

A General Law of Precise Asymptotics for the Complete Moment Convergence***

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Abstract The authors achieve a general law of precise asymptotics for a new kind of complete moment convergence of i.i.d. random variables, which includes complete convergence as a special case. It can describe the relations among the boundary function, weighted function, convergence rate and limit value in studies of complete convergence. This extends and generalizes the corresponding results of Liu and Lin in 2006.

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1 Introduction

Throughout this paper, let $\{X, X_n, n \geq 1\}$ be a sequence of i.i.d. random variables, $S_n = \sum_{i=1}^n X_i$ and N be the standard normal random variable. C denotes positive constants, possibly varying from place to place, and $[x]$ denotes the largest integer $\leq x$.

Since P. L. Hsu and H. Robbins [6] introduced the concept of complete convergence, there have been extensions in several directions. One of them is to discuss the precise rate and limit value of $\sum_{n=1}^{\infty} \varphi(n)P\{|S_n| \geq \varepsilon g(n)\}$ as $\varepsilon \downarrow a$, $a \geq 0$, where $\varphi(x)$ and $g(x)$ are the positive functions defined on $[0, \infty)$. We call $\varphi(x)$ and $g(x)$ weighted function and boundary function respectively. The first result in this direction was due to C. C. Heyde [5], who proved that

$$\lim_{\varepsilon \downarrow 0} \varepsilon^2 \sum_{n=1}^{\infty} P\{|S_n| \geq \varepsilon n\} = EX^2, \quad (1.1)$$

where $EX = 0$ and $EX^2 < \infty$. For analogous results in more general case, see [2, 3, 9, 11], etc. The research in this field is called the precise asymptotics. W. D. Liu and Z. Y. Lin [7] studied the precise asymptotics for a new kind of complete moment convergence of i.i.d. random variables.

W. D. Liu and Z. Y. Lin [7] achieved the following three results.

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Theorem 1.1 *Suppose that*

$$EX = 0, \quad EX^2 = \sigma^2 \quad \text{and} \quad EX^2 \log^+ |X| < \infty. \quad (1.2)$$

Then we have

$$\lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=1}^{\infty} \frac{1}{n^2} ES_n^2 I\{|S_n| \geq \varepsilon n\} = 2\sigma^2. \quad (1.3)$$

Conversely, if (1.3) is true, then (1.2) holds.

Theorem 1.2 *Suppose that*

$$EX = 0, \quad EX^2 = \sigma^2 < \infty. \quad (1.4)$$

Then we have

$$\lim_{\varepsilon \downarrow 0} \varepsilon^{2-p} \sum_{n=1}^{\infty} \frac{1}{n^p} E|S_n|^p I\{|S_n| \geq \varepsilon n\} = \frac{2}{2-p} \sigma^2 \quad (1.5)$$

for $0 \leq p < 2$. Conversely, if (1.5) is true for some $0 \leq p < 2$, then (1.4) holds.

Theorem 1.3 *Suppose that*

$$EX = 0, \quad EX^2 = \sigma^2 \quad \text{and} \quad EX^2 (\log^+ |X|)^\delta < \infty, \quad (1.6)$$

where $0 < \delta \leq 1$. Then we have

$$\lim_{\varepsilon \downarrow 0} \varepsilon^{2\delta} \sum_{n=1}^{\infty} \frac{(\log n)^{\delta-1}}{n^2} ES_n^2 I\{|S_n| \geq \varepsilon \sqrt{n \log n}\} = \frac{\sigma^{2\delta+2}}{\delta} E|N|^{2\delta+2}. \quad (1.7)$$

Conversely, if (1.7) is true, then (1.6) holds.

In this paper, we will extend the scope of the weighted functions and boundary functions, and give a general law of precise asymptotics of i.i.d. random variables, which extend and generalize the direct part of [7, Theorems 1.1–1.3].

2 Main Results

We will make some appropriate limitations to $\varphi(x)$ and $g(x)$ in the following theorems, and then get some corollaries according to the kind of $g(x)$. From these corollaries we can conclude a series of interesting results, which contain the direct part of [7, Theorems 1.1–1.3].

Theorem 2.1 *Let $g(x)$ be a positive and differentiable function defined on $[n_0, \infty)$, which is strictly increasing to ∞ . $g'(x)$ is monotone. If $g'(x)$ is monotone nondecreasing, we assume $\lim_{n \rightarrow \infty} \frac{g'(n+1)}{g'(n)} = 1$. Assume that $\varphi(x) = \frac{g'(x)}{g(x)}$ is monotone, and if $\varphi(x)$ is monotone nondecreasing, we assume $\lim_{n \rightarrow \infty} \frac{\varphi(n+1)}{\varphi(n)} = 1$. And assume that the following condition is satisfied:*

$$\limsup_{n \rightarrow \infty} n\varphi(n) < \infty. \quad (2.1)$$

Finally suppose that the following conditions of i.i.d. random variables $\{X, X_n, n \geq 1\}$ are satisfied:

$$EX = 0, \quad EX^2 = \sigma^2 \quad \text{and} \quad EX^2 \log^+ |X| < \infty. \quad (2.2)$$

Then we have

$$\lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=n_0}^{\infty} \varphi(n) E \left| \frac{S_n}{\sqrt{n}} \right|^2 I\{|S_n| \geq \varepsilon \sqrt{ng(n)}\} = 2\sigma^2. \quad (2.3)$$

Theorem 2.2 Let $g(x)$ be a positive and differentiable function defined on $[n_0, \infty)$, which is strictly increasing to ∞ . $g'(x)$ is monotone. If $g'(x)$ is monotone nondecreasing, we assume $\lim_{n \rightarrow \infty} \frac{g'(n+1)}{g'(n)} = 1$. Assume that $\varphi(x) = \frac{g'(x)}{g^{ps}(x)}$ is monotone, where $\frac{1}{s} > p \geq 0$. If $\varphi(x)$ is monotone nondecreasing, we assume $\lim_{n \rightarrow \infty} \frac{\varphi(n+1)}{\varphi(n)} = 1$. And assume that the following condition is satisfied:

$$\limsup_{n \rightarrow \infty} n^{\frac{p}{2}} \varphi(n) < \infty. \quad (2.4)$$

Finally suppose that the following conditions of i.i.d. random variables $\{X, X_n, n \geq 1\}$ are satisfied:

$$EX = 0, EX^2 = \sigma^2 < \infty \quad \text{for } 0 \leq p < 2; \quad (2.5)$$

$$EX = 0, EX^2 = \sigma^2, EX^2 \log^+ |X| < \infty \quad \text{for } p = 2; \quad (2.6)$$

$$EX = 0, EX^2 = \sigma^2, E|X|^p < \infty \quad \text{for } p > 2. \quad (2.7)$$

Then we have

$$\lim_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} \sum_{n=n_0}^{\infty} \varphi(n) E \left| \frac{S_n}{\sqrt{n}} \right|^p I\{|S_n| \geq \varepsilon \sqrt{ng^s(n)}\} = \frac{\sigma^{\frac{1}{s}}}{1-ps} E|N|^{\frac{1}{s}}. \quad (2.8)$$

Remark 2.1 In Theorem 2.1 or Theorem 2.2, $\lim_{n \rightarrow \infty} \frac{\varphi(n+1)}{\varphi(n)} = 1$, (2.1) and (2.4) are all mild conditions. $g(x) = x^\alpha$, $(\log x)^\beta$, $(\log \log x)^\gamma$ with some suitable conditions of $\alpha > 0$, $\beta > 0$, $\gamma > 0$ and some others all satisfy these conditions.

Remark 2.2 Letting $g(x) = x$ in Theorem 2.1, we can get the direct part of [7, Theorem 1].

Remark 2.3 If $s = \frac{1}{2}$, $0 \leq p < 2$ and $g(x) = x$, we can get the direct part of [7, Theorem 2].

Remark 2.4 If $s = \frac{1}{2\delta+2}$, $p = 2$ and $g(x) = (\log x)^{\delta+1}$, we can get the direct part of [7, Theorem 3] with $EX^2 \log^+ |X| < \infty$ instead of $EX^2 (\log^+ |X|)^\delta < \infty$. W. D. Liu and Z. Y. Lin [7] restricts $0 < \delta \leq 1$, but in our theorem we only restrict $\delta > 0$.

Remark 2.5 If $p = 0$, the conditions of Theorem 2.2 still hold, then we can get [1, Theorem 1] with $\alpha = 2$.

Remark 2.6 If $p = 0$, $s = \frac{1}{2}$, $g(x) = \log \log x$, we can get [3, Theorem 2].

Remark 2.7 If $p = 0$, $s = \frac{2-t}{2(r-t)}$, $g(x) = x^{\frac{r}{t}-1}$ for $0 < t < 2$, $r > t$, we can get [2, Corollary 1].

3 Several Lemmas

To prove our theorems, we need some lemmas as follows.

Lemma 3.1 (see [1]) Suppose that $0 < \alpha \leq 2$, $\{X, X_n, n \geq 1\}$ is a sequence of i.i.d. random variables which belongs to the normal domain of attraction of a nondegenerate stable distribution G_α with characteristic exponent α and $EX = 0$ when $1 < \alpha \leq 2$. Let $g(x)$ be a positive and differentiable function defined on $[n_0, \infty)$, which is strictly increasing to ∞ . $g'(x)$ is monotone. If $g'(x)$ is monotone nondecreasing, we assume $\lim_{n \rightarrow \infty} \frac{g'(n+1)}{g'(n)} = 1$. Then, $\forall s > \frac{1}{\alpha}$, we have

$$\lim_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}} \sum_{n=n_0}^{\infty} g'(n) P\{|S_n - a_n| \geq \varepsilon b_n g^s(n)\} = E|Z_\alpha|^{\frac{1}{s}},$$

where Z_α is a random variable having the distribution G_α , a_n and b_n are the centralizing and normalizing constants respectively.

Lemma 3.2 Suppose that $\{X, X_n, n \geq 1\}$ is a sequence of i.i.d. random variables with $E|X|^\beta < \infty$, where $1 < \beta \leq 2$. Let $S_n = \sum_{i=1}^n X_i$. Then $\forall x, y > 0$, we have

$$P\{|S_n| \geq x\} \leq nP\{|X| \geq y\} + 2n^{\frac{x}{y}} \left(\frac{eE|X|^\beta}{xy^{\beta-1}} \right)^{\frac{x}{y}}. \quad (3.1)$$

Proof To prove (3.1), it suffices to show that

$$P\{|S_n| \geq x\} \leq nP\{|X| \geq y\} + 2e^{\frac{x}{y}} \left(\frac{nE|X|^\beta}{nE|X|^\beta + xy^{\beta-1}} \right)^{\frac{x}{y}}. \quad (3.2)$$

However, (3.2) is [11, Lemma 2], which, in turn, is based on [8, Theorem 1.2].

Lemma 3.3 (see [10]) Suppose that $\{X, X_n, n \geq 1\}$ is a sequence of i.i.d. random variables, $S_n = \sum_{i=1}^n X_i$. We have

$$C_1 \lambda^{-2} EX^2 I\{|X| \geq \lambda\} \leq \sum_{n=1}^{\infty} P\{|S_n| \geq n\lambda\} \leq C_2 \lambda^{-2} EX^2 I\{|X| \geq \lambda\} \quad (3.3)$$

for any $\lambda > 0$, where C_1 and C_2 are positive absolute constants.

4 Proof of Theorem 2.1

Set $b(\varepsilon) = [g^{-1}(\varepsilon^{-2})]$, where $g^{-1}(x)$ is the inverse function of $g(x)$. Without loss of generality, we assume that $\sigma^2 = 1$.

Proposition 4.1

$$\lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=n_0}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2x P\{|N| \geq x\} dx = 2.$$

Proof At first, we discuss the relations between the integral and the series. If $\varphi(y)$ is nonincreasing, then $\varphi(y) \int_{\varepsilon \sqrt{g(y)}}^{\infty} 2x P\{|N| \geq x\} dx$ is nonincreasing. Hence we have

$$\begin{aligned} \int_{n_0+1}^{\infty} \varphi(y) \int_{\varepsilon \sqrt{g(y)}}^{\infty} 2x P\{|N| \geq x\} dx dy &\leq \sum_{n=n_0+1}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2x P\{|N| \geq x\} dx \\ &\leq \int_{n_0}^{\infty} \varphi(y) \int_{\varepsilon \sqrt{g(y)}}^{\infty} 2x P\{|N| \geq x\} dx dy. \end{aligned}$$

Then we have

$$\begin{aligned}
& \lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=n_0}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2xP\{|N| \geq x\} dx \\
&= \lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \int_{n_0}^{\infty} \frac{g'(y)}{g(y)} \int_{\varepsilon \sqrt{g(y)}}^{\infty} 2xP\{|N| \geq x\} dx dy \\
&= \lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \int_{g(n_0)}^{\infty} \frac{1}{t} \int_{\varepsilon \sqrt{t}}^{\infty} 2xP\{|N| \geq x\} dx dt \\
&= \lim_{\varepsilon \downarrow 0} \frac{2}{-\log \varepsilon} \int_{\varepsilon \sqrt{g(n_0)}}^{\infty} \frac{1}{y} \int_y^{\infty} 2xP\{|N| \geq x\} dx dy \\
&= \lim_{\varepsilon \downarrow 0} 2 \int_{\varepsilon \sqrt{g(n_0)}}^{\infty} 2xP\{|N| \geq x\} dx \\
&= 2.
\end{aligned} \tag{4.1}$$

If $\varphi(y)$ is nondecreasing, then by $\lim_{n \rightarrow \infty} \frac{\varphi(n+1)}{\varphi(n)} = 1$ for any $0 < \delta < 1$, there exists $n_1 = n_1(\delta)$, such that $\frac{\varphi(n+1)}{\varphi(n)} < 1 + \delta$ and $\frac{\varphi(n)}{\varphi(n+1)} > 1 - \delta$ for $n \geq n_1$. Thus we have

$$\begin{aligned}
& (1 + \delta)^{-1} \int_{n_1+1}^{\infty} \varphi(y) \int_{\varepsilon \sqrt{g(y)}}^{\infty} 2xP\{|N| \geq x\} dx dy \\
&\leq \sum_{n=n_1+1}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2xP\{|N| \geq x\} dx \\
&\leq (1 - \delta)^{-1} \int_{n_1}^{\infty} \varphi(y) \int_{\varepsilon \sqrt{g(y)}}^{\infty} 2xP\{|N| \geq x\} dx dy.
\end{aligned}$$

Therefore

$$\begin{aligned}
& \lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} (1 + \delta)^{-1} \int_{n_1+1}^{\infty} \varphi(y) \int_{\varepsilon \sqrt{g(y)}}^{\infty} 2xP\{|N| \geq x\} dx dy \\
&\leq \lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=n_0}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2xP\{|N| \geq x\} dx \\
&\leq \lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} (1 - \delta)^{-1} \int_{n_1}^{\infty} \varphi(y) \int_{\varepsilon \sqrt{g(y)}}^{\infty} 2xP\{|N| \geq x\} dx dy.
\end{aligned}$$

And then by (4.1), we know

$$2(1 + \delta)^{-1} \leq \lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=n_0}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2xP\{|N| \geq x\} dx \leq 2(1 - \delta)^{-1}.$$

Let $\delta \downarrow 0$. Then we can conclude

$$\lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=n_0}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2xP\{|N| \geq x\} dx = 2.$$

Remark 4.1 In the following, for simplicity, we will omit the discuss of $\varphi(x)$, but the process is similar to the discussion of Proposition 4.1.

Proposition 4.2

$$\lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=n_0}^{b(\varepsilon)} \varphi(n) \left| \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2x P\{|S_n| \geq \sqrt{n}x\} dx - \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2x P\{|N| \geq x\} dx \right| = 0. \quad (4.2)$$

Proof Obviously,

$$\begin{aligned} & \sum_{n=n_0}^{b(\varepsilon)} \varphi(n) \left| \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2x P\{|S_n| \geq \sqrt{n}x\} dx - \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2x P\{|N| \geq x\} dx \right| \\ &= \sum_{n=n_0}^{b(\varepsilon)} \frac{g'(n)}{g(n)} \left| \int_0^{\infty} 2(x + \varepsilon \sqrt{g(n)}) P\{|S_n| \geq \sqrt{n}(x + \varepsilon \sqrt{g(n)})\} dx \right. \\ & \quad \left. - \int_0^{\infty} 2(x + \varepsilon \sqrt{g(n)}) P\{|N| \geq (x + \varepsilon \sqrt{g(n)})\} dx \right| \\ &\leq \sum_{n=n_0}^{b(\varepsilon)} \frac{g'(n)}{g(n)} (\Delta_{n1} + \Delta_{n2} + \Delta_{n3}), \end{aligned}$$

where

$$\begin{aligned} \Delta_n &= \sup_x |P\{|S_n| \geq \sqrt{n}x\} - P\{|N| \geq x\}|, \\ \Delta_{n1} &= \int_0^{\Delta_n^{-\frac{1}{4}}} 2(x + \varepsilon \sqrt{g(n)}) |P\{|S_n| \geq \sqrt{n}(x + \varepsilon \sqrt{g(n)})\} - P\{|N| \geq (x + \varepsilon \sqrt{g(n)})\}| dx, \\ \Delta_{n2} &= \int_{\Delta_n^{-\frac{1}{4}}}^{\infty} 2(x + \varepsilon \sqrt{g(n)}) P\{|S_n| \geq \sqrt{n}(x + \varepsilon \sqrt{g(n)})\} dx, \\ \Delta_{n3} &= \int_{\Delta_n^{-\frac{1}{4}}}^{\infty} 2(x + \varepsilon \sqrt{g(n)}) P\{|N| \geq (x + \varepsilon \sqrt{g(n)})\} dx. \end{aligned}$$

Since $n \leq b(\varepsilon)$ implies $\varepsilon \sqrt{g(n)} \leq 1$, we have

$$\Delta_{n1} \leq \int_0^{\Delta_n^{-\frac{1}{4}}} 2(x + \varepsilon \sqrt{g(n)}) \Delta_n dx \leq \Delta_n (\Delta_n^{-\frac{1}{4}} + \varepsilon \sqrt{g(n)})^2 \leq (\Delta_n^{\frac{1}{4}} + \Delta_n^{\frac{1}{2}})^2. \quad (4.3)$$

For Δ_{n3} , by Markov inequality, we have

$$\Delta_{n3} \leq C \int_{\Delta_n^{-\frac{1}{4}}}^{\infty} \frac{1}{(x + \varepsilon \sqrt{g(n)})^3} dx \leq C \Delta_n^{\frac{1}{2}}. \quad (4.4)$$

Now we estimate Δ_{n2} . By Lemma 3.2, we have

$$\begin{aligned} \Delta_{n2} &\leq \int_{\Delta_n^{-\frac{1}{4}}}^{\infty} 2(x + \varepsilon \sqrt{g(n)}) n P\left\{|X| \geq \frac{\sqrt{n}}{2}(x + \varepsilon \sqrt{g(n)})\right\} dx \\ &\quad + C \int_{\Delta_n^{-\frac{1}{4}}}^{\infty} 2(x + \varepsilon \sqrt{g(n)}) n^2 \frac{1}{n^2(x + \varepsilon \sqrt{g(n)})^4} dx \\ &\triangleq I_1 + I_2. \end{aligned}$$

By Fubini Theorem and the fact $0 \leq \Delta_n \leq 1$, we have

$$\begin{aligned}
I_1 &= E \int_{\Delta_n^{-\frac{1}{4}}}^{\infty} 2(x + \varepsilon \sqrt{g(n)}) n I \left\{ |X| \geq \frac{\sqrt{n}}{2} (x + \varepsilon \sqrt{g(n)}) \right\} dx \\
&\leq EI \{4|X| \geq \sqrt{n}\} \int_0^{\infty} 2(x + \varepsilon \sqrt{g(n)}) n I \left\{ |X| \geq \frac{\sqrt{n}}{2} (x + \varepsilon \sqrt{g(n)}) \right\} dx \\
&\leq EI \{4|X| \geq \sqrt{n}\} \int_0^{\frac{2|X|}{\sqrt{n}} - \varepsilon \sqrt{g(n)}} 2n(x + \varepsilon \sqrt{g(n)}) dx \\
&\leq 4E|X|^2 I \{4|X| \geq \sqrt{n}\}
\end{aligned} \tag{4.5}$$

and

$$I_2 \leq C \int_{\Delta_n^{-\frac{1}{4}}}^{\infty} \frac{1}{(x + \varepsilon \sqrt{g(n)})^3} dx \leq C \Delta_n^{\frac{1}{2}}. \tag{4.6}$$

From (4.3)–(4.6) and the fact $\Delta_n \rightarrow 0$ as $n \rightarrow \infty$, we can get

$$\Delta_{n1} + \Delta_{n2} + \Delta_{n3} \rightarrow 0, \quad \text{as } n \rightarrow \infty. \tag{4.7}$$

Then by (4.7), the monotonicity of $\varphi(x)$ and Toeplitz Lemma (see [4]), we get (4.2). The proposition is now proved.

Proposition 4.3

$$\lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=b(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2x P\{|N| \geq x\} dx = 0. \tag{4.8}$$

Proof By the monotonicity of $\varphi(x)$ and Markov inequality, we have

$$\begin{aligned}
&\lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=b(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2x P\{|N| \geq x\} dx \\
&\leq \lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=b(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2x \frac{E|N|^4}{x^4} dx \\
&\leq \lim_{\varepsilon \downarrow 0} \frac{C}{-\varepsilon^2 \log \varepsilon} \sum_{n=b(\varepsilon)+1}^{\infty} \frac{g'(n)}{g^2(n)} \\
&\leq \lim_{\varepsilon \downarrow 0} \frac{C}{-\varepsilon^2 \log \varepsilon} \int_{\varepsilon^{-2}}^{\infty} \frac{1}{y^2} dy \leq \lim_{\varepsilon \downarrow 0} \frac{C}{-\log \varepsilon} = 0.
\end{aligned}$$

Proposition 4.4

$$\lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=b(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2x P\{|S_n| \geq \sqrt{n}x\} dx = 0. \tag{4.9}$$

Proof Set

$$\begin{aligned}
X'_i &= X_i I\{|X_i| \leq \lambda\}, \quad X''_i = X_i I\{|X_i| > \lambda\}, \\
S'_n &= \sum_{i=1}^n (X'_i - EX'_i), \quad S''_n = \sum_{i=1}^n (X''_i - EX''_i),
\end{aligned}$$

where $\lambda > 1$. Clearly, $S_n = S'_n + S''_n$. Therefore,

$$\begin{aligned} & \sum_{n=b(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon\sqrt{g(n)}}^{\infty} 2xP\{|S_n| \geq \sqrt{nx}\}dx \\ & \leq \sum_{n=b(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon\sqrt{g(n)}}^{\infty} 2xP\left\{|S'_n| \geq \frac{\sqrt{nx}}{2}\right\}dx + \sum_{n=b(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon\sqrt{g(n)}}^{\infty} 2xP\left\{|S''_n| \geq \frac{\sqrt{nx}}{2}\right\}dx \\ & \triangleq I_3 + I_4. \end{aligned}$$

For I_3 , by the monotonicity of $\varphi(x)$, Markov inequality and $E|S'_n|^4 \leq Cn^2\lambda^4$, we have

$$\begin{aligned} \lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} I_3 & \leq \lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=b(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon\sqrt{g(n)}}^{\infty} 2x \frac{4E|S'_n|^4}{n^2x^4} dx \\ & \leq \lim_{\varepsilon \downarrow 0} \frac{C}{-\varepsilon^2 \log \varepsilon} \sum_{n=b(\varepsilon)+1}^{\infty} \frac{g'(n)}{g^2(n)} \\ & \leq \lim_{\varepsilon \downarrow 0} \frac{C}{-\varepsilon^2 \log \varepsilon} \int_{\varepsilon^{-2}}^{\infty} \frac{1}{y^2} dy \leq \lim_{\varepsilon \downarrow 0} \frac{C}{-\log \varepsilon} = 0. \end{aligned} \quad (4.10)$$

For I_4 , by condition (2.1), Fubini Theorem and Lemma 3.3, we get

$$\begin{aligned} I_4 & = \sum_{n=b(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon\sqrt{g(n)}}^{\infty} 2xP\left\{|S''_n| \geq \frac{\sqrt{nx}}{2}\right\}dx \\ & = \sum_{n=b(\varepsilon)+1}^{\infty} n\varphi(n) \int_0^{\infty} 2(t+\varepsilon)P\left\{|S''_n| \geq \frac{n(t+\varepsilon)}{2}\right\}dt \\ & \leq C \int_0^{\infty} (t+\varepsilon) \sum_{n=1}^{\infty} P\left\{|S''_n| \geq \frac{n(t+\varepsilon)}{2}\right\}dt \\ & \leq C \int_0^{\infty} (t+\varepsilon) \frac{E|Y|^2 I\{|Y| \geq \frac{t+\varepsilon}{2}\}}{(t+\varepsilon)^2} dt \\ & = CE \left(|Y|^2 \int_0^{\infty} \frac{I\{|Y| \geq \frac{t+\varepsilon}{2}\}}{(t+\varepsilon)} dt \right) \\ & \leq CE|Y|^2 \log^+ 2|Y| - C(\log \varepsilon)E|Y|^2, \end{aligned}$$

where Y denotes $X'_1 - EX'_1$. Then by (2.2) we have

$$\lim_{\lambda \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} I_4 = 0. \quad (4.11)$$

From (4.10) and (4.11), we complete the proof of Proposition 4.4.

Proof of Theorem 2.1 Note that

$$\begin{aligned} & \sum_{n=n_0}^{\infty} \varphi(n) E \left| \frac{S_n}{\sqrt{n}} \right|^2 I\{|S_n| \geq \varepsilon\sqrt{ng(n)}\} \\ & = \varepsilon^2 \sum_{n=n_0}^{\infty} \varphi(n) g(n) P\{|S_n| \geq \varepsilon\sqrt{ng(n)}\} + \sum_{n=n_0}^{\infty} \varphi(n) \int_{\varepsilon\sqrt{g(n)}}^{\infty} 2xP\{|S_n| \geq \sqrt{nx}\}dx. \end{aligned}$$

In order to prove (2.3), we just need to show that

$$\lim_{\varepsilon \downarrow 0} \frac{\varepsilon^2}{-\log \varepsilon} \sum_{n=n_0}^{\infty} g'(n) P\{|S_n| \geq \varepsilon \sqrt{ng(n)}\} = 0 \quad (4.12)$$

and

$$\lim_{\varepsilon \downarrow 0} \frac{1}{-\log \varepsilon} \sum_{n=n_0}^{\infty} \varphi(n) \int_{\varepsilon \sqrt{g(n)}}^{\infty} 2x P\{|S_n| \geq \sqrt{nx}\} dx = 2. \quad (4.13)$$

By the same argument of Lemma 3.1, we know that for any $\frac{1}{s} > p$,

$$\lim_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}} \sum_{n=n_0}^{\infty} g'(n) P\{|S_n| \geq \varepsilon \sqrt{ng^s(n)}\} = E|N|^{\frac{1}{s}}. \quad (4.14)$$

Let $s = \frac{1}{2}$ in (4.14). Then we can obtain (4.12). (4.13) can be proved by Propositions 4.1–4.4 and the triangular inequality.

5 Proof of Theorem 2.2

Set $d(\varepsilon) = [g^{-1}(M\varepsilon^{-\frac{1}{s}})]$, where $g^{-1}(x)$ is the inverse function of $g(x)$, $M \geq 1$. Without loss of generality, we assume that $\sigma^2 = 1$.

Proposition 5.1 *For $p > 0$, we have*

$$\lim_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} \sum_{n=n_0}^{\infty} \varphi(n) \int_{\varepsilon g^s(n)}^{\infty} px^{p-1} P\{|N| \geq x\} dx = \frac{ps}{1-ps} E|N|^{\frac{1}{s}}. \quad (5.1)$$

Proof At first we discuss the relations between the integral and the series. If $\varphi(y)$ is nonincreasing, then $\varphi(y) \int_{\varepsilon g^s(y)}^{\infty} px^{p-1} P\{|N| \geq x\} dx$ is nonincreasing. Hence we have

$$\begin{aligned} \int_{n_0+1}^{\infty} \varphi(y) \int_{\varepsilon g^s(y)}^{\infty} px^{p-1} P\{|N| \geq x\} dx dy &\leq \sum_{n=n_0+1}^{\infty} \varphi(n) \int_{\varepsilon g^s(n)}^{\infty} px^{p-1} P\{|N| \geq x\} dx \\ &\leq \int_{n_0}^{\infty} \varphi(y) \int_{\varepsilon g^s(y)}^{\infty} px^{p-1} P\{|N| \geq x\} dx dy. \end{aligned}$$

Then we have

$$\begin{aligned} &\lim_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} \sum_{n=n_0}^{\infty} \varphi(n) \int_{\varepsilon g^s(n)}^{\infty} px^{p-1} P\{|N| \geq x\} dx \\ &= \lim_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} \int_{n_0}^{\infty} \varphi(y) \int_{\varepsilon g^s(y)}^{\infty} px^{p-1} P\{|N| \geq x\} dx dy \\ &= \lim_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} \int_{g(n_0)}^{\infty} \frac{1}{t^{ps}} \int_{\varepsilon t^s}^{\infty} px^{p-1} P\{|N| \geq x\} dx dt \end{aligned}$$

$$\begin{aligned}
&= \lim_{\varepsilon \downarrow 0} \frac{p}{s} \int_{\varepsilon g^s(n_0)}^{\infty} \frac{1}{t^{p+1-\frac{1}{s}}} \int_t^{\infty} x^{p-1} P\{|N| \geq x\} dx dt \\
&= \frac{p}{s} \int_0^{\infty} \frac{1}{t^{p+1-\frac{1}{s}}} \int_t^{\infty} x^{p-1} P\{|N| \geq x\} dx dt \\
&= \frac{p}{s} \int_0^{\infty} x^{p-1} P\{|N| \geq x\} \int_0^x \frac{1}{t^{p+1-\frac{1}{s}}} dt dx \\
&= \frac{ps}{1-ps} \int_0^{\infty} \frac{1}{s} x^{\frac{1}{s}-1} P\{|N| \geq x\} dx \\
&= \frac{ps}{1-ps} E|X|^{\frac{1}{s}}.
\end{aligned}$$

If $\varphi(y)$ is nondecreasing, then by $\lim_{n \rightarrow \infty} \frac{\varphi(n+1)}{\varphi(n)} = 1$, the proof is similar to that of Proposition 4.1. Thus we can get Proposition 5.1 by the above steps.

Remark 5.1 In the following, for simplicity, we will omit the discussion of $\varphi(x)$, but the process is similar to the discussion of Proposition 5.1.

Proposition 5.2 For $p > 0$, we have

$$\lim_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} \sum_{n=n_0}^{d(\varepsilon)} \varphi(n) \left| \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} P\{|S_n| \geq \sqrt{n}x\} dx - \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} P\{|N| \geq x\} dx \right| = 0. \quad (5.2)$$

Proof It is easy to see that

$$\begin{aligned}
&\varepsilon^{\frac{1}{s}-p} \sum_{n=n_0}^{d(\varepsilon)} \varphi(n) \left| \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} P\{|S_n| \geq \sqrt{n}x\} dx - \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} P\{|N| \geq x\} dx \right| \\
&\leq \sum_{n=n_0}^{d(\varepsilon)} \varphi(n) \int_0^{\infty} p(x + \varepsilon g^s(n))^{p-1} |P\{|S_n| \geq \sqrt{n}(x + \varepsilon g^s(n))\} - P\{|N| \geq (x + \varepsilon g^s(n))\}| dx \\
&\leq \sum_{n=n_0}^{d(\varepsilon)} \varphi(n) (\Delta'_{n1} + \Delta'_{n2} + \Delta'_{n3}),
\end{aligned}$$

where

$$\begin{aligned}
\Delta'_{n1} &= \int_0^{\Delta_n^{-\frac{1}{2p}}} p(x + \varepsilon g^s(n))^{p-1} |P\{|S_n| \geq \sqrt{n}(x + \varepsilon g^s(n))\} - P\{|N| \geq (x + \varepsilon g^s(n))\}| dx, \\
\Delta'_{n2} &= \int_{\Delta_n^{-\frac{1}{2p}}}^{\infty} p(x + \varepsilon g^s(n))^{p-1} P\{|S_n| \geq \sqrt{n}(x + \varepsilon g^s(n))\} dx, \\
\Delta'_{n3} &= \int_{\Delta_n^{-\frac{1}{2p}}}^{\infty} p(x + \varepsilon g^s(n))^{p-1} P\{|N| \geq (x + \varepsilon g^s(n))\} dx.
\end{aligned}$$

Since $n \leq d(\varepsilon)$ implies $\varepsilon g^s(n) \leq M^s$, we have

$$\Delta'_{n1} \leq \int_0^{\Delta_n^{-\frac{1}{2p}}} p(x + \varepsilon g^s(n))^{p-1} \Delta_n dx \leq \Delta_n (\Delta_n^{-\frac{1}{2p}} + \varepsilon g^s(n))^p \leq (\Delta_n^{\frac{1}{2p}} + M^s \Delta_n^{\frac{1}{p}})^p. \quad (5.3)$$

For Δ'_{n3} , by Markov inequality, we have

$$\Delta'_{n3} \leq C \int_{\Delta_n^{-\frac{1}{2p}}}^{\infty} \frac{1}{(x + \varepsilon g^s(n))^3} dx \leq C \Delta_n^{\frac{1}{p}}. \quad (5.4)$$

Now we estimate Δ'_{n2} . First we consider $0 < p < 2$. By Markov inequality, we have

$$\Delta'_{n2} \leq C \int_{\Delta_n^{-\frac{1}{2p}}}^{\infty} \frac{1}{(x + \varepsilon g^s(n))^{3-p}} dx \leq C \Delta_n^{\frac{1}{p}-\frac{1}{2}}. \quad (5.5)$$

For $p \geq 2$, by Lemma 3.2, choosing $\beta = 2$ and $x = py$, we know

$$\begin{aligned} \Delta'_{n2} &\leq \int_{\Delta_n^{-\frac{1}{2p}}}^{\infty} p(x + \varepsilon g^s(n))^{p-1} n P\left\{|X| \geq \frac{\sqrt{n}}{p}(x + \varepsilon g^s(n))\right\} dx \\ &\quad + C \int_{\Delta_n^{-\frac{1}{2p}}}^{\infty} p(x + \varepsilon g^s(n))^{p-1} n^p \frac{1}{n^p(x + \varepsilon g^s(n))^{2p}} dx \\ &\triangleq J_1 + J_2. \end{aligned}$$

By Fubini Theorem and the fact $0 \leq \Delta_n \leq 1$, we have

$$\begin{aligned} J_1 &= E \int_{\Delta_n^{-\frac{1}{2p}}}^{\infty} p(x + \varepsilon g^s(n))^{p-1} n I\left\{|X| \geq \frac{\sqrt{n}}{p}(x + \varepsilon g^s(n))\right\} dx \\ &\leq EI\{2p|X| \geq \sqrt{n}\} \int_0^{\infty} p(x + \varepsilon g^s(n))^{p-1} n I\left\{|X| \geq \frac{\sqrt{n}}{p}(x + \varepsilon g^s(n))\right\} dx \\ &\leq EI\{2p|X| \geq \sqrt{n}\} \int_0^{\frac{p|X|}{\sqrt{n}} - \varepsilon g^s(n)} p(x + \varepsilon g^s(n))^{p-1} n dx \\ &\leq CEI\{2p|X| \geq \sqrt{n}\} n \frac{|X|^p}{n^{\frac{p}{2}}} \\ &\leq CE|X|^p I\{2p|X| \geq \sqrt{n}\} \end{aligned} \quad (5.6)$$

and

$$J_2 \leq C \int_{\Delta_n^{-\frac{1}{2p}}}^{\infty} \frac{1}{(x + \varepsilon g^s(n))^{p+1}} dx \leq C \Delta_n^{\frac{1}{2}}. \quad (5.7)$$

From (5.3)–(5.7) and the fact $\Delta_n \rightarrow 0$ as $n \rightarrow \infty$, we can get

$$\Delta'_{n1} + \Delta'_{n2} + \Delta'_{n3} \rightarrow 0 \quad \text{as } n \rightarrow \infty. \quad (5.8)$$

Then by (5.8), the monotonicity of $\varphi(x)$ and Toeplitz Lemma (see [4]), we get (5.2). The proposition is now proved.

Proposition 5.3 *For $p > 0$, we have*

$$\lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} \sum_{n=d(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} P\{|N| \geq x\} dx = 0. \quad (5.9)$$

Proof By the monotonicity of $\varphi(x)$ and Markov inequality, we have

$$\begin{aligned} &\lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} \sum_{n=d(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} P\{|N| \geq x\} dx \\ &\leq \lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} C \varepsilon^{\frac{1}{s}-p} \sum_{n=d(\varepsilon)+1}^{\infty} \frac{g'(n)}{g^{ps}(n)} \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} \frac{E|N|^{\frac{2}{s}}}{x^{\frac{2}{s}}} dx \end{aligned}$$

$$\begin{aligned}
&\leq \lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} C\varepsilon^{-\frac{1}{s}} \sum_{n=d(\varepsilon)+1}^{\infty} \frac{g'(n)}{g^2(n)} \\
&\leq \lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} C\varepsilon^{-\frac{1}{s}} \int_{M\varepsilon^{-\frac{1}{s}}}^{\infty} \frac{1}{y^2} dy \\
&\leq \lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} C \frac{1}{M} = 0.
\end{aligned}$$

Proposition 5.4 For $p > 0$, we have

$$\lim_{M \rightarrow \infty} \lim_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} \sum_{n=d(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} P\{|S_n| \geq \sqrt{n}x\} dx = 0. \quad (5.10)$$

Proof Define X'_i , X''_i , S'_n and S''_n as in the proof of Proposition 4.4. Therefore

$$\begin{aligned}
&\sum_{n=d(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} P\{|S_n| \geq \sqrt{n}x\} dx \\
&\leq \sum_{n=d(\varepsilon)+1}^{\infty} \varphi(n) \left[\int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} P\left\{|S'_n| \geq \frac{\sqrt{n}x}{2}\right\} dx + \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} P\left\{|S''_n| \geq \frac{\sqrt{n}x}{2}\right\} dx \right] \\
&\triangleq J_3 + J_4.
\end{aligned}$$

For J_3 , by the monotonicity of $\varphi(x)$, Markov inequality and $E|S'_n|^{\frac{2}{s}} \leq C n^{\frac{1}{s}} \lambda^{\frac{2}{s}}$, we have

$$\begin{aligned}
\lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} J_3 &\leq \lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} C\varepsilon^{\frac{1}{s}-p} \sum_{n=d(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} \frac{E|S'_n|^{\frac{2}{s}}}{n^{\frac{1}{s}} x^{\frac{2}{s}}} dx \\
&\leq \lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} C\varepsilon^{\frac{1}{s}-p} \sum_{n=d(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon g^s(n)}^{\infty} \frac{1}{x^{\frac{2}{s}-p+1}} dx \\
&\leq \lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} C\varepsilon^{-\frac{1}{s}} \sum_{n=d(\varepsilon)+1}^{\infty} \frac{g'(n)}{g^2(n)} \\
&\leq \lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} C\varepsilon^{-\frac{1}{s}} \int_{M\varepsilon^{-\frac{1}{s}}}^{\infty} \frac{1}{y^2} dy \\
&\leq \lim_{M \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} C \frac{1}{M} = 0.
\end{aligned}$$

For J_4 , by condition (2.4), Fubini Theorem and Lemma 3.3, we get

$$\begin{aligned}
J_4 &= \sum_{n=d(\varepsilon)+1}^{\infty} \varphi(n) \int_{\varepsilon g^s(n)}^{\infty} p x^{p-1} P\left\{|S''_n| \geq \frac{\sqrt{n}x}{2}\right\} dx \\
&= \sum_{n=d(\varepsilon)+1}^{\infty} n^{\frac{p}{2}} \varphi(n) \int_0^{\infty} p(x+\varepsilon)^{p-1} P\left\{|S''_n| \geq \frac{n(x+\varepsilon)}{2}\right\} dx \\
&\leq C \int_0^{\infty} p(x+\varepsilon)^{p-1} \sum_{n=1}^{\infty} P\left\{|S''_n| \geq \frac{n(x+\varepsilon)}{2}\right\} dx
\end{aligned}$$

$$\begin{aligned}
&\leq C \int_0^\infty p(x+\varepsilon)^{p-1} \frac{E|Y|^2 I\{|Y| \geq \frac{x+\varepsilon}{2}\}}{(x+\varepsilon)^2} dx \\
&= CpEY^2 \int_0^\infty \frac{I\{|Y| \geq \frac{x+\varepsilon}{2}\}}{(x+\varepsilon)^{3-p}} dx,
\end{aligned}$$

where Y denotes $X_1'' - EX_1''$.

Note that

$$J_4 \leq CEY^2 \log^+ |Y| - C(\log \varepsilon) EY^2$$

for $p = 2$, and

$$J_4 \leq CE|Y|^P - C(\varepsilon^{p-2}) EY^2$$

for $p \neq 2$, and note that $\frac{1}{s} > p$, so we know

$$\lim_{\lambda \rightarrow \infty} \limsup_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} J_4 = 0.$$

From the above steps, we complete the proof.

Proof of Theorem 2.2 Since

$$E \left| \frac{S_n}{\sqrt{n}} \right|^p I\{|S_n| \geq \varepsilon \sqrt{n} g^s(n)\} = P\{|S_n| \geq \varepsilon \sqrt{n} g^s(n)\},$$

where $p = 0$, by (4.14) we can get Theorem 2.2. Therefore we just need to discuss the case $\frac{1}{s} > p > 0$. Note that

$$\begin{aligned}
&\sum_{n=n_0}^\infty \varphi(n) E \left| \frac{S_n}{\sqrt{n}} \right|^p I\{|S_n| \geq \varepsilon \sqrt{n} g^s(n)\} \\
&= \varepsilon^p \sum_{n=n_0}^\infty \varphi(n) g^{ps}(n) P\{|S_n| \geq \varepsilon \sqrt{n} g^s(n)\} + \sum_{n=n_0}^\infty \varphi(n) \int_{\varepsilon g^s(n)}^\infty p x^{p-1} P\{|S_n| \geq \sqrt{n} x\} dx.
\end{aligned}$$

In order to prove (2.8), we just need to show that

$$\lim_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}} \sum_{n=n_0}^\infty g'(n) P\{|S_n| \geq \varepsilon \sqrt{n} g^s(n)\} = E|N|^{\frac{1}{s}}, \quad (5.11)$$

$$\lim_{\varepsilon \downarrow 0} \varepsilon^{\frac{1}{s}-p} \sum_{n=n_0}^\infty \varphi(n) \int_{\varepsilon g^s(n)}^\infty p x^{p-1} P\{|S_n| \geq \sqrt{n} x\} dx = \frac{ps}{1-ps} E|N|^{\frac{1}{s}}. \quad (5.12)$$

By (4.14), we can get (5.11). (5.12) can be proved by Propositions 5.1–5.4 and the triangular inequality.

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References

- [1] Cheng, F. Y. and Wang, Y. B., Precise asymptotics of partial sums for IID and NA sequences (in Chinese), *Acta. Math. Sin., Ser. A*, **45**(5), 2004, 965–972.

- [2] Gut, A. and Spătaru, A., Precise asymptotics in the Baum-Katz and Davis law of large numbers, *J. Math. Anal. Appl.*, **248**, 2000, 233–246.
- [3] Gut, A. and Spătaru, A., Precise asymptotics in the law of the iterated logarithm, *Ann. Prob.*, **28**, 2000, 1870–1883.
- [4] Hall, P. and Heyde, C. C., *Martingale Limit Theory and Its Application*, Academic Press, New York, 1980.
- [5] Heyde, C. C., A supplement to the strong law of large numbers, *J. Appl. Prob.*, **12**, 1975, 173–175.
- [6] Hsu, P. L. and Robbins, H., Complete convergence and the strong law of large numbers, *Proc. Nat. Acad. Sci. USA*, **33**, 1947, 25–31.
- [7] Liu, W. D. and Lin, Z. Y., Precise asymptotics for a new kind of complete moment convergence, *Stat. Prob. Lett.*, **76**, 2006, 1787–1799.
- [8] Nagaev, S. V., Large deviations of sums of independent random variables, *Ann. Prob.*, **7**(5), 1979, 745–789.
- [9] Pang, T. X. and Wang, J. F., Precise asymptotics in Chung’s law of the iterated logarithm via self-normalization (in Chinese), *Chin. Ann. Math.*, **28A**(4), 2007, 507–518.
- [10] Pruss, A. R., A two-sided estimate in the Hsu-Robbins-Erdos law of large numbers, *Stoch. Proc. Appl.*, **70**, 1997, 173–180.
- [11] Spătaru, A., Precise asymptotics in Spitzer’s law of large numbers, *J. Theor. Prob.*, **12**, 1999, 811–819.