

# Probing New Physics and Quantum Entanglement through QCD Spin Effects at Colliders

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Based on Xin-Kai Wen, **Bin Yan**, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801 , PRD 112 (2025) 053004, 2408.07255

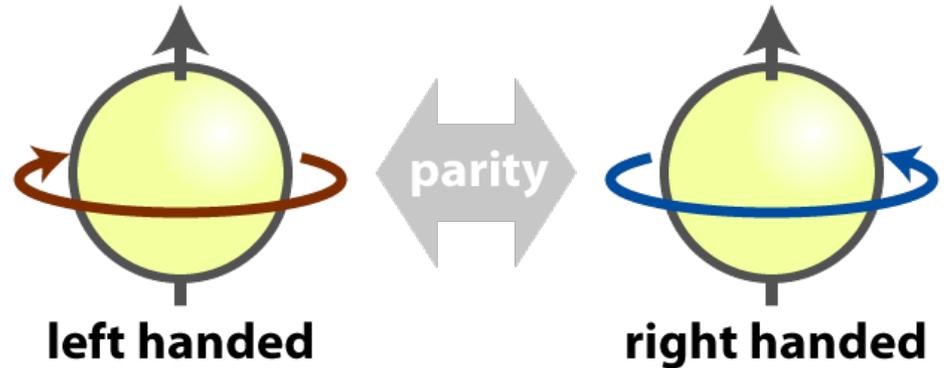
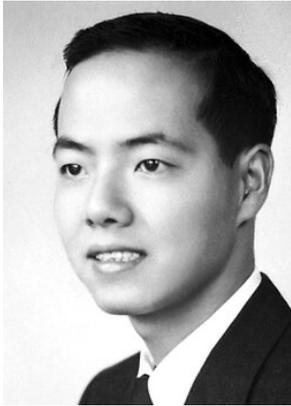
Kun Cheng and **Bin Yan**, PRL 135 (2025) 011902

Qing-Hong Cao, Guanghui Li, Xin-Kai Wen, **Bin Yan**, 2509.18276

Qing-Hong Cao, Xin-Kai Wen, **Bin Yan**, Shu-Tao Zhang, 2512.16492

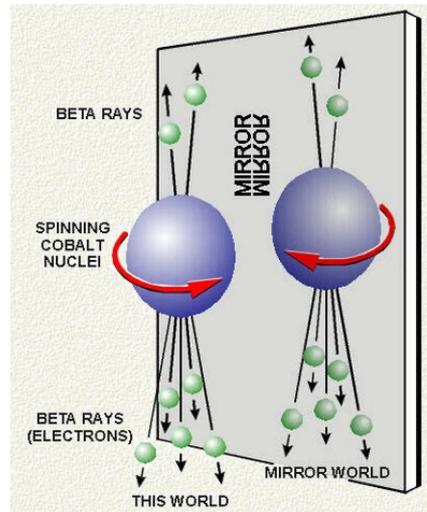
# Parity and weak interactions

1956,  $\tau - \theta$  puzzle: the violation of the parity in weak interactions

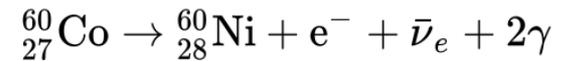


Chien-Shiung Wu

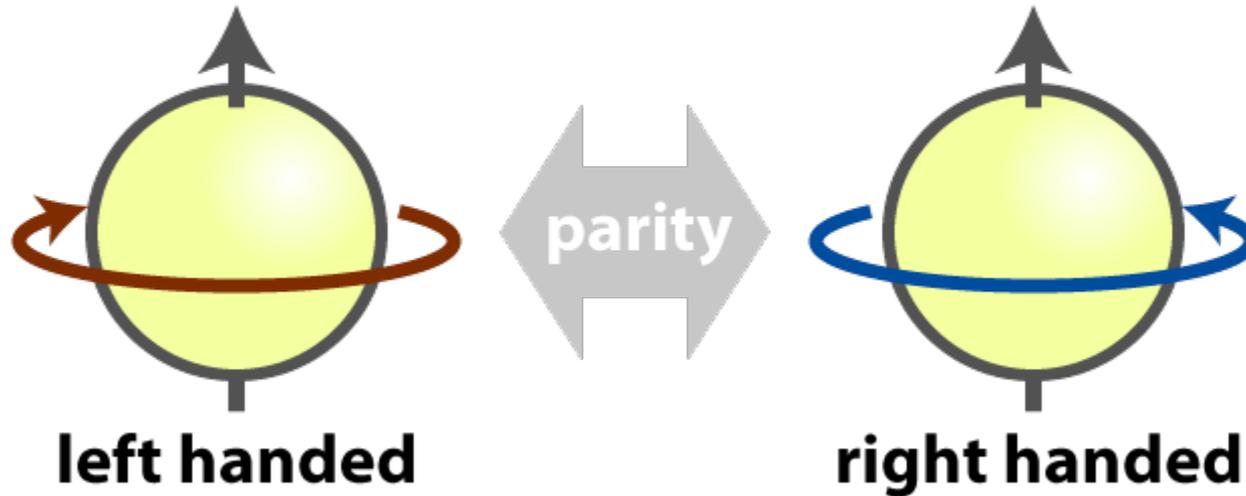
1957: testing the conservation of parity



**Wu experiment:**  
**Beta decay of cobalt-60**



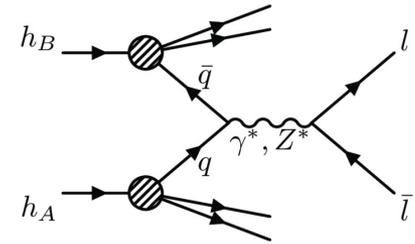
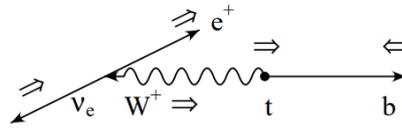
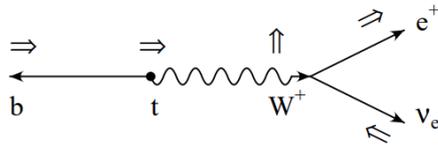
# Spin effects and New Physics



- ❖ Parity violation: left-handed  $\neq$  right-handed
- ❖ **The particle would be polarized** when involving the parity violation effects
- ❖ Polarization of particles: **A tool to probe the interactions**

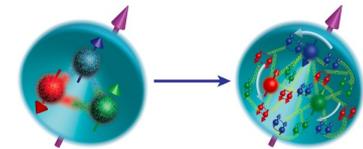
# Spin effects in Electroweak and QCD

- Spin is measured from **its decay products**: top quark, gauge bosons



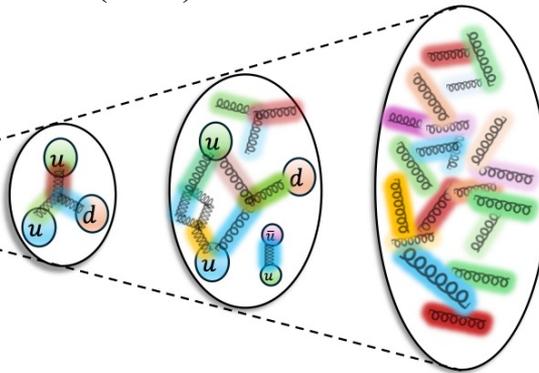
- Spin from **nonperturbative QCD**: PDFs and FFs

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



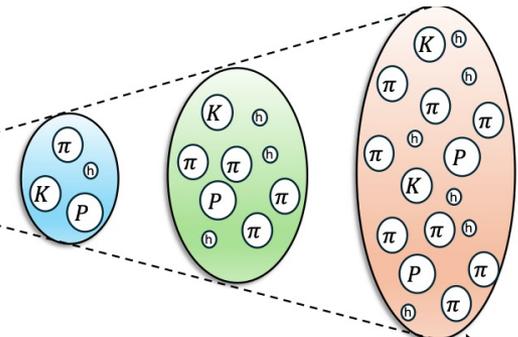
**Hadron**

*Parton distribution function describes the probability of finding a quark or gluon*



**Parton**

*Fragmentation function describes the probability of producing a specific hadron.*



- Spin phenomena in QCD arise from the intrinsic correlations between parton transverse momentum, spin, and hadronization dynamics

# Chiral-odd FFs: Transverse spin of quark

Leading Quark TMDFFs



Hadron Spin

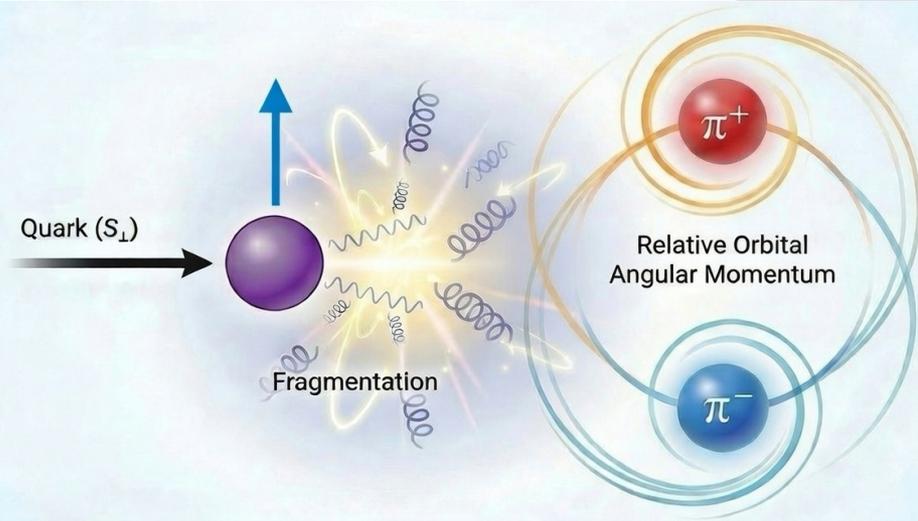


Quark Spin

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

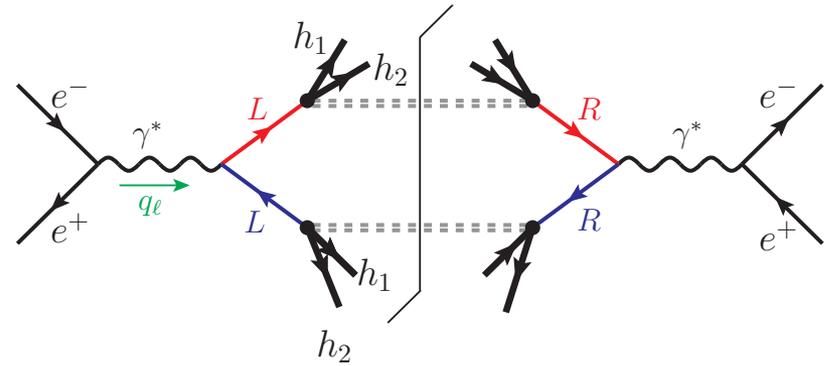
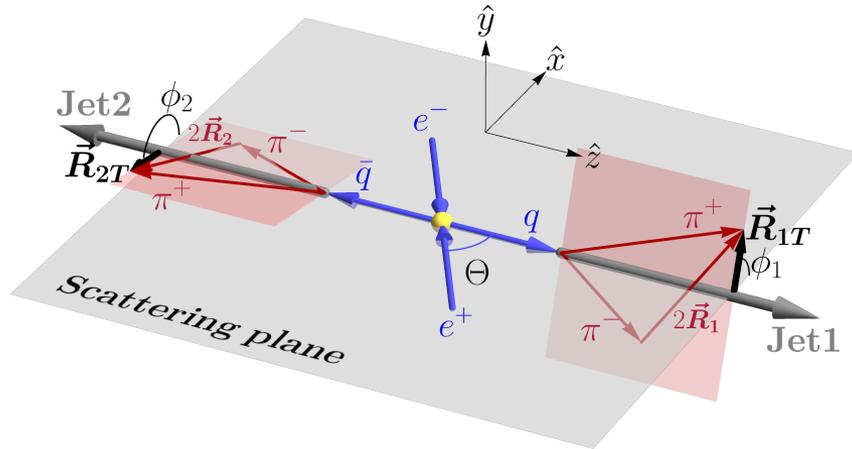
**Transverse spin of quark:**  
The interference between **the different helicity states**

Transverse momentum dependent factorization

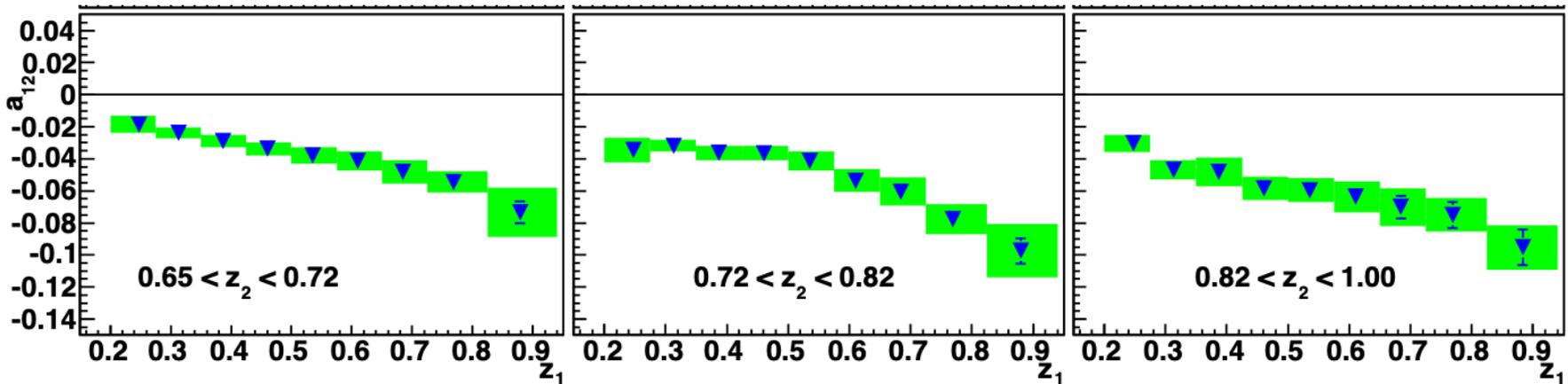


**Interference Dihadron Fragmentation**  
Collinear factorization

# 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**



$$-\mu_e \frac{\vec{S}}{|\vec{S}|} \cdot \vec{B} \Leftrightarrow e(\bar{e}\gamma_\mu e)A^\mu + a_e \frac{e}{4m_e} (\bar{e}\sigma_{\mu\nu} e)F^{\mu\nu}$$
$$-d_e \frac{\vec{S}}{|\vec{S}|} \cdot \vec{E} \Leftrightarrow + d_e \frac{i}{2} (\bar{e}\sigma_{\mu\nu}\gamma_5 e)F^{\mu\nu}$$

$$\mu_e = g_e \frac{e}{2m_e} \quad \text{and} \quad (g_e - 2) = 2a_e$$

# New physics and Dipole Operator

➤ Magnetic dipole moments: probing the **internal structures of particles**

## Elementary particle:

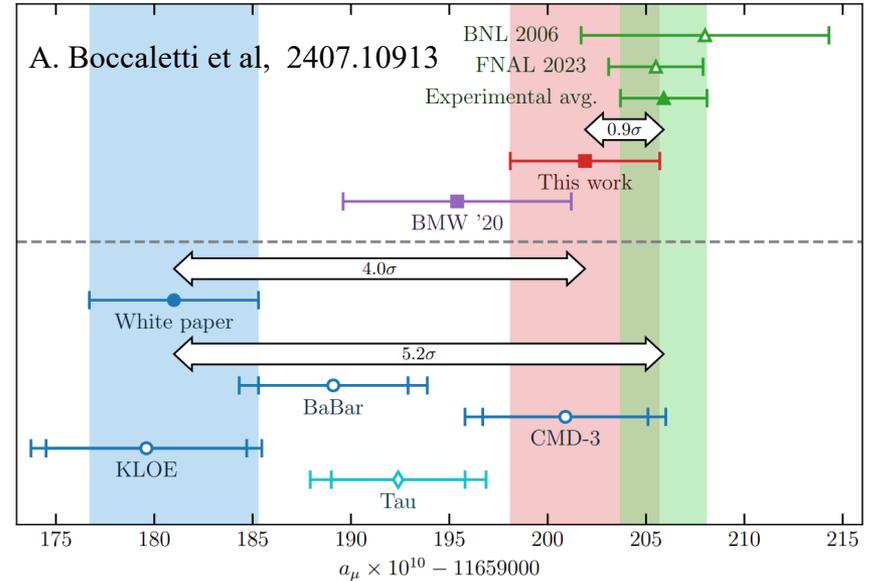
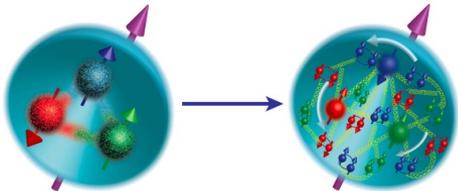
Electron:  $g/2=1.001159\dots$

Muon:  $g/2=1.0011659\dots$

## Composite particle:

Proton:  $g/2=2.7928444\dots$

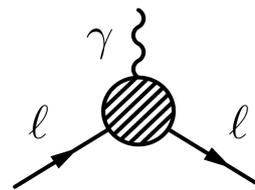
Neutron:  $g/2=-1.91394308\dots$



## Quarks: any internal structures?

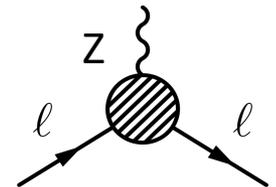
## From MDM and EDM to weak dipole moments?

$$\bar{\ell} \sigma^{\mu\nu} e \tau^I \varphi W_{\mu\nu}^I, \bar{\ell} \sigma^{\mu\nu} e \varphi B_{\mu\nu}$$



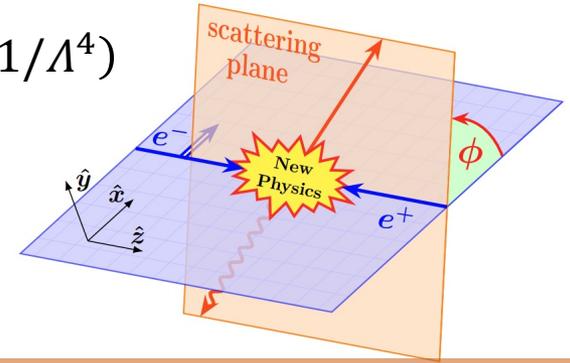
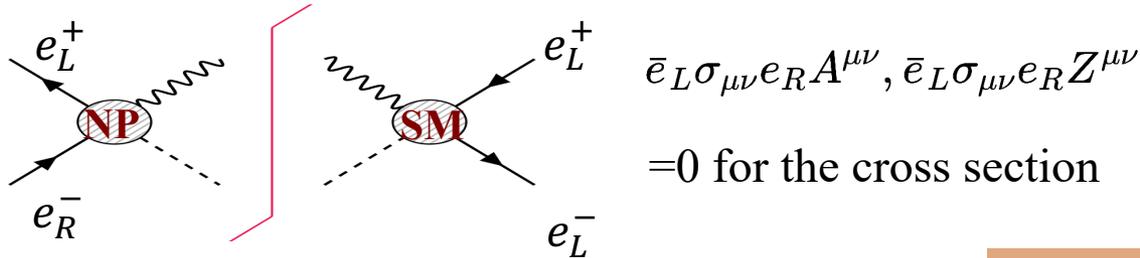
May have same physics source

$$B_{\mu\nu}, W_{\mu\nu}$$



# Example: electron weak dipole couplings

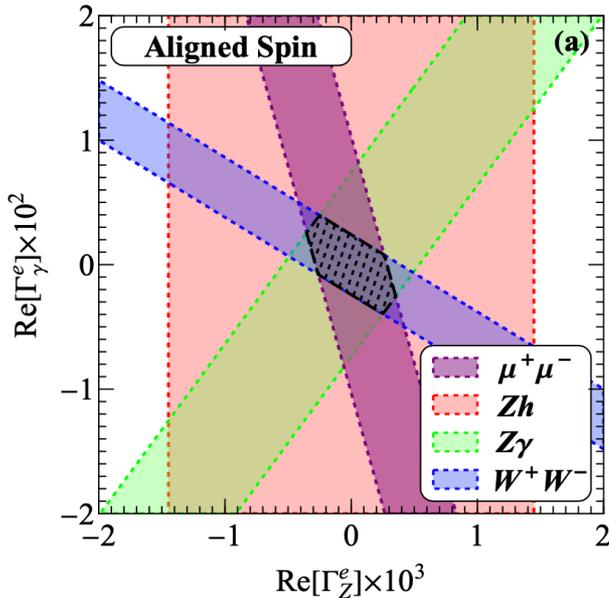
- The electroweak dipole couplings are poorly constrained:  $O(1/\Lambda^4)$



- 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$

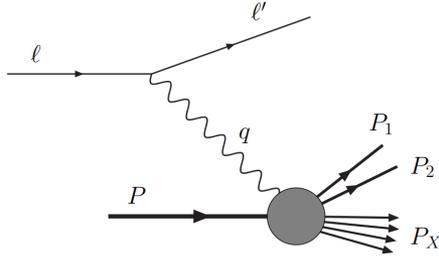
$$\sqrt{s} = 250 \text{ GeV}, \mathcal{L} = 5 \text{ ab}^{-1} \quad (b_T, \bar{b}_T) = (0.8, 0.3)$$

- 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

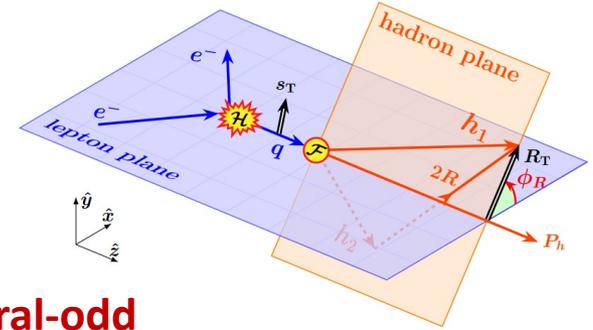
# Transverse spin effects of quark @ EIC

- 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**

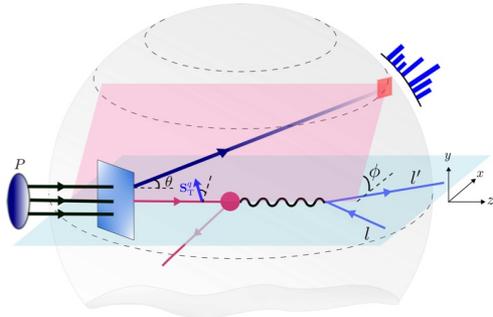
$$\frac{d\sigma}{dx dy dz dM_h d\phi_R} = \frac{N}{2\pi} \sum_q f_q(x, Q) [D_{h_1 h_2/q}(z, M_h; Q) - (\mathbf{s}_{T,q}(x, Q) \times \hat{\mathbf{R}}_T)^z H_{h_1 h_2/q}(z, M_h; Q)] C_q(x, Q)$$

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

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

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255

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



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

Yingsheng Huang, Xuan-Bo Tong, Hao-Lin Wang, 2508.08516

**The flat direction in flavor space of dipole couplings?**

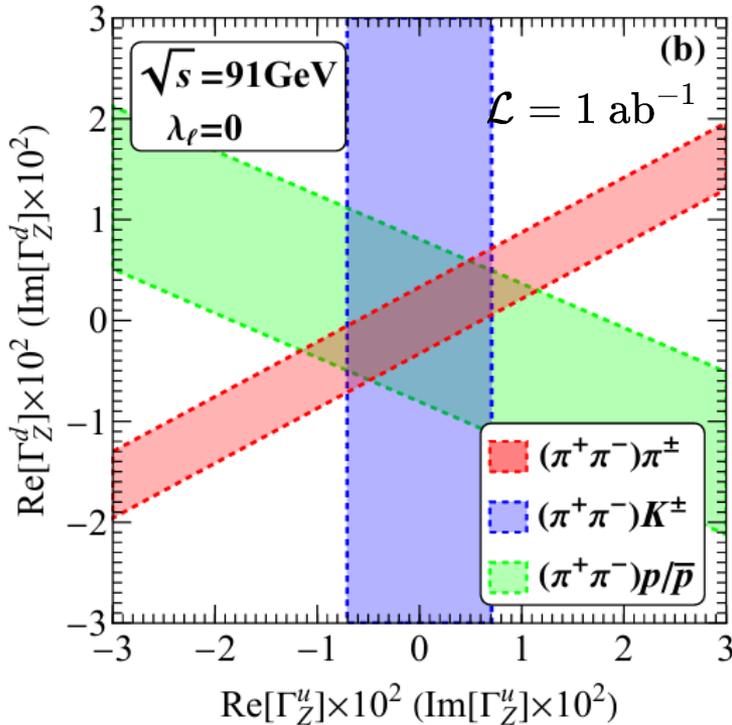
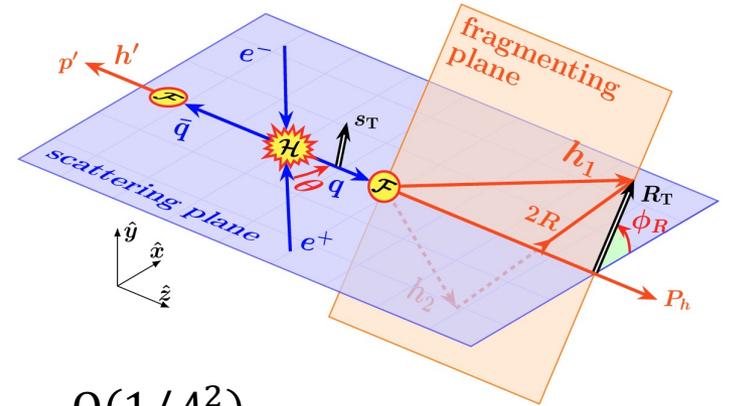
See: Yingsheng Huang's talk

# Transverse spin effects of quark @ CEPC

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

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

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



$O(1/\Lambda^2)$

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

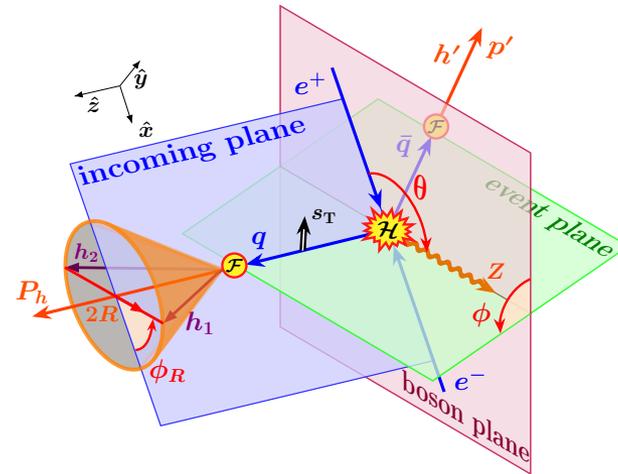
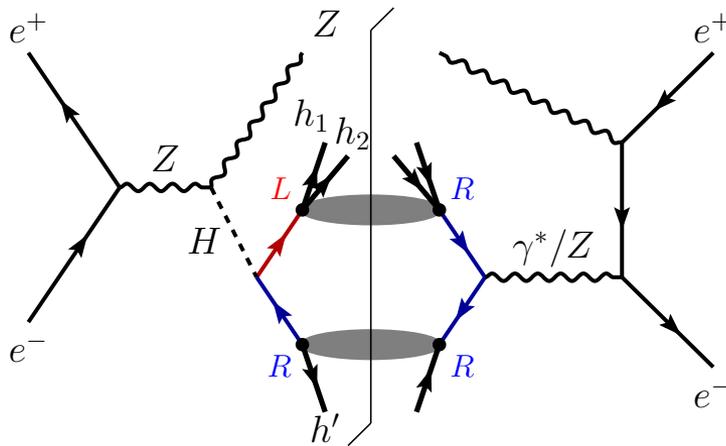
$$s_q^y = \frac{2}{C_q} (w_\gamma^q \text{Im} \Gamma_\gamma^q + w_Z^q \text{Im} \Gamma_Z^q)$$

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

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

# Dihadron FFs and Yukawa coupling

- Yukawa interactions generate **transverse quark polarization**
- Dihadron **interference FFs** provide a direct probe

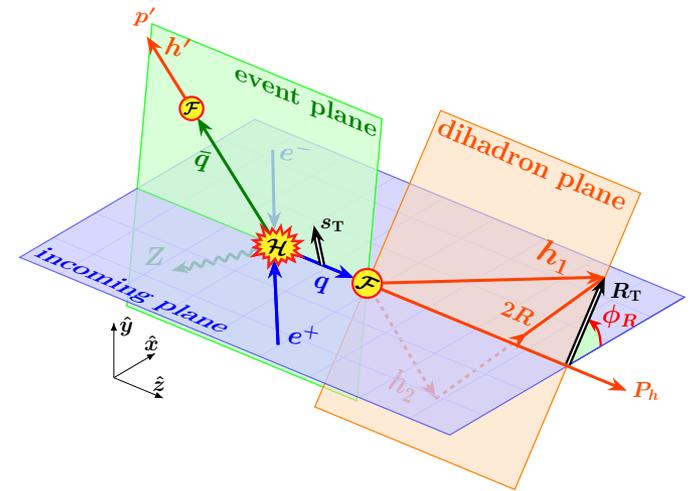
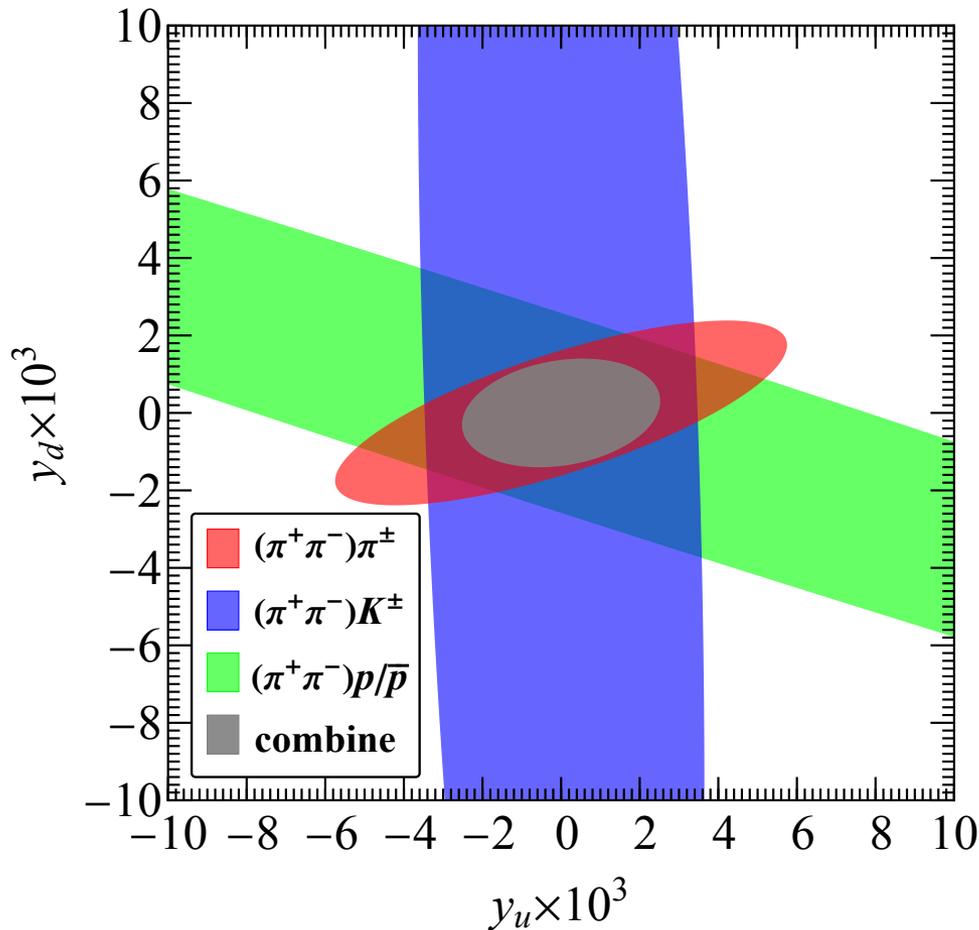


- ❖ Interference effects are **linear in the Yukawa couplings**
- ❖ Single-hadron tagging **lifts degeneracies** among up- and down-quark Yukawa couplings

# CP even Yukawa couplings @ CEPC

$$A_{UD}^{h'} = \frac{\sigma^{h'}(\sin \phi_R > 0) - \sigma^{h'}(\sin \phi_R < 0)}{\sigma^{h'}(\sin \phi_R > 0) + \sigma^{h'}(\sin \phi_R < 0)}$$

$$A_{LR}^{h'} = \frac{\sigma^{h'}(\cos \phi_R > 0) - \sigma^{h'}(\cos \phi_R < 0)}{\sigma^{h'}(\cos \phi_R > 0) + \sigma^{h'}(\cos \phi_R < 0)}$$



$$\sqrt{s} = 250 \text{ GeV}, \mathcal{L} = 50 \text{ ab}^{-1}$$

- Yukawa couplings  $0(10^{-4})$
- Single-hadron channels enable flavor separation

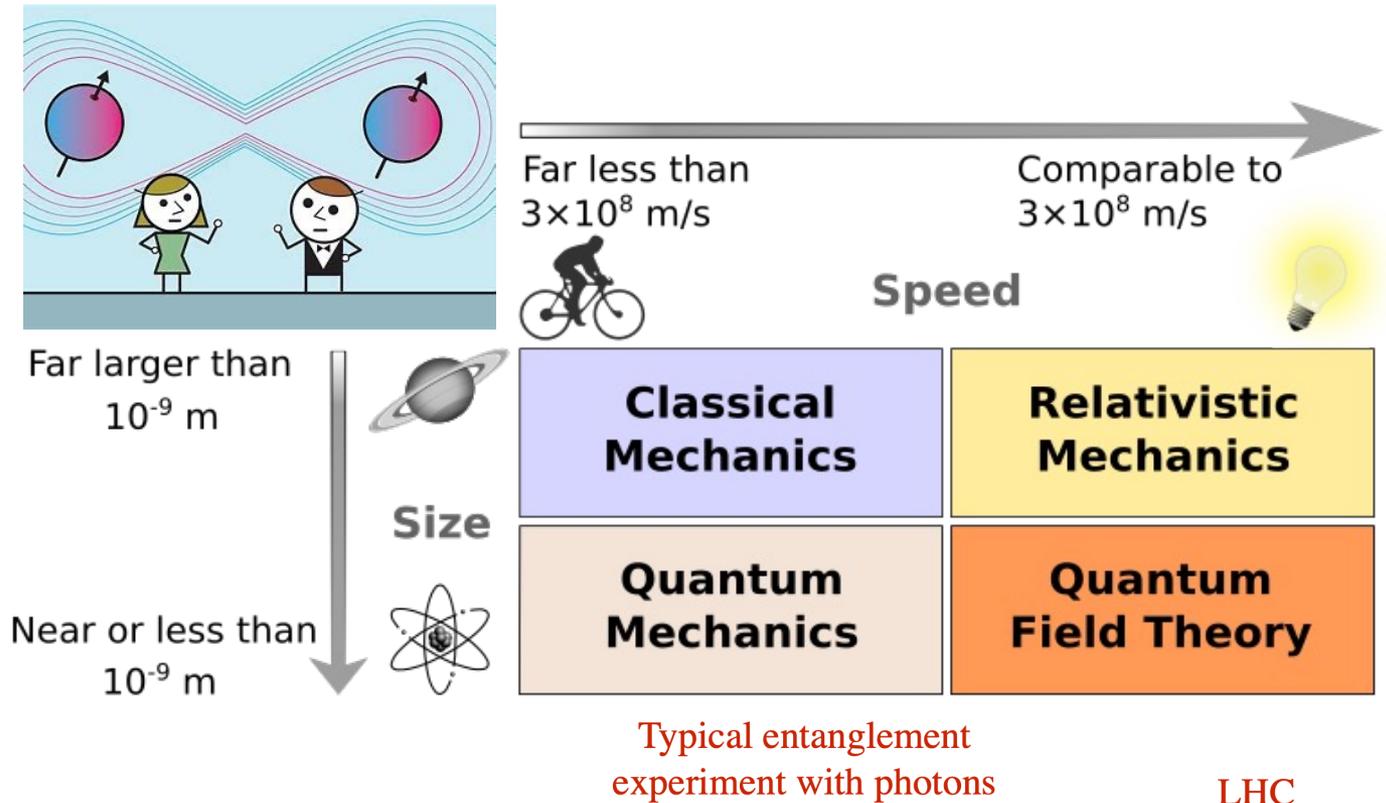
# Fragmentation functions encode the spin information of quarks



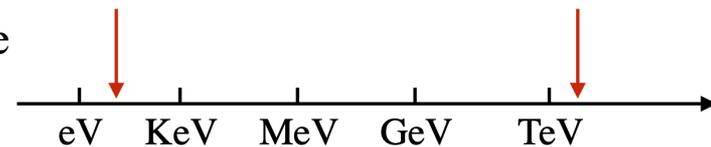
- Spin information as a tool for new physics searches
- Spin structure of quark systems: quark-quark spin correlations
- Emergence of entanglement in quark systems

# Quantum information at collider

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



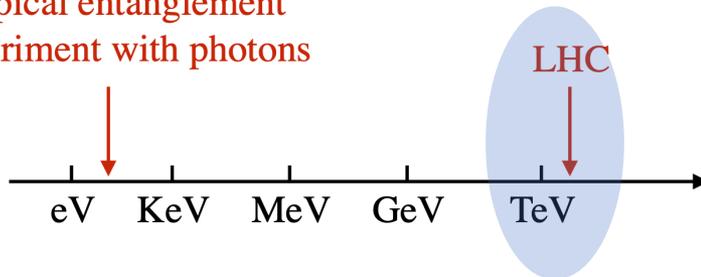
➤ Collider physics: high energy and small size



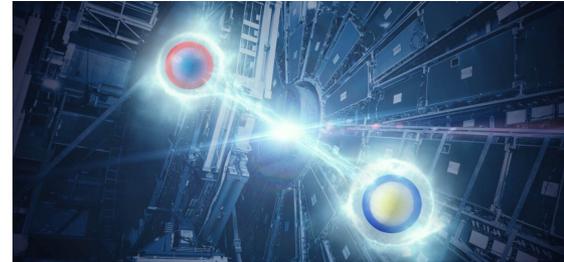
# Quantum information at collider

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

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 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

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

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

# Entanglement and Bell inequality

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

$$\left| \langle \hat{A}_1 \hat{B}_1 \rangle + \langle \hat{A}_1 \hat{B}_2 \rangle + \langle \hat{A}_2 \hat{B}_1 \rangle - \langle \hat{A}_2 \hat{B}_2 \rangle \right| \leq 2 \quad [\text{Clauser et al, PRL 23, 880 (1969)}]$$

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

- 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  $\vec{a}_{1,2}, \vec{b}_{1,2}$

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

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

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

$c_1^2, c_2^2$  are the largest two eigenvalue of  $C^T C$ .

# 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  
K. Chen, T. Han, M. Low, T. Wu, 2507.12513  
....

## ➤ Entanglement & NP

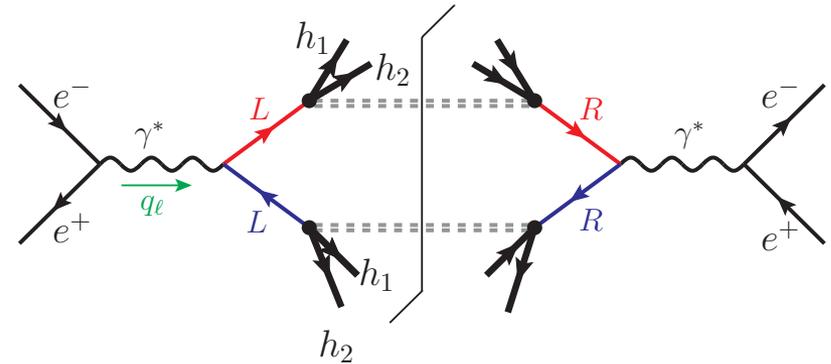
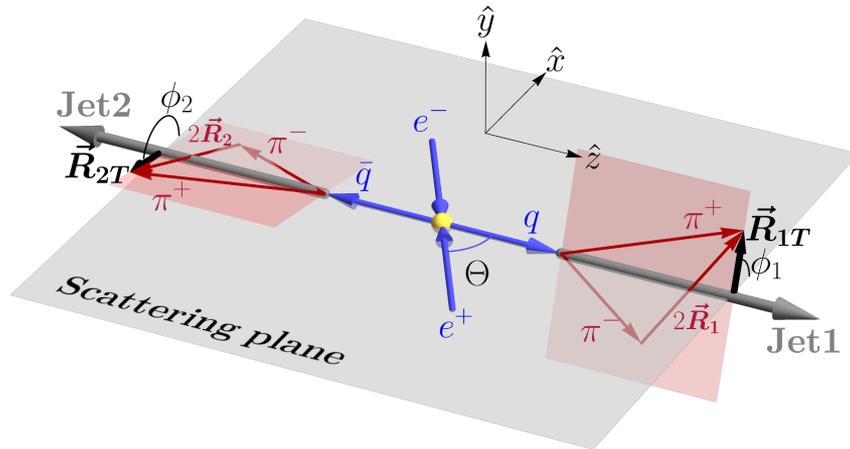
R. Aoude et al, PRD 106 (2022) 055007  
M. Fabbrichesi et al, EPJC 83 (2023) 162, JHEP 09 (2023) 195  
A. Bernal et al, EPJC 83 (2023) 11, 1050  
...

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



**How about the 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

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

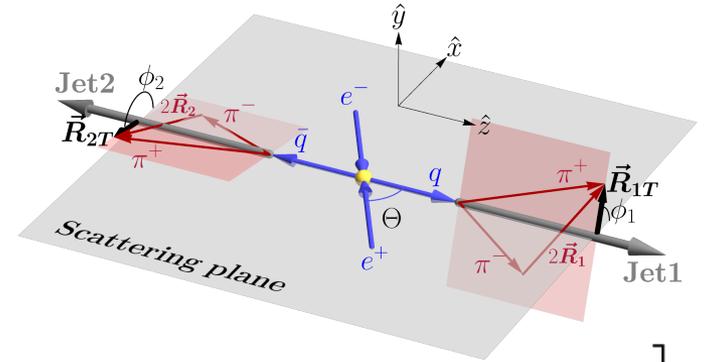
Transverse polarized diFF

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

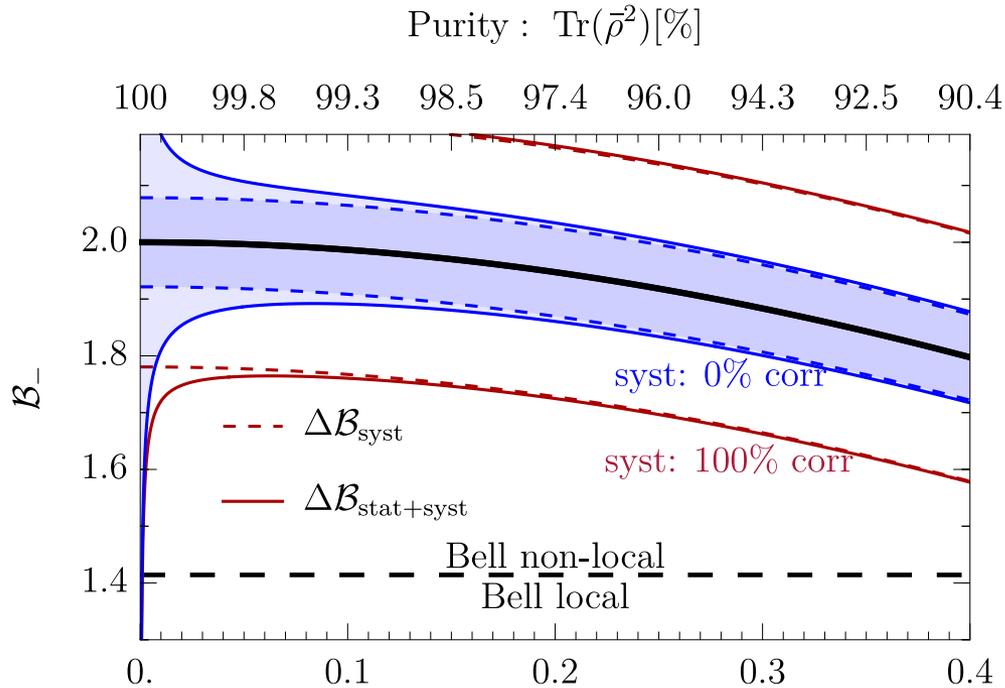
- ❖  $\mathcal{B}_+ = 0$  is a result of the **chiral symmetry of SM (massless quarks)**
- ❖ New spin structure  $\mathcal{B}_+ \neq 0$  from chiral symmetry breaking interactions: dipole couplings Qing-Hong Cao, Guanghui Li, Xin-Kai Wen and **Bin Yan**, 2509.18276

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

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



# Dihadron pair production



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

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

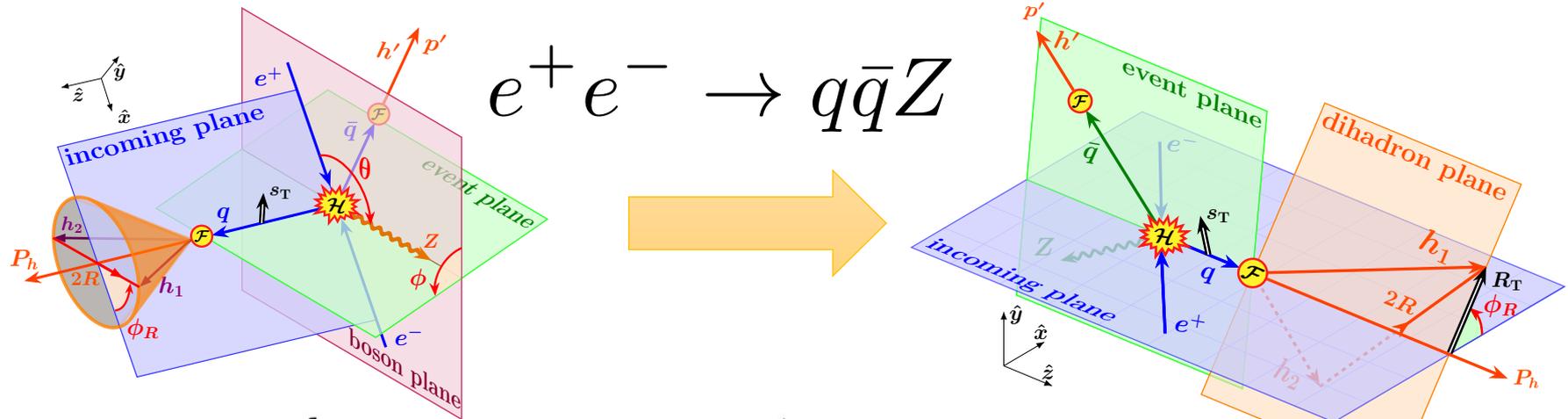
- ❖ The optimal cuts on scattering angle  $c_{\text{max}}$  will significantly improve the results
- ❖ The light quark pair would be a **highly pure spin Bell state**
- ❖ Combined results: **2.5  $\sigma$**  for **100% correlated** systematic uncertainties and **6.7  $\sigma$**  for the uncorrelated case

# Summary

- The quark dipole moments is crucial for probing the internal structure of quarks
- The electroweak dipole operators are difficult to be probed at colliders since their leading effects are from  $1/\Lambda^4$
- They can be probed at  $1/\Lambda^2$  via **transverse spin effects from non-perturbative functions: transversity and interference dihadron fragmentation functions**
- We proposed studying entanglement and Bell inequalities in **massless quark pair** via the hadron final states by the fragmentation mechanism
- The azimuthal correlations in Belle's  $\pi^+\pi^-$  dihadron pair could probe Bell inequality for massless quarks, **with  $> 5\sigma$  significance** when considering uncorrelated systematic uncertainties

*Thank you*

# Transverse spin effects of quark @ CEPC



$$\frac{d\sigma}{dx_q dx_{\bar{q}} d\cos\theta d\phi dz d\bar{z} dM_h d\phi_R} = \frac{1}{64(2\pi)^5} \sum_{q, q \rightarrow \bar{q}} C_q D_q^{h'}(\bar{z})$$

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

Unpolarized FFs

Polarized FFs

Energy fractions of quarks  $x_q, x_{\bar{q}}$ ; hadrons  $z, \bar{z}$

$$s_q^x C_q = 2 \operatorname{Re} \mathcal{H}_{+-}^q = \omega_q y_q + \tilde{\omega}_q \tilde{y}_q \quad (\mathbf{s}_{T,q} \times \hat{\mathbf{R}}_T)^z = s_q^x \sin \phi_R - s_q^y \cos \phi_R$$

$$s_q^y C_q = 2 \operatorname{Im} \mathcal{H}_{+-}^q = \tilde{\omega}_q y_q - \omega_q \tilde{y}_q \quad \text{CP even: } y_q, \text{ CP-odd: } \tilde{y}_q$$

# Transverse spin effects of quark @ CEPC

□ Isospin and charge conjugation symmetries for DiFFs

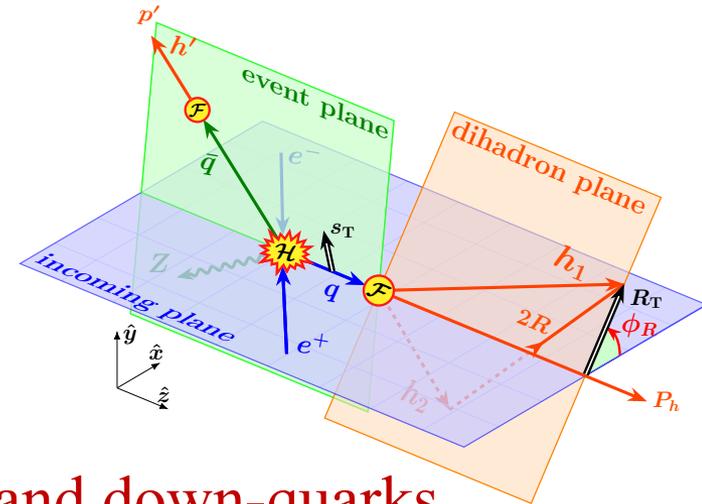
□ LO: the integration of the hard coefficients and FFs can be factorized

$$\langle \mathcal{O} \rangle \equiv \int dx_q dx_{\bar{q}} d\cos\theta d\phi \mathcal{O}_{\text{hard}}(x_q, x_{\bar{q}}, \cos\theta, \phi), \quad \langle \mathcal{O} \rangle \equiv \int dz d\bar{z} dM_h \mathcal{O}_{FF}(z, \bar{z}, M_h),$$

$$2\pi \frac{d\sigma}{d\phi_R} = \sum_{q=u,d} \langle \mathcal{C}_q \rangle \langle D_q^{h_1 h_2} \rangle \langle D_{\bar{q}}^{h'} + D_q^{h'} \rangle$$

$$- [y_q \sin\phi_R + \tilde{y}_q \cos\phi_R] \langle \omega_q \rangle \langle H_q^{h_1 h_2} \rangle \langle D_{\bar{q}}^{h'} - D_q^{h'} \rangle$$

$$- [\tilde{y}_q \sin\phi_R - y_q \cos\phi_R] \langle \tilde{\omega}_q \rangle \langle H_q^{h_1 h_2} \rangle \langle D_{\bar{q}}^{h'} + D_q^{h'} \rangle$$



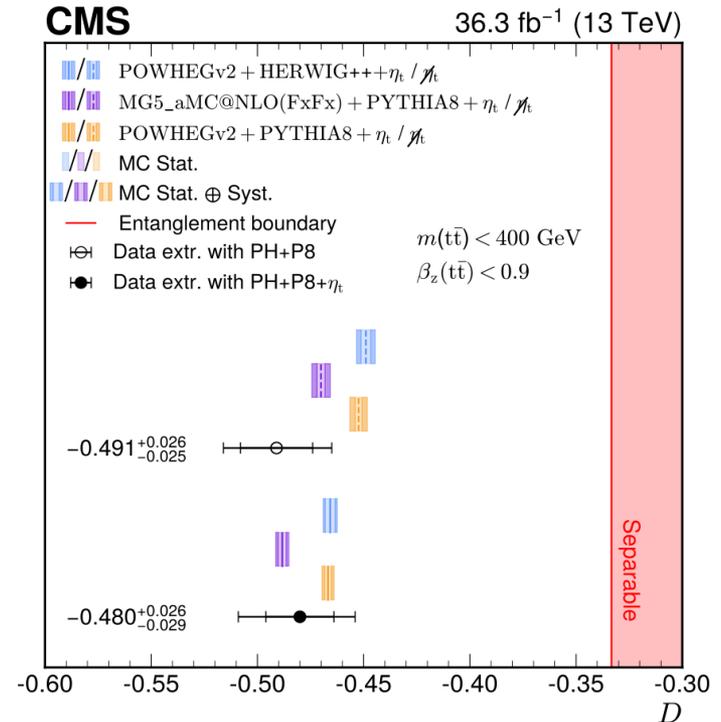
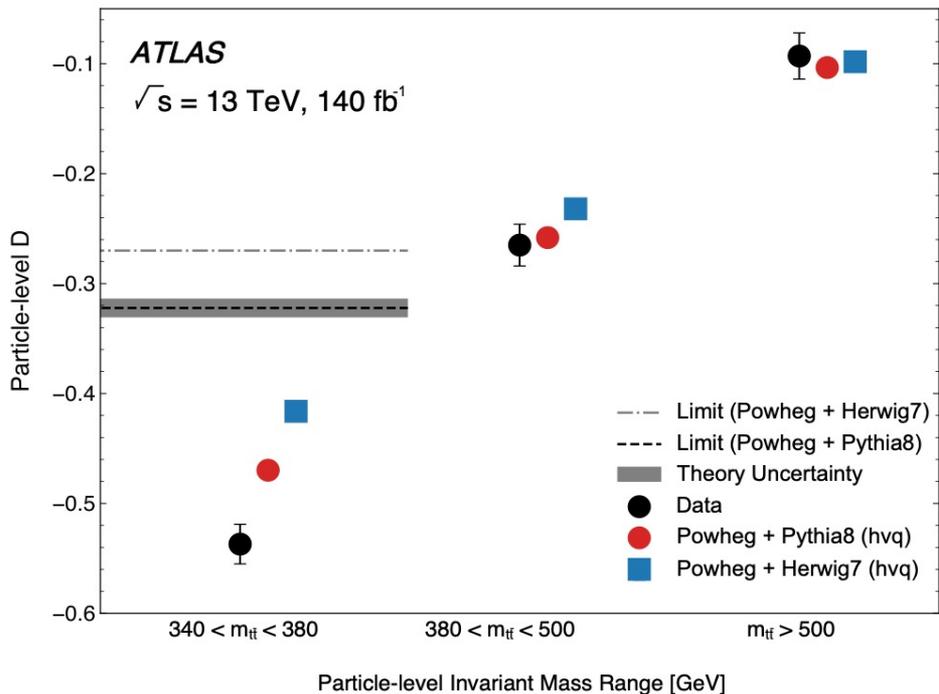
- ❖ The single hadron as flavor tags for up- and down-quarks
- ❖ CP properties are difficult to disentangle; we focus on the CP-even case

# Quantum spin entanglement

Top quark pair:  $\mathcal{E}[\rho] = \frac{-1 - 3D}{2}$        $\frac{1}{\sigma} \frac{d\sigma}{d \cos \varphi} = \frac{1}{2}(1 - D \cos \varphi)$

$$D = \min\left\{\frac{\text{tr}(C)}{3}, \frac{c_1 - c_2 - c_3}{3}, \frac{c_2 - c_1 - c_3}{3}, \frac{c_3 - c_1 - c_2}{3}\right\}, \quad c_i = \text{eig}(C)$$

Y. Afik, J. de Nova, EPJC 136 (2021) 907



Entangled :  $D < -1/3$ ,    separable :  $D > -1/3$