

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: **Xin-Kai Wen**, Bin Yan, Zhite Yu and C.-P. Yuan

Phys.Rev.Lett. **131** (2023) 24, 241801; *Phys.Rev.D* 112 (2025) 5, 053004

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

2025/10/30, Xinxiang, Henan, China

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 ?

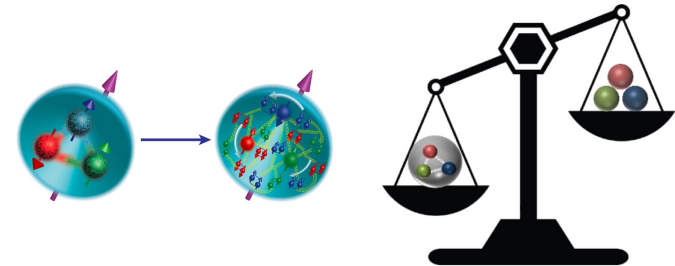
$$\mu_q = ???, \quad |d_q| = ???, \quad (q = u, d, s, \dots)$$



- To understand the strong interactions and confinement:

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

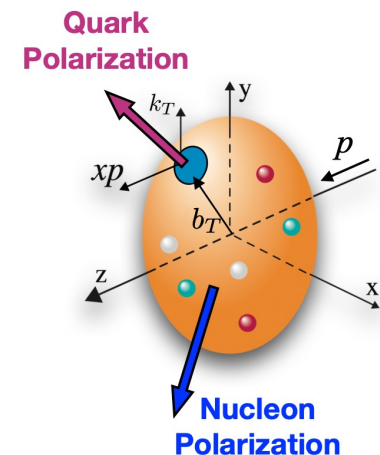
Mass problem: Where does mass come from ?



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

Spin puzzle: What makes a proton spin ?

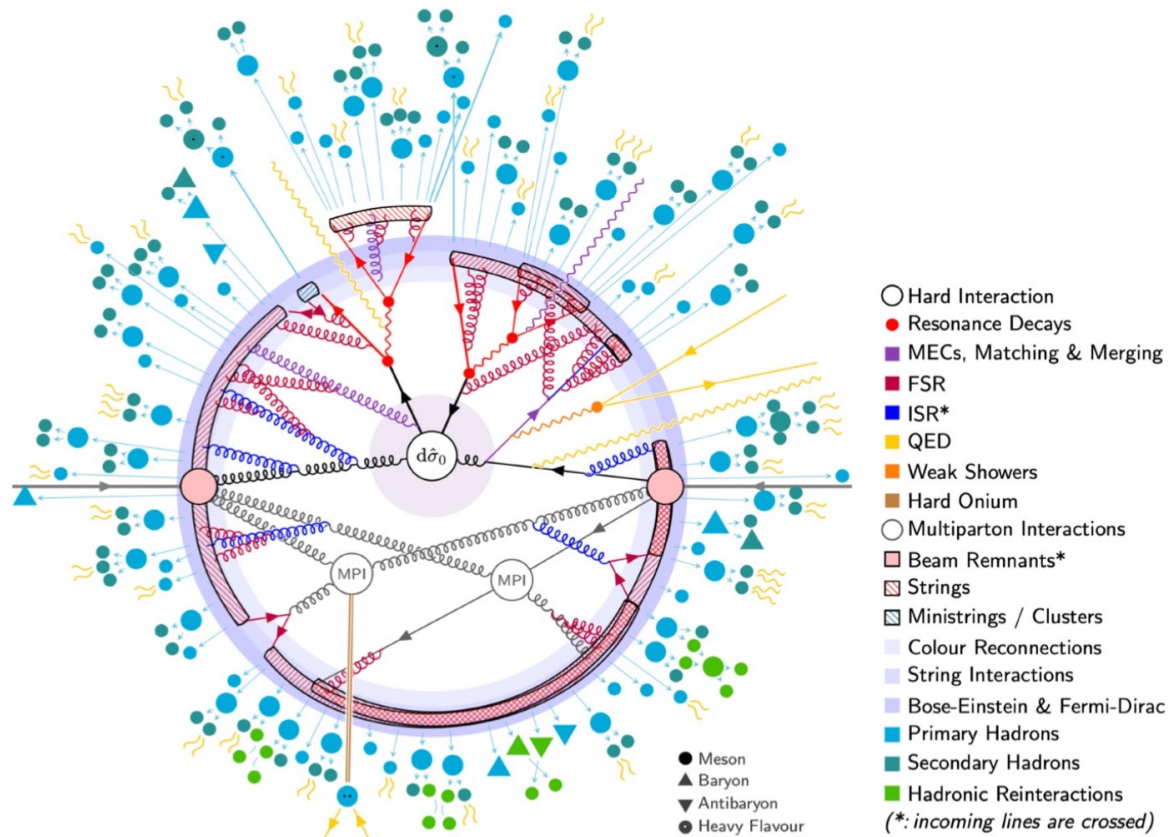
Spin transfer: How quark spin originates and evolves ?



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 ...)

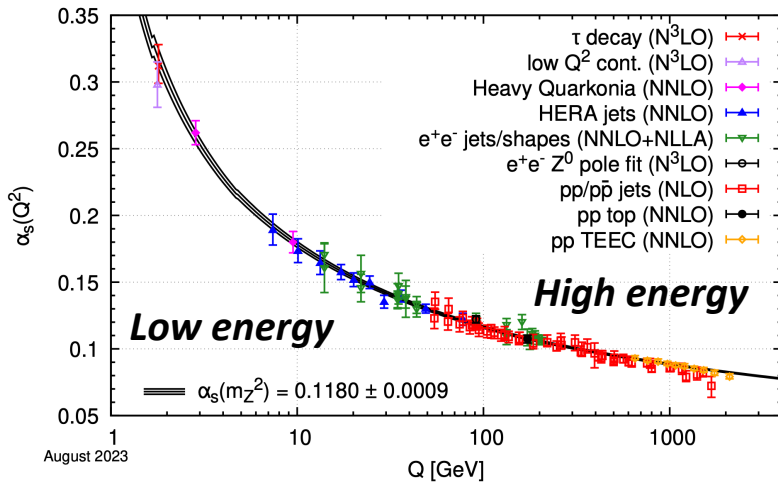


From PYTHIA 8.3

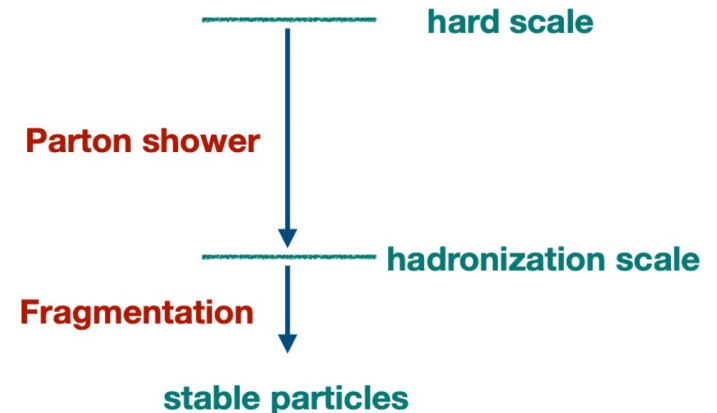
Asymptotic Freedom and Factorization

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

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



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



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

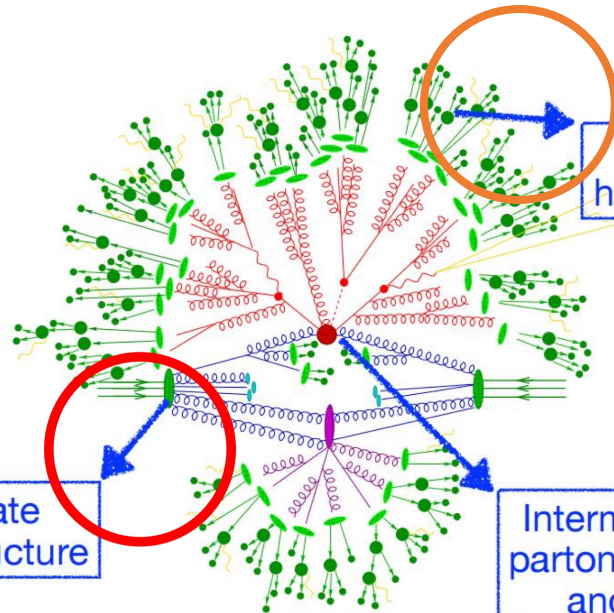
QCD asymptotic freedom and factorization pave an avenue to study quarks and gluons

QCD factorization:

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

f : Non-perturbative
parton distribution
function

Initial state
hadron structure



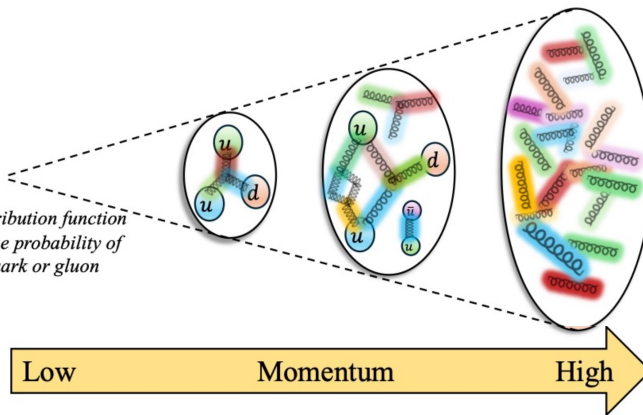
Final state
hadronization

D : Non-perturbative
fragmentation function

Intermediate state
partonic scatterings
and showers

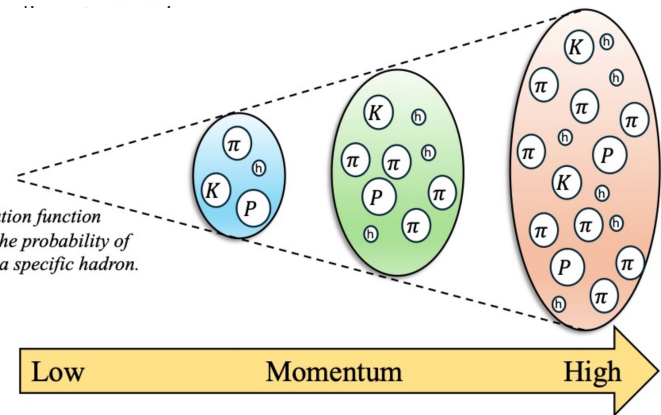
Hadron

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



Parton

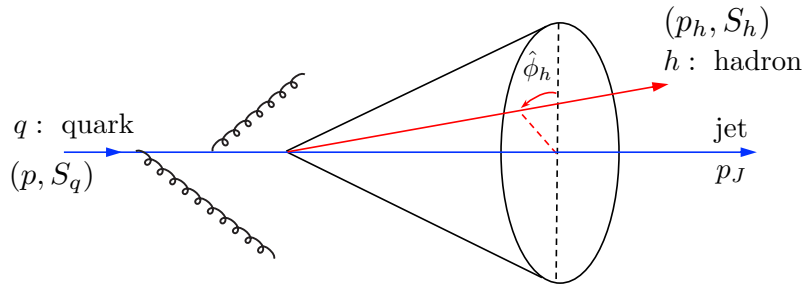
Fragmentation function
describes the probability of
producing a specific hadron.



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

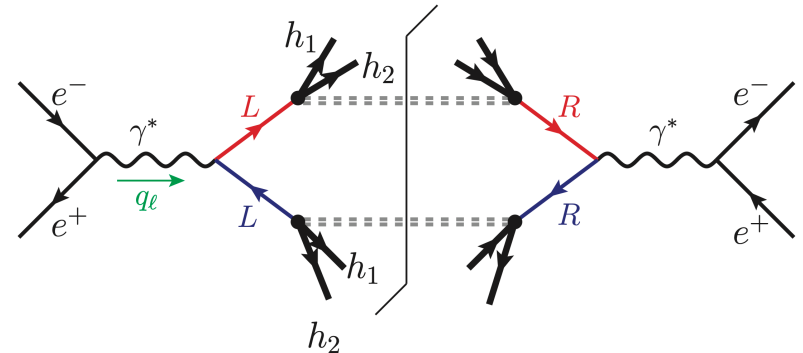
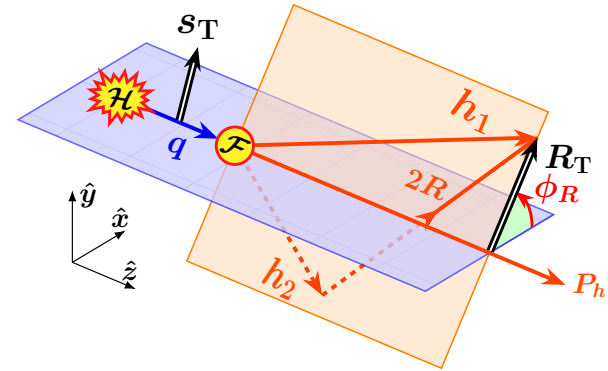


Leading Quark TMDFFs



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

➤ Dihadron Fragmentation Functions



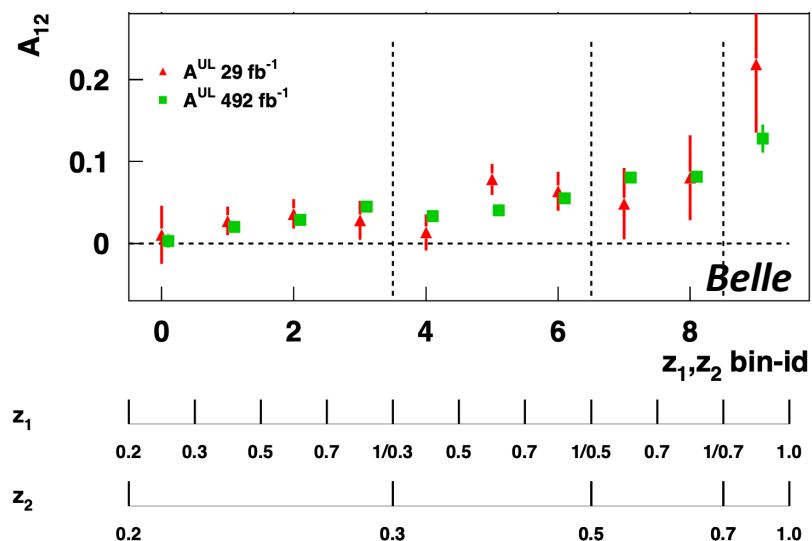
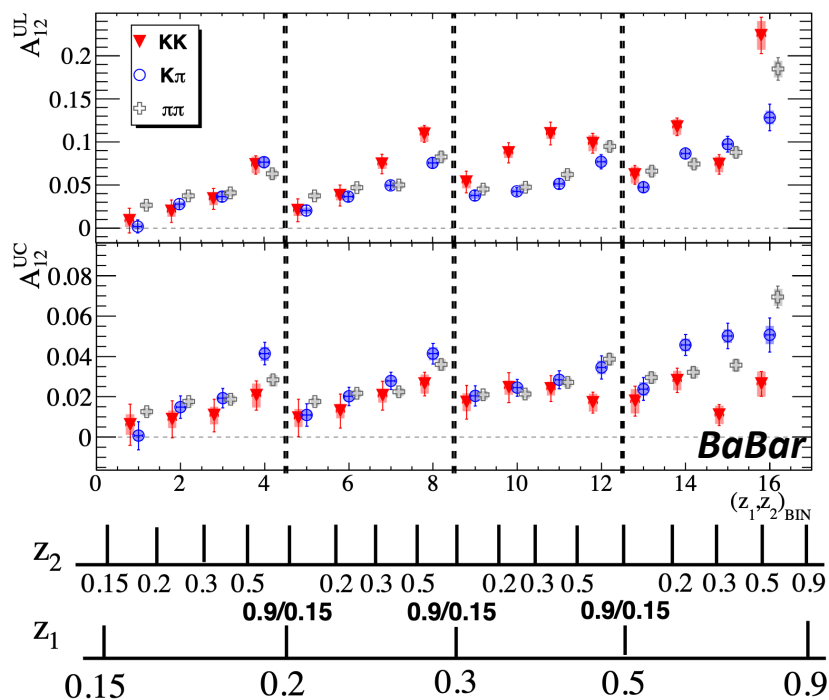
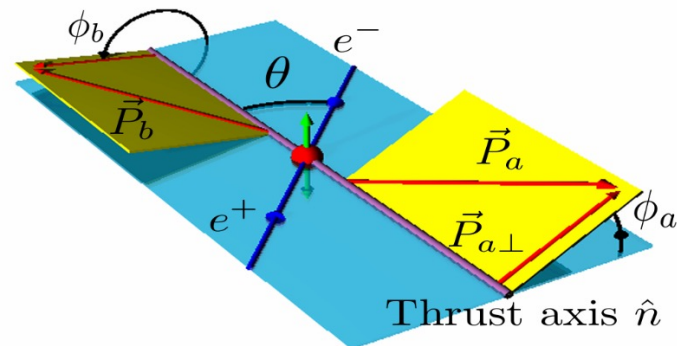
Kang, Prokudin, Sun, Yuan, *Phys.Rev.D* **93** (2016) 014009;
Zeng, Dong, Liu, Sun, Zhao, *Phys.Rev.D* **109** (2024) 056002;
TMD Handbook, *arXiv*: 2304.03302;

TMD: Collins Effects and Asymmetry

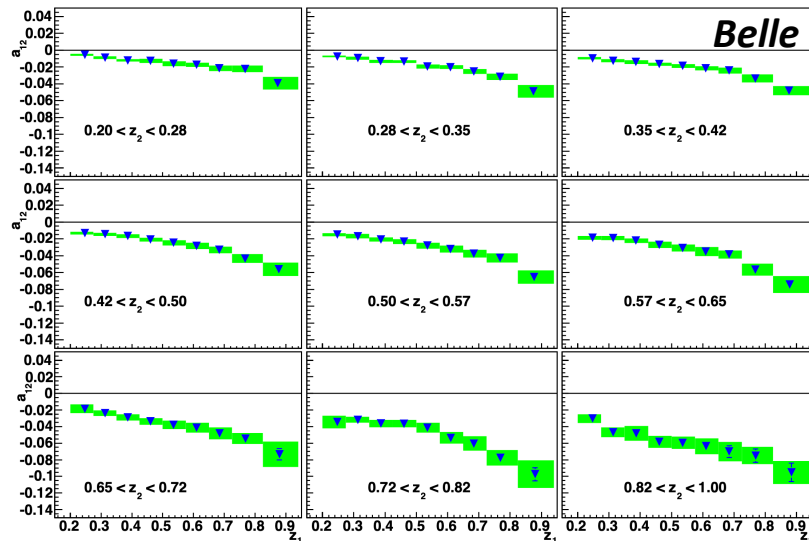
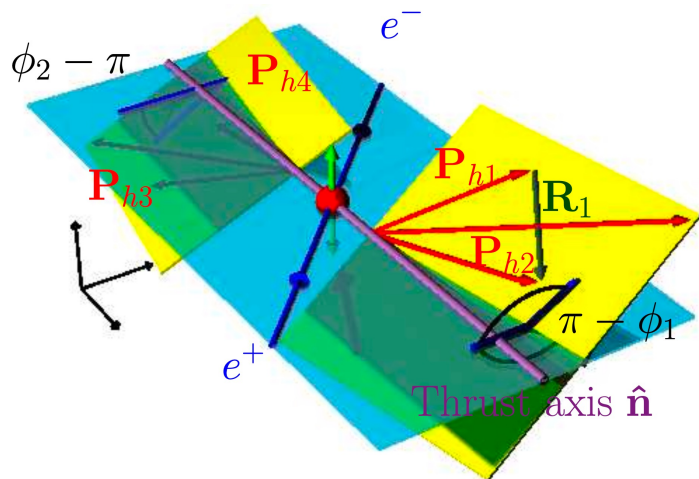
BaBar Collaboration, *Phys. Rev. D* **90** (2014) 052003

Belle Collaboration, *Phys. Rev. D* **78** (2008) 032011

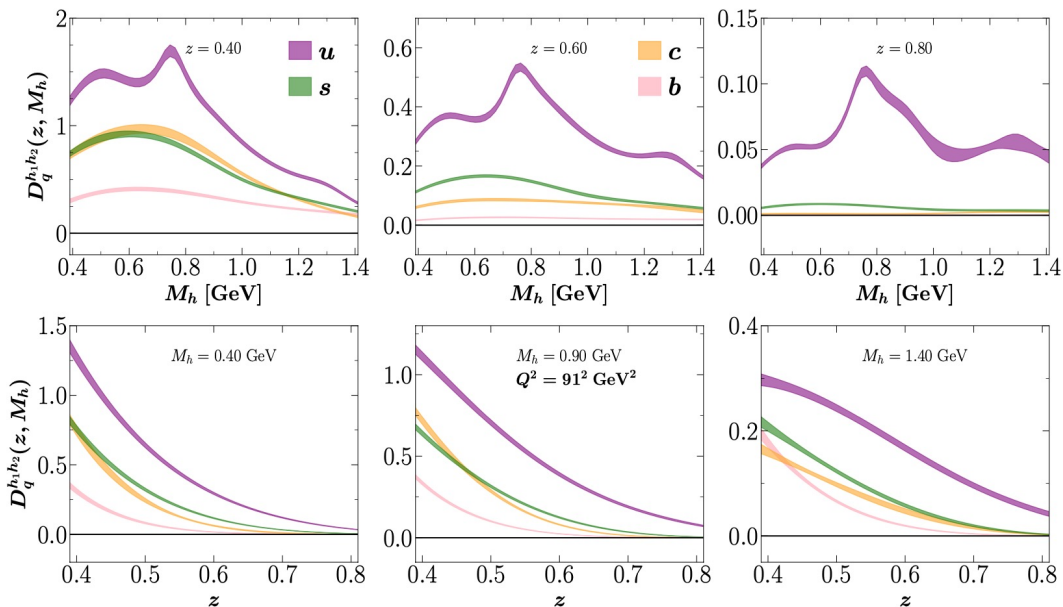
BaBar Collaboration, *Phys. Rev. D* **92** (2015) 111101



Artru-Collins Asymmetry and dihadron

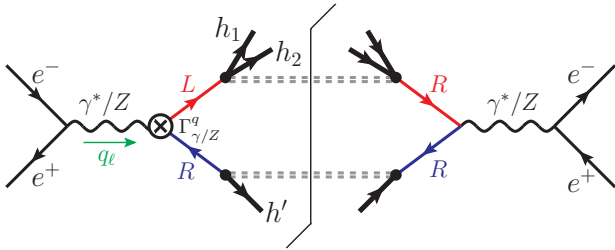


Belle Collaboration, *Phys. Rev. Lett.* **107** (2011) 072004
 JAM Collaboration, *Phys. Rev. Lett.* **132** (2024) 091901
 JAM Collaboration, *Phys. Rev. D* **109** (2024) 034024



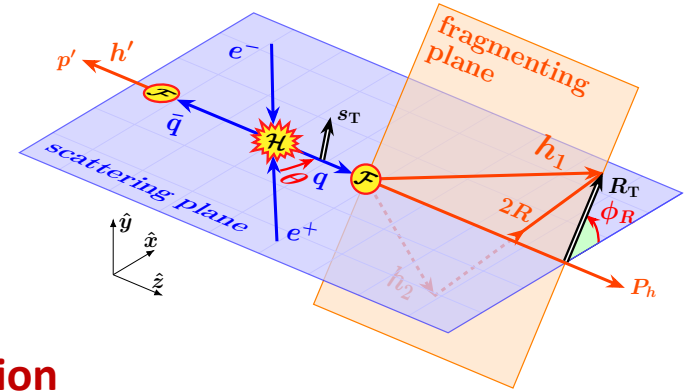
DiFFs and Single Spin Asymmetry

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



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

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



Dihadron chiral-odd **interference fragmentation function**

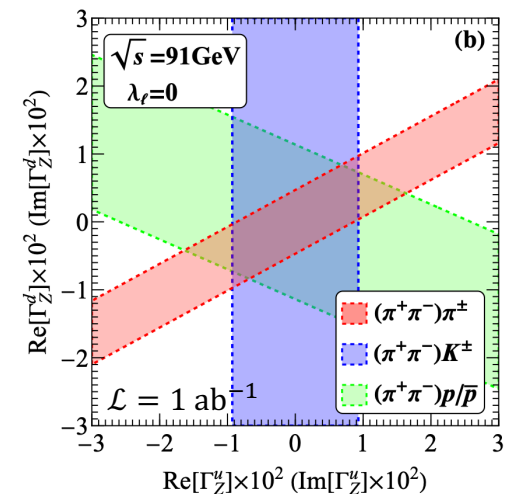
$\Rightarrow$ To project out transverse spin of single quarks with **azimuthal asymmetry**

$$\frac{d\sigma}{dy dz d\bar{z} dM_h d\phi_R} = \frac{1}{32\pi^2 s} \sum_{q, q \rightarrow \bar{q}} C_q(y) D_{\bar{q}}^{h'}(\bar{z}) \times [D_q^{h_1 h_2}(z, M_h) - (\mathbf{s}_{T,q}(y) \times \hat{\mathbf{R}}_T)^z H_q^{h_1 h_2}(z, M_h)]$$

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

- ✓ Stronger constraint: $\mathcal{O}(10^{-3} \sim 10^{-2})$, others: $\mathcal{O}(10^{-1} \sim 10^0)$
- ✓ Distinguishing u- and d-quark as well as photon and Z boson
- ✓ Null contamination from SM and other NP

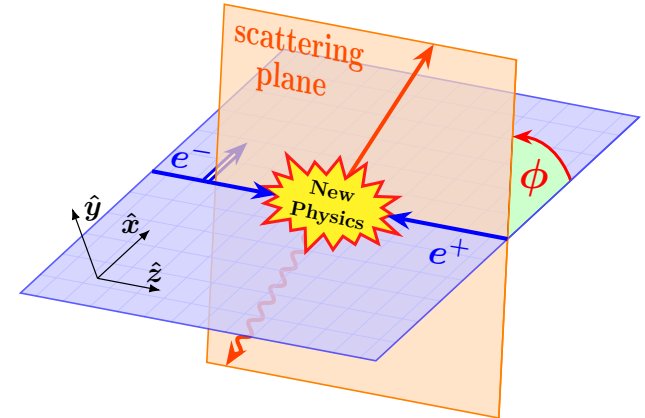
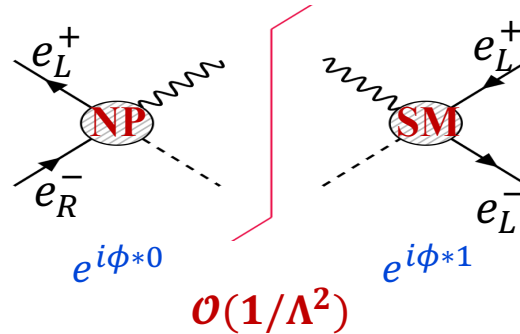
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, *Phys. Rev. D* 112 (2025) 5, 053004



A Simpler Example: Lepton Dipole Moments

Transverse spin effect of initial leptons $\Rightarrow$ Interference of the different helicity amplitudes

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



$$\frac{2\pi d\sigma^i}{\sigma^i d\phi} = 1 + \underbrace{A_R^i(b_T, \bar{b}_T)}_{\text{CP-conserving}} \cos \phi + \underbrace{A_I^i(b_T, \bar{b}_T)}_{\text{CP-violating}} \sin \phi$$

Linearly $\rightarrow$

$\text{Re}[\Gamma_f]$

CP-conserving

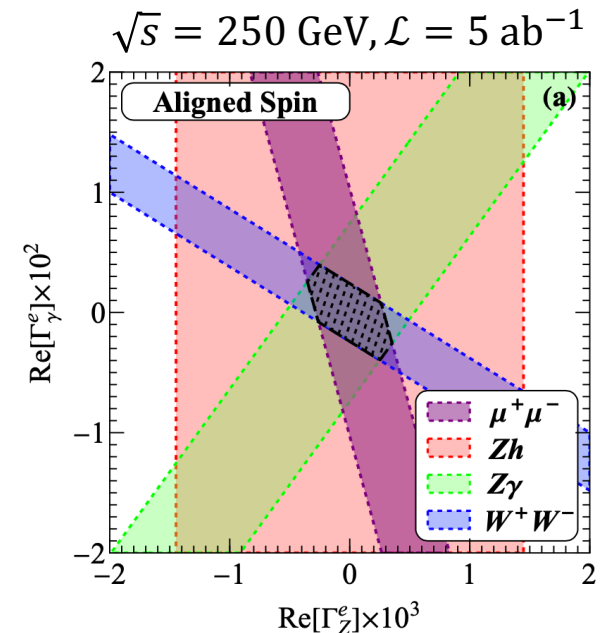
$\text{Im}[\Gamma_f]$

CP-violating

Transverse Spin Asymmetry

- ✓ Much stronger sensitivity: $\mathcal{O}(10^{-4} \sim 10^{-3})$, others: $\mathcal{O}(10^{-2} \sim 10^{-1})$
- ✓ Directly detect CP violation effect
- ✓ Much more sensitive to Weak couplings than EM couplings

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, *Phys.Rev.Lett.* 131 (2023) 24, 241801



From Single Spin to Spin Correlation

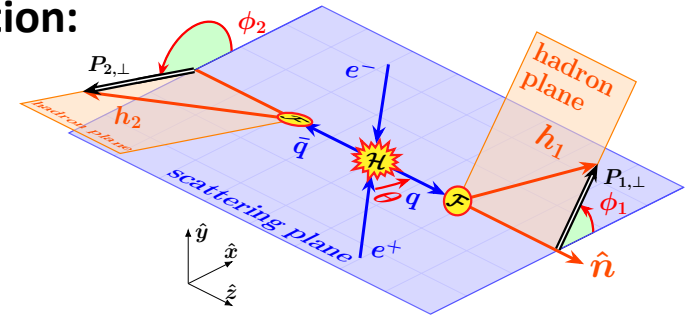
From **Single Transverse Spin of Single Quark** to **Spin Correlation of Entangled Quark Pairs**:

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

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

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

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

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

From Single Spin to Spin Correlation

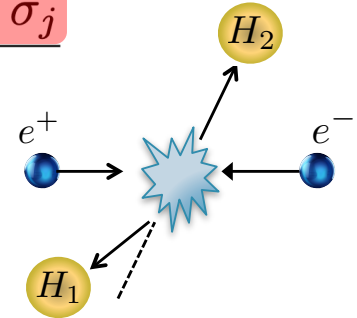
From **Single Transverse Spin of Single Quark** to **Spin Correlation of Entangled Quark Pairs**:

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

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 **B₋** nonzero !!

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

✓ Global fitting on DiFFs and TMDFFs

✓ Bell inequality violation

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

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

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

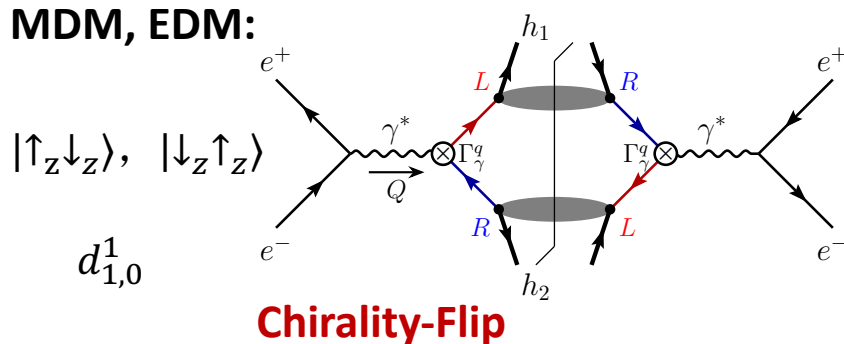
$$e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}$$

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

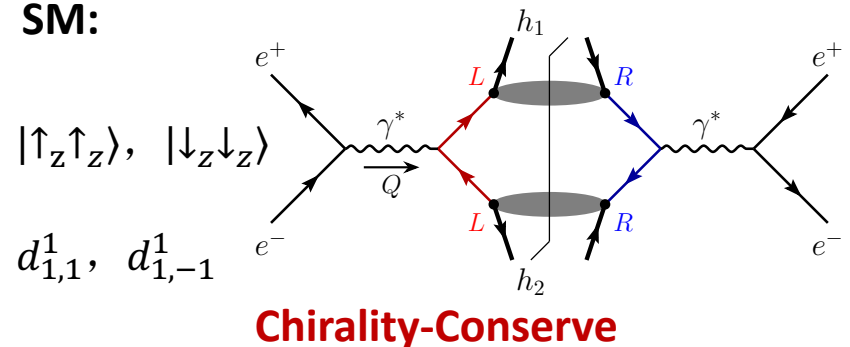
Up to $O(1/\Lambda^4)$ operators, $\mathcal{B}_+$ and $\mathcal{B}'_+$ uniquely sensitive to quark MDM and EDM

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

MDM, EDM:



SM:



Spin Correlation and Quark EM Properties

SM and four fermion interactions

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

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

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

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

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

$|1,0\rangle_z$

$|0,0\rangle$

$$\frac{1}{\sqrt{2}} (|\uparrow_z \downarrow_z\rangle + |\downarrow_z \uparrow_z\rangle)$$

$$\frac{1}{\sqrt{2}} (|\uparrow_z \downarrow_z\rangle - |\downarrow_z \uparrow_z\rangle)$$

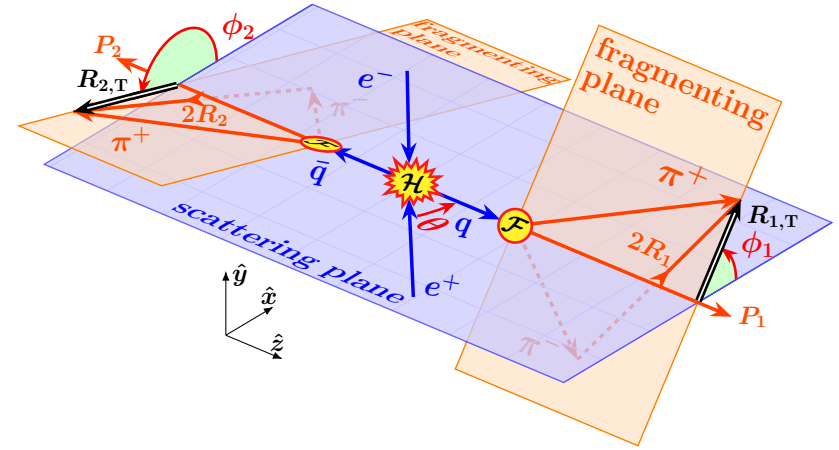
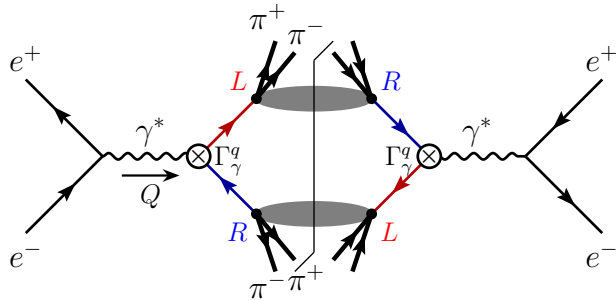
$$C_{ij}^{\text{Re}} = \text{diag}(1, 1, -1)$$

$$C_{ij}^{\text{Im}} = \text{diag}(-1, -1, -1)$$

Spin Transfer from Quarks to Hadrons

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

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



$$\frac{1}{\sigma_0} \frac{d\sigma(e^+e^- \rightarrow (\pi^+\pi^-)(\pi^+\pi^-)X)}{dz_1 dz_2 dM_1 dM_2 d\phi_1 d\phi_2 d\cos\theta}$$

Interference DiFFs (transverse polarized)

$$= (1 + \cos^2 \theta) \left[\sum_q Q_q^2 \underbrace{D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2)}_{\text{Unpolarized DiFFs}} + \frac{1}{2} \sum_q Q_q^2 \underbrace{H_1^{\triangleleft, q}(z_1, M_1) H_1^{\triangleleft, \bar{q}}(z_2, M_2)}_{\text{Interference DiFFs (transverse polarized)}} \left(\mathcal{B}_- \cos(\phi_1 + \phi_2) - \mathcal{B}_+ \cos(\phi_1 - \phi_2) + \mathcal{B}'_+ \sin(\phi_1 + \phi_2) + \mathcal{B}'_- \sin(\phi_1 - \phi_2) \right) \right]$$

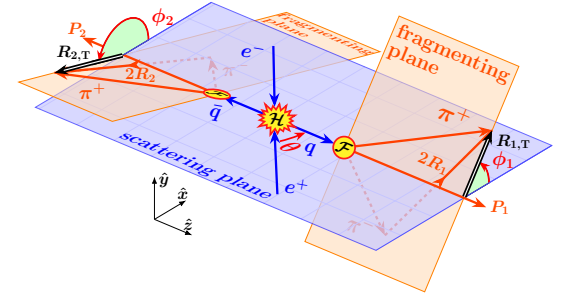
$\mathcal{B}'_+ = 0 \quad \mathcal{B}'_- \neq 0 \quad \text{quark and antiquark directions distinguishable or not ?}$

Spin Transfer from Quarks to Hadrons

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

$$\frac{1}{\sigma_0} \frac{d\sigma(e^+e^- \rightarrow (\pi^+\pi^-)(\pi^+\pi^-)X)}{dz_1 dz_2 dM_1 dM_2 d\phi_1 d\phi_2 d\cos\theta}$$

$$= (1 + \cos^2\theta) \left[\sum_q Q_q^2 \underbrace{D_1^q(z_1, M_1) D_1^{\bar{q}}(z_2, M_2)}_{\text{Unpolarized DiFFs}} + \frac{1}{2} \sum_q Q_q^2 \underbrace{H_1^{\triangleleft, q}(z_1, M_1) H_1^{\triangleleft, \bar{q}}(z_2, M_2)}_{\text{Interference DiFFs (transverse polarized)}} \left(\mathcal{B}_- \cos(\phi_1 + \phi_2) - \mathcal{B}_+ \cos(\phi_1 - \phi_2) \right) \right]$$



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

$$A_+ \quad \checkmark !$$

$$A_- \quad \square ?$$

- **New $\cos(\phi_1 - \phi_2)$ to hint new consideration of global fit or test presence of MDM, EDM**

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

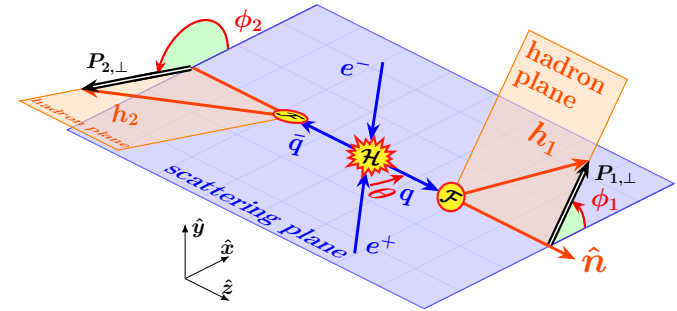
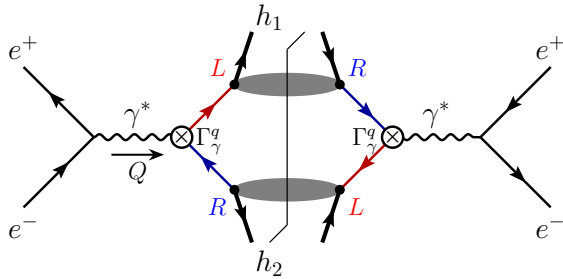
$$H_1^{\triangleleft, u} = -H_1^{\triangleleft, d}, \quad H_1^{\triangleleft, s, \bar{s}, c, \bar{c}, b, \bar{b}} = 0, \\ H_1^{\triangleleft, q} = -H_1^{\triangleleft, \bar{q}}$$

- **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

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

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



$$\frac{1}{\sigma_0} \frac{d\sigma(e^+e^- \rightarrow h_1 h_2 X)}{p_{1,\perp} p_{2,\perp} dz_1 dz_2 dp_{1,\perp} dp_{2,\perp} d\phi_1 d\phi_2 d\cos\theta}$$

$$= (1 + \cos^2 \theta) \left[\sum_q Q_q^2 \underbrace{D_1^q(z_1, p_{1,\perp}) D_1^{\bar{q}}(z_2, p_{2,\perp})}_{\text{Unpolarized TMDFFs}} + \frac{1}{2} \sum_q Q_q^2 \mathcal{F}_h \underbrace{H_1^{\perp,q}(z_1, p_{1,\perp}) H_1^{\perp,\bar{q}}(z_2, p_{2,\perp})}_{\text{Collins function (polarized TMDFFs)}} \left(\mathcal{B}_- \cos(\phi_1 + \phi_2) - \mathcal{B}_+ \cos(\phi_1 - \phi_2) + \mathcal{B}'_+ \sin(\phi_1 + \phi_2) + \mathcal{B}'_- \sin(\phi_1 - \phi_2) \right) \right],$$

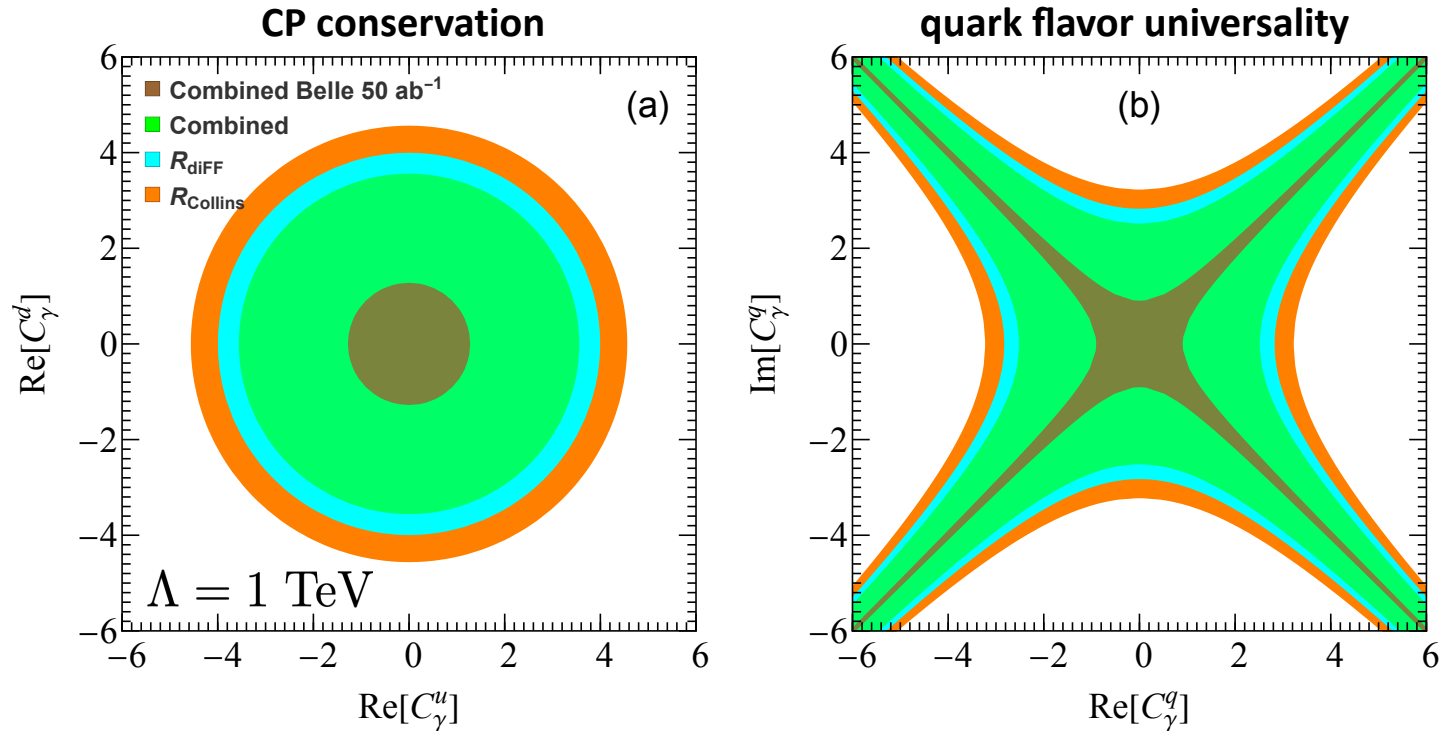
$$\frac{N_U}{N_L} \simeq 1 + \sum_q \mathcal{F}_{UL}^q [\mathcal{B}_- \cos(\phi_1 + \phi_2) - \mathcal{B}_+ \cos(\phi_1 - \phi_2)]$$

$$R_{\text{Collins}} = A_- / A_+$$

Similar with dihadron pair case

Sensitivity to Quark EM Properties

To reinterpret existing $(\pi^+\pi^-)$ -dihadron and $h_1h_2 = \pi\pi$ data at *Belle* and *BaBar* within both the collinear and TMD factorization frameworks **to constrain quark MDM and EDM**



- Current data yield $\mathcal{O}(1)$ bounds on light quark dipole couplings, dominated by R_{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 **$\cos(\phi_1 + \phi_2)$** are insensitive to nonperturbative FFs
- ✓ **Revisiting existing data at Belle and BaBar** within both the collinear and TMD factorization frameworks yields constraints on light-quark dipole couplings
- ✓ These robust constraints are **free from contamination by SM and other possible NP effects** in the hard scattering process
- ✓ **QCD transverse spin effect** improve the detection of the SM and New Physics

Thank you