ON NON-CONGRUENT NUMBERS AS MULTIPLES OF NON-CONGRUENT NUMBERS

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ABSTRACT. Let $n = PQ$ be a square-free positive integer, where P is a product of primes congruent to 1 mod 8, and Q is a non-congruent number with a trivial 2-primary Shafarevich-Tate group. Under certain conditions on the Legendre symbols $\left(\frac{q}{p}\right)$ for primes $p \mid P, q \mid Q$, we establish a criteria characterizing when n is non-congruent with a minimal or a second minimal 2-primary Shafarevich-Tate group. We also provide a sufficient condition for n to be non-congruent with a larger 2-primary Shafarevich-Tate group. These results involve the class groups and tame kernels of quadratic fields.

1. INTRODUCTION

1.1. **Background.** A square-free positive integer n is called *congruent* if it is the area of a right triangle with rational lengths. This is equivalent to say, the Mordell-Weil rank of E_n over $\mathbb{Q}$ is positive, where

$$E_n : y^2 = x^3 - n^2 x$$

is the associated congruent elliptic curve. Denote by $\mathrm{Sel}_2(E_n)$ the 2-*Selmer group* of E_n over $\mathbb{Q}$ and

$$s_2(n) := \dim_{\mathbb{F}_2} \left(\frac{\mathrm{Sel}_2(E_n)}{E_n(\mathbb{Q})[2]} \right) = \dim_{\mathbb{F}_2} \mathrm{Sel}_2(E_n) - 2$$

the *pure* 2-*Selmer rank*. Then

$$s_2(n) = \mathrm{rank}_{\mathbb{Z}} E_n(\mathbb{Q}) + \dim_{\mathbb{F}_2} Ш(E_n)[2]$$

by the exact sequence

$$0 \to E_n(\mathbb{Q})/2E_n(\mathbb{Q}) \to \mathrm{Sel}_2(E_n) \to Ш(E_n)[2] \to 0,$$

where $Ш(E_n)$ is the Shafarevich-Tate group of $E_n/\mathbb{Q}$.

Certainly, $s_2(n) = 0$ implies that n is non-congruent with $Ш(E_n)[2^\infty] = 0$. The examples of $s_2(n) = 0$ can be found in [Fen97], [Isk96] and [OZ15], which are corollaries of Monsky's formula (2.8) for $s_2(n)$. This case is fully characterized in terms of the 2-primary class groups of imaginary quadratic fields, and the full Birch-Swinnerton-Dyer conjecture holds, see [TYZ17, Theorem 1.1, Corollary 1.3] and [Smi16, Theorem 1.2].

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The examples of non-congruent n with $\text{Ш}(E_n)[2^\infty]\cong(\mathbb{Z}/2\mathbb{Z})^2$ can be found in [LT00], [OZ14], [OZ15] and [Zha23]. Denote by

$$r_{2^a}(A)=\dim_{\mathbb{F}_2}\left(\frac{2^{a-1}A}{2^aA}\right) \tag{1.1}$$

the 2^a-rank of a finite abelian group A. Denote by $h_{2^a}(m)$ the 2^a-rank of the narrow class group $\mathcal{A}_m$ of the quadratic field $\mathbb{Q}(\sqrt{m})$. Denote by $(a,b)_v$ the Hilbert symbol.

Theorem 1.1 ([Wan16, Theorem 1.1]). *Let $n=p_1\cdots p_k\equiv 1 \bmod 8$ be a square-free positive integer with prime factors p_i such that $p_i\equiv 1\bmod 4$ for all i. The following are equivalent:*

- *n is non-congruent with $\text{Ш}(E_n)[2^\infty]\cong(\mathbb{Z}/2\mathbb{Z})^2$;*
- *$h_4(-n)=1$ and $h_8(-n)\equiv(d-1)/4\bmod 2$,*

where d is a positive divisor of n such that either $(d,-n)_v=1,\forall v, d\neq 1,n$, or $(2d,-n)_v=1,\forall v$.

Theorem 1.2 ([WZ22, Theorem 1.1]). *Let $n=p_1\cdots p_k\equiv 1\bmod 8$ be a square-free positive integer with prime factors p_i such that $p_i\equiv\pm1\bmod 8$ for all i. The following are equivalent:*

- *n is non-congruent with $\text{Ш}(E_n)[2^\infty]\cong(\mathbb{Z}/2\mathbb{Z})^2$;*
- *$h_4(-n)=1, h_8(-n)=0$.*

Theorem 1.3 ([Zha23, Theorem 5.3]). *Let $n=p_1\cdots p_k\equiv 1\bmod 8$ be a square-free positive integer with prime factors p_i such that $p_i\equiv\pm1\bmod 8$ for all i. The following are equivalent:*

- *$2n$ is non-congruent with $\text{Ш}(E_{2n})[2^\infty]\cong(\mathbb{Z}/2\mathbb{Z})^2$;*
- *$h_4(-n)=1$ and $d\equiv 9\bmod 16$,*

where d is the unique divisor of n such that $(d,n)_v=1,\forall v$ and $d\neq 1, d\equiv 1\bmod 4$.

The condition that $d\equiv 9\bmod 16$ is equivalent to $h_8(-n)+h_8(-2n)=1$, see Proposition 2.9. This recovers [LQ23, Theorem 1.6].

Qin in [Qin22, Theorem 1.5] proved that if $p\equiv 1\bmod 8$ is a prime with trivial 8-rank of the tame kernel $K_2\mathcal{O}_{\mathbb{Q}(\sqrt{p})}$, then p is non-congruent. Moreover, if the 4-rank of $K_2\mathcal{O}_{\mathbb{Q}(\sqrt{p})}$ is 1, then $\text{Ш}(E_p/\mathbb{Q})[2^\infty]\cong(\mathbb{Z}/4\mathbb{Z})^2$.

1.2. **Main results.** In this paper, we want to construct non-congruent numbers n with the form $n=PQ$, where

- P is a product of different primes $\equiv 1\bmod 8$,
- Q is a non-congruent number prime to P, such that $\text{Ш}(E_Q)[2^\infty]=0$.

Denote the prime decomposition of n by

$$n=\gcd(2,Q)p_1\cdots p_kq_1\cdots q_\ell,$$

where $P=p_1\cdots p_k, Q=\gcd(2,Q)q_1\cdots q_\ell$. Assume that there exists two vectors

$$\mathbf{u}=(u_1,\dots,u_k)^{\mathrm{T}}\in\mathbb{F}_2^k\quad\text{and}\quad\mathbf{v}=(v_1,\dots,v_\ell)^{\mathrm{T}}\in\mathbb{F}_2^\ell$$

such that the Legendre symbol $\left(\frac{p_i}{q_j}\right)=(-1)^{u_iv_j}$. Denote by

$$\mathbf{U}_P=\operatorname{diag}\{u_1,\dots,u_k\}\quad\text{and}\quad\mathbf{A}_P=(a_{ij})_{k\times k}$$

matrices defined over $\mathbb{F}_2$, such that the Hilbert symbol $(p_j,-P)_{p_i}=(-1)^{a_{ij}}$.

1.2.1. $s_2(n) = 0$.

Theorem 1.4. *Assume that $\sum_{i=1}^{k} u_i = 0, \sum_{j=1}^{\ell} v_j = 1$, $p_1 \equiv \cdots \equiv p_k \equiv 1 \bmod 8$ and Q is non-congruent with $\Sha(E_Q)[2^\infty] = 0$. The following are equivalent:*

- *n is non-congruent with $\Sha(E_n)[2^\infty] = 0$;*
- *$\mathbf{A}_P + \mathbf{U}_P$ is invertible.*

1.2.2. $s_2(n) = 2$.

Theorem 1.5. *Assume that $\sum_{i=1}^{k} u_i = 0, \sum_{j=1}^{\ell} v_j = 1$, $p_1 \equiv \cdots \equiv p_k \equiv 1 \bmod 8$ and Q is non-congruent with $\Sha(E_Q)[2^\infty] = 0$. The following are equivalent:*

- *n is non-congruent with $\Sha(E_n)[2^\infty] \cong (\mathbb{Z}/2\mathbb{Z})^2$;*
- *$\operatorname{corank}(\mathbf{A}_P + \mathbf{U}_P) = 1$ and $\left(\frac{\gamma}{d}\right) = -\left(\frac{\sqrt{2}+1}{d}\right)$,*

where $d \neq 1$ is a positive divisor of P such that $(d, -P)_{p_i} = (-1)^{u_i}, \forall p_i \mid d$; $(d, -P)_{p_i} = 1, \forall p_i \mid \frac{P}{d}$, and (α, β, γ) is a primitive positive solution of $d\alpha^2 + \frac{n}{d}\beta^2 = 4\gamma^2$.

Here, a *primitive positive solution* of $d\alpha^2 + \frac{n}{d}\beta^2 = 4\gamma^2$ is an integer solution such that $\alpha, \beta, \gamma > 0$ and $\gcd(\alpha, \beta, \gamma) = 1$.

When $\mathbf{u} = \mathbf{0}$, we obtain the following result:

Corollary 1.6. *Assume that $\left(\frac{p_i}{q_j}\right) = 1, \forall i, j$, $p_1 \equiv \cdots \equiv p_k \equiv 1 \bmod 8$ and Q is non-congruent with $\Sha(E_Q)[2^\infty] = 0$. The following are equivalent:*

- *n is non-congruent with $\Sha(E_n)[2^\infty] \cong (\mathbb{Z}/2\mathbb{Z})^2$;*
- *$h_4(-P) = 1$ and $\left(\frac{\gamma}{P}\right) = (-1)^{h_8(-P)}$;*
- *$h_4(-P) = 1$ and $\left(\frac{\gamma}{P}\right) = (-1)^{r_4(K_2\mathcal{O}_{\mathbb{Q}(\sqrt{P})})}$,*

where (α, β, γ) is a primitive positive solution of $P\alpha^2 + Q\beta^2 = 4\gamma^2$.

When $\ell = 0$, we obtain the following results, which are special cases of Theorems 1.1,1.2 and 1.3.

Corollary 1.7. *Let $n = p_1 \cdots p_k$ be a square-free integer where $p_1 \equiv \cdots \equiv p_k \equiv 1 \bmod 8$.*

(1) The following are equivalent:
  - *n is non-congruent with $\Sha(E_n)[2^\infty] \cong (\mathbb{Z}/2\mathbb{Z})^2$;*
  - *$h_4(-n) = 1$ and $h_8(-n) = 0$;*
  - *$r_4(K_2\mathcal{O}_{\mathbb{Q}(\sqrt{n})}) = 0$.*

(2) The following are equivalent:
  - *$2n$ is non-congruent with $\Sha(E_{2n})[2^\infty] \cong (\mathbb{Z}/2\mathbb{Z})^2$;*
  - *$h_4(-n) = 1$ and $h_8(-n) + h_8(-2n) = 1$;*
  - *$r_4(K_2\mathcal{O}_{\mathbb{Q}(\sqrt{-2n})}) = 0$.*

1.2.3. *General case.*

Theorem 1.8. *Assume that $\left(\frac{p_i}{q_j}\right) = 1, \forall i, j$, $p_1 \equiv \cdots \equiv p_k \equiv 1 \bmod 8$ and Q is non-congruent with $\Sha(E_Q)[2^\infty] = 0$. If there is a decomposition $P = f_1 \cdots f_r$ such that*

- *$h_4(-f_i) = 1, \forall i$;*
- *$\left(\frac{p}{p'}\right) = 1$ for any $i \neq j$ and prime factors $p \mid f_i, p' \mid f_j$;*
- *$\left(\frac{\gamma_i}{f_j}\right) = 1$ if $i \neq j$; $\left(\frac{\gamma_i}{f_i}\right) = (-1)^{h_8(-f_i)}$,*

then n is non-congruent with $Ш(E_n)[2^\infty] \cong (\mathbb{Z}/2\mathbb{Z})^{2r}$, where $(\alpha_i, \beta_i, \gamma_i)$ is a primitive positive solution of $f_i\alpha_i^2 + \frac{n}{f_i}\beta_i^2 = 4\gamma_i^2$.

When $\ell = 0$, we obtain the following results, where (1) is just [Wan16, Theorem 1.2].

Corollary 1.9. *Let $n = p_1 \cdots p_k$ be a square-free integer where $p_1 \equiv \cdots \equiv p_k \equiv 1 \bmod 8$.*

(1) If there is a decomposition $n = f_1 \cdots f_r$ such that
- $h_4(-f_i) = 1, h_8(-f_i) = 0, \forall i;$
- $h_8(-n) = r$, *or* $h_8(-n) = r - 1$ *and* $[(2, \sqrt{-n})] \notin \mathcal{A}_{-n}^4$;
- $\left(\frac{p}{p'}\right) = 1$ *for any* $i \neq j$ *and prime factors* $p \mid f_i, p' \mid f_j$,

then n is non-congruent with $Ш(E_n)[2^\infty] \cong (\mathbb{Z}/2\mathbb{Z})^{2r}$.

(2) If there is a decomposition $n = f_1 \cdots f_r$ such that
- $h_4(-f_i) = 1, h_8(-f_i) = 0, \forall i;$
- $h_8(-2n) = r;$
- $\left(\frac{p}{p'}\right) = 1$ *for any* $i \neq j$ *and prime factors* $p \mid f_i, p' \mid f_j$,

then $2n$ is non-congruent with $Ш(E_{2n})[2^\infty] \cong (\mathbb{Z}/2\mathbb{Z})^{2r}$.

Let's sketch the proof of these results. Since the congruent elliptic curve E_n has full rational 2-torsion, the pure 2-Selmer group $\mathrm{Sel}_2'(E_n) := \mathrm{Sel}_2(E_n)/E_n(\mathbb{Q})[2]$ can be identified with a set of triples $(d_1, d_2, d_3) \in (\mathbb{Q}^\times/\mathbb{Q}^{\times 2})^3$, where d_1, d_2, d_3 may be taken as square-free integers. The local conditions for Selmer elements translate into certain quadratic residue conditions, which in turn correspond to the 4-ranks of class groups of associated quadratic fields. As established in [Wan16], $E_n(\mathbb{Q})$ is finite with $Ш(E_n)[2^\infty] \cong (\mathbb{Z}/2\mathbb{Z})^{s_2(n)}$ if and only if the Cassels pairing on $\mathrm{Sel}_2'(E_n)$ is non-degenerate. This condition can be expressed in terms of the 8-ranks of class groups and the 4-ranks of tame kernels of associated quadratic fields.

1.3. Notations.

Denote by
- $\gcd(m, n)$ the greatest common divisor of integers m, n, where $m \neq 0$ or $n \neq 0$;
- $(a, b)_v$ the Hilbert symbol;
- $[a, b]_v$ the additive Hilbert symbol, i.e., the image of $(a, b)_v$ under the isomorphism $\{\pm 1\} \xrightarrow{\sim} \mathbb{F}_2$;
- $\left(\frac{a}{b}\right) = \prod_{p \mid b}(a, b)_p$ the Jacobi symbol, where $\gcd(a, b) = 1$ and $b > 0$;
- $\left[\frac{a}{b}\right]$ the additive Jacobi symbol, i.e., the image of $\left(\frac{a}{b}\right)$ under the isomorphism $\{\pm 1\} \xrightarrow{\sim} \mathbb{F}_2$;
- v_p the normalized valuation on $\mathbb{Q}_p$;
- $\mathbf{0} = (0, \ldots, 0)^{\mathrm{T}}$ and $\mathbf{1} = (1, \ldots, 1)^{\mathrm{T}}$;
- $r_{2^a}(A)$ the 2^a-rank of a finite abelian group A, see (1.1);

If n is a square-free positive integer, then we denote by
- $E_n : y^2 = x^3 - n^2 x$ the congruent elliptic curve associated to n;
- $\mathrm{Sel}_2(E_n)$ the 2-Selmer group of $E_n/\mathbb{Q}$;
- $Ш(E_n)$ the Shafarevich-Tate group of $E_n/\mathbb{Q}$;
- $\mathrm{Sel}_2'(E_n) := \mathrm{Sel}_2(E_n)/E_n(\mathbb{Q})[2]$ the pure 2-Selmer group of $E_n/\mathbb{Q}$;
- $s_2(n) = \dim_{\mathbb{F}_2} \mathrm{Sel}_2'(E_n)$ the pure 2-Selmer rank of E_n.

If n is odd with a fixed ordered prime decomposition $n = p_1 \cdots p_k$, then we denote by

- $\mathbf{A}_n = \big([p_j, -n]_{p_i}\big)_{k\times k}$ a matrix associated to n, see (2.2);
- $\mathbf{D}_{n,\varepsilon} = \operatorname{diag}\big\{\big[\frac{\varepsilon}{p_1}\big], \dots, \big[\frac{\varepsilon}{p_k}\big]\big\}$ a matrix associated to n and ε, see (2.3);
- $\mathbf{b}_{n,\varepsilon} = \mathbf{D}_{n,\varepsilon}\mathbf{1} = \big(\big[\frac{\varepsilon}{p_1}\big], \dots, \big[\frac{\varepsilon}{p_k}\big]\big)^{\mathrm{T}}$;
- $\mathbf{M}_n$ (resp. $\mathbf{M}_{2n}$) the Monsky matrix of E_n (resp. E_{2n}), see (2.4) and (2.6);
- $\psi_n(d) = \big(v_{p_1}(d), \dots, v_{p_k}(d)\big)^{\mathrm{T}}$ a vector over $\mathbb{F}_2$ associated to $0 < d \mid n$.

If $m \neq 0, 1$ is a square-free integer, then we denote by

- $F_m = \mathbb{Q}(\sqrt{m})$ a quadratic field;
- $\mathbf{R}_m$ the Rédei matrix of F_m, with a submatrix $\mathbf{R}'_m$, see (2.9) and (2.12);
- $\mathcal{A}_m$ the narrow class group of F_m;
- D_m the discriminant of F_m;
- $\omega_m = (D_m + \sqrt{D_m})/2$;
- $\mathcal{O}_m = \mathbb{Z} + \mathbb{Z}\omega_m$ the ring of integers of F_m;
- $\mathscr{D}_m$ the set of all square-free positive divisors of D_m;
- $\theta_m : \mathscr{D}_m \to \mathcal{A}_m[2]$ a two-to-one onto homomorphism, see Proposition 2.2;
- $h_{2^a}(m)$ the 2^a-rank of $\mathcal{A}_m$;
- $K_2\mathcal{O}_m$ the tame kernel of F_m;
- $\mathbf{B}_m = \mathbf{A}_n + \mathbf{D}_{n,m/n}$ a matrix associated to m, where n is the odd part of $|m|$.

2. Preliminaries

2.1. **The Monsky matrix.**

By the 2-descent method, Monsky in [HB94, Appendix] represented the pure 2-Selmer group

$$\mathrm{Sel}'_2(E_n) := \frac{\mathrm{Sel}_2(E_n)}{E_n(\mathbb{Q})[2]}$$

as the kernel of a matrix $\mathbf{M}_n$ over $\mathbb{F}_2$. Let's recall it roughly. One can identify $\mathrm{Sel}_2(E_n)$ with

$$\{\Lambda = (d_1, d_2, d_3) \in (\mathbb{Q}^\times/\mathbb{Q}^{\times 2})^3 : D_\Lambda(\mathbb{A}_\mathbb{Q}) \neq \emptyset, d_1d_2d_3 \equiv 1 \bmod \mathbb{Q}^{\times 2}\},$$

where D_Λ is a genus one curve defined by

$$\begin{cases} H_1: & -nt^2 + d_2u_2^2 - d_3u_3^2 = 0, \\ H_2: & -nt^2 + d_3u_3^2 - d_1u_1^2 = 0, \\ H_3: & 2nt^2 + d_1u_1^2 - d_2u_2^2 = 0. \end{cases} \tag{2.1}$$

Under this identification, $O, (n, 0), (-n, 0), (0, 0)$ and other point $(x, y) \in E_n(\mathbb{Q})$ correspond to $(1, 1, 1), (2, 2n, n), (-2n, 2, -n), (-n, n, -1)$ and $(x - n, x + n, x)$ respectively.

Let n be an odd positive square-free integer with an ordered prime decomposition $n = p_1 \cdots p_k$. Denote by

$$\mathbf{A}_{2n} = \mathbf{A}_n := (a_{ij})_{k\times k} \quad \text{where} \quad a_{ij} = [p_j, -n]_{p_i} = \begin{cases} \big[\frac{p_j}{p_i}\big], & i \neq j; \\ \big[\frac{n/p_i}{p_i}\big], & i = j, \end{cases} \tag{2.2}$$

and

$$\mathbf{D}_{n,\varepsilon} := \operatorname{diag}\Big\{\Big[\frac{\varepsilon}{p_1}\Big], \dots, \Big[\frac{\varepsilon}{p_k}\Big]\Big\}. \tag{2.3}$$

Then $\mathbf{A}_n\mathbf{1} = \mathbf{0}$ and $\operatorname{corank} \mathbf{A}_n \geq 1$.

Monsky showed that each element in $\mathrm{Sel}_2'(E_n)$ can be represented as (d_1, d_2, d_3), where d_1, d_2, d_3 are all positive divisors of n. The system D_Λ is locally solvable everywhere if and only if certain conditions on the Hilbert symbols hold. Then we can express $\mathrm{Sel}_2'(E_n)$ as the kernel of the *Monsky matrix*

$$\mathbf{M}_n := \begin{pmatrix} \mathbf{A}_n + \mathbf{D}_{n,2} & \mathbf{D}_{n,2} \\ \mathbf{D}_{n,2} & \mathbf{A}_n + \mathbf{D}_{n,-2} \end{pmatrix} \tag{2.4}$$

via the isomorphism

$$\begin{aligned} \mathrm{Sel}_2'(E_n) &\to \operatorname{Ker} \mathbf{M}_n \\ (d_1, d_2, d_3) &\mapsto \begin{pmatrix} \psi_n(d_2) \\ \psi_n(d_1) \end{pmatrix}, \end{aligned} \tag{2.5}$$

where $\psi_n(d) := \big(v_{p_1}(d), \dots, v_{p_k}(d)\big)^{\mathrm{T}} \in \mathbb{F}_2^k$ for any positive divisor d of n.

Similarly, each element in $\mathrm{Sel}_2'(E_{2n})$ can be represented as (d_1, d_2, d_3), where d_1, d_2, d_3 are all divisors of n and $d_2 > 0, d_3 \equiv 1 \bmod 4$. Then we can express $\mathrm{Sel}_2'(E_{2n})$ as the kernel of the *Monsky matrix*

$$\mathbf{M}_{2n} := \begin{pmatrix} \mathbf{A}_n^{\mathrm{T}} + \mathbf{D}_{n,2} & \mathbf{D}_{n,-1} \\ \mathbf{D}_{n,2} & \mathbf{A}_n + \mathbf{D}_{n,2} \end{pmatrix} \tag{2.6}$$

via the isomorphism

$$\begin{aligned} \mathrm{Sel}_2'(E_{2n}) &\to \operatorname{Ker} \mathbf{M}_{2n} \\ (d_1, d_2, d_3) &\mapsto \begin{pmatrix} \psi_n(|d_3|) \\ \psi_n(d_2) \end{pmatrix}. \end{aligned} \tag{2.7}$$

In both cases, we have

$$s_2(n) := \dim_{\mathbb{F}_2} \mathrm{Sel}_2'(E_n) = \operatorname{corank} \mathbf{M}_n. \tag{2.8}$$

2.2. **The Cassels pairing.** Cassels in [Cas98] defined a (skew-)symmetric bilinear pairing $\langle -, - \rangle$ on the $\mathbb{F}_2$-vector space $\mathrm{Sel}_2'(E_n)$. For any $\Lambda \in \mathrm{Sel}_2(E_n)$, the equation H_i in (2.1) is locally solvable everywhere. Thus H_i is solvable over $\mathbb{Q}$ by the Hasse-Minkowski principal. Choose $Q_i \in H_i(\mathbb{Q})$ and let L_i be a linear form such that $L_i = 0$ defines the tangent plane of H_i at Q_i. For any $\Lambda' = (d_1', d_2', d_3') \in \mathrm{Sel}_2(E_n)$, define the *Cassels pairing*

$$\langle \Lambda, \Lambda' \rangle = \sum_v \langle \Lambda, \Lambda' \rangle_v \in \mathbb{F}_2 \quad \text{where} \quad \langle \Lambda, \Lambda' \rangle_v = \sum_{i=1}^3 \big[L_i(P_v), d_i'\big]_v,$$

where $P_v \in D_\Lambda(\mathbb{Q}_v)$ for each place v of $\mathbb{Q}$. This pairing is independent of the choice of P_v, Q_i and the representative Λ. It is (skew-)symmetric and satisfies $\langle \Lambda, \Lambda \rangle = 0$.

Lemma 2.1 ([Cas98, Lemma 7.2]). *The local Cassels pairing $\langle -, - \rangle_v = 0$ if*

- $v \nmid 2\infty$*,*
- *the coefficients of H_i and L_i are all integral at v for $i = 1, 2, 3$, and*
- *modulo D_Λ and $L_i = 0$ by v, they define a curve of genus 1 over $\mathbb{F}_v$ together with tangents to it.*

2.3. **The narrow class group.** Let $F_m = \mathbb{Q}(\sqrt{m})$ be a quadratic field, where $m \neq 0, 1$ is a square-free integer. We will use the notations introduced in §1.3. Denote by $\mathbf{N} = \mathbf{N}_{F_m/\mathbb{Q}}$ the norm map. Fix an ordered decomposition of the odd part n of $|m|$: $n = p_1 \cdots p_k$. If $2 \mid D$, denote by $p_{k+1} = 2$. Let t be the number of prime factors of D_m. Then the Gauss genus theory tells:

Proposition 2.2 ([Hec81, Chapter 7])**.** *(1) The map $\theta_m : \mathscr{D}_m \to \mathcal{A}_m[2]$ defined as*

$$\theta_m(d) = [(d, \omega_m)]$$

is a two-to-one onto homomorphism. In particular,

$$h_2(m) = \dim_{\mathbb{F}_2} \mathcal{A}_m[2] = t - 1.$$

(2) Let $\mathfrak{a}$ be a non-zero fractional ideal of F_m. Then the ideal class $[\mathfrak{a}] \in \mathcal{A}_m^2$ if and only if $\mathbf{N}\mathfrak{a} \in \mathbf{N}F_m$.

When $m < 0$, the kernel of θ_m is $\{1, |m|\}$.

To calculate $h_4(m)$, we need the Rédei matrix, which is defined as

$$\mathbf{R}_m = ([p_j, m]_{p_i})_{t \times t}. \tag{2.9}$$

Example 2.3. Let $n = p_1 \cdots p_k$ be an odd positive square-free integer. Denote by

$$\mathbf{b}_{n,\varepsilon} := \left(\left[\frac{\varepsilon}{p_1}\right], \dots, \left[\frac{\varepsilon}{p_k}\right]\right)^{\mathrm{T}} = \mathbf{D}_{n,\varepsilon}\mathbf{1}.$$

When $n \equiv 1 \bmod 4$, we have

$$\mathbf{R}_n = \mathbf{A}_n + \mathbf{D}_{n,-1}, \qquad \mathbf{R}_{-n} = \begin{pmatrix} \mathbf{A}_n & \mathbf{b}_{n,2} \\ \mathbf{b}_{n,-1}^{\mathrm{T}} & \left[\frac{2}{n}\right] \end{pmatrix},$$

$$\mathbf{R}_{2n} = \begin{pmatrix} \mathbf{A}_n + \mathbf{D}_{n,-2} & \mathbf{b}_{n,2} \\ \mathbf{b}_{n,2}^{\mathrm{T}} & \left[\frac{2}{n}\right] \end{pmatrix}, \qquad \mathbf{R}_{-2n} = \begin{pmatrix} \mathbf{A}_n + \mathbf{D}_{n,2} & \mathbf{b}_{n,2} \\ \mathbf{b}_{n,-2}^{\mathrm{T}} & \left[\frac{2}{n}\right] \end{pmatrix}.$$

When $n \equiv -1 \bmod 4$, we have

$$\mathbf{R}_n = \begin{pmatrix} \mathbf{A}_n + \mathbf{D}_{n,-1} & \mathbf{b}_{n,2} \\ \mathbf{b}_{n,-1}^{\mathrm{T}} & \left[\frac{2}{n}\right] \end{pmatrix}, \qquad \mathbf{R}_{-n} = \mathbf{A}_n,$$

$$\mathbf{R}_{2n} = \begin{pmatrix} \mathbf{A}_n + \mathbf{D}_{n,-2} & \mathbf{b}_{n,2} \\ \mathbf{b}_{n,-2}^{\mathrm{T}} & \left[\frac{2}{n}\right] \end{pmatrix}, \qquad \mathbf{R}_{-2n} = \begin{pmatrix} \mathbf{A}_n + \mathbf{D}_{n,2} & \mathbf{b}_{n,2} \\ \mathbf{b}_{n,2}^{\mathrm{T}} & \left[\frac{2}{n}\right] \end{pmatrix}.$$

One can see that the following are equivalent:

- $d \in \mathscr{D}_m \cap \mathbf{N}F_m$;
- $X^2 - mY^2 = dZ^2$ is solvable over $\mathbb{Q}$;
- the Hilbert symbols $(d, m)_v = 1, \forall v$;
- $\mathbf{R}_m\mathbf{d} = \mathbf{0}$, where $\mathbf{d} = \big(v_{p_1}(d), \dots, v_{p_t}(d)\big)^{\mathrm{T}}$.

Rédei showed that θ_m induces a two-to-one onto homomorphism

$$\theta_m : \mathscr{D}_m \cap \mathbf{N}F_m \to \mathcal{A}_m[2] \cap \mathcal{A}_m^2, \tag{2.10}$$

which induces that

$$h_4(m) = \operatorname{corank} \mathbf{R}_m - 1. \tag{2.11}$$

Denote by

$$\mathbf{R}'_m = ([p_j, m]_{p_i})_{k \times t}. \tag{2.12}$$

If $2 \mid D_m$, then $\mathbf{R}'_m$ is the submatrix of $\mathbf{R}_m$ by removing the last row; otherwise $\mathbf{R}'_m = \mathbf{R}_m$. Since $\mathbf{1}^{\mathrm{T}}\mathbf{R}_m = \mathbf{0}^{\mathrm{T}}$, we have

$$\operatorname{rank}\mathbf{R}'_m = \operatorname{rank}\mathbf{R}_m. \tag{2.13}$$

See [Rè34] and [LY20, Example 2.6].

The 8-rank $h_8(m)$ can be obtained by the following proposition, which is similar to [Wan16, Proposition 3.6]. See also [JY11, Lu15].

Proposition 2.4. *For any $d \in \mathscr{D}_m \cap \mathbf{N}F_m$, let (α, β, γ) be a primitive positive solution of*

$$d\alpha^2 - \frac{m}{d}\beta^2 = 4\gamma^2.$$

Then

1. *$\theta_m(d) \in \mathcal{A}_m^4$ if and only if $\big([\gamma, m]_{p_1}, \dots, [\gamma, m]_{p_t}\big)^{\mathrm{T}} \in \operatorname{Im}\mathbf{R}_m$;*
2. *$\sum_{i=1}^t [\gamma, m]_{p_i} = 0$.*

In particular, $\theta_m(d) \in \mathcal{A}_m^4$ if and only if $\mathbf{b}_{n,\gamma} \in \operatorname{Im}\mathbf{R}'_m$, where n is the odd part of $|m|$.

Proof. Denote by σ the non-trivial automorphism of $\mathbb{Q}(\sqrt{m})$. If p is an odd prime factor of γ, then $p \nmid m$ and $\left(\frac{m}{p}\right) = 1$. Thus $(p) = \mathfrak{p}\mathfrak{p}^\sigma$ is split in F_m and $[\gamma, m]_p = 0$. We will show that $x = (d\alpha + \beta\sqrt{m})/2 \in \mathcal{O}_m$.

- If d is odd and m is even, then both of α and β are even and $x \in \mathcal{O}_m$.
- If d, m are odd, then α and β have same parities. If moreover both of α and β are odd, then $4 \mid (d - m/d)$, $m \equiv 1 \bmod 4$ and $x \in \mathcal{O}_m$.
- If d is even, then β is even and $x \in \mathcal{O}_m$.

Certainly, x is totally positive and $p \mid d\gamma^2 = \mathbf{N}(x)$. If both $\mathfrak{p}, \mathfrak{p}^\sigma$ divide $x\mathcal{O}_m$, then $p\mathcal{O}_m \mid x\mathcal{O}_m$ and $p \mid \alpha, \beta, \gamma$, which contradicts to $\gcd(\alpha, \beta, \gamma) = 1$. Hence only one of $\mathfrak{p}$ and $\mathfrak{p}^\sigma$ divides $x\mathcal{O}_m$. We may assume that $\mathfrak{p}^\sigma \mid x\mathcal{O}_m$ for each odd $p \mid \gamma$.

Assume that d is odd. If γ is odd, we have

$$x\mathcal{O}_m = \mathfrak{d}\prod_{p \mid \gamma}(\mathfrak{p}^\sigma)^{2v_p(\gamma)} = \gamma^2\mathfrak{d}\mathfrak{c}^{-2}, \quad \text{where } \mathfrak{c} := \prod_{p \mid \gamma}\mathfrak{p}^{v_p(\gamma)} \text{ with } \mathbf{N}\mathfrak{c} = \gamma \tag{2.14}$$

and $\mathfrak{d} = (d, \omega_m)$. If γ is even, one can show that m is odd. Then both of α and β are odd, $8 \mid (d - m/d)$ and $m \equiv 1 \bmod 8$. Thus $2\mathcal{O}_m = \mathfrak{q}\mathfrak{q}^\sigma$ is split in F. Similarly, only one of $\mathfrak{q}$ and $\mathfrak{q}^\sigma$ divides $x\mathcal{O}_m$. We may assume that $\mathfrak{q}^\sigma \mid x\mathcal{O}_m$. Hence we also have (2.14), where $\mathfrak{p}$ is $\mathfrak{q}$ for $p = 2$.

Assume that d is even. Then D_m is even, $m \not\equiv 1 \bmod 4$ and $2\mathcal{O}_m = \mathfrak{q}^2$ is ramified in F. Similarly, we have (2.14), where $\mathfrak{p} = \mathfrak{p}^\sigma = \mathfrak{q}$ for $p = 2$.

(1) By (2.14), we have $[\mathfrak{d}] = [\mathfrak{c}]^2$. Clearly, $[\mathfrak{d}] \in \mathcal{A}_m^4$ if and only if $[\mathfrak{c}] + [(a, \omega_m)] \in \mathcal{A}_m^2$ for some $a \in \mathscr{D}_m$. This is equivalent to $a\mathbf{N}\mathfrak{c} = a\gamma \in \mathbf{N}F_m$ by Proposition 2.2. Note that

- $[a\gamma, m]_p = 1$ for any odd prime $p \mid \gamma$;
- $[a\gamma, m]_\infty = 1$ because $a\gamma > 0$;
- if $2 \nmid D_m$ and γ is odd, then a is odd and $m \equiv 1 \bmod 4$; if $2 \nmid D_m$ and γ is even, then $m \equiv 1 \bmod 8$.

In other words, $[a\gamma, m]_v = 1$ for all $v \nmid D_m$. Thus $a\gamma \in \mathbf{N}F_m$ if and only if $[a, m]_{p_i} = [\gamma, m]_{p_i}$ for all $p_i \mid D_m$, if and only if

$$\mathbf{R}_m\big(v_{p_1}(a), \dots, v_{p_t}(a)\big)^{\mathrm{T}} = \big([\gamma, m]_{p_1}, \dots, [\gamma, m]_{p_t}\big)^{\mathrm{T}}.$$

(2) Denote by γ_0 the odd part of γ. If $m \not\equiv 1 \bmod 4$, then D_m is even and

$$\sum_{i=1}^{t}[\gamma, m]_{p_i} = \sum_{p\mid\gamma_0}[\gamma, m]_p = 0.$$

Here, $[\gamma, m]_\infty = 0$ because $\gamma > 0$. If $m \equiv 1 \bmod 4$ and γ is odd, then $[\gamma, m]_2 = 0$; if $m \equiv 1 \bmod 4$ and γ is even, then $m \equiv 1 \bmod 8$ and $[\gamma, m]_2 = 0$, as shown in the proof of (1). Therefore

$$\sum_{i=1}^{t}[\gamma, m]_{p_i} = \sum_{p\mid\gamma_0}[\gamma_0, m]_p + [\gamma, m]_2 = 0. \qquad \square$$

2.4. **The tame kernel.** Denote by $K_2\mathcal{O}_m$ the tame kernel of F_m. We list the results about 2-rank and 4-rank of $K_2\mathcal{O}_m$ that we will use. Assume that $|m| > 2$.

Theorem 2.5 ([BS82])**.** *The subgroup $K_2\mathcal{O}_m[2]$ is generated by the Steinberg symbols*

- *$\{-1, d\}, d \mid m$;*
- *$\{-1, u + \sqrt{m}\}$, where $m = u^2 - cw^2$ for some $c = -1, \pm 2$ and $u, w \in \mathbb{N}$.*

Denote by k the number of odd prime factors of m. Then

$$r_2(K_2\mathcal{O}_m) = \begin{cases} k + \log_2 \#\big(\{\pm1, \pm2\} \cap \mathbf{N}F_m\big); & \text{if } m > 2; \\ k - 1 + \log_2 \#\big(\{1, 2\} \cap \mathbf{N}F_m\big); & \text{if } m < -2. \end{cases}$$

Theorem 2.6 ([Qin95b, Theorem 3.4])**.** *Suppose that $m > 2$. Denote by V_1 the set of positive $d \mid n$ satisfying: there exists $\varepsilon \in \{\pm1, \pm2\}$ such that $(d, -m)_p = \left(\frac{\varepsilon}{p}\right), \forall p \mid n$. If $2 \in \mathbf{N}F_m$, then write $m = 2\mu^2 - \lambda^2, \mu, \lambda \in \mathbb{N}$ and denote by V_2 the set of positive $d \mid n$ satisfying: there exists $\varepsilon \in \{\pm1\}$ such that $(d, -m)_p = \left(\frac{\varepsilon\mu}{p}\right), \forall p \mid n$. We have*

$$2^{r_4(K_2\mathcal{O}_m)+1} = \#V_1 + \#V_2.$$

Theorem 2.7 ([Qin95a, Theorem 4.1])**.** *Suppose that $m < -2$. Denote by V_1 the set of $d \mid n$ satisfying: there exists $\varepsilon \in \{1, 2\}$ such that $(d, -m)_p = \left(\frac{\varepsilon}{p}\right), \forall p \mid n$. If $2 \in \mathbf{N}F_m$, then write $m = 2\mu^2 - \lambda^2, \mu, \lambda \in \mathbb{N}$ and denote by V_2 the set of $d \mid n$ satisfying: $(d, -m)_p = \left(\frac{\mu}{p}\right), \forall p \mid n$. We have*

$$2^{r_4(K_2\mathcal{O}_m)+2} = \#V_1 + \#V_2.$$

Here, $V_2 = \emptyset$ if $2 \notin \mathbf{N}F_m$.

Let's translate these results into the language of matrices. Denote by n the odd part of $|m|$ and denote by $\mathbf{B}_m = \mathbf{A}_n + \mathbf{D}_{n,m/n}$, where $\mathbf{A}_n$ is defined as (2.2). If $m > 2$, then

$$\#\{\mathbf{x} : \mathbf{B}_m\mathbf{x} = \mathbf{b}_{n,\pm1}, \mathbf{b}_{n,\pm2}\} + \#\{\mathbf{x} : \mathbf{B}_m\mathbf{x} = \mathbf{b}_{n,\pm\mu}\} = 2^{r_4(K_2\mathcal{O}_m)+1}. \tag{2.15}$$

If $m < -2$, then

$$\#\{\mathbf{x} : \mathbf{B}_m\mathbf{x} = \mathbf{0}, \mathbf{b}_{n,2}\} + \#\{\mathbf{x} : \mathbf{B}_m\mathbf{x} = \mathbf{b}_{n,\mu}\} = \begin{cases} 2^{r_4(K_2\mathcal{O}_m)+2}, & \text{if } \mathbf{b}_{n,-1} \notin \operatorname{Im}\mathbf{B}_m; \\ 2^{r_4(K_2\mathcal{O}_m)+1}, & \text{if } \mathbf{b}_{n,-1} \in \operatorname{Im}\mathbf{B}_m. \end{cases} \tag{2.16}$$

Theorem 2.8. *Assume that $n = p_1 \cdots p_k$ is an odd positive square-free integer, where all prime factors p_i are congruent to ±1 modulo 8 and $n \equiv 1 \bmod 8$. Write $n = \lambda^2 - 2\mu^2$ where $\lambda, \mu \in \mathbb{N}$.*

(1) *We have* $h_4(n)+1 = h_4(2n) = h_4(-n) = h_4(-2n) = \operatorname{corank}\mathbf{A}_n$.

(2) *If* $h_4(-n)=1$, *then* $h_8(-n) = 1-\left[\frac{\lambda+\mu}{d}\right]$. *If moreover all* $p_i \equiv 1 \bmod 8$, *then* $h_8(-n) = 1-\left[\frac{\sqrt{2}+1}{n}\right]$.

(3) *If* $h_4(-2n)=1$, *then* $h_8(-2n) = 1-\left[\frac{\lambda}{d}\right]$. *If moreover all* $p_i \equiv 1 \bmod 8$, *then* $h_8(-2n) = 1-\left[\frac{\sqrt{2}}{n}\right]$.

(4) *Assume that all* $p_i \equiv 1 \bmod 8$. *We have* $r_4(K_2\mathcal{O}_{-2n}) = 0$ *if and only if* $h_4(-n)=1, h_8(-n)+h_8(-2n)=1$. *If* $h_4(-n)=1$, *then* $r_4(K_2\mathcal{O}_{-2n}) \le 1$.

(5) *Assume that all* $p_i \equiv 1 \bmod 8$. *We have* $r_4(K_2\mathcal{O}_{n}) = 0$ *if and only if* $h_4(-n)=1, h_8(-n)=0$. *If* $h_4(-n)=1$, *then* $r_4(K_2\mathcal{O}_{n}) \le 1$.

Here, $1 < d \mid n$ *such that* $\mathbf{A}_n^{\mathrm{T}}\psi_n(d) = \mathbf{0}$.

Proof. (1) By the quadratic reciprocity law, we have

$$\mathbf{A}_n^{\mathrm{T}} = \mathbf{A}_n + \mathbf{D}_{n,-1} + \mathbf{b}_{n,-1}\mathbf{b}_{n,-1}^{\mathrm{T}}. \tag{2.17}$$

By $\mathbf{b}_{n,-1}^{\mathrm{T}}\mathbf{b}_{n,-1} = \mathbf{b}_{n,-1}^{\mathrm{T}}\mathbf{1} = \left[\frac{-1}{n}\right] = 0$, one can show that

$$\mathbf{A}_n^{\mathrm{T}}(\mathbf{I}+\mathbf{1}\mathbf{b}_{n,-1}^{\mathrm{T}}) = \mathbf{A}_n + \mathbf{D}_{n,-1},$$

where $\mathbf{I}+\mathbf{1}\mathbf{b}_{n,-1}^{\mathrm{T}}$ is invertible since $(\mathbf{I}+\mathbf{1}\mathbf{b}_{n,-1}^{\mathrm{T}})^2 = \mathbf{I}$. Thus

$$\operatorname{rank}\mathbf{R}_n = \operatorname{rank}\mathbf{R}'_{-n} = \operatorname{rank}\mathbf{R}'_{\pm 2n} = \operatorname{rank}\mathbf{A}_n,$$

which concludes the result by (2.11) and (2.13).

(2) Since $\theta_{-n}(n) = [(\sqrt{-n})]$ is the trivial class, we have

$$\mathcal{A}_{-n}[2]\cap\mathcal{A}_{-n}^2 = \{[(1)], \theta_{-n}(2)\},$$

where $\theta_{-n}(2) = \theta_{-n}(2n)$. Note that $(\lambda+2\mu, 2, \lambda+\mu)$ is a primitive positive solution of $2\alpha^2 + \frac{n}{2}\beta^2 = 4\gamma^2$. Since $\operatorname{Im}\mathbf{R}'_{-n} = \{\mathbf{x} : \psi(d)^{\mathrm{T}}\mathbf{x} = 0\}$, by Proposition 2.4, we have $h_8(-n) = 1$ if and only if $\mathbf{b}_{n,\lambda+\mu} \in \operatorname{Im}\mathbf{R}'_{-n}$, if and only if $0 = \psi(d)^{\mathrm{T}}\mathbf{b}_{n,\lambda+\mu} = \left[\frac{\lambda+\mu}{d}\right]$.

If all $p_i \equiv 1 \bmod 8$, then $d = n$ since $\mathbf{A}_n^{\mathrm{T}}\mathbf{1} = \mathbf{0}$. Let μ' be the odd part of μ. Then

$$\left[\frac{\mu}{n}\right] = \left[\frac{n}{\mu'}\right] = \left[\frac{\lambda^2-2\mu^2}{\mu'}\right] = 0. \tag{2.18}$$

Since $\lambda \equiv \pm\sqrt{2}\mu \bmod p_i$, we have $\left[\frac{\lambda+\mu}{n}\right] = \left[\frac{\sqrt{2}+1}{n}\right]$.

(3) Note that $(2\mu, 2, \lambda)$ is a primitive positive solution of $2\alpha^2 + n\beta^2 = 4\gamma^2$. The result follows from arguments similar to (2).

(4) In this case, $\mathbf{B}_{-2n} = \mathbf{A}_n$ and $\mathbf{B}_{-2n}\mathbf{1} = \mathbf{b}_{n,-1}$. Note that

$$m = -2n = 2(\lambda+2\mu)^2 - (2\lambda+2\mu)^2.$$

By (2.16), $r_4(K_2\mathcal{O}_{-2n}) = 0$ if and only if $\operatorname{corank}\mathbf{A}_n = 1$ and $\mathbf{b}_{n,\lambda+2\mu} \notin \operatorname{Im}\mathbf{A}_n$, if and only if $h_4(-n) = 1$ and

$$1 = \mathbf{1}^{\mathrm{T}}\mathbf{b}_{n,\lambda+2\mu} = \left[\frac{\lambda+2\mu}{n}\right] = \left[\frac{\sqrt{2}+2}{n}\right] = \left[\frac{\sqrt{2}+1}{n}\right] + \left[\frac{\sqrt{2}}{n}\right],$$

i.e., $h_8(-n) + h_8(-2n) = 1$.

If $h_4(-n) = 1$, then $\operatorname{corank}\mathbf{A}_n = 1$. Thus $\mathbf{A}_n\mathbf{x} = \mathbf{0}$ has two solutions, $\mathbf{A}_n\mathbf{x} = \mathbf{b}_{n,\lambda+2\mu}$ has at most two solutions. Thus implies that $r_4(K_2\mathcal{O}_{-2n}) \le 1$ by (2.16).

(5) The proof is similar to (4). □

Proposition 2.9. *Let $n = p_1 \cdots p_k \equiv 1 \bmod 8$ be a square-free positive integer with odd prime factors p_i such that $p_i \equiv \pm 1 \bmod 8$ for all i. If $h_4(-n) = 1$, then*

$$h_8(-n) + h_8(-2n) \equiv \frac{d-1}{8} \bmod 2,$$

where d is the unique divisor of n such that $(d, n)_v = 1, \forall v$ and $d \neq 1, d \equiv 1 \bmod 4$.

Proof. Notice that $d = \left(\frac{-1}{|d|}\right)|d|$ and

$$\begin{aligned} 0 = [d, n]_{p_i} &= [d, -1]_{p_i} + [d, -n]_{p_i} \\ &= [d, -1]_{p_i} + [|d|, -n]_{p_i} + \left[\frac{-1}{|d|}\right][-1, -n]_{p_i} \\ &= [d, -1]_{p_i} + [|d|, -n]_{p_i} + \left[\frac{-1}{|d|}\right]\left[\frac{-1}{p_i}\right], \end{aligned}$$

we have

$$\begin{aligned} \mathbf{0} &= \mathbf{D}_{n,-1}\psi_n(|d|) + \mathbf{A}_n\psi_n(|d|) + \left[\frac{-1}{|d|}\right]\mathbf{b}_{n,-1} \\ &= (\mathbf{A}_n + \mathbf{D}_{n,-1})\psi_n(|d|) + \mathbf{b}_{n,-1}\mathbf{b}_{n,-1}^{\mathrm{T}}\psi_n(|d|) = \mathbf{A}_n^{\mathrm{T}}\psi_n(|d|) \end{aligned}$$

by (2.17). Write $n = \lambda^2 - 2\mu^2$ where $\lambda, \mu \in \mathbb{N}$. By Theorem 2.8 (2) and (3), $h_8(-n) + h_8(-2n) = 1$ if and only if

$$1 = \left[\frac{\lambda(\lambda+\mu)}{|d|}\right] = \left[\frac{1+\mu/\lambda}{|d|}\right] = \left[\frac{2+\sqrt{2}}{|d|}\right],$$

which is equivalent to $d \equiv 9 \bmod 16$ by [Zha23, Lemma 5.4]. □

3. The Selmer groups and the Cassles pairings

Let $n = PQ$ be a square-free positive integer with an ordered prime decomposition

$$n = \gcd(2, n)p_1 \cdots p_k q_1 \cdots q_\ell,$$

where $P = p_1 \cdots p_k, Q = \gcd(2, n)q_1 \cdots q_\ell$. Assume that $p_1 \equiv \cdots \equiv p_k \equiv 1 \bmod 8$ and there exists

$$\mathbf{u} = (u_1, \ldots, u_k)^{\mathrm{T}} \in \mathbb{F}_2^k, \qquad \mathbf{v} = (v_1, \ldots, v_\ell)^{\mathrm{T}} \in \mathbb{F}_2^\ell$$

such that the Legendre symbol $\left[\frac{p_i}{q_j}\right] = u_i v_j$. Clearly,

$$\mathbf{1}^{\mathrm{T}}\mathbf{u} = \sum_{i=1}^{k} u_i \quad \text{and} \quad \mathbf{1}^{\mathrm{T}}\mathbf{v} = \sum_{j=1}^{\ell} v_j.$$

Lemma 3.1. *Assume that $\mathbf{1}^{\mathrm{T}}\mathbf{u} = 0, \mathbf{1}^{\mathrm{T}}\mathbf{v} = 1$, $p_1 \equiv \cdots \equiv p_k \equiv 1 \bmod 8$ and Q is non-congruent with $\text{Ш}(E_Q)[2^\infty] = 0$. Then*

$$\operatorname{Ker}\mathbf{M}_n = \left\{ \begin{pmatrix} \mathbf{x} \\ \mathbf{0} \\ \mathbf{z} \\ \mathbf{0} \end{pmatrix} \middle| \ \mathbf{x}, \mathbf{z} \in \operatorname{Ker}(\mathbf{A}_P + \mathbf{U}_P) \right\}$$

In particular, $s_2(n) = 2\operatorname{corank}(\mathbf{A}_P + \mathbf{U}_P)$.

Proof. Note that $\mathbf{A}_n\mathbf{1}=\mathbf{0}$ and $\mathbf{A}_P^{\mathrm{T}}=\mathbf{A}_P$. By our assumptions,

$$\mathbf{A}_n=\begin{pmatrix}\mathbf{A}_P+\mathbf{U}_P & \mathbf{u}\mathbf{v}^{\mathrm{T}}\\ \mathbf{v}\mathbf{u}^{\mathrm{T}} & \mathbf{A}_Q\end{pmatrix}\quad\text{and}\quad \mathbf{A}_n^{\mathrm{T}}=\begin{pmatrix}\mathbf{A}_P+\mathbf{U}_P & \mathbf{u}\mathbf{v}^{\mathrm{T}}\\ \mathbf{v}\mathbf{u}^{\mathrm{T}} & \mathbf{A}_Q^{\mathrm{T}}\end{pmatrix}.$$

Note that $\mathbf{D}_{P,\pm 2}=\mathbf{O}_k$. If Q is odd, we have

$$\mathbf{M}_n=\begin{pmatrix}\mathbf{A}_P+\mathbf{U}_P & \mathbf{u}\mathbf{v}^{\mathrm{T}} & \mathbf{O}_k & \\ \mathbf{v}\mathbf{u}^{\mathrm{T}} & \mathbf{A}_Q+\mathbf{D}_{Q,2} & & \mathbf{D}_{Q,2}\\ \mathbf{O}_k & & \mathbf{A}_P+\mathbf{U}_P & \mathbf{u}\mathbf{v}^{\mathrm{T}}\\ & \mathbf{D}_{Q,2} & \mathbf{v}\mathbf{u}^{\mathrm{T}} & \mathbf{A}_Q+\mathbf{D}_{Q,-2}\end{pmatrix}.$$

If Q is even, we have

$$\mathbf{M}_n=\begin{pmatrix}\mathbf{A}_P+\mathbf{U}_P & \mathbf{u}\mathbf{v}^{\mathrm{T}} & \mathbf{O}_k & \\ \mathbf{v}\mathbf{u}^{\mathrm{T}} & \mathbf{A}_Q^{\mathrm{T}}+\mathbf{D}_{Q,2} & & \mathbf{D}_{Q,-1}\\ \mathbf{O}_k & & \mathbf{A}_P+\mathbf{U}_P & \mathbf{u}\mathbf{v}^{\mathrm{T}}\\ & \mathbf{D}_{Q,2} & \mathbf{v}\mathbf{u}^{\mathrm{T}} & \mathbf{A}_Q+\mathbf{D}_{Q,2}\end{pmatrix}.$$

If

$$\begin{pmatrix}\mathbf{x}\\ \mathbf{y}\\ \mathbf{z}\\ \mathbf{w}\end{pmatrix}\in\operatorname{Ker}\mathbf{M}_n,$$

then

$$(\mathbf{A}_P+\mathbf{U}_P)\mathbf{x}=\mathbf{u}\mathbf{v}^{\mathrm{T}}\mathbf{y},\qquad (\mathbf{A}_P+\mathbf{U}_P)\mathbf{z}=\mathbf{u}\mathbf{v}^{\mathrm{T}}\mathbf{w}$$

and

$$\mathbf{M}_Q\begin{pmatrix}\mathbf{y}\\ \mathbf{w}\end{pmatrix}=\begin{pmatrix}\mathbf{v}\mathbf{u}^{\mathrm{T}}\mathbf{x}\\ \mathbf{v}\mathbf{u}^{\mathrm{T}}\mathbf{z}\end{pmatrix}.$$

Since $\mathbf{A}_P=\mathbf{A}_P^{\mathrm{T}}$, we have $\mathbf{1}^{\mathrm{T}}\mathbf{A}_P=\mathbf{0}^{\mathrm{T}}$ and

$$0=\mathbf{1}^{\mathrm{T}}\mathbf{u}\mathbf{v}^{\mathrm{T}}\mathbf{y}=\mathbf{1}^{\mathrm{T}}(\mathbf{A}_P+\mathbf{U}_P)\mathbf{x}=\mathbf{1}^{\mathrm{T}}\mathbf{U}_P\mathbf{x}=\mathbf{u}^{\mathrm{T}}\mathbf{x}. \tag{3.1}$$

Similarly, $\mathbf{u}^{\mathrm{T}}\mathbf{z}=0$. Thus

$$\mathbf{M}_Q\begin{pmatrix}\mathbf{y}\\ \mathbf{w}\end{pmatrix}=\mathbf{0}.$$

Since $s_2(Q)=0$, $\mathbf{M}_Q$ is invertible and we have $\mathbf{y}=\mathbf{w}=\mathbf{0}$. Thus $\mathbf{x},\mathbf{z}\in\operatorname{Ker}(\mathbf{A}_P+\mathbf{U}_P)$,

$$\operatorname{Ker}\mathbf{M}_n=\left\{\begin{pmatrix}\mathbf{x}\\ \mathbf{0}\\ \mathbf{z}\\ \mathbf{0}\end{pmatrix}\ \middle|\ \mathbf{x},\mathbf{z}\in\operatorname{Ker}(\mathbf{A}_P+\mathbf{U}_P)\right\}$$

and $s_2(n)=2\operatorname{corank}(\mathbf{A}_P+\mathbf{U}_P)$. □

Proposition 3.2. *Let f_i,f_j be two positive divisors of P such that* $\gcd(f_i,f_j)=1$ *and $\psi_P(f_i),\psi_P(f_j)\in\operatorname{Ker}(\mathbf{A}_P+\mathbf{U}_P)$. Denote by*

$$\Lambda_t=(f_t,1,f_t)\quad\textit{and}\quad\Lambda_t'=(f_t,f_t,1)$$

for $t = i, j$. Then

$$\begin{aligned}
\langle \Lambda_i', \Lambda_i \rangle &= \left[\frac{\sqrt{2}+1}{f_i}\right] + \left[\frac{\gamma_i}{f_i}\right] = \left[\frac{\sqrt{2}+1}{f_i}\right] + \left[\frac{\gamma_i'}{f_i}\right],\\
\langle \Lambda_i', \Lambda_j \rangle &= \left[\frac{\gamma_i}{f_j}\right] = \left[\frac{\gamma_j'}{f_i}\right],\\
\langle \Lambda_i', \Lambda_i' \rangle &= \left[\frac{\gamma_i\gamma_i'}{f_i}\right], \qquad \langle \Lambda_i', \Lambda_j' \rangle = \left[\frac{\gamma_i\gamma_i'}{f_j}\right],
\end{aligned}$$

where $(\alpha_i, \beta_i, \gamma_i)$ $\big($resp. $(\alpha_i', \beta_i', \gamma_i')\big)$ is a primitive positive solution of

$$f_i\alpha_i^2 + \frac{n}{f_i}\beta_i^2 = 4\gamma_i^2 \qquad \left(\text{resp. } f_i\alpha_i'^2 - \frac{n}{f_i}\beta_i'^2 = 4\gamma_i'^2\right).$$

Proof. Let $(\alpha_i'', \beta_i'', \gamma_i'')$ be a primitive positive solution of $f_i\alpha_i''^2 - \frac{2n}{f_i}\beta_i''^2 = 4\gamma_i''^2$. It's easy to see that $\alpha_i, \beta_i, \gamma_i, \alpha_i', \beta_i', \gamma_i', \alpha_i'', \beta_i'', \gamma_i''$ are coprime to $n/\gcd(2,n)$.

(1) Recall that D_{Λ_i} is defined by

$$\begin{cases}
H_1: & -nt^2 + u_2^2 - f_iu_3^2 = 0,\\
H_2: & -\frac{n}{f_i}t^2 + u_3^2 - u_1^2 = 0,\\
H_3: & 2nt^2 + f_iu_1^2 - u_2^2 = 0.
\end{cases}$$

Choose

$$\begin{aligned}
Q_1 &= (\beta_i', f_i\alpha_i', 2\gamma_i') \in H_1(\mathbb{Q}), & L_1 &= \frac{n}{f_i}\beta_i't - \alpha_i'u_2 + 2\gamma_i'u_3,\\
Q_2 &= (0, 1, -1) \in H_2(\mathbb{Q}), & L_2 &= u_3 + u_1,\\
Q_3 &= (\beta_i'', 2\gamma_i'', f_i\alpha_i'') \in H_3(\mathbb{Q}), & L_3 &= \frac{2n}{f_i}\beta_i''t + 2\gamma_i''u_1 - \alpha_i''u_2.
\end{aligned}$$

By (3.1), we have $\mathbf{u}^{\mathrm{T}}\psi_P(f_t) = 0$, which implies that

$$\left[\frac{f_t}{q_s}\right] = \sum_{p_r \mid f_t} u_rv_s = v_s\mathbf{u}^{\mathrm{T}}\psi_P(f_t) = 0. \tag{3.2}$$

If $v = p_s \mid P$, then $\left[\frac{q_t}{p_s}\right] = \left[\frac{p_s}{q_t}\right] = u_sv_t$ and $p_s \equiv 1 \bmod 8$. Thus we have

$$\left[\frac{Q}{p_s}\right] = u_s\mathbf{v}^{\mathrm{T}}\mathbf{1} = u_s.$$

One can see that the s-th entry of the vector $(\mathbf{A}_P + \mathbf{U}_P)\psi_P(f_i)$ is

$$0 = u_s + \sum_{p \mid f_i}[p, -P]_{p_s} = \left[\frac{Q}{p_s}\right] + [f_i, -P]_{p_s} = \left[\frac{Q}{p_s}\right] + \left[\frac{P/f_i}{p_s}\right] = \left[\frac{n/f_i}{p_s}\right]$$

if $p_s \mid f_i$;

$$0 = \sum_{p \mid f_i}[p, -P]_{p_s} = [f_i, -P]_{p_s} = \left[\frac{f_i}{p_s}\right]. \tag{3.3}$$

if $p_s \mid \frac{P}{f_i}$.

(i) The case $v = p_s \mid f_i$. Take

$$P_v = (t, u_1, u_2, u_3) = \big(1, \sqrt{-2n/f_i}, 0, \sqrt{-n/f_i}\big).$$

Note that

$$\left(\beta_i'\sqrt{-n/f_i}+2\gamma_i'\right)\left(-\beta_i'\sqrt{-n/f_i}+2\gamma_i'\right)=f_i\alpha_i'^2$$

and one of $\pm\beta_i'\sqrt{-n/f_i}+2\gamma_i'$ is congruent to $4\gamma_i'$ modulo v. Since $[f_i,f_t]_v=0$ for $t=i,j$ by (3.3), we have

$$\left[\pm\beta_i'\sqrt{-n/f_i}+2\gamma_i',f_t\right]_v=[4\gamma_i',f_t]_v.$$

Then

$$\left[L_1(P_v),f_t\right]_v=\left[4\gamma_i'\sqrt{-n/f_i},f_t\right]_v=\left[\gamma_i'\sqrt{-n/f_i},f_t\right]_v.$$

Similarly,

$$\begin{aligned}\left[L_2(P_v),f_t\right]_v&=\left[(\sqrt{2}+1)\sqrt{-n/f_i},f_t\right]_v,\\ \left[L_3(P_v),f_t\right]_v&=\left[4\sqrt{2}\gamma_i''\sqrt{-n/f_i},f_t\right]_v=\left[\sqrt{2}\gamma_i''\sqrt{-n/f_i},f_t\right]_v.\end{aligned}$$

Thus

$$\begin{aligned}\left[L_1L_2(P_v),f_t\right]_v&=\left[(\sqrt{2}+1)\gamma_i',f_t\right]_v,\\ \left[L_1L_3(P_v),f_t\right]_v&=\left[\sqrt{2}\gamma_i'\gamma_i'',f_t\right]_v.\end{aligned}$$

(ii) The case $v=p_s\mid\frac{P}{f_i}$. Take

$$P_v=(t,u_1,u_2,u_3)=\left(0,1,\sqrt{f_i},1\right).$$

Similarly to (i), we have

$$\begin{aligned}\left[L_1(P_v),f_t\right]_v&=[4\gamma_i',f_t]_v=[\gamma_i',f_t]_v,\\ \left[L_2(P_v),f_t\right]_v&=[2,f_t]_v=0,\\ \left[L_3(P_v),f_t\right]_v&=[4\gamma_i'',f_t]_v=[\gamma_i'',f_t]_v,\end{aligned}$$

and then

$$\begin{aligned}\left[L_1L_2(P_v),f_t\right]_v&=[\gamma_i',f_t]_v,\\ \left[L_1L_3(P_v),f_t\right]_v&=[\gamma_i'\gamma_i'',f_t]_v.\end{aligned}$$

By Lemma 2.1 and (3.2), we have

$$\begin{aligned}\langle\Lambda_i,\Lambda_i\rangle&=\sum_{v\mid f_i}\left[\sqrt{2}\gamma_i'\gamma_i'',f_i\right]_v+\sum_{v\mid\frac{P}{f_i}}[\gamma_i'\gamma_i'',f_i]_v=\left[\frac{\sqrt{2}\gamma_i'\gamma_i''}{f_i}\right],\\ \langle\Lambda_i,\Lambda_j\rangle&=\sum_{v\mid f_i}\left[\sqrt{2}\gamma_i'\gamma_i'',f_j\right]_v+\sum_{v\mid\frac{P}{f_i}}[\gamma_i'\gamma_i'',f_j]_v=\left[\frac{\gamma_i'\gamma_i''}{f_j}\right],\\ \langle\Lambda_i,\Lambda_i'\rangle&=\sum_{v\mid f_i}\left[(\sqrt{2}+1)\gamma_i',f_i\right]_v+\sum_{v\mid\frac{P}{f_i}}[\gamma_i',f_i]_v=\left[\frac{(\sqrt{2}+1)\gamma_i'}{f_i}\right],\\ \langle\Lambda_i,\Lambda_j'\rangle&=\sum_{v\mid f_i}\left[(\sqrt{2}+1)\gamma_i',f_j\right]_v+\sum_{v\mid\frac{P}{f_i}}[\gamma_i',f_j]_v=\left[\frac{\gamma_i'}{f_j}\right],\end{aligned}\tag{3.4}$$

(2) Recall that $D_{\Lambda'_i}$ is defined by

$$\begin{cases} H_1: & -nt^2 + f_i u_2^2 - u_3^2 = 0, \\ H_2: & -nt^2 + u_3^2 - f_i u_1^2 = 0, \\ H_3: & \frac{2n}{f_i} t^2 + u_1^2 - u_2^2 = 0. \end{cases}$$

Choose

$$\begin{aligned} Q_1 &= (\beta_i, 2\gamma_i, f_i\alpha_i) \in H_1(\mathbb{Q}), & L_1 &= \frac{n}{f_i}\beta_i t - 2\gamma_i u_2 + \alpha_i u_3, \\ Q_2 &= (\beta'_i, f_i\alpha'_i, 2\gamma'_i) \in H_2(\mathbb{Q}), & L_2 &= \frac{n}{f_i}\beta'_i t - \alpha'_i u_3 + 2\gamma'_i u_1, \\ Q_3 &= (0, 1, -1) \in H_3(\mathbb{Q}), & L_3 &= u_1 + u_2. \end{aligned}$$

(i) The case $v \mid f_i$. Take

$$P_v = (t, u_1, u_2, u_3) = \big(1, \sqrt{-n/f_i}, \sqrt{n/f_i}, 0\big).$$

Similarly, we have

$$\begin{aligned} \big[L_1(P_v), f_t\big]_v &= \big[4\gamma_i\sqrt{n/f_i}, f_t\big]_v = \big[\gamma_i\sqrt{n/f_i}, f_t\big]_v, \\ \big[L_2(P_v), f_t\big]_v &= \big[4\gamma'_i\sqrt{-n/f_i}, f_t\big]_v = \big[\gamma'_i\sqrt{-n/f_i}, f_t\big]_v, \\ \big[L_3(P_v), f_t\big]_v &= \big[(\sqrt{-1}+1)\sqrt{n/f_i}, f_t\big]_v, \end{aligned}$$

and then

$$\begin{aligned} \big[L_1L_2(P_v), f_t\big]_v &= \big[\sqrt{-1}\gamma_i\gamma'_i, f_t\big]_v = \big[\gamma_i\gamma'_i, f_t\big]_v, \\ \big[L_1L_3(P_v), f_t\big]_v &= \big[(\sqrt{-1}+1)\gamma_i, f_t\big]_v = \big[(\sqrt{2}+1)\gamma_i, f_t\big]_v. \end{aligned}$$

Here, we use the fact that

$$4\sqrt{-1} = (\sqrt{2} + \sqrt{-2})^2,$$
$$(\sqrt{2}+1)(\sqrt{-1}+1) = \frac{1}{2}(\sqrt{2} + \sqrt{-1} + 1)^2$$

are squares in $\mathbb{Q}_v$.

(ii) The case $v \mid \frac{P}{f_i}$. Take

$$P_v = (t, u_1, u_2, u_3) = \big(0, 1, 1, \sqrt{f_i}\big).$$

Similarly, we have

$$\begin{aligned} \big[L_1(P_v), f_t\big]_v &= [-4\gamma_i, f_t]_v = [\gamma_i, f_t]_v, \\ \big[L_2(P_v), f_t\big]_v &= [4\gamma'_i, f_t]_v = [\gamma'_i, f_t]_v, \\ \big[L_3(P_v), f_t\big]_v &= [2, f_t]_v = 0, \end{aligned}$$

and then

$$\begin{aligned} \big[L_1L_2(P_v), f_t\big]_v &= [\gamma_i\gamma'_i, f_t]_v, \\ \big[L_1L_3(P_v), f_t\big]_v &= [\gamma_i, f_t]_v. \end{aligned}$$

By Lemma 2.1 and (3.2), we have

$$\begin{aligned}
\langle \Lambda_i', \Lambda_i' \rangle &= \sum_{v\mid f_i} [\gamma_i\gamma_i', f_i]_v + \sum_{v\mid \frac{P}{f_i}} [\gamma_i\gamma_i', f_i]_v = \left[\frac{\gamma_i\gamma_i'}{f_i}\right],\\
\langle \Lambda_i', \Lambda_j' \rangle &= \sum_{v\mid f_i} [\gamma_i\gamma_i', f_j]_v + \sum_{v\mid \frac{P}{f_i}} [\gamma_i\gamma_i', f_j]_v = \left[\frac{\gamma_i\gamma_i'}{f_j}\right],\\
\langle \Lambda_i', \Lambda_i \rangle &= \sum_{v\mid f_i} \big[(\sqrt{2}+1)\gamma_i, f_i\big]_v + \sum_{v\mid \frac{P}{f_i}} [\gamma_i, f_i]_v = \left[\frac{(\sqrt{2}+1)\gamma_i}{f_i}\right],\\
\langle \Lambda_i', \Lambda_j \rangle &= \sum_{v\mid f_i} \big[(\sqrt{2}+1)\gamma_i, f_j\big]_v + \sum_{v\mid \frac{P}{f_i}} [\gamma_i, f_j]_v = \left[\frac{\gamma_i}{f_j}\right],
\end{aligned} \tag{3.5}$$

Finally, we conclude the results by (3.4) and (3.5). □

4. Proof of main theorems

Lemma 4.1. *The following are equivalent:*

- *n is non-congruent with $\text{Ш}(E_n)[2^\infty] \cong (\mathbb{Z}/2\mathbb{Z})^{s_2(n)}$;*
- *the Cassels pairing on $\mathrm{Sel}_2'(E_n)$ is non-degenerate.*

Proof. The proof is due to [Wan16, pp 2146, 2157]. Since

$$0 \to E_n[2] \to E_n[4] \xrightarrow{\times 2} E_n[2] \to 0$$

is exact, we have the long exact sequence

$$0 \to \frac{E_n(\mathbb{Q})[2]}{2E_n(\mathbb{Q})[4]} \to \mathrm{Sel}_2(E_n) \to \mathrm{Sel}_4(E_n) \to \mathrm{Im}\,\mathrm{Sel}_4(E_n) \to 0,$$

where $\mathrm{Im}\,\mathrm{Sel}_4(E_n)$ is the image of $\mathrm{Sel}_4(E_n) \xrightarrow{\times 2} \mathrm{Sel}_2(E_n)$. It's known that the kernel of the Cassels pairing on $\mathrm{Sel}_2(E_n)$ is $\mathrm{Im}\,\mathrm{Sel}_4(E_n)$. Thus

$$\mathrm{rank}_{\mathbb{Z}}\, E_n(\mathbb{Q}) = 0, \quad \text{Ш}(E_n)[2^\infty] \cong (\mathbb{Z}/2\mathbb{Z})^{s_2(n)}$$

if and only if $\#\mathrm{Sel}_2(E_n) = \#\mathrm{Sel}_4(E_n)$, if and only if $\mathrm{Im}\,\mathrm{Sel}_4(E_n) = E_n[2]$ in $\mathrm{Sel}_2(E_n)$, if and only if the Cassels pairing on $\mathrm{Sel}_2'(E_n)$ is non-degenerate. □

Proof of Theorem 1.4. It follows from Lemma 3.1 that $s_2(n) = 0$ if and only if $\mathbf{A}_P + \mathbf{U}_P$ is invertible. This concludes the result. □

Proof of Theorem 1.5. By Lemma 3.1, $s_2(n) = 2$ if and only if $\mathrm{corank}(\mathbf{A}_P + \mathbf{U}_P) = 1$. Assume that $\mathrm{corank}(\mathbf{A}_P + \mathbf{U}_P) = 1$ from now on. By our assumptions, $\psi_P(d)$ is a non-zero vector lying in $\mathrm{Ker}(\mathbf{A}_P + \mathbf{U}_P)$. Then

$$\mathrm{Ker}\,\mathbf{M}_n = \left\{ \begin{pmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{pmatrix}, \begin{pmatrix} \mathbf{0} \\ \mathbf{0} \\ \psi_P(d) \\ \mathbf{0} \end{pmatrix}, \begin{pmatrix} \psi_P(d) \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{pmatrix}, \begin{pmatrix} \psi_P(d) \\ \mathbf{0} \\ \psi_P(d) \\ \mathbf{0} \end{pmatrix} \right\}.$$

Thus

$$\mathrm{Sel}_2'(E_n) = \{(1,1,1), (d,1,d), (1,d,d), (d,d,1)\}$$

by (2.5) and (2.7).

Denote by $\Lambda=(d,1,d)$ and $\Lambda'=(d,d,1)$. Then

$$\langle\Lambda,\Lambda'\rangle=\left[\frac{\sqrt{2}+1}{d}\right]+\left[\frac{\gamma}{d}\right]$$

by Proposition 3.2. Hence the Cassels pairing on $\mathrm{Sel}_2'(E_n)$ is non-degenerate if and only if $\left(\frac{\sqrt{2}+1}{d}\right)\left(\frac{\gamma}{d}\right)=-1$. Conclude the results by Lemma 4.1. □

Proof of Corollary 1.6. Take $\mathbf{u}=\mathbf{0}$ and $\mathbf{v}=(1,0,\dots,0)^{\mathrm{T}}$ in Theorem 1.5, we obtain that $\mathbf{U}_P=\mathbf{O}$. Thus $\operatorname{corank}(\mathbf{A}_P+\mathbf{U}_P)=1$ if and only if $\operatorname{corank}\mathbf{A}_P=1$, if and only if $h_4(-P)=1$ by (2.11).

Since $\mathbf{A}_P\mathbf{1}=\mathbf{0}$, the non-zero vector in $\operatorname{Ker}\mathbf{A}_P$ is $\psi_P(d)=\mathbf{1}$. Thus $d=P$ and we conclude the result by Theorem 2.8 (2) and (5). □

Example 4.2. We give two examples to show that our results produce new non-congruent numbers.

(1) Clearly, $\mathbf{M}_3=\begin{pmatrix}1&1\\1&0\end{pmatrix}$. Thus $q=3$ is a non-congruent number with $Ш(E_3)[2^\infty]=0$. If $p=193$, then $\left(\frac{p}{q}\right)=1$, $\mathbf{A}_p=0$ and $h_4(-p)=1$. Since $52^2\equiv 2 \bmod p$, we have

$$h_8(-p)=1-\left[\frac{\sqrt{2}+1}{p}\right]=1-\left[\frac{53}{193}\right]=0.$$

Since $193\times1^2+3\times1^2=4\times7^2$ and $\left(\frac{7}{p}\right)=1$, we obtain that $n=pq=3\times193$ is non-congruent with $Ш(E_n)[2^\infty]\cong(\mathbb{Z}/2\mathbb{Z})^2$ by Corollary 1.6.

(2) Clearly, $\mathbf{M}_{10}=\begin{pmatrix}1&0\\1&1\end{pmatrix}$. Thus $Q=2q=10$ is a non-congruent number with $Ш(E_{10})[2^\infty]=0$. If $p=241=23^2-2\times12^2$, then $\left(\frac{p}{q}\right)=1$, $\mathbf{A}_p=0$ and $h_4(-p)=1$. Since $22^2\equiv 2 \bmod p$, we have

$$h_8(-p)=1-\left[\frac{\sqrt{2}+1}{p}\right]=1-\left[\frac{23}{241}\right]=0.$$

Since $241\times2^2+10\times24^2=4\times41^2$ and $\left(\frac{41}{p}\right)=1$, we obtain that $n=2pq=10\times241$ is non-congruent with $Ш(E_n)[2^\infty]\cong(\mathbb{Z}/2\mathbb{Z})^2$ by Corollary 1.6.

Proof of Corollary 1.7. (1) Note that $(\alpha,\beta,\gamma)=(4,2n-2,n+1)$ is a positive primitive solution of $n\alpha^2+\beta^2=4\gamma^2$. Thus $\left[\frac{\gamma}{n}\right]=\left[\frac{n+1}{n}\right]=0$. This concludes the result by Corollary 1.6 and Theorem 2.8 (5).

(2) Write $n=\lambda^2-2\mu^2$ where $\lambda,\mu\in\mathbb{N}$. Then $(2,2\mu,\lambda)$ is a primitive positive solution of $n\alpha^2+2\beta^2=4\gamma^2$. By Theorem 2.8 (3), $\left[\frac{\lambda}{n}\right]=1-h_8(-2n)$. This conclude the result by Theorem 2.8 (4) and Corollary 1.6. □

Proof of Theorem 1.8. By our assumptions (we rearrange the order of prime factors of P),

$$\mathbf{A}_P+\mathbf{U}_P=\mathbf{A}_P=\operatorname{diag}\{\mathbf{A}_{f_1},\cdots\mathbf{A}_{f_r}\}.$$

Since $h_4(-f_i)=1$, we have $\operatorname{corank}\mathbf{A}_{f_i}=1$ by Theorem 2.8 (1). Since $\mathbf{A}_{f_i}\mathbf{1}=\mathbf{0}$, we have $s_2(n)=2r$ and the kernel of $\mathbf{M}_n$ is consists of vectors

$$\begin{pmatrix}\mathbf{c}_1\\ \vdots\\ \mathbf{c}_r\\ \mathbf{0}\\ \mathbf{d}_1\\ \vdots\\ \mathbf{d}_r\\ \mathbf{0}\end{pmatrix},$$

where $\mathbf{c}_i,\mathbf{d}_i=\mathbf{0}$ or $\mathbf{1}$ are vectors in $\operatorname{Ker}\mathbf{A}_{f_i}$. Thus $\mathrm{Sel}_2'(E_n)$ is generated by $\Lambda_1,\dots,\Lambda_r,\Lambda_1',\dots,\Lambda_r'$, where

$$\Lambda_i=(f_i,1,f_i),\quad \Lambda_i'=(f_i,f_i,1)$$

by (2.5) and (2.7). By Proposition 3.2, we have $\left[\frac{\gamma_i'}{f_j}\right]=\left[\frac{\gamma_j}{f_i}\right]$ and the Cassles pairing with respect to this basis is

$$\mathbf{X}=\begin{pmatrix} * & \mathbf{B}^{\mathrm{T}}+\mathbf{C}\\ \mathbf{B}+\mathbf{C} & \mathbf{B}+\mathbf{B}^{\mathrm{T}}\end{pmatrix},$$

where

$$\mathbf{B}=\left(\left[\frac{\gamma_i}{f_j}\right]\right)_{r\times r}\quad\text{and}\quad \mathbf{C}=\operatorname{diag}\left\{\left[\frac{\sqrt{2}+1}{f_1}\right],\cdots,\left[\frac{\sqrt{2}+1}{f_r}\right]\right\}.$$

Since $h_4(-f_i)=1$, we have

$$\mathbf{C}=\operatorname{diag}\{1-h_8(-f_1),\cdots,1-h_8(-f_r)\}$$

by Theorem 2.8 (2). By our assumptions,

$$\mathbf{B}=\operatorname{diag}\Big\{h_8(-f_1),\cdots,h_8(-f_r)\Big\}.$$

Therefore, $\mathbf{X}=\begin{pmatrix} * & \mathbf{I}\\ \mathbf{I} & \mathbf{O}\end{pmatrix}$ is invertible, i.e., the Cassles pairing on $\mathrm{Sel}_2'(E_n)$ is non-degenerate. Conclude the results by Lemma 4.1. □

Proof of Corollary 1.9. (1) Since

$$\mathbf{R}_{-n}=\operatorname{diag}\{\mathbf{A}_n,0\}=\operatorname{diag}\{\mathbf{A}_{f_1},\cdots\mathbf{A}_{f_r},0\},$$

we have $h_4(-n)=r$ and $\mathcal{A}_{-n}[2]\cap\mathcal{A}_{-n}^2$ is generated by $\theta_{-n}(f_1),\dots,\theta_{-n}(f_{r-1})$ and $\theta_{-n}(2)$ by (2.10) and (2.11). Here, one notice that

$$\theta_{-n}(f_1)\cdots\theta_{-n}(f_r)=\theta_{-n}(n)=[(\sqrt{-n})]$$

is the trivial class. If $h_8(-n)=r$, or $h_8(-n)=r-1$ and $[(2,\sqrt{-n})]\notin\mathcal{A}_{-n}^4$, then all $\theta_{-n}(f_i)\in\mathcal{A}_{-n}[2]\cap\mathcal{A}_{-n}^4$. By Proposition 2.4, this implies that $\mathbf{b}_{n,\gamma_i}\in\operatorname{Im}\mathbf{A}_n$, where $(\alpha_i,\beta_i,\gamma_i)$ is a primitive positive solution of $f_i\alpha_i^2-\frac{n}{f_i}\beta_i^2=4\gamma_i^2$. Thus $\mathbf{b}_{f_j,\gamma_i}\in\operatorname{Im}\mathbf{A}_{f_j}$ for all j. Since $\mathbf{1}^{\mathrm{T}}\mathbf{A}_{f_j}=\mathbf{0}^{\mathrm{T}}$, we have

$$0=\mathbf{1}^{\mathrm{T}}\mathbf{b}_{f_j,\gamma_i}=\left[\frac{\gamma_i}{f_j}\right].$$

Conclude the results by Theorem 1.8.

(2) Similar to (1), $h_4(-2n) = r$ and $\mathcal{A}_{-2n}[2] \cap \mathcal{A}_{-2n}^2$ is generated by $\theta_{-2n}(f_1)$, $\ldots$, $\theta_{-2n}(f_r)$ by (2.10) and (2.11). Here, one notice that

$$\theta_{-2n}(2) = \theta_{-2n}(f_1) \cdots \theta_{-2n}(f_r)$$

since $\theta_{-2n}(2n) = [(\sqrt{-2n})]$ is the trivial class. If $h_8(-2n) = r$, then all $\theta_{-2n}(f_i) \in \mathcal{A}_{-2n}[2] \cap \mathcal{A}_{-2n}^4$. One can conclude the results similar to (1). □

This paper reveals a new phenomenon: for a general non-congruent number n with the second minimal 2-primary Shafarevich group, the criterion cannot be expressed solely in terms of the 4-ranks and 8-ranks of class groups of quadratic fields, even though this is possible when the prime factors of n lie in certain residue classes. A key remaining problem is how to find simple arithmetic conditions that characterize non-congruent numbers with specific 2-primary Shafarevich groups.

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