

Charged and Neutral Particle Collisions in High-Energy Accelerators: A Unified Fractal Quantum Field Theory Perspective (UFQFT)

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Abstract

This paper presents the Unified Fractal Quantum Field Theory (UFQFT) as a geometric framework for describing high-energy collisions involving protons, neutrons, and electrons. In UFQFT, particle stability, resonance formation, and decay are governed by the interplay of two fundamental fields—the energy field (Φ) and the charge field (Ψ)—embedded in a fractal spacetime geometry. Proton stability ($D_p \approx 2.66$) and neutron semi-stability ($D_n \approx 2.67-2.69$) are interpreted as consequences of critical fractal dimensions, providing a unified resonance-based origin for both hadronic and leptonic systems. Collision dynamics are analyzed for proton–proton, proton–neutron, and electron–electron interactions, where transient Φ – Ψ resonances replace the role of gluons and gauge bosons. The framework predicts that resonance excitations follow fractal scaling laws, leading to distinct experimental signatures such as soft photon excesses, anomalous multiplicity distributions, and enhanced lepton production channels at high energies. Comparisons with the Standard Model show consistency at low energies but divergence in ultraviolet regimes, suggesting that UFQFT functions as an effective extension rather than a replacement of the current paradigm. The results motivate new experimental searches in collider and cosmic-ray experiments to test fractal scaling laws and resonance signatures. If validated, UFQFT may provide a deeper understanding of particle interactions by grounding them in the fractal geometry of spacetime, potentially marking a paradigm shift in high-energy physics.

Keywords: Unified Fractal Quantum Field Theory, UFQFT, high-energy particle collisions, fractal spacetime, quantum field theory, proton-proton collisions, proton-neutron collisions, electron-electron collisions.

1. Introduction

The Standard Model (SM) of particle physics, with Quantum Chromodynamics (QCD) as the strong force component, provides highly accurate and mathematically consistent results for high-energy collisions. The destructive regime of QCD yields precise predictions for hard scattering processes, which have been extensively validated by experiments at facilities such as the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) (Salam, 2020; Dokshitzer et al., 1991). However, this description presents significant difficulties in the non-destructive domain, particularly regarding the transition from quarks and gluons to observable hadrons, a process known as hadronization. The complexity of this transition necessitates highly phenomenological models such as the Lund String Model or Cluster Hadronization, which, while effective, rely on experimental calibration rather than first principles (Andersson et al., 1983; Webber, 1986). This inherent phenomenology, combined with the unresolved problem of confinement, has led to the need for complementary perspectives that can offer a more fundamental explanation for the nature of particles, resonances, and their interaction dynamics (Wilczek, 2004).

Unified Fractal Quantum Field Theory (UFQFT) emerges as one such alternative framework (Sogukpinar, 2025a). It challenges the point-particle paradigm by positing that fundamental particles are, in fact, stable resonance structures or standing waves within a fractal spacetime geometry, with a characteristic dimension converging around $D \approx 2.66\text{--}2.7$. This concept of spacetime fractionality and its implications for quantum mechanics has been explored in various mathematical and physical contexts (Nottale, 2011; Calcagni, 2010). Within UFQFT, the properties of mass and dynamics are governed by an energy density field (Φ), while electromagnetic properties are carried by a distinct charge density field (Ψ). This separation allows for a unified treatment of forces, where interactions are not mediated by force carriers like gluons but arise from the overlap and interference of these underlying fractal fields (El Naschie, 2004).

The primary objective of this paper is to analyze high-energy collision phenomena—specifically proton-proton (pp), proton-neutron (pn), and electron-electron (e^-e^-) interactions—from the UFQFT viewpoint. We will describe the formation and decay of transient resonant states (analogous to Δ baryons or pions) and the mechanisms of particle production without invoking gluons or color charge. This approach aims to provide a unified geometric mechanism for both hadronic and leptonic interactions, framing them as manifestations of Φ - Ψ field dynamics in a fractal vacuum. This perspective is not intended to replace the Standard Model but to offer a novel lens through which to interpret existing data from facilities like the LHC and the SLAC National Accelerator Laboratory (Franklin, 2016), potentially yielding new insights for the design and analysis of future collider experiments aimed at probing the fundamental structure of matter.

Unified Fractal Quantum Field Theory (UFQFT) offers a comprehensive theoretical framework with significant explanatory power across a broad scientific spectrum, from fundamental particle physics to cosmology. Sogukpinar (2025a-2025b) demonstrates how matter is reinterpreted as geometric resonances within UFQFT, while the same author (2025c) provides a crucial framework for explaining proton spin structure through this theoretical lens. Another study addressing dark matter and dark energy through UFQFT (Sogukpinar, 2025d) expands the theory to cosmological scales, proposing a model based on neutral resonances and non-material oscillations. The derivation of time's arrow within the fractal spacetime framework (Sogukpinar, 2025e) and the investigation of gravity's emergence from fractal field symmetry (Sogukpinar, 2025f) demonstrate the theory's potential to unify fundamental physical laws. Sogukpinar (2025g; 2025h) examines the elementary particle hierarchy from quarks to neutrinos within a fractal framework, emphasizing UFQFT's explanatory power in particle physics. Furthermore, studies of halo nuclei beyond the shell model using a fractal-dimensional approach (Sogukpinar, 2025k) and investigations of fractal geometry's effects on nuclear structure and decay processes in atomic nuclei (Sogukpinar, 2025l) reveal the theory's groundbreaking applications in nuclear physics. Finally, the Bubble-UFQFT framework proposed as a unified theory of cosmological structure (Sogukpinar, 2025m) and studies examining cosmological emergence from a quantum fluid perspective (Sogukpinar, 2025n) demonstrate UFQFT's potential to establish a solid foundation in cosmology and quantum gravity research. The behavior of ultra-dense matter in neutron stars can be reinterpreted through UFQFT, modeling them not as perfect fluids but as a fractal dipole liquid where nucleon interactions are governed by their intrinsic Φ - Ψ field geometry (Sogukpinar, 2025p). Furthermore, the theory makes a falsifiable prediction for a critical mass-limit in black hole evolution, suggesting a fundamental scale where traditional spacetime description breaks down (Sogukpinar, 2025p). At the most fundamental level, UFQFT provides a resonance-based approach to derive the mass, spin, and binding energy properties of protons and neutrons from first principles, offering a geometric alternative to phenomenological models (Sogukpinar, 2025r).

This work develops the Unified Fractal Quantum Field Theory (UFQFT), a framework in which particle interactions arise from the resonance dynamics of an energy field (Φ) and a charge field (Ψ) embedded in fractal spacetime geometry. Unlike the Standard Model, where gauge bosons mediate forces, UFQFT explains stability, resonance widths, and particle lifetimes through variations in the fractal dimension D . The theory predicts distinctive experimental signatures—such as fractal scaling in multiplicities, anisotropic jet substructure, enhanced lepton production, and soft photon excesses—which can be tested at colliders, cosmic-ray experiments, and neutrino observatories. If validated, UFQFT could establish a geometric foundation for fundamental interactions.

2. Particle Definition

In the Unified Fractal Quantum Field Theory (UFQFT), elementary particles are described as resonance structures of energy (Φ) and charge (Ψ) fields in a fractal spacetime of effective Hausdorff dimension D . Particles such as protons, neutrons, and electrons are distinct configurations of Φ - Ψ resonances, and transitions between them (e.g., proton \leftrightarrow neutron) are mediated by field reorganization. The proton consists primarily of two up-quark (u) and one down-quark (d) resonance configuration, embedded in a coherent Φ - Ψ field: $p \equiv R_p(\Phi, \Psi) = (u \otimes u \otimes d)_{\Phi-\Psi}$. Where, Φ_p is the energy density field of the proton resonance, Ψ_p is the charge field, yielding net electric charge $Q_p = +e$, $D_p \approx 2.66$ is the fractal dimension ensuring stability of the resonance. The proton's mass and charge are derived from the integrated fields:

$$m_p = \frac{1}{c^2} \int \Phi_p(r) d^3r, \quad Q_p = \int \Psi_p(r) d^3r \quad (1)$$

The neutron is a related resonance, composed of one up-quark (u) and two down-quark (d) resonances: $n \equiv R_n(\Phi, \Psi) = (u \otimes d \otimes d)_{\Phi-\Psi}$ with: $D_n \approx 2.67-2.69$, slightly different from the proton, Net charge $Q_n=0$, Φ and Ψ fields allow proton \leftrightarrow neutron transitions through field reconfigurations. The neutron mass is:

$$m_n = \frac{1}{c^2} \int \Phi_n(r) d^3r \quad (2)$$

The neutron's magnetic dipole moment is explained by an asymmetric Ψ distribution despite overall neutrality. Electrons and electron neutrinos are fundamental spin-1/2 particles, modeled as simple Φ - Ψ resonances: $e^- \equiv R_e(\Phi, \Psi)$, $\nu_e \equiv R_\nu(\Phi, \Psi = 0)$. with: $\Psi_{e^-} = -e$, $\Psi_{\nu_e} = 0$. Masses arise from Φ integration:

$$m_{e^-} = \frac{1}{c^2} \int \Phi_{e^-}(r) d^3r, \quad m_{\nu_e} = \frac{1}{c^2} \int \Phi_{\nu_e}(r) d^3r \quad (3)$$

Implications for High-Energy Collisions, Proton \leftrightarrow neutron transitions are mediated by Φ - Ψ reconfiguration of the u and d quark resonances. In high-energy accelerator collisions (proton-proton, proton-neutron, electron-proton), resonance overlap produces transient high-energy states and secondary particles, including pions, photons, and leptons. In the Unified Fractal Quantum Field Theory (UFQFT), particle dynamics are governed by two fundamental field components: the energy density field (Φ) and the charge density field (Ψ). These fields coexist within a fractal spacetime background characterized by Hausdorff dimension D , which ensures both resonance stability and well-defined interaction pathways. The energy field represents the spatial distribution of intrinsic particle energy and is responsible for both mass generation and kinetic interactions. For a particle resonance R , the total energy is given by:

$$E = \int_{R^3} \Phi(r, t) d^3r \quad (4)$$

Where, $\Phi(r,t)$ = local energy density ($J \cdot m^{-3}$), r = spatial coordinate, t = time. The rest mass of the particle follows directly from:

$$m = 1c^2 \int_{R^3} \Phi(r, t) d^3r \quad (5)$$

where c is the speed of light. The charge field encodes the distribution of electric charge and determines the electromagnetic interaction properties of the resonance. The net charge of a particle is defined as:

$$Q = \int_{R^3} \Psi(r, t) d^3r \quad (6)$$

Where, $\Psi(r,t)$ = charge density field ($C \cdot m^{-3}$), Q = total electric charge. Unlike conventional field theories where charge is an intrinsic attribute, UFQFT treats charge as an emergent resonance property of the Ψ field, dynamically coupled to the energy distribution. The interaction between the two fields is described through a resonance coupling functional:

$$L_{res} = \alpha(D) \Phi(r, t) \Psi(r, t) \quad (7)$$

Where, L_{res} = resonance interaction Lagrangian density, $\alpha(D)$ = fractal coupling coefficient, dependent on the local Hausdorff dimension D . This coupling ensures that charge distributions cannot exist independently of energy distributions, and vice versa, stabilizing particle resonances in fractal spacetime. The effective fields are embedded within a fractal metric background:

$$ds^2 = f(D) (c^2 dt^2 - dr^2) \quad (8)$$

Where, $f(D)$ is a scaling factor determined by the fractal dimension. For stable particles, $D \approx 2.66 - 2.70$, Deviations from this range correspond to unstable or short-lived resonances (e.g., mesons). Within the UFQFT framework, protons and neutrons are described as stable resonance states of the coupled energy (Φ) and charge (Ψ) fields, embedded in a fractal spacetime geometry. Their stability and mutual transitions are governed by the balance of energy density, charge distribution, and the local fractal dimension D . For a generic particle resonance R , stability requires that the effective fractal dimension D remains within a critical window:

$$D_{min} \leq D_R \leq D_{max} \quad (9)$$

with: $D_{min} \approx 2.66$, $D_{max} \approx 2.70$, Proton: $D_p \approx 2.66$ (most stable resonance). Neutron: $D_n \approx 2.67 - 2.69$ (meta-stable resonance). Stability can be quantified by a resonance lifetime functional:

$$\tau(D) \propto \exp[\beta (D_{crit} - D_R)^2] \quad (10)$$

Where, $\tau(D)$ = expected resonance lifetime, $D_{crit} \approx 2.66$, corresponding to maximal stability (proton), β = scaling parameter describing sensitivity to fractal deviation. Transitions between protons and neutrons are mediated by reconfigurations of the Φ and Ψ fields, corresponding to up-down quark conversions within UFQFT. The general transition condition can be expressed as:

$$\Phi_p + \Psi_p \leftrightarrow \Phi_n + \Psi_n \quad (11)$$

subject to conservation of total energy and charge:

$$E_p = E_n + \Delta E, Q_p - Q_n = e^- + \bar{\nu}_e \quad (12)$$

Where, E_p, E_n = total resonance energies of proton and neutron, $Q_p = +e$, $Q_n = 0$, e^- = emitted electron, $\bar{\nu}_e$ = emitted electron antineutrino. Equation (12) represents the UFQFT description of beta decay as a resonance-driven field transition, rather than as an exchange mediated by virtual gauge bosons. The

transition probability per unit time can be modeled by a coupling functional between the proton and neutron states:

$$\Gamma_{p \rightarrow n} \propto \left| \int \alpha(D) \Phi_p(r, t) \Psi_p(r, t) d^3r - \int \alpha(D) \Phi_n(r, t) \Psi_n(r, t) d^3r \right|^2 \quad (13)$$

where the difference in resonance overlap integrals determines the likelihood of a $p \leftrightarrow n$ conversion. High-energy collisions, such as those in the Large Hadron Collider (LHC), provide a unique environment for probing resonance dynamics within the UFQFT framework. When protons, neutrons, or electrons are accelerated to relativistic energies, their embedded Φ (energy) and Ψ (charge) fields undergo non-linear interactions, producing transient resonance states. These excitations manifest as short-lived composite structures that subsequently decay into observable particles. In a collider, two incoming resonances R_1 and R_2 are described by their respective fields (Φ_1, Ψ_1) and (Φ_2, Ψ_2) . At the point of maximal overlap:

$$I_{12} = \int_{R^3} [\Phi_1(r, t) \Psi_2(r, t) + \Phi_2(r, t) \Psi_1(r, t)] d^3r \quad (14)$$

defines the interaction functional I_{12} , which sets the scale of resonance excitation. Larger overlap integrals correspond to higher probabilities of producing transient states. The total available energy in the center-of-mass frame is:

$$E_{cm} = \sqrt{(E_1 + E_2)^2 - (p_1 + p_2)^2 c^2} \quad (15)$$

Where E_i, p_i are the energies and momenta of the colliding particles. When E_{cm} exceeds the stability threshold for higher fractal dimensions, new resonances can form:

$$\Phi_i + \Psi_i \rightarrow R^*(D > 2.70) \quad (16)$$

These excited resonances (R^*) are inherently unstable, as their fractal embedding dimension exceeds the stable window. They rapidly decay back into lower-D configurations. Unstable resonances relax by redistributing energy and charge into fundamental field excitations. Typical outcomes include:

- Meson-like states (π, K , etc.): transient $u\bar{d}, d\bar{u}$ configurations,
- Baryon resonances (Δ, Λ , etc.): higher-energy proton/neutron excitations,
- Leptons (e^\pm, μ, ν): emergent Ψ -field excitations,
- Photons (γ): pure energy-field (Φ) oscillations.

The general decay condition is:

$$\sum E_{in} = \sum E_{out}, \sum Q_{in} = \sum Q_{out} \quad (17)$$

ensuring conservation of both energy and charge across all channels. The probability of producing a given final state f from initial state i is proportional to the square of the resonance amplitude:

$$\sigma_{i \rightarrow f} \propto | \langle f | I_{12} | i \rangle |^2 \quad (18)$$

where $\sigma_{i \rightarrow f}$ denotes the effective cross-section. Unlike in the Standard Model, where cross-sections are determined by exchange bosons, UFQFT attributes them directly to field overlap integrals of Φ and Ψ .

3. Implications for Experimental Observables

The UFQFT framework predicts distinctive patterns in the outcomes of high-energy collisions, diverging in critical aspects from conventional Standard Model expectations. Because particle

interactions are described as resonance reconfigurations of the Φ (energy) and Ψ (charge) fields within fractal spacetime, experimental observables are linked to field overlap dynamics and fractal embedding stability, rather than to virtual mediator exchange. In proton–proton and electron–proton collisions, the number of secondary particles is determined by the number of unstable resonances excited beyond the critical fractal dimension. The average multiplicity can be expressed as:

$$\langle N \rangle \propto \ln \left(\frac{E_{cm}}{E_0} \right)^{\gamma(D)} \quad (19)$$

Where, E_{cm} = center-of-mass energy, E_0 = threshold energy for resonance excitation, $\gamma(D)$ = scaling exponent dependent on local fractal dimension. Thus, multiplicities are not universal constants but vary with the effective embedding dimension of the resonance environment. In the Standard Model, jets arise from parton fragmentation and QCD confinement. In UFQFT, jet-like structures emerge from the anisotropic decay of unstable resonances ($D > 2.70$) into lower-D states. The angular distribution of jet fragments is linked to the spatial anisotropy of the overlap integral:

$$\frac{dN}{d\Omega} \propto \left| \int \Phi(r, t) \Psi(r, t) e^{ik \cdot r} d^3r \right|^2 \quad (20)$$

Where, k is the momentum transfer vector. Prediction: jet substructure correlates more strongly with resonance geometry (fractal embedding) than with perturbative gluon emissions. UFQFT attributes lepton emergence to direct Ψ -field excitations during resonance decay. Thus, the ratio:

$$R_\ell = \frac{N_{e^\pm} + N_{\mu^\pm}}{N_\pi + N_K} \quad (21)$$

is expected to scale differently than in Standard Model QCD, particularly at high energies.

- UFQFT predicts an enhanced lepton fraction at higher E_{cm} , since Ψ excitations are more probable when unstable resonances collapse.

Since photons are modeled as pure oscillations of the Φ field without Ψ coupling, their production rate reflects the energy-field fragmentation spectrum:

$$\frac{dN_\gamma}{dE} \propto \rho_\Phi(E; D) \quad (22)$$

where ρ_Φ is the spectral density of the energy field determined by fractal embedding. Prediction: excess soft-photon production relative to Standard Model expectations. Potential link to “soft-photon anomalies” reported in collider data. UFQFT predicts that resonance widths are directly linked to deviation from the stable fractal dimension:

$$\Gamma(D) \propto (D - D_{crit})^2 \quad (23)$$

Where, Γ is the decay width. Wider resonances correspond to states further from $D_{crit} \approx 2.66$, This provides a geometric explanation for the observed spectrum of resonance lifetimes, unifying hadronic and leptonic resonances within the same framework.

4. Comparison with Standard Model Predictions

The Standard Model (SM) of particle physics describes interactions in terms of gauge fields mediated by bosons (gluons, W, Z, and photons), while UFQFT reinterprets these processes as field resonance dynamics governed by energy (Φ) and charge (Ψ) distributions in fractal spacetime. This distinction leads to measurable differences in predictions for high-energy collisions.

4.1 Interaction Mechanism

- SM:
Interactions are mediated by exchange bosons. For example, proton–proton scattering is described by perturbative QCD involving gluon exchange.

$$M_{SM} \propto g_s^2 \bar{u}(p') \gamma^\mu T^a u(p) \frac{1}{q^2} \bar{u}(k') \gamma_\mu T^a u(k) \quad (24)$$

where g_s is the QCD coupling, T^a the color matrices, and q the momentum transfer.

- UFQFT:
No mediating bosons; instead, interaction is the direct overlap of energy and charge fields:

$$M_{UFQFT} \propto \int \Phi_1(r, t) \Psi_2(r, t) + \Phi_2(r, t) \Psi_1(r, t) d^3r \quad (25)$$

Thus, the strength of the interaction is controlled by resonance geometry and fractal embedding rather than gauge coupling constants.

4.2 Multiplicity and Particle Production

- SM Prediction:
Multiplicity distributions in high-energy collisions are modeled by parton showers and hadronization, scaling approximately with center-of-mass energy:

$$\langle N \rangle_{SM} \propto \ln^2 \left(\frac{E_{cm}}{\Lambda_{QCD}} \right) \quad (26)$$

- UFQFT Prediction:
Multiplicity depends on fractal dimension:

$$\langle N \rangle_{UFQFT} \propto \ln \left(\frac{E_{cm}}{E_0} \right)^{\gamma(D)} \quad (19 \text{ revisited})$$

where $\gamma(D)$ changes with fractal embedding.

- Implication: deviations from SM multiplicity scaling may appear in specific energy ranges where D shifts.

4.3 Jet Substructure

- SM:
Jets arise from parton fragmentation and QCD showering, characterized by perturbative splitting functions $P_{q \rightarrow qq}$, $P_{g \rightarrow gg}$.
- UFQFT:
Jets originate from anisotropic resonance collapse:

$$\frac{dN}{d\Omega} \propto \left| \int \Phi(r, t) \Psi(r, t) e^{ik \cdot r} d^3r \right|^2 \quad (20 \text{ revisited})$$

Prediction: jet substructure reflects fractal spatial patterns, potentially observable as non-standard angular correlations.

4.4 Lepton and Photon Channels

- SM:
 - Leptons produced via weak boson exchange (W, Z).
 - Photons emitted through QED bremsstrahlung or quark–gluon interactions.
- UFQFT:
 - Leptons arise from direct Ψ -field excitations, without W/Z mediation.

Photons are coherent oscillatory modes of coupled Φ (energy) and Ψ (charge) fields in fractal spacetime, manifesting as stable resonance waves.

Prediction:

- Enhanced lepton fractions at high E_{cm} .
- Excess soft-photon emission, potentially explaining anomalies beyond SM expectations.

4.5 Resonance Widths

- SM:

Resonance widths (Γ) are determined by coupling constants and available decay channels:

$$\Gamma_{SM} \propto g^2 \rho(E_{decay}) \quad (27)$$

- UFQFT:

Resonance widths are determined geometrically by fractal deviation:

$$\Gamma_{UFQFT} \propto (D - D_{crit})^2 \quad (23 \text{ revisited})$$

Thus, lifetimes directly encode information about fractal embedding stability rather than interaction couplings.

4.6 Summary of Contrasts

Table 1. shows Comparison between Standard Model (SM) and Unified Fractal Quantum Field Theory (UFQFT) predictions for high-energy collision dynamics.

Table 1. Standard Model (SM) and UFQFT

Aspect	Standard Model (SM)	UFQFT Prediction
Interaction mechanism	Mediated by gauge bosons (gluons, W, Z, γ)	Direct Φ - Ψ resonance overlap
Multiplicity scaling	$\ln^2(E_{cm}/\Lambda)$	$\ln(E_{cm}/E_0)^{\gamma(D)}$
Jets	Parton fragmentation, QCD showers	Anisotropic resonance collapse (fractal patterns)
Lepton channels	Weak boson mediation	Direct Ψ excitations (enhanced ratios)
Photon production	Bremsstrahlung, parton-gluon processes	Φ oscillations, soft-photon excess
Resonance widths	Coupling-dependent decay rates	Fractal-dimension deviation $(D - D_{crit})^2$

5. Experimental Signatures and Tests

A central strength of the Unified Fractal Quantum Field Theory (UFQFT) framework lies in its ability to generate falsifiable predictions that diverge from Standard Model (SM) expectations. High-energy colliders, neutrino observatories, and cosmic-ray experiments provide multiple avenues to probe these predictions. One of the clearest signatures concerns particle multiplicity scaling. While the SM predicts that multiplicity distributions grow as $\ln^2(E_{cm})$, UFQFT introduces a fractal-dimension-dependent law (Eq. 19), where the scaling exponent $\gamma(D)$ encodes the underlying spacetime geometry. Precision multiplicity measurements at the LHC and future colliders such as FCC and CEPC could therefore reveal deviations from quadratic logarithmic scaling, particularly if such deviations correlate with resonance lifetime distributions. Another striking prediction concerns jet formation. Whereas the SM attributes jet substructure to QCD parton showers, UFQFT proposes that jet-like events emerge from

anisotropic resonance collapse. This mechanism would manifest in non-standard angular correlations between jet constituents and in fractal-like substructures within the energy flow patterns of jets. Experimental confirmation would require re-examining ATLAS and CMS jet-shape and jet-substructure analyses for evidence of power-law scaling in sub-jet multiplicities. Similarly, lepton-to-hadron ratios provide a distinct test: while the SM requires weak boson mediation for lepton production, UFQFT predicts that leptons emerge directly from Ψ -field excitations. Consequently, the lepton-to-hadron ratio $R_\ell = \frac{N_{e^\pm} + N_{\mu^\pm}}{N_\pi + N_K}$ should grow more rapidly with E_{cm} than SM expectations. This can be tested by comparing electron and muon yields to hadronic channel production in upcoming LHC Run-3 and Run-4 datasets. Soft photon production offers an especially direct experimental signature. In the SM, soft photons originate from QED bremsstrahlung with well-defined rates, whereas UFQFT introduces additional contributions from Φ -field oscillations (Eq. 22). This leads naturally to the prediction of a soft photon excess in high-energy collisions. Dedicated searches in LHCb and ALICE, as well as re-analyses of archival low-pT photon datasets, could test this hypothesis. Similarly, resonance widths provide a clean discriminant: UFQFT predicts that resonance widths follow a geometric scaling law of the form $\Gamma(D) \propto (D - D_{\text{crit}})^2$ in contrast to SM expectations based on coupling-dependent Breit–Wigner forms. Systematic measurement of baryonic and mesonic resonance widths at colliders could therefore reveal whether geometry, rather than couplings, governs decay lifetimes. Finally, cosmic-ray and neutrino observations offer complementary experimental probes at energies beyond collider reach. Ultra-high-energy air showers, observed by Pierre Auger and Telescope Array, can be analyzed for multiplicity scaling and anomalously high lepton fractions. Likewise, astrophysical neutrino detections in IceCube and KM3NeT may reveal excess lepton production consistent with direct Ψ -field excitations. Taken together, these multi-channel tests provide a comprehensive strategy to validate—or falsify—the UFQFT framework.

Conclusion

The Unified Fractal Quantum Field Theory (UFQFT) proposes a new view of particle physics by embedding energy (Φ) and charge (Ψ) fields within a fractal spacetime geometry. Unlike the Standard Model, which relies on gauge bosons in a smooth background, UFQFT links particle stability and resonance behavior to variations in fractal dimension (D). Proton stability ($D_p \approx 2.66$) and neutron semi-stability ($D_n \approx 2.67$ – 2.69) are reinterpreted as geometric consequences, while resonance excitations at collider energies follow fractal scaling laws rather than perturbative QCD. This framework not only aligns with low-energy phenomenology but also predicts deviations at high energies, such as fractal-like jet substructures, enhanced lepton production, and soft photon excesses.

Challenges remain—particularly the development of a rigorous covariant formulation, consistent quantization of Φ and Ψ , and determination of critical fractal dimensions from first principles. Yet UFQFT provides clear experimental directions: multiplicity scaling at colliders (LHC, FCC, CEPC), resonance collapse in heavy-ion collisions, and lepton-rich signatures in neutrino and cosmic-ray observations. If verified, these predictions could shift the foundations of particle physics by grounding interactions in the fractal geometry of spacetime.

This study outlined the UFQFT framework for high-energy collisions of protons, neutrons, and electrons. By treating interactions as overlaps of Φ and Ψ fields, UFQFT offers a unified description of hadronic and leptonic systems without invoking gluons or external gauge bosons. Resonance lifetimes and multiplicities follow geometric scaling laws, providing possible explanations for anomalies like soft photon excesses and lepton-rich channels in collider data. Rather than replacing the Standard Model, UFQFT extends it by emphasizing the role of fractal geometry at both low-energy stability and high-energy excitations. Future experimental tests—across colliders, heavy-ion studies, and cosmic-ray

platforms—will determine whether this fractal approach can serve as a deeper foundation for understanding the fundamental nature of matter and interactions.

References

Andersson, B., et al. "Parton Fragmentation and String Dynamics." *Physics Reports*, vol. 97, no. 2-3, 1983, pp. 31-145.

Calcagni, Gianluca. "Quantum Field Theory, Gravity and Cosmology in a Fractal Universe." *Journal of High Energy Physics*, vol. 2010, no. 3, 2010, p. 120.

Dokshitzer, Yuri L., et al. *Basics of Perturbative QCD*. Editions Frontières, 1991.

El Naschie, M.S. "A Review of E-Infinity Theory and the Mass Spectrum of High Energy Particle Physics." *Chaos, Solitons & Fractals*, vol. 19, no. 1, 2004, pp. 209-236.

Franklin, Allan, and Ephraim Fischbach. *The rise and fall of the fifth force: Discovery, pursuit, and justification in modern physics*. Springer, 2016.

Nottale, Laurent. *Scale Relativity and Fractal Space-Time: A New Approach to Unifying Relativity and Quantum Mechanics*. Imperial College Press, 2011.

Salam, G. P. "Elements of QCD for hadron colliders." CERN Yellow Reports: School Proceedings 5 (2020): 1-1.

^aSogukpinar, H. *Unified Fractal Quantum Field Theory (UFQFT): Matter as Geometric Resonances of Unified Energy-Charge Fields*. Preprint, Engineering Archive. 2025.

^bSogukpinar, H. *The Φ_0 - Ψ_0 Fractal Sea of Pre-Big Bang Universe : A Unified Origin of Matter, Dark Matter, and Cosmic Inflation from UFQFT*. Preprint, Engineering Archive. 2025.

^cSogukpinar, H. *Proton Spin Structure Reinterpreted through UFQFT*. Preprint, Engineering Archive. 2025.

^dSogukpinar, H. *Dark Matter and Dark Energy in Unified Fractal Quantum Field Theory (UFQFT): Neutral Resonances and Non-Material Oscillations*. Preprint, Engineering Archive. 2025.

^eSogukpinar, H. *What is Time: Deriving the Arrow of Fractal Spacetime Framework from UFQFT*. Preprint, Engineering Archive. 2025.

^fSogukpinar, H. *Gravity and Gravitation in UFQFT: An Emergent Phenomenon from Fractal Field Symmetry*. Preprint, Engineering Archive. 2025.

^gSogukpinar, H. *Fractal Quantum Architecture of Matter: A Unified Framework for Particle Physics*. Preprint, Engineering Archive. 2025.

^hSogukpinar, H. *From Quarks to Neutrinos: A Fractal Framework for Elementary Particle Hierarchy*. Preprint, Engineering Archive. 2025b

^kSogukpinar, H.. *HALO Nuclei Beyond the Shell Model: A Fractal-Dimensional Approach*. Preprint, Engineering Archive. 2025.

^lSogukpinar, H. *Fractal Geometry in Atomic Nuclei: A New Paradigm for Nuclear Structure and Decay*. Preprint, Engineering Archive. 2025.

^mSogukpinar, H. *The Bubble-UFQFT Framework: Unifying Quantum Gravity, Dark Energy, and Cosmological Structure*. Preprint, Engineering Archive.2025.

ⁿSogukpinar, H. *The Bubble Theory of the Universe: A Quantum Fluid Perspective on Cosmological Emergence*. Preprint, Engineering Archive.2025.

^pSogukpinar, H. Neutron Stars as Fractal Dipole Liquids: A Unified Fractal Quantum Field Theory Approach, Engineering Preprint, Archive.2025.

^rSogukpinar, H. The Critical Mass-Limit in Black Hole Evolution: A Prediction of Unified Fractal Quantum Field, Preprint, Engineering Archive.2025.

^sSogukpinar, H. Proton and Neutron Properties from Unified Fractal Quantum Field Theory (UFQFT): A Resonance-Based Approach to Mass, Spin, and Binding Energies Preprint, Engineering Archive.2025.

Webber, Bryan R. "Monte Carlo simulation of hard hadronic processes." *Annual Review of Nuclear and Particle Science* 36.1 (1986): 253-286.

Wilczek, Frank A. "Asymptotic freedom: From paradox to paradigm-Nobel lecture, December 8, 2004." *International Journal of Modern Physics A* 20.25 (2005): 5753-5777.