Testing the SM and probing new physics via QCD spin effects

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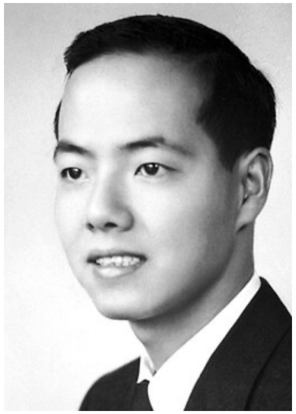
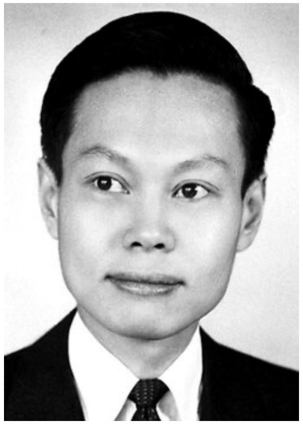
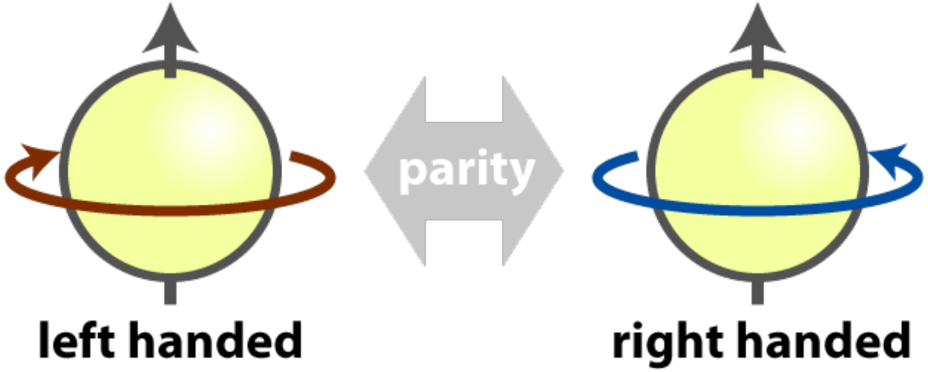
Parity and weak interactions

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

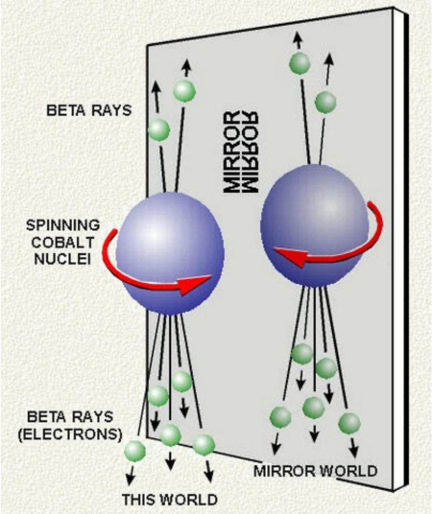






Chien-Shiung Wu

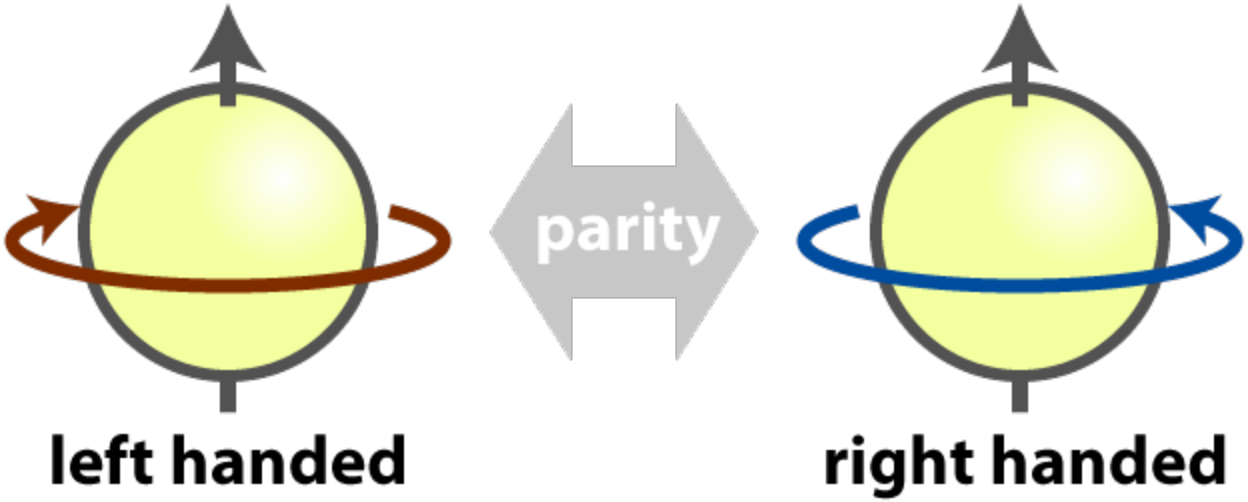
1957: testing the conservation of parity



Wu experiment:
Beta decay of cobalt-60

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + \mathrm{e}^{-} + \bar{\nu}_e + 2\gamma$$

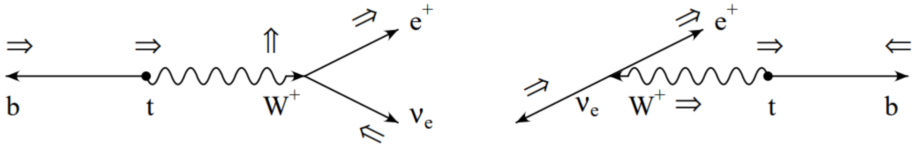
Spin effects and New Physics

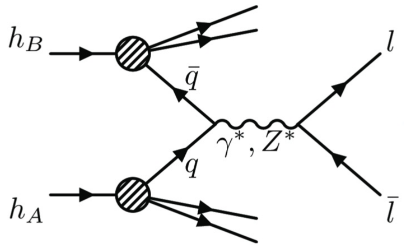


- Parity violation: left-handed ≠ right-handed
- The particle would be polarized when involving the parity violation effects
- Polarization of particles: A tool to probe the interactions

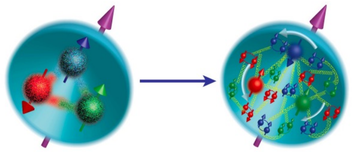
Spin effects in Electroweak and QCD

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

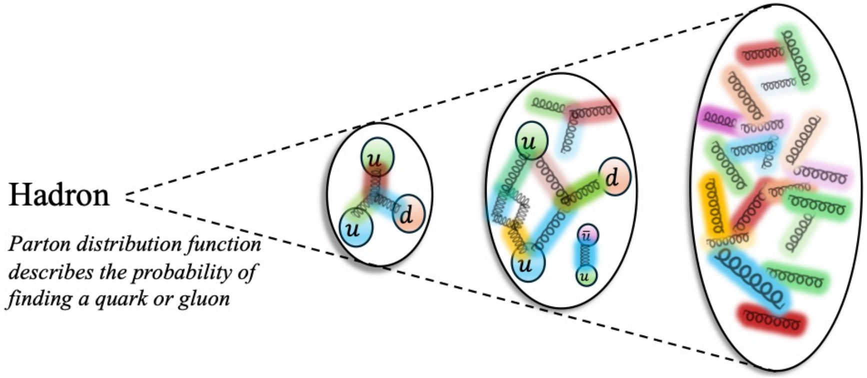




- Spin from nonperturbative QCD: PDFs and FFs

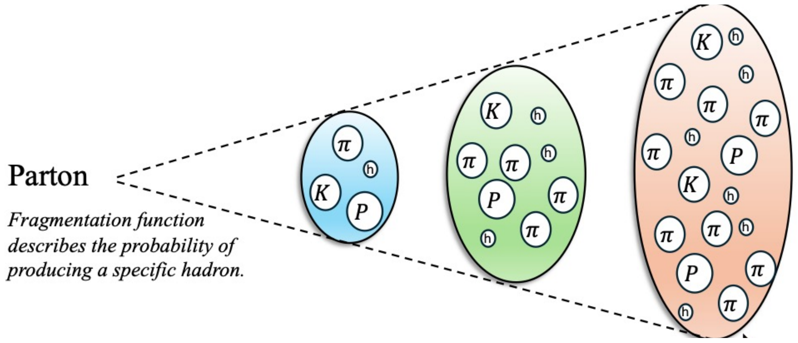


J. Datta et al, PRL 134 (2025) 111902



Hadron

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

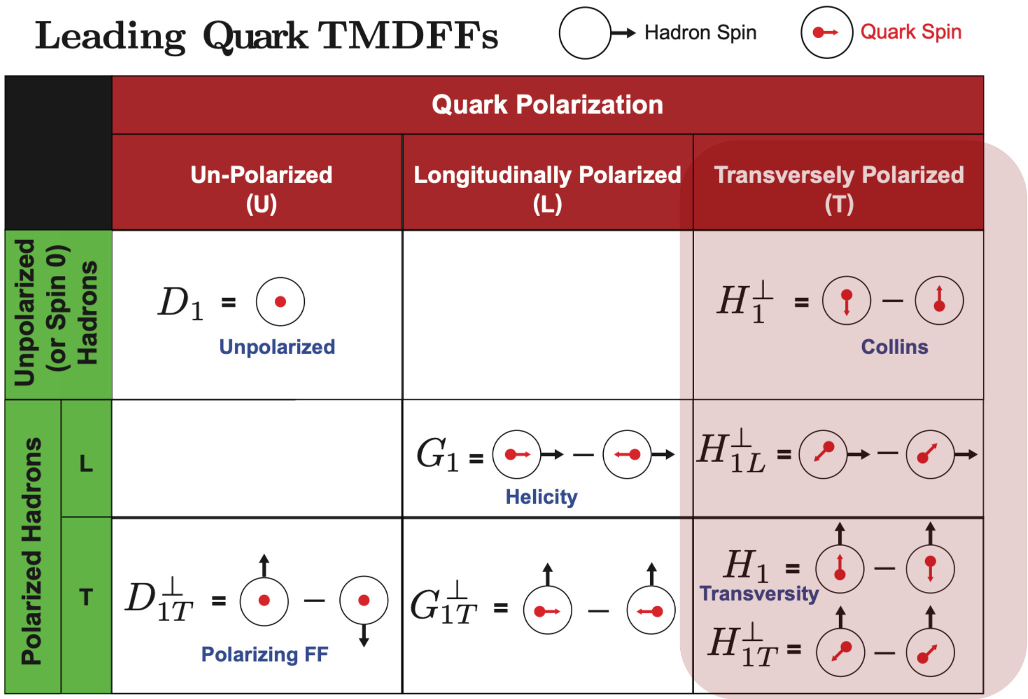


Parton

Fragmentation function describes the probability of producing a specific hadron.

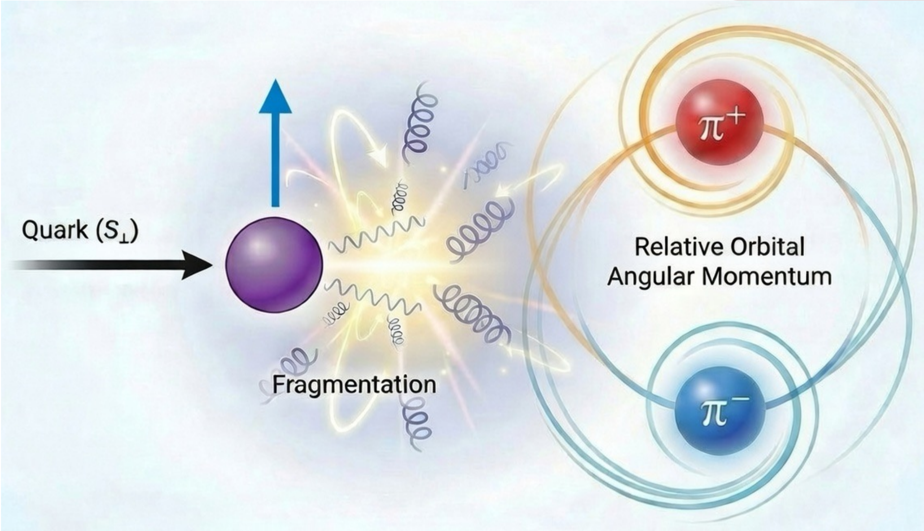
- Spin phenomena in QCD arise from the intrinsic correlations between parton transverse momentum, spin, and hadronization dynamics

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 = ⊙ 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 $H_{1T}^\perp$ = ⊙ − ⊙

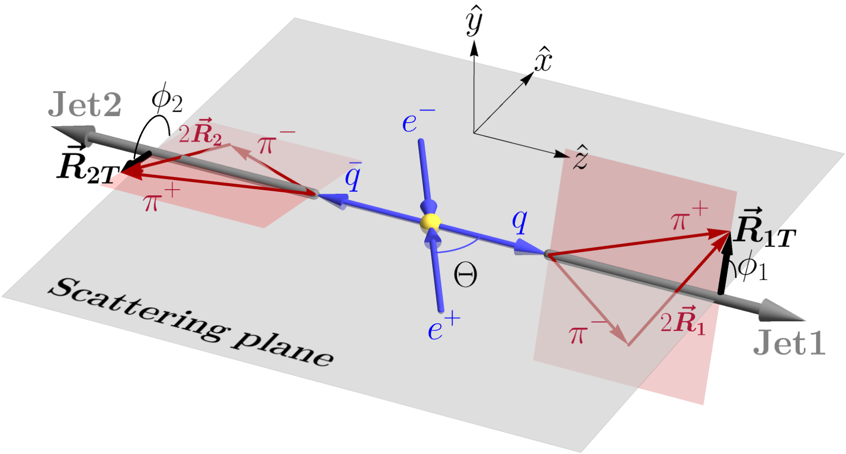


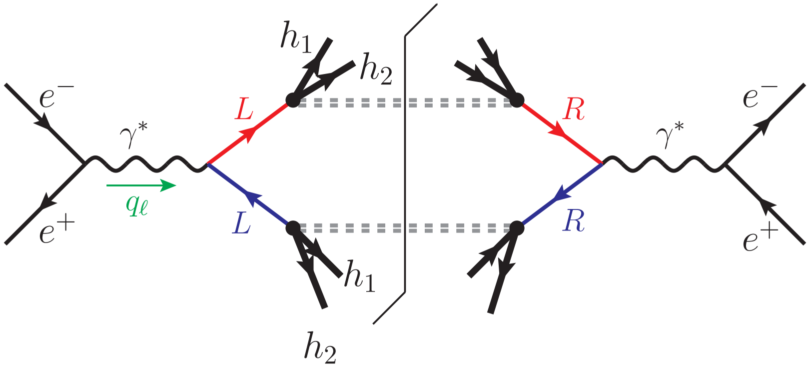
Transverse spin of quark:
The interference between the different helicity states

Transverse momentum dependent factorization

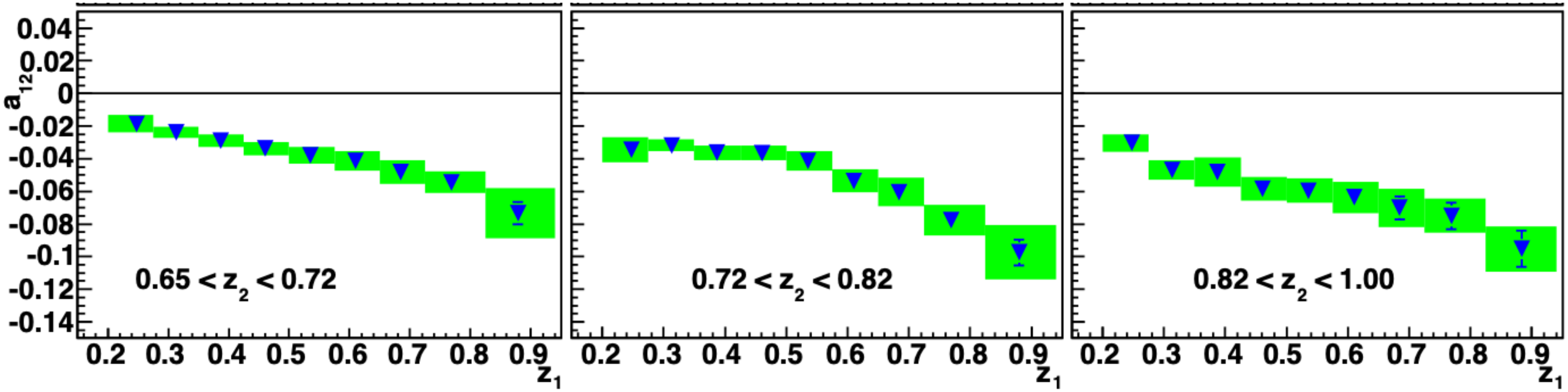
Interference Dihadron Fragmentation
Collinear factorization

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

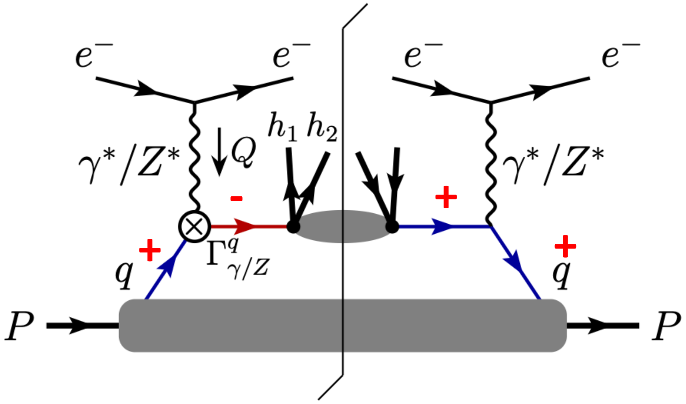
$$-\mu_e \frac{\vec{S}}{|\vec{S}|}\cdot\vec{B} \quad \Leftrightarrow \quad e\left(\bar{e}\gamma_\mu e\right)A^\mu + a_e \frac{e}{4m_e}\left(\bar{e}\sigma_{\mu\nu}e\right)F^{\mu\nu}$$

$$-d_e \frac{\vec{S}}{|\vec{S}|}\cdot\vec{E} \quad \Leftrightarrow \quad +d_e \frac{i}{2}\left(\bar{e}\sigma_{\mu\nu}\gamma_5 e\right)F^{\mu\nu}$$

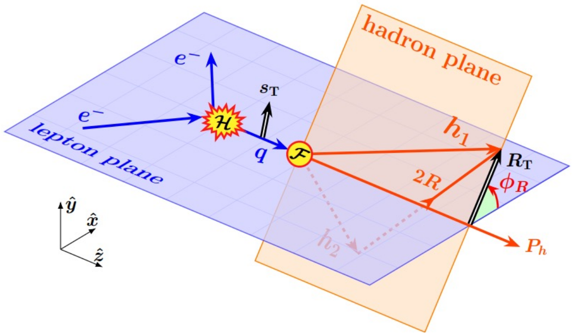
$$\mu_e = g_e \frac{e}{2m_e} \quad \text{and} \quad \left(g_e - 2\right) = 2a_e$$

Transverse spin effects of quark @ EIC

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



$O(1/\Lambda^2)$



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

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

$$\frac{d\sigma}{dx\,dy\,dz\,dM_h\,d\phi_R} = \frac{N}{2\pi}\sum_q f_q(x,Q)\big[D_{h_1h_2/q}(z,M_h;Q)$$

$$-\,(\boldsymbol{s}_{T,q}(x,Q)\times\hat{\boldsymbol{R}}_T)^z H_{h_1h_2/q}(z,M_h;Q)\big]C_q(x,Q)$$

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

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

Interference effects

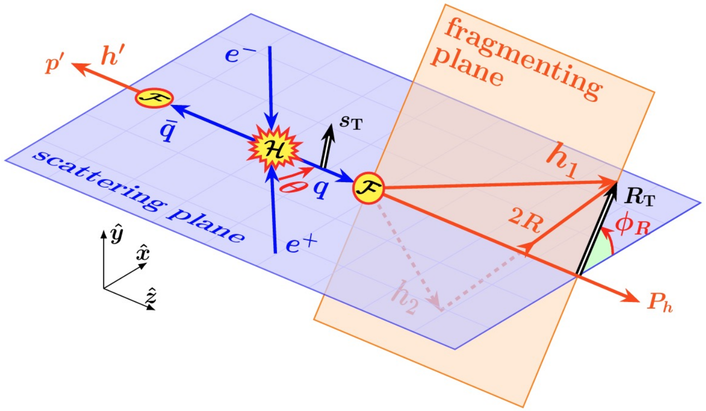
Nucleon energy correlator
See Hao-Lin Wang's talk

The flat direction in flavor space of dipole couplings?

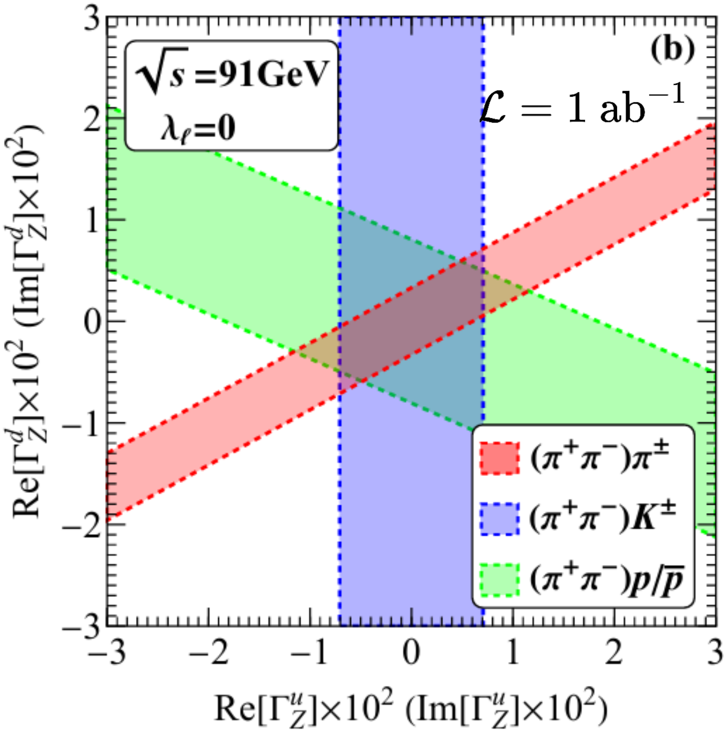
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255

Transverse spin effects of quark @ CEPC

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



$$\frac{d\sigma}{dy\,dz\,d\bar{z}\,dM_h\,d\phi_R} = \frac{1}{32\pi^2 s}\sum_{q,\,q\to\bar{q}} C_q(y)\,D_{\bar{q}}^{h'}(\bar{z})$$
$$\times\left[D_q^{h_1h_2}(z,M_h) - (\boldsymbol{s}_{T,q}(y)\times\hat{\boldsymbol{R}}_T)^z H_q^{h_1h_2}(z,M_h)\right]$$



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

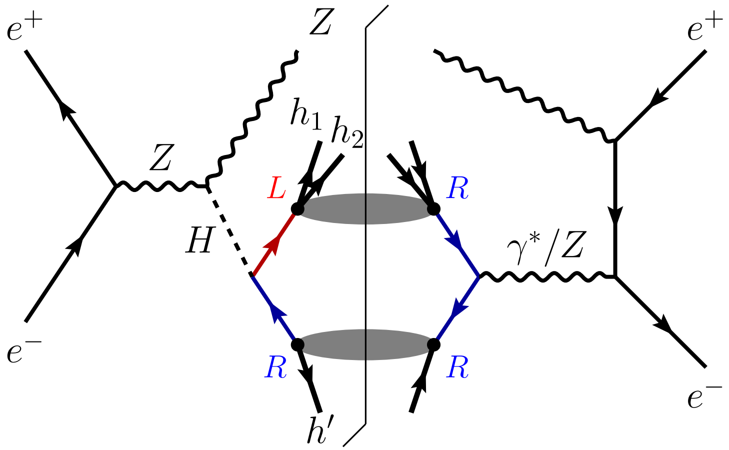
$O(1/\Lambda^2)$ $\quad\bar{q}_L\sigma_{\mu\nu}q_R A^{\mu\nu},\ \bar{q}_L\sigma_{\mu\nu}q_R Z^{\mu\nu}$

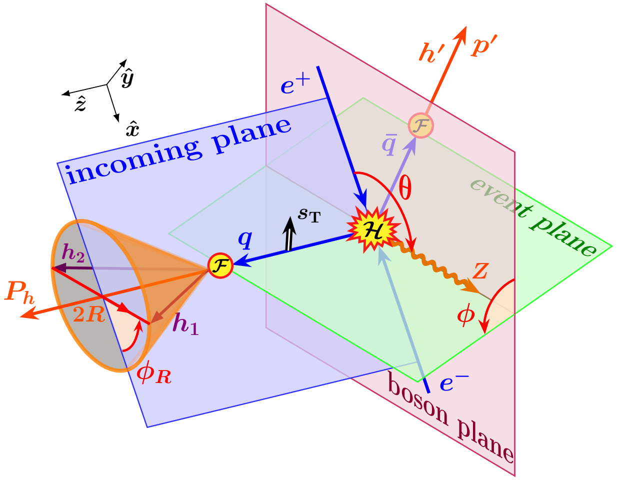
- ☐ The flat direction can be closed by combing more processes
- ☐ Z-boson dipole: O(0.001)

Dihadron FFs and Yukawa coupling

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

Q. H. Cao, X. K. Wen, B. Yan, S. T. Zhang, arxiv:2512.16492





See Xin-Kai Wen's talk

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

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 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
….

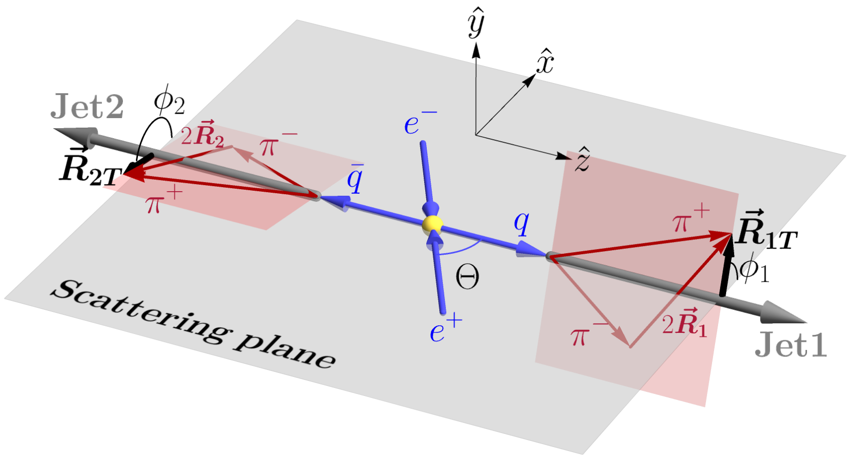
- Entanglement & NP

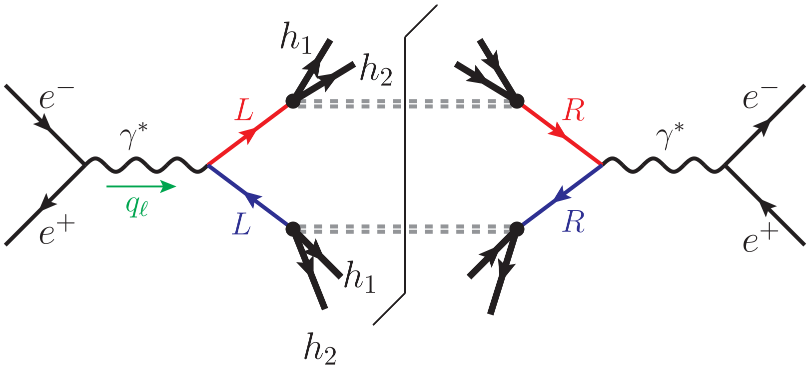
R. Aoude et al, PRD 106 (2022) 055007
M. Fabbrichesi et al, EPJC 83 (2023) 162, JHEP 09 (2023) 195
A. Bernal et al, EPJC 83 (2023) 11, 1050
…

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

How about the light quarks?

Dihadron pair production at lepton colldiers





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

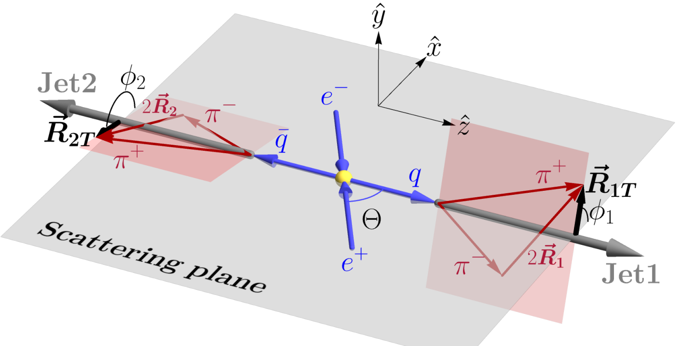
- The transverse spin correlation between light quarks: chiral-odd interference dihadron fragmentations (collinear factorization)

- Light quark pair are 100% correlated in the central scattering region

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

- The maximally entangled Bell state: Bell inequality violation effects

Bell inequality of light quarks



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

Unpolarized diFF

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

Transverse polarized diFF

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

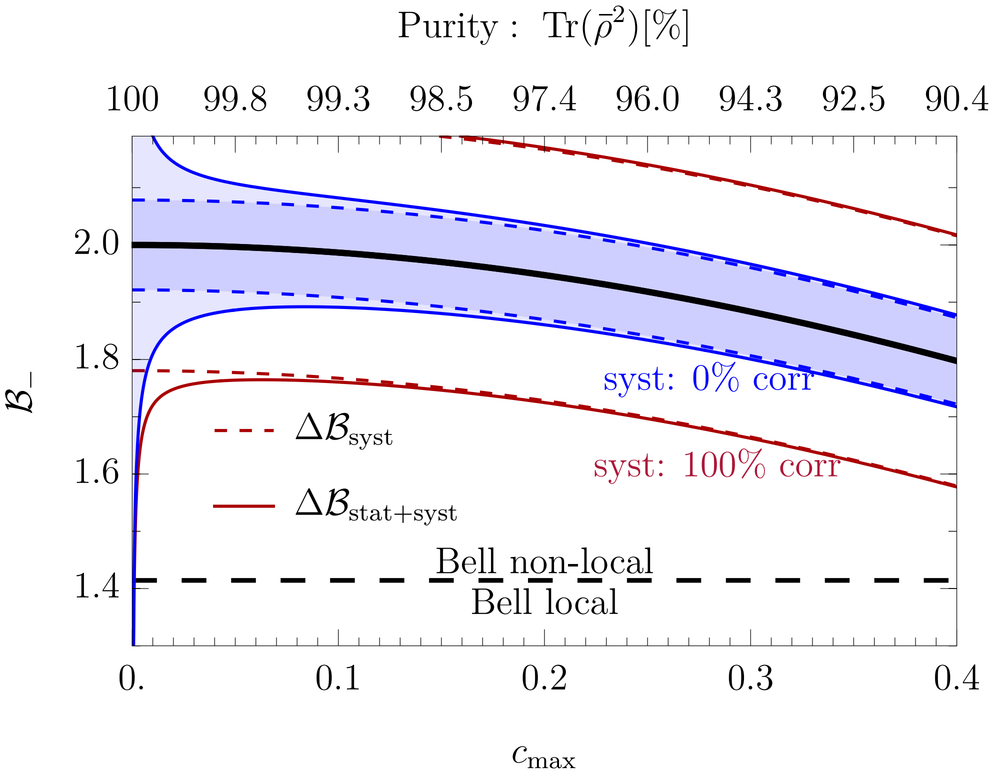
- $\mathcal{B}_+ = 0$ is a result of the chiral symmetry of SM (massless quarks)
- New spin structure $\mathcal{B}_+ \neq 0$ from chiral symmetry breaking interactions: dipole couplings Q. H. Cao, G. Li, X. K. Wen and B. Yan, 2509.18276; see G. Li's talk

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

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

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

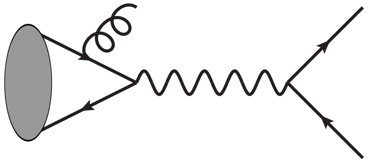
- The optimal cuts on scattering angle will significantly improve the results
- The light quark pair would be a highly pure spin Bell state
- Combined results: 2.5 σ for 100% correlated systematic uncertainties and 6.7 σ for the uncorrelated case

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-Octect Mechanism via Spin Observable**

NRQCD and Heavy Quarkonium

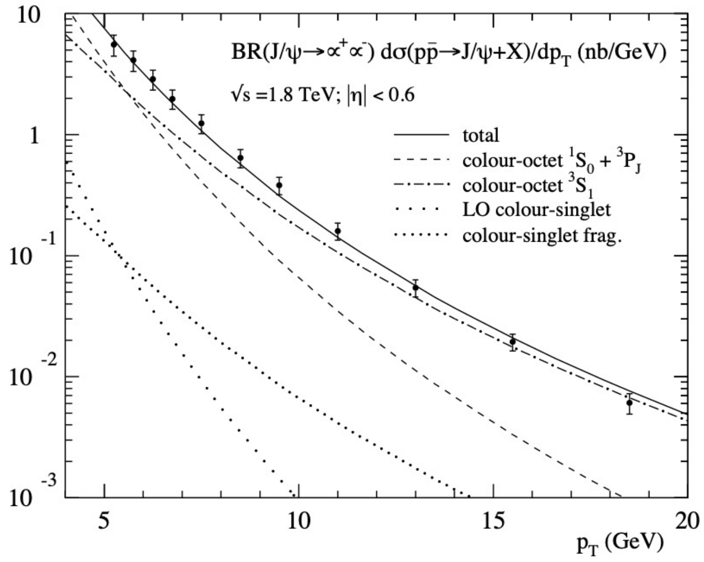
- ➢ NRQCD factorization G. T. Bodwin, E. Braaten, G. P. Lepage, PRD 51 (1995) 1125
- ❖ $Q\bar{Q}$ could be in all possible spin and color configurations
- ❖ Color-Octet Mechanism:

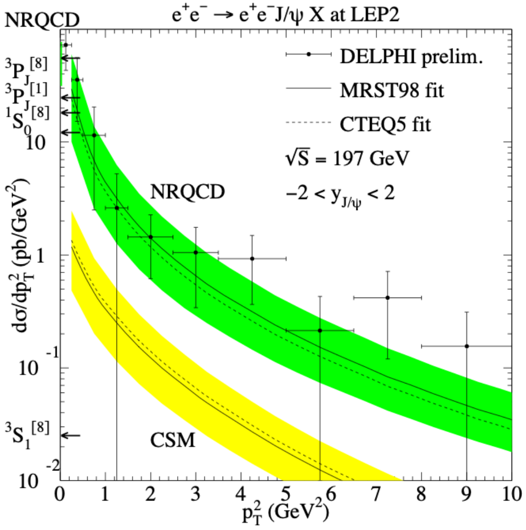


Physical quarkonium

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

- ❖ 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

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

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

- $\rho_8 = 0.044 \pm 0.015 \ (\text{Lattice})$
  $\rho_8 = 0.16^{+0.071}_{-0.047} \ (\text{CLEO})$

Anomaly!

G. T. Bodwin, E. Braaten, D. Kang, J. Lee, PRD 76 (2007) 054001
CLEO: PRD 78 (2008) 092007

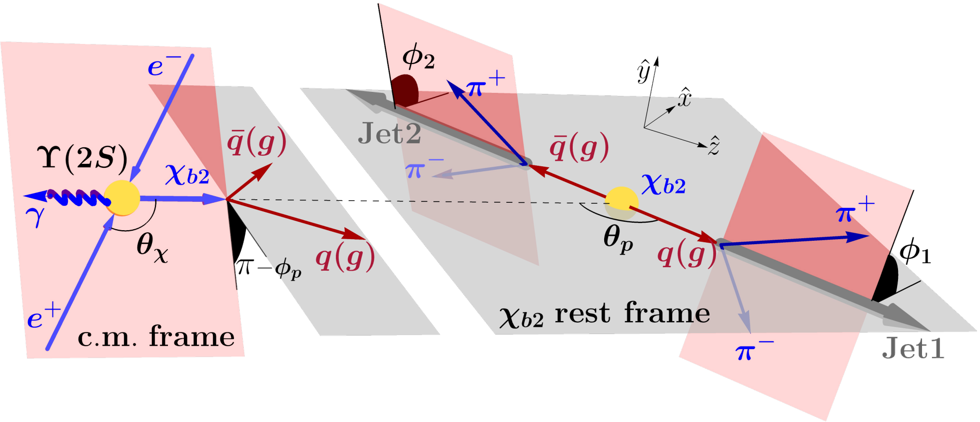
➡ An independent cross-check of ρ_8 is very important!

Z. G. He, G. Li, Y. J. Tian, X. K. Wen, B. Yan, arxiv: 2603.18874
see Y. J. Tian's talk

- Artru-Collins asymmetry

$$e^+e^- \to \Upsilon(2S) \to \gamma\chi_{bJ}$$

$$\chi_{bJ} \to q\bar{q}(gg) \to \pi^+\pi^-\pi^+\pi^- + X$$



Summary

- Polarization and correlations are powerful tools for testing SM interactions and searching for new physics
- Perturbative decay approaches: polarization and spin correlations determine the properties of unstable particles (top quark, weak bosons)
- Nonperturbative methods with PDFs and FFs: access polarization and correlation effects of light quarks
- Probing light quark dipole couplings $(1/\Lambda^2)$, quantum entanglement and propertries of NRQCD
- New opportunities in QCD spin physics: polarization and correlations as windows to new physics

Thank you