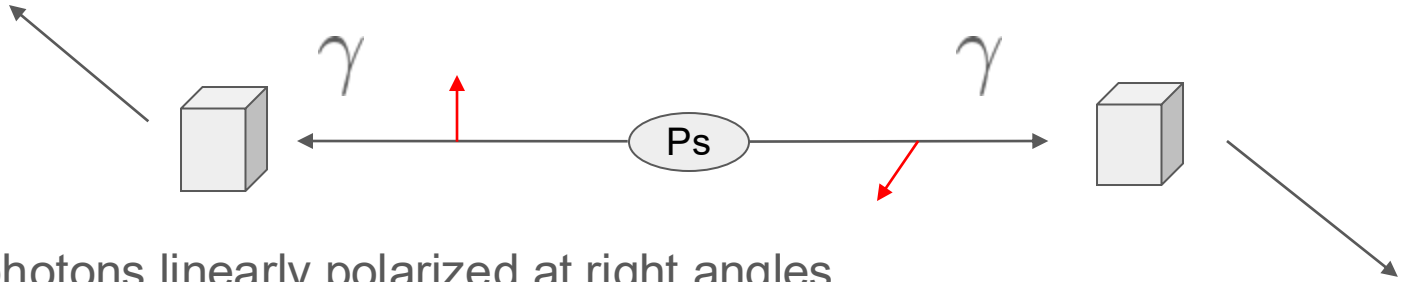
Spin-spin entanglement at the EIC

Yoshitaka Hatta
BNL/RIKEN BNL

PacSpin2026, Oct.27-30, 2026, Academia Sinica

The Wu-Shaknov experiment (1949)



Two photons linearly polarized at right angles.

$$\frac{1}{\sqrt{2}}(|x\rangle|y\rangle - |y\rangle|x\rangle)$$

Maximally entangled Bell state

The Angular Correlation of Scattered Annihilation Radiation*

C. S. Wu and I. Shaknov
Pupin Physics Laboratories, Columbia University, New York, New York
November 21, 1949

As early as 1946, J. A. Wheeler[1] proposed an experiment to verify a prediction of pair theory, that the two quanta emitted in the annihilation of a positron-electron pair, with zero relative angular momentum, are polarized at right angles to each other. This suggestion involves coincidence measurements of the scattering of both the annihilation photons at various azimuths. The detailed theoretical investigations were reported

Quantum entanglement at the LHC

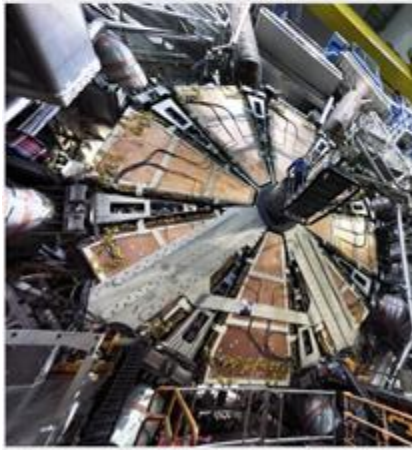
SCIAM $1 for 90 days

SEPTEMBER 25, 2024 | 4 MIN READ

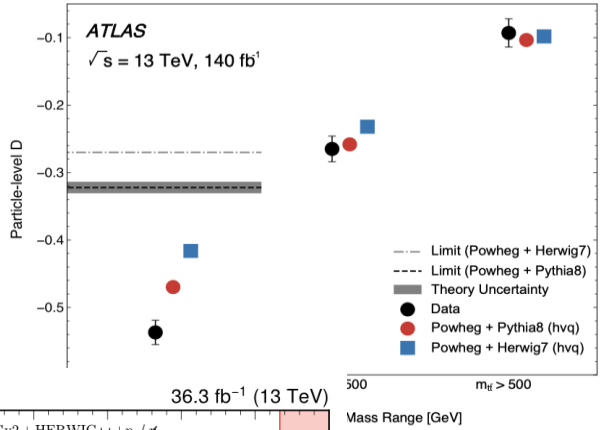
'Spooky Action at a Distance' Observed in Quarks for the First Time

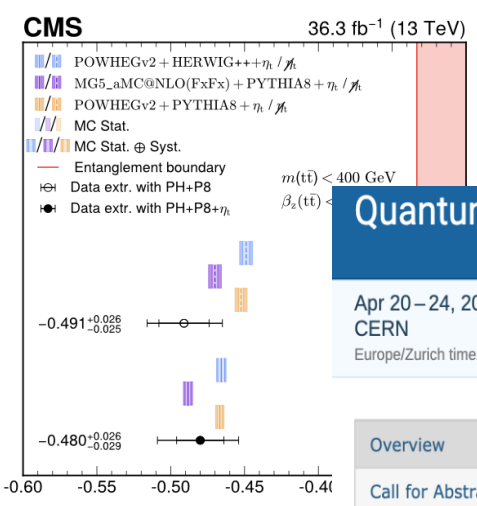
Physicists report the first observations of quantum entanglement in top and anti-top quarks, the heaviest known fundamental particles and their antimatter counterparts, inside the Large Hadron Collider

BY DAN GARISTO & NATURE MAGAZINE



The ATLAS detector, part of the Large Hadron Collider, sits 100 m… it measures various properties of high-energy particles. Maximilien Brice/CERN





Voir en Français

LHC experiments at CERN observe quantum entanglement at the highest energy yet

The results open up a new perspective on the complex world of quantum physics

18 SEPTEMBER, 2024



Artist's impression of a quantum-entangled pair of top quarks. (Image: CERN)

Quantum Observables for Collider Physics 2026

Apr 20 – 24, 2026
CERN
Europe/Zurich timezone

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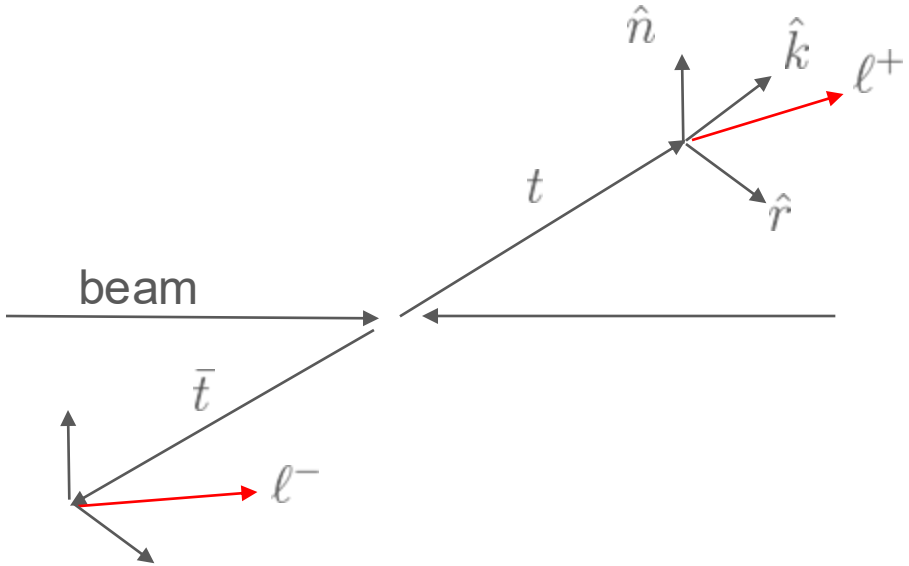
Please note that registration for this workshop is restricted to invited participants only; general applications for attendance are not being accepted at this time.

The workshop aims at gathering theorists and experimentalists interested in measuring quantum

Entanglement in $t\bar{t}$ production at the LHC

Angular correlation of leptons in their respective rest frames

$$\frac{d\sigma}{d\cos\varphi} \propto 1 - (\alpha_+)^2 \frac{\mathrm{Tr}[C]}{3} \cos\varphi$$



The pair is entangled if $D = \frac{1}{3}\mathrm{Tr}[C] < -\frac{1}{3}$

And at RHIC, BESIII, Belle-II, FCC,...

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Article | Open access | Published: 28 May 2025

Test of local realism via entangled $\Lambda\bar{\Lambda}$ system

BESIII Collaboration

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Measuring spin correlation between quarks during QCD confinement

STAR Collaboration

Nature 650, 65–71 (2026) | Cite this article

complex structure, characterized by
ual quark–antiquark pairs. The

Quantum information meets high-energy physics: input to the update of the European strategy for particle physics

Review | Open access | Published:

Volume 140, article number 855 (2

BELLE II OPENS NEW ROUTE TO PROBING MATTER–ANTIMATTER ASYMMETRY

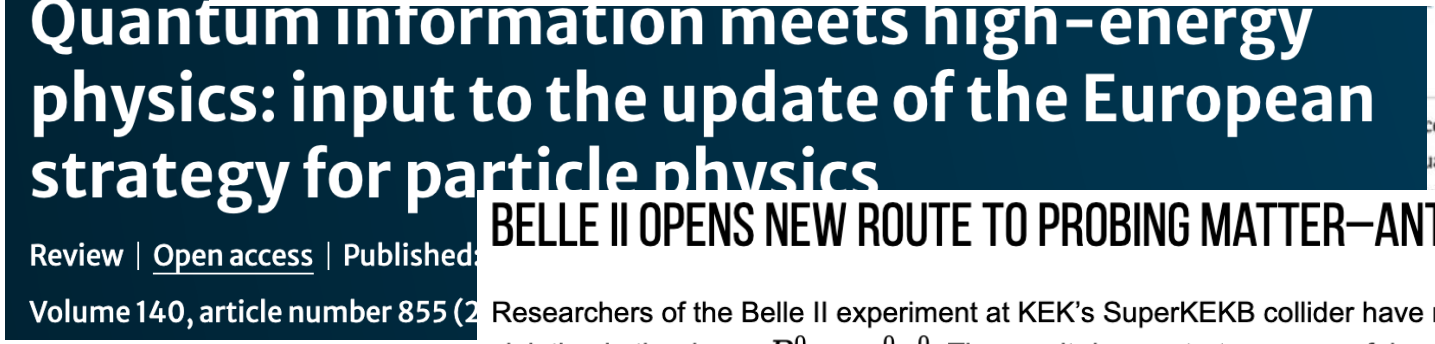
Researchers of the Belle II experiment at KEK's SuperKEKB collider have made the first measurement of time violation in the decay $B^0 \to \pi^0\pi^0$. The result demonstrates a powerful new method that significantly extends differences between matter and antimatter.

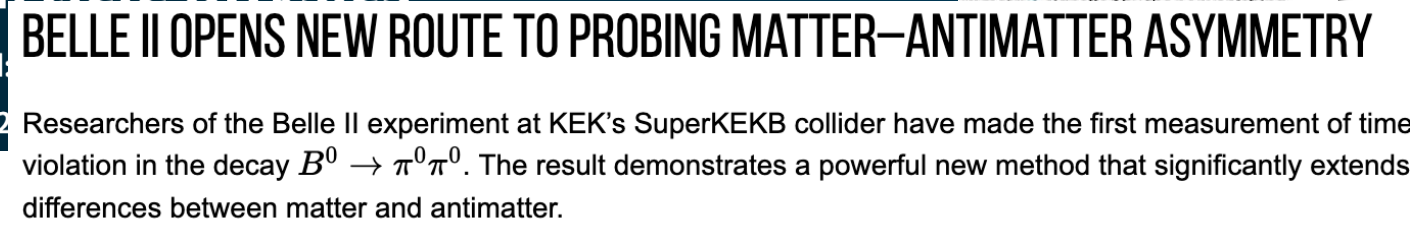
And at RHIC, BESIII, Belle-II, FCC,...





Why not at the EIC? Of course we can!





Preliminaries

Classical bit: 0 or 1

Qubit: Superposition of 0 and 1 $|\psi\rangle = a|0\rangle + b|1\rangle$ $|a|^2 + |b|^2 = 1$

Elementary particles (electron, quark, photon, proton...) are qubits/qutrits

A two-qubit system can be entangled

$|\psi\rangle = |0\rangle|1\rangle$ not entangled (separable)

$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|0\rangle|1\rangle - |1\rangle|0\rangle)$ entangled (Bell state)

Spin density matrix

At colliders, qubit pairs are produced millons of times with different spin states
→ mixed states described by the density matrix

$$\rho = \frac{1}{2}|00\rangle\langle 00| + \frac{1}{2}|11\rangle\langle 11|$$ mixed, not entangled

$$\rho = \frac{1}{2}(|01\rangle\langle 01| - |01\rangle\langle 10| - |10\rangle\langle 01| + |10\rangle\langle 10|) = |\Psi^-\rangle\langle\Psi^-|$$ pure, entangled

Most general density matrix for 2-qubit systems (15 unknown parameters)

$$\rho = \frac{1}{4}\left(\mathbb{I}\otimes\mathbb{I} + B^a\sigma^a\otimes\mathbb{I} + \bar{B}^b\mathbb{I}\otimes\sigma^b + C^{ab}\sigma^a\otimes\sigma^b\right)$$

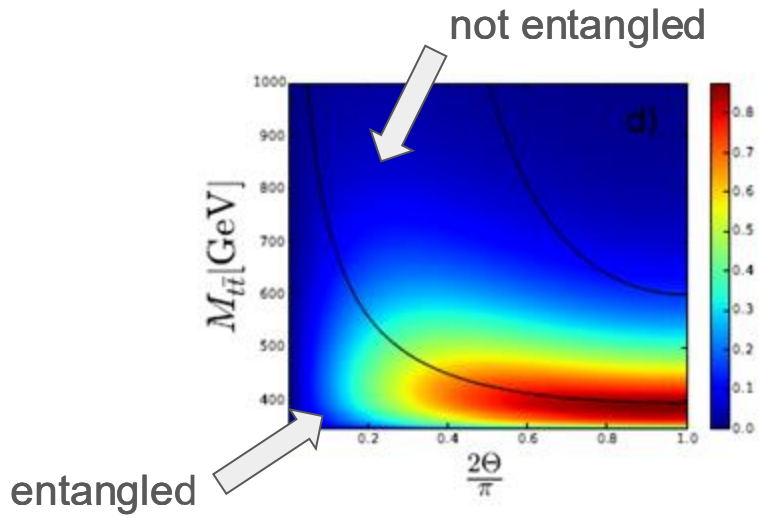
Peres-Horodecki criterion

The two qubits are entangled if and only if the partially transposed density matrix

$$\rho^{\mathcal{T}} \equiv \frac{1}{4}\left(\mathbb{1}\otimes\mathbb{1}^{\mathcal{T}} + B_a\sigma^a\otimes\mathbb{1}^{\mathcal{T}} + \bar{B}_b\mathbb{1}\otimes(\sigma^b)^{\mathcal{T}} + C_{ab}\sigma^a\otimes(\sigma^b)^{\mathcal{T}}\right)$$

has a negative eigenvalue $\lambda_{\min} < 0$

Density matrix calculable in perturbation theory
Entanglement is an observable.



Bell-nonlocality

Bell-Clauser-Horne-Shimony-Holt (CHSH) inequality

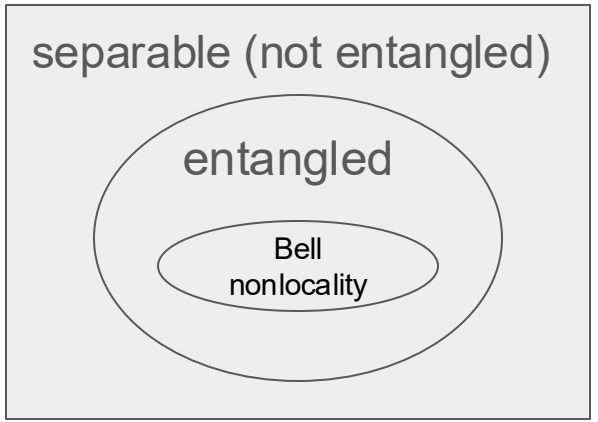
$$\left| n_1^i C_{ij} (n_2^j + n_4^j) + n_3^i C_{ij} (n_2^j - n_4^j) \right| \leq 2$$

This is violated for certain choices of n's if the largest two eigenvalues of $C^T C$ satisfy

Horodecki, Horodecki, Horodecki (1995)

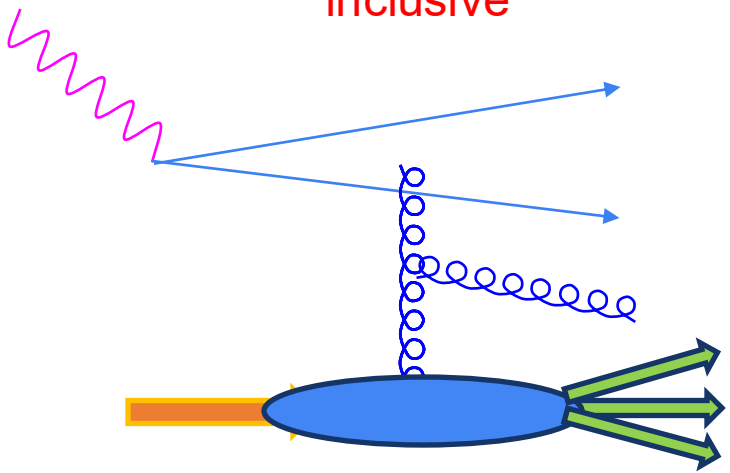
$$\mu_1 + \mu_2 > 1 \quad \rightarrow \text{`Bell nonlocality'}$$

In general, Bell nonlocality requires deeper quantum correlation than entanglement



Dijet ($q\bar{q}$) production in ep, eA, UPC

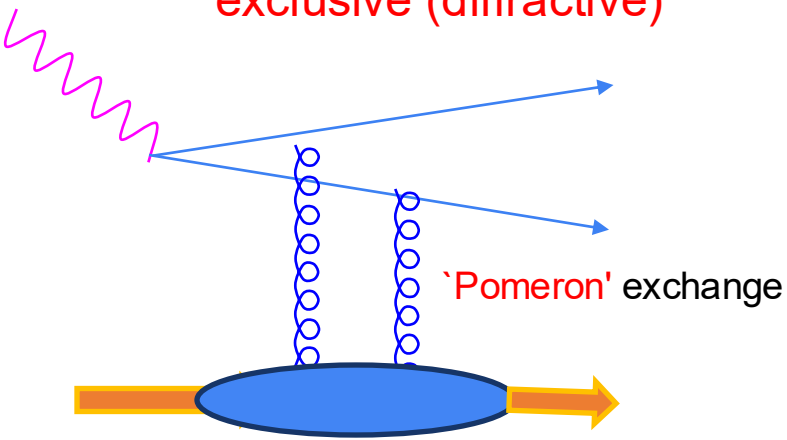
inclusive



Larger cross section
Messier environment

Qi, Guo, Xiao, 2506.12889
Fucilla, YH, Xiao, 2604.11697

exclusive (diffractive)



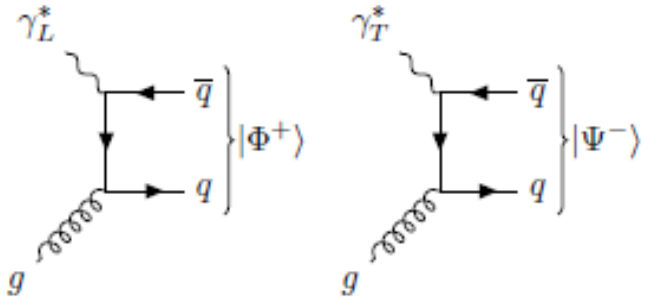
Smaller cross section
Cleaner environment

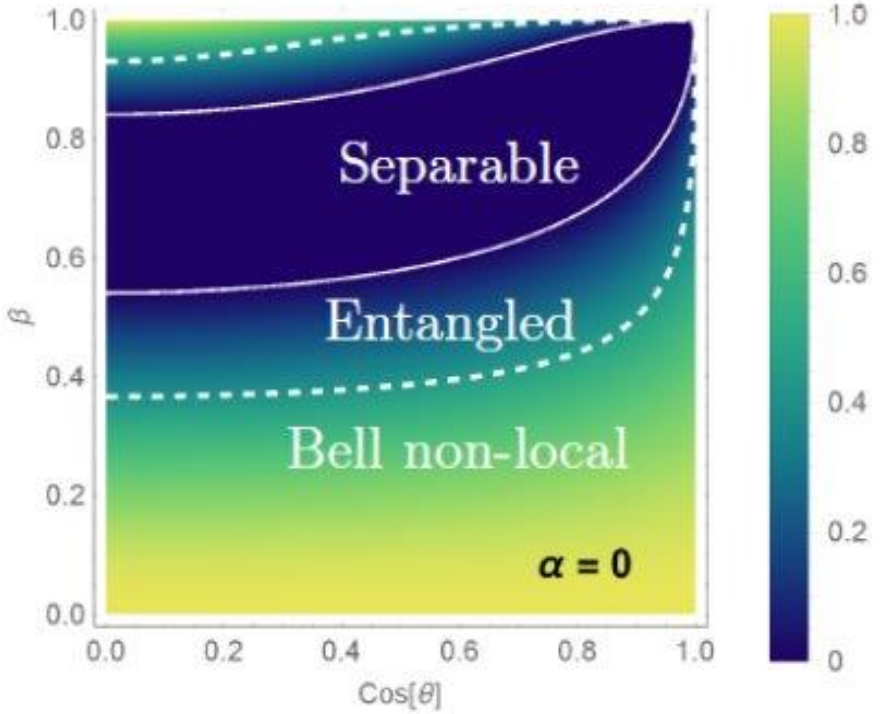
Fucilla, YH, 2509.05267
YH, Schoenleber, 2511.04537

Inclusive quark-antiquark production in DIS

Spin density matrix in one-gluon exchange

Qi, Guo, Xiao, 2506.12889





Longitudinal photon:
Always maximally entangled and
maximally violates Bell-CHSH inequality

Transverse photon:

Bell nonlocality $\subset$ entanglement

Exclusive dijet, the Regge limit

Fucilla, YH, 2509.05267

Longitudinal case: the same as before
→ maximal entanglement/Bell nonlocality

Transverse case:

$$\begin{pmatrix} C_{nn} & 0 & 0 \\ 0 & C_{rr} & C_{rk} \\ 0 & C_{kr} & C_{kk} \end{pmatrix}$$

Density matrix depends on the (G)TMD gluon distribution of the target.

$$\widetilde{C}^T_{nn} = -\frac{4\alpha_{em}e_q^2}{N_c} z\bar{z}k_\perp^2 (T_1+T_2)^2,$$

$$\begin{aligned}\widetilde{C}^T_{rr} &= \frac{\alpha_{em}e_q^2}{2z\bar{z}N_c}\Big[2T_1(T_1+T_2)k_\perp m\sqrt{1-\beta^2}\sin\theta(\beta+(1-2z)\cos\theta)+T_1^2m^2\left(1-\beta^2\right)\sin^2\theta \\ &\quad -(T_1+T_2)^2k_\perp^2\Big(\left(1-\beta^2\right)\sin^2\theta+2z(1-z)\left(\left(2-\beta^2\right)\cos^2\theta-1\right)\Big)\Big],\end{aligned}$$

$$\begin{aligned}\widetilde{C}^T_{kk} &= \frac{\alpha_{em}e_q^2}{2z\bar{z}N_c}\Big[2T_1(T_1+T_2)k_\perp m\sqrt{1-\beta^2}\sin\theta(\beta-(1-2z)\cos\theta)+T_1^2m^2\left(\cos^2\theta-\beta^2\right) \\ &\quad +(T_1+T_2)^2k_\perp^2\Big(\beta^2-2z(1-z)+\cos^2\theta\big(2z(1-z)\left(2-\beta^2\right)-1\big)\Big)\Big],\end{aligned}$$

$$\begin{aligned}\widetilde{C}^T_{rk} &= \frac{\alpha_{em}e_q^2}{2z\bar{z}N_c}\Big[2T_1(T_1+T_2)k_\perp m\left(z-\beta^2+\cos^2\theta\left(1-\left(2-\beta^2\right)z\right)\right) \\ &\quad +\sqrt{1-\beta^2}\sin\theta\left(T_1^2m^2(\cos\theta-\beta)+(T_1+T_2)^2k_\perp^2\left(\beta-(1-2z)^2\cos\theta\right)\right)\Big],\end{aligned}$$

$$\begin{aligned}\widetilde{C}^T_{kr} &= \frac{\alpha_{em}e_q^2}{2z\bar{z}N_c}\Big[2T_1(T_1+T_2)k_\perp m\left(z-\left(1-\beta^2\right)\sin^2\theta-\left(2-\beta^2\right)z\cos^2\theta\right) \\ &\quad +\sqrt{1-\beta^2}\sin\theta\left(T_1^2m^2(\beta+\cos\theta)-(T_1+T_2)^2k_\perp^2\left(\beta+(1-2z)^2\cos\theta\right)\right)\Big].\end{aligned}$$

Exclusive dijet, the Regge limit

Fucilla, YH, 2509.05267

Longitudinal case: the same as before
→ maximal entanglement/Bell nonlocality

$$\widetilde{C}^T_{nn} = -\frac{4\alpha_{em}e_q^2}{N_c} z\bar{z}k_\perp^2 (T_1+T_2)^2,$$

Tran

$$C^2_{nn} + C^2_{rk} + C^2_{kr} + C^2_{kk} - C^2_{nn} = 1$$

$$C_{nn} = -C_{rr}C_{kk} + C_{kr}C_{rk}$$

$$\begin{pmatrix} & & \\ & & \\ 0 & C_{kr} & C_{kk} \end{pmatrix}$$

$\sin^2\theta$

$-\beta^2)$

$$\widetilde{C}^T_{rk} = \frac{\alpha_{em}e_q^2}{2z\bar{z}N_c}\Big[2T_1(T_1+T_2)k_\perp m\left(z-\beta^2+\cos^2\theta\left(1-\left(2-\beta^2\right)z\right)\right)$$
$$+\sqrt{1-\beta^2}\sin\theta\left(T_1^2m^2(\cos\theta-\beta)+(T_1+T_2)^2k_\perp^2\left(\beta-(1-2z)^2\cos\theta\right)\right)\Big],$$

Density matrix depends on the (G)TMD gluon distribution of the target.

$$\widetilde{C}^T_{kr} = \frac{\alpha_{em}e_q^2}{2z\bar{z}N_c}\Big[2T_1(T_1+T_2)k_\perp m\left(z-\left(1-\beta^2\right)\sin^2\theta-\left(2-\beta^2\right)z\cos^2\theta\right)$$
$$+\sqrt{1-\beta^2}\sin\theta\left(T_1^2m^2(\beta+\cos\theta)-(T_1+T_2)^2k_\perp^2\left(\beta+(1-2z)^2\cos\theta\right)\right)\Big].$$

Entanglement = Bell nonlocality in the Regge limit

Fucilla, YH, 2509.05267

Entanglement (Peres-Horodecki)

$$\max(\Delta_1, \Delta_2) > 0$$

$$\Delta_1 = \sqrt{(C^T_{rr} - C^T_{kk})^2 + (C^T_{rk} + C^T_{kr})^2} - 1 + C^T_{nn},$$

$$\Delta_2 = \sqrt{(C^T_{rr} + C^T_{kk})^2 + (C^T_{rk} - C^T_{kr})^2} - 1 - C^T_{nn}.$$

Bell nonlocality (Horodecki^3)

$$1 < \mu_1 + \mu_2 \leq 2$$

Largest two of C^2_{nn}

$$\frac{C^2_{rr} + C^2_{kr} + C^2_{kk} + C^2_{rk} \pm \sqrt{\left(C^2_{rr} + C^2_{kr} - C^2_{kk} - C^2_{rk}\right)^2 + 4\left(C_{rr}C_{rk} + C_{kr}C_{kk}\right)^2}}{2}$$

Entanglement = Bell nonlocality in the Regge limit

Fucilla, YH, 2509.05267

Entanglement (Peres-Horodecki)

$$\max(\Delta_1, \Delta_2) > 0$$

$$\Rightarrow C_{nn} \neq 0$$

$$\Delta_1 = \sqrt{(C^T_{rr} - C^T_{kk})^2 + (C^T_{rk} + C^T_{kr})^2} - 1 + C^T_{nn},$$

$$\Delta_2 = \sqrt{(C^T_{rr} + C^T_{kk})^2 + (C^T_{rk} - C^T_{kr})^2} - 1 - C^T_{nn}.$$

Bell nonlocality (Horodecki^3)

$$1 < \mu_1 + \mu_2 \leq 2$$

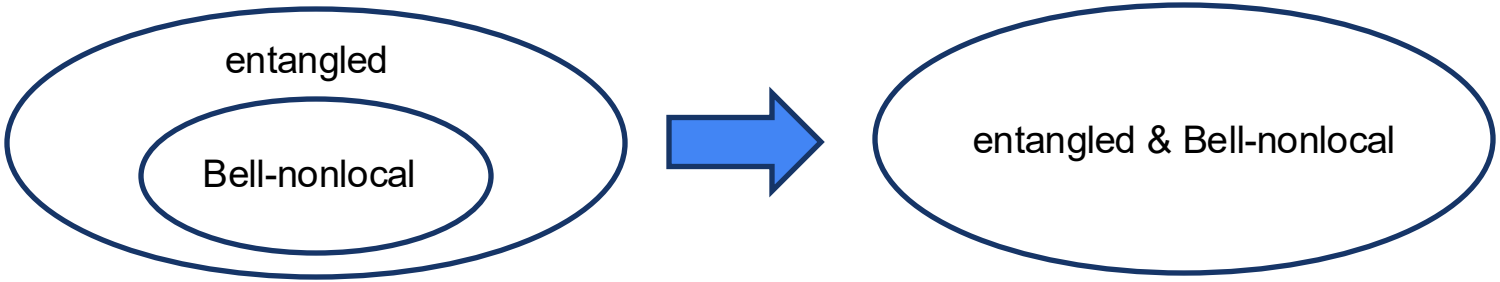
$$\Rightarrow C_{nn} \neq 0$$

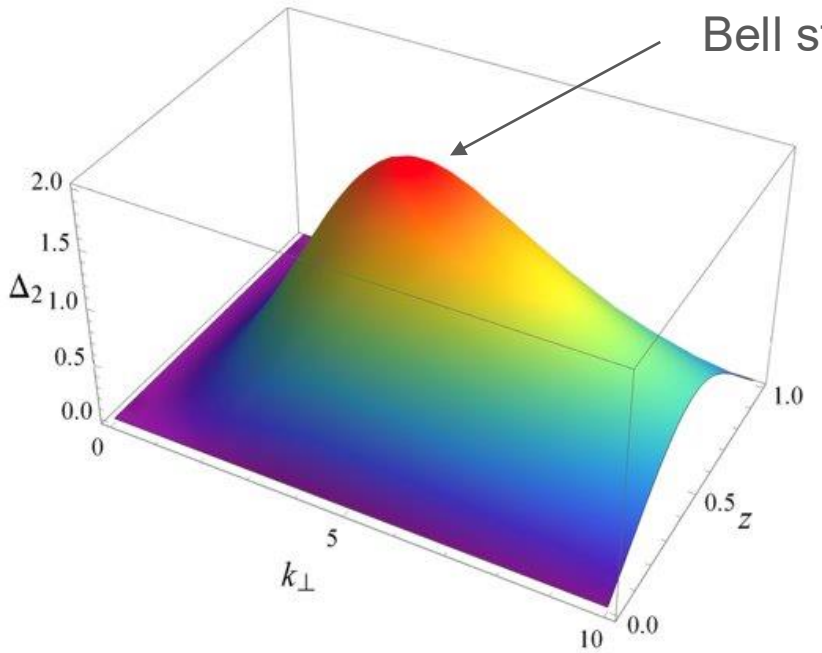
Largest two of C^2_{nn}

$$\frac{C^2_{rr} + C^2_{kr} + C^2_{kk} + C^2_{rk} \pm \sqrt{\left(C^2_{rr} + C^2_{kr} - C^2_{kk} - C^2_{rk}\right)^2 + 4\left(C_{rr}C_{rk} + C_{kr}C_{kk}\right)^2}}{2}$$

The two conditions become identical.

Entanglement and Bell nonlocality necessary and sufficient





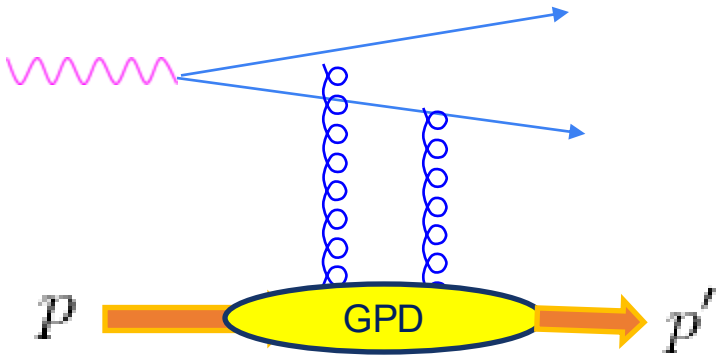
$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle_q^n|-\rangle_{\bar{q}}^n - i|-\rangle_q^n|+\rangle_{\bar{q}}^n\right)$$

Everywhere entangled,
Everywhere Bell-nonlocal

Maximal entanglement/Bell nonlocality
at one point in phase space

Spin density matrix in collinear factorization + GPD

YH, Schoenleber, 2511.04537



$$I_L^g = \int_{-1}^{1} dx F_g(x,\xi)\left(\frac{4\xi(1-\beta)(x^2+\xi^2)}{(x^2-\xi^2+i\epsilon)^2} - \frac{2\xi(1-2\beta)}{x^2-\xi^2+i\epsilon}\right)$$

GPD

$$C_{nn}^T = \frac{(|X|^2-|Y|^2)k_\perp^2}{k_\perp^2(|X|^2+|Y|^2)+2m^2|I_L^g|^2}$$

$$C_{rr}^T = \frac{k_\perp^2}{k_\perp^2(|X|^2+|Y|^2)+2m^2|I_L^g|^2}\left[-\frac{k_\perp^2-(1-2z)^2m^2}{k_\perp^2+(1-2z)^2m^2}|X|^2+\frac{k_\perp^2-m^2}{k_\perp^2+m^2}|Y|^2 + \frac{8z\bar{z}m^4|I_L^g|^2}{(k_\perp^2+(1-2z)^2m^2)(k_\perp^2+m^2)} + 4m^2\left(-\frac{(1-2z)\mathrm{Re}[XI_L^{g*}]}{k_\perp^2+(1-2z)^2m^2}+\frac{\mathrm{Re}[YI_L^{g*}]}{k_\perp^2+m^2}\right)\right],$$

$$C_{kk}^T = \frac{1}{k_\perp^2(|X|^2+|Y|^2)+2m^2|I_L^g|^2}\left[k_\perp^2\frac{k_\perp^2-(1-2z)^2m^2}{k_\perp^2+(1-2z)^2m^2}|X|^2+k_\perp^2\frac{k_\perp^2-m^2}{k_\perp^2+m^2}|Y|^2 - \frac{2m^2(k_\perp^4-(1-2z)^2m^4)|I_L^g|^2}{(k_\perp^2+(1-2z)^2m^2)(k_\perp^2+m^2)} + 4m^2k_\perp^2\left(\frac{(1-2z)\mathrm{Re}[XI_L^{g*}]}{k_\perp^2+(1-2z)^2m^2}+\frac{\mathrm{Re}[YI_L^{g*}]}{k_\perp^2+m^2}\right)\right],$$

$$C_{rk}^T = \frac{2k_\perp m}{k_\perp^2(|X|^2+|Y|^2)+2m^2|I_L^g|^2}\left[\frac{(1-2z)k_\perp^2|X|^2}{k_\perp^2+(1-2z)^2m^2}+\frac{k_\perp^2|Y|^2}{k_\perp^2+m^2} - \frac{2(1-z)m^2(k_\perp^2+(1-2z)m^2)|I_L^g|^2}{(k_\perp^2+m^2)(k_\perp^2+(1-2z)^2m^2)} - \frac{k_\perp^2-(1-2z)^2m^2}{k_\perp^2+(1-2z)^2m^2}\mathrm{Re}[XI_L^{g*}] - \frac{k_\perp^2-m^2}{k_\perp^2+m^2}\mathrm{Re}[YI_L^{g*}]\right],$$

$$C_{kr}^T = \frac{2k_\perp m}{k_\perp^2(|X|^2+|Y|^2)+2m^2|I_L^g|^2}\left[\frac{(1-2z)k_\perp^2|X|^2}{k_\perp^2+(1-2z)^2m^2}-\frac{k_\perp^2|Y|^2}{k_\perp^2+m^2} + \frac{2zm^2(k_\perp^2-(1-2z)m^2)|I_L^g|^2}{(k_\perp^2+m^2)(k_\perp^2+(1-2z)^2m^2)} - \frac{k_\perp^2-(1-2z)^2m^2}{k_\perp^2+(1-2z)^2m^2}\mathrm{Re}[XI_L^{g*}] + \frac{k_\perp^2-m^2}{k_\perp^2+m^2}\mathrm{Re}[YI_L^{g*}]\right].$$

Entanglement and Bell-nonlocality in DIS

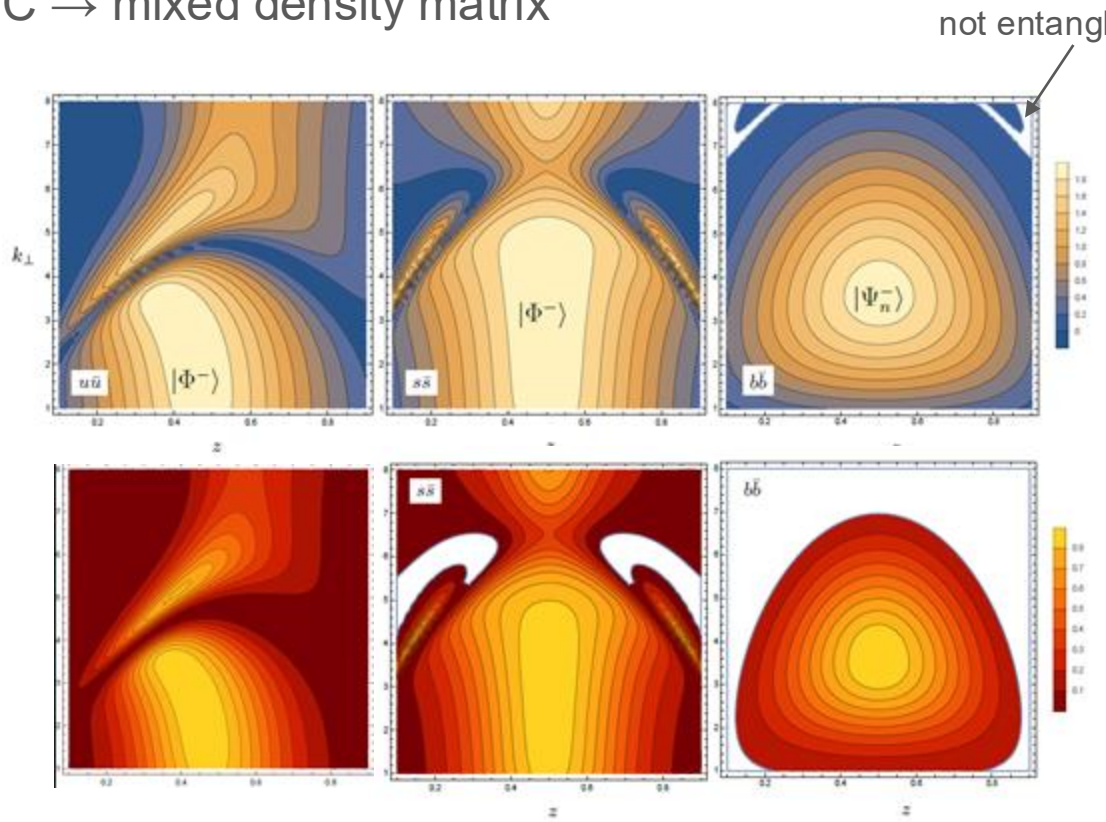
2511.04537

L/T separation challenging at EIC → mixed density matrix

$Q = 10$ GeV, $W = 30$ GeV

Pairs almost everywhere entangled

Bell nonlocality not everywhere seen for massive quarks



Quantum tomography

Quantum tomography

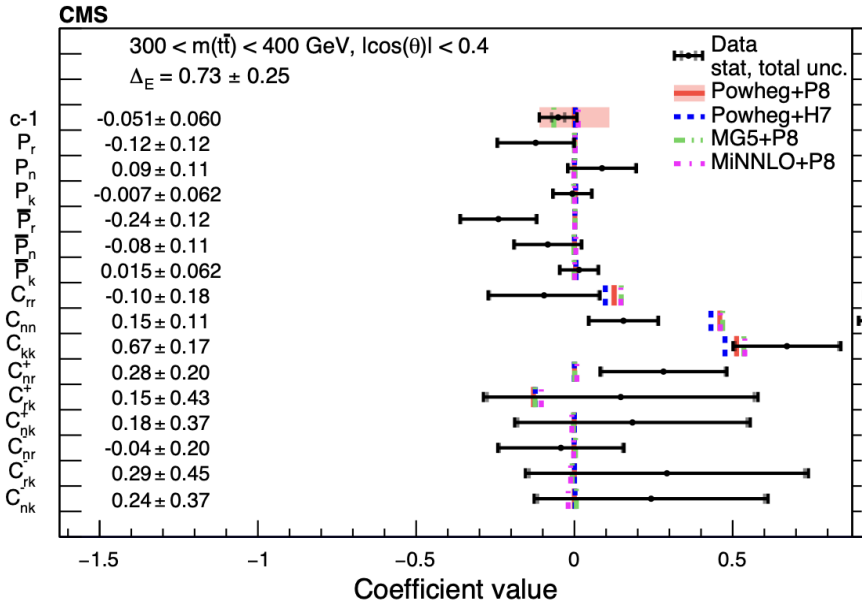
3 languages

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From Wikipedia, the free encyclopedia

Quantum tomography or **quantum state tomography** is the process by which a quantum state is reconstructed using measurements on an ensemble of identical quantum states.[1]

All 15 unknowns of the density matrix for ttbar pairs determined by the CMS collaboration!



Self-analyzing weak decays?

How does quark-level entanglement survive in observables?

Fragmentation into heavy baryons and their weak decay

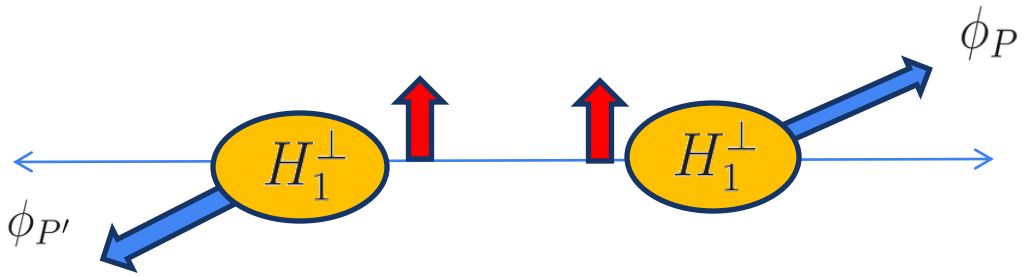
$$b \xrightarrow{7.0\%} \Lambda_b \xrightarrow{11\%} X_c^+ + \mu^- + \bar{\nu}_\mu,$$
$$c \xrightarrow{6.4\%} \Lambda_c^+ \xrightarrow{3.5\%} \Lambda + \mu^+ + \nu_\mu,$$
$$s \xrightarrow{2.8\%} \Lambda \xrightarrow{64\%} p + \pi^-,$$

Suppression factor by $10^{-4} \sim 10^{-6}$, too high price to pay for exclusive production whose cross section is in the picoban range.

Only works for massive quarks.

Single and dihadron fragmentation functions

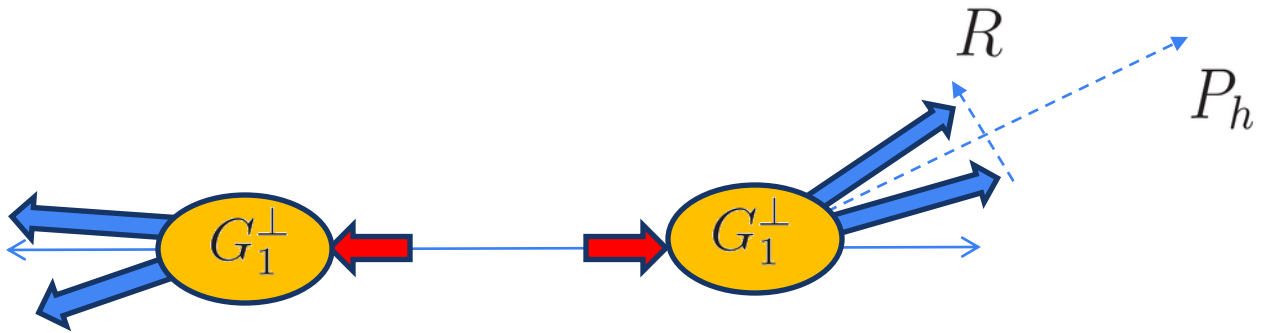
Measure angular correlations resulting from Collins FF in the CM frame



$$C^{xx} \sin\phi_P \sin\phi_{P'} + C^{yy} \cos\phi_P \cos\phi_{P'}$$

In e+e- annihilation, $C^{xx} \approx -C^{yy}$ $\longrightarrow$ $\cos(\phi_P + \phi_{P'})$

Dihadron TMD FF

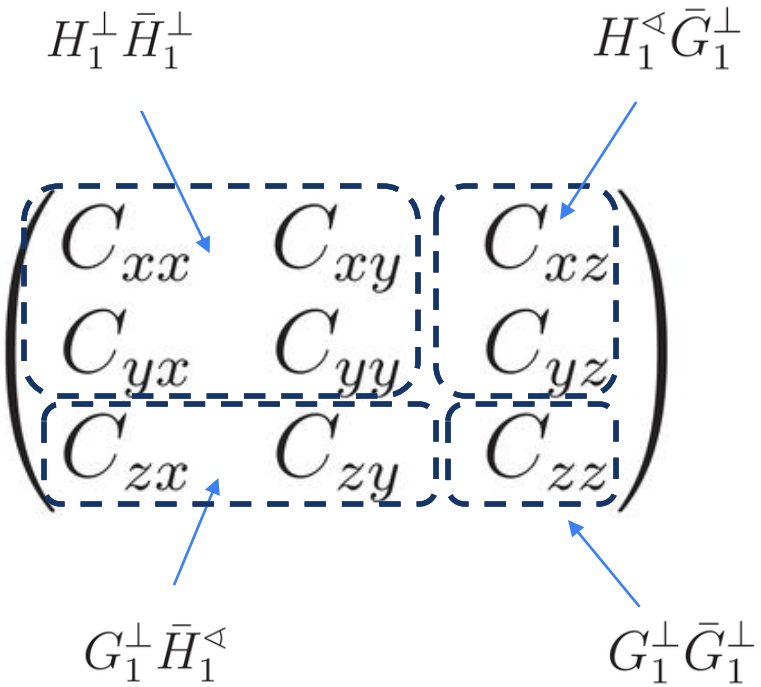


$$\gamma^- D_1^{h_1 h_2/q}(z,\zeta,P_h,R) + \gamma^-\gamma_5 \frac{\epsilon^{ij} R_\perp^i k_\perp^j}{M_1 M_2} G_1^{\perp h_1 h_2/q}(z,\zeta,P_h,R)$$

$$+i\sigma^{i-}\gamma_5 \left(H_1^{\sphericalangle h_1 h_2/q}(z,\zeta,P_h,R) \frac{\epsilon^{ij} R_\perp^j}{M_1+M_2} + H_1^{\perp h_1 h_2/q}(z,\zeta,P_h,R) \frac{\epsilon^{ij} k_\perp}{M_1+M_2} \right)$$

$$C_{\rm DIS}^{zz} G_1^{\perp(1)}(z) \bar{G}_1^{\perp(1)}(z') \sin(\phi_{RP}) \sin(\phi'_{RP})$$

Quantum tomography at the EIC



Fucilla, Guo, YH, 2609.32800

Complete reconstruction of the spin density matrix possible at the EIC

New class of observables sensitive to TMD and GPD of the target.

Density matrix --> QIS observables

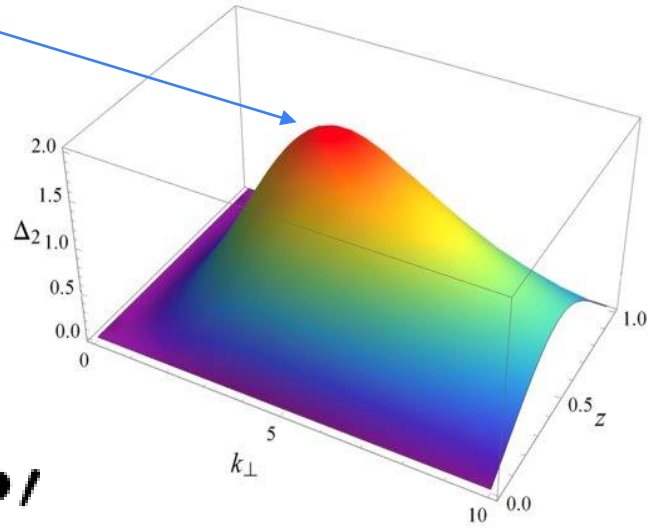
Exotic Collins asymmetry of D, B-mesons at the EIC

Fucilla, Guo, YH, 2609.32800

$$C^{xx} \sin\phi_P \sin\phi_{P'} + C^{yy} \cos\phi_P \cos\phi_{P'}$$

At this point

$$C^{xx} = 0$$



$$\cos(\phi_P + \phi_{P'})$$

$$\Rightarrow \quad \cos\phi_P \cos\phi_{P'}$$

Conclusions

Quantum entanglement at the EIC: novel topic beyond the NAS & Yellow report.

Initial polarization(s) makes entanglement pattern richer.

Cheng, Han, Trifinopoulos 2510.23773

YH, Martinez-Fernandez, 2608.05330 (Compton)

Cao, Guo, YH, Schoenleber, 2608.18030 (Bethe-Heitler)

Final state entanglement sensitive to initial state proton structure
Quantum tomography meets nucleon tomography,

Appeal to broader audiences far beyond the EIC community.
Entanglement is a common language of nuclear/particle physics