Dihadron Fragmentation as a Spin Analyzer at Lepton Colliders

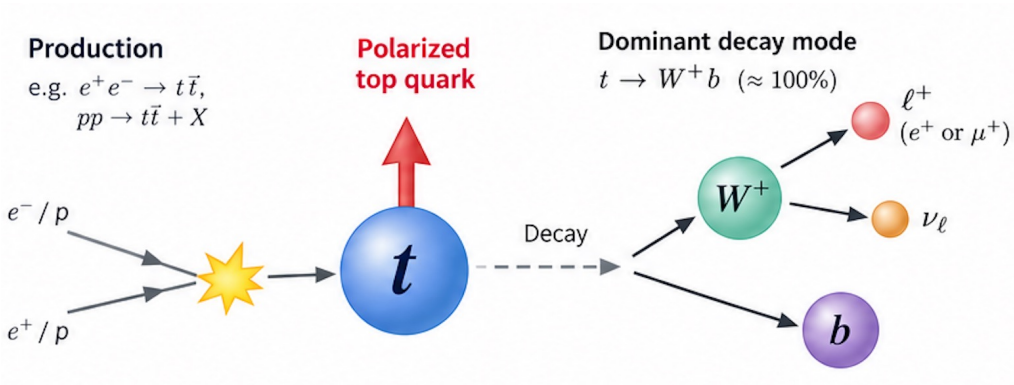
Bin Yan
Institute of High Energy Physics

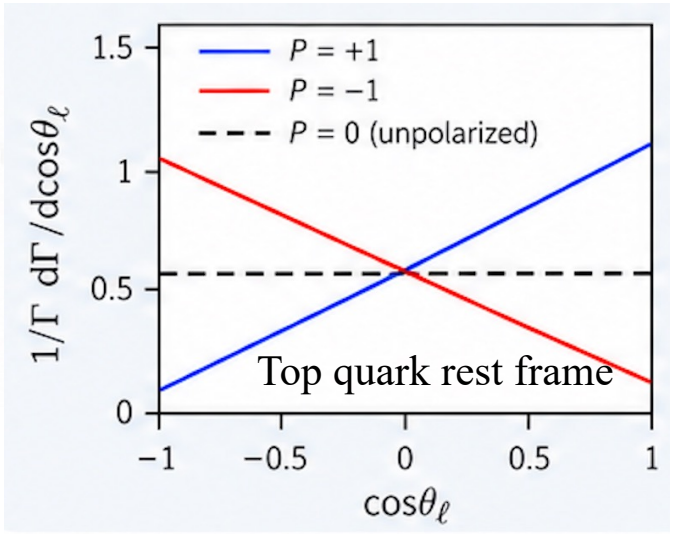
CEPC 2026 @ Shanghai
Oct. 21- 26, 2026

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
Z. G. He, G. Li, Y. J. Tian, X. K. Wen, B. Yan, PRL 137 (2026) 131903; w/ Y. Liu, 2608.10570

Spin Analyzer in particle physics

- Unstable particles, decay products carry spin information



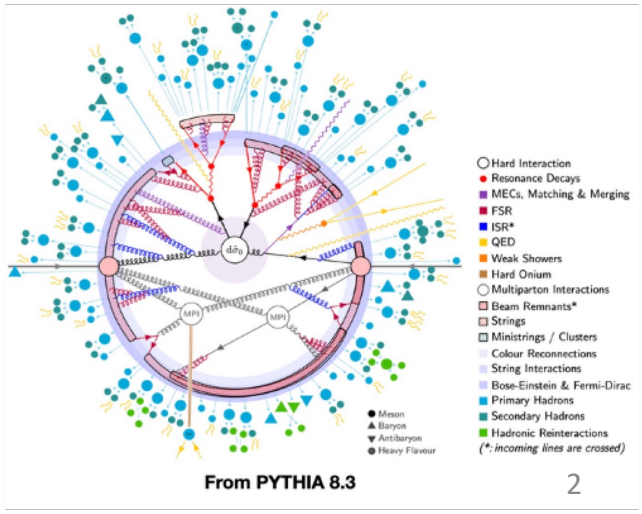


$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2}(1 + \alpha_i P \cos\theta_i)$$

Spin analyzing power

- How about light quark and gluon?

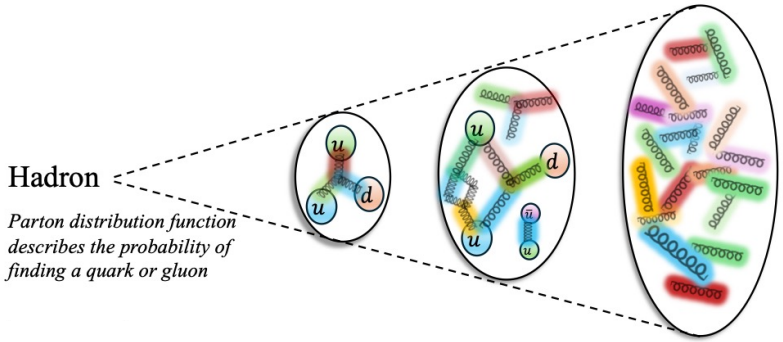
Hadronization hides spin information?

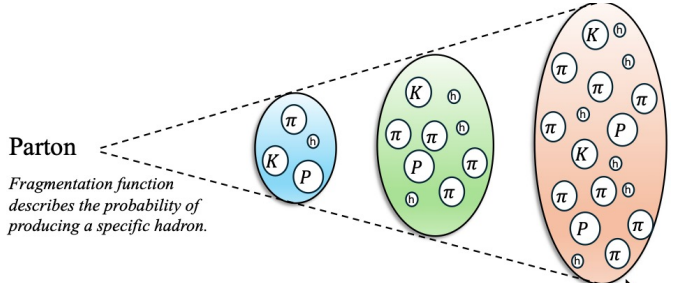


Spin Analyzer in particle physics

- Spin from nonperturbative QCD: PDFs and FFs

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





TMD factorization

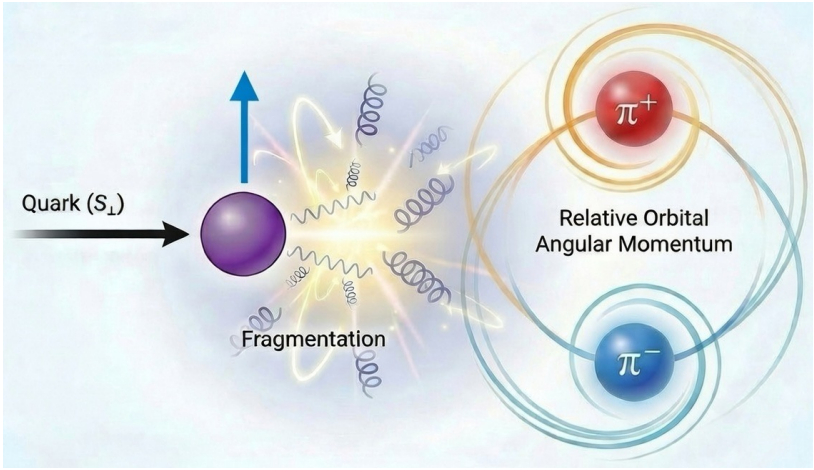
Leading Quark TMDFFs

Hadron Spin Quark Spin

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

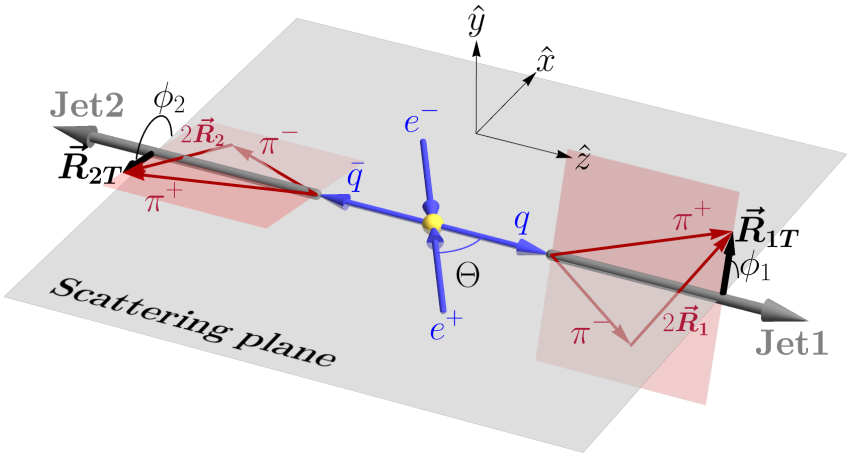
Collinear factorization

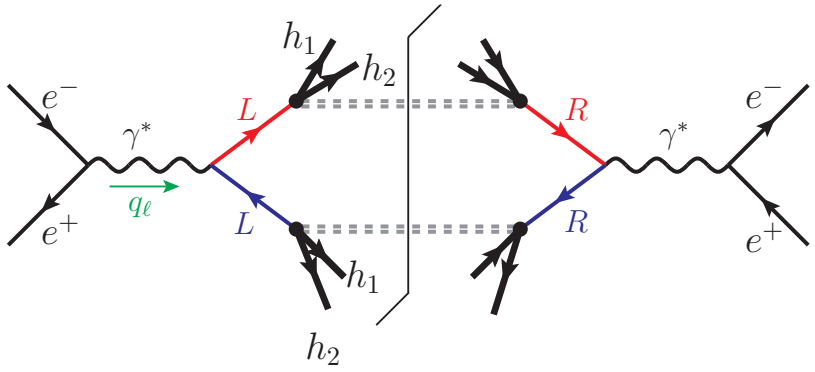
Interference Dihadron Fragmentation



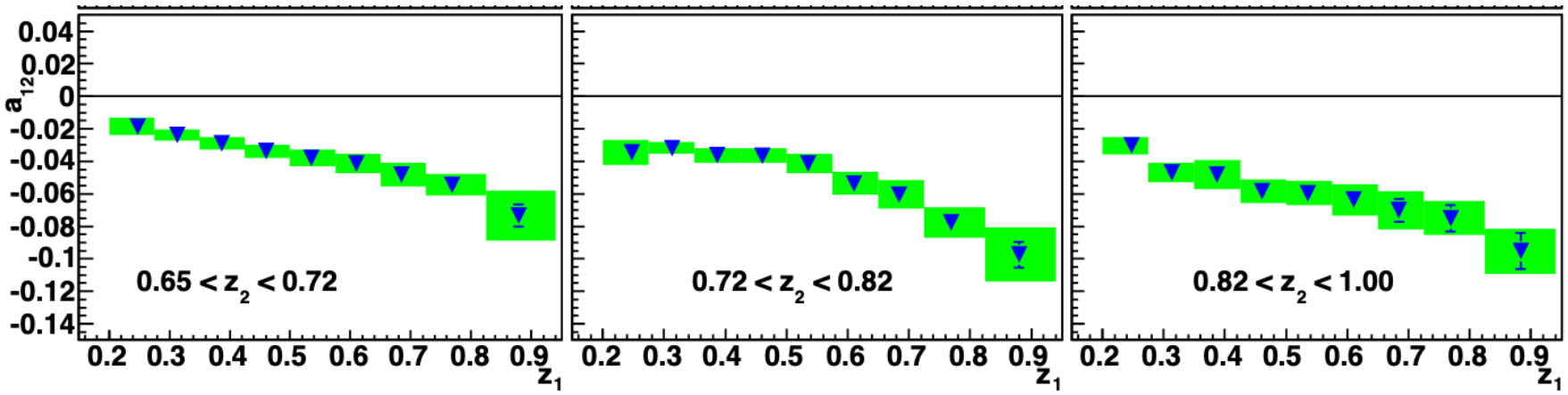
Transverse spin of quark: The interference between the different helicity states

Interference dihadron FFs





Belle, PRL 107 (2011) 072004



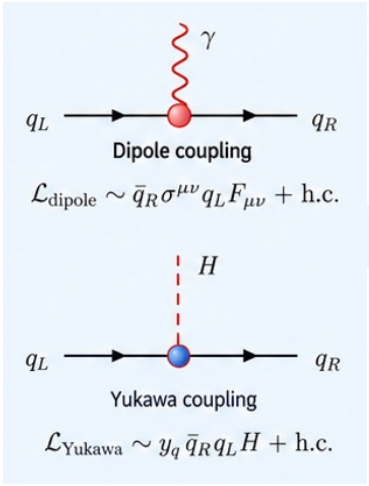
The transverse spin effects have been observed in dihadron pair production!

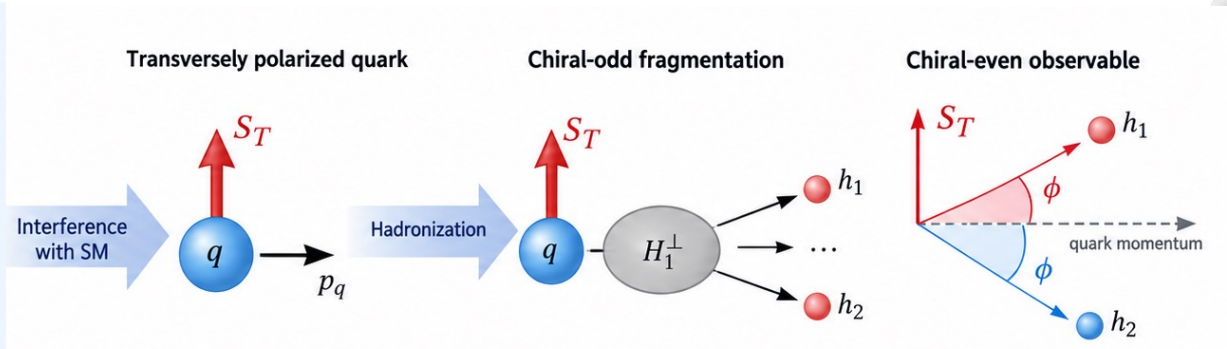
QCD Spin effects and New physics

- **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







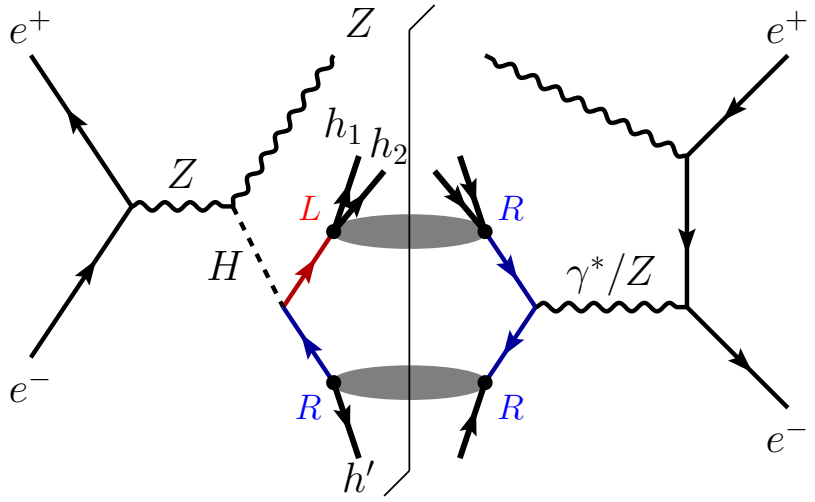
- X. K. Wen, B. Yan, Z. Yu, C.-P. Yuan, PRL 131 (2023) 241801, Sci. China Phys. Mech. Astron. 69 (2026) 271011, PRD 112 (2025) 053004

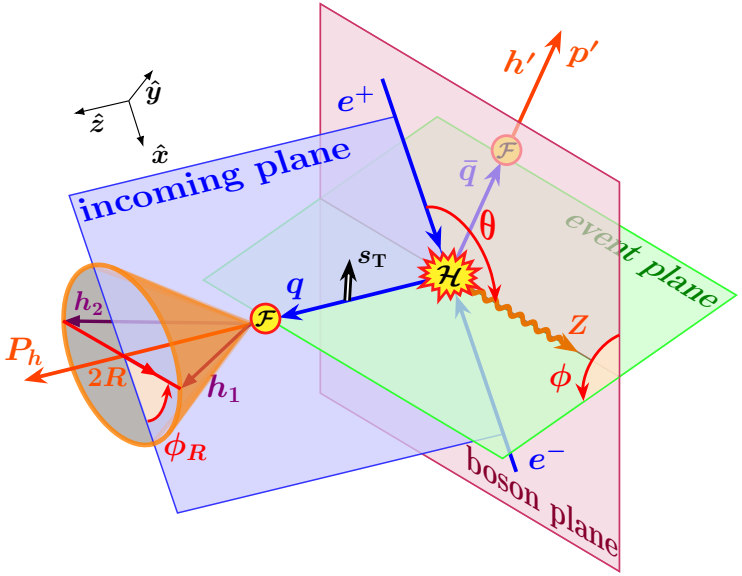
- Q. H. Cao, X. K. Wen, B. Yan, S. T. Zhang, PRL 136 (2026) 231901



Dihadron FFs and Yukawa coupling

- Yukawa interactions generate transverse quark polarization

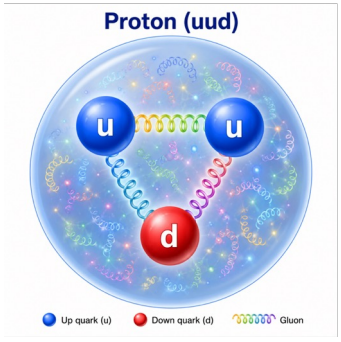




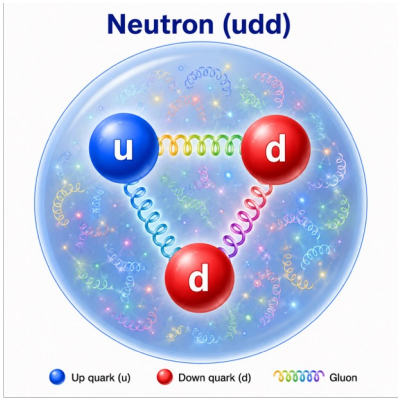
Qing-Hong Cao, Xin-Kai Wen, Bin Yan, Shutao Zhang, PRL 136 (2026) 231901

Why the Light quark Yukawa couplings

- The mass difference between proton and neutron—isospin



$\neq$

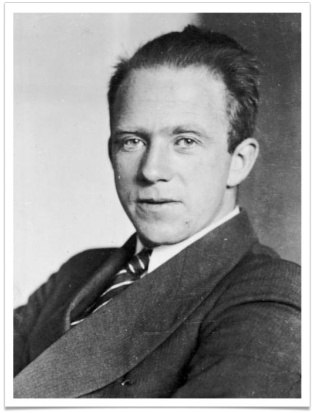




938.27231 MeV



939.56563 MeV



W. Heisenberg,
On the structure of atomic nuclei
Z. Phys. 77 (1932) 1-11

- BBN: primordial helium abundance

Thermal equilibrium: $\frac{n_n}{n_p} = e^{-\Delta m_{np}/T_f}$

$$Y_p = \frac{2\left(n_n/n_p\right)}{1+n_n/n_p}$$

Why the Light quark Yukawa couplings

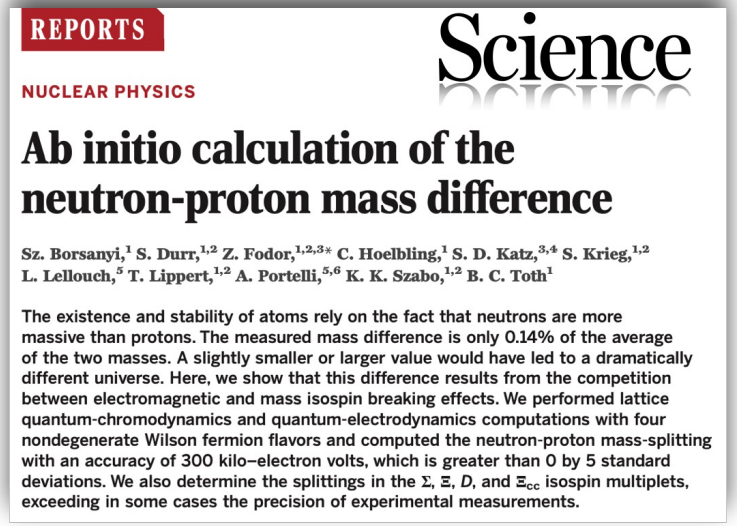
- Neutron-proton mass difference: **quark Yukawa** and electromagnetic interaction

$$\Delta M = \Delta M_{\mathrm{QCD}} + \Delta M_{\mathrm{QED}}$$

+ 1.29 MeV	+ 2.52 MeV	- 1.00 MeV
Fine cancellation of two large effects	$m_d > m_u$ Higgs Yukawa	Proton is charged, Coulomb self-energy

48% of 2.52 MeV cancelled by QED

Borsanyi, et al. Science 347, 1452–1455 (2015)



REPORTS

Science

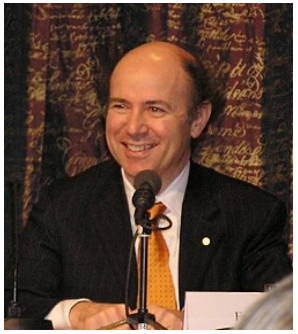
NUCLEAR PHYSICS

Ab initio calculation of the neutron-proton mass difference

Sz. Borsanyi,[1] S. Durr,[1,2] Z. Fodor,[1,2,3*] C. Hoelbling,[1] S. D. Katz,[3,4] S. Krieg,[1,2] L. Lellouch,[5] T. Lippert,[1,2] A. Portelli,[5,6] K. K. Szabo,[1,2] B. C. Toth[1]

The existence and stability of atoms rely on the fact that neutrons are more massive than protons. The measured mass difference is only 0.14% of the average of the two masses. A slightly smaller or larger value would have led to a dramatically different universe. Here, we show that this difference results from the competition between electromagnetic and mass isospin breaking effects. We performed lattice quantum-chromodynamics and quantum-electrodynamics computations with four nondegenerate Wilson fermion flavors and computed the neutron-proton mass-splitting with an accuracy of 300 kilo–electron volts, which is greater than 0 by 5 standard deviations. We also determine the splittings in the Σ, Ξ, *D*, and Ξ_{cc} isospin multiplets, exceeding in some cases the precision of experimental measurements.

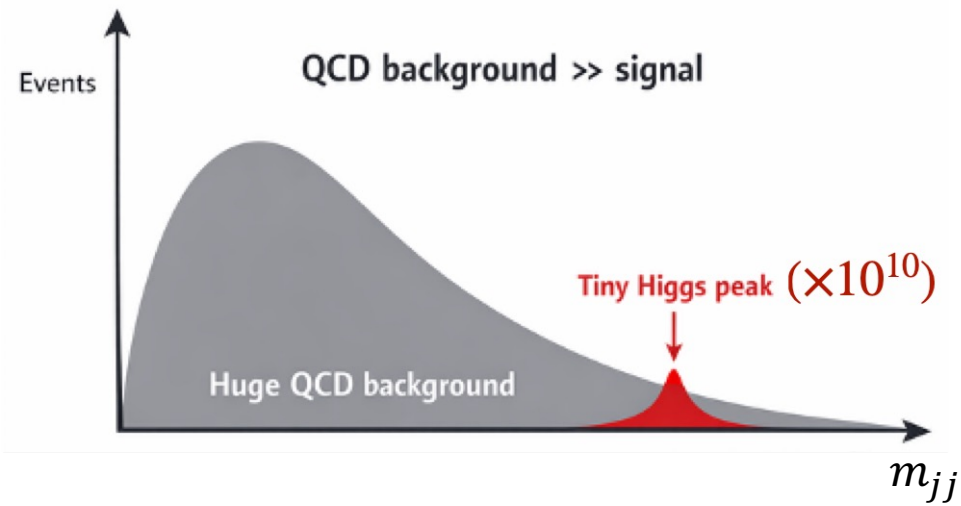
*"They have demonstrated, for the first time, that **fundamental theory gives the right sign** — not a trivial thing, because crude electrostatics gives the opposite result."*

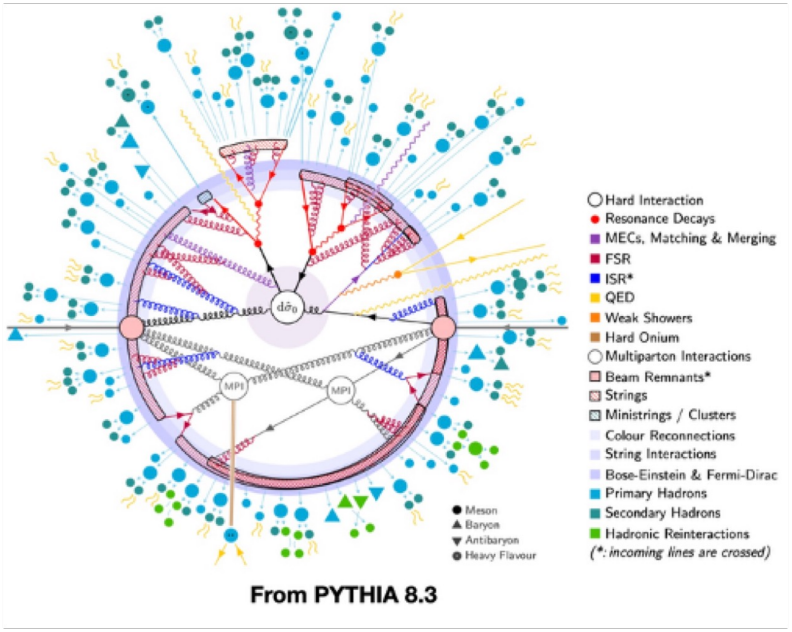


— Frank Wilczek, Nature 520, 303 (2015)

Challenges for Light Quark Case

- Huge QCD backgrounds and blind to charge of u, d after confinement





- The cross sections or decay rates $\propto y_q^2$

$$y_{u,d}^{\mathrm{SM}} \sim \mathcal{O}(10^{-6}) - \mathcal{O}(10^{-5})$$

- Current direct bounds three orders of magnitude above SM

$$|y_u| < 0.03, \quad |y_d| < 0.026$$

CMS: PRL 132 (2024) 121901, PRD 112 (2025) 112001

- **No (independent) sensitivity to up- and down-quark Yukawa couplings**

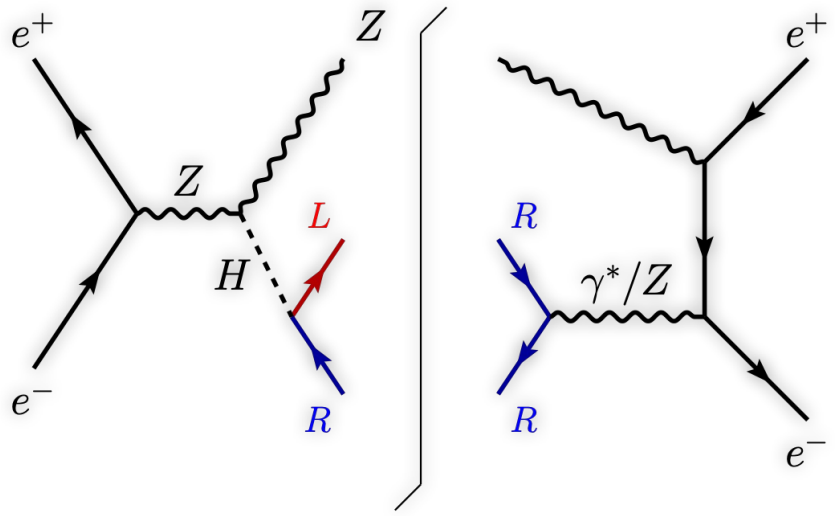
Linear sensitivity via interference

- Higgs-mediated amplitude interference with the SM background

$$\left|M_{\mathrm{SM}}+M_H\right|^2=\left|M_{\mathrm{SM}}\right|^2+2\,\mathrm{Re}\left(M_{\mathrm{SM}}^{*}M_H\right)+\left|M_H\right|^2$$

$$\propto y_q \qquad \propto y_q^2 \sim 10^{-10}$$

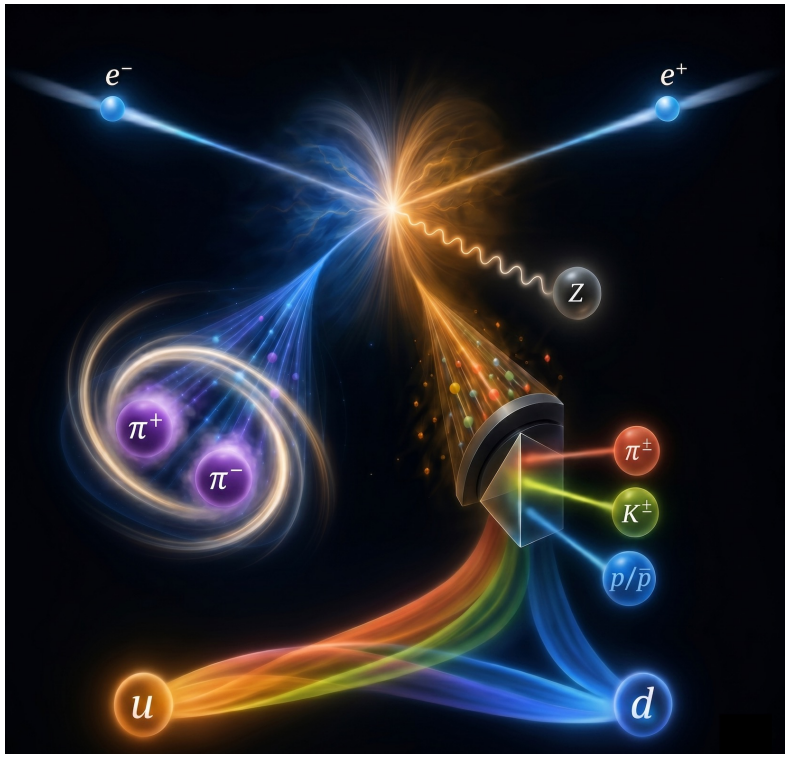
$e^+ + e^- \to Z + H(\to q\bar{q})$ $\qquad$ $e^+ + e^- \to Z + Z/\gamma^*(\to q\bar{q})$



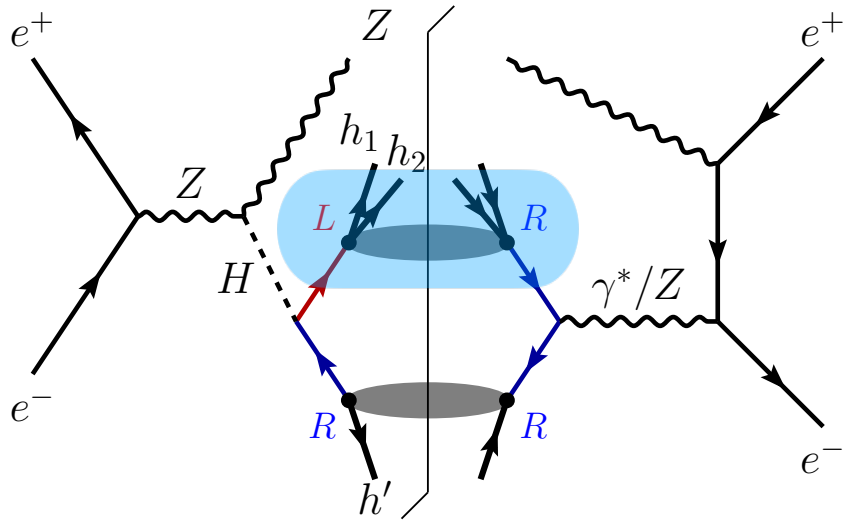
- The interference effects could be projected out by the Dihadron Fragmentation Functions (DiFFs)

Linear sensitivity via interference

- Yukawa couplings flip chirality: transverse polarization of quark $q \to \pi^+\pi^-$



$$\rho = \frac{1}{2}(1 + \mathbf{s}\cdot\sigma) = \begin{pmatrix} 1+s_z & s_x - is_y \\ s_x + is_y & 1 - s_z \end{pmatrix}$$

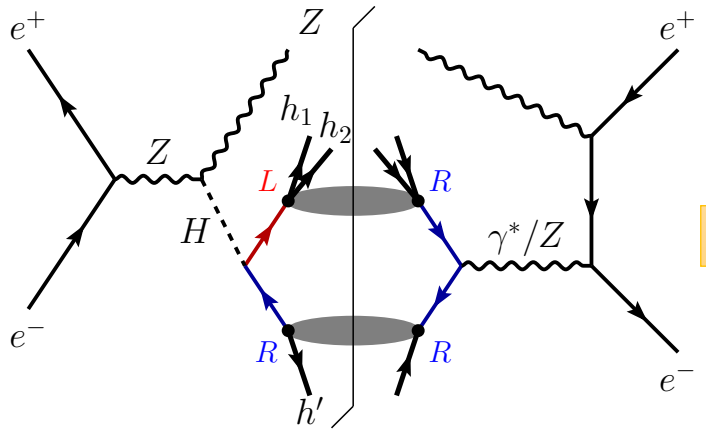


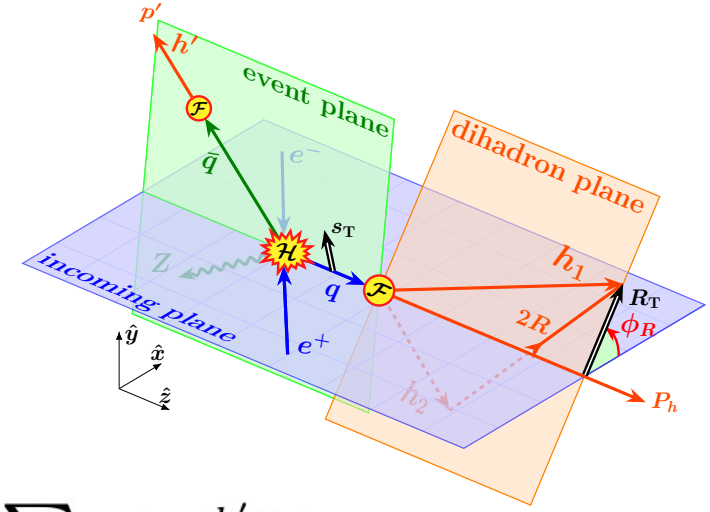
QHC, XKW, BY, STZ, PRL 136 (2026) 231901

$y_q^2 \to y_q$

- New flavor tagging: single hadron $\bar{q} \to h$

Transverse spin effects of quark @ CEPC





$$\frac{d\sigma}{dx_q\, dx_{\bar{q}}\, d\cos\theta\, d\phi\, dz\, d\bar{z}\, dM_h\, d\phi_R} = \frac{1}{64(2\pi)^5} \sum_{q,\, q\to\bar{q}} \mathcal{C}_q D_{\bar{q}}^{h'}(\bar{z})$$

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

Unpolarized FFs

Polarized FFs

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

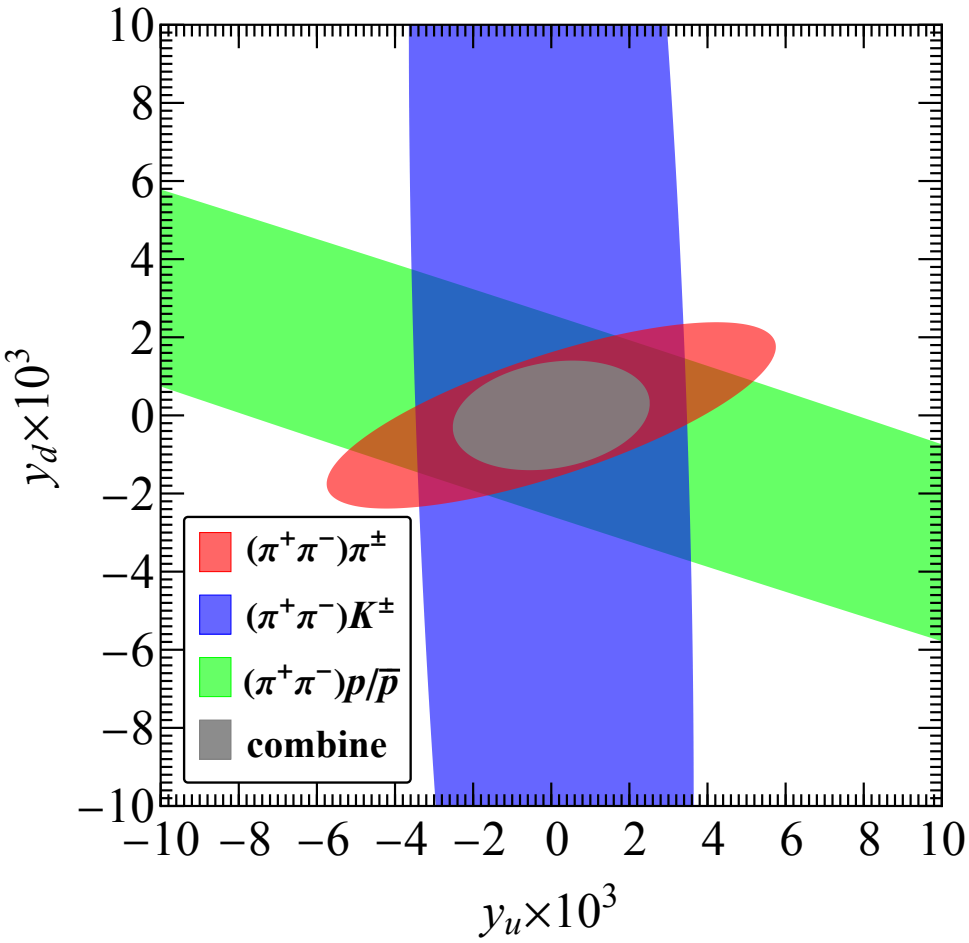
$$(\boldsymbol{s}_{T,q} \times \hat{\boldsymbol{R}}_T)^z = s_q^x \sin\phi_R - s_q^y \cos\phi_R$$

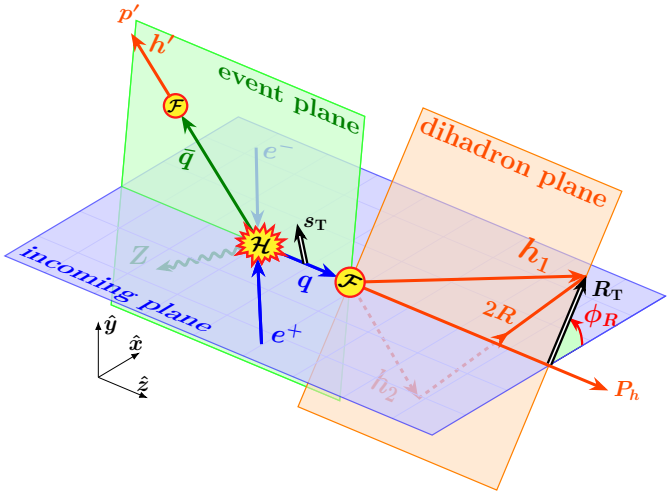
$$s_q^{x,y} \propto y_q$$

CP even Yukawa couplings @ CEPC

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

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





QHC, XKW, BY, STZ, PRL 136 (2026) 231901

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

- Yukawa couplings $O(10^{-4} - 10^{-3})$
- Single-hadron channels enable flavor separation

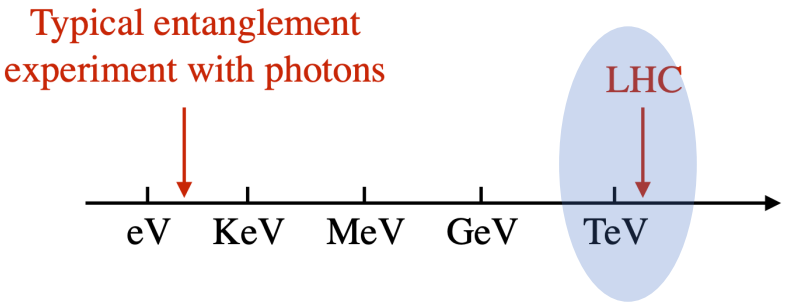
Fragmentation functions encode the spin information of quarks

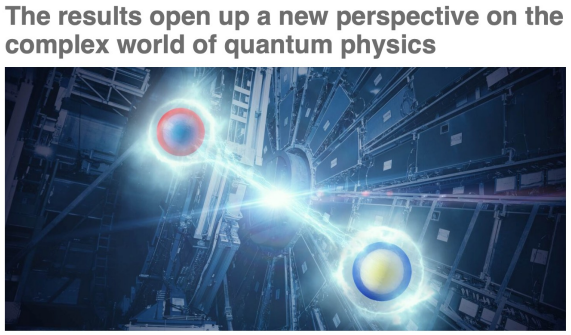


- Spin information as a tool for new physics searches
- Spin structure of quark systems: quark-quark spin correlations
- Emergence of entanglement in quark systems

Quantum information at collider

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





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. 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

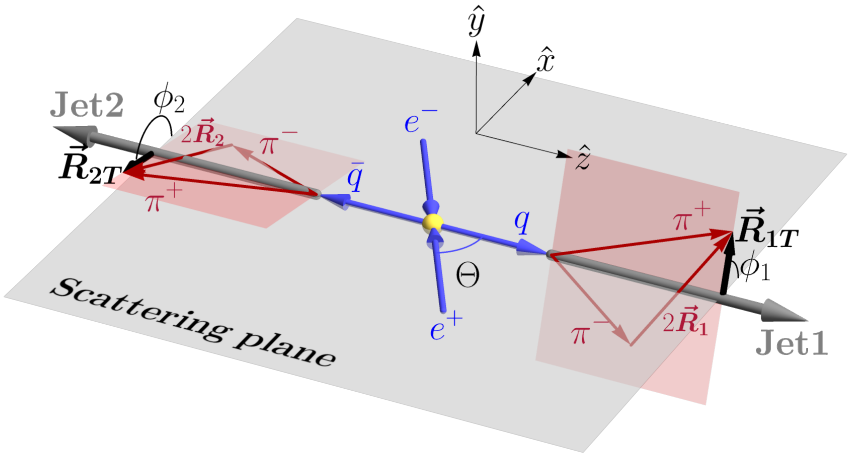
R. Aoude et al, PRD 106 (2022) 055007
M. Fabbrichesi et al, EPJC 83 (2023) 162, JHEP 09 (2023) 195
A. Bernal et al, EPJC 83 (2023) 11, 1050
…

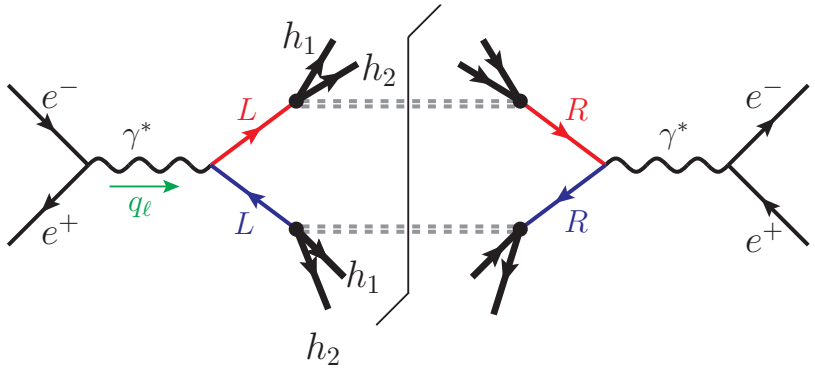
The spin correlation between particles can be measured from its decay products



How about the light quarks?

Dihadron pair production at lepton colldiers





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

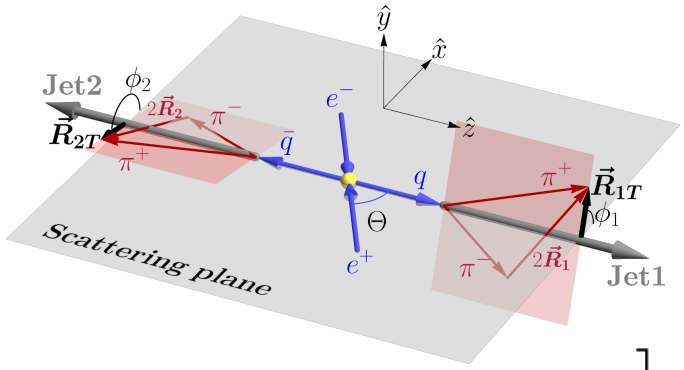
- The transverse spin correlation between light quarks: chiral-odd interference dihadron fragmentations (collinear factorization)
- Light quark pair are 100% correlated in the central scattering region

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

- 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

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

Transverse polarized diFF

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

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

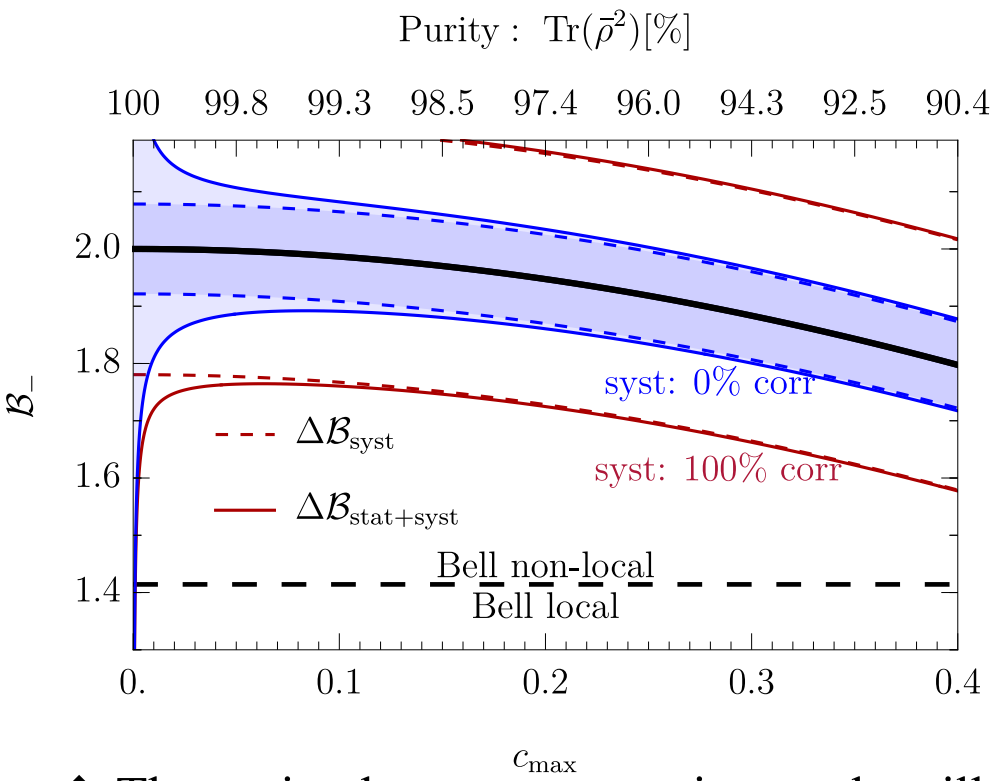
  Q. H. Cao, G. Li, X. K Wen and B. Yan, Rept. Prog. Phys. 89 (2026) 080501

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

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

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



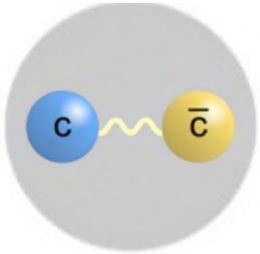
- Spin information as a tool for new physics searches
- Emergence of entanglement in quark systems
- **Probing the Color-Octect Mechanism via Spin Observable**

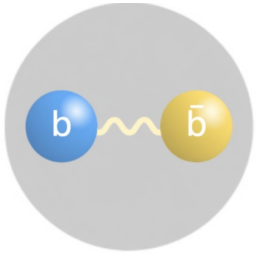
NRQCD and Heavy Quarkonium

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

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

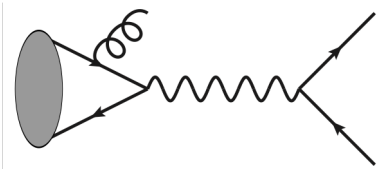
- Theoretical issues:

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

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

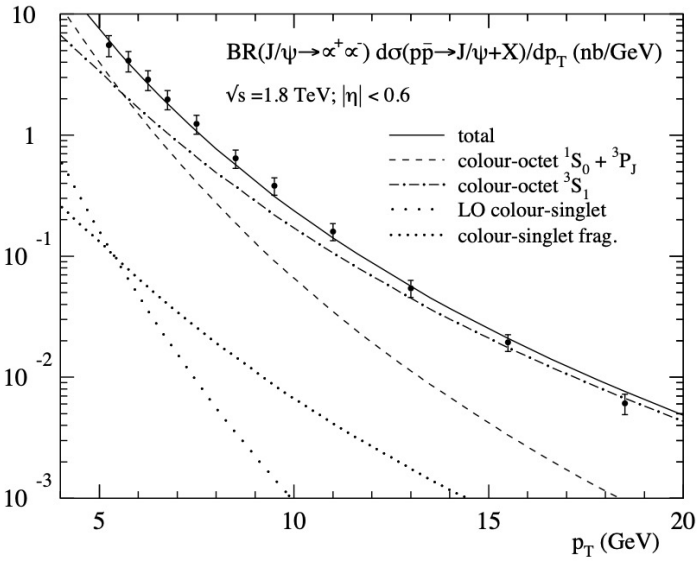
NRQCD and Heavy Quarkonium

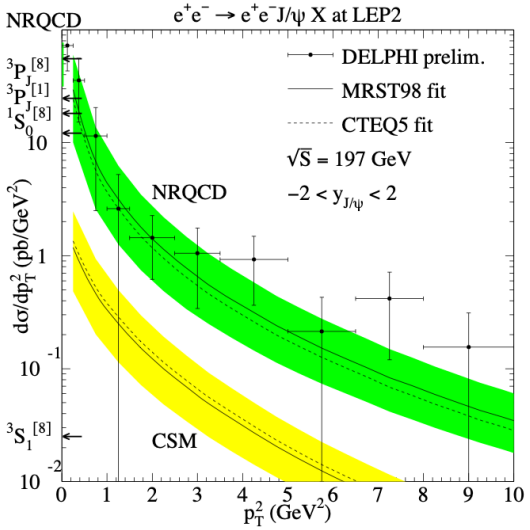
- NRQCD factorization — G. T. Bodwin, E. Braaten, G. P. Lepage, PRD 51 (1995) 1125
  - $Q\bar{Q}$ could be in all possible spin and color configurations
  - Color-Octet Mechanism:



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

Testing Color-Octet Mechanism

- Lattice VS Experiment (P-wave quarkonium)

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

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

- 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?

$$b\bar{b}(^3S_1^{[8]}) \to q\bar{q} \qquad\qquad b\bar{b}(^3P_J^{[1]}) \to gg$$



The spin of quark and gluon is different!

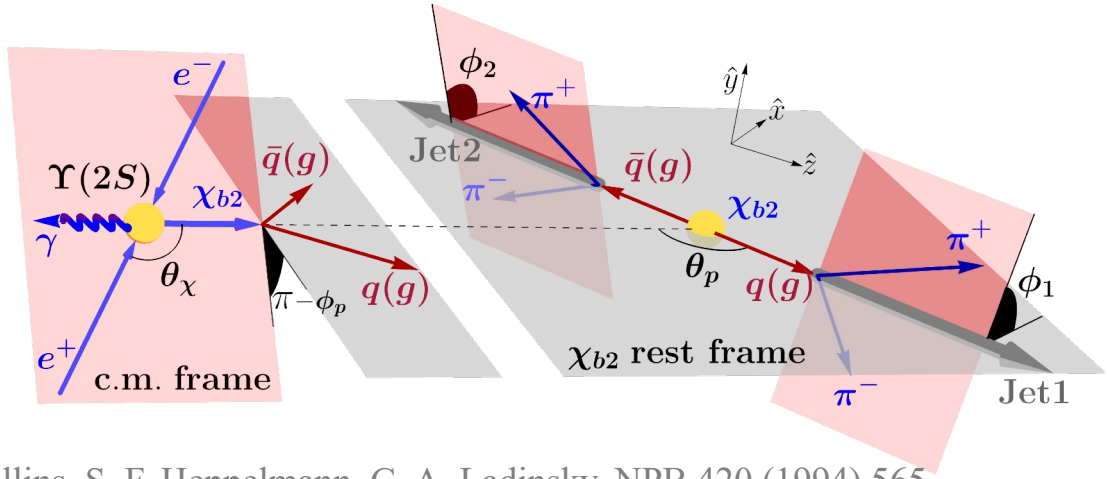
Z. G. He, G. Li, Y. J. Tian, X. K. Wen, B. Yan, PRL 137 (2026) 131903

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

$$\frac{d\sigma}{\sigma_0 dz_1 dz_2 dM_1 dM_2 d\phi_1 d\phi_2 d\cos\theta_\chi d\cos\theta_p d\phi_p}$$

$$= H_8^b \sum_q \mathcal{C}_q \left[D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2) \right]$$

Unpolarized quark diFF

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

Transverse polarized quark diFF

$$+ H_1^b \mathcal{C}_g\, D_1^g(z_1, M_1) D_1^g(z_2, M_2),$$

Unpolarized gluon diFF

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

Artru-Collins asymmetry

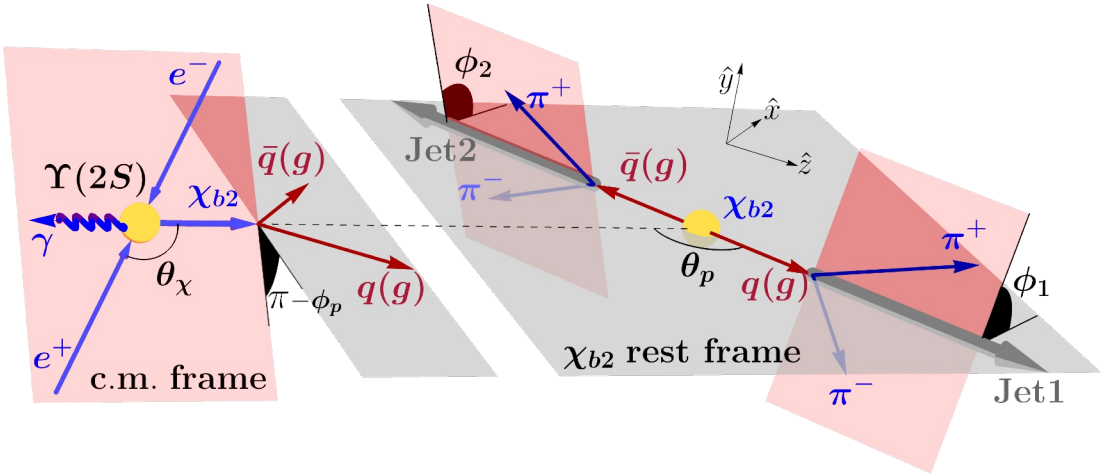
- Asymmetry

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

Asymmetry provides a clean probe of ρ_8

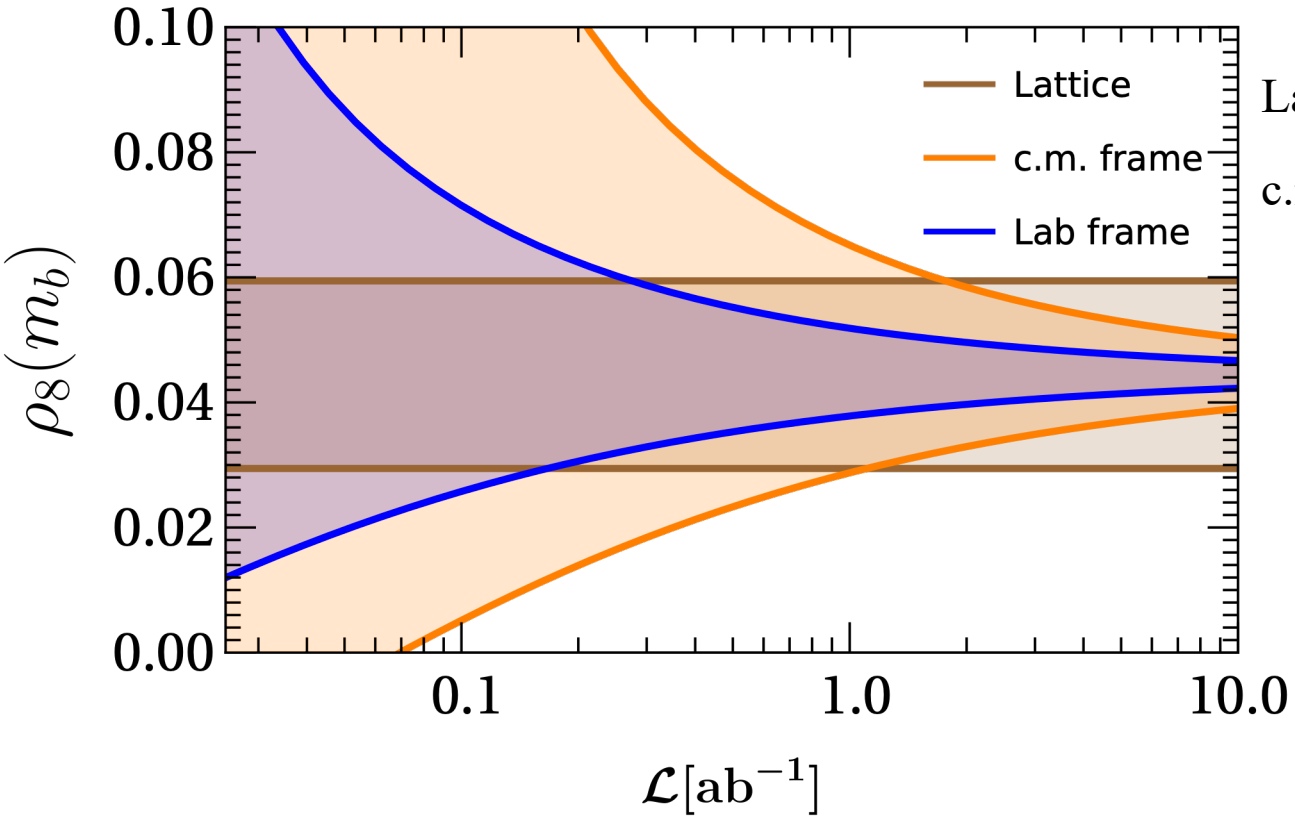
- Belle: boost effects

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



- ❖ 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



Lab frame (χ_{b2}): binned in θ_p

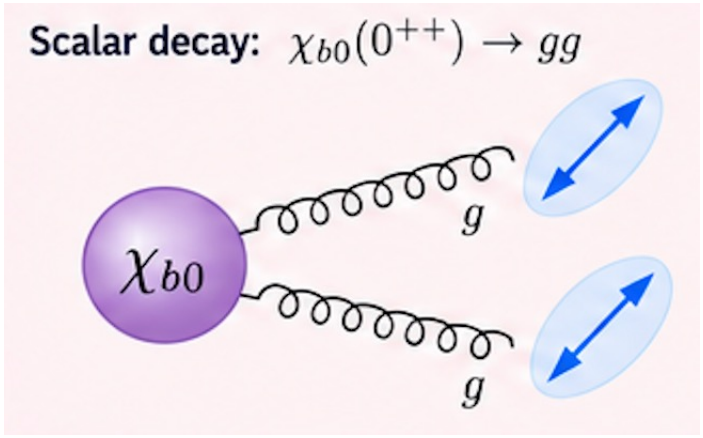
c.m. frame (χ_{b2}): binned in θ_χ

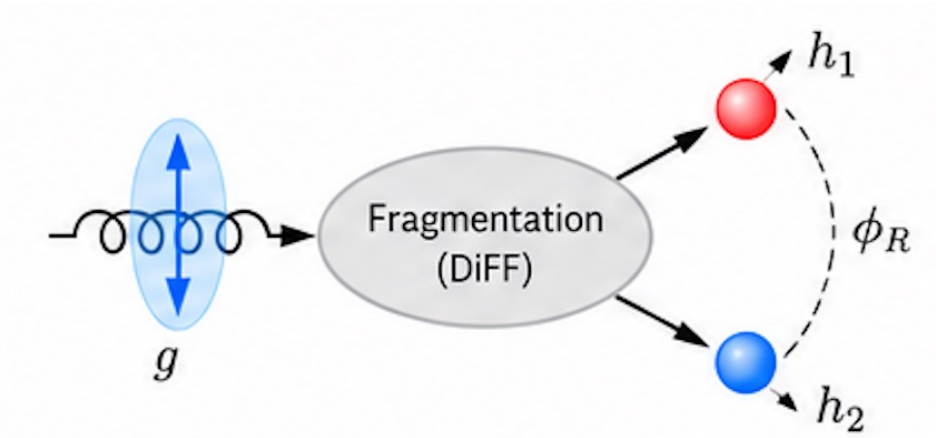
- Cancellation in phase space at c.m. frame
- Projected sensitivity surpasses current lattice uncertainty with $\mathcal{O}(0.1)\ \mathrm{ab}^{-1}$
- The potential to resolve the long-standing discrepancy in ρ_8

Z. G. He, G. Li, Y. J. Tian, X. K. Wen, B. Yan, PRL 137 (2026) 131903

From quark to gluon spin analysis







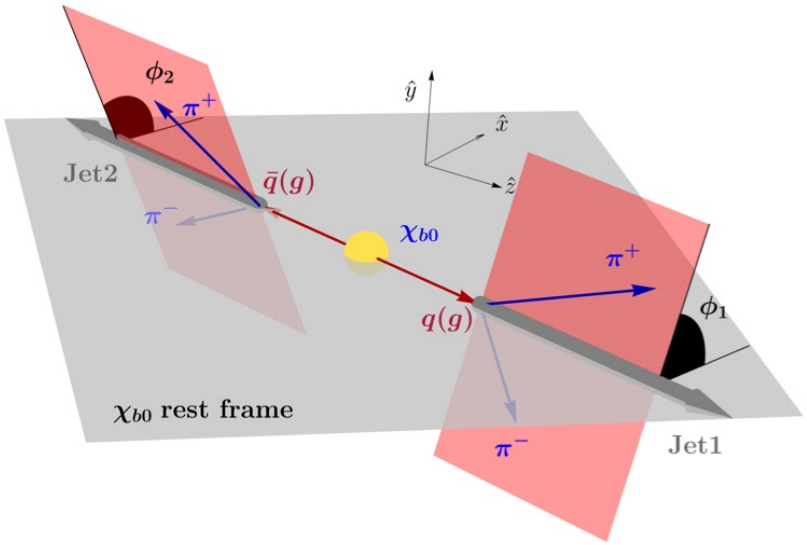
The linearly polarized gluon DiFF has not yet been accessed experimentally

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

From quark to gluon spin analysis

- Collinear Factorization

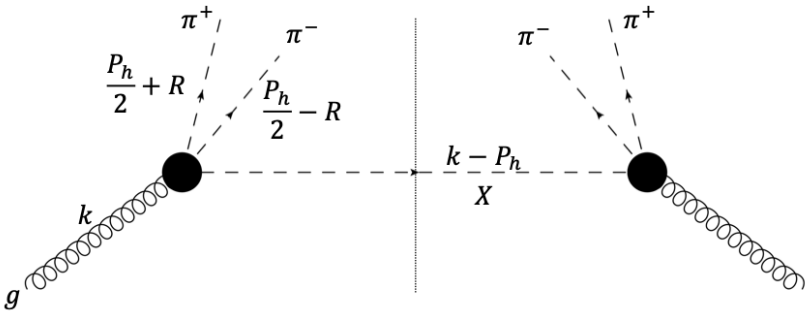
$$\frac{d\sigma}{\sigma_0\, dz_1\, dz_2\, dM_1\, dM_2\, d\phi_1\, d\phi_2}$$
$$= H_1^b \mathcal{C}_g \left[D_1^g(z_1, M_1) D_1^g(z_2, M_2) \right.$$
$$\left. + H_1^{\sphericalangle, g}(z_1, M_1) H_1^{\sphericalangle, g}(z_2, M_2) \cos(2\phi_1 - 2\phi_2) \right]$$
$$+ H_8^b \sum_q \mathcal{C}_q\, D_1^q(z_1,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



- Artru-Collins asymmetry

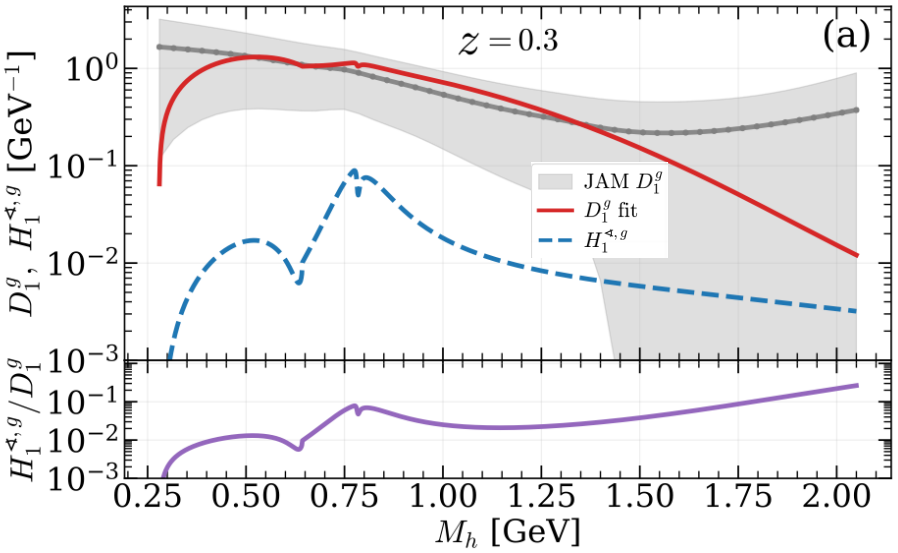
$$A_{12} \equiv 2\langle \cos(2\phi_1 - 2\phi_2) \rangle = \frac{m_b^2 \mathcal{C}_g H_1^{\sphericalangle, g}(z_1, M_1) H_1^{\sphericalangle, g}(z_2, M_2)}{\rho_8(m_b) \sum_q \mathcal{C}_q D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2) + m_b^2 \mathcal{C}_g D_1^g(z_1, M_1) D_1^g(z_2, M_2)}$$

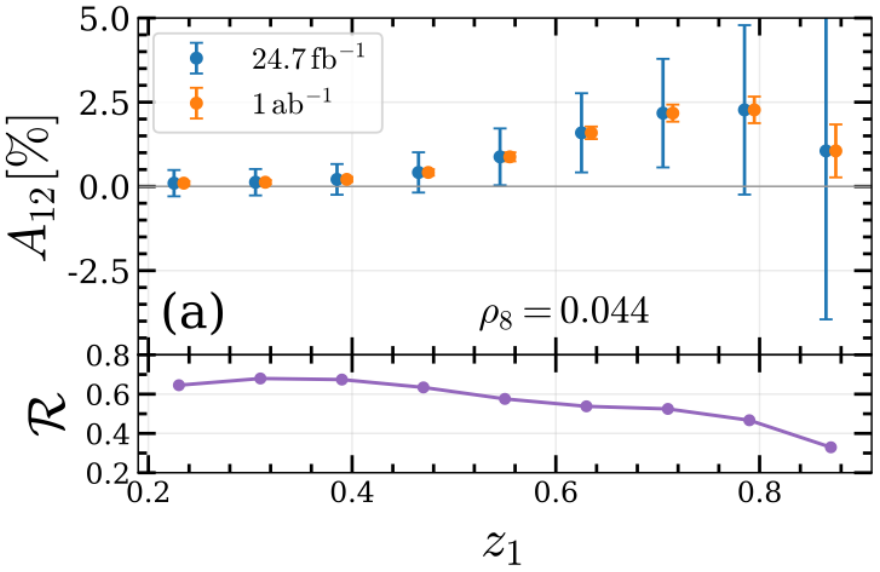
- Spectator Model



- ❖ Fitting unpolarized DiFF from JAM
- ❖ Predicted polarized DiFF

Artru-Collins asymmetry (Belle)





$$\mathcal{R} = A_{12}(\rho_8 = 0.16)/A_{12}(\rho_8 = 0.044)$$

- P-wave amplitudes are dominated by intermediate vector-meson, ρ, ω
- Asymmetry magnitude:~ 1%

Summary

- Light quark Yukawa couplings are extremely small and poorly constrained; conventional observables scale as y_q^2 and lack sensitivity
- The signal and background interference induces quark transverse polarization and the chiral-odd dihadron fragmentation functions, yielding azimuthal asymmetries linear in y_q
- 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 and gluon linear polarization

New opportunities in QCD spin physics!

Thank you