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CRYSTALLINE LIFTS OF TWO-DIMENSIONAL MOD $p$ AUTOMORPHIC GALOIS REPRESENTATIONS

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Abstract. We show that a sufficient condition for an irreducible automorphic Galois representation $\rho : G_F \to \mathrm{GL}_2(\mathbf{F}_p)$ of a totally real field $F$ to have an automorphic crystalline lift is that for each place $v$ of $F$ above $p$ the restriction $\det \rho|_{I_v}$ is a fixed power of the mod $p$ cyclotomic character. Moreover, we show that the only obstruction to controlling the level and character of such automorphic lifts arises for badly dihedral representations.

1. Introduction

Let $\rho : G_\mathbf{Q} \to \mathrm{GL}_2(\mathbf{F}_p)$ be a continuous irreducible odd representation of the absolute Galois group of the rationals. By Serre’s conjecture, now a theorem of Khare-Wintenberger and Kisin, $\rho$ is automorphic. It is moreover known that $\rho$ arises from a modular form of level prime to $p$.

The analogue of the last statement for automorphic mod $p$ representations of the absolute Galois group of an arbitrary number field is false in general. The purpose of this note is to give sufficient conditions for a mod $p$ Hilbert modular form to have a lift of level prime to $p$, or equivalently for the associated Galois representation to have an automorphic lift which is crystalline at all primes over $p$. The result is motivated by a question of Dieulefait and Pacetti; see [5, Lemma 8.32] where a special case of Theorem 1.1 is used in the construction of “chains” of compatible systems of Galois representations.

We first recall the existence of an obvious obstruction. Let $p$ be a prime number and $F$ a totally real number field. Denote by $\Sigma$ the set of embeddings of $F$ in $\mathbf{R}$. For integers $k \geq 2$ and $w$ having the same parity denote by $D_{k,w}$ the discrete series representation of $\mathrm{GL}_2(\mathbf{R})$ having Blatter parameters $(k,w)$. In particular $D_{k,w}$ has central character $t \mapsto t^{-w}$. Fix a tuple $\vec{k} = (k_\tau)_{\tau \in \Sigma} \in \mathbf{Z}_{\geq 2}^\Sigma$ and an integer $w$ all sharing the same parity. Let $\pi$ be a cuspidal automorphic representation of $\mathrm{GL}_2(\mathbf{A}_F)$ which is holomorphic of weight $(\vec{k},w)$, i.e., such that $\pi_\tau \simeq D_{k_\tau,w}$ for all $\tau \in \Sigma$. Assume moreover that the level of $\pi$ is coprime with $p$. If $\rho_\pi : G_F \to \mathrm{GL}_2(\mathbf{Q}_p)$ denotes the $p$-adic Galois representation attached to $\pi$, we have $\det \rho_\pi|_{I_v} = \epsilon_v^{w-1}$ for all primes $v$ of $F$ dividing $p$, where $I_v$ is the inertia subgroup of a decomposition group of $G_F$ at $v$, and $\epsilon_v$ is the $p$-adic cyclotomic character restricted to $I_v$ (cf. [2, Corollary 2.11] and [4]).

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We show that this condition on $\det \rho_v|_I$ is the only obstruction to the existence of a crystalline lift of an irreducible automorphic representation $\rho : G_F \to \GL_2(\mathbb{F}_p)$. Moreover we control the conductor and central character of such a lift provided only that $\rho$ is not badly dihedral (see Definition 3.3). More precisely, we prove:

**Theorem 1.1.** Suppose that $\rho : G_F \to \GL_2(\mathbb{F}_p)$ is automorphic, irreducible, and that for some integer $k$, we have $\det \rho_v|_I = \epsilon_v^{-1}$ for all $v|p$. Then there exists $n_0$ such that if $n \geq n_0$, there exists a cuspidal automorphic representation $\pi$ of $\GL_2(\mathbb{A}_F)$ such that

- if $v|p$, then $\pi_v$ is unramified principal series;
- if $v|\infty$, then $\pi_v \cong D_{k+n\delta,k+n\delta}$ where $\delta = \text{lcm}\{ (p - 1)/\gcd(p - 1, e_v) | v|p \}$;
- $\overline{\rho}_\pi \cong \rho$.

Suppose further that $\rho$ is automorphic with prime-to-$p$ conductor dividing $n \subset \mathcal{O}_F$, and that $\psi$ is a finite order Hecke character of $\mathbb{A}_F \times \mathbb{F}_p$ of conductor dividing $n$, totally of parity $w = k+n\delta$, and satisfying $\det \rho = \psi^{-w-1}$. Then if $\rho$ is not badly dihedral, we can choose $\pi$ as above with conductor dividing $n$ and central character $\psi^{-1} ||^{-w}$.

(Here $e_v$ denotes the ramification degree of $v$ over $p$). We remark that we have ensured in the conclusion that the lift has parallel weight since it seems no harder to achieve and slightly simplifies the statement.

There are two main ingredients to the proof of Theorem 1.1. The first of these is Proposition 2.1 below, which is a statement purely about mod $p$ representations of $\GL_2(\mathbb{F})$ where $\mathbb{F}$ is a finite field of characteristic $p$. The result can be deduced from the main result of [12], but we give instead a short self-contained proof that could be useful if one wishes to extract an explicit value of $n_0$ in the conclusion of Theorem 1.1.

We will then deduce Theorem 1.1 from standard arguments for producing congruences and liftings of cohomology classes (cf. section 3.2). We must do some work however to show that the only obstruction to controlling the level and character is in the case of badly dihedral representations, even for $p = 2$ (cf. sections 3.3 and 3.5). A related result is proved in [2, Lemma 4.11] using the Galois action on the cohomology of Shimura curves, but since we also wish to work with forms on definite quaternion algebras, we give a different argument in this paper by interpreting the obstruction in terms of the Hecke action. We remark that this obstruction is genuine, but that even in this case one can obtain slightly weaker results by modifying our arguments or by constructing CM lifts. We remark also that we could instead have attempted to deduce a version of Theorem 1.1 using level lowering or automorphy lifting theorems, as in [10] or [8], but this approach would have required additional hypotheses, such as adequacy of the image of $\rho$, and made the case of $p = 2$ even more problematic.

Finally we also give two more refined variants of the main result (Theorems 4.2 and 4.5) in the special case where the initial automorphic representation has weight $(2,\ldots,2)$ and is unramified or special at all primes over $p$. This is again with a view to applications along the lines of those in [5].

2. Grothendieck ring relations

In this section we denote by $\mathbb{F}$ a fixed finite field of characteristic $p > 0$. Fix an embedding $\tau_0 : \mathbb{F} \to \overline{\mathbb{F}}_p$ and let $\tau_i = \tau_0 \circ \text{Frob}^i$ where $\text{Frob}$ is the (arithmetic) Frobenius automorphism of $\mathbb{F}$ and we sometimes view $i \in \mathbb{Z}/f\mathbb{Z}$ where $f = [\mathbb{F} : \mathbb{F}_p]$. 


For $i = 0, 1, \ldots, f - 1$ and $n \geq 0$, we let $\text{Sym}_n^{[i]} = F_p \otimes_{F_\tau} \text{Sym}^n F^2$ where $\text{Sym}^n F^2$ denotes the $n$th symmetric power of the standard representation of $\text{GL}_2(F)$ for $n \geq 0$; by convention we let $\text{Sym}^{-1}_n F^2 = 0$. For $\vec{n} = (n_0, n_1, \ldots, n_{f-1})$ with $n_0, \ldots, n_{f-1} \geq -1$, we let $S_{\vec{n}} = \otimes_{i=0}^{f-1} \text{Sym}^{n_i}$.

Recall that $S_{\vec{n}}$ is an irreducible representation of $\text{GL}_2(F)$ if and only if $0 \leq n_i \leq p - 1$ for all $i$, and that every irreducible representation of $\text{GL}_2(F)$ over $F_p$ is of the form $\det^a \otimes S_{\vec{n}}$ for some $a \in \mathbb{Z}$ and $\vec{n}$ as above.

We let $G_0(\overline{F}_p[\text{GL}_2(F)])$ denote the Grothendieck group on finite-dimensional representations of $\text{GL}_2(F)$ over $\overline{F}_p$, which is thus isomorphic to the free abelian group generated by the classes $[\det^a \otimes S_{\vec{n}}]$ for $a = 0, \ldots, p^f - 2$ and $\vec{n} = (n_0, n_1, \ldots, n_{f-1})$ as above.

We use $\leq$ for the natural partial ordering on $G_0(\overline{F}_p[\text{GL}_2(F)])$: thus $R \leq R'$ whenever $R' - R$ is in the submonoid of $G_0(\overline{F}_p[\text{GL}_2(F)])$ consisting of classes of (actual) $\overline{F}_p$-representations of $\text{GL}_2(F)$. Note that if $\sigma$ and $\sigma'$ are $\overline{F}_p$-representations of $\text{GL}_2(F)$, then $[\sigma] \leq [\sigma']$ if and only if $\sigma$ is an embedding of the semisimplification of $\sigma'$ in that of $\sigma'$. In particular if $\sigma$ is irreducible, then $[\sigma] \leq [\sigma']$ if and only if $\sigma$ is a Jordan-H"{o}lder factor of $\sigma'$.

Assume $f \geq 1$ is arbitrary. If $k < -1$ for each $i \in \mathbb{Z}/f\mathbb{Z}$ define (cf. [13]):

$$[\text{Sym}^k_{n_i}] := - [\det^f(k+1) \otimes \text{Sym}^{k-2}_{n_i}] .$$

In what follows we slightly abuse notation by allowing taking brackets of virtual representations in $G_0(\overline{F}_p[\text{GL}_2(F)])$.

Denote by $N_{F/F_p}$ the field norm map for the extension $F/F_p$.

**Proposition 2.1.** Let $\sigma$ be an irreducible representation of $\text{GL}_2(F)$ over $\overline{F}_p$ with central character of the form $N_{F/F_p}^e \sigma$ for some $e, s \geq 1$. Then $[\sigma] \leq \left[ S_{(t_1, \ldots, t_r)}^{\otimes e} \right]$ for all sufficiently large $t \equiv s \mod (p - 1)/\gcd(p - 1, e)$.

The proof will be based on the following lemmas, which can be viewed as providing algebraic analogues of theta operators and Hasse invariants in order to shift weights of automorphic forms in characteristic $p$.

Let $n, m \geq 0$. The usual identification of graded $F$-algebras $\text{Sym} F^2 \cong F[t_1, t_2]$ induces an action of $\text{GL}_2(F)$ on $F[t_1, t_2]$. When $f = 1$, multiplication by the Dickson invariant $t_1^p t_2 - t_1 t_2^p \in F[t_1, t_2]^{\text{SL}_2(F)}$ induces a $\text{GL}_2(F)$-equivariant embedding $S_n \hookrightarrow \text{det}^{-1} \otimes S_{n+p+1}$ ([II section 3]). Similarly, when $f > 1$ we obtain a $\text{GL}_2(F)$-equivariant embedding $\text{Sym}^m_{[0]} \otimes \text{Sym}^n_{[1]} \hookrightarrow \text{det}^{-p} \otimes \text{Sym}^{m+p}_{[0]} \otimes \text{Sym}^{n+1}_{[1]}$ induced by $t_1^p \otimes t_2 - t_2^p \otimes t_1$ ([III section 3.5.1]). We obtain in particular:

**Lemma 2.2.** Suppose $f = 1$ and $n \geq 0$. Then $[S_n] \leq [\text{det}^{-1} \otimes S_{n+p+1}]$.

**Lemma 2.3.** Suppose $f > 1$ and $m, n \geq 0$. Then

$$[\text{Sym}^m_{[0]} \otimes \text{Sym}^n_{[1]}] \leq [\text{det}^{-p} \otimes \text{Sym}^{m+p}_{[0]} \otimes \text{Sym}^{n+1}_{[1]}].$$

**Lemma 2.4.** Suppose $f = 1$ and $n \geq 0$. Then $[S_n] \leq [S_{n+p-1}]$ unless $n = r(p + 1)$ for some $r$, in which case we have $[S_n] \leq [S_{n+p-1} + \text{det}^r]$.
Proof. Serre’s periodic relation:

\[ [S_{n+p-1} - S_n] = [\det \otimes (S_{n-2} - S_{n-p-1})], \]

valid in \( G_0(\mathbb{F}_p[\text{GL}_2(\mathbb{F})]) \) for all \( n \in \mathbb{Z} \) (cf. [13]) implies that positivity of \([S_{n+p-1} - S_n]\) depends only on \( n \mod p + 1 \). If \( 1 \leq n < p + 1 \) the term \([S_{n-p-1}]\) is non-positive, so that \([S_n] \leq [S_{n+p-1}]\) when \( n \neq 0 \mod p + 1 \). When \( n = r(p+1) \) we see by induction on \( r \) that \([S_{n+p-1} - S_n] = [\det^r \otimes (S_{p-1} - 1)]\). \( \square \)

Lemma 2.5. Suppose \( f > 1 \) and \( np > m \geq 0 \). Then

\[ \left[ \text{Sym}^m_{[0]} \otimes \text{Sym}^n_{[1]} \right] \leq \left[ \text{Sym}^{m+p}_{[0]} \otimes \text{Sym}^{n-1}_{[1]} \right]. \]

Proof. We proceed by induction on \( n \). The statement for \( n = 1 \) follows from the identity \([\text{Sym}^{m+p}_{[0]} = \text{Sym}^m_{[0]} \otimes \text{Sym}^1_{[1]} - \det^p \otimes \text{Sym}^{m-p}_{[0]} \otimes \text{Sym}^1_{[1]} \]) (cf. last equation in [11, Theorem 2.7]), together with the fact that \([\text{Sym}^{m-p}_{[0]} \leq 0 \) since \( m < p \)). Assuming now the statement for a fixed \( n = n_0 > 0 \) and letting \( 0 \leq m < (n_0 + 1)p \), we have, using again the above identity:

\[
\begin{align*}
\left[ \text{Sym}^{m+p}_{[0]} \otimes \text{Sym}^n_{[1]} \right] &= \left[ \text{Sym}^m_{[0]} \otimes \text{Sym}^1_{[1]} \otimes \text{Sym}^{n_0}_{[1]} - \det^p \otimes \text{Sym}^{m-p}_{[0]} \otimes \text{Sym}^n_{[1]} \right] \\
&= \left[ \text{Sym}^m_{[0]} \otimes \text{Sym}^{n_0+1}_{[1]} + \det^p \otimes \left( \text{Sym}^m_{[0]} \otimes \text{Sym}^{n_0-1}_{[1]} - \text{Sym}^{m-p}_{[0]} \otimes \text{Sym}^n_{[1]} \right) \right],
\end{align*}
\]

If \( m < p \), then \([\text{Sym}^{m-p}_{[0]} \leq 0 \) in \( G_0(\mathbb{F}_p[\text{GL}_2(\mathbb{F})]) \), so the expression between rounded parenthesis is positive, implying the statement for \( n_0 + 1 \). If \( m \geq p \), then \( 0 \leq m - p < n_0p \) so that \([\text{Sym}^{m-p}_{[0]} \otimes \text{Sym}^{n_0}_{[1]} \leq [\text{Sym}^m_{[0]} \otimes \text{Sym}^{n_0-1}_{[1]} \right]. \) The result follows. \( \square \)

We now proceed with the proof of Proposition 2.4. Suppose that \( \sigma = \det^a \otimes S_{\vec{n}} \) with \( a \geq 0 \) and \( \vec{n} = (n_0, n_1, \ldots, n_{f-1}) \) with \( 0 \leq n_i < p - 1 \).

We first treat the case \( e = f = 1 \). By Lemma 2.2 and induction on \( n \), we have \([\sigma] \leq [S_{n+a(p+1)}] \). Let \( t_0 = n + a(p+1) \), and note that \( t_0 \equiv s \mod p - 1 \). If \( n = 0 \), then we may replace \( a \) by \( a + p - 1 \) so as to assume \( t_0 \geq p^2 - 1 \). We claim that \([\sigma] \leq [S_t] \) for all \( t \equiv s \mod p - 1 \) with \( t \geq t_0 \). Indeed it suffices to prove that if \( t \geq t_0 \) and \([\sigma] \leq [S_t] \), then \([\sigma] \leq [S_{t+p-1}] \), and this is immediate from Lemma 2.4 except in the case \( \sigma = \det^r \), \( t = r(p+1) \). Note however that Lemma 2.2 implies that \((b+1)|\det^u| \leq [S_u(p+1)] \) if \( u \geq (p-1)b \); in particular \( 2|\det^r| \leq [S_t] \) if \( t = r(p+1) \geq p^2 - 1 \), so in this case it again follows from Lemma 2.4 that \([\sigma] = [\det^r] \leq [S_{t+p-1}] \).

Next we treat the case \( e = 1, f > 1 \). Note that Lemma 2.3 implies that

\[ \left[ \text{Sym}^m_{[i]} \otimes \text{Sym}^{n_{i+1}}_{[i+1]} \right] \leq \left[ \text{det}^{-p^{i+1}} \otimes \text{Sym}^m_{[i]} \right], \]

for any \( m, n \geq 0, i \in \mathbb{Z}/f\mathbb{Z} \), and hence that

\[ [S_{\vec{m}}] \leq \left[ \text{det}^{-\sum_{i=0}^{f-1} b_ip^i} \otimes S_{\vec{m}'} \right] \]

for any \( m_0, \ldots, m_{f-1}, b_0, \ldots, b_{f-1} \geq 0 \), where \( \vec{m} = (m_0, \ldots, m_{f-1}) \) and \( \vec{m}' = (m_0 + b_0 + pb_1, \ldots, m_{f-1} + b_{f-1} + pb_0) \). In particular, if \( a = \sum_{i=0}^{f-1} b_ip^i \) with \( b_0, \ldots, b_{f-1} \geq 0 \),
then $|\sigma| \leq [S_{\vec{n}'}]$ where $\vec{n}' = (n'_0, \ldots, n'_{f-1})$ with $n'_i = n_i + b_i + pb_{i+1}$. Note that

$$\sum_{i=0}^{f-1} n'_i p^i = 2a + \sum_{i=0}^{f-1} n_i p^i \equiv s \left(\sum_{i=0}^{f-1} p^i\right) \mod p^f - 1,$$

from which it follows that $\sum_{i=0}^{f-1} n'_i p^i$ is divisible by $\sum_{i=0}^{f-1} p^i$ for $j = 0, \ldots, f - 1$.

Now consider the system of equations

$$(2) \quad n'_0 - x_0 + px_1 = n'_1 - x_1 + px_2 = \cdots = n'_{f-1} - x_{f-1} + px_0.$$ 

For any $x_0 \in \mathbb{Z}$, we obtain a solution with $x_0, \ldots, x_{f-1} \in \mathbb{Z}$ by setting

$$x_j = x_{j-1} - n'_{j-1} + \left(\sum_{i=0}^{j-1} n'_{i+j} p^i\right) / \left(\sum_{i=0}^{j-1} p^i\right)$$

for $j = 1, \ldots, f - 1$. In particular we may choose a solution of (2) with $x_0, \ldots, x_{f-1}$ non-negative integers.

We now wish to apply Lemma 2.5 or rather its twist by $\text{Frob}$, iteratively $x_{i+1}$ times for $i = 0, \ldots, f - 1$ in order to conclude that $|\sigma| \leq [S_{(t, \ldots, t)}]$ where $t$ is the common value of $n'_i - x_i + px_{i+1}$, but we must first ensure that the inequality $np > m$ in the hypothesis of the lemma is satisfied at each stage. To this end, note that we may replace $\vec{n}'$ by $\vec{n}'' = \vec{n}' + r(p^2 - 1, \ldots, p^2 - 1)$ for any integer $r \geq 0$; indeed $|\sigma| \leq [S_{\vec{n}''}] \leq [S_{\vec{n}'}]$ by (1) and (2) still holds with each $n'_i$ replaced by $n''_i = n'_i + r(p^2 - 1)$. Choosing $r$ so that

$$r(p-1)(p^2 - 1) > n'_i - mn'_{i+1} + 2px_{i+1}$$

for each $i$, we find that $p(n''_{i+1} - x_{i+1}) > n''_i + px_{i+1}$. Now by Lemma 2.5 and induction on $\sum_{i=0}^{f-1} d_i$, we see that if $0 \leq d_i \leq x_i$ for $i = 0, \ldots, f - 1$, then $|\sigma| \leq [S_{\vec{n}''}]$ where $n''_i = n''_i - d_i + pd_{i+1}$. It follows that $|\sigma| \leq [S_{(t, \ldots, t)}]$ where $t$ is the common value of $n''_i - x_i + px_{i+1}$. Similarly we find that if $t > 0$, then $[S_{(t, \ldots, t)}] \leq [S_{(t+p-1, \ldots, t+p-1)}]$, which completes the proof in the case $e = 1, f > 1$.

Finally we treat the case $e > 1$. From the case $e = 1$, we have that $|\sigma| \leq [S_{(u, \ldots, u)}]$ for all sufficiently large $u \equiv es \mod p - 1$, hence $|\sigma| \leq [S_{(t, \ldots, t)}]$ for all sufficiently large $t \equiv s \mod (p-1)/\gcd(e,p-1)$. From the natural surjection

$$\left(\text{Sym}^t_{[s]}\right)^{\otimes e} \rightarrow \text{Sym}^t_{[t]}$$

we see that $[S_{(t, \ldots, t)}] \leq [S_{(t, \ldots, t)}^{\otimes e}]$, concluding the proof of Proposition 2.1.

**Remark 2.6.** When $f = 1$, multiplication by the Dickson invariant

$$(p^2 t_2 - t_1 p^2) / (p^2 t_2 - t_1 p^2) \in (\text{Sym}^2 \mathbb{F})^{H_{2}}$$

induces a $\text{GL}_2(\mathbb{F})$-equivariant injection $S_k \rightarrow S_{k+p(p-1)}$ for all $k \geq 0$. Notice that the change in weight produced by this operator does not allow us to prove the desired result.
3. Lifting to characteristic zero

The first part of Theorem 1.1 is proved in section 3.2 below. In sections 3.3 and 3.5 we refine the argument to control the level and character of the crystalline lifts we produce, thus proving the second part of Theorem 1.1. We begin by fixing some notation.

3.1. Notation. We normalize local and global class field theory so that geometric Frobenius elements correspond to uniformizers, and we adopt Hecke’s normalizations of local-global compatibility when associating a Galois representation to an automorphic form. These are the normalizations adopted in [4] and [2].

Let $p$ be a prime number. We fix an algebraic closure $\overline{Q}$ (resp. $\overline{Q}_p$) of the field $Q$ of rational numbers (resp. of the field $Q_p$ of $p$-adic numbers). We choose an embedding $\overline{Q} \to C$ and an isomorphism $\overline{Q}_p \cong C$, so that we also identify $\overline{Q}$ with a subfield of $\overline{Q}_p$. Denote by $\overline{F}_p$, a fixed algebraic closure of the field $F_p$ with $p$ elements.

Let $F \subset \overline{Q}$ be a totally real number field. Denote by $G_F = \text{Gal}(\overline{Q}/F)$ its absolute Galois group, and by $\epsilon : G_F \to Z^\times_p$ the $p$-adic cyclotomic character. Let $\Sigma$ be the set of embeddings of $F$ in $\overline{Q}$.

For each finite place $v$ of $F$ we denote by $F_v$ the completion of $F$ at $v$, and by $\mathcal{O}_{F_v}$ its ring of integers. We let $A_F$ (resp. $A_{F,f}$) denote the topological ring of adèles (resp. finite adèles) of $F$.

Let $v$ be a place of $F$ lying above $p$. Let $G_v$ denote the decomposition group of $G_F$ at $v$ induced by $\overline{Q} \subset \overline{Q}_p$, and $I_v$ be its inertia subgroup. We let $k_v$ be the residue field of $\mathcal{O}_{F_v}$, and we set $f_v := [k_v : F_p]$. Denote by $\epsilon_v$ the absolute inertial degree of $v$, and by $\Sigma_v$ be the set of embeddings of $k_v$ in $\overline{F}_p$. We let $\epsilon_v$ denote the restriction of the $p$-adic cyclotomic character to $G_v$ or to $I_v$. The reduction modulo $p$ of $\epsilon_v$ is denoted by $\tau_v$.

For any $\tau \in \Sigma_v$, we denote by $\omega_\tau$ the corresponding fundamental character of $I_v$, defined as the composition $I_v \to \mathcal{O}_v^\times \to k_v^\times \to \overline{F}_p^\times$, where the first map is the restriction of the inverse of the reciprocity isomorphism of local class field theory. Recall that the restriction to $I_v$ of the local mod $p$ cyclotomic character $\tau_v$ of $G_v$ is given by $\prod_{\tau \in \Sigma_v} \omega_\tau^{\epsilon_v}$

For integers $k$ and $w$ having the same parity we denote by $D_{k,w}$ the discrete series representation of $\text{GL}_2(R)$ having Blatter parameters $(k, w)$, and hence central character $t \mapsto t^{-w}$.

3.2. Existence of lifts. For each place $v|p$ of $F$, fix an embedding $\tau_v,0 : k_v \to \overline{F}_p$ and, as in Section 2, set $\tau_v,i = \tau_v,0 \circ \text{Frob}_{p}^{i}$ where $\text{Frob}_{p}$ denotes the arithmetic Frobenius of $k_v$ and $i \in \mathbb{Z}/f_v, \mathbb{Z}$. For any $\tilde{n} = (n_0, \ldots, n_{f_v-1})$ with $n_0, \ldots, n_{f_v-1} \geq -1$ let

$$S_{v,\tilde{n}} = \bigotimes_{i=0}^{f_v-1} (\overline{F}_p \otimes_{k_v, \tau_v,i} \text{Sym}^{n_i} k_v^2),$$

viewed as an $\overline{F}_p$-linear representation of $\text{GL}_2(k_v)$.

Suppose now that $\rho : G_F \to \text{GL}_2(\overline{F}_p)$ is the modular Galois representation in the statement of Theorem 1.1. Assume that $\sigma$ is a Serre weight for $\rho$ in the sense of [2]; in particular $\sigma$ is an $\overline{F}_p$-linear irreducible representation of $\text{GL}_2(\mathcal{O}_F/(p))$.
\[ \prod_{v \mid p} GL_2(O_F/(v^{e_v})) \], and therefore it can be written as \( \sigma = \otimes_{v \mid p} \sigma_v \) where each \( \sigma_v \) is an irreducible representation of \( GL_2(k_v) \).

Denote by \( N_{k_v/F_p} \) the norm map attached to the field extension \( k_v/F_p \). Slightly modifying the proof of [2 Corollary 2.11] by taking the map \( N : (O_F/(p))^\times \to F_p^\times \) considered there to be \( \prod_{v \mid p} N_{k_v/F_p} \), and by applying the generalization to the ramified settings of [2 Proposition 2.10], we deduce that if the central character of \( \sigma_v \) is given by \( \prod_{\tau \in \Sigma_v} \tau^{e_v} = 1 \) for some integers \( e_v \), then

\[ \det \rho|_{I_v} = \prod_{\tau \in \Sigma_v} \omega_{\tau}^{e_v} \phi_{\tau}. \]

For any prime \( v \) of \( F \) above \( p \) we have \( \det \rho|_{I_v} = c_v^{k-1} = \prod_{\tau \in \Sigma_v} \omega_{\tau}^{e_v(k-1)} \) by assumption. We deduce therefore that the central character of \( \sigma_v \) is given by:

\[ N_{k_v/F_p}^{e_v(k-2)} \].

Proposition 2.1 implies that \( \sigma_v \) is a Jordan-Hölder factor of \( S_{v,(t_1,\ldots,t_n)}^{k_0+\delta_0} \) for all sufficiently large \( t_v \equiv k - 2 \mod (p-1)/\gcd(p-1,e_v) \). Define

\[ \delta := \lcm\{ (p-1)/\gcd(p-1,e_v) \mid v \mid p \}. \]

We can thus find a non-negative integer \( n_0 \) such that for all \( n \geq n_0 \) we have \( k-2+n\delta \geq 0 \) and the weight \( \sigma \) is a Jordan-Hölder factor of the \( GL_2(O_F/(p)) \)-representation \( \otimes_{v \mid p} S_{v,(k-2+n\delta,\ldots,k-2+n\delta)}^{k_0+\delta_0} \). By (a generalization to the ramified settings of) [2 Proposition 2.5] we deduce that \( \rho \) arises from a cuspidal automorphic representation \( \pi \) of \( GL_2(A_F) \) having level prime to \( p \) and such that \( \pi_v \simeq D_{k+n\delta,k+n\delta}^\times \) for all places \( v \mid \infty \) of \( F \). This proves the first part of Theorem 1.1.

3.3. The refinement of the argument in the case \([F:Q]\) even. We now explain how to refine the argument above in order to control the level and character of \( \pi \), and prove the second half of Theorem 1.1. The case of \([F:Q]\) odd can be treated by modifying the argument above and using results in the proof of [2 Lemma 4.11] to show that obstructions arise only for badly dihedral representations. For the case of \([F:Q]\) even, we will need to use forms on definite quaternion algebras and prove analogous results concerning the obstructions, which we proceed to do first.

3.3.1. Automorphic forms on definite quaternion algebras. Suppose that \([F:Q]\) is even and let \( D \) be the totally definite quaternion algebra over \( F \) which splits at all finite places of \( F \). Let \( O_D \) be a fixed maximal order in \( D \), and choose isomorphisms of \( O_F \)-algebras \( O_{D,x} \cong M_2(O_F) \) for each finite place \( x \) of \( F \). Let \( U = \coprod_x U_x \) be an open compact subgroup of \( D_x^\times := (D \otimes_F A_{F,F})^\times \) such that \( U_x \subset O_{D,x}^\times \) for each finite place \( x \). Let \( A \) denote the field \( F_p \) or a topological \( \mathbb{Z}_p \)-algebra of finite type, and fix a continuous representation of \( U A_{F,F}^\times / F^\times \) on a finitely generated (topological) \( A \)-module \( V \). Let

\[ S_V(U) = \{ f : D_f^\times \to V \mid f(\gamma gu) = u^{-1}f(g) \ \text{for all} \ \gamma \in D^\times, \ g \in D_f^\times, \ u \in U A_{F,F}^\times \}. \]
Write $D_{\tau}^\times = \prod_{i \in I} D^\times x_i U A_{F_i}^\times$ where $I$ is a finite set, and let $\Gamma_i$ denote the finite group $F^\times \backslash (U A_{F_i}^\times \cap t_i^{-1} D^\times t_i)$, so that we have an isomorphism of $A$-modules:

\[(3) \quad S_V(U) \xrightarrow{\sim} \oplus_{i \in I} V^{\Gamma_i},\]

induced by $f \mapsto \oplus_{i \in I} f(t_i)$.

Let $S$ be a finite set of finite places of $F$ containing the places dividing $p$ and the places $x$ such that $U_x$ is not maximal. Let $U_S := \prod_{x \in S} U_x$ and suppose further that the action of $U$ on $V$ factors through the projection to $U_S$. For $x \notin S$ fix a choice of uniformizer $\omega_x$ of $O_{F_x}$, and write $U_x \Pi_x U_x = \prod_{\alpha} h_\alpha U_x$, where $\Pi_x = \left( \begin{smallmatrix} \pi_x & 0 \\ 0 & 1 \end{smallmatrix} \right) \in GL_2(F_x) \cong (D \otimes F_x)^\times$. We define the Hecke operator $T_x$ acting on $f \in S_V(U)$ by

$$(T_x f)(g) := \sum_\alpha f(gh_\alpha)$$

for all $g \in D_{\tau}^\times$. The Hecke algebra $T_A^S := A[T_x : x \notin S]$ acts on $S_V(U)$. With a slight abuse of notation, we will often not indicate the weight and level of automorphic forms on which $T_A^S$ acts.

Let $\mathbf{k} = (k_\tau)_{\tau \in \Sigma} \in \mathbb{Z}_{\geq 2}$ and $w \in \mathbb{Z}$ such that $k_\tau \equiv w \mod 2$ for all $\tau \in \Sigma$, and let $\psi$ a finite order Hecke character of $A_{F_i}^\times$, totally of parity $w$, so $\psi(x) = \psi_f(x) \prod_{i \in \Sigma} \sign(x_i) \omega_i^w$ for some character $\psi_f$ of $A_{F_i}^\times$. Let $E \subset \overline{Q}_p \cong \mathbb{C}$ be a sufficiently large finite extension of $Q_p$; in particular we assume $E$ contains the values of $\psi$ and the images of all the embeddings $F \to \overline{Q}_p$. We suppose further that for each embedding $\tau : F \to E$, we have a splitting $D \otimes_{F,\tau} E \cong M_2(E)$ so that if $v$ is the place of $F$ induced by $\tau$, then the projection of $U$ to $(D \otimes_{F} F_v)^\times$ is contained in $GL_2(O_v)$. Thus for each $\tau \in \Sigma$, we obtain a map $U \to GL_2(O_v)$, and hence an action of $U$ on $det^{(w-k_\tau+2)/2} \otimes \text{Sym}^{k_\tau-2}O_v^2$. Suppose now that $\psi_f$ is trivial on $U \cap A_{F_i}^\times$, and let $V_{\mathbf{k},w,\psi}$ be the representation of $GA_{F,F}$ whose restriction to $U$ is defined by

$$\otimes_{\tau \in \Sigma} (det^{(w-k_\tau+2)/2} \otimes \text{Sym}^{k_\tau-2}O_v^2),$$

and whose restriction to $A_{F_i}^\times$ is defined by the character $x \mapsto N(x)^w|w|\psi_f(x)$.

We write $S_{V_{\mathbf{k},w,\psi}}(U)$ for $S_{V_{\mathbf{k},w,\psi}}(U)$, and we define $S_{V_{\mathbf{k},w,\psi}}^{\text{triv}}(U) := \{0\}$, unless $\mathbf{k} = \mathbf{2}$, in which case we let $S_{V_{\mathbf{k},w,\psi}}^{\text{triv}}(U)$ consist of those functions in $S_{V_{\mathbf{k},w,\psi}}(U)$ that factor through the reduced norm map $D_{\tau}^\times \cong GL_2(A_{F,F}) \xrightarrow{\det} A_{F,F}^\times$. Setting $S_0 = S_{V_{\mathbf{k},w,\psi}}^{\text{triv}}(U)$, we have by the Jacquet-Langlands correspondence that $S_0 \otimes O_v^2 \cong C \cong \oplus_{\tau \in \Sigma} (det^{(w-k_\tau+2)/2} \otimes \text{Sym}^{k_\tau-2}O_v^2)$, the direct sum running over all holomorphic cuspidal automorphic representations $\pi \cong \pi_\infty \otimes \pi_f$ of $GL_2(A_F)$ such that $\pi_\tau \cong D_{k_\tau,w}$ for all $\tau \in \Sigma$, and $\pi$ has central character $\psi_f^{-1}|^{-w}$.

3.3.2. Conclusion of the argument. We fix an irreducible representation $\rho : G_F \to GL_2(F_p)$ as in Theorem [11]. Assume that $\rho$ arises from a holomorphic cuspidal automorphic form $\pi'$ for $GL_2(A_F)$ of paritious weight $(\mathbf{k},w) \in \mathbb{Z}_{\geq 2}^\times \times \mathbb{Z}$, central character $\psi_f^{-1}|^{-w}$, and level $U = U_p U_p$, where $U_p = \prod_{x \in S} U_x$, $U_p = \prod_{x \in S} U_x$, and $U_x \subset GL_2(O_{F_x})$ for all $x$. Let $S$ be a finite set of finite places of $F$ containing the places of $F$ above $p$ and the places at which $\pi'$ is ramified. Let $m_p$ denote the maximal
ideal of the Hecke algebra $T_{\mathcal{O}_E}^S$ attached to $\rho$; thus with our normalizations, $m_\rho$ is the kernel of the homomorphism $T_{\mathcal{O}_E}^S \to \overline{F}_p$ defined by

$$T_x \mapsto \det(\rho(Frob_x))^{-1}N(x)\text{tr}(\rho(Frob_x)) = \overline{\nu}(x)^{-1}N(x)^w\text{tr}(\rho(Frob_x))$$

for all $x \not\in S$. By what was recalled in [3.3.1] we know that $S_{k,w,\psi}(U)m_\rho \neq 0$.

In the next section we will prove the following:

**Lemma 3.1.** If $\rho$ is not badly dihedral in the sense of Definition 3.3 below, then the functor $V \mapsto S_{\nu}(U)m_\rho$ from finite dimensional $\overline{F}_p$-vector spaces endowed with a continuous action of $U_S\mathcal{A}_{F,f}^\times/F^\times$ to $T_{\mathcal{O}_E}^S$ -modules is exact.

Let $U_* := GL_2(\mathcal{O}_F \otimes \mathbb{Z}_p) \cdot U^p$, and notice there is a Hecke equivariant injection $S_{k,w,\psi}(U) \to S_{\nu}(U_*)$ where $V' = \text{Ind}_{U_*}^{U_S\mathcal{A}_{F,f}^\times/V_{k,w,\psi}}$. In particular, we also have that $S_{\nu}(U_*)m_\rho \neq 0$. Fix an embedding of the residue field of $\mathcal{O}_E$ into $\overline{F}_p$. Using Lemma 3.1 we see that $S_\sigma(U_*)m_\rho \neq 0$ for some Jordan-Hölder constituent $\sigma$ of $V' \otimes_{\mathcal{O}_E} \overline{F}_p$ for the action of $GL_2(\mathcal{O}_F \otimes \mathbb{Z}_p)$. The assumption on $\rho|_{I_i}$ implies by Proposition 2.1 that $\sigma$ is a constituent of the $\overline{F}_p$-linear representation

$$\otimes_{v|p}(\det \otimes S_{\nu_\delta}^{S_{\nu_\delta}})$$

for all sufficiently large $k' \equiv k \mod \delta$, where $\delta$ as in the statement of Theorem 1.1.

It follows that $m_\rho$ is in the support of $S_W(U_*)$, where $W$ is the $\mathcal{O}_E$-linear representation $V_{k',w,\psi}$ (this again uses Lemma 3.1). Now the result follows by applying the Jacquet-Langlands correspondence to $S_W(U_*) \otimes_{\mathcal{O}_E} \mathbf{C}$ to produce a holomorphic Hilbert modular form with desired weight, level, and central character.

**3.4. Proof of Lemma 3.1.** We keep the assumptions and notation from the previous section. Suppose that $0 \to V \to V_1 \to V_2 \to 0$ is an exact sequence of finite dimensional $\overline{F}_p$-vector spaces endowed with a continuous action of $U_S\mathcal{A}_{F,f}^\times$ factoring through $U_S\mathcal{A}_{F,f}^\times$. By (3) we obtain the exact sequence:

$$(4) \quad 0 \to S_{\nu}(U) \to S_{\nu}(U) \to S_{\nu}(U) \to \oplus_{i \in I} H^1(\Gamma_i, V),$$

where $\Gamma_i = F^x \setminus (U\mathcal{A}_{F,f}^\times \cap t_i^{-1}D^x t_i)$ and $D^x_i = \coprod_{i \in I} D^x t_i U\mathcal{A}_{F,f}^\times$. Notice the last term in (4) vanishes if $[F(\mu_p) : F] > 2$, which occurs for example when $p > 3$ is unramified in $F/\mathbb{Q}$. We will show that, in general, it vanishes after localization at $m_\rho$ if $\rho$ is not badly dihedral.

Note that if we choose another representative $t'_i = \delta t_i u$ for the double coset $D^x t_i U\mathcal{A}_{F,f}^\times$ with $\delta \in D^x$, $u \in U\mathcal{A}_{F,f}^\times$ and set $\Gamma'_i = F^x \setminus (U\mathcal{A}_{F,f}^\times \cap (t'_i)^{-1}D^x t'_i)$, then $\Gamma_i = u\Gamma'_i u^{-1}$ and we obtain canonical isomorphisms $H^1(\Gamma_i, V) \to H^1(\Gamma'_i, V)$ induced by the isomorphisms

$$\Gamma'_i \to \Gamma_i, \quad V \to \text{Res}_{\Gamma'_i}^\Gamma V, \quad g \mapsto ugu^{-1}, \quad v \mapsto uv.$$
We let $X_U = D^\times \backslash D^\times_f / UA_{F,f}$ and write $H^j(X_U, V)$ for $\oplus_{i \in I} H^j(\Gamma_i, V)$; this is independent of the choice of the $t_i$ up to canonical isomorphism\footnote{Alternatively one can arrive at this notation by defining a Grothendieck topology on the groupoid fibered over $X_U$ by the $\Gamma_i$ and viewing $V$ as a sheaf on the associated site.} which is moreover compatible with the isomorphism $S_V(U) \cong H^0(X_U, V)$ in the evident sense. We may thus rewrite the exact sequence (4) as

$$0 \to H^0(X_U, V) \to H^0(X_U, V_1) \to H^0(X_U, V_2) \to H^1(X_U, V).$$

### 3.4.1. The Hecke action on $H^1(X_U, V)$.

For $x \notin S$, the Hecke operator $T_x$ acting on $S_V(U)$ can be defined as a composite $\text{tr} \circ (\Pi_x)_* \circ \text{res}$ where $\text{res}$ (resp. $\text{tr}$) is a restriction (resp. trace) map to (resp. from) forms with respect to a smaller open compact subgroup, and $(\Pi_x)_*$ is induced by $\Pi_x$. More precisely, consider the natural projection $X_U' \to X_U$ where $U' = U \cap \Pi_x^{-1} U \Pi_x$, and for each double coset $D^\times t_i U A_{F,f}$ in $X_U$, let $\{t_{ij}\}$ be representatives of the preimage in $X_U'$ (so $D^\times t_i U A_{F,f}$ is the disjoint union over $j$ of the $D^\times t_{ij} U' A_{F,f}$). Let $\Gamma'_{ij}$ be the corresponding stabilizers, so $\Gamma'_{ij} = F^\times \backslash (U' A_{F,f} \backslash t_{ij} D^\times t_i U)$. Writing $t_i = \delta t_{ij} u$ for some $\delta \in D^\times$, $u \in U' A_{F,f}$, we see that $v \mapsto uv$ defines a map $V \to V$ compatible with the inclusion $\Gamma'_{ij} \to \Gamma_i$ defined by conjugation by $u$, and this gives a map

$$H^1(\Gamma_i, V) \to \oplus_j H^1(\Gamma'_{ij}, V).$$

Taking the direct sum over $i$ of these maps, the resulting map $\text{res} : H^1(X_U, V) \to H^1(X_U', V)$ is independent of the choices of double coset representatives.

Similarly we define $(\Pi_x)_*$ using the bijection $X_U' \to X_U$, induced by right multiplication by $\Pi_x$, where $U'' = \Pi_x U' \Pi_x^{-1}$. Since $D_f = \prod_{ij} D^\times t_{ij} U' A_{F,f}$, we have $D_f = \prod_{ij} D^\times t_{ij} U'' A_{F,f}$ and the corresponding stabilizer $\Gamma''_{ij}$ equals $\Pi_x \Gamma'_{ij} \Pi_x^{-1}$. Since $U_x$ acts trivially on $V$, the isomorphism between the groups $\Gamma'_{ij}$ and $\Gamma''_{ij}$ defined by conjugation by $\Pi_x$ is compatible with their action on $V$, so it induces an isomorphism $H^1(\Gamma'_{ij}, V) \to H^1(\Gamma''_{ij}, V)$. Taking the direct sum of these isomorphisms gives a well-defined map $(\Pi_x)_* : H^1(X_U', V) \to H^1(X_U, V)$.

Finally $\text{tr}$ is defined similarly to $\text{res}$ but using $X_U'' \to X_U$ and transfer maps on cohomology. It is then easy to see that the composite $\text{tr} \circ (\Pi_x)_* \circ \text{res}$ is compatible with the $\oplus$ and the Hecke operators on the $S_V(U)$ since each of res, $\Pi_x$ and $\text{tr}$ is compatible with the $\oplus$ in the obvious sense. Note that in fact $T_x = \text{tr} \circ (\Pi_x)_* \circ \text{res}$ on $H^0(X_U, V) = S_V(U)$.

More generally if $x_1, x_2, \ldots, x_m$ are distinct primes of $F$ not in $S$, then we define a Hecke operator $T_{x_1 x_2 \cdots x_m}$ exactly as above, but replacing $\Pi_x$ by the product of the $\Pi_{x_i}$, which we denote by $\Pi_{x_1 \cdots x_m}$.

**Lemma 3.2.** We have $T_{x_1 x_2 \cdots x_m} = T_{x_1} T_{x_2} \cdots T_{x_m}$. In particular the operators $T_{x_i}$ commute and $T_{x_i}^3$ acts on $H^1(X_U, V)$.\footnote{Alternatively one can arrive at this notation by defining a Grothendieck topology on the groupoid fibered over $X_U$ by the $\Gamma_i$ and viewing $V$ as a sheaf on the associated site.}
Proof. Consider the diagram:

\[
\begin{array}{cccc}
H^1(X_U, V) & \to & H^1(X_{U_1'}, V) & \to & H^1(X_{U_1''}, V) & \to & H^1(X_U, V) \\
\downarrow & & \downarrow & & \downarrow & & \downarrow \\
H^1(X_{U_1'\cap U_2'}, V) & \to & H^1(X_{U_1''\cap U_2'}, V) & \to & H^1(X_{U_2'}, V) \\
\downarrow & & \downarrow & & \downarrow \\
H^1(X_{U_1'\cap U_2''}, V) & \to & H^1(X_{U_2''}, V) \\
\downarrow & & \downarrow \\
& & H^1(X_U, V), \\
\end{array}
\]

where

- \(U_1' = U \cap \Pi_{x_1}^{-1}U\Pi_{x_1}, \ U_1'' = \Pi_{x_1}U_1'\Pi_{x_1}^{-1}, \ U_2' = U \cap \Pi_{x_2...x_m}^{-1}U\Pi_{x_2...x_m}\) and \(U_2'' = \Pi_{x_2...x_m}U_2'\Pi_{x_2...x_m}^{-1};\)
- the first row of vertical arrows and the first column of arrows (including the first diagonal) are defined by the evident restriction maps;
- the last row of arrows and the last column of horizontal arrows (including the last diagonal) are defined by the evident transfer maps;
- the middle column (resp. row) of horizontal (resp. vertical) arrows is of the form \((\Pi_{x_1})_*\) (resp. \((\Pi_{x_2...x_m})_*\)) and the middle diagonal arrow is \((\Pi_{x_1,x_2...x_m})_*\).

Note that the top row comprises \(T_{x_1}\), the last column \(T_{x_2...x_m}\) and the diagonal \(T_{x_1x_2...x_m}\), so the lemma follows by induction from the commutativity of all the triangles and squares in the diagram.

We only sketch the proof of commutativity of the top right corner, the rest being immediate from the definitions of the maps. Moreover to prove commutativity of the top right corner reduces to checking it for the corresponding diagram associated to each summand of \(H^1(X_{U_2'}, V)\). More precisely, given a double coset \(D^xU_2A_{F,F}^\times\) in \(X_{U_2'}\) mapping to \(D^xU_2A_{F,F}^\times\) in \(X_U\), let \(\Delta = F^x\backslash(U_2A_{F,F}^\times \cap t^{-1}D^xs)\) and \(\Gamma = F^x\backslash(U_2A_{F,F}^\times \cap s^{-1}D^xs)\). Writing

\[
D^xtU_2A_{F,F}^\times = \bigsqcup_{j \in J} D^x t_j(U_2 \cap U_2'')A_{F,F}^\times \quad \text{and} \quad D^xsU_2A_{F,F}^\times = \bigsqcup_{i \in I} D^xs_i U_2'' A_{F,F}^\times,
\]

we must check the commutativity of the diagram

\[
\begin{array}{ccc}
\bigsqcup_{i \in I} H^1(\Gamma_i, V) & \to & H^1(\Gamma, V) \\
\downarrow & & \downarrow \\
\bigsqcup_{j \in J} H^1(\Delta_j, V) & \to & H^1(\Delta, V)
\end{array}
\]

where \(\Delta_j = F^x\backslash((U_2 \cap U_2'')A_{F,F}^\times \cap t_j^{-1}D^xs_j), \ \Gamma_i = F^x\backslash(U_2''A_{F,F}^\times \cap s_i^{-1}D^xs_i)\) and the maps are defined as follows:
Choosing coset representatives $u$ where the maps are defined as follows:

1. The first downward arrow is defined by maps $\text{Res}^{\Delta}_{\Gamma_i} V \to \bigoplus_{i \in I} \text{Res}^{\Delta}_{\Gamma_i} V \to \bigoplus_{i \in I} \text{Res}^{\Delta}_{\Gamma_i} V$ where the inclusion $\Delta \to \Gamma$ is defined by $g \mapsto w^{-1}gw$ and $\text{Res}^{\Delta}_{\Gamma_i} V \to V$ is defined by $v \mapsto uv$.
2. The left-hand arrow is similarly defined component-wise as the composite

$$H^1(\Gamma_i, V) \to \bigoplus_{j} H^1(\Delta_j, \text{Res}^{\Delta}_{\Gamma_i} V) \to \bigoplus_{j} H^1(\Delta_j, V),$$

where the direct sum is over $j$ such that $s_i = \alpha_i t_j w_j$ for some $\alpha_i \in D^\times$, $w_j \in U_1^{\times} A^{\times}_{F_i, f}$.
3. Writing $s = \beta_i s_j y_i$ with $\beta_i \in D^\times$, $y_i \in U_{2}^{\times} A^{\times}_{F_i, f}$ for each $i \in I$, the top arrow is defined component-wise as the composite

$$H^1(\Gamma_i, V) \sim H^1(\Gamma, \text{Ind}^\Gamma_i V) \sim H^1(\Gamma, \text{Ind}^\Gamma_i, \text{Res}^{\Delta}_{\Gamma_i} V) \to H^1(\Gamma, V),$$

where the inclusion $\Gamma_i \to \Gamma$ is $g \mapsto y_i^{-1}gy_i$, the first isomorphism is that of Shapiro’s Lemma, the second is induced by $V \sim \text{Res}^{\Delta}_{\Gamma_i} V$ defined by $v \mapsto y_i^{-1}v$, and the last map is given by the trace $\text{Ind}^\Gamma_i, \text{Res}^{\Delta}_{\Gamma_i} V \to V$.
4. Writing $t = \gamma_j t_j z_j$ with $\gamma_j \in D^\times$, $z_j \in U_2^{\times} A^{\times}_{F_i, f}$ for each $j$, the bottom arrow is defined similarly by the composite

$$H^1(\Delta_j, V) \sim H^1(\Delta, \text{Ind}^{\Delta}_{\Delta_j} V) \sim H^1(\Delta, \text{Ind}^{\Delta}_{\Delta_j}, \text{Res}^{\Delta}_{\Delta_j} V) \to H^1(\Delta, V).$$

Note that for each $j \in J$, the resulting diagram of inclusions

$$\Delta_j \to \Delta \quad \text{and} \quad \Gamma_i \to \Gamma$$

commutes up to conjugation by the element $g_j = y_i^{-1}w_j^{-1} z_j w F^\times \in \Gamma$. Unravelling definitions and applying standard functorialities, one is reduced to checking commutativity of the following diagram of homomorphisms of $\Delta$-modules

$$\bigoplus_{i \in I} \text{Res}^{\Delta}_{\Gamma_i} V \to \bigoplus_{i \in I} \text{Res}^{\Delta}_{\Gamma_i}, \text{Res}^{\Delta}_{\Gamma_i} V \to \text{Res}^{\Delta}_{\Gamma_i} V$$

$$\downarrow \quad \downarrow$$

$$\bigoplus_{j \in J} \text{Ind}^{\Delta}_{\Delta_j} V \to \bigoplus_{j \in J} \text{Ind}^{\Delta}_{\Delta_j}, \text{Res}^{\Delta}_{\Delta_j} V \to \bigoplus_{j \in J} \text{Ind}^{\Delta}_{\Delta_j}, \text{Res}^{\Delta}_{\Delta_j} V \to V,$$

where the maps are defined as follows:

- The first downward arrow is defined by maps $\text{Res}^{\Delta}_{\Gamma_i} V \to \text{Ind}^{\Delta}_{\Gamma_i}, \text{Res}^{\Delta}_{\Gamma_i} V$ sending $f : \Gamma \to V$ to the map $\Delta \to V$ defined by $g \mapsto f(g_i w^{-1} gw)$.
- The final horizontal map in each row is defined by the evident trace map.
- The remaining maps are induced by the evident ones of the form $v \mapsto xv$ where $x = w, w_j, y_i^{-1}$ or $z_j^{-1}$.

Choosing coset representatives $u_a \in \text{GL}_2(F_{x_i})$ so that $U = \prod_{a \in A} u_a U_1^{\times}$, decomposing $A = \prod_{i \in I} A_i$ where

$$A_i = \{ a \in A \mid tu_a \in D^\times t_i U_1^{\times} A^{\times}_{F_i, f} \},$$
and writing $tu_a = \delta_a t_r a$ with $\delta_a \in D^\times$, $r_a \in U_1^{\mathbf{A}_{F_i}}$ for each $a \in A_i$, we find that
\[
\Gamma = \prod_{a \in A_i} y_i^{-1} \Gamma_i y_i h_a
\]
for each $i \in I$, where $h_a = y_i^{-1} r_a a^{-1}$. One can similarly choose coset representatives for each $\Delta_j$ in $\Delta$, and the desired commutativity then follows from a direct calculation using the resulting description of the trace maps as sums over $A$.

3.4.2. Badly dihedral representations.

Definition 3.3. We say that $F'$ is a $p$-bad quadratic extension of $F$ if $F'$ is a quadratic totally imaginary extension of $F$ of the form $F(\delta)$ for some $\delta$ such that $\delta^p \in F^\times$ and $\delta^p O_F = I^p O_F$ for some fractional ideal $I$ of $F$. We say that an irreducible representation $\rho : G_F \to \GL_2(\mathbf{F}_p)$ is badly dihedral if $\rho$ is induced from a character $G_F^p \to \mathbf{F}_p^\times$ for some $p$-bad quadratic extension $F'$ of $F$.

Remark 3.4. Note that $F$ has a $p$-bad quadratic extension if and only if $F$ contains the maximal real subfield of $F(\zeta_p)$. If this is the case and $p$ is odd, then the only $p$-bad quadratic extension of $F$ is $F(\zeta_p)$, but if $p = 2$, then there are still only finitely many such extensions, as follows for example from the fact that such an extension is necessarily unramified outside the primes dividing 2 and $\infty$.

Let $\rho : G_F \to \GL_2(\mathbf{F}_p)$ be the modular Galois representation from Theorem 3.1.1. Assume that $\rho$ arises from the definite quaternion algebra $D$ split at all finite places of $F$, in level $U$ and weight $V$ (here $V$ is a possibly reducible finite dimensional $\mathbf{F}_p$-linear representation of $\GL_2(\mathbf{O}_F/(p))$). We keep the assumptions and notation from the previous section, so that in particular $m_p$ is the ideal of $\mathbf{T}_S^S$ attached to $\rho$, where $S$ is a finite set containing the primes of $F$ dividing $p$ and the primes at which $\rho$ is ramified.

Let $F_1, F_2, \ldots, F_r$ denote the $p$-bad quadratic extensions of $F$ (so $r \leq 1$ unless $p = 2$), and for each $i = 1, \ldots, r$, let $J_i$ denote the ideal of $\mathbf{T}_S^S$ generated by the elements $T_x$ for those finite places $x$ of $F$ such that $x \notin S$ and $x$ is inert in $F_i$.

Lemma 3.5. If $J_1 J_2 \cdots J_r \subset m_p$ then $\rho$ is badly dihedral.

Proof. Since $m_p$ is prime, we may assume that $J_i \subset m_p$ for some $i$. We thus have that $\text{tr}(\rho(\text{Frob}_v)) = 0$ for all $v \notin S$ inert in $F_i$. By the Chebotarev Density Theorem, it follows that $\text{tr}(\rho(g)) = 0$ for all $g \in G_F \setminus G_{F_i}$. Let $L$ denote the projective splitting field of $\rho$, i.e., the fixed field of the kernel of the composite of $\rho$ with the projection to $\PGL_2(\mathbf{F}_p)$.

We claim that $F_i \subset L$. Indeed if not, then we may choose $g \in G_L \setminus G_F$, and observe that for any $h \in G_F$, we have that either $h \notin G_{F_i}$ so that $\text{tr}(\rho(h)) = 0$, or $gh \notin G_{F_i}$ in which case $\text{tr}(\rho(g) \rho(h)) = \text{tr}(\rho(gh)) = 0$ also implies that $\text{tr}(\rho(h)) = 0$ since $\rho(g)$ is a scalar. If $p > 2$, then taking $h$ to be the identity immediately gives a contradiction; if $p = 2$, then we see that every element of $\text{Gal}(L/F)$ has order dividing 2, which contradicts the irreducibility of $\rho$.

2There is a typo in the definition of badly dihedral in the discussion before Lemma 4.11 of [2]; $\delta^\ell \in K$ should be $\delta^\ell \in \mathbf{O}_K$. The definition here differs slightly from the one intended in [2] in the case $p = 2$ since we also wish to control the central character of the lift.
It follows that \( H = \text{Gal}(L/F_i) \) is subgroup of index 2 in \( G = \text{Gal}(L/F) \), and that every element of \( G \setminus H \) has order 2. Moreover \( G \) is isomorphic to a finite subgroup of \( \text{PGL}_2(F_p) \) which is not contained in a Borel subgroup. By Dickson’s classification of such subgroups, we see the only possibility is that \( G \) is isomorphic to a dihedral group and \( H \) is a cyclic subgroup of index 2. Therefore the projective image of \( \rho(G_{F_i}) \) is cyclic, from which it follows that \( \rho|_{G_{F_i}} \) is reducible, and hence that \( \rho \) is induced from a character of \( \text{PGL}_2(F_p) \).

**Lemma 3.6.** There is a finite set of places \( S' \) such that if \( x_\nu \notin S' \) and \( x_\nu \) is inert in \( F_\nu \) for \( \nu = 1, \ldots, r \), then \( T_{x_1} \cdots T_{x_r} \) annihilates \( H^1(X_U, V) \).

**Proof.** Write \( D^X = \bigsqcup_i D^X t_i \mathbf{A}_{F,f}^X \) and choose a representative \( t_i^{-1} \gamma t_i \) with \( \gamma \in D^X \) for each conjugacy class of elements of order \( p \) in each of the groups

\[
\Gamma_i = F^X \setminus (U \mathbf{A}_{F,f}^X \cap t_i^{-1} D^X t_i).
\]

Then \( F[\gamma] \) is \( p \)-bad, so \( F[\gamma] = F_\nu \) for some \( \nu \). Let \( S_\gamma \) be the finite set of places \( x \) of \( F \) inert in \( F_\nu \) such that \( \mathcal{O}_{F,x} \not\subset \mathcal{O}_{F_\nu,x} \), and let \( S' \) contain the union of the \( S_\gamma \) for all \( \gamma \) as above.

Now let \( x_1, \ldots, x_r \) be as in the statement of the lemma and let \( T = T_{x_1} \cdots T_{x_r} \), which by Lemma 3.2 coincides with \( T_{x_1} \cdots T_{x_r} \). Let \( U' \), \( t_{ij} \) and \( \Gamma'_{ij} \) be as in the definition of the Hecke operator \( T \) on \( \oplus_i H^1(\Gamma, V) \) (cf. 3.4.1). We claim that \( \Gamma'_{ij} \) has order prime to \( p \). Indeed if \( t_{ij}^{-1} \gamma t_{ij} \) is a representative of an element of order \( p \) in \( \Gamma'_{ij} \), then its image in \( \Gamma_i \) is of the form \( t_i^{-1} \gamma t_i \) for some \( \gamma \) as above, so \( \gamma \) is conjugate in \( \text{GL}_2(F_x) \) to an element of \( U'_x F_x^X \), where \( x = x_\nu \) for \( \nu \) chosen so that \( F[\gamma] = F_\nu \), and

\[
U'_x = U_0(x) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{GL}_2(\mathcal{O}_{F,x}) \mid c \equiv 0 \mod x \right\}.
\]

Since \( x \notin S_\gamma \), we see that \( \det \gamma \in \mathcal{O}_{F,x} \), so in fact \( \gamma \) is conjugate to an element of \( U_0(x) \), hence its characteristic polynomial is reducible mod \( x \). On the other hand since \( x \notin S_\gamma \), we see also that \( \gamma \) generates the ring of integers of an unramified quadratic extension of \( F_x \), so the characteristic polynomial of \( \gamma \) is irreducible mod \( x \), giving a contradiction.

Since all the \( \Gamma'_{ij} \) have order prime to \( p \), it follows that \( \oplus_{i,j} H^1(\Gamma'_{ij}, V) = 0 \), and therefore \( T = 0 \). \( \square \)

Lemma 3.4 follows easily from Lemmas 3.5 and 3.6. Indeed it suffices to prove that if \( m_\rho \) is in the support of \( H^1(X_U, V) \), then \( \rho \) is badly dihedral. Note that we may enlarge \( S \) since if \( m_\rho \) is in the support of \( H^1(X_U, V) \), then so is \( m'_\rho = m_\rho \cap T^S \) for any finite \( S' \supset S \). In particular choosing \( S' \) as in Lemma 3.6 we see that the ideal \( J_1 \cdots J_r \) of Lemma 3.5 is contained in the annihilator of \( H^1(X_U, V) \), so if \( H^1(X_U, V)_{m_\rho} \neq 0 \), then \( \rho \) is badly dihedral.

### 3.5. The refinement of the argument in the case \([F : \mathbb{Q}] > 1\) odd

Assume now that \([F : \mathbb{Q}] > 1\) is odd, and let \( \rho \) be as in the statement of Theorem 1.1.

Fix an infinite place \( \tau_0 \) of \( F \) and let \( D \) denote the quaternion algebra over \( F \) whose ramification set equals \( \Sigma - \{ \tau_0 \} \). Fix moreover isomorphisms \( D_f \cong M_2(\mathbf{A}_{F,f}) \) and \( D \otimes_{F, \tau_0} \mathbb{R} \cong M_2(\mathbb{R}) \). Let \( U = \prod_i U_{x_i} \) be an open compact subgroup of \( D^X \cong \prod_i D^X_{f,i} \).
GL_2(A_f). Set \( h^\pm = P^1(C) - P^1(R) \). We denote by \( X_U \) the Shimura curve over \( F \) which is the canonical model for the complex analytic space
\[
X_U(C) = D^x \setminus (D^y \times h^\pm) / U A^x_{F,f}
\]
as in [3] (we see \( F \subset C \) via \( \tau_0 \)). Notice that we quotient \( D^y \) also by the action of \( A^x_{F,f} \) in order to keep track of central characters in what follows.

We have the decomposition into connected components:
\[
X_U(C) = \bigsqcup_{i \in I} \Gamma_i \backslash h,
\]
where \( I \) is a finite set, and \( \Gamma_i = F^x \backslash \tilde{\Gamma}_i \) acts properly discontinuously on \( h \). Here \( \tilde{\Gamma}_i = U A^x_{F,f} \cap t_i^{-1} D^y_{+} t_i \) where \( D^y_+ = \prod_{l \in I} D^y_{+l} t_l U A^x_{F,f} \) and \( D^y_{+l} \) is the set of elements of \( D \) of totally positive reduced norm. The groups \( \tilde{\Gamma}_i \) are torsion free and act freely and properly on \( h \) if \( U \) is small enough, but not in general. Each component \( \Gamma_i \backslash h \) has a canonical model defined over a finite abelian extension of \( F \) by [3 1.2].

Let \( S \) denote a finite set of finite places of \( F \) containing the places above \( p \) and the places at which \( \rho \) is ramified. Let \( k \in \mathbb{Z}_{\geq 2} \) and \( w \in \mathbb{Z} \) such that \( k_\tau \equiv w \mod 2 \) for all \( \tau \in \Sigma \) and let \( \psi \) be a finite order Hecke character of \( A^x_{\infty} \) totally of parity \( w \). The systems of Hecke eigenvalues for the action of \( T^\infty \) on the space of holomorphic Hilbert modular forms of level \( U \), weight \( (k, w) \), and central character \( \psi^{-1} \cdot \cdot \cdot w \) coincide with those arising from the étale cohomology \( H^1(X_{U,F}, \mathcal{V}_{k,w,\psi} \otimes \mathcal{O}_E) \), where \( \mathcal{V}_{k,w,\psi} \) is the \( \mathcal{O}_E \)-sheaf associated to the homonymous representation of \( U_p A^x_{F,f} \) on a finite free \( \mathcal{O}_E \)-module (see [3.1] and [H]). Here \( E \) is a large enough finite extension of \( Q_p \), and we see \( E \subset \overline{Q}_p \cong C \). These Hecke eigensystems also coincide with the Hecke eigensystems arising from \( \bigoplus_{\iota \in I} H^1(\Gamma_i, \mathcal{V}_{k,w,\psi} \otimes \mathcal{O}_E) \). The action of the Hecke operators on the cohomology of the \( \Gamma_i \)'s is defined as in section [3.4.1]. We denote by \( m_\rho \) the prime ideal of \( T_{S,E} \) attached to \( \rho \).

To prove the second half of Theorem [1.1] we use the same strategy adopted in the case of a definite quaternion algebra, modulo guaranteeing that an analogue of Lemma [3.1] holds. We now consider the natural action of \( T^\infty \) on spaces \( \bigoplus_{\iota \in I} H^1(\Gamma_i, \chi, V) \))_{m_\rho} \), where \( V \) is a finite dimensional continuous \( F_p \)-linear representation of \( U_p A^x_{F,f} \); we wish to prove that if \( \rho \) is not badly dihedral, then the functor \( V \mapsto (\bigoplus_{\iota \in I} H^1(\Gamma_i, \chi, V))_{m_\rho} \) is exact, so it is enough to prove that \( (\bigoplus_{\iota \in I} H^1(\Gamma_i, \chi, V))_{m_\rho} = 0 \) for \( j = 0, 2 \).

First note that by the strong approximation theorem, the reduced norm induces a bijection \( \bigoplus_{\iota \in I} H^1(\Gamma, \chi, V))_{m_\rho} \rightarrow I \) where \( I = A^x_{F,F} / F^x \otimes F^{\times} det(U)(A^x_{F,f})^2 \). It follows that in the definition of the Hecke operator \( T_x \) for places \( x \notin S \), we may use the same index set \( I \) and representatives \( t_i \) when \( U \) is replaced by \( U' = U \cap \Pi^{-1} U \Pi \) and \( U'' = \Pi U' \Pi^{-1} \). We may thus write \( T_x \) as a direct sum of composite maps
\[
H^1(\Gamma_i, \chi, V) \rightarrow H^1(\Gamma_i', \chi, V) \rightarrow H^1(\Gamma_i''', \chi, V) \rightarrow H^1(\Gamma_i'''', \chi, V)
\]
where \( i \mapsto i' \) is induced by multiplication by \( (\varpi_x)_{x \in I} \). Let \( F_I \) denote the abelian extension of \( F \) corresponding to \( I \) by class field theory; we see that if \( x \) splits completely in \( F_I \), then \( T_x \) acts componentwise on \( \bigoplus_{\iota \in I} H^1(\Gamma_i, \chi, V) \). Moreover if \( j = 0 \), then for such \( x \) this action is simply multiplication by the index \( [\Gamma_i : \Gamma_i'] = [\Gamma_i : \Gamma_i''] = N(x) + 1 \) on each component.
Suppose now that \( m_{T_p} \) is in the support of \( \bigoplus_{i \in I} H^0(\Gamma_i, V) \), and let \( F' \) denote the composite of \( F_i(\zeta_p) \) with the splitting field of \( \det(\rho) \). If \( x \) splits completely in \( F' \), then \( T_x - N(x) - 1 \in m_{T_p} \) for all such \( x \), which implies that \( \text{tr}(\rho(\text{Frob}_x)) = 2 \). The Brauer-Nesbitt and Chebotarev Density Theorems then imply that \( \rho|_{G_{\rho'}} \) has trivial semi-simplification; since \( F' \) is an abelian extension of \( F \), this contradicts the irreducibility of \( \rho \).

To treat the case of \( j = 2 \), we use Farrell cohomology groups \( \hat{H}^j(\Gamma, V) \) (defined in [4]) for finite index subgroups \( \Gamma \) of the groups \( \Gamma_i \). Note that if \( F = Q \), then such \( \Gamma \) have virtual cohomological dimension one, so that \( H^2(\Gamma, V) = \hat{H}^2(\Gamma, V) \). If \( F \neq Q \), then \( \Gamma \) is a virtual duality group of dimension 2 with dualizing module isomorphic to \( Z \) (with trivial \( \Gamma \) action)\(^{1}\) so that \([7, \text{Thm. 2}]\) yields an exact sequence:

\[
H_0(\Gamma, V) \rightarrow H^2(\Gamma, V) \rightarrow \hat{H}^2(\Gamma, V) \rightarrow 0.
\]

We will assume \( F \neq Q \) since the case \( F = Q \) is easier and can be treated by minor modifications to the arguments below.

For \( \Gamma' \) a finite index subgroup of \( \Gamma \), we have restriction maps \( H_j(\Gamma, V) \rightarrow H_j(\Gamma', V) \) and \( \hat{H}^j(\Gamma, V) \rightarrow \hat{H}^j(\Gamma', V) \), as well as corestriction maps \( H_j(\Gamma', V) \rightarrow H_j(\Gamma, V) \) and \( \hat{H}^j(\Gamma', V) \rightarrow \hat{H}^j(\Gamma, V) \), allowing us to define Hecke operators \( T_x \) on \( \bigoplus_{i \in I} H_j(\Gamma_i, V) \) and \( \bigoplus_{i \in I} \hat{H}^j(\Gamma_i, V) \) for \( x \notin S \) exactly as on \( \bigoplus_{i \in I} H^j(\Gamma_i, V) \). By the following lemma (and the fact that the isomorphisms \( \Gamma_i \cong \Gamma_i^\vee \)) are orientation-preserving, the homomorphisms

\[
\bigoplus_{i \in I} H_0(\Gamma_i, V) \rightarrow \bigoplus_{i \in I} H^2(\Gamma_i, V) \rightarrow \bigoplus_{i \in I} \hat{H}^2(\Gamma_i, V)
\]

are compatible with the operators \( T_x \).

**Lemma 3.7.** Let \( \Gamma \) be a virtual duality group of dimension \( n \) with dualizing module \( D \). Let \( M \) be a left \( \mathbb{Z}\Gamma \)-module and \( \Gamma' \) a finite index subgroup of \( \Gamma \). Then the diagram:

\[
\begin{array}{c}
\cdots \rightarrow H_{n-j}(\Gamma, D \otimes_{\mathbb{Z}} M) \rightarrow H^j(\Gamma, M) \rightarrow \hat{H}^j(\Gamma, M) \rightarrow H_{n-j-1}(\Gamma, D \otimes_{\mathbb{Z}} M) \rightarrow \cdots \\
\downarrow \quad \downarrow \quad \downarrow \\
\cdots \rightarrow H_{n-j}(\Gamma', D \otimes_{\mathbb{Z}} M) \rightarrow H^j(\Gamma', M) \rightarrow \hat{H}^j(\Gamma', M) \rightarrow H_{n-j-1}(\Gamma', D \otimes_{\mathbb{Z}} M) \rightarrow \cdots
\end{array}
\]

commutes, where the rows are the exact sequences given by \([7, \text{Thm. 2}]\) and the vertical arrows are the natural restriction maps. Similarly the diagram commutes with the downward arrows replaced by the upward corestriction maps.

**Proof.** Let \((P_\bullet, d_\bullet)\) be a projective resolution of finite type of the trivial (left \( \mathbb{Z}\Gamma \))-module \( Z \), which we view also as a projective resolution of \( Z \) as a \( \Gamma' \)-module. We define \( P_\bullet^* := \text{Hom}_\mathbb{Z}(P_\bullet, \mathbb{Z}\Gamma) \) and \( P_\bullet^{*,*} := \text{Hom}_{\Gamma'}(P_\bullet^*, \mathbb{Z}\Gamma') \) and denote by \((P_\bullet^*, d_\bullet^*)\) and \((P_\bullet^{*,*}, d_\bullet^{*,*})\) the corresponding cochain complexes of right \( \mathbb{Z}\Gamma \)- and \( \mathbb{Z}\Gamma' \)-modules respectively. There is a natural map of cochain complexes of right \( \mathbb{Z}\Gamma' \)-modules \( \rho_\bullet : P_\bullet^* \rightarrow P_\bullet^{*,*} \) induced by the map \( \mathbb{Z}\Gamma \rightarrow \mathbb{Z}\Gamma' \) given by \( \sum_{\gamma \in \Gamma} n_\gamma \gamma \mapsto \sum_{\gamma \in \Gamma'} n_{\gamma \gamma} \gamma \). Note that \( \rho_\bullet \) is an isomorphism, with inverse \( \sigma_\bullet \) defined by \( (\sigma_j(f))(x) = \sum_{\gamma \in \Gamma'} \gamma^{-1} f(\gamma x) \) for \( f \in P_j^{*,*} \) and \( x \in P_j \), where \( \Gamma = \bigsqcup_{\gamma \in \Gamma'} \Gamma' \).

\(^{1}\)Note that there is a canonical choice of orientation \( H^2(\Gamma, \mathbb{Z}\Gamma) \cong \mathbb{Z} \) provided by the complex analytic structure on \( X(U_1(C)) \).

\(^{2}\)Some of the modules we consider will be naturally right \( \mathbb{Z}\Gamma \)-modules; they can be regarded as left \( \mathbb{Z}\Gamma \)-modules via the involution \( \gamma \mapsto \gamma^{-1} \) of \( \Gamma \) and vice versa. Some of the chain complexes we consider will be sometimes regarded as cochain complexes, after relabelling; and vice versa.
Recall that the dualizing module \( D \) is defined as \( H^n(\Gamma, \mathcal{O} \rightarrow \mathcal{O}) \), which we view as a right \( \mathcal{O} \rightarrow \mathcal{O} \)-module, and let \((Q_\bullet, e_\bullet)\) be a projective resolution of \( D \) as a right \( \mathcal{O} \rightarrow \mathcal{O} \)-module. Note that \( D = H^n(P_\bullet) = \ker d_n^* / \text{Im} d_{n-1}^* \), and then the natural inclusion \( D \hookrightarrow \text{coker} d_n^* \) can be extended to a map of chain complexes \( f_\bullet : Q_\bullet \rightarrow P_n^* \rightarrow \cdots \). Moreover if we let \( D' = H^n(\Gamma', \mathcal{O} \rightarrow \mathcal{O}) \) denote the dualizing module of \( \Gamma' \), then \( \rho_\bullet \) induces the canonical isomorphism \( D \cong D' \) of \( \mathcal{O} \rightarrow \mathcal{O} \)-modules, so that we may also view \((Q_\bullet, e_\bullet)\) as a projective resolution of \( D' \), and extend the natural inclusion \( D' \hookrightarrow \text{coker} (d_n^*)^* \) to a map of chain complexes \( f_\bullet' : Q_\bullet \rightarrow (P_n^*)^* \) where \( f_\bullet' = \rho_\bullet \circ f_\bullet \).

We now let \( X_\bullet \) denote the mapping cone of the chain map \( f_\bullet \), so that \( X_\bullet = Q_\bullet \oplus P_n^* \rightarrow \cdots \), and similarly let \( X'_\bullet \) be the mapping cone of \( f'_\bullet \). Then \( \oplus \rho_\bullet \) defines a chain map, giving a commutative diagram of morphisms \( \text{cochain} \) complexes of right \( \mathcal{O} \rightarrow \mathcal{O} \)-modules:

\[
\begin{align*}
0 & \rightarrow P_n^* \rightarrow X_{n-1} \rightarrow Q_{n-1} \rightarrow 0 \\
0 & \rightarrow P_n^{*'} \rightarrow X'_{n-1} \rightarrow Q_{n-1} \rightarrow 0
\end{align*}
\]

in which the rows are exact and the vertical maps are isomorphisms.

We now apply the functor \( (\cdot) \otimes_{\mathcal{O}} M \) to the first line of (6), and the functor \( (\cdot) \otimes_{\mathcal{O}} M \) to the second. For a right \( \mathcal{O} \rightarrow \mathcal{O} \)-module \( A \) and a left \( \mathcal{O} \rightarrow \mathcal{O} \)-module \( B \), we define the trace map \( \text{tr} : A \otimes_{\mathcal{O}} B \rightarrow A \otimes_{\mathcal{O}} B \) by \( \text{tr}(a \otimes b) = \sum_{\gamma \in \mathcal{O}} a \gamma^{-1} \otimes \gamma b \). We thus obtain a commutative diagram of complexes with exact rows:

\[
\begin{align*}
0 & \rightarrow P_n^* \otimes_{\mathcal{O}} M \rightarrow X_{n-1} \otimes_{\mathcal{O}} M \rightarrow Q_{n-1} \otimes_{\mathcal{O}} M \rightarrow 0 \\
0 & \rightarrow P_n^{*'} \otimes_{\mathcal{O}} M \rightarrow X'_{n-1} \otimes_{\mathcal{O}} M \rightarrow Q_{n-1} \otimes_{\mathcal{O}} M \rightarrow 0
\end{align*}
\]

where the left vertical arrow is given by \( P_n^* \otimes_{\mathcal{O}} M \xrightarrow{\text{tr}} P_n^* \otimes_{\mathcal{O}} M \xrightarrow{\rho_\bullet \otimes \text{id}} P_n^* \otimes_{\mathcal{O}} M \), the right vertical arrow is the trace map, and the middle vertical arrow is their direct sum.

Taking cohomology in (7) then yields the desired commutative diagram. Indeed the exact long sequences of (7) Thm. 2) are precisely those associated to the rows of (6), and it is straightforward to check that the vertical maps induce the corresponding restriction maps on homology and cohomology (for Farrell cohomology, this follows from the characterization of res following [7] Rem. 2)).

The proof of compatibility with corestriction is similar, so we omit the details. One just uses \( \sigma_\bullet \) instead of \( \rho_\bullet \) to obtain a diagram as in (6), but with upward arrows, and use the canonical projection \( A \otimes_{\mathcal{O}} B \rightarrow A \otimes_{\mathcal{O}} B \) to obtain the analogue of (7), again with upward arrows. \( \square \)

We can now use (5) to prove that \( m_\rho \) is not in the support of \( \oplus_{\ell \in I} \tilde{H}^2(\Gamma_i, V) \). Indeed the same argument as for \( H^0 \) shows that if \( x \) splits completely in \( F_i \cdot \mathcal{O} \), then \( T_x = N(x) + 1 \) on \( \oplus_{\ell \in I} H^0(\Gamma_i, V) \), so that the irreducibility of \( \rho \) implies that \( m_\rho \) is not in the support of the image of \( \oplus_{\ell \in I} H^0(\Gamma_i, V) \). Note also that the surjectivity of \( \oplus_{\ell \in I} \tilde{H}^2(\Gamma_i, V) \rightarrow \oplus_{\ell \in I} \tilde{H}^2(\Gamma_i, V) \) implies that the operators \( T_x \) commute, hence \( T_{S_E}^S \) acts on \( \oplus_{\ell \in I} \tilde{H}^2(\Gamma_i, V) \). Thus it suffices to prove that if \( \rho \) is not badly dihedral, then \( m_\rho \) is not in the support of \( \oplus_{\ell \in I} \tilde{H}^2(\Gamma_i, V) \).

Let \( S' \) be a finite set of finite places of \( F \) constructed as in the proof of Lemma 3.6. (Now \( D \) is an indefinite quaternion algebra, so the groups \( \Gamma_i \) are infinite, but each still...
Suppose that \( k \pi \). Moreover if equality holds then Theorem 1 of [14] Remark 4.1. ramified twist of the Steinberg representation. For any finite set of primes \( J \) we denote by \( \pi \) also in the current setting) we deduce that (\( x (\tau \rightarrow v \) via our choices of embeddings \( \vartheta \) and an isomorphism \( i \) does not contain any element of order \( p \). Therefore \( \Gamma'_i \) has a torsion-free subgroup of finite index prime to \( p \), so \( \tilde{H}^2(\Gamma'_i, V) = 0 \). It follows that the operator \( T \) annihilates \( \oplus_{i \in I} \tilde{H}^2(\Gamma'_i, V) \), since it factors through \( \oplus_{i \in I} \tilde{H}^2(\Gamma'_i, V) \). To prove that (\( (\oplus_{i \in I} \tilde{H}^2(\Gamma'_i, V))_{m_p} = 0 \), we may enlarge \( S \) so that \( S \supset S' \). For each \( \nu = 1, \ldots, r \) we denote by \( J_\nu \) the ideal of \( T^S_{O_F} \) generated by the Hecke operators \( T_x \) for those finite places \( x \) of \( F \) such that \( x \notin S \) and \( x \) is inert in \( F_v \). Observe that the ideal \( J_1 J_2 \cdots J_r \) annihilates \( (\oplus_{i \in I} \tilde{H}^2(\Gamma_i, V))_{m_p} \). By Lemma 3.5 (which holds, mut. mut., also in the current setting) we deduce that \( (\oplus_{i \in I} \tilde{H}^2(\Gamma_i, V))_{m_p} \) vanishes, since \( \rho \) is not badly dihedral. This completes the proof that \( (\oplus_{i \in I} \tilde{H}^2(\Gamma_i, V))_{m_p} = 0 \), and hence the functor \( V \mapsto (\oplus_{i \in I} H^1(\Gamma_i, V))_{m_p} \) is exact.

4. A variant in a special case

We now give a variant of the main result in a special case, with a view to producing forms satisfying the hypotheses of Assumption 8.15 in Section 8.3 of [13].

We must first introduce some notation. Recall that we have fixed an embedding \( \overline{Q} \to C \) and an isomorphism \( \overline{Q}_p \cong C \). Note that these choices induce a bijection between the set \( \Sigma \) of embeddings \( \tau : F \to R \) and the set of pairs \((v, \vartheta)\) where \( v \mid p \) and \( \vartheta \) is an embedding \( F_v \to \overline{Q}_p \). For each \( v \mid p \) we let \( \Sigma_v \) denote the set of embeddings \( \vartheta : F_v \to \overline{Q}_p \), which we identify with a subset of \( \Sigma \) via this bijection.

Let \( \pi \) be a cuspidal automorphic representation of \( GL_2(A_F) \) which is holomorphic of weight \((\hat{k}, w)\), where as usual \( \hat{k} \in \mathbb{Z}_{\geq 2}^\times \) and \( w \in \mathbb{Z} \) is such that \( w \equiv k_\tau \mod 2 \) for all \( \tau \in \Sigma \). Suppose further that for all \( v \mid p \), the local factor \( \pi_v \) is either unramified principal series or an unramified twist of the Steinberg representation. Let \( a_v(\pi) \) denote the eigenvalue of the Hecke operator \( T_v = U_v \Pi_v U_\vartheta \) on the one-dimensional vector space \( \pi_v^{U_v} \), where \( \Pi_v = \begin{pmatrix} \pi_v & 0 \\ 0 & 1 \end{pmatrix} \in GL_2(F_v) \) and \( U_v = GL_2(O_{F_v}) \) or \( U_\vartheta(\vartheta) \) according to whether \( \pi_v \) is unramified. Since \( a_v(\pi) \) is algebraic, we may view it as an element of \( \overline{Q} \) via our choices of embeddings \( \overline{Q} \to C \) and \( \overline{Q} \to \overline{Q}_p \). We say that \( \pi \) is ordinary at \( v \) (with respect to our choices of embeddings) if

\[
|a_v(\pi)|_p = p^{\sum_{e \in \Sigma_v}(k_\tau - 2 - w)/2e_v}.
\]

Remark 4.1. In general we have the expression on the right as an upper bound on \( |a_v(\pi)|_p \); this follows for example from [9] Thm. 4.11, but will also be clear from the proof of Theorem 4.3 below. Moreover if equality holds then Theorem 1 of [14] implies that the local Galois representation \( \rho_\pi|_{G_{F_v}} \) is reducible. Note that if \( \pi_v \) is an unramified twist of the Steinberg representation, then \( \pi \) is ordinary at \( v \) if and only if \( k_\tau = 2 \) for all \( \tau \in \Sigma_v \).

Theorem 4.2. Suppose that \( \rho : G_F \to GL_2(\overline{F}_p) \) is such that \( \rho \cong \overline{\sigma}_\pi \) for some cuspidal, holomorphic, automorphic representation \( \pi \) of \( GL_2(A_F) \) of weight \((\hat{k}, w) = (2, \ldots, 2) \) such that for each \( v \mid p \), \( \pi_v \) is either unramified principal series or an unramified twist of the Steinberg representation. For any finite set of primes \( T \) of \( F \),
there exist a cuspidal automorphic representation \( \pi' \) of \( GL_2(A_F) \) and a character \( \xi : G_F \rightarrow \mathbb{C}^\times \) of order at most 2 such that

- if \( \tau \in \Sigma, \) then \( \pi'_\tau \cong D_{k_\tau, w'} \) with \( k_\tau, w' \in \{2, w'\} \) where \( w' = p + 1 \) if \( p \) is odd and \( w' = 4 \) if \( p = 2; \)
- if \( \psi|_p, \) then \( \pi'_\psi \) is unramified principal series, and is ordinary if \( k'_\tau = w' \) for some \( \tau \in \Sigma; \)
- the prime-to-\( p \) part of the conductor of \( \xi \) divides a prime \( y \notin T \) which splits completely in \( F; \)
- \( \mathfrak{p}_w \cong \xi \otimes \rho. \)

Suppose further that \( \pi \) has prime-to-\( p \) conductor dividing \( \mathfrak{m} \subset \mathcal{O}_F, \) and that \( \psi \) is a totally even finite order Hecke character of \( A_F^{\times} \) of conductor dividing \( \mathfrak{m} \) satisfying \( \det \rho = \psi. \) Then if \( \rho \) is not badly dihedral, we can choose \( \pi' \) as above with conductor dividing \( \mathfrak{m}\mathfrak{n}_2^2, \) central character \( \psi^{-1} | -w' \) and \( \xi_y \otimes \pi'_y \) unramified principal series.

**Remark 4.3.** We will see from the proof that the conclusion can be made more precise as follows: For each \( v|p \) such that \( \pi_v \) is ramified, we can ensure that \( \pi'_v \) is ordinary and the set of \( \tau \in \Sigma_v \) such that \( k'_\tau = w' \) maps bijectively to \( \Sigma_v \) under the natural projection.

**Proof.** Let \( R \) denote the set of primes \( v|p \) such that \( \pi_v \) is ramified, and as usual let \( S \) be a sufficiently large finite set of primes containing all those dividing \( p \) and all those at which \( \pi \) is ramified. We suppose that \( E \) is a sufficiently large finite extension of \( Q_p \) in \( \mathcal{O}_E \) that contains the eigenvalue \( a_x(\pi) \) of \( T_x \) on \( \pi^{GL_2(\mathcal{O}_E)}_E \) for all \( x \notin S \) and (necessarily also) the eigenvalue \( a_x(\pi) \) of \( T_v \) on \( \pi^{U_0(v)}_v \) for all \( v \in R. \)

Let \( S' = S \setminus R \) and let \( T = T_{\mathcal{O}_E}^S \) denote the \( \mathcal{O}_E \)-algebra generated by the operators \( T_x \) for \( x \notin S'. \) Let \( m \) denote the kernel of the homomorphism \( T \rightarrow \mathbb{F}_p \) defined by sending \( T_x \) to the reduction of \( a_x(\pi \otimes [\det]) = a_x(\pi)N(x)^{-1} \) for \( x \notin S'. \) (For convenience in keeping track of ordinarity, we have replaced \( \pi \) by its twist by \( [\det] \) to ensure that \( T_v \notin m \) for \( v \in R.) \)

Let \( U = U_1(\mathfrak{m}) \cap U_0(\prod_{v \in R} v) \) where \( \mathfrak{m} \) is the prime-to-\( p \) conductor of \( \pi. \) If \( [F : Q] \) is even, then we let \( D \) be the definite quaternion algebra over \( F \) ramified at precisely the \( n \) infinite places of \( F. \) By the Jacquet–Langlands correspondence, \( m \) is in the support of \( S_{V'}(U) \) where \( V' \) is the representation of \( U A_{E,F}^{\times} \) on \( \mathbb{F}_p \) on which \( U \) acts trivially and \( A_{E,F}^{\times} \) acts via \( \psi. \) If \( [F : Q] \) is odd, then we let \( D \) be a quaternion algebra over \( F \) ramified at precisely all but one infinite place. In this case \( m \) is in the support of \( \bigoplus_{i \in I} H^j(\Gamma_i, V'), \) where \( D_i^K = \prod_{i \in I} D_i^K U A_{E,F}^{\times} \) and \( \Gamma_i = F^K \setminus (U A_{E,F}^{\times} \cap t_i^{-1} D_i^K). \)

Since the argument is the same in the case of either parity, we will make notation by writing \( S(U, V') \) for \( \bigoplus_{i \in I} H^j(\Gamma_i, V') \) where \( j = 0 \) or 1 according to the parity of \( [F : Q] \) (so \( S(U, V') = S_{V'}(U) \) if \( j = 0). \)

We will now show that \( m \) is in the support of \( S(U_1(\mathfrak{m}), V) \) where \( V = V' \otimes (\otimes_{v \in R} S_{v, (p-1, ..., p-1)}). \) We proceed by induction on \( |R'| \) to show that \( m \) is in the support of \( S(U_{R'}, V_{R'}) \) for \( R' \subset R, \) where \( U_{R'} = U \prod_{v \in R'} GL_2(\mathcal{O}_F,v) \) and \( V_{R'} = V' \otimes (\otimes_{v \in R'} S_{v, (p-1, ..., p-1)}). \) Note that \( U_R = U_1(\mathfrak{m}), U_0 = U, \) and we already know that \( m \) is in the support of \( S(U_0, V_0). \)

Suppose now that \( v \in R \setminus R'. \) The canonical isomorphisms

\[
S(U_{R'}, V_{R'}) \cong S(U_{R'\cup \{v\}}, \text{Ind}_{U_{R'}}^{U_{R'\cup \{v\}}} (V_{R'}))
\]
and $\text{Ind}_B^{GL_2(k_v)} \mathbb{F}_p \cong \mathbb{F}_p \oplus S_{p-1,\ldots,p-1}$ give rise to an exact sequence
\begin{equation}
0 \to S(U_{R\cup\{v\}}, V'_R) \to S(U_{R'}, V_{R'}) \to S(U_{R\cup\{v\}}, V_{R\cup\{v\}}) \to 0
\end{equation}
such that $\alpha_v$ and $\beta_v$ are compatible with the operators $T_v$ for $x \notin S' \cup \{v\}$, but not necessarily with the operator $T_v$. Note however that the matrix $w_v = \left( \begin{smallmatrix} 0 & 1 \\ \overline{\varphi}(w_v) & 0 \end{smallmatrix} \right) \in GL_2(F_v)$ normalizes $U_{R'}$ so that $W_v = (w_v)_* \text{ defines an} \text{ automorphism of } S(U_{R'}, V_{R'}) \text{ which is compatible with } T_v \text{ for } x \notin S' \cup \{v\} \text{ and satisfies } W_v^2 = \overline{\varphi}(w_v)^{-1}$. Moreover unravelling the definitions of the operator $T_v$ one finds that $T_v W_v \alpha_v = 0$ and $\beta_v W_v = T_v \beta_v W_v$. Therefore $\beta_v W_v$ is $T$-linear, and $m$ is not in the support of its kernel since $T_v \notin m$. It follows that if $m$ is in the support of $S(U_{R'}, V_{R'})$ then it is also in the support of $S(U_{R\cup\{v\}}, V_{R\cup\{v\}})$.

To set the stage for lifting to characteristic zero, we distinguish between the cases $p = 2$ and $p > 2$.

If $p > 2$, then we let $\xi$ be the trivial character, but we must make another modification instead of introducing a quadratic twist. For each $v \in R$ we have a GL$_2(k_v)$-equivariant inclusion $S_{(1,\ldots,1)} \to S_{(2,\ldots,2)}$, and these induce a $T$-equivariant map $S(U_1(n), V) \to S(U_1(n), V' \otimes (S_{e,v} R S_{e,(2,\ldots,2)}))$. One checks as usual that $S_{\{v\}}$ is not in the support of the kernel, so we can replace each $S_{e,v} \cap \bigcup \{v\}$ by $S_{e,(2,\ldots,2)}$ in the definition of $V$ for $p = 2$.

Now let $\tilde{R} \subset \Sigma = \bigcup v \in R \Sigma_v$ be a set of embeddings $F \to \overline{\mathbb{Q}}$ such that the $\tilde{R} \cap \Sigma_v = \emptyset$ if $v \notin R$ and the natural map $\tilde{R} \cap \Sigma_v \to \Sigma_v$ is bijective if $v \in R$. Define $\tilde{k}' \in \mathbb{Z}_{\geq 2}$ by setting $k_v' = 2$ if $v \notin R$ and $k_v' = w'$ if $v \in \tilde{R}$. (Recall that $w' = p + 1$ if $p > 2$ and $w' = 4$ if $p = 2$.) Consider the representation $V_{k',w'-2,\psi}$ of $U_1(n) \mathbb{A}_{f,F}$; recall that this is the free $\mathcal{O}_E$-module defined by

\[ V_{k',w'-2,\psi} = \bigotimes_{\tau \in \tilde{R}} \text{Sym}^{w'-2}(\mathbb{O}_E^2) \otimes \bigotimes_{\tau \notin \tilde{R}} \det^{(w'-2)/2}(\mathbb{O}_E) \]

as a representation of GL$_2(\mathcal{O}_{F,v})$, with $x \in \mathbb{A}_{F,f}$ acting via $N(x_p)w'-2|x|^{w'-2}\psi(x)$. We let $V_{\xi} = V_{k',w'-2,\psi}$ if $p = 2$ (or if $y = \mathcal{O}_F$); otherwise we let $V_{\xi}$ denote the twist of $V_{k',w'-2,\psi}$ by the Teichmuller lift of the character $\xi \circ \det$ of GL$_2(\mathcal{O}_{F,y})$.

One finds that if $p > 2$, then the reduction of $\prod_{\tau \in \Sigma_v \setminus \tilde{R}} \det^{(p-1)/2}$ is $\det^{(p-1)/2}$ if $v \notin R$, from which it follows that $V_{\xi}$ is isomorphic to the twist of $V$ by the character $\xi \circ \det$ of $U_1(n) \mathbb{A}_{F,f}$. The isomorphisms $V \to V_{\xi}$ of $\Gamma_v = F^x \cap (U_1(n) \mathbb{A}_{F,f} \cap t_v^{-1} D^a t_v)$ modules defined by $v \mapsto \xi(\det(t_v))v$ induce an isomorphism $S(U_1(n), V) \cong S(U_1(n), V_{\xi})$ under which $\xi(\varphi_v)T_v$ corresponds to $T_v$ for $v$ not dividing $yp$ and to $T_v^0$ for $v \in R$, where $T_v^0$ is compatible with an operator on
$S(U, V_{\xi})$ such that $T_v = T^0_v \prod_{\tau \in \Sigma_v \setminus K} \tau(\varpi_v)^{(w' - 2)/2}$. (Note that $T^0_v$ may depend on the choice of uniformizer $\varpi_v$.)

Now let $T'$ denote the $\mathcal{O}_E$-algebra generated by the operators $T_x$ for $x \not\in S \cup \{y\}$ and $T^0_v$ for $v \in R$, and let $\mathfrak{m}'$ denote the kernel of the homomorphism $T' \to F_p$ sending each $T_x$ to the reduction of $\xi(\varpi_x)\alpha_x(\pi)\mathcal{N}(x)^{-1}$ and each $T^0_v$ to the reduction of $\xi(\varpi_v)\alpha_v(\pi)\mathcal{N}(v)^{-1}$. We then have that $\mathfrak{m}'$ is in the support of $S(U_1(n), V_{\xi})$. If $\rho$ is not badly dihedral, it follows as in the proof of Theorem 1.1 that $\mathfrak{m}'$ is in the support of $S(U_1(n), V_{\xi} \otimes_{\mathcal{O}_E} E)$, and hence that there is an automorphic representation whose twist by $|\text{det}|^{-1}$ is the required $\tau'$. If $\rho$ is badly dihedral, then the proof goes through after replacing $U_1(n)$ by a smaller open compact subgroup $U$ so that the groups $\Gamma_i$ are torsion-free.

**Remark 4.4.** The necessity of the quadratic twist $\xi$ in the conclusion follows from consideration of the local Galois representations $\overline{p}_{\pi'}|G_{F_v}$ for $v \bmod p$. Furthermore one can construct explicit examples showing that $\xi$ may need to be ramified outside $p$; we are grateful to L. Dembélé for providing the following one. Over $F = \mathbb{Q}(\alpha)$ with $\alpha = \sqrt{10}$, there is a Hilbert modular form $\pi$ of weight $(2, 2)$, level $(\alpha + 2)$ and trivial character with leading Hecke eigenvalues (ordered by norm):

$$
\begin{array}{cccccccc}
\nu & (2, \alpha) & (3, \alpha + 2) & (3, \alpha + 4) & (5, \alpha) & (13, \alpha + 6) & (13, \alpha + 7) & (31, \alpha + 17) & (31, \alpha + 14) \\
\alpha & -1 & -1 & -1 & 1 & -7 & 0 & -3 & -3 \\
\end{array}
$$

The corresponding automorphic representation $\pi$ then satisfies the hypotheses of the theorem for $p = 3$, but one can show that the character $\xi$ in the conclusion must be ramified at $(3, \alpha + 4)$ but not $(3, \alpha + 2)$, from which it follows that $\xi$ must also be ramified at a prime $y$ not dividing $3$; in fact one can let $y$ be any non-principal prime of $\mathcal{O}_F$ not dividing $6$.

We now give another variant which under the same hypotheses produces lifts of parallel weight without the quadratic twist, at the expense of ordinarity.

**Theorem 4.5.** Suppose that $\rho : G_F \to \text{GL}_2(\mathbb{F}_p)$ is such that $\rho \cong \overline{\rho}_\pi$ for some cuspidal, holomorphic, automorphic representation $\pi$ of $\text{GL}_2(\mathcal{A}_F)$ of weight $(\vec{k}, w) = (2, \ldots, 2)$ such that for each $v \bmod p$, $\pi_v$ is either unramified principal series or an unramified twist of the Steinberg representation. Let $k' = 2 + (p - 1)n$ for any positive integer $n$. Then there exist a cuspidal automorphic representation $\pi'_v$ of $\text{GL}_2(\mathcal{A}_F)$, holomorphic of weight $(k', \ldots, k')$ such that

- if $v \bmod p$, then $\pi'_v$ is unramified principal series;
- $\overline{\rho}_\pi \cong \overline{\rho}$.

Suppose further that $\pi$ has prime-to-$p$ conductor dividing $n \subset \mathcal{O}_F$, and that $\psi$ is a finite order Hecke character of $\mathcal{A}_F^\times$ of conductor dividing $n$, totally of parity $k'$, and satisfying $\text{det} \rho = \psi(\pi)$. Then if $\rho$ is not badly dihedral, we can choose $\pi'$ as above with conductor dividing $n$ and central character $\psi^{-1} | -k'$.

**Remark 4.6.** Note that we may take $k' = p + 1$ in the conclusion, but in the case $p = 2$, this precludes using the Teichmüller lift of $\tau^{-1} \text{det} \rho$ for $\psi$ as this requires $k'$ to be even.

---

Dembélé also offers the equation $y^2 = x^3 + (990144\alpha + 3127248)x - 545501952\alpha - 1726178688$ for the associated elliptic curve.
Proof. By Lemmas 2.4 and 2.5, we see that \([S_{(p-1,...,p-1)}] \leq [S_{(n(p-1),...,n(p-1))}]\) for all \(n, e \geq 1\), so by the arguments of Section 3 it suffices to prove that \(m_{\rho \otimes \tau^{-1}} \subset T_{\mathcal{O}_E}^\times\) is in the support of \(S(U_1(n), V_{\{v|p\}})\) (with notation as in the proof of Theorem 4.2) so in particular \(V_{\{v|p\}}\) is the representation of \(U_1(n)\A_{F,f}^\infty\) on which \(U_p\) acts as \(\otimes_{v|p} S_{\psi(v,p-1,...,p-1)}\), \(U_x\) acts trivially for \(x\) not dividing \(p\), and \(A_{\psi,f}^\infty\) acts via \(\psi\).

For \(v|p\), define the representation \(L_v\) of \(GL_2(\mathcal{O}_{F,v})\) to be the cokernel of the natural inclusion \(\mathcal{O}_{E} \to \text{Ind}_{U_{\psi}(v)}^{GL_2(\mathcal{O}_{F,v})} \mathcal{O}_{E}\). We let \(L_{\{v|p\}}\) denote the representation of \(U_1(n)\A_{F,f}^\infty\) on which \(U_p\) acts as \(\otimes_{v|p} L_v\), \(U_x\) acts trivially for \(x\) not dividing \(p\), and \(A_{\psi,f}^\infty\) acts via \(\psi\), where \(v^{-1} |^{-2}\) is the central character of \(\Pi\). Note that \(\overline{\psi}_v = \overline{\psi}\), so that \(L_{\{v|p\}} \otimes_{\mathcal{O}_E} \mathbb{F}_p \cong V_{\{v|p\}}\); moreover the induced inclusion \(S(U_1(n), L_{\{v|p\}}) \otimes_{\mathcal{O}_E} \mathbb{F}_p \to S(U_1(n), V_{\{v|p\}})\) is compatible with the natural action of \(T_{\mathcal{O}_E}^\times\). Therefore it suffices to prove that \(m_{\rho \otimes \tau^{-1}} \subset \text{the support of}\)

\[
S_{0}(U_1(n), L_{\{v|p\}}) = S(U_1(n), L_{\{v|p\}}) / S_{\text{triv}}(U_1(n), L_{\{v|p\}}),
\]

which in turn follows from it being in the support of

\[
S_{0}(U_1(n), L_{\{v|p\}}) \otimes_{\mathcal{O}_E} \mathbb{C} \cong \bigoplus_{\Pi} (\Pi_f \otimes_{\mathcal{O}_E} L_{\{v|p\}})^{U_1(n)A_{\psi,f}^\infty},
\]

where the sum is over all cuspidal automorphic representations \(\Pi = \Pi_f \otimes_{\Pi_\infty} \text{GL}_2(\mathcal{A}_F)\) such that \(\Pi_{\tau} \cong D_{2,0}\) for all \(\tau \in \Sigma\). For \(v|p\), \((\Pi_f \otimes_{\mathcal{O}_E} L_{\psi_f})^{\text{GL}_2(\mathcal{O}_{F,v})} \neq 0\) if and only if \(\Pi_{f}\) has unramified central character and conductor dividing \(v\), so that \((\Pi_f \otimes_{\mathcal{O}_E} L_{\{v|p\}})^{U_1(n)A_{\psi,f}^\infty} \neq 0\) if and only if \(\Pi\) has central character \(\psi^{-1}\) and conductor dividing \(n \prod_{v|p} v\). Furthermore note that \(m_{\rho \otimes \tau^{-1}} \subset \text{the support of such a summand if and only if } p_{\Pi} \cong \rho \otimes \tau^{-1}\). Finally our hypotheses ensure that \(\Pi = \pi \otimes [\det]\) is exactly such an automorphic representation. \(\square\)

Remark 4.7. Under the assumption that \(\pi_v\) is an unramified principal series for all \(v|p\) and other technical conditions (\(p\) unramified in \(F\), \([F : \mathbb{Q}]\) even or \(F = \mathbb{Q}\), Theorem 4.5 is proved in Sections 2 and 4 of \([6]\).\

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References


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