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CENTRAL LIMIT THEOREM FOR A STRATONOVICH INTEGRAL WITH MALLIAVIN CALCULUS

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The purpose of this paper is to establish the convergence in law of the sequence of "midpoint" Riemann sums for a stochastic process of the form $f'(W)$, where W is a Gaussian process whose covariance function satisfies some technical conditions. As a consequence we derive a change-of-variable formula in law with a second order correction term which is an Itô integral of $f''(W)$ with respect to a Gaussian martingale independent of W. The proof of the convergence in law is based on the techniques of Malliavin calculus and uses a central limit theorem for q-fold Skorohod integrals, which is a multidimensional extension of a result proved by Nourdin and Nualart [*J. Theoret. Probab.* **23** (2010) 39–64]. The results proved in this paper are generalizations of previous work by Swanson [*Ann. Probab.* **35** (2007) 2122–2159] and Nourdin and Réveillac [*Ann. Probab.* **37** (2009) 2200–2230], who found a similar formula for two particular types of bifractional Brownian motion. We provide three examples of Gaussian processes W that meet the necessary covariance bounds. The first one is the bifractional Brownian motion with parameters $H \leq 1/2$, $HK = 1/4$. The others are Gaussian processes recently studied by Swanson [*Probab. Theory Related Fields* **138** (2007) 269–304], [*Ann. Probab.* **35** (2007) 2122–2159] in connection with the fluctuation of empirical quantiles of independent Brownian motion. In the first example the Gaussian martingale is a Brownian motion, and expressions are given for the other examples.

1. Introduction. The aim of this paper is to obtain a change-of-variable formula in distribution for a class of Gaussian stochastic processes $W = \{W_t, t \geq 0\}$ under certain conditions on the covariance function. These conditions are in the form of upper bounds on the covariance of process increments. For example, the variance on the increment on an interval of length s is bounded by $C\sqrt{s}$, and the covariance between the increments in the intervals $[t-s, t]$, and $[r-s, r]$ is bounded by

$$s^2|t-r|^{-\alpha}(r-s)^{-\beta} + s^2|t-r|^{-3/2},$$

if $0 < 2s \leq r < t$ and $|t-r| \geq 2s$, where $1 < \alpha \leq \frac{3}{2}$ and $\alpha + \beta = \frac{3}{2}$.

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For this process and a suitable function f, we study the behavior of the "midpoint" Riemann sum

$$\Phi_n(t) := \sum_{j=1}^{\lfloor nt/2 \rfloor} f'(W_{(2j-1)/n})(W_{2j/n} - W_{(2j-2)/n}).$$

The limit of this sum as n tends to infinity is the Stratonovich midpoint integral, denoted by $\int_0^t f'(W_s)^\circ \, dW_s$. We show that the couple of processes $\{(W_t, \Phi_n(t)), t \geq 0\}$ converges in distribution in the Skorohod space $(\mathbb{D}[0, \infty))^2$ to $\{(W_t, \Phi(t)), t \geq 0\}$, where

$$\Phi(t) = f(W_t) - f(W_0) - \frac{1}{2}\int_0^t f''(W_s)\, dB_s,$$

and $B = \{B_t, t \geq 0\}$ is a Gaussian martingale independent of W with variance $\eta(t)$, depending on the covariance properties of W. This limit theorem can be reformulated by saying that the following Itô formula in distribution holds:

$$f(W_t) \stackrel{\mathcal{L}}{=} f(W_0) + \int_0^t f'(W_s)^\circ \, dW_s + \frac{1}{2}\int_0^t f''(W_s)\, dB_s. \tag{1}$$

The above mentioned convergence is proven by showing the stable convergence of a d-dimensional vector $(\Phi_n(t_1), \ldots, \Phi_n(t_d))$ and a tightness argument. To show the convergence in law of the finite-dimensional distributions, we show first, using the techniques of Malliavin calculus, that $\Phi_n(t)$ is asymptotically equivalent to a sequence of iterated Skorohod integrals involving $f''(W_t)$. We then apply our d-dimensional version of the central limit theorem for multiple Skorohod integrals proved by Nourdin and Nualart in [5].

Recent papers by Swanson [10], Nourdin and Réveillac [6] and Burdzy and Swanson [2] presented results comparable to (1) for a specific stochastic process. In [10], a change-of-variable form was found for a process equivalent to the bifractional Brownian motion with parameters $H = K = 1/2$, arising as the solution to the one-dimensional stochastic heat equation with an additive space–time white noise. This result was proven mostly by martingale methods. In [2] and [6], the respective authors considered fractional Brownian motion with Hurst parameter $1/4$. In [2], the authors covered integrands of the form $f(t, W_t)$, which can be applied to fBm on $[\varepsilon, \infty)$. The authors of [6] proved a change-of-variable formula that holds on $[0, \infty)$ in the sense of marginal distributions. The proof in [6] uses Malliavin calculus; several similar methods were used in the present paper. More recently, Nourdin, Réveillac and Swanson [7] studied the case of fractional Brownian motion with $H = 1/6$. In that paper, weak convergence was proven in the Skorohod space, and the Riemann sums are based on the trapezoidal approximation.

It happens that the conditions on the process W are satisfied by a bifractional Brownian motion with parameters $H \leq 1/2$, $HK = 1/4$. In this case, $\eta(t) = Ct$ and the process B is a Brownian motion. This includes both cases studied in [6]

and [10], and extends to a larger class of processes. For another example, we consider a class of centered Gaussian processes with twice-differentiable covariance function of the form

$$\mathbb{E}[W_r W_t] = r\phi\left(\frac{t}{r}\right), \qquad t \geq r,$$

where ϕ is a bounded function on $[1, \infty)$ such that

$$\phi'(x) = \frac{\kappa}{\sqrt{x-1}} + \frac{\psi(x)}{\sqrt{x}},$$

and ψ is bounded, differentiable and $|\psi'(x)| \leq C(x-1)^{-1/2}$. This class of Gaussian processes includes the process arising as the limit of the median of a system of independent Brownian motions studied by Swanson in [9]. For this process,

$$\phi(x) = \sqrt{x}\arctan\left(\frac{1}{\sqrt{x-1}}\right).$$

It is surprising to remark that in this case $\eta(t) = Ct^2$. This is related to the fact that the variance of the increments of W on the interval $[t-s, t]$ behaves as $C\sqrt{s}$, when s is small, although the variance of $W(t)$ behaves as Ct. Our third example is another Gaussian process studied by Swanson in [11]. This process also arises from the empirical quantiles of a system of independent Brownian motions. Let $B = \{B(t), t \geq 0\}$ be a Brownian motion, where $B(0)$ is a random variable with density $f \in C^\infty$. Given certain growth conditions on f, Swanson proves there is a Gaussian process $F = \{F(t), t \geq 0\}$ with covariance given by

$$\mathbb{E}\big[F(r)F(t)\big] = \rho(r,t) = \frac{\mathbb{P}(B(r) \leq q(r), B(t) \leq q(t)) - \alpha^2}{u(q(r), r)u(q(t), t)},$$

where $\alpha \in (0, 1)$ and $q(t)$ are defined by $\mathbb{P}(B(t) \leq q(t)) = \alpha$. It is shown that this family of processes satisfies the required conditions, where $\eta(t)$ is determined by f and α.

The outline of this paper is as follows: In Section 2, we introduce the basic environment and recall some aspects of Malliavin calculus that will be used. In Section 3, a multi-dimensional version of a central limit theorem that appears in [5] is given. In Section 4, the theorem is applied to prove convergence of $\Phi_n(t)$. Section 5 discusses three examples of suitable process families. Finally, Section 6 contains proofs of three of the longer lemmas from Section 4. Most of the notation in this paper follows that of [5].

2. Preliminaries and notation. Let $W = \{W(t), t \geq 0\}$ be a centered Gaussian process defined on a probability space $(\Omega, \mathcal{F}, P)$ with continuous covariance function

$$\mathbb{E}\big[W(t)W(s)\big] = R(t,s).$$

We will always assume that $\mathcal{F}$ is the σ-algebra generated by W. Let $\mathcal{E}$ denote the set of step functions on $[0, T]$ for $T > 0$; and let $\mathfrak{H}$ be the Hilbert space defined as the closure of $\mathcal{E}$ with respect to the scalar product

$$\langle \mathbf{1}_{[0,t]}, \mathbf{1}_{[0,s]} \rangle_{\mathfrak{H}} = R(t, s).$$

The mapping $\mathbf{1}_{[0,t]} \mapsto W(t)$ can be extended to a linear isometry between $\mathfrak{H}$ and the Gaussian space spanned by W. We denote this isometry by $h \mapsto W(h)$. In this way, $\{W(h), h \in \mathfrak{H}\}$ is an isonormal Gaussian process. For integers $q \geq 1$, let $\mathfrak{H}^{\otimes q}$ denote the qth tensor product of $\mathfrak{H}$. We use $\mathfrak{H}^{\odot q}$ to denote the symmetric tensor product.

For integers $q \geq 1$, let $\mathcal{H}_q$ be the qth Wiener chaos of W, that is, the closed linear subspace of $L^2(\Omega)$ generated by the random variables $\{H_q(W(h)), h \in \mathfrak{H}, \|h\|_{\mathfrak{H}} = 1\}$, where $H_q(x)$ is the qth Hermite polynomial, defined as

$$H_q(x) = (-1)^q e^{x^2/2} \frac{d^q}{dx^q} e^{-x^2/2}.$$

For $q \geq 1$, it is known that the map

$$I_q\big(h^{\otimes q}\big) = H_q\big(W(h)\big) \tag{2}$$

provides an isometry between the symmetric product space $\mathfrak{H}^{\odot q}$ (equipped with the modified norm $\frac{1}{\sqrt{q!}} \| \cdot \|_{\mathfrak{H}^{\otimes q}}$) and $\mathcal{H}_q$. By convention, $\mathcal{H}_0 = \mathbb{R}$ and $I_0(x) = x$.

2.1. *Elements of Malliavin calculus.* Following is a brief description of some identities that will be used in the paper. The reader may refer to [5] for a brief survey, or to [8] for detailed coverage of this topic. Let $\mathcal{S}$ be the set of all smooth and cylindrical random variables of the form $F = g(W(\phi_1), \ldots, W(\phi_n))$, where $n \geq 1$; $g : \mathbb{R}^n \to \mathbb{R}$ is an infinitely differentiable function with compact support, and $\phi_i \in \mathfrak{H}$. The Malliavin derivative of F with respect to W is the element of $L^2(\Omega, \mathfrak{H})$ defined as

$$DF = \sum_{i=1}^{n} \frac{\partial g}{\partial w_i}\big(W(\phi_1), \ldots, W(\phi_n)\big)\phi_i.$$

In particular, $DW(h) = h$. By iteration, for any integer $q > 1$, we can define the qth derivative $D^q F$, which is an element of $L^2(\Omega, \mathfrak{H}^{\odot q})$. For example, if $F = g(W(t))$, then $D^2 F = g''(W(t))\mathbf{1}_{[0,t]}^{\otimes 2}$.

For any integer $q \geq 1$ and real number $p \geq 1$, let $\mathbb{D}^{q,p}$ denote the closure of $\mathcal{S}$ with respect to the norm $\| \cdot \|_{\mathbb{D}^{q,p}}$ defined as

$$\|F\|_{\mathbb{D}^{q,p}}^p = \mathbb{E}\big[|F|^p\big] + \sum_{i=1}^{q} \mathbb{E}\big[\big\|D^i F\big\|_{\mathfrak{H}^{\otimes i}}^p\big].$$

We denote by δ the Skorohod integral, which is defined as the adjoint of the operator D. This operator is also referred to as the divergence operator in [8]. A random element $u \in L^2(\Omega, \mathfrak{H})$ belongs to the domain of δ, $\operatorname{Dom}\delta$, if and only if

$$\left|\mathbb{E}\left[\langle DF, u\rangle_{\mathfrak{H}}\right]\right| \leq c_u\sqrt{E\left[F^2\right]}$$

for any $F \in \mathbb{D}^{1,2}$, where c_u is a constant which depends only on u. If $u \in \operatorname{Dom}\delta$, then the random variable $\delta(u) \in L^2(\Omega)$ is defined for all $F \in \mathbb{D}^{1,2}$ by the duality relationship,

$$\mathbb{E}\left[F\delta(u)\right] = \mathbb{E}\left[\langle DF, u\rangle_{\mathfrak{H}}\right].$$

This is sometimes called the Malliavin integration by parts formula. We iteratively define the multiple Skorohod integral for $q \geq 1$ as $\delta(\delta^{q-1}(u))$, with $\delta^0(u) = u$. For this definition we have

$$\mathbb{E}\left[F\delta^q(u)\right] = \mathbb{E}\left[\left\langle D^q F, u\right\rangle_{\mathfrak{H}^{\otimes q}}\right],$$

where $u \in \operatorname{Dom}\delta^q$ and $F \in \mathbb{D}^{q,2}$. Moreover, if $h \in \mathfrak{H}^{\odot q}$, then we have $\delta^q(h) = I_q(h)$.

For $f, g \in \mathfrak{H}^{\otimes p}$, the following integral multiplication formula holds:

$$\delta^p(f)\delta^p(g) = \sum_{r=0}^{p} r!\binom{p}{r}\delta^{2p-2r}(f \otimes_r g), \tag{3}$$

where $\otimes_r$ is the contraction operator; see, for example, [5], Section 2.

We will use the Meyer inequality for the Skorohod integral; see, for example, Proposition 1.5.7 of [8]. Let $\mathbb{D}^{k,p}(\mathfrak{H}^{\otimes k})$ denote the corresponding Sobolev space of $\mathfrak{H}^{\otimes k}$-valued random variables. Then for $p \geq 1$ and integers $k \geq q \geq 1$, we have

$$\left\|\delta^q(u)\right\|_{\mathbb{D}^{k-q,p}} \leq c_{k,p}\|u\|_{\mathbb{D}^{k,p}(\mathfrak{H}^{\otimes q})} \tag{4}$$

for all $u \in \mathbb{D}^{k,p}(\mathfrak{H}^{\otimes k})$ and some constant $c_{k,p}$.

The following three results will be used in the proof of Theorem 4.3. The reader may refer to [5] and [8] for details.

LEMMA 2.1. *Let $q \geq 1$ be an integer.*

(1) *Assume $F \in \mathbb{D}^{q,2}$, u is a symmetric element of $\operatorname{Dom}\delta^q$, and $\langle D^r F, \delta^j(u)\rangle_{\mathfrak{H}^{\otimes r}} \in L^2(\Omega, \mathfrak{H}^{\otimes q-r-j})$ for all $0 \leq r + j \leq q$. Then $\langle D^r F, u\rangle_{\mathfrak{H}^{\otimes r}} \in \operatorname{Dom}\delta^r$ and*

$$F\delta^q(u) = \sum_{r=0}^{q}\binom{q}{r}\delta^{q-r}\left(\left\langle D^r F, u\right\rangle_{\mathfrak{H}^{\otimes r}}\right).$$

(2) *Suppose that u is a symmetric element of $\mathbb{D}^{j+k,2}(\mathfrak{H}^{\otimes j})$. Then we have*

$$D^k\delta^j(u) = \sum_{i=0}^{j\wedge k}\binom{k}{i}\binom{j}{i}i!\delta^{j-i}\left(D^{k-i}u\right).$$

(3) *Let u, v be symmetric functions in $\mathbb{D}^{2q,2}(\mathfrak{H}^{\otimes q})$. Then*

$$\mathbb{E}\big[\delta^q(u)\delta^q(v)\big] = \sum_{i=0}^{q} \binom{q}{i}^2 \mathbb{E}\big[\langle D^{q-i}u, D^{q-i}v\rangle_{\mathfrak{H}^{\otimes(2q-i)}}\big].$$

In particular,

$$\|\delta^q(u)\|^2_{L^2(\Omega)} = \mathbb{E}\big[\delta^q(u)^2\big] = \sum_{i=0}^{q} \binom{q}{i}^2 \mathbb{E}\big[\|D^{q-i}u\|^2_{\mathfrak{H}^{\otimes(2q-i)}}\big].$$

Proof of (1). This is proved in [5]; see Lemma 2.1. It follows by induction from the relation $F\delta(u) = \delta(Fu) + \langle DF, u\rangle_{\mathfrak{H}}$; see [8], Proposition 1.3.3.

Proof of (2). This follows from repeated application of the relation $D\delta(u) = u + \delta(Du)$; see [8], Proposition 1.3.2.

Proof of (3). This follows from repeated application of the duality property; see [5], equation (2.12).

3. A central limit theorem for multiple Skorohod integrals. Let $X = \{X(h), h \in \mathfrak{H}\}$ be an isonormal Gaussian process associated with a real-separable Hilbert space $\mathfrak{H}$, defined on a probability space $(\Omega, \mathcal{F}, P)$. We assume that $\mathcal{F}$ is generated by X. The purpose of this section is to prove a multi-dimensional version of a theorem proved in [5]; see Theorem 3.1. We begin by defining the notion of stable convergence.

DEFINITION 3.1. Assume F_n is a sequence of d-dimensional random variables defined on a probability space $(\Omega, \mathcal{F}, P)$, and F is a d-dimensional random variable defined on $(\Omega, \mathcal{G}, P)$, where $\mathcal{F} \subset \mathcal{G}$. We say that F_n *converges stably* to F as $n \to \infty$, if, for any continuous and bounded function $f : \mathbb{R}^d \to \mathbb{R}$ and bounded, $\mathbb{R}$-valued, $\mathcal{F}$-measurable random variable Z, we have

$$\lim_{n\to\infty} \mathbb{E}\big(f(F_n)Z\big) = \mathbb{E}\big(f(F)Z\big).$$

THEOREM 3.2. *Let $q \geq 1$ be an integer, and suppose that F_n is a sequence of random variables in $\mathbb{R}^d$ of the form $F_n = \delta^q(u_n) = (\delta^q(u_n^1), \ldots, \delta^q(u_n^d))$, for a sequence of $\mathbb{R}^d$-valued symmetric functions u_n in $\mathbb{D}^{2q,2q}(\mathfrak{H}^{\otimes q})$. Suppose that the sequence F_n is bounded in $L^1(\Omega, \mathfrak{H})$ and that*:

(a) *$\langle u_n^j, \bigotimes_{\ell=1}^m (D^{a_\ell} F_n^{j_\ell}) \otimes h\rangle_{\mathfrak{H}^{\otimes q}}$ converges to zero in $L^1(\Omega)$ for all integers $1 \leq j, j_\ell \leq d$, all integers $1 \leq a_1, \ldots, a_m, r \leq q-1$ such that $a_1 + \cdots + a_m + r = q$; and all $h \in \mathfrak{H}^{\otimes r}$.*

(b) *For each* $1 \le i, j \le d$, $\langle u_n^i, D^q F_n^j \rangle_{\mathfrak{H}^{\otimes q}}$ *converges in* $L^1(\Omega, \mathfrak{H})$ *to a random variable* s_{ij}, *such that the matrix* $\Sigma := (s_{ij})_{d\times d}$ *is nonnegative definite* (*i.e.*, $\lambda^T \Sigma \lambda \ge 0$ *for all nonzero* $\lambda \in \mathbb{R}^d$).

Then F_n *converges stably to a random variable in* $\mathbb{R}^d$ *with conditional Gaussian law* $\mathcal{N}(0, \Sigma)$ *given* X.

REMARK 3.3. Conditions (a) and (b) mean that for $q \ge 1$, some combinations of lower-order derivative products are negligible. For example, for $q = 2$, then the following scalar products will converge to zero in $L^1(\Omega, \mathfrak{H})$:

- $\langle u_n^i, h_1 \otimes h_2 \rangle_{\mathfrak{H}^{\otimes 2}}$ for all $h_1, h_2 \in \mathfrak{H}$;
- $\langle u_n^i, DF_n^j \otimes h \rangle_{\mathfrak{H}^{\otimes 2}}$ for all $h \in \mathfrak{H}$ and all j (including $i = j$);
- $\langle u_n^i, DF_n^j \otimes DF_n^k \rangle_{\mathfrak{H}^{\otimes 2}}$ for all $1 \le k, j \le d$.

Only the qth-order derivative products converge to a nontrivial random variable. Usually (see Section 6), the term $\langle u_n^i, D^q F_n^j \rangle_{\mathfrak{H}^{\otimes q}}$ has the same asymptotic behavior as $\langle u_n^i, u_n^j \rangle_{\mathfrak{H}^{\otimes q}}$.

REMARK 3.4. It suffices to impose condition (a) for $h \in \mathcal{S}_0$, where $\mathcal{S}_0$ is a total subset of $\mathfrak{H}^{\otimes r}$.

PROOF OF THEOREM 3.2. As in the one-dimensional case considered in [5], we will use the conditional characteristic function. Given any $h_1, \dots, h_m \in \mathfrak{H}$, we want to show that the sequence

$$\xi_n = \big(F_n^1, \dots, F_n^d, X(h_1), \dots, X(h_m)\big)$$

converges in distribution to a vector $(F_\infty^1, \dots, F_\infty^d, X(h_1), \dots, X(h_m))$, where, for any vector $\lambda \in \mathbb{R}^d$, F_∞ satisfies

$$\mathbb{E}\big(e^{i\lambda \cdot F_\infty} | X(h_1), \dots, X(h_m)\big) = \exp\big(-\tfrac{1}{2}\lambda^T \Sigma \lambda\big), \tag{5}$$

where $\lambda \cdot F_n = \sum_{j=1}^d \lambda_j F_n^j$ denotes the usual scalar product in $\mathbb{R}^d$, and we use this notation to avoid confusion with the scalar product in $\mathfrak{H}$.

Since F_n is bounded in $L^1(\Omega, \mathfrak{H})$, the sequence ξ_n is tight in the sense that for any $\varepsilon > 0$, there is a $K > 0$ such that $P(F_n \in [-K, K]^d) > 1 - \varepsilon$, which follows from Chebyshev inequality. Dropping to a subsequence if necessary, we may assume that ξ_n converges in distribution to a limit $(F_\infty^1, \dots, F_\infty^d, X(h_1), \dots, X(h_m))$. Let $Y := g(X(h_1), \dots, X(h_m))$, where $g \in \mathcal{C}_b^\infty(\mathbb{R}^m)$, and consider $\phi_n(\lambda) = \phi(\lambda, \xi_n) := \mathbb{E}(e^{i\lambda \cdot F_n} Y)$ for $\lambda \in \mathbb{R}^d$. The convergence in law of ξ_n implies that for each $1 \le j \le d$,

$$\lim_{n\to\infty} \frac{\partial \phi_n}{\partial \lambda_j} = \lim_{n\to\infty} i\mathbb{E}\big(F_n^j e^{i\lambda \cdot F_n} Y\big) = i\mathbb{E}\big(F_\infty^j e^{i\lambda \cdot F_\infty} Y\big), \tag{6}$$

where convergence in distribution follows from a truncation argument applied to F_n^j.

On the other hand, using the duality property of the Skorohod integral and the Malliavin derivative,

$$\frac{\partial \phi_n}{\partial \lambda_j} = i\mathbb{E}\big(\delta^q(u_n^j)e^{i\lambda\cdot F_n}Y\big) = i\mathbb{E}\big(\langle u_n^j, D^q\big(e^{i\lambda\cdot F^n}Y\big)\rangle_{\mathfrak{H}^{\otimes q}}\big)$$

$$= i\sum_{a=0}^{q}\binom{q}{a}\mathbb{E}\big(\langle u_n^j, D^a\big(e^{i\lambda\cdot F_n}\big)\widetilde{\otimes} D^{q-a}Y\rangle_{\mathfrak{H}^{\otimes q}}\big) \tag{7}$$

$$= i\left\{\mathbb{E}\langle u_n^j, YD^q e^{i\lambda\cdot F_n}\rangle_{\mathfrak{H}^{\otimes q}} + \sum_{a=0}^{q-1}\binom{q}{a}\mathbb{E}\langle u_n^j, D^a e^{i\lambda\cdot F_n}\widetilde{\otimes} D^{q-a}Y\rangle_{\mathfrak{H}^{\otimes q}}\right\}.$$

By condition (a), we have that $\langle u_n^j, D^a e^{i\lambda\cdot F_n}\widetilde{\otimes} D^{q-a}Y\rangle_{\mathfrak{H}^{\otimes q}}$ converges to zero in $L^1(\Omega)$ when $a<q$, so the sum term vanishes as $n\to\infty$, and this leaves

$$\lim_{n\to\infty} i\mathbb{E}\langle u_n^j, YD^q e^{i\lambda\cdot F_n}\rangle_{\mathfrak{H}^{\otimes q}}$$

$$= \lim_{n\to\infty} i\sum_{k=1}^{d}\mathbb{E}\big(i\lambda_k e^{i\lambda\cdot F_n}\langle u_n^j, YD^q F_n^k\rangle_{\mathfrak{H}^{\otimes q}}\big)$$

$$= -\sum_{k=1}^{d}\mathbb{E}\big(\lambda_k e^{i\lambda\cdot F_\infty}s_{kj}Y\big),$$

because the lower-order derivatives in $D^q e^{i\lambda\cdot F_n}$ also vanish by condition (a). Combining this with (6), we obtain

$$i\mathbb{E}\big(F_\infty^j e^{i\lambda\cdot F_\infty}Y\big) = -\sum_{k=1}^{d}\lambda_k\mathbb{E}\big(e^{i\lambda\cdot F_\infty}s_{kj}Y\big).$$

This leads to the PDE system,

$$\frac{\partial}{\partial\lambda_j}\mathbb{E}\big(e^{i\lambda\cdot F_\infty}|X(h_1),\ldots,X(h_m)\big)$$

$$= -\sum_{k=1}^{d}\lambda_k s_{kj}\mathbb{E}\big(e^{i\lambda\cdot F_\infty}|X(h_1),\ldots,X(h_m)\big),$$

which has unique solution (5). □

4. Central limit theorem for the Stratonovich integral. Suppose that $W=\{W_t, t\ge 0\}$ is a centered Gaussian process, as in Section 2, that meets conditions (i) through (v), below, for any $T>0$, where the constants C_i may depend on T:

(i) For any $0 < s \le t \le T$, there is a constant C_1 such that

$$\mathbb{E}\big[(W_t - W_{t-s})^2\big] \le C_1 s^{1/2}.$$

(ii) For any $s > 0$ and $2s \le r, t \le T$ with $|t - r| \ge 2s$,

$$\begin{aligned}&\big|\mathbb{E}\big[(W_t - W_{t-s})(W_r - W_{r-s})\big]\big| \\ &\quad \le C_1 s^2 |t-r|^{-\alpha}(t \wedge r - s)^{-\beta} + s^2 |t-r|^{-3/2}\end{aligned}$$

for positive constants α, β, γ, such that $1 < \alpha \le \frac{3}{2}$ and $\alpha + \beta = \frac{3}{2}$.

(iii) For $0 < t \le T$ and $0 < s \le r \le T$,

$$\begin{aligned}&\big|\mathbb{E}\big[W_t(W_{r+s} - 2W_r + W_{r-s})\big]\big| \\ &\quad \le \begin{cases} C_2 s^{1/2}, & \text{if } r < 2s \text{ or } |t-r| < 2s, \\ C_2 s^2\big((r-s)^{-3/2} + |t-r|^{-3/2}\big), & \text{if } r \ge 2s \text{ and } |t-r| \ge 2s, \end{cases}\end{aligned}$$

for some positive constant C_2.

(iv) For any $0 < s \le t \le T - s$,

$$\begin{aligned}&\big|\mathbb{E}\big[W_t(W_{t+s} - W_{t-s})\big]\big| \\ &\quad \le \begin{cases} C_3 s^{1/2}, & \text{if } t < 2s, \\ C_3 s (t-s)^{-1/2}, & \text{if } t \ge 2s, \end{cases}\end{aligned}$$

and for each $0 < s \le r \le T$,

$$\begin{aligned}&\big|\mathbb{E}\big[W_r(W_{t+s} - W_{t-s})\big]\big| \\ &\quad \le \begin{cases} C_3 s^{1/2}, & \text{if } t < 2s \text{ or } |t-r| < 2s, \\ C_3 s (t-s)^{-1/2} + C_3 s |t-r|^{-1/2}, & \text{if } t \ge 2s \text{ and } |t-r| \ge 2s, \end{cases}\end{aligned}$$

for some positive constant C_3. In addition, for $t > 2s$,

$$\big|\mathbb{E}\big[W_s(W_t - W_{t-s})\big]\big| \le C_3 s^{1/2+\gamma}(t-2s)^{-\gamma}$$

for some $\gamma > 0$.

(v) Consider a uniform partition of $[0, \infty)$ with increment length $1/n$. Define for integers $j, k \ge 0$ and $n \ge 1$,

$$\beta_n(j,k) = \mathbb{E}\big[(W_{(j+1)/n} - W_{j/n})(W_{(k+1)/n} - W_{k/n})\big].$$

Next, define

$$\eta_n^+(t) = \sum_{j,k=1}^{\lfloor nt/2 \rfloor} \beta_n(2j-1, 2k-1)^2 + \beta_n(2j-2, 2k-2)^2;$$

$$\eta_n^-(t) = \sum_{j,k=1}^{\lfloor nt/2 \rfloor} \beta_n(2j-2, 2k-1)^2 + \beta_n(2j-1, 2k-2)^2.$$

Then for each $t \geq 0$,

$$\lim_{n\to\infty} \eta_n^+(t) = \eta^+(t) \quad \text{and} \quad \lim_{n\to\infty} \eta_n^-(t) = \eta^-(t)$$

both exist, where $\eta^+(t)$, $\eta^-(t)$ are nonnegative and nondecreasing functions.

Consider a real-valued function $f \in \mathcal{C}^9(\mathbb{R})$, such that f and all its derivatives up to order 9 have at most exponential growth, that is,

$$\left|f^{(k)}(x)\right| < K_1 \exp\left(K_2|x|^\alpha\right), \qquad x \in \mathbb{R}, \alpha < 2,$$

for $k = 0, \ldots, 9$, and positive constants K_1, K_2. We will refer to this as condition (0).

In the following, the term C represents a generic positive constant, which may change from line to line. The constant C may depend on T and the constants in conditions (0) and (i)–(v), listed above.

The results of the next lemma follow from conditions (i) and (ii).

LEMMA 4.1. *Using the notation described above, for integers* $0 \leq a < b$ *and integers* $r, n \geq 1$, *we have the estimate*

$$\sum_{j,k=a}^{b} |\beta_n(j,k)|^r \leq C(b-a+1)n^{-r/2}.$$

PROOF. Suppose first that $r = 1$. Let $I = \{(j,k) : a \leq j, k \leq b, |k-j| \geq 2, j \wedge k \geq 2\}$ and $J = \{(j,k) : a \leq j, k \leq b, (j,k) \notin I\}$. Consider the decomposition

$$\sum_{j,k=a}^{b} |\beta_n(j,k)| = \sum_{(j,k)\in I} |\beta_n(j,k)| + \sum_{(j,k)\in J} |\beta_n(j,k)|.$$

Then by condition (ii), the first sum is bounded by

$$\sum_{(j,k)\in I} n^{-1/2}|j-k|^{-\alpha} \leq Cn^{-1/2}(b-a+1),$$

and the second sum, using condition (i) and Cauchy–Schwarz, is bounded by $Cn^{-1/2}(b-a+1)$. For the case $r > 1$, condition (i) implies $|\beta_n(j,k)| \leq C_1 n^{-1/2}$ for all j, k. It follows that we can write

$$\begin{aligned}\sum_{j,k=a}^{b} |\beta_n(j,k)|^r &\leq C_1 n^{-(r-1)/2} \sum_{j,k=a}^{b} |\beta_n(j,k)| \\ &\leq C(b-a+1)n^{-r/2}.\end{aligned}$$

□

COROLLARY 4.2. *Using the notation of Lemma 4.1, for each integer* $r \geq 1$,

$$\sum_{j,k=1}^{\lfloor nt/2 \rfloor} \big(|\beta_n(2j-1,2k-1)|^r + |\beta_n(2j-1,2k-2)|^r + |\beta_n(2j-2,2k-1)|^r + |\beta_n(2j-2,2k-2)|^r\big) \leq C\left\lfloor \frac{nt}{2} \right\rfloor n^{-r/2}.$$

PROOF. Note that

$$\sum_{j,k=1}^{\lfloor nt/2 \rfloor} \big(|\beta_n(2j-1,2k-1)|^r + |\beta_n(2j-1,2k-2)|^r + |\beta_n(2j-2,2k-1)|^r + |\beta_n(2j-2,2k-2)|^r\big) = \sum_{j,k=0}^{2\lfloor nt/2 \rfloor - 1} |\beta_n(j,k)|^r.$$

□

Consider a uniform partition of $[0,\infty)$ with increment length $1/n$. The Stratonovich midpoint integral of $f'(W)$ will be defined as the limit in distribution of the sequence (see [10])

$$\Phi_n(t) := \sum_{j=1}^{\lfloor nt/2 \rfloor} f'(W_{(2j-1)/n})(W_{2j/n} - W_{(2j-2)/n}). \tag{8}$$

We introduce the following notation, as used in [5]: $\varepsilon_t := \mathbf{1}_{[0,t]}$; and $\partial_{j/n} := \mathbf{1}_{[j/n,(j+1)/n]}$.

The following is the major result of this section.

THEOREM 4.3. *Let* f *be a real function satisfying condition* (0), *and let* $W = \{W_t, t \geq 0\}$ *be a Gaussian process satisfying conditions* (i) *through* (v). *Then*

$$\big(W_t, \Phi_n(t)\big) \xrightarrow{\mathcal{L}} \left(W_t,\, f(W_t) - f(W_0) - \frac{1}{2}\int_0^t f''(W_s)\,dB_s\right)$$

as $n \to \infty$ *in the Skorohod space* $(\mathbb{D}[0,\infty))^2$, *where* $\eta(t) = \eta^+(t) - \eta^-(t)$ *for the functions defined in condition* (v); *and* $B = \{B_t, t \geq 0\}$ *is scaled Brownian motion, independent of* W, *and with variance* $\mathbb{E}[B_t^2] = 2\eta(t)$.

The rest of this section consists of the proof of Theorem 4.3, and is presented in a series of lemmas. The proofs of Lemmas 4.4, 4.5 and 4.9, which are rather technical, are deferred to Section 6. We begin with an expansion of $f(W_t)$, following

the methodology used in [10]. Consider the telescoping series

$$f(W_t) = f(W_0) + \sum_{j=1}^{\lfloor nt/2 \rfloor} \bigl[f(W_{2j/n}) - f(W_{(2j-2)/n}) \bigr] + f(W_t) - f(W_{(2/n)\lfloor nt/2 \rfloor}),$$

where the sum is zero by convention if $\lfloor \frac{nt}{2} \rfloor = 0$. Using a Taylor series expansion of order 2, we obtain

$$\begin{aligned} \Phi_n(t) &= f(W_t) - f(W_0) \\ &\quad - \frac{1}{2} \sum_{j=1}^{\lfloor nt/2 \rfloor} f''(W_{(2j-1)/n}) \bigl(\Delta W_{2j/n}^2 - \Delta W_{(2j-1)/n}^2 \bigr) \\ &\quad - \sum_{j=1}^{\lfloor nt/2 \rfloor} R_0(W_{2j/n}) + \sum_{j=1}^{\lfloor nt/2 \rfloor} R_1(W_{(2j-2)/n}) \\ &\quad - \bigl(f(W_t) - f(W_{(2/n)\lfloor nt/2 \rfloor}) \bigr), \end{aligned}$$

where R_0, R_1 represent the third-order remainder terms in the Taylor expansion, and can be expressed in integral form as

$$R_0(W_{2j/n}) = \frac{1}{2} \int_{W_{(2j-1)/n}}^{W_{2j/n}} (W_{2j/n} - u)^2 f^{(3)}(u)\, du \tag{9}$$

and

$$R_1(W_{(2j-2)/n}) = -\frac{1}{2} \int_{W_{(2j-2)/n}}^{W_{(2j-1)/n}} (W_{(2j-2)/n} - u)^2 f^{(3)}(u)\, du. \tag{10}$$

By condition (0) we have for any $T > 0$ that

$$\lim_{n \to \infty} \mathbb{E} \sup_{0 \le t \le T} \bigl| f(W_t) - f(W_{(2/n)\lfloor nt/2 \rfloor}) \bigr| = 0,$$

so this term vanishes uniformly on compacts in probability (ucp), and may be neglected. Therefore, it is sufficient to work with the term

$$\Delta_n(t) := f(W_t) - f(W_0) - \tfrac{1}{2} \Psi_n(t) + R_n(t), \tag{11}$$

where

$$\Psi_n(t) = \sum_{j=1}^{\lfloor nt/2 \rfloor} f''(W_{(2j-1)/n}) \bigl(\Delta W_{2j/n}^2 - \Delta W_{(2j-1)/n}^2 \bigr)$$

and

$$R_n(t) = \sum_{j=1}^{\lfloor nt/2 \rfloor} \bigl(R_1(W_{(2j-2)/n}) - R_0(W_{2j/n}) \bigr).$$

We will first decompose the term $\Psi_n(t)$, using a Skorohod integral representation. Using (2) and the second Hermite polynomial, one can write $\Delta W^2(h) = H_2(\Delta W(h)) + 1 = \delta^2(h^{\otimes 2}) + 1$ for any $h \in \mathfrak{H}$ with $\|h\|_{\mathfrak{H}} = 1$. It follows that

$$\Psi_n(t) = \sum_{j=1}^{\lfloor nt/2 \rfloor} f''(W_{(2j-1)/n})\delta^2\big(\partial_{(2j-1)/n}^{\otimes 2} - \partial_{(2j-2)/n}^{\otimes 2}\big).$$

From Lemma 2.1, we have for random variables u, F,

$$F\delta^2(u) = \delta^2(Fu) + 2\delta\big(\langle DF, u\rangle_{\mathfrak{H}}\big) + \big\langle D^2F, u\big\rangle_{\mathfrak{H}^{\otimes 2}},$$

so we can write

$$\begin{aligned}\Psi_n(t) &= \sum_{j=1}^{\lfloor nt/2 \rfloor} \delta^2\big(f''(W_{(2j-1)/n})\big(\partial_{(2j-1)/n}^{\otimes 2} - \partial_{(2j-2)/n}^{\otimes 2}\big)\big) \\ &\quad + \sum_{j=1}^{\lfloor nt/2 \rfloor} 2\delta\big(f^{(3)}(W_{(2j-1)/n})\big\langle \varepsilon_{(2j-1)/n}, \partial_{(2j-1)/n}^{\otimes 2} - \partial_{(2j-2)/n}^{\otimes 2}\big\rangle_{\mathfrak{H}}\big) \\ &\quad + \sum_{j=1}^{\lfloor nt/2 \rfloor} f^{(4)}(W_{(2j-1)/n})\big(\langle \varepsilon_{(2j-1)/n}, \partial_{(2j-1)/n}\rangle_{\mathfrak{H}}^2 \\ &\qquad\qquad - \langle \varepsilon_{(2j-1)/n}, \partial_{(2j-2)/n}\rangle_{\mathfrak{H}}^2\big) \\ &:= F_n(t) + B_n(t) + C_n(t).\end{aligned}$$

Hence, we have $\Delta_n(t) = f(W_t) - f(W_0) - \frac{1}{2}(F_n(t) + B_n(t) + C_n(t)) + R_n(t)$. In the next two lemmas, we show that the terms $B_n(t)$, $C_n(t)$ and $R_n(t)$ converge to zero in probability as $n \to \infty$. The proofs of these lemmas are deferred to Section 6.

LEMMA 4.4. *Let $0 \le r < t \le T$. Using the notation defined above,*

$$\mathbb{E}\big[\big(R_n(t) - R_n(r)\big)^2\big] \le C\left(\left\lfloor \frac{nt}{2} \right\rfloor - \left\lfloor \frac{nr}{2} \right\rfloor\right)n^{-3/2}$$

for some positive constant C, which may depend on T. It follows that for any $0 \le t \le T$, $R_n(t)$ converges to zero in probability as $n \to \infty$.

LEMMA 4.5. *Let $0 \le r < t \le T$. Using the above notation, there exist constants C_B, C_C such that*

$$\mathbb{E}\big[\big(B_n(t) - B_n(r)\big)^2\big] \le C_B\left(\left\lfloor \frac{nt}{2} \right\rfloor - \left\lfloor \frac{nr}{2} \right\rfloor\right)n^{-3/2}$$

and

$$\mathbb{E}\big[\big(C_n(t) - C_n(r)\big)^2\big] \le C_C\left(\left\lfloor \frac{nt}{2} \right\rfloor - \left\lfloor \frac{nr}{2} \right\rfloor\right)n^{-3/2}.$$

It follows that for any $0 \le t \le T$, $B_n(t)$ *and* $C_n(t)$ *converge to zero in probability as* $n \to \infty$.

COROLLARY 4.6. *Let* $Z_n(t) := R_n(t) - \frac{1}{2}B_n(t) - \frac{1}{2}C_n(t)$. *Then given* $0 \le t_1 < t < t_2 \le T$, *there exists a positive constant* C *such that*

$$\mathbb{E}\big[|Z_n(t) - Z_n(t_1)||Z_n(t_2) - Z_n(t)|\big] \le C(t_2 - t_1)^{3/2}.$$

PROOF. By Lemmas 4.4 and 4.5,

$$\begin{aligned}\mathbb{E}\big[\big(Z_n(t_2) - Z_n(t_1)\big)^2\big] &\le 3\mathbb{E}\big[\big(R_n(t_2) - R_n(t_1)\big)^2\big] \\ &\quad + 2\mathbb{E}\big[\big(B_n(t_2) - B_n(t_1)\big)^2\big] \\ &\quad + 2\mathbb{E}\big[\big(C_n(t_2) - C_n(t_1)\big)^2\big] \\ &\le C\left(\left\lfloor \frac{nt_2}{2} \right\rfloor - \left\lfloor \frac{nt_1}{2} \right\rfloor\right)n^{-3/2}.\end{aligned}$$

Then by the Cauchy–Schwarz inequality,

$$\begin{aligned}&\mathbb{E}\big[|Z_n(t) - Z_n(t_1)||Z_n(t_2) - Z_n(t)|\big] \\ &\quad \le \big(\mathbb{E}\big[\big(Z_n(t) - Z_n(t_1)\big)^2\big]\mathbb{E}\big[\big(Z_n(t) - Z_n(t_1)\big)^2\big]\big)^{1/2} \\ &\quad \le C\left(\left\lfloor \frac{nt_2}{2} \right\rfloor - \left\lfloor \frac{nt_1}{2} \right\rfloor\right)^{3/2} n^{-3/2}.\end{aligned}$$

This estimate implies the required bound $C(t_2 - t_1)^{3/2}$; see, for example, [1], page 156. □

Next, we will develop a comparable estimate for differences of the form $F_n(t) - F_n(r)$. In order to prove this estimate, we need a technical lemma which will be used here and also in Section 6.

LEMMA 4.7. *Suppose* a, b *are nonnegative integers such that* $a + b \le 9$. *For fixed* $T > 0$ *and interval* $[t_1, t_2] \subset [0, T]$, *let*

$$g_a = \sum_{\ell=\lfloor nt_1/2 \rfloor + 1}^{\lfloor nt_2/2 \rfloor} f^{(a)}(W_{(2\ell-1)/n})\big(\partial^{\otimes 2}_{(2\ell-1)/n} - \partial^{\otimes 2}_{(2\ell-2)/n}\big).$$

Then we have for $1 \le p < \infty$

$$\mathbb{E}\big[\|D^b g_a\|^p_{\mathfrak{H}^{\otimes 2+b}}\big] \le C\left(\left\lfloor \frac{nt_2}{2} \right\rfloor - \left\lfloor \frac{nt_1}{2} \right\rfloor\right)^{p/2} n^{-p/2}.$$

PROOF. We may assume $t_1 = 0$ with $t_2 \le T$. For each b we can write

$$\begin{aligned}
&\mathbb{E}\big[\big(\|D^b g_a\|^2_{\mathfrak{H}^{\otimes 2+b}}\big)^{p/2}\big] \\
&\quad = \mathbb{E}\Bigg[\Bigg(\sum_{\ell,m=1}^{\lfloor nt_2/2\rfloor} f^{(a+b)}(W_{(2\ell-1)/n}) f^{(a+b)}(W_{(2m-1)/n}) \\
&\qquad\qquad \times \big\langle \varepsilon^{\otimes b}_{(2\ell-1)/n}, \varepsilon^{\otimes b}_{(2m-1)/n}\big\rangle_{\mathfrak{H}^{\otimes b}} \\
&\qquad\qquad \times \big\langle \partial^{\otimes 2}_{(2\ell-1)/n} - \partial^{\otimes 2}_{(2\ell-2)/n}, \partial^{\otimes 2}_{(2m-1)/n} - \partial^{\otimes 2}_{(2m-2)/n}\big\rangle_{\mathfrak{H}^{\otimes 2}}\Bigg)^{p/2}\Bigg] \\
&\quad \le \mathbb{E}\Big[\sup_{0\le s\le t} \big|f^{(a+b)}(W_s)\big|^p\Big]\Big(\sup_{\ell,m} \big|\langle \varepsilon_{(2\ell-1)/n}, \varepsilon_{(2m-1)/n}\rangle_{\mathfrak{H}}\big|^b\Big)^{p/2} \\
&\qquad \times \Bigg(\sum_{\ell,m=1}^{\lfloor nt_2/2\rfloor} \big|\big\langle \partial^{\otimes 2}_{(2\ell-1)/n} - \partial^{\otimes 2}_{(2\ell-2)/n}, \partial^{\otimes 2}_{(2m-1)/n} - \partial^{\otimes 2}_{(2m-2)/n}\big\rangle_{\mathfrak{H}^{\otimes 2}}\big|\Bigg)^{p/2}.
\end{aligned}$$

Recall that condition (0) holds for f and its first 9 derivatives, so the first two terms are bounded. For the last term, note that by Corollary 4.2 with $r = 2$,

$$\begin{aligned}
&\sum_{\ell,m=1}^{\lfloor nt_2/2\rfloor} \big|\big\langle \partial^{\otimes 2}_{(2\ell-1)/n} - \partial^{\otimes 2}_{(2\ell-2)/n}, \partial^{\otimes 2}_{(2m-1)/n} - \partial^{\otimes 2}_{(2m-2)/n}\big\rangle_{\mathfrak{H}^{\otimes 2}}\big| \\
&\quad = \sum_{\ell,m=1}^{\lfloor nt_2/2\rfloor} \big|\beta_n(2\ell-1, 2m-1)^2 - \beta_n(2\ell-1, 2m-2)^2 \\
&\qquad\qquad - \beta_n(2\ell-2, 2m-1)^2 + \beta_n(2\ell-2, 2m-2)^2\big| \\
&\quad \le C\left\lfloor \frac{nt_2}{2}\right\rfloor n^{-1}.
\end{aligned}$$

□

LEMMA 4.8. *For $0 \le s < t \le T$, write*

$$F_n(t) - F_n(s) = \sum_{j=\lfloor ns/2\rfloor+1}^{\lfloor nt/2\rfloor} \delta^2\big(f''(W_{(2j-1)/n})\big(\partial^{\otimes 2}_{(2j-1)/2} - \partial^{\otimes 2}_{(2j-2)/n}\big)\big).$$

Then given $0 \le t_1 < t < t_2 \le T$, there exists a positive constant C such that

$$\mathbb{E}\big[\big|F_n(t) - F_n(t_1)\big|^2 \big|F_n(t_2) - F_n(t)\big|^2\big] \le C(t_2 - t_1)^2. \tag{12}$$

PROOF. First, for each $n \ge 1$, we want to show that there is a C such that

$$\mathbb{E}\big[\big(F_n(t_2) - F_n(t_1)\big)^4\big] \le C\left(\left\lfloor \frac{nt_2}{2}\right\rfloor - \left\lfloor \frac{nt_1}{2}\right\rfloor\right)^2 n^{-2}.$$

By the Meyer inequality (4) there exists a constant $c_{2,4}$ such that

$$\mathbb{E}\big|\big(\delta^2(u_n)\big)^4\big| \le c_{2,4}\|u_n\|^4_{\mathbb{D}^{2,4}(\mathfrak{H}^{\otimes 2})},$$

where in this case

$$u_n = \sum_{j=\lfloor \frac{nt_1}{2}\rfloor+1}^{\lfloor nt_2/2\rfloor} f''(W_{(2j-1)/n})\big(\partial^{\otimes 2}_{(2j-1)/n} - \partial^{\otimes 2}_{(2j-2)/n}\big)$$

and

$$\|u_n\|^4_{\mathbb{D}^{2,4}(\mathfrak{H}^{\otimes 2})} = \mathbb{E}\|u_n\|^4_{\mathfrak{H}^{\otimes 2}} + \mathbb{E}\|Du_n\|^4_{\mathfrak{H}^{\otimes 3}} + \mathbb{E}\|D^2u_n\|^4_{\mathfrak{H}^{\otimes 4}}.$$

From Lemma 4.7 we have $\mathbb{E}\|u_n\|^4_{\mathfrak{H}^{\otimes 2}}, \mathbb{E}\|Du_n\|^4_{\mathfrak{H}^{\otimes 3}}, \mathbb{E}\|D^2u_n\|^4_{\mathfrak{H}^{\otimes 4}} \le C(\lfloor \frac{nt_2}{2}\rfloor - \lfloor \frac{nt_1}{2}\rfloor)^2 n^{-2}$, and so it follows that

$$\mathbb{E}\big[\big(\delta^2(u_n)\big)^4\big] \le C\left(\left\lfloor \frac{nt_2}{2}\right\rfloor - \left\lfloor \frac{nt_1}{2}\right\rfloor\right)^2 n^{-2}.$$

From this result, given $0 \le t_1 < t < t_2$, it follows from the Hölder inequality that

$$\begin{aligned}
&\mathbb{E}\big[\big|F_n(t) - F_n(t_1)\big|^2\big|F_n(t_2) - F_n(t)\big|^2\big] \\
&\quad\le \big(\mathbb{E}\big[\big|F_n(t) - F_n(t_1)\big|^4\big]\big)^{1/2}\big(\mathbb{E}\big[\big|F_n(t_2) - F_n(t)\big|^4\big]\big)^{1/2} \\
&\quad\le C\left(\left\lfloor \frac{nt_2}{2}\right\rfloor - \left\lfloor \frac{nt_1}{2}\right\rfloor\right)^2 n^{-2}.
\end{aligned}$$

As in Corollary 4.6, this implies the required bound $C(t_2 - t_1)^2$. □

By Corollary 4.6 and Lemma 4.8, it follows that $\Delta_n(t) = f(W_t) - f(W_0) - \frac{1}{2}F_n(t) + Z_n(t)$ is tight, since both sequential parts $F_n(t)$, $Z_n(t)$ are tight. Further, we have that $Z_n(t)$ tends to zero in probability, and $F_n(t)$ is in a form suitable for Theorem 3.2. In the next lemma, we show that the conditions of Theorem 3.2 are satisfied by $F_n(t)$ evaluated at a finite set of points.

LEMMA 4.9. *Fix $0 = t_0 < t_1 < t_2 < \cdots < t_d$. Set $F_n^i = F_n(t_i) - F_n(t_{i-1})$ for $i = 1, \ldots, d$, and let $F_n = (F_n^i, \ldots, F_n^d)$. Then under conditions* (0), *and* (i)–(v), *F_n satisfies conditions* (a) *and* (b) *of Theorem* 3.2, *and so given W, F_n converges stably as $n \to \infty$ to a random variable $\xi = (\xi_1, \ldots, \xi_d)$ with distribution $\mathcal{N}(0, \Sigma)$, where Σ is a diagonal $d \times d$ matrix with the following entries*:

$$s_i^2 = \int_{t_{i-1}}^{t_i} f''(W_s)^2\eta(ds),$$

where $\eta(t) = \eta^+(n) - \eta^-(t)$ is as defined in condition (v).

REMARK 4.10. As we will see later, $\eta(t)$ is continuous, nonnegative and nondecreasing.

It follows from the structure of Σ that, given W, F_n converges stably to a d-dimensional vector with conditionally independent components of the form

$$F_\infty^i = \zeta_i \sqrt{\int_{t_{i-1}}^{t_i} f''(W_s)^2 \eta(ds)},$$

where each $\zeta_i \sim \mathcal{N}(0,1)$. Thus, we may conclude that for each i,

$$F_n^i \xrightarrow{\mathcal{L}} \int_{t_{i-1}}^{t_i} f''(W_s)\, dB_s$$

for a scaled Brownian motion $B = \{B_t, t \geq 0\}$ that is independent of W_t, with $\mathbb{E}[B_t^2] = \eta(t)$.

PROOF OF THEOREM 4.3. To prove Theorem 4.3, it is enough to show that for any finite set of times $0 = t_0 < t_1 < t_2 < \cdots < t_d$, we have

$$\begin{aligned}&\big(\Delta_n(t_1), \Delta_n(t_2) - \Delta_n(t_1), \ldots, \Delta_n(t_d) - \Delta_n(t_{d-1})\big)\\ &\quad\xrightarrow{\mathcal{L}} \big(\Delta(t_1), \Delta(t_2) - \Delta(t_1), \ldots, \Delta(t_d) - \Delta(t_{d-1})\big)\end{aligned}$$

as $n \to \infty$; and that $\Delta_n(t)$ satisfies the tightness condition

$$\mathbb{E}\big[\big|\Delta_n(t) - \Delta_n(t_1)\big|^\gamma \big|\Delta_n(t_2) - \Delta_n(t)\big|^\gamma\big] \leq C(t_2 - t_1)^\alpha \tag{13}$$

for $0 \leq t_1 < t < t_2 < \infty$, $\gamma > 0$ and $\alpha > 1$.

For $\Delta_n(t) = f(W_t) - f(W_0) - \frac{1}{2}F_n(t) + Z_n(t)$, we have shown in Lemmas 4.4 and 4.5 that

$$Z_n(t) = R_n(t) - \tfrac{1}{2}\big(B_n(t) + C_n(t)\big) \xrightarrow{\mathcal{P}} 0$$

for each $0 \leq t \leq T$, and hence $Z_n(t_i) - Z_n(t_{i-1}) \xrightarrow{\mathcal{P}} 0$ for each t_i, $1 \leq i \leq d$. By Lemma 4.9, the pair (W, F_n) converges in law to (W, F_∞), where F_∞ is a d-dimensional random vector with conditional Gaussian law and whose covariance matrix is diagonal with entries

$$s_i^2 = \int_{t_{i-1}}^{t_i} f''(W_s)^2 \eta(ds).$$

It follows that, conditioned on W, each component may be expressed as an independent Gaussian random variable, equivalent in law to

$$\int_{t_{i-1}}^{t_i} f''(W_s)\, dB_s,$$

where $B = \{B_t, t \geq 0\}$ is a scaled Brownian motion independent of W with $\mathbb{E}[B_t^2] = \eta(t)$. Finally, tightness follows from Lemma 4.8 and Corollary 4.6. Theorem 4.3 is proved. □

5. Examples.

5.1. *Bifractional Brownian motion.* The bifractional Brownian motion is a generalization of fractional Brownian motion, first introduced by Houdré and Villa [3]. It is defined as a centered Gaussian process $B^{H,K} = \{B^{H,K}(t), t \geq 0\}$, with covariance defined by

$$\mathbb{E}\big[B_t^{H,K} B_s^{H,K}\big] = \frac{1}{2^K}\big(t^{2H} + s^{2H}\big)^K + \frac{1}{2^K}|t-s|^{2HK},$$

where $H \in (0,1)$, $K \in (0,1]$. (Note that the case $K = 1$ corresponds to fractional Brownian motion with Hurst parameter H.) The reader may refer to [4] and its references for further discussion of properties.

In this section, we show that the results of Section 4 are valid for bifractional Brownian motion with parameter values H, K such that $H \leq 1/2$ and $2HK = 1/2$. In particular, this includes the endpoint cases $H = 1/4$, $K = 1$ studied in [6], and $H = 1/2$, $K = 1/2$ studied in [10].

PROPOSITION 5.1. *Let* $\{B_t^{H,K}, t \geq 0\}$ *denote a bifractional Brownian motion. The covariance conditions* (i)–(iv) *of Section* 4 *are satisfied for values of* $0 < H \leq 1/2$ *and* $0 < K \leq 1$ *such that* $2HK = 1/2$.

PROOF. *Condition* (i).

$$\begin{aligned}
&\mathbb{E}\big[\big(B_t^{H,K} - B_{t-s}^{H,K}\big)^2\big] \\
&\quad = t^{2HK} + \frac{2}{2^K}(t-s)^{2HK} - \big[t^{2H} + (t-s)^{2H}\big]^K - \frac{2}{2^K}s^{2HK} \\
&\quad \leq \bigg[\bigg|\sqrt{t} - \frac{1}{2^K}\big(t^{2H} + (t-s)^{2H}\big)^K\bigg| \\
&\qquad + \bigg|\sqrt{t-s} - \frac{1}{2^K}\big(t^{2H} + (t-s)^{2H}\big)^K\bigg| + \frac{1}{2^K}s^{1/2}\bigg] \\
&\quad \leq Cs^{1/2},
\end{aligned}$$

where we used the inequality $a^m - b^m \leq (a-b)^m$ for $a > b > 0$ and $m < 1$.

Condition (ii).

$$\begin{aligned}
&\mathbb{E}\big[\big(B_t^{H,K} - B_{t-s}^{H,K}\big)\big(B_r^{H,K} - B_{r-s}^{H,K}\big)\big] \\
&\quad = \frac{1}{2^K}\big(\big[t^{2H} + r^{2H}\big]^K - \big[t^{2H} + (r-s)^{2H}\big]^K \\
&\qquad - \big[(t-s)^{2H} + r^{2H}\big]^K + \big[(t-s)^{2H} + (r-s)^{2H}\big]^K\big) \\
&\qquad + \frac{1}{2^K}\big(|t-r+s|^{2HK} - 2|t-r|^{2HK} + |t-r-s|^{2HK}\big).
\end{aligned}$$

This can be interpreted as the sum of a position term, $\frac{1}{2^K}\varphi(t,r,s)$, and a distance term, $\frac{1}{2^K}\psi(t-r,s)$, where

$$\varphi(t,r,s) = \left[t^{2H}+r^{2H}\right]^K - \left[t^{2H}+(r-s)^{2H}\right]^K - \left[(t-s)^{2H}+r^{2H}\right]^K + \left[(t-s)^{2H}+(r-s)^{2H}\right]^K$$

and

$$\psi(t-r,s) = |t-r+s|^{2HK} - 2|t-r|^{2HK} + |t-r-s|^{2HK}.$$

We begin with the position term. Note that if $K=1$, then $\varphi(t,r,s)=0$, so we may assume $K<1$ and $H>\frac{1}{4}$. Assume $0<s\le r\le t$, and let $p:=t-r$. By the fundamental theorem of calculus, we can write $\varphi(t,t-p,s)$ as

$$\begin{aligned}
&2HK\int_0^s \left[t^{2H}+(t-p-\xi)^{2H}\right]^{K-1}(t-p-\xi)^{2H-1} \\
&\quad - \left[(t-s)^{2H}+(t-p-\xi)^{2H}\right]^{K-1}(t-p-\xi)^{2H-1}\,d\xi \\
&\quad = \int_0^s\int_0^s 4H^2K(1-K)\left[(t-\eta)^{2H}+(t-p-\xi)^{2H}\right]^{K-2} \\
&\qquad\qquad \times (t-\eta)^{2H-1}(t-p-\xi)^{2H-1}\,d\xi\,d\eta \\
&\quad \le 4H^2K(1-K)s^2\left[(t-r)^{2H}+(r-s)^{2H}\right]^{K-2}(t-r)^{2H-1}(r-s)^{2H-1} \\
&\quad \le Cs^2(t-r)^{2HK-2H-1}(r-s)^{2H-1}.
\end{aligned}$$

This implies condition (ii) for the position term taking $\alpha=\frac{1}{2}+2H>1$ and $\beta=1-2H$.

Next, consider the distance term $\psi(t-r,s)$. Without loss of generality, assume $r<t$. Again using an integral representation, we have

$$\begin{aligned}
\psi(t-r,s) &= |t-r+s|^{2HK} - 2|t-r|^{2HK} + |t-r-s|^{2HK} \\
&= \int_0^s 2HK\left[(t-r+\xi)^{2HK-1} - (t-r-\xi)^{2HK-1}\right]d\xi \\
&= \int_0^s\int_{-\xi}^{\xi} 2HK(2HK-1)[t-r+\eta]^{2HK-2}\,d\eta\,d\xi \\
&\le Cs^2(t-r-s)^{2HK-2} \le Cs^2|t-r|^{-3/2},
\end{aligned}$$

since $|t-r|\ge 2s$ implies $(t-r-s)^{-3/2}\le 2^{3/2}|t-r|^{-3/2}$.

Condition (iii).

$$\begin{aligned}
&\left|\mathbb{E}\left[B_t^{H,K}\left(B_{r+s}^{H,K}-2B_r^{H,K}+B_{r-s}^{H,K}\right)\right]\right| \\
&\quad = \frac{1}{2^K}\Big|\left[t^{2H}+(r+s)^{2H}\right]^K - 2\left[t^{2H}+r^{2H}\right]^K + \left[t^{2H}+(r-s)^{2H}\right]^K \\
&\qquad\qquad - \frac{1}{2^K}\left[|t-r+s|^{2HK} - 2|t-r|^{2HK} + |t-r-s|^{2HK}\right]\Big|.
\end{aligned}$$

Take first the term, $\varphi(t,r,s)$. If $r<2s$, then

$$\left|\left[t^{2H}+(r+s)^{2H}\right]^K-2\left[t^{2H}+r^{2H}\right]^K+\left[t^{2H}+(r-s)^{2H}\right]^K\right|\le Cs^{2HK}=Cs^{1/2},$$

based on the inequality $a^K-b^K\le(a-b)^K$ for $a>b>0$ and $K<1$. Hence, we will assume $r\ge 2s$. If $K=1$, then $H=\frac{1}{4}$, and we have

$$\begin{aligned}|\sqrt{r+s}-2\sqrt{r}+\sqrt{r-s}| &= \left|\int_0^s \frac{1}{2\sqrt{r+x}}\,dx-\int_0^s \frac{1}{2\sqrt{r-s+x}}\,dx\right| \\ &= \frac{1}{4}\int_0^s\int_0^s \frac{1}{(r-s+x+y)^{3/2}}\,dy\,dx \\ &\le \frac{1}{4}s^2(r-s)^{-3/2};\end{aligned}$$

and if $K<1$,

$$\begin{aligned}&|\varphi(t,r,s)| \\ &\quad=\left|\int_0^s 2HK\left[t^{2H}+(r+x)^{2H}\right]^{K-1}(r+x)^{2H-1}\,dx\right. \\ &\qquad\left.-\int_0^s 2HK\left[t^{2H}+(r-s+x)^{2H}\right]^{K-1}(r-s+x)^{2H-1}\,dx\right| \\ &\quad\le\left|\int_0^s\int_0^s 4H^2K(K-1)\right. \\ &\qquad\left.\times\left[t^{2H}+(r-s+x+y)^{2H}\right]^{K-2}(r-s+x+y)^{4H-2}\,dy\,dx\right| \\ &\qquad+\left|\int_0^s\int_0^s 2H(2H-1)K\left[t^{2H}+(r-s+x+y)^{2H}\right]^{K-1}\right. \\ &\qquad\left.\times(r-s+x+y)^{2H-2}\,dy\,dx\right| \\ &\quad\le 4H^2K(1-K)s^2(r-s)^{2HK-2}+2H(1-2H)Ks^2(r-s)^{2HK-2} \\ &\quad\le Cs^2(r-s)^{-3/2}.\end{aligned}$$

This bound for $\varphi(t,r,s)$ also holds in the case $|t-r|<2s$, so the bound of $Cs^{1/2}$ is valid for this case. Next for the second term. Note that if $|t-r|<2s$, then

$$\left|\frac{1}{2^K}\left(|t-r+s|^{2HK}-2|t-r|^{2HK}+|t-r-s|^{2HK}\right)\right|\le 2(3s)^{2HK}\le Cs^{1/2}.$$

If $|t-r|\ge 2s$, then we have

$$\begin{aligned}&|\sqrt{|t-r|+s}-2\sqrt{|t-r|}+\sqrt{|t-r|-s}| \\ &\quad=\left|\int_0^s \frac{1}{2\sqrt{|t-r|+x}}\,dx-\int_0^s \frac{1}{2\sqrt{|t-r|-s+x}}\,dx\right|\end{aligned}$$

$$= \int_0^s \int_0^s \frac{1}{(|t-r|-s+x+y)^{3/2}}\,dy\,dx$$
$$\leq \frac{s^2}{4(|t-r|-s)^{3/2}} \leq \frac{s^2}{2|t-r|^{3/2}},$$

using the inequality $\frac{1}{|t-r|-s} \leq \frac{2}{|t-r|}$ for $|t-r| \geq 2s$. This bound for $\psi(t-r,s)$ holds even in the case $r < 2s$, so the bound of $Cs^{1/2}$ when $r < 2s$ is verified as well.

Condition (iv). For the first part, we have for all $t \geq s$,

$$|\mathbb{E}[B_t^{H,K}(B_{t+s}^{H,K} - B_{t-s}^{H,K})]|$$
$$= \left|\frac{1}{2^K}[t^{2H} + (t+s)^{2H}]^K - \frac{1}{2^K}[t^{2H} + (t-s)^{2H}]^K\right|.$$

This is bounded by $Cs^{1/2}$ if $t < 2s$. On the other hand, if $t \geq 2s$,

$$\left|\frac{1}{2^K}[t^{2H} + (t+s)^{2H}]^K - \frac{1}{2^K}[t^{2H} + (t-s)^{2H}]^K\right|$$
$$= \left|\frac{1}{2^K}\int_{-s}^{s} 2HK[t^{2H} + (t+x)^{2H}]^{K-1}(t+x)^{2H-1}\,dx\right|$$
$$\leq Cs(t-s)^{2HK-1}$$
$$= Cs(t-s)^{-1/2}.$$

For $0 < s \leq r \leq T$ with $t \geq 2s$ and $|t-r| \geq 2s$,

$$|\mathbb{E}[B_r^{H,K}(B_{t+s}^{H,K} - B_{t-s}^{H,K})]|$$
$$\leq \left|\frac{1}{2^K}[r^{2H} + (t+s)^{2H}]^K - \frac{1}{2^K}[r^{2H} + (t-s)^{2H}]^K\right|$$
$$+ \left|\frac{1}{2^K}|r-t+s|^{2HK} - \frac{1}{2^K}|r-t-s|^{2HK}\right|$$
$$\leq Cs(t-s)^{-1/2} + Cs|r-t|^{-1/2}.$$

If $t < 2s$ or $|t-r| < 2s$, then we have an upper bound of $Cs^{1/2}$ by condition (i) and Cauchy–Schwarz.

For the third bound, if $t > 2s$,

$$|\mathbb{E}[B_s^{H,K}(B_t^{H,K} - B_{t-s}^{H,K})]|$$
$$\leq \left|\frac{1}{2^K}[s^{2H} + t^{2H}]^K - \frac{1}{2^K}[s^{2H} + (t-s)^{2H}]^K\right|$$
$$+ \left|\frac{1}{2^K}(t-s)^{2HK} - \frac{1}{2^K}(t-2s)^{2HK}\right|$$

$$\le \frac{2}{2^K}\int_0^s HK\big[s^{2H}+(t-s+x)^{2H}\big]^K(t-s+x)^{2H-1}\,dx$$
$$+\frac{1}{2^{K+1}}\int_0^s (t-2s+x)^{-1/2}\,dx$$
$$\le Cs(t-2s)^{-1/2} = Cs^{1/2+\gamma}(t-2s)^{-\gamma}$$

for $\gamma=\frac{1}{2}$. $\square$

PROPOSITION 5.2. *Let $B^{H,K}$ be a bifractional Brownian motion with parameters $H\le 1/2$ and $HK=1/4$. Then condition* (v) *of Section 4 holds, with the functions $\eta^+(t)=2C_K^+t$ and $\eta^-(t)=2C_K^-t$, where*

$$C_K^+ = \frac{1}{4^K}\left(2+\sum_{m=1}^{\infty}(\sqrt{2m+1}-2\sqrt{2m}+\sqrt{2m-1})^2\right),$$

$$C_K^- = \frac{(2-\sqrt{2})^2}{2^{2K}}+\frac{1}{4^K}\sum_{m=1}^{\infty}(\sqrt{2m+2}-2\sqrt{2m+1}+\sqrt{2m})^2.$$

PROOF. As in Proposition 5.1, we use the decomposition

$$\beta_n(j,k)=\frac{1}{2^K}\varphi\left(\frac{j}{n},\frac{k}{n},\frac{1}{n}\right)+\frac{1}{2^K}\psi\left(\frac{j-k}{n},\frac{1}{n}\right)$$
$$=2^{-K}n^{-1/2}\varphi(j,k,1)+2^{-K}n^{-1/2}\psi(j-k,1).$$

The first task is to show that

$$\lim_{n\to\infty}\sum_{j,k=1}^{\lfloor nt\rfloor} n^{-1}\varphi(j,k,1)^2=0. \tag{14}$$

Proof of (14). We consider two cases, based on the value of H. First, assume $H<\frac{1}{2}$. Then

$$\varphi(j,k,1)=\big[(j+1)^{2H}+(k+1)^{2H}\big]^K-\big[(j+1)^{2H}+k^{2H}\big]^K$$
$$-\big[j^{2H}+(k+1)^{2H}\big]^K+\big[j^{2H}+k^{2H}\big]^K$$
$$=\int_0^1 2HK\big[(j+1)^{2H}+(k+x)^{2H}\big]^{K-1}(k+x)^{2H-1}\,dx$$
$$-\int_0^1 2HK\big[j^{2H}+(k+x)^{2H}\big]^{K-1}(k+x)^{2H-1}\,dx$$
$$=\int_0^1\int_0^1 4H^2K(1-K)\big[(j+y)^{2H}+(k+x)^{2H}\big]^{K-2}$$
$$\times(k+x)^{2H-1}(j+y)^{2H-1}\,dy\,dx$$
$$\le Ck^{2HK-2H-1}j^{2H-1}=Ck^{-1/2-2H}j^{2H-1}.$$

With this bound, it follows that

$$\begin{aligned}\frac{1}{n}\sum_{j,k=1}^{\lfloor nt\rfloor}\varphi(j,k,1)^2 &\le \frac{C}{n}\sum_{j=1}^{\lfloor nt\rfloor} j^{4H-2}\sum_{k=1}^{\infty} k^{-1-4H}\\ &\le \frac{C}{n}\lfloor nt\rfloor^{4H-1}\\ &\le Ctn^{4H-2},\end{aligned}$$

which tends to zero as $n\to\infty$ because $H<\frac{1}{2}$.

Next, we have the case $H=\frac{1}{2}$. Note that this implies $K=\frac{1}{2}$, and we have

$$\begin{aligned}|\varphi(j,k,1)| &= |\sqrt{j+k+2}-2\sqrt{j+k+1}+\sqrt{j+k}|\\ &\le C(j+k)^{-3/2}.\end{aligned}$$

So with this bound,

$$\begin{aligned}\sum_{j,k=1}^{\lfloor nt\rfloor} n^{-1}\varphi(j,k,1)^2 &\le \frac{C}{n}\sum_{j,k=1}^{\lfloor nt\rfloor}(j+k)^{-3}\\ &\le \frac{C}{n}\sum_{j=1}^{\lfloor nt\rfloor}\sum_{m=j+1}^{\infty} m^{-3}\\ &\le \frac{C}{n}\sum_{j=1}^{\lfloor nt\rfloor} j^{-2},\end{aligned}$$

which tends to zero as $n\to\infty$ because j^{-2} is summable. Hence, (14) is proved.

From (14), it follows that to investigate the limit behavior of $\eta_n^+(t)$, $\eta_n^-(t)$, it is enough to consider

$$\frac{1}{n}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\psi(2j-2k,1)^2+\psi(2j-2k,1)^2=\frac{2}{n}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\psi(2j-2k,1)^2$$

and

$$\begin{aligned}&\frac{1}{n}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\psi(2j-2k+1,1)^2+\psi(2j-2k-1,1)^2\\ &\quad=\frac{2}{n}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\psi(2j-2k+1,1)^2;\end{aligned}$$

since the sums of $\psi(2j-2k+1,1)^2$ and $\psi(2j-2k-1,1)^2$ are equal by symmetry. We start with

$$\begin{aligned}
&\frac{1}{n}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\psi(2j-2k,1)^2\\
&\quad=\frac{1}{4^K n}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\bigl(\sqrt{|2j-2k+1|}-2\sqrt{|2j-2k|}+\sqrt{|2j-2k-1|}\bigr)^2\\
&\quad=\frac{1}{4^K n}\sum_{j=1}^{\lfloor nt/2\rfloor}4\\
&\qquad+\frac{2}{4^K n}\sum_{j=1}^{\lfloor nt/2\rfloor}\sum_{k=1}^{j-1}(\sqrt{2j-2k+1}-2\sqrt{2j-2k}+\sqrt{2j-2k-1})^2\\
&\quad=\frac{4\lfloor nt/2\rfloor}{4^K n}+\frac{2}{4^K n}\sum_{j=1}^{\lfloor nt/2\rfloor}\sum_{m=1}^{j-1}(\sqrt{2m+1}-2\sqrt{2m}+\sqrt{2m-1})^2\\
&\quad=\frac{4\lfloor nt/2\rfloor}{4^K n}+\frac{2}{4^K n}\sum_{j=1}^{\lfloor nt/2\rfloor}\sum_{m=1}^{\infty}(\sqrt{2m+1}-2\sqrt{2m}+\sqrt{2m-1})^2\\
&\qquad-\frac{2}{4^K n}\sum_{j=1}^{\lfloor nt/2\rfloor}\sum_{m=j}^{\infty}(\sqrt{2m+1}-2\sqrt{2m}+\sqrt{2m-1})^2,
\end{aligned}$$

where the last term tends to zero since

$$\sum_{m=j}^{\infty}(\sqrt{2m+1}-2\sqrt{2m}+\sqrt{2m-1})^2\le\sum_{m=j}^{\infty}(2m-1)^{-3}\le C(2j-1)^{-2}$$

and

$$\frac{C}{n}\sum_{j=1}^{\lfloor nt/2\rfloor}(2j-1)^{-2}\longrightarrow 0$$

as $n\to\infty$. We therefore conclude that

$$\begin{aligned}
\eta^+(t)&=\lim_{n\to\infty}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\bigl(\beta_n(2j-1,2k-1)^2+\beta_n(2j-2,2k-2)^2\bigr)\\
&=\lim_{n\to\infty}\frac{2}{n}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\psi(2j-2k,1)^2=2C_K^+t,
\end{aligned}$$

where

$$C_K^+ = \frac{1}{4^K}\left(2 + \sum_{m=1}^{\infty}(\sqrt{2m+1} - 2\sqrt{2m} + \sqrt{2m-1})^2\right).$$

For the other term,

$$\begin{aligned}\frac{1}{n}\sum_{j,k=1}^{\lfloor nt/2\rfloor} \psi(2j-2k+1,1)^2 &= \frac{1}{4^K n}\sum_{j=1}^{\lfloor nt/2\rfloor}(2-\sqrt{2})^2 \\ &\quad + \frac{2}{4^K n}\sum_{j=1}^{\lfloor nt/2\rfloor}\sum_{k=1}^{j-1}(\sqrt{2j-2k+2} - 2\sqrt{2j-2k+1} - \sqrt{2j-2k})^2.\end{aligned}$$

Hence, by a similar computation,

$$\eta^-(t) = \lim_{n\to\infty}\sum_{j,k=1}^{\lfloor nt/2\rfloor} \beta_n(2j-1,2k-2)^2 + \beta_n(2j-2,2k-1)^2 = 2C_K^- t,$$

where

$$C_K^- = \frac{(2-\sqrt{2})^2}{2^{2K}} + \frac{1}{4^K}\sum_{m=1}^{\infty}(\sqrt{2m+2} - 2\sqrt{2m+1} + \sqrt{2m})^2. \qquad \square$$

As a concluding remark, it is easy to show that $C_K^+ > C_K^-$, and in general we have $\eta^+(t) \geq \eta^-(t)$.

5.2. *A Gaussian process with differentiable covariance function.* Consider the following class of Gaussian processes. Let $\{F_t, 0 \leq t \leq T\}$ be a mean-zero Gaussian process with covariance defined by

$$\mathbb{E}[F_r F_t] = r\phi\left(\frac{t}{r}\right), \qquad t \geq r, \tag{15}$$

where $\phi : [1,\infty) \to \mathbb{R}$ is twice-differentiable on $(1,\infty)$ and satisfies the following:

(ϕ.1) $\|\phi\|_\infty := \sup_{x\geq 1}|\phi(x)| \leq c_{\phi,0} < \infty$.
(ϕ.2) For $1 < x < \infty$,

$$|\phi'(x)| \leq \frac{c_{\phi,1}}{\sqrt{x-1}}.$$

($\phi.3$) For $1 < x < \infty$,

$$|\phi''(x)| \le c_{\phi,2} x^{-1/2}(x-1)^{-3/2},$$

where $c_{\phi,j}$, $j = 0, 1, 2$ are nonnegative constants.

PROPOSITION 5.3. *The process* $\{F_t, 0 \le t \le T\}$ *described above satisfies conditions* (i)–(iv) *of Section* 4.

PROOF. *Condition* (i). By conditions ($\phi.1$) and ($\phi.2$),

$$\begin{aligned}
\mathbb{E}\big[(F_t - F_{t-s})^2\big] &= t\phi(1) + (t-s)\phi(1) - 2(t-s)\phi\left(1 + \frac{s}{t-s}\right) \\
&\le 2(t-s)\left|\phi\left(1 + \frac{s}{t-s}\right) - \phi(1)\right| + s|\phi(1)| \\
&\le 2(t-s)\left|\int_1^{1+s/(t-s)} \phi'(x)\,dx\right| + s\|\phi\|_\infty \\
&\le 2(t-s)\int_1^{1+s/(t-s)} \frac{c_{\phi,1}}{\sqrt{x-1}}\,dx + s\|\phi\|_\infty \\
&\le Cs^{1/2}\sqrt{t-s} + s\|\phi\|_\infty \\
&\le Cs^{1/2},
\end{aligned}$$

where the constant C depends on $\max\{\sqrt{T}, \|\phi\|_\infty\}$.

Condition (ii). For $2s \le r \le t - 2s$ we have by the mean value theorem

$$\begin{aligned}
&\big|\mathbb{E}[F_t F_r - F_{t-s}F_r - F_t F_{r-s} + F_{t-s}F_{r-s}]\big| \\
&\quad = \left|r\left[\phi\left(\frac{t}{r}\right) - \phi\left(\frac{t-s}{r}\right)\right] - (r-s)\left[\phi\left(\frac{t}{r-s}\right) - \phi\left(\frac{t-s}{r-s}\right)\right]\right| \\
&\quad \le s \sup_{[(t-s)/r,\, t/(r-s)]} |\phi''(x)|\left(\frac{t}{r-s} - \frac{t-s}{r}\right) \\
&\quad \le c_{\phi,2} s\left(\frac{t-s}{r}\right)^{-1/2}\left(\frac{t-s}{r} - 1\right)^{-3/2}\left(\frac{ts}{r(r-s)}\right) \\
&\quad \le \frac{C\sqrt{T}s^2}{(t-r)^{3/2}} = C\sqrt{T}s^2|t-r|^{-3/2}.
\end{aligned}$$

Condition (iii). By symmetry we can assume $r \le t$. Consider the following cases: First, suppose $2s \le r \le t - 2s$. Then we have

$$\begin{aligned}
&\big|\mathbb{E}\big[F_t(F_{r+s} - 2F_r + F_{r-s})\big]\big| \\
&\quad = \left|(r+s)\phi\left(\frac{t}{r+s}\right) - 2r\phi\left(\frac{t}{r}\right) + (r-s)\phi\left(\frac{t}{r-s}\right)\right|
\end{aligned}$$

$$
\begin{aligned}
&= \left|(r+s)\left[\phi\left(\frac{t}{r+s}\right)-\phi\left(\frac{t}{r}\right)\right]-(r-s)\left[\phi\left(\frac{t}{r}\right)-\phi\left(\frac{t}{r-s}\right)\right]\right| \\
&\leq \frac{st}{r}\sup_{[t/(r+s),t/(r-s)]}|\phi''(x)|\left(\frac{t}{r-s}-\frac{t}{r+s}\right) \\
&\leq \frac{2s^2t^2c_{\phi,2}}{r(r-s)(r+s)}\left(\frac{r+s}{t}\right)^{1/2}\left(\frac{r+s}{t-r-s}\right)^{3/2} \\
&\leq \frac{Cs^2t^{3/2}}{r(t-r)^{3/2}}.
\end{aligned}
$$

There are two possibilities, depending on the value of r. If $r \geq \frac{t}{2}$, then $\frac{t}{r} \leq 2$, and we have a bound of

$$
Cs^2\left(\frac{t}{r}\right)\left(\frac{\sqrt{T}}{(t-r)^{3/2}}\right) \leq 2C\sqrt{T}s^2|t-r|^{-3/2}.
$$

On the other hand, if $r < \frac{t}{2}$, then $\frac{t}{t-r} \leq 2$ and $r < t-r$. Then the bound is

$$
Cs^2\left(\frac{t}{t-r}\right)\left(\frac{\sqrt{T}}{r\sqrt{t-r}}\right) \leq 2C\sqrt{T}s^2\left[(r-s)^{-3/2}+|t-r|^{-3/2}\right].
$$

For the case $|t-r| < 2s$, assume that $t = r + ks$ for some $0 \leq k < 2$. Then

$$
\begin{aligned}
&\left|\mathbb{E}\left[F_t(F_{r+s}-2F_r+F_{r-s})\right]\right| \\
&\quad= \left|(t\wedge(r_s))\phi\left(\frac{t\vee(r+s)}{t\wedge(r+s)}\right)-2r\phi\left(\frac{t}{r}\right)+(r-s)\phi\left(\frac{t}{r-s}\right)\right| \\
&\quad= \left|(t\wedge(r_s))\phi\left(\frac{t\vee(r+s)}{t\wedge(r+s)}\right)-(r+s)\phi(1)\right. \\
&\qquad\left.-2r\phi\left(\frac{t}{r}\right)+2r\phi(1)+(r-s)\phi\left(\frac{t}{r-s}\right)-(r-s)\phi(1)\right| \\
&\quad\leq 3(r+s)\left|\phi\left(1+\frac{(k+1)s}{r-s}\right)-\phi(1)\right| \\
&\quad\leq 3(r+s)\left|\int_1^{1+(k+1)s/(r-s)}\phi'(x)\,dx\right| \\
&\quad\leq 3(r+s)\int_1^{1+(k+1)s/(r-s)}\frac{c_{\phi,1}}{\sqrt{x-1}}\,dx \\
&\quad\leq C\sqrt{T}s^{1/2}.
\end{aligned}
$$

For the last case, note that if $t \wedge r < 2s$, then we have an upper bound of $Cs^{1/2}$, since $\mathbb{E}[F_sF_t] \leq s\|\phi\|_\infty$.

Condition (iv). Take first the bound for $\mathbb{E}[F_t(F_{t+s}-F_{t-s})]$. Note that if $t<2s$, then an upper bound of $Cs^{1/2}$ is clear, so we will assume $t\geq 2s$. We have

$$\begin{aligned}
&\bigl|\mathbb{E}[F_tF_{t+s}-F_tF_{t-s}]\bigr|\\
&\quad=\left|t\phi\left(\frac{t+s}{t}\right)-(t-s)\phi\left(\frac{t}{t-s}\right)\right|\\
&\quad\leq (t-s)\sup_{[(t+s)/t,t/(t-s)]}\bigl|\phi'(x)\bigr|\left|\frac{t+s}{t}-\frac{t}{t-s}\right|+s\left|\phi\left(\frac{t+s}{t}\right)\right|\\
&\quad\leq c_{\phi,1}\frac{s^2}{t}\sqrt{\frac{t}{t+s}}\sqrt{\frac{t}{s}}+c_{\phi,0}s\frac{\sqrt{T}}{\sqrt{t-s}}\\
&\quad\leq Cs\sqrt{T}(t-s)^{-1/2}.
\end{aligned}$$

For the case $r\neq t$, first assume $r\leq t-2s$. By condition (ϕ.2),

$$\begin{aligned}
\bigl|\mathbb{E}[F_rF_{t+s}-F_rF_{t-s}]\bigr|&=\left|r\phi\left(\frac{t+s}{r}\right)-r\phi\left(\frac{t-s}{r}\right)\right|\\
&\leq 2s\sup_{[(t-s)/r,(t+s)/r]}\bigl|\phi'(x)\bigr|\\
&\leq\frac{2s\sqrt{r}c_{\phi,1}}{\sqrt{t-r-s}}\leq\frac{C\sqrt{T}s}{\sqrt{t-r}}.
\end{aligned}$$

If $r\geq t+2s$, then

$$\begin{aligned}
\bigl|\mathbb{E}[F_rF_{t+s}-F_rF_{t-s}]\bigr|&=\left|(t+s)\phi\left(\frac{r}{t+s}\right)-(t-s)\phi\left(\frac{r}{t-s}\right)\right|\\
&\leq t\int_0^{2s}\left|\phi'\left(\frac{r}{t-s+x}\right)\right|dx+2s\|\phi\|_\infty\\
&\leq\frac{2stc_{\phi,1}\sqrt{t+s}}{\sqrt{r-t}}+\frac{2sc_{\phi,0}\sqrt{T}}{\sqrt{t-s}}\\
&\leq Cs(r-t)^{-1/2}+Cs(t-s)^{-1/2}.
\end{aligned}$$

For the case $t<2s$ or $|r-t|<2s$, the bound follows from condition (i) and Cauchy–Schwarz.

For the third part of condition (iv), we have for $t>2s$,

$$\begin{aligned}
\mathbb{E}[F_sF_t-F_sF_{t-s}]&=s\phi\left(\frac{t}{s}\right)-s\phi\left(\frac{t-s}{s}\right)\\
&\leq s\sup_{[(t-s)/s,t/s]}\bigl|\phi'(x)\bigr|\left(\frac{t}{s}-\frac{t-s}{s}\right)\leq\frac{c_{\phi,1}s}{\sqrt{(t-s)/s-1}}\\
&\leq Cs^{3/2}(t-2s)^{-1/2}=Cs^{1/2+\gamma}(t-2s)^{-\gamma},
\end{aligned}$$

where $\gamma = \frac{1}{2}$. $\square$

PROPOSITION 5.4. *Suppose $\phi(x)$ satisfies conditions $(\phi.1)$, $(\phi.3)$, and in addition, $\phi(x)$ satisfies*

$$(\phi.4): \quad \phi'(x) = \frac{\kappa}{\sqrt{x-1}} + \frac{\psi(x)}{\sqrt{x}},$$

where $\kappa \in \mathbb{R}$ and $\psi : (1, \infty) \to \mathbb{R}$ is a bounded differentiable function satisfying $|\psi'(1+x)| \leq C_\psi x^{-1/2}$ for some positive constant C_ψ. Then condition (v) *of Section 4 is satisfied, with $\eta^+(t) = C_\beta^+ t^2$, and $\eta^-(t) = C_\beta^- t^2$ for positive constants C_β^+, C_β^-.*

REMARK 5.5. Observe that condition $(\phi.4)$ implies $(\phi.2)$, but not $(\phi.3)$.

PROOF OF PROPOSITION 5.4. We want to show

$$\sum_{j,k=1}^{\lfloor nt/2 \rfloor} \beta_n(2j-1, 2k-1)^2 \longrightarrow C_{\beta,1} t^2; \tag{16}$$

$$\sum_{j,k=1}^{\lfloor nt/2 \rfloor} \beta_n(2j-2, 2k-2)^2 \longrightarrow C_{\beta,2} t^2; \tag{17}$$

$$\sum_{j,k=1}^{\lfloor nt/2 \rfloor} \beta_n(2j-1, 2k-2)^2 \longrightarrow C_{\beta,3} t^2, \tag{18}$$

so that $C_\beta^+ = C_{\beta,1} + C_{\beta,2}$ and $C_\beta^- = 2C_{\beta,3}$. We will show computations for (16), with the others being similar. As in Proposition 5.2,

$$\sum_{j,k=1}^{\lfloor nt/2 \rfloor} \beta_n(2j-1, 2k-1)^2 = \sum_{j=1}^{\lfloor nt/2 \rfloor} \beta_n(2j-1, 2j-1)^2 + 2 \sum_{j=1}^{\lfloor nt/2 \rfloor} \sum_{k=1}^{j-1} \beta_n(2j-1, 2k-1)^2,$$

so it is enough to show

$$\lim_{n\to\infty} \sum_{j=1}^{\lfloor nt/2 \rfloor} \sum_{k=1}^{j-1} \beta_n(2j-1, 2k-1)^2 = C_1 t^2 \tag{19}$$

and

$$\lim_{n\to\infty} \sum_{j=1}^{\lfloor nt/2 \rfloor} \beta_n(2j-1, 2j-1)^2 = C_2 t^2. \tag{20}$$

Proof of (19). For $1 \le k \le j-1$, we have

$$\begin{aligned}\beta_n(2j-1,2k-1) &= \frac{2k}{n}\left(\phi\left(\frac{2j}{2k}\right)-\phi\left(\frac{2j-1}{2k}\right)\right)\\ &\quad -\frac{2k-1}{n}\left(\phi\left(\frac{2j}{2k-1}\right)-\phi\left(\frac{2j-1}{2k-1}\right)\right)\\ &= \frac{2k}{n}\int_{(2j-1)/(2k)}^{2j/(2k)}\phi'(x)\,dx\\ &\quad -\frac{2k-1}{n}\int_{(2j-1)/(2k-1)}^{2j/(2k-1)}\phi'(x)\,dx.\end{aligned}$$

Using the change of index $j = k+m$ and a change of variable for the two integrals, this becomes

$$\begin{aligned}\beta_n(2j-1,2k-1) &= \frac{1}{n}\int_{2m-1}^{2m}\phi'\left(1+\frac{y}{2k}\right)dy\\ &\quad -\frac{1}{n}\int_{2m}^{2m+1}\phi'\left(1+\frac{y}{2k-1}\right)dy.\end{aligned}\tag{21}$$

With the decomposition of $(\phi.4)$, we will address (21) in two parts. Using the first term, we have

$$\begin{aligned}&\frac{\kappa}{n}\int_{2m-1}^{2m}\sqrt{\frac{2k}{y}}\,dy-\frac{\kappa}{n}\int_{2m}^{2m+1}\sqrt{\frac{2k-1}{y}}\,dy\\ &\quad=\frac{2\kappa}{n}\left[\sqrt{2k}\left(\sqrt{2m}-\sqrt{2m-1}\right)-\sqrt{2k-1}\left(\sqrt{2m+1}-\sqrt{2m}\right)\right].\end{aligned}$$

We are interested in the sum

$$\sum_{k=1}^{\lfloor nt/2\rfloor}\sum_{m=1}^{\lfloor nt/2\rfloor-k}\frac{4\kappa^2}{n^2}\left[\sqrt{2k}\left(\sqrt{2m}-\sqrt{2m-1}\right)-\sqrt{2k-1}\left(\sqrt{2m+1}-\sqrt{2m}\right)\right]^2.\tag{22}$$

We can write

$$\begin{aligned}&\sqrt{2k}\left(\sqrt{2m}-\sqrt{2m-1}\right)-\sqrt{2k-1}\left(\sqrt{2m+1}-\sqrt{2m}\right)\\ &\quad=-\sqrt{2k-1}\left(\sqrt{2m+1}-2\sqrt{2m}+\sqrt{2m-1}\right)\\ &\qquad+\left(\sqrt{2k}-\sqrt{2k-1}\right)\left(\sqrt{2m}-\sqrt{2m-1}\right).\end{aligned}$$

Observe that

$$\left[\left(\sqrt{2k}-\sqrt{2k-1}\right)\left(\sqrt{2m}-\sqrt{2m-1}\right)\right]^2\le\frac{1}{(2k-1)(2m-1)}$$

and so

$$\frac{4\kappa^2}{n^2}\sum_{k=1}^{\lfloor nt/2\rfloor}\sum_{m=1}^{\lfloor nt/2\rfloor-k}\frac{1}{(2k-1)(2m-1)}\le\frac{4\kappa^2}{n^2}\left(\sum_{k=1}^{\lfloor nt/2\rfloor}\frac{1}{2k-1}\right)^2\le\frac{C\log(nt)^2}{n^2}.$$

Therefore the contribution of this term is zero, and it follows by Cauchy–Schwarz that the only significant term is

$$\begin{aligned}
&\frac{4\kappa^2}{n^2}\sum_{k=1}^{\lfloor nt/2\rfloor}\sum_{m=1}^{\lfloor nt/2\rfloor-k}(2k-1)(\sqrt{2m+1}-2\sqrt{2m}+\sqrt{2m-1})^2\\
&\quad=4\kappa^2\sum_{m=1}^{\lfloor nt/2\rfloor}(\sqrt{2m+1}-2\sqrt{2m}+\sqrt{2m-1})^2\sum_{k=1}^{\lfloor nt/2\rfloor-m}\frac{2k-1}{n^2}\\
&\quad=4\kappa^2\sum_{m=1}^{\lfloor nt/2\rfloor}(\sqrt{2m+1}-2\sqrt{2m}+\sqrt{2m-1})^2\frac{(\lfloor nt/2\rfloor-m)^2}{n^2},
\end{aligned}$$

which converges as $n\to\infty$ to

$$\kappa^2t^2\sum_{m=1}^{\infty}(\sqrt{2m+1}-2\sqrt{2m}+\sqrt{2m-1})^2.$$

Next, we consider the term $\frac{1}{\sqrt{x}}\psi(x)$. The contribution of this term to (21) is

$$\begin{aligned}
&\frac{1}{n}\int_{2m-1}^{2m}\sqrt{\frac{2k}{2k+y}}\psi\left(1+\frac{y}{2k}\right)dy\\
&\quad-\frac{1}{n}\int_{2m}^{2m+1}\sqrt{\frac{2k-1}{2k-1+y}}\psi\left(1+\frac{y}{2k-1}\right)dy.
\end{aligned}\tag{23}$$

We can bound (23) by

$$\begin{aligned}
&\frac{1}{n}\left|\int_{2m-1}^{2m}\sqrt{\frac{2k}{2k+y}}\psi\left(1+\frac{y}{2k}\right)dy-\int_{2m}^{2m+1}\sqrt{\frac{2k-1}{2k-1+y}}\psi\left(1+\frac{y}{2k-1}\right)dy\right|\\
&\quad\le\frac{1}{n}\Bigg[\sup_{(1,\infty)}|\psi(x)|\frac{\sqrt{2k}-\sqrt{2k-1}}{\sqrt{2k+2m-1}}\\
&\qquad+\sqrt{\frac{2k}{2k+2m-1}}\left|\int_{2m-1}^{2m}\psi\left(1+\frac{y}{2k}\right)dy\right.\\
&\qquad\qquad\left.-\int_{2m}^{2m+1}\psi\left(1+\frac{y}{2k-1}\right)dy\right|\Bigg]\\
&\quad=\frac{1}{n}(A_{k,m}+B_{k,m}).
\end{aligned}$$

Since $|\psi(x)|$ is bounded, we have

$$A_{k,m}\le\frac{C}{\sqrt{2k-1}\sqrt{2k+2m-1}}\le\frac{C}{\sqrt{2k-1}\sqrt{2m-1}}.\tag{24}$$

For $B_{k,m}$ using that $|\psi'(x+1)| \le Cx^{-1/2}$,

$$\begin{aligned}
&\left|\int_{2m-1}^{2m} \psi\left(1+\frac{y}{2k}\right)dy - \int_{2m}^{2m+1} \psi\left(1+\frac{y}{2k-1}\right)dy\right| \\
&\quad = \left|\int_{2m-1}^{2m} \psi\left(1+\frac{u}{2k}\right) - \psi\left(1+\frac{u+1}{2k-1}\right)du\right| \\
&\quad \le \int_{2m-1}^{2m} \left|\int_{(u+1)/(2k-1)}^{u/(2k)} \psi'(1+v)\,dv\right| du \\
&\quad \le C\int_{2m-1}^{2m}\int_{u/(2k)}^{(u+1)/(2k-1)} v^{-1/2}\,dv\,du \\
&\quad \le \frac{C}{\sqrt{2k-1}}(\sqrt{2m+1}-\sqrt{2m}) \\
&\quad \le \frac{C}{\sqrt{2k-1}\sqrt{2m-1}}
\end{aligned}$$

so that

$$B_{k,m} \le \sqrt{\frac{2k}{2k+2m-1}}\cdot\frac{C}{\sqrt{2k-1}\sqrt{2m-1}} \le \frac{C}{\sqrt{2k-1}\sqrt{2m-1}}. \tag{25}$$

Hence, from (24) and (25), we obtain

$$\begin{aligned}
&\sum_{k=1}^{\lfloor nt/2\rfloor}\sum_{m=1}^{\lfloor nt/2\rfloor-k} \frac{C}{n^2}\left(\frac{1}{\sqrt{2k-1}\sqrt{2m-1}}\right)^2 \\
&\qquad \le \frac{C}{n^2}\sum_{k,m=1}^{\lfloor nt/2\rfloor}\frac{1}{(2m-1)(2k-1)} \le \frac{C\log(n)^2}{n^2},
\end{aligned}$$

so the portion represented by (23) tends to zero as $n\to\infty$. Since this term is not significant, it follows by Cauchy–Schwarz that the behavior of

$$\sum_{j=1}^{\lfloor nt/2\rfloor}\sum_{k=1}^{j-1}\beta_n(2j-1,2k-1)^2$$

is dominated by equation (22), and we have result (19), with

$$C_1 = \kappa^2\sum_{m=1}^{\infty}(\sqrt{2m+1}-2\sqrt{2m}+\sqrt{2m-1})^2.$$

Proof of (20). For each j,

$$\begin{aligned}
&\beta_n(2j-1,2j-1)^2 \\
&\quad = \left(\frac{2j}{n}\phi(1) - 2\frac{2j-1}{n}\phi\left(\frac{2j}{2j-1}\right) + \frac{2j-1}{n}\phi(1)\right)^2
\end{aligned}$$

$$= \frac{1}{n^2}\left[\phi(1) + (4j-2)\left(\phi(1) - \phi\left(1 + \frac{1}{2j-1}\right)\right)\right]^2$$
$$= \frac{\phi(1)^2}{n^2} + \frac{4(2j-1)\phi(1)}{n^2}\left(\phi(1) - \phi\left(1 + \frac{1}{2j-1}\right)\right)$$
$$+ \frac{4(2j-1)^2}{n^2}\left(\phi(1) - \phi\left(1 + \frac{1}{2j-1}\right)\right)^2.$$

Since $|\phi(1) - \phi(1 + \frac{1}{2j-1})| \le \frac{c_{\phi,3}}{\sqrt{2j-1}}$ by $(\phi.3)$, we see that

$$\sum_{j=1}^{\lfloor nt/2 \rfloor}\left[\frac{\phi(1)^2}{n^2} + \frac{4(2j-1)\phi(1)}{n^2}\left|\phi(1) - \phi\left(1 + \frac{1}{2j-1}\right)\right|\right] \le Cn^{-1/2},$$

which implies only the last term is significant in the limit. Again we use $(\phi.4)$ to obtain

$$\phi(1) - \phi\left(1 + \frac{1}{2j-1}\right)$$
$$= -\int_1^{1+1/(2j-1)} \phi'(x)\,dx$$
$$= -\kappa \int_1^{1+1/(2j-1)} \frac{1}{\sqrt{x-1}}\,dx - \int_1^{1+1/(2j-1)} \frac{1}{\sqrt{x}}\psi(x)\,dx$$
$$= -\frac{2\kappa}{\sqrt{2j-1}} + O\left(\frac{1}{2j-1}\right);$$

hence

$$\frac{4(2j-1)^2}{n^2}\left(\phi(1) - \phi\left(1 + \frac{1}{2j}\right)\right)^2 = \frac{16\kappa^2(2j-1)^2}{n^2(2j-1)} + O\left(\frac{j^{1/2}}{n^2}\right)$$

and taking $n \to \infty$,

$$\lim_{n\to\infty} \sum_{j=1}^{\lfloor nt/2 \rfloor} \frac{16\kappa^2(2j-1)}{n^2} + O\left(\frac{j^{1/2}}{n^2}\right) = 4\kappa^2 t^2,$$

which gives (20). Thus (16) is proved with $C_{\beta,1} = 4\kappa^2 + 2\kappa^2 \sum_{m=1}^{\infty}(\sqrt{2m+1} - 2\sqrt{2m} + \sqrt{2m-1})^2$.

By similar computations,

$$C_{\beta,2} = 4\kappa^2 + 2\kappa^2 \sum_{m=1}^{\infty}(\sqrt{2m+1} - 2\sqrt{2m} + \sqrt{2m-1})^2$$

and

$$C_{\beta,3} = 4\kappa^2 + 2\kappa^2 \sum_{m=1}^{\infty}(\sqrt{2m+2} - 2\sqrt{2m+1} + \sqrt{2m})^2$$

and so

$$C_\beta^+ = C_{\beta,1} + C_{\beta,2} = 8\kappa^2 + 4\kappa^2 \sum_{m=1}^{\infty} (\sqrt{2m+1} - 2\sqrt{2m} + \sqrt{2m-1})^2,$$

$$C_\beta^- = 2C_{\beta,3} = 8\kappa^2 + 4\kappa^2 \sum_{m=1}^{\infty} (\sqrt{2m+2} - 2\sqrt{2m+1} + \sqrt{2m})^2.$$

Note that $C_\beta^+ \geq C_\beta^-$, and it follows that $\eta(t) = \eta^+(t) - \eta^-(t)$ is nonnegative, and strictly positive if $\kappa \neq 0$. $\square$

For a particular example, we consider a mean-zero Gaussian process $\{F_t, t \geq 0\}$, with covariance given by

$$\mathbb{E}[F_r F_t] = \sqrt{rt} \sin^{-1}\left(\frac{r \wedge t}{\sqrt{rt}}\right).$$

This process was studied by Swanson in a 2007 paper [9], and it appears in the limit of normalized empirical quantiles of a system of independent Brownian motions.

COROLLARY 5.6. *The process* $\{F_t, 0 \leq t \leq T\}$, *with the covariance described above*, *satisfies the conditions of Section* 4, *with* $\eta(t) = (C_\beta^+ - C_\beta^-)t^2$, *where* C_β^+, C_β^- *are as given in Proposition* 5.4, *with* $\kappa^2 = 1/4$.

PROOF. Assume $0 \leq r < t \leq T$. We can write

$$\sqrt{rt} \sin^{-1}\left(\sqrt{\frac{r}{t}}\right) = \sqrt{rt} \tan^{-1}\left(\sqrt{\frac{r}{t-r}}\right) = r\phi\left(\frac{t}{r}\right),$$

where

$$\phi(x) = \begin{cases} \sqrt{x} \tan^{-1}\left(\dfrac{1}{\sqrt{x-1}}\right), & \text{if } x > 1, \\ \dfrac{\pi}{2}, & \text{if } x = 1. \end{cases} \tag{26}$$

Condition (ϕ.1) is clear by continuity and L'Hôpital. Conditions (ϕ.2) and (ϕ.3) are easily verified by differentiation. For (ϕ.4) we can write,

$$\phi'(x) = -\frac{1}{2\sqrt{x-1}} + \frac{1}{2\sqrt{x}}\left(\frac{\sqrt{x}-1}{\sqrt{x-1}} - \tan^{-1}\left(\frac{1}{\sqrt{x-1}}\right)\right)$$

so that $\kappa = -1/2$, and

$$\psi(x) = \frac{1}{2}\left(\frac{\sqrt{x}-1}{\sqrt{x-1}} - \tan^{-1}\left(\frac{1}{\sqrt{x-1}}\right)\right)$$

satisfies (ϕ.4). $\square$

5.3. *Empirical quantiles of independent Brownian motions*. For our last example, we consider a family of processes studied by Swanson in [11]. Similar to [9], this Gaussian family arises from the empirical quantiles of independent Brownian motions, but this case is more general, and does not have a covariance representation (15).

Let $B = \{B(t), t \geq 0\}$ be a Brownian motion with random initial position. Assume $B(0)$ has a density function $f \in \mathcal{C}^\infty(\mathbb{R})$ such that

$$\sup_{x\in\mathbb{R}} \bigl(1 + |x|^m\bigr)\bigl|f^{(n)}(x)\bigr| < \infty$$

for all nonnegative integers m and n. It follows that for $t > 0$, B has density

$$u(x,t) = \int_{\mathbb{R}} f(y)p(t, x-y)\,dy,$$

where $p(t,x) = (2\pi t)^{-1/2}e^{-x^2/(2t)}$. For fixed $\alpha \in (0,1)$, define the α-quantile $q(t)$ by

$$\int_{-\infty}^{q(t)} u(x,t)\,dx = \alpha,$$

where we assume $f(q(0)) > 0$. It is proved in [11] (Theorem 1.4) that there exists a continuous, centered Gaussian process $\{F(t), t \geq 0\}$ with covariance

$$\mathbb{E}[F_r F_t] = \rho(r,t) = \frac{\mathbb{P}(B(r) \leq q(r),\, B(t) \leq q(t)) - \alpha^2}{u(q(r),r)u(q(t),t)}. \tag{27}$$

In [11], the properties of ρ are studied in detail, and we follow the notation and proof methods given in Section 3 of that paper. Swanson defines the following factors:

$$\tilde{\rho}(r,t) = \mathbb{P}\bigl(B(r) \leq q(r),\, B(t) \leq q(t)\bigr) - \alpha^2 \quad \text{and} \quad \theta(t) = \bigl(u\bigl(q(t),t\bigr)\bigr)^{-1}$$

so that $\rho(r,t) = \theta(r)\theta(t)\tilde{\rho}(r,t)$. For fixed $T > 0$ and $0 < r < t \leq T$, the first partial derivatives of $\tilde{\rho}$ are calculated in [11] [see equations (3.4), (3.7)]

$$\begin{aligned}\frac{\partial}{\partial t}\tilde{\rho}(r,t) &= q'(t)\int_{-\infty}^{q(r)} p\bigl(t-r, x-q(t)\bigr)u(x,r)\,dy\,dx \\ &\quad - \frac{1}{2}p\bigl(t-r, q(r)-q(t)\bigr)u\bigl(q(r),r\bigr) \\ &\quad + u\bigl(q(r),r\bigr)q'(r)\int_{-\infty}^{q(t)} p\bigl(t-r, q(r)-y\bigr)\,dy \\ &\quad + \frac{1}{2}\int_{-\infty}^{q(t)}\int_{-\infty}^{q(r)} p(t-r, x-y)\frac{\partial^2}{\partial x^2}u(x,r)\,dx\,dy;\end{aligned} \tag{28}$$

$$\frac{\partial}{\partial r}\tilde{\rho}(r,t) = \frac{1}{2}p\bigl(t-r, q(t)-q(r)\bigr)u\bigl(q(r),r\bigr). \tag{29}$$

LEMMA 5.7. *Let* $0 < T$, *and* $0 < r < t \le T$. *Then there exist constants* C_i, $i = 1, 2, 3, 4$, *such that*:

(a)
$$\left|\frac{\partial}{\partial r}\rho(r,t)\right| \le C_1|t-r|^{-1/2};$$

(b)
$$\left|\frac{\partial^2}{\partial r^2}\rho(r,t)\right| \le C_2|t-r|^{-3/2};$$

(c)
$$\left|\frac{\partial}{\partial t}\rho(r,t)\right| \le C_3|t-r|^{-1/2};$$

(d)
$$\left|\frac{\partial^2}{\partial t^2}\rho(r,t)\right| \le C_4|t-r|^{-3/2}.$$

PROOF. Results (a) and (c) are proved in Theorem 3.1 of [11]. Bounds for (b) and (d) follow by differentiating the expressions for $\partial_r\rho(r,t)$ and $\partial_t\rho(r,t)$ given in the proof of that theorem. □

PROPOSITION 5.8. *Let* $T > 0$, $0 < s < T \wedge 1$ *and* $s \le r \le t \le T$. *Then* $\rho(r,t)$ *satisfies conditions* (i)–(iv) *of Section* 4.

PROOF. Conditions (i) and (ii) are proved in [11] (Corollaries 3.2, 3.5 and Remark 3.6). For condition (iii), there are several cases to consider.

Case 1: $s \le r \le t - 2s$. Using Lemma 5.7(a),
$$\begin{aligned}\left|\mathbb{E}\left[F_t(F_{r+s} - 2F_r + F_{r-s})\right]\right| &\le \left|\rho(r+s,t) - \rho(r,t)\right| + \left|\rho(r,t) - \rho(r-s,t)\right| \\ &\le \int_0^s \left|\frac{\partial}{\partial r}\rho(r+x,t)\right| dx + \int_{-s}^0 \left|\frac{\partial}{\partial r}\rho(r+y,t)\right| dy \\ &\le 2\int_0^s C_1|t-r-x|^{-1/2}\,dx \le Cs^{1/2}.\end{aligned}$$

Case 2: If $|t-r| < 2s$, the computation is similar to case 1, where we use the fact that
$$\int_0^s x^{-1/2}\,dx = 2s^{1/2}.$$

Case 3: For $r, t \ge 2s$ and $|t-r| \ge 2s$, the results follow from Lemma 5.7(b) and (d) for $r < t$ and $r > t$, respectively.

Now to condition (iv). For the first part, we first assume $t \geq 2s$. Then using the above decomposition,

$$\begin{aligned}\mathbb{E}\big[F_t(F_{t+s} - F_{t-s})\big] &= \rho(t, t+s) - \rho(t, t-s) \\ &= \theta(t)\big[\theta(t+s)\tilde{\rho}(t, t+s) - \theta(t-s)\tilde{\rho}(t, t-s)\big] \\ &= \theta(t)\big[\tilde{\rho}(t, t+s)\Delta\theta + \theta(t-s)\Delta\tilde{\rho}\big],\end{aligned}$$

where $\Delta\theta = \theta(t) - \theta(t-s)$ and $\Delta\tilde{\rho} = \tilde{\rho}(t, t+s) - \tilde{\rho}(t, t-s)$. First, note that

$$\big|u'\big(q(t), t\big)\big| = \left|\frac{\partial}{\partial x}u\big(q(t), t\big)q'(t) + \frac{\partial}{\partial t}u\big(q(t), t\big)\right| \leq C,$$

where we used that $q'(t)$ is bounded; see Lemma 1.1 of [11]. Since $u(q(t), t)$ is continuous and strictly positive on $[0, T]$, it follows that $\theta(t)$ is bounded and

$$|\theta'(t)| = \frac{|u'(q(t), t)|}{u^2(q(t), t)} \leq C, \tag{30}$$

hence,

$$|\Delta\theta| \leq \int_{-s}^{s} \big|\theta'(t+x)\big|\,dx \leq Cs.$$

For $\Delta\tilde{\rho}$, we have

$$\begin{aligned}|\Delta\tilde{\rho}| &= \big|\mathbb{P}\big(B(t) \leq q(t), B(t+s) \leq q(t+s)\big) \\ &\quad - \mathbb{P}\big(B(t) \leq q(t), B(t-s) \leq q(t-s)\big)\big| \\ &= \int_{-\infty}^{q(t)} \int_{-\infty}^{q(t+s)} p(s, x-y)u(x, t)\,dy\,dx \\ &\quad - \int_{-\infty}^{q(t-s)} \int_{-\infty}^{q(t)} p(s, x-y)u(x, t-s)\,dy\,dx \\ &\leq \left|\int_{-\infty}^{q(t-s)} \int_{-\infty}^{q(t)} p(s, x-y)u(x, t) - p(s, x-y)u(x, t-s)\,dy\,dx\right| + Cs \\ &\leq \int_{-\infty}^{q(t-s)} \big|u(x, t-s) - u(x, t)\big|\,dx + Cs \\ &\leq \int_{-\infty}^{\infty} \left|\int_{t-s}^{t} \frac{\partial}{\partial r}u(x, r)\,dr\right| dx + Cs \\ &= \frac{1}{2}\int_{-\infty}^{\infty} \left|\int_{t-s}^{t} \frac{\partial^2}{\partial x^2}u(x, r)\,dr\right| dx + Cs \\ &\leq \frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{t-s}^{t} \big|f''(y)\big|p(r, x-y)\,dr\,dy\,dx + Cs \leq Cs.\end{aligned}$$

When $t < 2s$, we write

$$\begin{aligned}\bigl|\mathbb{E}\bigl[F_t(F_{t+s} - F_{t-s})\bigr]\bigr| &\le \bigl|\rho(t, t+s) - \rho(t,t)\bigr| + \bigl|\rho(t,t) - \rho(t-s,t)\bigr| \\ &\le \int_0^s \left|\frac{\partial}{\partial t}\rho(t, t+x)\right| dx + \int_{-s}^0 \left|\frac{\partial}{\partial r}\rho(t+y,t)\right| dy \\ &\le Cs^{1/2},\end{aligned}$$

using Lemma 5.7 and the fact that

$$\int_0^s x^{-1/2}\,dx = 2s^{1/2}.$$

For the second part of condition (iv), we consider

$$\bigl|\mathbb{E}\bigl[F_r(F_{t+s} - F_{t-s})\bigr]\bigr| \quad \text{and} \quad \bigl|\mathbb{E}\bigl[F_s(F_t - F_{t-s})\bigr]\bigr|.$$

When $r < t - s$ (including $r = s$), an upper bound of $Cs|t-r|^{-1/2}$ is proved in [11]; see Corollary 3.4 and Remark 3.6. When $r \ge t + 2s$, or $|t - r| < 2s$, the bounds follow from Lemma 5.7. □

The rest of this section is dedicated to verifying condition (v). We start with two useful estimates. As in Proposition 5.8, suppose $0 < s \le r \le t \le T$. It follows from Lemma 1.1 of [11] that for some positive constant C,

$$\bigl|q(t) - q(r)\bigr| \le C(t-r). \tag{31}$$

Using this estimate and the fact that $e^{-a} - e^{-b} \le b - a$ for $0 \le a \le b$, we obtain

$$\bigl|e^{-(q(t)-q(r))^2/(2(t-r))} - e^{-(q(t)-q(r-s))^2/(2(t-r+s))}\bigr| \le Cs \le 1. \tag{32}$$

Recalling the definitions in condition (v), we can write for $t \in [0, T]$,

$$\begin{aligned}\eta_n^+(t) - \eta_n^-(t) = \sum_{\ell=1}^{2\lfloor nt/2\rfloor} \beta_n(\ell-1,\ell-1)^2 &+ 2\sum_{k\le j-1}\beta_n(2k-1,2j-1)^2 \\ &+ 2\sum_{k\le j-1}\beta_n(2k-2,2j-2)^2 - 2\sum_{k\le j-1}\beta_n(2k-2,2j-1)^2 \\ &- 2\sum_{k\le j-1}\beta_n(2k-1,2j-2)^2.\end{aligned}$$

For the first sum, since $F_{\ell/n} - F_{(\ell-1)/n}$ is Gaussian, we have

$$\beta_n(\ell-1,\ell-1)^2 = \bigl(\mathbb{E}\bigl[(F_{\ell/n} - F_{(\ell-1)/n})^2\bigr]\bigr)^2 = \tfrac{1}{3}\mathbb{E}\bigl[(F_{\ell/n} - F_{(\ell-1)/n})^4\bigr].$$

By Theorem 3.7 of [11],

$$\sum_{\ell=1}^{\lfloor nt\rfloor}(F_{\ell/n} - F_{(\ell-1)/n})^4 \longrightarrow \frac{6}{\pi}\int_0^t \bigl(u\bigl(q(s),s\bigr)\bigr)^{-2}\,ds$$

in L^2 as $n \to \infty$. For the second sum, assume $1 \leq k < j$, and we study the term

$$\begin{aligned}
&\beta_n(2k-1, 2j-1) \\
&\quad = \rho\left(\frac{2k}{n}, \frac{2j}{n}\right) - \rho\left(\frac{2k-1}{n}, \frac{2j}{n}\right) - \rho\left(\frac{2k}{n}, \frac{2j-1}{n}\right) + \rho\left(\frac{2k-1}{n}, \frac{2j-1}{n}\right) \\
&\quad = \theta\left(\frac{2j}{n}\right) \int_{(2k-1)/n}^{2k/n} \left[\theta'(r)\tilde{\rho}\left(r, \frac{2j}{n}\right) + \theta(r)\partial_r \tilde{\rho}\left(r, \frac{2j}{n}\right)\right] dr \\
&\qquad - \theta\left(\frac{2j-1}{n}\right) \int_{(2k-1)/n}^{2k/n} \left[\theta'(r)\tilde{\rho}\left(r, \frac{2j-1}{n}\right) + \theta(r)\partial_r \tilde{\rho}\left(r, \frac{2j-1}{n}\right)\right] dr.
\end{aligned}$$

We can write this as

$$\theta\left(\frac{2j}{n}\right) \int_{(2k-1)/n}^{2k/n} \theta(r)\left(\partial_r \tilde{\rho}\left(r, \frac{2j}{n}\right) - \partial_r \tilde{\rho}\left(r, \frac{2j-1}{n}\right)\right) dr \tag{33}$$

$$+ \left[\theta\left(\frac{2j}{n}\right) - \theta\left(\frac{2j-1}{n}\right)\right] \int_{(2k-1)/n}^{2k/n} \theta(r)\left(\partial_r \tilde{\rho}\left(r, \frac{2j-1}{n}\right)\right) dr \tag{34}$$

$$+ \int_{(2k-1)/n}^{2k/n} \theta'(r)\left[\theta\left(\frac{2j}{n}\right)\tilde{\rho}\left(r, \frac{2j}{n}\right) - \theta\left(\frac{2j-1}{n}\right)\tilde{\rho}\left(r, \frac{2j-1}{n}\right)\right] dr. \tag{35}$$

The first task is to show that components (34) and (35) have a negligible contribution to $\eta(t)$. For (34), it follows from (30) that

$$\left|\theta\left(\frac{2j}{n}\right) - \theta\left(\frac{2j-1}{n}\right)\right| \leq Cn^{-1}, \tag{36}$$

and using (29), we have

$$\begin{aligned}
&\int_{(2k-1)/n}^{2k/n} \theta(r)\partial_r \tilde{\rho}\left(r, \frac{2j-1}{n}\right) dr \\
&\qquad = \int_{(2k-1)/n}^{2k/n} p\left(\frac{2j-1}{n} - r, q\left(\frac{2j-1}{n}\right) - q(r)\right) dr \\
&\qquad \leq Cn^{-1/2}.
\end{aligned}$$

Hence, the contribution of (34) to the sum of $\beta_n(2k-1, 2j-1)^2$ is bounded by $C(n^{-3/2})^2 \cdot n^2 \leq Cn^{-1}$. We can write component (35) as

$$\begin{aligned}
\int_{(2k-1)/n}^{2k/n} \theta'(r)\Bigg[&\theta\left(\frac{2j}{n}\right)\left(\tilde{\rho}\left(r, \frac{2j}{n}\right) - \tilde{\rho}\left(r, \frac{2j-1}{n}\right)\right) \\
&+ \left(\theta\left(\frac{2j}{n}\right) - \theta\left(\frac{2j-1}{n}\right)\right)\tilde{\rho}\left(r, \frac{2j-1}{n}\right)\Bigg] dr.
\end{aligned}$$

Using (29), we have for each $r \in [\frac{2k-1}{n}, \frac{2k}{n}]$,

$$\left|\tilde{\rho}\left(r, \frac{2j}{n}\right) - \tilde{\rho}\left(r, \frac{2j-1}{n}\right)\right| \leq Cn^{-1/2}(2j-2k-1)^{-1/2}.$$

Then, using (36) and (30), we have (35) bounded by

$$C\big[n^{-1/2}(2j-2k-1)^{-1/2}+n^{-1}\big]n^{-1}.$$

Hence, the contribution of (35) to the sum of $\beta_n(2k-1,2j-1)^2$ is bounded by

$$Cn^{-2}\sum_{j=1}^{\lfloor nt/2\rfloor}\sum_{k=1}^{j-1}\big[n^{-1}(2j-2k-1)^{-1}+n^{-2}\big]\le Cn^{-1}.$$

We now turn to component (33). By (29),

$$\theta(r)\frac{\partial}{\partial r}\tilde\rho\Big(r,\frac{2j}{n}\Big)=\frac{1}{2}p\Big(\frac{2j}{n}-r,q\Big(\frac{2j}{n}\Big)-q(r)\Big).$$

To simplify notation, define

$$\psi_n(j,r)=e^{-(q(j/n)-q(r))^2/(2(j/n-r))}.$$

By (31), we have for the interval $I_{2k}=[\frac{2k-1}{n},\frac{2k}{n}]$,

$$\sup_{r\in I_{2k}}\left\{\frac{((q(2j/n)-q(r))^2}{2(2j/n-r)}\right\}\le\frac{C(2j-2k+1)}{n}.$$

This implies that $\inf\{\psi_n(2j,r),r\in I_{2k}\}\ge e^{-C(2j-2k+1)/n}$, and hence when j,k are small compared to n, $|\psi|$ is close to unity. We can write

$$\begin{aligned}&\int_{(2k-1)/n}^{2k/n}\theta(r)\Big(\partial_r\tilde\rho\Big(r,\frac{2j}{n}\Big)-\partial_r\tilde\rho\Big(r,\frac{2j-1}{n}\Big)\Big)\,dr\\&\quad=\frac{1}{2\sqrt{2\pi}}\int_{(2k-1)/n}^{2k/n}\frac{1}{\sqrt{2j/n-r}}-\frac{1}{\sqrt{(2j-1)/n-r}}\,dr\qquad(37)\\&\qquad-\frac{1}{2\sqrt{2\pi}}\int_{(2k-1)/n}^{2k/n}\big(1-\psi_n(2j-1,r)\big)\\&\qquad\qquad\times\Big(\frac{1}{\sqrt{2j/n-r}}-\frac{1}{\sqrt{(2j-1)/n-r}}\Big)\,dr\qquad(38)\\&\qquad+\frac{1}{2\sqrt{2\pi}}\int_{(2k-1)/n}^{2k/n}\frac{\psi_n(2j,r)-\psi_n(2j-1,r)}{\sqrt{2j/n-r}}\,dr.\qquad(39)\end{aligned}$$

For component (38), by the above estimate for $\inf\{\psi_n(2j,r),r\in I_{2k}\}$, we have

$$\sup_{r\in I_{2k}}\big|1-\psi(2j,r)\big|\le Cn^{-1}(2j-2k+1)\le 1,$$

hence (38) is bounded by

$$Cn^{-3/2}(2j-2k+1)(\sqrt{2j-2k+1}-2\sqrt{2j-2k}+\sqrt{2j-2k-1}).$$

Given $\varepsilon > 0$, we can find an $M > 1$ such that

$$\sum_{m=M}^{\infty} (\sqrt{2m+1} - 2\sqrt{2m} + \sqrt{2m-1})^2 < \varepsilon.$$

The contribution of (38) to the sum of $\beta_n(2k-1, 2j-1)^2$ is thus bounded by

$$\begin{aligned}
&(2\pi n)^{-1} \sum_{j=1}^{\lfloor nt/2 \rfloor} \theta^2\Big(\frac{2j}{n}\Big) \sum_{k=1}^{j-1} \sup_{r \in I_{2k}} \big(1 - \psi_n(2j, r)\big)^2 \\
&\qquad\qquad \times (\sqrt{2j-2k+1} - 2\sqrt{2j-2k} + \sqrt{2j-2k-1})^2 \\
&\leq Cn^{-1} \sum_{j=1}^{\lfloor nt/2 \rfloor} \sum_{k=1}^{j-M-1} (\sqrt{2j-2k+1} - 2\sqrt{2j-2k} + \sqrt{2j-2k-1})^2 \\
&\quad + Cn^{-1} \sum_{j=1}^{\lfloor nt/2 \rfloor} \sum_{k=j-M}^{j-1} Cn^{-1}(2j-2k+1) \\
&\qquad\qquad \times (\sqrt{2j-2k+1} - 2\sqrt{2j-2k} + \sqrt{2j-2k-1})^2 \\
&\leq Cn^{-1} \sum_{j=1}^{\lfloor nt/2 \rfloor} \varepsilon + Cn^{-1} \sum_{j=1}^{\lfloor nt/2 \rfloor} \frac{M^2}{n^2},
\end{aligned}$$

which is less than $C\varepsilon$ as $n \to \infty$, since $\theta(t)$ is bounded.

For (39), by we have $\sup\{|\psi_n(2j, r) - \psi_n(2j-1, r)|, r \in I_{2k}\} \leq Cn^{-1}$, and hence (39) is bounded by $Cn^{-3/2}(2j-2k-1)^{-1/2}$. Therefore the contribution of the term including (39) to the sum of $\beta_n(2k-1, 2j-1)^2$ is bounded by

$$Cn^{-3} \sum_{j=1}^{\lfloor nt/2 \rfloor} \sum_{k=1}^{j-1} (2j-2k-1)^{-1} \leq Cn^{-2} \log(nt),$$

because $\theta(t)$ is bounded.

It follows that the sum of $\beta_n(2k-1, 2j-1)^2$ is dominated by (33), and the significant term in (33) is given by (37). Hence, it is enough to consider

$$\frac{2}{n\pi} \sum_{j \leq k-1} \theta^2\Big(\frac{2j}{n}\Big)(\sqrt{2j-2k+1} - 2\sqrt{2j-2k} + \sqrt{2j-2k-1})^2.$$

Using the change of index $j = k + m$, this is

$$\frac{2}{n\pi} \sum_{j=1}^{\lfloor nt/2 \rfloor} \theta^2\Big(\frac{2j}{n}\Big) \sum_{m=1}^{j-1} (\sqrt{2m+1} - 2\sqrt{2m} + \sqrt{2m-1})^2.$$

Taking $n \to \infty$, this behaves like

$$\frac{a}{\pi}\int_0^t \theta^2(s)\,ds,$$

where

$$a = \sum_{m=1}^{\infty} (\sqrt{2m+1} - 2\sqrt{2m} + \sqrt{2m-1})^2.$$

By similar computation,

$$\sum_{k\le j-1} \beta_n(2k-2, 2j-2)^2 \longrightarrow \frac{a}{\pi}\int_0^t \theta^2(s)\,ds,$$

$$\sum_{k\le j-1} \beta_n(2k-2, 2j-1)^2 \longrightarrow \frac{b_1}{\pi}\int_0^t \theta^2(s)\,ds$$

and

$$\sum_{k\le j-1} \beta_n(2k-1, 2j-2)^2 \longrightarrow \frac{b_2}{\pi}\int_0^t \theta^2(s)\,ds,$$

where

$$b_1 = \sum_{m=1}^{\infty} (\sqrt{2m+2} - 2\sqrt{2m+1} + \sqrt{2m})^2,$$

$$b_2 = \sum_{m=1}^{\infty} (\sqrt{2m} - 2\sqrt{2m-1} + \sqrt{2m-2})^2.$$

We have proved the following result:

PROPOSITION 5.9. *Under the above assumptions, $\rho(r,t)$ satisfies condition* (v) *of Section* 4, *where*

$$\eta(t) = \frac{2 + 4a - 2b_1 - 2b_2}{\pi}\int_0^t \big(u(q(s),s)\big)^{-2}\,ds.$$

The coefficient $2 + 4a - 2b_1 - 2b_2$ is approximately 1.3437, while $u(q(t),t)$ depends on f and α.

6. Proof of the technical lemmas. We begin with two technical lemmas. The first is a version of Corollary 4.2 with disjoint intervals.

LEMMA 6.1. *For $0 \le t_0 < t_1 \le t_2 < t_3 \le T$,*

$$\lim_{n\to\infty} \sum_{j=\lfloor nt_0/2\rfloor+1}^{\lfloor nt_1/2\rfloor} \sum_{k=\lfloor nt_2/2\rfloor+1}^{\lfloor nt_3/2\rfloor} \big|\langle \partial^{\otimes 2}_{(2j-1)/n} - \partial^{\otimes 2}_{(2j-2)/n}, \partial^{\otimes 2}_{(2k-1)/n} - \partial^{\otimes 2}_{(2k-2)/n}\rangle_{\mathfrak{H}^{\otimes 2}}\big| = 0.$$

PROOF. We may assume $t_0 = 0$ and $t_1 = t_2$. Observe that

$$\begin{aligned}&\langle \partial^{\otimes 2}_{(2j-1)/n} - \partial^{\otimes 2}_{(2j-2)/n}, \partial^{\otimes 2}_{(2k-1)/n} - \partial^{\otimes 2}_{(2k-2)/n} \rangle_{\mathfrak{H}^{\otimes 2}} \\ &\quad = \beta_n(2j-1, 2k-1)^2 - \beta_n(2j-1, 2k-2)^2 - \beta_n(2j-2, 2k-1)^2 \\ &\qquad + \beta_n(2j-2, 2k-2)^2.\end{aligned}$$

Therefore, it is enough to show that

$$\sum_{j=0}^{\lfloor nt_2 \rfloor} \sum_{k=\lfloor nt_2 \rfloor + 1}^{\lfloor nt_3 \rfloor} \beta_n(j,k)^2 \le Cn^{-\varepsilon} \tag{40}$$

for some $\varepsilon > 0$. We can decompose the sum in (40) as

$$\sum_{k=\lfloor nt_2 \rfloor + 1}^{\lfloor nt_3 \rfloor} \beta_n(0,k)^2 + \sum_{k=\lfloor nt_2 \rfloor + 1}^{\lfloor nt_3 \rfloor} \beta_n\big(\lfloor nt_2 \rfloor, k\big)^2 + \sum_{j=1}^{\lfloor nt_2 \rfloor - 1} \sum_{k=\lfloor nt_2 \rfloor + 1}^{\lfloor nt_3 \rfloor} \beta_n(j,k)^2.$$

By condition (iv), for some $\gamma > 0$ we have

$$\begin{aligned}\sum_{k=\lfloor nt_2 \rfloor + 1}^{\lfloor nt_3 \rfloor} \beta_n(0,k)^2 &\le \sup_{1 \le j \le \lfloor nt_3 \rfloor} \big|\beta_n(0,k)\big| \sum_{k=\lfloor nt_2 \rfloor + 1}^{\lfloor nt_3 \rfloor} \big|\beta_n(0,k)\big| \\ &\le Cn^{-1} \sum_{k=\lfloor nt_2 \rfloor + 2}^{\lfloor nt_3 \rfloor} (k-1)^{-\gamma} + Cn^{-1} \le Cn^{-\gamma}.\end{aligned}$$

By condition (ii), for some $1 < \alpha \le \frac{3}{2}$,

$$\begin{aligned}\sum_{k=\lfloor nt_2 \rfloor + 1}^{\lfloor nt_3 \rfloor} \beta_n\big(\lfloor nt_2 \rfloor, k\big)^2 &\le \beta_n\big(\lfloor nt_2 \rfloor, \lfloor nt_2 \rfloor + 1\big)^2 + Cn^{-1} \sum_{k=\lfloor nt_2 \rfloor + 2}^{\lfloor nt_3 \rfloor} \beta_n\big(\lfloor nt_2 \rfloor, k\big) \\ &\le Cn^{-1} + Cn^{-1} \sum_{k=\lfloor nt_2 \rfloor + 1}^{\lfloor nt_3 \rfloor} \big(k - \lfloor nt_2 \rfloor\big)^{-\alpha} \le Cn^{-1}\end{aligned}$$

and again by condition (ii), for $\beta = \frac{3}{2} - \alpha$,

$$\begin{aligned}&\sum_{j=1}^{\lfloor nt_2 \rfloor - 1} \sum_{k=\lfloor nt_2 \rfloor + 1}^{\lfloor nt_3 \rfloor} \beta_n(j,k)^2 \\ &\quad \le Cn^{-1} \sum_{j=1}^{\lfloor nt_2 \rfloor - 1} \sum_{k=\lfloor nt_2 \rfloor + 1}^{\lfloor nt_3 \rfloor} \big[\big(k - \lfloor nt_2 \rfloor\big)^{-\alpha} j^{-\beta} + (k-j)^{-3/2}\big] \\ &\quad \le Cn^{-1} \Bigg(\sum_{k=1}^{\lfloor nt_3 \rfloor} k^{-\alpha} \Bigg) \Bigg(\sum_{j=1}^{\lfloor nt_2 \rfloor} j^{-\beta} \Bigg) + Cn^{-1} \sum_{j=1}^{\lfloor nt_2 \rfloor} \big(\lfloor nt_2 \rfloor - j\big)^{-1/2} \\ &\quad \le Cn^{-\beta} + Cn^{-1/2};\end{aligned}$$

hence the sum is bounded by $Cn^{-\varepsilon}$ for $\varepsilon = \min\{\beta, \gamma, \frac{1}{2}\}$. $\square$

LEMMA 6.2. *For $0 \le t \le T$ and integer $j \ge 1$,*

$$\left|\langle \varepsilon_t, \partial_{j/n}\rangle_{\mathfrak{H}}\right| \le Cn^{-1/2}$$

for a positive constant C which depends on T.

PROOF. By conditions (i) and (ii), we have for $j \ge 1$ and $t > 0$,

$$\begin{aligned}\left|\langle \varepsilon_t, \partial_{j/n}\rangle_{\mathfrak{H}}\right| &\le \sum_{k=0}^{\lfloor nt\rfloor - 1} \left|\langle \partial_{k/n}, \partial_{j/n}\rangle_{\mathfrak{H}}\right| + \left|\langle \varepsilon_t - \varepsilon_{\lfloor nt\rfloor}, \partial_{j/n}\rangle_{\mathfrak{H}}\right| \\ &\le C\sum_{k=0}^{\infty} n^{-1/2}\left(|j-k|^{-\alpha} \wedge 1\right) + O\left(n^{-1/2}\right) \le Cn^{-1/2}.\end{aligned} \tag{41}$$

$\square$

6.1. *Proof of Lemma 4.4.* By the Lagrange theorem for the Taylor expansion remainder, the terms $R_0(W_{2j/n})$, $R_1(W_{(2j-2)/n})$ can be expressed in integral form,

$$R_0(W_{2j/n}) = \frac{1}{2}\int_{W_{(2j-1)/n}}^{W_{2j/n}} (W_{2j/n} - u)^2 f^{(3)}(u)\, du$$

and

$$R_1(W_{(2j-2)/n}) = -\frac{1}{2}\int_{W_{(2j-2)/n}}^{W_{(2j-1)/n}} (W_{(2j-2)/n} - u)^2 f^{(3)}(u)\, du.$$

After a change of variables, we obtain

$$\begin{aligned}&R_0(W_{2j/n}) \\ &\quad = \frac{1}{2}(W_{2j/n} - W_{(2j-1)/n})^3 \int_0^1 v^2 f^{(3)}\left(vW_{(2j-1)/n} + (1-v)W_{2j/n}\right) dv\end{aligned}$$

and

$$\begin{aligned}R_1(W_{(2j-2)/n}) &= \frac{1}{2}(W_{(2j-2)/n} - W_{(2j-1)/n})^3 \\ &\quad \times \int_0^1 v^2 f^{(3)}\left(vW_{(2j-1)/n} + (1-v)W_{(2j-2)/n}\right) dv.\end{aligned}$$

Define

$$G_0(2j) = \frac{1}{2}\int_0^1 v^2 f^{(3)}\left(vW_{(2j-1)/n} + (1-v)W_{2j/n}\right) dv$$

and

$$G_1(2j-2) = \frac{1}{2}\int_0^1 v^2 f^{(3)}\big(vW_{(2j-1)/n} + (1-v)W_{(2j-2)/n}\big)\,dv.$$

We may assume $r = 0$. Define $\Delta W_{\ell/n} = W_{(\ell+1)/n} - W_{\ell/n}$. We want to show that

$$\begin{aligned}\mathbb{E}\Bigg[\Bigg(\sum_{j=1}^{\lfloor nt/2\rfloor}\{G_0(2j)\Delta W_{(2j-1)/n}^3 + G_1(2j-2)\Delta W_{(2j-2)/n}^3\}\Bigg)^2\Bigg] \\ \le C\left\lfloor\frac{nt}{2}\right\rfloor n^{-3/2}.\end{aligned} \tag{42}$$

This part of the proof was inspired by a computation in [6]; see Lemma 4.2. Consider the Hermite polynomial identity $x^3 = H_3(x) + 3H_1(x)$. We use the map $\delta^q(h^{\otimes q}) = H_q(W(h))$ [see (2) in Section 2], for $h \in \mathfrak{H}$ with $\|h\|_{\mathfrak{H}} = 1$. For each j, let $w_j := \|\Delta W_{j/n}\|_{\mathfrak{H}}$, and note that condition (i) implies $w_j \le Cn^{-1/4}$ for all j. Then

$$\begin{aligned}\frac{\Delta W_{j/n}^3}{w_j^3} &= H_3\left(\frac{\Delta W_{j/n}}{w_j}\right) + 3H_1\left(\frac{\Delta W_{j/n}}{w_j}\right) \\ &= \delta^3\left(\frac{\partial_{j/n}^{\otimes 3}}{w_j^3}\right) + 3\delta\left(\frac{\partial_{j/n}}{w_j}\right)\end{aligned}$$

so that

$$\Delta W_{j/n}^3 = \delta^3\big(\partial_{j/n}^{\otimes 3}\big) + 3w_j^2\delta(\partial_{j/n}).$$

It follows that we can write

$$\begin{aligned}&G_0(2j)\Delta W_{(2j-1)/n}^3 - G_1(2j-2)\Delta W_{(2j-2)/n}^3 \\ &\quad= G_0(2j)\delta^3\big(\partial_{(2j-1)/n}^{\otimes 3}\big) - G_1(2j-2)\delta^3\big(\partial_{(2j-2)/n}^{\otimes 3}\big) \\ &\qquad+ 3w_{2j}^2 G_0(2j)\delta(\partial_{(2j-1)/n}) - 3w_{2j-1}^2 G_1(2j-2)\delta(\partial_{(2j-2)/n}).\end{aligned}$$

It is enough to verify the individual inequalities

$$\mathbb{E}\left[\left|\sum_{j=1}^{\lfloor nt/2\rfloor} G_0(2j)\delta^3\big(\partial_{(2j-1)/n}^{\otimes 3}\big)\right|^2\right] \le C\left\lfloor\frac{nt}{2}\right\rfloor n^{-3/2}, \tag{43}$$

$$\mathbb{E}\left[\left|\sum_{j=1}^{\lfloor nt/2\rfloor} G_1(2j-2)\delta^3\big(\partial_{(2j-2)/n}^{\otimes 3}\big)\right|^2\right] \le C\left\lfloor\frac{nt}{2}\right\rfloor n^{-3/2}, \tag{44}$$

$$\mathbb{E}\left[\left|\sum_{j=1}^{\lfloor nt/2\rfloor} w_{2j}^2 G_0(2j)\delta(\partial_{(2j-1)/n})\right|^2\right] \le C\left\lfloor\frac{nt}{2}\right\rfloor n^{-3/2} \tag{45}$$

and

$$\mathbb{E}\Bigg[\Bigg|\sum_{j=1}^{\lfloor nt/2\rfloor} w_{2j-1}^2 G_1(2j-2)\delta\big(\partial_{(2j-2)/n}\big)\Bigg|^2\Bigg] \le C\Big\lfloor \frac{nt}{2}\Big\rfloor n^{-3/2}. \tag{46}$$

We will show (43) and (45), with (44) and (46) being essentially similar.

Proof of (43). Using (3) and the duality property,

$$\begin{aligned}
&\mathbb{E}\Bigg[\Bigg(\sum_{j=1}^{\lfloor nt/2\rfloor} G_0(2j)\delta^3\big(\partial_{(2j-1)/n}^{\otimes 3}\big)\Bigg)^2\Bigg] \\
&\quad= \mathbb{E}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\Bigg[G_0(2j)G_0(2k) \\
&\qquad\qquad\times\Bigg(\sum_{r=0}^{3}\delta^{6-2r}\big(\partial_{(2j-1)/n}^{\otimes 3-r}\otimes\partial_{(2k-1)/n}^{\otimes 3-r}\big)\langle\partial_{(2j-1)/n},\partial_{(2k-1)/n}\rangle_{\mathfrak{H}}^{r}\Bigg)\Bigg] \\
&\quad\le \sum_{j,k=1}^{\lfloor nt/2\rfloor}\sum_{r=0}^{3}\big|\langle\partial_{(2j-1)/n},\partial_{(2k-1)/n}\rangle_{\mathfrak{H}}^{r}\big| \\
&\qquad\qquad\times\mathbb{E}\big[\big|\big\langle D^{6-2r}\big(G_0(2j)G_0(2k)\big),\partial_{(2j-1)/n}^{\otimes 3-r}\otimes\partial_{(2k-1)/n}^{\otimes 3-r}\big\rangle_{\mathfrak{H}^{\otimes 6-2r}}\big|\big].
\end{aligned}$$

For integers $r\ge 0$, we have

$$\begin{aligned}
D^r G_0(2j) &= D^r\int_0^1 \frac{1}{2}v^2 f^{(3)}\big(vW_{(2j-1)/n}+(1-v)W_{2j/n}\big)\,dv \\
&= \frac{1}{2}\int_0^1 v^2 f^{(3+r)}\big(vW_{(2j-1)/n}+(1-v)W_{2j/n}\big) \\
&\qquad\times\big(v\varepsilon_{(2j-1)/n}^{\otimes r}+(1-v)\varepsilon_{2j/n}^{\otimes r}\big)\,dv.
\end{aligned} \tag{47}$$

By product rule and (47) we have

$$\begin{aligned}
&\mathbb{E}\big[\big|\big\langle D^{6-2r}\big(G_0(2j)G_0(2k)\big),\partial_{(2j-1)/n}^{\otimes 3-r}\otimes\partial_{(2k-1)/n}^{\otimes 3-r}\big\rangle_{\mathfrak{H}^{\otimes 6-2r}}\big|\big] \\
&\quad\le C\sum_{a+b=6-2r}\mathbb{E}\Big[\sup_{0\le v,w\le 1}\big|f^{(a)}\big(vW_{(2j-1)/n}+(1-v)W_{(2j-2)/n}\big) \\
&\qquad\qquad\times f^{(b)}\big(wW_{(2k-1)/n}+(1-w)W_{(2k-2)/n}\big)\big|\Big] \\
&\qquad\times\int_0^1\int_0^1\big|\big\langle\big(v\varepsilon_{(2j-1)/n}^{\otimes a}+(1-v)\varepsilon_{2j/n}^{\otimes a}\big) \\
&\qquad\qquad\otimes\big(w\varepsilon_{(2k-1)/n}^{\otimes b}+(1-w)\varepsilon_{2k/n}^{\otimes b}\big), \\
&\qquad\qquad\partial_{(2j-1)/n}^{\otimes 3-r}\otimes\partial_{(2k-1)/n}^{\otimes 3-r}\big\rangle_{\mathfrak{H}^{\otimes 6-2r}}\big|\,dv\,dw.
\end{aligned} \tag{48}$$

Notice that by condition (0), $\mathbb{E}[\sup|f^{(3+r)}(\xi)|^p] < \infty$, where the supremum is taken over the random variables $\{\xi = vW_{s_1} + (1-v)W_{s_2}, 0 \le v \le 1, 0 \le s_1, s_2 \le T\}$. From Lemma 6.2, for integers a and b with $a + b = 6 - 2r$, we have the following estimate:

$$\begin{aligned}\int_0^1 \int_0^1 \big|\big\langle \big(v\varepsilon_{(2j-1)/n}^{\otimes a} + (1-v)\varepsilon_{2j/n}^{\otimes a}\big) \\ \otimes \big(w\varepsilon_{(2k-1)/n}^{\otimes b} + (1-w)\varepsilon_{2k/n}^{\otimes b}\big), \\ \partial_{(2j-1)/n}^{\otimes 3-r} \otimes \partial_{(2k-1)/n}^{\otimes 3-r}\big\rangle_{\mathfrak{H}^{\otimes 6-2r}}\big| \, dv\, dw \\ \le Cn^{-(3-r)}.\end{aligned} \tag{49}$$

It follows that if $r \neq 0$, then by Lemma 4.1, equation (48) and equation (49),

$$\begin{aligned} & C \sum_{j,k=1}^{\lfloor nt/2 \rfloor} \big|\langle \partial_{(2j-1)/n}, \partial_{(2k-1)/n}\rangle_{\mathfrak{H}}^r\big| \\ & \qquad \times \mathbb{E}\big[\big|\big\langle D^{6-r}\big(G_0(2j)G_0(2k)\big), \partial_{(2j-1)/n}^{\otimes 3-r} \otimes \partial_{(2k-1)/n}^{\otimes 3-r}\big\rangle_{\mathfrak{H}^{\otimes 6-2r}}\big|\big] \\ & \le Cn^{r-3} \sum_{j,k=1}^{\lfloor nt/2 \rfloor} \big|\langle \partial_{(2j-1)/n}, \partial_{(2k-1)/n}\rangle_{\mathfrak{H}}^r\big| \\ & \le C\left\lfloor \frac{nt}{2} \right\rfloor n^{r/2-3}, \end{aligned}$$

which satisfies (42) because $\frac{r}{2} - 3 \le -\frac{3}{2}$. On the other hand, if $r = 0$, then

$$\sum_{j,k=1}^{\lfloor nt/2 \rfloor} Cn^{-3} \le C\left\lfloor \frac{nt}{2} \right\rfloor n^{-2},$$

and we are done with (43).

Proof of (45). Proceeding along the same lines as above,

$$\begin{aligned} & \mathbb{E}\left[\left(\sum_{j=1}^{\lfloor nt/2 \rfloor} w_{2j}^2 G_0(2j)\delta(\partial_{(2j-1)/n})\right)^2\right] \\ & \quad = \mathbb{E}\Bigg[\sum_{j,k=1}^{\lfloor nt/2 \rfloor} w_{2j}^2 w_{2k}^2 G_0(2j)G_0(2k) \\ & \qquad \times \big\{\delta^2(\partial_{(2j-1)/n} \otimes \partial_{(2k-1)/n}) + \langle \partial_{(2j-1)/n}, \partial_{(2k-1)/n}\rangle_{\mathfrak{H}}\big\}\Bigg] \end{aligned}$$

$$\le Cn^{-1}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\mathbb{E}\Big[\mathbb{E}\sup_{0\le\ell\le\lfloor nt/2\rfloor}\big|G_0(\ell)\big|^2\big|\langle\partial_{(2j-1)/n},\partial_{(2k-1)/n}\rangle_{\mathfrak{H}}\big|\Big]$$

$$+Cn^{-1}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\mathbb{E}\Big[\sum_{a+b=2}\mathbb{E}\big|\big\langle D^aG_0(2j)D^bG_0(2k),\delta^2(\partial_{(2j-1)/n}\otimes\partial_{(2k-1)/n})\big\rangle_{\mathfrak{H}^{\otimes 2}}\big|\Big].$$

By Lemma 4.1 we have an estimate for the second term,

$$Cn^{-1}\sum_{j,k=1}^{\lfloor nt/2\rfloor}\big|\langle\partial_{(2j-1)/n},\partial_{(2k-1)/n}\rangle_{\mathfrak{H}}\big|\le C\left\lfloor\frac{nt}{2}\right\rfloor n^{-3/2}.$$

Then the first term has the same estimate as (48) when $r=2$, which proves (45) and the lemma.

6.2. *Proof of Lemma* 4.5. As in Lemma 4.4, we may assume $r=0$. Start with $B_n(t)$. Define

$$\gamma_n(t):=\sum_{j=1}^{\lfloor nt/2\rfloor}f^{(3)}(W_{(2j-1)/n})\big\langle\varepsilon_{(2j-1)/n},\partial_{(2j-1)/n}^{\otimes 2}-\partial_{(2j-2)/n}^{\otimes 2}\big\rangle_{\mathfrak{H}}$$

$$=\sum_{j=1}^{\lfloor nt/2\rfloor}f^{(3)}(W_{(2j-1)/n})\langle\varepsilon_{(2j-1)/n},\partial_{(2j-1)/n}-\partial_{(2j-2)/n}\rangle_{\mathfrak{H}}\times(\partial_{(2j-1)/n}-\partial_{(2j-2)/n}),$$

so that $B_n(t)=2\delta(\gamma_n(t))$. By Lemma 2.1, we have

$$\big\|\delta(\gamma_n(t))\big\|_{L^2(\Omega)}^2\le\mathbb{E}\big\|\gamma_n(t)\big\|_{\mathfrak{H}}^2+\mathbb{E}\big\|D\gamma_n(t)\big\|_{\mathfrak{H}^{\otimes 2}}^2.$$

We can write

$$\big\|\gamma_n(t)\big\|_{\mathfrak{H}}^2=\sum_{j,k=1}^{\lfloor nt/2\rfloor}f^{(3)}(W_{(2j-1)/n})f^{(3)}(W_{(2k-1)/n})\times\langle\varepsilon_{(2j-1)/n},\partial_{(2j-1)/n}-\partial_{(2j-2)/n}\rangle_{\mathfrak{H}}\times\langle\varepsilon_{(2k-1)/n},\partial_{(2k-1)/n}-\partial_{(2k-2)/n}\rangle_{\mathfrak{H}}\times\langle\partial_{(2j-1)/n}-\partial_{(2j-2)/n},\partial_{(2k-1)/n}-\partial_{(2k-2)/n}\rangle_{\mathfrak{H}}$$

$$\le\sup_{0\le s\le t}\big|f^{(3)}(W_s)\big|^2\sup_{1\le j\le\lfloor nt\rfloor}\langle\varepsilon_{(2j-1)/n},\partial_{(2j-1)/n}-\partial_{(2j-2)/n}\rangle_{\mathfrak{H}}^2\times\sum_{j,k=1}^{\lfloor nt/2\rfloor}\big|\langle\partial_{(2j-1)/n}-\partial_{(2j-2)/n},\partial_{(2k-1)/n}-\partial_{(2k-2)/n}\rangle_{\mathfrak{H}}\big|.$$

Note that $\mathbb{E}[\sup_{0\le s\le t}|f^{(3)}(W_s)|^2]=C$ by condition (0), and by Lemma 6.2, $|\langle \varepsilon_t, \partial_{(2j-1)/n}-\partial_{(2j-2)/n}\rangle_{\mathfrak{H}}|\le C_2 n^{-1/2}$ for all j,t. By Corollary 4.2 we know

$$\sum_{j,k=1}^{\lfloor nt/2\rfloor}\left|\langle \partial_{(2j-1)/n}-\partial_{(2j-2)/n}, \partial_{(2k-1)/n}-\partial_{(2k-2)/n}\rangle_{\mathfrak{H}}\right| \le C\left\lfloor \frac{nt}{2}\right\rfloor n^{-1/2}.$$

Hence, it follows that $\mathbb{E}\|\gamma_n(t)\|_{\mathfrak{H}}^2\le C\lfloor\frac{nt}{2}\rfloor n^{-1}n^{-1/2}\le C\lfloor\frac{nt}{2}\rfloor n^{-3/2}$. Next,

$$D\gamma_n(t)=\sum_{j=1}^{\lfloor nt/2\rfloor} f^{(4)}(W_{(2j-1)/n})\langle \varepsilon_{(2j-1)/n}, \partial_{(2j-1)/n}-\partial_{(2j-2)/n}\rangle_{\mathfrak{H}} \times\big(\varepsilon_{(2j-1)/n}\otimes(\partial_{(2j-1)/n}-\partial_{(2j-2)/n})\big),$$

and this implies

$$\begin{aligned}\big\|D\gamma_n(t)\big\|_{\mathfrak{H}^{\otimes 2}}^2 &\le \sup_{0\le s\le t}\big|f^{(4)}(W_s)\big|^2 \\ &\quad\times\left|\sum_{j,k=1}^{\lfloor nt/2\rfloor}\langle \varepsilon_{(2j-1)/n}, \partial_{(2j-1)/n}-\partial_{(2j-2)/n}\rangle_{\mathfrak{H}} \right.\\ &\qquad\left.\times\langle \varepsilon_{(2k-1)/n}, \partial_{(2k-1)/n}-\partial_{(2k-2)/n}\rangle_{\mathfrak{H}}\right| \\ &\quad\times\big|\big\langle \varepsilon_{(2j-1)/n}\otimes(\partial_{(2j-1)/n}-\partial_{(2j-2)/n}), \\ &\qquad \varepsilon_{(2k-1)/n}\otimes(\partial_{(2k-1)/n}-\partial_{(2k-2)/n})\big\rangle_{\mathfrak{H}^{\otimes 2}}\big| \\ &\le \sup_{0\le s\le t}\big|f^{(4)}(W_t)\big|^2\Big(\sup_j\langle \varepsilon_{(2j-1)/n}, \partial_{(2j-1)/n}-\partial_{(2j-2)/n}\rangle_{\mathfrak{H}}^2\Big) \\ &\quad\times\sup_{0\le s,r\le t}\big|\langle \varepsilon_s,\varepsilon_r\rangle_{\mathfrak{H}}\big| \\ &\quad\times\sum_{j,k=1}^{\lfloor nt/2\rfloor}\big|\langle \partial_{(2j-1)/n}-\partial_{(2j-2)/n}, \partial_{(2k-1)/n}-\partial_{(2k-2)/n}\rangle_{\mathfrak{H}}\big|.\end{aligned}$$

By condition (0), $\mathbb{E}[\sup_{0\le s\le t}|f^{(4)}(W_s)|]$ is bounded, and $\sup_{0\le s,r\le t}|\langle\varepsilon_r,\varepsilon_s\rangle_{\mathfrak{H}}|$ is bounded. Hence, it can be seen that $\mathbb{E}\|D\gamma_n(t)\|_{\mathfrak{H}^{\otimes 2}}^2$ gives the same estimate as $\gamma_n(t)$.

For $C_n(t)$, using condition (0) and the identity $a^2 - b^2 = (a-b)(a+b)$, we can write

$$\mathbb{E}\big[C_n(t)^2\big] \le \mathbb{E}\Big[\sup_{0\le s\le t} \big|f^{(4)}(W_s)\big|^2\Big] \times \Bigg(\sup_{1\le j\le nt/2} \big|\langle \varepsilon_{(2j-1)/n}, \partial_{(2j-1)/n} - \partial_{(2j-2)/n}\rangle_{\mathfrak{H}}\big| \times \sum_{j=1}^{\lfloor nt/2\rfloor} \big|\langle \varepsilon_{(2j-1)/n}, \partial_{(2j-1)/n} + \partial_{(2j-2)/n}\rangle_{\mathfrak{H}}\big|\Bigg)^2.$$

By Lemma 6.2, $|\langle \varepsilon_{(2j-1)/n}, \partial_{(2j-1)/n} - \partial_{(2j-2)/n}\rangle_{\mathfrak{H}}| \le C_2 n^{-1/2}$ and by condition (iv),

$$\sum_{j=1}^{\lfloor nt/2\rfloor} \big|\langle \varepsilon_{(2j-1)/n}, \mathbf{1}_{[(2j-2)/n,2j/n)}\rangle_{\mathfrak{H}}\big| \le Cn^{-1/2} + Cn^{-1/2} \sum_{j=2}^{\lfloor nt/2\rfloor} (2j-2)^{-1/2} \le C\left\lfloor \frac{nt}{2}\right\rfloor^{1/2} n^{-1/2}.$$

Hence it follows that $\mathbb{E}[C_n(t)^2] \le C\lfloor \frac{nt}{2}\rfloor n^{-2}$ for some constant C, and the lemma is proved.

6.3. *Proof of Lemma 4.9.* For $i = 1, \dots, d$, set

$$u_n^i = \sum_{j=\lfloor nt_{i-1}/2\rfloor+1}^{\lfloor nt_i/2\rfloor} f''(W_{(2j-1)/n})\big(\partial_{(2j-1)/n}^{\otimes 2} - \partial_{(2j-2)/n}^{\otimes 2}\big)$$

and recall that $F_n^i = \delta^2(u_n^i)$. As in Remark 3.3, we want to show:

Condition (a). For each $1 \le i \le d$, the following converge to zero in $L^1(\Omega)$:
(a.1) $\langle u_n^i, h_1 \otimes h_2\rangle_{\mathfrak{H}^{\otimes 2}}$ for all $h_1, h_2 \in \mathfrak{H}$ of the form ε_τ (see Remark 3.4).
(a.2) $\langle u_n^i, DF_n^j \otimes h\rangle_{\mathfrak{H}^{\otimes 2}}$ for each $1 \le j \le d$ and $h \in \mathfrak{H}$.
(a.3) $\langle u_n^i, DF_n^j \otimes DF_n^k\rangle_{\mathfrak{H}^{\otimes 2}}$ for each $1 \le j, k \le d$.

Condition (b).
(b.1) $\langle u_n^i, D^2F_n^j\rangle_{\mathfrak{H}^{\otimes 2}} \longrightarrow 0$ in L^1 if $i \ne j$.
(b.2) $\langle u_n^i, D^2F_n^i\rangle_{\mathfrak{H}^{\otimes 2}}$ converges in L^1 to a random variable of the form

$$F_\infty^j = c\int_{t_{i-1}}^{t_i} f''(W_s)^2 \eta(ds).$$

The proofs of (a.1) and (a.2) are essentially the same as those given in [5] (see Theorem 5.2), but the proof of (a.3) is new.

Proof of (a.1). We may assume $i = 1$. Let $h_1 \otimes h_2 = \varepsilon_s \otimes \varepsilon_\tau \in \mathfrak{H}^{\otimes 2}$ for some values $s, \tau \in [0, t]$. Then

$$\langle u_n^1, h_1 \otimes h_2 \rangle_{\mathfrak{H}^{\otimes 2}} = \sum_{j=1}^{\lfloor nt_1/2 \rfloor} f''(W_{(2j-1)/n}) \langle \partial_{(2j-1)/n} - \partial_{(2j-2)/n}, \varepsilon_s \rangle_{\mathfrak{H}} \times \langle \partial_{(2j-1)/n} - \partial_{(2j-2)/n}, \varepsilon_\tau \rangle_{\mathfrak{H}};$$

so that

$$\begin{aligned} &\left| \langle u_n^1, h_1 \otimes h_2 \rangle_{\mathfrak{H}^{\otimes 2}} \right| \\ &\quad \le \sup_{0 \le s \le t} |f''(W_s)| \sup_{1 \le j \le \lfloor nt_1/2 \rfloor} \sup_{0 \le s \le t_1} \left| \langle \partial_{(2j-1)/n} - \partial_{(2j-2)/n}, \varepsilon_s \rangle_{\mathfrak{H}} \right| \\ &\qquad \times \sum_{j=1}^{\lfloor nt_1/2 \rfloor} \left| \langle \partial_{(2j-1)/n} - \partial_{(2j-2)/n}, \varepsilon_\tau \rangle_{\mathfrak{H}} \right|. \end{aligned}$$

It follows from condition (iii) that for fixed $\tau \ge 0$,

$$\begin{aligned} &\sum_{j=1}^{\lfloor nt_1/2 \rfloor} \left| \langle \partial_{(2j-1)/n} - \partial_{(2j-2)/n}, \varepsilon_\tau \rangle_{\mathfrak{H}} \right| \\ &\quad = \sum_{j=1}^{\lfloor nt_1/2 \rfloor} \left| \mathbb{E}\left[W_\tau (W_{2j/n} - 2W_{(2j-1)/n} + W_{(2j-2)/n}) \right] \right| \\ &\quad \le Cn^{-1/2} + Cn^{-1/2} \sum_{j=2}^{\lfloor nt_1/2 \rfloor} \left((2j-2)^{-3/2} + |\tau - 2j|^{-3/2} \wedge 1 \right) \\ &\quad \le Cn^{-1/2}, \end{aligned} \tag{50}$$

and Lemma 6.2 implies

$$\sup_{1 \le j \le \lfloor nt_1/2 \rfloor} \sup_{0 \le s \le t} \left| \langle \partial_{(2j-1)/n} - \partial_{(2j-2)/n}, \varepsilon_s \rangle_{\mathfrak{H}} \right| \le Cn^{-1/2}$$

so that

$$\mathbb{E}\left(\left| \langle u_n^1, h_1 \otimes h_2 \rangle_{\mathfrak{H}^{\otimes 2}} \right| \right) \le Ct_1 n^{-1} \longrightarrow 0.$$

Proof of (a.2). As in (a.1), assume $i = 1$. Using the same technique as in (a.1), we can write $DF_n^j \otimes h$ as $DF_n^j \otimes \varepsilon_\tau$ for some $\tau \in [0, T]$. By Lemma 2.1, $DF_n^j = D\delta^2(u_n^j) = \delta^2(Du_n^j) + \delta(u_n^j)$, which gives

$$\langle u_n^1, DF_n^j \otimes \varepsilon_\tau \rangle_{\mathfrak{H}^{\otimes 2}} = \langle u_n^1, \delta^2(Du_n^j) \otimes \varepsilon_\tau \rangle_{\mathfrak{H}^{\otimes 2}} + \langle u_n^1, \delta(u_n^j) \otimes \varepsilon_\tau \rangle_{\mathfrak{H}^{\otimes 2}}.$$

For the first term,

$$\begin{aligned}
&\mathbb{E}\big|\langle u_n^1, \delta^2(Du_n^j)\otimes\varepsilon_\tau\rangle_{\mathfrak{H}^{\otimes 2}}\big| \\
&\quad= \sum_{\ell=1}^{\lfloor nt_1/2\rfloor} \mathbb{E}\big| f''(W_{(2\ell-1)/n})\big\langle \partial_{(2\ell-1)/n}-\partial_{(2\ell-2)/n}, \delta^2(Du_n^j)\big\rangle_{\mathfrak{H}} \\
&\qquad\qquad\qquad\qquad \times \langle \partial_{(2\ell-1)/n}-\partial_{(2\ell-2)/n}, \varepsilon_\tau\rangle_{\mathfrak{H}}\big| \\
&\quad\le 2\mathbb{E}\Big[\sup_{0\le s\le t_1}|f''(W_s)|\Big]\mathbb{E}\Big[\sup_{1\le\ell\le\lfloor nt_1/2\rfloor}\big|\big\langle \partial_{\ell/n}, \delta^2(Du_n^j)\big\rangle_{\mathfrak{H}}\big|\Big] \\
&\qquad\times \sum_{\ell=1}^{\lfloor nt_1/2\rfloor}\big|\langle \partial_{(2\ell-1)/n}-\partial_{(2\ell-2)/n}, \varepsilon_\tau\rangle_{\mathfrak{H}}\big|.
\end{aligned}$$

By (50), the sum has estimate $Cn^{-1/2}$, and for the second term we can take

$$\big|\big\langle \partial_{\ell/n}, \delta^2(Du_n^j)\big\rangle_{\mathfrak{H}}\big| \le \sup_\ell \|\partial_{\ell/n}\|_{\mathfrak{H}}\big\|\delta^2(Du_n^j)\big\|_{\mathfrak{H}}.$$

It follows from condition (i) that $\|\partial_{\ell/n}\|_{\mathfrak{H}}\le Cn^{-1/4}$. This leaves the $\|\delta^2(Du_n^j)\|_{\mathfrak{H}}$ term. By the Meyer inequality for a process taking values in $\mathfrak{H}$,

$$\mathbb{E}\big[\big\|\delta^2(Du_n^j)\big\|_{\mathfrak{H}}^2\big] \le c_1\mathbb{E}\big\|Du_n^j\big\|_{\mathfrak{H}^{\otimes 3}}^2 + c_2\mathbb{E}\big\|D^2u_n^j\big\|_{\mathfrak{H}^{\otimes 4}}^2 + c_3\mathbb{E}\big\|D^3u_n^j\big\|_{\mathfrak{H}^{\otimes 5}}^2, \tag{51}$$

so that by Lemma 4.7, $\mathbb{E}[\|\delta^2(Du)\|_{\mathfrak{H}}^2]\le C$, and we have

$$\mathbb{E}\big|\langle u_n^1, \delta^2(Du_n^j)\otimes\varepsilon_\tau\rangle_{\mathfrak{H}^{\otimes 2}}\big| \le Cn^{-3/4}.$$

Then similarly,

$$\begin{aligned}
&\big|\langle u_n^1, \delta(u_n^j)\otimes\varepsilon_t\rangle_{\mathfrak{H}^{\otimes 2}}\big| \\
&\quad\le 2\Big[\sup_{0\le s\le t_1}|f''(W_s)|\sup_\ell\big|\big\langle \partial_{\ell/n}, \delta(u_n^j)\big\rangle_{\mathfrak{H}}\big|\sum_\ell\big|\langle \partial_{(2\ell-1)/n}-\partial_{(2\ell-2)/n}, \varepsilon_t\rangle_{\mathfrak{H}}\big|\Big].
\end{aligned}$$

Similar to the above case, for each $1\le\ell\le\lfloor\frac{nt_1}{2}\rfloor$,

$$\begin{aligned}
\mathbb{E}\big[\big|\big\langle \partial_{\ell/n}, \delta(u_n^j)\big\rangle_{\mathfrak{H}}\big|\big] &\le \mathbb{E}\big[\|\partial_{\ell/n}\|_{\mathfrak{H}}\big\|\delta(u_n^j)\big\|_{\mathfrak{H}}\big] \\
&\le Cn^{-1/4}\big(\mathbb{E}\big\|u_n^j\big\|_{\mathfrak{H}^{\otimes 2}} + \mathbb{E}\big\|Du_n^j\big\|_{\mathfrak{H}^{\otimes 3}}\big) \\
&\le Cn^{-1/4},
\end{aligned}$$

and hence with (50) we have

$$\mathbb{E}\big[\big|\langle u_n^1, \delta(u_n^j)\otimes\varepsilon_\tau\rangle_{\mathfrak{H}^{\otimes 2}}\big|\big] \le Cn^{-3/4}.$$

Proof of (a.3). For this term we consider the product $\langle u_n^i, DF_n^j\otimes DF_n^k\rangle_{\mathfrak{H}^{\otimes 2}}$. Lemma 6.1 shows that scalar products of this kind are small in absolute value

when the time intervals are disjoint, and therefore it is enough to consider the worst case $\langle u_n^1, DF_n^1 \otimes DF_n^1 \rangle_{\mathfrak{H}^{\otimes 2}}$, and assume $t_1 = t$. We have

$$\begin{aligned}
&\mathbb{E}\big[\big|\langle u_n^1, DF_n^1 \otimes DF_n^1 \rangle_{\mathfrak{H}^{\otimes 2}}\big|\big] \\
&\quad \le \sum_{\ell=1}^{\lfloor nt/2 \rfloor} \big|\mathbb{E}\big[\big\langle f''(W_{(2\ell-1)/n})\big(\partial_{(2\ell-1)/n}^{\otimes 2} - \partial_{(2\ell-2)/n}^{\otimes 2}\big), DF_n^1 \otimes DF_n^1 \big\rangle_{\mathfrak{H}^{\otimes 2}}\big]\big| \\
&\quad \le C \sum_{\ell=1}^{\lfloor nt/2 \rfloor} \mathbb{E}\big[\big|\big\langle \partial_{(2\ell-1)/n}, DF_n^1 \big\rangle_{\mathfrak{H}}^2 - \big\langle \partial_{(2\ell-2)/n}, DF_n^1 \big\rangle_{\mathfrak{H}}^2\big|\big] \\
&\quad \le C \sum_{\ell=1}^{\lfloor nt/2 \rfloor} \mathbb{E}\big[\big|\big\langle \partial_{(2\ell-1)/n} - \partial_{(2\ell-2)/n}, DF_n^1 \big\rangle_{\mathfrak{H}}\big|\big|\big\langle \mathbf{1}_{[(2\ell-2)/n, 2\ell/n]}, DF_n^1 \big\rangle_{\mathfrak{H}}\big|\big].
\end{aligned}$$

Using the decomposition $DF_n^1 = \delta^2(Du_n^1) + \delta(u_n^1)$, the above summand expands into four terms:

(1) $\big|\big\langle \partial_{(2\ell-1)/n} - \partial_{(2\ell-2)/n}, \delta^2\big(Du_n^1\big)\big\rangle_{\mathfrak{H}}\big|\big|\big\langle \mathbf{1}_{[(2\ell-2)/n, 2\ell/n]}, \delta^2\big(Du_n^1\big)\big\rangle_{\mathfrak{H}}\big|$;

(2) $\big|\big\langle \partial_{(2\ell-1)/n} - \partial_{(2\ell-2)/n}, \delta^2\big(Du_n^1\big)\big\rangle_{\mathfrak{H}}\big|\big|\big\langle \mathbf{1}_{[(2\ell-2)/n, 2\ell/n]}, \delta\big(u_n^1\big)\big\rangle_{\mathfrak{H}}\big|$;

(3) $\big|\big\langle \partial_{(2\ell-1)/n} - \partial_{(2\ell-2)/n}, \delta\big(u_n^1\big)\big\rangle_{\mathfrak{H}}\big|\big|\big\langle \mathbf{1}_{[(2\ell-2)/n, 2\ell/n]}, \delta^2\big(Du_n^1\big)\big\rangle_{\mathfrak{H}}\big|$;

(4) $\big|\big\langle \partial_{(2\ell-1)/n} - \partial_{(2\ell-2)/n}, \delta\big(u_n^1\big)\big\rangle_{\mathfrak{H}}\big|\big|\big\langle \mathbf{1}_{[(2\ell-2)/n, 2\ell/n]}, \delta\big(u_n^1\big)\big\rangle_{\mathfrak{H}}\big|$.

We will show computations for the terms (1) and (4) only, with the others being similar. For (1) we have

$$\begin{aligned}
&C \sum_{\ell=1}^{\lfloor nt/2 \rfloor} \mathbb{E}\big[\big|\big\langle \partial_{(2\ell-1)/n} - \partial_{(2\ell-2)/n}, \delta^2\big(Du_n^1\big)\big\rangle_{\mathfrak{H}}\big|\big|\big\langle \mathbf{1}_{[(2\ell-2)/n, 2\ell/n]}, \delta^2\big(Du_n^1\big)\big\rangle_{\mathfrak{H}}\big|\big] \\
&\quad = C \sum_{\ell,m,m'=1}^{\lfloor nt/2 \rfloor} \mathbb{E}\big|\big\langle \partial_{(2\ell-1)/n} - \partial_{(2\ell-2)/n}, \\
&\qquad\qquad \delta^2\big(f^{(3)}(W_{(2m-1)/n})\varepsilon_{(2m-1)/n}\big(\partial_{(2m-1)/n}^{\otimes 2} - \partial_{(2m-2)/n}^{\otimes 2}\big)\big)\big\rangle_{\mathfrak{H}}\big| \\
&\qquad\qquad \times \big|\big\langle \mathbf{1}_{[(2\ell-2)/n, 2\ell/n]}, \\
&\qquad\qquad\quad \delta^2\big(f^{(3)}(W_{(2m'-1)/n})\varepsilon_{(2m'-1)/n}\big(\partial_{(2m'-1)/n}^{\otimes 2} - \partial_{(2m'-2)/n}^{\otimes 2}\big)\big)\big\rangle_{\mathfrak{H}}\big| \\
&\quad \le C \sup_{1 \le k \le \lfloor nt/2 \rfloor} \big(\mathbb{E}\big[\big\|\delta^2\big(f^{(3)}(W_{(2k-1)/n})\big(\partial_{(2k-1)/n}^{\otimes 2} - \partial_{(2k-2)/n}^{\otimes 2}\big)\big)\big\|_{\mathfrak{H}^{\otimes 2}}\big]\big)^2 \\
&\qquad \times \sum_{\ell,m,m'=1}^{\lfloor nt/2 \rfloor} \big|\big\langle \partial_{(2\ell-1)/n} - \partial_{(2\ell-2)/n}, \varepsilon_{(2m-1)/n} \big\rangle_{\mathfrak{H}}\big| \\
&\qquad\qquad \times \big|\big\langle \mathbf{1}_{[(2\ell-2)/n, 2\ell/n]}, \varepsilon_{(2m'-1)/n} \big\rangle_{\mathfrak{H}}\big|.
\end{aligned}$$

By Lemmas 2.1 and 4.7, the Skorohod integral term is bounded by $Cn^{-1/2}$, and we use conditions (iii) and (iv) for the scalar products to obtain an estimate of the form

$$\begin{aligned} &Cn^{-2}\sum_{\ell,m,m'=1}^{\lfloor nt/2\rfloor}\bigl((2m-1)^{-3/2}+|2\ell-2m|^{-3/2}\bigr)\\ &\qquad\qquad\times\bigl((2\ell-2)^{-1/2}+\bigl|2\ell-2m'\bigr|^{-1/2}\bigr)\\ &\quad\le Cn^{-1/2}. \end{aligned}$$

For term (4), we have by a computation similar to the proof of Lemma 4.7,

$$\mathbb{E}\bigl[\bigl\|\delta\bigl(f^{(3)}(W_{(2k-1)/n})(\partial_{(2k-1)/n}-\partial_{(2k-2)/n})\bigr)\bigr\|_{\mathfrak{H}}\bigr]\le Cn^{-1/4},$$

and by conditions (i) and (ii) we have

$$\begin{aligned} &Cn^{-3/2}\sum_{\ell,m,m'=1}^{\lfloor nt/2\rfloor}\bigl|\langle\partial_{(2\ell-1)/n}-\partial_{(2\ell-2)/n},\partial_{(2m-1)/n}-\partial_{(2m-2)/n}\rangle_{\mathfrak{H}}\bigr|\\ &\qquad\qquad\times\bigl|\langle\mathbf{1}_{[(2\ell-2)/n,2\ell/n]},\partial_{(2m'-1)/n}-\partial_{(2m'-2)/n}\rangle_{\mathfrak{H}}\bigr|\\ &\quad\le Cn^{-3/2}\sum_{\ell,m,m'=1}^{\lfloor nt/2\rfloor}\bigl(|2\ell-2m|^{-\alpha}\bigr)\bigl(\bigl|2\ell-2m'\bigr|^{-\alpha}\bigr)\\ &\quad\le Cn^{-1/2}. \end{aligned}$$

Proof of (b.1). By Lemma 2.1, we can expand D^2F_n as follows:

$$\begin{aligned} \langle u_n^i,D^2F_n^j\rangle_{\mathfrak{H}^{\otimes 2}}&=\langle u_n^i,\delta^2\bigl(D^2u_n^j\bigr)\rangle_{\mathfrak{H}^{\otimes 2}}+4\langle u_n^i,\delta\bigl(Du_n^j\bigr)\rangle_{\mathfrak{H}^{\otimes 2}}\\ &\quad+2\langle u_n^i,u_n^j\rangle_{\mathfrak{H}^{\otimes 2}}. \end{aligned}\tag{52}$$

Without loss of generality, we may assume that u_n^i is defined on $[0,t_1]$, and F_n^j is defined on $[t_1,t_2]$ for $t_1<t_2$, so that the sums are over

$$u_n^i=\sum_{\ell=1}^{\lfloor nt_1/2\rfloor}f''(W_{(2\ell-1)/n})\bigl(\partial_{(2\ell-1)/n}^{\otimes 2}-\partial_{(2\ell-2)/n}^{\otimes 2}\bigr)$$

and

$$u_n^j=\sum_{m=\lfloor nt_1/2\rfloor+1}^{\lfloor nt_2/2\rfloor}f''(W_{(2m-1)/n})\bigl(\partial_{(2m-1)/n}^{\otimes 2}-\partial_{(2m-2)/n}^{\otimes 2}\bigr).$$

First term.

$$
\begin{aligned}
&\mathbb{E}\big|\langle u_n^i, \delta^2(D^2 u_n^j)\rangle_{\mathfrak{H}^{\otimes 2}}\big| \\
&\quad = \mathbb{E}\Bigg|\Bigg\langle \sum_{\ell=1}^{\lfloor nt_1/2\rfloor} f''(W_{(2\ell-1)/n})\big(\partial_{(2\ell-1)/n}^{\otimes 2} - \partial_{(2\ell-2)/n}^{\otimes 2}\big), \\
&\qquad\qquad \delta^2\Bigg(\sum_{m=\lfloor nt_1/2\rfloor+1}^{\lfloor nt_2/2\rfloor} f^{(4)}(W_{(2m-1)/n})\varepsilon_{(2m-1)/n}^{\otimes 2} \\
&\qquad\qquad\qquad\qquad \otimes \big(\partial_{(2m-1)/n}^{\otimes 2} - \partial_{(2m-2)/n}^{\otimes 2}\big)\Bigg)\Bigg\rangle_{\mathfrak{H}^{\otimes 2}}\Bigg| \\
&\quad \le \mathbb{E}\Big[\sup_{0\le s\le t}\big|f''(W_s)\big|\Big] \\
&\qquad \times \mathbb{E}\Big[\sum_{\ell}\sum_{m}\big|\langle \varepsilon_{(2m-1)/n}^{\otimes 2}, \partial_{(2\ell-1)/n}^{\otimes 2} - \partial_{(2\ell-2)/n}^{\otimes 2}\rangle_{\mathfrak{H}^{\otimes 2}}\big| \\
&\qquad\qquad \times \big|\delta^2\big(f^{(4)}(W_{(2m-1)/n})\big(\partial_{(2m-1)/n}^{\otimes 2} - \partial_{(2m-2)/n}^{\otimes 2}\big)\big)\big|\Big] \\
&\quad \le \mathbb{E}\Big[\sup_{0\le s\le t}\big|f''(W_s)\big|\Big] \\
&\qquad \times \sup_m \big\|\delta^2(g_4)\big\|_{L^2(\Omega)} \sum_{\ell=1}^{\lfloor nt_2/2\rfloor}\sum_{m=1}^{\lfloor nt_2/2\rfloor}\big[\langle \varepsilon_{(2m-1)/n}, \partial_{(2\ell-1)/n}\rangle_{\mathfrak{H}}^2 \\
&\qquad\qquad - \langle \varepsilon_{(2m-1)/n}, \partial_{(2\ell-2)/n}\rangle_{\mathfrak{H}}^2\big].
\end{aligned}
$$

First we need an estimate for the $\delta^2(g_4)$ term, where in the notation of Lemma 4.7,

$$
g_4 := f^{(4)}(W_{(2m-1)/n})\big(\partial_{(2m-1)/n}^{\otimes 2} - \partial_{(2m-2)/n}^{\otimes 2}\big).
$$

By Lemma 2.1, $\|\delta^2(g_4)\|_{L^2(\Omega)} \le c_1\mathbb{E}\|g_4\|_{\mathfrak{H}^{\otimes 2}} + c_2\mathbb{E}\|Dg_4\|_{\mathfrak{H}^{\otimes 3}} + c_3\mathbb{E}\|D^2 g_4\|_{\mathfrak{H}^{\otimes 4}}$, and so $\|\delta^2(g_4)\|_{L^2(\Omega)} \le Cn^{-1/2}$ for each $\lfloor \frac{nt_1}{2}\rfloor < m \le \lfloor \frac{nt_2}{2}\rfloor$. We can write

$$
\begin{aligned}
&\mathbb{E}\big|\langle u_n^i, \delta^2(D^2 u_n^i)\rangle_{\mathfrak{H}^{\otimes 2}}\big| \\
&\quad \le Cn^{-1/2}\sum_{\ell,m=1}^{\lfloor nt_2/2\rfloor}\big|\langle \varepsilon_{(2m-1)/n}, \partial_{(2\ell-1)/n}\rangle_{\mathfrak{H}}^2 \\
&\qquad\qquad - \langle \varepsilon_{(2m-1)/n}, \partial_{(2\ell-2)/n}\rangle_{\mathfrak{H}}^2\big|.
\end{aligned}
$$

We need an estimate for the double sum. We have by condition (iii),

$$\begin{aligned}
&\sum_{\ell,m=1}^{\lfloor nt_2/2\rfloor}\big[\big|\langle \varepsilon_{(2m-1)/n}, \partial_{(2\ell-1)/n}\rangle_{\mathfrak{H}}^2 - \langle \varepsilon_{(2m-1)/n}, \partial_{(2\ell-2)/n}\rangle_{\mathfrak{H}}^2\big|\big]\\
&\quad\le \sup_{\ell,m}\big|\langle \varepsilon_{(2m-1)/n}, \mathbf{1}_{[(2\ell-2)/n,2\ell/n]}\rangle_{\mathfrak{H}}\big|\\
&\qquad\quad\times \sum_{\ell,m=1}^{\lfloor nt_2/2\rfloor}\big|\langle \varepsilon_{(2m-1)/n}, \partial_{(2\ell-1)/n} - \partial_{(2\ell-2)/n}\rangle_{\mathfrak{H}}\big|\\
&\quad\le Cn^{-1/2}\sum_{\ell,m=1}^{\lfloor nt_2/2\rfloor} C_2 n^{-1/2}\big[\big(|\ell-m|^{-3/2} + (\ell-1)^{-3/2}\big)\wedge 1\big]\\
&\quad\le Cn^{-1}\sum_{\ell=1}^{\lfloor nt_2/2\rfloor}\sum_{p=1}^{\infty} p^{-3/2} \le C.
\end{aligned}$$

This provides an upper bound for the double sum, and hence the first term of (52) is $O(n^{-1/2})$. Note that in the above estimate the double sum is taken over $1 \le \ell, m \le \lfloor \frac{nt_2}{2}\rfloor$. It follows that this estimate also holds for the case $i = j$, that is, $\mathbb{E}|\langle u_n^i, \delta^2(D^2 u_n^i)\rangle_{\mathfrak{H}^{\otimes 2}}| \le Cn^{-1/2}$.

Second term. Using $t_1 < t_2$ as above,

$$\begin{aligned}
&\mathbb{E}\big|\big\langle u_n^i, \delta\big(Du_n^j\big)\big\rangle_{\mathfrak{H}^{\otimes 2}}\big|\\
&\quad= \mathbb{E}\Bigg|\Bigg\langle \sum_{j=1}^{\lfloor nt_1/2\rfloor} f''(W_{(2j-1)/n})\big(\partial_{(2j-1)/n}^{\otimes 2} - \partial_{(2j-2)/n}^{\otimes 2}\big),\\
&\qquad\qquad \delta\Bigg(\sum_{k=\lfloor nt_1/2\rfloor}^{\lfloor nt_2/2\rfloor} f^{(3)}(W_{(2k-1)/n})\varepsilon_{(2k-1)/n}\otimes\big(\partial_{(2k-1)/n}^{\otimes 2} - \partial_{(2k-2)/n}^{\otimes 2}\big)\Bigg)\Bigg\rangle_{\mathfrak{H}^{\otimes 2}}\Bigg|\\
&\quad= \mathbb{E}\Bigg|\sum_j\sum_k f''(W_{(2j-1)/n})\big\langle \varepsilon_{(2k-1)/n}\otimes(\partial_{(2k-1)/n} - \partial_{(2k-2)/n}),\\
&\qquad\qquad\qquad\qquad (\partial_{(2j-1)/n} - \partial_{(2j-2)/n})^{\otimes 2}\big\rangle_{\mathfrak{H}^{\otimes 2}}\Bigg|\\
&\qquad\times\big|\delta\big(f^{(3)}(W_{(2k-1)/n})(\partial_{(2k-1)/n} - \partial_{(2k-2)/n})\big)\big|\\
&\quad\le C\mathbb{E}\Big[\sup_{0\le s\le t}|f''(W_s)|\Big]\Big(\sup_{s,j}|\langle \varepsilon_s, \partial_{j/n}\rangle_{\mathfrak{H}}|\Big)\Big(\sup_k\|\delta(g_3)\|_{L^2(\Omega)}\Big)\\
&\qquad\times\sum_{j=0}^{\lfloor nt_2\rfloor}\sum_{k=0}^{\lfloor nt_2\rfloor}|\langle \partial_{j/n}, \partial_{k/n}\rangle_{\mathfrak{H}}|,
\end{aligned}$$

where in this case, g_3 corresponds to the term including $f^{(3)}(W_t)$. It follows from Lemma 6.2 that $\sup|\langle \varepsilon_s, \partial_{k/n}\rangle_{\mathfrak{H}}| \le Cn^{-1/2}$; and the double sum is bounded by $Cn^{1/2}$ by Corollary 4.2. This leaves an estimate for $\|\delta(g_3)\|_{L^2(\Omega)}$. By Lemma 2.1, $\|\delta(g_3)\|_{L^2(\Omega)} \le c_1\|g_3\|_{\mathfrak{H}} + c_2\|Dg_3\|_{\mathfrak{H}^{\otimes 2}}$. For this case,

$$\|g_3\|_{\mathfrak{H}}^2 \le \mathbb{E}\Big[\sup_{0\le s\le t}|f^{(3)}(W_s)|^2\Big]\|\partial_{(2k-1)/n} - \partial_{(2k-2)/n}\|_{\mathfrak{H}}^2 \le Cn^{-1/2},$$

hence $\|g_3\|_{\mathfrak{H}} \le Cn^{-1/4}$. Similarly,

$$\begin{aligned}\|Dg_3\|_{\mathfrak{H}^{\otimes 2}} &\le \mathbb{E}\Big[\sup_{0\le s\le t}|f^{(4)}(W_s)|\Big]\sup_{0\le s\le t}\|\varepsilon_s\|_{\mathfrak{H}}\|\partial_{(2k-1)/n} - \partial_{(2k-2)/n}\|_{\mathfrak{H}}\\ &\le Cn^{-1/4},\end{aligned}$$

hence the second term is $O(n^{-1/4})$. As in the first term, the double sum estimate shows that this result also holds for $\langle u_n^i, \delta(DF_n^i)\rangle_{\mathfrak{H}^{\otimes 2}}$.

Third term. We can write

$$\begin{aligned}|\langle u_n^i, u_n^j\rangle_{\mathfrak{H}^{\otimes 2}}| \le \sup_{0\le s\le t}|f''(W_s)|^2 \sum_{\ell=1}^{\lfloor nt_1/2\rfloor}\sum_{m=\lfloor nt_1/2\rfloor+1}^{\lfloor nt_2/2\rfloor} &|\langle \partial_{(2\ell-1)/n}^{\otimes 2} - \partial_{(2\ell-2)/n}^{\otimes 2},\\ &\partial_{(2m-1)/n}^{\otimes 2} - \partial_{(2m-2)/n}^{\otimes 2}\rangle_{\mathfrak{H}^{\otimes 2}}|,\end{aligned}$$

and it follows from Lemma 6.1 that $\mathbb{E}|\langle u_n^i, u_n^j\rangle_{\mathfrak{H}^{\otimes 2}}| \le Cn^{-\varepsilon}$, for some $\varepsilon > 0$.

Proof of (b.2). As in case (b.1), this has the expansion (52). From remarks in the proof of (b.1), the first two terms have the same estimate as the $i \ne j$ case, hence only the term $\langle u_n^i, u_n^i\rangle_{\mathfrak{H}^{\otimes 2}}$ is significant.

Third term. Assume for the summation terms that the indices run over $\lfloor \frac{nt_{i-1}}{2}\rfloor + 1 \le j, k \le \lfloor \frac{nt_i}{2}\rfloor$. We have

$$\begin{aligned}\langle u_n^i, u_n^i\rangle_{\mathfrak{H}^{\otimes 2}} = \sum_{j,k} &f''(W_{(2j-1)/n})f''(W_{(2k-1)/n})\\ &\times\langle \partial_{(2j-1)/n}^{\otimes 2} - \partial_{(2j-2)/n}^{\otimes 2}, \partial_{(2k-1)/n}^{\otimes 2} - \partial_{(2k-2)/n}^{\otimes 2}\rangle_{\mathfrak{H}^{\otimes 2}}.\end{aligned}$$

Expanding the product, observe that

$$\begin{aligned}&\langle \partial_{(2j-1)/n}^{\otimes 2} - \partial_{(2j-2)/n}^{\otimes 2}, \partial_{(2k-1)/n}^{\otimes 2} - \partial_{(2k-2)/n}^{\otimes 2}\rangle_{\mathfrak{H}^{\otimes 2}}\\ &\quad= \beta_n(2j-1, 2k-1)^2 - \beta_n(2j-1, 2k-2)^2\\ &\qquad- \beta_n(2j-2, 2k-1)^2 + \beta_n(2j-2, 2k-2)^2,\end{aligned}$$

where $\beta_n(\ell, m)$ is as defined for condition (v). For each n, define discrete measures on $\{1, 2, \ldots\}^{\otimes 2}$ by

$$\mu_n^+ := \sum_{j,k=1}^{\infty} \beta_n(2j-1, 2k-1)^2 + \beta_n(2j-2, 2k-2)^2 \delta_{jk};$$

$$\mu_n^- := \sum_{j,k=1}^{\infty} \beta_n(2j-1, 2k-2)^2 + \beta_n(2j-2, 2k-1)^2 \delta_{jk},$$

where in this case δ_{jk} denotes the Kronecker delta. In the following, we show only η_n^+, with η_n^- being similar. It follows from condition (v) that for each $t > 0$,

$$\begin{aligned}\mu^+([0,t]^2) &:= \lim_{n\to\infty} \mu_n\left(\left\lfloor \frac{nt}{2} \right\rfloor, \left\lfloor \frac{nt}{2} \right\rfloor\right) \\ &= \lim_n \sum_{j,k=1}^{\lfloor nt/2 \rfloor} \beta_n(2j-1, 2k-1)^2 + \beta_n(2j-2, 2k-2)^2 \\ &= \eta^+(t).\end{aligned}$$

Moreover, if $0 < s < t$, then

$$\begin{aligned}&\mu_n\left(\left\lfloor \frac{ns}{2} \right\rfloor, \left\lfloor \frac{nt}{2} \right\rfloor\right) \\ &\quad = \mu_n\left(\left\lfloor \frac{ns}{2} \right\rfloor, \left\lfloor \frac{ns}{2} \right\rfloor\right) \\ &\qquad + \sum_{j=1}^{\lfloor ns/2 \rfloor} \sum_{k=\lfloor ns/2 \rfloor + 1}^{\lfloor nt/2 \rfloor} \beta_n(2j-1, 2k-1)^2 + \beta_n(2j-2, 2k-2)^2,\end{aligned}$$

which converges to $\mu^+([0,s]^2)$ because the disjoint sum vanishes by Lemma 6.1. Hence, we can conclude that μ_n converges weakly to the measure given by $\mu^+([0,s] \times [0,t]) = \eta^+(s \wedge t)$. It follows by continuity of $f''(W_t)$ and Portmanteau theorem that

$$\begin{aligned}&\sum_{j,k=1}^{\lfloor nt/2 \rfloor} f''(W_{(2j-1)/n}) f''(W_{(2k-1)/n}) \big(\beta_n(2j-1, 2k-1)^2 + \beta_n(2j-2, 2k-2)^2\big) \\ &\quad = \int_{\mathbb{R}^2} f''(W_s) f''(W_u) \mathbf{1}_{s<t} \mathbf{1}_{u<t} \mu_n^+(ds, du)\end{aligned}$$

converges to

$$\int_0^t f''(W_s)^2 \eta^+(ds).$$

Combining this result with a similar integral defined for μ^-, we have for $t > 0$,

$$\lim_{n\to\infty} \sum_{j,k=1}^{\lfloor nt/2 \rfloor} f''(W_{(2j-1)/n}) f''(W_{(2k-1)/n}) \times \langle \partial^{\otimes 2}_{(2j-1)/n} - \partial^{\otimes 2}_{(2j-2)/n}, \partial^{\otimes 2}_{(2k-1)/n} - \partial^{\otimes 2}_{(2k-2)/n} \rangle_{\mathfrak{H}^{\otimes 2}} = \int_0^t f''(W_s)\mu^+(ds) - \int_0^t f''(W_s)\mu^-(ds) = \int_0^t f''(W_s)\eta(ds),$$

where we define $\eta(t) = \eta^+(t) - \eta^-(t)$. It follows that on the subinterval $[t_{i-1}, t_i]$ we have the result

$$\langle u_n^i, u_n^i \rangle_{\mathfrak{H}^{\otimes 2}} \longrightarrow \int_{t_{i-1}}^{t_i} f''(W_s)^2 \eta(ds)$$

in $L^1(\Omega)$ as $n \to \infty$.

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