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ON THE UNIVERSALITY OF THE EPSTEIN ZETA FUNCTION

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Abstract. We study universality properties of the Epstein zeta function $E_n(L, s)$ for lattices $L$ of large dimension $n$ and suitable regions of complex numbers $s$. Our main result is that, as $n \to \infty$, $E_n(L, s)$ is universal in the right half of the critical strip as $L$ varies over all $n$-dimensional lattices $L$. The proof uses an approximation result for Dirichlet polynomials together with a recent result on the distribution of lengths of lattice vectors in a random lattice of large dimension and a strong uniform estimate for the error term in the generalized circle problem. Using the same basic approach we also prove that, as $n \to \infty$, $E_n(L_1, s) - E_n(L_2, s)$ is universal in the full half-plane to the right of the critical line as $(L_1, L_2)$ varies over all pairs of $n$-dimensional lattices. Finally, we prove a more classical universality result for $E_n(L, s)$ in the $s$-variable valid for almost all lattices $L$ of dimension $n$. As part of the proof we obtain a strong bound of $E_n(L, s)$ on the critical line that is subconvex for $n \geq 5$ and almost all $n$-dimensional lattices $L$.

1. Introduction

In 1975 Voronin \cite{22, 23} proved the following remarkable approximation theorem for the Riemann zeta function:

Theorem 1.1 (Voronin). Let $K = \{ s \in \mathbb{C} : |s - \frac{3}{4}| \leq r \}$ for some $r < \frac{1}{4}$, and suppose that $f$ is any nonvanishing continuous function on $K$ that is analytic in the interior of $K$. Then, for any $\varepsilon > 0$,

$$\liminf_{T \to \infty} \frac{1}{T} \text{meas} \{ t \in [0, T] : \max_{s \in K} |\zeta(s + it) - f(s)| < \varepsilon \} > 0.$$

This theorem, known as Voronin’s Universality Theorem, shows that any nonvanishing analytic function in a small disc may be approximated by a vertical shift of the Riemann zeta function. It has been improved and generalized in various directions (see Steuding’s monograph \cite{16} and Matsumoto’s survey paper \cite{11} for detailed discussions); for example it is known that the set $K$ may be chosen as any compact set with connected complement that lies in the vertical strip

$$D := \{ s \in \mathbb{C} : \frac{1}{2} < \text{Re}(s) < 1 \}.$$  

Let us also note that, since $\zeta(s)$ has an Euler product, it is necessary to assume that the function $f$ in Theorem 1.1 is nonvanishing on $K$. However, for zeta functions without an Euler product, such as the Hurwitz zeta function $\zeta(s, \alpha)$ with rational or transcendental parameter $0 < \alpha < 1$, $\alpha \neq \frac{1}{2}$, this condition can be removed.

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1For the case of algebraic irrational $\alpha$, the Hurwitz zeta function does not have an Euler product and it is likely to be universal without assuming the nonvanishing condition. However, proving any
Similar universality theorems have been proved for large classes of zeta functions and \( L \)-functions. Here we will content ourselves with a short review of the situation for Dirichlet \( L \)-functions. In his thesis, Voronin \cite{25} proved the joint universality of Dirichlet \( L \)-functions, i.e. that vertical shifts of Dirichlet \( L \)-functions attached to nonequivalent Dirichlet characters can be used to simultaneously approximate any finite number of nonvanishing analytic functions on \( K \). In a different direction, Bagchi \cite{1} has proved a universality theorem for Dirichlet \( L \)-functions in which the imaginary shifts in the complex argument \( s \) from Theorem 1.1 has been replaced by a variation of the character \( \chi \) over the set of characters of prime modulus. To be precise, let \( K \) be a compact subset of \( D \) with connected complement and let \( f \) be a nonvanishing continuous function on \( K \) that is analytic in the interior of \( K \). Then, for any \( \varepsilon > 0 \),

\[
\liminf_{p \to \infty} \frac{1}{\varphi(p)} \# \left\{ \chi \mod p : \max_{s \in K} |L(s, \chi) - f(s)| < \varepsilon \right\} > 0.
\]

Recently Mishou and Nagoshi \cite{12, 13} proved a related result for Dirichlet \( L \)-functions associated with real characters. Let \( D^+ \) (resp. \( D^- \)) denote the set of positive fundamental discriminants (resp. negative fundamental discriminants) and define

\[
D^\pm(X) := \{ d \in D^\pm : |d| \leq X \}.
\]

For a discriminant \( d \), we let \( \chi_d \) denote the quadratic Dirichlet character modulo \( |d| \) defined by the Kronecker symbol \( \chi_d(n) = (\frac{d}{n}) \).

**Theorem 1.2** (Mishou-Nagoshi). Let \( \Omega \) be a simply connected region in \( D \) that is symmetric with respect to the real axis. Then, for any \( \varepsilon > 0 \), any compact set \( K \subset \Omega \) and any nonvanishing holomorphic function \( f \) on \( \Omega \) which takes positive real values on \( \Omega \cap \mathbb{R} \), we have

\[
\liminf_{X \to \infty} \frac{1}{\#D^\pm(X)} \# \left\{ d \in D^\pm(X) : \max_{s \in K} |L(s, \chi_d) - f(s)| < \varepsilon \right\} > 0.
\]

The purpose of the present paper is to prove universality results for the Epstein zeta function that turn out to have similarities with both Theorem 1.2 and Bagchi’s result describe in (1.2) above. In order to state and describe our results, we first need to properly introduce the setting.

Let \( X_n \) denote the space of all \( n \)-dimensional lattices \( L \subset \mathbb{R}^n \) of covolume one and let \( \mu_n \) denote Siegel’s measure \cite{15} on \( X_n \), normalized to be a probability measure. For \( L \in X_n \) and \( \text{Re}(s) > \frac{n}{2} \), the Epstein zeta function is defined by

\[
E_n(L, s) := \sum_{m \in L \setminus \{0\}} |m|^{-2s}.
\]

\( E_n(L, s) \) has an analytic continuation to \( \mathbb{C} \) except for a simple pole at \( s = \frac{n}{2} \) with residue \( \pi^{\frac{n}{2}} \Gamma(\frac{n}{2})^{-1} \). Furthermore, \( E_n(L, s) \) satisfies the functional equation

\[
F_n(L, s) = F_n(L^*, \frac{n}{2} - s),
\]

where \( F_n(L, s) := \pi^{-s} \Gamma(s) E_n(L, s) \) and \( L^* \) is the dual lattice of \( L \). The Epstein zeta function has many properties in common with the Riemann zeta function. In type of universality result in this case seems quite difficult and constitutes a major open problem in the theory of universality.

\(^2\)Similar results were established (independently) by Gonek \cite{7} and Bagchi \cite{1}.
fact, the functions $E_n(L, s)$ (actually a slightly more general family of functions) were introduced by Epstein [4, 5] in an attempt to find the most general form of a function satisfying a functional equation of the same type as the Riemann zeta function. Note in particular the relation

$$E_1(Z, s) = 2\zeta(2s).$$

However, we stress that there are also important differences between $E_n(L, s)$ and $\zeta(s)$. Typically $E_n(L, s)$ has no Euler product and it is well known that the Riemann hypothesis for $E_n(L, s)$ generally fails (cf., e.g., [17] and the references therein).

Let $V_n$ denote the volume of the $n$-dimensional unit ball. We recall the explicit formula

$$V_n = \frac{\pi^{n/2}}{\Gamma\left(\frac{n}{2} + 1\right)},$$

and stress that $V_n$ decays extremely fast as $n \to \infty$. In most of our results $V_n$ will appear naturally as part of a factor normalizing $E_n(L, s)$.

Our first main result is a universality theorem for $E_n(L, s)$ in the lattice aspect, i.e. a universality result where the lattice $L$ varies over the space $X_n$ but no vertical shifts are applied to the complex variable $s$. The situation is related to the one in Bagchi’s theorem (1.2), and similarly, in order to obtain still finer approximations, we are forced to consider the limit $n \to \infty$. Let us also point out that the relation with Theorem 1.2 lies in the fact that both $L(s, \chi_d)$ and $E_n(L, s)$ are real-valued for real values of $s$, resulting in the same sort of conditions on the involved functions and regions. However, since $E_n(L, s)$ typically has no Euler product, the nonvanishing condition on the function $f$ can be removed.

**Theorem 1.3.** Let $\Omega$ be a simply connected region in $D$ that is symmetric with respect to the real axis. Then, for any $\varepsilon > 0$, any compact set $K \subset \Omega$ and any holomorphic function $f$ on $\Omega$ that is real-valued on $\Omega \cap \mathbb{R}$, we have

$$\liminf_{n \to \infty} \text{Prob}_{\mu_n}\left\{ L \in X_n : \max_{s \in K} \left| 2^{s-1}V_n^{-s}E_n\left( L, \frac{ns}{2} \right) - f(s) \right| < \varepsilon \right\} > 0.$$

**Remark 1.4.** In particular it follows from Theorem 1.3 that, given $\varepsilon > 0$, $K \subset \Omega$ and $f$ as above, there exists some $n \in \mathbb{Z}^+$ and a lattice $L \in X_n$ such that

$$\max_{s \in K} \left| 2^{s-1}V_n^{-s}E_n\left( L, \frac{ns}{2} \right) - f(s) \right| < \varepsilon.$$

As an immediate consequence of Theorem 1.3 we have the following denseness result.

**Corollary 1.5.** For any fixed $s \in D \setminus (D \cap \mathbb{R})$ the set

$$\left\{ 2^{s-1}V_n^{-s}E_n\left( L, \frac{ns}{2} \right) : n \in \mathbb{Z}^+, L \in X_n \right\}$$

is dense in $\mathbb{C}$. Moreover, for any fixed $s \in D \cap \mathbb{R}$, we have

$$\left\{ 2^{s-1}V_n^{-s}E_n\left( L, \frac{ns}{2} \right) : n \in \mathbb{Z}^+, L \in X_n \right\} = \mathbb{R}.$$

We note that in contrast to the situation in [12, Corollary 1.2], the lattice variable $L$ varies continuously in $X_n$. Hence, since the Epstein zeta function is continuous in the lattice variable, this allows us to use the intermediate value theorem to prove that the left-hand side of (1.4) is not only dense in $\mathbb{R}$, but in fact equal to $\mathbb{R}$.

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3Here the words *typically* and *generally* are to be interpreted in terms of the measure $\mu_n$. 
Let us also point out that Theorem 1.3 together with the Weierstrass approximation theorem, readily gives a universality result for approximation of continuous functions on closed subintervals of \((\frac{1}{2}, 1)\).

**Corollary 1.6.** Let \(\frac{1}{2} < a < b < 1\). Then, for any \(\varepsilon > 0\) and any continuous real-valued function \(f\) on \([a, b]\), we have

\[
\liminf_{n \to \infty} \text{Prob}_{\mu_n} \left\{ L \in X_n : \max_{x \in [a, b]} \left| 2^{s-1}V_n^{-s}E_n \left( L, \frac{nx}{2} \right) - f(x) \right| < \varepsilon \right\} > 0.
\]

We will now use Corollary 1.6 to give a short and more elementary proof of (one part of) [21, Corollary 1.5]. Let \(\varepsilon < 1\) and let, for any \(\delta \in (0, \frac{1}{4})\), \(K_{\delta}\) denote the closed interval \([\frac{1}{2} + \delta, 1 - \delta]\) \(\subset (\frac{1}{2}, 1)\). Now, by applying Corollary 1.6 with the continuous function \(f(x) = -1\) on \(K_{\delta}\), we obtain the following result.

**Corollary 1.7.** For any \(\delta \in (0, \frac{1}{4})\), we have

\[
\liminf_{n \to \infty} \text{Prob}_{\mu_n} \left\{ L \in X_n : E_n \left( L, \frac{nx}{2} \right) < 0 \text{ for all } x \in [\frac{1}{2} + \delta, 1 - \delta] \right\} > 0.
\]

**Remark 1.8.** It follows from [21, Corollary 1.5] that we can replace the \(\liminf\) in Corollary 1.7 by a proper limit. Let us also point out that it follows from [21, Corollary 1.7] that this limit probability tends to zero as \(\delta\) tends to zero.

Our next corollary discusses zeros of \(E_n \left( L, \frac{nx}{2} \right)\) in the interval \(\frac{1}{2} < x < 1\). Its proof is an application of Theorem 1.3 with the function \(f(s) = \sin \left( \pi \left( \frac{m(s-a)}{b-a} + \frac{1}{2} \right) \right)\), together with Rouche’s theorem and the observation that since \(E_n \left( L, \frac{na}{2} \right)\) is real-valued the zeros of \(E_n \left( L, \frac{na}{2} \right)\) approximating the zeros of \(f(s)\) must remain on the real line.

**Corollary 1.9.** Let \(\frac{1}{2} < a < b < 1\) and let \(m \in \mathbb{Z}^+\). Then we have

\[
\liminf_{n \to \infty} \text{Prob}_{\mu_n} \left\{ L \in X_n : E_n \left( L, \frac{nx}{2} \right) \text{ has exactly } m \text{ zeros in } [a, b] \right\} > 0.
\]

Let us give a brief sketch of the proof of Theorem 1.3 which is given in full detail in Section 3. To begin, we decompose the expression under consideration into two parts as

\[
\left( 2^{s-1}V_n^{-s}E_n \left( L, \frac{ns}{2} \right) - \zeta(s) \right) + \left( \zeta(s) - f(s) \right),
\]

and approximate the second part, i.e. \(\zeta(s) - f(s)\) (which is holomorphic on the compact set \(K\)), to any desired accuracy by a Dirichlet polynomial. We continue by dividing the first part of (1.5) into a main term and a tail term. Using a recent result of the second author [18] on the distribution of lengths of lattice vectors in a random lattice of large dimension, we show that the main term approximate the Dirichlet polynomial found above as well as desired for a positive proportion of lattices \(L \in X_n\). To conclude the proof we use a strong uniform estimate of the error term in the generalized circle problem (cf. [21, 14]; see also Section 2.1) to show that the tail term is sufficiently small.

Using the same general idea of proof, we arrive at our second main result. As far as we are aware, this is the first example of a universality theorem that is valid in the half-plane of absolute convergence (of the Dirichlet series under consideration).

\[\text{If we allow the number of zeros to also be greater than } m, \text{ then this result is an immediate consequence of Corollary 1.6}\]
Theorem 1.10. Let $\Omega$ be a simply connected region in the half-plane $\text{Re}(s) > \frac{1}{2}$ that is symmetric with respect to the real axis. Then, for any $\varepsilon > 0$, any compact set $K \subset \Omega$ and any holomorphic function $f$ on $\Omega$ that is real-valued on $\Omega \cap \mathbb{R}$, we have
\[
\liminf_{n \to \infty} \text{Prob}_{\mu_n \times \mu_n} \left\{ (L_1, L_2) \in X_n^2 : \max_{s \in K} \left| 2^{s-1} V_n^{-s} E_n \left( L_1, \frac{n(s+it)}{2} \right) - 2^{s-1} V_n^{-s} E_n \left( L_2, \frac{n(s+it)}{2} \right) - f(s) \right| < \varepsilon \right\} > 0.
\]

Classical Voronin universality (variants of Theorem 1.1) for the Epstein zeta function follows in some special cases, such as when the Epstein zeta function is (a constant multiple of) a Dedekind zeta function of an imaginary quadratic number field, since then it is a product of $\zeta(s)$ and a Dirichlet $L$-function, and universality follows from the joint universality of Dirichlet $L$-functions. Universality has also been proved in the case when the Epstein zeta function can be written as a linear combination of Hecke $L$-functions by joint universality for such functions, see [10, pp. 279-284] and [24]. The general case seems to be more difficult. While we cannot prove classical universality for $E_n(L, s)$ with any single given lattice, we will prove universality for almost every lattice $L \in X_n$. At present time we can only prove our result in the strip $\frac{3}{4} < \text{Re}(s) < 1$.

Theorem 1.11. Let $n \geq 2$. Then, for almost all $L \in X_n$ and for any $\varepsilon > 0$, any compact set $K \subset \{ s \in \mathbb{C} : \frac{3}{4} < \text{Re}(s) < 1 \}$ with connected complement, and any function $f$ that is continuous on $K$ and analytic in the interior of $K$, we have
\[
\liminf_{T \to \infty} \frac{1}{T} \text{meas} \left\{ t \in [0, T] : \max_{s \in K} \left| E_n \left( L, \frac{n(s+it)}{2} \right) - f(s) \right| < \varepsilon \right\} > 0.
\]

There are a number of standard corollaries of this type of universality (see, e.g., [10]). As one such example, we mention an immediate consequence of Theorem 1.11 that follows by approximating $f(s) = s - \frac{\pi i}{2}$ on $K = \{ s \in \mathbb{C} : |s - \frac{\pi i}{2}| \leq \frac{\pi}{2} \}$ and using Rouche’s theorem.

Corollary 1.12. Let $n \geq 2$ and let $\frac{3}{4} < a < b < 1$. Then, for almost all $L \in X_n$, we have
\[
\liminf_{T \to \infty} \frac{1}{T} \# \left\{ \rho \in \mathbb{C} : |\text{Im}(\rho)| < T, a < \text{Re}(\rho) < b, E_n \left( L, \frac{n\rho}{2} \right) = 0 \right\} > 0.
\]

This corollary complements the recent results in [17], that treats zeros in the half-plane $\text{Re}(s) > 1$, by showing that also the zeros in the strip $\{ s : \frac{3}{4} < \text{Re}(s) < 1 \}$ violates the Riemann hypothesis in a strong way. We also note that the corresponding result for $c$-values (values $s$ such that $E_n \left( L, \frac{n\rho}{2} \right) = c$) follows by a similar argument.

Finally, we mention that the proof of Theorem 1.11 uses a result of Drungilas-Garunkštis-Kačėnas [3] on universality of general Dirichlet series following classical lines. The main ingredient in the proof is a new mean square estimate that is valid for $\text{Re}(s) > \frac{3}{4}$ and almost all lattices $L \in X_n$ (cf. Theorem 5.1). In the process of proving this estimate, we stumble across a strong bound on the growth of the Epstein zeta function on the critical line, which we find interesting in its own right.

Theorem 1.13. Let $\varepsilon > 0$. Then, for almost all $L \in X_n$, we have
\[
E_n \left( L, \frac{n}{4} + it \right) = O_{L, \varepsilon} \left( t^{1+\varepsilon} \right).
\]
Recalling that the corresponding convexity bound states that \( E_n(L, \frac{n}{2} + it) = O_L(t^n) \) for all \( L \in X_n \), it follows that (1.6) provides a subconvex estimate for almost all \( L \in X_n \) as soon as \( n \geq 5 \). In fact, the bound (1.6) is majorized by any positive power \( \delta \) of the convexity bound, in all sufficiently large dimensions \( n \) (depending on \( \delta \)).

2. Preliminaries

2.1. Poisson distribution of vector lengths. Recall that we use \( V_n \) to denote the volume of the unit ball in \( \mathbb{R}^n \). Given a lattice \( L \in X_n \), we order its nonzero vectors by increasing lengths as \( \pm v_1, \pm v_2, \pm v_3, \ldots \), set \( \ell_j = |v_j| \) (thus \( 0 < \ell_1 \leq \ell_2 \leq \ell_3 \leq \ldots \)), and define

\[
V_j(L) := \frac{1}{2} V_n \ell_j^n,
\]

so that \( V_j(L) \) equals one half of the volume of an \( n \)-dimensional ball of radius \( \ell_j \). The main result in [18] states that the volumes \( \{V_j(L)\}_{j=1}^{\infty} \) determined by a random lattice \( L \in X_n \) converges in distribution, as \( n \to \infty \), to the points of a Poisson process on the positive real line with constant intensity 1. In other words, if we for \( t \geq 0 \) let

\[
N_{n,L}(t) := \# \{ j : V_j(L) \leq t \},
\]

then we have the following theorem.

**Theorem 2.1.** Let \( \mathcal{P} = \{N(t), t \geq 0\} \) be a Poisson process on the positive real line with intensity 1. Then the stochastic process \( \{N_{n,L}(t), t \geq 0\} \) converges weakly to \( \mathcal{P} \) as \( n \to \infty \).

Given \( L \in X_n \) and \( t \geq 0 \), we define

\[
R_{n,L}(t) := N_{n,L}(t) - t.
\]

Note that \( 1 + 2R_{n,L}(t/2) \) equals the error term in the circle problem generalized to an \( n \)-dimensional ball of volume \( t \) and a general lattice \( L \in X_n \). We recall the following bound on \( R_{n,L}(t) \) and refer to [21, Theorem 1.3] (see also [14]) for a proof.

**Theorem 2.2.** For all \( \varepsilon > 0 \) there exists \( C_\varepsilon > 0 \) such that for all \( n \geq 3 \) and \( C \geq 1 \) we have

\[
\text{Prob}_{\mu_n}\left\{ L \in X_n : |R_{n,L}(t)| \leq C_\varepsilon (Ct)^{\frac{1}{2}} (\log t)^{\frac{3}{2} + \varepsilon}, \quad \forall t \geq 5 \right\} \geq 1 - C^{-1}.
\]

In our discussion, we will often find it convenient to work with a close relative of \( R_{n,L}(t) \), namely

\[
S_{n,L}(t) := N_{n,L}(t) - \# \{ j \in \mathbb{Z}^+ : j \leq t \} \quad (t \geq 0).
\]

The following estimate is an immediate corollary of Theorem 2.2.

**Corollary 2.3.** For all \( \varepsilon > 0 \) there exists \( C_\varepsilon > 0 \) such that for all \( n \geq 3 \) and \( C \geq 1 \) we have

\[
\text{Prob}_{\mu_n}\left\{ L \in X_n : |S_{n,L}(t)| \leq C_\varepsilon (Ct)^{\frac{1}{2}} (\log t)^{\frac{3}{2} + \varepsilon}, \quad \forall t \geq 5 \right\} \geq 1 - C^{-1}.
\]

**Remark 2.4.** Let us note that in the case \( n = 2 \), Schmidt [14, Theorem 2] has proved that for almost all \( L \in X_2 \) and for all sufficiently large \( t \) (depending on \( L \) and \( \varepsilon \)), we have

\[
|R_{2,L}(t)| \ll_{L,\varepsilon} t^\frac{1}{4} (\log t)^{\frac{5}{2} + \varepsilon}.
\]
Hence, for the same $L$ and $t$, we also have

$$|S_{2,L}(t)| \ll_{L,\varepsilon} t^{\frac{1}{2}} (\log t)^{\frac{3}{2}+\varepsilon}.$$  

2.2. Normalization of $E_n(L, s)$. For any complex number $s$ with $\text{Re}(s) > 1$, we can use (2.1) to write $E_n(L, \frac{ns}{2})$ in the form

$$E_n(L, \frac{ns}{2}) = 2^{1-s} V_n^s \sum_{j=1}^{\infty} V_j(L)^{-s}.$$  

We find it natural to consider the normalized function

$$E_n(L, s) := 2^{s-1} V_n^{-s} E_n(L, \frac{ns}{2}),$$

so that

$$E_n(L, s) = \sum_{j=1}^{\infty} V_j(L)^{-s} \quad (\text{Re}(s) > 1).$$

Note in particular that if $\{T_j\}_{j=1}^{\infty}$ are the points of a Poisson process on the positive real line with intensity 1, then [20, Theorem 1 and Remark 4] state that $E_n(L, s)$ converges in distribution to $\sum_{j=1}^{\infty} T_j^{-s}$, for any fixed $s$ with $\text{Re}(s) > 1$, as $n \to \infty$.

3. Proof of Theorem 1.3

To begin with we state the following lemma of Mishou and Nagoshi (cf. [12, Proposition 2.4] for a more general statement). We recall that $D$ denotes the right half of the critical strip (see [L.1]).

**Lemma 3.1.** Let $\Omega$ be a simply connected region in $D$ that is symmetric with respect to the real axis. Then, for any $\varepsilon > 0$, any compact set $K \subset \Omega$ and any holomorphic function $f$ on $\Omega$ that is real-valued on $\Omega \cap \mathbb{R}$, there exist $N_0 \in \mathbb{Z}^+$ and numbers $a_j \in \{-1, 0, 1\}, 1 \leq j \leq N_0$, such that

$$\max_{s \in K} \sum_{j=1}^{N_0} a_j j^{-s} - f(s) < \varepsilon.$$  

Given $N \in \mathbb{Z}^+$, $L \in X_n$ and $s \in \mathbb{C}$, we define

$$P_N(L, s) := \sum_{V_j(L) \leq N} V_j(L)^{-s} - \sum_{j=1}^{N} j^{-s} + \zeta(s).$$

Clearly $P_N$ is analytic in $\mathbb{C}$ except for a simple pole at $s = 1$ with residue 1. The following approximation result is the key technical ingredient in the proof of Theorem 1.3.

**Proposition 3.2.** Let $\Omega$ be a simply connected region in $D$ that is symmetric with respect to the real axis. Then, for any $\varepsilon > 0$, any compact set $K \subset \Omega$ and any holomorphic function $f$ on $\Omega$ that is real-valued on $\Omega \cap \mathbb{R}$, there exist $N \in \mathbb{Z}^+$ and a constant $\delta > 0$ such that

$$\liminf_{n \to \infty} \text{Prob}_{\mu_n} \left\{ L \in X_n : \max_{s \in K} |P_M(L, s) - f(s)| < \varepsilon \right\} > \delta$$

holds for any fixed $M \geq N$. 

Proof. Let \( h(s) := \zeta(s) - f(s) \) and note that \( h \) is holomorphic on \( \Omega \) and real-valued on \( \Omega \cap \mathbb{R} \). By Lemma 3.1 there exist \( N_0 \in \mathbb{Z}^+ \) and coefficients \( a_j \in \{-1, 0, 1\} \), \( 1 \leq j \leq N_0 \), such that

\[
\max_{s \in K} \left| \sum_{j=1}^{N_0} a_j j^{-s} - h(s) \right| < \frac{\varepsilon}{3}.
\]

We let \( N > \max(N_0, 5) \) be an integer satisfying \( 10(N - 1)^{-1/2} < \frac{\varepsilon}{100} \) and set

\[
b_j = \begin{cases} 1 - a_j & \text{if } 1 \leq j \leq N_0, \\ 1 & \text{if } N_0 < j \leq N. \end{cases}
\]

Hence

\[
P_N(L, s) - f(s) = \sum_{\mathcal{V}_j \leq N} \mathcal{V}_j(L)^{-s} - \sum_{j=1}^{N} b_j j^{-s} + \left( h(s) - \sum_{j=1}^{N_0} a_j j^{-s} \right).
\]

In addition it is useful to note that

\[
\sum_{j=1}^{N} b_j j^{-s} = \sum_{j=1}^{\tilde{N}} n_j^{-s},
\]

for some \( N - N_0 \leq \tilde{N} \leq N + N_0 \) and a certain nondecreasing sequence \( \{n_j\}_{j=1}^{\tilde{N}} \) of positive integers.\(^5\)

Next, we find that there exist \( N_1 \in \mathbb{Z}^+ \) and \( \delta_0 > 0 \) (depending on \( K \), \( N \) and \( \varepsilon \)) such that for \( n \geq N_1 \), we have

\[
\operatorname{Prob}_{\mu_n} \left\{ L \in X_n : \max_{s \in K} \left| \sum_{\mathcal{V}_j \leq N} \mathcal{V}_j(L)^{-s} - \sum_{j=1}^{\tilde{N}} n_j^{-s} \right| < \frac{\varepsilon}{3} \right\} > \delta_0.
\]

To prove this, we first recall that \( \{\mathcal{V}_1(L)\} \cup \{\mathcal{V}_{j+1}(L) - \mathcal{V}_{j}(L)\}_{j=1}^{N+9} \) tend in distribution, as \( n \to \infty \), to a collection of independent exponentially distributed random variables of mean \( 1 \). In other words, by choosing \( N_1 \) large enough we can guarantee that \( \{\mathcal{V}_1(L)\} \cup \{\mathcal{V}_{j+1}(L) - \mathcal{V}_{j}(L)\}_{j=1}^{N+9} \) are as close as we desire to a collection of independent exponential distributions of mean \( 1 \) in the Lévy-Prohorov metric (see, e.g., [2]) for all \( n \geq N_1 \). Hence it follows that we can assure, with a positive probability, that \( N_{n,L}(N) - N_{n,L}(N-1) \leq 10 \) (say), and that the volumes \( \{\mathcal{V}_j(L)\}_{j=1}^{\tilde{N}} \) are of size at most \( N \) and approximate the integers \( \{n_j\}_{j=1}^{\tilde{N}} \), \( \tilde{N} \) sufficiently well in order to make (3.5) hold. Now, in the special case where \( M = N \) and \( \delta = \delta_0 \), the inequality (3.1) follows from (3.2), (3.3), (3.5) and an application of the triangle inequality. It is also clear from the argument above that we can increase \( N \) as we like at the cost of having a possibly smaller constant \( \delta_0 \).

\(^5\)It is in principal straightforward, but notationally impractical, to write down explicit formulas for the integers \( n_j \).
It remains to show that (3.1) holds with the same right-hand side \( \delta \) for any fixed \( M \geq N \). Hence, for \( M \geq N \), we study the finite sums
\[
Q_{N,M}(L, s) := P_M(L, s) - P_N(L, s)
\]
\[
= \sum_{N < V_j(L) \leq M} V_j(L)^{-s} - \sum_{j = N+1}^M j^{-s} = \int_N^M t^{-s} dS_{n,L}(t),
\]
where \( S_{n,L}(t) \) is defined in (2.24). Let \( \sigma_0 = \min \{ \text{Re}(s) : s \in K \} \) and \( \eta = (\sigma_0 - \frac{1}{2})/2 \). It follows from Corollary 2.3 with \( C = 2 \) that for each \( n \geq 3 \) there exists a set \( Y_n \subset X_n \) with \( \mu_n(Y_n) \geq \frac{1}{2} \) and such that for all lattices \( L \in Y_n \) and all \( t \geq 5 \) we have \( |S_{n,L}(t)| \ll \eta t^{\frac{1}{2}+\eta} \). Here it is important to note that the implied constant is independent of both \( n \) and \( L \). Integrating by parts we get, for any \( L \in Y_n \) and all \( M \geq N \),
\[
|Q_{N,M}(L, s)| = \left| \int_N^M t^{-s} dS_{n,L}(t) \right|
\]
\[
= \left| \left[ t^{-s}S_{n,L}(t) \right]_N^M + s \int_N^M t^{-s-1}S_{n,L}(t) dt \right| \ll \eta, K \ N^{\frac{1}{2}+\eta-\sigma_0},
\]
uniformly for all \( s \in K \). Since we can make the right-hand side above as small as we desire by increasing \( N \) as needed, we obtain, for any \( M \geq N \) and \( n \geq 3 \),
(3.6)
\[
\text{Prob}_{\mu_n}\left\{ L \in X_n : \max_{s \in K} |Q_{N,M}(L, s)| \left( \frac{e}{3} \right) \right\} \geq \frac{1}{2}.
\]
Finally, given \( M \geq N \), we use (3.2), (3.3), (3.5) and (3.6), together with the fact that for any fixed \( J \in \mathbb{Z}^+ \) the volumes \( \{V_j(L)\}_{j=1}^M \) tend in distribution (as \( n \to \infty \)) to the first \( J \) points of a Poisson process \( \mathcal{P} \) on the positive real line of intensity 1, and the fact that \( \mathcal{P} \) may be realized as a union of a Poisson process on \((0, N) \) and an independent process on \((N, \infty) \), both of intensity 1 (see [9, Section 2.2]), to conclude that when \( n \geq \max(N_1, 3) \) (where we might need to increase \( N_1 \) depending on \( M \)) we have
(3.7)
\[
\text{Prob}_{\mu_n}\left\{ L \in X_n : \max_{s \in K} |P_M(L, s) - f(s)| \left( \frac{\eta}{4} \right) \right\} > \delta_0 \delta.
\]
In fact, as \( n \to \infty \) we have the above inequality with any right-hand side smaller than \( \frac{\delta_0}{2} \). Since the lower bound in (3.7) holds for any fixed \( M \geq N \), the proof is complete.

Next we define, for \( N \in \mathbb{Z}^+ \) and \( \text{Re}(s) > 1 \), the function
\[
Q_N(L, s) := \sum_{V_j(L) > N} V_j(L)^{-s} - \sum_{j = N+1}^\infty j^{-s} = \int_N^\infty t^{-s} dS_{n,L}(t),
\]
and note that this integral representation is holomorphic in the half-plane \( \text{Re}(s) > \frac{1}{2} \) for almost every \( L \in X_n \).

**Lemma 3.3.** Let \( n \geq 3 \). Let \( \varepsilon, \delta > 0 \) and let \( K \) be a compact subset of the half-plane \( \text{Re}(s) > \frac{1}{2} \). Then there exists \( M \in \mathbb{Z}^+ \) such that
\[
\text{Prob}_{\mu_n}\left\{ L \in X_n : \max_{s \in K} \left| \int_{M'}^\infty t^{-s} dS_{n,L}(t) \right| < \varepsilon \right\} \geq 1 - \delta
\]
for all \( M' \geq M \).
Proof. Let \( \delta > 0 \) be given. Recall from the proof of Proposition 3.2 that \( \sigma_0 = \min \{ \Re(s) : s \in K \} \) and \( \eta = (\sigma_0 - \frac{1}{2})/2 \). It follows from Corollary 2.3 that for each \( n \geq 3 \) there exists a set \( Z_n \subset X_n \) with \( \mu_n(Z_n) \geq 1 - \delta \) and such that for all lattices \( L \in Z_n \) and all \( t \geq 5 \) we have \( |S_{n,L}(t)| \ll \delta, \eta, t^{\frac{1}{2} + \eta} \), where the implied constant is independent of \( n \) and \( L \). Now, for any \( L \in Z_n \) and all \( M \geq 5 \), we get

\[
\left| \int_M^\infty t^{-s} dS_{n,L}(t) \right| = \left| \int_M^\infty t^{-s} S_{n,L}(t) \, dt \right| \ll \delta, \eta, K \left( \frac{1}{2} + \eta - \sigma_0 \right),
\]

uniformly for all \( s \in K \). Since we can make the right-hand side above as small as desired by choosing \( M \) large enough, the proof is complete. \( \square \)

**Proof of Theorem 1.3.** Let \( \varepsilon > 0 \) be given and let \( N \) and \( \delta \) be given by Proposition 3.2 applied with \( \varepsilon/2 \), \( K \) and \( f \). Let furthermore \( M \) be given by Lemma 3.3 applied with \( \varepsilon/2 \), \( \delta/2 \) and \( K \). (Note that we without loss of generality may assume that \( M \geq N \).) Hence, by Proposition 3.2 and Lemma 3.3, we find that

\[
|E_n(L, s) - f(s)| = |E_n(L, s) - \zeta(s) + \zeta(s) - f(s)| \leq |P_M(L, s) - f(s)| + |Q_M(L, s)| < \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon
\]

holds, in the limit as \( n \to \infty \), with a probability of at least \( \delta/2 \). This finishes the proof. \( \square \)

4. **Proof of Theorem 1.10**

The general strategy for the proof of Theorem 1.10 is the same as in the proof of Theorem 1.3. The main difference is that Lemma 3.1 is no longer at our disposal. The following approximation lemma will take its place in the present argument.

**Lemma 4.1.** Let \( \Omega \) be a simply connected region in \( \mathbb{C} \) that is symmetric with respect to the real axis. Then, for any \( \varepsilon > 0 \), any compact set \( K \subset \Omega \) and any holomorphic function \( f \) on \( \Omega \) that is real-valued on \( \Omega \cap \mathbb{R} \), there exists a Dirichlet polynomial

\[
A(s) = \sum_{k=0}^{M} a_k \lambda_k^{-s}
\]

with integer coefficients such that

\[
\max_{s \in K} |f(s) - A(s)| < \varepsilon.
\]

**Proof.** The conditions on \( f \) and \( \Omega \) are sufficient to ensure that

\[
f(s) = \overline{f(\overline{s})} \quad (s \in \Omega).
\]

Let \( K^\sharp = K \cup K \), where \( K \) is the reflection of \( K \) in the real axis. By Runge’s theorem (applied to a simply connected compact set \( K' \) satisfying \( K^\sharp \subset K' \subset \Omega \)) there exists a polynomial \( P(s) \) such that

\[
|P(s) - f(s)| < \frac{\varepsilon}{2} \quad (s \in K^\sharp).
\]

By the symmetry of \( K^\sharp \), we have

\[
|P(\overline{s}) - f(\overline{s})| < \frac{\varepsilon}{2} \quad (s \in K^\sharp),
\]

where \( \overline{s} \) is the complex conjugate of \( s \). Hence, for \( |s - \overline{s}| \leq \delta \), we have

\[
|P(s) - P(\overline{s})| \leq |P(s) - f(s)| + |P(\overline{s}) - f(\overline{s})| < \delta.
\]

This completes the proof.
and by (4.1) and the triangle inequality it follows that
\begin{equation}
|p(s) - f(s)| < \frac{\varepsilon}{2} \quad (s \in K),
\end{equation}
where
\[ p(s) = \frac{P(s) + \overline{P(s)}}{2} = \frac{P(s) + \overline{P(s)}}{2} \]
is a polynomial with real coefficients.

We now proceed to approximate the polynomial \( p(s) \) by Dirichlet polynomials of the desired type. It is sufficient to prove that
\[ p_m(s) = b_m s(s-1) \cdots (s-m+1) \]
may be approximated by a Dirichlet polynomial \( A_m(s) \), since \( p(s) \) can be written as a sum of such polynomials, that is,
\[ p(s) = \sum_{m=0}^{M} p_m(s) \]
for some nonnegative integer \( M \) and suitable real numbers \( \{b_m\}_{m=0}^{M} \). Let \( g(x) = b_m x^s \).

It is clear that
\[ g^{(m)}(x) = b_m s(s-1) \cdots (s-m+1)x^{s-m}. \]
Note that this derivative can be approximated up to any given accuracy by \( \Delta_h g(x) \), where
\[ \Delta_h g(x) := \frac{g(x+h) - g(x)}{h}, \]
by choosing \( h \) small enough. Any such \( \Delta_h g(x) \), where we choose \( x = 1 \) and \( h \) such that \( b_m / h^m \) is an integer, will be of the desired type and can be chosen as our Dirichlet polynomial \( A_m(s) \). Thus, by choosing \( h \) sufficiently small, we can ensure that
\begin{equation}
|A_m(s) - p_m(s)| < \frac{\varepsilon}{2(M+1)} \quad (0 \leq m \leq M, s \in K).
\end{equation}
The result follows by choosing
\[ A(s) = \sum_{m=0}^{M} A_m(s) \]
and applying the triangle inequality together with the inequalities (4.2) and (4.3). \( \square \)

Given \( \Lambda \in \mathbb{R}^+ \), two lattices \( L_1, L_2 \in X_n \) and a complex number \( s \in \mathbb{C} \), we define
\[ \widehat{P}_\Lambda(L_1, L_2, s) := \sum_{V_j(L_1) \leq \Lambda} V_j(L_1)^{-s} - \sum_{V_j(L_2) \leq \Lambda} V_j(L_2)^{-s}, \]
which clearly is an entire function of \( s \).

**Proposition 4.2.** Let \( \Omega \) be a simply connected region in the half-plane \( \text{Re}(s) > \frac{1}{2} \) that is symmetric with respect to the real axis. Then, for any \( \varepsilon > 0 \), any compact set \( K \subset \Omega \) and any holomorphic function \( f \) on \( \Omega \) that is real-valued on \( \Omega \cap \mathbb{R} \), there exist constants \( \delta, \Lambda_0 \in \mathbb{R}^+ \) such that
\begin{equation}
\liminf_{n \to \infty} \text{Prob}_{\mu_n \times \mu_n} \left\{ (L_1, L_2) \in X_n^2 : \max_{s \in K} \left| \widehat{P}_\Lambda(L_1, L_2, s) - f(s) \right| < \varepsilon \right\} > \delta
\end{equation}
holds for any fixed $\Lambda \geq \Lambda_0$.

Proof. By Lemma 2.1 there exist an integer $M \geq 0$ and sequences $\{\lambda_m\}_{m=0}^M$ and $\{a_m\}_{m=0}^M$ of positive real numbers and integers respectively, such that

$$
\max_{s \in K} \left| \sum_{m=0}^M a_m \lambda_m^{-s} - f(s) \right| < \frac{\varepsilon}{3}.
$$

Let $\lambda_1 = 5$, $C_1 = \sum_{a_m > 0} a_m$ and $C_2 = \sum_{a_m < 0} |a_m|$. By choosing $\Lambda_0 \geq \max \{\lambda_m : -1 \leq m \leq M\}$ sufficiently large, we find that there exist $N_1 \in \mathbb{Z}^+$ and $\delta_0 > 0$ (depending on $K$, $\Lambda_0$ and $\varepsilon$) such that for $n \geq N_1$, we have

$$
\left| \tilde{P}_{\lambda_0}(L_1, L_2, s) - \sum_{m=0}^M a_m \lambda_m^{-s} \right| < \frac{\varepsilon}{3}.
$$

The proof of (4.6) is essentially the same as the proof of (3.5) (see the proof of Proposition 3.2). The only difference is that we in this case use the sequence $\{V_j(L_1)\}_{j=1}^{C_1}$ to approximate the numbers $\lambda_m$ with positive coefficients $a_m$ and the sequence $\{V_j(L_2)\}_{j=1}^{C_2}$ to approximate the numbers $\lambda_m$ with negative coefficients $a_m$ (in both cases with multiplicities according to the sizes of the corresponding $|a_m|$). Now, in the case where $\Lambda = \Lambda_0$ and $\delta = \delta_0$, the inequality (4.4) follows from (4.3), (4.6) and an application of the triangle inequality. Note that we may increase $\Lambda_0$ at the cost of having a possibly smaller constant $\delta_0$.

In order to show that (4.4) holds with the same right-hand side $\delta$ for any fixed $\Lambda \geq \Lambda_0$, we study the finite sums

$$
\tilde{Q}_{\Lambda_0, \Lambda}(L_1, L_2, s) := \tilde{P}_{\Lambda}(L_1, L_2, s) - \tilde{P}_{\Lambda_0}(L_1, L_2, s)
$$

$$
= \sum_{\Lambda_0 < \lambda \leq \Lambda} V_j(L_1)^{-s} - \sum_{\Lambda_0 < \lambda \leq \Lambda} V_j(L_2)^{-s}
$$

$$
= \int_{\Lambda_0}^{\Lambda} t^{-s} dR_{n, L_1}(t) - \int_{\Lambda_0}^{\Lambda} t^{-s} dR_{n, L_2}(t),
$$

where $R_{n, L}(t)$ is defined in (2.2). Let $\sigma_0 = \min \{\text{Re}(s) : s \in K\}$ and $\eta = (\sigma_0 - \frac{1}{2})/2$. It follows from Theorem 2.2 with $C = 2$ that for each $n \geq 3$ there exists a set $U_n \subset X_n$ with $\mu_n(U_n) \geq \frac{1}{2}$ and such that for all lattices $L \in U_n$ and all $t \geq 5$ we have $|R_{n, L}(t)| \ll_n t^{\frac{1}{2} - \eta}$. Integrating by parts we get, for all $L_1, L_2 \in U_n$ and all $\Lambda \geq \Lambda_0$,

$$
\left| \tilde{Q}_{\Lambda_0, \Lambda}(L_1, L_2, s) \right| \leq \int_{\Lambda_0}^{\Lambda} t^{-s} dR_{n, L_1}(t) + \int_{\Lambda_0}^{\Lambda} t^{-s} dR_{n, L_2}(t) \ll_{n, K} \Lambda^{\frac{1}{2} + \eta - \sigma_0},
$$

uniformly for all $s \in K$. Thus, since we can make the right-hand side above as small as we like by a sufficient increase of $\Lambda_0$, we obtain, for any $\Lambda \geq \Lambda_0$ and $n \geq 3$,

$$
\text{Prob}_{\mu_n \times \mu_n}\left\{(L_1, L_2) \in X_n^2 : \max_{s \in K} \left| \tilde{Q}_{\Lambda_0, \Lambda}(L_1, L_2, s) \right| < \frac{\varepsilon}{3} \right\} \geq \frac{1}{4}.
$$

Finally, given $\Lambda \geq \Lambda_0$, we use (4.5), (4.6), (4.8) and Theorem 2.1 to conclude that when $n \geq \max(N_1, 3)$ (where we might need to increase $N_1$ depending on $\Lambda$) we have

$$
\text{Prob}_{\mu_n \times \mu_n}\left\{(L_1, L_2) \in X_n^2 : \max_{s \in K} \left| \tilde{P}_{\Lambda}(L_1, L_2, s) - f(s) \right| < \varepsilon \right\} > \frac{\delta_0}{8}.
$$
This finishes the proof. □

We define, for each $\Delta \in \mathbb{R}^+$ and $\text{Re}(s) > 1$, the function

$$\tilde{Q}_\Delta(L_1, L_2, s) := \sum_{V_j(L_1) > \Delta} V_j(L_1)^{-s} - \sum_{V_j(L_2) > \Delta} V_j(L_2)^{-s}$$

$$= \int_\Delta^\infty t^{-s} dR_n,L_1(t) - \int_\Delta^\infty t^{-s} dR_n,L_2(t),$$

and note that this integral representation is holomorphic in the half-plane $\text{Re}(s) > 1/2$ for almost every $(L_1, L_2) \in X_n^2$.

**Lemma 4.3.** Let $n \geq 3$. Let $\varepsilon, \delta > 0$ and let $K$ be a compact subset of the half-plane $\text{Re}(s) > 1/2$. Then there exists $\Lambda \in \mathbb{R}^+$ such that

$$\text{Prob}_{\mu_n \times \mu_n} \left\{ (L_1, L_2) \in X_n^2 : \max_{s \in K} \left| \int_\Lambda^\infty t^{-s} dR_n,L_1(t) - \int_\Lambda^\infty t^{-s} dR_n,L_2(t) \right| < \varepsilon \right\} \geq 1 - \delta$$

for all $\Lambda' \geq \Lambda$.

**Proof.** The result follows from Theorem 2.2 applied with $C \geq 2/\delta$ to an estimate similar to the one in (4.7). □

**Proof of Theorem 1.10.** Let $\varepsilon > 0$ be given and let $\Lambda_0$ and $\delta$ be given by Proposition 4.2 applied with $\varepsilon/2$, $K$ and $f$. Let furthermore $\Lambda$ be given by Lemma 4.3 applied with $\varepsilon/2$, $\delta/2$ and $K$. (We may assume that $\Lambda \geq \Lambda_0$.) Then, it follows from Proposition 4.2 and Lemma 4.3 that

$$|E_n(L_1, s) - E_n(L_2, s) - f(s)| \leq \left| \tilde{P}_\Lambda(L_1, L_2, s) - f(s) \right| + \left| \tilde{Q}_\Lambda(L_1, L_2, s) \right| < \varepsilon$$

holds, in the limit as $n \to \infty$, with a probability of at least $\delta/2$. □

5. **Proof of the imaginary shift case (Theorem 1.11)**

We will use Drungilas-Garunkštis-Kačėnas variant [3, Theorem 2.1] of a result of Gonek [7] for general Dirichlet series. To do this we need a mean square estimate in a half-plane.

**Theorem 5.1.** Let $n \geq 2$. Then, for $\sigma > 3/4$ and for almost all $L \in X_n$, we have

$$\int_1^T \left| E_n \left( L, n \frac{(\sigma + it)}{2} \right) \right|^2 \, dt \ll_{L,\sigma} T.$$

By the definition of the normalized Epstein zeta function, the triangle inequality and the well known mean square estimate for the Riemann zeta function in the half-plane $\sigma > 1/4$ (see e.g. Ivić [8]), it is sufficient to prove that

$$\left(5.1\right) \int_1^T \left| E_n(L, \sigma + it) - \zeta(\sigma + it) \right|^2 \, dt \ll_{L,\sigma} T.$$

We will prove this estimate using Gallagher’s lemma [6, Lemma 1].

**Lemma 5.2 (Gallagher).** Let $\delta = \theta/T$, with $0 < \theta < 1$, and let

$$S(t) := \sum_k c_k e(v_k t)$$
be an absolutely convergent exponential sum having only real frequencies \( v_k \). Then

\[
\int_{-T}^{T} |S(t)|^2 \, dt \ll \int_{-\infty}^{\infty} \left| \delta^{-1} \sum_{x \leq v_k \leq x + \delta} c_k \right|^2 \, dx.
\]

We will not be able to apply Gallagher’s lemma directly, since it assumes that the exponential sum \( S(t) \) is absolutely convergent. Thus, we will need to truncate our Dirichlet series; in fact, we will apply the following weak approximate functional equation.

**Lemma 5.3.** Let \( \varepsilon > 0 \). Let \( n \geq 2 \) and assume that \( \Re(s) > \frac{1}{2} \). Then, for any \( X \geq 5 \) and almost every \( L \in X_n \), we have

\[
\mathcal{E}_n(L, s) - \zeta(s) = \sum_{V_j(L) \leq X} V_j(L)^{-s} - \sum_{1 \leq j \leq X} j^{-s} + O_{L, \varepsilon} \left( |s| X^{\frac{1}{2} - \Re(s) + \varepsilon} \right).
\]

**Proof.** The lemma follows immediately from Lemma 3.3 and its proof (using the estimate in Remark 2.4 in place of Corollary 2.3 in the case \( n = 2 \)). \( \square \)

**Proof of Theorem 1.13.** The theorem is a direct consequence of Lemma 5.3, the functional equation (1.3) and the Phragmén-Lindelöf principle. \( \square \)

In order to apply Gallagher’s lemma, we also need estimates for short partial sums of \( \mathcal{E}_n(L, s) - \zeta(s) \). We define

\[
\Delta(x) = \Delta_{\sigma, L, X}(x) = \Delta_1(x) - \Delta_2(x),
\]

where

\[
\Delta_1(x) = \Delta_{\sigma, L, X; 1}(x) = \sum_{V_j(L) \leq X} V_j(L)^{-\sigma}
\]

and

\[
\Delta_2(x) = \Delta_{\sigma, L, X; 2}(x) = \sum_{1 \leq j \leq \min(e^x, X)} j^{-\sigma}.
\]

To be precise, we need the following result.

**Lemma 5.4.** Let \( \varepsilon > 0 \). Let further \( n \geq 2 \), \( \sigma > \frac{1}{2} \), \( 0 \leq \delta \leq 1 \) and \( \alpha \in \mathbb{R} \). Then, for almost all \( L \in X_n \), we have

\[
\int_{\alpha}^{\alpha+1} \left| \Delta_{\sigma, L, X}(x + \delta) - \Delta_{\sigma, L, X}(x) \right|^2 \, dx \ll_{L, \sigma, \varepsilon} \delta e^{\alpha(\frac{3}{2} - 2\sigma + \varepsilon)}.
\]

**Proof.** To begin, we have

\[
\int_{\alpha}^{\alpha+1} |\Delta(x + \delta) - \Delta(x)|^2 \, dx
\]

\[
\leq \max_{x \in [\alpha, \alpha+1]} |\Delta(x + \delta) - \Delta(x)| \int_{\alpha}^{\alpha+1} |\Delta(x + \delta) - \Delta(x)| \, dx.
\]

By Corollary 2.3 (or Remark 2.4 in the case \( n = 2 \)) and integration by parts, we obtain

\[
|\Delta(x + \delta) - \Delta(x)| = \int_{\min(e^x, X)}^{\min(e^{x+\delta}, X)} t^{-\sigma} \, dS_{n, L}(t) \ll_{L, \sigma, \varepsilon} e^{x(\frac{1}{2} - \sigma + \varepsilon)}
\]
for almost all \( L \in X_n \). For the rest of this proof we restrict our attention to the set of lattices satisfying the above estimate, for which we have

\[
(5.3) \quad \int_\alpha^{\alpha+1} |\Delta(x + \delta) - \Delta(x)|^2 \, dx \ll_L,\sigma,\varepsilon e^{\alpha(\frac{1}{2} - \sigma + \varepsilon)} \int_\alpha^{\alpha+1} |\Delta(x + \delta) - \Delta(x)| \, dx.
\]

Using (5.2) and the triangle inequality, we find that the latter integral is bounded by

\[
(5.4) \quad 2 \sum_{i=1}^2 \int_\alpha^{\alpha+1} |\Delta_i(x + \delta) - \Delta_i(x)| \, dx.
\]

Since \( \Delta_i(t) \) is nondecreasing for \( i = 1, 2 \), the absolute values in (5.4) can be removed and the above sum equals

\[
2 \sum_{i=1}^2 \left( \int_\alpha^{\alpha+1} \Delta_i(x + \delta) \, dx - \int_\alpha^{\alpha+1} \Delta_i(x) \, dx \right).
\]

Changing variables \( y = x + \delta \) in the first integral, we obtain

\[
2 \sum_{i=1}^2 \left( \int_\alpha^{\alpha+\delta} \Delta_i(y) \, dy - \int_\alpha^{\alpha+\delta} \Delta_i(x) \, dx \right) = 2 \sum_{i=1}^2 \int_\alpha^{\alpha+\delta} \left( \Delta_i(x + 1) - \Delta_i(x) \right) \, dx,
\]

which by Corollary 2.3 (or Remark 2.4 in the case \( n = 2 \)) is \( O_L,\sigma(\delta e^{\alpha(1 - \sigma)}) \). Using this estimate, together with (5.3), we obtain the desired result. \( \square \)

**Proof of Theorem 5.1** Let \( \sigma > \frac{3}{4} \) be given. By the triangle inequality, the mean square estimate for the Riemann zeta function and Lemma 5.3 (applied with \( X = T^4 \)) we have, for almost all \( L \in X_n \),

\[
(5.5) \quad \int_1^T \left| E_n \left( L, \frac{n(\sigma + it)}{2} \right) \right|^2 \, dt \ll_L,\sigma \int_1^T \left| \sum_{\nu_j(L) \leq T^4} \nu_j(L)^{-s} - \sum_{1 \leq j \leq T^4} j^{-s} \right|^2 \, dt + T.
\]

The integral in the right-hand side of (5.5) can be estimated by an application of Lemma 5.2 with \( \theta = \frac{1}{2} \), resulting in the upper bound

\[
(5.6) \quad O(T^2) \int_{-\infty}^{\infty} \left| \Delta \left( x + \frac{1}{2T} \right) - \Delta(x) \right|^2 \, dx,
\]

where \( \Delta(x) = \Delta_{\sigma, L, X}(x) \) is defined in (5.2). The integrand has compact support contained in \( [A, B] \), where \( A = \log(\min(\nu_j(L), 1)) + O(T^{-1}) \) and \( B = 4 \log T \). By dividing the integral into parts of length 1 and using Lemma 5.4 to estimate each term, we find that the expression in (5.6) is bounded by

\[
O_{L,\sigma,\varepsilon}(T) \sum_{k=\lfloor A \rfloor}^{\lfloor B \rfloor} e^{k(\frac{3}{2} - 2\sigma + \varepsilon)},
\]

where the geometric sum is bounded with respect to \( T \) whenever we choose \( 0 < \varepsilon < 2\sigma - \frac{3}{2} \). This finishes the proof. \( \square \)
Proof of Theorem 1.11. To prove our theorem it suffices to verify that the four conditions in [3, Theorem 2.1] are satisfied. The first condition, the so-called packing condition, follows directly from Theorem 2.2 which implies that for almost every $L \in X_n$, we have

$$\left| N_{n,L}(e^{x+\frac{c}{x^2}}) - N_{n,L}(e^x) \right| \gg \frac{e^{x}}{x^2} \gg e^{(1-\varepsilon)x}$$

for any $c > 0$ and any $\varepsilon > 0$. The second condition, the linear independence of $\{\log V_j(L)\}_{j=1}^{\infty}$ over $\mathbb{Q}$, follows for almost all $L \in X_n$ by [17, Lemma 2]. The third condition follows immediately from the fact that $E(L, \frac{ms}{x})$ is absolutely convergent in the half-plane $\text{Re}(s) > 1$. Finally, the fourth condition (on approximation) follows for almost all $L \in X_n$ from the mean square estimate Theorem 5.1 and [3, Proposition 2.2].

References


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