Maximal Entanglement and Bell Nonlocality at an Electron-Ion Collider

Bo-Wen Xiao

School of Science and Engineering, CUHK-Shenzhen

Wei Qi, Zijing Guo, and BX, arXiv:2506.12889v1 [hep-ph]

The Einstein-Podolsky-Rosen Paradox

- **The EPR Paper** [Phys. Rev. 47, 777 (1935)]
  - Can Quantum-Mechanical Description of Physical Reality be Considered Complete?
  - Challenge to Copenhagen orthodox interpretation
- **Quantum Entanglement**
  - The quintessential phenomenon of QM introduced by Schrödinger in response to the EPR paper.
  - Non-local correlations between particles
  - Violates local realism assumptions
- Einstein's famous phrase: **"God does not play dice"**
  - To which Bohr replied: **"Einstein, stop telling God what to do"**
- **The EPR paradox revealed the profound nature of quantum entanglement!**

Einstein, Podolsky, and Rosen

"Spooky action at a distance"

Schrödinger, Bohr and Einstein in 1925

ER=EPR Conjecture: Entanglement as Wormhole Geometry

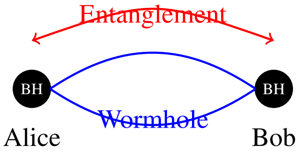
The ER=EPR Conjecture
[Maldacena & Susskind, 2013]

Einstein-Rosen Bridge =
Einstein-Podolsky-Rosen Pair
Entanglement $\Leftrightarrow$ Wormhole

- **EPR correlations** create geometric connections
- **Wormhole Geometry** is holographic manifestation of entanglement
- **Non-traversable wormhole** - no superluminal signaling
- **Bridge between QM and GR:** unifying general relativity and quantum mechanics into string theory.

Supporting Evidence: **Holographic Realization:** [Jensen & Karch, 2013]

- EPR pair in AdS_5 space [Xiao, 2008]
- The holographic dual of the EPR pair has two horizons and a string (wormhole) connecting them.



"Entanglement weaves the fabric of spacetime"

Separable vs Entangled States: Two-Qubit Systems

Separable States

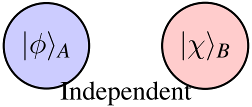
- Can be written as: $|\psi\rangle = |\phi\rangle_A \otimes |\chi\rangle_B$
- No quantum correlations

Examples:

$$|00\rangle = |0\rangle_A \otimes |0\rangle_B, \quad |01\rangle = |0\rangle_A \otimes |1\rangle_B$$

$$|\psi_{\text{sep}}\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)_A \otimes |0\rangle_B$$

$$= \frac{1}{\sqrt{2}}(|00\rangle + |10\rangle)$$



Entangled States

- **Cannot** be written as product
- Genuine quantum correlations

Bell States (Maximally Entangled):

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

Bell's Theorem

- **Quantum Indeterminacy**
  - **Realism:** Quantum indeterminacy reflects our ignorance of hidden variables; outcomes are determined but unknown.
  - **Copenhagen:** Indeterminacy is fundamental; outcomes are truly probabilistic until measured.
  - **Agnosticism:** The reality behind quantum events is unknowable; only predictive power of the theory matters.
- **Bell Nonlocality** [Bell, 1964]
  - Bell inequality: It makes an observable difference for Realism vs Copenhagen, and eliminates Agnostic view.
  - Decisive evidence supporting QM (Copenhagen).
- **CHSH Inequality** [Clauser et al., 1969]
  - Generalized Bell inequality
  - Foundation for quantum information theory

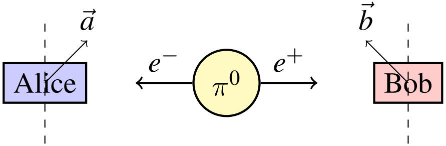
Entangled State

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

John Stewart Bell

EPRB Experiment: Testing Bell Nonlocality

Einstein-Podolsky-Rosen-Bohm Experiment



Spin-singlet: $|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$

Correlation: $E(\vec{a}, \vec{b}) = \langle A(\vec{a}) \cdot B(\vec{b}) \rangle$

Bell CHSH Inequality:

$$\mathbb{B}_{HT} = |E(a,b) - E(a,b') + E(a',b) + E(a',b')| \leq 2$$

$$\mathbb{B}_{QM} = |\cos\theta_{ab} - \cos\theta_{ab'} + \cos\theta_{a'b} + \cos\theta_{a'b'}| \leq 2\sqrt{2}$$

Local Hidden Variable Theory

- Pre-existing density $P(\lambda)$ for λ
- $A(\vec{a}, \lambda) = \pm 1$ predetermined
- $E(\vec{a}, \vec{b}) = \int P(\lambda) A(\vec{a}, \lambda) B(\vec{b}, \lambda) d\lambda$
- Local realism: $\mathbb{B}_{HT} \leq 2$

Quantum Mechanics

- No predetermined values
- $E(\vec{a}, \vec{b}) = -\vec{a} \cdot \vec{b} = -\cos\theta_{ab}$
- Nonlocality: $2 < \mathbb{B}_{QM} \leq 2\sqrt{2}$
  Elementary proof with:
  $\alpha \cos\theta + \beta \sin\theta \leq \sqrt{\alpha^2 + \beta^2}$

QM violates Bell inequality $\Rightarrow$ Nature is nonlocal!

Time Reversal Operation and Kramers Degeneracy

Time Reversal for Spin-1/2

$$\boxed{\mathcal{T} = -i\sigma_y \mathcal{K}}$$

$$\mathcal{T}|\uparrow\rangle = |\downarrow\rangle \quad \mathcal{T}|\downarrow\rangle = -|\uparrow\rangle$$

- $\mathcal{K}$ is complex conjugation

$$\tilde{\chi} = \mathcal{T}\begin{pmatrix}\alpha \\ \beta\end{pmatrix} = \begin{pmatrix}-\beta^* \\ \alpha^*\end{pmatrix}$$

- $\langle\tilde{\chi}|\chi\rangle = 0$
- $[\mathcal{T}, H] = 0$ (if time-reversal invariant)
- **anti-unitary**: $\langle\mathcal{T}\psi|\mathcal{T}\phi\rangle = \langle\psi|\phi\rangle^*$

Kramers Degeneracy

For half-integer spin systems with time-reversal symmetry:
Every energy level is at least doubly degenerate

Proof Sketch:

- If $H|\psi\rangle = E|\psi\rangle$
- Then $H\mathcal{T}|\psi\rangle = E\mathcal{T}|\psi\rangle$
- But $\langle\psi|\mathcal{T}\psi\rangle = 0$ (since $\mathcal{T}^2 = -1$)
- So $|\psi\rangle$ and $\mathcal{T}|\psi\rangle$ are orthogonal
- $\Rightarrow$ At least 2-fold degeneracy

$\mathcal{T}^2 = -1$ **for fermions leads to fundamental degeneracy protection**

Concurrence: Measuring the Degree of Entanglement (Pure States)

Time Reversal Operation flips spins:

- $|\psi\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$
- $\mathcal{C}(|\psi\rangle) \equiv |\langle\tilde{\psi}|\psi\rangle|$, $|\tilde{\psi}\rangle = -\sigma_y \otimes \sigma_y|\psi^*\rangle$
- [Wootters, 98] flip spins with $\hat{T} = -i\sigma^y\hat{K}$ (Anti-Unitary)
- $|\tilde{\psi}\rangle = \delta^*|00\rangle - \gamma^*|01\rangle - \beta^*|10\rangle + \alpha^*|11\rangle$, the spin-flipped complex conjugate.
- $\mathcal{C}(|\psi\rangle) = 2|\alpha\delta - \beta\gamma|$ measures overlap with time-reversed state.
- $\mathcal{C} = 0$: Separable (no entanglement)
- $0 < \mathcal{C} < 1$: Partially entangled
- $\mathcal{C} = 1$: Maximally entangled

$\mathcal{C}$ = invariance under time reversal

Separable State

$|\psi_1\rangle = |00\rangle$ and $\alpha = 1, \beta = \gamma = \delta = 0$

$\mathcal{C} = 2|1 \cdot 0 - 0 \cdot 0| = 0$

Bell State (Maximally Entangled)

$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

$\mathcal{C} = 2|\frac{1}{2} - 0| = 1$

Partially Entangled

$|\psi_2\rangle = \frac{1}{\sqrt{3}}|00\rangle + \sqrt{\frac{2}{3}}|11\rangle$

$\mathcal{C} = 2|\frac{1}{\sqrt{3}} \cdot \sqrt{\frac{2}{3}}| = \frac{2\sqrt{2}}{3} \approx 0.94$

Spin Density Matrix for Spin-1/2 Particles

Density Matrix Formalism

For a spin-1/2 particle, the density matrix is:

$$\boxed{\rho = \frac{\mathbb{1}_2 + \vec{n} \cdot \vec{\sigma}}{2}}$$

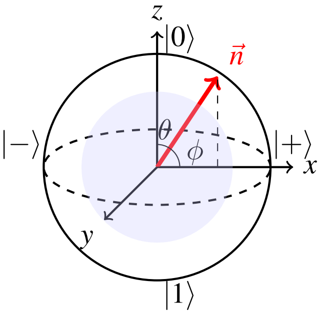
Bloch Vector: $n_i = \langle \sigma_i \rangle = \mathrm{Tr}(\rho \sigma_i)$

- $|\vec{n}| = 1$: Pure state
- $|\vec{n}| < 1$: Mixed state
- $\vec{n} = 0$: Maximally mixed state

For a heavy quark:

- **Production mechanism:** QCD processes determine initial Bloch vectors
- **Experimental access:** Weak decay measures spin projections $\langle \vec{n} \cdot \vec{\sigma} \rangle$

Bloch Sphere Representation



Geometry encodes quantum information

- $\vec{n} = (0, 0, 1)$: $\rho = |0\rangle\langle 0|$
- $\vec{n} = (1, 0, 0)$: $\rho = |+\rangle\langle +|$
- $\vec{n} = (0, 0, 0)$: $\rho = \frac{1}{2}\mathbb{1}_2$ (classical)

Density Matrix and Concurrence for Two-Qubit Systems

Extending to mixed states

Density Matrix Representation:

- Pure state: $\rho = |\psi\rangle\langle\psi|$
- Mixed state: $\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i|$
- General form in computational basis:

$$\rho = \begin{pmatrix} \rho_{00,00} & \rho_{00,01} & \rho_{00,10} & \rho_{00,11} \\ \rho_{01,00} & \rho_{01,01} & \rho_{01,10} & \rho_{01,11} \\ \rho_{10,00} & \rho_{10,01} & \rho_{10,10} & \rho_{10,11} \\ \rho_{11,00} & \rho_{11,01} & \rho_{11,10} & \rho_{11,11} \end{pmatrix}$$

Properties:

- Hermitian: $\rho^\dagger = \rho$
- Trace $\mathrm{Tr}(\rho) = 1$; Non-negative.

Concurrence in general:

[Hill, Wootters, 97; Wootters, 98]

- Define: $\tilde{\rho} = (\sigma_y \otimes \sigma_y)\rho^*(\sigma_y \otimes \sigma_y)$
- Compute: $\mathcal{R} = \sqrt{\sqrt{\rho}\tilde{\rho}\sqrt{\rho}}$
- Eigenvalues of $\mathcal{R}$: $\{\lambda_1, \lambda_2, \lambda_3, \lambda_4\}$ (descending order)

$$\mathcal{C}(\rho) = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\}$$

Example - Werner State:

$$\rho_W = p|\Psi^-\rangle\langle\Psi^-| + \frac{1-p}{4}\mathbb{1}_4$$

- $p = 1$: Pure Bell state
- $\mathcal{C}(\rho_W) = \max\{0, \frac{3p-1}{2}\}$
- Entangled when $p > 1/3$

Spin Density Matrix: Physical Interpretation

The most general two-qubit density matrix:

$$\rho = \frac{1}{4}\left(\mathbb{1}_4 + B_i^+\sigma^i \otimes \mathbb{1}_2 + B_j^-\mathbb{1}_2 \otimes \sigma^j + C_{ij}\sigma^i \otimes \sigma^j\right)$$

Physical Quantities:

- $B_i^+ = \mathrm{Tr}\,\rho(\sigma_i \otimes \mathbb{1}_2)$
- $B_j^- = \mathrm{Tr}\,\rho(\mathbb{1}_2 \otimes \sigma_j)$
- $C_{ij} = \mathrm{Tr}\,\rho(\sigma_i \otimes \sigma_j)$
  Spin correlation /NB: Not $[\mathcal{C}]$

Special Case:

For Bell states: $B_i^+ = B_j^- = 0$
(No individual spin polarization)

Bell States & Correlation Matrices:

State	Correlation Matrix
$\lvert\Psi^-\rangle = \frac{1}{\sqrt{2}}(\lvert\uparrow\downarrow\rangle - \lvert\downarrow\uparrow\rangle)$	$C_{ij} = \mathrm{diag}(-1,-1,-1)$
$\lvert\Psi^+\rangle = \frac{1}{\sqrt{2}}(\lvert\uparrow\downarrow\rangle + \lvert\downarrow\uparrow\rangle)$	$C_{ij} = \mathrm{diag}(1,1,-1)$
$\lvert\Phi^+\rangle = \frac{1}{\sqrt{2}}(\lvert\uparrow\uparrow\rangle + \lvert\downarrow\downarrow\rangle)$	$C_{ij} = \mathrm{diag}(1,-1,1)$
$\lvert\Phi^-\rangle = \frac{1}{\sqrt{2}}(\lvert\uparrow\uparrow\rangle - \lvert\downarrow\downarrow\rangle)$	$C_{ij} = \mathrm{diag}(-1,1,1)$

For singlet state:

$C_{ij} = -\delta_{ij}$ means spins are always anti-parallel.

Correlation matrix C_{ij} fully characterizes entanglement structure for Bell states

Entanglement and Bell Nonlocality Conditions

Starting from the spin density matrix: $\rho_{\alpha\alpha',\beta\beta'} = \frac{1}{4}\left(\mathbb{1}_{\alpha\alpha',\beta\beta'} + C_{ii}\sigma^i_{\alpha\beta} \otimes \sigma^i_{\alpha'\beta'}\right)$

- Anti-correlated spins: $C_{xx}, C_{yy}, C_{zz} < 0$
- Def: $D = (C_{xx} + C_{yy} + C_{zz})/3 = \mathrm{tr}C/3$
- $D = -1$: Perfect anti-correlation

Four eigen values of $\mathcal{R} = \rho$ (since $\tilde{\rho} = \rho$)

$$
\begin{aligned}
\lambda_1 &= \frac{1}{4}(1 - C_{xx} - C_{yy} - C_{zz}), \\
\lambda_2 &= \frac{1}{4}(1 + C_{xx} + C_{yy} - C_{zz}), \\
\lambda_3 &= \frac{1}{4}(1 + C_{xx} - C_{yy} + C_{zz}), \\
\lambda_4 &= \frac{1}{4}(1 - C_{xx} + C_{yy} + C_{zz}).
\end{aligned}
$$

Entanglement Condition

- Concurrence $\mathcal{C}[\rho] = \frac{1}{2}(-3D - 1) > 0$:

$$\boxed{D < -\frac{1}{3}}$$

Bell Nonlocality Condition

- For CHSH violation $\mathbb{B} > 2$: [Horodecki, et al, 95]

$$\boxed{D < -\frac{1}{\sqrt{2}} \approx -0.707}$$

Hierarchy: Bell Nonlocality $\subset$ Entanglement $\subset$ All Quantum States

Top Quark Weak Decay and Spin Transfer

Top Quark Decay: Choose its rest frame

$$t \to W^+ b \to \ell^+ \nu_\ell b, \ \bar{t} \to W^- \bar{b} \to \ell^- \bar{\nu}_\ell \bar{b}$$

Decay Spin Density Matrix:

$$\Gamma_\pm = \frac{\mathbb{1}_2 + \kappa_\pm \vec{\sigma}_t \cdot \hat{l}_\pm}{2}$$

Parity Violating Angular Distribution:

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \kappa_\pm \cos\theta$$

- Weak decay (parity violation) provides **Spin-momentum correlation**
- $\kappa_\pm = \pm 1$ ($t\bar{t}$) **spin analyzing power**
- $\sigma_{l_+ l_-} \propto \mathrm{tr}[\Gamma_+ \otimes \Gamma_- \rho]$ NB $\mathrm{tr}[\sigma^i \sigma^j] = 2\delta^{ij}$

Correlation between di-leptons

$$\frac{d^2\sigma}{\sigma d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left[1 - \hat{l}_+ \cdot C \cdot \hat{l}_-\right]$$

Entanglement Signature

$$\boxed{\langle \cos\varphi \rangle = -\frac{1}{3} D = -\frac{1}{9} \mathrm{Tr}(C)}$$

Experimental Reach:

- Extract $D = \mathrm{Tr}(C)/3$ parameter directly
- **Quantum Tomography**: all elements of ρ can be measured. [Bernreuther, Heisler, Si, 15; ATLAS, 1612.07004; CMS, 1907.03729]

First Observation of Quark Entanglement at the LHC

[ATLAS (Nature 2024):] First observation of entanglement in quarks at the highest-energy.

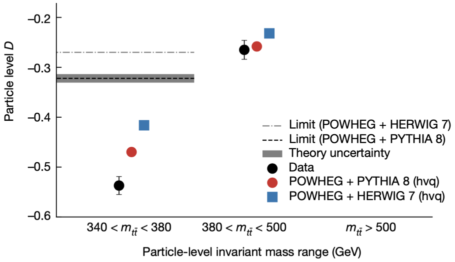
Entanglement Measure:

$$D = \mathrm{tr}[C]/3 = -3\langle \cos\phi \rangle$$

where ϕ is the angle between charged leptons in their parent top/antitop rest frames

Key Features:

- Spin transferred to decay products
- Measured near $t\bar{t}$ threshold
- From atomic physics to high-energy collisions: **A new frontier!**
- **CMS, STAR, BES-III** more to come.



$\sqrt{s} = 13$ TeV, 140 fb^{-1} data (2015-2018)

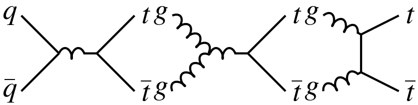
Measured: $D < -1/3$ (Entanglement criterion)
$D = -0.547 \pm 0.002$ (stat.) ± 0.021 (syst.)

- Observed: $> 5\sigma$ from no entanglement
- **Yet, Bell Nonlocality**: $D < -1/\sqrt{2}$

Theory vs Experiment: Top Quark Entanglement

Quantum State Tomography $\rho_{\alpha\alpha',\beta\beta'} = R_{\alpha\alpha',\beta\beta'}/\mathrm{tr}R$ [Afik, de Nova, 2022]

Top quark pair production



$$R_{\alpha\alpha',\beta\beta'} = \frac{1}{N}\sum \mathcal{M}^{*}_{t_\alpha \bar{t}_{\alpha'}} \mathcal{M}_{t_\beta \bar{t}_{\beta'}}$$

- **Measured** $D \approx -0.54$ near threshold
- **Gluon fusion dominance** at LHC
- **Angular momentum conservation** determines spin correlations
- **Statistical mixture** of $q\bar{q}$ and gg

Near Threshold ($\beta \to 0$):

- $q\bar{q}$: Separable state ($\mathcal{C} = 0$), since $t\bar{t}$ spin (± 1) is equally mixed along beam.
- gg: Maximally entangled singlet Ψ^-

High Energy ($\beta \to 1$) with $\theta = \pi/2$:

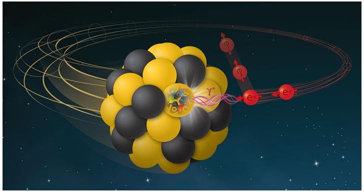
- Both channels: Maximally entangled triplet Ψ^+ along $\hat{n}$ with nonzero OAM.

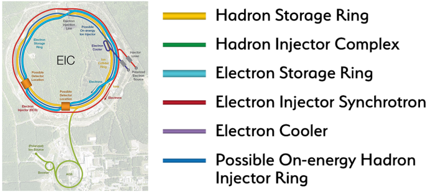
Mixed State at LHC

$$\rho = w_{q\bar{q}}\rho_{q\bar{q}} + w_{gg}\rho_{gg}$$

"Observation of Entanglement but not Bell Nonlocality due to Quark channel mixture"

EIC Status Update





Aiming to the start of operation in 2031, EIC has reached several milestones:

- Five stages of project Critical Decision approvals:
  1. CD-0 Approve Mission Need ✓
     January 9, 2020: EIC CD-0 and site selection ▸ Link
  2. CD-1 Approve Alternative Selection and Cost Range ✓
     June 29, 2021: EIC CD1 and start of project execution ▸ Link
  3. CD-2 Approve Performance Baseline
  4. CD-3 Approve Start of Construction
  5. CD-4 Approve Start of Operations or Project Completion
- RHIC $\rightarrow$ eRHIC; Energy: $20 \rightarrow 141$ GeV; Luminosity: $10^{34}\mathrm{cm}^{-2}/\mathrm{s}$; Polarized electron and hadron beams

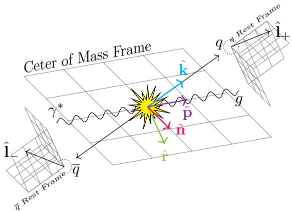
Quark Pair Production in Photon-Gluon Fusion: Longitudinal case

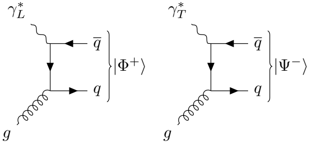
[Qi, Guo, Xiao] arXiv:2506.12889v1 [hep-ph]

Photon-Gluon Fusion Process

$$\gamma^*_{\lambda=\pm,0} + g \to q + \bar{q}$$

$$\rho_L = \frac{1}{4}\left(\mathbb{1}_4 + C_{ij}\sigma^i \otimes \sigma^j\right)$$





For $q\bar{q}$ with $\beta \to 0$ and $\theta = \frac{\pi}{2}$

Longitudinal photons contribution:

$$C_{ij} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\chi_1 & -\chi_2 \\ 0 & -\chi_2 & \chi_1 \end{pmatrix}$$

with $$\chi_1 = \frac{1 - 2z^2 + z^2\beta^2}{1 - z^2\beta^2}, \quad \chi_2 = \sqrt{1 - \chi_1^2}.$$

- ρ_L is given by a pure state $= |\Psi\rangle\langle\Psi|$, with

$$|\Psi\rangle = \frac{1}{2}\left(\sqrt{1+\chi_1}, \mathrm{i}\sqrt{1-\chi_1}, \mathrm{i}\sqrt{1-\chi_1}, \sqrt{1+\chi_1}\right).$$

- **Near Threshold ($\beta \to 0$)** with $\theta = \frac{\pi}{2}$: $|\Phi^+\rangle$.
- **High Energy ($\beta \to 1$)**: $|\Phi^+\rangle$.
- $q\bar{q}$ has spin 1 with nonzero OAM and $\mathcal{C}[\rho_L] \equiv 1$!

Always Maximally Entangled! Very Special!

Maximal Entanglement $\Rightarrow$ Pure State: A Simple Proof

Given Conditions

Two-qubit system with:

- $B_i^{\pm} = 0$ (no final polarization)
- $\mathcal{C}[\rho] = 1$ (maximal entanglement)
- $\tilde{\rho} = \rho$ (since $B_i^{\pm} = 0$)

Concurrence Formula:

$$\mathcal{C}[\rho] = \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4$$

where λ_i are eigenvalues of $\mathcal{R} = \rho$

Proof

$$\mathcal{C}[\rho] = \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4 = 1$$
$$\mathrm{tr}[\rho] = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 = 1$$
$$0 \leq \lambda_i \leq 1 \text{ for all } i$$

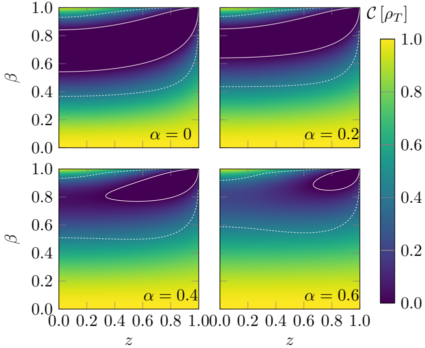
Conclusion

ρ has rank 1 ($\rho^2 = \rho$) $\Rightarrow$ **Pure State**
Also true for non-zero $B_i^{\pm}$

Since we find $\mathcal{C}[\rho] \equiv 1$ for the longitudinal photon channel,
the $q\bar{q}$ pair **must always be in a pure state** by this theorem.

Quark Pair Production in Photon-Gluon Fusion: Transverse case

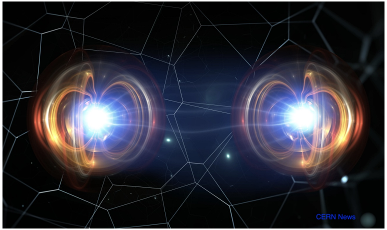
[Qi, Guo, Xiao] arXiv:2506.12889v1 [hep-ph] **Transverse photons**: similar to $gg \to q\bar{q}$ channel.

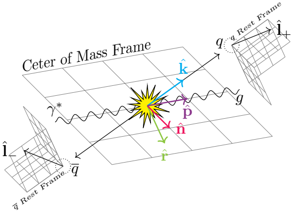


- Density plots of the concurrence for transverse photon as functions of β and $z = \cos\theta$ at given $\alpha \equiv Q^2/\hat{s}$.
- Solid lines (entanglement ($\mathcal{C}[\rho_T] = 0$)) and dashed lines (Bell nonlocality).
- **Near Threshold ($\beta \to 0$):** Maximally entangled singlet Ψ^-
- **High Energy ($\beta \to 1$) with $\theta = \pi/2$:** Maximally entangled triplet Φ^-.

- Low background and Maximal signal. Better to have *LT* separation! (Also UPC)
- Possible measurements: $b\bar{b}$ or $c\bar{c}$ or hyperon $\Lambda\bar{\Lambda}$.
- Diffractive production also see [Fucilla and Hatta, 2509.05267].
- Quantum Information at EIC [Cheng, Han, Trifinopoulos, 2510.23773]

Summary and Outlook

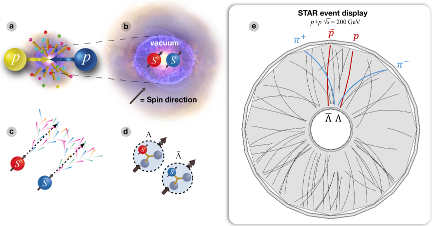




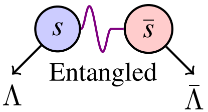
- Entanglement and Bell Nonlocality are measurable at high energy collisions.
- EIC offers a unique and clean experimental environment for measuring entanglement and Bell Nonlocality.
- Using entanglement as a tool to probe **nuclear environment** and other QCD effects.
- **New opportunities** to explore the interplay of quantum information phenomena and high energy and hadronic physics in the years to come.

First evidence of spin correlation in $\Lambda\bar{\Lambda}$ hyperon pairs (backup 1)

STAR Collaboration [arXiv:2506.05499] with data from $p + p$ collisions at $\sqrt{s} = 200$ GeV



Entanglement as a Tool



- **QCD Confinement**
- **Chiral Symmetry**
- **Spin Dynamics**
- **Decoherence**
- **Bell Nonlocality**
- **Nuclear Medium !?**

- Relative polarization (same as D): $P_{\Lambda\bar{\Lambda}} = (18 \pm 4)\%$
- Parallel: $1/3$; Antiparallel: -1; no spin correlation 0.
- Short-range pairs show maximal entanglement
- Long-range pairs: correlation vanishes (decoherence)
- Evidence for quantum entanglement in QCD vacuum

"Entanglement: A new paradigm for exploring QCD phenomena"

Λ Hyperon: Nature's Built-in Spin Analyzer (backup 2)

The Hyperon Decays

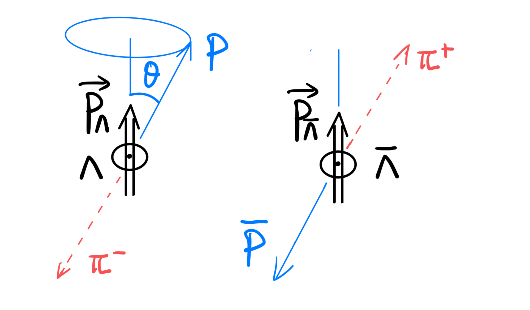
$$\Lambda \to p + \pi^-$$
$$\bar{\Lambda} \to \bar{p} + \pi^+$$

Anisotropic Angular Distribution:

$$\frac{dN_\Lambda}{N_\Lambda d\cos\theta} = \frac{1}{2}\left(1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{p}_p\right)$$
$$\frac{dN_{\bar{\Lambda}}}{N_{\bar{\Lambda}} d\cos\theta} = \frac{1}{2}\left(1 + \alpha_{\bar{\Lambda}} \vec{P}_{\bar{\Lambda}} \cdot \hat{p}_{\bar{p}}\right)$$

- Asymmetry parameter $\alpha_\Lambda \simeq -\alpha_{\bar{\Lambda}} = 0.75$
- Proton predominantly is going off in the direction of the spin of the Lambda.

Self-Analyzing Property



- Weak decay violates parity.
- Proton direction reveals Λ spin direction