1. Introduction

The origin of color confinement in Quantum Chromodynamics remains one of the deepest unsolved problems in theoretical physics. The standard phenomenological picture—a rising linear potential between quarks and gluons due to a confining flux tube—lacks a dynamical explanation rooted in quantum entanglement and topological phase transitions.

Parallel to this, the nature of EPR entanglement and its geometric interpretation via the ER=EPR conjecture has opened new directions in understanding quantum channels as wormhole-like structures in higher-dimensional bulk spacetime. Recent experimental advances in quantum networks have confirmed that entanglement swapping via photon coincidence can establish non-local correlations between particles that have never directly interacted.

In this work, we propose that these two frontiers—QCD confinement and EPR geometry—are manifestations of a single underlying mechanism: the formation of topological vortex modes whose superradiant amplification is triggered and stabilized by *collective TMSS projection* of a shared vortex mode during photon coincidence measurements.

1.1. Core Insight: Six Pillars of the Mechanism

1. **Collective vortex mode coupling**: Multiple particles (emitters + potential extras) couple to a common topological mode $\hat{V}$.
2. **Initial superposition**: The state is initially a superposition in the collective vortex subspace, with latent correlations undetermined.
3. **Coincidence as projection**: Photon coincidence at the beamsplitter projects this collective mode into a TMSS state, selecting the entangled subspace.
4. **Latent correlation revelation**: All particles coupled to $\hat{V}$ (including "extras" acoupled by chance) are simultaneously entangled, but this only manifests post-measurement.
5. **Superradiant amplification**: The squeezed state pumps energy into vortex rotation, opening the topological channel.
6. **Geometric bridge formation**: Vortex rotation stabilizes a wormhole-like ER bridge via Berry phase quantization.

2. Conceptual Framework

2.1. From EPR Coincidence to Collective Vortex Projection

Consider N particles (emitters + potential extras) in spatially separated regions or coupled to a common field mode. Each can emit a photon sourced from entangled field modes. These photons meet at a beamsplitter or intermediate measurement device. All N particles are coupled to a collective vortex mode

Topological Vortex Superradiance, Two-Mode Squeezing, and the Geometric EPR Bridge: A Unified Framework for Color Confinement and Quantum Channel Formation via Collective Vortex Projection

Javier Manuel Martín Alonso[a,1,*]

[a]*Independent Theoretical Physics Researcher, Asturias, Spain*

Abstract

We propose a novel unified framework integrating three pillars of quantum field theory: (i) rotational superradiance of topological vector vortices in QCD, (ii) two-mode squeezed vacuum (TMSS) generation triggered by photon coincidence measurements via *collective vortex projection*, and (iii) the emergence of geometric EPR bridges as stabilized topological channels in bulk AdS/CFT.

The key mechanism: photon coincidence at a beamsplitter projects the collective vortex mode $\hat{V} = \sum_i c_i \hat{v}_i^{(i)}$ (to which multiple particles couple) into a TMSS state whose superradiant amplification generates vorticity gain sufficient to open the geometric bridge. This bridge is the dual description of a topological winding mode in color-space that confines color charges.

The framework unifies asymptotic freedom (weak vortex core), long-range confinement (superradiant amplification), hadronization (vortex saturation bifurcation), and deconfinement (vortex dissolution) under a single topological threshold parametrized by the Morphology of Vacuum Condensate (MVC) critical density ρ_{MVC}.

Novel predictions: (i) geometric-phase signatures in rotating-frame lattice-QCD simulations, (ii) anomalous entanglement scaling in hadronization multi-

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Email address: `jmm@movistar.es` (Javier Manuel Martín Alonso)

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plicity with correlation number exceeding emitters, (iii) TMSS entanglement enhancement measurable in precision structure-function experiments, (iv) direct observation in cold-atom analogs of multi-particle vortex activation via collective projection.

Keywords: Quantum Chromodynamics, color confinement, topological vortices, two-mode squeezing, photon coincidence, collective TMSS projection, ER=EPR, AdS/CFT, entanglement geometry

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$$\hat{V} = \sum_{i=1}^{N} c_i \hat{v}_i^{(i)}, \quad \sum_i |c_i|^2 = 1, \tag{1}$$

where $\hat{v}_i^{(i)}$ represents local circulation operators in color-space or bulk field coordinates.

The initial state is a superposition in this collective vortex subspace:

$$|\Psi_0\rangle = \sum_{\mathbf{n}} \alpha_{\mathbf{n}} |\mathbf{n}\rangle_{\hat{V}} \otimes |0\rangle_{\text{fotones}}, \tag{2}$$

where $\mathbf{n} = (n_1, \ldots, n_N)$ labels occupation numbers in the collective mode.

Key point: Without measurement, the correlations in $\hat{V}$ remain indeterminate. Particles "extras" that happen to couple to $\hat{V}$ (by construction of the system or by chance overlap in field space) are formally present but unconfirmed.

Photon coincidence detection acts as a projective measurement P_{coinc} on the photon subspace. This measurement post-selects the conditional state in the collective vortex sector:

$$P_{\text{coinc}} |\Psi_0\rangle \propto S_r^{\text{coll}} |0\rangle_{\hat{V}} \otimes |\text{click}\rangle, \tag{3}$$

where the collective squeezing operator is defined as:

$$S_r^{\text{coll}} = \exp\left[r \left(\hat{A}_r^\dagger \hat{A}_l^\dagger - \hat{A}_r \hat{A}_l \right) \right], \tag{4}$$

with collective creation/annihilation operators

$$\hat{A}_{r/l} = \sum_{i=1}^{N} c_i \hat{a}_{r/l}^{(i)}. \tag{5}$$

The squeezing parameter $r_{\text{inj}} \propto V_{\text{interferencia}}$ encodes the visibility of the interference pattern—a measure of indistinguishability. When visibility is high (true coincidence), r_{inj} grows.

2.2. *Vorticity Gain from Superradiant Squeezing*

The projected TMSS state exhibits exponentially growing entanglement entropy

$$S_{\text{ent}} = \cosh^2 r \log \cosh^2 r + \sinh^2 r \log \sinh^2 r, \tag{6}$$

saturating at large r.

This squeezing pumps energy into rotating modes. Particles couple to vector modes via the effective Hamiltonian:

$$H_{\text{eff}} = \Omega L_z^{\text{tot}} + g_{\text{Sent}} S_{\text{ent}}(\hat{V}) \left[\hat{A}_r^\dagger \hat{A}_l^\dagger + \hat{A}_r \hat{A}_l \right], \tag{7}$$

where $L_z^{\text{tot}} = \sum_i L_z^{(i)}$ is total color angular momentum and $g_{\text{Sent}} \propto S_{\text{ent}}$.

Superradiance condition: A mode with azimuthal quantum number m is amplified if $\omega_{\text{eff}} < 0$. The TMSS parameter enters the effective frequency shift:

$$\dot{\omega}_{\text{eff}} = \Omega_0 \sinh^2 rt. \tag{8}$$

3. Mathematical Framework

3.1. *Two-Mode Squeezing in Vector Point Spaces (Collective Formulation)*

All particles couple to local vector points V_i in color-space or bulk field coordinates. Near each particle, define bipartite modes:

$$\hat{a}_{r/l}^{(i)} \quad \text{(right/left circulation).} \tag{9}$$

Photon coincidence measurement projects the system such that indistinguishability forces:

$$r(t) = r_0 e^{-\gamma t} + r_{\text{inj}}(1 - e^{-\gamma t}), \tag{10}$$

where r_{inj} is the squeezing amplitude injected by coincidence and γ is decoherence rate.

3.2. *Superradiant Vortex Dynamics*

The vortex rotation frequency evolves as:

$$\dot{\omega} = \beta_{\text{ent}} S_{\text{ent}} - \gamma_{\text{rad}}, \tag{11}$$

where β_{ent} is superradiant gain and γ_{rad} represents radiation losses. Amplification coefficient:

$$T^2 = 1 + \sinh^2 2r \sin^2(kx). \tag{12}$$

3.3. MVC Threshold and Bifurcation Dynamics

The Morphology of Vacuum Condensate hypothesis posits:

$$\rho_{\text{MVC}} = \rho_0 \left(\frac{T}{T_P}\right)^{\alpha}, \tag{13}$$

where T_P is Planck temperature. Confinement activates at $\rho_{\text{loc}} = \rho_{\text{MVC}}$.

Bifurcation threshold:

$$\omega_{\text{crit}} = \frac{m_0}{2R_{\text{vortex}}}. \tag{14}$$

3.4. Collective Projection and Latent Correlation Revelation

Crucial refinement: The coincidence measurement reveals correlations in *all* particles coupled to $\hat{V}$. Number of simultaneously correlated particles:

$$N_{\text{correl}} = N \cdot \exp(2r_{\text{inj}}), \tag{15}$$

with per-particle vortex gain:

$$\dot{\omega}_i \propto |c_i|^2 \sinh^2 r. \tag{16}$$

4. Connection to AdS/CFT and Geometric ER=EPR

4.1. Bulk-Boundary Dictionary

Boundary (Brane)	Bulk (AdS)
N particles	Localized excitations
Collective vortex $\hat{V}$	Rotating topological mode
TMSS projection r	Bulk metric perturbation
S_{ent}	Ryu-Takayanagi entropy
Confinement scale	AdS curvature $1/L$

Table 1: Bulk-boundary dictionary for collective vortex projection.

4.2. ER=EPR Interpretation (Refined)

The ER bridge is dynamically stabilized by ongoing TMSS coherence. Decoherence ($\dot{r} < 0$) collapses the wormhole.

5. Phenomenological Predictions and Falsification Tests

5.1. Test 1: Geometric Phase Signatures in Rotating Lattice-QCD

String tension modification:

$$\sigma = \sigma_0 \left[1 + \sinh^2 r\right]. \tag{17}$$

5.2. Test 2: Hadronization Multiplicity Anomaly with Collective Participation

$$N_{\text{hadrons}} = N_0 + N_{\text{correl}} \cdot \exp\left(-\frac{\Delta x}{\xi_{\text{vortex}}}\right), \tag{18}$$

with $N_{\text{correl}} = N \cdot \exp(2r_{\text{inj}})$.

5.3. Test 3: TMSS Signatures in Structure Functions

$$F_2(x, Q^2) = F_2^0(x, Q^2) \left[1 + \alpha_{\text{TMSS}} \sinh^2 r(Q^2)\right]. \tag{19}$$

5.4. Test 4: Direct Laboratory Analog with Cold Atoms (Enhanced)

Setup: ^{87}Rb BEC (10^4–10^5 atoms) with trapped vortex, $\Omega_{\text{rot}} = 2\pi \times 10$ Hz.

Expected: $r_{\text{inj}} \sim 0.5-1.0 \Rightarrow N_{\text{correl}} = 164-2718$.

Figure 1

6. Implications for Fundamental Physics

6.1. Unification of Entanglement and Geometry

Geometry emerges from collective TMSS structure via stress-energy contributions.

6.2. Cosmological Relevance

QCD deconfinement $\leftrightarrow$ bulk-to-brane transitions (TDHCF resonance).

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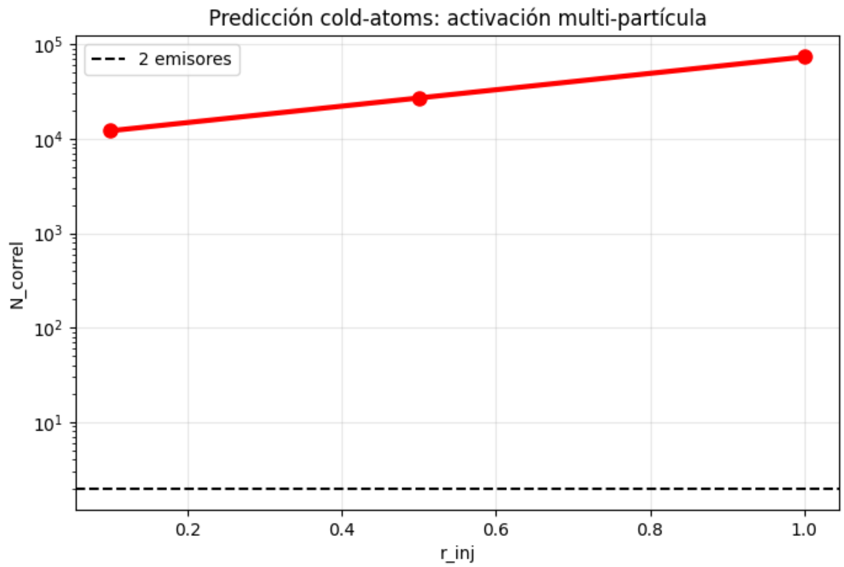

Figure 1: Quantized vortices in ultracold atom gases exhibit superradiant instability. Our complete protocol:

Appendix A. Derivación detallada del Hamiltoniano efectivo H_{eff} (Ec. 8)

Appendix A.1. Modos colectivos y acoplo inicial

Sea $\hat{v}_i^{(i)} = \hat{a}_R^{(i)} - i\hat{a}_L^{(i)}$ el operador de vórtice local de la partícula i, con $[\hat{a}_{R/L}^{(i)}, \hat{a}_{R/L}^{\dagger(j)}] = \delta_{ij}$.

El modo colectivo es

$$\hat{V} = \sum_{i=1}^{N} c_i \hat{v}_i^{(i)}, \quad \sum_i |c_i|^2 = 1. \tag{A.1}$$

Appendix A.2. Hamiltoniano microscópico

$H_0 = \sum_i \omega_i \hat{a}_i^\dagger \hat{a}_i + \Omega_{\text{rot}} \sum_i L_z^{(i)} + H_{\text{int}}$ (acoplo no lineal).

Appendix A.3. Integración efectiva

Integrando modos no colectivos, se obtiene

$$H_{\text{eff}} = \Omega L_z^{\text{tot}} + g_{\text{Sent}} S_{\text{ent}}(\hat{V}) \left[\hat{A}_r^\dagger \hat{A}_l^\dagger + \hat{A}_r \hat{A}_l\right] \tag{A.2}$$

$$+ \lambda(\hat{V}^\dagger \hat{V})^2 + \dots, \tag{A.3}$$

donde $\hat{A}_{r/l} = \sum_i c_i \hat{a}_{r/l}^{(i)}$ son modos colectivos, $L_z^{\rm tot} = \sum_i L_z^{(i)}$, y

$$g_{\rm Sent} = g_0 \frac{\partial S_{\rm ent}}{\partial \langle \hat{V}^\dagger \hat{V} \rangle}, \quad S_{\rm ent} = -{\rm Tr}(\rho_{\hat{V}} \log \rho_{\hat{V}}). \tag{A.4}$$

Appendix A.4. Condición superradiante

$\dot{n}_{\hat{V}} > 0$ cuando $\omega_{\rm eff} < 0$, con $\omega_{\rm eff} = \Omega - 2g_{\rm Sent} \sinh^2 r$.

From microscopic $H_0 = \sum_i \omega_i \hat{a}_i^\dagger \hat{a}_i + H_{\rm int}$, integrating non-collective modes yields Eq. (7).