

Dihadron Fragmentation as a Spin Analyzer at Lepton Colliders

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第二届 TeV 前沿物理研讨会暨第33届LHC Mini-Workshop
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X. K. Wen, **B. Yan**, Z. Yu, C.-P. Yuan, *PRL* 131 (2023) 241801,
PRD 112 (2025) 053004, Sci. China Phys. Mech. Astron. 69 (2026) 271011

K. Cheng, **B. Yan**, *PRL* 135 (2025) 011902

Q. H. Cao, X. K. Wen, **B. Yan**, S. T. Zhang, *PRL* 136 (2026) 231901

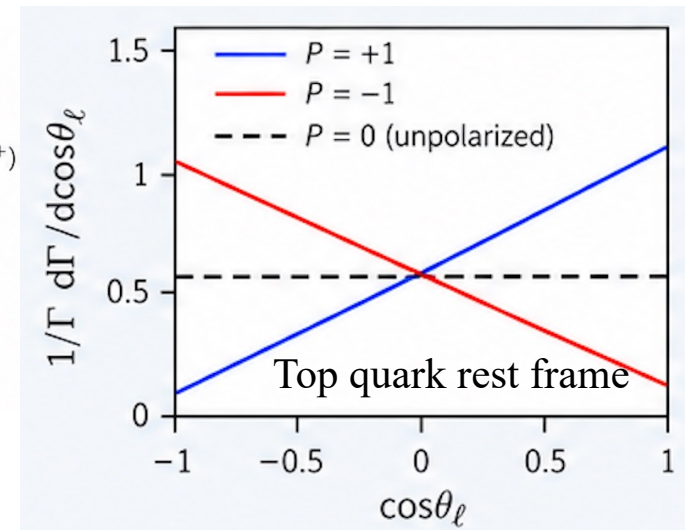
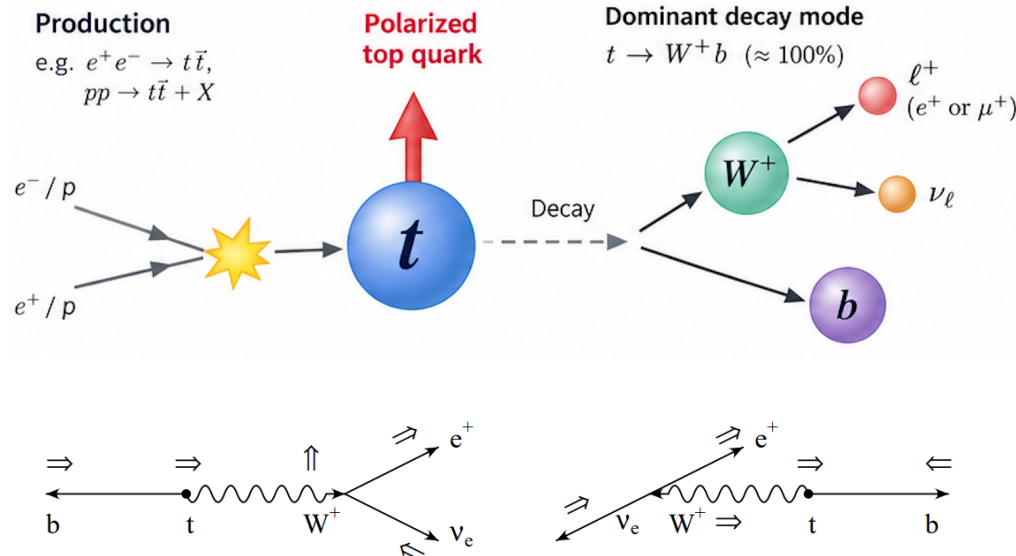
Q. H. Cao, G. Li, X. K. Wen, **B. Yan**, *Rept. Prog. Phys.* 89 (2026) 080501

Kun Cheng, Tao Han, Guanghui Li and **Bin Yan**, 2606.30759

Z. G. He, G. Li, Y. J. Tian, X. K. Wen, **B. Yan**, 2603.18874 (*accepted by PRL*); w/ Y. Liu, 2608.10570

Spin Analyzer in particle physics

- Unstable particles, decay products carry spin information

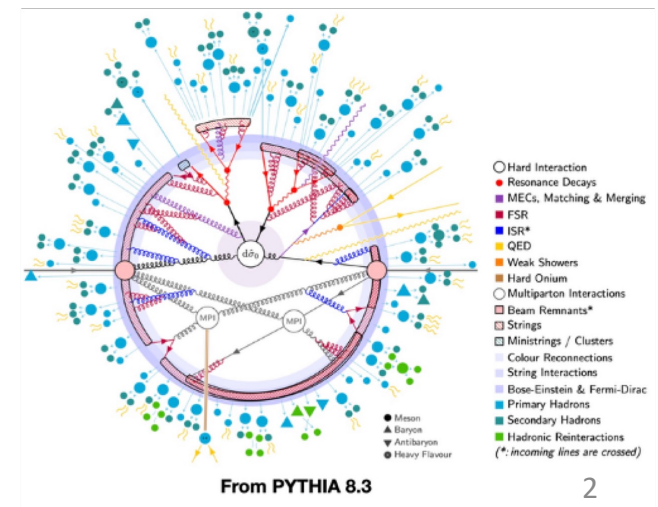


$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2} (1 + \alpha_i P \cos\theta_i)$$

Spin analyzing power

- How about light quark and gluon?

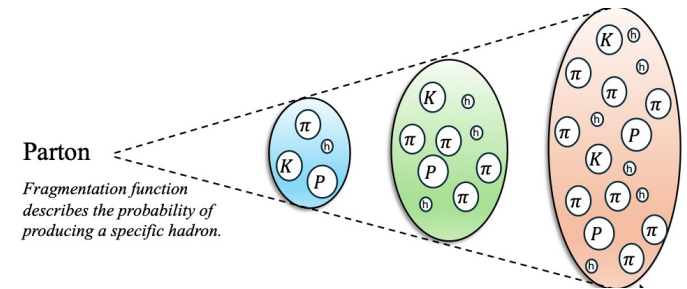
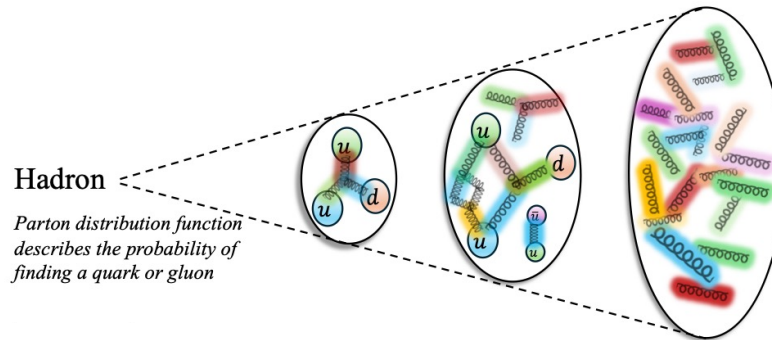
Hadronization hides spin information?



Spin Analyzer in particle physics

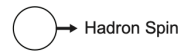
➤ Spin from **nonperturbative QCD**: PDFs and FFs

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



TMD factorization

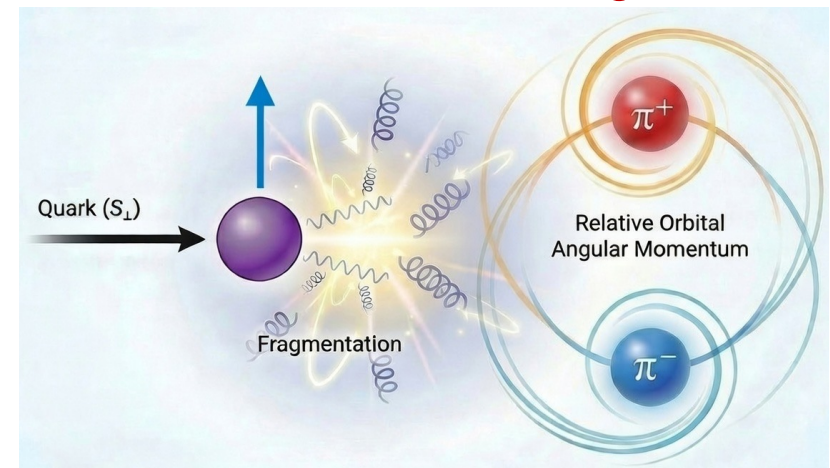
Leading Quark TMDFFs



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

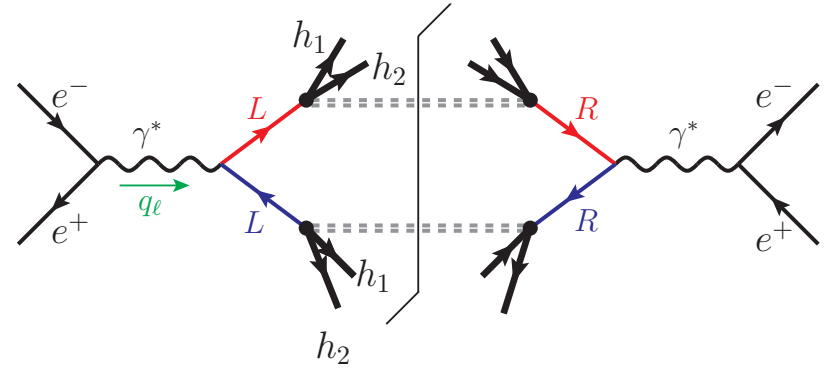
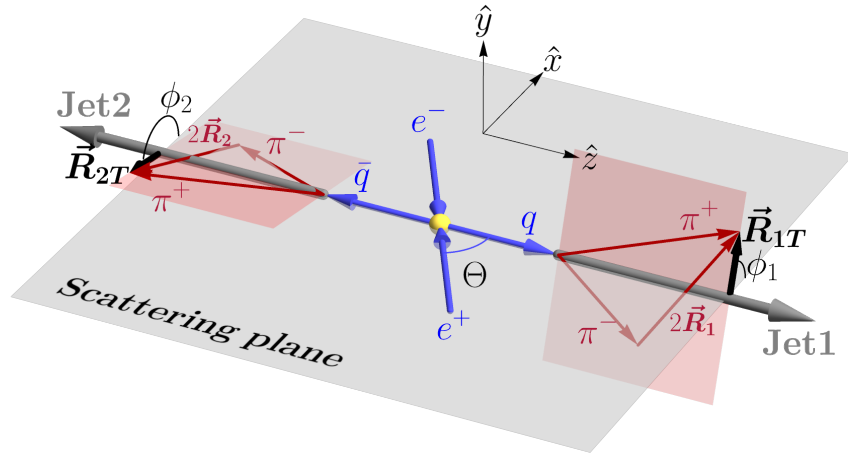
Collinear factorization

Interference Dihadron Fragmentation

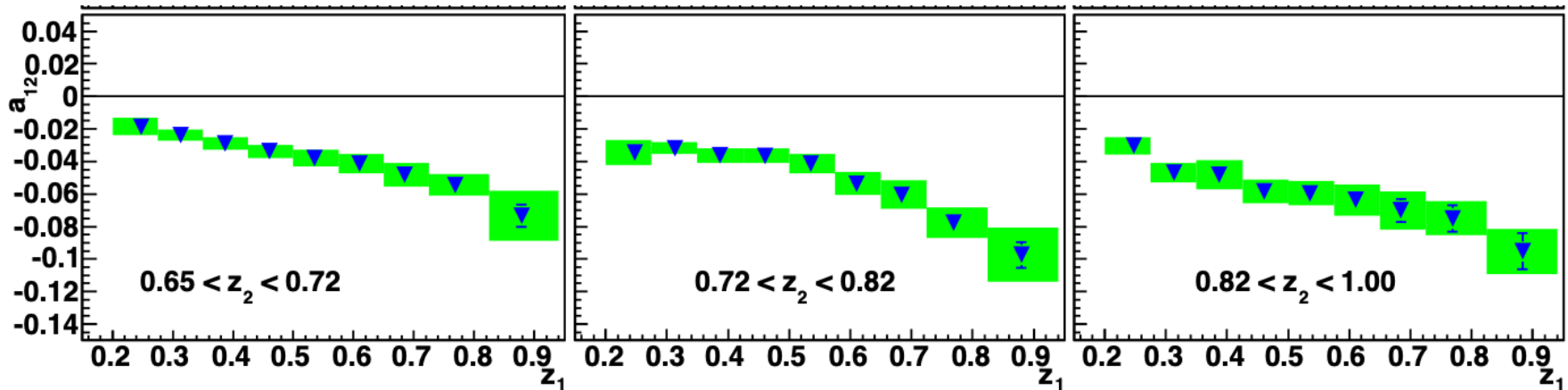


Transverse spin of quark: The interference between the different helicity states

Interference dihadron FFs



Belle, PRL 107 (2011) 072004

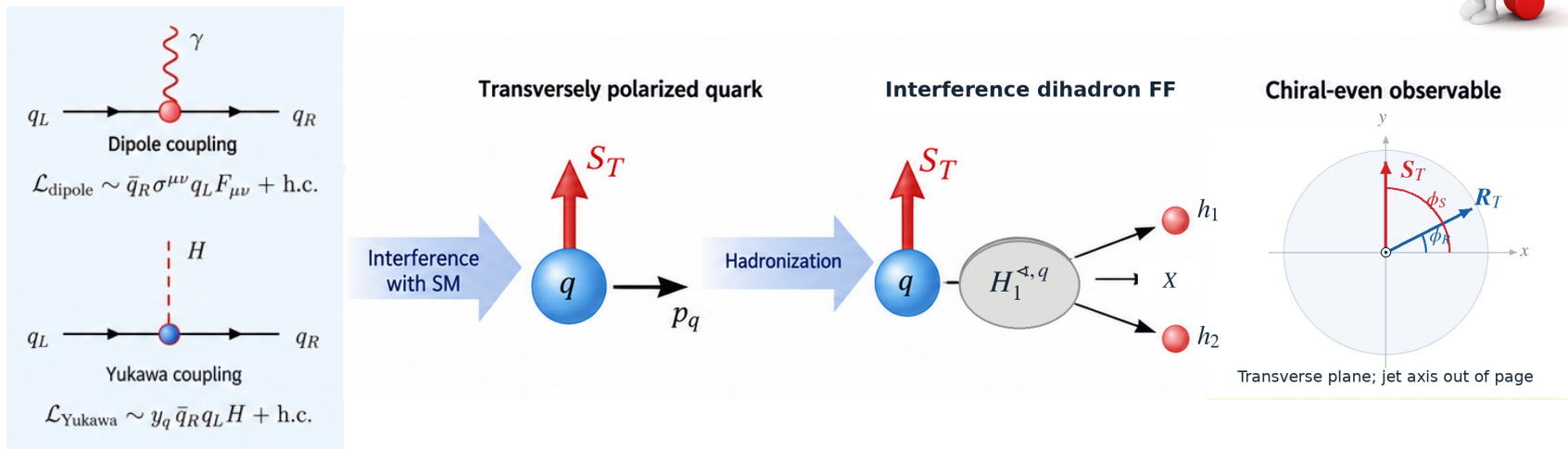


The transverse spin effects have been observed in dihadron pair production!

QCD Spin effects and New physics

- What type of new physics would exhibit sensitivity to the effects of QCD spin (Chiral-odd transverse spin effects)?

➡ **Chirality flip interactions: (Chiral-odd effects)**
Linearly probing dipole and Yukawa couplings



- X. K. Wen, **B. Yan**, Z. Yu, C.-P. Yuan, PRL 131 (2023) 241801, Sci. China Phys. Mech. Astron. 69 (2026) 271011, PRD 112 (2025) 053004

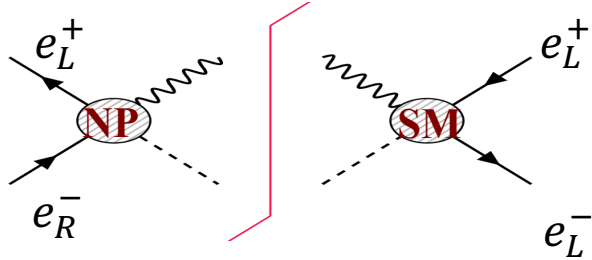


- Q. H. Cao, X. K. Wen, **B. Yan**, S. T. Zhang, PRL 136 (2026) 231901

See Shu-Tao's talk

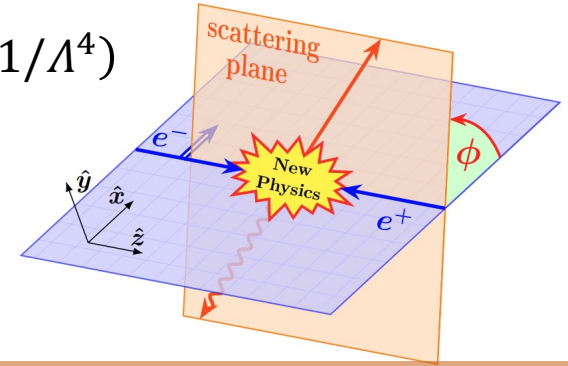
Example: electron weak dipole couplings

- The electroweak dipole couplings are poorly constrained: $O(1/\Lambda^4)$



$$\bar{e}_L \sigma_{\mu\nu} e_R A^{\mu\nu}, \bar{e}_L \sigma_{\mu\nu} e_R Z^{\mu\nu}$$

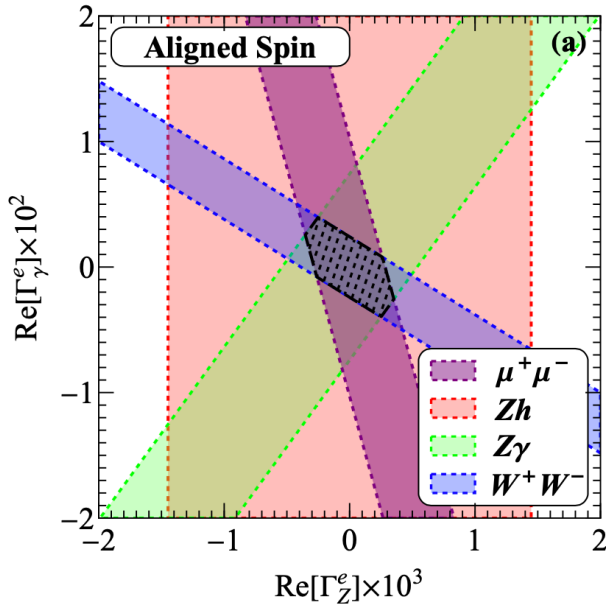
=0 for the cross section



- The interference effects: transverse spin of lepton

Observables must be chiral-even

- Transversely polarized effect of beams @ lepton collider



	U	L	T
U	$ \mathcal{M} _{UU}^2 \rightarrow 1$	$ \mathcal{M} _{UL}^2 \rightarrow 1$	$ \mathcal{M} _{UT}^2 \rightarrow \cos \phi, \sin \phi$
L	$ \mathcal{M} _{LU}^2 \rightarrow 1$	$ \mathcal{M} _{LL}^2 \rightarrow 1$	$ \mathcal{M} _{LT}^2 \rightarrow \cos \phi, \sin \phi$
T	$ \mathcal{M} _{TU}^2 \rightarrow \cos \phi, \sin \phi$	$ \mathcal{M} _{TL}^2 \rightarrow \cos \phi, \sin \phi$	$ \mathcal{M} _{TT}^2 \rightarrow 1, \cos 2\phi, \sin 2\phi$

$$\sqrt{s} = 250 \text{ GeV}, \mathcal{L} = 5 \text{ ab}^{-1}$$

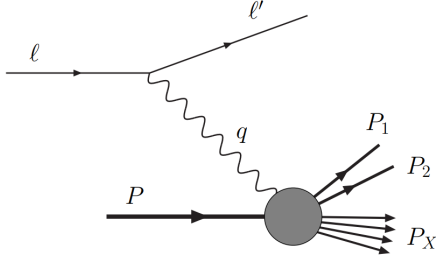
$$(b_T, \bar{b}_T) = (0.8, 0.3)$$

- Our bounds are much stronger than other approaches by 2 orders of magnitude

X. K. Wen, **B. Yan**, Z. Yu, C.-P. Yuan, PRL 131 (2023) 241801

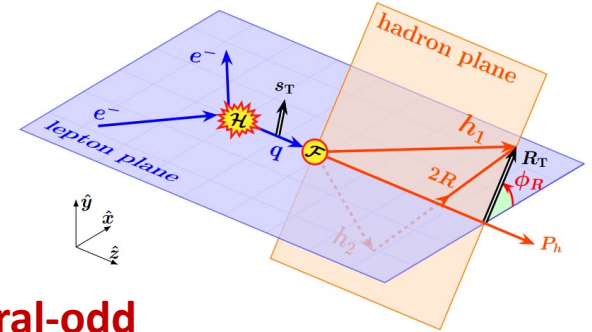
Transverse spin effects of quark @ EIC

- The transverse spin of quarks can be generated by the quark dipole moments



$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu}, \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$

Interference effects



- The interference dihadron fragmentation function: **chiral-odd**

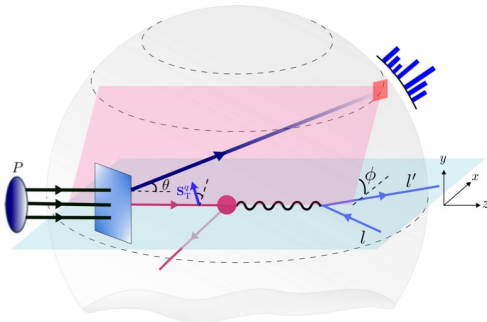
$$\frac{d\sigma}{dx dy dz dM_h d\phi_R} = \frac{N}{2\pi} \sum_q f_q(x, Q) [D_{h_1 h_2 / q}(z, M_h; Q) - (\mathbf{s}_{T,q}(x, Q) \times \hat{\mathbf{R}}_T)^z H_{h_1 h_2 / q}(z, M_h; Q)] C_q(x, Q)$$

$$s_q^x = \frac{2}{C_q} (w_\gamma^q \text{Re } \Gamma_\gamma^q + w_Z^q \text{Re } \Gamma_Z^q)$$

$$s_q^y = \frac{2}{C_q} (w_\gamma^q \text{Im } \Gamma_\gamma^q + w_Z^q \text{Im } \Gamma_Z^q)$$

X-K Wen, B. Yan, Z. Yu, C.-P. Yuan, Sci. China Phys. Mech. Astron. 69 (2026) 271011

- Nucleon energy correlator: related to Boer-Mulder quark TMD PDFs



$$\Sigma(\theta, \phi) = \sum_{i \in X} \int d\sigma^{l+p \rightarrow l'+X} \frac{E_i}{E_N} \delta(\theta^2 - \theta_i^2) \delta(\phi - \phi_i)$$

Y. S. Huang, X. B Tong, H. L. Wang, PRL 136 (2026) 131902

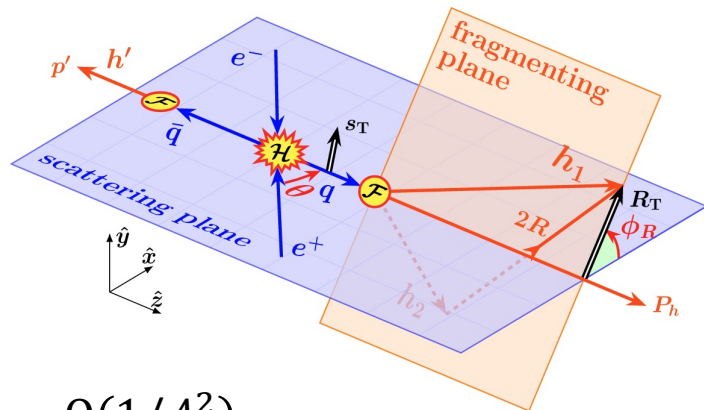
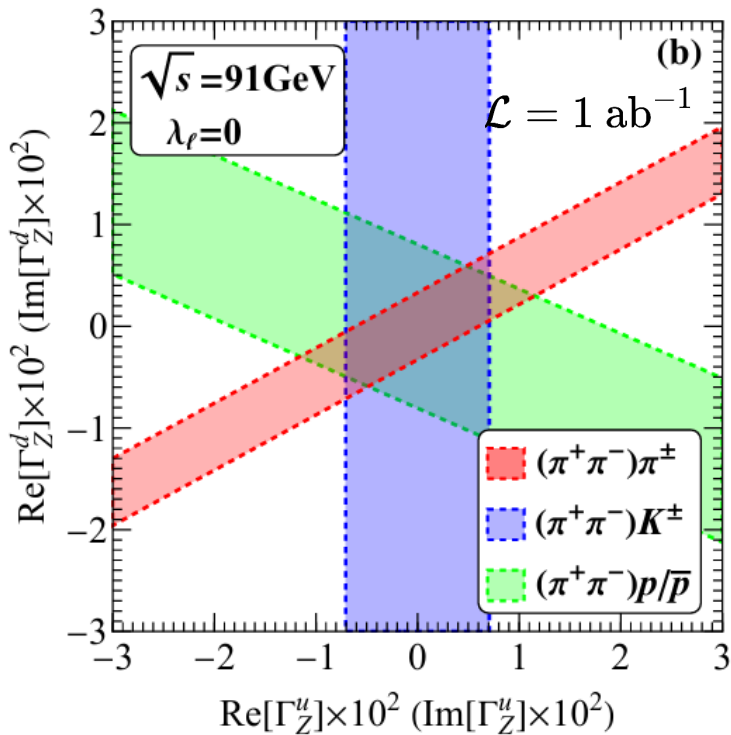
The flat direction in flavor space of dipole couplings?

Transverse spin effects of quark @ CEPC

Xin-Kai Wen, **Bin Yan**, Zhite Yu, C.-P. Yuan, PRD 112 (2025) 053004

$$\frac{d\sigma}{dy\,dz\,d\bar{z}\,dM_h\,d\phi_R} = \frac{1}{32\pi^2 s} \sum_{q, q \rightarrow \bar{q}} C_q(y) D_{\bar{q}}^{h'}(\bar{z})$$

$$\times [D_q^{h_1 h_2}(z, M_h) - (\mathbf{s}_{T,q}(y) \times \hat{\mathbf{R}}_T)^z H_q^{h_1 h_2}(z, M_h)]$$



$$O(1/\Lambda^2)$$

$$s_q^x = \frac{2}{C_q} (w_\gamma^q \operatorname{Re} \Gamma_\gamma^q + w_Z^q \operatorname{Re} \Gamma_Z^q)$$

$$s_q^y = \frac{2}{C_q} (w_\gamma^q \operatorname{Im} \Gamma_\gamma^q + w_Z^q \operatorname{Im} \Gamma_Z^q)$$

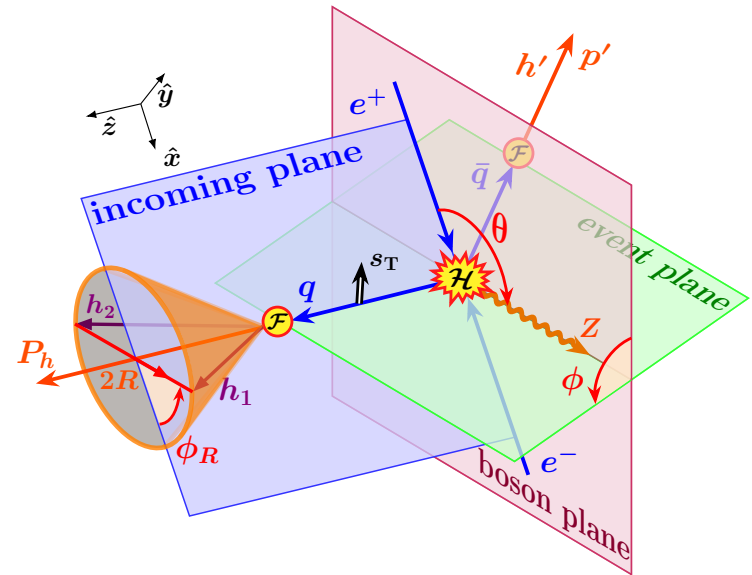
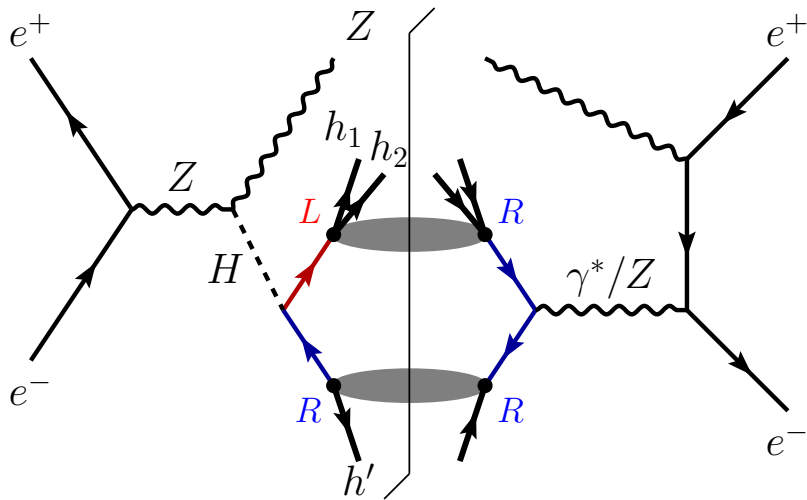
$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu}, \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$

- ❑ The flat direction can be closed by combining more processes
- ❑ Z-boson dipole: $O(0.001)$

Dihadron FFs and Yukawa coupling

- Yukawa interactions generate **transverse quark polarization**

See Shu-Tao's talk



Qing-Hong Cao, Xin-Kai Wen, **Bin Yan**, Shutao Zhang, PRL 136 (2026) 231901

Fragmentation functions encode the spin information of quarks

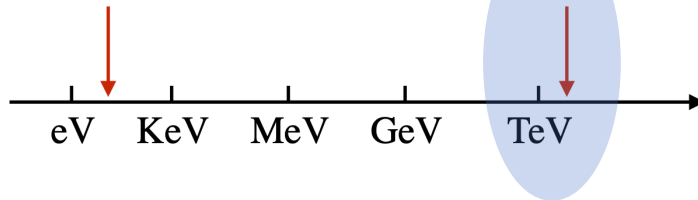


- Spin information as a tool for new physics searches
- Spin structure of quark systems: quark-quark spin correlations
- Emergence of entanglement in quark systems

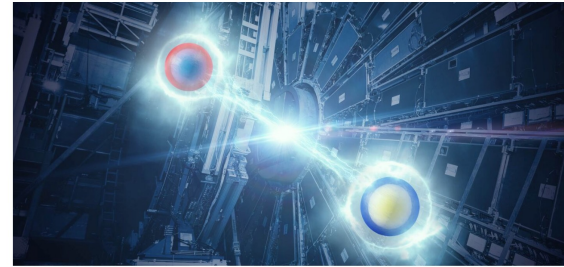
Quantum information at collider

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

Typical entanglement
experiment with photons



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

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

Quantum entanglement at colliders

- Top quark pair

Y. Afik, J. R. M. II. 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
K. Chen, T. Han, M. Low, T. Wu, 2507.12513

- ## ► Entanglement & NP

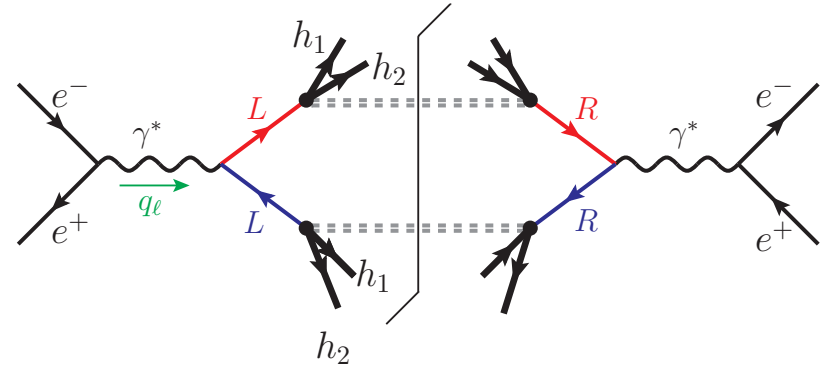
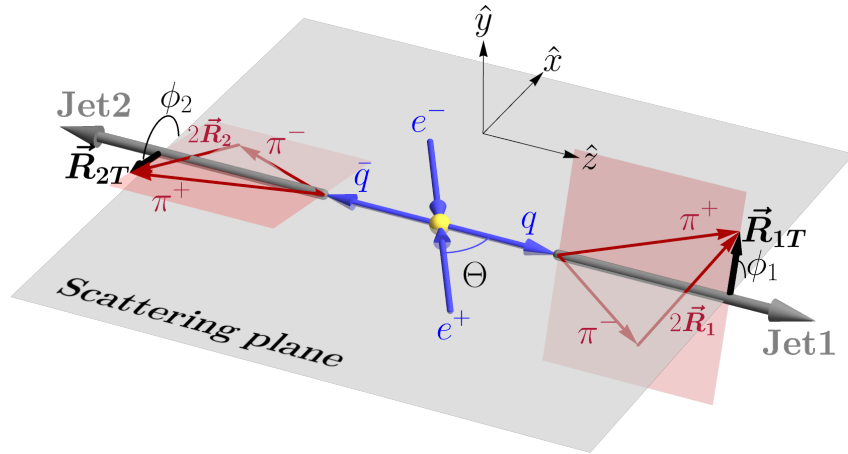
R. Aoude et al, PRD 106 (2022) 055007
M. Fabbri et al, EPJC 83 (2023) 162, JHEP 09 (2023) 195
A. Bernal et al, EPJC 83 (2023) 11, 1050

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



How about the light quarks?

Dihadron pair production at lepton colliders



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

- 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

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

- The **maximally entangled Bell state**: Bell inequality violation effects

Bell inequality of light quarks

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

Unpolarized diFF

$$\frac{d\sigma}{dz_1 dz_2 dM_1 dM_2 d\phi_1 d\phi_2} = \sigma_{\text{hard}} \left[\sum_q e_q^2 D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2) + \frac{1}{2} \sum_q e_q^2 H_1^{\triangleleft, q}(z_1, M_1) H_1^{\triangleleft, \bar{q}}(z_2, M_2) \left(\mathcal{B}_- \cos(\phi_1 + \phi_2) - \mathcal{B}_+ \cos(\phi_1 - \phi_2) \right) \right]$$

Transverse polarized diFF

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

- ❖ $\mathcal{B}_+ = 0$ 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

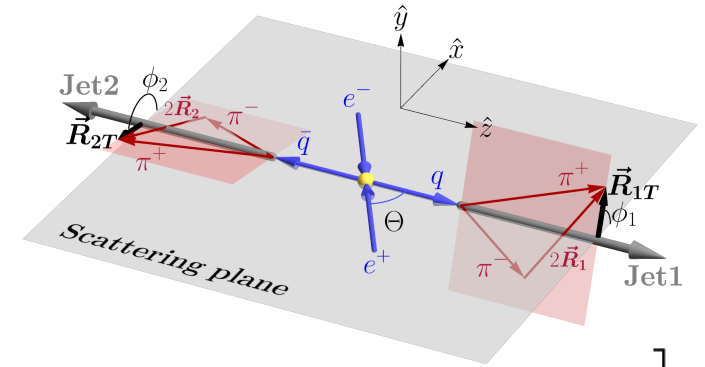
Q. H. Cao, G. Li, X. K Wen and **B. Yan**, Rept. Prog. Phys. 89 (2026) 080501

See Xin-Kai's talk

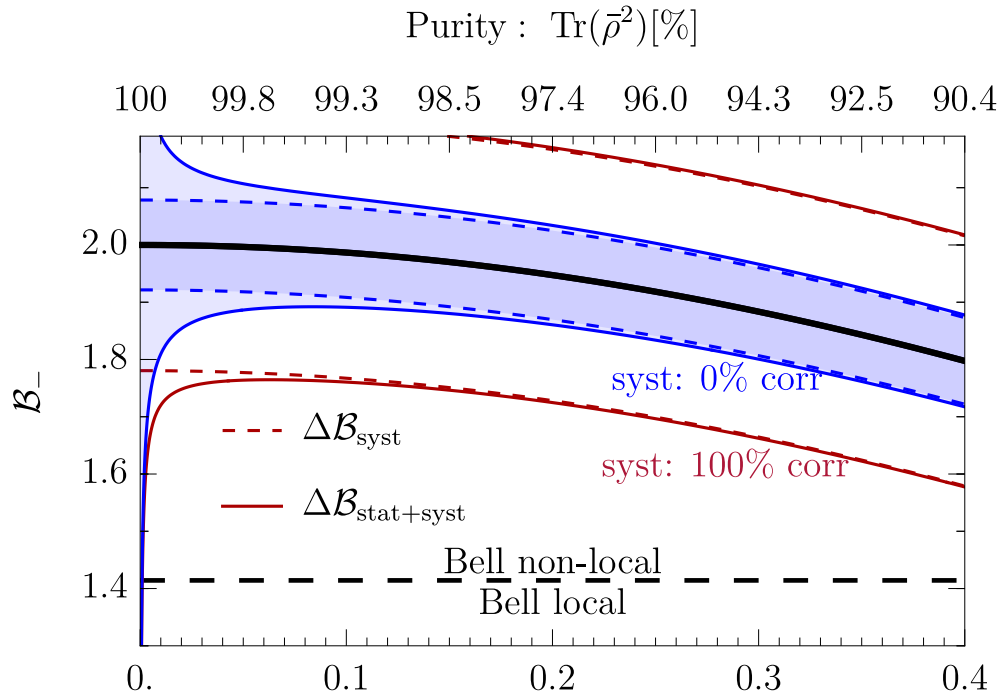
- ❖ CHSH type Bell inequality $|\mathcal{B}| > \sqrt{2}$

$$\alpha_{M_1, M_2}^{z_1, z_2} = \frac{1}{2} \frac{\sum_q e_q^2 H_1^{\triangleleft, q}(z_1, M_1) H_1^{\triangleleft, \bar{q}}(z_2, M_2)}{\sum_q e_q^2 D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2)}.$$

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



Dihadron pair production



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

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

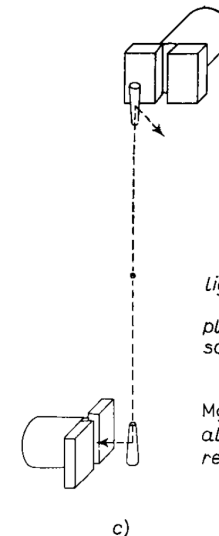
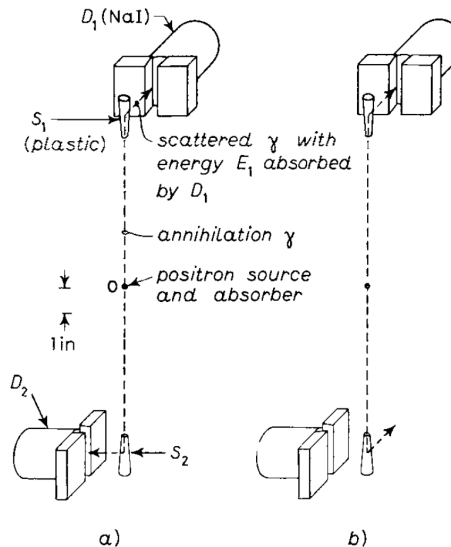
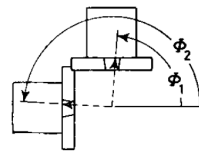
- The quark fragmentation method can be extended to the **photon pair production**

photon pair state (linear polarized):

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

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

Compton Scattering



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

Quantum information of photon pair

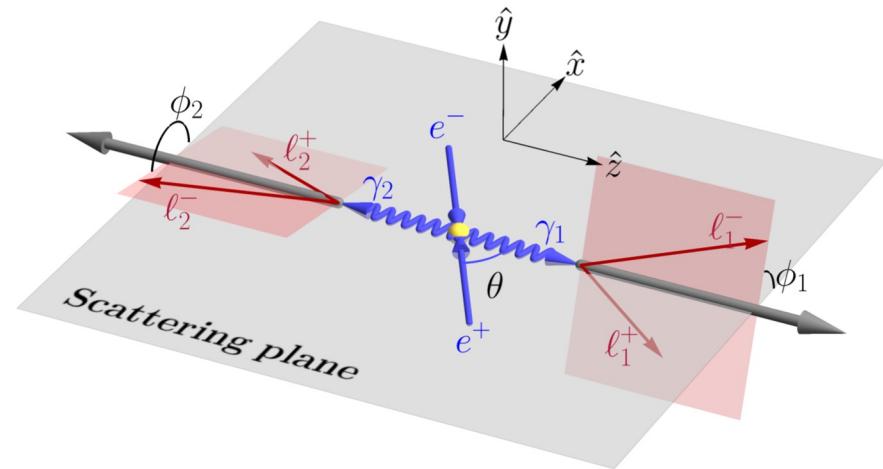
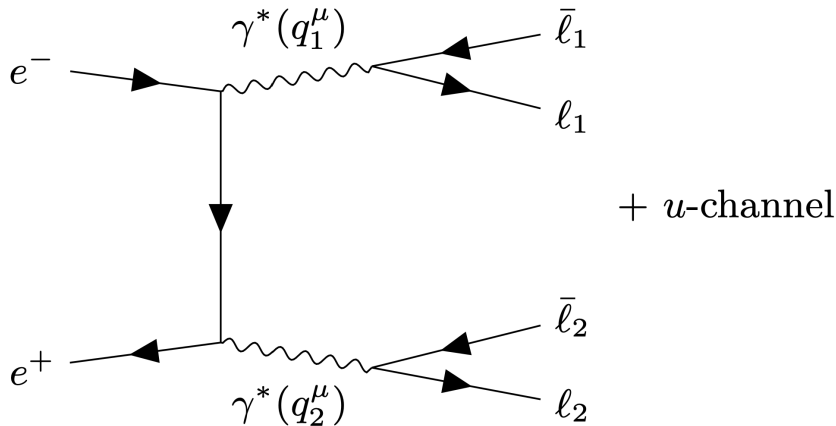
➤ Virtual-photon splitting as a polarimeter

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

➤ For **nearly on-shell** photons, we can use an effective **two-qubit** description

➤ The splitting process

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

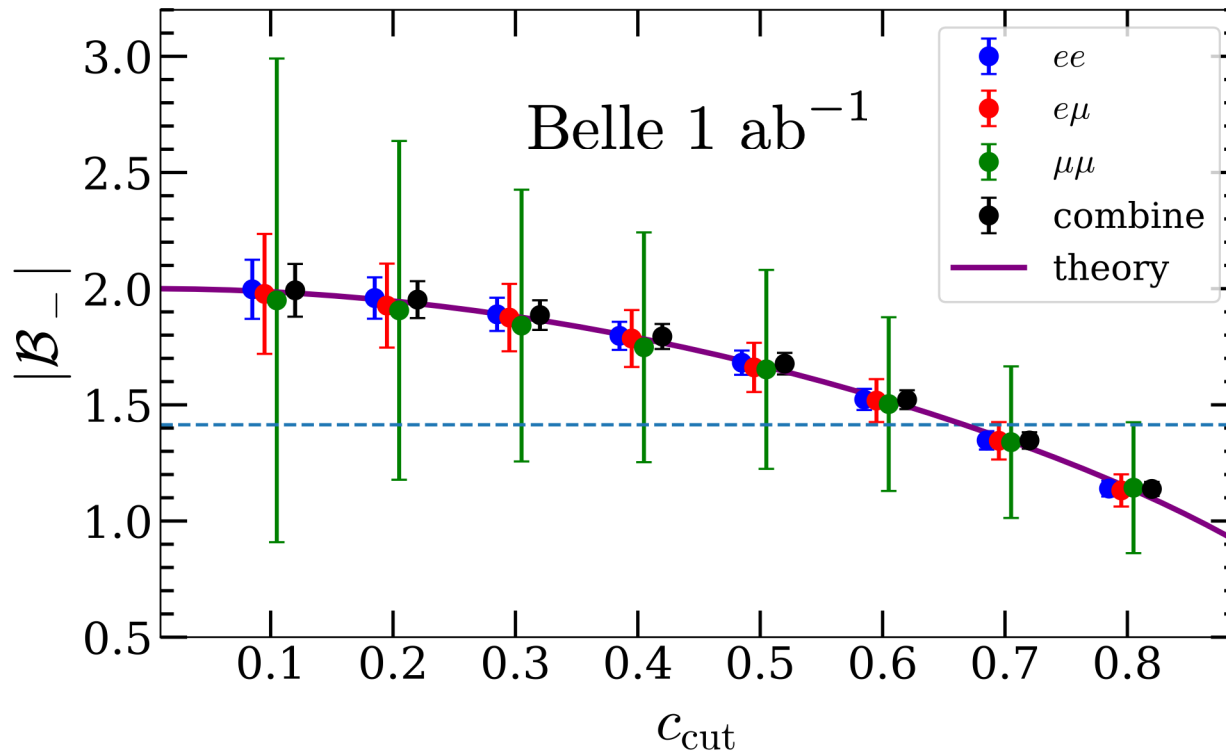


Quantum information of photon pair

➤ Bell variable:

Kun Cheng, Tao Han, Guanghui Li and Bin Yan, 2606.30759

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



➤ CHSH type Bell inequality violation @ Belle: **7.3 σ** for $c_{\text{cut}} = 0.3$

Fragmentation functions encode the spin information of quarks



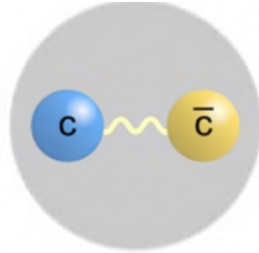
- Spin information as a tool for new physics searches
- Emergence of entanglement in quark systems
- **Probing the Color-Octet Mechanism via Spin Observable**

NRQCD and Heavy Quarkonium

- Heavy quarkonium: the non-relativistic bound state

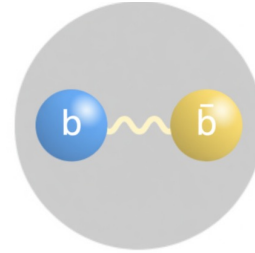
Charmonium

$$v_c^2 \simeq 0.23$$



Bottomonium

$$v_b^2 \simeq 0.08$$



- Color-Singlet Model

$Q\bar{Q}$ with the same quantum numbers as the final bound state $2S+1 L_J^{[c]}$

$$c\bar{c}(^3S_1^{[1]}) \rightarrow J/\Psi$$

$$b\bar{b}(^3S_1^{[1]}) \rightarrow \Upsilon$$

- Theoretical issues:

Infrared divergences in P-wave production and decay at higher orders in QCD

- Exp issues: Huge cross section discrepancy $\sigma_{pp \rightarrow J/\Psi} \gg \sigma_{CSM}$

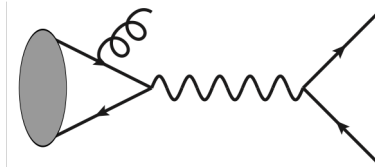
NRQCD and Heavy Quarkonium

➤ NRQCD factorization

G. T. Bodwin, E. Braaten, G. P. Lepage, PRD 51 (1995) 1125

❖ $Q\bar{Q}$ could be in all possible spin and color configurations

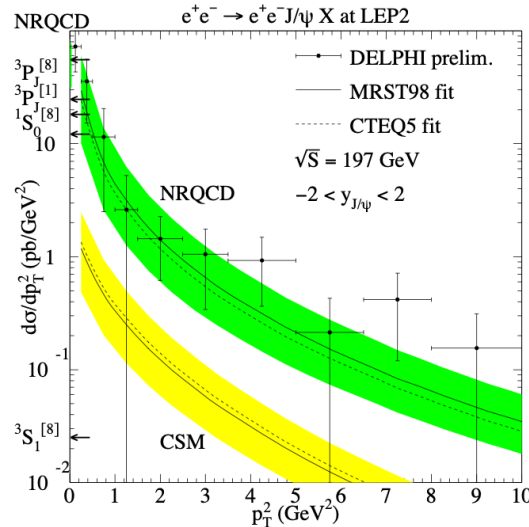
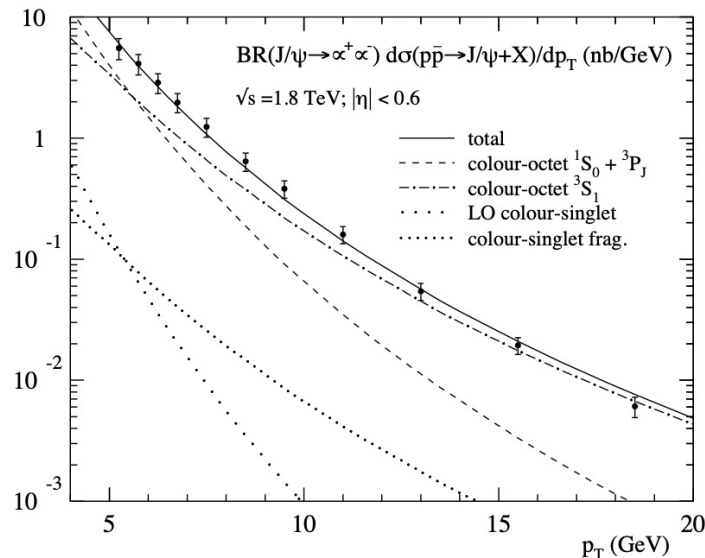
❖ Color-Octet Mechanism:



Physical quarkonium

$$|H\rangle = |Q\bar{Q}(1)\rangle + |Q\bar{Q}g(8)\rangle + \dots$$

❖ IR divergences in Color-Singlet are absorbed into Color-Octet matrix elements



CO contributions
can dominate in
some regimes

G. T. Bodwin,
hep-ph/0509203

Testing Color-Octet Mechanism

- Lattice VS Experiment (P-wave quarkonium)

$$H_1^Q = \langle \chi_{QJ} | \mathcal{O}(^3P_J^{[1]}) | \chi_{QJ} \rangle$$

$$\rho_8(m_Q) = H_8^Q(m_Q) m_Q^2 / H_1^Q \quad H_8^Q(\mu_\Lambda) = \langle \chi_{QJ} | \mathcal{O}(^3S_1^{[8]}, \mu_\Lambda) | \chi_{QJ} \rangle$$

- Charmonium $\rho_8 = 0.128(2)(9)_{-47}^{+61}$ (Lattice)

$$\rho_8 = 0.095(43) \text{ (Exp)}$$

G. T. Bodwin, D. K. Sinclair, S. Kim, PRL 77 (1996) 2376

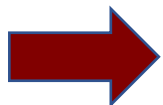
- Bottomonium $\rho_8 = 0.044 \pm 0.015$ (Lattice)

$$\rho_8 = 0.16_{-0.047}^{+0.071} \text{ (CLEO)}$$

Anomaly!

G. T. Bodwin, E. Braaten, D. Kang, J. Lee, PRD 76 (2007) 054001

CLEO: PRD 78 (2008) 092007



An independent cross-check of ρ_8 is very important!

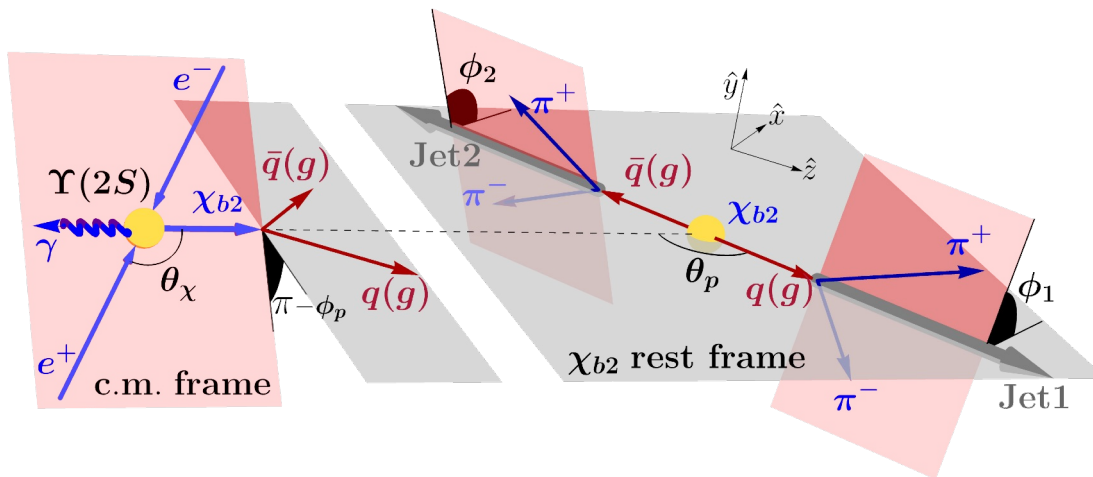
How to separate CO from CS?

$$b\bar{b}(^3S_1^{[8]}) \rightarrow q\bar{q}$$

$$b\bar{b}(^3P_J^{[1]}) \rightarrow gg$$



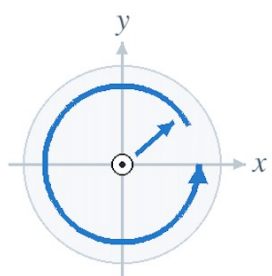
The spin of quark and gluon is different!



See Zhiguo's talk

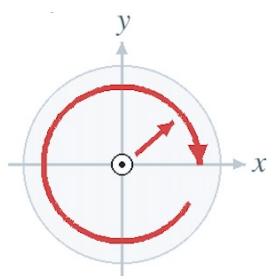
Z. G. He, G. Li, Y. J. Tian, X. K. Wen, **B. Yan**, 2603.18874 (accepted by PRL)

From quark to gluon spin analysis



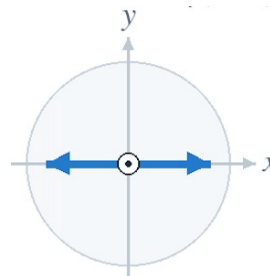
$$\lambda = +1$$

Counterclockwise



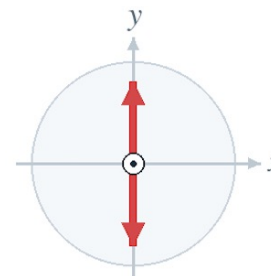
$$\lambda = -1$$

Clockwise



$$\epsilon_x = \hat{x}$$

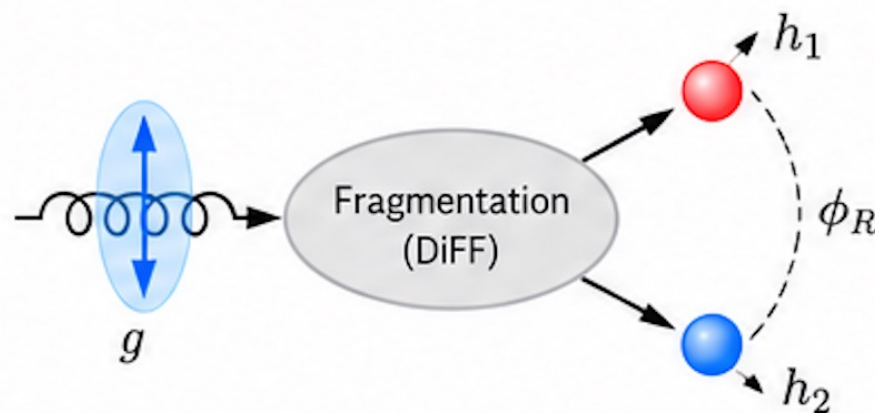
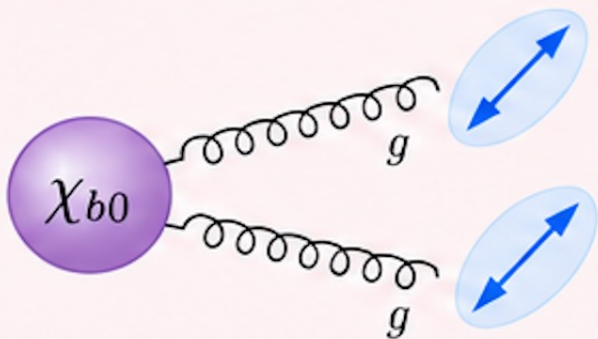
x-linear polarization



$$\epsilon_y = \hat{y}$$

y-linear polarization

Scalar decay: $\chi_{b0}(0^{++}) \rightarrow gg$



See Zhiguo's talk

The linearly polarized gluon DiFF has not yet been accessed experimentally

Z. G. He, G. Li, Y. Liu, Y. J. Tian, X. K. Wen, **B. Yan**, 2608.10570

Summary

- Light-quark dipole and Yukawa couplings are weakly constrained, as conventional observables are quadratic in these couplings
- SM-BSM interference generates transverse quark polarization, enabling linear probes through chiral-odd dihadron fragmentation
- 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
- Dihadron fragmentation also provides novel probe of the NRQCD color-octet mechanism and gluon linear polarization

New opportunities in QCD spin physics!

Thank you

CLHCP2026 第十二届中国 LHC 物理会议 The 12th China LHC Physics Conference

2026年10月28日—11月1日
October 28 – November 1, 2026

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Wuhan East Lake Hotel, Wuhan, China

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CLHCP 2026 Theory talk

Deadline: Oct. 8, 2026