

The Holographic Circlette: Unifying the Standard Model, Gravity, and Cosmology

via Error-Correcting Codes on a Fisher-Information Lattice

D.G. Elliman*

Neuro-Symbolic Ltd, United Kingdom

February 2026 (v2)

*The lattice does not obey quantum mechanics.
Quantum mechanics obeys the lattice.*

Abstract

We propose a unified physical framework in which the Standard Model fermion spectrum corresponds to the set of valid codewords of an 8-bit quantum error-correcting code defined on a holographic lattice. Four local constraints select exactly 45 valid matter states from 256 possibilities. The dynamics are governed by a unique update rule - a CNOT gate at the bridge-isospin boundary - identified as the weak interaction.

From this information-theoretic foundation, we derive: the charged lepton mass ratios to 0.007% precision from a single geometric parameter $\delta = 2/9$; the weak mixing angle $\sin^2 \theta_W = 2/9$ (0.5% error); the W/Z boson mass ratio $M_W/M_Z = \sqrt{7}/9$ (0.06% error); and the PMNS neutrino mixing angles under a bimaximal lattice ansatz. Gravity emerges as the curvature of the Fisher information metric; special relativity as a bandwidth constraint; and the cosmological constant as the vacuum information floor. A dynamic dark energy model matches DESI DR2 observations to within 1.5%.

The 3+1D Dirac equation is derived exactly as the continuum limit of a discrete quantum walk whose coin operator is the CNOT gate. Rest mass is the CNOT execution frequency. The complex unit i is forced by the unitarity of a reversible Boolean swap.

The central result of this paper is that the integer ratio $\delta = 2/9$ - the ratio of a 2-bit topological defect to a 9-bit plaquette - determines the charged lepton mass spectrum, the electroweak mixing angle, the Cabibbo angle, and the PMNS mixing matrix, with one continuous free parameter (the overall mass scale).

Keywords: quantum error-correcting code, holographic principle, cellular automaton, Fisher information geometry, Standard Model fermions, CNOT gate, Koide relation, weak mixing angle, Dirac equation, quantum walk

*Email: dave@neusym.ai

Contents

1	Introduction	4
2	Part I: The Code and the Spectrum	4
2.1	The 8-Bit Encoding	4
2.2	The Parity Checks	5
2.3	The 9-Qubit Plaquette	5
2.4	Pseudocodewords and the ν_R Defect	5
2.5	Colour as XOR Closure	6
3	Part II: Dynamics and the Unique Weak Rule	6
3.1	The Information Action Principle	6
3.2	Physical Identification: The Weak Interaction	6
3.3	Special Relativity as a Bandwidth Constraint	6
4	Part III: Gravity as Information Geometry	6
4.1	The Holographic Lattice	6
4.2	The Fisher Information Metric	7
4.3	The Information Action	7
5	Part IV: The Vacuum	7
5.1	The Order Parameter $\Phi = 45/256$	7
5.2	The Schwinger Effect as Dielectric Breakdown	7
5.3	Three Sterile Neutrinos	7
6	Part V: Black Holes and Computational Phase Transitions	7
7	Part VI: Cosmology and Dynamic Dark Energy	8
7.1	The Cosmological Constant as Information Floor	8
7.2	The Dynamic $F_{\text{vac}}(a)$ Model	8
7.3	Comparison with DESI DR2	8
8	Part VII: The Emergence of Quantum Kinematics	8
8.1	Mass as CNOT Execution Frequency	8
8.2	The Boolean Origin of i	8
8.3	The 4-Component Internal State	8
8.4	Three Spatial Dimensions from Two Bits	9
8.5	The 3+1D Dirac Equation	9
9	Part VIII: The Mass Hierarchy - Deriving the Lepton Spectrum	9
9.1	Mass as Constraint Violation Energy	9
9.2	The Circulant Ring Eigenvalues	10
9.3	Derivation of $B/A = \sqrt{2}$	10
9.4	Derivation of $\delta = 2/9$	10
9.5	The Charged Lepton Mass Spectrum	10
9.6	What Is and Is Not Derived	11

10 Part VIII-B: Extension to the Quark Sector	11
10.1 Colour Dilution of the Twist	11
10.2 The Structure Factor and Colour Paths	12
10.3 Mass Predictions from Integer Geometry	12
10.4 Summary: The Colour Dilution Pattern	13
11 Part IX: The Electroweak Sector	13
11.1 Geometric Identification of Gauge Fields	13
11.2 The Weak Mixing Angle	13
11.3 The W/Z Boson Mass Ratio	14
12 Part X: Flavour Mixing	14
12.1 The Bimaximal Lattice Basis	14
12.2 The Cabibbo Angle	15
12.3 The Solar Angle θ_{12}	15
12.4 The Reactor Angle θ_{13}	15
12.5 Summary of Mixing Predictions	15
13 Part XI: Gauge Fields and Anomaly Cancellation	15
13.1 Lattice Gauge Theory on the Circlette	15
13.2 Anomaly Cancellation	16
13.3 The Phase Coherence Bound on α	16
14 The Zero-Parameter Geometric Standard Model	16
15 Discussion	17
15.1 Complete Parameter Table	17
15.2 Physical Interpretation	17
15.3 Relation to Grand Unification	17
15.4 Epistemic Status	18
15.5 Falsifiable Predictions	18
15.5.1 Near-term: the tau mass	18
15.5.2 Near-term: $ V_{us} $ and the Cabibbo angle	18
15.5.3 Near-term: dynamic dark energy	19
15.5.4 Medium-term: sterile neutrinos	19
15.5.5 Medium-term: the weak mixing angle at FCC-ee precision	19
15.5.6 Long-term: the quark sector	19
15.5.7 Long-term: neutrino mass scale	19
15.6 Falsification Criteria	19
15.7 Open Questions	20
16 Summary of Predictions	20
17 Conclusion	21
17.1 Precision vs. Approximation: The Geometry of Mass	21
17.2 The Central Equation	22
17.3 Final Implications	22

1 Introduction

The search for a unified theory of physics has long oscillated between geometric approaches (General Relativity) and algebraic approaches (Quantum Field Theory). In 1990, Wheeler proposed a third path: “It from Bit” - the idea that the physical world derives its existence from binary choices Wheeler [1990]. While the holographic principle ’t Hooft [1993], Susskind [1995], Maldacena [1999], Verlinde’s entropic gravity Verlinde [2011], and ’t Hooft’s cellular automaton interpretation have all strengthened this view, a concrete realisation has been elusive: which bits? What code? What rules?

This paper presents that realisation. We show that the complexity of the Standard Model - its gauge groups, particle spectrum, mass hierarchy, electroweak mixing, and flavour structure - emerges naturally from a minimal 8-bit error-correcting code (the “circlette”) operating on a 2D holographic lattice.

The framework develops in stages:

1. **The Code** (Part I): The static encoding - 45 fermions as codewords of an 8-bit ring code on a 9-qubit plaquette.
2. **The Dynamics** (Part II): A unique CNOT update rule that is the weak interaction, with special relativity as a bandwidth constraint.
3. **The Geometry** (Parts III–VI): Gravity, vacuum structure, black hole physics, and cosmology from the Fisher information geometry.
4. **The Kinematics** (Part VII): The Dirac and Schrödinger equations as the continuum limit of the CNOT lattice walk.
5. **The Mass Spectrum** (Part VIII): Charged lepton masses from the Koide formula with $\delta = 2/9$, derived from the defect-to-plaquette ratio.
6. **The Electroweak Sector** (Part IX): The weak mixing angle and boson mass ratio from the integer partition $9 = 7 + 2$.
7. **Flavour Mixing** (Part X): The CKM and PMNS mixing angles from the geometric twist δ combined with the bimaximal lattice symmetry.

2 Part I: The Code and the Spectrum

2.1 The 8-Bit Encoding

A fundamental fermion is specified by an 8-bit string arranged on an oriented ring. The bits partition into sectors mirroring the gauge structure of the Standard Model: Generation (G), Colour (C), and Electroweak (I_3 , χ , W), connected by a Bridge bit (LQ).

The ring topology is essential. Of all 5,040 circular orderings of 8 bits, exactly 48 achieve perfect constraint locality at window size 3. The 8 orderings with the best locality score are all equivalent (up to colour-bit swap and ring reversal) to:

$$G_0 - G_1 - C_0 - C_1 - \text{LQ} - I_3 - \chi - W - (\text{back to } G_0) \quad (1)$$

Position	Bit	Field	Values	Interpretation
0	b_1	G_0	0,1	2*Generation (11 forbidden)
1	b_2	G_1	0,1	
2	b_3	C_0	0,1	2*Colour (White/Red/Green/Blue)
3	b_4	C_1	0,1	
4	b_5	LQ	0,1	Lepton (0) / Quark (1)
5	b_6	I_3	0,1	Up-type (0) / Down-type (1)
6	b_7	χ	0,1	Left (0) / Right (1)
7	b_8	W	0,1	Doublet (0) / Singlet (1)

Table 1: The 8-bit fermion encoding.

2.2 The Parity Checks

Of the $2^8 = 256$ possible configurations, exactly 45 are selected by four local constraints:

R1 (Generation Bound): $(G_0, G_1) \neq (1, 1)$. Three generations only.

R2 (Chirality–Weak Coupling): $\chi = W$. Left-handed particles are weak doublets; right-handed are singlets.

R3 (Colour–Lepton Exclusion): $LQ = 0 \Rightarrow (C_0, C_1) = (0, 0)$; $LQ = 1 \Rightarrow (C_0, C_1) \neq (0, 0)$.

R4 (No Right-Handed Neutrino): $(LQ = 0 \wedge I_3 = 0 \wedge \chi = 1)$ is forbidden.

All four rules involve adjacent bits on the ring. The 45 valid states comprise 15 per generation (3 leptons + 12 quarks).

2.3 The 9-Qubit Plaquette

The 8-bit ring describes the boundary of a plaquette on the 4.8.8 (truncated square) Archimedean tiling. The plaquette interior contributes one additional degree of freedom - a parity or syndrome bit - bringing the total to 9 effective qubits per unit cell. In a 3×3 grid representation:

- 8 boundary sites correspond to the 8 ring bits,
- 1 centre site corresponds to the bulk parity.

The vacuum state (ground state of the stabiliser Hamiltonian) is delocalised across all 9 sites. A topological defect - a violation of the $(1, 1)$ exclusion - is localised to the 2 boundary sites where the constraint is violated.

2.4 Pseudocodewords and the ν_R Defect

Three states satisfy R1, R2, R3 but violate only R4: one per generation, each a right-handed neutrino. These *pseudocodewords* are colourless, generation-indexed, and invisible to the CNOT rule ($LQ = 0$).

The ν_R pseudocodeword has three key properties:

1. **Localisation:** It is pinned to the 2 sites of the violated constraint and cannot spread without additional energy cost.
2. **Three-fold degeneracy:** The Z_3 symmetry of the generation ring admits three ν_R states.
3. **Boundary character:** It lives on the boundary of the plaquette, not in the bulk.

2.5 Colour as XOR Closure

With $R = 01$, $G = 10$, $B = 11$, $W = 00$ in \mathbb{F}_2^2 : $R \oplus G \oplus B = 00$. Colour confinement is XOR closure.

3 Part II: Dynamics and the Unique Weak Rule

3.1 The Information Action Principle

Searching all non-trivial invertible maps over \mathbb{F}_2 that preserve the 45-state spectrum, exactly one rule survives:

$$I_3(t+1) = I_3(t) \oplus \text{LQ}(t) \quad (2)$$

This is a CNOT gate: Bridge bit LQ is the control, Isospin I_3 is the target.

3.2 Physical Identification: The Weak Interaction

Leptons ($\text{LQ} = 0$): control off, I_3 unchanged. Quarks ($\text{LQ} = 1$): control on, I_3 toggles ($u \leftrightarrow d$, $c \leftrightarrow s$, $t \leftrightarrow b$) with period 2 in Planck units. The rule is an involution ($M^2 = I$), guaranteeing unitarity.

3.3 Special Relativity as a Bandwidth Constraint

The lattice propagates information at one cell per Planck time = c . A pattern moving at v must allocate bandwidth for spatial re-encoding:

$$f_{\text{internal}} = \sqrt{1 - v^2/c^2} = 1/\gamma \quad (3)$$

Lorentz invariance is a consistency requirement: the lattice enforces c -invariance to prevent frame-dependent parity check results.

4 Part III: Gravity as Information Geometry

4.1 The Holographic Lattice

The holographic principle Bekenstein [1973], 't Hooft [1993], Susskind [1995] bounds information by surface area at one bit per four Planck areas. We take this literally: the universe is a 2D lattice of bits. A circlette is a stable, self-propagating pattern on this surface.

4.2 The Fisher Information Metric

The Fisher information metric Fisher [1925], Amari and Nagaoka [2000], Frieden [2004]:

$$g_{\mu\nu}(\theta) = \frac{\ell_P^2}{\kappa} F_{\mu\nu}(\theta) = \frac{\ell_P^2}{\kappa} \sum_b p^*(b|\theta) \frac{\partial \ln p^*}{\partial \theta^\mu} \frac{\partial \ln p^*}{\partial \theta^\nu} \quad (4)$$

provides a natural Riemannian metric on the lattice. Matter creates sharply peaked distributions (non-zero Fisher curvature). Vacuum is flat.

4.3 The Information Action

The information action along a lattice path γ :

$$S_I[\gamma] = \int_\gamma \sqrt{F_{ij} d\theta^i d\theta^j} \quad (5)$$

The Feynman propagator is the sum over all lattice paths weighted by $\exp(iS_I/\hbar_I)$. In the classical limit, stationary phase selects the Fisher geodesic.

5 Part IV: The Vacuum

5.1 The Order Parameter $\Phi = 45/256$

The ratio $\Phi = N_{\text{valid}}/N_{\text{total}} = 45/256 \approx 0.176$ is the fundamental order parameter. Its information-theoretic content is $-\log_2 \Phi \approx 2.51$ bits per ring.

5.2 The Schwinger Effect as Dielectric Breakdown

Pair production in strong fields is the dielectric breakdown of the error-correcting code. The critical field $E_{\text{cr}} = m_e^2 c^3 / (e\hbar)$ is the threshold where externally supplied bit-correction exceeds the vacuum noise rate.

5.3 Three Sterile Neutrinos

Three states satisfying R1–R3 but violating only R4 are candidate sterile neutrinos: one per generation, colourless, interacting only gravitationally.

6 Part V: Black Holes and Computational Phase Transitions

At the black hole horizon, the bandwidth for particle dynamics vanishes: $B_{\text{free}} \rightarrow 0$. The CNOT rule cannot execute - this is clock death. Hawking radiation is the emission of broken codewords when Fisher curvature creates decoherence exceeding the code's correction threshold. The CNOT rule's involutory structure ($M^2 = I$) guarantees reversibility, dissolving the information paradox.

7 Part VI: Cosmology and Dynamic Dark Energy

7.1 The Cosmological Constant as Information Floor

The cosmological constant is identified with the vacuum Fisher information: $\Lambda = F_{\text{vac}}/\ell_P^2$. This is the minimum bit density for causal connectivity - the percolation threshold.

7.2 The Dynamic $F_{\text{vac}}(a)$ Model

Two competing effects:

- **Constraint establishment (growth):** As the universe cools, F_{vac} grows as $\sim a^\alpha$.
- **Matter dilution (decay):** Matter anchors dilute as $\sim \exp(-\beta a^\gamma)$.

The resulting model:

$$F_{\text{vac}}(a) = \mathcal{N}^{-1} a^\alpha \exp(-\beta a^\gamma) \quad (6)$$

with dark energy equation of state $w(a) = -1 - \frac{1}{3}(\alpha - \beta\gamma a^\gamma)$.

7.3 Comparison with DESI DR2

Three DESI observables DESI Collaboration [2025] determine $\gamma = 1.035$, $\alpha = 1.749$, $\beta = 2.409$. The model reproduces DESI dark energy density to within 1.5% across the full observed range $0.3 \leq a \leq 1.2$.

8 Part VII: The Emergence of Quantum Kinematics

8.1 Mass as CNOT Execution Frequency

For quarks ($LQ = 1$), the CNOT toggles I_3 at every Planck tick. This Boolean oscillation is Zitterbewegung Schrödinger [1930]. Rest mass m is the CNOT execution frequency.

8.2 The Boolean Origin of i

The CNOT toggle is a Boolean NOT: $I_3 \rightarrow I_3 \oplus 1$. To embed this discrete toggle in a continuous rotation group (preserving unitarity):

$$U(\theta) = e^{-i\theta\sigma_x} = \cos \theta I - i \sin \theta \sigma_x \quad (7)$$

The complex unit i is forced by the requirement that a reversible Boolean swap ($M^2 = I$) must embed in a unitary rotation.

8.3 The 4-Component Internal State

The electroweak sector contains two kinematically relevant bits: I_3 (CNOT target) and χ (chirality, locked to W by R2). These span a 4-dimensional internal Hilbert space $\mathbb{C}^2 \otimes \mathbb{C}^2$, identified with the Dirac spinor.

The Dirac matrices decompose as tensor products over $\chi \otimes I_3$:

$$\beta = \sigma_z^{(x)} \otimes I^{(I_3)}, \quad \alpha_1 = \sigma_x^{(x)} \otimes \sigma_x^{(I_3)}, \quad (8)$$

$$\alpha_2 = \sigma_x^{(x)} \otimes \sigma_y^{(I_3)}, \quad \alpha_3 = \sigma_x^{(x)} \otimes \sigma_z^{(I_3)}, \quad (9)$$

$$\gamma^5 = \sigma_y^{(x)} \otimes I^{(I_3)} \quad (10)$$

All ten anticommutation relations of the Clifford algebra $\text{Cl}(3, 1)$ are exactly satisfied (computationally verified).

8.4 Three Spatial Dimensions from Two Bits

The commutator of the two surface translations generates γ^5 :

$$[\alpha_1, \alpha_2] = 2i\gamma^5 \quad (11)$$

Two non-commuting translations on a 2D surface, acting on a 4-component internal state, generate three independent momentum operators. The third arises from the algebra of $SU(2)_{I_3}$, not from the lattice geometry D'Ariano and Perinotti [2014], Bisio et al. [2015], Bialynicki-Birula [1994].

8.5 The 3+1D Dirac Equation

The continuum limit of the quantum walk on the 2D lattice:

$$i\hbar \frac{\partial \Psi}{\partial t} = \left[-i\hbar c \left(\alpha_1 \frac{\partial}{\partial x} + \alpha_2 \frac{\partial}{\partial y} + \alpha_3 \frac{\partial}{\partial z} \right) + mc^2 \beta \right] \Psi \quad (12)$$

This is exact, not an approximation. The Schrödinger equation follows as the non-relativistic limit via the Pauli identity $(\boldsymbol{\sigma} \cdot \mathbf{p})^2 = |\mathbf{p}|^2 I$:

$$i\hbar \frac{\partial \varphi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \varphi \quad (13)$$

9 Part VIII: The Mass Hierarchy - Deriving the Lepton Spectrum

9.1 Mass as Constraint Violation Energy

We identify fermion mass with the energy cost of propagation through the forbidden ν_R channel. Massless fermions propagate within the code subspace; massive fermions must tunnel through the ν_R boundary via a Feshbach resonance. For a fermion coupling to the ν_R state at energy ε :

$$H_{\text{eff}} = \begin{pmatrix} 0 & \xi_k \\ \xi_k^* & \varepsilon \end{pmatrix} \quad (14)$$

At $k = 0$, the massive pole gives $m_n = \varepsilon_n$.

9.2 The Circulant Ring Eigenvalues

The three ν_R states form a ring in generation space. The effective Hamiltonian is a 3×3 circulant matrix with eigenvalues:

$$\lambda_n = A + B \cos\left(\frac{2\pi n}{3} + \delta\right), \quad n = 0, 1, 2 \quad (15)$$

The physical mass is the *square* of this eigenvalue (from the second-order Feshbach self-energy):

$$m_n = \mu \left(1 + \frac{B}{A} \cos\left(\delta + \frac{2\pi n}{3}\right)\right)^2 \quad (16)$$

Important: This is $(1 + \sqrt{2} \cos \theta)^2$, the square of a *real* eigenvalue from the circulant ring - *not* $|1 + \sqrt{2} e^{i\theta}|^2$ (the modulus-squared of a complex number), which gives a different spectrum.

9.3 Derivation of $B/A = \sqrt{2}$

On the 2D spatial lattice, the Dirac operators for the x - and y -directions are $\alpha_1 = \sigma_x \otimes \sigma_x$ (real) and $\alpha_2 = \sigma_y \otimes \sigma_x$ (imaginary), from Eqs. (8)–(9). Both map $\nu_R \rightarrow e_L$:

$$\langle e_L | \alpha_1 | \nu_R \rangle = 1, \quad \langle e_L | \alpha_2 | \nu_R \rangle = i \quad (17)$$

The effective generation hopping adds these in quadrature:

$$T_{\text{eff}} = 1 + i, \quad |T_{\text{eff}}| = \sqrt{2} \quad (18)$$

This fixes $B/A = \sqrt{2}$ exactly. The $\sqrt{2}$ in the Koide formula [1983] is not empirical - it is forced by the tensor product structure of the Dirac operators on a 2D lattice.

9.4 Derivation of $\delta = 2/9$

The phase δ is the Berry phase acquired by the ν_R defect traversing the generation ring. It is determined by the ratio of the defect's topological support to the unit cell (Section 2.3):

- The ν_R defect occupies $d = 2$ sites (the violated constraint pair).
- The full plaquette contains $N = 9$ sites (8 boundary + 1 bulk).

The vacuum is delocalised over all $N = 9$ sites, so its translation amplitude scales as $T_{\text{vac}} \propto 9t$. The defect, pinned to its 2-site support, has $T_{\text{def}} \propto 2t$. The geometric phase is:

$$\delta = \frac{T_{\text{def}}}{T_{\text{vac}}} = \frac{d}{N} = \frac{2}{9} \text{ radians} \quad (19)$$

9.5 The Charged Lepton Mass Spectrum

Combining these results:

$$m_n = \mu \left(1 + \sqrt{2} \cos\left(\frac{2}{9} + \frac{2\pi n}{3}\right)\right)^2 \quad (20)$$

Lepton	Predicted (MeV)	Measured (MeV)	Error
e	0.5110	0.5110	0.007%
μ	105.652	105.658	0.006%
τ	1776.86	1776.86	(input)

Table 2: Charged lepton masses from Eq. (20) with $\delta = 2/9$ and one free parameter (the overall scale μ).

with one free parameter μ . Every symbol has a geometric origin: the 1 is the on-site energy, $\sqrt{2}$ the quadrature of real and imaginary Dirac paths, the cos from the circulant ring, $2/9$ the defect-to-cell ratio, and $2\pi n/3$ labels the three generations.

Fixing μ from the tau mass Particle Data Group et al. [2024]:

The Koide ratio $Q = \sum m_i / (\sum \sqrt{m_i})^2 = 2/3$ is satisfied identically - it is a mathematical consequence of the $(1 + \sqrt{2} \cos \theta)^2$ functional form, not an additional constraint.

9.6 What Is and Is Not Derived

Derived (zero free parameters): Three generations (from $(1, 1)$ exclusion); the Koide functional form (circulant eigenvalues squared); the coefficient $\sqrt{2}$ (quadrature of α_1 and α_2); $Q = 2/3$ (mathematical identity); $\delta = 2/9$ (defect/plaquette ratio).

Not derived (one free parameter): The overall mass scale μ .

10 Part VIII-B: Extension to the Quark Sector

The generalised mass formula Eq. (16) applies to any charge sector if the structure factor R and twist δ are allowed to depend on the colour quantum numbers. We test this by fitting R , δ , and μ independently to the up-type (u, c, t) and down-type (d, s, b) quark masses and asking: do the fitted values correspond to integer geometric counts involving the colour multiplicity $N_c = 3$?

10.1 Colour Dilution of the Twist

The fitted Koide parameters for each charge sector are:

Sector	δ_{fit} (rad)	$\delta_{\text{fit}}/\delta_\ell$	R_{fit}	Integer candidate
Leptons	0.2222	1.000	1.414	$R = \sqrt{2}, \delta = 2/9$
Up quarks	0.0806	0.363	1.778	$R \approx \sqrt{3}, \delta \approx 2/27$
Down quarks	0.1099	0.494	1.546	$\delta \approx 1/9$

Table 3: Fitted Koide parameters by charge sector. With 3 parameters for 3 masses, the fit is unconstrained (always perfect). The test is whether the fitted values correspond to integer geometric ratios.

The twist ratios are suggestive:

- **Up quarks:** $\delta_u/\delta_\ell \approx 1/3$. This suggests $\delta_u = \delta_\ell/N_c = 2/27$: the boundary defect (2 bits) is shared equally across $N_c = 3$ colour sheets, diluting the Berry phase by a factor of 3.
- **Down quarks:** $\delta_d/\delta_\ell \approx 1/2$. This gives $\delta_d = \delta_\ell/2 = 1/9$. The physical origin of the factor 2 is less clear; it may relate to the hypercharge difference between up-type ($Y = 2/3$) and down-type ($Y = -1/3$) quarks, or to the isospin-doublet structure of the electroweak sector.

10.2 The Structure Factor and Colour Paths

For leptons, $R = \sqrt{2}$ arises from the quadrature of 2 spatial hopping paths (real and imaginary Dirac operators, Section 9). For quarks, the colour degree of freedom introduces additional hopping channels.

- **Up quarks:** The fitted $R_u = 1.778$ is 2.6% above $\sqrt{3} = 1.732$. The hypothesis $R = \sqrt{N_c} = \sqrt{3}$ corresponds to the quadrature sum of 3 colour paths, extending the lepton argument ($R = \sqrt{2}$ from 2 spatial paths) to include the colour multiplicity.
- **Down quarks:** The fitted $R_d = 1.546$ is extremely close to $\sqrt{12/5} = 1.549$ (0.2% error). This value, while not as immediately transparent as $\sqrt{2}$ or $\sqrt{3}$, can be written as $R_d = \sqrt{N_c \cdot 4/5}$, suggesting a fractional effective path count modified by the isospin coupling.

10.3 Mass Predictions from Integer Geometry

The critical test is whether the integer values of R and δ predict the quark masses (with only the overall scale fitted from the heaviest mass).

Sector	Geometry	Lightest	Middle	Status
Leptons	$R = \sqrt{2}, \delta = 2/9$	m_e : 0.007%	m_μ : 0.006%	Excellent
Down quarks	$R = \text{fit}, \delta = 1/9$	m_d : 3.6%	m_s : 1.0%	Good
Up quarks	$R = \sqrt{3}, \delta = 2/27$	m_u : 590%	m_c : 11%	Poor

Table 4: Mass predictions from integer geometry (1 free parameter per sector). The down sector works well; the up sector fails for m_u due to node sensitivity.

The down sector performs well: with $\delta = 1/9$ and the fitted R , the predicted m_d and m_s fall within or near the experimental uncertainties ($m_d = 4.67 \pm 0.48$ MeV, $m_s = 93.4 \pm 8.6$ MeV).

The up sector fails for the lightest mass. This is a *sensitivity* problem, not a structural one: the up quark mass sits near a node of the cosine function, where $(1 + R \cos \theta) \approx 0$. Near this node, the predicted mass is exponentially sensitive to small changes in R and δ .

To understand why this matters for quarks but not for leptons, note that the electron is *also* near a node: $(1 + \sqrt{2} \cos \theta_e) = 0.040$, even closer to zero than the up quark value of 0.025. Yet the electron mass is predicted to 0.007%. The difference is that for leptons, $R = \sqrt{2}$ and $\delta = 2/9$ are the *exact* geometric values - the fit recovers them to high precision, so there is no approximation error to amplify. For the up quark sector, $R = \sqrt{3}$ and $\delta = 2/27$ are *hypothesised* leading-order values that deviate from the fit by 2.6% and

9% respectively. These small deviations, amplified by the node proximity, produce the 590% error in m_u .

This suggests that the quark-sector geometry requires sub-leading corrections - from QCD running, colour-sector Berry phases, or higher-order Feshbach terms - that are absent in the lepton sector because the lepton geometry is exact at leading order.

10.4 Summary: The Colour Dilution Pattern

Sector	δ	Source	R	Source
Leptons	2/9	d/N base geometry	$\sqrt{2}$	2 spatial paths
Up quarks	2/27	$(d/N)/N_c$ colour dilution	$\sqrt{3}$	3 colour paths
Down quarks	1/9	$(d/N)/2$ isospin factor	~ 1.55	(intermediate)

Table 5: The geometric parameters for each charge sector. Colour introduces a dilution factor in the twist and additional hopping paths in the structure factor.

The pattern is clear: colour *dilutes* the geometric twist (dividing δ by N_c or 2) and *enhances* the structure factor (increasing R from $\sqrt{2}$ toward $\sqrt{3}$). This produces the steeper mass hierarchies observed in the quark sector compared to the lepton sector. The down quark anomaly ($\delta_d = \delta_\ell/2$ rather than δ_ℓ/N_c) and the non-integer R_d remain open questions that may be resolved by a more detailed analysis of the (C_0, C_1) colour bits within the code.

11 Part IX: The Electroweak Sector

The electroweak sector emerges from a counting argument on the 9-bit unit cell. We propose that electroweak symmetry breaking is determined by the partition of the code geometry into bulk and boundary logic.

11.1 Geometric Identification of Gauge Fields

Weak Isospin $SU(2)_L$: Mediates transitions preserving the boundary conditions. Couples to the *bulk geometry* - the $N - d = 7$ qubits not involved in the defect.

Hypercharge $U(1)_Y$: Mediates the phase associated with the boundary defect. Couples to the *twist geometry* - the $d = 2$ qubits defining the $(1, 1)$ violation.

11.2 The Weak Mixing Angle

The weak mixing angle measures the fraction of the unit cell carrying the twist:

$$\sin^2 \theta_W = \frac{d}{N} = \frac{2}{9} = 0.2222\dots \quad (21)$$

Note that $\sin^2 \theta_W$ and the Koide phase δ are numerically identical ($= 2/9$) but enter the physics differently: δ is a Berry phase on the generation ring, while $\sin^2 \theta_W$ is a coupling-strength ratio. Their equality reflects the common geometric origin - the defect density of the plaquette.

Quantity	Predicted	Experimental	Error
$\sin^2 \theta_W$	$2/9 = 0.2222$	0.2232 (on-shell)	0.5%

Table 6: Weak mixing angle prediction.

Unlike GUTs, which predict $\sin^2 \theta_W = 3/8$ at the unification scale and require 14 orders of magnitude of running, this framework predicts the low-energy on-shell value directly, suggesting the geometry sets an infrared boundary condition.

11.3 The W/Z Boson Mass Ratio

The mass-squared of a gauge boson is proportional to the Hamming weight of the corresponding logical operator:

$$M_W^2 \propto N_{\text{bulk}} = 7, \quad M_Z^2 \propto N_{\text{total}} = 9 \quad (22)$$

Therefore:

$$\frac{M_W}{M_Z} = \sqrt{\frac{7}{9}} = 0.8819\dots \quad (23)$$

Quantity	Predicted	Experimental	Error
M_W/M_Z	$\sqrt{7/9} = 0.8819$	0.8814	0.06%

Table 7: W/Z boson mass ratio. This is equivalent to $\cos \theta_W = \sqrt{1 - 2/9}$ and is therefore the same prediction as Eq. (21).

The W is lighter than the Z because it couples to fewer qubits.

12 Part X: Flavour Mixing

The geometric twist $\delta = 2/9$ also governs the mixing angles between flavour and mass eigenstates. The predictions in this section rest on a bimaximal lattice ansatz rather than a first-principles calculation, but they demonstrate that a single parameter unifies the CKM and PMNS matrices.

12.1 The Bimaximal Lattice Basis

The 4.8.8 tiling has a natural C_4 symmetry. For the neutral neutrino sector, which does not couple to the boundary twist, the mixing matrix retains the full lattice symmetry - the Bimaximal (BM) pattern Harrison et al. [2002]:

$$\theta_{12}^{\text{lattice}} = 45^\circ, \quad \theta_{23}^{\text{lattice}} = 45^\circ, \quad \theta_{13}^{\text{lattice}} = 0^\circ \quad (24)$$

The physical PMNS matrix arises from the mismatch between this lattice basis and the twisted basis of the charged leptons.

12.2 The Cabibbo Angle

The dominant quark mixing angle is identified with the geometric twist:

$$\theta_C \approx \delta = \frac{2}{9} \text{ rad} \approx 12.73^\circ \quad (\text{Exp: } 13.04^\circ, \text{ error } 2.4\%) \quad (25)$$

12.3 The Solar Angle θ_{12}

The twist erodes the bimaximal 45° symmetry Raidal [2004]:

$$\theta_{12} \approx 45^\circ - \delta \approx 32.27^\circ \quad (\text{Exp: } 33.41^\circ, \text{ error } 3.4\%) \quad (26)$$

This is formally equivalent to Quark-Lepton Complementarity ($\theta_{12} + \theta_C \approx 45^\circ$), which in our framework is a geometric identity.

12.4 The Reactor Angle θ_{13}

The 2D defect projects onto the 3D generation space with a factor $1/\sqrt{2}$:

$$\theta_{13} \approx \frac{\delta}{\sqrt{2}} \approx 9.00^\circ \quad (\text{Exp: } 8.57^\circ, \text{ error } 5.0\%) \quad (27)$$

This explains why $\theta_{13} \neq 0$ (unlike the Tri-Bimaximal ansatz) and relates it to the Cabibbo angle via $\theta_{13} \approx \theta_C/\sqrt{2}$.

12.5 Summary of Mixing Predictions

Angle	Formula	Predicted	Experimental	Error
θ_C	δ	12.73°	13.04°	2.4%
θ_{12}	$45^\circ - \delta$	32.27°	33.41°	3.4%
θ_{13}	$\delta/\sqrt{2}$	9.00°	8.57°	5.0%
θ_{23}	$\approx 45^\circ$	45°	42.2°	$\sim 7\%$

Table 8: Flavour mixing angle predictions from $\delta = 2/9$ and the bimaximal lattice ansatz.

13 Part XI: Gauge Fields and Anomaly Cancellation

13.1 Lattice Gauge Theory on the Circlette

Following Wilson Wilson [1974], gauge bosons reside on lattice links. The U(1) gauge field emerges from local variation in the CNOT execution phase during spatial hops:

$$|\psi(y)\rangle = U(x, y) \cdot C(\theta) \cdot |\psi(x)\rangle, \quad U(x, y) = e^{ieA_\mu \Delta x^\mu} \quad (28)$$

13.2 Anomaly Cancellation

Computing the electric charge $Q = T_3 + Y/2$ for each valid state:

$$\sum_{\text{45 states}} Q = 0 \quad (29)$$

The gravitational anomaly cancellation follows automatically from R1–R4.

The sum of squared charges gives the 1-loop QED beta function coefficient:

$$\sum_{\text{45 states}} Q^2 = 16 \quad (30)$$

This is exactly the Standard Model value. The 45 states carry the precise quantum numbers needed for gauge dynamics.

13.3 The Phase Coherence Bound on α

The electromagnetic coupling α is bounded by the code’s fault-tolerance threshold Dennis et al. [2002], Fowler et al. [2012] during the mandatory chirality-flip vulnerability window. The empirical value $\alpha \approx 0.0073$ falls within the typical 10^{-2} thresholds of 2D quantum codes.

14 The Zero-Parameter Geometric Standard Model

The preceding sections have derived the major parameters of the Standard Model from the integer geometry of a single 3×3 code block. Table 9 collects these results. With the exception of the overall mass scale μ (one free parameter), every entry is determined by the discrete geometry of the 9-bit plaquette.

The framework moves the Standard Model from a list of arbitrary constants to a list of integer geometric properties:

- **Mass** is the cost of violating the code.
- **Mixing** is the twist of the code boundary.
- **Generations** are the winding numbers of the code ring.

15 Discussion

15.1 Complete Parameter Table

15.2 Physical Interpretation

The Standard Model, in this framework, is the effective field theory of a 9-bit topological code on the 4.8.8 lattice:

- **Mass** is the energy cost of constraint violation (leakage through the ν_R boundary).
- **Forces** are the logical operations of the code: $SU(2)_L$ on the 7-bit bulk, $U(1)_Y$ on the 2-bit defect.
- **Generations** are the topological sectors of the Z_3 ring.
- **Mixing** is the Berry phase of defects traversing the lattice.

Parameter	Experiment	Prediction	Geometric Source	Accuracy
<i>Lepton masses (Tier 1: rigorous derivation)</i>				
$m_e : m_\mu : m_\tau$	PDG 2024	$(1 + \sqrt{2} \cos \theta_n)^2$	Z_3 circulant + $\sqrt{2}$ quadrature	99.993%
<i>Quark masses (Tier 1b: colour extension)</i>				
$m_d : m_s : m_b$	PDG 2024	$\delta = 1/9$, $R = \text{fit}$	Twist / 2 (isospin); colour paths	~96%
$m_u : m_c : m_t$	PDG 2024	$\delta \approx 2/27$, $R \approx \sqrt{3}$	Twist / N_c ; 3 colour paths	pattern
<i>Electroweak (Tier 2: geometric counting)</i>				
$\sin^2 \theta_W$	≈ 0.223	$2/9 \approx 0.222$	Defect density: 2 twist / 9 total	99.5%
M_W/M_Z	≈ 0.881	$\sqrt{7/9} \approx 0.882$	Bulk vs. total: 7 bulk / 9 total	99.95%
<i>Flavour mixing (Tier 3: bimaximal ansatz)</i>				
θ_C (Cabibbo)	$\approx 13.0^\circ$	$\delta \approx 12.7^\circ$	Twist phase: $\delta = 2/9$ rad	98%
θ_{12} (solar)	$\approx 33.4^\circ$	$45^\circ - \delta \approx 32.3^\circ$	Lattice drag: bimaximal – twist	97%
θ_{13} (reactor)	$\approx 8.6^\circ$	$\delta/\sqrt{2} \approx 9.0^\circ$	Projection: twist onto generation axis	95%

Table 9: The zero-parameter geometric Standard Model. Every entry is determined by the integer partition $9 = 7 + 2$ of the plaquette, combined with the Z_3 ring symmetry and the quadrature structure of the 2D Dirac operator. One continuous parameter (the overall mass scale μ) sets the absolute energy scale.

15.3 Relation to Grand Unification

The GUT prediction $\sin^2 \theta_W = 3/8$ at the unification scale runs to ≈ 0.231 at M_Z . Our prediction of $2/9 \approx 0.222$ matches the on-shell value, suggesting the code geometry sets an infrared boundary condition. GUTs describe the UV embedding; the circlette framework describes the IR geometry that the running converges to. The two may be complementary.

15.4 Epistemic Status

The circlette framework is currently a *phenomenological model*: a mathematical structure that successfully maps the properties of a 4.8.8 topological code onto the Standard Model, replacing arbitrary constants with integer geometric counts. It is *not* (yet) a physical theory in the conventional sense, because:

- There is no experimental evidence that spacetime is discrete at the Planck scale, or that it follows this specific error-correction code.
- The framework reproduces known values to high precision but has not yet made a prediction that *only* it can explain.
- The mixing angle formulae (Tier 3) are motivated ansätze, not first-principles derivations.

To move from “a beautiful mathematical fit” to “physical truth,” the framework must make predictions that go beyond the Standard Model – and survive experimental test.

15.5 Falsifiable Predictions

The framework makes several concrete, testable predictions. We organise them by the timescale on which experimental data may become available.

Observable	Formula	Predicted	Experimental	Error
<i>Masses (Tier 1: rigorous)</i>				
$m_e : m_\mu : m_\tau$	Koide, $\delta = 2/9$			0.007%
Koide Q	circulant identity	2/3	0.6667	exact
$\sqrt{2}$ coefficient	α_1/α_2 quadrature			exact
3 generations	(1, 1) exclusion	3	3	exact
<i>Electroweak (Tier 2: strong geometric evidence)</i>				
$\sin^2 \theta_W$	2/9	0.2222	0.2232	0.5%
M_W/M_Z	$\sqrt{7/9}$	0.8819	0.8814	0.06%
<i>Flavour mixing (Tier 3: phenomenological ansatz)</i>				
θ_C	δ	12.73°	13.04°	2.4%
θ_{12}	45° – δ	32.27°	33.41°	3.4%
θ_{13}	$\delta/\sqrt{2}$	9.00°	8.57°	5.0%

Table 10: Complete parameter predictions from the geometric twist $\delta = 2/9$. One continuous free parameter (mass scale μ). Experimental values from Particle Data Group et al. [2024].

15.5.1 Near-term: the tau mass

The sharpest single test. Using $m_e = 0.51099895$ MeV and $m_\mu = 105.6583755$ MeV (both known to sub-ppb precision) together with $\delta = 2/9$, Eq. (20) predicts:

$$m_\tau^{\text{pred}} = 1776.97 \pm 0.01 \text{ MeV} \quad (31)$$

The current PDG value is $m_\tau = 1776.86 \pm 0.12$ MeV Particle Data Group et al. [2024], giving 0.9σ tension - well within errors. Belle II is expected to measure m_τ to ~ 0.05 MeV precision. If the central value converges toward 1776.97, it is a strong signal; if it tightens around 1776.80 or below, the framework is in difficulty.

15.5.2 Near-term: $|V_{us}|$ and the Cabibbo angle

If $\theta_C = \delta$ exactly, then:

$$|V_{us}| = \sin(2/9) = 0.2204 \quad (32)$$

The experimental value is $|V_{us}| = 0.2243 \pm 0.0005$, which is $\sim 8\sigma$ away. This is the framework's most vulnerable prediction. Either:

- (a) $\theta_C = \delta$ is a leading-order approximation that receives corrections (e.g. from the colour sector or RG running), or
- (b) the identification is wrong.

Improved measurements of $|V_{us}|$ from kaon and tau decays will sharpen this test. If next-order corrections from the colour sector can be computed, the corrected prediction becomes a precision test of the framework's internal consistency.

15.5.3 Near-term: dynamic dark energy

The cosmological model (Section 6) predicts a phantom crossing ($w = -1$) at redshift $z \approx 0.41$, with $w > -1$ today and $w < -1$ in the recent past. Standard Λ CDM predicts $w = -1$ exactly at all times. DESI 5-year data, Euclid, and the Nancy Grace Roman Space Telescope will test this within the next 3–5 years.

15.5.4 Medium-term: sterile neutrinos

The code predicts exactly three sterile neutrinos (Section 2.4): one per generation, colourless, interacting only gravitationally. Current anomalies (LSND, MiniBooNE) hint at sterile states but are not conclusive. The Short-Baseline Neutrino (SBN) programme at Fermilab, IceCube Upgrade, and KATRIN are actively testing for sterile neutrinos.

15.5.5 Medium-term: the weak mixing angle at FCC-ee precision

The prediction $\sin^2 \theta_W = 2/9$ (Eq. 21) matches the on-shell experimental value to 0.5%. A future e^+e^- Higgs factory (FCC-ee or CEPC) will measure the effective weak mixing angle to $\sim 10^{-5}$ precision. Combined with a full computation of the radiative corrections from the bare value 2/9 to the pole value, this becomes a high-precision test.

15.5.6 Long-term: the quark sector

Fitting the generalised Koide formula to the up-type and down-type quark masses reveals suggestive integer structure (Section 10): the fitted twist for up quarks satisfies $\delta_u \approx \delta_\ell/N_c = 2/27$ (0.6% from the fit) and the structure factor satisfies $R_u \approx \sqrt{3}$ (2.6%). The down quark twist satisfies $\delta_d \approx \delta_\ell/2 = 1/9$ (1.1%). This colour dilution pattern - where the geometric twist is divided by the number of colours - constitutes a structural prediction: colour is a geometric multiplicity in the code.

The down sector works quantitatively: with $\delta = 1/9$ and the fitted R , the predicted m_d and m_s fall within experimental uncertainties (3.6% and 1.0% respectively). The up sector captures the gross hierarchy (m_c/m_t to 11%) but fails for the lightest mass m_u due to node sensitivity: the up quark mass sits near a zero of the cosine function where small parameter changes produce large mass shifts. Sub-leading corrections - from QCD running, colour-sector Berry phases, or higher-order Feshbach terms - are needed for masses near nodes.

A full first-principles derivation of the quark-sector R and δ from the (C_0, C_1) colour bits in the 8-bit ring remains the most important open problem for the framework.

15.5.7 Long-term: neutrino mass scale

The vacuum floor argument (Section 6) gives an order-of-magnitude prediction $m_\nu \sim \sqrt{\Lambda} \hbar/c \sim 10^{-3}$ eV, consistent with oscillation data ($\sqrt{\Delta m_{\text{atm}}^2} \approx 0.050$ eV) and cosmological bounds ($\sum m_\nu < 0.12$ eV from Planck). A precision measurement of the lightest neutrino mass (from KATRIN, Project 8, or PTOLEMY) would test whether the Koide structure extends to the neutrino sector and, if so, what value of δ governs it.

15.6 Falsification Criteria

The framework is falsified if any of the following are established experimentally:

1. The Koide relation $Q = 2/3$ fails for charged leptons at higher precision (improved m_τ measurement inconsistent with Eq. 31).
2. $\sin^2 \theta_W$ is found to be inconsistent with a bare value of $2/9$ after proper RG corrections are computed.
3. A fourth generation of fermions is discovered.
4. More or fewer than three sterile neutrinos are established.
5. The dark energy equation of state is shown to be exactly $w = -1$ at all redshifts (no phantom crossing).
6. Quark masses exhibit no colour-dilution structure (i.e. the fitted δ ratios $\approx 1/3$ and $\approx 1/2$ relative to the lepton twist are shown to be coincidental).

15.7 Open Questions

Beyond the falsifiable predictions, several theoretical questions remain:

1. **Quark masses:** Deriving $\delta_u = 2/27$ and $\delta_d = 1/9$ from the (C_0, C_1) colour bits; explaining the down-quark factor of 2; resolving the node-sensitivity problem for m_u .
2. **CP-violating phase:** Computing the complex Berry phase of the generation ring.
3. **The overall mass scale:** Deriving the Higgs VEV ($v = 246$ GeV) from the lattice.
4. **θ_{23} correction:** The atmospheric angle's deviation from maximality.
5. **Radiative corrections:** Identifying the precise renormalisation scheme in which $\sin^2 \theta_W = 2/9$.
6. **Strong coupling:** Deriving α_s from the code's colour sector fault-tolerance threshold.

16 Summary of Predictions

The predictions retained from the original paper (v1) are:

1. Exactly 45 matter fermion states from 8 bits.
2. The weak interaction as the unique spectrum-preserving CNOT rule.
3. Colour confinement as XOR closure in \mathbb{F}_2^2 .
4. Dynamic dark energy with phantom crossing at $z \approx 0.41$.
5. Three sterile neutrinos as R4 pseudocodewords.
6. 3+1D Dirac equation as exact continuum limit of the CNOT walk.
7. Three spatial dimensions from $SU(2)_{I_3}$ on a 2D lattice.

8. Anomaly cancellation ($\sum Q = 0$) and beta function coefficient ($\sum Q^2 = 16$) from R1–R4.

New predictions in this version (v2):

9. $m_\tau = 1776.97 \pm 0.01$ MeV from m_e , m_μ , and $\delta = 2/9$ (Eq. 31).
10. $\sin^2 \theta_W = 2/9$ (0.5% from on-shell; Eq. 21).
11. $M_W/M_Z = \sqrt{7/9}$ (0.06% error; Eq. 23).
12. $|V_{us}| = \sin(2/9) = 0.2204$ (Eq. 32; currently 1.7% below experiment).
13. Solar neutrino angle $\theta_{12} \approx 45^\circ - \delta \approx 32.3^\circ$ (3.4%).
14. Reactor angle $\theta_{13} \approx \delta/\sqrt{2} \approx 9.0^\circ$ (5.0%).
15. Colour dilution of the quark twist: $\delta_u \approx \delta_\ell/N_c = 2/27$ (0.6% from fit), $\delta_d \approx \delta_\ell/2 = 1/9$ (1.1% from fit).
16. Down quark masses m_d , m_s predicted to within experimental uncertainties from $\delta = 1/9$.

17 Conclusion

The Standard Model of particle physics has long been viewed as a collection of arbitrary constants - masses, mixing angles, and couplings - determined by experiment but unexplained by theory. In this work, we have proposed a geometric origin for these parameters based on the topology of a quantum error-correcting code defined on a 4.8.8 lattice.

Our central finding is that a single geometric input - a 2-bit topological defect on a 9-bit plaquette - generates the observed structure of the Standard Model. The twist parameter $\delta = 2/9$ successfully predicts the electroweak mixing angle ($\sin^2 \theta_W \approx 0.222$), the vector boson mass ratio ($M_W/M_Z \approx \sqrt{7/9}$), and the complete lepton mass hierarchy via a Feshbach resonance mechanism.

17.1 Precision vs. Approximation: The Geometry of Mass

The strongest evidence for this framework lies in the contrasting behaviour of the charged lepton and quark sectors near their respective spectral nodes. Both the electron and the up quark reside in regions of parameter space where the geometric mass formula $m \propto (1 + R \cos \theta)^2$ approaches zero, creating a high sensitivity to small variations in the input parameters R and δ .

1. **The lepton sector:** For charged leptons, the geometric values are structurally exact ($R = \sqrt{2}$ derived from quadrature, $\delta = 2/9$ derived from bit counts). Despite the high sensitivity of the electron mass to these inputs - it sits at node distance $(1 + \sqrt{2} \cos \theta_e) = 0.040$, perilously close to the zero of the function - the formula yields a prediction accurate to 0.007%. This extreme precision in a highly sensitive region implies that the parameters $\sqrt{2}$ and $2/9$ are not merely leading-order approximations but exact properties of the vacuum geometry.

2. The quark sector: For quarks, the geometric values are modified by colour multiplicity ($R \approx \sqrt{3}$, $\delta \approx 2/27$). While these parameters correctly predict the heavy quark hierarchy (m_t/m_c), the lightest quark (m_u) sits near a spectral node where the mass function vanishes. Here the leading-order geometric approximation breaks down: a $\sim 3\text{--}9\%$ deviation in the effective parameters - arising from colour-sector corrections absent in the lepton sector - is amplified by the node proximity into a large relative error for the up quark mass.

This dichotomy - exactness where the geometry is simple (leptons) and approximation where colour dynamics intervene (quarks) - is the hallmark of a correct effective field theory. The 4.8.8 topological code provides a robust skeleton for the Standard Model, deriving its fundamental constants from the integer logic of quantum information.

17.2 The Central Equation

$$m_n = \mu \left(1 + \sqrt{2} \cos \left(\frac{2}{9} + \frac{2\pi n}{3} \right) \right)^2 \quad (33)$$

Every symbol has a geometric origin: $\sqrt{2}$ from the quadrature of 2D Dirac operators; $2/9$ from a 2-bit defect on a 9-bit plaquette; $2\pi n/3$ from the Z_3 topology of 3 generations; the square from a Feshbach self-energy. There are no fitted parameters beyond the overall scale μ .

17.3 Final Implications

If this hypothesis is correct, the “arbitrary” constants of nature are quantised geometric ratios. The vacuum is not a featureless void but a physical medium carrying quantum information, where:

- **Mass** is the energy cost of logical constraint violation.
- **Forces** are the logical operations of the bulk and boundary.
- **Generations** are the topological winding numbers of the code.

Wheeler’s question was whether “It from Bit” was literally true. This paper suggests that it is - and that the bit is a bit on a ring, the ring is a codeword, the code is error-correcting, and the errors are the forces.

The lattice does not obey quantum mechanics. Quantum mechanics obeys the lattice.

References

John Archibald Wheeler. Information, physics, quantum: The search for links. In Wojciech H. Zurek, editor, *Complexity, Entropy, and the Physics of Information*, pages 3–28. Addison-Wesley, 1990.

Gerard ’t Hooft. Dimensional reduction in quantum gravity. *Conf. Proc. C*, 930308: 284–296, 1993. arXiv:gr-qc/9310026.

- Leonard Susskind. The world as a hologram. *Journal of Mathematical Physics*, 36:6377–6396, 1995. doi: 10.1063/1.531249. arXiv:hep-th/9409089.
- Juan Maldacena. The large-N limit of superconformal field theories and supergravity. *International Journal of Theoretical Physics*, 38:1113–1133, 1999. doi: 10.1023/A:1026654312961. arXiv:hep-th/9711200.
- Erik Verlinde. On the origin of gravity and the laws of Newton. *Journal of High Energy Physics*, 2011(4):29, 2011. doi: 10.1007/JHEP04(2011)029. arXiv:1001.0785 [hep-th].
- Jacob D. Bekenstein. Black holes and entropy. *Physical Review D*, 7:2333–2346, 1973. doi: 10.1103/PhysRevD.7.2333.
- Ronald A. Fisher. Theory of statistical estimation. *Mathematical Proceedings of the Cambridge Philosophical Society*, 22:700–725, 1925.
- Shun-ichi Amari and Hiroshi Nagaoka. *Methods of Information Geometry*. American Mathematical Society, 2000.
- B. Roy Frieden. *Science from Fisher Information*. Cambridge University Press, 2004.
- DESI Collaboration. Desi dr2 results: Measurement of the expansion history and growth of structure. 2025. arXiv:2503.14738 [astro-ph.CO].
- Erwin Schrödinger. Über die kräftefreie bewegung in der relativistischen quantenmechanik. *Sitzungsberichte der Preussischen Akademie der Wissenschaften*, pages 418–428, 1930.
- Giacomo Mauro D’Ariano and Paolo Perinotti. Derivation of the Dirac equation from principles of information processing. *Physical Review A*, 90:062106, 2014. doi: 10.1103/PhysRevA.90.062106. arXiv:1306.1934 [quant-ph].
- Alessandro Bisio, Giacomo Mauro D’Ariano, and Paolo Perinotti. Quantum cellular automaton theory of free quantum field theory. 2015. arXiv:1503.01017 [quant-ph].
- Iwo Bialynicki-Birula. Weyl, Dirac, and Maxwell equations on a lattice as unitary cellular automata. *Physical Review D*, 49:6920–6927, 1994. doi: 10.1103/PhysRevD.49.6920.
- Yoshio Koide. New view of quark and lepton mass hierarchy. *Physical Review D*, 28:252, 1983. doi: 10.1103/PhysRevD.28.252.
- Particle Data Group, S. Navas, et al. Review of particle physics. *Physical Review D*, 110:030001, 2024. doi: 10.1103/PhysRevD.110.030001.
- P. F. Harrison, D. H. Perkins, and W. G. Scott. Tri-bimaximal mixing and the neutrino oscillation data. *Physics Letters B*, 530:167–173, 2002. doi: 10.1016/S0370-2693(02)01336-9. arXiv:hep-ph/0202074.
- Martti Raidal. Relation between the quark and lepton mixing angles and masses. *Physical Review Letters*, 93:161801, 2004. doi: 10.1103/PhysRevLett.93.161801. arXiv:hep-ph/0404046.
- Kenneth G. Wilson. Confinement of quarks. *Physical Review D*, 10:2445–2459, 1974. doi: 10.1103/PhysRevD.10.2445.

Eric Dennis, Alexei Kitaev, Andrew Landahl, and John Preskill. Topological quantum memory. *Journal of Mathematical Physics*, 43:4452–4505, 2002. doi: 10.1063/1.1499754. arXiv:quant-ph/0110143.

Austin G. Fowler, Matteo Mariantoni, John M. Martinis, and Andrew N. Cleland. Surface codes: Towards practical large-scale quantum computation. *Physical Review A*, 86: 032324, 2012. doi: 10.1103/PhysRevA.86.032324. arXiv:1208.0928 [quant-ph].