

UNIFORM APPROXIMATIONS IN THE CLT FOR BALLS IN EUCLIDIAN SPACES

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1. INTRODUCTION AND MAIN RESULTS

Let X, X_1, X_2, \dots be independent identically distributed random elements with values in a real separable Hilbert space H . Let (x, y) for $x, y \in H$ denote the inner product in H and put $|x| = (x, x)^{1/2}$. We assume that $\mathbb{E}|X_1|^2 < \infty$ and denote by V a covariance operator of X_1

$$(Vx, y) = \mathbb{E}(X_1 - \mathbb{E}X_1, x)(X_1 - \mathbb{E}X_1, y).$$

Let $\sigma_1^2 \geq \sigma_2^2 \geq \dots$ be the eigenvalues of V and let e_1, e_2, \dots be the corresponding eigenvectors which we assume to be orthonormal. We define

$$S_n = n^{-1/2} \sigma^{-1} \sum_{i=1}^n (X_i - \mathbb{E}X_i),$$

where $\sigma^2 = \mathbb{E}|X_1 - \mathbb{E}X_1|^2$. Without loss of generality we may assume that $\mathbb{E}X_1 = 0$ and $\mathbb{E}|X_1|^2 = 1$. The general case can be reduced to this one when we consider $(X_i - \mathbb{E}X_i)/\sigma$ instead of X_i , $i = 1, 2, \dots$. For any integer $k > 0$ we put

$$c_k(V) = \prod_1^k \sigma_i^{-1}, \quad \bar{c}_k(V) = \left(\prod_1^k \sigma_i^{-1} \right)^{(k-1)/k}. \quad (1.1)$$

In what follows we use c and $c(\cdot)$, with or without indices, to denote generic constants and constants depending on parameters in brackets. Except for $c_i(V)$ and $\bar{c}_i(V)$ the same symbol may be used for various constants. Let Y, Y_1, Y_2, \dots be independent H -valued Gaussian $(0, V)$ random elements. Put for any $a \in H$

$$F(x) = P\{|S_n - a|^2 \leq x\}, \quad F_0(x) = P\{|Y - a|^2 \leq x\},$$

$$\delta_n(a) = \sup_x |F(x) - F_0(x)|.$$

It is known (see e.g. Sazonov (1968) and Bentkus (1986)) that in the case $H = \mathbb{R}^d$, $d < \infty$, i.e. in the finite dimensional case, we have

$$\delta_n(a) \leq c \mathbb{E}|X_1|^3 \sigma_d^{-3} n^{-1/2}$$

and the bound is optimal with respect to the dependence on moments, eigenvalues as well as n .

However in the infinite dimensional case the situation essentially changes. Here we have (see e.g. Sazonov (1981), ch.2)

$$\sup_a \delta_n(a) \geq 1/2.$$

The development of bounds for $\delta_n(a)$ in the infinite dimensional case can be divided roughly into three phases: proving bounds with optimal

- dependence on n ;
- moment conditions;
- dependence on the eigenvalues of V .

The first phase started in the middle of 60-s with bounds of logarithmic order for $\delta_n(a)$ (see Kandelaki (1965)) and ended with the result:

$$\delta_n(a) = \mathcal{O}(n^{-1/2}),$$

due to Götze (1979), which was based on a Weyl type symmetrization inequality, which since then has been successfully applied and developed by a number of authors.

The second phase finishes with a paper by Yurinskii (1982) proving

$$\delta_n(a) \leq \frac{c(V)}{\sqrt{n}} (1 + |a|^3) \mathbb{E}|X_1|^3,$$

where $c(V)$ is denotes a constant depending on V only.

At the end of the third phase it was proved (see Sazonov, Ulyanov and Zaleskii (1988b), Nagaev (1989), Senatov (1989))

$$\delta_n(a) \leq \frac{c \, c_6(V)}{\sqrt{n}} (1 + |a|^3) \mathbb{E}|X_1|^3, \quad (1.2)$$

where $c_6(V)$ is defined in (1.1). It is known that for any $c_0 > 0$ and for any given eigenvalues $\sigma_1^2, \dots, \sigma_6^2$ of a covariance operator V there exist (see example 3 in Senatov (1985)) a vector $a \in H$, $|a| > c_0$, and a sequence X_1, X_2, \dots of i.i.d. random elements in H with zero mean and covariance operator V such that

$$\liminf_{n \rightarrow \infty} \sqrt{n} \, \delta_n(a) \geq c \, c_6(V) (1 + |a|^3) \mathbb{E}|X_1|^3. \quad (1.3)$$

Thus, bound (1.2) is the best possible in case of finite third moment of $|X_1|$. For further refinements see Senatov (1997).

At the same time better approximations for $F(x)$ are available using an additional term, say $F_1(x)$, of its asymptotic expansion. This term $F_1(x)$ is

defined as the unique function satisfying $F_1(-\infty) = 0$ with Fourier-Stieltjes transform equal to

$$\hat{F}_1(t) = -\frac{2t^2}{3\sqrt{n}} \mathbb{E} e\{t|Y - a|^2\} (3(X, Y - a)|X|^2 + 2it(X, Y - a)^3). \quad (1.4)$$

Here and in the following we write $e\{x\} = \exp\{ix\}$.

Introduce the error

$$\Delta_n(a) = \sup_x |F(x) - F_0(x) - F_1(x)|.$$

Note that $\hat{F}_1(t) = 0$ and hence $F_1(x) = 0$ when $a = 0$ or X has a symmetric distribution, i.e. when X and $-X$ are identically distributed. Therefore, we get

$$\Delta_n(0) = \delta_n(0).$$

Similar to the developments of bounds for $\delta_n(a)$ the first task has been to derive bounds for $\Delta_n(a)$ with optimal dependence on n . Starting with a seminal paper by Esseen (1945) for finite dimensional spaces $H = \mathbb{R}^d$, $d < \infty$ who proved

$$\Delta_n(0) = \mathcal{O}(n^{-d/(d+1)}), \quad (1.5)$$

a comparable bound

$$\Delta_n(0) = \mathcal{O}(n^{-\gamma})$$

with $\gamma = 1 - \varepsilon$ for any $\varepsilon > 0$. was finally proved in Götze(1979, 1984), based on Weyl type inequalities mentioned above. Further refinements and generalizations in the case $a \neq 0$ and $\gamma < 1$ are due to Bentkus and Zaleskii (1985), Nagaev and Chebotarev (1986), Sazonov, Ulyanov and Zaleskii (1988a). Note however, that the results in the infinite dimensional case did not even yield (1.5) as corollary when $\sigma_{d+1} = 0$. Fifty years after Essen's result the optimal bounds (in n)

$$\Delta_n(0) \leq \frac{c(9, V)}{n} \mathbb{E}|X_1|^4, \quad (1.6)$$

$$\Delta_n(a) \leq \frac{c(13, V)}{n} (1 + |a|^6) \mathbb{E}|X_1|^4, \quad (1.7)$$

where $c(i, V) \leq \exp\{c\sigma_i^{-2}\}$, $i = 9, 13$. were finally established in Bentkus and Götze (1997), using new techniques which allowed to prove optimal bounds in classical lattice point problems as well.

The bounds (1.6) and (1.7) are optimal with respect to the dependence on n (Götze 1998b) and on moments. The bound (1.6) improves as well Esseen's result (1.5) for Euclidean spaces \mathbb{R}^d with $d > 8$. However the dependence on covariance operator V in (1.6), (1.7) can be improved. Nagaev and Chebotarev

(1999) considered the case $a = 0$ and got a bound of type (1.6) replacing $c(9, V)$ by the following function $c(V)$:

$$c(V) = c \left(\bar{c}_{13}(V) + (c_4(V))^{4/9} \sigma_9^{-6} \right),$$

where $\bar{c}_{13}(V)$ and $c_9(V)$ are defined by (1.1). This improves the dependence on the eigenvalues of V (compared to (1.6)) but still requires that $\sigma_{13} > 0$ instead of the weaker condition $\sigma_9 > 0$ in (1.6).

The aim of the present paper is to derive a bound for $\Delta_n(a)$ in the general case $a \neq 0$ depending on *twelve* largest eigenvalues of V only (see Remarks after Corollary 1.4).

Theorem 1.1. *There exist absolute constants c, c_1, c_2 such that for any $a \in H$*

$$\begin{aligned} \Delta_n(a) &\leq \frac{c}{n} \cdot c_{12}(V) \cdot (\mathbb{E}|X_1|^4 + \mathbb{E}(X_1, a)^4) (1 + (Va, a)) \\ &\quad + c \int_{N_0 \leq |t| \leq N} \frac{|f_n(t)|}{|t|} dt, \end{aligned} \tag{1.8}$$

where $f_n(t) = \mathbb{E}e\{t|S_n - a|^2\}$ and

$$N_0 = \left(\frac{c_1 n \sigma_9^4}{(\mathbb{E}|X_1|^3)^2} \right)^{4/9}, \quad N = \frac{c_2 \sigma_9^8 n}{\sigma_1^4 (c_9(V))^{2/9} \mathbb{E}|X_1|^4}.$$

Theorem 1.2. *There exists an absolute constant c such that*

$$\int_{N_0 \leq |t| \leq N} \frac{|f_n(t)|}{|t|} dt \leq \frac{c}{n} \mathbb{E}|X_1|^4 \left(\sigma_1^4 (c_9(V))^{4/9} \sigma_9^{-8} + (c_9(V))^{1/2} \sigma_9^{-4} \right).$$

Remark. The proof of Theorem 1.2 is based on Lemma 2.12. See the examples following Lemma 2.12 explaining why the bound of Theorem 1.2 depends on first *nine* eigenvalues of V only. Theorems 1.1 and 1.2 together imply

Corollary 1.3. *There exists an absolute constant c such that*

$$\begin{aligned} \Delta_n(a) &\leq \frac{c}{n} (c_{12}(V) + \sigma_1^4 \sigma_9^{-8} (c_9(V))^{4/9} + \sigma_9^{-4} (c_9(V))^{1/2}) \\ &\quad \times (\mathbb{E}|X_1|^4 + \mathbb{E}(X_1, a)^4) (1 + (Va, a)). \end{aligned}$$

Corollary 1.4. *If*

$$c_{12}(V) \geq \sigma_1^4 \sigma_9^{-8} (c_9(V))^{1/2}, \tag{1.9}$$

then there exists c such that

$$\Delta_n(a) \leq \frac{c}{n} c_{12}(V) (1 + |a|^6) \mathbb{E}|X_1|^4. \tag{1.10}$$

Remark. Condition (1.9) is not very restrictive. For example, it is satisfied when $\sigma_1 = \dots = \sigma_9$ and arbitrary σ_i , $i = 10, 11, \dots$.

It follows from Lemma 2.6 (see below) that for any given eigenvalues $\sigma_1^2, \dots, \sigma_{12}^2 > 0$ of a covariance operator V there exist $a \in H$, $|a| > 1$, and a sequence X_1, X_2, \dots of i.i.d. random elements in H with zero mean and covariance operator V such that

$$\liminf_{n \rightarrow \infty} n \Delta_n(a) \geq c c_{12}(V) (1 + |a|^6) \mathbb{E}|X_1|^4.$$

Hence, (1.10) is best possible in the sense that it is impossible that $\Delta_n(a)$ is of order $\mathcal{O}(n^{-1})$ *uniformly* for distributions of X_1 with arbitrary eigenvalues $\sigma_1^2, \sigma_2^2, \dots$. This means any explicit bound in terms of eigenvalues has to depend on the first 12 eigenvalues of V .

For earlier versions of this result on the optimality of 12 eigenvalues and a detailed discussion of the connection of the rate problems in the central limit theorem with classical lattice point problems in analytic number theory, see the ICM-1998 Proceedings paper by Götze (1998b), and also *ibid.* (1998a).

Note however that in special 'symmetric' cases of the distribution of X_1 or of the center, say a , of the ball, the number of eigenvalues which are necessary for optimal bounds may well decrease below 12. For example, when $\mathbb{E}(X, b)^3 = 0$ for all $b \in H$, by Corollary 2.7 (see below) for any given eigenvalues $\sigma_1^2, \dots, \sigma_8^2 > 0$ of a covariance operator V there exists a center $a \in H$, $|a| > 1$, and a sequence X, X_1, X_2, \dots of i.i.d. random elements in H with zero mean and covariance operator V such that

$$\liminf_{n \rightarrow \infty} n \Delta_n(a) \geq c c_8(V) (1 + |a|^4) \mathbb{E}|X_1|^4.$$

Hence, in this case an upper bound of order $\mathcal{O}(n^{-1})$ for $\Delta_n(a)$ has to involve at least the *eight* largest eigenvalues of V .

Furthermore, lower bounds for $n\Delta_n(a)$ in the case $a = 0$ are not available. A conjecture, see Götze (1998b), says that in this case the five first eigenvalues of V suffice. This conjecture is motivated by the special case where the sums of random vectors have independent coordinates where indeed we have $\Delta_n(a) = \mathcal{O}(n^{-1})$ provided that $\sigma_5 > 0$ only, see Bentkus and Götze (1996).

The proofs of the Theorems are given in Section 3. They are based on the Lemmas from Section 2.

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2. AUXILIARY RESULTS

Let Z_j for $j = 1, 2, \dots$ be i.i.d. random elements with distribution Q such that $Q = (Q_1 + Q_2)/2$, where Q_1, Q_2 are probability measures, $Q_1(B_L) = 1$ for a ball $B_L = \{x \in H : |x|^2 < L\}$ with some $L > 0$ and a covariance operator V' of Q_1 has a trace $\text{tr} V' \leq 2$. Let Y be a Gaussian random element with parameters $(0, \alpha V)$, $\alpha > 0$. Assume that Y, Z_0, Z_{0j}, Z_j for $j = 1, 2, \dots$ are independent random elements. Let l, m, n_0, n be positive integers such that $l \leq m$, $l + m \leq n$, $n_0 \leq n$. Put

$$U_1 = n^{-1/2} \sum_1^{l+m} Z_j, \quad U_2 = n^{-1/2} \sum_1^{n_0} Z_{0j}.$$

Lemma 2.1. (see Lemma 4 in Sazonov, Ulyanov and Zaleskii (1991)) For any $A > 0$, any integer $r \geq 0$, $l > L^2$, and t satisfying

$$|t| \leq c(A) L^{-1} n (l \ln(L^{-2} l))^{-1/2}$$

as well as for arbitrary t if $l \leq L^2$, we have

$$\begin{aligned} & |\mathbb{E} \exp \{i t |U_1 + U_2 + Z_0|^2\} (x, U_1 + U_2)^r| \\ & \leq c_1 K_1 (\exp\{-c_2 l\} + c(A) (L^2/l)^A + h^{1/2}(c_3 t_1^2 l m / n^2, V')), \end{aligned}$$

where $c_j = c_j(r)$, $j = 1, 2, 3$,

$$K_1 = \mathbb{E} |(x, U_1 + U_2)^r| \quad \text{when } l < r + 1,$$

and for $l \geq r + 1$

$$K_1 = \sum_{j=1}^{r+1} \mathbb{E} |(x, U_{1j} + U_{2j})^r|$$

with $U_{1j} = n^{-1/2} \sum_{k=k_{j-1}}^{k_j} Z_k$, $k_j = j[(l+m)/(r+1)]$, $j = \overline{0, r}$, $k_{r+1} = l+m$ and U_{2j} for $j = \overline{1, r+1}$, form a partition of a sum U_2 into $r+1$ parts (some of which may be empty);

$$t_1 = \min\{|t|, L^{-1} n (m \ln(m/L^2))^{-1/2}\},$$

$$h(s, V') = \prod_{j=1}^{\infty} (1 + 2s(\sigma'_j)^4)^{-1/2}$$

and $(\sigma'_1)^2 \geq (\sigma'_2)^2 \geq \dots$ denote the eigenvalues of V' .

Moreover, for any t we have

$$|\mathbb{E} \exp \{i t |Y + U_2 + Z_0|^2\} (x, Y + U_2)^r| \leq c_4 K_2 h^{1/2}(c_5 t^2 \alpha, V),$$

where $c_j = c_j(r)$, $j = 4, 5$ and

$$K_2 = \sum_{j=1}^{r+1} \mathbb{E}|(x, Y_j + U_{2j})|^r,$$

where Y_j , $j = \overline{1, r+1}$ are i.i.d. Gaussian random elements in the representation $Y = \sum_{j=1}^{r+1} Y_j$ and U_{2j} , $j = \overline{1, r+1}$, form a partition of a sum U_2 into $r+1$ parts some of which may be empty.

We shall use the following *Rosenthal type inequality* (see e.g. Pinelis (1980) and de Acosta (1981)):

for independent random elements X_1, \dots, X_n in H with mean zero and for any $q \geq 2$ we have

$$\mathbb{E} \left| \sum_{i=1}^n X_i \right|^q \leq c(q) \left(\sum_{i=1}^n \mathbb{E}|X_i|^q + \left(\sum_{i=1}^n \mathbb{E}|X_i|^2 \right)^{q/2} \right).$$

Lemma 2.2. Let $T > 0$, $b \in \mathbb{R}^1$, $b \neq 0$, l be an integer, $l \geq 1$, $Y = (Y_1, \dots, Y_{2l})$ be a Gaussian random vector with values in \mathbb{R}^{2l} , Y_1, \dots, Y_{2l} are independent and $\mathbb{E}Y_i = 0$, $\mathbb{E}Y_i^2 = \sigma_i^2$ for $i = 1, 2, \dots, 2l$; $\sigma_1^2 \geq \sigma_2^2 \geq \dots \geq \sigma_{2l}^2 > 0$ and $a \in \mathbb{R}^{2l}$. Then there exists a positive constant $c = c(l)$ such that

$$\begin{aligned} I &\equiv \left| \int_{-T}^T s^{l-1} \mathbb{E} \exp\{is|Y + a|^2\} e^{ibs} ds \right| \\ &\leq c \prod_{j=1}^{2l} \sigma_j^{-1}. \end{aligned} \tag{2.1}$$

Proof. It is known that

$$\mathbb{E} \exp\{is|Y + a|^2\} = \prod_{j=1}^{2l} (1 - 2is\sigma_j^2)^{-1/2} \exp\{ia_j^2 s / (1 - 2is\sigma_j^2)\}.$$

Using Euler's formula for complex exponentials we get for positive g and any $d \in \mathbb{R}^1$

$$g + id = \sqrt{g^2 + d^2} e^{i\zeta} \quad \text{with } \zeta = \arcsin \frac{d}{\sqrt{g^2 + d^2}}.$$

Therefore, for I we have

$$\begin{aligned}
I &= \left| \int_{-T}^T s^{l-1} e^{isb} \prod_{j=1}^{2l} (1 + 4s^2 \sigma_j^4)^{-1/4} \right. \\
&\quad \times \exp \left(-\frac{2a_j^2 s^2 \sigma_j^2}{1 + 4s^2 \sigma_j^4} \right) \cdot \exp \left(\frac{ia_j^2 s}{1 + 4s^2 \sigma_j^4} + \frac{i\varphi_j}{2} \right) ds \Big| \\
&= \left| \int_{-T}^T s^{l-1} \text{trig} \left(sb + \sum_{j=1}^{2l} \left(\frac{a_j^2 s}{1 + 4s^2 \sigma_j^4} + \frac{\varphi_j}{2} \right) \right) \right. \\
&\quad \times \exp \left(-\sum_{j=1}^{2l} \frac{2a_j^2 s^2 \sigma_j^2}{1 + 4s^2 \sigma_j^4} \right) \prod_{j=1}^{2l} (1 + 4s^2 \sigma_j^4)^{-1/4} ds \Big|,
\end{aligned}$$

where $\varphi_j = \arcsin(2s\sigma_j^2/(1 + 4s^2\sigma_j^4)^{1/2})$ and

$$\text{trig}(x) = \begin{cases} \cos x & \text{if } l \text{ is odd,} \\ \sin x & \text{if } l \text{ is even.} \end{cases}$$

This decomposition has been suggested to us by N. Blagoveshchenskii.
We may write

$$\begin{aligned}
I &= 2 \prod_{j=1}^{2l} \sigma_j^{-1} \left| \int_0^T \frac{1}{s} \sin \left(sb + \sum_{j=1}^{2l} \left(\frac{a_j^2 s}{1 + 4s^2 \sigma_j^4} + \frac{1}{2}(\varphi_j - \frac{\pi}{2}) \right) \right) \right. \\
&\quad \times \exp \left(-\sum_{j=1}^{2l} \frac{2a_j^2 s^2 \sigma_j^2}{1 + 4s^2 \sigma_j^4} \right) \prod_{j=1}^{2l} \left(\frac{s^2 \sigma_j^4}{1 + 4s^2 \sigma_j^4} \right)^{1/4} ds \Big|. \tag{2.2}
\end{aligned}$$

Note that

$$\prod_{j=1}^{2l} \left(\frac{s^2 \sigma_j^4}{1 + 4s^2 \sigma_j^4} \right)^{1/4} \leq \sqrt{|s|} \sigma_{2l}.$$

Therefore it follows from (2.2) that in order to prove (2.1) it is enough to show

$$\begin{aligned}
&\left| \int_{1/\sigma_{2l}^2}^T \frac{1}{s} \sin \left(sb + \sum_{j=1}^{2l} \left(\frac{a_j^2 s}{1 + 4s^2 \sigma_j^4} + \frac{1}{2}(\varphi_j - \frac{\pi}{2}) \right) \right) \right. \\
&\quad \times \exp \left(-\sum_{j=1}^{2l} \frac{2a_j^2 s^2 \sigma_j^2}{1 + 4s^2 \sigma_j^4} \right) \prod_{j=1}^{2l} \left(\frac{s^2 \sigma_j^4}{1 + 4s^2 \sigma_j^4} \right)^{1/4} ds \Big| \leq c. \tag{2.3}
\end{aligned}$$

We shall use the following obvious inequalities

$$\begin{aligned} 0 < 1 - \left(\frac{4s^2\sigma_j^4}{1 + 4s^2\sigma_j^4} \right)^{1/4} &\leq \frac{1}{4s^2\sigma_{2l}^4} \text{ for } j = 1, 2, \dots, 2l; \\ |\sin(x + y) - \sin x| &\leq |y| \text{ and } |x|e^{-|x|} \leq 1 \text{ for any } x, y \in \mathbb{R}^1; \\ 0 &\leq \frac{\pi}{2} - \arcsin(1 - z) \leq 2^{3/2}z^{1/2} \text{ for } z : 0 \leq z \leq 1. \end{aligned}$$

In view of these inequalities the bound (2.3) follows from

$$\left| \int_{1/\sigma_{2l}^2}^T \frac{1}{s} \sin(sb) \exp \left(- \sum_{j=1}^{2l} \frac{2a_j^2 s^2 \sigma_j^2}{1 + 4s^2 \sigma_j^4} \right) ds \right| \leq c. \quad (2.4)$$

The inequality (2.4) is a consequence of the second mean-value formula for integrals (Bonnet's theorem) since the function

$$\exp \left(- \sum_{j=1}^{2l} \frac{2a_j^2 s^2 \sigma_j^2}{1 + 4s^2 \sigma_j^4} \right)$$

is a bounded and monotone function of s for $s > 0$ and for any positive a and b we have

$$\left| \int_a^b \frac{\sin x}{x} dx \right| \leq 2 \int_0^\pi \frac{\sin x}{x} dx$$

The Lemma is proved.

Lemma 2.3. *Let $Y_1, \dots, Y_d, Y'_1, \dots, Y'_d$ be i.i.d. Gaussian $(0, C)$ random elements in a Hilbert space H . Let $\sigma_1^2 \geq \sigma_2^2 \geq \dots$ be the eigenvalues of C . Put $W = (\det A)^2$, where $A = \{a_{ij}\}_{i,j=1}^d$ and $a_{ij} = (Y_i, Y'_j)$. Then*

$$\mathbb{E}W = (d!)^2 \sum_{1 \leq i_1 < \dots < i_d < \infty} \sigma_{i_1}^4 \dots \sigma_{i_d}^4, \quad (2.5)$$

$$(\mathbb{E}W^2)^{1/2} \leq d^2 9^{d+1} \mathbb{E}W. \quad (2.6)$$

Proof. Without loss of generality we may assume that an orthonormal base $\{e_i\}$ in H consists from the eigenvectors of C . By the assumptions of the Lemma we have

$$Y_i = \sum_{j=1}^{\infty} Y_{ij} e_j, \quad Y'_i = \sum_{j=1}^{\infty} Y'_{ij} e_j,$$

where $\{Y_{ij}\}, \{Y'_{ij}\}$ are independent real normal random variables

$$\mathbb{E}Y_{ij} = \mathbb{E}Y'_{ij} = 0, \quad \mathbb{E}Y_{ij}^2 = \mathbb{E}(Y'_{ij})^2 = \sigma_j^2, \quad i = 1, \dots, d; \quad j = 1, 2, \dots$$

According to the extension of the Lagrange identity for the determinants to Hilbert spaces, (see e.g. Greub (1978), ch. 5, §5.7, problem 4 or Smirnov (1964), ch. 1, §1, sect. 7) we can write

$$\det A = \sum_{<} \det Y(i) \cdot \det Y'(i), \quad (2.7)$$

where $Y(i)$ and $Y'(i)$ are the matrices $\{Y_{ki_l}\}_{k,l=1}^d$ and $\{Y'_{ki_l}\}_{k,l=1}^d$ respectively and the symbol $<$ indicates that the indices (i_1, \dots, i_d) are subject to the condition $1 \leq i_1 < \dots < i_d < \infty$. Note that $\mathbb{E} \det Y(i) = 0$,

$$\mathbb{E}(\det Y(i))^2 = d! \sigma_{i_1}^2 \cdots \sigma_{i_d}^2$$

and $\mathbb{E} \det Y(i) \cdot \det Y(j) = 0$ for any $i = (i_1, \dots, i_d)$ with $1 \leq i_1 < \dots < i_d < \infty$ and $i \neq j$, i.e. there exists $l \in \{1, \dots, d\}$ for which $i_l \neq j_l$. Using (2.7) we get

$$\mathbb{E} W = \sum_{<} \mathbb{E}(\det Y(i))^2 \cdot \mathbb{E}(\det Y'(i))^2,$$

which implies (2.5).

The inequality (2.6) is a direct corollary of the logarithmic inequalities for Gaussian measures (see e.g. Bogachev (1998), Corollary 5.5.9, p. 228).

Let X, X_1, \dots, X_n denote i.i.d. random elements in a Hilbert space H with $\mathbb{E} X = 0$, $\text{cov}(X) = C$ and $\sigma_1^2 \geq \sigma_2^2 \geq \dots$ be the eigenvalues of C .

Put $S_m = m^{-1/2}(X_1 + \dots + X_m)$. Let $S_{m1}, S'_{m1}, S_{m2}, \dots, S'_{md}$ be $2d$ independent copies of S_m . Put $W_m(X) = (\det A_m(X))^2$, where $A_m(X) = \{a_{ij}(X)\}_{i,j=1}^d$ and $a_{ij}(X) = (S_{mi}, S'_{mj})$. Denote by W the same variable as in Lemma 2.3.

Lemma 2.4. *There exist the constants c_{1d} and c_{2d} such that for any integer m satisfying*

$$\frac{\mathbb{E}|X|^4}{m\sigma_d^8} \left(\sigma_1^4 + \frac{\mathbb{E}|X|^4}{m} \right) \leq c_{1d}, \quad (2.8)$$

we have

$$|\mathbb{E} W^2 - \mathbb{E} W_m^2(X)| \leq c_{2d}(\mathbb{E} W)^2. \quad (2.9)$$

Proof. Let $Y, Y_1, Y'_1, \dots, Y_d, Y'_d$ denote independent Gaussian $(0, C)$ random elements in H .

Since

$$\mathbb{E} X = \mathbb{E} Y = 0, \quad \text{cov}(X) = \text{cov}(Y),$$

for any $b_1, b_2, b_3, b_4 \in H$ we obtain

$$\mathbb{E} \prod_{i=1}^4 (S_m, b_i) = \mathbb{E} \prod_{i=1}^4 (Y, b_i) + \frac{1}{m} \left(\mathbb{E} \prod_{i=1}^4 (X, b_i) - \mathbb{E} \prod_{i=1}^4 (Y, b_i) \right). \quad (2.10)$$

Applying (2.10) sequentially to variables $S_{m1}, S'_{m1}, S_{m2}, \dots, S'_{md}$ we get

$$\mathbb{E} W_m^2(X) = \mathbb{E} W^2 + \sum_{i=1}^d m^{-2i+1} \sum_1 + \sum_{i=1}^d m^{-2i} \sum_2, \quad (2.11)$$

where \sum_1 and \sum_2 are sums of 2^{2i-1} resp. 2^{2i} summands of type

$$c \mathbb{E} W^2(Z_1, Z'_1, Z_2, Z'_2, \dots, Z_i, Y'_i, Y_{i+1}, Y'_{i+1}, Y'_{i+1}, \dots, Y_d, Y'_d)$$

resp.

$$c \mathbb{E} W^2(Z_1, Z'_1, \dots, Z_i, Z'_i, Y_{i+1}, Y'_{i+1}, \dots, Y_d, Y'_d);$$

here the cofactors c are real numbers uniformly bounded by a constant c_d , i.e.

$$|c| \leq c_d$$

and c_d depends on d only; Z_i resp. Z'_i are either equal to X_i or Y_i resp. X'_i or Y'_i ; and

$$W(Z_1, Z'_1, \dots, Z_i, Z'_i, Y_{i+1}, Y'_{i+1}, \dots, Y_d, Y'_d) = (\det B)^2$$

where $B = \{b_{kj}\}_{k,j=1}^d$ with $b_{kj} = (T_k, T'_j)$ and

$$T_k = \begin{cases} Z_k & \text{for } k \leq i, \\ Y_k & \text{for } k > i, \end{cases} \quad T'_k = \begin{cases} Z'_k & \text{for } k \leq i, \\ Y'_k & \text{for } k > i. \end{cases}$$

Moreover, it is easy to see that for a non-increasing sequence $\{a_i\}$ of non-negative numbers such that $\sum a_i < \infty$, we have for any integer $d \geq 2$

$$\sum_{1 \leq i_1 < \dots < i_d < \infty} a_{i_1} \dots a_{i_d} \geq 2^{-d} a_d \sum_{1 \leq i_1 < \dots < i_{d-1} < \infty} a_{i_1} \dots a_{i_{d-1}} \quad (2.12)$$

Using an expansion of the determinant in the elements of rows and cofactors, together with Lemma 2.3, (2.11) and (2.12) we arrive at (2.9) provided that m satisfies (2.8).

Lemma 2.5. (Cf. Lemma 4.7 in Bentkus, Götze (1997)). Let A be a non-degenerate $d \times d$ matrix. Let $X \in \mathbb{R}^d$ be a random vector with a covariance matrix B . Assume that there exists a constant c_d such that

$$P\{|X| \leq c_d\} = 1, \quad |A| \leq c_d, \quad |B^{-1}| \leq c_d.$$

Let U and V be independent random vectors which are sums of n independent copies of X . Then

$$|\mathbb{E} e\{t(AU, V)\}| \leq c(d) | \det A |^{-1} \mathcal{M}^{2d}(t; n) \text{ for } |t| > 0,$$

where

$$\mathcal{M}(t; n) = 1/\sqrt{|t|n} + \sqrt{|t|} \text{ for } |t| > 0.$$

Proof. It is enough to repeat the proof of Lemma 4.7 in Bentkus, Götze (1997) with minor modifications using

$$\int_{|x| \leq 1} \exp\{-|Ax|^2\} dx \leq 2 |\det A|^{-1}.$$

Let X, X_1, X_2, \dots, X_n denote i.i.d. random vectors in \mathbb{R}^d with zero mean and covariance operator V and eigenvalues $\sigma_1^2 \geq \sigma_2^2 \geq \dots \geq \sigma_d^2$. Put $S_n = n^{-1/2}(X_1 + \dots + X_n)$ and

$$F(x) = P\{|S_n - a|^2 < x\}.$$

Let Y be a Gaussian vector distributed according to $N(0, V)$ in \mathbb{R}^d . Put

$$F_0(x) = P\{|Y - a|^2 < x\}$$

and denote by $F_1(x)$ the function of bounded variation satisfying $F_1(-\infty) = 0$ with Fourier-Stieltjes transform given by

$$\hat{F}_1(t) = \frac{-2t^2}{3\sqrt{n}} \mathbb{E} e\{t|Y - a|^2\} (3(X, Y - a)|X|^2 + 2it(X, Y - a)^3).$$

In fact (see e.g. Bentkus, Götze (1997)) $F_1(x)$ can be written as a signed measure μ of a ball $B(a, x) = \{y \in \mathbb{R}^d : |y - a|^2 < x\}$. We have

Lemma 2.6. *In the Euclidean spaces $\mathbb{R}^d, d = 2, 3, \dots, 13$, there exists a distribution P of X and balls $B(a, r)$ with $|a| > 1$ such that for given values $\sigma_1^2, \dots, \sigma_{d-1}^2$ of the eigenvalues of the covariance operator V and all sufficiently small σ_d*

$$\begin{aligned} & \liminf_{n \rightarrow \infty} n \sup_r |P\{|S_n - a| < r\} - P\{|Y - a| < r\} - \mu\{B(a, r)\}| \\ & \geq c(P) |a|^{(d-1)/2} (\sigma_1 \dots \sigma_{d-1})^{-1} \left[\sigma_d^{(d-13)/2} \alpha_3^2 + \sigma_d^{(d-9)/2} (\alpha_4 - 3\alpha_2^2) \right], \end{aligned} \quad (2.13)$$

where $\alpha_i = \mathbb{E} X_d^i$ and $X = (X_1, \dots, X_d)$.

Corollary 2.7. *Assume that $\alpha_3 = 0$ and that the conditions of Lemma 2.6 are satisfied. Then we have for all $d = 2, \dots, 9$*

$$\begin{aligned} & \liminf_{n \rightarrow \infty} n \sup_r |P\{|S_n - a| < r\} - P\{|Y - a| < r\} - \mu\{B(a, r)\}| \\ & \geq c(P) |a|^{(d-1)/2} (\sigma_1 \dots \sigma_{d-1})^{-1} \sigma_d^{(d-9)/2} (\alpha_4 - 3\alpha_2^2). \end{aligned} \quad (2.14)$$

Proof. We shall follow the arguments of Example 3 in Senatov (1985).

We choose a distribution P in \mathbb{R}^d such that the projections onto vectors of an orthonormal basis e_1, \dots, e_{d-1} in \mathbb{R}^d are normal distributed with zero mean and variances $\sigma_1^2, \dots, \sigma_{d-1}^2$. Furthermore we may choose P such that

the projection onto e_d has zero mean, $\mathbb{E}(X, e_d)^2 = \sigma_d^2$, $\alpha_3 > 0$, $\alpha_4 - 3\alpha_2 > 0$ and it satisfies a Cramer condition of smoothness. Moreover we assume that the components of this random vector X under P are independent. Let G denote the distribution function of the projection of P onto e_d . Obviously, the projections of distribution of S_n onto e_1, \dots, e_{d-1} for any n will be normal with zero means and variances $\sigma_1^2, \dots, \sigma_{d-1}^2$ while the distribution function G_n of the projection of distribution of S_n onto e_d has the following asymptotic behaviour (this follows from classical results on Edgeworth approximations of sums of i.i.d. vectors, see e.g. Petrov (1987))

$$R_n(x) = G_n(x) - \Phi(x) = \frac{Q_1(x)}{\sqrt{n}} + \frac{Q_{21}(x) + Q_{22}(x)}{n} + o(n^{-1}) \text{ as } n \rightarrow \infty,$$

where $\Phi(x)$ is the distribution function of the normal law with zero mean and variance σ_d^2 ,

$$\begin{aligned} Q_1(x) &= -\frac{\alpha_3}{6\sqrt{2\pi}\sigma_d^3} \left(\frac{x^2}{\sigma_d^2} - 1 \right) \exp(-x^2/(2\sigma_d^2)), \\ Q_{21}(x) &= -\frac{\alpha_3^2}{72\sqrt{2\pi}\sigma_d^6} \left(\left(\frac{x}{\sigma_d} \right)^5 - 10 \left(\frac{x}{\sigma_d} \right)^3 + 15 \left(\frac{x}{\sigma_d} \right) \right) \exp(-x^2/(2\sigma_d^2)), \\ Q_{22}(x) &= -\frac{(\alpha_4 - 3\alpha_2^2)}{24\sqrt{2\pi}\sigma_d^4} \left(\left(\frac{x}{\sigma_d} \right)^3 - 3 \frac{x}{\sigma_d} \right) \exp(-x^2/(2\sigma_d^2)). \end{aligned}$$

Consider the ball $B = \{y \in \mathbb{R}^d : |y - ae_d| < R\}$, where a is a positive number depending on R to be determined later.

We have

$$I \equiv \Phi_1(B) - P_n(B) = \sum_{i=1}^2 \int_{b_R(0)} (R_{ni}(x_1) - R_{ni}(x_2)) \tilde{\Phi}(du) + o(n^{-1}),$$

where $P_n(B) = P\{|S_n - a| < R\}$, $\Phi_1(B) = P\{|Y - a| < R\} + \mu(B)$, $R_{ni}(x) = -Q_{2i}(x)/n$, $\tilde{\Phi}$ is the projection of P onto \mathbb{R}^{d-1} which coincides with the corresponding projection of the distribution of Y , $b_R(0)$ is the ball in \mathbb{R}^{d-1} with center at 0 and radius R , $x_1 = a - r$, $x_2 = a + r$, $r^2 = R^2 - |u|^2$ and $|u|^2 = u_1^2 + \dots + u_{d-1}^2$.

It is easy to see that there exists c_0 such that for $x > c_0\sigma_d$ the functions $R_{ni}(x)$ are positive and decreasing. Put $a = R + c_0\sigma_d$. Then for any $u \in b_R(0)$ the differences $R_{ni}(x_1) - R_{ni}(x_2)$ are non-negative.

The arguments are similar for the first two summands in the expression for I . Therefore we shall give a proof for

$$I_1 = \int_{b_R(0)} (R_{n1}(x_1) - R_{n1}(x_2)) \tilde{\Phi}(du)$$

only. There exists a constant c_1 such that for all $v \geq c_0\sigma_d$

$$R_{n1}(v) \geq 2R_{n1}(v + c_1\sigma_d).$$

Since $x_2 - x_1 = 2\sqrt{R^2 - |u|^2}$, there exists c_2 such that for $u : |u| \leq \sqrt{R\sigma_d}$ and $R \geq c_2\sigma_d$ we have

$$R_n(x_1) \geq 2R_n(x_2).$$

Therefore for $R \geq c_2\sigma_d$ we get

$$I_1 \geq \frac{1}{2} \int_{b_{\sqrt{R\sigma_d}}(0)} R_{n1}(x_1) \tilde{\Phi}(du)$$

and, since $c_3\sigma_d \leq x_1 \leq c_4\sigma_d$,

$$I_1 \geq c\alpha_3^2\sigma_d^{-6}n^{-1}\tilde{\Phi}(b_{\sqrt{R\sigma_d}}(0)).$$

Since for sufficiently small σ_d we have

$$\tilde{\Phi}(b_{\sqrt{R\sigma_d}}(0)) \geq c \prod_{i=1}^{d-1} \min(1, \sqrt{R\sigma_d}/\sigma_i) \geq c(R\sigma_d)^{(d-1)/2}(\sigma_1 \cdots \sigma_{d-1})^{-1}$$

with some constant c depending only on d , we arrive at the first summand on the right-hand side of (2.13) as a lower bound. Repeating similar arguments for

$$\int_{b_R(0)} (R_{n2}(x_1) - R_{n2}(x_2)) \tilde{\Phi}(du)$$

concludes the proof of the Lemma.

Lemma 2.8. (See Sazonov (1981), p.85). Let X be a random element with values in H such that $\mathbb{E}X = 0$, $\mathbb{E}|X|^3 < \infty$. Denote by V the covariance operator of X . Let Y denote a Gaussian $(0, V/2)$ distributed random element and let ζ denote a real random variable such that

$$\mathbb{E}\zeta = 0, \quad \mathbb{E}\zeta^2 = 1/2, \quad \mathbb{E}\zeta^3 = 1.$$

Suppose that X , Y and ζ are independent. Then $Z = \zeta X + Y$ has mean zero, covariance operator V and for any $h_1, h_2, h_3 \in H$ we have

$$\mathbb{E}(X, h_1)(X, h_2)(X, h_3) = \mathbb{E}(Z, h_1)(Z, h_2)(Z, h_3).$$

Lemma 2.9. *Let k and n be natural numbers, $n \geq k$, and X_1, \dots, X_{kn} be $k \cdot n$ i.i.d. random elements with values in H . Let $f(x_1, \dots, x_k)$ be a functional of $x_1, \dots, x_k \in H$ with values in \mathbb{R}^1 such that it is linear with respects to each variable. Assume that $g : H \rightarrow \mathbb{R}$ is such that $\mathbb{E}f(X_1, \dots, X_k)g(T)$ exists, where $T = X_1 + X_2 + \dots + X_{kn}$. Put $S = \mathbb{E}g(T) \sum f(X_{i_1}, \dots, X_{i_k})$, where the summation is taken over all values of $i_1, \dots, i_k \in \{1, 2, \dots, kn\}$ which are pairwise different. Then S can be splitted into $m = m(k)$ summands of type $\mathbb{E}g(T)f(W_1, \dots, W_k)$, where $W_i = \sum_{j \in N(i)} X_j$, $N(1) \cup \dots \cup N(k) = \{1, 2, \dots, kn\}$, $N(i) \cap N(j) = \emptyset$ for $i \neq j$ and $N(i)/n \rightarrow 1$ as $n \rightarrow \infty$ for all $i \in \{1, 2, \dots, k\}$.*

Proof. We prove the Lemma in the case $k = 2$ and $g = 1$. In this case it is enough to show that

$$S \equiv \sum_{\substack{i,j=1 \\ i \neq j}}^{2n} \mathbb{E}f(X_i, X_j) = 2(\mathbb{E}f(T_1, T_2') + \mathbb{E}f(T_1, T_2)), \quad (2.15)$$

where

$$T_1 = \sum_{i=1}^n X_i, \quad T_2' = \sum_{j=n+2}^{2n} X_j, \quad T_2 = X_{n+1} + T_2'.$$

We have

$$S = S_1 + S_2, \quad (2.16)$$

where

$$S_1 = \sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^{2n} \mathbb{E}f(X_i, X_j).$$

It follows from the conditions of the Lemma that

$$\begin{aligned} \sum_{j=2}^{2n} \mathbb{E}f(X_1, X_j) &= \sum_{j=2}^n \mathbb{E}f(X_1, X_j) + \mathbb{E}f(X_1, T_2) \\ &= \sum_{j=2}^n \mathbb{E}f(X_1, X_{n+j}) + \mathbb{E}f(X_1, T_2) \\ &= \mathbb{E}f(X_1, T_2') + \mathbb{E}f(X_1, T_2). \end{aligned} \quad (2.17)$$

Since X_1, X_2, \dots, X_{2n} are identically distributed we get similarly to (2.17) for any $i \in \{1, \dots, n\}$

$$\sum_{\substack{j=1 \\ j \neq i}}^{2n} \mathbb{E}f(X_i, X_j) = \mathbb{E}f(X_i, T_2') + \mathbb{E}f(X_i, T_2) \quad (2.18)$$

and for any $i \in \{n+1, n+2, \dots, 2n\}$

$$\sum_{\substack{j=1 \\ j \neq i}}^{2n} \mathbb{E}f(X_i, X_j) = \mathbb{E}f(X_{i-n}, T_2') + \mathbb{E}f(X_{i-n}, T_2). \quad (2.19)$$

Combining (2.16) - (2.19) we obtain (2.15). Thus the Lemma is proved in the case $k = 2$ and $g = 1$. It is easy to see that similar but more tedious arguments prove the Lemma in the general case.

Let $Z, \bar{Z}, Z_1, \dots, Z_n$ be i.i.d. random elements,

$$Z_1 = \zeta_1 X_1 + Y_1, \quad (2.20)$$

where ζ_1 and X_1 have the same distribution as ζ and X resp. in Lemma 2.8. Let Y, \bar{Y} be the independent Gaussian $(0, V)$ random elements. According to Lemma 2.8 we have

$$\mathbb{E}Z_1 = \mathbb{E}Y = 0, \quad \text{cov}(Z_1) = \text{cov}(Y) = V, \quad (2.21)$$

where $\text{cov}(Z_1)$ denotes the covariance operator of Z_1 .

Put $T_n = n^{-1/2}(Z_1 + \dots + Z_n)$,

$$I_0 = \mathbb{E}e\{t|T_n - a|^2\}(\mathbb{E}_Z L(Z) - \mathbb{E}_Y L(Y))(\mathbb{E}_{\bar{Z}}(\bar{Z}) - \mathbb{E}_{\bar{Y}}L(\bar{Y})),$$

where

$$L(u) = e\{t(|u/\sqrt{n}|^2 + 2(T_n - a, u/\sqrt{n}))\}$$

and $\mathbb{E}_X f(X, Y)$ means that we consider expectation with respect to X only.

Lemma 2.10. *If*

$$n^{-1}(\mathbb{E}|X|^4 + \mathbb{E}(X, a)^4)(1 + (Va, a)) \leq 1, \quad (2.22)$$

then for any $T > 0$ and $x > 0$

$$\left| \int_{-T}^T \frac{e\{-xt\}}{t} I_0 dt \right| \leq \frac{c_{12}(V)}{n^2} (\mathbb{E}|X|^4 + \mathbb{E}(X, a)^4)(1 + (Va, a)). \quad (2.23)$$

Proof. In the following we say that a function $f(n, t)$ belongs to a class of functions \mathcal{F} iff for any $T > 0$ and $x > 0$ the quantity

$$\left| \int_{-T}^T \frac{e\{-xt\}}{t} f(n, t) dt \right|$$

can be bounded from above by the right-hand side of (2.23), provided that (2.22) holds. Thus we have to show that $I_0 \in \mathcal{F}$.

Below we shall use often the Taylor formula for a smooth function $f(s)$

$$f(s) = \sum_{j=0}^{m-1} f^{(j)}(0) s^j / j! + ((m-1)!)^{-1} \int_0^s f^{(m)}(\lambda) (s-\lambda)^{m-1} d\lambda. \quad (2.24)$$

Using (2.24) we can write

$$\begin{aligned} e\{t(|u|^2 + (b, u))\} &= e\{t(b, u)\} (1 + it|u|^2 + (it)^2 |u|^4 \mathbb{E}_\tau e\{t\tau|u|^2\} (1 - \tau)) \\ &= 1 + it(b, u) + it|u|^2 + \sum_{j=0}^2 K_j(b, u), \end{aligned} \quad (2.25)$$

where τ is a random variable uniformly distributed on $[0; 1]$ and

$$\begin{aligned} K_0(b, u) &= -t^2 |u|^4 \mathbb{E}_\tau e\{t((b, u) + \tau|u|^2)\} (1 - \tau), \\ K_1(b, u) &= -t^2 |u|^2 (b, u) \mathbb{E}_\tau e\{t\tau(b, u)\}, \\ K_2(b, u) &= -t^2 (b, u)^2 \mathbb{E}_\tau e\{t\tau(b, u)\} (1 - \tau). \end{aligned}$$

It follows from (2.21) and (2.25) that

$$\begin{aligned} I_0 &= \mathbb{E} e\{t|T_n - a|^2\} \sum_{j,l=0}^2 (K_l(2T_n - 2a, Z/\sqrt{n}) - K_l(2T_n - 2a, Y/\sqrt{n})) \\ &\quad \times (K_j(2T_n - 2a, \bar{Z}/\sqrt{n}) - K_j(2T_n - 2a, \bar{Y}/\sqrt{n})) \\ &= \sum_{j,l=0}^2 I_{jl} = I_{22} + I_{12} + I_{21} + R_0(t). \end{aligned} \quad (2.26)$$

Note that up to absolute constants $R_0(t)$ is a sum of terms of the type

$$t^4 \mathbb{E} \left| \frac{U}{\sqrt{n}} \right|^{2\alpha_1} \left| \frac{\bar{U}}{\sqrt{n}} \right|^{2\alpha_2} \left(T_n - a, \frac{U}{\sqrt{n}} \right)^{\alpha_3} \left(T_n - a, \frac{\bar{U}}{\sqrt{n}} \right)^{\alpha_4} e\{t|T_n + b_1|^2 + b_2 t\},$$

where U (resp. \bar{U}) is either Z or Y (resp. either \bar{Z} or \bar{Y}); random elements U, \bar{U}, T_n, b_1 and b_2 are independent; $P\{b_2 = 0\} = 0$; $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ are non-negative integers such that

$$\alpha_1 \leq 2, \quad \alpha_2 \leq 2, \quad \alpha_3 + \alpha_4 \leq 2,$$

$$2\alpha_1 + \alpha_3 \leq 4, \quad 2\alpha_2 + \alpha_4 \leq 4,$$

$$2\alpha_1 + 2\alpha_2 + \alpha_3 + \alpha_4 \geq 6.$$

Using the wellknown techniques of splitting sums and conditioning on corresponding sets of random variables, together with Rosenthal type inequality, Lemmas 2.1 and 2.2 and Fubini's theorem we get

$$R_0(t) \in \mathcal{F}. \quad (2.27)$$

Now we consider I_{22} . We have

$$\begin{aligned} I_{22} &= -4t^4 \mathbb{E} e\{t|T_n - a|^2\} \sum_{j,l=0}^2 (K_{2j}(T_n, Z/\sqrt{n}) - K_{2j}(T_n, Y/\sqrt{n})) \\ &\quad \times (K_{2l}(T_n, \overline{Z}/\sqrt{n}) - K_{2l}(T_n, \overline{Y}/\sqrt{n})) \\ &= \sum_{j,l=0}^2 L_{jl}. \end{aligned} \quad (2.28)$$

where for $j = 0, 1, 2$

$$K_{2j}(b, u) = \binom{2}{j} (b, u)^j (a, u)^{2-j} \mathbb{E}_\tau e\{t\tau(2b - 2a, u)\} (1 - \tau). \quad (2.29)$$

The further arguments are based on the following ideas:

- a) Since the covariance operators of Y, Z, \overline{Y} and \overline{Z} coincide we obtain for $j = 0, 1, 2$ and any $a, b \in H$ that

$$\begin{aligned} \mathbb{E} (b, Z)^j (a, Z)^{2-j} &= \mathbb{E} (b, Y)^j (a, Y)^{2-j} = \mathbb{E} (b, \overline{Z})^j (a, \overline{Z})^{2-j} \\ &= \mathbb{E} (b, \overline{Y})^j (a, \overline{Y})^{2-j} \end{aligned} \quad (2.30)$$

Therefore, applying the Taylor expansion (2.24) with respect to s for a function

$$f(s, u) = e\{st\tau(2b - 2a, u)\}$$

(see (2.29)) with $m = 1$ we have to bound the remainder terms in (2.28) only.

- b) While using Taylor expansions to show that $I_{22} \in \mathcal{F}$, we have to make sure that the error terms occuring in our arguments involve moments of random elements of order at most four.

This tedious but straightfoward procedure has been described in detail in similar problems in Bentkus, Götze (1999), Lemma 8.4. Therefore we restrict ourselves to necessary remarks which are specific to our task only.

Applying (2.24) for $f(s, U)$ and $f(s, \overline{U})$ we can write $\sum_{0 \leq j+l \leq 2} L_{jl}$ as a sum of terms of the type

$$c \mathbb{E} \left(T_n, \frac{U}{\sqrt{n}} \right)^{\beta_1} \left(a, \frac{U}{\sqrt{n}} \right)^{\beta_2} \left(T_n, \frac{\overline{U}}{\sqrt{n}} \right)^{\beta_3} \left(a, \frac{\overline{U}}{\sqrt{n}} \right)^{\beta_4} e\{t|T_n + b_1|^2 + b_2 t\},$$

where $U, \bar{U}, T_n, b_1, b_2$ are independent and $\beta_1, \beta_2, \beta_3, \beta_4$ are non-negative integers such that

$$\beta_1 + \beta_2 = \beta_3 + \beta_4 = 3, \quad \beta_1 + \beta_3 \leq 4.$$

Similarly to (2.27) we can show that

$$\sum_{0 \leq j+l \leq 2} L_{jl} \in \mathcal{F}.$$

Now we show that

$$L_{22} \in \mathcal{F} \tag{2.31}$$

We have

$$\begin{aligned} L_{22} &= -4t^4 \mathbb{E}\{t|T_n - a|^2\} (1 - \tau_1) (1 - \tau_2) \\ &\quad \times \sum_{i,j,k,l=1}^n \left[(Z_i/\sqrt{n}, Z/\sqrt{n})(Z_j/\sqrt{n}, Z/\sqrt{n}) e\{t\tau_1(2T_n - 2a, Z/\sqrt{n})\} \right. \\ &\quad \left. - (Z_i/\sqrt{n}, Y/\sqrt{n})(Z_j/\sqrt{n}, Y/\sqrt{n}) e\{t\tau_1(2T_n - 2a, Y/\sqrt{n})\} \right] \\ &\quad \times \left[(Z_k/\sqrt{n}, \bar{Z}/\sqrt{n})(Z_l/\sqrt{n}, \bar{Z}/\sqrt{n}) e\{t\tau_2(2T_n - 2a, \bar{Z}/\sqrt{n})\} \right. \\ &\quad \left. - (Z_k/\sqrt{n}, \bar{Y}/\sqrt{n})(Z_l/\sqrt{n}, \bar{Y}/\sqrt{n}) e\{t\tau_2(2T_n - 2a, \bar{Y}/\sqrt{n})\} \right] \\ &= \sum_{m=1}^3 D_m, \end{aligned} \tag{2.32}$$

where

D_1 represents the summands with $i = j = k = l$;

D_2 represents those summands where three of four indices i, j, k and l coincide;

D_3 represents all remaining summands.

Since D_1 is a sum of n terms of type

$$\begin{aligned} &c t^4 \mathbb{E} e\{t|T_n - a|^2 + t(2T_n - 2a, (\tau_1 U + \tau_2 \bar{U})/\sqrt{n})\} \\ &\quad \times (1 - \tau_1)(1 - \tau_2) \left(\frac{Z_1}{\sqrt{n}}, \frac{U}{\sqrt{n}} \right)^2 \left(\frac{Z_1}{\sqrt{n}}, \frac{\bar{U}}{\sqrt{n}} \right)^2, \end{aligned}$$

it follows from Fubini's theorem and Lemmas 2.1 and 2.2 that

$$D_1 \in \mathcal{F}.$$

In order to bound D_2 it is enough to consider without loss of generality the part D_{21} of D_2 which corresponds to the case when $i = j = k \neq l$. We shall

use (2.24) for a function $f(s) = f(s, \bar{U})$ with $m = 1$. Then we get that D_{21} can be written as a sum of n terms of the type

$$\begin{aligned} & c t^5 \mathbb{E} e\{t|T_n - a|^2 + 2t(T_n - a, (\tau_1 U + \tau_2 \tau_3 \bar{U})/\sqrt{n})\} \\ & \times \tau_2(1 - \tau_1)(1 - \tau_2) \left(\frac{Z_1}{\sqrt{n}}, \frac{U}{\sqrt{n}}\right)^2 \left(\frac{Z_1}{\sqrt{n}}, \frac{\bar{U}}{\sqrt{n}}\right) \\ & \times \left(T_{n(1)}, \frac{\bar{U}}{\sqrt{n}}\right) \left(\frac{Z_1}{\sqrt{n}} + T_{n(1)} - a, \frac{\bar{U}}{\sqrt{n}}\right), \end{aligned}$$

where $T_{n(1)} = T_n - Z_1/\sqrt{n}$.

Similar to (2.27) we get $D_{21} \in \mathcal{F}$ and therefore

$$D_2 \in \mathcal{F}.$$

In order to obtain bounds for D_3 we argue in a similar way using (2.24) for both functions $f(s, U)$ and $f(s, \bar{U})$ and additionally apply Lemma 2.9. Thus, (2.31) holds.

Similar arguments show that

$$I_{12} + I_{21} \in \mathcal{F}.$$

The Lemma is proved.

Let X, X_1, \dots, X_n be i.i.d. random elements satisfying the conditions of Theorem 1.1. Let Z, Z_1, \dots, Z_n be i.i.d. random elements constructed in Lemma 2.8. Put $T_n = n^{-1/2}(W_1 + \dots + W_n)$, where W_1, \dots, W_n are independent random elements and W_i is either X_i or Z_i .

Lemma 2.11. *If*

$$n^{-1}(\mathbb{E}|X|^4 + \mathbb{E}(X, a)^4)(1 + (Va, a)) \leq 1$$

then

$$\begin{aligned} & \int_{-N_0}^{N_0} \frac{1}{|t|} |\mathbb{E} e\{t|T_n + X/\sqrt{n} - a|^2\} - \mathbb{E} e\{t|T_n + Z/\sqrt{n} - a|^2\}| dt \\ & \leq \frac{\bar{c}_9(V)}{n^2} (\mathbb{E}|X|^4 + \mathbb{E}(X, a)^4), \end{aligned}$$

where

$$N_0 = \left(c \frac{n\sigma_9^4}{(\mathbb{E}|X_1|^3)^2} \right)^{4/9}.$$

Proof. The arguments are similar to those used in Lemma 2.10. Just note that instead of (2.25) we use

$$e\{t(|u|^2 + (b, u))\} = 1 + it(b, u) - \frac{1}{2}t^2(b, u)^2 + it|u|^2 - t^2|u|^2(b, u) + \sum_{j=0}^2 K'_j(b, u),$$

where $K'_0(b, u) = K_0(b, u)$ with $K_0(b, u)$ from (2.25),

$$\begin{aligned} K'_1(b, u) &= -it^3|u|^2\mathbb{E}_\tau e\{t\tau(b, u)\}, \\ K'_2(b, u) &= -\frac{i}{2}t^3(b, u)^3\mathbb{E}_\tau e\{t\tau(b, u)\}(1 - \tau)^2. \end{aligned}$$

We shall apply Lemmas 2.1 and 2.2 as well.

Lemma 2.12. (See Lemma 3.2, Theorem 10.1 and formulas (10.7)–(10.8) in Bentkus and Götze (1999)). Let $\varphi(t)$, $t \geq 0$ denote a continuous function such that $0 \leq \varphi \leq 1$. Assume that

$$\varphi(t) \varphi(t + \tau) \leq \theta \mathcal{M}^d(\tau, N) \quad (2.33)$$

for all $t \geq 0$ and $\tau \geq 0$ with some $\theta \geq 1$ independent of t and τ . Then for any $0 < B \leq 1$ and $N \geq 1$

$$\int_{B/\sqrt{N}}^1 \frac{\varphi(t)}{t} dt \leq c(s) \theta (N^{-1} + (B\sqrt{N})^{-d/2}) \quad \text{for } d > 8. \quad (2.34)$$

Examples. Assuming condition (2.33) the bound (2.34) has an optimal dependence on N in the following sense. There are two examples of sequences of functions $\varphi_N(t)$ and $\psi_N(t)$, $N = 1, 2, \dots$ satisfying (2.33) with $\theta = 1$ and such that

$$\begin{aligned} \int_{N^{-1/4}}^1 \frac{\varphi_N(t)}{t} dt &\geq \frac{\ln N}{4N} \quad \text{for } d = 8, N = 2, 3, \dots, \\ \int_{N^{-2/d}}^1 \frac{\psi_N(t)}{t} dt &\geq \frac{c(d)}{N} \quad \text{for } d \geq 9, N \geq \frac{3}{2^{2/d} - 1}. \end{aligned}$$

See Seleznev (1999). In fact, it is enough to take

$$\begin{aligned} \varphi_N(t) &= \begin{cases} 1 - Nt & \text{for } 0 \leq t \leq N^{-1}, \\ 0 & \text{for } N^{-1} \leq t \leq N^{-1/4} - N^{-2}, \\ N(t - N^{-1/4}) + N^{-1} & \text{for } N^{-1/4} - N^{-2} \leq t \leq N^{-1/4}, \\ N^{-1} & \text{for } N^{-1/4} \leq t, \end{cases} \\ \psi_N(t) &= \begin{cases} 1 - Nt & \text{for } 0 \leq t \leq N^{-1}, \\ 0 & \text{for } N^{-1} \leq t \leq 1 - N^{-1}, \\ N(t - 1 + N^{-1})/2 & \text{for } 1 - N^{-1} \leq t, \end{cases} \\ c(d) &= (4 - (2^{2/d} - 1)^2)^{-1}. \end{aligned}$$

3. PROOFS OF THE THEOREMS

Proof of Theorem 1.1 We write

$$\Delta_n(a) \leq \Delta_{n1} + \Delta_{n2}, \quad (3.1)$$

where

$$\begin{aligned} \Delta_{n1} &= \sup_x |F(x) - G(x)|, \\ \Delta_{n2} &= \sup_x |G(x) - F_0(x) - F_1(x)|, \\ G(x) &= P\{|(Z_1 + \dots + Z_n)/\sqrt{n} - a|^2 \leq x\} \end{aligned}$$

and Z_1, Z_2, \dots, Z_n are i.i.d. random elements constructed in Lemma 2.8 when we take $X = X_1$. Denote

$$\hat{G}(t) = \mathbb{E}e\{t|(Z_1 + \dots + Z_n)/\sqrt{n} - a|^2\}.$$

Using Theorem 2 in Petrov (1987), ch.5, sect.1. we get

$$\Delta_{n1} \leq c_1 \int_{-N}^N \frac{|\hat{F}(t) - \hat{G}(t)|}{|t|} dt + \frac{c_2}{N} \sup_{x>0} \left| \int_{-\infty}^{\infty} e\{-tx\} \hat{G}(t) dt \right|. \quad (3.2)$$

According to the construction of Z_1 it follows from Lemma 2.2 that

$$\sup_{x>0} \left| \int_{-\infty}^{\infty} e\{-tx\} \hat{G}(t) dt \right| \leq c \cdot c_2(V). \quad (3.3)$$

We write

$$\int_{-N}^N \frac{|\hat{F}(t) - \hat{G}(t)|}{|t|} dt \leq I_1 + I_2 + I_3, \quad (3.4)$$

where

$$\begin{aligned} I_1 &= \int_{-N_0}^{N_0} \frac{|\hat{F}(t) - \hat{G}(t)|}{|t|} dt, \\ I_2 &= \int_{N_0 < |t| \leq N} \frac{|\hat{F}(t)|}{|t|} dt, \\ I_3 &= \int_{N_0 < |t| \leq N} \frac{|\hat{G}(t)|}{|t|} dt. \end{aligned}$$

It follows from Lemma 2.1 that

$$I_3 \leq c \cdot \frac{c_5(V)}{N_0}. \quad (3.5)$$

Using the coincidence of the moments of the first three orders for the distributions of X_1 and Z_1 (see Lemma 2.8) and applying Lemma 2.11 and standard arguments (see e.g. Sazonov, Ulyanov and Zaleskii (1988a, 1991)) we get

$$I_1 \leq c \cdot \frac{\bar{c}_9(V)}{n} (\mathbb{E}|X_1|^4 + \mathbb{E}(X_1, a)^4). \quad (3.6)$$

We now consider Δ_{n2} .

We shall use the following approximation formulae for the Fourier inversion. A smoothing inequality of Prawitz (1972) implies (see Bentkus and Götze (1996), Section 4) that

$$F(x) = \frac{1}{2} + \frac{i}{2\pi} V.P. \int_{-K}^K e\{-xt\} \hat{F}(t) \frac{dt}{t} + R, \quad (3.7)$$

for any $K > 0$ and any distribution F with characteristic function \hat{F} , where

$$|R| \leq \frac{1}{K} \int_{-K}^K |\hat{F}(t)| dt.$$

Here $V.P. \int f(t) dt = \lim_{\varepsilon \rightarrow 0} \int_{|t| > \varepsilon} f(t) dt$ denotes the principal value of the integral.

For any function $F : \mathbb{R} \rightarrow \mathbb{R}$ of bounded variation such that $F(-\infty) = 0$ and $2F(x) = F(x+) + F(x-)$ for all $x \in \mathbb{R}$ the following Fourier-Stieltjes inversion formula holds (see e.g. Chung (1974))

$$F(x) = \frac{1}{2} F(\infty) + \frac{i}{2\pi} \lim_{M \rightarrow \infty} V.P. \int_{|t| \leq M} e\{-xt\} \hat{F}(t) \frac{dt}{t}. \quad (3.8)$$

The formula is well-known for the distribution functions. For functions of bounded variation it extends by linearity arguments.

Using (3.7) we can write

$$G(x) - F_0(x) = \frac{i}{2\pi} V.P. \int_{-n}^n e\{-xt\} (\hat{G}(t) - \hat{F}_0(t)) \frac{dt}{t} + R_1, \quad (3.9)$$

where similarly to (3.5) we obtain

$$|R_1| \leq c \cdot \frac{\bar{c}_3(V)}{n}. \quad (3.10)$$

Applying (3.8) to $F_1(x)$ and using (3.9) we get

$$\begin{aligned} & G(x) - F_0(x) - F_1(x) \\ &= \frac{i}{2\pi} V.P. \int_{-n}^n \frac{e\{-xt\}}{t} (\hat{G}(t) - \hat{F}_0(t) - \hat{F}_1(t)) dt + R_2, \end{aligned} \quad (3.11)$$

where by Lemma 2.1 and (3.10) we have for R_2

$$|R_2| \leq c \cdot \frac{\bar{c}_5(V)}{n} (\mathbb{E}|X_1|^3 + \mathbb{E}|(X_1, a)|^3). \quad (3.12)$$

By Lemmas 2.2 and 2.10 combining (3.11) and (3.12) we get

$$\Delta_{n2} \leq c \cdot \frac{c_{12}(V)}{n} (\mathbb{E}|X_1|^4 + \mathbb{E}(X_1, a)^4)(1 + (Va, a)). \quad (3.13)$$

Combining (3.1)-(3.6) and (3.13) we arrive at (1.8).

Proof of Theorem 1.2. Let m_0 denote an integer satisfying (2.8) with $d = 9$. Put $S_{m_0} = m_0^{-1/2}(\bar{X}_1 + \dots + \bar{X}_{m_0})$, where \bar{X}_i denotes the symmetrization of X_i .

Since for any real non-negative random variable Z such that $\mathbb{E}Z = 1$, $\mathbb{E}Z^2 \leq A$ we have

$$\mathbb{P}\{Z > 0.5\} \geq 0.25 A^{-2},$$

it follows from Lemmas 2.3 and 2.4 that

$$\mathbb{P}\{W_{m_0}(\bar{X}) > \sigma_1^4 \dots \sigma_9^4\} \geq c. \quad (3.14)$$

Replacing the nondegeneracy condition $\mathcal{N}(p, \delta, s, Z)$ (see (3.2) in Bentkus and Götze (1999)) by the condition (3.14) and applying Lemmas 6.3, 6.7 and 7.1 from Bentkus and Götze (1999) and our Lemma 2.5 we get

$$\int_{N_0 \leq t \leq N} \frac{|f_n(t)|}{|t|} dt \leq c \left(\frac{m_0}{n} + \int_{N_0/N}^1 \frac{\varphi(t)}{t} dt \right), \quad (3.15)$$

where $\varphi(t)$ is a continuous function such that $0 \leq \varphi \leq 1$ and

$$\varphi(t) \varphi(t + \tau) \leq c c_9(V) \mathcal{M}^9(\tau N m_0 / n, n / m_0). \quad (3.16)$$

Since for any $\varepsilon > 0$

$$\mathcal{M}(\tau \varepsilon, n) = \sqrt{\varepsilon} \mathcal{M}(\tau, n \varepsilon^2),$$

an application of Lemmas 2.12, (3.15) and (3.16) concludes the proof of Theorem 1.2.

REFERENCES

- [1] A. de Acosta, *Inequalities for B-valued random vectors with applications to the strong law of large numbers*, Ann.Prob., **9** (1981), 157–161.
- [2] V. Bentkus, *On dependence of Berry–Esseen bounds on dimensionality*, Lithuanian Math. J., **26**, 205–210.
- [3] V. Bentkus and F. Götze, *Optimal rates of convergence in the CLT for quadratic forms*, Ann.Prob., **24** (1996), no.1, 466–490.
- [4] V. Bentkus and F. Götze, *Uniform rates of convergence in the CLT for quadratic forms in multidimensional spaces*, Probab. Theory Relat. Fields, **109** (1997), 367–416.

- [5] V. Bentkus and F. Götze, *Optimal bounds in non-Gaussian limit theorems for U-statistics*, Ann.Prob., **27** (1999), no.1, 454–521.
- [6] V. Bogachev, *Gaussian Measures*, AMS, Providence, RI, 1998.
- [7] K.L. Chung, *A course in probability theory*, Academic Press, New York and London, 1974.
- [8] C.G. Esseen, *Fourier analysis of distribution functions*, Acta Math., **77** (1945), 1–125.
- [9] F. Götze, *Asymptotic expansion for bivariate von Mises functionals*, Z. Wahrsch. Verw. Gebiete, **50** (1979), 333–355.
- [10] F. Götze, *Talks delivered in June, 1998a in Steklov Mathematical Institute, Moscow, and at the conference, devoted to 50th anniversary of probability theory and mathematical statistics department of St.Petersburg University, St.Petersburg.*
- [11] F. Götze, *Lattice point problems and the central limit theorem in Euclidean spaces*, Doc. Math. J.DMV, Extra Vol. ICM 1998b, III, 245–255.
- [12] W. Greub, *Multilinear algebra*, Springer-Verlag, New York Inc, 1978.
- [13] N.P. Kandelaki, *On limit theorem in Hilbert space*, Trudy Vychisl. Centra Akad. Nauk Gruzin. SSR, **11** (1965), 46–55.
- [14] S.V. Nagaev, *On new approach to study of distribution of a norm of a random element in a Hilbert space*, Fifth Vilnius conference on probability theory and mathematical statistics. Abstracts, **4** (1989), 77–78.
- [15] S.V. Nagaev and V.I. Chebotarev, *A refinement of the error estimate of the normal approximation in a Hilbert space*, Siberian Math. J., **27** (1986), 434–450.
- [16] S.V. Nagaev and V.I. Chebotarev, *On the accuracy of Gaussian approximation in Hilbert space*, Acta Applicandae Mathematicae, **58** (1999), 189–215.
- [17] V.V. Petrov, *Limit theorems for sums of independent random variables*, Nauka, Moscow, 1987 (in Russian).
- [18] I.F. Pinelis, *Bounds for the infinite-dimensional martingales*, Matemat.Zametki, **27** (1980), 953–958 (in Russian).
- [19] H. Prawitz, *Limits for a distribution, if the characteristic function is given in a finite domain*, Scand.Aktuar.Tidskr., (1972), 138–154.
- [20] V.V. Sazonov, *On the multi-dimensional central limit theorem*, Sankhya Ser. A, **30** (1968), no.2, 181–204.
- [21] V.V. Sazonov, *Normal approximation – some recent advances*, Lecture Notes in Mathematics, 879, Springer-Verlag, Berlin, NY, 1981.
- [22] V.V. Sazonov, V.V. Ulyanov and B.A. Zalesskii, *Normal approximation in a Hilbert space. I, II*, Theory Probab. Appl., **33** (1988a), 207–227, 473–483.
- [23] V.V. Sazonov, V.V. Ulyanov and B.A. Zalesskii, *A sharp estimate for the accuracy of the normal approximation in a Hilbert space*, Theory Probab. Appl., **33** (1988b), 700–701.
- [24] V.V. Sazonov, V.V. Ulyanov and B.A. Zalesskii, *A precise estimate of the rate of convergence in the CLT in Hilbert space*, Mat.USSR Sbornik, **68** (1991), 453–482.
- [25] V.V. Seleznev, *Lower integral bounds for functions satisfying multiplicative inequality*, Obozrenie prikladn. i promyshl. matematiki, **6** (1999), 198–199. (in Russian)
- [26] V.V. Senatov, *Four examples of lower bounds in the multidimensional central limit theorem*, Theory Probab.Appl. **30** (1985), 797–805.
- [27] V.V. Senatov, *On rate of convergence in the central limit theorem in a Hilbert space*, Fifth Vilnius conference on probability theory and mathematical statistics. Abstracts, **4** (1989), 222.

- [28] V.V. Senatov, *Qualitative effects in the rates of convergence in the central limit theorem in multi- dimensional spaces*, Trudy Matemat. Instituta V.A. Steklova, Moscow, Nauka, 1997. (in Russian)
- [29] V.I. Smirnov, *A course of higher mathematics*, Pergamon Press, Oxford, vol. 3, 1964.
- [30] V.V. Yurinskii, *On the accuracy of normal approximation of the probability of hitting a ball*, Theory Probab. Appl., **27** (1982), 280–289.