山东大学 SHANDONG UNIVERSITY 北京大學 PEKING UNIVERSITY 高能物理研究中心 Center for High Energy Physics, PKU

Probing Quark Electromagnetic Properties via Entangled Quark Pairs in Fragmentation Hadrons at Lepton Colliders

Xin-Kai Wen (文新锴)

Institute of High Energy Physics (IHEP, CAS)

China Center of Advanced Science and Technology (CCAST)

Base on: Qing-Hong Cao, Guanghui Li, **Xin-Kai Wen**, and Bin Yan, *arXiv:* 2509.18276

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Quarks: Fundamental to almost Everything

Quarks are crucial for testing the Standard Model and probing the New Physics

- **To be the fundamental component of matter and universe:**

  Internal structure: Are quarks truly fundamental ?

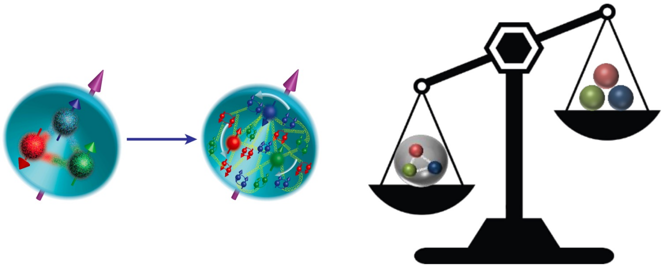
  Intrinsic property**: **How to probe quark properties ?

  $$\mu_q = ???,\ \ |d_q| = ???,\ \ (q = u, d, s, \ldots)$$

- **To understand the strong interactions and confinement:**

  Quark confinement: Why can't we isolate a quark ?

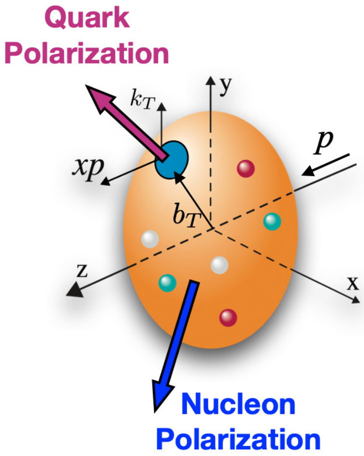
  Mass problem: Where does mass come from ?



- **To form the diversity of hadron and the spin structure:**

  Spin puzzle: What makes a proton spin ?

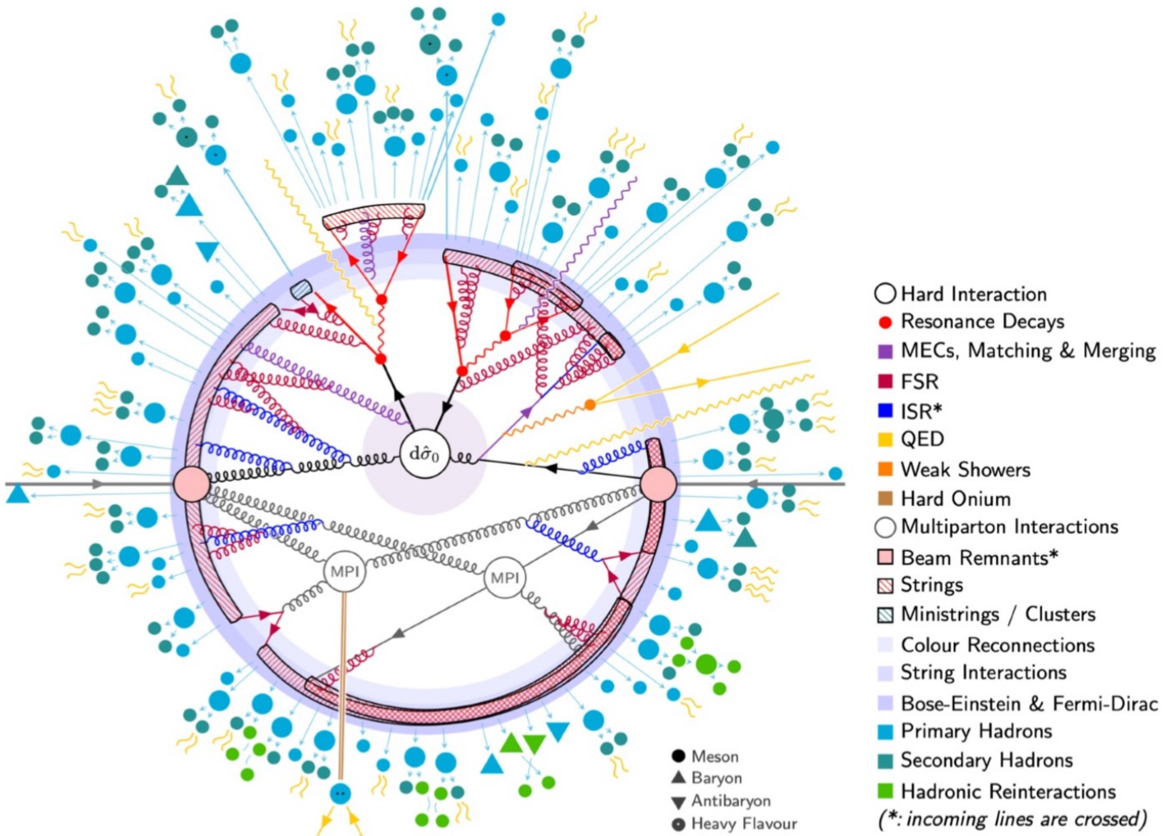
  Spin transfer: How quark spin originates and evolutes ?



Well Known Color Confinement

QCD color confinement prevents the direct handle or measurement of quark interactions

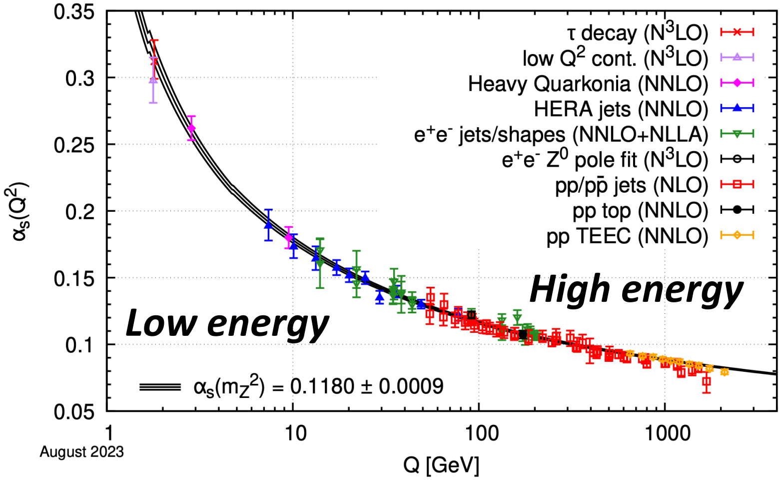
- **Only from observable particles to observable particles (hadrons / leptons / photons …)**



From PYTHIA 8.3

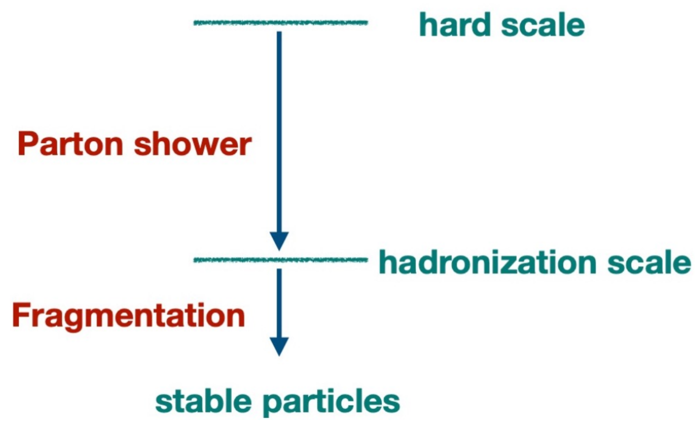
Asymptotic Freedom and Factorization

QCD asymptotic freedom and factorization pave an avenue to study quarks and gluons



Particle Data Group, *Phys.Rev.D* 110 (2024) 3, 030001

- ☐ Hard process in high energy
- ☐ Transition from high energy to low energy
  —parton shower
- ☐ Low energy soft regime
  —fragmentation



How to probe the properties and the spin information of quarks?

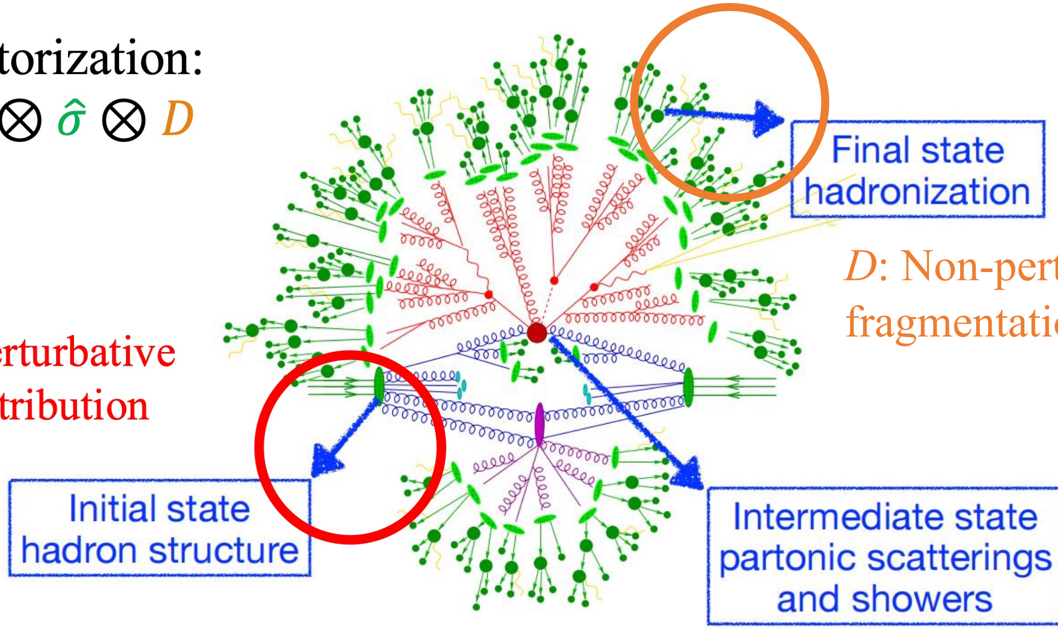
- ➢ **Heavy quarks: decay products**
- ➢ **Light quarks: non-perturbative functions, i.e., the parton distribution functions and the fragmentation functions**

Factorization and Spin Effects in QCD

QCD asymptotic freedom and factorization pave an avenue to study quarks and gluons

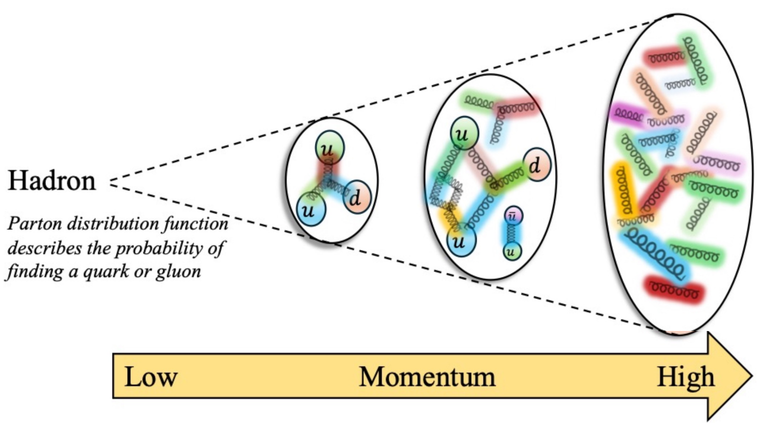
QCD factorization:

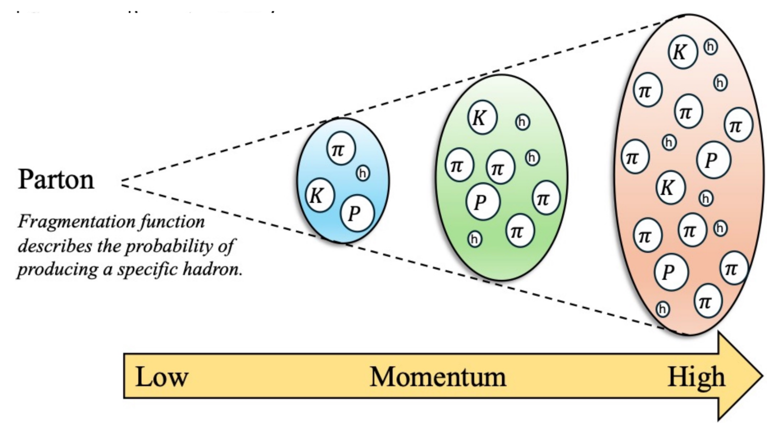
$$\sigma = f \otimes \hat{\sigma} \otimes D$$



D: Non-perturbative fragmentation function

f: Non-perturbative parton distribution function

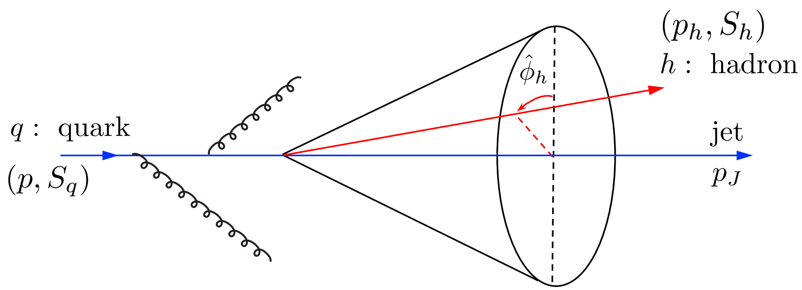




Lepton Collider: A Clean QCD Spin Probe

The light quarks do not decay but instead fragment into a jet of hadrons after produced from hard scattering with their spin information transferring to the hadrons

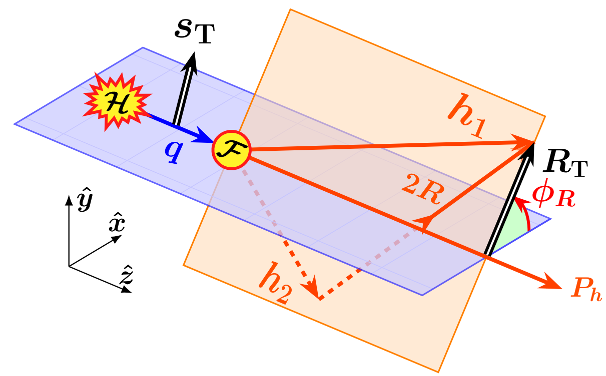
➢ *TMD Fragmentation Functions*

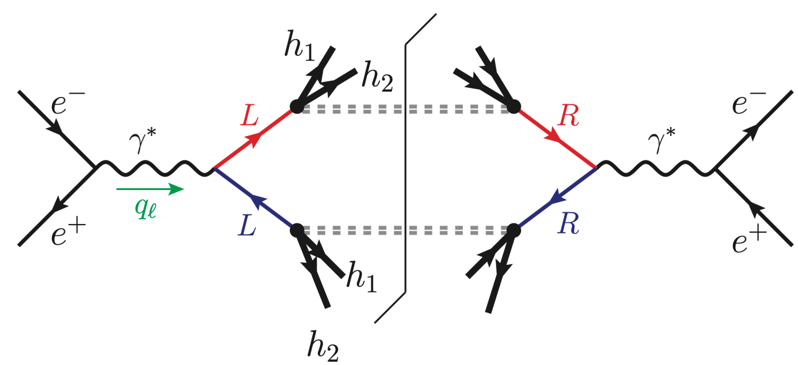


Leading Quark TMDFFs — Hadron Spin — Quark Spin

		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	$H_{1L}^\perp$ = −
Polarized Hadrons	T	$D_{1T}^\perp$ = − Polarizing FF	$G_{1T}^\perp$ = −	H_1 = − Transversity $H_{1T}^\perp$ = −

➢ *Dihadron Fragmentation Functions*

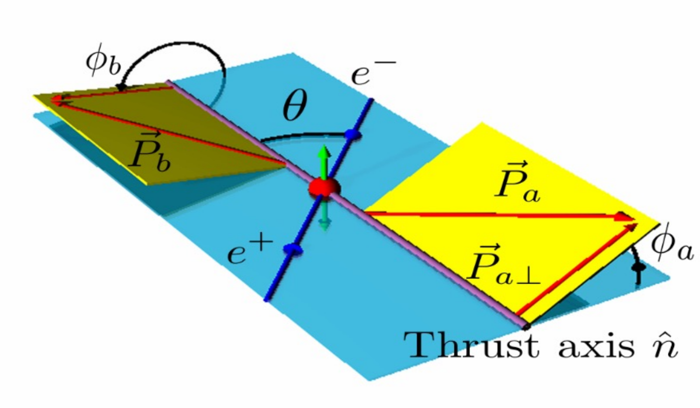


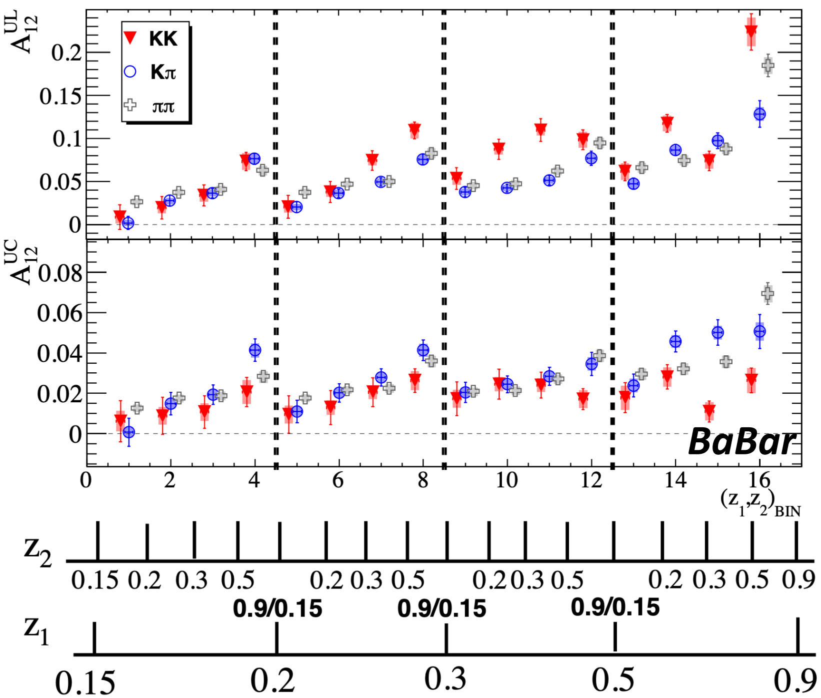


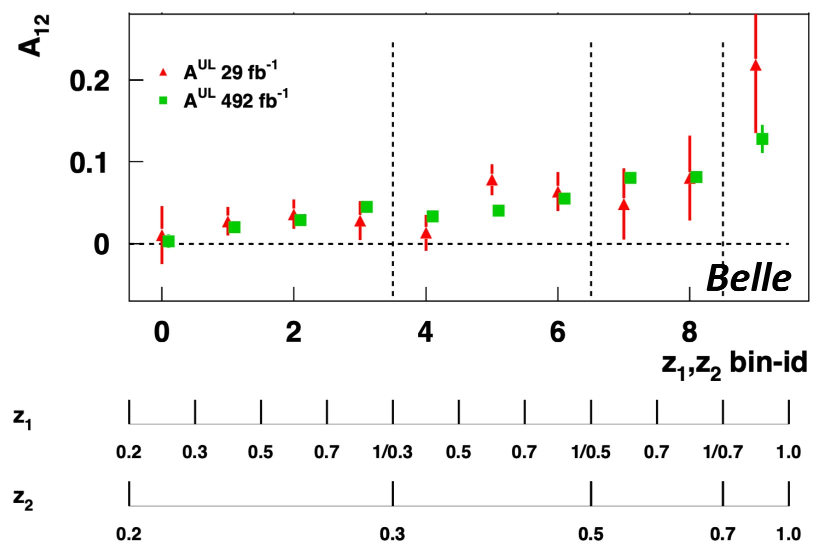
Kang, Prokudin, Sun, Yuan, *Phys.Rev.D* **93** (2016) 014009;
Zeng, Dong, Liu, Sun, Zhao, *Phys.Rev.D* **109** (2024) 056002;
TMD Handbook, *arXiv:* 2304.03302; ......

TMD: Collins Effects and Asymmetry

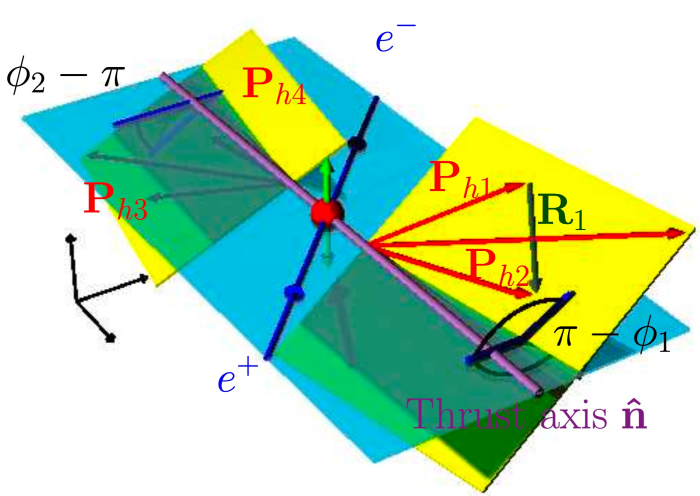
BaBar Collaboration, *Phys. Rev. D* **90** (2014) 052003
Belle Collaboration, *Phys. Rev. D* **78** (2008) 032011
BaBar Collaboration, *Phys. Rev. D* **92** (2015) 111101

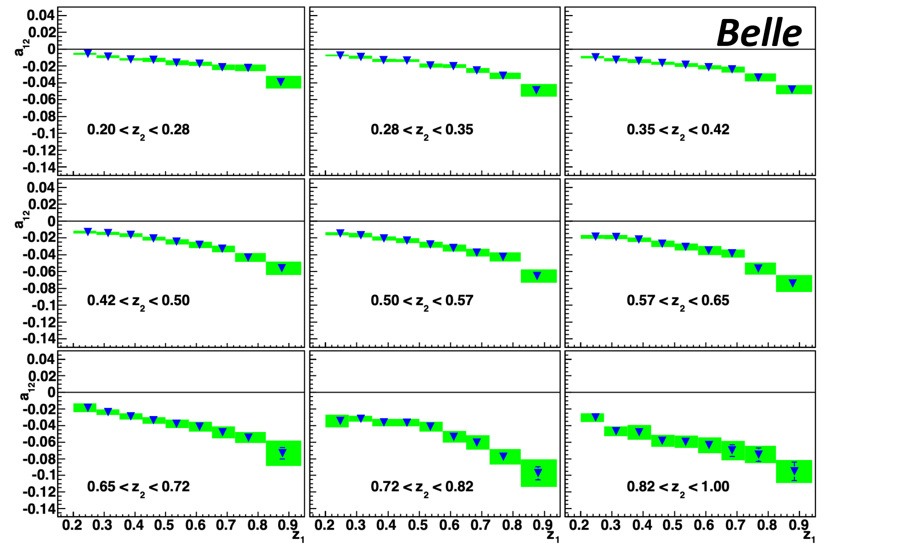


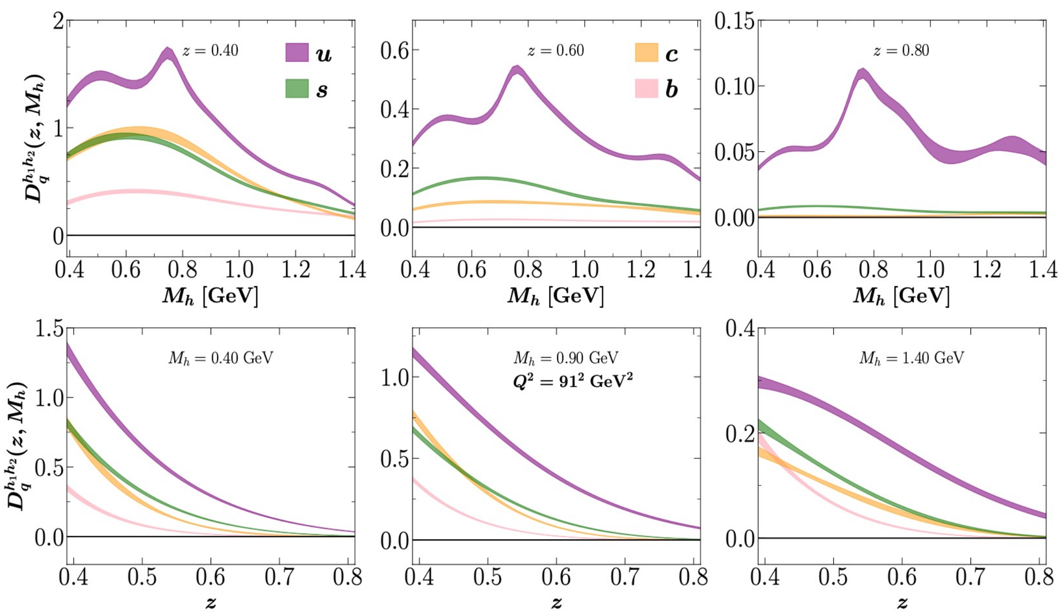




Artru-Collins Asymmetry and dihadron



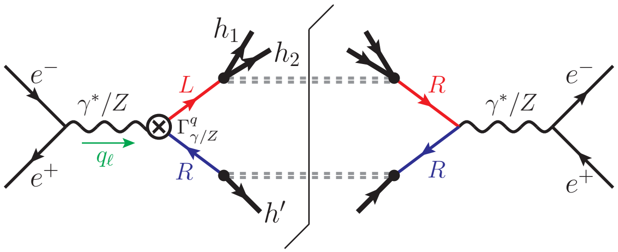




Belle Collaboration, *Phys. Rev. Lett.* **107** (2011) 072004
JAM Collaboration, *Phys. Rev. Lett* **132** (2024) 091901
JAM Collaboration, *Phys. Rev. D* **109** (2024) 034024

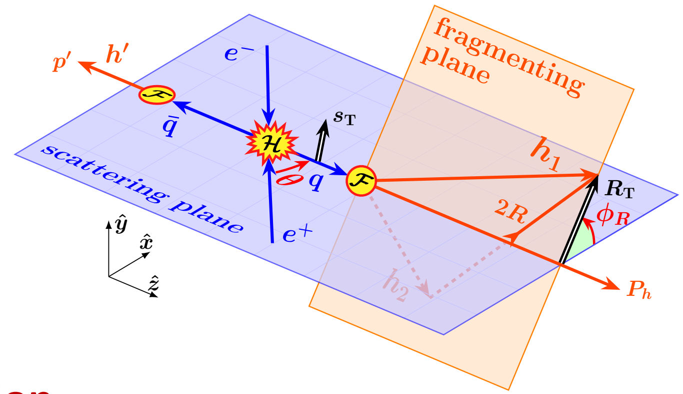
DiFFs and Single Spin Asymmetry

Light-quark dipole moments produce transverse spin of quarks via interference effects



$\mathcal{O}(1/\Lambda^2)$

$$\rho = \frac{1}{2}\begin{pmatrix} 1+\lambda & b_{\mathrm{T}} e^{-i\phi_0} \\ b_{\mathrm{T}} e^{i\phi_0} & 1-\lambda \end{pmatrix}$$

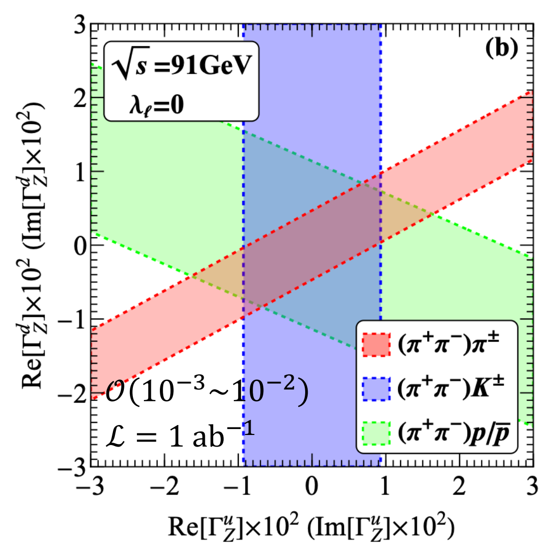


Dihadron chiral-odd interference fragmentation function

$\Longrightarrow$ To project out transverse spin of single quarks with azimuthal asymmetry

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

$$\frac{d\sigma}{dz\,d\bar{z}\,dM_h\,d\phi_R} = \frac{B^0 - B^x\sin\phi_R + B^y\cos\phi_R}{32\pi^2 s}$$



Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, *Phys. Rev. D* 112 (2025) 5, 053004

From Single Spin to Spin Correlation

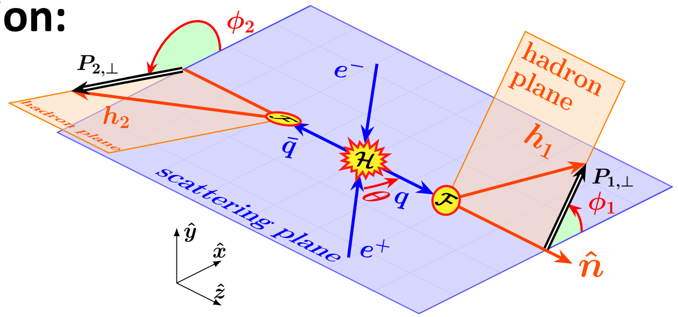
From Single Transverse Spin of Single Quark to Spin Correlation of Entangled Quark Pairs:

$$\rho = \frac{I_2 \otimes I_2 + B_i \sigma_i \otimes I_2 + \bar{B}_i I_2 \otimes \sigma_i + C_{ij} \sigma_i \otimes \sigma_j}{4}$$

Bell variable for entanglement and Bell inequality violation:

$$\mathcal{B}_{\pm} \equiv C_{xx} \pm C_{yy} \quad \Leftrightarrow \quad \cos(\phi_1 \mp \phi_2)$$

$$\mathcal{B}'_{\pm} = C_{xy} \pm C_{yx} \quad \Leftrightarrow \quad \sin(\phi_1 \pm \phi_2)$$



In the SM, light quark pair exhibit 100% transverse spin correlation forming a maximally entangled Bell state along $\hat{y}$-direction in the central scattering region

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

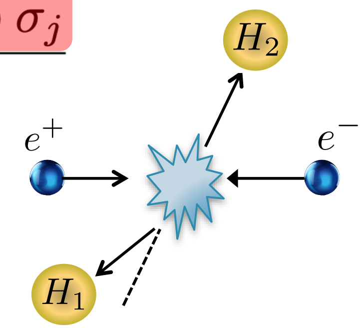
$$|1,0\rangle_y = \frac{1}{\sqrt{2}}\left(|\uparrow_y \downarrow_y\rangle + |\downarrow_y \uparrow_y\rangle\right)$$

$$\mathcal{B}_+ = 0 \qquad \mathcal{B}_- = 2\sin^2\theta/(1+\cos^2\theta)$$

From Single Spin to Spin Correlation

From Single Transverse Spin of Single Quark to Spin Correlation of Entangled Quark Pairs:

$$\rho = \frac{I_2 \otimes I_2 + B_i \sigma_i \otimes I_2 + \bar{B}_i I_2 \otimes \sigma_i + C_{ij} \sigma_i \otimes \sigma_j}{4}$$



Bell variable for entanglement and Bell inequality violation:

$$\mathcal{B}_{\pm} \equiv C_{xx} \pm C_{yy} \quad \Leftrightarrow \quad \cos(\phi_1 \mp \phi_2)$$

$$\mathcal{B}'_{\pm} = C_{xy} \pm C_{yx} \quad \Leftrightarrow \quad \sin(\phi_1 \pm \phi_2)$$

In the SM, Only $\mathcal{B}_-$ nonzero !!

In $e^- e^+ \to \gamma^* \to q\bar{q} \to (\pi^+\pi^-) + (\pi^+\pi^-) + X$ via $\cos(\phi_1 + \phi_2)$ asymmetry:

- ✓ **Global fitting on DiFFs and TMDFFs**
- ✓ **Bell inequality violation**

$$A^{e^+e^-} = \frac{\sin^2\theta \sum_q e_q^2 H_1^{\sphericalangle,q}(z, M_h) H_1^{\sphericalangle,\bar{q}}(\bar{z}, \overline{M}_h)}{(1+\cos^2\theta) \sum_q e_q^2 D_1^q(z, M_h) D_1^{\bar{q}}(\bar{z}, \overline{M}_h)}$$

How about the other three Bell variables ?

What type of physics effect would exhibit sensitivity ?

Spin Correlation and Quark EM Properties

From Single Transverse Spin of Single Quark to Spin Correlation of Entangled Quark Pairs:

$$\rho = \frac{I_2 \otimes I_2 + B_i \sigma_i \otimes I_2 + \bar{B}_i I_2 \otimes \sigma_i + C_{ij} \sigma_i \otimes \sigma_j}{4}$$

Bell variable :

$$\mathcal{B}_\pm \equiv C_{xx} \pm C_{yy} \quad \Leftrightarrow \quad \cos(\phi_1 \mp \phi_2)$$

$$\mathcal{B}'_\pm = C_{xy} \pm C_{yx} \quad \Leftrightarrow \quad \sin(\phi_1 \pm \phi_2)$$

$$e^+ e^- \to \gamma^* \to q\bar{q}$$

Any nonzero $\mathcal{B}_+$ would hint the NP, free from SM contamination as only $\mathcal{B}_-$ nonzero in SM

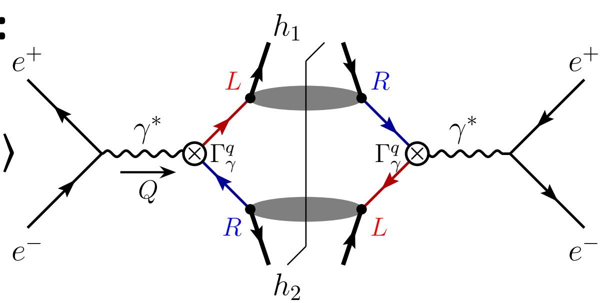
Up to $O(1/\Lambda^4)$ operators, $\mathcal{B}_+$ and $\mathcal{B}'_\pm$ uniquely sensitive to quark MDM and EDM

$$\frac{v}{\sqrt{2}\Lambda^2} \left(C_\gamma^u \bar{u}_L \sigma^{\mu\nu} u_R + C_\gamma^d \bar{d}_L \sigma^{\mu\nu} d_R \right) A_{\mu\nu}$$

MDM, EDM:

$|\uparrow_z \downarrow_z\rangle, \quad |\downarrow_z \uparrow_z\rangle$

$d^1_{1,0}$

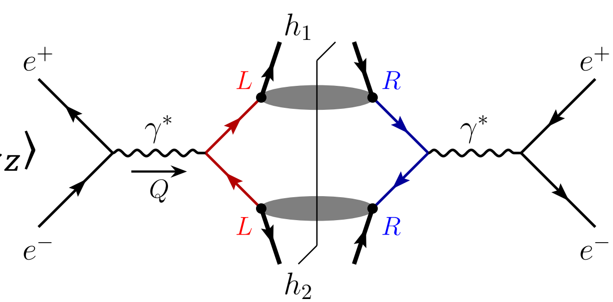


Chirality-Flip

SM:

$|\uparrow_z \uparrow_z\rangle, \quad |\downarrow_z \downarrow_z\rangle$

$d^1_{1,1}, \quad d^1_{1,-1}$



Chirality-Conserve

Spin Correlation and Quark EM Properties

SM and four fermion interactions

$$C_{xx} - C_{yy} = \frac{\sin^2\theta}{1+\cos^2\theta}\left(2 + \frac{1}{\Lambda^2}\mathcal{F}_1 + \frac{1}{\Lambda^4}\mathcal{F}_2\right) \qquad |1,0\rangle_y = \frac{1}{\sqrt{2}}(|\uparrow_z\uparrow_z\rangle + |\downarrow_z\downarrow_z\rangle)$$

Chiral symmetry breaking due to chirality-flip property: Spin patterns distinct from SM

CP symmetry and CP transformation ($q(s)\bar{q}(\bar{s}) \to q(\bar{s})\bar{q}(s)$): Spin patterns distinct between MDM and EDM

$$C_{xy} = -C_{yx} = -\frac{\sin^2\theta}{1+\cos^2\theta}\frac{sv^2}{\pi\alpha\Lambda^4 Q_q^2}[\mathrm{Re}C_\gamma^q][\mathrm{Im}C_\gamma^q] \quad \rightarrow \quad \mathcal{B}'_\pm = C_{xy} \pm C_{yx}$$

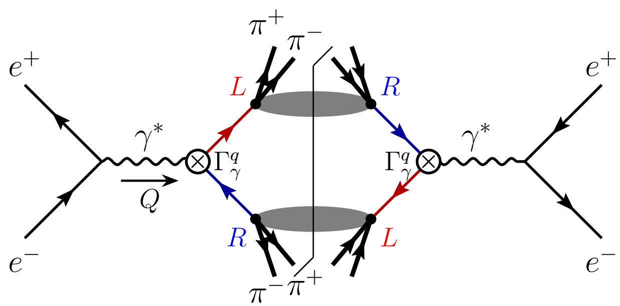
$$C_{xx} + C_{yy} = \frac{\sin^2\theta}{1+\cos^2\theta}\frac{sv^2}{\pi\alpha\Lambda^4 Q_q^2}\left([\mathrm{Re}C_\gamma^q]^2 - [\mathrm{Im}C_\gamma^q]^2\right) \quad \rightarrow \quad \mathcal{B}_+$$

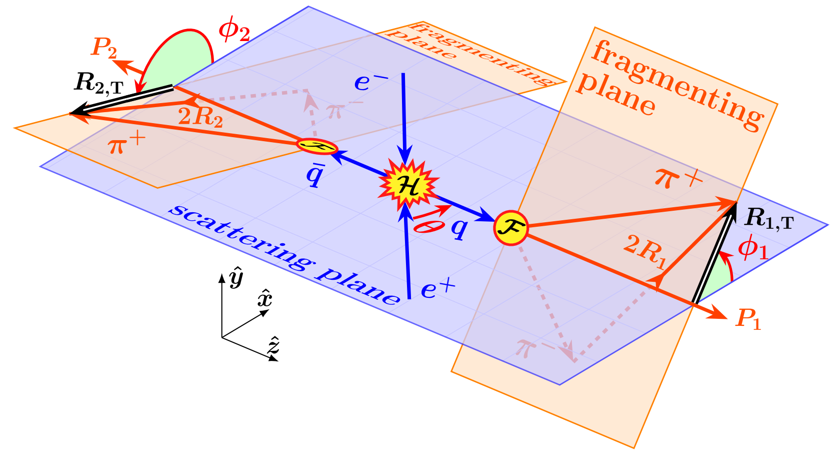
$\lvert 1,0\rangle_z$	$\lvert 0,0\rangle$
$\frac{1}{\sqrt{2}}(\lvert\uparrow_z\downarrow_z\rangle + \lvert\downarrow_z\uparrow_z\rangle)$	$\frac{1}{\sqrt{2}}(\lvert\uparrow_z\downarrow_z\rangle - \lvert\downarrow_z\uparrow_z\rangle)$
$C_{ij}^{\mathrm{Re}} = \mathrm{diag}(1,1,-1)$	$C_{ij}^{\mathrm{Im}} = \mathrm{diag}(-1,-1,-1)$

Spin Transfer from Quarks to Hadrons

$$C_{xx}+C_{yy}=\frac{\sin^2\theta}{1+\cos^2\theta}\frac{sv^2}{\pi\alpha\Lambda^4Q_q^2}\left([\mathrm{Re}C_\gamma^q]^2-[\mathrm{Im}C_\gamma^q]^2\right) \quad \rightarrow \quad \mathcal{B}_+ \ \cos(\phi_1-\phi_2)$$

- **Dihadron pair: $(\pi^+\pi^-)+(\pi^+\pi^-)+X$**





$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma(e^+e^-\to(\pi^+\pi^-)(\pi^+\pi^-)X)}{\mathrm{d}z_1\mathrm{d}z_2\mathrm{d}M_1\mathrm{d}M_2\mathrm{d}\phi_1\mathrm{d}\phi_2\mathrm{d}\cos\theta}$$

Interference DiFFs (transverse polarized)

$$=(1+\cos^2\theta)\Bigg[\sum_q Q_q^2 D_1^q(z_1,M_1)D_1^{\bar{q}}(z_2,M_2)+\frac{1}{2}\sum_q Q_q^2 H_1^{\sphericalangle,q}(z_1,M_1)H_1^{\sphericalangle,\bar{q}}(z_2,M_2)\Big(\mathcal{B}_-\cos(\phi_1+\phi_2)$$

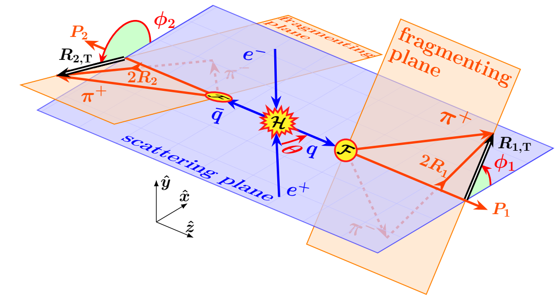
Unpolarized DiFFs

$$-\mathcal{B}_+\cos(\phi_1-\phi_2)+\mathcal{B}'_+\sin(\phi_1+\phi_2)+\mathcal{B}'_-\sin(\phi_1-\phi_2)\Big)\Bigg]$$

$\mathcal{B}'_+=0 \qquad \mathcal{B}'_-\neq 0$ **quark and antiquark directions distinguishable or not ?**

Spin Transfer from Quarks to Hadrons

- **Dihadron pair: $(\pi^+\pi^-) + (\pi^+\pi^-) + X$**



$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma(e^+e^- \to (\pi^+\pi^-)(\pi^+\pi^-)X)}{\mathrm{d}z_1\mathrm{d}z_2\mathrm{d}M_1\mathrm{d}M_2\mathrm{d}\phi_1\mathrm{d}\phi_2\mathrm{d}\cos\theta}$$

$$= (1+\cos^2\theta)\Bigg[\sum_q Q_q^2 D_1^q(z_1,M_1)D_1^{\bar{q}}(z_2,M_2) + \frac{1}{2}\sum_q Q_q^2 H_1^{\sphericalangle,q}(z_1,M_1)H_1^{\sphericalangle,\bar{q}}(z_2,M_2)\Big(\mathcal{B}_-\cos(\phi_1+\phi_2)$$

Unpolarized DiFFs

$$-\mathcal{B}_+\cos(\phi_1-\phi_2)\Big)\Bigg]$$

Interference DiFFs (transverse polarized)

$$A_\pm \equiv 2\langle\cos(\phi_1\pm\phi_2)\rangle = \pm\frac{\sum_q Q_q^2 H_1^{\sphericalangle,q}(z_1,M_1)H_1^{\sphericalangle,\bar{q}}(z_2,M_2)\mathcal{B}_\mp}{2\sum_q Q_q^2 D_1^q(z_1,M_1)D_1^{\bar{q}}(z_2,M_2)}$$

$$R_{\mathrm{diFF}} = \frac{A_-}{A_+} \simeq -\frac{sv^2}{2\pi\alpha\Lambda^4}\frac{\sum_{q=u,d}([\mathrm{Re}C_\gamma^q]^2 - [\mathrm{Im}C_\gamma^q]^2)}{\sum_{q=u,d}Q_q^2}$$

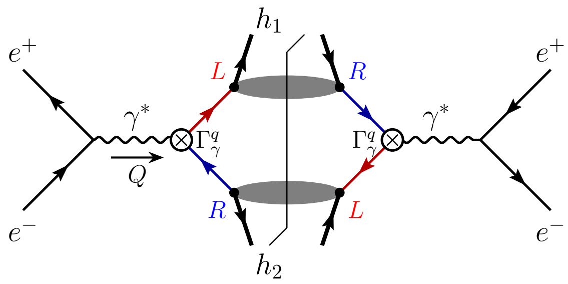
$$H_1^{\sphericalangle,u} = -H_1^{\sphericalangle,d},\ H_1^{\sphericalangle,s,\bar{s},c,\bar{c},b,\bar{b}} = 0,$$
$$H_1^{\sphericalangle,q} = -H_1^{\sphericalangle,\bar{q}}$$

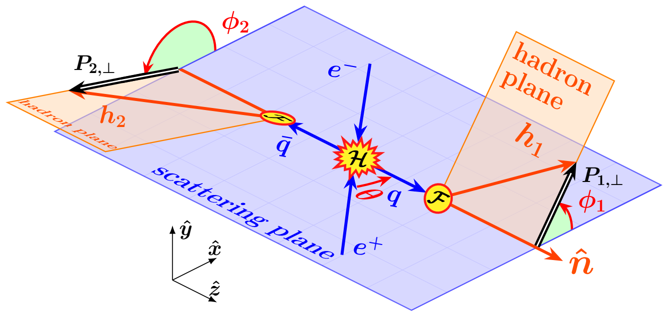
- **New $\cos(\phi_1-\phi_2)$ to hint new consideration of global fit or test presence of MDM, EDM**
- **The ratios of $\cos(\phi_1-\phi_2)$ and $\cos(\phi_1+\phi_2)$ to robustly constrain dipole couplings, eliminating dependence on nonperturbative DiFFs**

Spin Transfer from Quarks to Hadrons

$$C_{xx}+C_{yy}=\frac{\sin^2\theta}{1+\cos^2\theta}\frac{sv^2}{\pi\alpha\Lambda^4Q_q^2}([\mathrm{Re}C_\gamma^q]^2-[\mathrm{Im}C_\gamma^q]^2) \quad \Rightarrow \quad \mathcal{B}_+ \ \cos(\phi_1-\phi_2)$$

- **Back-to back hadron pair: h_1+h_2+X ($h_1h_2=\pi\pi$ / KK / $K\pi$) with TMD Collins FFs**





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

Collins function (polarized TMDFFs)

$$=(1+\cos^2\theta)\Bigg[\sum_q Q_q^2 D_1^q(z_1,p_{1,\perp})D_1^{\bar{q}}(z_2,p_{2,\perp})+\frac{1}{2}\sum_q Q_q^2\mathcal{F}_h H_1^{\perp,q}(z_1,p_{1,\perp})H_1^{\perp,\bar{q}}(z_2,p_{2,\perp})\Big(\mathcal{B}_-\cos(\phi_1+\phi_2)$$

Unpolarized TMDFFs

$$-\mathcal{B}_+\cos(\phi_1-\phi_2)+\mathcal{B}'_+\sin(\phi_1+\phi_2)+\mathcal{B}'_-\sin(\phi_1-\phi_2)\Big)\Bigg],$$

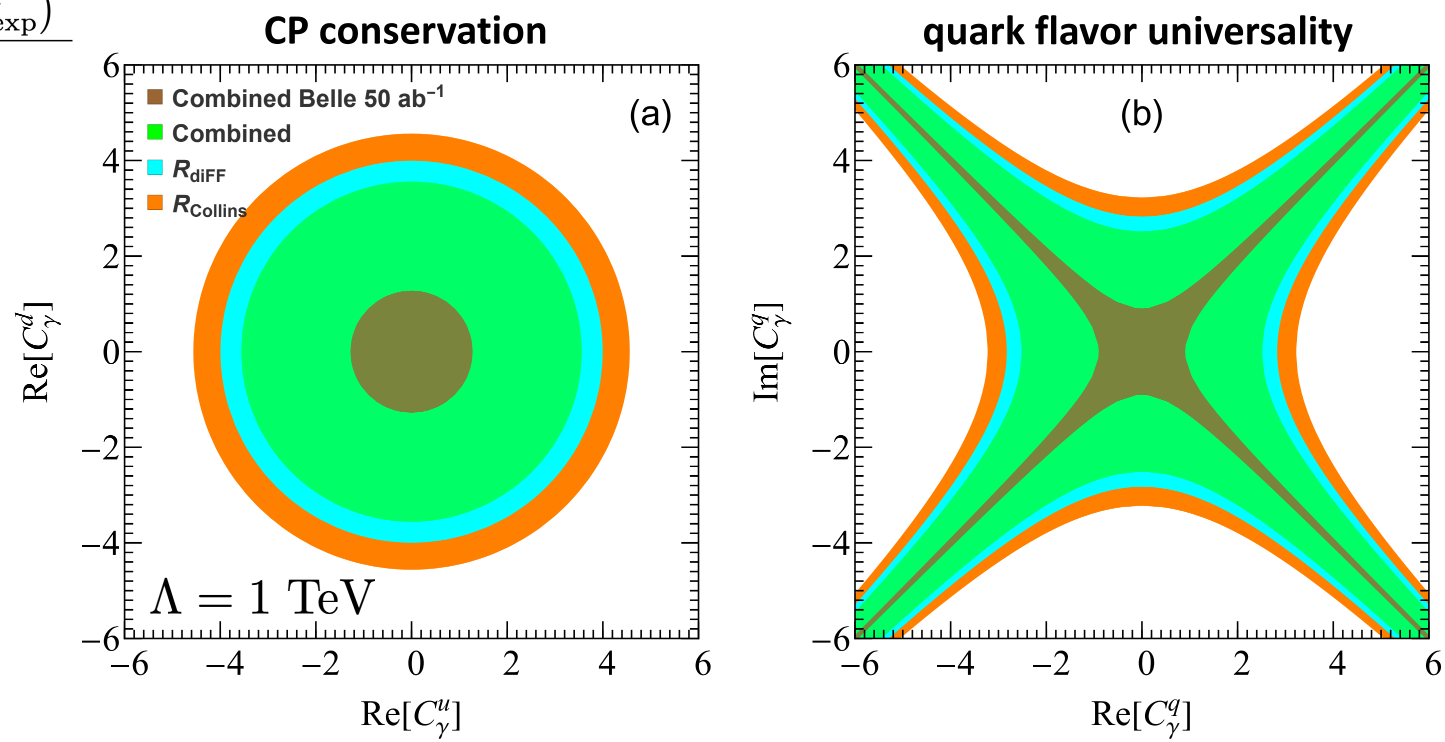
$$\frac{N_U}{N_L}\simeq 1+\sum_q\mathcal{F}_{UL}^q\left[\mathcal{B}_-\cos(\phi_1+\phi_2)-\mathcal{B}_+\cos(\phi_1-\phi_2)\right] \qquad R_{\mathrm{Collins}}=A_-/A_+$$

Similar with dihadron pair case

Sensitivity to Quark EM Properties

To reinterpret existing $(\pi^+\pi^-)$-dihadron and $h_1 h_2 = \pi\pi$ data at *Belle* and *BaBar* within both the collinear and TMD factorization frameworks to constrain quark MDM and EDM

$$\chi^2 = \sum_i \frac{\left(R^i_{\rm th} - R^i_{\rm exp}\right)^2}{\delta R_i^2}$$



- **Current data yield $O(1)$ bounds on light quark dipole couplings, dominated by $R_{\rm diFF}$**
- **Unique to light quark MDM and EDM, free from contamination of SM and other NP**
- **Directly sensitivity without additional ad hoc assumptions**

Summary

- ✓ Quarks are crucial for testing the Standard Model and probing the New Physics
- ✓ Light quark EM dipole properties drive quark pair into **entangled spin triplet and singlet**, yielding transverse spin correlation patterns distinct from the SM and other NP
- ✓ New unique $cos(\phi_1 - \phi_2)$ absent in the SM can probe the quark MDM / EDM
- ✓ The ratios of $cos(\phi_1 - \phi_2)$ and $cos(\phi_1 + \phi_2)$ insensitive to nonperturbative FFs
- ✓ Revisiting existing data at Belle and BaBar within both the collinear and TMD factorization frameworks yields $O(1)$ bounds on light-quark dipole couplings
- ✓ This provides robust constraints on quark dipole couplings that are free from contamination by SM and other possible NP effects in the hard scattering process

Thank you