

The optimal fourth moment theorem

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Abstract

We compute the exact rates of convergence in total variation associated with the ‘fourth moment theorem’ by Nualart and Peccati (2005), stating that a sequence of random variables living in a fixed Wiener chaos verifies a central limit theorem (CLT) if and only if the sequence of the corresponding fourth cumulants converges to zero. We also provide an explicit illustration based on the Breuer-Major CLT for Gaussian-subordinated random sequences.

Keywords: Berry-Esseen bounds; Central Limit Theorem; Fourth Moment Theorem; Gaussian Fields; Stein’s method; Total variation.

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1 Introduction and main result

On a suitable probability space (Ω, \mathcal{F}, P) , let $X = \{X(h) : h \in \mathfrak{H}\}$ be an isonormal Gaussian process over a real separable Hilbert space \mathfrak{H} , and let $\{C_q : q = 0, 1, \dots\}$ be the sequence of Wiener chaoses associated with X (see Section 2.4 for details). The aim of the present work is to prove an optimal version of the following quantitative ‘fourth moment’ central limit theorem (CLT) — which combines results from [12] and [20].

Theorem 1.1 (Fourth moment theorem [12, 20]) *Fix an integer $q \geq 2$ and let $N \sim \mathcal{N}(0, 1)$ be a standard Gaussian random variable. Consider a sequence $\{F_n : n \geq 1\}$ living in the q th Wiener chaos C_q of X , and assume that $E[F_n^2] = 1$. Then, F_n converges in distribution to $N \sim \mathcal{N}(0, 1)$ if and only if $E[F_n^4] \rightarrow 3 = E[N^4]$. Also, the following upper bound on the total variation distance holds for every n :*

$$d_{TV}(F_n, N) \leq \sqrt{\frac{4q-4}{3q}} \sqrt{|E[F_n^4] - 3|}. \quad (1.1)$$

Recall that, given two real-valued random variables Y, Z , the *total variation distance* between the law of Y and Z is given by

$$d_{TV}(Y, Z) = \sup_{A \in \mathcal{B}(\mathbb{R})} |P[Y \in A] - P[Z \in A]| \quad (1.2)$$

$$= \frac{1}{2} \sup |E[g(Y)] - E[g(Z)]|, \quad (1.3)$$

where, in view e.g. of Lusin’s Theorem, the supremum is taken over the class of continuously differentiable functions g that are bounded by 1 and have compact support. Also, if the distributions of Y, Z have densities (say f_Y, f_Z) then one has the integral representation

$$d_{TV}(Y, Z) = \frac{1}{2} \int_{\mathbb{R}} |f_Y(t) - f_Z(t)| dt. \quad (1.4)$$

It is a well-known fact that the topology induced by d_{TV} , over the class of all probabilities on \mathbb{R} , is strictly stronger than the topology of convergence in distribution (see e.g. [7]). It is also important to notice that bounds analogous to (1.1) hold for other distances, like for instance the Kolmogorov and 1-Wasserstein distances (see [15, Chapter 5]).

The first part of Theorem 1.1 was first proved in [20] by using tools of continuous-time stochastic calculus. The upper bound (1.1) comes from reference [12], and is obtained by combining the *Malliavin calculus of variations* (see e.g. [15, 19]) with the *Stein's method* for normal approximations (see [5, 15]). The content of Theorem 1.1 has sparked a great amount of generalisations and applications, ranging from density estimates [18] to entropic CLTs [17], and from estimates for Gaussian polymers [21] to universality results [16]. The reader is referred to the monograph [15] for a self-contained introduction to the theoretical aspects of this direction of research, as well as to [8, 10] for applications, respectively, to the high-frequency analysis of fields defined on homogeneous spaces, and to the power variation of stochastic processes related to fractional Brownian motion. One can also consult the constantly updated webpage

<http://www.iecn.u-nancy.fr/~nourdin/steinmalliavin.htm>

for literally hundreds of results related to Theorem 1.1 and its ramifications.

One challenging question is whether the upper bound (on the rate of convergence in total variation) provided by (1.1) is optimal, or rather it can be ameliorated in some specific situations. Recall that a positive sequence $\{\phi(n) : n \geq 1\}$ decreasing to zero yields an *optimal rate of convergence*, with respect to some suitable distance $d(\cdot, \cdot)$, if there exist two finite constants $0 < c < C$ (independent of n) such that

$$c\phi(n) \leq d(F_n, N) \leq C\phi(n), \quad \text{for all } n \geq 1.$$

There are indeed very few references studying optimal rates of convergence for CLTs on a Gaussian space. Our paper [13] provides some partial characterisation of optimal rates of convergence in the case where $d = d_{Kol}$ (the Kolmogorov distance), whereas [4] contains similar findings for multidimensional CLTs and distances based on smooth mappings. Of particular interest for the present analysis is the work [2], that we cowrote with H. Biermé and A. Bonami, where it is proved that, whenever the distance d is defined as the supremum over a class of *smooth enough* test functions (e.g., twice differentiable with a bounded second derivative), an optimal rate of convergence in Theorem 1.1 is given by the sequence

$$\mathbf{M}(F_n) := \max \{ |E[F_n^3]|, |E[F_n^4] - 3| \}, \quad n \geq 1. \quad (1.5)$$

In particular, if $E[F_n^3] = 0$ (for instance, if q is odd), then the rate suggested by the estimate (1.1) is suboptimal by a whole square root factor. We observe that, if F is a non-zero element of the q th Wiener chaos of X , for some $q \geq 2$, then $E[F^4] > 3E[F^2]^2$; see e.g. [20] or [15, Chapter 5].

The statement of the subsequent Theorem 1.2, which is the main achievement of the present paper, provides a definitive characterisation of the optimal rate of convergence in the total variation distance for the fourth moment CLT appearing in Theorem 1.1. It was somehow unexpected that our optimal rate only relies on the simple quantity (1.5) and also that we do not need to impose a further restriction than being an element of a given Wiener chaos. One remarkable consequence of our findings is that this optimal rate exactly coincides with the one related to the smooth test functions considered in [2]. We will see that the proof relies on estimates taken from the paper [2], that we combine with a new fine analysis of the main upper bound proved in [12] (see Proposition 2.3).

Theorem 1.2 (Optimal fourth moment theorem in total variation) Fix $q \geq 2$. Let $\{F_n : n \geq 1\}$ be a sequence of random variables living in the q th Wiener chaos of X , such that $E[F_n^2] = 1$. Then, F_n converges in distribution to $N \sim \mathcal{N}(0,1)$ if and only if $E[F_n^4] \rightarrow 3 = E[N^4]$. In this case, one has also that $E[F_n^3] \rightarrow 0$ and there exist two finite constants $0 < c < C$ (possibly depending on q and on the sequence $\{F_n\}$, but not on n) such that the following estimate in total variation holds for every n :

$$c \mathbf{M}(F_n) \leq d_{TV}(F_n, N) \leq C \mathbf{M}(F_n), \quad (1.6)$$

where the quantity $\mathbf{M}(F_n)$ is defined according to (1.5).

The rest of the paper is organised as follows. Section 2 contains some notation and useful preliminaries. Our main result, Theorem 1.2, is proved in Section 3. Finally, in Section 4 we provide an explicit illustration based on the Breuer-Major CLT for Gaussian-subordinated random sequences.

2 Notation and preliminaries

2.1 Cumulants

In what follows, the notion of *cumulant* is sometimes used. Recall that, given a random variable Y with finite moments of all orders and with characteristic function $\psi_Y(t) = E[\exp(itY)]$ ($t \in \mathbb{R}$), one defines the sequence of cumulants (sometimes known as *semi-invariants*) of Y , noted $\{\kappa_n(Y) : n \geq 1\}$, as

$$\kappa_n(Y) = (-i)^n \frac{d^n}{dt^n} \log \psi_Y(t) |_{t=0}, \quad n \geq 1. \quad (2.7)$$

For instance, $\kappa_1(Y) = E[Y]$, $\kappa_2(Y) = E[(Y - E[Y])^2] = \text{Var}(Y)$, and, if $E[Y] = 0$,

$$\kappa_3(Y) = E[Y^3] \quad \text{and} \quad \kappa_4(Y) = E[Y^4] - 3E[Y^2]^2.$$

2.2 Hermite polynomials

We will also denote by $\{H_q : q = 0, 1, \dots\}$ the sequence of *Hermite polynomials* given by the recursive relation $H_0 = 1$ and $H_{q+1}(x) = xH_q(x) - H'_q(x)$, in such a way that $H_1(x) = x$, $H_2(x) = x^2 - 1$, $H_3(x) = x^3 - 3x$ and $H_4(x) = x^4 - 6x^2 + 3$. We recall that Hermite polynomials constitute a complete orthogonal system of the space $L^2(\mathbb{R}, \mathcal{B}(\mathbb{R}), (2\pi)^{-1/2}e^{-x^2/2}dx)$.

2.3 Stein's equations

See [15, Chapter 3] for more details on the content of this section. Let $N \sim \mathcal{N}(0,1)$. Given a bounded and continuous function $g : \mathbb{R} \rightarrow \mathbb{R}$, we define the *Stein's equation* associated with g to be the ordinary differential equation

$$f'(x) - xf(x) = g(x) - E[g(N)]. \quad (2.8)$$

It is easily checked that every solution to (2.8) has the form $ce^{x^2/2} + f_g(x)$, where

$$f_g(x) = e^{x^2/2} \int_{-\infty}^x \{g(y) - E[g(N)]\} e^{-y^2/2} dy, \quad x \in \mathbb{R}. \quad (2.9)$$

Some relevant properties of f_g appear in the next statement (see e.g. [15, Section 3.3] for proofs).

Proposition 2.1 (Stein's bounds) *Assume $g : \mathbb{R} \rightarrow \mathbb{R}$ is continuous and bounded. Then f_g given by (2.9) is C^1 and satisfies*

$$\|f_g\|_\infty \leq \sqrt{\pi/2} \|g - E[g(N)]\|_\infty \quad \text{and} \quad \|f'_g\|_\infty \leq 2 \|g - E[g(N)]\|_\infty.$$

2.4 The language of Gaussian analysis and Malliavin calculus

We now briefly recall some basic notation and results connected to Gaussian analysis and Malliavin calculus. The reader is referred to [15, 19] for details.

Let \mathfrak{H} be a real separable Hilbert space with inner product $\langle \cdot, \cdot \rangle_{\mathfrak{H}}$. Recall that an *isonormal Gaussian process* over \mathfrak{H} is a centered Gaussian family $X = \{X(h) : h \in \mathfrak{H}\}$, defined on an adequate probability space (Ω, \mathcal{F}, P) and such that $E[X(h)X(h')] = \langle h, h' \rangle_{\mathfrak{H}}$, for every $h, h' \in \mathfrak{H}$. For every $q = 0, 1, 2, \dots$, we denote by C_q the q th *Wiener chaos* of X . We recall that $C_0 = \mathbb{R}$ and, for $q \geq 1$, C_q is the L^2 -closed space composed of those random variables having the form $I_q(f)$ where I_q indicates a *multiple Wiener-Itô* integral of order q and $f \in \mathfrak{H}^{\odot q}$ (the q th symmetric tensor power of \mathfrak{H}). Recall that $L^2(\sigma(X), P) := L^2(P) = \bigoplus_{q=0}^{\infty} C_q$, that is: every square-integrable random variable F that is measurable with respect to $\sigma(X)$ (the σ -field generated by X) admits a unique decomposition of the type

$$F = E[F] + \sum_{q=1}^{\infty} I_q(f_q), \quad (2.10)$$

where the series converges in $L^2(P)$, and $f_q \in \mathfrak{H}^{\odot q}$, for $q \geq 1$. This last result is known as the *Wiener-Itô chaotic decomposition* of $L^2(P)$. When the kernels f_q in (2.10) all equal zero except for a finite number, we say that F has a *finite chaotic expansion*. According to a classical result (discussed e.g. in [15, Section 2.10]) the distribution of non-zero random variables with a finite chaotic expansion has necessarily a density with respect to the Lebesgue measure.

We will use some standard operators from Malliavin calculus. The *Malliavin derivative* D has domain $\mathbb{D}^{1,2} \subset L^2(P)$, and takes values in the space $L^2(P; \mathfrak{H})$ of square-integrable \mathfrak{H} -valued random variables that are measurable with respect to $\sigma(X)$. The *divergence operator* δ is defined as the adjoint of D . In particular, denoting by $\text{dom } \delta$ the domain of δ , one has the so-called *integration by parts formula*: for every $D \in \mathbb{D}^{1,2}$ and every $u \in \delta(u)$,

$$E[F\delta(u)] = E[\langle DF, u \rangle_{\mathfrak{H}}]. \quad (2.11)$$

We will also need the so-called *generator of the Ornstein-Uhlenbeck semigroup*, written L , which is defined by the relation

$$L = -\delta D,$$

meaning that F is in $\text{dom } L$ (the domain of L) if and only if $F \in \mathbb{D}^{1,2}$ and $DF \in \text{dom } \delta$, and in this case $LF = -\delta DF$. The *pseudo-inverse* of L is denoted by L^{-1} . It is important to note that L and L^{-1} are completely determined by the following relations, valid for every $c \in \mathbb{R}$, every $q \geq 1$ and every $f \in \mathfrak{H}^{\odot q}$:

$$Lc = L^{-1}c = 0, \quad LI_q(f) = -qI_q(f), \quad L^{-1}I_q(f) = -\frac{1}{q}I_q(f).$$

We will exploit the following *chain rule* (see e.g. [15, Section 2.3]): for every $F \in \mathbb{D}^{1,2}$ and every mapping $\varphi : \mathbb{R} \rightarrow \mathbb{R}$ which is continuously differentiable and with a bounded derivative, one has that $\varphi(F) \in \mathbb{D}^{1,2}$, and moreover

$$D\varphi(F) = \varphi'(F)DF. \quad (2.12)$$

We conclude this section by recalling the definition of the operators Γ_j , as first defined in [14]; see [15, Chapter 8] for a discussion of recent developments.

Definition 2.2 (Gamma operators) Let F be a random variable having a finite chaotic expansion. The sequence of random variables $\{\Gamma_j(F) : j \geq 0\}$ is recursively defined as follows. Set $\Gamma_0(F) = F$ and, for every $j \geq 1$,

$$\Gamma_j(F) = \langle DF, -DL^{-1}\Gamma_{j-1}(F) \rangle_{\mathfrak{H}}.$$

In view of the product formulae for multiple integrals (see e.g. [15, Theorem 2.7.10]), each $\Gamma_j(F)$ is a well-defined random variable having itself a finite chaotic expansion.

2.5 Some useful bounds

The next bound contains the main result of [12], in a slightly more general form (whose proof can be found in [9]) not requiring that the random variable F has a density.

Proposition 2.3 (General total variation bound) Let F be a centered element of $\mathbb{D}^{1,2}$, and let $N \sim \mathcal{N}(0, 1)$. Then,

$$d_{TV}(F, N) \leq 2E |E[1 - \langle DF, -DL^{-1}F \rangle_{\mathfrak{H}} | F]| \leq 2E |1 - \langle DF, -DL^{-1}F \rangle_{\mathfrak{H}}|. \quad (2.13)$$

In particular, if $F = I_q(f)$ belongs to the q th Wiener chaos C_q and F has unit variance, one has that $\langle DF, -DL^{-1}F \rangle_{\mathfrak{H}} = \frac{1}{q} \|DF\|_{\mathfrak{H}}^2$, $E[F^4] > 3$, and the following inequality holds:

$$E \left| 1 - \frac{1}{q} \|DF\|_{\mathfrak{H}}^2 \right| \leq \sqrt{\frac{q-1}{3q} (E[F^4] - 3)}. \quad (2.14)$$

Of course, relation (2.14) is equivalent to (1.1). In particular, using the language of cumulants, the estimates in the previous statement yield that, for $F = I_q(f)$ ($q \geq 2$) with unit variance,

$$d_{TV}(F, N) \leq \frac{2}{\sqrt{3}} \sqrt{\kappa_4(F)}. \quad (2.15)$$

The following result (which is taken from [2]) provides some useful bounds on the Gamma operators introduced in Definition 2.2.

Proposition 2.4 (Estimates on Gamma operators) For each integer $q \geq 2$ there exists positive constants c_0, c_1, c_2 (only depending on q) such that, for all $F = I_q(f)$ with $f \in \mathfrak{H}^{\odot q}$ and $E[F^2] = 1$, one has

$$\begin{aligned} E \left[\left(\Gamma_2(F) - \frac{1}{2} \kappa_3(F) \right)^2 \right]^{1/2} &\leq c_0 \kappa_4(F)^{\frac{3}{4}}; \\ E[|\Gamma_3(F)|] &\leq c_1 \kappa_4(F); \\ E[|\Gamma_4(F)|] &\leq c_2 \kappa_4(F)^{\frac{5}{4}}. \end{aligned} \quad (2.16)$$

Proof. See [2, Proposition 4.3]. ■

3 Proof of Theorem 1.2

Since $E[F_n^2] = 1$, the fact that F_n converges in distribution to $N \sim \mathcal{N}(0, 1)$ if and only if $E[F_n^4] \rightarrow 3$ is a direct consequence of the main result of [20]. Whenever $E[F_n^4] \rightarrow 3$, one has that the collection of random variables $\{F_n^3 : n \geq 1\}$ is uniformly integrable, in such

a way that, necessarily, $E[F_n^3] \rightarrow E[N^3] = 0$. The upper and lower bounds appearing in formula (1.6) will be proved separately.

(Upper bound) We first establish some preliminary estimates concerning a general centered random variable $F \in \mathbb{D}^{1,2}$. We have

$$\begin{aligned} \frac{1}{2}d_{TV}(F, N) &\leq E[|E[1 - \langle DF, -DL^{-1}F \rangle | F]|] \\ &= E\left[E[1 - \langle DF, -DL^{-1}F \rangle | F] \times \text{sign}\{E[1 - \langle DF, -DL^{-1}F \rangle | F]\}\right] \\ &\leq \sup_{g \in C_c^1: \|g\|_\infty \leq 1} E[g(F)(1 - \langle DF, -DL^{-1}F \rangle)], \end{aligned}$$

where C_c^1 denotes the class of all continuously differentiable functions with compact support, and we have implicitly applied Lusin's Theorem. Fix a test function $g \in C_c^1$ bounded by 1, and consider a random variable $N \sim \mathcal{N}(0, 1)$ independent of F . By virtue of Proposition 2.1, writing $\varphi = f_g$ for the solution of the Stein's equation associated with g (see (2.9)), one has that $\|\varphi\|_\infty \leq 2\sqrt{\frac{2}{\pi}}$ and $\|\varphi'\|_\infty \leq 4$. Exploiting independence together with the fact that $E[1 - \langle DF, -DL^{-1}F \rangle] = 1 - \text{Var}(F) = 0$, we deduce that

$$\begin{aligned} &E[g(F)(1 - \langle DF, -DL^{-1}F \rangle)] \\ &= E[(g(F) - E[g(N)])(1 - \langle DF, -DL^{-1}F \rangle)] \\ &= E[(\varphi'(F) - F\varphi(F))(1 - \langle DF, -DL^{-1}F \rangle)] \\ &= E[\varphi'(F)(1 - \langle DF, -DL^{-1}F \rangle)] - E[\varphi'(F)\langle DF, -DL^{-1}F \rangle(1 - \langle DF, -DL^{-1}F \rangle)] \\ &\quad + E[\varphi(F)\Gamma_2(F)] \\ &= E[\varphi'(F)(1 - \langle DF, -DL^{-1}F \rangle)^2] + E[\varphi(F)\Gamma_2(F)], \end{aligned}$$

where we have used several times the integration by parts formula (2.11). In order to properly assess the term $E[\varphi(F)\Gamma_2(F)]$, we shall consider the function $\psi = f_\varphi$, corresponding to the solution of the Stein's equation associated with φ . Using again Proposition 2.1, we deduce the estimates $\|\psi\|_\infty \leq \frac{8}{\pi}$ and $\|\psi'\|_\infty \leq 16$, and moreover

$$\begin{aligned} &E[\varphi(F)\Gamma_2(F)] - \frac{1}{2}E[\varphi(N)\kappa_3(F)] \\ &= E[(\varphi(F) - E[\varphi(N)])\Gamma_2(F)] = E[(\psi'(F) - F\psi(F))\Gamma_2(F)] \\ &= E[\psi'(F)\Gamma_2(F)] - E[\psi'(F)\langle DF, -DL^{-1}F \rangle\Gamma_2(F)] + E[\psi(F)\Gamma_3(F)] \\ &= E[\psi'(F)(1 - \langle DF, -DL^{-1}F \rangle)\Gamma_2(F)] + E[\psi(F)\Gamma_3(F)], \end{aligned}$$

where we used once again independence and integration by parts. Combining the previous bounds, one infers that

$$\begin{aligned} d_{TV}(F, N) &\leq \sqrt{\frac{2}{\pi}}|\kappa_3(F)| + 2\sqrt{\frac{2}{\pi}}E[(1 - \langle DF, -DL^{-1}F \rangle)^2] \\ &\quad + 16\sqrt{E[(1 - \langle DF, -DL^{-1}F \rangle)^2]}\sqrt{E[\Gamma_2(F)^2]} + \frac{8}{\pi}E[|\Gamma_3(F)|]. \end{aligned}$$

To conclude, let us consider a sequence $F_n = I_q(f_n)$, $n \geq 1$, living in the q th Wiener chaos of X and such that each F_n has variance 1. Assume that F_n converges in distribution to N . Then, for n large enough one has that $|\kappa_3(F_n)| \leq 1$ and $\kappa_4(F_n) \leq 1$. Using Proposition 2.4, we immediately deduce that, for some universal constant $c_q > 0$ (depending only on q),

$$\begin{aligned} d_{TV}(F_n, N) &\leq c_q \left(|\kappa_3(F_n)| + \kappa_4(F_n) + \sqrt{\kappa_4(F_n)}\sqrt{\kappa_3(F_n)^2 + \kappa_4(F_n)^{3/2}} \right) \\ &\leq C \max(|\kappa_3(F_n)|, \kappa_4(F_n)), \end{aligned}$$

where C is the constant appearing in the statement.

(Lower bound) According to the representation (1.3), the distance $d_{TV}(F_n, N)$ is bounded from below by the quantity

$$\frac{1}{2} \max \{ |E[\cos(F_n)] - E[\cos(N)]|, |E[\sin(F_n)] - E[\sin(N)]| \}. \quad (3.17)$$

Combining [2, Corollary 3.12] with Proposition 2.4, one can write

$$\begin{aligned} \left| E[\sin(F_n)] - E[\sin(N)] - \frac{1}{2} E[f''_{\sin}(F_n)] \kappa_3(F_n) - \frac{1}{6} E[f'''_{\sin}(F_n)] \kappa_4(F_n) \right| &\leq 2E|\Gamma_4(F_n)| \\ &\leq C \kappa_4(F_n)^{\frac{5}{4}}. \end{aligned}$$

Here, C denotes a positive constant which is independent of n and whose value can change from line to line, whereas f_{\sin} stands for the solution of the Stein's equation associated with the sine function, as given in (2.9). From [2, formula (5.2)], one has that $E[f''_{\sin}(N)] = -\frac{1}{3}E[\sin(N)H_3(N)] = \frac{1}{\sqrt{e}}$. Similarly, $E[f'''_{\sin}(N)] = -\frac{1}{4}E[\sin(N)H_4(N)] = 0$. Moreover, from [6, Theorem 1.1] it comes that f''_{\sin} and f'''_{\sin} are both bounded by 2. Finally, from (2.15) one has that $d_{TV}(F_n, N) \leq C\sqrt{\kappa_4(F_n)}$. Combining all these facts leads to

$$\begin{aligned} \frac{1}{4} |E[f''_{\sin}(F_n)] - E[f''_{\sin}(N)]| \leq d_{TV}(F_n, N) &\leq C\sqrt{\kappa_4(F_n)}; \\ \frac{1}{4} |E[f'''_{\sin}(F_n)] - E[f'''_{\sin}(N)]| \leq d_{TV}(F_n, N) &\leq C\sqrt{\kappa_4(F_n)} \end{aligned}$$

so that

$$\left| E[\sin(F_n)] - E[\sin(N)] - \frac{1}{2\sqrt{e}} \kappa_3(F_n) \right| \leq C \max \{ |\kappa_3(F_n)|, \kappa_4(F_n) \} \times \kappa_4(F_n)^{\frac{1}{4}}.$$

Similarly, one shows that

$$\left| E[\cos(F_n)] - E[\cos(N)] + \frac{1}{4\sqrt{e}} \kappa_4(F_n) \right| \leq C \max \{ |\kappa_3(F_n)|, \kappa_4(F_n) \} \times \kappa_4(F_n)^{\frac{1}{4}}.$$

As a consequence, exploiting the lower bound (3.17) we deduce that

$$d_{TV}(F_n, N) \geq \left(\frac{1}{4\sqrt{e}} - C\kappa_4(F_n)^{\frac{1}{4}} \right) \max (|\kappa_3(F_n)|, \kappa_4(F_n)),$$

so that the proof of the theorem is concluded.

4 Application to the Hermite variations of the discrete-time fractional Brownian motion

We now discuss an application of Theorem 1.2 to non-linear functionals of a fractional Brownian motion. Consider a fractional Brownian motion with Hurst index $H \in (0, 1)$. We recall that $B_H = \{B_H(t) : t \in \mathbb{R}\}$ is a centered Gaussian process with continuous paths such that

$$E[B_H(t)B_H(s)] = \frac{1}{2} (|t|^{2H} + |s|^{2H} - |t-s|^{2H}), \quad s, t \in \mathbb{R}.$$

The process B_H is self-similar with stationary increments. We refer the reader to Nourdin [10] for a self-contained introduction to its main properties.

In this section, we shall rather work with the so-called *fractional Gaussian noise* associated with B_H , which is the Gaussian sequence given by

$$X_k = B_H(k+1) - B_H(k), \quad k \in \mathbb{Z}. \quad (4.18)$$

Note that the family $\{X_k : k \in \mathbb{Z}\}$ constitutes a centered stationary Gaussian family with covariance

$$\rho(k) = E[X_r X_{r+k}] = \frac{1}{2} (|k+1|^{2H} - 2|k|^{2H} + |k-1|^{2H}), \quad r, k \in \mathbb{Z}.$$

Also, it is readily checked that $\rho(k)$ behaves asymptotically as $\rho(k) \sim H(2H-1)|k|^{2H-2}$ as $|k| \rightarrow \infty$.

Now fix an integer $q \geq 2$, consider the q th Hermite polynomial H_q , and set

$$F_n := \frac{1}{\sqrt{n} v_n} \sum_{k=0}^{n-1} H_q(X_k),$$

with $v_n > 0$ chosen so that $E[F_n^2] = 1$. An important problem in modern Gaussian analysis is to characterise those values of H, q such that the sequence F_n verifies a CLT. The following statement is the celebrated *Breuer-Major CLT*, first proved in [3] (see [15, Chapter 7] for a modern proof and for an overview of its many ramifications).

Theorem 4.1 (Breuer-Major CLT [3]) *Let the previous notation and assumptions prevail. Then, one has that*

$$F_n \xrightarrow{\text{Law}} N \sim \mathcal{N}(0, 1), \quad \text{as } n \rightarrow \infty, \quad (4.19)$$

if and only if H belongs to the interval $(0, 1 - \frac{1}{2q}]$.

Deducing explicit estimates on the speed of convergence in the CLT (4.19) is a difficult problem, that has generated a large amount of research (see [10, 15] for an overview of the available literature, as well as [1, 2, 11] for recent developments). Using our Theorem 1.2 together with the forthcoming Proposition 4.2 allows one to deduce exact rates of convergence in total variation for every value of q, H such that $H \in (0, 1 - \frac{1}{2q})$. We adopt the following convention for non-negative sequences (u_n) and (v_n) : we write $v_n \propto u_n$ to indicate that $0 < \liminf_{n \rightarrow \infty} v_n/u_n \leq \limsup_{n \rightarrow \infty} v_n/u_n < \infty$.

Proposition 4.2 (See [2]) *Let the above notation and assumptions prevail.*

1. If q is odd, then $\kappa_3(F_n) = E[F_n^3] = 0$ for every n .
2. For every even integer $q \geq 2$,

$$\kappa_3(F_n) \propto \begin{cases} n^{-\frac{1}{2}} & \text{if } 0 < H < 1 - \frac{2}{3q} \\ n^{-\frac{1}{2}} \log^2 n & \text{if } H = 1 - \frac{2}{3q} \\ n^{\frac{3}{2} - 3q + 3qH} & \text{if } 1 - \frac{2}{3q} < H < 1 - \frac{1}{2q} \end{cases}.$$

3. For $q \in \{2, 3\}$, one has that

$$\kappa_4(F_n) \propto \begin{cases} n^{-1} & \text{if } 0 < H < 1 - \frac{3}{4q} \\ n^{-1} \log^3 n & \text{if } H = 1 - \frac{3}{4q} \\ n^{4qH - 4q + 2} & \text{if } 1 - \frac{3}{4q} < H < 1 - \frac{1}{2q} \end{cases}. \quad (4.20)$$

4. For every integer $q > 3$,

$$\kappa_4(F_n) \propto \begin{cases} n^{-1} & \text{if } 0 < H < \frac{3}{4} \\ n^{-1} \log(n) & \text{if } H = \frac{3}{4} \\ n^{4H-4} & \text{if } \frac{3}{4} < H < 1 - \frac{1}{2q-2} \\ n^{4H-4} \log^2 n & \text{if } H = 1 - \frac{1}{2q-2} \\ n^{4qH-4q+2} & \text{if } 1 - \frac{1}{2q-2} < H < 1 - \frac{1}{2q} \end{cases}. \quad (4.21)$$

Considering for example the cases $q = 2$ and $q = 3$ yields the following exact asymptotics, which are outside the scope of any other available technique.

Proposition 4.3 1. If $q = 2$, then

$$d_{TV}(F_n, N) \propto \begin{cases} n^{-\frac{1}{2}} & \text{if } 0 < H < \frac{2}{3} \\ n^{-\frac{1}{2}} \log^2 n & \text{if } H = \frac{2}{3} \\ n^{6H - \frac{9}{2}} & \text{if } \frac{2}{3} < H < \frac{3}{4} \end{cases}.$$

2. If $q = 3$, then

$$d_{TV}(F_n, N) \propto \begin{cases} n^{-1} & \text{if } 0 < H < \frac{3}{4} \\ n^{-1} \log^3 n & \text{if } H = \frac{3}{4} \\ n^{12H - 10} & \text{if } \frac{3}{4} < H < \frac{5}{6} \end{cases}.$$

References

- [1] H. Biermé, A. Bonami and J.R. León (2011). Central limit theorems and quadratic variations in terms of spectral density. *Electron. J. Probab.* **16**(13), 362-395.
- [2] H. Biermé, A. Bonami, I. Nourdin and G. Peccati (2012). Optimal Berry-Esseen rates on the Wiener space: the barrier of third and fourth cumulants. *ALEA* **9**(2), 473-500.
- [3] P. Breuer and P. Major (1983). Central limit theorems for non-linear functionals of Gaussian fields. *J. Mult. Anal.* **13**, 425-441.
- [4] S. Campese (2013). Optimal convergence rates and one-term Edgeworth expansions for multidimensional functionals of Gaussian fields. In preparation.
- [5] L. H. Y. Chen, L. Goldstein, and Q.-M. Shao (2011). *Normal approximation by Stein's method*. Probability and its Applications (New York). Springer, Heidelberg.
- [6] F.A. Daly (2008). Upper bounds for Stein-type operators. *Electron. J. Probab.* **13**, paper 20, 566-587.
- [7] R. M. Dudley (1989). *Real analysis and probability*. The Wadsworth & Brooks/Cole Mathematics Series. Wadsworth & Brooks/Cole Advanced Books & Software, Pacific Grove, CA.
- [8] D. Marinucci and G. Peccati (2011). *Random fields on the sphere : Representation, limit theorems and cosmological applications*, volume 389 of *London Mathematical Society Lecture Note Series*. Cambridge University Press, Cambridge.
- [9] I. Nourdin (2013). Lectures on Gaussian approximations with Malliavin calculus. To appear in: *Séminaire de probabilités*.
- [10] I. Nourdin (2012). *Selected Aspects of Fractional Brownian Motion*. Springer-Verlag.
- [11] I. Nourdin, D. Nualart and C.A. Tudor (2010). Central and non-central limit theorems for weighted power variations of fractional Brownian motion. *Ann. I.H.P.* **46**(4), 1055-1079.
- [12] I. Nourdin and G. Peccati (2009): Stein's method on Wiener chaos. *Probab. Theory Relat. Fields* **145**, no. 1, 75-118.
- [13] I. Nourdin and G. Peccati (2009): Stein's method and exact Berry-Esseen asymptotics for functionals of Gaussian fields. *Ann. Probab.* **37**, no. 6, 2231-2261.
- [14] I. Nourdin and G. Peccati (2010). Cumulants on the Wiener space. *J. Funct. Anal.* **258**, 3775-3791.
- [15] I. Nourdin and G. Peccati (2012). *Normal approximations with Malliavin calculus : from Stein's method to universality*. Cambridge Tracts in Mathematics. Cambridge University Press.

- [16] I. Nourdin, G. Peccati, and G. Reinert (2010). Invariance principles for homogeneous sums: universality of Gaussian Wiener chaos. *Ann. Probab.* **38**(5):1947–1985.
- [17] I. Nourdin, G. Peccati and Y. Swan (2013). Entropy and the fourth moment phenomenon. Preprint.
- [18] I. Nourdin and F. G. Viens (2009). Density formula and concentration inequalities with Malliavin calculus. *Electron. J. Probab.* **14**, 2287–2309.
- [19] D. Nualart (2006). *The Malliavin calculus and related topics*. Probability and its Applications (New York). Springer-Verlag, Berlin, second edition.
- [20] D. Nualart and G. Peccati (2005). Central limit theorems for sequences of multiple stochastic integrals. *Ann. Probab.* **33**(1), 177–193.
- [21] F. G. Viens (2009). Stein’s lemma, Malliavin calculus, and tail bounds, with application to polymer fluctuation exponent. *Stochastic Process. Appl.* **119**(10), 3671–3698.