Testing the SM and probing new physics via QCD spin effects

Bin Yan
Institute of High Energy Physics

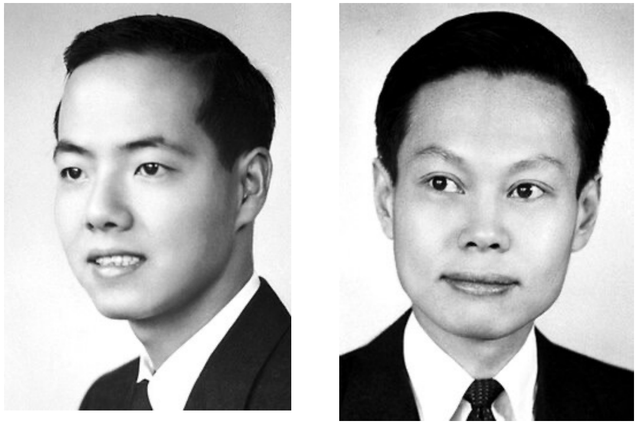
中国科学技术大学
2026年04月02日

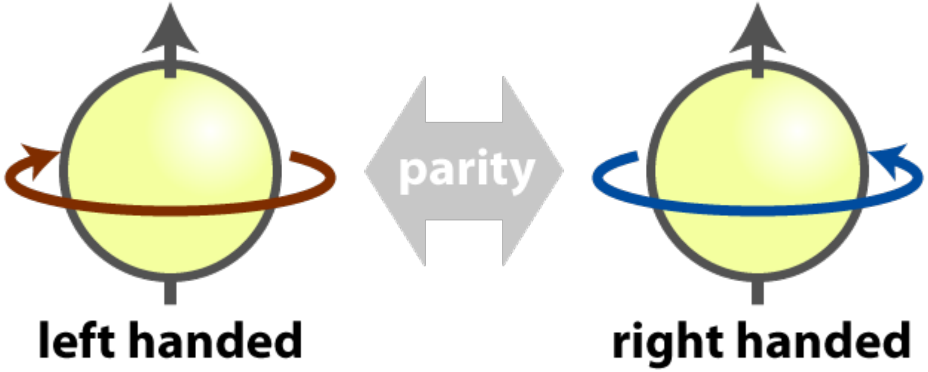
Outline

- Single particle polarization
  - ☐ Transverse Spin Polarization and Sensitivity to New Physics
- Spin correlation effects of particles
  - ☐ Quantum Entanglement of Light Quarks
  - ☐ Probing the Color-Octect Mechanism

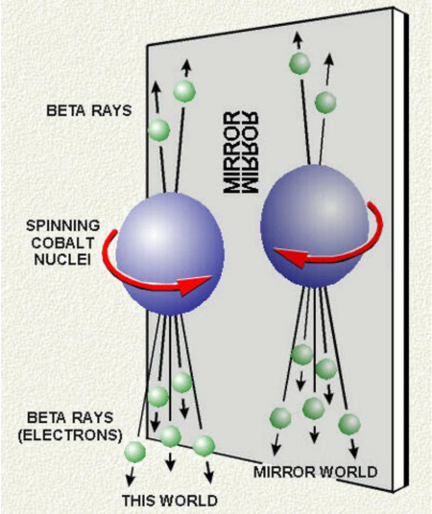
Parity and weak interactions

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





Chien-Shiung Wu

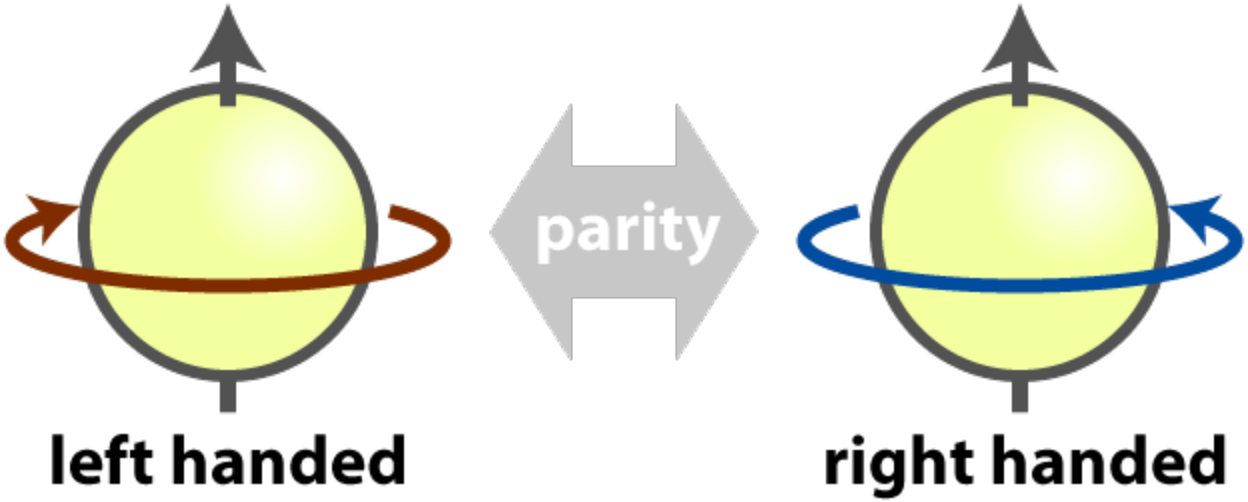


Wu experiment:
Beta decay of cobalt-60

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

1957: testing the conservation of parity

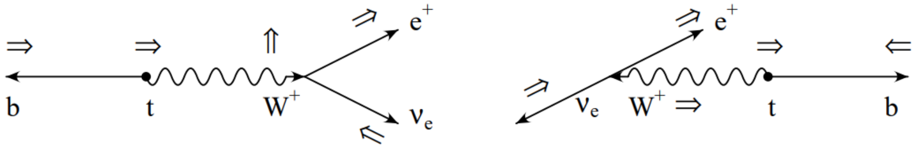
Spin effects and New Physics

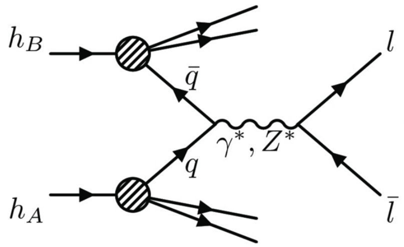


- Parity violation: left-handed ≠ right-handed
- The particle would be polarized when involving the parity violation effects
- Polarization of particles: A tool to probe the interactions

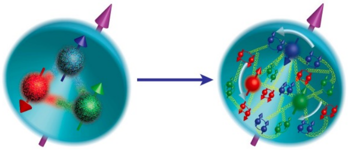
Spin effects in Electroweak and QCD

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

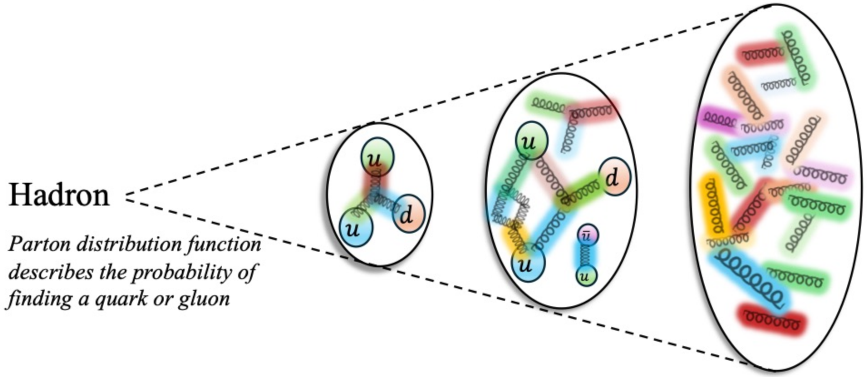


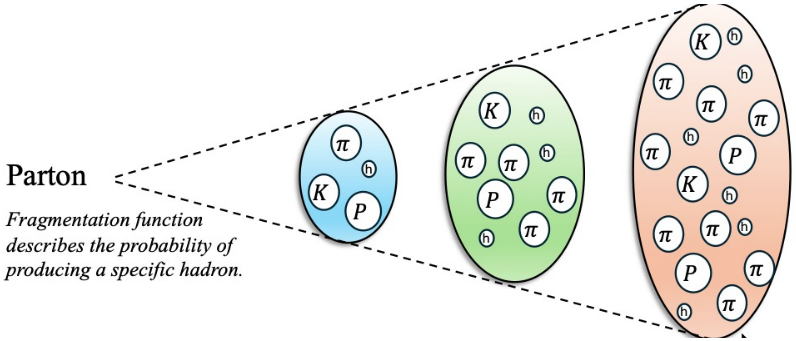


- Spin from nonperturbative QCD: PDFs and FFs



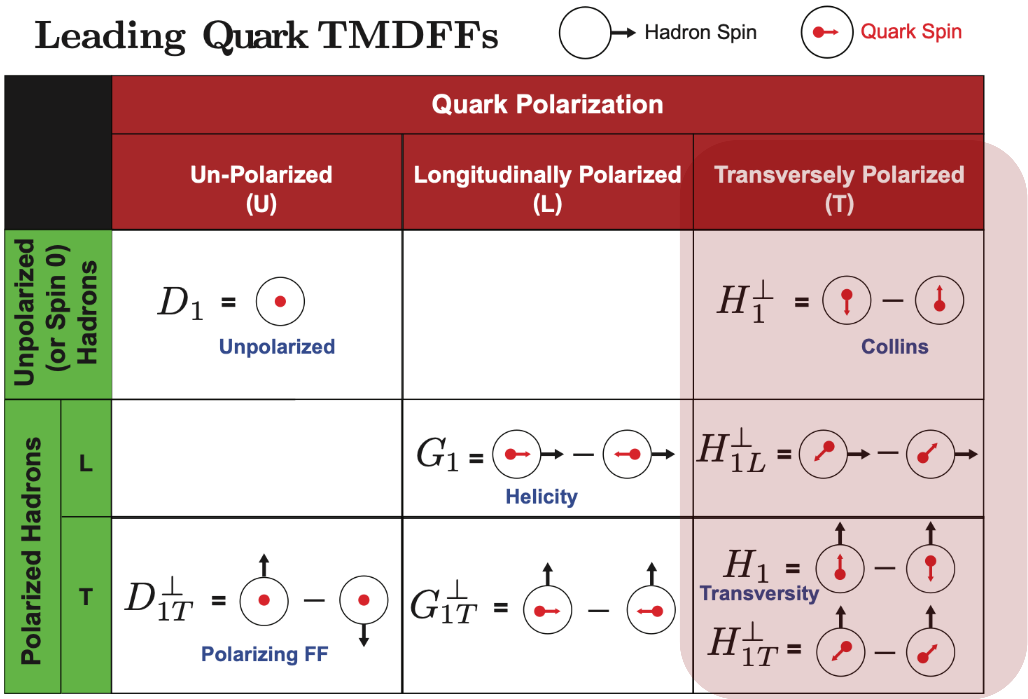
J. Datta et al, PRL 134 (2025) 111902





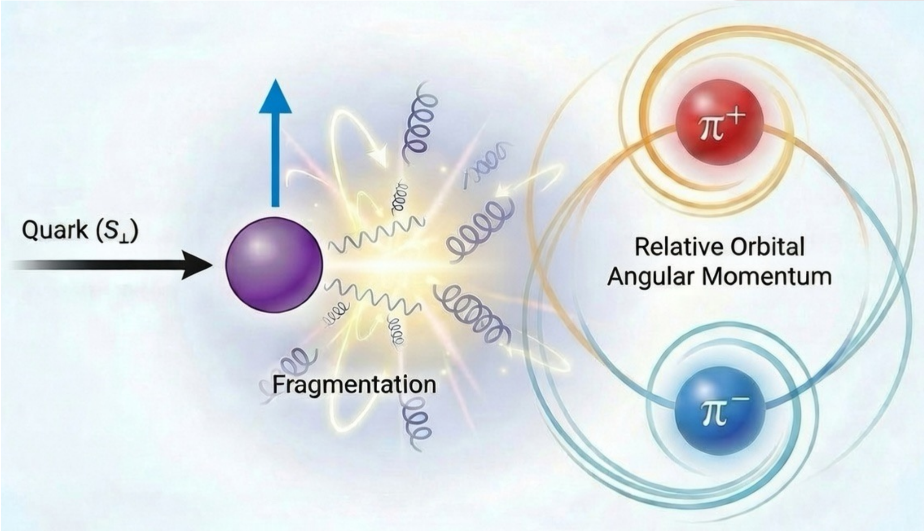
- Spin phenomena in QCD arise from the intrinsic correlations between parton transverse momentum, spin, and hadronization dynamics

Chiral-odd FFs: Transverse spin of quark



Leading Quark TMDFFs

		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 $H_{1T}^\perp$ = −

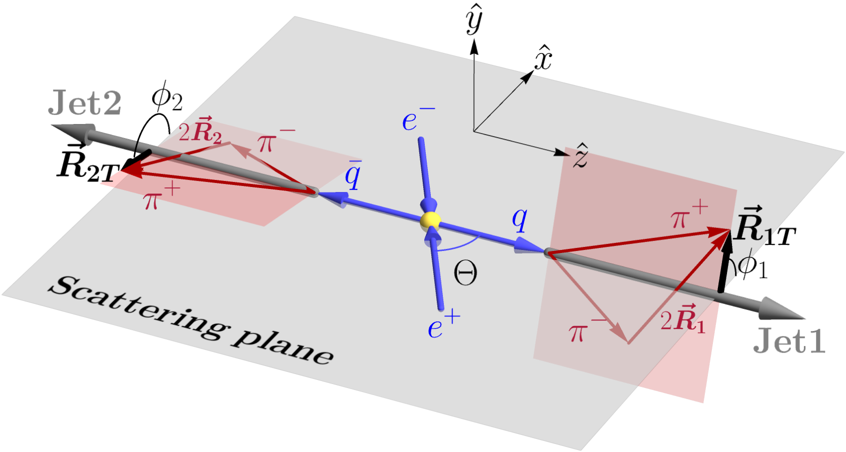


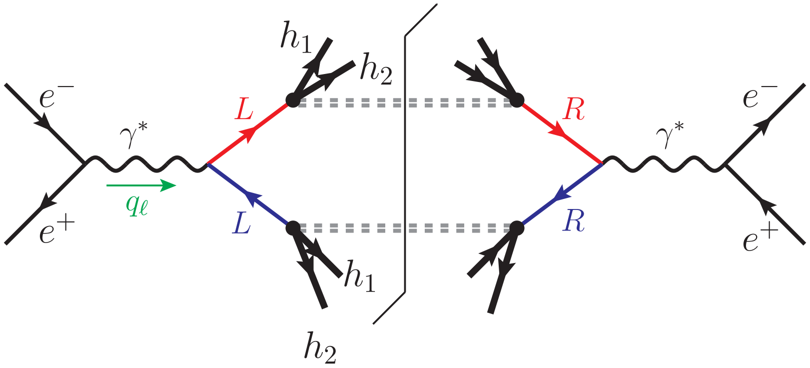
Transverse spin of quark:
The interference between the different helicity states

Transverse momentum dependent factorization

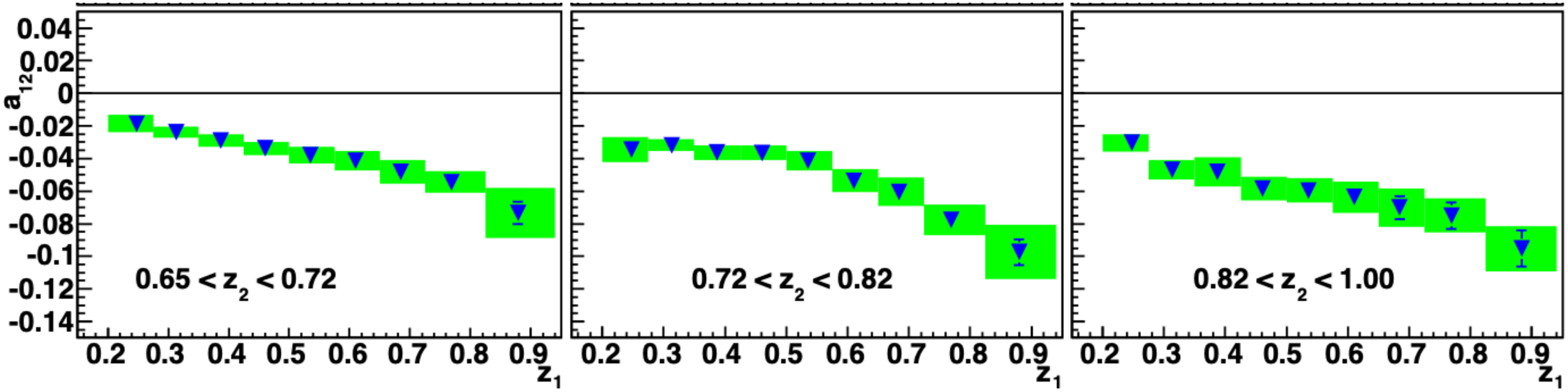
Interference Dihadron Fragmentation
Collinear factorization

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

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

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

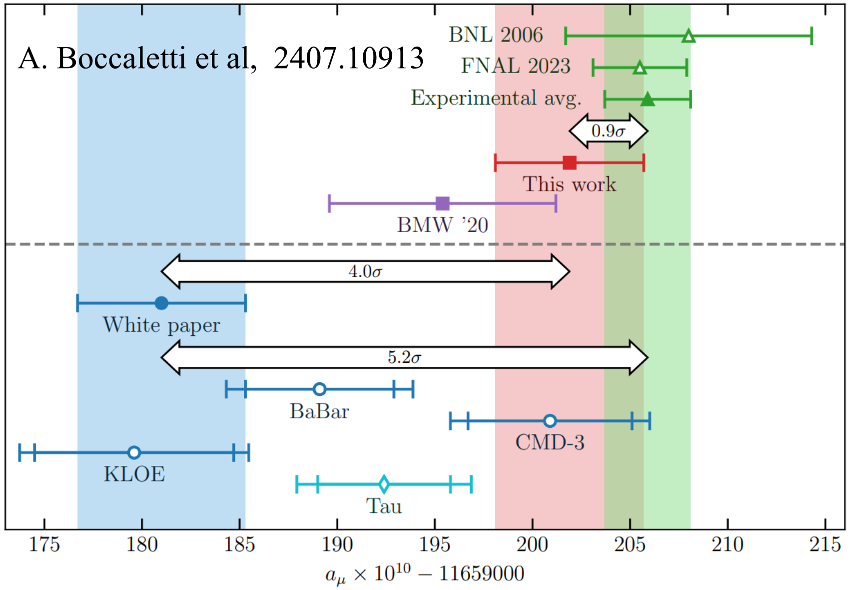
$$\mu_e = g_e \frac{e}{2m_e} \quad \text{and} \quad \left(g_e - 2\right) = 2a_e$$

New physics and Dipole Operator

- Magnetic dipole moments: probing the internal structures of particles

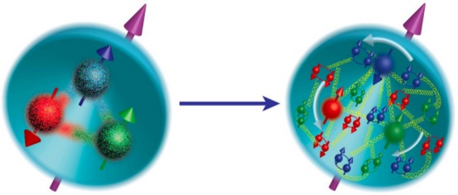
☐ Elementary particle:

Electron: g/2=1.001159…
Muon: g/2=1.0011659..



☐ Composite particle:

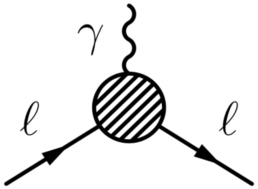
Proton: g/2=2.7928444..
Neutron: g/2=-1.91394308..



☐ Quarks: any internal structures?

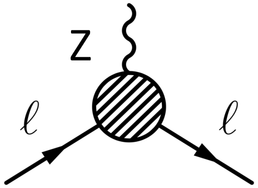
☐ From MDM and EDM to weak dipole moments?

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



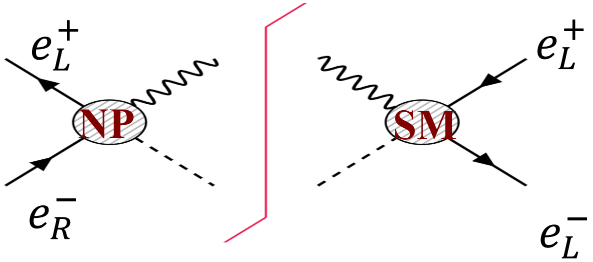
May have same physics source

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



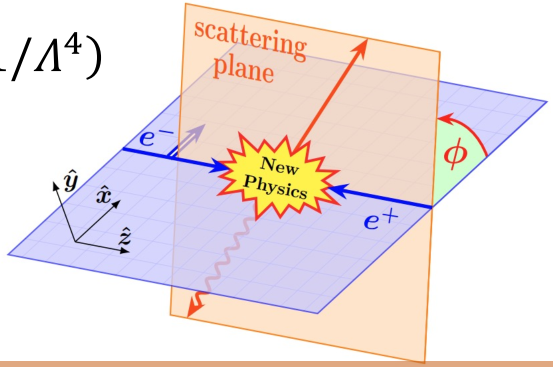
Example: electron weak dipole couplings

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



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

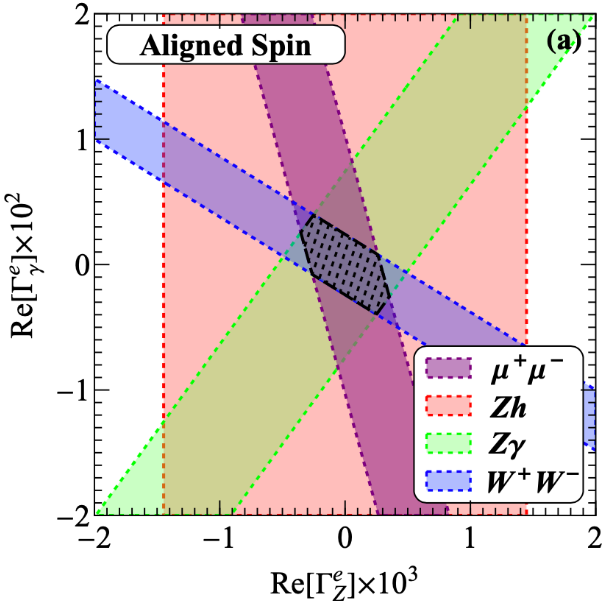
=0 for the cross section



- The interference effects: transverse spin of lepton

Observables must be chiral-even

- Transversely polarized effect of beams @ lepton collider



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

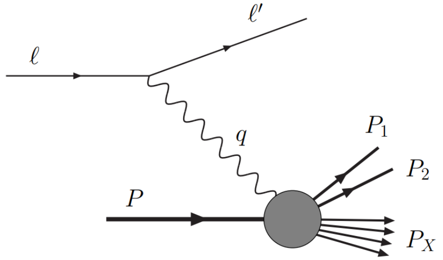
$\sqrt{s} = 250\ \mathrm{GeV}, \mathcal{L} = 5\ \mathrm{ab}^{-1}$ $\quad (b_T, \bar{b}_T) = (0.8, 0.3)$

- 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

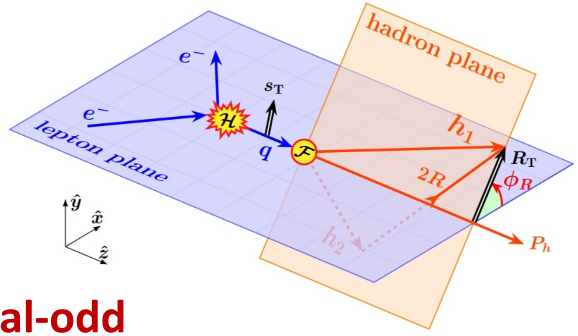
Transverse spin effects of quark @ EIC

- 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



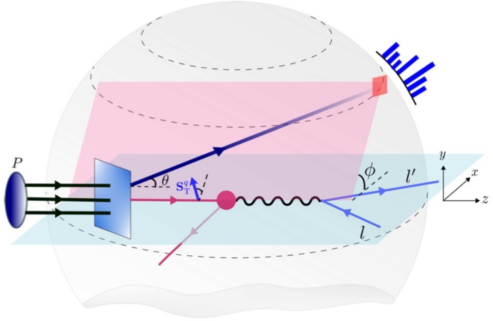
- The interference dihadron fragmentation function: **chiral-odd**

$$\frac{d\sigma}{dx\,dy\,dz\,dM_h\,d\phi_R} = \frac{N}{2\pi}\sum_q f_q(x,Q)\big[D_{h_1h_2/q}(z,M_h;Q)$$
$$-\,(\boldsymbol{s}_{T,q}(x,Q)\times\hat{\boldsymbol{R}}_T)^z H_{h_1h_2/q}(z,M_h;Q)\big]C_q(x,Q)$$

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

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

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



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

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

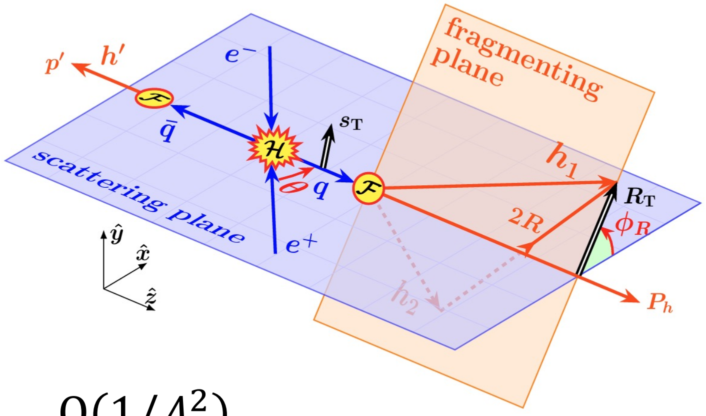
The flat direction in flavor space of dipole couplings?

Transverse spin effects of quark @ CEPC

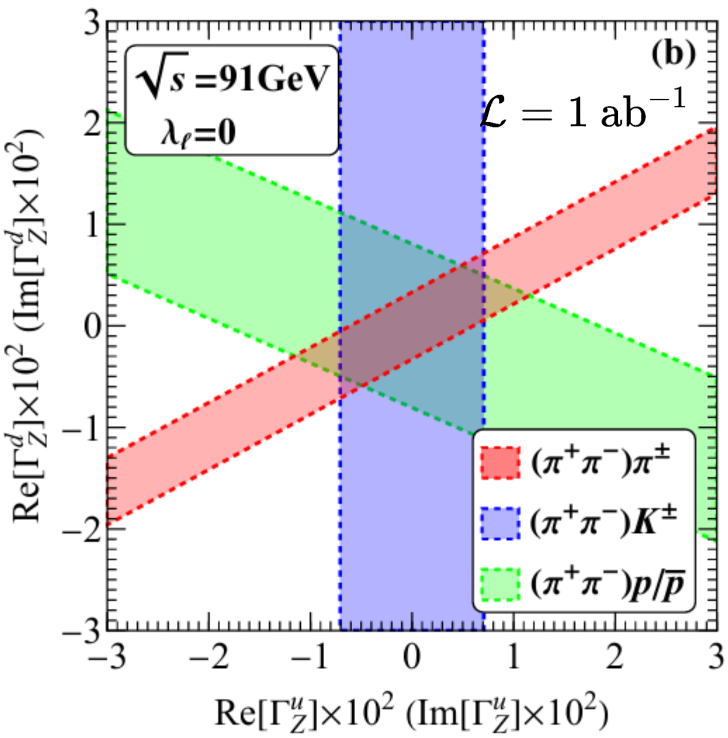
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, PRD 112 (2025) 053004

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

$$\times\left[D_q^{h_1h_2}(z,M_h) - (\boldsymbol{s}_{T,q}(y)\times\hat{\boldsymbol{R}}_T)^z\,H_q^{h_1h_2}(z,M_h)\right]$$



$O(1/\Lambda^2)$



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

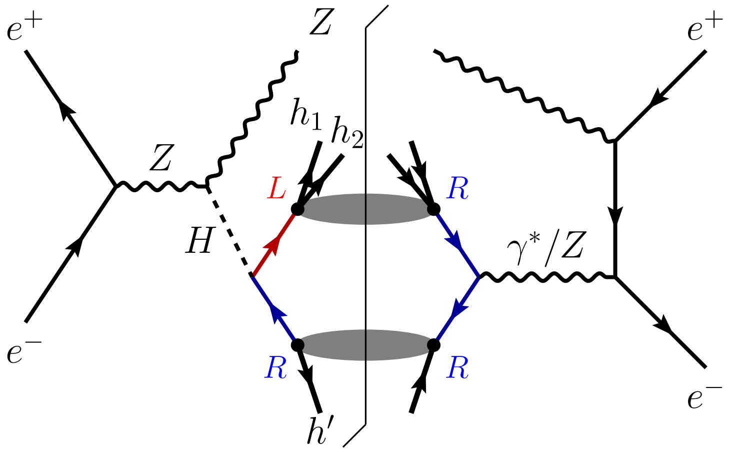
$$s_q^y = \frac{2}{C_q}\left(w_\gamma^q\ \mathrm{Im}\,\Gamma_\gamma^q + w_Z^q\ \mathrm{Im}\,\Gamma_Z^q\right)$$

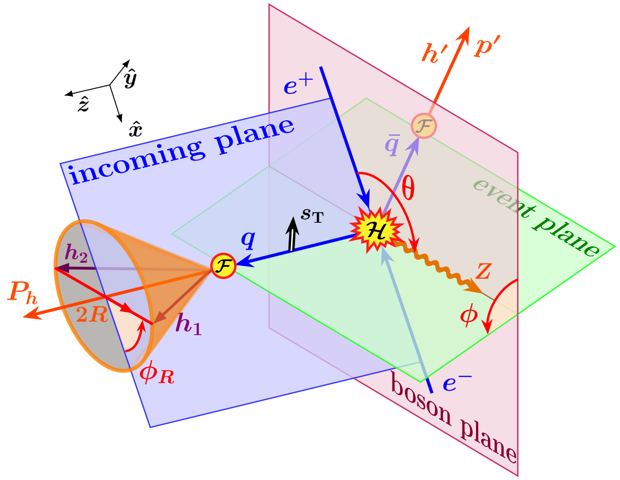
$$\bar{q}_L\sigma_{\mu\nu}q_R A^{\mu\nu},\ \bar{q}_L\sigma_{\mu\nu}q_R Z^{\mu\nu}$$

- ☐ 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



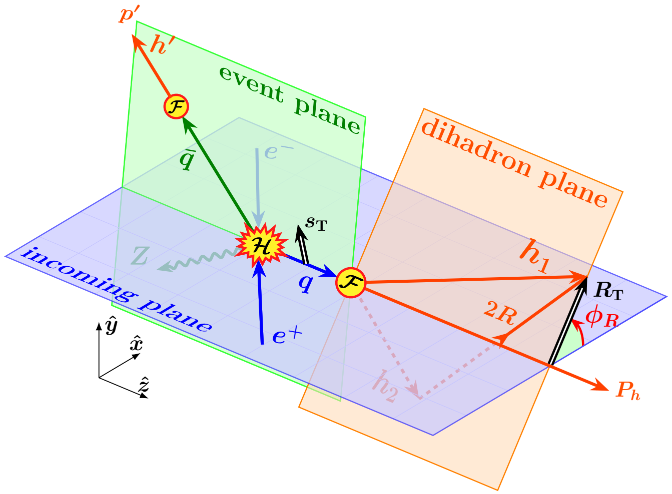


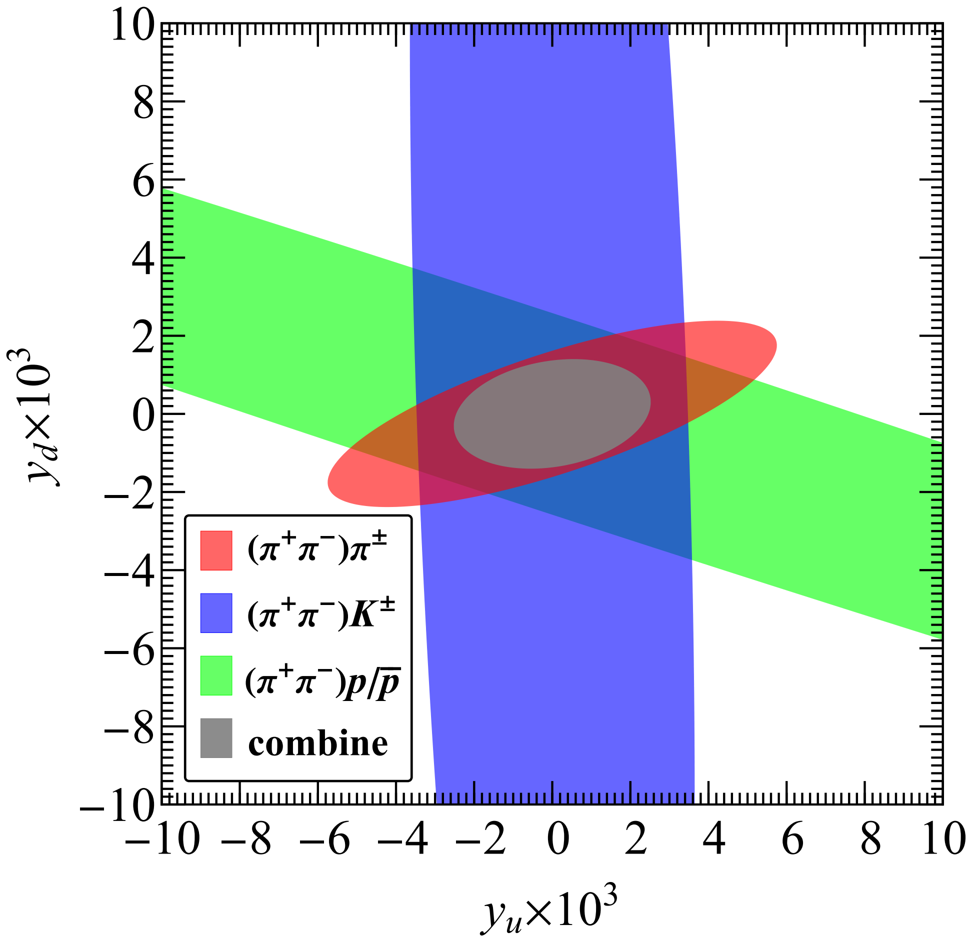
- ❖ Interference effects are linear in the Yukawa couplings
- ❖ Single-hadron tagging lifts degeneracies among up- and down-quark Yukawa couplings

CP even Yukawa couplings @ CEPC

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

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





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

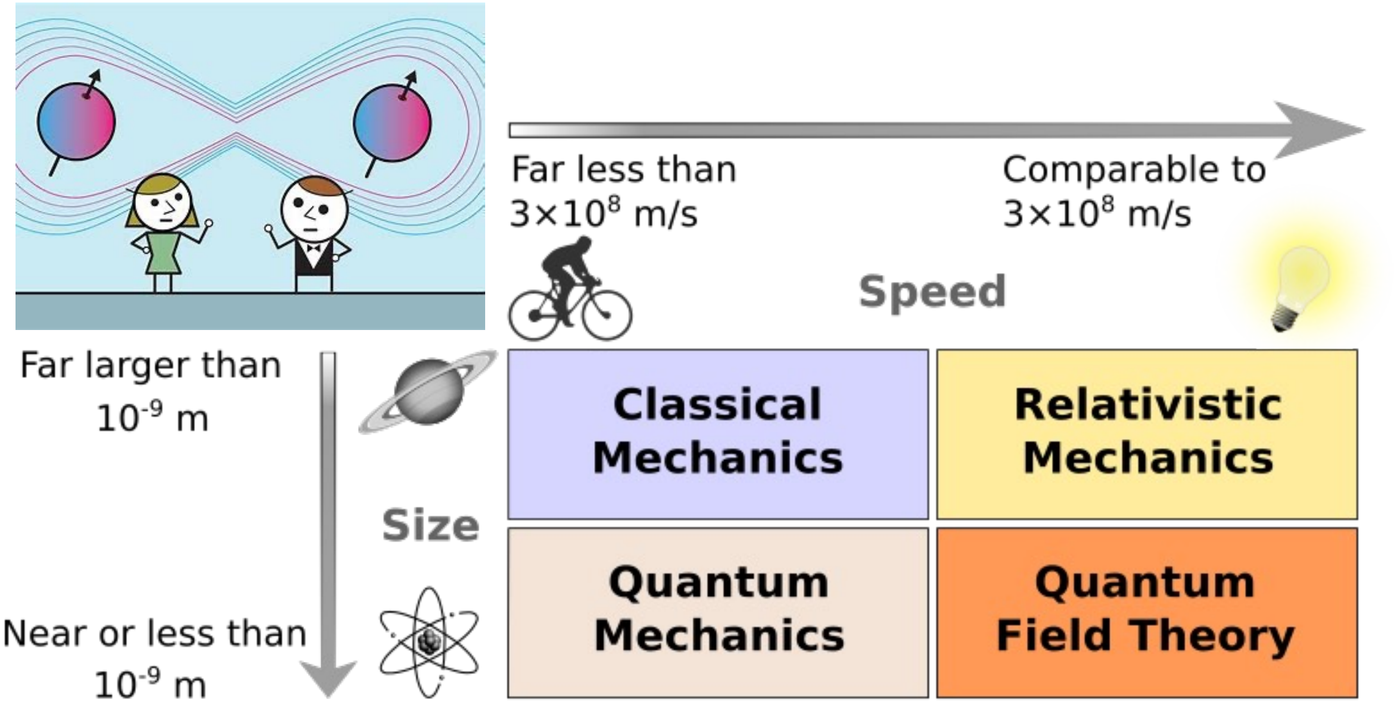
- Yukawa couplings $< 10^{-3}$
- Single-hadron channels enable flavor separation

Fragmentation functions encode the spin information of quarks

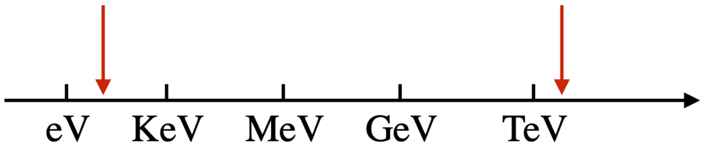
- Spin information as a tool for new physics searches
- Spin structure of quark systems: quark-quark spin correlations
- Emergence of entanglement in quark systems

Quantum information at collider

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



- Collider physics: high energy and small size



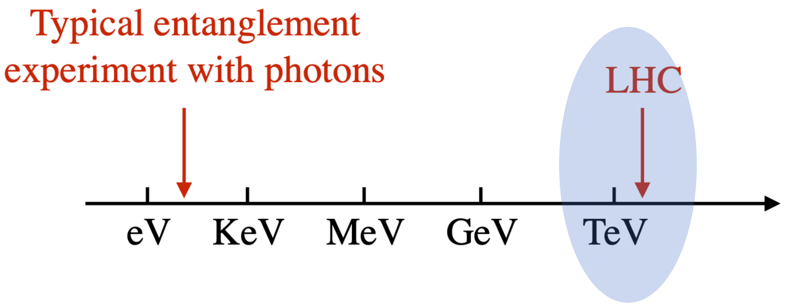
Typical entanglement experiment with photons

LHC

eV KeV MeV GeV TeV

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

➢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

Entanglement and Bell inequality

The spin correlation of top quark 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 top quark pair

- Entanglement (non-seperable): concurrence observable

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

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

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

Seperable Maximal entangled

λ_i: eigenvalues of matrix: $\sqrt{\sqrt{\rho}\tilde{\rho}\sqrt{\rho}}$

$$\tilde{\rho} = (\sigma_2 \otimes \sigma_2)\rho^*(\sigma_2 \otimes \sigma_2)$$

Entanglement and Bell inequality

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

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

[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

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

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

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

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

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

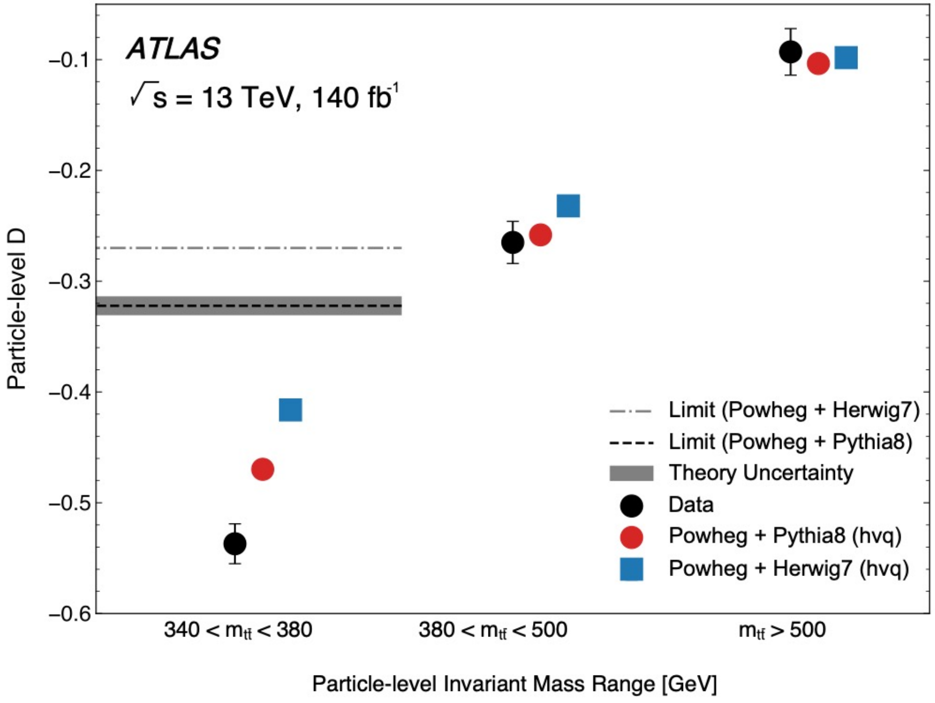
c_1^2, c_2^2 **are the largest two eigenvalue of $C^T C$.**

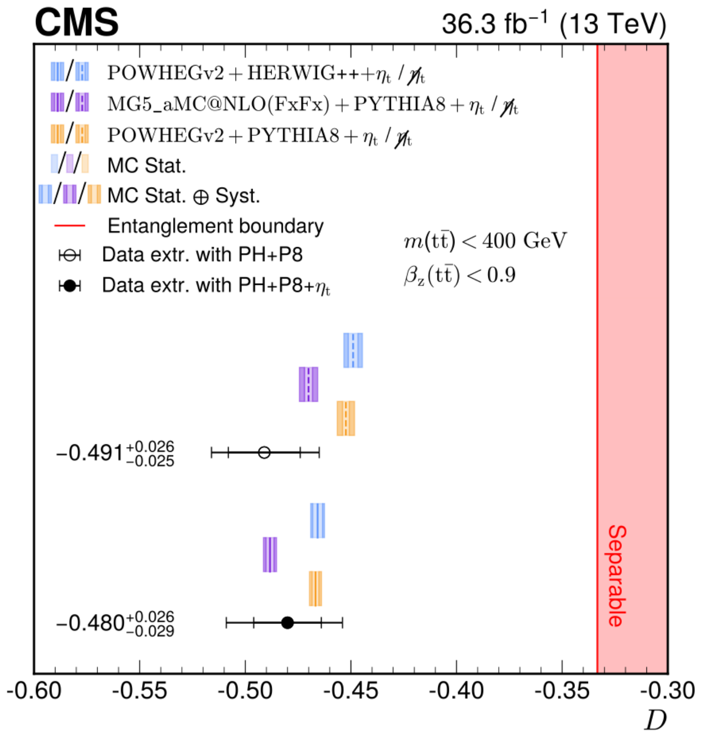
Quantum spin entanglement

Top quark pair: $\mathscr{C}[\rho] = \dfrac{-1-3D}{2}$ $\qquad \dfrac{1}{\sigma}\dfrac{\mathrm{d}\sigma}{\mathrm{d}\cos\varphi} = \dfrac{1}{2}(1 - D\cos\varphi)$

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

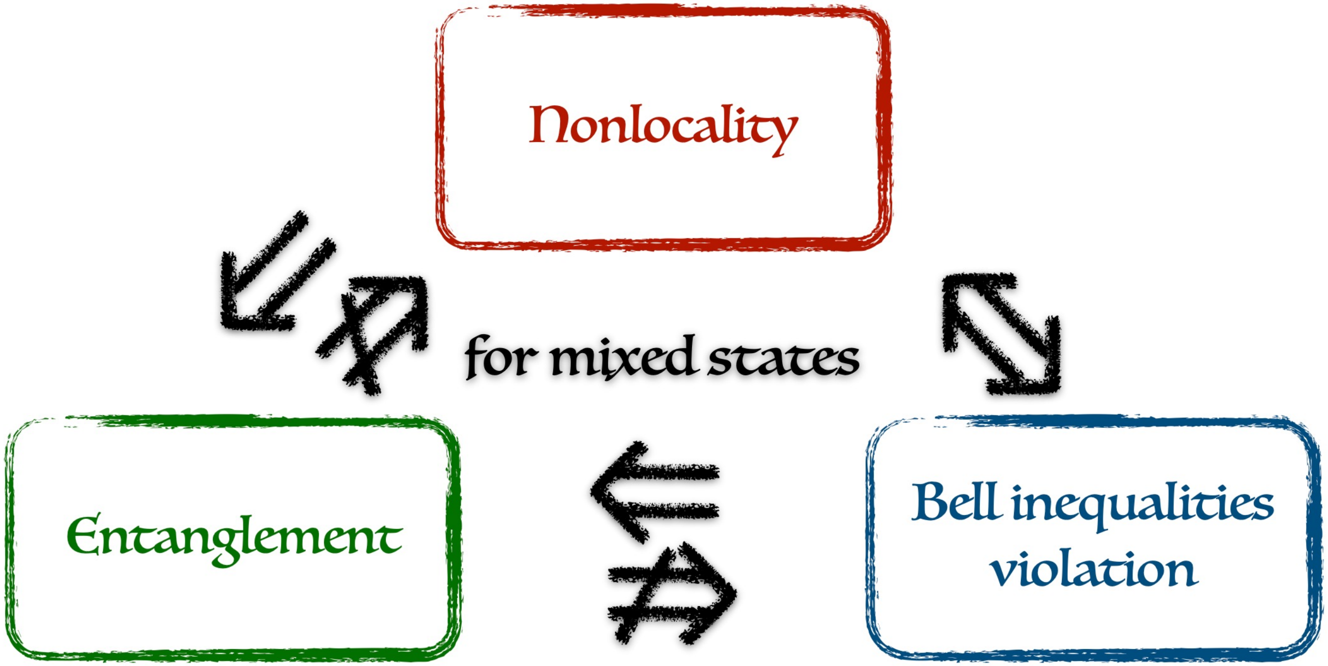
Y. Afik, J. de Nova, EPJC 136 (2021) 907





$$\text{Entangled}: \quad D < -1/3, \qquad \text{separable}: \quad D > -1/3$$

Quantum entanglement and nonlocality



Nonlocality

for mixed states

Entanglement

Bell inequalities violation

e.g. Werner states in quantum information

$$\rho_{\text{Werner}}(\alpha) = \underbrace{\alpha|\Psi_0\rangle\langle\Psi_0|}_{\text{Bell singlet}} + \frac{1-\alpha}{4}\hat{I}_4$$

$\frac{1}{3} < \alpha < 1$ Entanglement

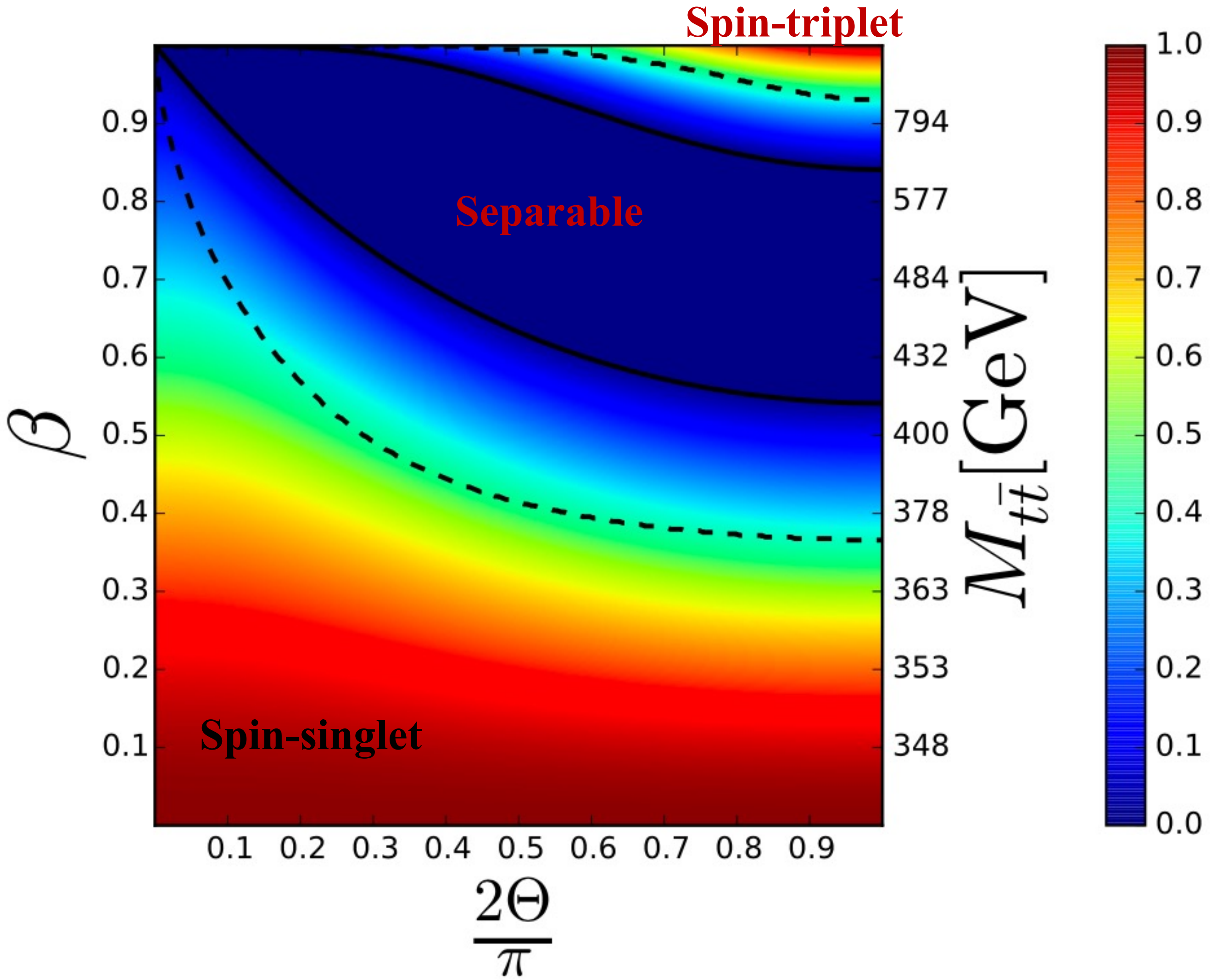
$\frac{1}{\sqrt{2}} < \alpha < 1$ Bell inequalities violation

Testing Bell inequalities violation is much more difficult than entanglement

Quantum entanglement of top quark

Solid: Entanglement
Dashed: Belle inequality violation

Y. Afik, J. de Nova, Quantum 6 (2022) 820



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
….

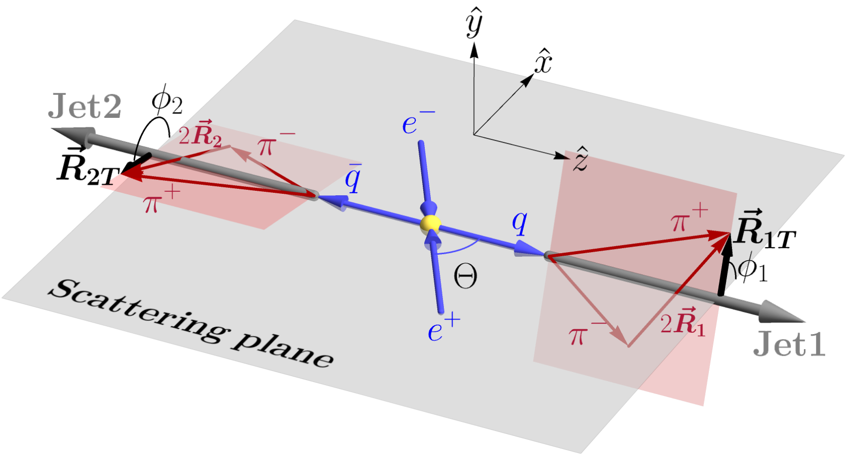
- Entanglement & NP

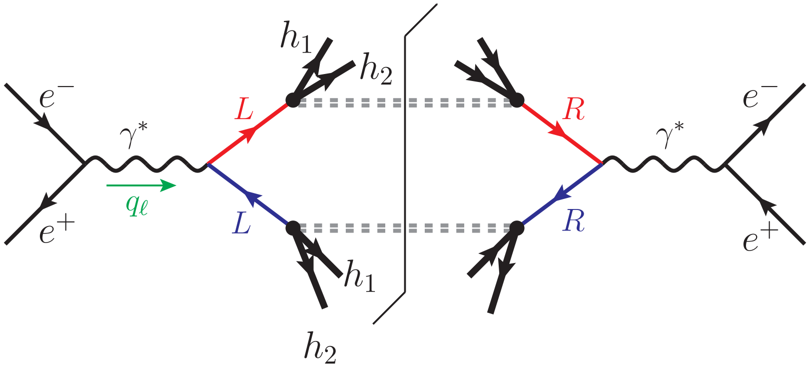
R. Aoude et al, PRD 106 (2022) 055007
M. Fabbrichesi et al, EPJC 83 (2023) 162, JHEP 09 (2023) 195
A. Bernal et al, EPJC 83 (2023) 11, 1050
…

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

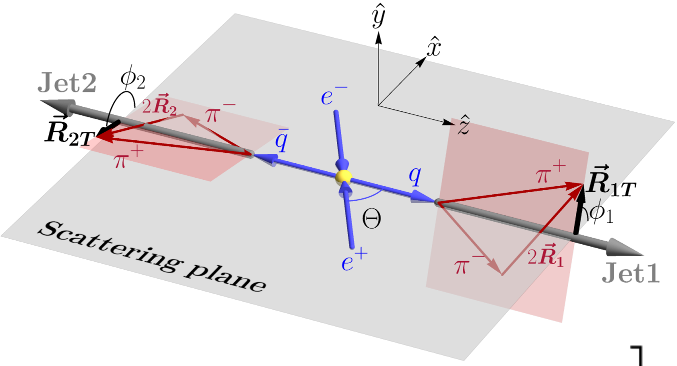
- The transverse spin correlation between light quarks: chiral-odd interference dihadron fragmentations (collinear factorization)

- 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

$$\frac{d\sigma}{dz_1 dz_2 dM_1 dM_2 d\phi_1 d\phi_2} = \sigma_{\text{hard}} \Big[\sum_q e_q^2 D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2)$$

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

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

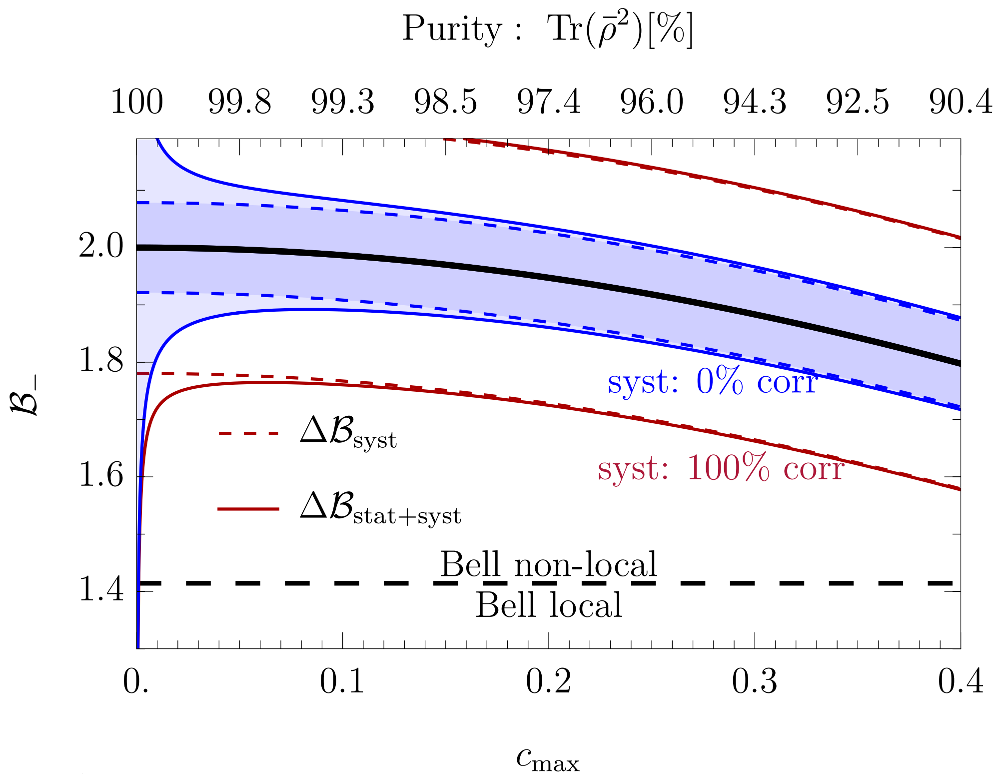
Qing-Hong Cao, Guanghui Li, Xin-Kai Wen and Bin Yan, 2509.18276

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

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

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

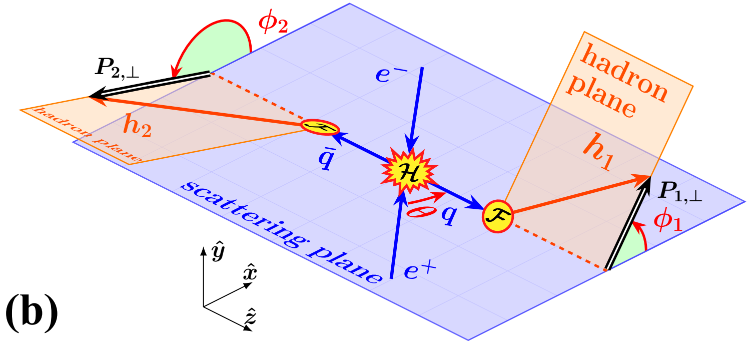
TMD hadron pair production

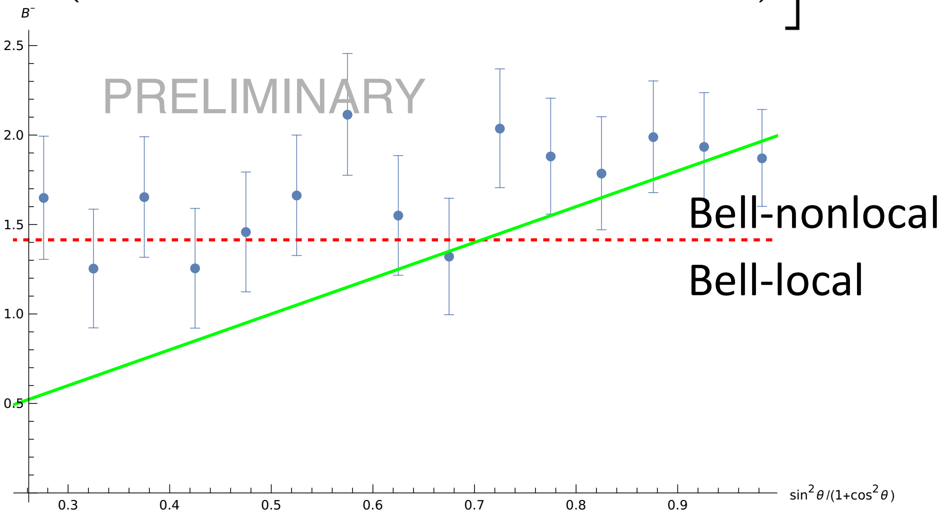
- The transverse spin correlation between light quarks can also be described by the Collins functions under the TMD framework

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma(e^+e^-\to h_1h_2X)}{p_{1,\perp}p_{2,\perp}\mathrm{d}z_1\mathrm{d}z_2\mathrm{d}p_{1,\perp}\mathrm{d}p_{2,\perp}\mathrm{d}\phi_1\mathrm{d}\phi_2\mathrm{d}\cos\theta}$$

$$=(1+\cos^2\theta)\Bigg[\sum_q Q_q^2 D_1^q(z_1,p_{1,\perp})D_1^{\bar q}(z_2,p_{2,\perp})$$

$$+\frac{1}{2}\sum_q Q_q^2\mathcal{F}_h H_1^{\perp,q}(z_1,p_{1,\perp})H_1^{\perp,\bar q}(z_2,p_{2,\perp})\Big(\mathcal{B}_-\cos(\phi_1+\phi_2)-\mathcal{B}_+\cos(\phi_1-\phi_2)\Big)\Bigg],$$





Kun Cheng, Tao Han, Guanghui Li and Bin Yan, working in progress

Fragmentation functions encode the spin information of quarks

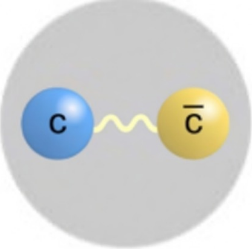
- Spin information as a tool for new physics searches
- Emergence of entanglement in quark systems
- **Probing the Color-Octect Mechanism via Spin Observable**

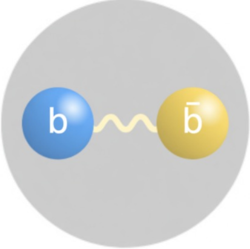
NRQCD and Heavy Quarkonium

- 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 $^{2S+1}L_J^{[c]}$

  $c\bar{c}(^3S_1^{[1]}) \to J/\Psi$ $\qquad$ $b\bar{b}(^3S_1^{[1]}) \to \Upsilon$

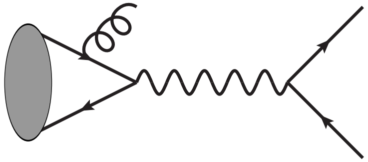
- Theoretical issues:

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

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

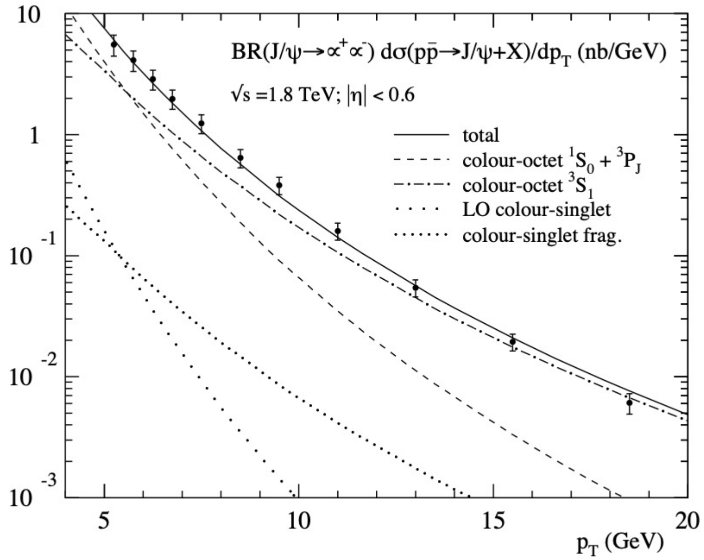
NRQCD and Heavy Quarkonium

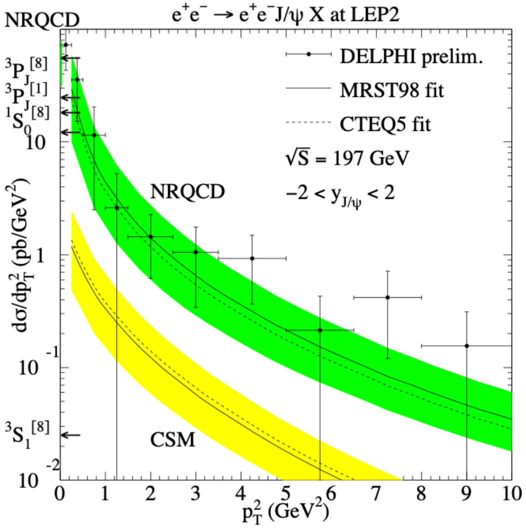
- ➢ NRQCD factorization G. T. Bodwin, E. Braaten, G. P. Lepage, PRD 51 (1995) 1125
- ❖ $Q\bar{Q}$ could be in all possible spin and color configurations
- ❖ Color-Octet Mechanism:



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

- ❖ 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

NRQCD and Heavy Quarkonium

- NRQCD factorization

$$\Gamma(H \to LH) = \sum_n \frac{2\,\mathrm{Im} f_n(\Lambda)}{m_Q^{d_n-4}} \langle H|\,\mathcal{O}_n(\Lambda)\,|H\rangle$$

Short distance coefficients
$\alpha_s$expansion

Long distance matrix elements
v^2 expansion

- Fock state expansion

$$\begin{aligned}
|H({}^{2S+1}L_J)\rangle &= O(1)\,|Q\overline{Q}({}^{2S+1}L_J^{[1]})\rangle \\
&+ O(v)\,|Q\overline{Q}({}^{2S+1}(L\pm1)_{J'}^{[8]})g\rangle && \mathrm{E1} \\
&+ O(v^2)\,|Q\overline{Q}({}^{2S'+1}L_{J'}^{[8]})g\rangle && \mathrm{M1} \\
&+ O(v^2)\,|Q\overline{Q}({}^{2S+1}L_J^{[1,8]})gg\rangle && \mathrm{E1}\cdot\mathrm{E1} \\
&+ \ldots
\end{aligned}$$

Power counting

$$\langle H|\,\mathcal{O}_n(\Lambda)\,|H\rangle \sim v^{2i+j}$$

i for Fock state
j for operator

Testing Color-Octet Mechanism

- P-wave quarkonium χ_{QJ}

$$|H({}^{2S+1}L_J)\rangle = O(1)\,|Q\overline{Q}({}^{2S+1}L_J^{[1]})\rangle + O(v)\,|Q\overline{Q}({}^{2S+1}(L\pm 1)_{J'}^{[8]})g\rangle$$

$$\langle H|\,\mathcal{O}_n(\Lambda)\,|H\rangle \sim v^{2i+j}$$

$i = 0, j = 2$: Color-Singlet
$i = 1, j = 0$: Color-Octet

Leading order in NRQCD!

- Testing Color-Octet Mechanism

CS: $b\bar{b}({}^3P_J^{[1]}) \to gg$ **CO:** $b\bar{b}({}^3S_1^{[8]}) \to q\bar{q}$

How to distinguish the quark and gluon final state?

- ❖ Quark jet and gluon jet?
- ❖ Parton fragments into hadrons? PRD 78 (2008) 092007, CLEO

$$\chi_{bJ}(1P) \to D^0 X$$

CS and CO contributions are experimentally indistinguishable

Testing Color-Octet Mechanism

- Lattice VS Experiment

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

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

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

$\rho_8 = 0.095(43)$ (Exp)

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

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

$\rho_8 = 0.16^{+0.071}_{-0.047}$ (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?

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

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

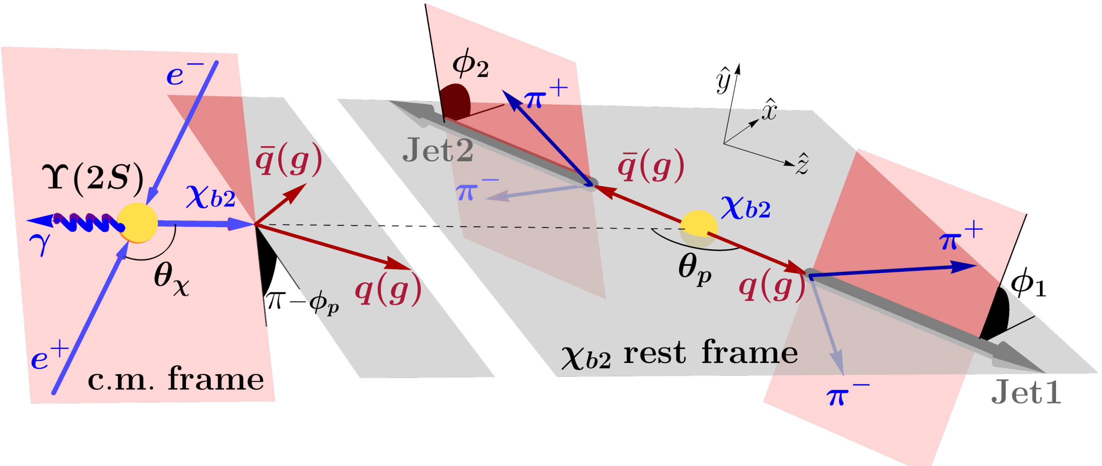
➡ The spin of quark and gluon is different!

Artru-Collins asymmetry

- Kinematics

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

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



- Collinear Factorization

J. C. Collins, S. F. Heppelmann, G. A. Ladinsky, NPB 420 (1994) 565

$$\frac{d\sigma}{\sigma_0 dz_1 dz_2 dM_1 dM_2 d\phi_1 d\phi_2 d\cos\theta_\chi d\cos\theta_p d\phi_p}$$
$$= H_8^b \sum_q \mathcal{C}_q \left[D_1^q(z_1,M_1) D_1^{\bar{q}}(z_2,M_2) \right.$$
$$\left. + \frac{1}{2}\mathcal{B}\, H_1^{\sphericalangle,q}(z_1,M_1) H_1^{\sphericalangle,\bar{q}}(z_2,M_2)\cos(\phi_1+\phi_2) \right]$$
$$+ H_1^b \mathcal{C}_g\, D_1^g(z_1,M_1) D_1^g(z_2,M_2),$$

Unpolarized quark diFF

Transverse polarized quark diFF

Unpolarized gluon diFF

- Gluon fragmentation does not generate the asymmetry
- Allows separation of CO ($q\bar{q}$) from CS (gg)

Artru-Collins asymmetry

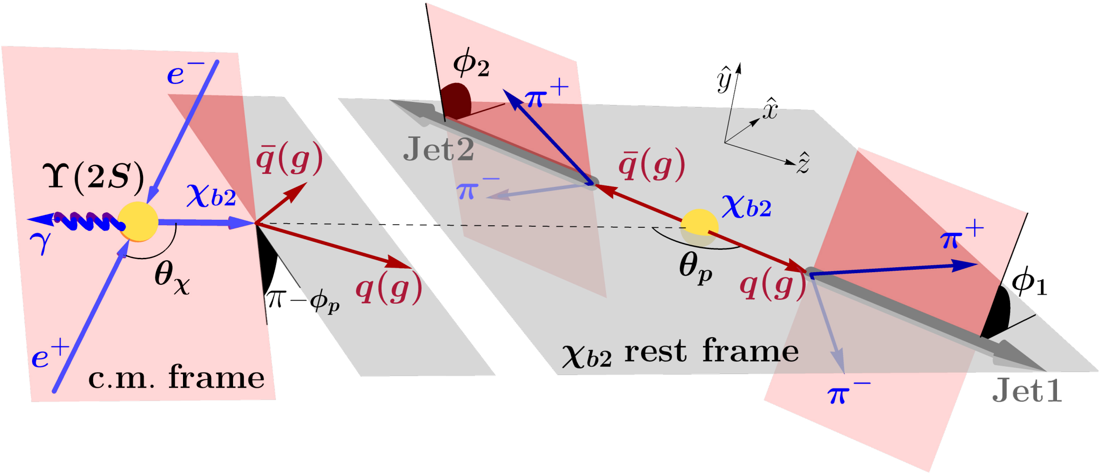
- Asymmetry

$$A_{12} \equiv 2\left\langle \cos(\phi_1+\phi_2)\right\rangle = \frac{1}{2}\frac{\rho_8(m_b)\mathcal{B}\sum_q \mathcal{C}_q H_1^{\sphericalangle,q}(z_1,M_1)H_1^{\sphericalangle,\bar{q}}(z_2,M_2)}{\rho_8(m_b)\sum_q \mathcal{C}_q D_1^q(z_1,M_1)D_1^{\bar{q}}(z_2,M_2)+m_b^2\mathcal{C}_g D_1^g(z_1,M_1)D_1^g(z_2,M_2)}$$

Asymmetry provides a clean probe of ρ_8

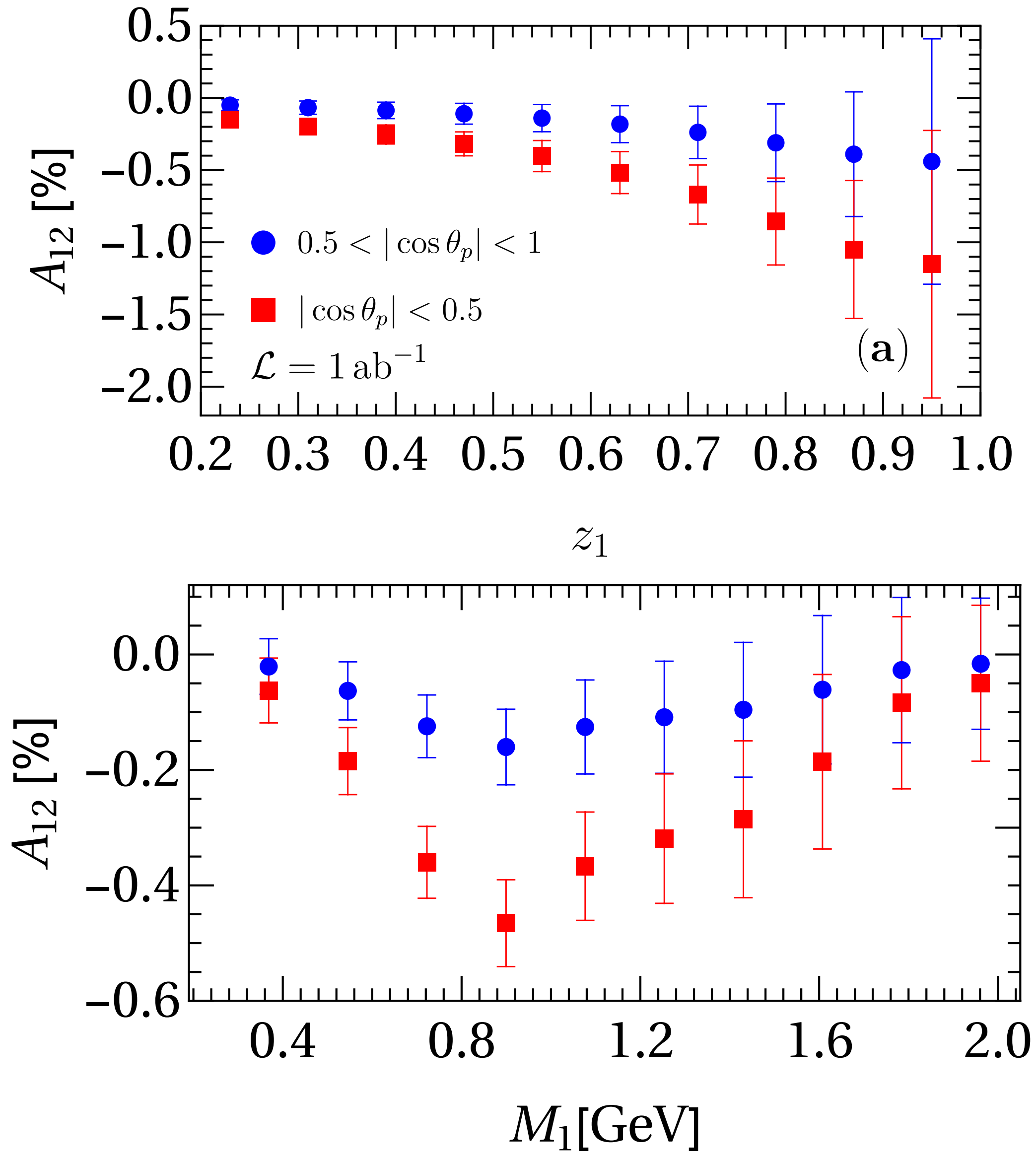
- Belle: boost effects

$$\mathcal{B} = \frac{42\sin^2\theta_p}{21\cos^2\theta_p + 73}$$



- ❖ χ_{b2} nearly collinearly with $\Upsilon(2S)$ in the Lab frame
- ❖ The coefficients does not depend on θ_χ, ϕ_p
- ❖ Enhanced in the central region

Artru-Collins asymmetry



$\rho_8 = 0.044$ χ_{b2}: Lab frame

- ❖ Asymmetry magnitude:~ 1%
- ❖ Enhanced in the central region

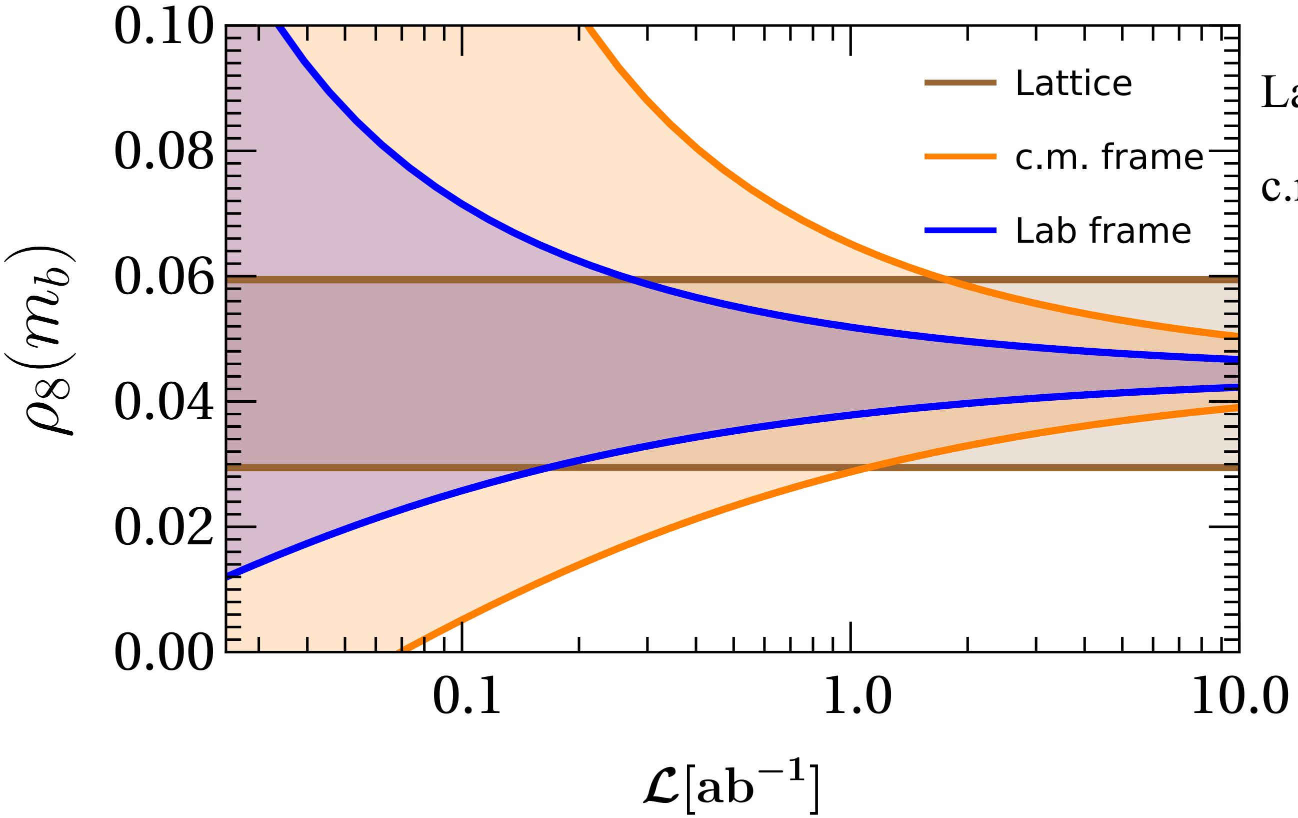
$$\mathcal{B} = \frac{42\sin^2\theta_p}{21\cos^2\theta_p + 73}$$

- ❖ Sign determined by DiFF properties

$$H_1^{\sphericalangle,q} = -H_1^{\sphericalangle,\bar{q}}$$

- ❖ Observable is measurable at Belle

Artru-Collins asymmetry



Lab frame (χ_{b2}): binned in θ_p

c.m. frame (χ_{b2}): binned in θ_χ

- Cancellation in phase space at c.m. frame
- Projected sensitivity surpasses current lattice uncertainty with $\mathcal{O}(0.1)\ \mathrm{ab}^{-1}$
- The potential to resolve the long-standing discrepancy in ρ_8

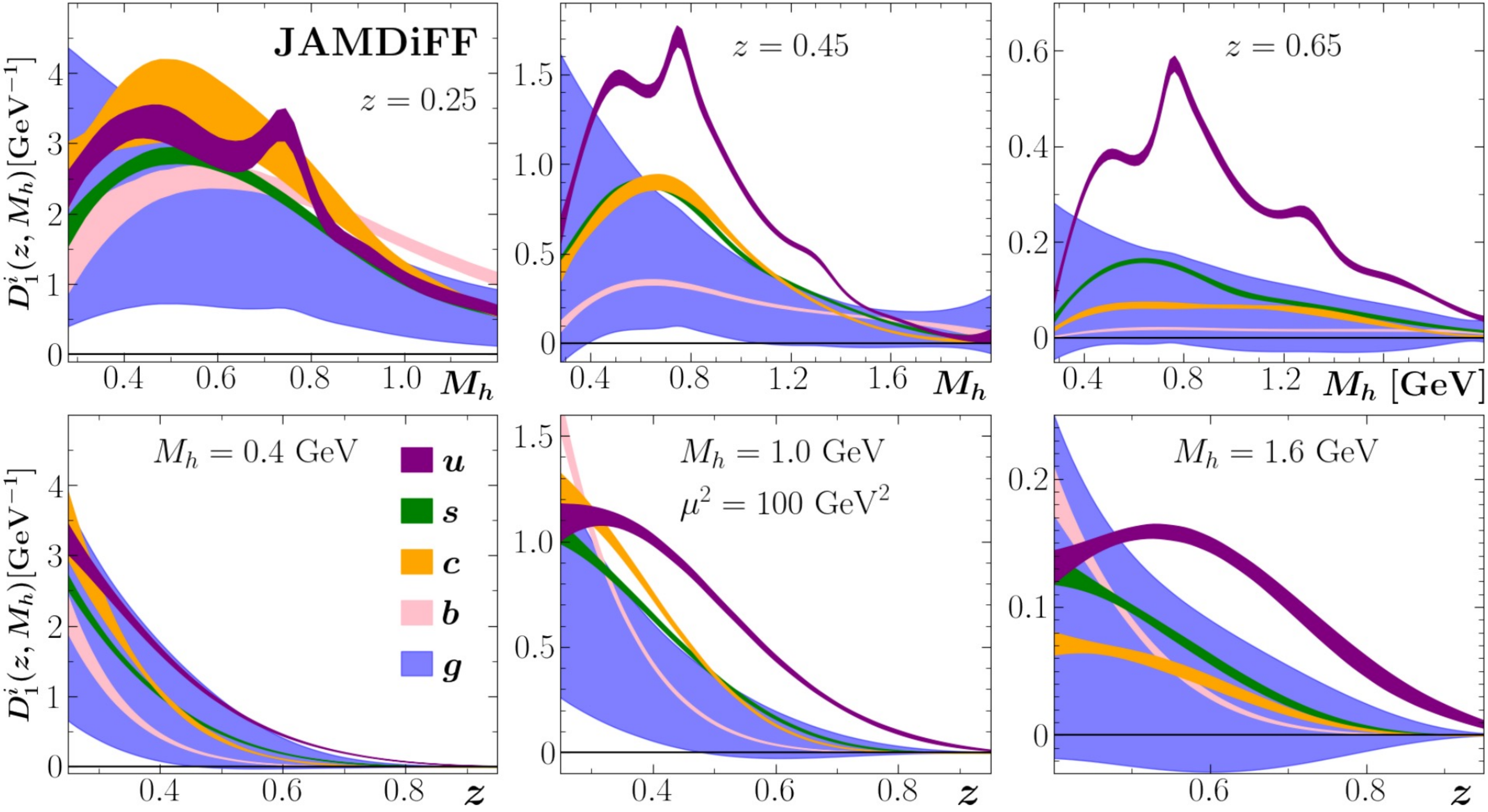
Summary

- 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
- 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
- We proposed a novel observable based on dihadron fragmentation to probe the color-octet mechanism

New opportunities in QCD spin physics!

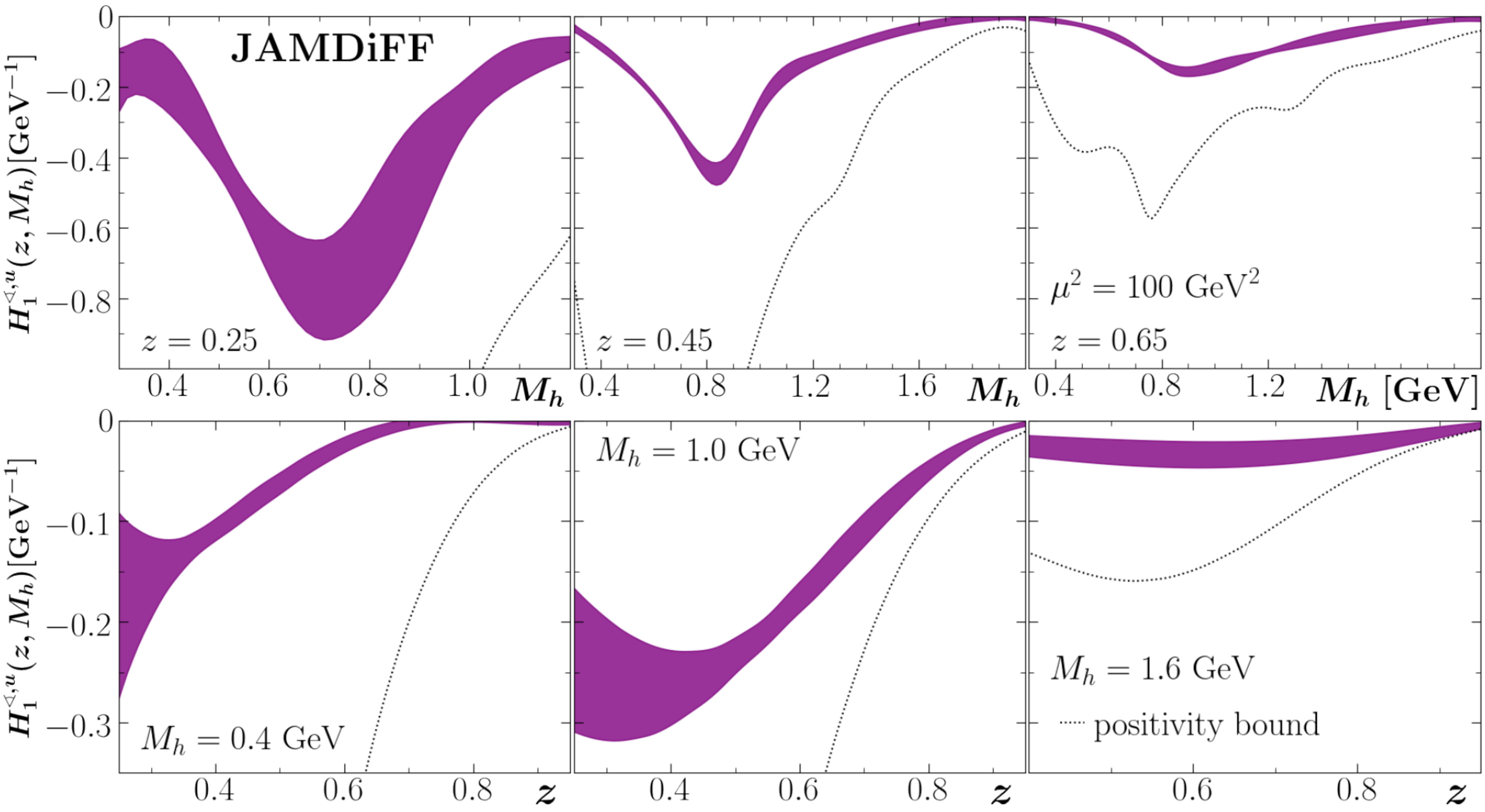
Thank you

$\pi^+\pi^-$ Dihadron fragmentation functions



JAM Collaboration, PRL 132 (2024) 091901 , PRD 109 (2024) 034024

$\pi^+\pi^-$ Dihadron fragmentation functions



JAM Collaboration, PRL 132 (2024) 091901 , PRD 109 (2024) 034024