ON THE NON-VANISHING OF HECKE $L$-VALUES MODULO $p$

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Abstract. In this article, we follow Hida's approach to establish an analogue of Washington's theorem on the non-vanishing modulo $p$ of Hecke $L$-values for CM fields with anticyclotomic twists.

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Introduction

The purpose of this paper is to study the non-vanishing modulo $p$ property of Hecke $L$-values for CM fields via arithmetic of Eisenstein series. Let $F$ be a totally real field of degree $d$ over $\mathbb{Q}$ and $K$ be a totally imaginary quadratic extension of $F$. Let $\Sigma$ be a CM type of $K$. Then we can attach the CM period $\Omega_{\infty} = (\Omega_{\infty, \sigma})_\sigma \in (\mathbb{C}^\times)_{\Sigma}$ to a Néron differential on an abelian scheme $A_{l, \mathbb{Z}}$ of CM type $(K, \Sigma)$. Let $p > 2$ be a rational prime and let $\ell \neq p$ be a rational prime and $l = \ell$ be the prime of $F$ above $\ell$. Let $c$ be the nontrivial element in $\text{Gal}(K/F)$. We fix an arithmetic Hecke character $\chi$ and let $\Sigma = \text{Gal}(K/F)$. Then we can attach the CM period $\Omega_{\infty} = (\Omega_{\infty, \sigma})_\sigma \in (\mathbb{C}^\times)_{\Sigma}$ to a Néron differential on an abelian scheme $A_{l, \mathbb{Z}}$ of CM type $(K, \Sigma)$. Let $p > 2$ be a rational prime and let $\ell \neq p$ be a rational prime and $l = \ell$ be the prime of $F$ above $\ell$. Let $c$ be the nontrivial element in $\text{Gal}(K/F)$. We fix an arithmetic Hecke character $\chi$ of $\mathbb{C}^\times$ with infinity type $k \Sigma + \kappa(1 - c)$, where $k$ is a positive integer and $\kappa = \sum_{\sigma \in \Sigma} \kappa_{\sigma} \sigma$ with integers $\kappa_{\sigma} \geq 0$. For a multi-index $\kappa = \sum_{\sigma \in \Sigma} \kappa_{\sigma} \sigma \in \mathbb{Z}[\Sigma]$, we write $\Omega_{\infty}^\kappa = \Omega_{\infty, \sigma}^\kappa_{\sigma}$ and $a^{\kappa} = a^{\sum_{\sigma \in \Sigma} \kappa_{\sigma}}$ for $a \in \mathbb{C}^\times$.

Let $K_{1, \infty}$ be the ray class field of conductor $n$ and let $K_{1, \infty} = \cup_{\ell} K_{1, \ell}$. Let $K_{1, \infty}$ be the maximal pro-$\ell$ anticyclotomic extension of $K$ in $K_{1, \infty}$ and let $\Gamma = \text{Gal}(K_{1, \infty}/K)$. Let $X_{1, \infty}$ be the set of finite order characters of $\Gamma$. For every $\nu \in X_{1, \infty}$, we consider the complex number

$$L^{\text{alg},1}(0, \chi \nu) := \frac{\pi^n \Gamma_{\Sigma}(k \Sigma + \kappa) L^{(0)}(0, \chi \nu)}{\Omega_{\infty}^{k \Sigma + 2k}},$$

where $\Gamma_{\Sigma}(k \Sigma + \kappa) = \prod_{\sigma \in \Sigma} \Gamma(k + \kappa_{\sigma})$. It is known that $L^{\text{alg},1}(0, \chi \nu) \in Z_{(p)}$ if $p$ is unramified in $F$ and prime to the conductor of $\chi$. We are interested in the non-vanishing property of $L^{\text{alg},1}(0, \chi \nu)$ modulo $p$ when $\nu$ varies in $X_{1, \infty}$. To be precise, we fix two embeddings $\iota_\infty : \mathbb{Q} \hookrightarrow \mathbb{C}$ and $\iota_p : \mathbb{Q} \hookrightarrow \mathbb{C}_p$ once and for all and let $m$ be the maximal ideal of $Z_{(p)}$ induced by $\iota_p$. We ask if the following non-vanishing modulo $p$ property holds for $(\chi, l)$.

(NV) $\iota_\infty^{-1}(L^{\text{alg},1}(0, \chi \nu)) \not\equiv 0 \mod m$ for almost all $\nu \in X_{1, \infty}$.

Here almost all means "except for finitely many $\nu \in X_{1, \infty}$" if dim$_{\mathbb{Q}} F_1 = 1$ and "Zariski dense subset of $X_{1, \infty}$" if dim$_{\mathbb{Q}} F_1 > 1$ (See [Hid04a, p.737]).

This problem has been studied extensively by Hida for general CM fields in [Hid04a] and [Hid07] under the hypothesis that $\Sigma$ is $p$-ordinary and by T. Finis in [Fin06] for imaginary quadratic fields under a different

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Theorem. Suppose that $\Sigma$ is $p$-ordinary and $p > 2$ is unramified in $F$. If $(pl, \mathcal{C}) = 1$ and $\mathcal{C}$ is a product of split prime factors over $F$, then (NV) holds for $(\chi, l)$ unless the following three conditions are satisfied simultaneously:

(M1) $K/F$ is unramified everywhere,
(M2) $\tau_{K/F}(\chi)$ has value $-1$, where $\mathcal{C}$ is the polarization ideal of $A_{\mathbb{Z}}$.
(M3) For all ideal $a$ of $F$ prime to $p\mathcal{C}$, $\chi_{N_{F/Q}(a)} \equiv \tau_{K/F}(\chi) (\text{mod } m)$.

We shall say $\chi$ is residually self-dual if the condition (M3) holds for $\chi$. By [Hid10, Lemma 5.2], the hypotheses (M1-3) is equivalent to the condition (V): $\chi$ is residually self-dual, and the root number associated to $\chi$ is congruent to $-1$ modulo $m$.

We are mainly concerned about the (NV) property of self-dual characters. Recall that $\chi$ is self-dual if $\chi|_{\mathbb{F}_p^\times} = \tau_{K/F}|_{\mathbb{F}_p^\times}$. Such characters are of its own interest because an important class of them arises from Hecke characters associated to CM abelian varieties over totally real fields (cf. [Shi98, Thm.20.15]). Note that as the conductor of self-dual characters by definition is divisible by ramified primes, these characters in general are not covered in Hida’s theorem unless $K/F$ is unramified. Our main motivation for the (NV) property of self-dual characters is the application to Iwasawa main conjecture for CM fields (cf. [Hid07] and [Hsi11]). In our subsequent work [Hsi11], this property is used to show the non-vanishing modulo $p$ of the period integral of certain theta functions which is related to Fourier-Jacobi coefficients of Eisenstein series on unitary groups of degree three. When $K$ is an imaginary quadratic field and $l$ splits in $K$, the problem of the non-vanishing modulo $p$ of Hecke $L$-values associated to self-dual characters has been solved completely by T. Finis in [Fin06] through direct study on the period integral of theta functions modulo $p$ (self-dual characters are called anticyclotomic in [Fin06]).

We shall state our main result after preparing some notation. Write $\mathcal{C} = \mathcal{C}^+ \mathfrak{I}$, where $\mathcal{C}^+$, $\mathfrak{I}$ and $\mathfrak{R}$ are a product of split, inert and ramified prime factors over $F$ respectively. Let $v_p$ be the $p$-adic valuation induced by $\iota_p$. For each $v|\mathcal{C}^+$, let $\mu_p(\chi_v) := \inf_{x \in K^x_v} v_p(\chi(x) - 1)$.

Note that $\mu_p(\chi_v)$ agrees with the one defined in [Fin06] when $\chi$ is self-dual. Following Hida, we make the following hypotheses for $(p, K, \Sigma)$:

(ur) $p > 2$ is unramified in $F$;
(ord) $\Sigma$ is $p$-ordinary.

Our main result is as follows.

Theorem A. Let $\chi$ be a self-dual Hecke character of $K^\times$ such that

(L) $\mu_p(\chi_v) = 0$ for every $v|\mathcal{C}^+$,
(R) The global root number $W(\chi^*) = 1$, where $\chi^* := \chi|_{\mathbb{F}_p^\times}^{-\frac{1}{2}}$.
(C) $\mathfrak{R}$ is square-free.

In addition to (ur), (ord), we further assume

- $(pl, D_{K/F} \mathcal{C}) = 1$,
- $l$ splits in $K$.

Then (NV) holds for $(\chi, l)$.

Note that as $\chi$ is self-dual, the assumption (R) is equivalent to Hida’s condition (V). Indeed, the assumptions (L) and (R) are necessary for the (NV) property. The assumption (R) is due to the functional equation of the complex $L$-function $L(s, \chi)$, and the failure of (NV) without (L) has been observed by Gillard (cf. [Fin06, Theorem 1.1]). We remark that our result in particular can be applied to Hecke characters attached to certain CM elliptic curves over totally real fields. For example, let $E$ be an elliptic curve over $F$ with CM by an imaginary quadratic field $\mathcal{M}$. Let $K = F\mathcal{M}$ and let $\chi$ be the Hecke character of $K^\times$ such that $L(s, \chi^{-1}) = L(E_{K/F}, s)$. Then it is well known that the assumptions (L) and (C) hold if $(D_{K/F}, \#(O_{\mathcal{M}}^\times)) = 1$ and $p > 3$. In general, (C) is expected to be unnecessary. The very reason we impose them is due to the
difficulty of the computation of certain Gauss sums \( A_\beta(\chi) = A_\beta(\chi_s) \) defined in (4.14). We leave the removal of (C) to our forthcoming paper [Hsi12, §6].

We also consider the case \( \chi \) is not residually self-dual. In particular, this implies the failure of (V). We prove the following result in Cor. 6.5, which gives a partial generalization of Hida’s theorem.

**Theorem B.** Suppose that (unr), (ord) and \((p, D_{K/F}\mathcal{C}) = 1\). Suppose further that the following conditions hold:

1. \( \mu_p(\chi_v) = 0 \) for every \( v \mid \mathcal{C}^+ \),
2. \( \chi \) is not residually self-dual.

Then (NV) holds for \((\chi, l)\).

The proof is based on Hida’s ideas in [Hid04a], where Hida provided a general strategy to study the problem of the non-vanishing of Hecke \( L \)-values modulo \( p \) via a study on the Fourier coefficients of Eisenstein series. The starting point of Hida is Damerell’s formula, which relates a sum of suitable Eisenstein series evaluated at CM points to Hecke \( L \)-values for CM fields. And then he proves a key result on Zariski density of CM points in Hilbert modular varieties modulo \( p \), by which he is able to reduce the problem to non-vanishing of an Eisenstein series modulo \( p \) using a variant of Simnot’s argument. The assumption that \( \mathcal{C} \) is a product of split primes solely results from the difficulty of the calculation of Fourier coefficients of Eisenstein series. Following Hida’s strategy, we first construct an Eisenstein measure which interpolates the Hecke \( L \)-values by the evaluation at CM points. The construction of our Eisenstein measure is from representation theoretic point of view, and Damerell’s formula is actually a period integral of Eisenstein series against a non-split torus. Fourier coefficients of our Eisenstein series are decomposed into a product of local Whittaker integrals. Through an explicit calculation of these local integrals, we find that some Fourier coefficient is non-zero modulo \( p \) provided that certain epsilon dichotomy holds (See Prop. 6.7).

Here is the outline of this article. We fix notation and recall some basic facts about Hilbert modular varieties and CM points in the first three sections. We basically follow the exposition in [Hid04a] except that we use an adelic description of CM points. Readers who are familiar with [Hid04a] may begin with §4, which is the bulk of this paper. In §4, we give the construction of Eisenstein series and the calculation of some local Whittaker integrals. The formulas of the key integrals \( \tilde{A}_\beta(\chi) \) are summarized in Prop. 4.4 and Prop. 4.5. The explicit calculation of the period integral of our Eisenstein series is carried out in §5. Finally we show some Fourier coefficient of our Eisenstein series is non-zero modulo \( p \) in §6.

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### 1. Notation and definitions

1.1. Throughout \( \mathcal{F} \) is a totally real field of degree \( d \) over \( \mathbb{Q} \) and \( K \) is a totally imaginary quadratic extension of \( \mathcal{F} \). Let \( c \) be the complex conjugation, the unique non-trivial element in \( \text{Gal}(K/F) \). Let \( O \) (resp. \( R \)) be the ring of integer of \( K \) (resp. \( \mathcal{F} \)). Let \( D_\mathcal{F} \) (resp. \( D_F \)) be the different (resp. discriminant) of \( K/F \). Let \( D_K/F \) be the different of \( K/F \). For every fractional ideal \( b \) of \( O \), set \( b^* = b^{-1}D_F^{-1} \). Denote by \( a = \text{Hom}(\mathcal{F}, \mathbb{C}) \) the set of archimedean places of \( \mathcal{F} \). Denote by \( h \) (resp. \( h_K \)) the set of finite places of \( \mathcal{F} \) (resp. \( K \)). We often write \( v \) for a place of \( \mathcal{F} \) and \( w \) for the place of \( K \) above \( v \). Denote by \( \mathcal{F}_v \) the completion of \( \mathcal{F} \) at \( v \) and by \( \mathcal{F}_v \) a uniformizer of \( \mathcal{F}_v \). Let \( \mathcal{K}_v = \mathcal{F}_v \otimes_{\mathcal{F}} K \).

Fix two rational primes \( p \neq \ell \). Let \( \ell \) be a prime of \( \mathcal{F} \) above \( \ell \). Let \( \Sigma \) be a fixed CM type of \( K \) as in the introduction. We shall identify \( \Sigma \) with \( a \) by the restriction to \( \mathcal{F} \). We assume (unr) and (ord) for \((p, K, \Sigma)\) throughout this article. Let

\[
\Sigma_p = \{ w \in h_K \mid w \mid p \text{ and } w \text{ is induced by } \iota_p \circ \sigma \text{ for } \sigma \in \Sigma \}.
\]

We recall that \( \Sigma \) is \( p \)-ordinary if \( \Sigma_p \cap \Sigma \ell c = \emptyset \) and \( \Sigma_p \cup \Sigma_\ell c = \{ w \in h_K \mid w \mid p \} \). Note that (ord) implies that every prime of \( \mathcal{F} \) above \( p \) splits in \( K \).
1.2. If $L$ is a number field, $A_L$ is the adele of $L$ and $A_{L,f}$ is the finite part of $A_L$. The ring of integers of $L$ is denoted by $O_L$. For $a \in A_L$, we put

$$i_L(a) := a(O_L \otimes \mathbb{Z}) \cap L.$$ 

Let $\psi_F$ be the standard additive character of $\mathbb{Q}_F$ such that $\psi_F(x) = \exp(2\pi i x)$, $x \in \mathbb{R}$. We define $\psi_L : A_{L_f}/L \to \mathbb{C}^\times$ by $\psi_L(x) = \psi_F \circ \mathbb{T}_f \psi_F(x)$. For $\beta \in L$, $\psi_{L,\beta}(x) = \psi_L(\beta x)$. If $L = \mathcal{F}$, we write $\psi$ for $\psi_{\mathcal{F}}$.

We choose once and for all an embedding $\iota : \mathcal{C} \hookrightarrow \mathbb{C}$ and an isomorphism $\iota : \mathcal{C} \cong C_p$, where $C_p$ is the completion of an algebraic closure of $\mathbb{Q}_p$. Let $\iota_p = \iota_{\infty} : \mathbb{Q} \hookrightarrow \mathbb{C}$ be their composition. We regard $L$ as a subfield in $\mathbb{C}$ (resp. $C_p$) via $\iota_{\infty}$ (resp. $\iota_p$) and $\text{Hom}(L, \mathbb{Q}) = \text{Hom}(L, C_p)$.

Let $\mathcal{Z}$ be the ring of algebraic integers of $\mathbb{Q}$ and let $\mathcal{Z}_p$ be the $p$-adic completion of $\mathcal{Z}$ in $C_p$ with the maximal ideal $\mathfrak{m}_p$. Let $m = \iota_p^{-1}(\mathfrak{m}_p)$.

1.3. Let $F$ be a local field. Denote by $| \cdot |_F$ the absolute value of $F$. We often drop the subscript $F$ if it is clear from the context. We fix for the choice of our Haar measure $dx$ on $F$. If $F = \mathbb{R}$, $dx$ is the Lebesgue measure on $\mathbb{R}$.

If $F = \mathbb{C}$, $dx$ is the twice the Lebesgue measure. If $F$ is a non-archimedean local field, $dx$ (resp. $d^x$) is the Haar measure on $F$ (resp. $F^x$) normalized so that $\text{vol}(O_F, dx) = 1$ (resp. $\text{vol}(O_F^x, d^x x) = 1$). If $\mu : F^x \to C^x$ is a character of $F^x$, define

$$a(\mu) = \inf \{ n \in \mathbb{Z}_{\geq 0} \mid |\mu|_{1+\pi^2 O_v} = 1 \}.$$ 

2. Hilbert modular varieties and Hilbert modular forms

2.1. We follow the exposition in [Hid04b, §4.2]. Let $V = \mathcal{V}_F \oplus \mathcal{V}_F$ be a two dimensional $\mathcal{F}$-vector space and $\langle \cdot, \cdot \rangle : V \times V \to \mathcal{F}$ be the $\mathcal{F}$-bilinear alternating pairing defined by $\langle e_1, e_2 \rangle = 1$. Let $\mathcal{L} = O_v^e \oplus O_v^e$ be the standard $O$-lattice in $V$. Let $G = \text{GL}_2(\mathcal{F})$. For $g = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in M_2(\mathcal{F})$, we define an involution $g' = \begin{bmatrix} c & -b \\ -d & a \end{bmatrix}$.

If $g \in G(\mathcal{F}) = \text{GL}_2(\mathcal{F})$, then $g' = g^{-1} \cdot g$. We identify vectors in $V$ with row vectors according to the basis $e_1, e_2$, so $G$ has a natural right action on $V$. Define a left action of $G$ on $V$ by $g \ast x := x \cdot g'$, $x \in V$.

For each finite place $v$ of $F$, put

$$K^0_v = \{ g \in G(F_v) \mid g \ast (\mathcal{L} \otimes O_v) = \mathcal{L} \otimes O_v \}.$$ 

Let $K^0 = \prod_{v | \mathfrak{p}} K^0_v$ and $K^0_p = \prod_{v \nmid \mathfrak{p}} K^0_v$. For a prime-to-$p$ positive integer $N$, we define an open-compact subgroup $U(N)$ of $G(A_F)$ by

$$U(N) := \{ g \in G(A_F) \mid g \equiv 1 \pmod{N \mathcal{L}} \}.$$ 

Let $K$ be an open-compact subgroup of $G(A_F)$ such that $K_p = K^0_p$. We assume that $K \supset U(N)$ for some $N$ as above and that $K$ is sufficiently small so that the following condition holds:

$$(\text{neat}) \quad K \text{ is neat and } \text{det}(K) \cap O^+_F \subset (K \cap O^+_F)^2.$$ 

2.2. Kottwitz models. We first review Kottwitz models of Hilbert modular varieties.

Definition 2.1. ($S$-quadruples). Let $\square$ be a finite set of rational primes and let $\mathcal{W}_{[\square]} = Z_{\square} [\xi_N]$, $\xi = \exp(\frac{2\pi i}{N})$.

The fibered category $A^{[\square]}_K$ over $SCH/\mathcal{W}_{[\square]}$ is as follows. Let $S$ be a locally noetherian connected $\mathcal{W}_{[\square]}$-scheme and let $\pi$ be a geometric point of $S$. Objects are abelian varieties with real multiplication (AVRM) over $S$ of level $K$, i.e. a $S$-quadruple $\Delta = (A, \lambda, \iota, \overline{\eta}^{[\square]})_S$ consisting of the following data:

1. $A$ is an abelian scheme of dimension $d$ over $S$.
2. $\iota : O \hookrightarrow \text{End}_S A \otimes_{\mathbb{Z}} Z_{\square}$.
3. $\lambda$ is a prime-to-$\square$ polarization of $A$ over $S$ and $\overline{\lambda}$ is the $O_{\square,+}$-orbit of $\lambda$. Namely

$$\overline{\lambda} = O_{\square,+} \lambda = \{ \lambda' \in \text{Hom}(A, A^t) \otimes_{\mathbb{Z}} Z_{\square} \mid \lambda' = \lambda \circ a, a \in O_{\square,+} \}.$$ 

4. $\overline{\eta}^{[\square]} = \eta^{[\square]} K^{[\square]}$ is a $\pi_1(S, \overline{\pi})$-invariant $K^{(p)}$-orbit of isomorphisms of $O_K$-modules $\eta^{[\square]} : \mathcal{L} \otimes_{\mathbb{Z}} A^{[\square]}_f \to V^{[\square]}(A^t_{\mathcal{F}})$.

Here we define $\eta^{[\square]}(x)$ for $g \in G(A^{[\square]}_f)$ by $\eta^{[\square]}(g(x) = \eta^{[\square]}(g \ast x)$. Furthermore, $(A, \overline{\lambda}, \overline{\iota}, \overline{\eta}^{[\square]})_S$ satisfies the following conditions:

- For $\lambda$ the Rosati involution induced by $\lambda$ on $\text{End}_S A \otimes Z_{\square}$. Then $\iota(b) = \iota(b)$, $\forall b \in O$. 

• Let $e^\lambda$ be the Weil pairing induced by $\lambda$. Lifting the isomorphism $\mathbb{Z}/N\mathbb{Z} \cong \mathbb{Z}/NZ(1)$ induced by $\zeta_N$ to an isomorphism $\zeta : \mathbb{Z} \cong \hat{\mathbb{Z}}(1)$, we can regard $e^\lambda$ as an $F$-alternating form $e^\lambda : V(\mathcal{O})(A) \times V(\mathcal{O})'(A') \to D_{F,1} \otimes \mathbb{Z}(\lambda)$.

Let $\eta^\lambda$ denote the $F$-alternating form on $V(\mathcal{O})(A)$ induced by $e^\lambda(x, x') = \langle xy, x'y' \rangle$. Then $e^\lambda = u \cdot e^\lambda$ for some $u \in A_{F,j}$.

• As $O \otimes \mathcal{O}_S$-modules, we have an isomorphism $\text{Lie} A \cong O \otimes \mathcal{O}_S$ locally under Zariski topology of $S$. Similarly we define the functor $\mathcal{E}$.

In [Kot92], Kottwitz shows $\mathcal{E}$.

We say $A \sim A'$ (resp. $A \simeq A'$) if there exists a prime-to-$\mathfrak{p}$ isogeny (resp. isomorphism) in $\text{Hom}_{\mathcal{A}_K(\mathcal{O})}(A, A')$.

We consider the cases when $\square = \emptyset$ and $\{p\}$. When $\square = \emptyset$ is the empty set and $W(\square) = \mathbb{Q}(\zeta_N)$, we define the functor $\mathcal{E}_K : \text{Sch}/\mathbb{Q}(\zeta_N) \to \text{SETS}$ by

$$\mathcal{E}_K(S) = \left\{ (A, \lambda, \tau, \eta) \in \mathcal{A}_K(\mathcal{O})(S) \mid \eta(\mathcal{L} \otimes \mathbb{Z}) = H_1(A, \mathbb{Z}) \right\} / \sim .$$

By the theory of Shimura-Deligne, $\mathcal{E}_K$ is represented by a quasi-projective scheme $\text{Sh}_K$ over $\mathbb{Q}(\zeta_N)$. We define the functor $\mathcal{E}_K : \text{Sch}/\mathbb{Q} \to \text{SETS}$ by

$$\mathcal{E}_K(S) = \left\{ (A, \lambda, \tau, \eta) \in \mathcal{A}_K(\mathcal{O})(S) \mid \eta(\mathcal{L} \otimes \mathbb{Z}^j) = H_1(A, \mathbb{Z}^j) \right\} / \sim .$$

In [Kot92], Kottwitz shows $\mathcal{E}_K^{(p)}$ is representable by a quasi-projective scheme $\text{Sh}_K^{(p)}$ over $W$ if $K$ is neat. Similarly we define the functor $\mathcal{E}_K^{(p)} : \text{Sch}/W \to \text{SETS}$ by

$$\mathcal{E}_K^{(p)}(S) = \left\{ (A, \lambda, \tau, \eta^{(p)}) \in \mathcal{A}_K^{(p)}(\mathcal{O})(S) \mid \eta^{(p)}(\mathcal{L} \otimes \mathbb{Z}^j) = H_1(A, \mathbb{Z}^j) \right\} / \sim .$$

It is shown in [Hid04b, §4.2.1] that $\mathcal{E}_K^{(p)} \cong \mathcal{E}_K^{(p)}$.

2.3. Igusa schemes.

Definition 2.2 ($S$-quintuples). Let $n$ be a positive integer. We define the fibered category $\mathcal{A}_K^{(p)}$ whose objects are AVRM over an $W$-scheme of level $K^n$, i.e. a $S$-quintuple $(A, j)_S$ consisting of a $S$-quadruple $A = (A, \lambda, \tau, \eta^{(p)}) \in \mathcal{A}_K^{(p)}(S)$ and a monomorphism

$$j : O^* \otimes \mathbb{Z}_{p^n} \hookrightarrow A[p^n]$$

as $O$-group schemes over $S$. We call $j$ a level-$p^n$ structure of $A$. Morphisms are

$$\text{Hom}_{\mathcal{A}_K^{(p)}(S)}((A, j), (A', j')) = \left\{ \phi \in \text{Hom}_{\mathcal{A}_K^{(p)}(S)}(A, A') \mid \phi j = j' \right\} .$$

Define the functor $\mathcal{H}_K^{(p)} : \text{Sch}/W \to \text{SETS}$ by

$$\mathcal{H}_K^{(p)}(S) = \left\{ (A, j) \in \mathcal{A}_K^{(p)}(S) \mid \eta^{(p)}(\mathcal{L} \otimes \mathbb{Z}^j) = H_1(A, \mathbb{Z}^j) \right\} / \sim .$$

It is known that $\mathcal{H}_K^{(p)}$ are relatively representable over $\mathcal{E}_K^{(p)}$ (cf. [SGA64, Prop. 3.12]), so it is represented by a scheme over $W$, which we denote by $I_K$. For $n \geq n' > 0$, the natural morphism $\pi_{n,n'} : I_K \to I_{K,n'}$ induced by the inclusion $O^* \otimes \mathbb{Z}_{p^n} \hookrightarrow O^* \otimes \mathbb{Z}_{p^{n'}}$ is finite étale. The forgetful morphism $\pi : I_K \to \text{Sh}_K^{(p)}$ defined by $\pi : (A, j) \mapsto A$ are étale for all $n > 0$. Hence $I_K$ is smooth over Spec $W$. The image of $\pi$ is the pre-image of ordinary abelian schemes in $I_K \otimes \mathbb{F}_p$. 
2.4. Complex uniformization. We describe the complex points $Sh_K(C)$. Put
\[ X^+ = \{ \tau = (\tau_\sigma)_{\sigma \in a} \in C^a \mid \text{Im} \tau_\sigma > 0 \text{ for all } \sigma \in a \} \].
Let $A_{\sigma}$ be the set of totally positive elements in $A$ and let $G(A)^+ = \{ g \in G(A) \mid \det g \in A_+ \}$. Define the complex Hilbert modular variety by
\[ M(X^+, K) := G(F)^+ \times G(A_{\sigma}, f)/K. \]
It is well known that $M(X^+, K) \sim Sh_K(C)$ by the theory of abelian varieties over $C$.

For $\tau = (\tau_\sigma)_{\sigma \in a} \in X^+$, we let $p_\tau$ be the period map $V \otimes Q R \sim C^n$ defined by $p_\tau(\omega_1 + \omega_2) = \alpha + \beta$, $\alpha, \beta \in F \otimes Q R = R^n$. We can associate a AVR to $(\tau, g) \in X^+ \times G(A_{\sigma}, f)$ as follows.

- The complex abelian variety $A_{\sigma} = C^n/p_\tau(g \ast \mathcal{L})$.
- The $\mathcal{F}_1$-orbit of polarization $(\cdot)$ on $A_{\sigma}(\tau)$ is given by the Riemann form $(\cdot, \cdot)_{can}$ of $p_\tau^{-1}$.
- The $t_C : O \leftrightarrow End A_{\sigma}(\tau) \otimes Q$ is induced from the pull back of the natural $\mathcal{F}$-action on $V$ via $p_\tau$.
- The level structure $\eta_\tau : L \otimes Z A_{\tau} \sim (g \ast \mathcal{L}) \otimes Z A_{\tau} = H_1(A_{\sigma}(\tau), A_f)$ is defined by $\eta_\tau(v) = g \ast v$.

Let $A_{\sigma}(\tau)$ denote the $C$-quadruple $(A_{\sigma}(\tau), \{\tau\}_{can+1}, K_{\eta_\tau})$. Then $[\tau, g] \mapsto [A_{\sigma}(\tau)]$ gives rise to an isomorphism $M(X^+, K) \sim Sh_K(C)$.

Let $c \in C^n$ be the standard complex coordinates of $C^n$ and $d \in \{ z_\sigma \}_{\sigma \in a}$. Then $O$-action on $d$ is given by $t_{\sigma}^C(\alpha)z_\sigma = \sigma(\alpha)z_\sigma$, $\sigma \in a = Hom(F, C)$. Let $z = z_{id}$ be the coordinate corresponding to $\iota_{\infty} : \mathcal{F} \sim Q \sim C$. Then
\[ (O \otimes Z C)dz = H^0(A_{\sigma}(\tau), \Omega_{A_{\sigma}(\tau)}/C). \]

2.5. Hilbert modular forms.

2.5.1. For $\tau \in C$ and $g = \left[ \begin{array}{cc} a & b \\ c & d \end{array} \right] \in GL_2(R)$, we put
\[ J(g, \tau) = cr + d. \]
For $\tau = (\tau_\sigma)_{\sigma \in a} \in X^+$ and $g_\infty = (g_\sigma)_{\sigma \in a} \in G(\mathcal{F} \otimes Q R)$, we put
\[ J(g_\infty, \tau) = \prod_{\sigma \in a} J(g_\sigma, \tau_\sigma). \]

**Definition 2.3.** Denote by $M_k(K, C)$ the space of holomorphic Hilbert modular form of parallel weight $k$ and level $K$. Each $f \in M_k(K^n, C)$ is a $C$-valued function $f : X^+ \times G(A_{\sigma}, f) \to C$ such that the function $f(\cdot, g_\sigma) : X^+ \to C$ is holomorphic for each $g_\sigma \in G(A_{\sigma}, f)$ and
\[ f(\alpha(\tau, g_\sigma)u) = \xi(\alpha, \tau)^kg_{\sigma}(\tau, g_\sigma) \quad \text{for all } u \in K_1^n \text{ and } \alpha \in G(A_{\sigma}, f). \]

2.5.2. Fourier expansion. For every $f \in M_k(K^n, C)$, we have the Fourier expansion
\[ f(\tau, g_f) = \sum_{\beta \in \mathcal{F}_{\tau} \cup \{0\}} W_\beta(f, g_f)e^{2\pi i \tau \beta}/q(\beta). \]
We call $W_\beta(f, g_f)$ the $\beta$-th Fourier coefficient of $f$ at $g_f$.

For a semi-group $L$ in $F$, let $L_+ = F_+ \cap L$ and $L_{\geq 0} = L_+ \cup \{0\}$. If $B$ is a ring, we denote by $B[L]$ the set of all formal series
\[ \sum_{\beta \in L} a_\beta q^\beta, \quad a_\beta \in B. \]
Let $a, b \in (A_{\sigma})^{(p)}_f$ and let $a = i_f(a)$ and $b = i_f(b)$. The $q$-expansion of $f$ at the cusp $(a, b)$ is given by

\[ f_{(a,b)}(q) = \sum_{\beta \in (N^{-1}ab)_{\geq 0}} W_\beta(f, \left[ \begin{array}{cc} a^{-1} & 0 \\ 0 & b \end{array} \right])q^\beta \in C[[N^{-1}ab]_{\geq 0}]. \]

If $B$ is a $W$-algebra in $C$, we put
\[ M_k(K, B) = \{ f \in M_k(K, C) \mid f_{(a,b)}(q) \in B[[N^{-1}ab]_{\geq 0}] \text{ at all cusps } (a, b) \}. \]
2.5.3. Tate objects. Let $\mathcal{S}$ be a set of $d$-linear $\mathbb{Q}$-independent elements in $\text{Hom}(F, \mathbb{Q})$ such that $l(F_+) > 0$ for $l \not\in \mathcal{S}$. If $L$ is a lattice in $F$ and $n$ a positive integer, let $L_{\mathcal{S}, n} = \{ x \in L \mid l(x) > -n \text{ for all } l \not\in \mathcal{S} \}$ and put $B((L; \mathcal{S}, n)) = \lim_{n \to \infty} B[L_{\mathcal{S}, n}]$. To a pair $(a, b)$ of two prime-to-$pN$ fractional ideals, we can attach the Tate $\text{AVRM} \text{Tate}_{a,b}(q)$ = $\Omega^* \otimes_{\mathbb{Z}} G_m/q^b$ over $\mathbb{Z}(ab; \mathcal{S})$ with $O$-action $\iota_{can}$. As described in [Kat78], $\text{Tate}_{a,b}(q)$ has a canonical $ab^{-1}$-polarization $\lambda_{can}$ and also carries $\omega_{can}$, a canonical $O \otimes \mathbb{Z}(ab; \mathcal{S})$-generator of $\Omega_{\text{Tate}_{a,b}}$ induced by the isomorphism Lie(\text{Tate}_{a,b}(q)/\mathbb{Z}(ab; \mathcal{S})) = $\Omega^* \otimes_{\mathbb{Z}} \text{Lie}(G_m) \cong \Omega^* \otimes \mathbb{Z}(ab; \mathcal{S})$. Let $\mathcal{L}_{a,b} = \mathcal{L}$, $[b]_{a-1} = \text{be}_1 \otimes \text{a}^* \text{e}_2$. Then we have a level $N$-structure $\eta_{can} : N^{-1} \mathcal{L}_{a,b}/\mathcal{L}_{a,b} \sim \text{Tate}_{a,b}(q)[N]$ over $\mathbb{Z}[[\xi_N]]((N^{-1}ab; \mathcal{S}))$ induced by the fixed primitive $N$-th root of unity $\xi_N$. We write $\text{Tate}_{a,b}$ for the Tate $\mathbb{Z}(ab; \mathcal{S})$-quadraple $(\text{Tate}_{a,b}(q), \lambda_{can}, \iota_{can}, \eta(p)_{can})$ (at $(a, b)$. In addition, since $a$ is prime to $p$, we let $\eta_{p,can}^p : O^* \otimes \mathbb{Z} \mu_p^\infty = \text{a}^* \otimes \mathbb{Z} \mu_p^\infty \sim \text{Tate}_{a,b}(q)$ be the canonical level $p^n$-structure induced by the natural inclusion $\text{a}^* \otimes \mathbb{Z} \mu_p^n \sim \text{a}^* \otimes \mathbb{Z} G_m$.

2.5.4. Geometric modular forms. We collect here definitions and basic facts of geometric modular forms. For the precise theory, we refer to [Kat78] or [Hid04b]. Let $T = \text{Re}_{O}/\mathbb{Z} G_m$ and $k \in \text{Hom}(T, G_m)$. Let $B$ be a $\mathbb{Z}(p)$-algebra. Consider $[A] = [(A, \alpha, \iota, \eta(p))] \in \mathcal{E}_K(C)$ for a $B$-algebra $C$ with a differential form $\omega$ generating $H^0(A, \Omega_{A/C})$ over $O \otimes \mathbb{Z} C$. A geometric modular form $f$ over $B$ of weight $k$ and $L$ is a functorial rule assigning a value $f(A, \omega) \in C$ satisfying the following axioms.

(G1) $f(A, \omega) = f(A', \omega')$ if $\omega'$ is independent of the auxiliary choice $(A', \omega')$ over $C$.

(G2) For a $B$-algebra homomorphism $\varphi : C \to C'$, we have $f((A, \omega) \otimes_{C} C') = \varphi(f(A, \omega))$.

(G3) $f(A, \omega) = \kappa(a^{-1})f(A, \omega)$ for all $a \in T(C) = (O \otimes \mathbb{Z} C)^\times$.

(G4) $f(\text{Tate}_{a,b}(\omega_{can})) \in B[\xi_N]/[[N^{-1}ab]_{\geq 0}]$ at all cusps $(a, b)$.

For a positive integer $k$, we regard $k \in \text{Hom}(T, G_m)$ as the character $t \mapsto N_{T/Q}(t)^k$. We denote by $\mathcal{M}_k(K, B)$ the space of geometric modular forms over $B$ of weight $k$ and level $K$.

For each $f \in \mathcal{M}_k(K, C)$, we regard $f$ as a holomorphic Hilbert modular form of weight $k$ and level $K$ by

$$f(\tau, \gamma f) = f(A_g(\tau), (\varsigma)_\gamma, (c, \gamma, \tau_{id}), dz),$$

where $dz$ is the differential form in (2.2). By GAGA principle, this gives rise to an isomorphism $\mathcal{M}_k(K, C) \sim \mathcal{M}_k(K, B)$. As discussed in [Kat78, §1.7], the evaluation $f(\text{Tate}_{a,b}(\omega_{can}))$ is independent of the auxiliary choice of $\mathcal{S}$ in the construction of the Tate object. Moreover, we have the following important identity which bridges holomorphic modular forms and geometric modular forms.

$$f|_{(a,b)}(q) = f(\text{Tate}_{a,b}(\omega_{can})) \in C[[(N^{-1}ab)_{\geq 0}]]$$

By $q$-expansion principle, if $B$ is $W$-algebra in $C$, then $\mathcal{M}_k(K, B) = \mathcal{M}_k(K, B)$.

2.5.5. $p$-adic modular forms. Let $B$ be a $p$-adic ring in $C_p$. Let $V(K, B)$ be the space of Katz $p$-adic modular forms over $B$ defined by

$$V(K, B) := \lim_{n \to \infty} \lim_{m \to \infty} H^0(I_{K,n}/B/p^mB, O_{K,n}).$$

In other words, Katz $p$-adic modular forms are formal functions on Igusa towers.

Let $C$ be a $B/p^mB$-algebra. For each $C$-point $[(A, j)] \in \lim_{m \to \infty} \lim_{n \to \infty} I_{K,n}(C)$, the level $p^\infty$-structure $j$ induces an isomorphism $j_+ : O^* \otimes \mathbb{Z} \text{Lie}((\widehat{G}_m)_C) = O^* \otimes \mathbb{Z} C \sim \text{Lie}(A)$. Let $dt/t$ be the canonical invariant differential form of $\widehat{G}_m$. Then $j^*dt/t := dt/t \circ j_+$ is a generator of $H^0(A, \Omega_A)$ as a $O \otimes \mathbb{Z} C$-module. We thus have a natural injection

$$\mathcal{M}_k(K, B) \hookrightarrow V(K, B)$$

$$f \mapsto \widehat{f}(A, j) := f(A, j_+ dt/t)$$

which preserves the $q$-expansions in the sense that $\widehat{f}|_{(a,b)}(q) := \widehat{f}(\text{Tate}_{a,b}(\iota_{p,can}^0), f|_{(a,b)}(q))$. We will call $\widehat{f}$ the $p$-adic avatar of $f$. 
2.6. Hecke action. Let $h \in G(A_{\mathbb{A},f}^{(p)})$ and let $hK := hKH^{-1}$. We define a morphism $|h| : \mathcal{E}_{hK}^{(p)} \rightarrow \mathcal{E}_{K}^{(p)}$ by

$$
\mathbb{A} = (A, \lambda, \iota, \bar{\varphi}^{(p)}) \mapsto \mathbb{A}|h = (A, \lambda, \iota, h\bar{\varphi}^{(p)}).
$$

Then $|h|$ induces a $\mathcal{W}$-isomorphism $Sh_{hK}^{(p)} \rightarrow Sh_{K}^{(p)}$, and $|h|$ thus acts on spaces of modular forms. In particular, for $F \in V(K, \mathcal{W})$, we define $F|h \in V(hK, \mathcal{W})$ by

$$
F|h(\mathbb{A}) = F(\mathbb{A}|h).
$$

Let $K_{0}(l) := \{ g \in K \mid e_{2}g \in O^{*}e_{2} \, (\text{mod} \, \mathcal{L}) \}$. Define the $U_{l}$-operator on $V(K_{0}(l), \mathcal{W})$ by

$$
F|U_{l} = \sum_{u \in O^{*}/lO^{*}} F\left[ \begin{array}{c} \varpi_{l}^{u} \\ 0 \\ 1 \end{array} \right].
$$

Using the description of complex points of $Sh_{hK}^{(p)}(\mathbb{C})$ in §2.4, it is not difficult to verify by definition that for $(\tau, g) \in X^{+} \times G(A_{\mathbb{A},f}^{(p)})$ two pairs $(A_{\varphi}(\tau), \omega)$ and $(\bar{A}_{\varphi}(\tau), \omega)$ of $\mathbb{C}$-quadruples and invariant differential forms are $Z_{(p)}$-isogenous, so we have the isomorphism:

$$
M_{k}(K, \mathbb{C}) \cong M_{k}(hK, \mathbb{C})
$$

$$
\theta \mapsto \theta|h(\tau, g) = \theta(\tau, gh).
$$

3. CM points

3.1. In this section, we give an adelic description of CM points in Hilbert modular varieties. Fix a prime-to-$p$ integral ideal $\mathfrak{c}$ of $R$ such that $(p, \mathfrak{c}D_{K/f}) = 1$. Write $\mathcal{E} = \mathbb{C}^{+} \mathcal{E}^{-}$, where $\mathcal{E}^{-} = \mathfrak{f} \mathfrak{R}$, $\mathfrak{f}$ (resp. $\mathfrak{R}$) is a product of inert (resp. ramified) primes in $K/F$ and $\mathcal{E}^{-} = \mathfrak{f} \mathfrak{R}$ is a product of split primes in $K/F$ such that $(\mathfrak{f}, \mathfrak{R}) = 1$ and $\mathfrak{f} \subset \mathfrak{R}^{*}$. Recall that we have assumed (unr) and (ord) in the introduction. Let $\Sigma$ be a $p$-ordinary CM type of $K$ and identify $\Sigma$ with $\mathbf{a}$ such that the restriction to $\mathcal{F}$. We choose $\vartheta \in K$ such that $\vartheta \in \mathcal{W}$ and $\vartheta^{2} = V$.

$$
\vartheta^{(p)} = -\vartheta \quad \text{and} \quad \text{Im}(\vartheta^{(p)}) > 0 \quad \text{for all} \quad \vartheta \in \Sigma.
$$

Let $\vartheta^{(p)} := \{ \vartheta^{(p)} \}_{\vartheta \in \Sigma} \subset X^{+}$. Let $D = -\vartheta^{2} \in \mathcal{F}_{+}$ and define $\rho : K \hookrightarrow M_{2}(\mathbb{F})$ by

$$
\rho(\vartheta\alpha + b) = \begin{bmatrix} b & -Da \\ a & b \end{bmatrix}.
$$

Consider the isomorphism $q_{\vartheta} : K \cong \mathcal{F}^{2} = V$ defined by $q_{\vartheta}(\vartheta\alpha + b) = ac_{1} + bc_{2}$. It is clear that $(0, 1)\rho(\alpha) = q_{\vartheta}(\vartheta\alpha)$ and $q_{\vartheta}(c_{x}) = q_{\vartheta}(\rho(\alpha))$ for $\alpha, x \in K$. Let $C(\Sigma)$ be the $K$-module whose underlying space is $\mathcal{C}^{\Sigma}$ with the $K$-action given by $c_{x}\alpha = (c_{x})\alpha$. Then we have a canonical isomorphism $K \otimes_{Q} R = C(\Sigma)$, and $p\rho := q_{\vartheta}^{-1} : V \otimes_{Q} R \hookrightarrow K \otimes_{Q} R = C(\Sigma)$ is the period map associated to $\vartheta^{2}$.

3.2. A good level structure.

3.2.1. For each $\nu|\mathfrak{p}^{2}\mathfrak{f}\mathfrak{R}$, we decompose $\nu = \nu\vartheta$ into two places $\nu$ and $\vartheta$ of $K$ with $w|\mathfrak{f}\mathfrak{R}_{p}$. Here $w|\mathfrak{f}\mathfrak{R}_{p}$ means $w|\mathfrak{f}$ or $w \in \mathfrak{R}_{p}$. Let $c_{w}$ (resp. $\vartheta|_{w}$) be the idempotent associated to $w$ (resp. $\vartheta$). Then $\{c_{w}, \vartheta|_{w}\}$ gives an $O_{w}$-basis of $R_{w}$. Let $\vartheta|_{w} \in \mathcal{F}_{w}$ such that $\vartheta = -\vartheta_{w}|_{\vartheta} + \vartheta_{w}c_{w}$.

For inert or ramified place $\nu$ and the place of $K$ above $\nu$, we fix a $O_{w}$-basis $\{1, \theta_{\nu}\}$ such that $\theta_{\nu}$ is a uniformizer if $\nu$ is ramified and $\vartheta = -\theta_{\nu} \nu^{1/2}$ if $\nu \not| p\mathfrak{f}\mathfrak{R}$. By (d2), we may choose $d_{\mathcal{F}_{w}} = 2\delta \vartheta_{w}^{-1}$ if $\nu|\mathfrak{p}^{2}\mathfrak{f}\mathfrak{R}\mathfrak{f}$ (resp. $d_{\mathcal{F}_{w}} = 2\delta \vartheta_{w}^{-1}$ if $\nu|\mathfrak{f}\mathfrak{R}_{p}$).

3.2.2. We shall choose a basis $\{\nu_{1}, \nu_{2}, \nu_{3}\}$ of $R \otimes_{O} O_{w}$ for each finite place $\nu \not| \mathcal{F}$. If $\nu \not| p\mathfrak{f}\mathfrak{R}$, we choose $\{\nu_{1}, \nu_{2}, \nu_{3}\}$ in $R \otimes_{O} O_{w}$ such that $R \otimes_{O} O_{w} = O_{w}e_{1,d} \oplus O_{w}e_{2,d} \oplus O_{w}e_{3,d}$. It is clear that $\{\nu_{1}, \nu_{2}, \nu_{3}\}$ can be taken to be $\{\vartheta, 1\}$ except for finitely many $v$. If $\nu|\mathfrak{p}^{2}\mathfrak{f}\mathfrak{R}$, let $\{\nu_{1}, \nu_{2}, \nu_{3}\} = \{e_{2}, d_{w}, c_{w}\}$ with $w|\mathfrak{f}\mathfrak{R}_{p}$. If $\nu$ is inert or ramified, let $\{\nu_{1}, \nu_{2}, \nu_{3}\} = \{\theta_{\nu}, d_{\mathcal{F}_{w}}, 1\}$. For every integer $n \geq 0$, we let $R_{n} = R^{1/2}R$, and let $\{\nu_{1}, \nu_{2}\} := \{\nu_{1}, \nu_{2}\}$ be a basis of $R_{n} \otimes_{O} O_{w}$. 
For $v \in \mathfrak{h}$, let $\zeta_v$ (resp. $\zeta^{(n)}_v$) be the element in $GL_2(F_v)$ such that $e_i \zeta_v = q_{\theta}(e_i \zeta_v)$ (resp. $e_i \zeta^{(n)}_v) = q_{\theta}(e_i^{(n)} \zeta_v)$). For $v = \sigma \in \mathfrak{a}$, let $\zeta_v = \left[ \begin{array}{cc} \operatorname{im} \sigma(\theta) & 0 \\ 0 & 1 \end{array} \right]$. Define $\zeta = \prod_{v \neq \mathfrak{a}} \zeta_v \in GL_2(A_{\mathfrak{a}})$ and $\zeta^{(n)} = \zeta \times \zeta_v^{(n)} \in GL_2(A_{\mathfrak{a}})$. Let $\zeta_f$ and $\zeta^{(n)}_f$ be the finite components of $\zeta$ and $\zeta^{(n)}$ respectively. By the definition of $\zeta^{(n)}$, we have

$$\zeta_f^{(n)} + (L \otimes_{\mathbb{Z}} \bar{Z}) = (L \otimes_{\mathbb{Z}} \bar{Z}) \cdot (\zeta^{(n)}_f)' = q_{\theta}(R_n \otimes_{\mathbb{Z}} \bar{Z}).$$

The matrix representation of $\zeta_v$ according to the basis $\{e_1, e_2\}$ for $v|pD_{K,f} \mathfrak{C}^{c}$ is given as follows:

$$\zeta_v = \left[ \begin{array}{cc} d_{x_v} & -2^{-1}t_v \\ 0 & d_{x_v}^{-1} \end{array} \right], \quad t_v = \theta_v + \bar{\theta}_v \text{ if } v|D_{K,f} \mathfrak{J},$$

$$\zeta_v = \left[ \begin{array}{cc} d_{x_v} & -\frac{1}{2} \frac{1}{2} \\ 0 & d_{x_v}^{-1} \end{array} \right], \quad \text{if } v|p \mathfrak{J}^{\mathfrak{c}} \text{ and } w|\mathfrak{J} \Sigma_p,$$

$$\zeta_v^{(n)} = \left[ \begin{array}{cc} -d_{x_v} \bar{w}^{t_{i,v}} b_i \\ d_{x_v} \bar{w}^{-t_{i,v}} a_i \\ 1 \end{array} \right], \quad (\theta_i = a_i \theta + b_i, a_i \in \mathcal{F}_c^\mathfrak{c}, b_i \in \mathcal{F}_l).$$

### 3.3. For every $a \in A_{K,f}^\times$, we let

$$\mathcal{A}_n(a)/\mathfrak{p} := \mathcal{A}_{n(a),\zeta^{(n)}}(\zeta^{\mathfrak{a}}) = (A_{\mathfrak{p}(a),\zeta^{(n)}}(\zeta^{\mathfrak{a}}), \mathcal{J}, \mathcal{I}, \mathcal{C}, \bar{\mathcal{C}}) \in Sh_K(\mathfrak{C})$$

be the $\mathfrak{C}$-quadruple associated to $(\zeta^{\mathfrak{a}}, \rho(a)\zeta^{(n)}_f)$ as in §2.4. Then $\mathcal{A}_n(a)/\mathfrak{p}$ is an abelian variety by $\mathcal{K}$. Let $W$ be the $p$-adic completion of the maximal unramified extension of $\mathbb{Z}_p$ in $\mathbb{C}_p$. By the general theory of CM abelian varieties, the $\mathfrak{C}$-quadruple $\mathcal{A}_n(a)/\mathfrak{p}$ descends to a $W$-quadruple $\mathcal{A}_n(a)$. Moreover, since $\mathcal{K}$ is $p$-ordinary, $\mathcal{A}_n(a)$ is an ordinary abelian variety, hence the level $p^n$-structure $\eta(a)_p$ over $\mathcal{C}$ descends to a level $p^n$-structure over $W$. Thus we obtain a map $x_n : A_{K,f}^\times \to \lim_{\longrightarrow} \mathcal{I}_{K,m}(W) \subset I_{K,\infty}(W)$, which factors through $C_{\mathcal{K}} := A_{K,f}^\times / K^{\times}$ the idele class group of $\mathcal{K}$. The collection of points $C_{\mathcal{K}}^\infty := \bigsqcup_{\nu=1}^{\infty} x_n(C_{\mathcal{K}})$ in $I_{K,\infty}(W)$ is called CM points in Hilbert modular varieties.

### 3.4. Polarization ideal. The alternating pairing $(\cdot, \cdot) : \mathcal{K} \times \mathcal{K} \to \mathcal{F}$ defined by $(x, y) = (c(x)y - xc(y))/2\theta$ induces an isomorphism $R_{\mathcal{A}_n} \otimes R = \zeta^{\mathfrak{a}}(R)^{-1}D_{\mathfrak{f}}^{-1}$ for the fractional ideal $\zeta(R) = D_{\mathfrak{f}}^{-1}(2\theta D_{\mathfrak{f}}^{-1})$. Then $\zeta(R)$ is the polarization of CM points $x_0(1)$. From the equation

$$D_{\mathfrak{f}}^{-1} \det(\zeta_f) = \lambda^2 L^2_{\zeta_f} = \lambda^2 R = \zeta(R)^{-1}D_{\mathfrak{f}}^{-1},$$

we find that $\zeta(R) = (\det(\zeta_f))^{-1}$. Moreover, for $a \in A_{K}^\times$, the polarization ideal of $x_0(a)$ is $\zeta(a) := \zeta(R)\mathcal{N}_{\mathfrak{K}/\mathfrak{f}}(a)^{-1}$, $a = i\mathcal{K}(a)$.

### 3.5. Measures associated to $U_1$-eigenforms.

#### 3.5.1. We briefly recall Hida’s construction of the measure associated to an $U_1$-eigenform in [Hid04a, §3]. Define the compact subgroup $U_n = (C_1)^{\times} \times (\mathbb{Z}_n \otimes \bar{Z})^\times$ in $A_{K}^\times = (C_1)^{\times} \times A_{K,f}^\times$, where $C_1$ is the unit circle in $\mathbb{C}^{\times}$. Let $Cl_n = K^{\times} A_{K}^\times / A_{K}^\times$ and let $[\cdot] : A_{K}^\times \to Cl_n$ be the quotient map. Let $Cl_{\infty} = \lim_{\longrightarrow} Cl_n$. For $a \in A_{K}^\times$, we let $[a] := \lim_{\longrightarrow} [a]_n \in Cl_{\infty}$ be the holomorphic image in $Cl_{\infty}$. Henceforth, every $\nu \in \mathbb{X}^\nu$ will be regarded implicitly as a $p$-adic character of $Cl_{\infty}$ by geometrically normalized reciprocity law.

Let $\xi \in V(K_n(t), \mathfrak{O})$ for some finite extension $\mathfrak{O}$ of $\mathbb{Z}_p$ and let $\chi$ be the $p$-adic avatar of $\xi$. Assuming the following:

1. $\xi$ is a $U_1$-eigenform with the eigenvalue $a_1(\xi) \in \mathbb{Z}_p^\times$;
2. $\xi(x_n(t)) = \chi^{-1}(a_1(\xi))x_n(t), \quad a_1 \in U_n \cdot A_{K}^\times$,

Hida in [Hid04a, (3.9)] associates a $\mathbb{Z}_p$-valued measure $\varphi_{\xi}$ on $Cl_{\infty}$ to the $U_1$-eigenform $\xi$ such that for a function $\phi : Cl_n \to \mathbb{Z}_p$, we have

$$\int_{Cl_{\infty}} \phi \varphi_{\xi} := a_1(\xi)^{-n} \cdot \sum_{[l]_n \in Cl_n} \xi(l)(\chi(l)) \phi([l]_n).$$
3.5.2. Let $\Delta$ be the torsion subgroup of $Cl_\infty$. Let $Cl^{alg}$ be the subgroup of $Cl_\infty$ generated by $[a]$ for $a \in (\mathbb{A}^{(1)}_F)^\times$ and $\Delta^{alg} = Cl^{alg} \cap \Delta$. We choose a set of representatives $\mathcal{B} = \{b\}$ of $\Delta/\Delta^{alg}$ in $\Delta$ and a set of representatives $\mathcal{R} = \{r\}$ of $\Delta^{alg}$ in $(\mathbb{A}^{(p)}_F)^\times$. Thus $\Delta = \mathcal{B}[\mathcal{R}] = \{b[r]\}_{b \in \mathcal{B}, r \in \mathcal{R}}$. For $a \in (\mathbb{A}^{(p)}_F)^\times$, we define

$$E[a] := E[\rho_a(a)], \rho_a(a) := \zeta^{-1} \rho(a) \varsigma \in G(\mathbb{A}^{(p)}_F).$$

By definition, $E[a](x_n(t)) = E(x_n(ta))$. Following Hida (cf. [Hid07, (4.4) p.25]), we put

$$(3.3) \quad E = \sum_{r \in \mathcal{R}} \hat{\chi}(r)E[r].$$

In [Hid04a], Hida reduces the non-vanishing of $L$-values to the non-vanishing of Eisenstein series by proving the following theorem.

**Theorem 3.1** (Theorem 3.2 and Theorem 3.3 [Hid04a]). Suppose the following conditions in addition to (unr) and (ord):

(H) Write the order of the Sylow $\ell$-subgroup of $\mathbb{F}[\chi]^{\times}$ as $\ell^{r(\chi)}$. Then there exists a strict ideal class $c \in Cl_F$ such that $c = c(a)$ for some $R$-ideal $a$ and for every $u \in O$ prime to $l$, we can find $\beta \equiv u \mod l^{r(\chi)}$ with $a_\beta(E^R, c) \not\equiv 0 \mod m_p$,

where $a_\beta(E^R, c)$ is the $\beta$-th Fourier coefficient of $E^R$ at the cusp $(O, c^{-1})$. Then

$$\int_{Cl_{\infty}} \nu dE \not\equiv 0 \mod m_p$$

for almost all $\nu \in \mathcal{X}^\ast$.

**Remark.** As pointed by the referee, if $\mathfrak{l}$ has degree one over $\mathbb{Q}$, the above theorem is Theorem 3.2 [Hid04a]. In general, the theorem holds under the assumption (h) in Theorem 3.3 loc. cit., which is slightly weaker than (H) (See the discussion [Hid04a, p.778]).

4. **Construction of the Eisenstein series**

4.1. Let $\chi$ be a Hecke character of $K^\times$ with infinity type $k\Sigma + \kappa(1-c)$, where $k \geq 1$ is an integer and $\kappa = \sum \kappa_\sigma \sigma \in \mathbb{Z}[\Sigma], \kappa_\sigma \geq 0$. Let $c(\chi)$ be the conductor of $\chi$. We assume that $C = c(\chi)\mathcal{S}$, where $\mathcal{S}$ is only divisible by primes split in $K/F$ and $(c(\chi)l, \mathcal{S}) = 1$. Put

$$\chi^* = \chi|_{A^\times_S} \text{ and } \chi^+_\mathcal{S} = \chi|_{A^\times_{\mathcal{S}}}.$$ 

Let $K^0_{\mathfrak{a}} := \prod_{\mathfrak{a} \in \Lambda} SO(2, \mathbb{R})$ be a maximal compact subgroup of $G(F \otimes \mathbb{Q})$. For $s \in C$, we let $I(s, \chi^+_\mathcal{S})$ denote the space consisting of smooth and $K^0_{\mathfrak{a}}$-finite functions $\phi : G(\mathbb{A}_F) \rightarrow C$ such that

$$\phi\left(\begin{bmatrix} a & b \\ 0 & d \end{bmatrix} \right) g = \chi^+_\mathcal{S}(d) \left| \begin{bmatrix} a & \chi^* \\ 0 & d \end{bmatrix} \right| \phi(g).$$

Conventionally, functions in $I(s, \chi^+_\mathcal{S})$ are called sections. Let $B$ be the upper triangular subgroup of $G$. The adelic Eisenstein series associated to a section $\phi \in I(s, \chi^+_\mathcal{S})$ is defined by

$$E_{\mathcal{A}}(g, \phi) = \sum_{\gamma \in B(\mathbb{F}) \backslash G(\mathbb{F})} \phi(\gamma g).$$

The series $E_{\mathcal{A}}(g, \phi)$ is absolutely convergent for $Re s > 0$.

4.2. **Fourier coefficients of Eisenstein series.** Put $w = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$. Let $v$ be a place of $F$ and let $I_v(s, \chi^+_\mathcal{S})$ be the local constituent of $I(s, \chi^+_\mathcal{S})$ at $v$. For $\phi_v \in I_v(s, \chi^+_\mathcal{S})$ and $\beta \in \mathcal{J}_v$, we recall that the $\beta$-th local Whittaker integral $W_\beta(\phi_v, g_v)$ is defined by

$$W_\beta(\phi_v, g_v) = \int_{\mathcal{J}_v} \phi_v(w \begin{bmatrix} 1 & x_v \\ 0 & 1 \end{bmatrix} g_v) \psi(-\beta x_v) dx_v,$$

and the intertwining operator $M_w$ is defined by

$$M_w \phi_v(g_v) = \int_{\mathcal{J}_v} \phi_v(w \begin{bmatrix} 1 & x_v \\ 0 & 1 \end{bmatrix} g_v) dx_v.$$
By definition, $M_{\omega}\phi_{\nu}(g_{\nu})$ is the 0-th local Whittaker integral. It is well known that local Whittaker integrals converge absolutely for $\text{Re} \, s \gg 0$, and have meromorphic continuation to all $s \in \mathbb{C}$.

If $\phi = \otimes_{v} \phi_{v}$ is a decomposable section, then it is well known that $E_{\lambda}(g, \phi)$ has the following Fourier expansion:

$$E_{\lambda}(g, \phi) = \phi(g) + \sum_{\beta \in \mathcal{F}} W_{\beta}(E_{\lambda}, g),$$

where

$$M_{\omega}(\phi)(g) = \frac{1}{\sqrt{|D_{\mathbb{R}}|}} \prod_{v} M_{\omega}(\phi_{v}(g_{v})).$$

The sum $\phi(g) + M_{\omega}(\phi)(g)$ is called the constant term of $E_{\lambda}(g, \phi)$.

### 4.3. The choice of local sections and Fourier coefficients.

In this subsection, we will choose for each place $v$ a good local section $\phi_{\lambda, v}$ in $I_{v}(s, \chi_{+})$ and calculate its local $\beta$-th Fourier coefficient for $\beta \in \mathcal{F}^{\times}$.

#### 4.3.1. We first introduce some notation and definitions. Let $S^{v} = \{v \in h \mid v \in \mathbb{C}^{c}D_{L^{F}}^{v}\}$. Let $v$ be a place of $\mathcal{F}$. Let $L/F_{v}$ be a finite extension and let $d_{L}$ be a generator of the absolute different $D_{L}$ of $L$. Let $\psi_{L} := \psi \circ T_{L/F_{v}}$. Given a character $\mu: L^{\times} \to \mathbb{C}$, we recall that the epsilon factor $\epsilon(s, \mu, \psi_{L})$ in [Tat79] is defined by

$$\epsilon(s, \mu, \psi_{L}) = |c|^{1}_L \int_{c^{-1} \mathcal{O}_{L}^{1}} \mu^{-1}(x) \psi_{L}(x) d_{L}x, \quad (c = d_{L} \infty_{L}^{(\mu)}).$$

Here $d_{L}x$ is the Haar measure on $L$ self-dual with respect to $\psi_{L}$. If $\varphi$ is a Bruhat-Schwartz function on $L$, the zeta integral $Z(s, \mu, \varphi)$ is given by

$$Z(s, \mu, \varphi) = \int_{L} \varphi(x) \mu(x) |x|^{s}_{L} d^{\times}x, \quad (s \in \mathbb{C}).$$

The local root number $W(\mu)$ is defined by

$$W(\mu) := \epsilon(\frac{1}{2}, \mu, \psi_{L})$$

(see [MS00, p.281 (3.8)]). It is well known that $|W(\mu)|_{\mathbb{C}} = 1$ if $\mu$ is unitary.

To simplify the notation, we let $F = F_{v}$ (resp. $E = \mathcal{K} \otimes_{\mathcal{F}} F_{v}$) and let $d_{F} = d_{F_{v}}$ be the fixed generator of the absolute different $D_{F}$ in §3.2.1. Write $\chi$ (resp. $\chi_{+}, \chi_{-}$) for $\chi_{v}$ (resp. $\chi_{+}, \chi_{-}$). If $v \in h$, we let $O_{v} = \mathcal{O}_{F}$ (resp. $R_{v} = R \otimes_{O} O_{v}$) and let $\varpi = \varpi_{v}$ be a uniformizer of $F$. For a set $Y$, denote by $\mathcal{I}_{Y}$ the characteristic function of $Y$.

#### 4.3.2. $v$ is archimedean. Let $v = \sigma$ and $F = \mathbb{R}$. For $g \in G(F) = \text{GL}_{2}(\mathbb{R})$, we put

$$\delta(g) = |\text{det}(g)| \cdot |J(g, i)J(g, i)|^{-1}.$$

Define the section $\phi^{h}_{k, \sigma, \sigma} \in I_{v}(s, \chi_{+})$ of weight $k$ by

$$\phi^{h}_{k, \sigma, \sigma}(g) := J(g, i)^{-k} \delta(g)^{s}.$$

The intertwining operator $M_{\omega}(\phi^{h}_{k, \sigma, \sigma})$ is given by

$$M_{\omega}(\phi^{h}_{k, \sigma, \sigma})(g) = i^{k}(2\pi)^{\frac{1}{2}} \Gamma(k + 2s - 1) \Gamma(k + s) \Gamma(s) \cdot |J(g, i)|^{s} \delta(g)^{1-s}.$$

For $(x, y) \in \mathbb{R} \times \mathbb{R}_{+}$ and $\beta \in \mathbb{R}^{\times}$, it is well known that

$$W_{\beta}(\phi^{h}_{k, \sigma, \sigma}, \begin{bmatrix} y & x \\ 0 & 1 \end{bmatrix})_{k=0} = (2\pi i)^{k} \sigma(\beta)^{-k} \exp(2\pi i \sigma(\beta)(x + iy)) \cdot \mathcal{I}_{\mathbb{R}_{+}}(\sigma(\beta)).$$

Define the section $\phi^{h, h}_{k, \sigma, \sigma} \in I(s, \chi_{+})$ of weight $k + 2\kappa_{\sigma}$ by

$$\phi^{h, h}_{k, \kappa_{\sigma}, \sigma}(g) := J(g, i)^{-k-\kappa_{\sigma}} \delta(g)^{s}.$$

Let $V_{+}$ be the weight raising differential operator in [JL70, p.165] given by

$$V_{+} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \otimes 1 + \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \otimes i \in \text{Lie}(\text{GL}_{2}(\mathbb{R})) \otimes_{\mathbb{R}} \mathbb{C}.$$
Denote by $V_{+}^{\kappa}$ the operator $(V^{+})^{\kappa}$ acting on $I_v(s, \chi_{+})$. By [JL70, Lemma 5.6 (iii)], we have

\[(4.6)\quad V_{+}^{\kappa} \phi_{b, s, \sigma}^{\Delta} = \frac{2^{2\kappa} \Gamma(k + \kappa + 2s)}{\Gamma(k + 2s)} \phi_{b, s, \sigma, \kappa}^{\Delta, \rho}.
\]

4.3.3. $v \in S^0$. In this case, $\chi$ is unramified. Define $\phi_{\chi, s, v}(g)$ to be the spherical Godement section in $I_v(s, \chi_{+})$. To be precise, put

\[\phi_{\chi, s, v}(g) = f_{\phi_{\chi, s, v}}(g) := \left| \det g \right|^s \int_{F^x} \Phi_v((0, t)g) \chi_{+}(t) |t|^{2s} d^\times t, \]

where $\Phi_v = I_{O_v @ O_v^*}$.

It is well known that the local Whittaker integral is

\[(4.7)\quad W_{\beta}(\phi_{\chi, s, v}, \left[ \begin{array}{c} 1 \\ c_v^{-1} \end{array} \right])_{|s = 0} = \chi_{+}(c_v) \cdot \frac{1 - \chi^*(\varpi)^{\nu(\beta c_v) + 1}}{1 - \chi^*(\varpi)} \cdot |D_F|^{-1} \cdot I_{O_v}(\beta c_v),
\]

and the intertwining operator is given by

\[(4.8)\quad M_w \phi_{\chi, s, v}(\left[ \begin{array}{c} 1 \\ c_v^{-1} \end{array} \right]) = L_w(2s - 1, \chi_{+}) |c_v|^{1-s}.
\]

4.3.4. $v|\mathfrak{F}$. If $v|\mathfrak{F}$ is split in $\mathcal{K}$, write $v = w\overline{w}$ with $w|\mathfrak{F}$ and $\chi_v = (\chi_{w}, \chi_{\overline{w}})$. Then $a(\chi_{w}) \geq a(\chi_{\overline{w}})$. We shall define our local section at $v$ to be the Godement section associated to certain Bruhat-Schwartz functions. We first introduce some Bruhat-Schwartz functions. For a character $\mu : F^\times \to \mathbf{C}^\times$, we define

\[\varphi_{\mu}(x) = I_{O_v^*}(x) \mu(x) \quad (x \in F).
\]

Define $\varphi_w = \varphi_{\chi_{w}}$ and

\[\varphi_{\varpi} = \begin{cases} \varphi_{\chi_w}^{-1} & \text{if } \chi_{\varpi} \text{ is ramified}, \\ \|_{O_v} & \text{if } \chi_{\varpi} \text{ is unramified}. \end{cases}
\]

Let $\Phi_v(x, y) = \varphi_{\varpi}(x) \hat{\varphi}_w(y)$, where $\hat{\varphi}_w$ is the Fourier transform of $\varphi_w$ defined by

\[\hat{\varphi}_w(y) = \int_F \varphi_w(x) \psi(xy) dx.
\]

Define $\phi_{\chi, s, v} \in I_v(s, \chi_{+})$ by

\[(4.9)\quad \phi_{\chi, s, v}(g) = f_{\varphi_{\chi, s, v}}(g) := \left| \det g \right|^s \int_{F^x} \Phi_v((0, t)g) \chi_{+}(t) |t|^{2s} d^\times t.
\]

A straightforward calculation shows that the local Whittaker integral is

\[(4.10)\quad W_{\beta}(\phi_{\chi, s, v}, 1) = \int_{F^x} \varphi_{\varpi}(x) \hat{\varphi}_w(-\beta x^{-1}) \cdot \chi_{+}(x) |x|^{2s-1} d^\times x
\]

\[= \chi_{+}(\beta) \varphi_{\varpi}(\beta) \hat{\varphi}_w(\beta x^{-1}) \cdot |D_F|^{-1} \cdot \chi_{+}(x) |x|^{2s-1} d^\times x
\]

\[= \chi_{+}(\beta) \varphi_{\varpi}(\beta) |\beta|^{2s-1} \cdot |D_F|^{-1},
\]

and the intertwining operator is given by

\[(4.11)\quad M_w \phi_{\chi, s, v}(1) = 0.
\]

4.3.5. $v = 1$. Let $\phi_{\chi, s, v} \in I_v(s, \chi_{+})$ be the unique $N(O_v)$-invariant section supported in the big cell $B(F)wN(O_v^*)$ and $\phi_{\chi, s, v}(w) = 1$. One checks easily that $\phi_{\chi, s, v}|U_1$ given by

\[\phi_{\chi, s, v}|U_1(g) = \sum_{u \in O_v^*/O_v^*} \phi_{\chi, s, v}(g \left[ \begin{array}{c} \varpi \\ 0 \\ 1 \end{array} \right])
\]

is also supported in the big cell and is invariant by $N(O_v^*)$. In particular, $\phi_{\chi, s, v}$ is an $U_1$-eigenform, and the eigenvalue is $\chi_{+}^{-1}(\varpi_1)$. 

The local $\beta$-th Whittaker integral is given by
\begin{equation}
W_\beta(\phi_{X,v}, \left[\begin{array}{c} a \\ b \\ c \\ d \end{array} \right])_{s=0} = \int_{F} \phi_{X,v}(w \left[\begin{array}{c} a \\ b \\ c \\ d \end{array} \right]) \psi(-\beta x) dx|_{s=0} = |c| \Omega_{X}(\beta|c|),
\end{equation}
and the intertwining operator is given by $M_{w}\phi_{X,v}(\left[\begin{array}{c} 1 \\ 0 \\ 1 \\ -1 \end{array} \right])_{s=0} = |c|$. 

4.3.6. $v|D_{K/F}\mathcal{E}^-$. In this case, $E$ is a field and $G(F) = B(F)\rho(E^\times)$. Let $w$ be the place of $E$ above $v$ and let $\varpi_E$ be a uniformizer of $E$. Let $\mathcal{O}'$ be the product of ramified primes where $\chi$ is unramified, i.e. $\mathcal{O}' = \prod_{q|D_{K/F}\mathcal{E}^-} q$. Let $\phi_{X,v,\nu}$ be a generator of $M_{\nu}$ for Re $s$ sufficiently large. This shows that $L(s, \chi, \nu)$ is a uniformizer of $\mathcal{O}'$.

To calculate the local Whittaker integral of $\phi_{X,v,\nu}$, we recall that in §3.2.1, we have fixed $\delta = \delta_v = 2d_F^{-1}$ a generator of $D_{K/F}$ and an $O_{\nu}$-basis $\{1, \sigma_1\}$ of $R_v$ so that $\delta = 2\delta$ if $v | 2$ and $\delta = \theta - \overline{\theta}$ if $v | 2$. In addition, $\theta$ is a uniformizer of $R_v$ if $v$ is ramified. Let $t = t_v = 2\theta - \delta = \theta + \overline{\theta} \in O_v$. Let $\psi^\circ(x) := \psi(-d_F^{-1}x)$ and $\chi_s = \chi|_{v}^{-1}|_{\mathcal{E}}$ for $s \in \mathbb{C}$. For $Re s > 0$, we have
\begin{equation}
1 \quad L(s, \chi_v) \cdot W_\beta(\phi_{X,v,\nu}, 1) \quad = \int_{F} \phi_{X,v}(w \left[\begin{array}{c} a \\ b \\ c \\ d \end{array} \right]) \psi^\circ(d_F^{-1}x) dx,
\end{equation}
\begin{align*}
&= \psi^\circ(-2^{-1}t\beta) \chi_s(d_F^{-1}) \cdot \int_{F} \phi_{X,v}(x + 2^{-1}\delta x) \psi^\circ(d_F^{-1}x) dx \\
&= \psi^\circ(-2^{-1}t\beta) \chi_s(d_F^{-1}) \cdot \int_{F} \phi_{X,v}(x + 2^{-1}\delta x) \psi^\circ(d_F^{-1}x) dx.
\end{align*}
We put
\begin{equation}
A_\beta(\chi_s) := \int_{F} \chi_s^{-1}(x + 2^{-1}\delta) \psi^\circ(\beta x) dx.
\end{equation}
Making change of variable, we find that
\begin{equation}
A_\beta(\chi_s) = \psi^\circ(2^{-1}t\beta) \cdot \tilde{A}_\beta(\chi_s),
\end{equation}
where
\begin{equation}
\tilde{A}_\beta(\chi_s) = \int_{F} \chi_s^{-1}(x + \theta) \psi^\circ(\beta x) dx.
\end{equation}
In particular, the intertwining operator $M_{w}\phi_{X,v,\nu}(1) = |d_F^{-1}| \cdot L(s, \chi_v)\tilde{A}_0(\chi_s)$. We investigate the analytic behavior of $\tilde{A}_\beta(\chi_s)$. For $\beta \in F$ and $M \geq v(\mathcal{E}^-)$, we have
\begin{equation}
\tilde{A}_\beta(\chi_s) = \int_{\varpi_M^{\mathcal{O}_v}} \chi_s^{-1}(x + \theta) \psi^\circ(\beta x) dx + \sum_{j \geq M} \chi^\star s |^{\star}(\varpi^j) \int_{\mathcal{O}_v^{\star}} \chi_s^{-1}(x) \psi^\circ(\beta \varpi^{-j}x) dx
\end{equation}
for Re $s$ sufficiently large. This shows that $\tilde{A}_\beta(\chi_s)$ has meromorphic continuation to all $s \in \mathbb{C}$, and $\tilde{A}_\beta(\chi_s)$ is holomorphic at $s = 0$ except when $\beta = 0$, $\chi_v$ is unramified and $\chi^\star(\varpi) = 1$. In particular, when $k \geq 2$, $\tilde{A}_0(\chi_s)$ and the intertwining operator $M_{w}\phi_{X,v,\nu}(1)$ are finite at $s = 0$. 
In what follows, we let \( W(E_{2,\beta}) := A_{\beta}(\chi_{s}) \) (resp. \( A_{\beta}(\chi_{s}) := A_{\beta}(\chi_{s}) \)). Then \( A_{\beta}(\chi_{s}) = w(2^{-t}t) \cdot A_{\beta}(\chi_{s}) \). On the other hand, by our choice of \( \Theta \) it is clear that \( \beta \in \mathcal{E} \) for all \( x \in \mathcal{E} \).

Let \( M_{E_{\beta}} = \max \{ v(\mathcal{E}^{-}), v(\mathcal{E}^{+}) + v(\beta) \} \). Then for \( M \geq M_{E_{\beta}} \), we have

\[
\tilde{A}_{\beta}(\chi_{s}) = \int_{\mathbb{C}_{\mathcal{E}}} \chi_{s}^{-1}(x + \theta) d_{\chi_{s}}(\beta x) dx
\]

\[
= \int_{\mathbb{C}_{\mathcal{E}}} \chi_{s}^{-1}(x + \theta) \psi(\beta x) dx + \sum_{j=0}^{v(\beta)} \chi_{s}^{-1}(x_{\beta}) \int_{O_{\mathcal{E}}} \psi(\beta x_{\beta}) dx
\]

\[
= \chi_{s}^{-1}(\theta) \int_{\mathbb{C}_{\mathcal{E}}} \psi(\beta x) + \sum_{j=0}^{v(\beta)} \alpha_{s}^{j} \cdot (\int_{O_{\mathcal{E}}} \psi(\beta x_{\beta}) dx - \int_{O_{\mathcal{E}}} \psi(\beta x_{\beta}) dx).
\]

If \( v(\beta) > 0 \), we find that

\[
\tilde{A}_{\beta}(\chi_{s}) = \chi_{s}^{-1}(\theta) \cdot \beta S_{S_{\beta}}(\beta x) + \frac{1 - \alpha_{s}^{v(\beta)+1}}{1 - \alpha_{s}} \cdot (1 - |\mathbb{C}|) - |\mathbb{C}| \cdot \alpha_{s}^{v(\beta)+1}
\]

\[
= (1 - \chi_{s}(\theta))(1 + |\mathbb{C}|) \frac{1 - \alpha_{s}^{v(\beta)+2}}{1 - \alpha_{s}}.
\]

In addition, we have \( \tilde{A}_{\beta}(\chi_{s}) = 0 \) if \( v(\beta) < 1 \) and

\[
\tilde{A}_{\beta}(\chi_{s}) = (1 - \chi_{s}(\theta)) \cdot \chi_{s}^{-1}(\theta) \cdot \beta S_{S_{\beta}}(\beta x) \text{ if } v(\beta) = 1.
\]

In any case, the assertions in the case \( v(\mathcal{E}^{-}) \) follow immediately from (4.16) and the formulas of \( \tilde{A}_{\beta}(\chi_{s}) \).

4.3.7. Calculation of \( \tilde{A}_{\beta}(\chi_{s}) \). We give an explicit calculation of the local integral \( \tilde{A}(\chi_{s}) \) under the assumption \( w(\mathcal{E}^{-}) = 1 \). Introduce an auxiliary integral \( I(\beta) \) for \( \beta \in F \) defined by

\[
I(\beta) := \int_{O_{\mathcal{E}}} \chi_{s}^{-1}(x + \theta) \psi(\beta x) dx.
\]

The explicit formulas of \( \tilde{A}_{\beta}(\chi_{s}) \) are deduced from the following two lemmas.

**Lemma 4.2.** Suppose \( w(\mathcal{E}^{-}) \leq 1 \).
Proposition 4.4.

(1) If $v(\beta) \geq 0$ and $\chi|_{O_E^*} \neq 1$, then

\[
\tilde{A}_\beta(\chi) = \mathcal{I}(0) + \chi^{-1} \cdot (\sum e^{-d_P^{-1}\beta} \cdot \epsilon(1, \chi |^{-1}, \psi).
\]

(2) If $v(\beta) \geq 0$ and $\chi|_{O_E^*} = 1$, then

\[
\tilde{A}_\beta(\chi) = \mathcal{I}(0) + \sum_{j=1}^{v(\beta)} \chi^*(\varpi^j) \cdot (1 - |\varpi|) - \chi^*(\varpi^{v(\beta) + 1}) \cdot |\varpi| \quad (\chi^* = \chi |^{-1} \beta^{-1/2}).
\]

(3) If $v(\beta) < 0$, then $\tilde{A}_\beta(\chi) = \mathcal{I}(\beta)$.

Proof. It is clear that under our assumption on the conductor of $\chi$, we have

\[
\tilde{A}_\beta(\chi) = \int_F \chi^{-1}(x + \theta) \psi^*(\beta x) \int \mathcal{I}(\beta) + \sum_{j=1}^{v(\beta)} |\varpi|^{-j} \int_{O_E^*} \chi^{-1}(\frac{x}{\varpi}) \psi^*(\frac{\beta x}{\varpi}) dx.
\]

Then the lemma follows immediately.

\[\square\]

Lemma 4.3.

(1) If $v(\beta) < -1$, then $\mathcal{I}(\beta) = 0$.

(2) If $v$ is ramified, then $\mathcal{I}(\beta) = \chi^*(\theta^{-1}) |\varpi|^{1/2}$.

(3) If $v$ is inert and $\chi|_{O_E^*} = 1$, then $\mathcal{I}(\beta) = - |\varpi|$.

Proof. Note that if $v$ is ramified, then $\chi|_{O_E^*} \neq 1$. (1) and (2) follows from the assumption on the conductor of $\chi$ and a simple calculation. (3) follows from the following equation:

\[
0 = \int_{R_E^*} \chi^{-1}(r) dr = \int_{O_E^*} da \int_{O_E^*} db \chi^{-1}(a + b\theta) + \int_{O_E^*} da \int_{O_E^*} db \chi^{-1}(a + b\theta) = (1 - |\varpi|) \int_{O_E^*} \chi^{-1}(a + \theta) da + \int_{O_E^*} |\varpi| (1 - |\varpi|). \quad \square
\]

We summarize the formulas of $\tilde{A}_\beta(\chi)$ in the following two propositions.

Proposition 4.4. Suppose that $v|\mathbb{C}^-\text{ is ramified such that } w(\mathbb{C}^-) = 1$. Then the formula of $\tilde{A}_\beta(\chi)$ is given as follows.

(1) If $v(\beta) \geq -1$, then

\[
\tilde{A}_\beta(\chi) = \chi^*(\theta^{-1}) |\varpi|^{1/2} + \chi^*(-(\beta d_P^{-1}) \cdot \epsilon(1, \chi |^{-1}, \psi).
\]

(2) If $v(\beta) < -1$, then $\tilde{A}_\beta(\chi) = 0$.

(3) If $v \nmid 2$ and $v(\beta) \geq -1$, then

\[
\tilde{A}_\beta(\chi) = (\chi^*(-2\delta^{-1} d_P) + \chi^*(2^{-1} \beta) W(\chi^*) \cdot \chi(-d_P^{-1}) |\varpi|^{1/2}.
\]

Proof. In this case, $\theta$ is a uniformizer of $R_E$. It is straightforward to verify that if $v(\beta) = -1$, then

\[
\mathcal{I}(\beta) = \chi^*(\beta d_P^{-1}) \epsilon(1, \chi |^{-1}, \psi) + \chi^*(\theta^{-1}) |\varpi|^{1/2}.
\]

Thus (1) and (2) follows from Lemma 4.2 and Lemma 4.3.

Suppose $v \nmid 2$. Then $\delta = 2\theta$, and (3) follows from (1) and the identity ([Roh82, Prop.8])

\[
W(\chi^*) = \chi^*(2) W(\chi^* |x) = \chi(2) |\varpi|^{-1} \epsilon(1, \chi |^{-1}, \psi). \quad \square
\]

Proposition 4.5. Suppose that $v|\mathbb{C}^-\text{ is inert such that } w(\mathbb{C}^-) = 1$. Then the formula of $\tilde{A}_\beta(\chi)$ is given as follows.

(1) If $v(\beta) = -1$, then

\[
\tilde{A}_\beta(\chi) = |\varpi| \cdot \sum_{a \in O_E/(\varpi)} \chi^{-1}(a + \theta) \psi^*(\beta a).
\]
Then
\( (4.21) \)

Suppose either of the following conditions holds:

1. Let \( \chi|O_F = 1 \), then

\[
\tilde{A}_\beta(\chi) = -|w| + \sum_{j=1}^{v(\beta)} \chi^*(w^j) \cdot (1 - |w|) - \chi^*(w^{v(\beta)+1})|w|.
\]

2. If \( v(\beta) \geq 0 \) and \( \chi|O_F \neq 1 \), then

\[
\tilde{A}_\beta(\chi) = I(0) + \chi^*(-\beta d_F^{-1})e(1, \chi_+|\cdot|^{-1}, \psi).
\]

**Proof.** In this case, both \( \delta \) and \( \theta \) are units of \( R^n \). It follows from the definition of \( I(\beta) \) that if \( v(\beta) = -1 \), then

\[
I(\beta) = |w| \cdot \sum_{a \in O_{\bar{\mathbb{F}}}(\bar{\mathbb{Z}})} \chi^{-1}(a + \theta)\psi^0(\beta a).
\]

The proposition follows from Lemma 4.2 and Lemma 4.3 immediately. \( \square \)

### 4.4. Normalization of Eisenstein series.

**Definition 4.6.** For \( \bullet = h \) or \( n.h. \), we put

\[
\phi_{\chi,s}^\bullet = \bigotimes_{\sigma \in \mathfrak{n}} \phi_{\chi,s,\sigma} \otimes \phi_{\chi,s,v}.
\]

Define the adelic Eisenstein series \( E_{\chi}^\bullet \) by

\[
E_{\chi}^\bullet(g) = E_{\mathfrak{A}}(g, \phi_{\chi,s}^\bullet)|_{s=0}, \quad \bullet = h, n.h.
\]

We define the holomorphic (resp. nearly holomorphic) Eisenstein series \( \mathbb{E}_\chi^h \) (resp. \( \mathbb{E}_\chi^{n.h.} \)) by

\[
\mathbb{E}_\chi^h(\tau, g_f) := \frac{\Gamma_\Sigma(k\Sigma)}{\sqrt{|D_F|}\sqrt{2\pi}^{k\Sigma}} \cdot E_{\chi}^h(g_\infty, g_f) \cdot \mathcal{I}(g_\infty, i)^{k\Sigma},
\]

\[
\mathbb{E}_\chi^{n.h.}(\tau, g_f) := \frac{\Gamma_\Sigma(k\Sigma)}{\sqrt{|D_F|}\sqrt{2\pi}^{k\Sigma}} \cdot E_{\chi}^{n.h.}(g_\infty, g_f) \cdot \mathcal{I}(g_\infty, i)^{k\Sigma + 2\kappa} \cdot (\det g_\infty)^{-\kappa},
\]

\((\tau, g_f) \in X^* \times G(\mathbb{A}_F), g_\infty \in G(F \otimes \mathbb{Q}), g_\infty i = \tau, i = (i)_{\sigma \in \Sigma}.\)

Choose \( N = \mathbb{N}_{K/\mathbb{Q}}^m(\mathbb{E}D_{K/F}) \) for a sufficiently large integer \( m \) so that \( \phi_{\chi,s,v} \) are invariant by \( U(N) \) for every \( v|N \), and put \( K := U(N) \). Then the section \( \phi_{\chi,s} \) is invariant by \( K_0(l) \).

**Proposition 4.7.** Let \( \mathfrak{c} = (c_v) \in \mathbb{A}_F^\times \). Be a finite idele such that \( c_v = 1 \) at \( v|\mathfrak{p}\mathfrak{c} \infty D_{K/F} \). Let \( \epsilon = \text{if}(\mathfrak{c}) \). Suppose either of the following conditions holds:

1. \( k > 2 \),
2. \( \mathfrak{f} \neq O \),
3. \( \chi_+ = \pi_{K/F}^{-1}|_{\mathbb{A}_E} \) and \( l \) is split in \( \mathbb{K} \).

Then \( \mathbb{E}_\chi^h \in M_k(K_0(l), \mathbb{C}) \). The \( q \)-expansion of \( \mathbb{E}_\chi^h \) at the cusp \((O, c^{-1})\) has no constant term and is given by

\[
\mathbb{E}_\chi^h|_{(O, c^{-1})} = \sum_{\beta \in (N^{-1}c^{-1})^+} a_\beta(\mathbb{E}_\chi^h, \epsilon) \cdot q^\beta \in \mathcal{O}[[N^{-1}c^{-1})^+]\]

for some finite extension \( \mathcal{O} \) of \( \mathcal{O}_{K, (\mathfrak{p})} \) in \( \bar{\mathbb{Z}} \), where

\[
a_\beta(\mathbb{E}_\chi^h, \epsilon) = \frac{1}{|D_F|^k} \cdot N_{F/\mathbb{Q}}^{k-1} \cdot \prod_{v \in \mathfrak{c}} W_\beta(\phi_{\chi,s,v}, [1 - c_v^{-1}])|_{s=0}.
\]

**Proof.** Let \( \phi_{\chi,s}^{(\infty)} = \otimes_{v \in \mathfrak{n}} \phi_{\chi,s,v} \). First we claim that for \( g_\infty = (g_\sigma)_{\sigma \in \Sigma} \in G(F \otimes \mathbb{Q}) \),

\[
M_{\mathfrak{w}} \phi_{\chi,s}^{(\infty)}(g_\infty, [1 - c^{-1}] )|_{s=0} = \prod_{v \in \sigma \in \Sigma} M_{\mathfrak{w}} \phi_{\chi,s,v}^{h}(g_\sigma) \cdot M_{\mathfrak{w}} \phi_{\chi,s}^{(\infty)}([1 - c^{-1}] )|_{s=0} = 0.
\]

\( (4.21) \)
Indeed, if \( k > 2 \), then (4.21) follows from (4.3) together with the finiteness of \( L^{(n)}(-1, \chi_{+}) \), while if there exists some place \( v|\mathfrak{F} \), then we find (4.21) in view of (4.11) immediately. If \( \chi_{+} = \tau_{K/F}|_{\mathcal{A}_{F}} \) and \( I \) splits in \( K \), then \( k = 1 \) and \( \chi \) is ramified at \( v|D_{K/F} \). By (4.8), we find that

\[
M_{w} \phi_{\chi,s}^{(\infty)} \left[ \frac{1}{c-1} \right] |_{s=0} = \prod_{v|\mathfrak{F}} M_{w} \phi_{\chi,s,v}(1) |_{s=0} \cdot L^{(\infty)}(0, \tau_{K/F}) |_{c|_{\mathcal{A}_{F}}},
\]

so (4.21) follows from the fact that

\[
L^{(\infty)}(0, \tau_{K/F}) = L^{(\infty)}(0, \tau_{K/F})(1 - \tau_{K/F}(1)) = 0.
\]

This proves the claim. In addition, we have \( \phi_{\chi,s}^{(\infty)} \left[ \frac{1}{c-1} \right] = 0 \) since \( \phi_{\chi,1,s} \) is supported in the big cell.

Note that

\[
\chi_{+}^{-1}(\mathfrak{F}) = \chi^{-1}(\mathfrak{F}) \chi_{+}^{-1}(\mathfrak{F}) \text{ if } \chi_{+} \text{ is unramified at } p.
\]

We study the \( p \)-integrality of \( a_{\beta}(E_{\chi}^{h}, \epsilon) \). It is well known that \( \chi \) takes value in a number field. By the inspection of formulas in (4.7), (4.10), (4.12), Lemma 4.1, (4.17), we find that

\[
\prod_{\mathfrak{p} \mid \mathcal{O}} W_{\beta}(\phi_{\chi,s,v}, \left[ \frac{1}{c-1} \right]) |_{s=0} = \emptyset
\]

for some finite extension \( \mathcal{O} \) of \( O_{\mathfrak{F}}(p) \). Since \( \chi \) is unramified at \( p \), we have \( a_{\beta}(E_{\chi}^{h}, \epsilon) = 0 \) if \( \beta \notin \mathcal{O} \otimes \mathbb{Z}_{p} \) by (4.7). Note that \( v(\chi^{*}(\varpi_{v})) = 1 - k \) and \( v'(\chi^{*}(\varpi_{v})) = 0 \) if \( v|p \) and \( v' \neq v \). Thus if \( \beta \notin \mathcal{O} \otimes \mathbb{Z}_{p} \), then

\[
|D_{\mathfrak{F}}|_{R}^{-1} N_{\mathfrak{F}/Q}(\beta)^{k-1} \prod_{\mathfrak{p} \mid \mathcal{O}} W_{\beta}(\phi_{\chi,s,v}, 1) |_{s=0} = N_{\mathfrak{F}/Q}(\beta)^{k-1} \prod_{\mathfrak{p} \mid \mathcal{O}} (1 + \chi^{*}(\varpi_{v}) + \cdots + \chi^{*}(\varpi_{v})^{v(\beta)}) \cdot |D_{\mathfrak{F}}|_{R}^{-1} |D_{\mathfrak{F}}|_{Q}^{-1} \in \emptyset.
\]

The following proposition is directly deduced from the construction of the section \( \phi_{\chi,s} \) and the description of Hecke action (2.6). The details are omitted.

**Proposition 4.8.** Set \( D_{\mathfrak{F}} := \prod_{\mathfrak{p} \mid \mathcal{O}} K_{\mathfrak{p}}^{-1} \). Under the assumptions in Prop. 4.7, we have

1. \( E_{\chi}^{h} \) is an \( U_{1} \)-eigenform in \( M_{k}(K_{0}(1), \emptyset) \) with the eigenvalue \( \chi_{+}^{-1}(\mathfrak{F}) \),
2. \( E_{\chi}^{h} | r = \chi^{-1}(r)E_{\chi}^{h} \) for \( r \in D_{\mathfrak{F}} \),
3. \( E_{\chi}^{h}(x_{n}(ta)) = \chi^{-1}(a)E_{\chi}^{h}(x_{n}(t)) \) for \( a \in D_{\mathfrak{F}}A_{\mathfrak{F}}U_{n} \).

### 4.5

For \( \sigma \in \mathfrak{a} \) and an integer \( n \), let

\[
\delta_{\sigma}^{n} := \frac{1}{2\pi i} \left( \frac{\partial}{\partial \tau_{\sigma}} + \frac{n}{2\pi i y_{\sigma}} \right)
\]

be the Maass-Shimura’s differential operator. Put

\[
\delta_{k}^{\kappa,\sigma} := \delta_{k+2n_{\sigma}}^{\kappa} \circ \cdots \delta_{k+2}^{\kappa} \circ \delta_{k}^{\kappa} \quad \text{and} \quad \delta_{k}^{\kappa} = \prod_{\sigma \in \Sigma} \delta_{k}^{\kappa,\sigma}.
\]

Then the weight raising differential operator \( V_{+}^{\kappa} \) in §4.3.2 is the representation theoretic avatar of \( \delta_{k}^{\kappa,\sigma} \) in virtue of the following identity:

\[
\delta_{k}^{\kappa} = (-8\pi)^{\kappa} V_{+}^{\kappa}.
\]

We thus have

\[
\delta_{k}^{\kappa,\infty} = \frac{1}{(-4\pi)^{\kappa}} \cdot \frac{\Gamma(\kappa + \kappa)}{\Gamma(\kappa)} \cdot E_{\chi}^{h}.
\]
5. Evaluation of Eisenstein series at CM points

5.1. Period integral. Let \( \mathcal{E}_\chi := \mathbb{H}^1_\chi \) be the \( p \)-adic avatar of \( \mathbb{E}^1_\chi \) as in (2.5). Let \( \{ \theta(\sigma) \}_{\sigma \in \Sigma} \) be the Dwork-Katz \( p \)-adic differential operators on \( p \)-adic modular forms introduced in [Kat78, Cor.(2.6.25)] and let \( \theta^\epsilon = \prod_{\sigma \in \Sigma} (\theta(\sigma))^{h(\sigma)} \). We consider the Hida’s measure \( \varphi^\epsilon = \varphi_{\theta^\epsilon, \mathcal{E}_\chi} \) attached to the \( U_1 \)-eigenform \( \theta^\epsilon \mathcal{E}_\chi \in V(K_0(1), Z_p) \) as in (3.2). Let \( \nu \) be a character on \( C_n \). We have

\[
\int_{C_n} \nu \, d\varphi^\epsilon_n = \chi_+ (\varpi_1)^n \cdot \sum_{[l]_n \in C_n} \theta^\epsilon \mathcal{E}_\chi (x_n(t)) \hat{\chi}(t). \tag{5.1}
\]

Let \( (\Omega_{\infty}, \Omega_n) \in (\mathbb{C}^\times)^{\times} \times (\mathbb{Z}_p)^{\Sigma} \) be the complex and \( p \)-adic CM periods of \( (K, \Sigma) \) introduced in [HT93, (4.4 a,b) p.211] (cf. (2, 3) in [Kat78, (5.1.46), (5.1.48)]). From [Kat78, (2.4.6), (2.6.8), (2.6.33)] we can deduce the following important identity:

\[
\frac{1}{\Omega_p^k \chi + 2\kappa} \, \cdot \theta^\epsilon \mathcal{E}_\chi (x_n(t)) = \frac{(2\pi i)^{k \Sigma + 2\kappa}}{\Omega_{\infty} \chi + 2\kappa} \cdot \sum_{[l]_n \in C_n} \nu \, d\varphi^\epsilon_n (x_n(t)) \chi(t), \tag{5.2}
\]

\[
\int_{C_n} \nu \, d\varphi^\epsilon_n = \chi_+ (\varpi_1)^n \cdot \frac{(2\pi i)^{k \Sigma + 2\kappa}}{\Omega_{\infty} \chi + 2\kappa} \cdot \sum_{[l]_n \in C_n} \nu \, d\varphi^\epsilon_n (x_n(t)) \chi(t). \tag{5.3}
\]

Here we choose \( t \in (\mathbb{A}^{(p)}_K)^{\times} \) for a set of representatives \([t]_n \in C_n \) (so \( \hat{\chi}(t) = \chi(t) \)).

We shall relate (5.3) to certain period integral of Eisenstein series. First we fix the choices of measures. For each finite place \( v \) of \( F \), let \( d^v z_v \) be the normalized Haar measure on \( K_v \) so that \( \text{vol}(R_v \times d^v z_v) = 1 \) and let \( d^v t_v = d^v x_v/d^v z_v \) be the quotient measure on \( K_v/F_v \). For \( v \) archimedean, let \( d^v t_v \) be the Haar measure on \( K_v/F_v \) normalized so that \( \text{vol}(\mathbb{C}^\times / \mathbb{R}^\times, d^v t_v) = 1 \). Let \( d^v t = \prod_v d^v t_v \) be a Haar measure on \( \mathbb{A}_K^{\times} / \mathbb{A}_F^{\times} \) and \( d^v l \) be the quotient measure of \( d^v t \) on \( \mathbb{K}^\times \mathbb{A}_K^{\times} \mathbb{A}_F^{\times} \) by the counting measure on \( \mathbb{K}^\times \mathbb{A}_F^{\times} \). We define the period integral of \( E_n^{h, \chi} \) by

\[
l_K(E_n^{h, \chi}, \nu) := \int_{\mathbb{A}_K^{\times} / \mathbb{A}_F^{\times}} E_n^{h, \chi} (\rho(t) \varsigma(n)) \chi(t) d^v t.
\]

Then the last term in (5.3) can be expressed as the following period integral

\[
\sum_{[l]_n \in C_n} E_n^{h, \chi} (\rho(t) \varsigma(n)) \chi(t) = \frac{1}{\text{vol}(U_n, d^v t)} l_K(E_n^{h, \chi}, \nu).
\]

The rest of this section is devoted to the calculation of \( l_K(E_n^{h, \chi}, \nu) \). For brevity, we write \( \phi_v \) for \( \phi_{\chi, v, v} \) if \( v \in \mathfrak{a} \) and for \( \phi_n \) in (4.5) if \( v = \sigma \in \mathfrak{a} \). The first step is to decompose \( l_K(E_n^{h, \chi}, \nu) \) into a product of local integrals \( l_{K_v}(\phi_v, \nu) \), where

\[
l_{K_v}(\phi_v, \nu) = \int_{\mathbb{K}_v^{\times} / \mathbb{F}_v^{\times}} \phi_v (\rho(t) \varsigma(n)) \chi(t) d^v t_v.
\]

Since \( \rho : \mathcal{F} \setminus \mathbb{K}^{\times} \to B(F) \setminus \mathbb{G}(F) \) is a bijection, we find that

\[
l_K(E_n^{h, \chi}, \nu) = \int_{\mathbb{K}^{\times} / \mathbb{F}^{\times}} E_{\mathcal{A}}(\rho(t) \varsigma(n), \phi_n) \chi(t) d^v t \big|_{s=0} = \prod_v l_{K_v}(\phi_v, \nu) \big|_{s=0}.
\]
Write $E$ for $\mathcal{K}_v$ and $F$ for $\mathcal{F}_v$. In what follows, we suppress $v$ from the notation and proceed to calculate the local integral $l_E(\phi_v, \nu)$.

5.2. $v \in S^\circ$ or $v|\mathfrak{f}$. In this case, $\phi = f_{\phi_v, s}$ is the Godement section associated to the Bruhat-Schwartz function $\Phi_v$ defined in $\S 4.3.4$. We have

$$l_E(\phi, \nu) = \int_{E^\times/F^\times} f_\phi(\rho(t)) \chi_\nu(t) d^\times t$$

where $\Phi_E$ is defined by

$$\Phi_E(z) := \Phi_v((0, 1) \rho(z) \chi_v).$$

Suppose $v \in S^\circ$. By definition, $\Phi_v = 1_{O_v \otimes G^\circ},$ and hence $\Phi_E = 1_{R_v}$ is the characteristic function of $R_v$. It is clear that

$$Z(s, \chi_\nu, \Phi_E) = L(s, \chi_\nu).$$

Suppose $v|\mathfrak{f}$ is a split prime. We write $E = F_{\mathfrak{e}_v} \oplus F_{\mathfrak{e}_w}$ and $\vartheta = -\vartheta_w \mathfrak{e}_w + \vartheta_w \mathfrak{e}_w$ with $w|\mathfrak{f}$ as in $\S 3.2$. Then by definition,

$$\Phi_E(z) = \Phi_v((0, 1) \rho(z) \left[ \begin{array}{cc} -\vartheta_w & -\frac{1}{2} \\ 1 & -2\vartheta_w \end{array} \right]) = \varphi_\mathfrak{e}_w(\chi_v) \varphi_w(-\frac{y}{2\vartheta_w}) (z = x\mathfrak{e}_w + ye_w).$$

As $l \nmid \mathfrak{f}$, $\nu = (\nu_{\mathfrak{e}_w}, \nu_w)$ is unramified at $v$. Therefore,

$$Z(s, \chi_\nu, \Phi_E) = \chi_w(-2\vartheta_w) \int_{E^\times} \chi_\nu \varphi_\mathfrak{e}_w(x) \chi_w \nu_w(y) \varphi_\mathfrak{e}_w(y) |xy|^s d^\times x d^\times y = \chi_w(-2\vartheta_w) Z(s, \chi_\nu \varphi_\mathfrak{e}_w, \varphi_\mathfrak{e}_w) Z(s, \chi_w \nu_w, \varphi_w).$$

By Tate’s local functional equation, we have

$$Z(s, \chi_w \nu_w, \varphi_w) = \frac{L(s, \chi_w \nu_w, \psi) \cdot \chi_w \nu_w(-1)}{\epsilon(s, \chi_w \nu_w, \psi) L(1-s, \chi_w^{-1} \nu_w^{-1})} : Z(1-s, \chi_w^{-1} \nu_w^{-1}, \varphi_w).$$

We find that

$$Z(s, \chi_\nu, \Phi_E)|_{s=0} = L(0, \chi_\nu) \cdot L_0 \cdot C_{\mathfrak{f}},$$

where

$$L_0 = \prod_{q|\mathfrak{f}} L(1, \chi_q^{-1} \nu_q^{-1})$$

and $C_{\mathfrak{f}} = \prod_{w|\mathfrak{f}} \chi_w(2\vartheta_w) \cdot \nu_w^{-1}(d_{\mathfrak{e}} \varphi_\mathfrak{e}(\chi_w)) / \epsilon(0, \chi_w, \psi)$.

Note that $C_{\mathfrak{f}} \in Z_p^\times$.

5.3. $v$ is archimedean or $v|\mathfrak{f}$. Note that $\nu$ is trivial on $E^\times$ if $v$ is inert or ramified because $\nu$ is a character of $\text{Gal}(\mathcal{K}_v^\circ/K)$. If $v|\mathfrak{f} \cap \mathfrak{f}$, by the very definition of $\phi = \phi_{\chi_v, v}$ in (4.13), we find that

$$l_E(\phi, \nu) = \int_{E^\times/F^\times} \phi(\rho(t)\chi_v) \chi_\nu(t) d^\times t$$

$$= \text{vol}(E^\times/F^\times, d^\times t) \cdot \begin{cases} 1 & \text{if } v|\mathfrak{f}, \\ L(s, \chi_v) & \text{if } v|\mathfrak{f}. \end{cases}$$
If \( v = \sigma |\infty \) and \( \phi = \phi_{k,n,s}^{h} \) is defined in (4.5), then

\[
l_E(\phi, \nu) = \int_{E^{\infty} / F^{\infty}} \phi_{k,n,s}^{h}(\rho(t) \begin{bmatrix} \text{Im } \sigma \vartheta(t)|_{1} \end{bmatrix}) \chi \nu(t) d^\infty t
\]

\[= \text{vol}(C^\infty / R^\infty, d^\infty t).\]

**5.4.** \( v = 1 \). A direct computation shows that

\[
\rho(t)_{\chi}^{(n)}(v) = \rho(x + y \theta_1) \begin{bmatrix} -b d_{x} \varpi_{1}^n & 1 \\ a d_{x} \varpi_{1}^n & 0 \end{bmatrix} = \begin{bmatrix} x d_{x} \varpi_{1}^n a_1 & * \\ y b_1 \end{bmatrix} \quad (t = x + y \theta_1).
\]

We thus find that

\[
\rho(t)_{\chi}^{(n)}(v) \in B(F) \omega N(O^\infty) \iff t \in F^\infty(1 + \varpi_{1}^n \theta_1 O^\infty).
\]

Let \( R_{n,1} = R_n \otimes_{\mathbb{O}} O^\infty \). Then \( R_{n,1}^\infty = O^\infty(1 + \varpi_{1}^n \theta_1 O^\infty) \). Let \( \pi : E^\infty \to E^\infty / F^\infty \) be the quotient map. Thus we have

\[
l_E(\phi, \nu) = \int_{E^{\infty} / F^{\infty}} \phi(\rho(t)_{\chi}^{(n)}) \chi \nu(t) d^\infty t
\]

\[= \chi_{\varpi}^{-n} \int_{E^{\infty} / F^{\infty}} \mathbb{I}_{\pi(R_{n,1}^\infty)}(t) d^\infty t = \chi_{\varpi}^{-n} \text{vol}(\pi(R_{n,1}^\infty), d^\infty t).
\]

**5.5. Evaluation formula.** We summarize our local calculations in the following proposition.

**Proposition 5.1.** Suppose that either of the conditions (1-3) in Prop. 4.7 holds. Then we have the following evaluation formula:

\[
\frac{1}{\Omega_{D}^{2\Sigma + 2}} \cdot \int_{C_{1}\infty} \nu d\varepsilon_{\chi}^{\infty} = \frac{\pi^{n} \Gamma_{\Sigma}(k \Sigma + \kappa) L^{(1)}(0, \chi \nu)}{\Omega_{D}^{2\Sigma + 2}} \cdot \frac{2^{r} L_{\chi} C_{3}}{\sqrt{|D_{\chi}| R(\text{Im } \vartheta)^{\kappa}}},
\]

where \( r \) is the number of prime factors of \( D_{\chi} / F \).

**Proof.** We note that

\[
\sum_{\nu_{\chi} \in C_{1}\infty} E_{\chi}^{n,h}(\rho(t)_{\chi}^{(n)}) \chi \nu(t) = \frac{1}{\text{vol}(U, d^\infty t)} \cdot l_{\chi}(E_{\chi}^{n,h}, \nu)
\]

\[= \frac{1}{\text{vol}(U, d^\infty t)} \cdot \prod_{\nu} l_{\chi_{\nu}}(\phi_{\chi,s, v}, \nu) \big|_{s=0}
\]

\[= L^{(1)}(0, \chi \nu) \cdot 2^{r} L_{\chi} C_{3} \cdot \chi_{\varpi}^{-n}.
\]

The proposition follows from (5.3) immediately. \( \square \)

6. **Non-vanishing of Eisenstein series modulo \( p \)**

6.1. Throughout this section, we retain the assumptions (unn), (ord) and (pl, \( D_{\chi} / F \mathbb{C} \) \( = 1 \). Let \( \chi \) be a Hecke character of \( K^\infty \) and take \( \mathfrak{p} \) to be a split prime \( q \) as in §4.1. We remark that an auxiliary split prime \( q \) is introduced to assure the assumption (2) in Prop. 4.7, so the \( L \)-value in the evaluation formula Prop. 5.1 has an extra local factor \( L_{q} = L(1, \chi_{q}^{-1} \vartheta_{q}^{-1})^{-1} \). However, this is harmless to (NV) property since the closed subgroup generated by associated Frobenious \( \text{Frob}_{q} \) in \( \text{Gal}(K_{1} / K) \) is non-trivial, and hence the set \{ \( \nu \in \mathbb{X}^{-}_{1} \mid L(1, \nu^{-1}_{q} \chi_{q}^{-1})^{-1} \equiv 0 \) mod \( m \) \} is a proper closed subset of \( \mathbb{X}^{-}_{1} \).

To establish the (NV) property for \( (\chi, \mathfrak{q}) \), by Hida’s non-vanishing criterion of a \( p \)-adic measure associated to eigenforms (Theorem 3.1) and the evaluation formula of our Eisenstein measure \( d\varphi_{\chi}^{n} \) (Prop. 5.1), it suffices to show the non-vanishing modulo \( p \) of some Fourier coefficient of \( (\theta^{e} \varepsilon_{\chi}^{n})^{\mathfrak{R}} = \theta^{e} \varepsilon_{\chi}^{n} \) at some cusp \( (\mathfrak{o}, \chi(a)^{-1}) \).

**Lemma 6.1.** Put \( (E_{\chi}^{n,h})^{\mathfrak{R}} = \sum_{\mathfrak{R}} E_{\chi}^{n,h} \|_{\mathfrak{R}}. \) Then we have

\[(E_{\chi}^{n,h})^{\mathfrak{R}} = \# \Delta_{\text{alg}}^{n,h} \cdot E_{\chi}^{n,h}.\]

**Proof.** It can be shown that \( \Delta_{\text{alg}} \) is generated by ramified primes, so \( \mathfrak{R} \) can chosen from elements in \( \prod_{\nu} D_{\chi / F} K_{\nu}^{-}. \) The lemma follows from Prop. 4.8 (2). \( \square \)
Remark 6.2. Since $E^R$ is the $p$-adic avatar of $(E^h)^R$ and $\#\Delta_{alg}$ is a power of 2, from the above lemma and the following identity (cf. [HT93, (1.23)])

$$a_{\beta}(\theta^eE\chi, c) = \beta^n a_{\beta}(E^h, c),$$

we conclude that (NV) property for $(\chi, l)$ holds if the following hypothesis (H') is verified:

(H') For every $u \in O_l$ and a positive integer $r$, there exist $\beta \in O^\times_{(p)}$ and $c = c(a)$ such that $\beta \equiv u \ (mod \ P')$ and

$$a_{\beta}(E^h, c) \neq 0 \ (mod \ m).$$

6.2. Let $\bar{\chi}$ be the reduction modulo $m$ of the $p$-adic avatar of $\chi$ and let $\bar{\chi}_+ = \bar{\chi}|_{A^\times_F}$. Let $\omega_F: A_F^\times/F^\times \to \mu_{p-1}$ be the Teichmüller character regarded as a Hecke character of $F^\times$ via geometrically normalized reciprocity law. We first treat the case $\chi$ is not residually self-dual, namely

$$\bar{\chi}_+ \neq \chi|_{F^\times}\omega_F \ (mod \ m).$$

The following proposition is due to Hida [Hid04a].

Proposition 6.3 (Hida). Suppose that $\chi$ is not residually self-dual. Then (NV) holds for $(\chi, l)$ if for every $v|\mathcal{C}^-$ there exists $\eta_v \in F_v^\times$ such that

$$(6.1) \quad A_{\eta_v}(\chi_v) \neq 0 \ (mod \ m).$$

**Proof.** We have to verify the hypothesis (H') in Remark 6.2. Given $u \in O_l$ and a positive integer $r$, we extend $\eta_v = (\eta_v)_{v|e}$ to an idele $\eta = (\eta_v)_{v|e}$ in $A^\times_F$ by taking $\eta_v = 1$ for $v \notin \mathcal{D}_K/F$ or $v|p\mathcal{D}_K/F$, $\eta = u$ and $\eta_v = \varpi_v^{-1}$ as in (4.19) if $v|\mathcal{Y}'$. Let $b^- := \prod_{q|e} q^{M_q}$, $M_q = \max\{v_q(\mathcal{C}^-), v_q(\mathcal{C}^-) - v_q(\eta_v)\}$ and put

$$U = \left\{(x_{\infty}, x_f) \in R^{|\mathcal{Y}':\mathcal{Q}|} \times (O \otimes \mathbb{Z})^\times \mid x_f \equiv 1 \ (mod \ D_{K/F}^\times b^{-})\right\}.$$

Let $c = c(a)$ and $c$ be the associated idele as in Prop. 4.7 and consider the idele class $[c\eta^{-1}] := F^\times c\eta^{-1}U$ in $A^\times_F$. For each idele $a \in O \otimes \mathbb{Z}$ in the class $[c\eta^{-1}]$ such that each local component $a_v = 1$ at $v|p\mathcal{D}_K/F\mathcal{C}^\times$, we can write $a = \beta c\eta^{-1}u$ for $\beta \in O^\times_{(p)}$ and $u \in U$, and from the explicit formula of $a_{\beta}(E^h, c)$ (Prop. 4.7 combined with Lemma 4.1, (4.7), (4.10) and (4.12)), we find that

$$a_{\beta}(E^h, c) = \prod_{v|e} \frac{1 - \chi^e(\varpi_v)^{v(a_v)+1}}{1 - \chi^e(\varpi_v)} \cdot \chi_v(c_v),$$

where

$$C_{\beta} = |D_{F/F}^\times|_F (N_F/Q(\beta)^{k-1}. \prod_{w|\beta} \chi_w(\beta) \varphi(\beta) |D_{F,F}^{-1}|_{F_v} \cdot |c|_{F_v} \prod_{w|\mathcal{Y}'} \chi_w^{-1}(\theta_v) |\varpi_v D_{F|^\times}|_{F_v}$$

$$\times \prod_{v|\mathcal{C}^-} A_{\eta_v}(\chi_v) |D_{F,F}^{-1}|_{F_v} \psi_o((-2^{-1} t_v \beta)).$$

By our choices of $\eta$ and $a$, $C_{\beta} \neq 0 \ (mod \ m)$. Suppose that $a_{\beta}(E^h, c) \equiv 0 \ (mod \ m)$ for all $\beta \in O^\times_{(p)}$ such that $\beta \equiv u \ (mod \ P')$. In particular, for every uniformizer $\varpi_v \in [c\eta^{-1}]$ at $v | p\mathcal{C}^\times D_{K/F}$, we deduce from (6.2) that $\chi^e(\varpi_v) \equiv \chi^e\omega_F^{-1}(\varpi_v) \equiv -1 \ (mod \ m)$.

Moreover, the argument in [Hid04a, p.780] shows that $\chi^e\omega_F^{-1}$ is a quadratic character of level $U$ and takes value $-1$ on $[c\eta^{-1}]$. Moving $c = c(a)$ among prime-to-$p\mathcal{D}_F$ ideals $a$ of $R$, we conclude that $\chi^e\omega_F^{-1} \equiv \tau_K/F \ (mod \ m)$, which is a contradiction.

**Lemma 6.4.** Let $v|\mathcal{C}^-$ and $w$ be the place of $K$ above $v$. Suppose that $\mu_p(\chi_v) = 0$. Then there exists $\eta_v \in F_v^\times$ such that

$$A_{\eta_v}(\chi_v) \not\equiv 0 \ (mod \ m).$$

Moreover, if $v$ is inert and $\chi_v|_{F_v^\times} = \tau_{K_v/F_v}$, then $\eta_v$ can be further chosen so that $v(\eta_v) = -w(\mathcal{C}^-)$.

**Proof.** First we make some observations. Notation is as in §4.3.6. We let $F = F_v$ and $E = K_v$. Let $\varpi = \varpi_v$ be a uniformizer of $F$ and $\theta = \theta_v$. Recall that $\mu_p(\chi_v) = \inf_{x \in E^\times} v_p(\chi_v(x) - 1)$, so the assumption
\( \mu_\beta(\chi_v) = 0 \) is equivalent to \( \chi|_{E^\times} \not\equiv 1 \pmod{m} \). Since \( A_\beta(\chi) = \psi^{\ast}(t\beta)\tilde{A}_\beta(\chi) \), it is equivalent to showing the lemma for \( \tilde{A}_\beta(\chi) \). For an integer \( m \) and \( a \in F \), we put
\[
c_m(a) = \int_{O_v} \chi^{-1}(a + \omega^m x + \theta)dx.
\]
By (4.17), for \( \eta \in \omega^{-m}O_v^\times \) and every sufficiently large positive integer \( M \) (depending on \( m \)) we have
\[
\tilde{A}_\beta(\chi) = \int_{\omega^{-m}O_v} \chi^{-1}(x + \theta)\psi^\ast(\eta x)dx.
\]
Thus for each \( a \in F \) we find that
\[
\int_{\omega^{-m}O_v} \tilde{A}_\eta(\chi)\psi^\ast(-\eta a)dx = \int_{\omega^{-m}O_v} \chi^{-1}(x + \theta)dx \int_{\omega^{-m}O_v} \psi^\ast(\eta(x-a))dx
\]
(6.3)
\[
\int_{O_v} \chi^{-1}(a + \omega^m x + \theta)dx - \int_{O_v} \chi^{-1}(a + \omega^{m-1} x + \theta)dx
\]
\[
= c_m(a) - c_{m-1}(a).
\]
Now we prove the first assertion by contradiction. Suppose that \( \tilde{A}_\eta(\chi) \equiv 0 \pmod{m} \) for all \( \eta \in F^\times \).
The equation (6.3) implies that for every \( a \in F \), \( c_m(a) \pmod{m} \) is a constant independent of \( m \). Taking a sufficiently large \( m \), we find that \( c_m(a) = c_m(a') \pmod{m} \) for every integer \( m \) and \( a \in F \).
On the other hand, it is clear that \( c_m(a) = c_m(a') \pmod{m} \) whenever \( a, a' \in \omega^mO_v \), so we conclude that the function \( a \mapsto \chi^{-1}(a + \theta) \pmod{m} \) is the constant function \( \chi^{-1}(\theta) \) on \( F \), and hence \( \chi(1 + a\theta) \equiv 1 \pmod{m} \) for all \( a \in F \). This implies that \( \chi_v \equiv 1 \pmod{m} \), which is a contradiction.
We proceed to prove the second assertion. Suppose that \( v \) is inert and \( \chi|_{F} = \tau_{E/F} \). Note that in this case \( \mu_\beta(\chi_v) = 0 \) is equivalent to \( \chi_v|_{\Omega_v^\times} \not\equiv 1 \pmod{m} \). Let \( m = \omega(\mathfrak{c}^{-}) \geq 1 \). If \( \tilde{A}_\eta(\chi) \equiv 0 \pmod{m} \) for all \( \eta \in \omega^{-m}O_v^\times \), then it follows from (6.3) that
\[
\chi^{-1}(a + \theta) = c_m(a) \equiv c_{m-1}(0) \pmod{m} \text{ for } a \in \omega^{m-1}O_v.
\]
Therefore, \( a \mapsto \chi^{-1}(a + \theta) \pmod{m} \) is the constant function \( \chi^{-1}(\theta) \) on \( \omega^{m-1}O_v \), and hence \( \chi(1 + a\theta) \equiv 1 \pmod{m} \) for all \( a \in \omega^{m-1}O_v \). If \( m = \omega(\mathfrak{c}^{-}) > 1 \), this is impossible, and if \( m = 1 \), this contradicts to the assumption that \( \chi|_{\Omega_v^\times} \not\equiv 1 \pmod{m} \).

The following corollary is an immediate consequence of Prop. 6.3 and Lemma 6.4, which gives a partial generalization of Hida’s theorem.

Corollary 6.5. Suppose that the following conditions hold:

(L) \( \mu_\beta(\chi_v) = 0 \) for every \( v|\mathfrak{c}^{-} \).

(N) \( \chi \) is not residually self-dual.

Then \( \textbf{(NV)} \) holds for \( (\chi, l) \).

6.3. We consider the self-dual case. First we recall the following lemma on local root numbers of self-dual characters.

Lemma 6.6 (Prop. 3.7 [MS00]). Let \( \chi \) be a self-dual character, i.e. \( \chi|_{A^x} = \tau_{K/F}|_{A^x} \). Then

(1) \( W(\chi^*) = \pm \chi^*(2\theta) \).

(2) If \( v \) is split, \( W(\chi^*) = \chi^*(2\theta) \).

(3) If \( v \) is inert, \( W(\chi^*) = (-1)^{\nu(\chi^*)+\nu(c(R))}\chi^*(2\theta) \) \( (c(R) = D^{-1}_{\mathfrak{c}}(2\theta D^{-1}_{K/F})) \).

Proposition 6.7. Let \( \chi \) be a self-dual character of the global root number \( W(\chi^*) = +1 \) \( (\chi^* = \chi|_{A_{\mathfrak{c}}^x}^{\pm \frac{1}{2}}) \). Suppose that \( l \) splits in \( K \) and that there exists \( \eta_v \in F_v^\times \) for each \( v|\mathfrak{c}^{-} \) such that

(i) \( A_{\eta_v}(\chi) \not\equiv 0 \pmod{m} \).

(ii) \( W(\chi^*)_{\kappa_{\mathfrak{c}}F}(\eta_v) = \chi^*(2\theta) \).

Then \( \textbf{(NV)} \) holds for \( (\chi, l) \).

Proof. We need to verify the hypothesis \( \textbf{(H')} \) in Remark 6.2. Given \( u \in O_l \) and a positive integer \( r \), we extend \( (\eta_v)_{v|\mathfrak{c}^{-}} \) to an idele \( \eta = (\eta_v) \) in \( A_{\mathfrak{c}}^x \) such that
Moreover by the approximation theorem, the idele \( \tau \equiv \eta \mod \Gamma \) and \( \eta_v = 1 \) for every split prime \( v \neq 1 \),

\[ W(\chi_v^*) \tau_{K/F}(\eta_v) = \chi_v^*(2\theta) \]

for every \( \eta \in h \).

By Lemma 6.6, this is possible since \( I \) splits in \( K \). On the other hand, it is well known that \( W(\chi_v^*) = i^{2g_\sigma + 1} = \chi_v^*(\theta) \) since \( \chi_v^* = z \) for \( \sigma \in \Sigma \) (cf. [Tat79, p.13]). From the assumption on the global root number \( W(\chi^*) = \prod_v W(\chi_v^*) = 1 \), we deduce that

\[ \prod_{v \in h} W(\chi_v^*) = \prod_{v \in h} \chi_v^*(2\theta). \]

This implies that \( \tau_{K/F}(\eta) = 1 \), so we can write

\[ \eta = \beta N_{K/F}(a), \beta \in F_+, a \in A_K^\times. \]

Moreover by the approximation theorem, the idele \( a \) can be further chosen so that \( a \equiv 1 \mod pF \mathbb{C}^\times \) for any sufficiently large \( N \). Note that

\[ W(\chi_v^*) \tau_{K/F}(\beta) = W(\chi_v^*)(\eta_v) = \chi_v^*(2\theta). \]

For every sufficiently small \( \epsilon \), we have thus constructed \( \beta \in F_+ \cap O_{(p\delta\beta)}^\times \) such that

- \( \beta \equiv u \mod \Gamma' \),
- \( \beta - \eta_v \mid \gamma_v < \epsilon \) for all \( v \mid \mathbb{C}^\times \),
- \( W(\chi_v^*) \chi_v^*(\beta) = \chi_v^*(2\theta) \) for all \( v \in h \).

Here we let \( \epsilon \) be sufficiently small so that \( A_{\eta}(\chi_v) = A_{\eta_v}(\chi_v^*) \) for \( v \mid \mathbb{C}^\times \). Recall that \( v(\epsilon(R)) = 0 \) for \( v \mid \mathbb{C}^\times \) by our choice of \( \theta \). By Lemma 6.6 (3), we find that \( v(\beta) \equiv v(\epsilon(R)) \mod 2 \) for every inert place \( v \mid \mathbb{C}^\times \). It follows that there exists a fractional \( a \) of \( R \) such that

\[ \prod_{v \mid \mathbb{C}^\times} q_v(\beta) = (\beta) c(R) N_{K/F}(a)^{-1} = (\beta, c(a)). \]

Define \( c \in A_\mathbb{F}_F \) as follows: \( c_v = \beta^{-1} \) if \( v \mid \mathbb{P} \mathbb{C}^\times \), \( c_v = 1 \) if \( v \mid \mathbb{C}^\times \). Then \( (\epsilon(c)) = c(a) \) by the choice of \( \beta \) and \( c(a) \). From Prop. 4.7. (4.7), (4.10), (4.12) and (4.18), we find that the \( \beta \)-th Fourier coefficient \( a_\beta(E^h_\chi, \epsilon) \) of \( E_\chi^h \) at the cusp \( (O, c^{-1}) \) is given by

\[ a_\beta(E^h_\chi, \epsilon) = \frac{1}{|D_\mathbb{F}|} \prod_{v \in h} W_\beta(\phi_{\chi, s, v}, \left[ 1_{c_v^{-1}} \right])_{s=0} = \chi(\epsilon) \prod_{v \mid \mathbb{C}^\times} \chi_v(\beta) \prod_{v \mid \mathbb{C}^\times} A_\beta(\chi_v) \mid |D_\mathbb{F}| \chi_v^*(\psi^\delta(\theta - 1_{v}, \beta)). \]

It is clear that the non-vanishing of \( A_\beta(E^h_\chi, \epsilon) \mod m \) is equivalent to

\[ A_\beta(\chi_v) = A_{\eta_v}(\chi_v^*) \neq 0 \mod m \]

for every \( v \mid \mathbb{C}^\times \).

Now we are ready to prove our main result.

**Theorem 6.8.** Suppose that \( I \) splits in \( K \). Let \( \chi \) be a self-dual Hecke character such that

- (L) \( \mu_\mu(\chi_v) = 0 \) for every \( v \mid \mathbb{C}^\times \),
- (R) The global root number \( W(\chi^*) = 1 \),
- (C) \( \mathcal{R} \) is square-free.

Then (NV) holds for \( (\chi, 0) \).

**Proof.** It suffice to verify that for each \( v \mid \mathbb{C}^\times \) there exists \( \eta_v \in F_v^\times \) which satisfies (i) and (ii) in Prop. 6.7. For \( v \mid \mathcal{R} \), we take \( \eta_v \in F_v^\times \) such that \( W(\chi_v^*) = \tau_{K/F}(\eta_v) \chi_v^*(2\theta) \). Note that the assumption (C) implies that \( v \mid 2 \). By Prop. 4.4 (3) we find that

\[ A_{\eta_v}(\chi) = (\chi_v^*(-2\delta_v d_{\mathbb{F}}) + \chi_v^*(2-1 \eta_v) W(\chi_v^*)) \chi_v(-2^{-1} d_{\mathbb{F}}) \| \varepsilon \|^2 = (\chi_v^*(\theta) + \chi_v^*(\delta_v)) \chi_v(-2^{-1} d_{\mathbb{F}}) \| \varepsilon \|^2 \]

\[ = 2 \chi_v^*(\theta) \chi_v(-2^{-1} d_{\mathbb{F}}) \| \varepsilon \|^2 \neq 0 \mod m. \]
For $v|3$, we choose $\eta_v$ to be as in Lemma 6.4, so $A_{\eta_v}(\chi_v) \neq 0$ (mod m) and
\[ v(\eta_v) = w(C^\times) = a(\chi_v^w) + v(\epsilon(R)). \]
It follows from Lemma 6.6 (3) that $W(\chi_v^w) = \tau_{K/F}(\eta_v)\chi_v^w(2\theta)$. \qed

**Remark 6.9.** We give a few remarks on Theorem 6.8:

1. The assumption (C) has been removed in view of [Hsi12, Prop. 6.3].
2. Let $\chi_1$ be a self-dual character and $\nu$ be a finite order character such that $\nu$ has prime-to-$p$ conductor and $\nu \equiv 1 (\text{mod } m)$. As pointed out by the referee, one can prove Theorem 6.8 for $\chi := \chi_1\nu$, keeping (L) and (C) but replacing (R) by the condition (Rm): $W(\chi^\times) \equiv 1 (\text{mod } m)$, which implies the condition (R) for $\chi_1$. Indeed, as $\nu$ must have square-free conductor, (C) holds for $\chi_1$, and (L) obviously holds for $\chi$ as well. Thus $\chi_1$ satisfies the hypothesis in Theorem 6.8, and for every $u \in O_l$ and $r$, we can choose $\beta \in F_\nu$ as in the proof of Prop. 6.7 such that $a_{\beta}(E^h_{\chi_1}, \epsilon) \neq 0 (\text{mod } m)$. By the condition (L) the supports of the conductors of $\chi$ and $\chi_1$ only differ by split primes, we find that $a_{\beta}(E^h_{\chi}, \epsilon) \neq 0 (\text{mod } m)$. (For example, when $l$ is inert, this dichotomy holds precisely when $v(\eta_v) \equiv v(\epsilon(R))$ (mod 2). To treat nonsplit $l$, it seems that one has to refine Theorem 3.2 in [Hid04a] (at least when $l$ has degree one over $\mathbb{Q}$).

**References**


