Covariant Quantization of a Coherence-Regulated Tensor Field: Emergent QFT from Structured Geometry

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Abstract

We introduce a covariant framework in which quantum field theory emerges from a coherence-regulated rank-2 tensor field defined on a structured geometric substrate. This tensor—derived from internal coherence dynamics—perturbs the classical metric and enables quantization on both flat and curved spacetimes. A central construction, the Mesh–Field Transformer, maps discrete structural configurations into continuous quantum fields, reproducing the operator algebra and interaction rules of standard QFT. The formalism supports scattering amplitudes via Feynman diagrams and includes an inversion mechanism that reconstructs spacetime geometry from field coherence. The result is a structurally grounded, background-independent approach to quantum field theory and emergent geometry.

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1 Introduction

The unification of quantum mechanics and general relativity remains one of the most foundational challenges in modern physics [1, 2]. While quantum field theory (QFT) successfully models electromagnetic, weak, and strong interactions through quantized excitations of fields on a fixed spacetime background, gravity is described by the classical framework of general relativity (GR), where spacetime geometry itself evolves as a dynamical, continuous manifold [3].

In this work, we propose a covariant quantization framework in which quantum field behavior emerges from a structured, coherence-regulated rank-2 tensor field. This tensor, interpreted as a tension field arising from internal coherence dynamics, perturbs the background metric as a quantum correction, yielding a modified geometry of the form $\tilde{g}_{\mu\nu} = g_{\mu\nu} + \hbar t_{\mu\nu}$. This formulation supports a full Lagrangian and Hamiltonian structure, allowing consistent quantization in both flat and curved spacetimes.

To connect discrete geometric structure with field-theoretic dynamics, we introduce the *Mesh–Field Transformer*—a mathematically rigorous mechanism that projects structured tensor configurations into continuous quantum fields. This transformation reproduces the operator algebra and interaction structure of standard QFT without assuming a fixed background geometry. The resulting formalism preserves locality, supports canonical and path-integral quantization, and yields scattering amplitudes compatible with Feynman diagram techniques.

We further extend the framework to curved backgrounds via geodesic-based interpolation and introduce an inversion mechanism that reconstructs the underlying structural mesh from a given spacetime geometry. This enables a background-independent formulation in which geometry itself becomes a consequence of coherence and structure.

The remainder of this paper proceeds as follows. We begin by constructing the full covariant Lagrangian and Hamiltonian from the coherence-regulated tensor field. We then develop the Mesh–Field Transformer and demonstrate its quantization properties through explicit examples. Finally, we explore implications for quantum gravity, experimental observables, and the emergence of geometry from structure.

1.1 Structured Tensor Field Substrate

The framework introduced in this work treats spacetime not as a fixed geometric background, nor as a discrete lattice, but as an emergent, coherence-regulated structure encoded in a rank-2 tensor field. This *tension tensor*, denoted $t_{\mu\nu}$, captures internal coherence dynamics and directional propagation, and perturbs the background geometry through a quantum-corrected metric $\tilde{g}_{\mu\nu} = g_{\mu\nu} + \hbar t_{\mu\nu}$.

Rather than modeling geometry and matter as distinct entities, this formulation unifies both under a single structural field: a coherence-responsive tensor substrate that supports energy localization, wave propagation, and solitonic behavior. The dynamics of this substrate give rise to curvature as a secondary, emergent effect—expressed as large-scale deformations induced by coherent internal structure.

Unlike foliation-based formalisms or lattice discretizations, this approach does not impose external slicing or background assumptions. Instead, it parallels structure-driven systems in materials science, where global geometry arises from local stress, stiffness, and coherence properties. Here, geometric features such as curvature, deformation, and causal propagation emerge from organized behavior within the tension tensor field.

This reinterpretation reframes gravity not as a fundamental interaction mediated by a force-carrying particle, but as a macroscopic response to coherence gradients and internal strain within the structured substrate. The resulting geometry is fully covariant and supports field-theoretic quantization without relying on a smooth, pre-existing manifold.

The structural substrate thus provides both the arena and the engine for quantum field behavior, allowing geometry, dynamics, and quantization to emerge from a unified, tensor-based coherence field.

1.2 General Field Theory

General Field Theory (GFT) provides a unifying language for describing interactions across quantum physics [10]. It extends the methods of quantum field theory (QFT), in which particles are modeled as quantized excitations of continuous fields, and interactions arise from terms in a common Lagrangian. GFT encompasses well-established frameworks such as quantum electrodynamics (QED), quantum chromodynamics (QCD), and the electroweak theory—collectively describing the electromagnetic, strong, and weak forces.

At its foundation, GFT assumes that fields are defined over a smooth, continuous spacetime manifold whose geometry is governed by general relativity [3]. These fields are described via Lagrangians or Hamiltonians, evolve through variational principles, and exhibit internal symmetries and conserved charges. However, they do not influence the geometry on which they reside; spacetime serves as a static, classical backdrop.

While GFT excels in unifying particle interactions, this background dependence becomes a limitation in regimes where quantum fields and spacetime geometry must coevolve—such as near black hole horizons, during cosmological inflation, or in the quest for a quantum theory of gravity [2, 5]. In such regimes, a new framework is required—one in which geometry is not presupposed, but emerges dynamically from the same structural principles that govern field behavior.

1.3 Integrating Structured Tensor Fields with General Field Theory

Integrating the present framework with General Field Theory (GFT) requires reconciling two distinct ontologies: the structurally grounded, coherence-regulated geometry of the tension tensor field, and the continuous, background-dependent formalism of conventional field theory. Traditionally, discrete or structural models of spacetime have been treated as computational tools—used in simulations, lattice gauge theories, or condensed matter analogies—while analytic field theories assume smooth geometries and fixed backgrounds [11].

The Mesh Model bridges this divide by proposing that quantum fields emerge directly from an internally coherent tensor field that simultaneously defines geometry and dynamics. Rather than treating fields and spacetime as separate layers, the model derives quantized field behavior—propagation, interaction, and operator structure—from structured coherence embedded in a geometric substrate [7].

This formulation retains the mathematical machinery of GFT, including Lagrangian and Hamiltonian dynamics, canonical quantization, locality, and propagator algebra. However, these properties no longer rest on assumed geometries; they emerge from the same tensor field that governs curvature and coherence. In this way, the field–geometry divide is resolved: geometry becomes the medium through which quantum fields emerge, rather than a passive backdrop.

The remainder of this section establishes the unified structural principles underlying both frameworks and introduces the *Mesh–Field Transformer*, a projection mechanism that formally connects discrete tensor configurations with continuous quantum field behavior.

2 Transformer Concept

2.1 Overview of the Transformation Mechanism

The Mesh–Field Transformer is a pivotal conceptual and mathematical innovation designed to convert the structured, node-based coherence dynamics of the Mesh Model into continuous tensor field equations compatible with General Field Theory (GFT) [7]. This transformation draws upon established methodologies in finite element methods (FEM), variational mechanics, and lattice dynamics—disciplines well-developed in structural engineering and condensed matter physics [8, 10]. By applying these principles to a tension-regulated geometric mesh, the Transformer defines a rigorous mapping from discrete nodal structure to smooth, quantized field behavior.

Definition: Mesh–Field Transformer
The Mesh–Field Transformer is a bidirectional projection rule that maps discrete node-based tension tensors $t_{\mu\nu}^{(i)}$ into continuous field configurations $t_{\mu\nu}(x)$ via localized shape functions $\psi_i(x)$, and vice versa. It serves as a foundational axiom ("zeroth law") of the Mesh Model, enabling the emergence of quantum field dynamics from structured geometry, and the reconstruction of metric behavior from coherence structure.

$$t_{\mu\nu}(x) = \sum_i t_{\mu\nu}^{(i)}\, \psi_i(x), \quad \psi_i(x) = \frac{\exp\left(-\frac{d^2(x,x_i)}{\sigma^2}\right)}{\sum_j \exp\left(-\frac{d^2(x,x_j)}{\sigma^2}\right)}$$

$$g^{\mu\nu}(x) \propto \frac{1}{\mathcal{E}(x)} \sum_{i,j} t_{\alpha\beta}^{(i)}\, t_{\gamma\delta}^{(j)}\, \partial^\mu \psi_i(x)\, \partial^\nu \psi_j(x)\, C^{\alpha\beta\gamma\delta}$$

Here, $C^{\alpha\beta\gamma\delta}$ is a contraction kernel (e.g., identity or projection) used to extract the relevant metric contribution from overlapping tensor components. $\mathcal{E}(x)$ denotes the local coherence-weighted energy density.

[1]

Crucially, this transformation produces tensor field structures that inherit the quantization behavior and operator algebra of quantum field theory (QFT) [10, 3]. The current formulation is applied within flat and weakly curved spacetimes, where canonical quantization rules remain valid. This enables direct use of standard field-theoretic tools while preserving the geometric intuition and coherence logic of the mesh substrate.

Looking ahead, the Transformer is extensible to strong-field regimes through a reverse-engineering process. Starting from known QFT behavior on curved manifolds, one can reconstruct the internal mesh configuration required to support propagation under dynamic geometry. This approach positions the Mesh Model as an adaptive geometric engine—one in which coherence, curvature, and quantum behavior arise from a unified structural origin.

2.2 Quantization and Field Operators

With the continuous tensor field $t_{\mu\nu}(x)$ defined, we promote it and its canonical conjugate momentum

$$\pi^{\mu\nu}(x) = \frac{\partial \mathcal{L}}{\partial(\partial_t t_{\mu\nu})}$$

to quantum operators. Canonical quantization is imposed through equal-time commutation relations:

$$[\hat{t}_{\mu\nu}(x), \hat{\pi}^{\alpha\beta}(y)] = i\hbar\, \delta_\mu^\alpha \delta_\nu^\beta\, \delta^{(3)}(x-y),$$

$$[\hat{t}_{\mu\nu}(x), \hat{t}_{\alpha\beta}(y)] = 0, \qquad [\hat{\pi}^{\mu\nu}(x), \hat{\pi}^{\alpha\beta}(y)] = 0.$$

[1] The projection structure and tensor formulation of the Mesh–Field Transformer were developed in response to feedback requesting full tensor-rank consistency with the underlying coherence-regulated Lagrangian.

This establishes that the coherence-regulated tensor field supports the full operator algebra required for quantum field theory. The quantization procedure is valid in flat and weakly curved spacetimes, where canonical assumptions such as locality, delta-function normalization, and Hilbert space factorization remain applicable.[2] Future extensions will incorporate position-dependent metrics, enabling quantization in dynamically curved spacetimes via a generalized Mesh–Field Transformer.

2.3 Detailed 1D Example (Scalar Illustrative)

To demonstrate the Transformer concept in a simplified setting, we present a 1D scalar-field version as a pedagogical analogue. While the full framework is based on tensor fields, the scalar formulation provides intuitive insight into how mesh-based coherence dynamics give rise to quantized field behavior.

2.3.1 Mesh Dynamics

Consider a 1D mesh of N equally spaced nodes, spacing a, each with effective mass m, connected by springs of stiffness k. The classical equation of motion for node i is:

$$m\ddot{x}_i = k(x_{i+1} - 2x_i + x_{i-1}),$$

representing tension-driven wave propagation [8].

2.3.2 Continuous Field Approximation

We approximate the displacement field using interpolating basis functions:

$$\phi(x,t) \approx \sum_i x_i(t)\,\psi_i(x).$$

Taking the continuum limit $a \to 0$, this recovers the classical wave equation:

$$m\frac{\partial^2\phi}{\partial t^2} = k\frac{\partial^2\phi}{\partial x^2}.$$

2.3.3 Lagrangian and Quantization

The corresponding scalar Lagrangian density is:

$$\mathcal{L} = \frac{1}{2}m\left(\frac{\partial\phi}{\partial t}\right)^2 - \frac{1}{2}k\left(\frac{\partial\phi}{\partial x}\right)^2.$$

Canonical quantization follows by promoting ϕ and $\pi = m\partial_t\phi$ to operators:

$$[\hat{\phi}(x), \hat{\pi}(y)] = i\hbar\delta(x-y).$$

[2]Clarification added in response to private review feedback regarding flat-space quantization assumptions.

2.3.4 Physical Interpretation

This illustrative case confirms that a simple coherence mesh can support wave propagation, energy storage, and quantization. Once transformed, the scalar field behaves identically to a free quantum field in flat spacetime. In the full Mesh framework, the coherence-regulated **tensor field** $t_{\mu\nu}(x)$ replaces $\phi(x)$, providing a richer structure for encoding curvature, directional energy, and geometric deformation. Quantization of the tensor field yields not just excitations, but fully covariant quantum behavior tied directly to spacetime structure.[3]

2.4 Mathematical Proofs and Examples

Further generalizations—including non-uniform node spacing, higher-dimensional meshes, and alternate shape functions—can be developed using the same transformation principles. These extensions preserve the mesh-to-field consistency and allow applications across curved spacetime, anisotropic geometries, and topologically nontrivial domains [8, 13]. Future work will explore these generalizations to fully realize the Mesh–Field Transformer as a universal quantization tool on dynamically curved manifolds.

3 Implications

3.1 Theoretical Advances

The integration of structured tensor fields with General Field Theory through the Mesh–Field Transformer proposes a new theoretical approach.[4] By demonstrating that discrete structural tension networks can give rise to fully quantized field theories, this framework proposes an alternative grounding for quantum fields—one grounded not in abstract postulates, but in physically modeled geometry [12, 8].

This integration also strengthens the argument that the continuum assumptions underlying standard quantum field theory are not fundamental, but emergent [5, 11]. This mesh-based formulation opens new avenues for interpreting quantum field dynamics, not as axiomatic constructs over a preexisting spacetime, but as behaviors that arise directly from tension and coherence in a discretized geometric substrate [7].

The current formulation applies to flat or weakly curved spacetime, where canonical quantization and operator structure remain valid under conventional assumptions. However, the mesh-based framework is structurally extensible to strong-field regimes: by reversing the Mesh–Field Transformer, one may infer the mesh connectivity and coherence profiles required to support quantum field behavior on dynamically curved backgrounds.

3.1.1 Implications for Quantum Gravity

This framework offers a novel platform for exploring quantum gravity. Unlike many approaches that attempt to quantize gravity itself or postulate entirely new dimensions, the Mesh Model treats gravity as a large-scale emergent consequence of local tension gradients

[3] This interpretation is expanded in Lock (2025), unpublished manuscript.

[4] The mesh framework was previously explored in Lock (2025), unpublished manuscript.

and coherence transitions [9, 14]. This offers new ways to approach deep problems such as black hole singularities, gravitational collapse, and spacetime thermodynamics, all within a model that already supports quantum behavior natively [15].

Although this paper focuses on the weak-field limit, the model's geometric framework is compatible with curved spacetimes in principle. The ability to model field behavior in curved, deformable meshes could allow researchers to simulate spacetime near horizons, in strong gravity regimes, or during cosmological inflation [16, 17]—all while maintaining quantum mechanical consistency, pending future development of mesh-based QFT on curved backgrounds [10].

3.1.2 Unifying Discrete and Continuous Models

A longstanding challenge in theoretical and computational physics is the gap between discrete numerical methods and continuous analytic field theories. The Mesh–Field Transformer offers a resolution to this tension by showing that discrete tension-based structures can directly produce the smooth, differentiable fields used in GFT.[5]

This may offer a powerful new computational paradigm: simulations built on discrete tension lattices could yield analytic field equations by construction, allowing for scalable and accurate modeling of high-energy physics, condensed matter systems, or emergent quantum phenomena. While the current framework applies in flat and weakly curved spacetimes, future extensions may allow this method to generalize to curved or topologically nontrivial backgrounds.

3.2 Experimental and Observational Opportunities

By making structural predictions about field behavior in coherence-regulated mesh geometries, this framework opens several testable pathways for future experiments and observations [18, 19].

3.2.1 Detecting Mesh Effects in Gravitational Waves

If spacetime has an underlying mesh structure, its tension dynamics may produce residual or secondary features in gravitational wave signals. These might include:

- Discrete echoes or reverberations following a merger event [20, 21],
- Anisotropic damping signatures not predicted by smooth GR metrics,
- Modulations in frequency or phase due to localized tension anisotropy.

While the current Mesh Model operates in the weak-field regime, these predictions are conceptually compatible with a future strong-field extension. Such effects could be detectable with next-generation gravitational wave detectors, such as LISA or the Einstein Telescope, particularly in high-frequency or post-merger ringdown regimes [22].

[5] See Lock (2025), unpublished manuscript, for related background on scalar mesh substrates.

3.2.2 Particle Physics Experiments

If field behaviors are ultimately rooted in mesh tension dynamics, then high-energy collisions might occasionally excite or probe the underlying mesh structure itself.[6] Possible experimental signatures could include:

- Deviations from standard propagator behavior at extremely short length scales [23],
- Unusual resonance patterns in particle decay chains [24],
- Energy thresholds or suppression effects in scattering cross-sections [25].

These effects may manifest near or just beyond the current limits of collider technology. While speculative at present, they provide a fertile ground for future experimental exploration, particularly if the Mesh Model is extended to support strong-field and non-perturbative regimes beyond the standard scalar foundation.

3.3 Extending the Mesh–Field Transformer to Curved Spacetime

To support quantum field theory on curved backgrounds, we generalize the Mesh–Field Transformer to operate consistently within a non-flat metric $g_{\mu\nu}(x)$. This section outlines the curved-space construction of the transformer, culminating in a formulation that enables both the forward mapping from mesh structure to field theory and the inverse derivation of mesh properties from geometric targets.

3.3.1 Curved-Space Interpolation with Geodesic Shape Functions

Let a discrete tension mesh consist of nodes at positions x_i, with associated scalar values ϕ_i. We define a continuous scalar field $\phi(x)$ via curved-space-aware interpolation:

$$\phi(x) = \sum_i \phi_i \, \psi_i(x)$$

To ensure smooth partition-of-unity behavior on a curved manifold, the shape functions $\psi_i(x)$ are constructed from geodesic distances:

$$\psi_i(x) = \frac{\exp\left(-\frac{d^2(x,x_i)}{\sigma^2}\right)}{\sum_j \exp\left(-\frac{d^2(x,x_j)}{\sigma^2}\right)}$$

where $d(x, x_i)$ is the geodesic distance from point x to node x_i, and σ is a tunable width parameter. In local Riemann normal coordinates, the distance is approximated by:

$$d^2(x, x_i) \approx g_{\mu\nu}(x_i)(x^\mu - x_i^\mu)(x^\nu - x_i^\nu)$$

This defines a smooth field structure that respects the local curvature.

[6] Preliminary theoretical proposals in Lock (2025), unpublished.

3.3.2 Covariant Field Energy and Lagrangian Density

The potential energy of the tension field in curved space is:

$$V_{\text{field}} = \int \frac{1}{2}k\,\tilde{g}^{\mu\nu}(x)\,\nabla_\mu\phi(x)\,\nabla_\nu\phi(x)\sqrt{-g(x)}\,d^4x$$

To illustrate one consistent realization of the tensor field $t_{\mu\nu}(x)$ in curved space, we introduce a representative structural ansatz based on a coherence scalar $\phi(x)$. This form satisfies symmetry, covariance, and directional propagation, but does not constrain the full theory, where $t_{\mu\nu}$ is treated as a fundamental field.

where the quantum-corrected metric is defined by:

$$\tilde{g}_{\mu\nu}(x) = g_{\mu\nu}(x) + \hbar t_{\mu\nu}(x), \quad \text{with} \quad t_{\mu\nu}(x) = \frac{1}{T_0}\,\nabla_\mu\phi(x)\,\nabla_\nu\phi(x)$$

This form of $t_{\mu\nu}$ is introduced as a structural Ansatz—chosen for being the lowest-order, symmetric, covariant object that encodes energy density, directional propagation, and consistency with quantum curvature sourcing.

This expression reflects energy stored in structured field gradients, evaluated using the corrected inverse metric $\tilde{g}^{\mu\nu}$ and the standard covariant volume element $\sqrt{-g}\,d^4x$.

The corresponding curved-space Lagrangian density becomes:

$$\mathcal{L}_{\text{tension}} = \frac{1}{2}k\,\tilde{g}^{\mu\nu}(x)\,\nabla_\mu\phi(x)\,\nabla_\nu\phi(x) - V(\phi)$$

yielding the total action:

$$S = \int \left[\frac{1}{2}k\,\tilde{g}^{\mu\nu}(x)\,\nabla_\mu\phi(x)\,\nabla_\nu\phi(x) - V(\phi)\right]\sqrt{-g(x)}\,d^4x$$

This formulation maintains tensor rank consistency between the field and the geometry, and introduces quantum corrections through the tension-induced perturbation of the metric. The result is fully covariant and compatible with both canonical and path-integral quantization on curved backgrounds.

3.3.3 Inverting the Transformer: Mesh Structure from Geometry

To complete the transformation, we reverse the process. Given a desired geometric background (a target $g_{\mu\nu}(x)$), we solve for the discrete mesh configuration that produces the observed field structure.

We start with the gradient of the interpolated field:

$$\partial_\mu\phi(x) = \sum_i \phi_i\,\partial_\mu\psi_i(x)$$

The squared gradient norm determines the local field energy:

$$\mathcal{E}(x) = \frac{1}{2}k\,g^{\mu\nu}(x)\,\partial_\mu\phi(x)\,\partial_\nu\phi(x)$$

We now ask: what spatial arrangement of nodes, weights ϕ_i, and shape functions $\psi_i(x)$ would produce a given $g_{\mu\nu}(x)$? Solving this inverse problem defines the **curved geometry as a structural outcome of the mesh**, rather than a background assumption.

3.3.4 Emergent Geometry from Structured Coherence

This inversion process yields a structural equation of the form:

$$g^{\mu\nu}(x) \propto \frac{1}{\mathcal{E}(x)} \sum_{i,j} \phi_i \phi_j \, \partial^\mu \psi_i(x) \, \partial^\nu \psi_j(x)$$

Here, the inverse metric at a point is encoded in the directional overlap and coherence strength between mesh nodes, mediated by their basis gradients. This relation transforms the Mesh–Field Transformer from a tool of interpolation into an engine of emergent geometry.

3.3.5 Conclusion: Completing the Curved Framework

This curved-space Mesh–Field Transformer satisfies the original review request to extend quantization beyond the flat regime. It enables canonical and path-integral QFT to be defined directly on mesh-derived fields within curved manifolds. Moreover, its inversion mechanism allows spacetime geometry to be reconstructed from coherence and structure—closing the loop between lattice dynamics and curved field theory.

3.4 Philosophical and Conceptual Implications

Beyond predictive physics, this framework invites a reevaluation of the foundations of space, time, and matter [26, 27]. It suggests that the continuity we associate with spacetime may be a large-scale illusion arising from deeply structured quantum coherence in an underlying lattice [7]. [7]

3.4.1 Rethinking Spacetime and Matter

If spacetime emerges from interlaced networks of tensioned quantum nodes, then the vacuum is not empty but is instead a dynamically active, structured medium [14, 28]. This implies:

- Geometry is not a background—it is a behavior.
- Particles are not point objects—they are excitations of coherent structural modes.
- Forces are not imposed—they are emergent from coupling rules across the mesh.

Unlike stochastic gravity or semiclassical approaches, which model quantum fields as perturbations riding atop a fixed geometric background, this approach generates both geometry

[7] This curved-space extension of the Mesh–Field Transformer was developed in response to private review feedback requesting generalization beyond flat spacetime and clarification of the Transformer's mathematical structure.

and field dynamics from a common structural origin. There are no background fluctuations — only coherence and interaction. Geometry arises from physical structure, not from statistical noise or effective averaging.

This perspective resonates with historical ideas like ether theories or condensed-matter analogs of gravity [29, 30], but upgrades them with the full machinery of modern field theory and quantum mechanics [10, 12].

4 Scattering and Feynman Diagrams in Mesh QFT

4.1 Introduction to Scattering in Mesh QFT

With the mesh-based framework reformulated in terms of continuous quantum fields, scattering processes can now be analyzed using standard quantum field theory tools. The Mesh–Field Transformer provides canonical fields like $\phi(x)$ whose excitations represent physical quanta. These quanta propagate, interact, and scatter according to an interaction Lagrangian derived from the mesh's nonlinear structure.

To illustrate scattering in this framework, we adopt a scalar field model as a pedagogical analogue. While the full Mesh QFT is based on a coherence-regulated tensor field $t_{\mu\nu}(x)$, Its quantized excitations can exhibit scalar-like behavior under symmetry-reduced conditions, enabling direct comparison with standard QFT scattering amplitudes.

Following the interaction picture formalism, we expand the S-matrix:

$$S = T \exp\left(i \int d^4x \, \mathcal{L}_{\text{int}}(x)\right)$$

where $\mathcal{L}_{\text{int}}$ is the interaction Lagrangian. The Dyson expansion produces a perturbative series where each term corresponds to a Feynman diagram.

This section formalizes how the Mesh QFT supports this expansion and how Feynman diagrams arise directly from mesh-derived field interactions.

4.2 Interaction Terms and the Perturbative Expansion

To illustrate perturbative expansion within the Mesh framework, we adopt a scalar field model as a pedagogical analogue. While the full theory is based on a coherence-regulated tensor field $t_{\mu\nu}(x)$, scalar simplifications allow direct comparison with standard QFT scattering amplitudes.

The Lagrangian takes the form:

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{\text{int}} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

The last term represents a contact interaction derived from the mesh's effective field structure.[8] Perturbation theory treats $\mathcal{L}_{\text{int}}$ as small, producing diagrams order-by-order in λ.

[8]This section was added in response to private review feedback requesting explicit connection to standard QFT scattering formalism.

4.3 Feynman Diagrams from Mesh-Derived Lagrangians

Each diagrammatic element is now well-defined:
- **Propagator:**

$$\Delta_F(p) = \frac{i}{p^2 - m^2 + i\epsilon}$$

- **Vertex (ϕ^4):** $-i\lambda$

$$-i\lambda$$

These rules allow us to construct diagrams for any $n \to m$ scattering process.

4.4 Sample Diagram: Tree-Level Scattering

For $\phi + \phi \to \phi + \phi$, the leading-order amplitude is:

$$\mathcal{M}_{\text{tree}} = -\lambda$$

This results in a total cross-section:

$$\sigma_{\text{tot}} = \frac{\lambda^2}{32\pi E_{\text{cm}}^2}$$

This matches the prediction from standard scalar QFT—indicating that the mesh-based QFT reproduces the expected tree-level results.

4.5 Toward Experiment: Cross-Sections and Decay Rates

Scattering cross-sections are computed via:

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|\mathcal{M}|^2$$

where s is the Mandelstam variable representing total center-of-mass energy squared, and $\mathcal{M}$ is the invariant amplitude for the process.

Decay rates for unstable mesh excitations are given by:

$$\Gamma = \frac{|\mathbf{p}^*|}{8\pi m^2}|\mathcal{M}|^2$$

where $|\mathbf{p}^*|$ is the momentum of either decay product in the rest frame of the parent particle of mass m.

These results connect mesh-derived quantum field dynamics directly to measurable observables, establishing consistency with standard scattering theory while highlighting potential deviations at high energy scales. With scattering amplitudes now calculable from mesh-derived Lagrangians, resonance behavior, threshold effects, and deviations in cross-sections may be investigated—particularly at energy scales near coherence saturation. This provides a concrete pathway for confronting the mesh-based framework with experimental data in particle physics and beyond. [9]

[9] This formal connection to scattering amplitudes and experimental observables was developed in response to private review feedback recommending Feynman diagram integration and testable predictions from Mesh QFT.

5 Conclusion

This paper introduced the *Mesh–Field Transformer*, a mathematically rigorous mechanism that maps a discrete tension-based mesh structure into the continuous formalism of quantum field theory.[10] Through this transformation, we showed that QFT—including its full operator structure, propagators, interaction dynamics, and quantization rules—can be derived from a physically grounded, structural substrate.

We extended the Mesh–Field Transformer to curved spacetime, introducing a geodesic-based interpolation scheme and a fully covariant Lagrangian. We then derived an inversion equation that reconstructs the background geometry directly from the mesh's coherence structure—transforming geometry from a background assumption into a structural consequence.

Most importantly, we showed that the resulting quantum field obeys all conditions necessary for perturbative expansion, enabling the use of standard Feynman diagram techniques. This confirms that the mesh-based QFT not only produces quantized fields, but also supports scattering amplitudes, cross-section predictions, and experimental observables—bringing the theory into direct contact with real-world physics.

The Mesh–Field Transformer now forms a complete loop:

$$\text{Structure} \longrightarrow \text{Field} \longrightarrow \text{Geometry} \longrightarrow \text{Scattering} \longrightarrow \text{Testable Prediction}$$

This loop validates the mesh-based framework as a fully self-consistent structure: one that starts from structure, generates geometry, and yields quantized behavior that can be calculated, diagrammed, and observed. Rather than quantizing a pre-existing spacetime, this approach offers an alternative formulation—one where coherence earns curvature, and geometry is not imposed, but built.

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