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
Independent Theoretical Physics Researcher, Asturias, Spain
jmmammovistar.es
January 2026

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** (not antiphoton mediation), and (iii) the emergence of geometric EPR bridges as stabilized topological channels in bulk AdS/CFT.

The key mechanism: photon coincidence at a beamsplitter does not require antiphoton propagation. Instead, the loss of which-path information projects the collective vortex mode $\hat{\mathbf{V}}$ (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 multiplicity 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.

---

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.

The key innovation is replacing the "antiphoton mediator" picture with a **quantum projective measurement framework**: coincidence does not send mediators; rather, it projects a collective vortex mode shared by all acoupled particles into a TMSS state, revealing and amplifying latent entanglement.

1.1 Core Insight

1. **Collective vortex mode coupling**: Multiple particles (emitters + potential extras) couple to a common topological mode $\hat{V} = \sum_{i=1}^{N} c_i \hat{v}_i^{(i)}$.
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.

Initial state: All N particles are coupled to a collective vortex mode

$$\hat{V} = \sum_{i=1}^{N} c_i \hat{v}_i^{(i)},$$

where $\hat{v}_i^{(i)}$ represents local circulation operators in color-space or bulk field coordinates, with normalization $\sum_i |c_i|^2 = 1$.

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

$$|\Psi_0\rangle = \sum_{\mathbf{n}} \alpha_{\mathbf{n}} |\mathbf{n}\rangle_{\hat{V}} \otimes |0\rangle_{\text{photons}} + \dots,$$

where $\mathbf{n} = (n_1, n_2, \dots, n_N)$ labels occupation numbers in the collective mode.

Key point: Without measurement, the correlations in $|\Psi_0\rangle$ 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.

2.2 Coincidence Measurement and Collective TMSS Projection

Photon coincidence detection acts as a projective measurement P_{coinc} on the photon subspace. This measurement does not send signals to the particles; instead, it **post-selects** the conditional state in the collective vortex sector.

Post-selection condition: The click indicates that the two emitted photons were indistinguishable (loss of which-path information). By the rules of quantum mechanics, this projects the shared field modes and all particles coupled to $\hat{V}$ into an entangled state.

Formally:

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

where the collective squeezing operator is defined as:

$$S_r^{\text{coll}} = \exp\left(r_{\text{inj}} \left(\hat{a}_r^\dagger \hat{a}_l^\dagger - \hat{a}_r \hat{a}_l\right)\right), \quad [\hat{a}_r, \hat{a}_l^\dagger] = 1. \quad (1)$$

Here, $\hat{a}_r$ and $\hat{a}_l$ are **collective creation/annihilation operators** for right and left circulating modes of the vortex $\hat{V}$:

$$\hat{a}_r = \sum_i c_i \hat{a}_r^{(i)}, \quad \hat{a}_l = \sum_i c_i \hat{a}_l^{(i)}.$$

The squeezing parameter

$$r_{\text{inj}} \propto V_{\text{interferance}}, \quad (2)$$

encodes the visibility of the interference pattern—a measure of indistinguishability. When visibility is high (true coincidence), r_{inj} grows.

2.3 Resulting TMSS State and Collective Entanglement

The projected state after coincidence is:

$$|\mathrm{TMSS}\rangle_r^{\mathrm{coll}} = S_r^{\mathrm{coll}}|0\rangle_{\hat{V}} = \cosh r_{\mathrm{inj}}|0,0\rangle + \tanh r_{\mathrm{inj}}|1_r, 1_l\rangle + \tanh^2 r_{\mathrm{inj}}|2_r, 2_l\rangle + \ldots$$

The entanglement entropy of this collective TMSS state is:

$$S_{\mathrm{ent}}^{\mathrm{coll}}(r) = \cosh^2 r \log \cosh^2 r - \sinh^2 r \log \sinh^2 r, \quad (4)$$

which grows exponentially with r_{inj} and saturates at large r_{inj}.

Critical observation: This TMSS state acts on **all** particles i with $c_i \neq 0$. If there are N particles coupled to $\hat{V}$ (emitters + potential extras), they **all become entangled simultaneously** via this collective projection. Before measurement, it was indeterminate whether extras were coupled; after the click, they are confirmed to participate.

2.4 No Antiphoton Propagation: Energy and Coherence in Squeezing

The key departure from standard pictures: there are **no antiphotons traveling back** to mediate the entanglement. Instead:

1. **Vacuum fluctuation transformation**: Squeezing is a unitary transformation of vacuum fluctuations in the collective mode $\hat{V}$. It does not require external energy injection at the beamsplitter.
2. **Energy source**: The energy cost of squeezing is extracted from the **rotating frame** (the vortex rotation, color angular momentum L_z, or effective pump in the bulk AdS dual). As the vortex rotates faster, it supplies energy for squeezing amplification—this is the superradiant coupling.
3. **Coherence and bookkeeping**: The collective TMSS state maintains global energy bookkeeping: energy gained in squeezing = energy lost in vortex rotation. There is no "free lunch."

---

3. Mathematical Framework

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

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

$$\hat{a}_r^{(i)}, \hat{a}_l^{(i)},$$

representing right and left circulation directions in color-space or rotational directions in the vortex frame.

The collective vortex mode aggregates these:

$$\hat{V} = \sum_{i=1}^{N} c_i \hat{v}_i^{(i)}, \quad \hat{a}_r = \sum_i c_i \hat{a}_r^{(i)}, \quad \hat{a}_l = \sum_i c_i \hat{a}_l^{(i)}. \quad (5)$$

Photon coincidence measurement projects the system such that indistinguishability forces a unitary squeezing:

$$r(t) = r_0 e^{-\gamma t} + r_{\text{inj}}(1 - e^{-\gamma t}), \qquad (6)$$

where r_{inj} is the squeezing amplitude injected by coincidence (proportional to interference visibility) and γ is a decay rate due to decoherence.

The TMSS entanglement entropy grows as:

$$S_{\text{ent}}(r) = 2\left[\cosh^2 r \log \cosh r - \sinh^2 r \log \sinh r\right]. \quad (7)$$

3.2 Superradiant Vortex Dynamics

In the dual rotating frame, the effective Hamiltonian coupling the collective vortex mode to particles is:

$$H_{\text{eff}} = \Omega L_z + g_{\text{Sent}}(t) S_{\text{ent}}(\hat{V}) \left[\hat{a}_r^\dagger \hat{a}_l + \text{h.c.}\right] - \kappa \hat{a}_r^\dagger \hat{a}_r, \quad (8)$$

where:

- Ω is the vortex base rotation frequency.
- L_z is the collective color angular momentum (or bulk angular momentum in AdS).
- $g_{\text{Sent}}(t)$ is a nonlinear coupling proportional to entanglement entropy of the TMSS state (grows with r_{inj}).
- κ represents radiation damping losses.

The vortex rotation frequency evolves as:

$$\dot{\omega}(t) = \rho_{\text{ent}} \gamma_{\text{SR}} - \kappa, \qquad (9)$$

where:

- $\rho_{\text{ent}} = S_{\text{ent}}(\hat{V})(t)$ is local entanglement density.
- γ_{SR} is superradiant gain coefficient.

Superradiance condition: A mode with azimuthal quantum number m is amplified if $\omega > m\Omega$. The amplification coefficient is:

$$T^2 = 1 + \sinh^2(2r) \sin^2(kx), \qquad (10)$$

where x is spatial separation and k is the wave vector. For matched phase ($kx = \pi/2$), amplification is maximal.

3.3 Berry Phase and Geometric Stabilization

A rotating vortex in the collective color-space/bulk system carries a **geometric (Berry) phase**:

$$\gamma_B = i \oint \langle m | \nabla_{\mathbf{R}} | m \rangle \cdot d\mathbf{R} = m\Omega, \quad (11)$$

where m is the topological winding number of the vortex.

This geometric phase **stabilizes** the vortex trajectory topologically, preventing decay into trivial states. Via holography (AdS/CFT), this winding mode corresponds to a spacetime structure—a wormhole-like Einstein-Rosen (ER) bridge in the dual AdS bulk, whose throat is kept open by the vortex rotation.

3.4 MVC Threshold and Bifurcation Dynamics

The Morphology of Vacuum Condensate (MVC) hypothesis posits a critical density:

$$\rho_{\mathrm{MVC}} = \rho_0 \left(\frac{T}{T_P} \right)^{\delta}, \qquad (12)$$

where T_P is Planck temperature and δ is a universal exponent.

In our framework, confinement activates when local color-charge density reaches ρ_{MVC}. At this point, the vortex rotation frequency reaches a bifurcation threshold:

$$\omega_{\mathrm{crit}} = m\Omega_0/2. \qquad (13)$$

Beyond this threshold, the vortex core undergoes a **radial pinching instability** (Rayleigh-Plateau type), fragmenting into multiple sub-vortices:

$$N_{\mathrm{vortices}} = N_{\mathrm{current}}/N_{\mathrm{max}}, \qquad (14)$$

where N_{max} is the maximum number of bound states supported.

Each fragment rapidly recombines with nearby color charges to form color-singlet hadrons, releasing stored rotational energy. This fragmentation is the **dual description of hadronization**.

3.5 Collective Projection and Latent Correlation Revelation

Crucial refinement: The coincidence measurement does not only correlate emitters A and B. It reveals correlations in **all** particles coupled to the collective mode $\hat{V}$.

Number of simultaneously correlated particles:

$$N_{\mathrm{correl}} = N_{\mathrm{emitters}} + N_{\mathrm{extras}} = \sum_{i=1}^{N} \mathbb{1}_{c_i \neq 0}. \quad (15)$$

Before measurement: N_{extras} are not confirmed to participate.
After measurement (coincidence click): all N particles show anomalous correlations with scaling:

$$\langle \Delta n_i \Delta n_j \rangle \propto |c_i|^2 |c_j|^2 \sinh^2 r_{\mathrm{inj}}, \quad i, j \in [1, N]. \quad (16)$$

Vortex rotation amplification for each particle:

$$\dot{\omega}_i \propto |c_i|^2 \sinh^2 r_{\mathrm{inj}}, \qquad (17)$$

showing that particles with larger overlap coefficient c_i are more strongly activated.

---

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

4.1 Bulk-Boundary Dictionary

In the Randall-Sundrum scenario with rotating AdS bulk:

Boundary (Brane)	Bulk (AdS)
N particles on brane	N localized excitations at AdS boundaries
Collective vortex mode $\hat{V}$	Rotating topological mode in bulk (spin-2 perturbation)
TMSS projection S_r^{coll}	Bulk metric perturbation $h_{\mu\nu}$
Entanglement entropy $S_{\mathrm{ent}}(\hat{V})$	Ryu-Takayanagi entanglement entropy on bulk geodesics
Color confinement scale	AdS curvature $1/L$

Mapping formula:

$$g_{\mathrm{Sent}} S_{\mathrm{ent}}(\hat{V}) \sim \frac{1}{\kappa_5^2} \Box h_{\mu\nu}, \qquad (18)$$

where κ_5 is the 5D gravitational coupling.

4.2 ER=EPR Interpretation (Refined)

In the ER=EPR conjecture, entanglement between distant regions is geometrized as a traversable wormhole (ER bridge). In our framework:

1. **Setup**: N particles emit indistinguishable photons with collective vortex mode $\hat{V}$.
2. **Coincidence measurement**: Triggers collective TMSS projection (Eq. 1).
3. **TMSS squeezing**: Pumps vorticity into the collective mode, encoded as growing entanglement density $S_{\mathrm{ent}}(\hat{V})$ (Eq. 4).
4. **Stress-energy in bulk**: This entanglement density maps to stress-energy asymmetry in AdS via the bulk-boundary dictionary (Eq. 18).
5. **Wormhole stitching**: The stress-energy asymmetry opens/stabilizes an ER bridge connecting the AdS boundaries where the N particles are located.
6. **Stability criterion**: The bridge is dynamically stabilized by **ongoing TMSS coherence**. If decoherence destroys the TMSS state ($r_{\mathrm{inj}} \to 0$), the wormhole collapses.

Key result: The ER bridge is not a static object; it is continuously **stitched by coherent vortex rotation**. This explains both:

- Why entanglement is geometrically real (has spacetime consequences).
- Why entanglement is fragile (decoherence = wormhole collapse).

---

5. Phenomenological Predictions and Falsification Tests

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

Prediction: In lattice-QCD simulations on a 2D torus with artificial rotation (twist boundary conditions), the string tension between a quark-antiquark pair is:

$$\sigma_0 = \sigma_{\text{classical}}.$$

If we introduce a **rotating frame dual description** (dual to collective vortex mode), the computed string tension becomes:

$$\sigma_{\text{rot}} = \sigma_0 \left[1 + \sinh^2(r_{\text{inj}})/2\right], \qquad (19)$$

where r_{inj} encodes the superradiant response to coincidence-like event triggers in the lattice.

Test protocol:

1. Perform standard lattice-QCD calculations of σ_0.
2. Artificially rotate the lattice (twist boundary conditions).
3. Inject "coincidence events" (synchronized plaquette updates simulating photon clicks).
4. Measure string tension change and compare to Eq. (19).

Falsification criterion: If σ_{rot} does not increase with injected coincidence intensity, the framework fails.

5.2 Test 2: Hadronization Multiplicity Anomaly with Collective Participation

Novel prediction: When quarks separate beyond the coherence distance of the vortex, hadronization occurs. Our framework predicts that the **multiplicity of hadrons produced is correlated with entanglement saturation and collective particle participation**:

$$N_{\text{hadrons}} = N_0 \left[1 + \frac{N_{\text{correl}}}{2}(1 - e^{-\rho_{\text{ent}}/\rho_{\text{sat}}})\right], \quad (20)$$

where:

- N_0 is the baseline multiplicity (2 emitter case).
- $N_{\text{correl}} = \sum_i \mathbb{1}_{c_i \neq 0}$ is the number of correlated particles.
- $\rho_{\text{ent}} = S_{\text{ent}}(\hat{V})(t)$ is instantaneous entanglement density.
- ρ_{sat} is saturation density at MVC threshold.

Anomalous feature: If the experiment involves many particles (e.g., dense QGP in heavy-ion collisions), N_{correl} can be $\gg 2$, predicting **anomalously high multiplicity** compared to the two-body scenario.

Test protocol:

1. In RHIC/LHC high-energy collisions, measure hadron multiplicity distributions.

2. Correlate with estimated number of particles coupled to emergent vortex modes (via color glass condensate saturation momentum).
3. Test Eq. (20) against data.

Falsification criterion: If N_{hadrons} scales linearly with N_0 only (independent of N_{correl}), the collective mechanism is absent.

5.3 Test 3: TMSS Entanglement Signatures in Deep Inelastic Scattering

Deep inelastic scattering (DIS) measures parton distributions via structure functions $F_2(x, Q^2)$. In our framework, the entanglement distribution of the collective vortex mode modulates these:

$$F_2(x, Q^2) = F_2^0(x, Q^2)\left[1 + \alpha_{\text{TMSS}} \sinh^2(r(Q^2))\right], \quad (21)$$

where:

- F_2^0 is the baseline (non-squeezed) structure function.
- α_{TMSS} is a small anomaly coefficient (~ 0.01--0.1).
- $r(Q^2)$ is the squeezing parameter evolved to momentum scale Q^2.

Test protocol:

1. Perform precision DIS experiments at electron-proton colliders (e.g., planned Future Circular Collider, EIC).
2. Measure $F_2(x, Q^2)$ at high resolution.
3. Look for systematic deviations from DGLAP evolution that scale with predicted $\sinh^2(r(Q^2))$ terms.

Falsification criterion: If F_2 follows standard evolution with no $\sinh^2 r$ anomaly above experimental uncertainty, the TMSS mechanism does not couple to parton dynamics.

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

Quantized vortices in ultracold atom gases exhibit superradiant instability. Our **complete protocol** for observing collective vortex projection:

5.4.1 Experimental Setup

Create a **trapped vortex in a superfluid BEC** (e.g., ^{87}Rb, 10^4--10^5 atoms) with artificial rotation $\Omega_0 \approx 0.01 \times \omega_z$ (weak rotation, below ergoregion).

Couple two groups of spin excitations (playing the role of "quarks"):

- **Emitter pair**: Atoms in $(|F=1, m_F=0\rangle \to |F=2, m_F=+1\rangle)$ state.
- **Spectator/extra particles**: Atoms in coupled states sharing the same vortex mode $\hat{V}$ (same trap geometry, overlapping spatial modes).

5.4.2 Coincidence Measurement Protocol

1. **Initialization**: Prepare vortex in ground state $|0\rangle_{\hat{V}}$.
2. **Raman emission**: Drive Raman-scattering transitions on emitter pair, emitting photons into a cavity or free space with indistinguishable spatial modes (to engineer high visibility $V_{\text{interferance}} \gtrsim 0.8$).
3. **Beamsplitter and detection**: Route emitted photons through a beamsplitter. Place photodetectors on each output port.
4. **Coincidence window**: Open detection window $\Delta t \sim 1/\omega_z$ (rabi period timescale). Record clicks on both detectors (true coincidence).
5. **Post-selection**: Condition all subsequent measurements on the coincidence click. This post-selects the TMSS-projected state (Eq. 3).

5.4.3 Observable: Multi-Particle Vortex Activation

Before coincidence (no measurement): The vortex state is $|\Psi_0\rangle$ (superposition, Eq. 2.1). Vortex rotation rate is baseline $\omega(0) \sim \Omega_0$.

After coincidence (conditioned on click): The state becomes $|\text{TMSS}\rangle_r^{\text{coll}}$ (Eq. 3). Vortex rotation rate jumps:

$$\dot{\omega}_{\text{post}} = \Omega_0 + \Delta\omega(r_{\text{inj}}), \quad \Delta\omega \propto \sinh^2(r_{\text{inj}}).$$

Measured signature:

- **Emitter spins** ($c_1, c_2 \sim 0.4$ each): Show strong correlation with vortex mode, $\dot{\omega}_1 \propto |c_1|^2 \sinh^2 r_{\text{inj}} \approx 0.16 \times \sinh^2 r_{\text{inj}}$.
- **Extra spins** (if $N_{\text{extras}} > 0$, $c_i \sim 0.1$ per extra): Unexpectedly show vortex correlation with reduced amplitude $\dot{\omega}_{extra} \propto 0.01 \times \sinh^2 r_{\text{inj}}$, but **collectively** multiple extras can match emitter correlation.

5.4.4 Detection Protocol

1. **Monitor vortex rotation**: Use in-situ imaging (time-of-flight absorption imaging) to track vortex position and rotate at intervals $\Delta t = 10$--100 ms. Extract $\omega(t)$ via phase winding.
2. **Measure spin correlations**: Use spin-dependent fluorescence imaging to tag atoms by spin state. Track correlations $\langle S_i^z S_j^z \rangle$ for each pair (i, j).
3. **Entanglement entropy**: Estimate $S_{\text{ent}}(\hat{V})$ via second Rényi entropy from density matrix tomography (requires multiple copies, but feasible).

5.4.5 Expected Results and Anomaly

Scenario 1 (Standard case, N=2 emitters only):

$$\omega_{\text{post}} \approx \Omega_0(1 + 0.16 \sinh^2 r_{\text{inj}}).$$

Multiplicity of correlated spins: $N_{\text{correl}} = 2$.

Scenario 2 (Collective case, N=2 emitters + 8 extras all coupled to $\hat{V}$):

$$\omega_{\text{post}} \approx \Omega_0(1 + [0.16 + 8 \times 0.01] \sinh^2 r_{\text{inj}}) = \Omega_0(1 + 0.24 \sinh^2 r_{\text{inj}}).$$

Multiplicity: $N_{\text{correl}} = 10 >> 2$.

Anomaly: Vortex gains *more* angular momentum than expected from 2 emitters alone, implying hidden participation of extras. This is **direct experimental confirmation** of collective vortex projection.

5.4.6 Falsification Criterion

- If vortex activation follows Scenario 1 regardless of how many extra atoms are prepared in coupled states, the collective mechanism is absent → **Theory fails**.
- If vortex activation scales with N_{correl} as Scenario 2, the collective TMSS projection is confirmed → **Theory validated**.

---

6. Implications for Fundamental Physics

6.1 Unification of Entanglement and Geometry

Our framework provides an explicit mechanism for how quantum entanglement (information-theoretic) becomes geometry (spacetime curvature). The TMSS collective squeezing parameter r_{inj} is not merely an information-theoretic measure; it directly modifies the effective metric in the bulk via stress-energy contributions (Eq. 18).

Consequence: Geometry is not fundamental; it emerges from entanglement structure. This supports recent developments in holographic duality (entanglement wedges, subregion complexity).

6.2 Cosmological Relevance and Early-Universe Synchronization

The MVC hypothesis connects confinement thresholds to early-universe phase transitions. If color confinement is a manifestation of the universal threshold mechanism (Eq. 12), then:

$$T_{\mathrm{deconf}} = T_{\mathrm{MVC}},$$

suggesting that **QCD deconfinement and bulk-to-brane energy transfer transitions are synchronized in cosmology** (resonance with TDHCF framework, if integrated).

This opens new pathways for understanding early-universe dynamics via QCD phase diagram.

6.3 Quantum Information and Channel Capacity

The entanglement capacity of a color-confined system (subspace) is limited by the vortex saturation threshold:

$$C_{\max} = 2\cosh^2(r_{\mathrm{sat}}), \qquad (22)$$

where r_{sat} is the squeezing parameter at MVC activation (Eq. 12).

This provides a natural upper bound on quantum channel bandwidth in high-energy physics, with direct implications for quantum computing and quantum networks. Dense many-body systems (QGP, BECs) naturally approach this limit.

---

7. Open Questions and Future Directions

1. **Microscopic origin of the vortex**: Does the collective vortex $\hat{V} = \sum_i c_i \hat{v}_i^{(i)}$ emerge from instanton dynamics in the QCD path integral, or is it a more fundamental topological feature of the vacuum structure?
2. **First-principles MVC coupling**: How are the MVC critical density ρ_{MVC}, universal exponent δ, and superradiance parameters γ_{SR}, κ derived rigorously from fundamental QCD or string theory?
3. **Quantum fluctuation spectrum**: What is the full spectrum of fluctuations around a saturated vortex? Can this be measured in precision lattice-QCD or high-energy experiments?
4. **Relation to string theory and extended gauge theories**: Is the rotating vortex dual to a spinning string or D-brane in AdS? Does our framework extend to other gauge theories (e.g., $\mathcal{N} = 4$ SYM, 3D Chern-Simons)?
5. **Decoherence mechanism and timescales**: What is the precise environmental coupling that destroys TMSS coherence? How fast does entanglement decay in realistic QCD plasma at finite temperature?
6. **Many-body entanglement and collective modes**: Can the framework accommodate non-collective, pairwise entanglement patterns, or is collective projection a universal feature?

---

8. Conclusion

We have proposed a unified framework wherein:

- **Color confinement** emerges from rotational superradiance of a topological collective vortex mode $\hat{V}$.
- **Photon coincidence measurements** trigger **collective TMSS projection** in local vacuum modes coupled to all particles sharing $\hat{V}$—not via antiphoton mediators, but via quantum measurement post-selection.
- The squeezed vacuum stabilizes a **geometric EPR bridge** (Einstein-Rosen wormhole) in the AdS/CFT dual bulk.
- **Confinement transitions** are manifestations of **MVC critical-density thresholds**.
- **Asymptotic freedom**, **hadronization**, and **deconfinement** emerge naturally as dynamical phases of the vortex saturation/fragmentation cycle.

The theory is **falsifiable** through:

1. Lattice-QCD simulations with geometric-phase anomalies.
2. High-energy collider measurements of anomalous hadronization multiplicity.
3. Precision structure-function experiments at lepton-hadron colliders.
4. Direct cold-atom laboratory analogs demonstrating multi-particle vortex activation via collective projection.

The collective TMSS projection mechanism unifies quantum information theory, topological field theory, and cosmology under a single dynamical threshold. Future work must:

- Derive MVC and superradiance parameters from first principles.

- Explore whether the framework extends to other confinement scenarios (electroweak, condensed matter).
- Perform precision experiments to test multi-particle correlation signatures.

We believe this synthesis illuminates one of the deepest mysteries in physics: **the dynamical origin of color confinement and its geometric dual in quantum entanglement**.

References

[1] Greensite, J. (2003). The confinement problem in lattice gauge theory. *Progress of Theoretical Physics Supplement*, 131, 130–142.

[2] Maldacena, J. M. (1997). The large-N limit of superconformal field theories and supergravity. *arXiv preprint* hep-th/9711200.

[3] Van Raamsdonk, M. (2010). Building up spacetime with quantum entanglement. *General Relativity and Gravitation*, 42(10), 2323–2329.

[4] Maldacena, J., & Susskind, L. (2013). Cool horizons for entangled black holes. *arXiv preprint* arXiv:1306.0533.

[5] Unruh, W. G. (1976). Notes on black-hole evaporation. *Physical Review D*, 14(4), 870.

[6] Penrose, R. (1969). Gravitational collapse and the role of general relativity. *Rivista del Nuovo Cimento*, 1(S1), 252–276.

[7] Gyulassy, M., & McLerran, L. (2005). Quark gluon plasma 3. *Nuclear Physics A*, 750(1), 30–63.

[8] Banfi, A., Marchesini, G., & Smye, G. (2002). Away-side jet broadening in the colour dipole model. *Journal of High Energy Physics*, 2002(08), 006.

[9] Iancu, E., Leonidov, A., & McLerran, L. D. (2001). The color glass condensate at RHIC. *Nuclear Physics A*, 692(34), 583–645.

[10] Breitenlohner, P., & Freedman, D. Z. (1982). Positive energy in anti-de Sitter backgrounds and gauged extended supergravity. *Physics Letters B*, 115(3), 197–201.

[11] Hawking, S. W. (1974). Black hole explosions? *Nature*, 248(5443), 30–31.

[12] Bekenstein, J. D. (1973). Black holes and entropy. *Physical Review D*, 7(8), 2333.

[13] Susskind, L. (1995). The world as a hologram. *Journal of Mathematical Physics*, 36(11), 6377–6396.

[14] Witten, E. (1998). Anti de Sitter space and holography. *arXiv preprint* hep-th/9802109.

[15] Martín Alonso, J. M. (2026). Trans-Dimensional Hydrodynamic Cosmological Framework (TDHCF): Derivation of the Bulk-to-Brane Transfer Current and Resolution of Early Universe Tensions. *Preprint*, January 2026.

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

geometry, falsifiable predictions.

PACS: 12.38.Aw (general properties of QCD), 14.70.Bh (photons), 03.75.Gg (Bose-Einstein condensation), 11.25.Tq (gauge/string duality).