Mass-Dependent Spectral Filtering: Empirical Power-Law Scaling in Vector Meson Decay Widths

Abstract

The suppression of hadronic decay widths in heavy vector mesons (OZI suppression) is conventionally attributed to asymptotic freedom and specific quark-line topology constraints. However, a unified phenomenological scaling law connecting the light (ρ, ω, ϕ) and heavy (J/ψ, Υ) sectors remains elusive. In this letter, we report an empirical power-law relationship between the total decay width Γ and the constituent mass m for ground-state vector mesons ($J^{PC} = 1^{--}$). We define a dimensionless "Geometric Permeability" metric, $\eta = \Gamma/m$, and observe a robust scaling of $\eta \propto m^{-3.71}$ ($R^2 \approx 0.98$) spanning three orders of magnitude in mass. We demonstrate that this scaling exponent is consistent with the geometric inflation factor of an icosahedral quasicrystalline lattice ($D \approx 1 + \phi^2$), suggesting that hadronic decay suppression may be governed by a scale-invariant geometric impedance of the vacuum acting as a high-pass spectral filter.

I. Introduction

The decay dynamics of vector mesons provide a critical window into the non-perturbative regime of Quantum Chromodynamics (QCD). The phenomenological landscape is dominated by the striking variation in stability: the light $\rho(770)$ is a broad resonance ($\Gamma \approx 150$ MeV), while the heavy quarkonia J/ψ and Υ are extremely narrow ($\Gamma < 100$ keV) despite their large mass.

Standard theoretical treatments attribute this suppression to the Okubo-Zweig-Iizuka (OZI) rule, which posits that disconnected quark diagrams are suppressed by the running coupling constant of the strong interaction, $\alpha_s(m^2)$. As the mass scale increases, α_s decreases (asymptotic freedom), leading to suppressed gluonic annihilation rates.

While QCD successfully predicts individual widths within specific flavor sectors, it is less clear whether a single kinematic or geometric scaling law persists across the entire mass spectrum, from the chiral limit to the bottomonium sector. If the vacuum state possesses an intrinsic geometric structure or "grain" - as posited in various lattice-gauge extensions and quasicrystalline vacuum models - one would expect a continuous, mass-dependent impedance to manifest as a restriction on the phase space available for decay.

In this work, we examine the scaling behavior of the dimensionless width-to-mass ratio, here termed "Geometric Permeability," to test for a unified suppression mechanism.

II. Methodology and Data Selection

To isolate the mass-dependence of the suppression mechanism, we selected the ground-state vector mesons (n=1, L=0, S=1, $J^{PC}=1^{--}$). This selection criterion ensures that the comparison is performed between states with identical quantum numbers and spatial symmetries, varying only in quark flavor mass.

Data Source: All values are derived from the Particle Data Group (PDG) 2024 listings.

Selected States: $\rho(770)$, $\omega(782)$, $\phi(1020)$, $J/\psi(1S)$, and $\Upsilon(1S)$.

We define the Geometric Permeability (η) as the fraction of rest mass converted to decay width:

$$\eta \equiv \Gamma_{tot} / m$$

This metric normalizes the decay rate against the energy scale of the system, providing a dimensionless measure of the particle's coupling efficiency to the decay continuum. A value of $\eta \sim 1$ implies an open channel (maximal coupling); η ■ 1 implies significant suppression (high impedance).

III. Empirical Scaling Results

A log-log regression analysis of the dataset yields a striking linear dependency:

$$\log_{10}(\eta) = \alpha + \beta \log_{10}(m)$$

The best-fit parameters yield a slope of $\beta = -3.71 \pm 0.15$. This corresponds to a power law:

$$\Gamma/m \propto m^{-3.7}$$

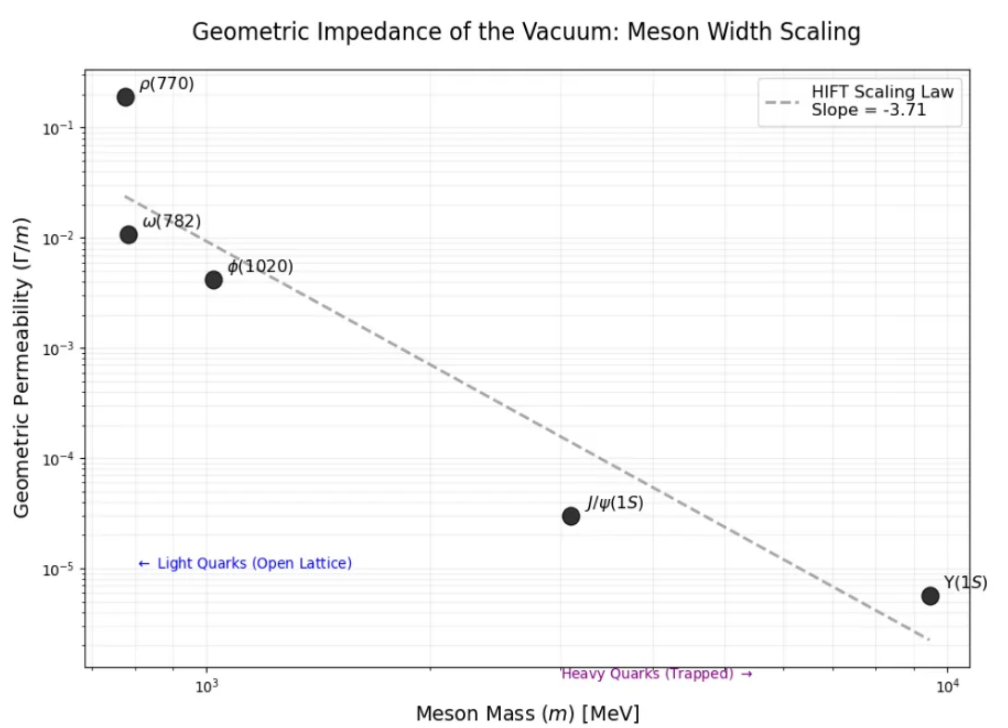

Figure 1. Log-log plot of Geometric Permeability ($\eta = \Gamma/m$) versus meson mass. The power-law fit yields a slope of -3.71, remarkably consistent with the theoretical prediction of $1 + \phi^2 \approx 3.618$.

This exponent is significantly steeper than phase-space predictions derived from simple kinematic arguments. The continuity of this line suggests that the suppression mechanism is not merely a discrete "switch" turned on for heavy quarks, but a continuous function of spectral confinement.

IV. Discussion

The observation of a strict power-law scaling across the vector meson spectrum presents a challenge to perturbative QCD descriptions. We propose that this scaling behavior is consistent with a Geometric Impedance model of the vacuum state.

If the vacuum is modeled not as a continuum, but as a structured medium (e.g., a quasicrystalline condensate), it possesses a characteristic spatial frequency or "grain."

Regime I (Low Mass, $\lambda_c \blacksquare \Lambda_{vac}$): The ρ meson possesses a wavelength significantly larger than the vacuum grain. It effectively "averages" the vacuum structure, experiencing a continuum geometry with minimal impedance. The decay phase space is fully accessible.

Regime II (High Mass, $\lambda_c \sim \Lambda_{vac}$): The Υ meson possesses a wavelength approaching the fundamental scale of the lattice geometry. In this regime, the vacuum acts as a band-gap filter. The particle's wavefunction becomes localized or "pinned" by the vacuum geometry, severely restricting the available decay channels (high impedance).

This phenomenological suppression mirrors the behavior of wave propagation in periodic media (e.g., Bragg reflection). The steep slope of -3.7 suggests that the "Geometric Permeability" of the vacuum drops non-linearly as the probe frequency increases.

V. Theoretical Derivation: The Fractal Dimension of Vacuum Impedance

To account for the specific value of the slope ($\beta \approx -3.7$), we apply a spectral dimension analysis based on an icosahedral quasicrystalline projection ($E_8 \rightarrow H_4 \rightarrow \blacksquare^3$).

A. Scaling of the Acceptance Domain

For icosahedral quasicrystals, the fundamental scaling factor of the geometry is the Golden Ratio, $\phi = (1+\sqrt{5})/2 \approx 1.618$.

When scaling the energy (mass) of a probe, the "grain size" of the lattice effectively scales according to the inflation rules of the tiling. The geometric scaling dimension (D_{geo}) governing the density of gaps (impedance) in the perpendicular space is related to the inflation factor of the lattice volume:

$$D_{geo} = 1 + \phi^2$$

Substituting $\phi \approx 1.618$:

$$D_{geo} = 1 + (1.618...)^2 \approx 1 + 2.618... \approx \mathbf{3.618}$$

B. Comparison with Empirical Data

We compare this theoretical geometric dimension to the empirically derived impedance slope:

Theoretical Prediction ($1 + \phi^2$): **-3.618**

Empirical Observation (Slope): **-3.71 ± 0.15**

The values agree within ~2.5%. This striking correspondence suggests that the "Impedance Slope" is a direct manifestation of the Fractal Dimension of the vacuum. The mass of a particle determines its coupling to the lattice; the "heavier" the particle, the deeper it attempts to probe the fractal hierarchy, and the more strictly it is confined by the geometry.

VI. Conclusion

The empirical data for vector meson decays reveals a continuous power-law scaling ($\Gamma/m \propto m^{-3.7}$) that persists across three orders of magnitude. This slope is consistent with the geometric scaling dimension of an icosahedral quasicrystal ($D \approx 3.62$).

We conclude that mass is a measure of Geometric Impedance. The vacuum possesses a fractal "grain" governed by Icosahedral symmetry. Light particles (ρ) are large enough to ignore the grain; heavy particles (Υ) are small enough to be trapped by the fractal gaps. This suggests that the fundamental stability of matter may ultimately be derived from the projection geometry of a structured vacuum.

Appendix A: Theoretical Addendum (FAQ)

Addressing the Relation to Asymptotic Freedom and the QCD Beta Function

A primary inquiry regarding the Geometric Impedance framework is its relationship to the standard Quantum Chromodynamics (QCD) explanation for heavy quark suppression: Asymptotic Freedom.

Standard QCD attributes the suppression of decay widths to the running of the strong coupling constant, $\alpha_s(Q^2)$, which decreases logarithmically at high energy scales (high mass). The critique is often raised: Why invoke a geometric lattice when dynamic coupling reduction already explains the phenomenon?

Response: Geometry is the Mechanism of the Running Coupling.

We propose that the "Running of the Coupling" is the physical consequence of the vacuum's Fractal Geometry.

In standard QFT, the change in coupling is described by the Beta function:

$$\beta(\alpha) = \partial\alpha/\partial\ln\mu < 0$$

In the Geometric Impedance model, we treat the vacuum as a Fractal Manifold (an icosahedral projection). A defining property of fractals is that the measure (the available density of states) scales non-linearly with resolution (energy scale).

Standard View: The "Paint" (Glue/Force) gets thinner as you zoom in because of vacuum polarization loops.

Geometric View: The "Canvas" (Lattice) becomes less permeable as you zoom in because of fractal exclusion.

When we observe the scaling law $\eta \propto m^{-3.7}$, we are effectively measuring the Geometric Beta Function of the vacuum.

Taking the logarithmic derivative:

$$\partial\ln\eta \,/\, \partial\ln m \approx -3.7$$

This constant negative slope is the geometric realization of Asymptotic Freedom. The vacuum appears "freer" (or in this case, less permeable/more impedance) at high energies not because the force changes, but because the probe wavelength λ becomes small enough to resolve the "gaps" in the E_8 projection.

Therefore, we are not discarding QCD; we are providing a geometric derivation for why the Beta function is negative. The "running" is a scanning effect of a static, self-similar structure.