Quantum Information at Lepton Colliders: From Light Quarks to Photons

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Quantum Entanglement Studies in Nuclear nad Particle Physics
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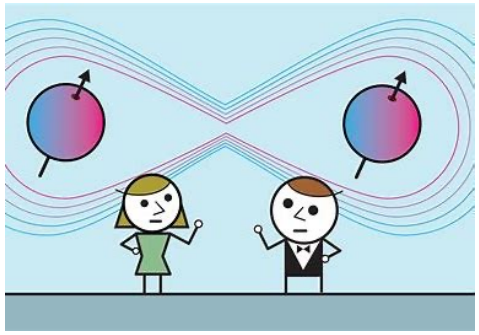
K. Cheng, B. Yan, PRL 135 (2025) 011902
Q. H. Cao, G. Li, X. K. Wen, B. Yan, Rept. Prog. Phys. 89 (2026) 080501
K. Cheng, T. Han, G. Li, B. Yan, 2606.30759

Quantum information at collider

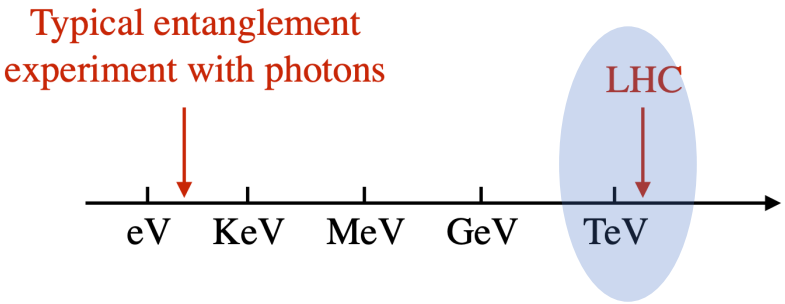
➢Quantum entanglement and non-locality are distinctive features of quantum systems



➢Collider physics: high energy and small size

Quantum information at collider

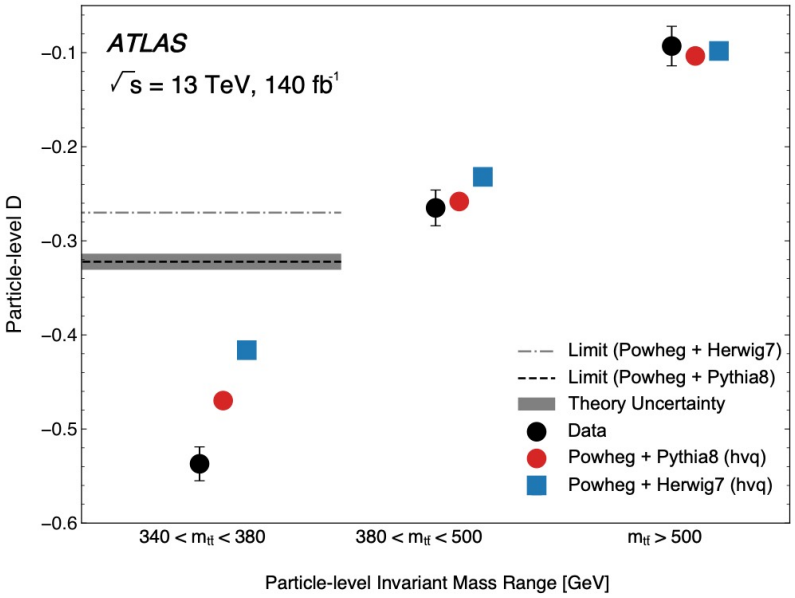
➢High energy: the scattering involves both the QCD and electroweak interactions



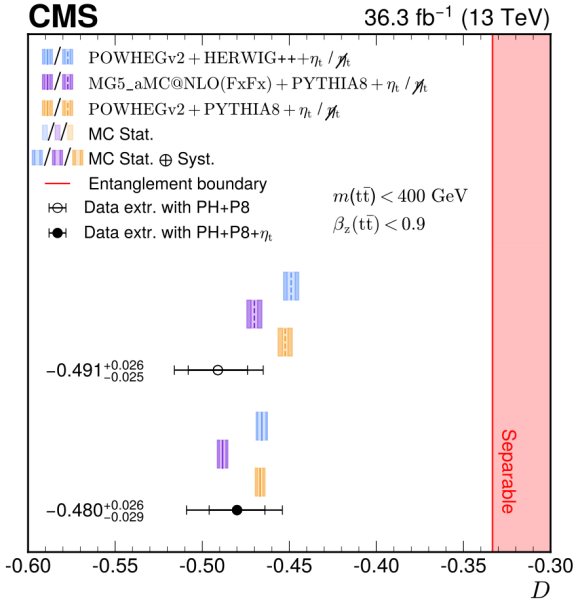
The results open up a new perspective on the complex world of quantum physics

ATLAS and CMS has observed the spin entanglement of top quark pair

Nature 633, 542 (2024)

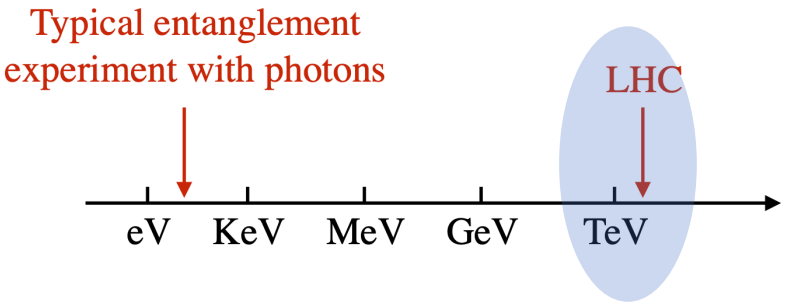


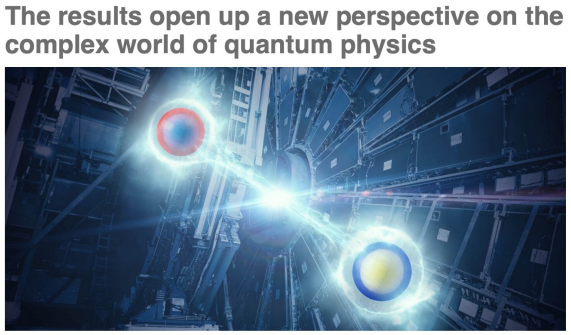
Rept. Prog. Phys. 87 (2024) 117801



Quantum information at collider

➢High energy: the scattering involves both the QCD and electroweak interactions





➢New features:

- ❑ Particle spin can not be measured directly
- ❑ New degree of freedom for spin-1 particle (Longitudinal mode)
- ❑ New features from interactions: parity violation, QCD confinement
- ❑ Entanglement beyond the spin space: flavor
- ❑ Quantum information and QCD confinement
- ❑ ……

Quantum information in high-energy physics is an emerging and rapidly growing field at the intersection of particle physics and quantum theory

Quantum spin entanglement

The spin correlation of fermion pair can be described by the general density matrix

$$\rho = \frac{I_2 \otimes I_2 + B_i \sigma_i \otimes I_2 + \bar{B}_i I_2 \otimes \sigma_i + C_{ij} \sigma_i \otimes \sigma_j}{4}$$

- $B_i, \bar{B}_i$: the polarization of each particle
- C_{ij} : the spin correlation of fermion pair

A separable state can: $\rho_{AB} = \sum_w p_w \rho_w^A \otimes \rho_w^B$, Entangled is non-separable

Entanglement can be measured by the concurrence observable

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

$$0 \leq \mathcal{C}(\rho) \leq 1$$

Seperable — Maximal entangled

λ_i: eigenvalues of matrix: $\sqrt{\sqrt{\rho}\tilde{\rho}\sqrt{\rho}}$ $\quad \tilde{\rho} = (\sigma_2 \otimes \sigma_2)\rho^*(\sigma_2 \otimes \sigma_2)$

W. K. Wootters, PRL 80 (1998) 2245

Bell inequality

- Bell (CHSH) inequality: $\hat{A}_i = \pm 1,\ \hat{B}_i = \pm 1$

$$\left|\langle \hat{A}_1\hat{B}_1\rangle + \langle \hat{A}_1\hat{B}_2\rangle + \langle \hat{A}_2\hat{B}_1\rangle - \langle \hat{A}_2\hat{B}_2\rangle\right| \le 2$$

[Clauser et al, *PRL* 23, 880 (1969)]

$$\hat{A} = \vec{a}\cdot\hat{\sigma},\quad \hat{B} = \vec{a}\cdot\hat{\sigma},\quad \langle \hat{A}\hat{B}\rangle = \vec{a}\cdot C\cdot\vec{b}$$

- Bell inequality is violated iff we can find four directions $\vec{a}_{1,2}, \vec{b}_{1,2}$ so that

$$\left|\vec{a}_1\cdot C\cdot(\vec{b}_1-\vec{b}_2) + \vec{a}_2\cdot C\cdot(\vec{b}_1+\vec{b}_2)\right| > 2$$

Fix some direction $\vec{a}_{1,2}, \vec{b}_{1,2}$

e.g. $\sqrt{2}|C_{xx} \pm C_{yy}| > 2$

Scan $\vec{a}_{1,2}, \vec{b}_{1,2}$ **to maximize**

$$\mathcal{B}[\rho] = 2\sqrt{c_1^2 + c_2^2} > 2$$

c_1^2, c_2^2 **are the largest two eigenvalue of** C^TC.

Quantum entanglement at colliders

- Top quark pair

Y. Afik, J. R. M. n. de Nova Eur. Phys. J. Plus 136, 907 (2021)
M. Fabbrichesi, R. Floreanini, G. Panizzo, PRL 127, 161801 (2021)
C. Severi. C. D. E. Boschi, F. Maltoni, and M. Sioli, EPJC 82, 285 (2022)
T. Han, M. Low, T. A. Wu, JHEP 07, 192 (2024)
T. Han, M. Low, N. McGinnis, and S. Su, 2412.21158
K. Cheng, T. Han and M. Low, 2410.08303,
…

- Tau lepton pair

M. M. Altakach et al, PRD 107, 093002 (2023)
K. Ehataht et al, PRD 109, 032005 (2024)
Y. Du, X.-G. He, C.-W. Liu and J.-P. Ma, 2409.15418
Y. Zhang et al, 2504.01496
T. Han, M. Low, Y. Su, 2501.04801
…

- Gauge boson pair

A. J. Barr et al, Quantum 7, 1070 (2023)
Q. Bi, Q.-H. Cao, K. Cheng, H. Zhang, PRD 109, 036022 (2024)
R. Ding et al, 2504.09832
…

- Flavor

K. Chen, Z. Xing, R. Zhu, 2407.19242
H. Feng. H. Tang, W. Guo Q. Qin, 2504.15798
….

- Entanglement & NP

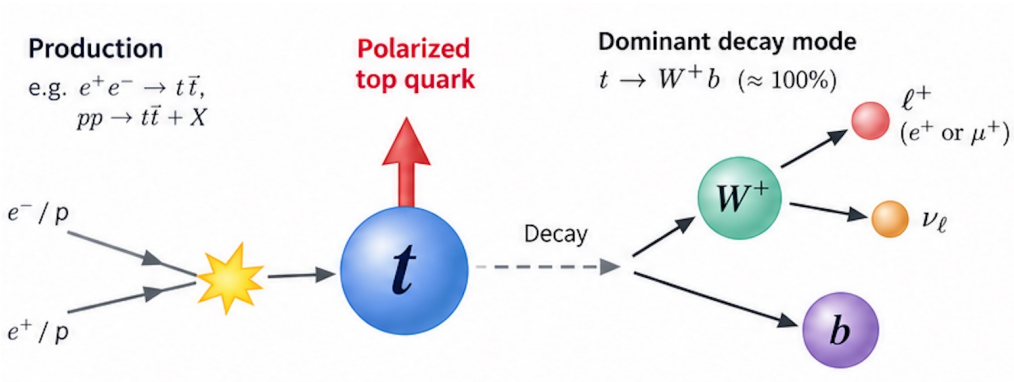
R. Aoude et al, PRD 106 (2022) 055007
M. Fabbrichesi et al, EPJC 83 (2023) 162, JHEP 09 (2023) 195
A. Bernal et al, EPJC 83 (2023) 11, 1050
…

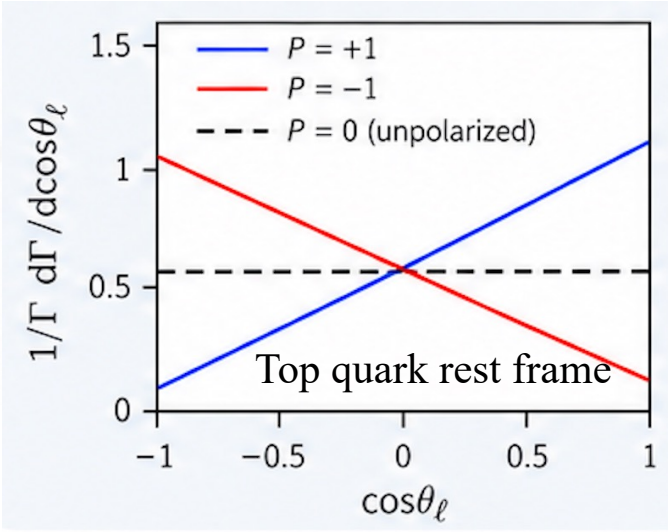
The spin correlation between particles can be measured from its decay products

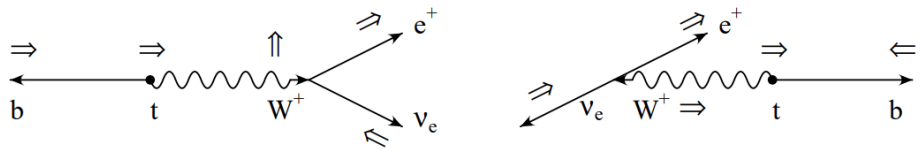
How about the stable particles, e.g. light quarks and photons?

Spin Analyzer in particle physics

- Unstable particles, decay products carry spin information





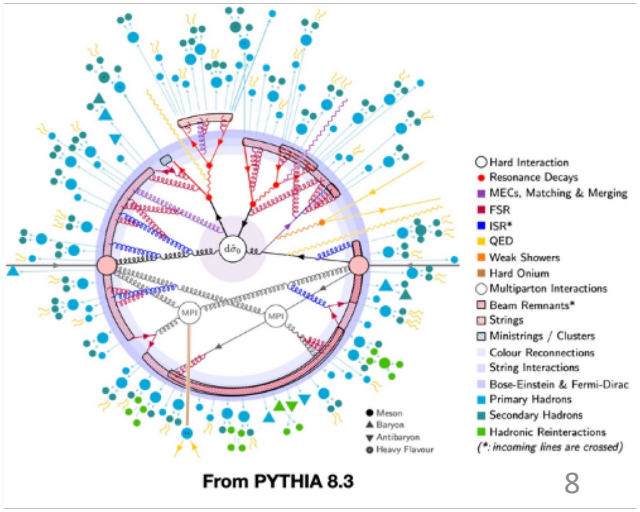


$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2}(1 + \alpha_i P \cos\theta_i)$$

Spin analyzing power

- How about light quark and gluon?

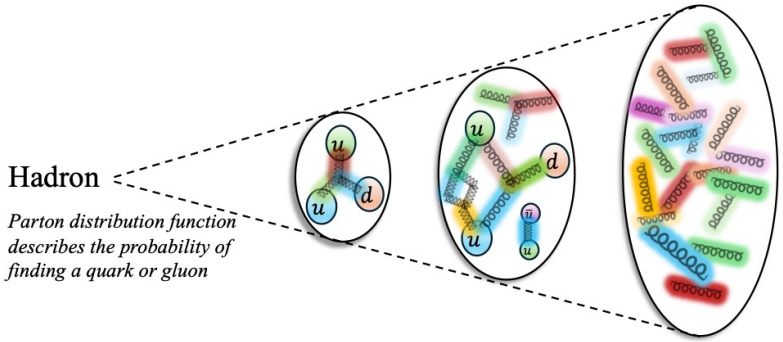
Hadronization hides spin information?

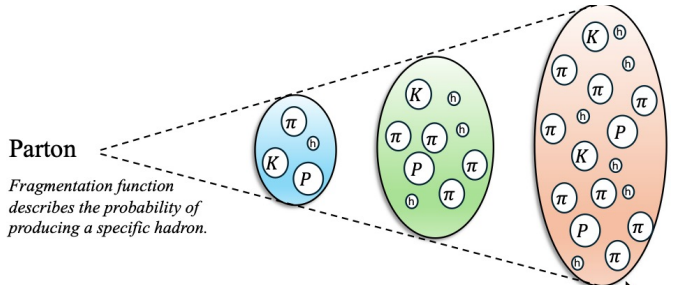


Spin Analyzer in particle physics

- Spin from nonperturbative QCD: PDFs and FFs

J. Datta et al, PRL 134 (2025) 111902





TMD factorization

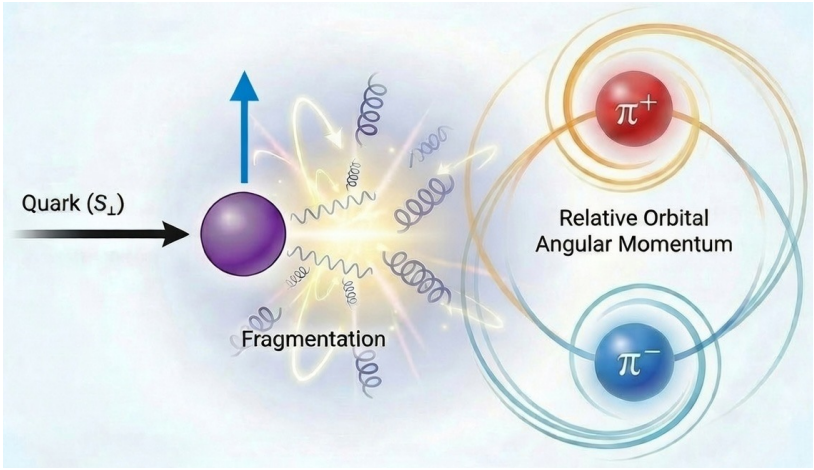
Leading Quark TMDFFs

Hadron Spin Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		D_1 = Unpolarized		$H_1^\perp$ = Collins
Polarized Hadrons	L		G_1 = Helicity	$H_{1L}^\perp$ =
	T	$D_{1T}^\perp$ = Polarizing FF	$G_{1T}^\perp$ =	H_1 = Transversity $H_{1T}^\perp$ =

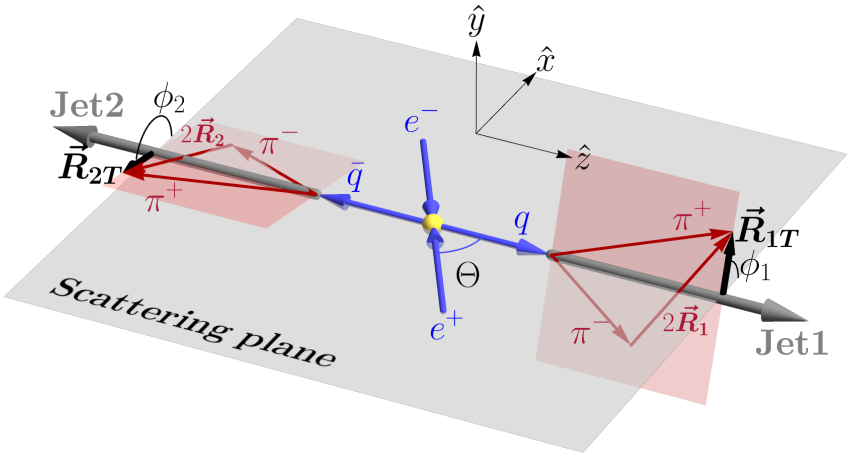
Collinear factorization

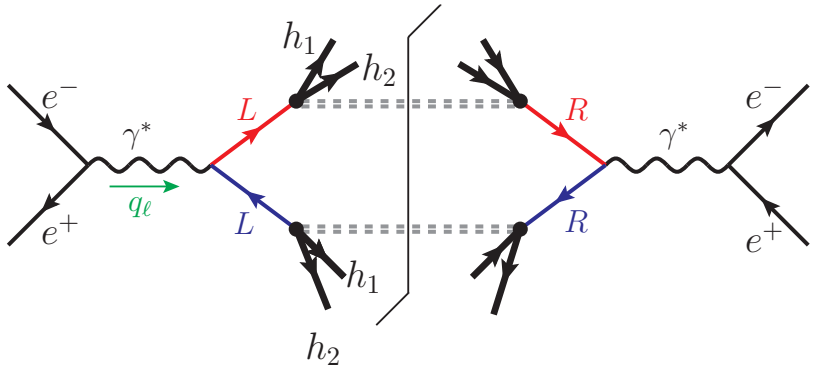
Interference Dihadron Fragmentation



Transverse spin of quark: The interference between the different helicity states

Dihadron pair production at lepton colldiers





- The transverse spin correlation between light quarks: chiral-odd interference dihadron fragmentations (collinear factorization)
- Light quark pair are 100% correlated in the central scattering region

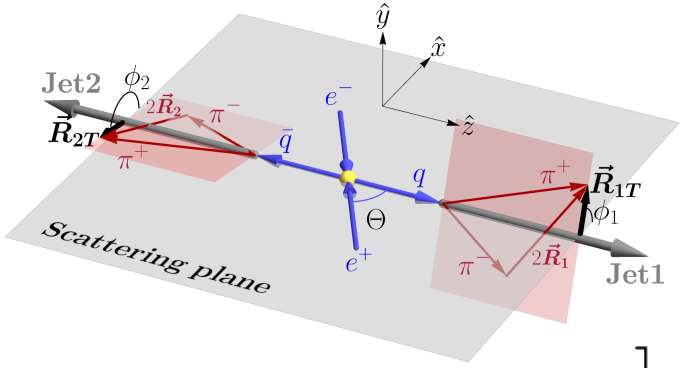
$$C_{ij} = \mathrm{diag}\left(\frac{\sin^2\Theta}{1+\cos^2\Theta}, -\frac{\sin^2\Theta}{1+\cos^2\Theta}, 1\right)$$

- The maximally entangled Bell state: Bell inequality violation effects

Kun Cheng and Bin Yan, PRL 135 (2025) 011902

Bell inequality of light quarks

J. C. Collins et al, NPB 420, 565 (1994)



Unpolarized diFF

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_1\mathrm{d}z_2\mathrm{d}M_1\mathrm{d}M_2\mathrm{d}\phi_1\mathrm{d}\phi_2} = \sigma_{\rm hard}\left[\sum_q e_q^2 D_1^q(z_1,M_1)D_1^{\bar{q}}(z_2,M_2)\right.$$

$$\left. + \frac{1}{2}\sum_q e_q^2 H_1^{\sphericalangle,q}(z_1,M_1)H_1^{\sphericalangle,\bar{q}}(z_2,M_2)\Big(\mathcal{B}_-\cos(\phi_1+\phi_2)-\mathcal{B}_+\cos(\phi_1-\phi_2)\Big)\right]$$

Transverse polarized diFF

$$\mathcal{B}_\pm \equiv C_{xx} \pm C_{yy} \qquad \mathcal{B}_+ = 0, \quad \mathcal{B}_- = \frac{2\sin^2\Theta}{1+\cos^2\Theta}. \qquad \mathcal{B}_- = \frac{2\langle\cos(\phi_1+\phi_2)\rangle}{\alpha_{M_1,M_2}^{z_1,z_2}} = \frac{A_{12}}{\alpha_{M_1,M_2}^{z_1,z_2}}$$

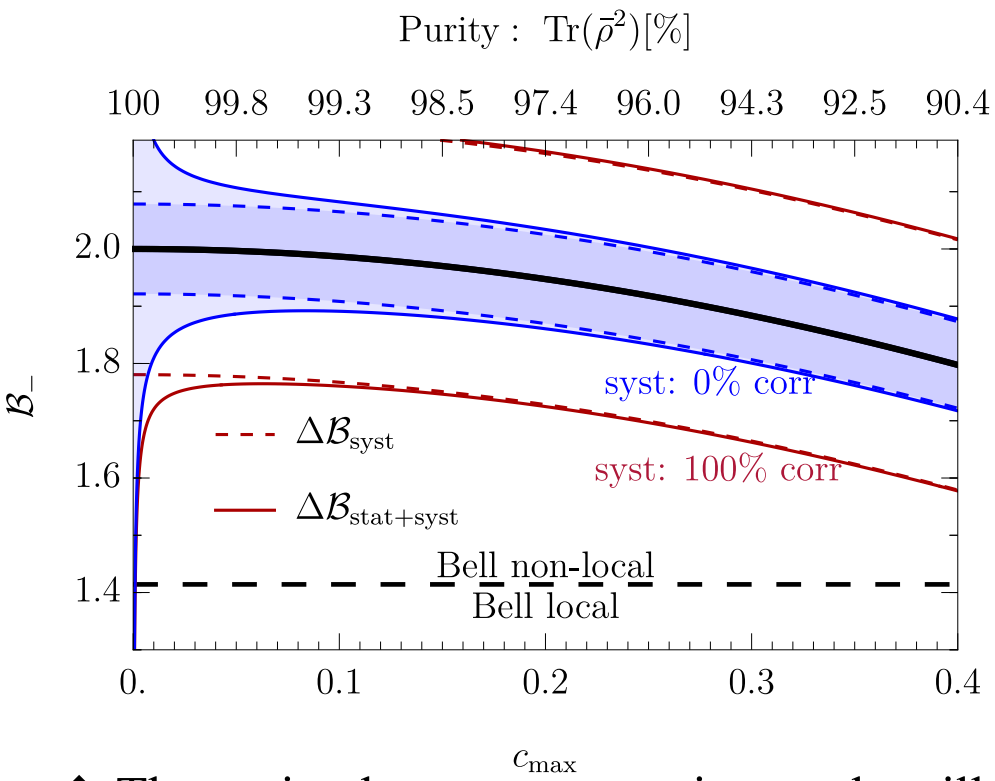
- $\mathcal{B}_+ = 0$ is a result of the chiral symmetry of SM (massless quarks)
- New spin structure $\mathcal{B}_+ \neq 0$ from chiral symmetry breaking interactions: dipole couplings

Q.-H. Cao, G. Li, X. K. Wen and B. Yan, Rept. Prog. Phys. 89 (2026) 080501

- CHSH type Bell inequality $|\mathcal{B}| > \sqrt{2}$ $\qquad \alpha_{M_1,M_2}^{z_1,z_2} = \frac{1}{2}\frac{\sum_q e_q^2 H_1^{\sphericalangle,q}(z_1,M_1)H_1^{\sphericalangle,\bar{q}}(z_2,M_2)}{\sum_q e_q^2 D_1^q(z_1,M_1)D_1^{\bar{q}}(z_2,M_2)}$.

Kun Cheng and Bin Yan, PRL 135 (2025) 011902

Dihadron pair production



$$\mathcal{B}_- = \frac{2\sin^2\Theta}{1+\cos^2\Theta}.$$

Kun Cheng and Bin Yan, PRL 135 (2025) 011902

- The optimal cuts on scattering angle will significantly improve the results
- The light quark pair would be a highly pure spin Bell state
- Combined results: 2.5 σ for 100% correlated systematic uncertainties and 6.7 σ for the uncorrelated case

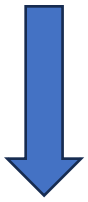
Quantum information of photon pair

- The quark fragmentation method can be extended to the photon pair production

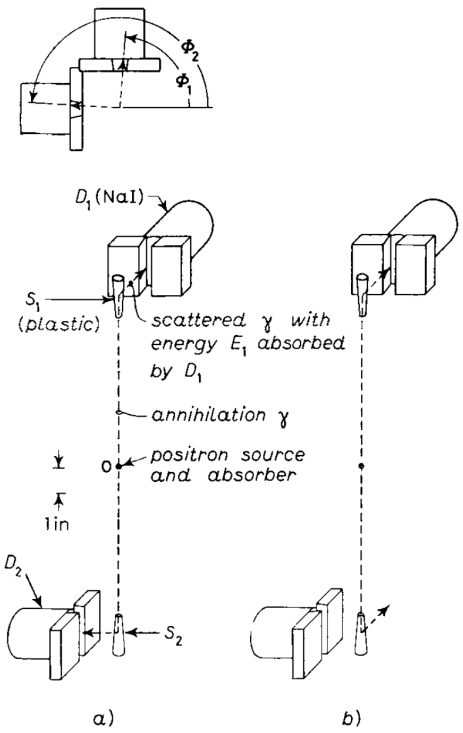
photon pair state (linear polarized):

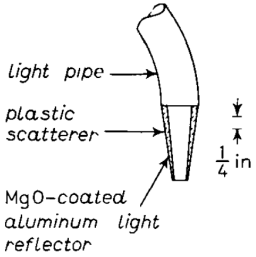
$$e^+e^- \rightarrow \gamma\gamma$$

$$\psi = \frac{|XY\rangle - |YX\rangle}{\sqrt{2}}$$



Compton Scattering





$$P(E_1E_2\Phi_1\Phi_2) = \frac{1}{4\pi^2}F(E_1)F(E_2)[1 - m(E_1)m(E_2)\cos 2(\Phi_2 - \Phi_1)]$$

L. R. Kasday, J. D. Ullman, and C.-S. Wu, Il Nuovo Cimento B (1971-1996) 25, 633 (1975).

Quantum information of photon pair

- Virtual-photon splitting as a polarimeter
- The virtual photon should be described by a qutrit state

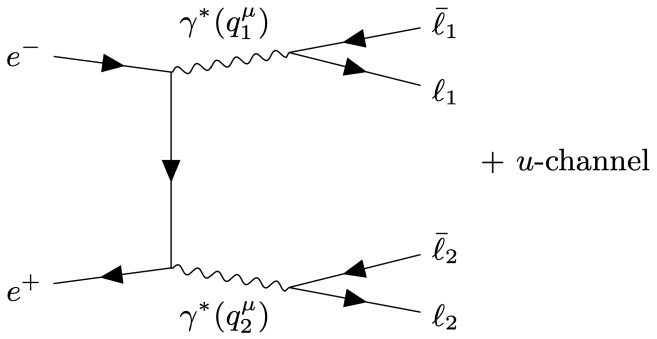
$$\epsilon_0^\mu(q_i) = \frac{q_i^\mu}{\sqrt{q_i^2}} + \mathcal{O}(\delta_i)$$

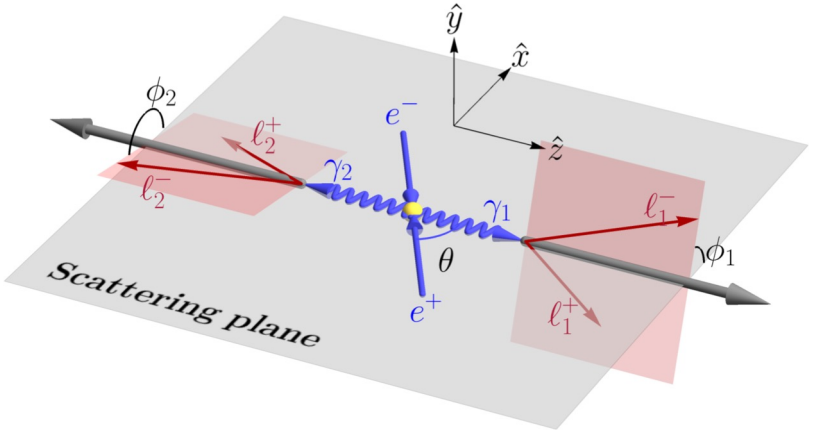
- For nearly on-shell photons, the longitudinal contributions are suppressed, we can use an effective two-qubit description
- The splitting process

$$\frac{1}{16q^2}\Gamma_{\lambda\lambda'} = D(z,q^2)\delta_{\lambda\lambda'} + H(z,q^2)\left[\cos(2\phi)(\sigma_x)_{\lambda\lambda'} + \sin(2\phi)(\sigma_y)_{\lambda\lambda'}\right]$$

Unpolarized linearly polarized

$$z = \frac{E_\ell + p_\ell^z}{E_\gamma + p_\gamma^z}$$ light-cone momentum fraction





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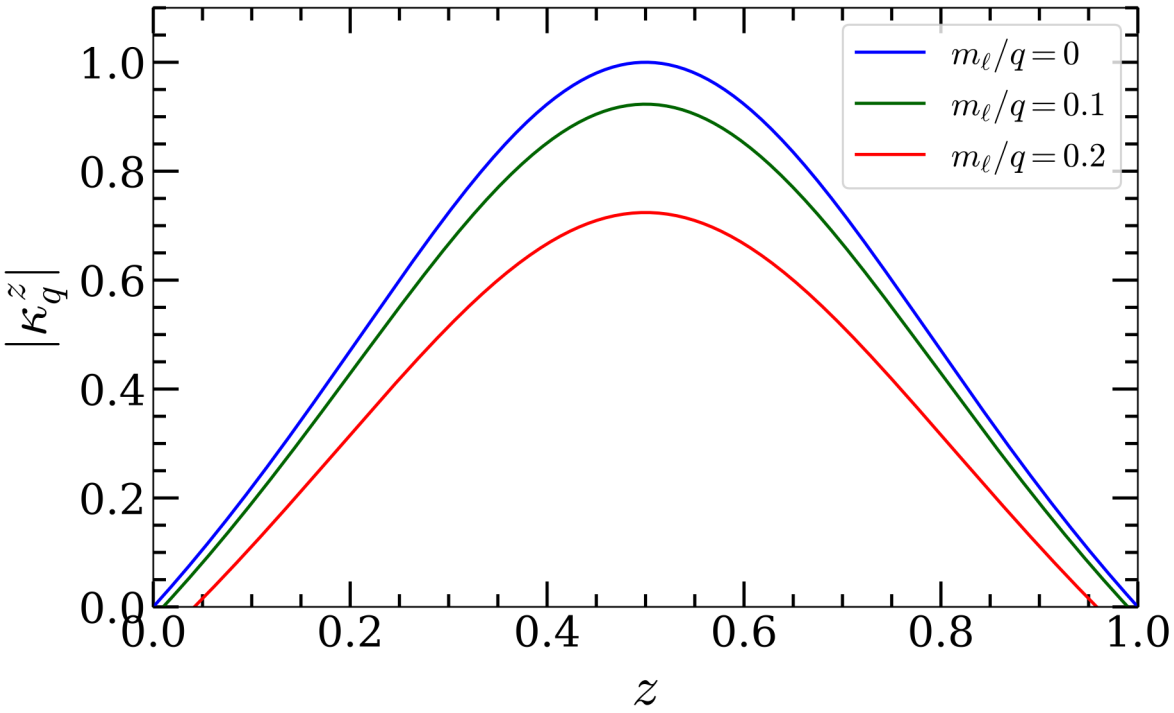
Spin analyzing power

- Spin analyzing power from splitting

$$D(z,q^2)=\frac{1}{2}+\frac{m_\ell^2}{q^2}-z(1-z) \qquad H(z,q^2)=\frac{m_\ell^2}{q^2}-z(1-z) \qquad \kappa_q^z=\frac{H(z,q^2)}{D(z,q^2)}$$



- The electron has a larger spin analyzing power

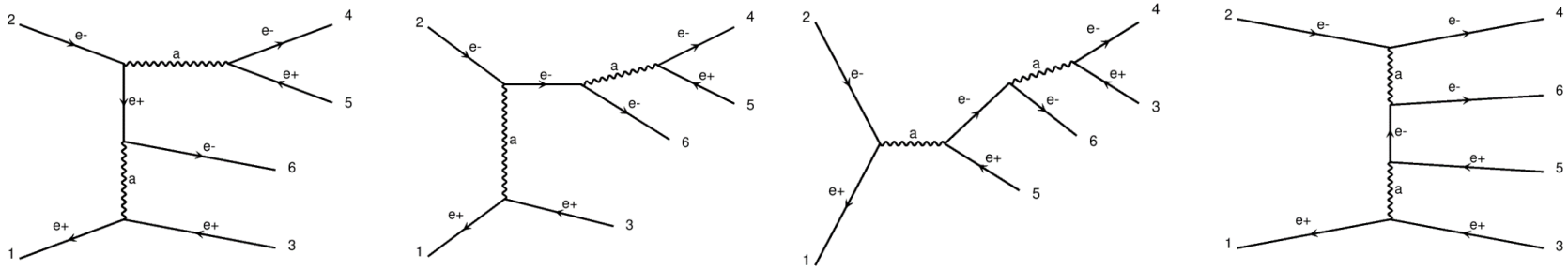
Quantum information of photon pair

- Bell variable:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_1\mathrm{d}\Omega_2} \propto \frac{D(z_1,q_1^2)D(z_2,q_2^2)}{q_1^2 q_2^2}\sigma_{\mathrm{hard}}\left[1+\alpha_{q_1,q_2}^{z_1,z_2}\times\left(\mathcal{B}_-\cos 2(\phi_1+\phi_2)+\mathcal{B}_+\cos 2(\phi_1-\phi_2)\right)\right].$$

$$\alpha_{q_1,q_2}^{z_1,z_2}=\frac{\kappa_{q_1}^{z_1}\kappa_{q_2}^{z_2}}{2} \qquad \mathcal{B}_\pm \equiv C_{xx}\pm C_{yy} \qquad B_+=0,\quad B_-=\frac{2\sin^2\theta}{1+\cos^2\theta}$$

- Backgrounds:



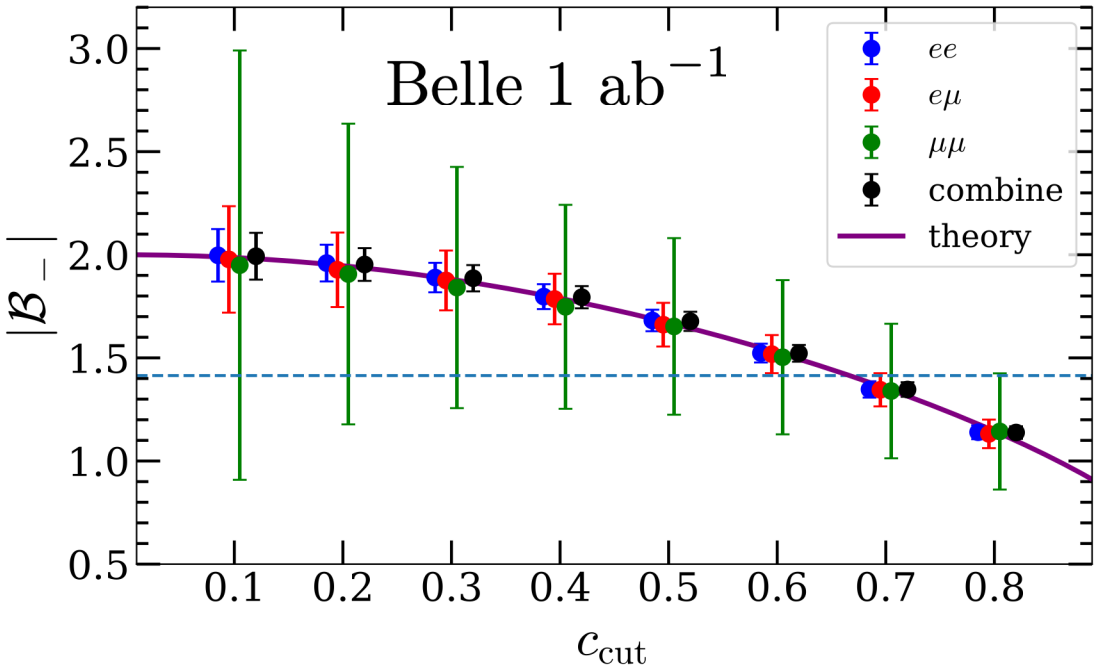
- Cuts: Lepton angle, energy, Photon virtuality, scattering angle and ΔR

$$|\cos\theta_\ell|<0.9, E_\ell>0.1\ \mathrm{GeV}, m_{ee}<0.5\ \mathrm{GeV}, m_{\mu\mu}<1\ \mathrm{GeV}, \Delta R>10^{-3}$$

Quantum information of photon pair

- Bell variable:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_1 \mathrm{d}\Omega_2} \propto \frac{D(z_1, q_1^2) D(z_2, q_2^2)}{q_1^2 q_2^2} \sigma_{\mathrm{hard}} \left[1 + \alpha_{q_1,q_2}^{z_1,z_2} \times \left(\mathcal{B}_- \cos 2(\phi_1 + \phi_2) + \mathcal{B}_+ \cos 2(\phi_1 - \phi_2) \right) \right].$$

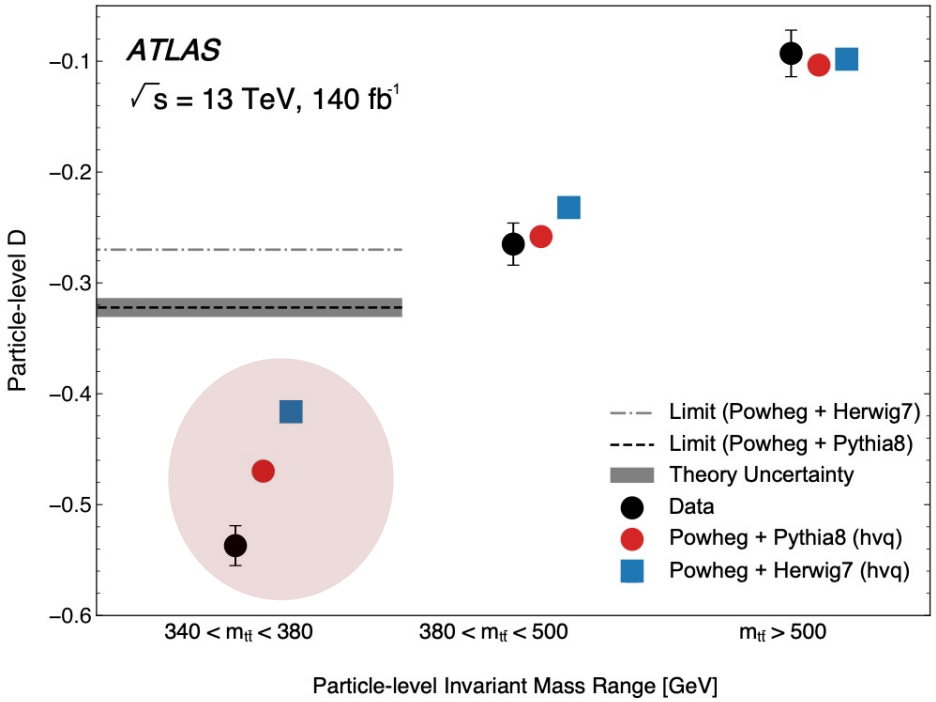


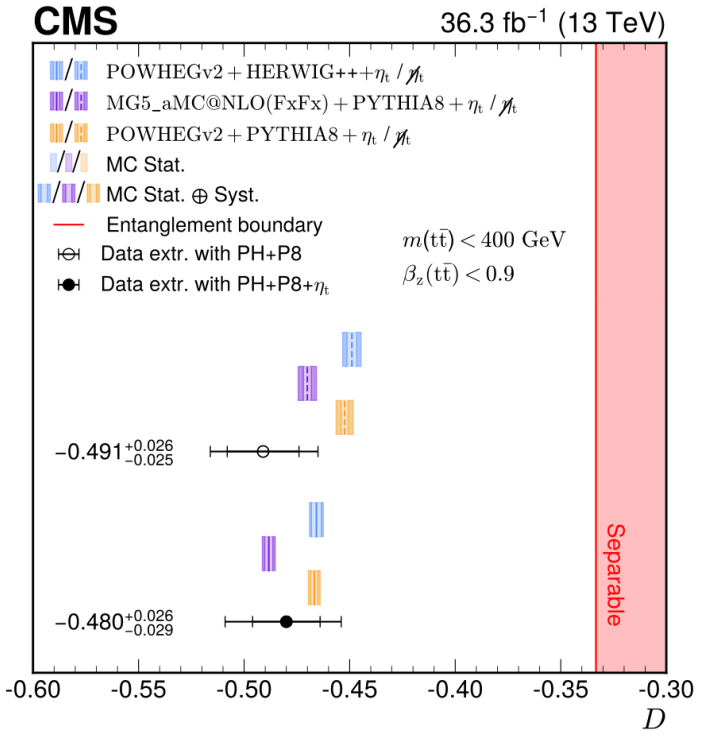
$$B_- = \frac{2\sin^2\theta}{1+\cos^2\theta}$$

$$|\cos\theta| < c_{\mathrm{cut}}$$

- Low virtuality sample is well described by the effective two-qubit approximation
- Belle variable will be enhanced in the central scattering region
- CHSH type Bell inequality violation @ Belle: 7.3 σ for $c_{\mathrm{cut}} = 0.3$

Quantum spin entanglement and new physics

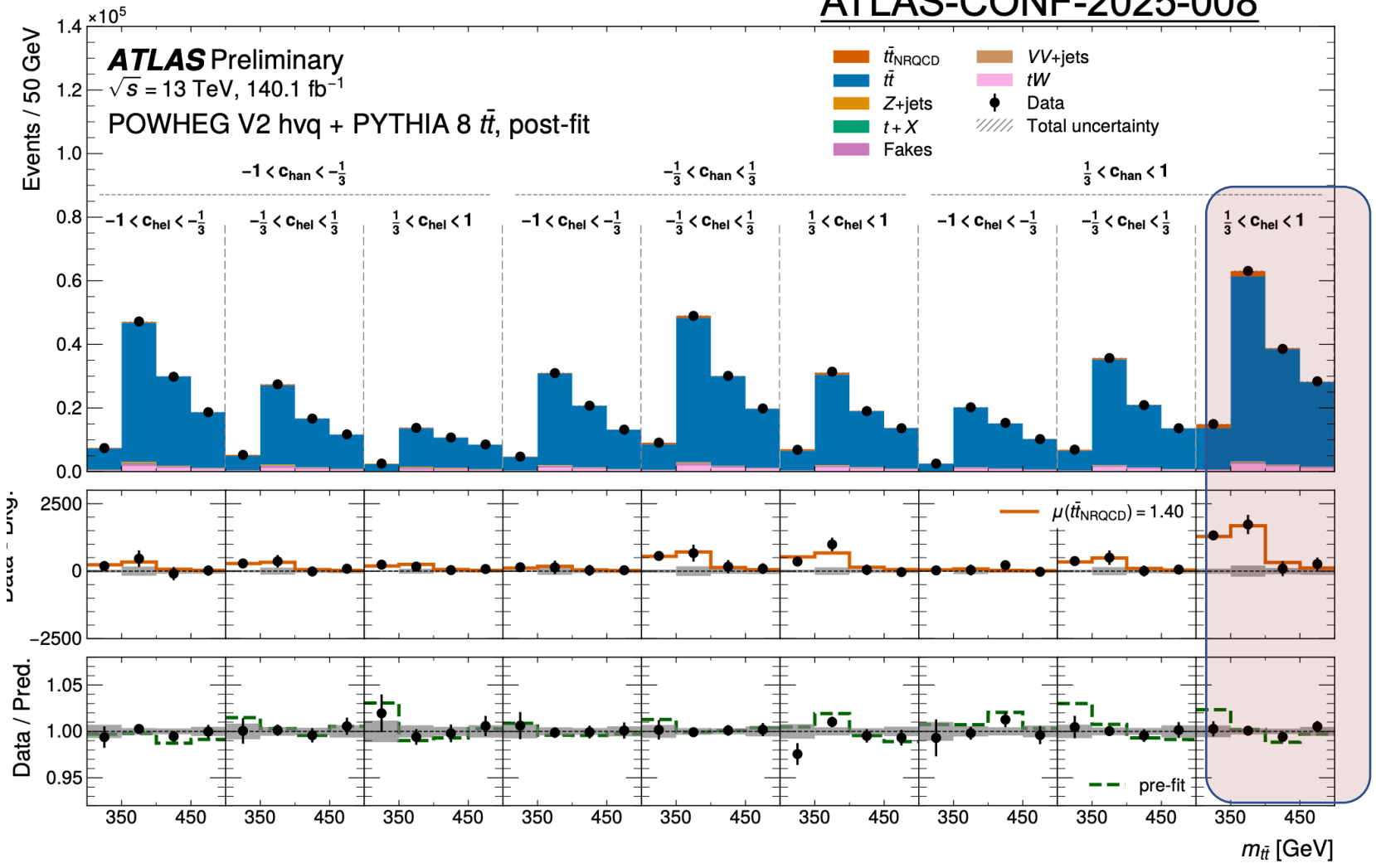




The hint of the toponium contributions from the entanglement measurements

Quantum spin entanglement and new physics

ATLAS-CONF-2025-008

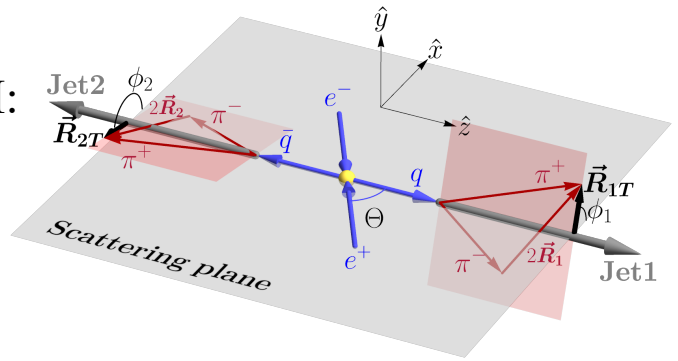


7.7σ quasi-bound state

$C_{\mathrm{hel}} = \vec{\ell}_+ \cdot \vec{\ell}_-$ Entanglement observable

New physics and entangled quarks

- The entangled triplet nature of the quark pair in SM:



$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_1\mathrm{d}z_2\mathrm{d}M_1\mathrm{d}M_2\mathrm{d}\phi_1\mathrm{d}\phi_2} = \sigma_{\rm hard}\Bigg[\sum_q e_q^2 D_1^q(z_1,M_1)D_1^{\bar{q}}(z_2,M_2) + \frac{1}{2}\sum_q e_q^2 H_1^{\sphericalangle,q}(z_1,M_1)H_1^{\sphericalangle,\bar{q}}(z_2,M_2)\Big(\mathcal{B}_-\cos(\phi_1+\phi_2)-\mathcal{B}_+\cos(\phi_1-\phi_2)\Big)\Bigg]$$

$$\mathcal{B}_\pm \equiv C_{xx} \pm C_{yy}$$

$$\mathcal{B}_+ = 0,\quad \mathcal{B}_- = \frac{2\sin^2\Theta}{1+\cos^2\Theta}.\qquad C_{ij} = \mathrm{diag}\left(\frac{\sin^2\Theta}{1+\cos^2\Theta}, -\frac{\sin^2\Theta}{1+\cos^2\Theta}, 1\right)$$

- $\mathcal{B}_+ = 0$ is a result of the chiral symmetry of SM (massless quarks)
- New spin structure from chiral symmetry breaking interactions: dipole couplings

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New physics and entangled quarks

- Chiral symmetry breaking effects:

$$\mathcal{L}_{\text{eff}} \supset \frac{v}{\sqrt{2}\Lambda^2}\left(C_\gamma^u \bar{u}_L \sigma^{\mu\nu} u_R + C_\gamma^d \bar{d}_L \sigma^{\mu\nu} d_R\right) A_{\mu\nu} + \text{h.c.}$$

- Entangled states for quark pair $|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow_z\downarrow_z\rangle + e^{i\phi}|\downarrow_z\uparrow_z\rangle)$

- CP transformation interchanges the spins of quark and antiquark: $\phi = \begin{cases} 0 & \text{CP even} \\ \pi & \text{CP odd} \end{cases}$

$$C_{xx} + C_{yy} = \frac{\sin^2\theta}{1+\cos^2\theta}\frac{sv^2}{\pi\alpha\Lambda^4 Q_q^2}([\text{Re}C_\gamma^q]^2 - [\text{Im}C_\gamma^q]^2),$$

$$C_{xx} - C_{yy} = \frac{\sin^2\theta}{1+\cos^2\theta}(2 + \frac{1}{\Lambda^2}\mathcal{F}_1 + \frac{1}{\Lambda^4}\mathcal{F}_2),$$

$$C_{xy} = -C_{yx} = -\frac{\sin^2\theta}{1+\cos^2\theta}\frac{sv^2}{\pi\alpha\Lambda^4 Q_q^2}[\text{Re}C_\gamma^q][\text{Im}C_\gamma^q],$$

New spin structures

$C_{ij}^{\text{Re}} = \text{diag}(1, 1, -1)$

$C_{ij}^{\text{Im}} = \text{diag}(-1, -1, -1)$

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New physics and fragmentation hadrons

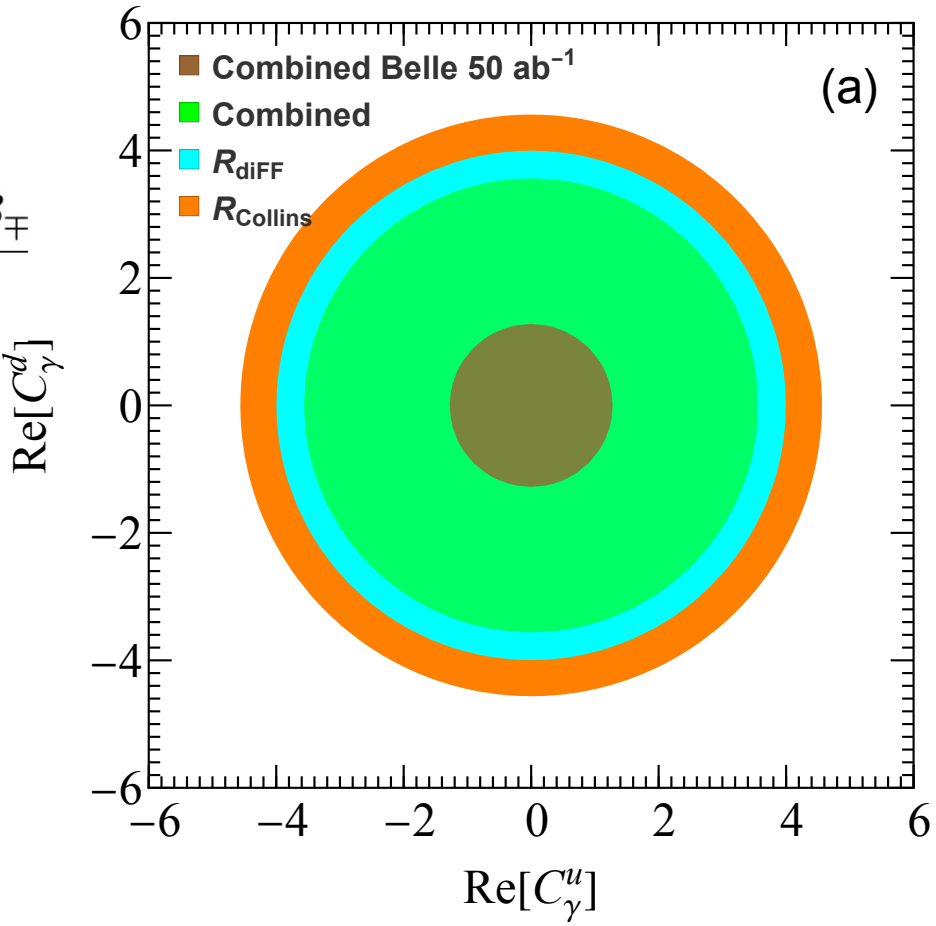
- The chiral symmetry breaking effects:

$$\Lambda = 1 \text{ TeV}$$

$$A_{\pm} \equiv 2\langle \cos(\phi_1 \pm \phi_2) \rangle$$
$$= \pm \frac{\sum_q Q_q^2 H_1^{\sphericalangle,q}(z_1, M_1) H_1^{\sphericalangle,\bar{q}}(z_2, M_2) \mathcal{B}_{\mp}}{2 \sum_q Q_q^2 D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2)}$$

$$R = \frac{A_-}{A_+} = \frac{\langle \cos(\phi_1 - \phi_2) \rangle}{\langle \cos(\phi_1 + \phi_2) \rangle}$$

The non-perturbaitve fragmenetaion functions are cancelled!



Summary

- Quantum information studies at colliders have only just begun
- Prior work limited to massive particles; massless quark unexplored
- Hadron fragmentation enables entanglement and Bell tests for massless quarks, while an analogous strategy can be extended to photon pairs
- Bell-inequality violation for massless quarks and photons could be observed with $> 5\sigma$ significance
- The chiral symmetry breaking effects from dipole interactions can induce new spin structures and can be measured in fragmentation hadrons

New opportunities in QCD spin physics!

Thank you!