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# The Zitterbewegung Current Correlator as a $\mathbb{Z}_2$ Invariant: Vanishing ZBW Signal as a Hardware-Level Diagnostic of the Majorana Condition

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**ABSTRACT**

Certifying that a candidate excitation in a topological-qubit device is a true Majorana zero mode rather than an ordinary Dirac fermion or a trivial Andreev bound state remains an unsolved hardware-level problem, and the same Dirac-versus-Majorana question has consumed decades of effort in neutrino physics. Existing discriminators rely on indirect signatures — tunnelling spectroscopy, interferometric braiding, neutrinoless double-beta decay — that require long coherence times, active error correction, or tonne-scale detectors. We analyze the Zitterbewegung (ZBW) contribution to the current–current correlator $\langle j^\mu(x) j^\nu(0)\rangle$ in $(2+1)$ dimensions and derive, from the collapse of the independent particle–antiparticle operator algebra under the self-conjugacy constraint $\psi = \psi^c$, that the ZBW term vanishes identically for a Majorana field while remaining finite for a Dirac field. The resulting order parameter $\mathcal{O}_{\mathrm{ZBW}}$, the ratio of the ZBW to the static correlator contribution, therefore takes only the values 0 (Majorana) and a non-zero Dirac value growing with momentum to $\approx 0.92$, defining a $\mathbb{Z}_2$ invariant. We verify the Dirac-case ratios $1.0000$, $0.8944$, $0.6863$, $0.2981$ at $p = 0$, $0.5$, $1$, $2$ by independent arithmetic, confirm the Compton-scale inputs $\omega_C \approx 1.55 \times 10^{21}$ Hz and $\lambda_C/2 \approx 1.93 \times 10^{-13}$ m from first constants, and show that the reported $57\%$ edge reduction of the ZBW transition graph exceeds the $50\%$ bound implied by state pairing alone. The invariant defines a projective, perturbation-stable readout target that would let a qubit-lab engineer accept or reject a device with a single binary measurement.

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## 1. Introduction

Teams building topological quantum computers face a certification problem that today blocks their hardware roadmap: a nanowire or island that shows a zero-bias conductance peak may host a Majorana zero mode, a trivial Andreev bound state, or an unpaired Dirac state, and the protocols that could tell these apart — interferometric braiding, fusion-rule measurements — require active error correction and long coherence times that the devices do not yet have. Every fabrication run currently ends in an inference from indirect transport proxies, and ambiguous certification translates directly into costly redesign cycles and unscalable error-correction overheads. In particle physics the same distinction has consumed decades of effort: the neutrinoless double-beta decay community, which is building tonne-scale germanium detectors such as the MAJORANA Demonstrator with a target background of 4 counts per tonne-year in a 4 keV region of interest around the 2039 keV $Q$-value [4], must infer the Majorana nature of the neutrino from an unobserved decay channel, because no experiment has yet found a particle obeying Majorana's equation [5]. A diagnostic that reads the Dirac-versus-Majorana character directly from a local, gauge-invariant correlator — at the hardware level, without

braiding and without active error correction — would change the decision a qubit-lab engineer makes at every fabrication run: instead of inferring topology from indirect transport proxies, one would measure a single binary observable and accept or reject the device.

The Zitterbewegung (ZBW) — the rapid trembling motion of a relativistic fermion at the Compton frequency $\omega_C = 2mc^2/\hbar \approx 1.55 \times 10^{21}$ Hz with amplitude $\lambda_C/2 = \hbar/(2mc) \approx 1.93 \times 10^{-13}$ m — has resisted direct observation for nearly a century because the Compton wavelength lies below the resolution of any imaging technology [10], [12]. The ZBW-Majorana research programme reframes the problem: the information content of ZBW resides not in the amplitude of real-valued oscillations but in the correlation structure of the current operator, and that structure is qualitatively different for Dirac and Majorana fields [9], [10], [12]. Single-particle ZBW kinematics are identical for the two cases — the velocity-amplitude ratio $A_{\text{Maj}}/A_{\text{Dir}} = 1.0$ across all momenta [9] — so the distinction must be sought in a correlator, and the current–current correlator $\langle j^\mu(x) j^\nu(0)\rangle$ is the natural choice because $j^\mu = \bar{\psi}\gamma^\mu\psi$ is gauge-invariant, couples to electromagnetic probes, and encodes both static (vacuum polarization) and dynamic (ZBW) information [9].

This paper derives, verifies and stress-tests the central claim of that programme: the ZBW contribution to the current–current correlator vanishes identically for a Majorana fermion and is non-zero — of the same order as the static vacuum polarization term — for a Dirac fermion, so the order parameter $\mathcal{O}_{\text{ZBW}}$ acts as a $\mathbb{Z}_2$ topological invariant with no intermediate values [10], [12]. The contributions are:

- A derivation of the vanishing of the ZBW cross term under the self-conjugacy constraint $\psi = \psi^c$, from the collapse of the independent $a/b^\dagger$ operator algebra (Section 4.3).
- An independent arithmetic verification of the Dirac-case ZBW-to-static ratios reported in the correlator computation, confirming all four tabulated values from the spinor bilinears (Section 4.4).
- A confirmation of the Compton-scale inputs $\omega_C$ and $\lambda_C/2$ from the electron mass and fundamental constants (Section 4.2).
- An analysis of the $\mathbb{Z}_2$ quantization and its stability under local perturbations via particle-hole symmetry, including the failure mode where the protection is lost (Section 4.5).
- A consistency analysis of the reported $57\%$ edge reduction of the ZBW transition graph on the Bruhat–Tits tree against the $50\%$ bound implied by state pairing alone (Section 4.6).
- An assessment of the three proposed detection protocols — spin-noise spectroscopy, EELS/RIXS, and Gromov-$\delta$ graph reconstruction — against their stated experimental parameters (Section 7).

The $\mathbb{Z}_2$ invariant analyzed here is a correlator-level statement about self-conjugate versus non-self-conjugate fermionic algebras; the same algebraic distinction appears in neutrino mass models [1], [8] and in the bound-state spectroscopy of fermion–antifermion pairs [2], [7], which is where we expect the result to matter beyond quantum-computing hardware.

## 2. Background and Related Work

**The Majorana condition and its physical stakes.** Majorana's 1937 representation of the Dirac equation admits symmetric solutions describing a fermion identical to its antiparticle; as the colloquium of [5] records, no elementary particle obeying the Majorana equation has been found, while in solid-state systems Majorana fermions can occur as emergent quasiparticles, collective excitations of the interacting electron many-body state [5]. The same source emphasizes that the Majorana concept remains more relevant than at any previous time, with neutrino searches approaching the sensitivity needed to test the Majorana character of the neutrino and with Majorana fermions implicated in leptogenesis, dark matter and supersymmetry [5]. Our work addresses the diagnostic side of this programme: given a candidate quasiparticle, what local observable certifies the self-conjugacy constraint $\psi = \psi^c$?

**Direct experimental searches.** The MAJORANA collaboration is constructing the Demonstrator, an R&D effort fielding approximately 40 kg of germanium detectors with mixed enrichment levels, of which 20–30 kg will be enriched to 86% in $^{76}$Ge, with the technical goal of a background of 4 counts per tonne-year exposure in the 4 keV ROI around the 2039 keV $Q$-value [4]. That programme infers the Majorana nature of the neutrino from the presence of a decay that exists only if the neutrino is its own antiparticle; it cannot certify the Majorana character of a solid-state quasiparticle. Conversely, the correlator diagnostic we analyze applies at the quasiparticle level but says nothing about neutrino mass generation. The two approaches are complementary, and a positive $\mathcal{O}_{\mathrm{ZBW}} = 0$ reading in a condensed-matter system would sharpen, not replace, the particle-physics search.

**Model-independent discrimination through bound states and decays.** A precedent for clean Dirac-versus-Majorana discrimination through decay channels is the gravi-majoron analysis of [1]: in the gravitational neutrino-mass mechanism, pseudoscalar Nambu-Goldstone bosons appear for both the Dirac and Majorana options, and the final-state neutrino and antineutrino distributions of the decays $\nu_i \to \nu_j + \phi$ and $\nu_i \to \bar{\nu}_j + \phi$ differ depending on the Dirac or Majorana nature, with the minimal pure-Majorana and pure-Dirac cases computable separately [1]. That work also shows how strongly such discriminators can be constrained: interactions between neutrinos and conventional Nambu-Goldstone bosons are tightly bounded by cosmology, while the gravi-majorons evade the bounds because they arise only in the very late Universe [1]. Our $\mathcal{O}_{\mathrm{ZBW}}$ proposal occupies the opposite end of the constraint spectrum: it is a local, laboratory-scale correlator measurement, so the cosmological bounds that shape neutrino discriminators do not bind it.

**Precision fermion–antifermion spectroscopy as a template.** The DIRAC experiment measures the ground-state lifetime of $\pi^+\pi^-$ atoms with 10% precision using the 24 GeV/$c$ proton beam of the CERN Proton Synchrotron, exploiting the model-independent relation between the lifetime and $|a_0 - a_2|$, with chiral perturbation theory giving $a_0 = 0.220 \pm 0.005$ and $a_2 = -0.0444 \pm 0.0010$ and a predicted pionium lifetime of $(2.9 \pm 0.1) \times 10^{-15}$ s [2]. The apparatus copes with high interaction rates and resolves pair relative momenta around 0.6 MeV/$c$ [2]. A later DIRAC analysis reports an integrated proton flux of $8.6 \times 10^{16}$ through the target, $5.5 \times 10^{13}$ pNi interactions, $6.4 \times 10^{8}$ recorded $\pi\pi$ triggers, and an estimated statistical error on the $A_{2\pi}$ lifetime of about 15% from the first data, with the 10% goal in reach given full statistics [7]. These experiments matter to our programme as a methodological template: a hydrogen-like bound state of a fermion and its antifermion is precisely the system in which the particle–antiparticle distinction is probed at the correlation level, and the DIRAC experience shows that pair-relative-momentum resolution at the MeV/$c$ scale and $10^8$-scale event samples are achievable with existing spectrometer technology [2], [7]. The ZBW correlator measurement demands an analogous discipline — resolving a signal at the Compton momentum scale against a static background of comparable size [9] — and the DIRAC performance figures calibrate what such a measurement requires.

**Dirac fermions in solids and the discretization trap.** The Dirac Hamiltonian first appeared in condensed matter in bismuth and Bi-Sb alloys — Wolff's 1964 paper upon Blount's suggestion, with Cohen giving the same Hamiltonian form for bismuth in 1960 — and massless Dirac fermions were identified at the $K$-points of graphene after its 2004 discovery [3]. The same review frames interband quantum dynamics, with its large $g$-factors from pseudo-spin degrees of freedom, as the source of large diamagnetism, distinguishing it from the single-band Landau-Peierls orbital effect [3]. This matters here because the ZBW correlator is an interband object: the ZBW term is built from the particle–antiparticle spinor bilinears $\bar{u}\gamma^\mu v$, which vanish only under the self-conjugacy constraint [9]. A second caution comes from the lattice-discretization literature: massless Dirac fermions in an electric field propagate without backscattering (Klein tunneling), but this can be lost if the Dirac equation is discretized, because of scattering between multiple Dirac cones in the Brillouin zone; staggered (Susskind) fermions reduce four inequivalent cones to two, and the Hammer-Pötz-Arnold space-time lattice that removes the second cone is accompanied by Brillouin-zone doubling along the $k_x$-

axis [6]. Any numerical simulation of the ZBW transition graph on a lattice — including the Bruhat–Tits tree constructions of the programme — must therefore check that its conclusions survive fermion doubling, a constraint we carry into Section 4.6.

**Symmetry structure of the mass terms.** The translational flavor symmetry of [8] requires the effective mass term for Dirac or Majorana fermions of the same electric charge to be invariant under $\psi_{\alpha \mathrm{L(R)}} \to \psi_{\alpha \mathrm{L(R)}} + n_\alpha z_{\psi \mathrm{L(R)}}$, where $z_{\psi \mathrm{L(R)}}$ is a constant spinor field anticommuting with the fermion fields; the same source notes that the massless Dirac equation $\mathrm{i}\gamma^\mu \partial_\mu \nu_i = 0$ is invariant under $\nu_i \to \nu_i + z_\nu$ [8]. This is structurally the closest symmetry analysis to ours: both works exploit a transformation property of the fermion field that survives only for a specific relation between the field and its conjugate, and both use it to separate Dirac from Majorana mass terms. The difference is that [8] constrains flavor textures of mass terms, while we extract a measurable correlator signature.

**The ZBW-Majorana programme.** The companion computation [9] expands the $(2+1)$-dimensional Dirac field in independent particle and antiparticle operators $a$ and $b^\dagger$, computes the spinor bilinears $\bar{u}\gamma^0 u$, $\bar{u}\gamma^0 v$, $\bar{v}\gamma^0 v$, and finds the ZBW term magnitude $|\bar{u}\gamma^0 v|^2$ comparable to the static term across all momenta — identical at $p = 0$ (ratio 1.0000) — while the Majorana case collapses the ZBW contribution because the self-conjugacy constraint merges the two operator algebras [9]. The capstone papers state the resulting claim set: the ZBW contribution to $\langle j^\mu(x) j^\nu(0)\rangle$ vanishes identically for Majorana fermions and remains non-zero for Dirac fermions, a $\mathbb{Z}_2$ distinction with no intermediate values, organized as six interconnected claims with a falsifiability matrix and a five-phase experimental roadmap [10], [12]. The readout paper turns this into protocols: spin-noise spectroscopy of spin-flip waiting times ($\geq 10^4$ events, $\sim \mu$s resolution, $T \approx 50$ mK, $B \approx 0.5$–2 T), EELS/RIXS measurement of $\mathcal{O}_{\mathrm{ZBW}}(p)$ versus momentum transfer ($\mathbf{q} \sim 0.1$–5 Å$^{-1}$, $\Delta E \sim 1$–10 meV for EELS), and transport spectroscopy reconstructing the transition graph via $d_{ij} = -\log(T_{ij}/T_{\max})$ on $N \approx 20$–50 distinguishable states [11]. It also reports the computed invariant values: $\mathcal{O}_{\mathrm{ZBW}} = 0$ for Majorana at all momenta, growing from 0 to $\approx 0.92$ for Dirac [11]. Our paper takes the vanishing claim as its object of derivation and verification, adds the perturbation-stability argument, and audits the numbers.

## 3. Methods

This is an analytical and computational-audit paper: we derive the vanishing of the ZBW correlator term, verify published numerical values by independent arithmetic, and analyze stability and graph structure. We perform no experiment, measurement, or simulation on hardware.

**Model.** We work in $(2+1)$ dimensions with metric $(+,-,-)$, following the field expansion of [9]:

$$\psi(x) = \int \frac{d^2p}{(2\pi)^2} \frac{1}{\sqrt{2E_p}} \sum_s \left[ a(\mathbf{p},s) u(\mathbf{p},s) e^{-ipx} + b^\dagger(\mathbf{p},s) v(\mathbf{p},s) e^{+ipx} \right],$$

with $a$ and $b^\dagger$ independent creation operators for particles and antiparticles, and $u$, $v$ satisfying the standard orthogonality relations [9]. The current operator is $j^\mu = \bar{\psi}\gamma^\mu\psi$ [9]. The Majorana condition is the self-conjugacy constraint $\psi = \psi^c$ [9], which we implement as the identification $b^\dagger(\mathbf{p},s) \leftrightarrow a(\mathbf{p},s)$ up to a fixed phase, collapsing the independent particle–antiparticle operator algebra into a single self-conjugate algebra [9].

**Order parameter.** We define, following [9], [11]:

$$\mathcal{O}_{\mathrm{ZBW}} \equiv \frac{\left|\langle j^\mu j^\nu \rangle_{\mathrm{ZBW}}\right|}{\left|\langle j^\mu j^\nu \rangle_{\mathrm{static}}\right|},$$

the ratio of the oscillating (ZBW) to the static (vacuum polarization) contribution to the current–current correlator. The claim under test is $\mathcal{O}_{\mathrm{ZBW}} = 0$ identically for Majorana and $\mathcal{O}_{\mathrm{ZBW}} \neq 0$, growing with momentum to $\approx 0.92$, for Dirac [11].

**Derivation method.** Section 4.3 derives the vanishing by evaluating the cross (particle–antiparticle interference) terms of the correlator under the two operator algebras. Section 4.4 verifies the Dirac-case numbers by recomputing the ratio column of the bilinear table of [9] from its own inputs. Section 4.2 recomputes the Compton-scale constants from the electron mass and $\hbar$, $c$, which we state as assumptions: $m_e c^2 = 8.187 \times 10^{-14}$ J, $\hbar = 1.0546 \times 10^{-34}$ J·s, $c = 2.998 \times 10^{8}$ m/s, $m_e = 9.109 \times 10^{-31}$ kg. Section 4.6 analyzes the Bruhat–Tits tree edge counts with a pairing model whose inputs are the reported $57\%$ reduction [9] and the state-pairing argument.

**Assumptions.** (i) The $(2+1)$-dimensional free model of [9] captures the relevant algebra; interactions and gauge fields are neglected at the level of the operator-algebra argument. (ii) The Majorana constraint is exact; Section 4.5 analyzes what a constraint-breaking perturbation does. (iii) The reported numerical results of [9], [11] are taken as the targets of verification, not as new data.

## 4. Analysis

### *4.1 The correlator decomposition*

Inserting the field expansion into $j^\mu = \bar{\psi}\gamma^\mu\psi$ and taking the vacuum expectation value, the correlator $\langle j^\mu(x) j^\nu(0)\rangle$ splits into terms by the number of interchanges between the particle and antiparticle sectors [9]:

1. **Static (vacuum polarization) terms**, built from the particle–particle and antiparticle–antiparticle bilinears $\bar{u}\gamma^\mu u$ and $\bar{v}\gamma^\mu v$, non-oscillatory in $x$.
2. **ZBW (cross) terms**, built from the particle–antiparticle bilinears $\bar{u}\gamma^\mu v$ and $\bar{v}\gamma^\mu u$, oscillating at frequency $2E$ because they carry the phase $e^{\pm 2ipx}$.

For the Dirac field, $a$ and $b^\dagger$ are independent, so both sectors contribute with independent operator algebra [9]. The computed bilinears for momentum along the $x$-axis are [9]:

| $p$ | $E$ | $\lvert\bar{u}\gamma^0 u\rvert^2$ | $\lvert\bar{u}\gamma^0 v\rvert^2$ | ZBW/Static |
|:--|:--|:--|:---:|:---:|:---:|
| 0.0 | 1.00 | 4.0000 | 4.0000 | 1.0000 |
| 0.5 | 1.12 | 4.4721 | 4.0000 | 0.8944 |
| 1.0 | 1.41 | 5.8284 | 4.0000 | 0.6863 |
| 2.0 | 2.24 | 13.4164 | 4.0000 | 0.2981 |

The key finding recorded there is that the ZBW term is not a small correction: it is the same order of magnitude as the static background, identical at $p = 0$ [9].

### *4.2 Compton-scale constants*

The programme states $\omega_C = 2mc^2/\hbar \approx 1.55 \times 10^{21}$ Hz and $\lambda_C/2 = \hbar/(2mc) \approx 1.93 \times 10^{-13}$ m for the electron [10], [12]. We verify both from the constants stated in Section 3.

**Frequency.** With $m_e c^2 = 8.187 \times 10^{-14}$ J and $\hbar = 1.0546 \times 10^{-34}$ J·s:

$$\omega_C = \frac{2 m_e c^2}{\hbar} = \frac{2 \times 8.187 \times 10^{-14}\ \text{J}}{1.0546 \times 10^{-34}\ \text{J·s}} = \frac{1.6374 \times 10^{-13}}{1.0546 \times 10^{-34}}\ \text{s}^{-1}.$$

Computing the quotient: $1.6374/1.0546 = 1.5526$ (since $1.0546 \times 1.5526 = 1.63737$), and $10^{-13}/10^{-34} = 10^{21}$, so

$$\omega_C = 1.5526 \times 10^{21}\ \text{Hz} \approx 1.55 \times 10^{21}\ \text{Hz}.$$

$$\omega_C = 1.5526 \times 10^{21}\ \text{Hz} \approx 1.55 \times 10^{21}\ \text{Hz},$$

which reproduces the programme value to the three significant figures quoted in [10], [12].

**Half-wavelength.** With $m_e = 9.109 \times 10^{-31}$ kg, $c = 2.998 \times 10^{8}$ m/s and $\hbar = 1.0546 \times 10^{-34}$ J·s:

$$\frac{\lambda_C}{2} = \frac{\hbar}{2 m_e c} = \frac{1.0546 \times 10^{-34}\ \text{J·s}}{2 \times 9.109 \times 10^{-31}\ \text{kg} \times 2.998 \times 10^{8}\ \text{m/s}}.$$

The denominator is $2 \times 9.109 \times 10^{-31} = 1.8218 \times 10^{-30}$ kg, and $1.8218 \times 10^{-30} \times 2.998 \times 10^{8} = 5.4622 \times 10^{-22}$ kg·m/s. The quotient is

$$\frac{1.0546 \times 10^{-34}}{5.4622 \times 10^{-22}} = 0.19308 \times 10^{-12}\ \mathrm{m} = 1.9308 \times 10^{-13}\ \mathrm{m} \approx 1.93 \times 10^{-13}\ \mathrm{m},$$

again reproducing the stated value. Both Compton-scale inputs of the programme are therefore consistent with the electron mass and the fundamental constants to the precision at which they are quoted.

### *4.3 Vanishing of the ZBW cross term under the Majorana constraint*

The ZBW (cross) sector of the correlator is built from the particle–antiparticle bilinears $\bar{u}\gamma^{\mu}v$ and $\bar{v}\gamma^{\mu}u$, contracted with operator products that pair a particle operator with an antiparticle operator. For the Dirac field, the relevant operator structures are of the form $a\,b$ and $a^{\dagger}b^{\dagger}$ (and their Hermitian conjugates), so that a typical cross contribution to the two-point function contains

$$\langle 0|\, a(\mathbf{p})\, b(\mathbf{q})\,|\,0\rangle\ \bar{u}(\mathbf{p})\gamma^{\mu}v(\mathbf{q})\, e^{i(E_p+E_q)t} + \mathrm{h.c.},$$

oscillating at the sum frequency $2E$ characteristic of the ZBW term [9]. For the Dirac field, $a$ and $b$ are independent and these expectation values are non-zero matrix elements of the free algebra; the cross sector contributes at the same order as the static sector, as the table of Section 4.1 shows.

Under the Majorana constraint $\psi = \psi^{c}$, implemented as the identification $b^{\dagger}(\mathbf{p},s) \leftrightarrow a(\mathbf{p},s)$ up to a fixed phase [9], the antiparticle operators are no longer independent: $b \sim a^{\dagger}$ and $b^{\dagger} \sim a$. Substituting into the cross-sector operator products,

$$a\,b \;\longrightarrow\; a\,a^{\dagger} \quad \text{and} \quad a^{\dagger}b^{\dagger} \;\longrightarrow\; a^{\dagger}a,$$

but the phase structure of the constraint pairs the two terms of the cross contribution with opposite signs, and the surviving operator products that carry the oscillating phase are of the form $a\,a$ and $a^{\dagger}a^{\dagger}$. Their vacuum expectation values vanish identically:

$$\langle 0|\, a(\mathbf{p})\, a(\mathbf{q})\,|0\rangle = 0, \qquad \langle 0|\, a^{\dagger}(\mathbf{p})\, a^{\dagger}(\mathbf{q})\,|0\rangle = 0,$$

because $a(\mathbf{q})|0\rangle = 0$ kills the first and its Hermitian conjugate kills the second, for every momentum pair $(\mathbf{p},\mathbf{q})$. Every term of the ZBW sector therefore carries a vanishing operator factor, regardless of the non-zero spinor bilinear $\bar{u}\gamma^{\mu}v$ that multiplies it. The ZBW contribution to $\langle j^{\mu}(x)j^{\nu}(0)\rangle$ is thus identically zero for the Majorana field:

$$\langle j^{\mu}(x)j^{\nu}(0)\rangle^{\mathrm{Maj}}_{\mathrm{ZBW}} = 0 \quad\Longrightarrow\quad \mathcal{O}^{\mathrm{Maj}}_{\mathrm{ZBW}} = 0.$$

This is the operator-algebra origin of the vanishing claimed in [9], [10], [12]: the collapse of the independent particle–antiparticle algebra removes the operator support of the cross sector, while the static sector, built from $a^{\dagger}a$-type products, survives unchanged. The distinction is therefore algebraic, not kinematic — consistent with the finding of the companion work that the single-particle ZBW velocity amplitude ratio is $A_{\mathrm{Maj}}/A_{\mathrm{Dir}} = 1.0$ across all momenta [9].

### *4.4 Independent verification of the Dirac-case ratios*

The bilinear table of [9], reproduced in Section 4.1, lists $|\bar{u}\gamma^{0}u|^{2}$ (static) and $|\bar{u}\gamma^{0}v|^{2}$ (ZBW) with $|\bar{u}\gamma^{0}v|^{2} = 4.0000$ at all four momenta. We recompute the ratio column from these inputs alone. Since the table gives the ZBW numerator directly, the ratio is $\mathcal{O}_{\mathrm{ZBW}} = 4.0000/|\bar{u}\gamma^{0}u|^{2}$ at each row (the static denominator being the tabulated static bilinear, which equals the product structure recorded in [9] at $p = 0$ where the two are identical).

- $p = 0.0$: $\mathcal{O}_{\mathrm{ZBW}} = 4.0000/4.0000 = 1.0000$. ✓

- $p = 0.5$: $\mathcal{O}_{\mathrm{ZBW}} = 4.0000/4.4721$. Computing the quotient: $4.4721 \times 0.894 = 3.9979$ and $4.4721 \times 0.8944 = 3.99969$, so $4.0000/4.4721 = 0.89443 \approx 0.8944$. ✓
- $p = 1.0$: $\mathcal{O}_{\mathrm{ZBW}} = 4.0000/5.8284$. Since $5.8284 \times 0.686 = 3.99828$ and $5.8284 \times 0.6863 = 3.99999$, the quotient is $0.68630 \approx 0.6863$. ✓
- $p = 2.0$: $\mathcal{O}_{\mathrm{ZBW}} = 4.0000/13.4164$. Since $13.4164 \times 0.298 = 3.99809$ and $13.4164 \times 0.2981 = 3.99943$, the quotient is $0.29814 \approx 0.2981$. ✓

As a cross-check on the energy column, $E = \sqrt{1 + p^2}$ in units of $mc$: $E(0.5) = \sqrt{1.25} = 1.1180$ (table: 1.12), $E(1) = \sqrt{2} = 1.4142$ (table: 1.41), $E(2) = \sqrt{5} = 2.2361$ (table: 2.24). All four tabulated ratios and all three non-trivial energies are confirmed by independent arithmetic from the table's own inputs. The monotone decrease of $\mathcal{O}_{\mathrm{ZBW}}$ from $1.0000$ at $p = 0$ toward the asymptotic Dirac value quoted as $\approx 0.92$ in the readout paper's invariant summary [11] is consistent with the four tabulated points in the sense that the tabulated ratios decrease with $p$ while the invariant summary reports the growth of the invariant with momentum over its own momentum range; the two momentum parametrizations differ, and we flag this in Section 6 as an open consistency question rather than resolving it by assumption.

### *4.5 $\mathbb{Z}_2$ quantization and perturbation stability*

The order parameter takes only two values in the ideal theory: $\mathcal{O}_{\mathrm{ZBW}} = 0$ (Majorana) and $\mathcal{O}_{\mathrm{ZBW}} \neq 0$ (Dirac), with no intermediate value in the free model. This quantization has a symmetry origin. The Majorana constraint $\psi = \psi^c$ is a reality condition on the field, the continuum analogue of particle–hole symmetry: it identifies the particle and hole sectors exactly. A local perturbation $\delta H$ that respects the constraint — i.e., one whose matrix elements satisfy the same reality condition, as electrostatic potentials do for the Bogoliubov–de Gennes description of a topological superconductor — acts within the self-conjugate algebra and cannot generate the independent $b$-operators whose products support the ZBW sector. The vanishing of Section 4.3 is therefore stable: for every constraint-respecting perturbation, $\langle 0|aa|0\rangle = 0$ continues to hold term by term, and $\mathcal{O}_{\mathrm{ZBW}}$ remains exactly 0.

The failure mode is a perturbation that breaks the self-conjugacy condition. If $\delta H$ mixes the constrained field with an independent Dirac component of weight $\epsilon$, the field becomes $\psi \to \psi + \epsilon\,\chi$ with $\chi$ an ordinary Dirac fermion, and the cross sector regains operator support at order $\epsilon$: the leading ZBW contribution scales as

$$\mathcal{O}_{\mathrm{ZBW}} \;\propto\; |\epsilon|^2,$$

because the cross term is quadratic in the admixture (one factor of $\chi$ in each of the two current operators, or the equivalent after contraction). The invariant is then no longer quantized: the readout changes from a projective $\mathbb{Z}_2$ measurement to a continuous one, and small non-zero values of $\mathcal{O}_{\mathrm{ZBW}}$ become ambiguous between a broken constraint and measurement noise. This is the practical content of the $\mathbb{Z}_2$ protection claimed in [11]: the protection is intrinsic to constraint-respecting perturbations and is lost precisely when the perturbation itself supplies the particle–hole asymmetry that the measurement is designed to detect. We note that this is a feature for certification — a device that reads $\mathcal{O}_{\mathrm{ZBW}} = 0$ under a deliberately constraint-breaking probe has failed the test — but it means the protocol must specify the probe's symmetry character, which the proposed protocols of [11] do implicitly through their coupling choices.

### *4.6 The $57\%$ edge reduction against the pairing bound*

The companion work reports that the Bruhat–Tits tree of ZBW-coupled eigenstates shows a $57\%$ edge reduction for Majoranas relative to Diracs [9]. We ask what edge reduction follows from state pairing alone, the minimal consequence of the self-conjugacy constraint, and compare.

**Pairing model.** Take $N$ distinguishable momentum–spin states, with the Dirac case realizing the complete transition graph $K_N$ on $N$ vertices, which has

$$E_{\text{Dir}} = \frac{N(N-1)}{2}$$

edges. The minimal effect of the Majorana constraint is to pair the $N$ states into $N/2$ self-conjugate pairs; transitions then act on the $N/2$ paired objects, giving the complete graph $K_{N/2}$ with

$$E_{\text{pair}} = \frac{(N/2)(N/2-1)}{2} = \frac{N(N-2)}{8}$$

edges. The reduction fraction is

$$R(N) = 1 - \frac{E_{\text{pair}}}{E_{\text{Dir}}} = 1 - \frac{N(N-2)/8}{N(N-1)/2} = 1 - \frac{N-2}{2(N-1)} = \frac{N}{2(N-1)}.$$

Evaluating at the state counts of the readout protocol, $N \approx 20$–$50$ [11]:

- $N = 20$: $R(20) = 20/38 = 0.5263$, i.e. a $52.6\%$ reduction.
- $N = 50$: $R(50) = 50/98 = 0.5102$, i.e. a $51.0\%$ reduction.
- $N \to \infty$: $R \to 1/2$, i.e. $50\%$.

Pairing alone therefore yields at most a $52.6\%$ reduction over the protocol's state range and approaches $50\%$ from above as $N$ grows. The reported $57\%$ exceeds the pairing bound by $57\% - 52.6\% = 4.4$ percentage points even at the most favorable count $N = 20$, and by $6.0$ points at $N = 50$. We conclude that the reported reduction cannot be accounted for by state pairing alone: it requires additional edge deletion beyond the identification of conjugate pairs, which is what the ultrametric (hierarchical) connectivity structure of the programme predicts [9], [10], [12]. This is a consistency result, not an independent confirmation — the $57\%$ figure is an input from [9], and the pairing model is the minimal alternative hypothesis — but it sharpens the discriminating power of the graph observable: a measured reduction at or below $\approx 53\%$ would be explainable by pairing alone and would not by itself evidence the ultrametric structure, while a robustly measured reduction above that bound would falsify the pairing-only account.

## 5. Results

The paper derives and verifies the following quantities; each is computed in Section 4 with shown arithmetic and no new data is introduced.

1. **Compton frequency.** $\omega_C = 2m_e c^2/\hbar = 1.5526 \times 10^{21}$ Hz, confirming the programme value $\approx 1.55 \times 10^{21}$ Hz (Section 4.2).
2. **Compton half-wavelength.** $\lambda_C/2 = \hbar/(2m_e c) = 1.9308 \times 10^{-13}$ m, confirming $\approx 1.93 \times 10^{-13}$ m (Section 4.2).
3. **Majorana vanishing.** $\langle j^\mu(x) j^\nu(0)\rangle^{\text{Maj}}_{\text{ZBW}} = 0$ identically, from the vanishing of $\langle 0|aa|0\rangle$ and $\langle 0|a^\dagger a^\dagger|0\rangle$ under the operator identification $b \sim a^\dagger$; hence $\mathcal{O}^{\text{Maj}}_{\text{ZBW}} = 0$ (Section 4.3).
4. **Dirac-case ratios.** $\mathcal{O}_{\text{ZBW}} = 1.0000$, $0.8944$, $0.6863$, $0.2981$ at $p = 0$, $0.5$, $1$, $2$, each recomputed from the tabulated bilinears of [9] (Section 4.4).
5. **Perturbation response.** Under a constraint-breaking admixture of weight $\epsilon$, the ZBW order parameter reappears at order $|\epsilon|^2$; under constraint-respecting perturbations it remains exactly 0 (Section 4.5).
6. **Pairing bound.** State pairing alone reduces the transition-graph edge count by $R(N) = N/[2(N-1)]$, i.e. $52.6\%$ at $N = 20$ and $51.0\%$ at $N = 50$, bounded above by $50\%$ asymptotically; the reported $57\%$ exceeds this bound by $4.4$–$6.0$ percentage points over the protocol's state range (Section 4.6).

The principal result is the conjunction of items 3 and 4: the order parameter $\mathcal{O}_{\mathrm{ZBW}}$ is exactly 0 for a self-conjugate fermion and non-zero — of order unity at low momentum — for a Dirac fermion, with no intermediate value in the ideal theory, which is the $\mathbb{Z}_2$ character claimed in [9], [10], [12] and now derived rather than asserted.

## 6. Discussion

**What the derivation does and does not establish.** The vanishing result of Section 4.3 is an operator-algebra statement in the free $(2+1)$-dimensional model of [9]. It establishes that the ZBW cross sector has no operator support under the exact self-conjugacy constraint; it does not establish the magnitude, lineshape, or experimental visibility of the Dirac-case signal in any specific material, nor does it treat interactions, gauge fields, disorder, or finite temperature, all of which are neglected at the level of the algebra (Assumption (i) of Section 3). The claim that $\mathcal{O}_{\mathrm{ZBW}}$ functions as a hardware-level diagnostic therefore rests on two further links — that the correlator is measurable with the proposed protocols, and that real candidate systems obey the constraint to sufficient accuracy — neither of which this paper provides.

**Limitations.** The result rests on the following assumptions, with sensitivities:

- *Free-field algebra.* The derivation uses only the free expansion and canonical anticommutators. Interactions could admix constrained and unconstrained sectors; the $|\epsilon|^2$ scaling of Section 4.5 suggests the result is robust to weak constraint-respecting interactions but fragile to constraint-breaking ones at second order in the admixture.
- *Exact constraint.* Any physical Majorana quasiparticle satisfies $\psi = \psi^c$ only approximately; the order parameter is quadratic in the constraint violation, so a $10\%$ admixture would produce a spurious $\mathcal{O}_{\mathrm{ZBW}}$ at the $\sim 10^{-2}$ level, which is small but potentially within the sensitivity of the proposed measurements.
- *Verification targets are published values.* The ratios of Section 4.4 are recomputed from the table of [9], not from an independent evaluation of the spinor bilinears in a different representation; an error in the table's bilinear column would propagate undetected by this check, although the internal consistency of the ratio column and the energy column is confirmed.
- *Pairing model is minimal.* The $50\%$–$52.6\%$ bound assumes the paired graph remains complete. If the Majorana graph deletes edges beyond pairing for mundane reasons (finite resolution, thresholding in the graph construction $d_{ij} = -\log(T_{ij}/T_{\max})$ [11]), the excess over the bound would not evidence ultrametric structure.
- *Momentum-parametrization discrepancy.* The tabulated ratios of [9] decrease with $p$ while the invariant summary of [11] reports $\mathcal{O}_{\mathrm{ZBW}}$ growing from 0 to $\approx 0.92$ with momentum; the two works use different momentum variables or normalizations, and until this is reconciled the Dirac-case momentum dependence should be regarded as not yet internally consistent across the programme.

**Falsification.** The central claim — that $\mathcal{O}_{\mathrm{ZBW}}$ is a quantized $\mathbb{Z}_2$ diagnostic — would be falsified by any of the following observations: (a) a system independently certified as Majorana (e.g., by fusion-rule measurements) that shows a persistently non-zero ZBW correlator signal under constraint-respecting probes, at a level above the $|\epsilon|^2$ admixture floor; (b) a continuous, smoothly varying $\mathcal{O}_{\mathrm{ZBW}}$ across a controlled Dirac-to-Majorana transition in the same device, rather than a jump between 0 and a non-zero plateau; or (c) a computed Majorana-case cross term that does not vanish when evaluated in a representation-independent formulation, which would indicate that the vanishing is an artifact of the specific operator identification of Section 4.3 rather than a consequence of self-conjugacy. Observation (b) is the sharpest: the entire practical value of the invariant rests on its two-valuedness, and a continuous interpolating signal would reduce it to one more continuous transport proxy of the kind the programme is designed to replace.

**Open questions.** Whether the $(2+1)$-dimensional free-model algebra carries over unchanged to the $(3+1)$-dimensional nanowire geometry in which candidate Majorana modes are actually realized; whether the ZBW frequency scale $\omega_C \approx 1.55 \times 10^{21}$ Hz for the bare electron maps to a measurable scale for quasiparticles with $m^* \ll m_e$ (the readout

protocol assumes $m^* \sim 0.1\, m_e$ for its momentum range [11], which raises $\omega_C$ by a factor $\sim 10$ and shifts the signal bandwidth); and whether the fermion-doubling constraint identified in the lattice literature [6] affects any future numerical simulation of the transition graph, are all unresolved here.

## 7. Practical Implications and Engineering Pathways

**(a) Who would use the result and what changes.** The direct user is the qubit-lab engineer or materials group running Majorana nanowire or topological-superconductor fabrication campaigns: teams working with InSb/NbTiN nanowires or Fe-based topological superconductors at $T \approx 50$ mK and $B \approx 0.5$–$2$ T, the parameter regime specified in the readout protocol [11]. If the result holds, the accept/reject decision at each fabrication run changes from an inference over indirect transport proxies to a single binary measurement of $\mathcal{O}_{\mathrm{ZBW}}$: a device reading 0 under a constraint-respecting probe is accepted as hosting a self-conjugate excitation, and a device reading non-zero is rejected or routed to a Dirac-control characterization stream. The same readout would serve as a projective measurement of the topological state in the sense described in [11], replacing active error correction for this specific certification task. A secondary user community is the neutrino-physics instrumentation community, for which the correlator-level formulation offers a complementary, laboratory-scale discriminator to the decay-channel searches of [1], [4], though the paper establishes no path from the condensed-matter observable to a neutrino measurement.

**(b) Current readiness.** This work is purely analytical and computational-audit research that has not been peer reviewed: under the NASA Technology Readiness Level definitions it sits at TRL 1–2 (basic principles observed and reported; concept formulated). The derivation of Section 4.3 and the verification of Section 4.4 are analytical; no measurement, prototype, or breadboard validation exists, and analytical work of this kind does not exceed TRL 3 in any case. The experimental protocols of [11] — spin-noise spectroscopy with $\geq 10^4$ events at $\sim \mu$s resolution, EELS/RIXS with $\mathbf{q} \sim 0.1$–$5$ Å$^{-1}$ and $\Delta E \sim 1$–$10$ meV, and transport-spectroscopic graph reconstruction on $N \approx 20$–$50$ states — are proposals, not demonstrated measurements.

**(c) The smallest next test.** The smallest de-risking measurement is the Protocol B variant proposed in the programme's own roadmap [10], [12]: an EELS or RIXS measurement of $\mathcal{O}_{\mathrm{ZBW}}(\mathbf{q})$ on a hBN-encapsulated graphene Dirac control and a proximitized topological-superconductor candidate, over $\mathbf{q} \sim 0.1$–$5$ Å$^{-1}$ with energy resolution $\Delta E \sim 1$–$10$ meV [11]. The measurement would record the momentum-resolved dynamic structure factor proportional to $\mathrm{Im}[\epsilon^{-1}(\mathbf{q}, \omega)]$ and extract the ZBW-to-static ratio at each $\mathbf{q}$. The falsifying outcome is a candidate system certified as topological that yields a non-zero ZBW signal persisting under constraint-reserving probe geometries, or a Dirac control that yields zero; either contradicts the $\mathbb{Z}_2$ assignment derived in Section 4.3. A still smaller preliminary step is purely computational: re-derive the bilinear table of [9] in an independent gamma-matrix representation and reconcile the momentum-parametrization discrepancy flagged in Section 4.4, which requires no beamtime.

**(d) Binding constraints.** In likely order of first binding: (i) *energy and momentum resolution* — the ZBW signal sits at the Compton scale of the quasiparticle, and for $m^* \sim 0.1\, m_e$ the required momentum transfer $\sim 1/\lambda_C$ falls at the upper end of the $\mathbf{q} \sim 0.5$–$5$ Å$^{-1}$ EELS range stated in [11]; (ii) *signal-to-background* — the Dirac-case ratios of Section 4.4 show the ZBW term is of the same order as the static background, so the measurement is a small-difference extraction against a comparable static contribution, demanding the same discipline as the pair-relative-momentum resolution at the MeV/$c$ scale demonstrated in the DIRAC programme [2], [7]; (iii) *constraint purity* — the $|\epsilon|^2$ admixture floor of Section 4.5 sets the maximum tolerable particle–hole asymmetry in the device; (iv) *statistics* — the spin-noise protocol requires $\geq 10^4$ resolved events [11], which at $\mu$s resolution sets a floor on acquisition time that depends on the device's telegraph-noise rate, an open question this paper does not quantify. Whether fermion doubling affects any lattice simulation of the transition graph, per the caution of [6], is a further open question for the computational arm.

**(e) Order-of-magnitude bounds.** As a labeled projection with stated assumptions: if the EELS measurement integrates for a time comparable to the spin-noise protocol's event budget — assuming $10^4$ events at a $\mu$s-scale event rate of $10^4$ s $^{-1}$, i.e. an acquisition of order 1 s per configuration — and if the ZBW-to-static ratio must be resolved to $10\%$ absolute accuracy to separate 0 from the low-momentum Dirac value $1.0000$ (Section 4.4), then the required fractional precision is comparable to the $10\%$ lifetime-precision benchmark of the DIRAC experiment [2], which was achieved with $10^8$-scale event samples [7]. The projection assumes the correlator signal couples to the electron beam with efficiency comparable to ordinary dynamic structure-factor measurements; no source in this paper quantifies that coupling, so the projection bounds only the statistical, not the systematic, requirement.

**(f) Risks and misuse.** The principal misuse path is over-claiming certification: a single $\mathcal{O}_{\mathrm{ZBW}} = 0$ reading does not certify a topological qubit, because trivial Andreev bound states and fine-tuned accidental zero modes can mimic local signatures, and the invariant diagnoses self-conjugacy of the excitation algebra, not the non-Abelian fusion statistics that topological quantum computation requires. A secondary risk is circular validation within the programme: the $57\%$ edge-reduction figure originates in the same research chain that proposes its measurement [9], [11], and independent replication of the graph observable by an outside group is the safeguard.

## 8. Conclusion

This paper derived, from the collapse of the independent particle–antiparticle operator algebra under the self-conjugacy constraint, that the Zitterbewegung contribution to the current–current correlator vanishes identically for a Majorana fermion while remaining of order unity for a Dirac fermion, making the order parameter $\mathcal{O}_{\mathrm{ZBW}}$ a $\mathbb{Z}_2$ quantity with no intermediate value in the ideal theory. The derivation was accompanied by an independent arithmetic verification of the Dirac-case ratios $1.0000$, $0.8944$, $0.6863$, $0.2981$ at $p = 0$, $0.5$, $1$, $2$ from the published bilinears, a first-principles confirmation of the Compton-scale inputs $\omega_C = 1.5526 \times 10^{21}$ Hz and $\lambda_C/2 = 1.9308 \times 10^{-13}$ m, a stability analysis showing the vanishing is protected against constraint-respecting perturbations and restored at order $|\epsilon|^2$ by constraint-breaking ones, and a pairing-bound analysis showing that the reported $57\%$ edge reduction exceeds the $50\%$–$52.6\%$ bound implied by state pairing alone and therefore requires structure beyond pairing. The result, if confirmed by the smallest proposed test — a momentum-resolved EELS/RIXS comparison of a Dirac control against a topological-superconductor candidate — would convert Majorana certification from an inference over indirect proxies into a single binary measurement at the fabrication line. The same algebraic distinction between self-conjugate and non-self-conjugate fermions underlies the neutrino-nature question addressed by decay-channel searches [1], [4], [5] and the flavor-symmetry structure of Dirac and Majorana mass terms [8], which is where the correlator-level viewpoint may find further use.

## Provenance and AI Involvement

- This paper was drafted, reconciled, reviewed, revised and checked by the QNFO automated research pipeline (qnfo-research-exec 0.45.4). Language models were tools in that process; they are not authors. The named author is accountable for the content.
- Models: drafting by openai/gpt-oss-120b, zai-org/glm-5.3-flash; reconciliation, completion, review, revision and verification by zai-org/glm-5.3-flash, openai/gpt-oss-120b, moonshotai/kimi-k2.6, with the QNFO model router as a fallback.
- Sources: every reference is drawn from a bibliography retrieved from arXiv and the QNFO corpus before drafting; every cited work's full text was retrieved (arXiv HTML, or the QNFO paper's body) and the writers were given excerpts of its own sections; statements about a cited work are restricted to its retrieved title, abstract and those excerpts.

- Checks passed before publication: required sections present and finished, cross-references resolve, reference list rendered from the retrieved bibliography, no assistant residue or placeholders, adversarial model review with its blocking findings resolved, and a citation existence check at publication.
- Independent recomputation: the execution sandbox was unavailable, so a second language model recomputed 13 quantitative claims step by step in text from the paper's stated inputs (no code was executed); 0 differed from the stated value at the stated precision.
- Not checked: whether each cited source supports the sentence that cites it beyond the retrieved full-text excerpts; derivation steps other than the recomputed claims. This paper has not been peer reviewed, and this version was published by the pipeline without a prior manual review by the author.

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