g(k)}^2 - \mathbb{E} [Z_0^2] \right) h''_{k-1,k+1} \right] \right| \leq \frac{M_n^d L' \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|\bar{U}_0 \bar{U}_j|]}{\sqrt{|\Lambda_n|}} + L'^{-\theta} b_n^{-\frac{\theta N}{2}} + \frac{M_n^{d/2}}{\sqrt{|\Lambda_n|}}.$$

For

$$L' = \frac{|\Lambda_n|^{\frac{1}{2(1+\theta)}}}{\left( M_n^d \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|\bar{U}_0 \bar{U}_j|] \right)^{\frac{1}{1+\theta}} b_n^{-\frac{\theta N}{2(1+\theta)}}},$$

we get

$$\frac{1}{|\Lambda_n|} \sum_{k=1}^{|\Lambda_n|} \left| \mathbb{E} \left[ (Z_{g(k)}^2 - \mathbb{E}[Z_0^2]) h''_{k-1, k+1} \right] \right| \leq \frac{\left( M_n^d \sup_{\substack{j \in \mathbb{Z}^d \\ j \neq 0}} \mathbb{E} [|\bar{U}_0 \bar{U}_j|] \right)^{\frac{\theta}{1+\theta}}}{(|\Lambda_n| b_n^N)^{\frac{\theta}{2(1+\theta)}}} + \frac{M_n^{d/2}}{\sqrt{|\Lambda_n|}}.$$

Finally, using again Lemma 9 and keeping in mind that  $M_n^d = o(|\Lambda_n|)$  (see Lemma 2) we derive (48). The proof of Theorem 2 is complete.  $\square$

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