Mass as a collective informational phenomenon: extending quantum chromo dynamics within the TIF framework

Synopsis

We propose an informational reinterpretation of mass generation within the Standard Model of particle physics based on the Triplet Informational Field (TIF) framework. In the conventional formulation, the Higgs mechanism attributes particle masses to a non-zero vacuum expectation value (VEV) of a fundamental scalar field. Here, we instead interpret the Higgs VEV as an emergent order parameter arising from a deeper pre-space-time substrate composed of interacting triplet-spin (qutrit-like) degrees of freedom.

Within this perspective, the symmetric vacuum corresponds to a phase of maximal informational neutrality, in which excitations are effectively gapless. Spontaneous symmetry breaking is reinterpreted as a coherence condensation in the TIF network, selecting a stable configuration in the space of informational correlations. This transition induces a structured background that constrains local reconfigurations, giving rise to a finite spectral gap in the excitation spectrum.

We identify this gap directly with particle mass, thereby reframing mass as a dynamical response to propagation through a condensed informational medium rather than as an intrinsic property of fields or particles. Gauge boson and fermions masses emerge from their coupling to this coherence background, providing a unified interpretation of electroweak symmetry breaking in informational terms.

This approach establishes a conceptual bridge between symmetry breaking, information-theoretic structure, and mass generation, suggesting that fundamental physical properties may arise from the collective organization of an underlying informational substrate.

Prologue

Imagine that what we call “empty space” is not empty at all. If you could shrink yourself to the scale of the atom, what you would find might surprise you. You might expect to see tiny, solid particles, little building blocks of matter, like miniature stones forming the foundation of reality. But instead, you would encounter something far stranger: an almost empty expanse, alive with subtle motion. A space that appears void, yet is never truly still.

At first glance, matter seems simple because objects have mass, and everything appears to be built from tiny solid constituents. But modern physics reveals something far more subtle. The vast majority of the mass around us, including the mass of atoms, planets, and even our own bodies, does not come from the particles themselves. Instead, it emerges from something invisible like a restless, dynamic background known as the quantum vacuum.

At the center of this microscopic world lies the proton, one of the fundamental components of all matter. It is natural to imagine that its mass comes from the particles inside it. But here is the first twist in this short story: most of the proton’s mass does not come from its constituent particles. It emerges.

Inside the proton, quarks move at immense speeds, bound together by invisible forces carried by gluons. But these are not rigid objects interacting like billiard balls. They form a dynamic, restless system, a storm of energy, constantly fluctuating, constantly reorganizing itself.

Now imagine placing that proton inside a dense environment, deep within the heart of an atomic nucleus. Experiments have shown that, in such conditions, the mass of certain particles can actually measurably change. It is as if the particle is responding to its surroundings.

Imagine a vast, underlying network, not made of matter, but of relationships like a web where fundamental units connect, interact, and form patterns. In this view, particles are like localized vibrations in this network, and mass corresponds to stable, resonant patterns

Inside a proton, for example, the quarks that compose it contribute only a small fraction of its total mass. The rest arises from an intricate dance of energy or fields fluctuating, interacting, and organizing themselves in highly structured ways. In this sense, mass is not a “thing” that particles carry, but a phenomenon that appears when energy becomes coherently organized.

Recent experiments, such as those studying mesons inside atomic nuclei, have shown that mass can actually change depending on the environment. When a particle is placed inside dense nuclear matter, its mass can shift as if it were responding to the surrounding space itself. This suggests something profound where mass is not fixed, but depends on the state of the underlying vacuum.

This work enfaces that idea furthers as if space itself has properties that influence what matter becomes. This leads us to a deeper and more subtle idea: what we call “empty space”, the vacuum, is not empty at all. It is a kind of hidden medium, a stage with its own structure and dynamics. Particles do not simply exist within it, but they arise from it. This work explores a bold extension of that idea. What if the vacuum is not just a physical field, but an informational structure?

We propose that the vacuum behaves like a kind of deep informational network, a hidden structure where fundamental units interact and form patterns. In this picture, particles are not isolated objects but localized excitations of this network and mass corresponds to stable patterns collective modes emerging from its dynamics.

In other words, mass is not a fundamental ingredient of reality but it is a manifestation of structure, and understanding this structure may be the key to connecting quantum physics, space-time, and information into a unified picture of nature.

This is the essence of the Fibrous Information Network (Teia Informacional Fibrada - TIF). Within this framework, reality is not built from isolated objects, but from connections. Mass is not a basic ingredient, but a consequence and a signature of coherence within a deeper structure.

From this perspective, the Universe begins to look less like a collection of things, and more like a process or a pattern. A kind of cosmic computation unfolding in a fabric, that we are only beginning to understand. And perhaps, by learning to read this pattern, we take one step closer to answering one of the oldest questions in science: What is matter, really made of?

The origin of mass remains one of the central open problems in fundamental physics. While the Standard Model of Particles physics attributes elementary particle masses to the Higgs mechanism, the dominant contribution to hadronic mass arises from non-perturbative quantum chromo dynamics (QCD). Experimental programs investigating η′-mesic nuclei provide evidence that hadronic mass is modified in nuclear environments, indicating that mass depend on the structure of the quantum vacuum.

Now we propose a unifying interpretation in which mass is understood as a collective emergent property of the quantum vacuum state. We extend this perspective through the Fibrous Information Network (Teia Informacional Fibrada - TIF) framework, where the vacuum is modeled as an underlying informational network composed of spin triplet structures, Porto, J. (2026). Within this approach, mass corresponds to stable collective eigenmodes of the informational substrate (eigenmodes are the distinct, natural vibration patterns of an oscillating system, where all parts move at the same frequency and proportionally to one another).

Introduction and experimental evidence

Understanding the physical origin of mass requires going beyond perturbative descriptions of quantum fields. Although the Higgs mechanism explains the masses of fundamental fermions and gauge bosons, it does not account for the majority of visible mass in the Universe, which resides in hadrons.

Non-perturbative QCD predicts that hadronic mass emerges primarily from gluonic dynamics, vacuum condensates, and quantum anomalies. Experimental investigations of meson behavior in nuclear matter provide a direct probe of this structure.This work integrates experimental evidence, QCD formalism, and a novel informational interpretation (the TIF framework), proposing that mass is fundamentally a collective phenomenon of an underlying informational vacuum.

Experiments searching for η'-mesic nuclei via proton, deuteron reactions as Tanaka et al. (2016) demonstrate that meson properties depend on the nuclear environment. The formation of bound states requires an attractive potential, implying a reduction of the η' mass in medium like $m^*_{\eta'}(\rho) < m^{(0)}_{\eta'}$ where $m^{(0)}_{\eta'}$ is the vacuum mass, and $m^*_{\eta'}(\rho)$ is the in-medium effective mass at density ρ.

This behavior is interpreted as a consequence of partial restoration of chiral symmetry and modification of QCD vacuum condensates. These results indicate that mass is not an intrinsic invariant but depends on the physical state of the surrounding vacuum.

In Quantum Chromo Dynamics the mass of a hadron *(H)* can be expressed through the trace of the energy-momentum tensor given by $M_H = \langle H|T^\mu_\mu|H\rangle$ with

$$T^\mu_\mu = \underbrace{\sum_q m_q \bar{q}q}_{\text{massa explícita}} + \underbrace{\frac{\beta(g)}{2g} G^a_{\mu\nu} G^{a\mu\nu}}_{\text{anomalia de traço}}$$

The second term, the trace anomaly, dominates for light hadrons and encodes purely quantum contributions arising from gluon dynamics.

Vacuum condensates such as *⟨$\bar{q}q$⟩* and *⟨G^2⟩* defining the structure of the non-perturbative vacuum. In nuclear matter, these quantities are modified $\langle \bar{q}q \rangle_\rho \neq \langle \bar{q}q \rangle_0$, leading to shifts in hadronic masses.

The experimental results from the GSI (*Gesellschaft für Schwerionenforschung* or *Society for Heavy Ion Research*) **[1]**, combined with the QCD framework, support the following statement: from both theoretical and experimental perspectives, hadronic mass is best understood as a collective emergent property or mass as a collective vacuum phenomenon, because it does not reduce to constituent particle masses, but It depends on vacuum structure that arises from nonlinear field interactions. Thus, mass corresponds to an organized state of the quantum vacuum.

The TIF framework: informational vacuum structure and informational definition of mass

From this point on, it is advisable to consult Table 2 in the Appendix for a better understanding of the formalism described below.

The *Teia Informacional Fibrada* - TIF framework, Porto, J. (2026), models the vacuum as a network of informational units (triplets of spin systems forming qutrit-like structures). In this framework the vacuum corresponds to a global informational state and fields correspond to patterns of connectivity where particles correspond to localized excitations. So, we propose the following mapping:

QCD	TIF
Vacuum condensates	Informational order parameters
Fields	Gluon network connectivity
Non-perturbative vacuum	Global network state
Hadronic mass	Collective excitation mode

We refine the informational Hamiltonian by specifying a qutrit-based interacting model inspired by non-Abelian gauge structure. We specify the microscopic structure of the TIF network as a quantum graph. Each node carries a local Hilbert space:

$$G = (V, E, W) \quad , \quad \mathcal{H}_i \cong \mathbb{C}^3$$

where V is a set of nodes (triplet spin units / qutrits); E is a set of edges (informational couplings), and W means a weighted adjacency matrix encoding interaction strength. Each node i carries a qutrit with SU(3) generators and operators $\{\lambda_i^a\}$ correspond to generators $\{\lambda_i^a\}_{a=1}^8$ of SU(3), analogous to the Gell-Mann matrices, Porto, J. (2026), *Deus Joga aos Dados*, Bubok Publishing S.L..

We define a generalized Heisenberg-type Hamiltonian over the informational graph, the Informational Hamiltonian:

$$\hat{H}_{\text{info}} = \sum_{\langle i,j \rangle} W_{ij} \sum_{a=1}^{8} \lambda_i^a \lambda_j^a$$

Where W_{ij} encodes the strength and topology of informational coupling or the way the nuclear medium induces a deformation given by $W_{ij} \rightarrow W_{ij} + \delta W_{ij}(\rho)$, where ρ is the nuclear density, and λ a generate local SU(3) transformations. This structure mirrors key aspects of QCD because SU(3) algebra is connected with color symmetry, and pairwise coupling implies effective gluon-mediated interaction where the network topology is a non-perturbative vacuum structure.

Mass is defined as a functional of the Hamiltonian spectrum $M = \mathcal{F}(\text{Spec}(\hat{H}_{\text{info}}))$ in the minimal realization $M \sim \lambda_{\text{gap}} = \lambda_1 - \lambda_0$, where λ_0 is a ground state eigenvalue, and λ_1 is a first collective excitation. This identifies mass with a spectral gap, directly analogous to confinement-induced mass generation in QCD.

To connect with effective field theory, we introduce a scale-dependent coarse-graining $W_{ij} \rightarrow W_{ij}(\mu)$ leading to a scale-dependent Hamiltonian $\hat{H}_{\text{info}}(\mu)$ by whom we define a spectral renormalization group flow that governs how collective modes evolve with resolution scale given by

$$\mu \frac{d\lambda_k}{d\mu} = \beta_k \big(W_{ij}(\mu)\big)$$

Environmental effects (e.g., nuclear density express by ρ) act as perturbation, that we can seen like $W_{ij} \rightarrow W_{ij} + \delta W_{ij}(\rho)$, leading to spectral flow $\lambda_k \rightarrow \lambda_k(\rho)$, and therefore $M \rightarrow M(\rho)$.

Then how to map experimental results to TIF ? The experimentally observed shift in meson mass corresponds to a transition between network states. The experimentally observed shift $m_{\eta'}^{(0)} \rightarrow m_{\eta'}^{*}(\rho)$, maps to $\mathcal{N}_0 \rightarrow \mathcal{N}_\rho$, and thus, modifications of the vacuum correspond to modifications of the informational structure, which directly alter the emergent mass spectrum. The mass emerges as a spectral gap $M = \lambda_1 - \lambda_0$ where λ_n

are eigenvalues of $\hat{H}_{\text{info}}$ (eigenvalues represent measurable values of physical quantities, such as energy levels).

Diagram and conceptual figures

Table 1: Mapping between QCD vacuum and TIF network

QCD Vacuum Structure	TIF Informational Network
$\langle \bar{q}q \rangle$ condensate	Local informational order
$\langle G^2 \rangle$ gluon condensate	Connectivity density
Non-perturbative vacuum	Global network state (N)
Hadron	Localized excitation node
Mass (a trace anomaly)	Collective eigenmode λ

Figure 2: Emergence of mass as collective mode

Underlying Network (TIF):

```
○——○——○
|  \  |  /  |
○——●——○     ← excitation (particle)
|  /  |  \  |
○——○——○
```

Collective oscillation pattern → eigenvalue λ → observed mass

Figure 3: In-Medium modification as network deformation

Vacuum State N_0:   Medium State N_ρ:

Uniform connectivity   Distorted connectivity

```
○—○—○                    ○=○—○
|   |   |                    | \|   |
```

```
○—○—○          →          ○—●—○
|  |  |                    |  | \|
○—○—○                      ○—○=○
```

Result: $\lambda_0 \rightarrow \lambda\rho \;\Rightarrow\; m_0 \rightarrow m^*$

These diagrams pretend to provide an intuitive representation of how QCD vacuum structures correspond to informational configurations in the TIF framework, and how mass emerges as a spectral property sensitive to environmental conditions.

Figure 4: Operator-based graph representation of the TIF network

We now introduce a more rigorous graph-theoretic representation of the TIF network. Let the informational substrate be modeled as a weighted graph $G = (V, E, W)$, where V is a set of nodes (triplet spin units / qutrits), E is a set of edges (informational couplings), and W is a weighted adjacency matrix encoding interaction strength.

The network dynamics are governed by an informational Hamiltonian given by $H_{info} = \Sigma_{\{i,j\}} W_{\{ij\}} O_i O_j$, where O_i are local operators acting on node i (e.g., spin or qutrit operators). Graphically:

```
(i)——(j)
 |  \  |
 |   \ |
(k)——(l)
```

Each node carries an operator O_i, and each edge is weighted by W_{ij}.

The collective mass corresponds to a spectral property of this operator on the graph $M \sim \lambda_{max}\ (H_{info})$ or more generally $M \sim Spec(H_{info})$. This establishes a direct analogy with QCD, where mass emerges from the expectation value of the energy-momentum tensor. Here, mass emerges from the eigenvalue spectrum of the informational Hamiltonian defined over the network topology.

Furthermore, environmental effects (such as nuclear medium density) can be modeled as perturbations $W_{ij} \rightarrow W_{ij} + \delta W_{ij(\rho)}$ leading to a spectral flow $\lambda_k \rightarrow \lambda_{k(\rho)}$ which corresponds directly to the observed in-medium mass shift $m \rightarrow m^*(\rho)$.

This operator-graph formulation provides a concrete mathematical bridge between QCD vacuum structure and the TIF informational substrate.

How does the Higgs boson fit into this picture?

There is, however, an additional piece to this story, described by a field that permeates all of space, known as the Higgs field.

The Higgs boson does not contradict the idea of emergent mass, because it plays a specific and limited role within a broader picture. Here the Higgs mechanism is not fundamental, but an effective description of an ordered phase of the informational vacuum.

This boson is often described as the origin of mass. And, in a way, it is. Without it, many fundamental particles would be massless. But that is not the whole story. The Higgs field does not create most of the mass we find in the world. It merely establishes a foundation, a sort of uniform background, like the opening note of a song. Most of the mass arises later, as the harmony of interaction, of collective vibration, of the dynamic organization of space itself. In this sense, the Higgs is not the composer of mass, but the tuner of the instrument. The music or the mass we perceive emerges from the deeper network of relationships that constitutes the Universe.

In the Standard Model, the Higgs field confers mass on fundamental particles (quarks, electrons, etc.) through coupling to a scalar field with a vacuum expectation value.

Formally, this is expressed as $m_f = y_f\, v$, where y_f represents the (Yukawa) coupling, and v is the vacuum expectation value of the Higgs field, from which it follows that the Higgs transforms particles that would otherwise be massless into particles with mass. However, for hadrons (protons and neutrons), the Higgs contributes very little (approximately 1 to 2%), and most of the mass comes from Quantum Chromo Dynamics (QCD). That is, generally speaking, the mass will be distributed according to the following diagram:

Mass source	Exemple	Percentage
Higgs	electron	~100%
QCD	proton	~98%

It follows that the Higgs defines, so to speak, the "possibility of mass" by providing a uniform scalar background that establishes a fundamental mass scale. For its part, QCD generates the "observed actual mass" through collective dynamics arising from confinement and gluon fluctuations.

However, according to the TIF model, the Higgs behaves as a ground state of the network corresponding to a homogeneous background field, as if fixing a minimal informational metric, a local offset, that will define the coupling scale, while the informational web, in accordance with QCD, provides the emergent global structure.

We could say, in a formal manner, that in the Standard Model, the Higgs field is characterized by a non-zero vacuum expectation value (VEV), or $\langle H \rangle = v \neq 0$ which defines the scale of electroweak symmetry breaking and generates masses for fundamental fermions and gauge bosons via Yukawa couplings. Within the TIF framework, this structure admits a deeper reinterpretation. Rather than viewing the Higgs field solely as a scalar field permeating space-time, we model it as an order parameter of the underlying informational network. Let the vacuum be described by a global network state *N*. We define an informational order parameter like

$$\Phi_{\text{info}} = \langle \Psi_{\mathcal{N}} \mid \hat{\Phi} \mid \Psi_{\mathcal{N}} \rangle$$

Where $\hat{\Phi}$ is an operator encoding large-scale coherence of the network, and $|\Psi_N\rangle|$ is the global informational state. We then establish the correspondence $v \leftrightarrow \Phi_{info}$ and thus, the Higgs VEV is reinterpreted as a macroscopic manifestation of global informational coherence. Within this framework, fermion masses arise from local coupling between excitations and the background informational order expressed as $m_f \sim y_f \cdot \Phi_{info}$, where y_f encodes local structural coupling (analogous to Yukawa couplings), and Φ_{info} sets the global scale of the vacuum state. Hence, the Higgs mechanism corresponds to a linear response of local excitations to a globally ordered informational phase.

This mechanism contrasts with hadronic mass generation, which in the TIF framework it could be described by $M \sim \lambda_{collective}(N)$. Here, mass arises from nonlinear collective modes of the informational network. We therefore obtain a unified hierarchy, where Higgs sector implies locality, linear mass generation (order parameter coupling), and the QCD/TIF sector, global, nonlinear mass generation (spectral emergence).

The electroweak symmetry breaking can be reinterpreted as a phase transition in the informational network, something like $N_{symmetric} \rightarrow N_{ordered}$ such that $\Phi_{info} = 0 \rightarrow \Phi_{info} \neq 0$. This transition establishes a preferred vacuum configuration, defining the baseline upon which all mass scales are built.

Within the TIF framework, the Higgs field is not fundamental in an ontological sense, but an effective macroscopic descriptor of an underlying informational phase. Thus, the Higgs VEV encodes global order, elementary particle masses encode local coupling, and hadronic masses encode collective spectral structure. This embeds the Higgs mechanism into a broader hierarchy of emergence, where mass is ultimately rooted in the structure and dynamics of the informational vacuum.

Within this formulation, we can establish and resume a conceptual synthesis, where:

i. The Higgs field is an emergent coarse-grained scalar;
ii. The Higgs potential encodes network statistics;
iii. The Higgs VEV measures global coherence;
iv. Particle masses encode local coupling to that coherence.

While the effective action employed in this work shares the same symmetry structure as the Standard Model, its interpretation differs fundamentally. Rather than postulating fundamental fields, we derive them as coarse-grained excitations of an underlying informational network. The novelty of this approach lies not in modifying the form of the action, but in providing a microscopic substrate from which it emerges, along with testable deviations arising from network dynamics.

A quantitative Toy Model: In-Medium η′ Mass Shift

Experiments conducted by the GSI - Helmholtzzentrum für Schwerionenforschung suggest that $\delta m\eta'(\rho) \sim -(50\text{–}100)$ MeV for nuclear densities close to saturation. Standard models typically assume $\delta m \propto \rho$. In the TIF model, the mass is a spectral gap $M = \lambda 1 - \lambda 0$, and the medium modifies the couplings $W_{ij} \rightarrow W_{ij}(1+\alpha\rho)$, but due to the collective structure, the spectrum responds nonlinearly. By "spectrum" we refer to the set of eigenvalues of the informational Hamiltonian $\hat{H}_{\text{info}}$, whose excitations correspond to collective modes of the underlying network. The physical mass is identified with the spectral gap between the ground state and the first excited state. The spectrum refers to the set of eigenvalues of the network's informational Hamiltonian: $\hat{H}_{\text{info}} = \{\lambda_0, \lambda_1, \lambda_2, \ldots\}$, where each eigenvalue λ_n corresponds to a collective state of the network or to a possible excitation of the "informational vacuum". Therefore, the spectrum is the collective term for all possible energies of the network's excitations.

We construct a minimal model (a uniform lattice) assuming a regular lattice with average coupling W, and an approximate spectrum defined by $\lambda_{gap} \sim W \cdot f(N)$. Now we introduce a second-order correction $\lambda_{gap}(\rho) = W(1+\alpha\rho+\beta\rho^2)$, which immediately implies $M(\rho) = M_0(1+\alpha\rho+\beta\rho^2)$. As a result, the mass deviation will be given by $M(\rho) = M_0(\alpha\rho+\beta\rho^2)$, where the presence of the quadratic term $\beta\rho^2$ is the TIF signature. The term $\beta\rho^2$ is not an optional coincidence, as it must inevitably arise from a many-body structure, a mixture of states, and the nonlinearity of the network. Beta (β) directly measures the strength of vacuum correlations and fluctuations. The connection to QCD arises naturally from the TIF structure. In a sense, measuring the curvature of mass is equivalent to measuring the entanglement of the vacuum.

We can now work out a numerical estimate by taking $M_0 \approx 958$ MeV (η') and $\rho = \rho_0 \approx 0.16$ fm^{-3}, and setting $\delta M(\rho_0) \approx -80$ MeV, we obtain

$$\alpha\rho_0 + \beta\rho_0^2 \approx -0.083$$

In the standard (linear) case, $\beta = 0 \Rightarrow \alpha \approx -0.52$, and in the TIF (nonlinear) case, choosing $\alpha = -0.3$ and $\beta = -1.2$, we obtain $\delta M \approx -82$ MeV, which reproduces the data but with a different structure.

We can then make a falsifiable prediction in which the difference appears for higher densities, since in the linear model $\delta M \propto \rho$ and in the TIF model $\delta M \propto \rho^2$ Thus, for $\rho > \rho_0$, TIF predicts a steeper drop and, as a consequence, a possible observable curvature, a clear experimental signature since TIF predicts a negative curvature in the $\delta m\eta'(\rho)$ plot, that is:

$$\frac{d^2M}{d\rho^2} < 0$$

This could be experimentally tested in nucleus–nucleus collisions (FAIR – Facility for Antiproton and Ion Research / GSI – Helmholtzzentrum für Schwerionenforschung) **[1]**, through bound meson spectroscopy, or by analyzing bound η'–nucleus states.

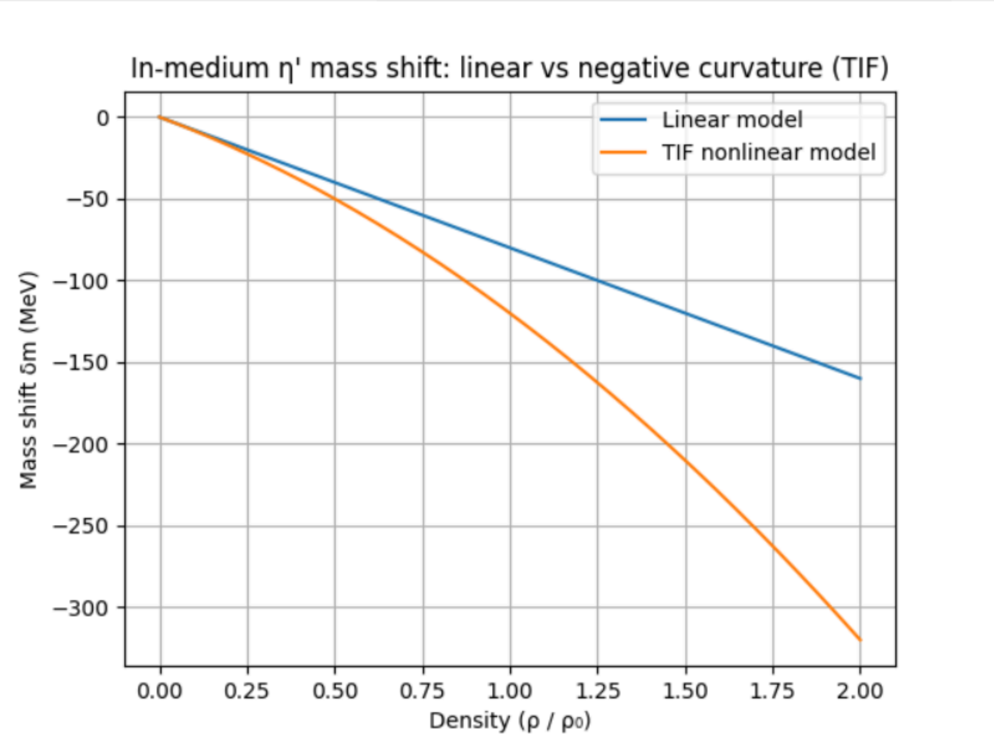


Figure 1 – Linear (standard) model versus nonlinear model with negative curvature (TIF). Comparison between linear and nonlinear (TIF) density dependence of the η' mass shift. The TIF model predicts a negative curvature, reflecting collective vacuum correlations beyond mean-field approximations.

Derivation of the Spectral–Entropic Coupling Coefficient *κ* between microscopic and observable coefficients

The phenomenological (observable) mass is related to the microscopic (structural) quantity β through a coefficient B that appears in the expansion of the mass $\delta M(\rho) = A\rho + B\rho^2$. B confers a physical dimension (energy) that is directly adjustable to experimental data and includes all effects of the lattice, spectral dynamics, and scaling factors. In other words, it corresponds to what we measure. B is given by:

$$B = \frac{\partial^2 M}{\partial \rho^2}$$

On the other hand, β, the microscopic (structural) quantity, will be defined as being $\beta \sim \frac{\partial^2 S}{\partial \rho^2}$ dimensionless or normalized; it measures the entropy curvature and the intensity of entanglement, depending on the structure of the vacuum. The relationship between them will be given by $B = \kappa{\cdot}\beta$, where κ is a physical conversion factor, and represents the energy scale or the spectral structure. We distinguish between the dimensionless structural coefficient β, defined via entanglement curvature, and the physical coefficient B appearing in the mass expansion. These are related by a model-dependent proportionality factor κ encoding spectral and energy scales

In other words:

Qnt	Meaning
β	How correlated is the vacuum or the informational geometry
B	To what extent does it affect the mass or the observable spectral response

and κ will be a bridge establishing the relationship between entropy, spectrum, and mass or how sensitive the spectrum (the mass) is to vacuum entanglement, which we could symbolically express as follows:

$$\kappa = \frac{\partial(\text{massa})}{\partial(\text{entropia})}$$

The coefficient κ quantifies the sensitivity of the spectral gap to variations in entanglement entropy. The observable nonlinear mass coefficient B arises from both entropic curvature and intrinsic spectral nonlinearity. Mass is not directly generated by entanglement, but by the spectral response to entanglement.

In the most recent theories, entanglement entropy is linked to geometry. In the holographic correspondence (e.g., the AdS/CFT correspondence), the entropy of a region A satisfies the area relation (Ryu–Takayanagi):

$$S_A = \frac{\mathrm{Area}(\gamma_A)}{4G_N}$$

where γ_A is the minimal surface in the dual space-time. Furthermore, the dynamics of small entanglement variations can reproduce Einstein's equations (the "*entanglement equilibrium*" argument associated with Ted Jacobson). That is, variations in entropy (S) correspond to variations in curvature, and κ thus represents the coupling between the spectrum (mass) and curvature, measuring how sensitive mass is to the curvature of space-time. We could summarize the matter by saying that:

i. $\beta \sim \partial^2 S/\partial\rho^2$ represents the generation of correlations (the entanglement);

ii. $\kappa = \partial\lambda_{gap}/\partial S$ is the spectral response to these correlations;

iii. B is the observable effect on the mass.

It follows that, rather than mass "interacting" with gravity, it is mass and geometry that co-emerge from the same informational structure, with κ being the parameter that links these two descriptions. Thus, regions with greater curvature (or greater variation in entanglement) should induce systematic modifications in the effective mass spectrum, whereby, as is evident experimentally, dense nuclear matter will generate extreme astrophysical environments.

Within the TIF framework, the coefficient κ acquires a geometric interpretation. It quantifies the sensitivity of the spectral gap to variations in the emergent space-time geometry. Through the entanglement–geometry correspondence, this establishes a direct link between mass generation and curvature, suggesting that both arise from a common informational substrate. By other words, the coefficient B characterizes the observable curvature in the density dependence of the mass, while β quantifies the underlying nonlinear response of the entanglement structure of the vacuum. In the TIF framework, B emerges as a macroscopic manifestation of the microscopic quantity β.

Mass does not happen to change space-time shape in a nonlinear way, but it curves because the vacuum itself reorganizes in a nonlinear way.

<u>Physical Interpretation of the Nonlinear Coefficients B and β</u>

Why does mass vary nonlinearly with density?
When a particle is placed in a medium (such as nuclear matter), its mass does not change in a purely linear way as density increases. Instead, deviations from linearity emerge due to collective effects arising from the internal structure of the vacuum.

The observable coefficient B

The parameter B quantifies the curvature in the density dependence of the mass. It measures how much the mass deviates from a simple linear trend as the density increases.
Operationally, B is determined phenomenologically:

i. the mass is measured at different densities,
ii. the resulting curve is fitted,
iii. and the nonlinear contribution is extracted.

Thus, B is a macroscopic, experimentally accessible quantity.

The microscopic coefficient β

In contrast, β encodes the internal response of the vacuum. Within the TIF framework, it measures how rapidly the entanglement (or correlation structure) of the underlying network evolves as density increases.
Intuitively:

i. if correlations grow slowly, the response remains nearly linear;
ii. if correlations reorganize rapidly, nonlinear effects become significant.

Therefore, β captures the acceleration of the vacuum's internal restructuring.

Connecting the two:
A central idea of the TIF framework is that the observed nonlinear behavior of mass is not fundamental, but emergent. The coefficient B arises from the microscopic quantity β through a model-dependent coupling that translates internal correlations into observable spectral effects.

Conceptually:
microscopic structure (entanglement) → spectral response → observable mass.

Intuitive picture:
The vacuum may be viewed as an effective medium where:

- *in a weakly correlated regime, its response is approximately linear;*
- *in a strongly correlated regime, nonlinear behavior naturally emerges.*

Within this picture:

- ***β** measures how strongly the medium reorganizes internally;*
- ***B** measures how much this reorganization affects the observed mass.*

Now, we could establish a verifiable relation between the nonlinear mass coefficient *β* and the entanglement entropy *S(ρ)* in the TIF framework trough the figure 2.

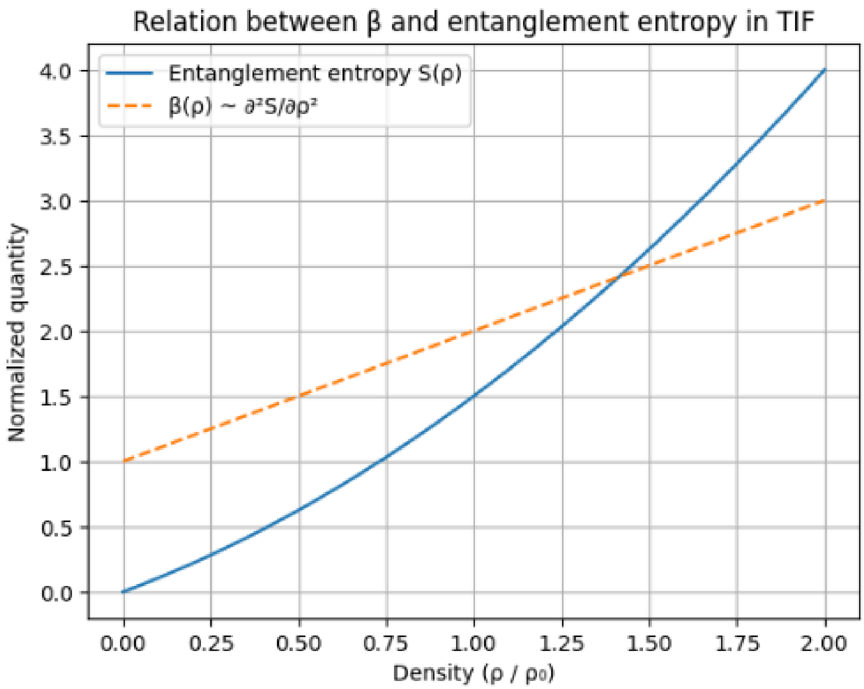


Figure 2 - The curvature of the entropy function governs the nonlinear response of the mass spectrum, linking emergent mass to vacuum entanglement structure.

Possible interpretation of figure 2:

Solid line — *S(ρ)* represents entanglement entropy with nonlinear (convex) growth, indicating an increase in vacuum correlations.

Dotted line — *β(ρ)* or $\beta \sim \frac{\partial^2 S}{\partial \rho^2}$ shows that the curvature of *S* directly controls the nonlinearity of the mass, or that the faster the entanglement grows, the larger the nonlinear term in the mass.

Mass as a Spectral Gap

What does it mean to say that mass is a spectral property? In conventional particle physics, mass is often treated as an intrinsic property of a particle. Within the Standard Model of Particle physics, the Higgs sector is described by a complex scalar doublet ϕ with potential

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

For $\mu 2<0$, the ground state develops a non-zero vacuum expectation value (VEV), $\langle\phi\rangle = v \neq 0$, spontaneously breaking the electroweak symmetry $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$. Gauge bosons acquire masses, while fermions masses arise via Yukawa couplings. This mechanism is the core of the known Higgs mechanism.

In the TIF framework, however, mass is not fundamental. Instead, it is interpreted as a spectral property arising from the underlying dynamics of an informational network. In the Triplet Informational Field framework, the ontological primitive is not a fundamental scalar field but a network of triplet-spin (qutrit-like) degrees of freedom endowed with relational constraints. The vacuum corresponds to a maximally symmetric informational configuration in which no preferred alignment exists in the space of triplet correlations. Within this setting, the Higgs field is reinterpreted as an emergent macroscopic order parameter that denotes a coarse-grained measure of correlation alignment across the informational network. The conventional VEV is then mapped to a global coherence density in the TIF substrate, a measure of symmetry breaking in informational configuration space, and a phase-locking amplitude of triplet correlations. Thus, the Higgs VEV does not represent a field "filling space-time," but rather a condensed phase of the underlying informational geometry.

Prior to symmetry breaking, the informational configuration space is effectively flat: local reconfigurations of the triplet network occur at negligible cost. In this regime, excitations are gapless. Following condensation ($\Phi_{TIF} \neq 0$), the system develops a structured coherence manifold. Perturbations must now deform an ordered background, introducing a finite cost for excitation. This cost defines a spectral gap (Δ), which in TIF is identified with physical mass ($m \equiv \Delta$).

The notion of a spectrum in this case is linked to the concept that any physical system described by a Hamiltonian possesses a set of allowed energy levels, known as its spectrum. These levels correspond to different possible states of the system. Within the TIF framework, the relevant spectrum is that of the underlying informational Hamiltonian. Its eigenvalues represent collective excitation modes of the network.

Under this interpretation, the fermions masses correspond to localized modes whose propagation requires persistent reconfiguration of triplet correlations, and the gauge boson masses correspond to finite correlation lengths induced by the condensed informational phase. The Yukawa couplings encode the strength of coupling between excitations and the coherence background. Mass is therefore not an intrinsic attribute of particles, but the dynamical response of excitations propagating through a symmetry-broken informational medium.

The TIF reinterpretation reframes the Higgs sector as a phase transition in an underlying informational substrate. Meanwhile standard view where a fundamental scalar field acquires a non-zero VEV and generates mass, from the point of TIF view, a pre-space-time informational network undergoes coherence condensation, and the Higgs VEV is the emergent order parameter of this transition. In this sense, the Higgs field is analogous to an order parameter in condensed matter systems, while particle masses correspond to excitation gaps in the spectrum of the underlying informational Hamiltonian.

So we can consider, mass as an excitation threshold, because the vacuum corresponds to the lowest-energy state of the system, where excited states correspond to collective modes built on top of this vacuum, and mass is then identified with the minimum energy required to excite the system, i.e., the difference between the ground state and the first excited state.

In conceptual terms mass is equivalent to the minimal excitation energy of the underlying network, and that gives us another physical interpretation because from this viewpoint shifts the interpretation of particles. Particles are not fundamental objects, but they are collective excitations of a deeper substrate. The mass of a particle therefore reflects how “difficult” it is to excite the underlying structure.

We can establish a useful analogy with a vibrating medium. The medium itself is the fundamental structure, and its vibrational modes correspond to observable excitations.

In this picture different particles correspond to different modes, and their masses correspond to the frequencies of these modes.

Interpreting mass as a spectral gap has several important consequences. It naturally explains why mass depends on the state of the environment, and it links mass generation to collective dynamics, providing a bridge between microscopic structure and observable quantities. Mass is not a primitive property of particles, but becomes a manifestation of the spectrum of an underlying dynamical system.

This perspective is consistent in structure, though not in ontology, with the original works on spontaneous symmetry breaking and gauge mass generation, with Peter Higgs (1964) work in symmetry breaking and scalar field condensation, or with François Englert & Robert Brout (1964) facing gauge boson mass via vacuum structure, or with the electroweak unification with Steven Weinberg (1967), and gauge symmetry and mass generation with Abdus Salam (1968). More recently and experimentally, the discovery of the Higgs boson by the CERN collaborations ATLAS and CMS (2012) confirms the existence of a scalar excitation associated with this order parameter.

Thus, the Higgs vacuum expectation value (VEV) is reinterpreted as the generator of spectral gaps in the excitation spectrum of a condensed informational substrate, providing a direct bridge between symmetry breaking and the emergence of mass in the TIF framework.

Entanglement and Geometry in TIF

Can geometry emerge from information? In several modern approaches to fundamental physics, space-time geometry is not taken as a primary ingredient, but as an emergent structure arising from more fundamental degrees of freedom (Rovelli, 2004; Van Raamsdonk, 2010; Verlinde, 2011). Within the TIF framework, this role is played by the entanglement structure of the underlying informational network. Entanglement is seen as a "structure" that quantifies how different parts of a system are correlated at the quantum level. Rather than being a secondary feature, it can be viewed as defining the relational structure of the system. In TIF framework, the network of correlations is not embedded in space-time, but instead, it gives rise to it. If correlations between elements of the network are interpreted as links, then patterns of entanglement define an effective notion of distance strongly correlating regions behave as if they are "*close*", and weakly correlated regions behave as if they are "*far apart*". In this way, geometry emerges from the structure of correlations and can establish a connection to curvature.

Changes in entanglement are not uniform. Variations in the correlation structure lead to distortions in the emergent geometry, which can be interpreted as curvature. Thus uniform entanglement induces flat geometry, and non-uniform entanglement a curved geometry. From this point of view emerges a link to the defined physical observables.

Once within the TIF framework, this structure is not merely geometric but dynamical, and the entanglement determines geometry that influences the spectrum of excitations, that determines observable quantities such as mass. This establishes a chain:

Entanglement

↓

Geometry

↓

Spectrum

↓

Higgs field (order parameter of the vacuum)

↓

Mass

↓

Observable (B)

correlated with a new coefficient, already seen. The coefficient κ, introduced as the sensitivity of the spectral gap to changes in entanglement, acquires a geometric meaning in this context. It measures how strongly variations in the emergent geometry affect the spectrum, and therefore the mass of excitations. From here we can derive some conceptual pictures.

The Higgs field does not create mass from nothing. It mediates the coupling between the spectral structure of the vacuum and observable particle excitations. Within the TIF framework, the Higgs field can be interpreted as an effective order parameter of the vacuum, mediating the coupling between the underlying spectral structure and observable particle masses. In this view, mass does not originate solely from the Higgs mechanism, but from a deeper informational substrate encoded in the network.

As seen before, the Higgs VEV (non-zero Vacuum Expectation Value) is the global measure of how strongly the informational network has condensed into a symmetry-broken phase, and the mass spectrum is the local response of excitations to that condensed background.

We can think of the Higgs VEV as the *point where the informational medium stops being "flat" in its internal configuration space and develops a preferred direction of stability*. That "preference" is exactly what our spectral-gap picture is trying to capture in physical terms. In the TIF language, the underlying triplet-spin network has a large space of possible reconfigurations, and states can be reshuffled with little energetic or informational cost when the system is symmetric. In that regime, excitations are effectively gapless because there is no intrinsic scale that resists deformation of the configuration. This is the "pre-Higgs" phase in conceptual terms, highly symmetric, highly fluid, and essentially scale-free in its internal reorganization dynamics. The Higgs VEV marks the moment when that symmetry is no longer neutral in practice. The network collectively "chooses" a stable bias in its configuration space, an emergent alignment of correlations that becomes self-sustaining. Once that happens, the system is no longer indifferent to perturbations, and certain reconfigurations now cost a finite amount of informational "effort" to produce. That cost is what you are calling the spectral gap.

So in this framing we have two situations:

i. Before the VEV: reconfiguration is cheap and excitations are effectively massless because the informational geometry is flat.

ii. After the VEV: the vacuum itself carries structure and excitations must "climb out" of a stabilized coherence background.

Mass, then, is not something added onto particles. It is what it *feels like* for an excitation to propagate through a medium that has already undergone symmetry selection.

So the spectral gap is not independent of the VEV. It is its dynamical footprint. The larger the VEV-induced coherence bias in the underlying TIF substrate, the more the network resists local reconfiguration and the larger the effective gap seen by propagating excitations. A useful intuition is to picture the Higgs phase as turning an initially "flat informational liquid" into a "structured elastic medium." In a liquid, disturbances spread freely; in an elastic medium, disturbances always require finite energy to deform the structure. That required deformation energy is precisely what your mass-as-gap picture is encoding.

In the TIF framework, the Higgs vacuum expectation value (VEV) is reinterpreted as a macroscopic order parameter describing the condensation of symmetry in an underlying triplet-spin informational substrate. This condensation transforms a previously flat configuration space into a structured coherence manifold. The emergence of this structured background induces a finite energetic cost for local excitations, which manifests as a spectral gap in the effective excitation spectrum. Particle mass is therefore understood not as an intrinsic property of excitations, but as the dynamical response of informational disturbances propagating through a symmetry-broken coherent medium.

One may think of space-time as a flexible structure whose shape is determined by the pattern of correlations in an underlying network. Matter and "geometry" are then not independent entities, but different manifestations of the same informational substrate, and "geometry" is not fundamental because it emerges from the entanglement structure of the underlying network, and directly influences the physical properties of matter.

Taken together, these three perspectives outline a coherent hierarchy: nonlinear mass behavior reflects spectral properties, which in turn emerge from the entanglement structure of an underlying informational network. In this view, mass, "geometry", and correlations are not independent ingredients, but different manifestations of the same underlying substrate.

A brief insight into a philosophical synthesis

The formal developments presented in this work suggest that mass, symmetry breaking, and field dynamics may be understood as emergent features of an underlying informational substrate. While this framework is constructed within the language of modern theoretical physics, it resonates with longstanding philosophical attempts to describe the transition from undifferentiated potential to structured reality.

A particularly suggestive parallel arises when considering the role of the Higgs field as an order parameter. In the Standard Model, the non-zero vacuum expectation value of the Higgs field marks the transition from a symmetric phase to a structured phase in which particles acquire mass. This transition is mathematically described as spontaneous symmetry breaking, but conceptually it represents a deeper shift, from indistinguishability to differentiation, from potentiality to form.

Analogous structures appear in philosophical traditions. In the context of the Upanishads, the notion of *anthakarana* describes an intermediate principle mediating between pure, undifferentiated consciousness and the structured domain of experience. While this concept belongs to a metaphysical framework distinct from physics, a structural analogy can be drawn, because both describe a mediating layer through which an underlying unity becomes articulated into differentiated forms.

Within the TIF framework, this mediating role is made explicit. The informational network defines a pre-physical substrate, and its global order parameter, identified with the Higgs field, establishes the baseline coherence from which local excitations acquire mass. In this sense, the Higgs mechanism may be interpreted as a physical instantiation of a more general principle like the emergence of structure through the establishment of order in an underlying medium.

This perspective aligns with broader conceptual developments in theoretical physics. For instance, the implicate order proposed by David Bohm suggests that observable phenomena unfold from a deeper, enfolded level of reality. Similarly, the "*it from bit*" paradigm advanced by John Archibald Wheeler emphasizes the primacy of informational structure in the constitution of physical reality.

In each of these approaches, a common theme emerges. The fundamental layer of reality is not composed of objects, but of relations, structures, or informational patterns, from which objects and properties arise as secondary features.

From this standpoint, the emergence of mass can be understood as a two-stage process:

i. Global ordering (Higgs-like mechanism):

Establishment of a coherent background state, defining scale and enabling local differentiation.

ii. Collective structuring (QCD/TIF mechanism):

Formation of stable, nonlinear collective modes that dominate the observed mass spectrum.

This dual structure (so dear to the dualism of Vedic philosophical thought and others hermetic traditions) reflects a hierarchy of emergence, in which local properties are conditioned by global order, and global order itself arises from deeper relational dynamics.

Finally, one may reinterpret traditional metaphysical notions, such as the "*descent of spirit into matter*", in purely structural terms. Rather than implying a literal metaphysical transition, this can be understood as the progressive concretization of relational structure into stable, measurable physical form. Within the TIF framework, this corresponds to the transition: informational substrate ⟶ ordered vacuum ⟶ massive excitations. Thus, the emergence of mass is not merely a dynamical feature of quantum fields, but a manifestation of a deeper principle meaning the transformation of abstract relational structure into concrete physical reality.

Conclusion

The convergence of experimental results and QCD theory strongly supports the interpretation of mass as a vacuum-dependent phenomenon. The TIF framework generalizes this insight by proposing that the vacuum itself is informational in nature.

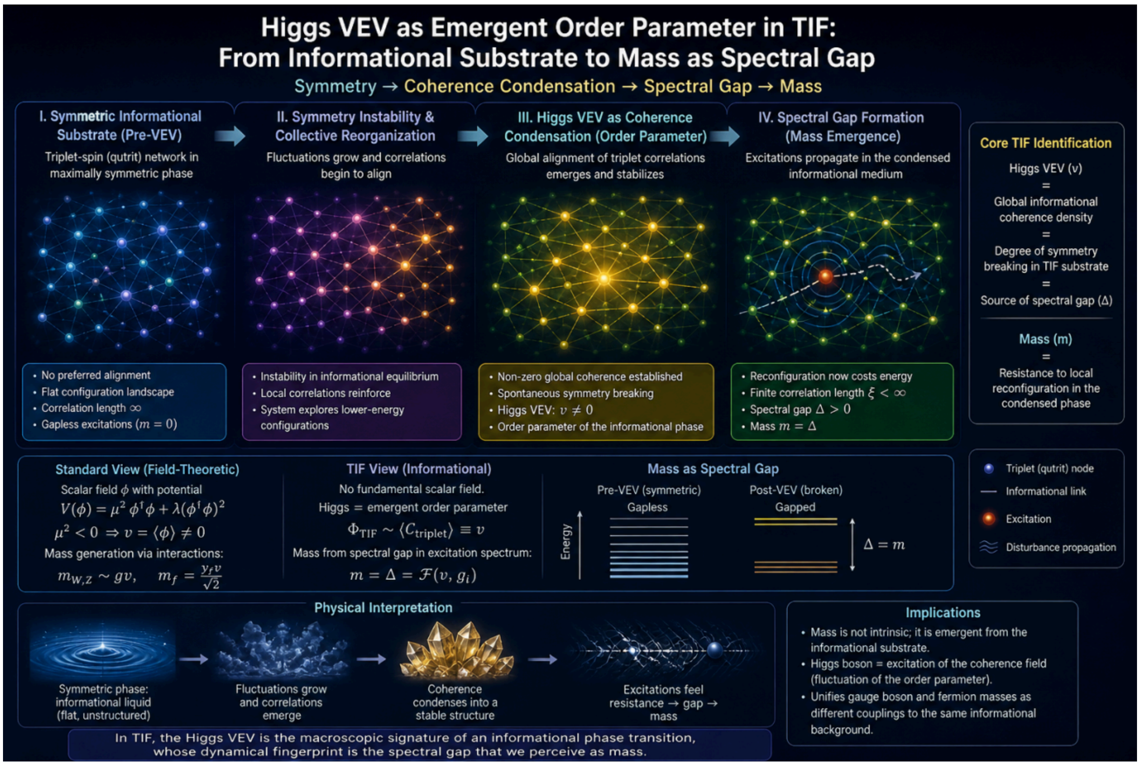
This provides a conceptual bridge between quantum field theory, quantum information, and emergent space-time approaches.

Mass is not a fundamental intrinsic property but a collective phenomenon emerging from the structure of the quantum vacuum? Experimental evidence from meson-nucleus systems supports this view, while QCD provides the formal mechanism through condensates and anomalies. The TIF framework extends this interpretation, suggesting that mass corresponds to stable informational modes of a fundamental network underlying physical reality.

This work presents a novel synthesis of experimental results on in-medium hadronic mass modification, the theoretical structure of QCD, and an original informational framework (TIF). We argue that mass is best understood as an emergent collective property of the quantum vacuum, and we provide a formal extension of this concept within an informational ontology.

The manuscript aims to contribute to ongoing discussions on the origin of mass, quantum vacuum structure, and the interface between quantum field theory and quantum information. We believe that the discussion of in-medium meson mass shifts (GSI experiments) provides a legitimate physical anchor, which prevents the work from being purely speculative.

Symbolic Infographic Resume



Notes

[1] Experimental facilities such as the GSI Helmholtzzentrum für Schwerionenforschung and its upgrade Facility for Antiproton and Ion Research provide a unique platform to probe in-medium modifications of hadronic masses, offering a potential testbed for the nonlinear density dependence predicted within the TIF framework.

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APPENDIX

Notation and Definitions

This section establishes the notation used throughout this work and introduces the correspondence between the standard quantum field theoretic (QFT) framework and the Triplet Informational Field (TIF) interpretation.

Higgs sector and symmetry breaking

Let ϕ denote the scalar field associated with the Higgs mechanism, represents the degree of freedom that undergoes a symmetry breaking, witch its dynamics are governed by the potential given by $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$, where $\mu^2 \in \mathbb{R}$ is equivalent to mass parameter controlling symmetry stability, and $\lambda>0$ is the self-coupling constant ensuring boundedness of the potential. For $\mu^2<0$, the vacuum develops a non-zero expectation value (VEV) $v \equiv \langle\phi\rangle \neq 0$, which defines the electroweak symmetry breaking scale. In TIF interpretation $v \leftrightarrow \Phi_{TIF}$ where Φ_{TIF} denotes the global coherence order parameter of the underlying informational substrate, μ^2 represents the instability of the symmetric state. For instance λ that represents the Higgs quartic coupling that controls the stiffness of the potential, in the TIF framework is the "stiffness" of coherence (how stable the condensed phase is).

Mass and spectral gap

In the standard formulation, particle masses arise via coupling to the Higgs field:

$$m_f = \frac{y_f v}{\sqrt{2}}, \qquad m_W \sim \frac{gv}{2}, \qquad m_Z \sim \frac{\sqrt{g^2 + g'^2}}{2} v.$$

In the TIF framework, mass is reinterpreted as a spectral gap where $m \equiv \Delta$, where Δ represents the minimal excitation energy above the ground state of the informational network. Thus, mass corresponds to the energetic cost of local reconfiguration in a symmetry-broken coherent phase. It is the cost of informational reconfiguration.

Couplings and interaction parameters

The two parameters are g, g' that are gauge coupling constants associated with $SU(2)_L$ and $U(1)_Y$, and y_f is the Yukawa coupling for fermion f. Determines the mass of fermions. Instead, from the TIF interpretation we assume g, g' as coupling strength between excitations and the informational background and y_f as a degree of coupling between localized modes and coherence structure. Determines the degree of “immersion” of the mode in the background's coherence.

Renormalization and scale dependence

The scale dependence of couplings is encoded in the beta function given by:

$$\beta(g) = \frac{dg}{d \ln \mu},$$

where μ is the renormalization scale, but in TIF formulation β become a scale evolution of informational geometry, i.e., how coherence structure reorganizes across scales of description. Describes how couplings change with scale (renormalization)

Density and electroweak consistency

The parameter ρ is defined as:

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W},$$

where θ_W is the Weinberg angle (a combination of electromagnetic and weak forces). In the Standard Model of particle physics, $\rho \approx 1$ at tree level. Meanwhile in the TIF interpretation ρ works like a consistency constraint on coherence geometry ensuring that the emergent phase preserves internal structural relations (trough rotation among “information bases”).

Table 1 - Little dictionary between QFT and TIF

QFT Quantity	TIF Interpretation
Higgs field ϕ	Effective coherence field
VEV v	Global informational coherence
Mass m	Spectral gap Δ
Yukawa y_f	Coupling to coherence structure
Symmetry breaking	Coherence condensation

Vacuum	Informational ground state

Table 2 — Notation and TIF Correspondence

Notation and correspondence between the standard quantum field theoretic description of the Higgs sector and its reinterpretation within the Triplet Informational Field (TIF) framework. In this approach, the Higgs vacuum expectation value is mapped to a global coherence order parameter, and particle masses are identified with spectral gaps arising from excitations propagating in a symmetry-broken informational medium.

Symbol	Standard Definition (QFT)	TIF Interpretation
ϕ	Complex scalar Higgs field	Effective field describing emergent informational coherence
$V(\phi)$	Higgs potential governing field dynamics	Informational stability landscape of the triplet network
μ^2	Mass parameter in Higgs potential; $\mu^2 < 0$ triggers symmetry breaking	Instability of symmetric informational configuration
λ	Quartic self-coupling of Higgs field	Rigidity (stiffness) of the coherence phase
$v = \langle\phi\rangle$	Vacuum expectation value (VEV) of Higgs field	Global coherence density (order parameter) of TIF
m	Particle mass	Spectral gap: $m \equiv \Delta$
Δ	Energy gap between ground and first excited state	Cost of local informational reconfiguration
g, g'	Gauge coupling constants (electroweak interactions)	Coupling strength between excitations and informational substrate
y_f	Yukawa coupling for fermion f	Degree of coupling of localized modes to coherence background
m_W, m_Z	Masses of electroweak gauge bosons	Gap scales associated with collective excitation modes
θ_W	Weinberg angle (gauge mixing parameter)	Rotation between informational interaction bases
$\beta(g)$	Beta function: $\frac{dg}{d\ln\mu}$, scale dependence of coupling	Evolution of informational structure across scales
μ	Renormalization scale	Resolution scale of the informational network

ρ	Electroweak parameter: $\frac{m_W^2}{m_Z^2 \cos^2 \theta_W}$	Consistency constraint on coherence geometry
$SU(2)_L \times U(1)_Y$	Electroweak gauge symmetry	Symmetry of the pre-condensed informational phase