

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

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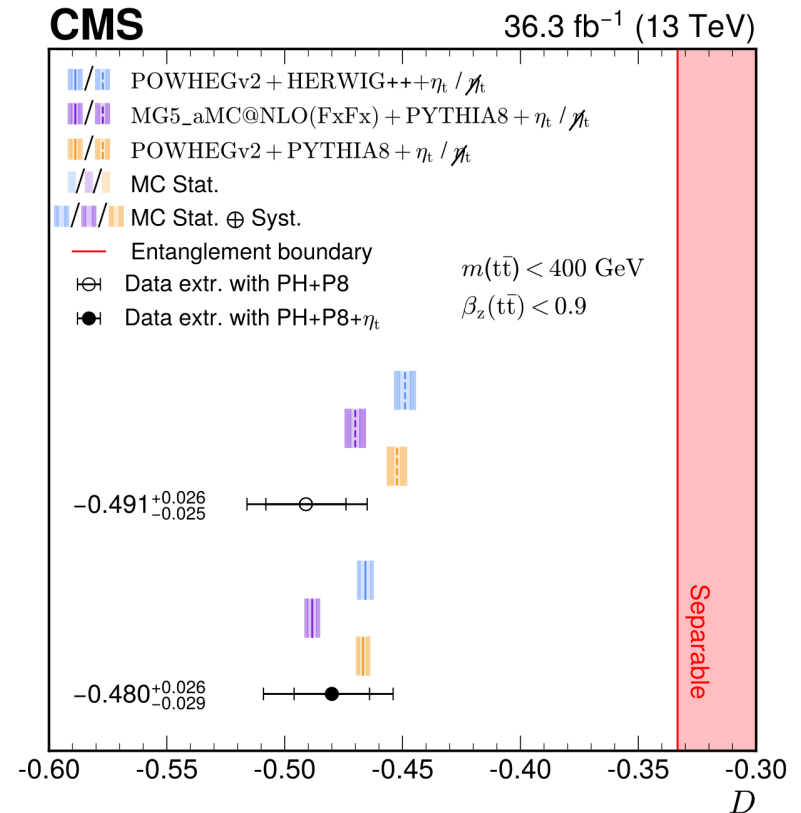
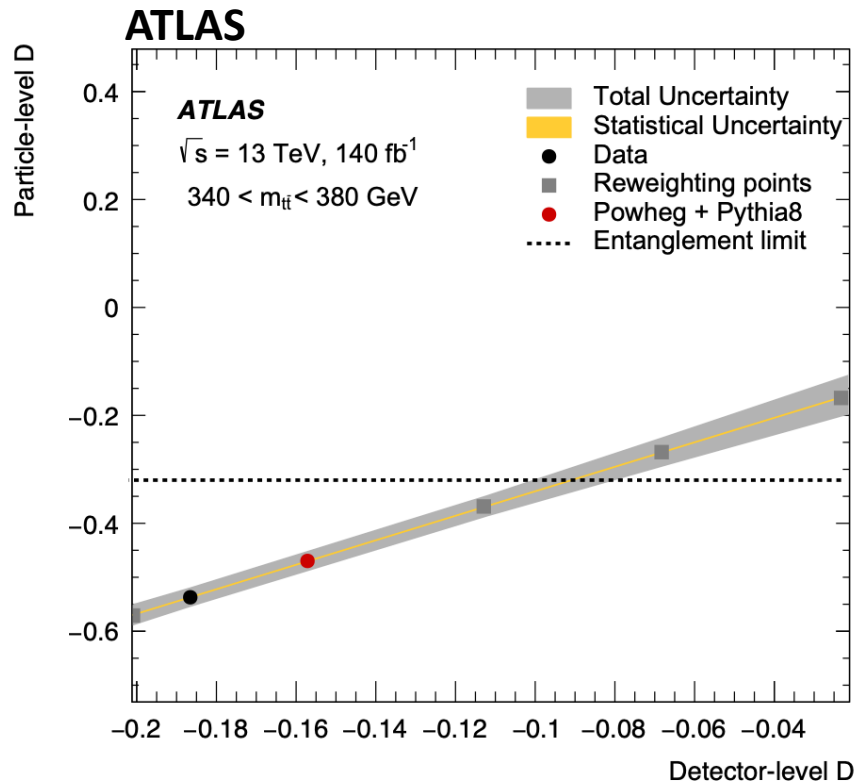
China Center of Advanced Science and Technology (CCAST)

Base on: Qing-Hong Cao, Guanghui Li, **Xin-Kai Wen**, and Bin Yan, *Rept. Prog. Phys.* 89 (2026) 080501

2026/09/20, Beijing, China

Spin Entanglement at High Energy

ATLAS/CMS measured the entanglement of top pair: **First observation of QE at colliders**

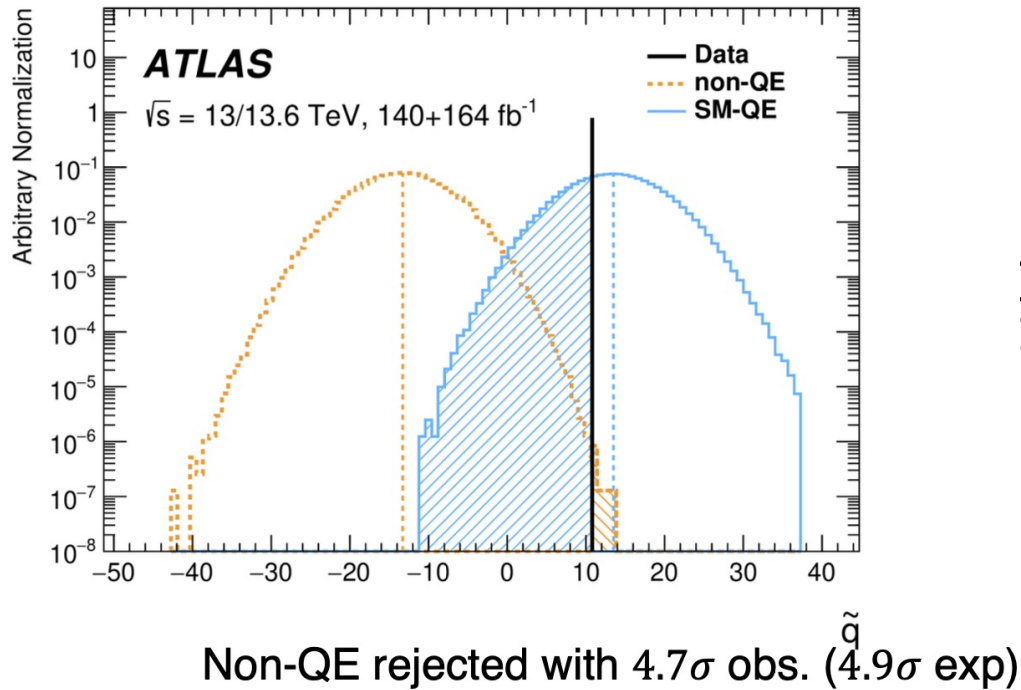


$$D = -\frac{1}{3}\text{Tr}[C]$$

ATLAS: Nature 633 (2024) 542
 CMS: ROPP 87(2024)117801

Spin Entanglement at High Energy

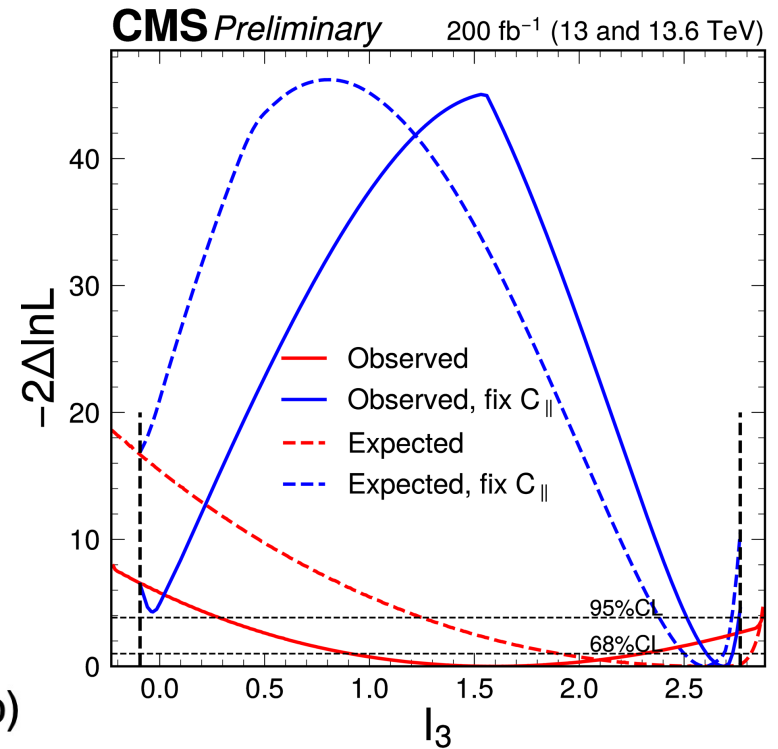
ATLAS/CMS recently measured the entanglement of Z-boson pair from Higgs decay (Qutrits)



ATLAS based on the C_{212-1} distribution

ATLAS: PRL 137 (2026) 111804

CMS: CMS-PAS-HIG-25-011



CMS measured the CGLMP inequality I_3
 $I_3 > 2$: violation of Bell-type inequality

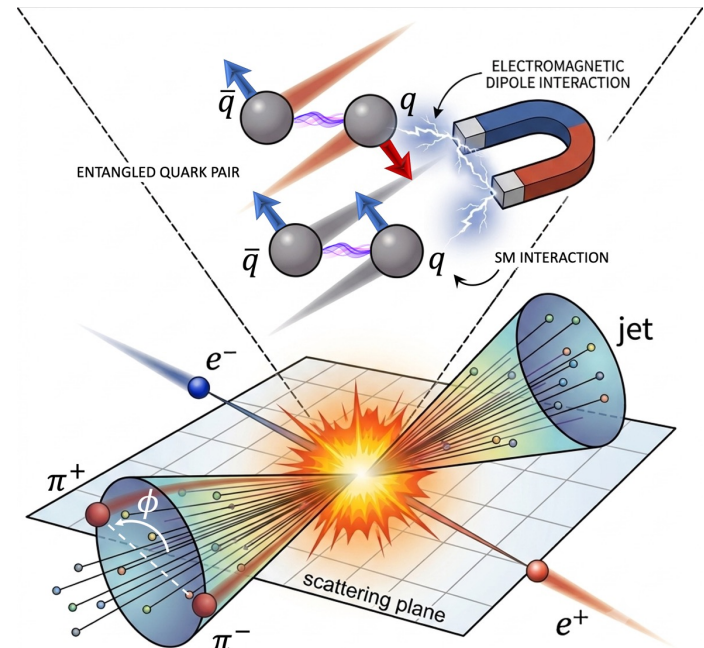
Spin Entanglement at High Energy

Quantum states	Process	Results	From Lailin Xu's talk
Qubits $2 \otimes 2$	$t\bar{t}$	ATLAS (leptonic): Nature 633 (2024) 542	First observation of QE
		CMS (leptonic): ROPP 87 (2024) 117801 CMS (semi-leptonic): PRD 110 (2024) 112016	
Qutrits $3 \otimes 3$	$H \rightarrow ZZ^*$	ATLAS: PRL 137 (2026) 111804	Separable-state hypothesis disfavored at 4.7σ obs. / 4.9σ exp.
		CMS: CMS-PAS-HIG-25-011	

How about the spin entanglement of light quarks ?

- How to measure light quark spin?
- What could their entanglement tell us?

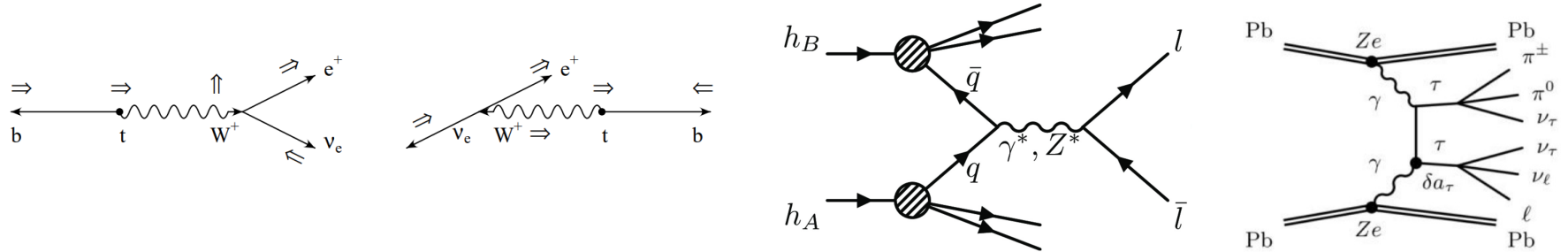
Qing-Hong Cao, Guanghui Li, **Xin-Kai Wen**, and Bin Yan,
Rept. Prog. Phys. 89 (2026) 080501



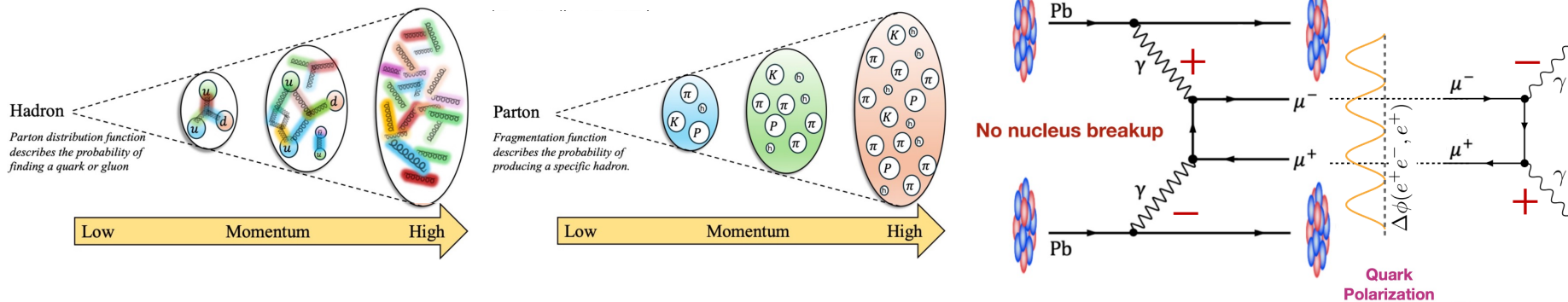
Spin effects in EW and QCD at Colliders

Spin Polarization of particles: A powerful tool to probe the interactions

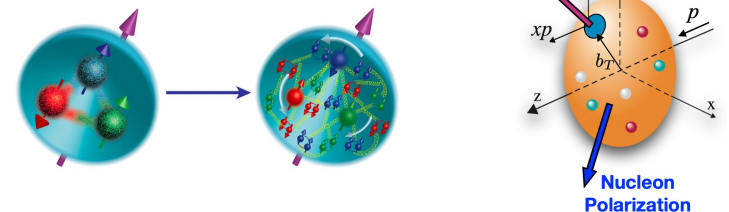
- Spin is measured from its decay products: top quark, gauge bosons, tau lepton, ...



- Spin from nonperturbative QCD like PDFs and FFs, and QED, ...

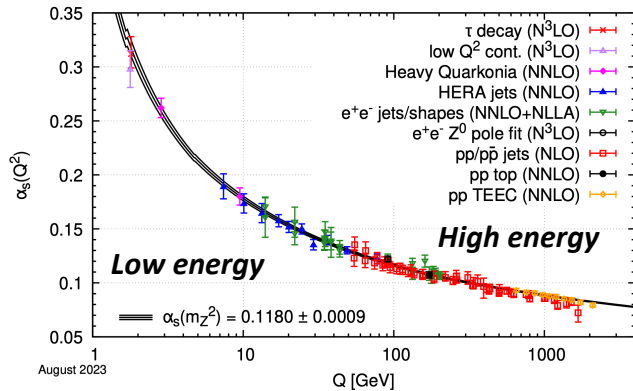


Spin phenomena in QCD arise from the intrinsic correlations between parton transverse momentum, spin, and hadronization dynamics



Asymptotic Freedom and Factorization

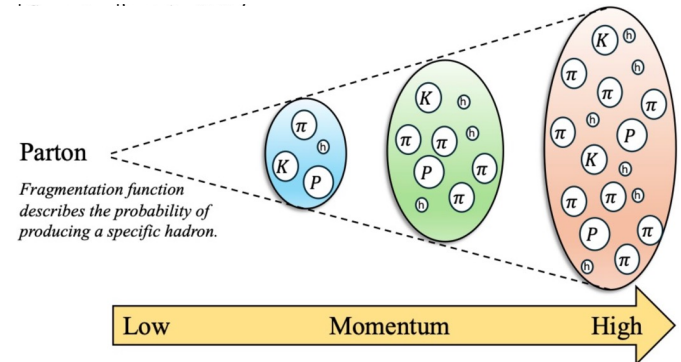
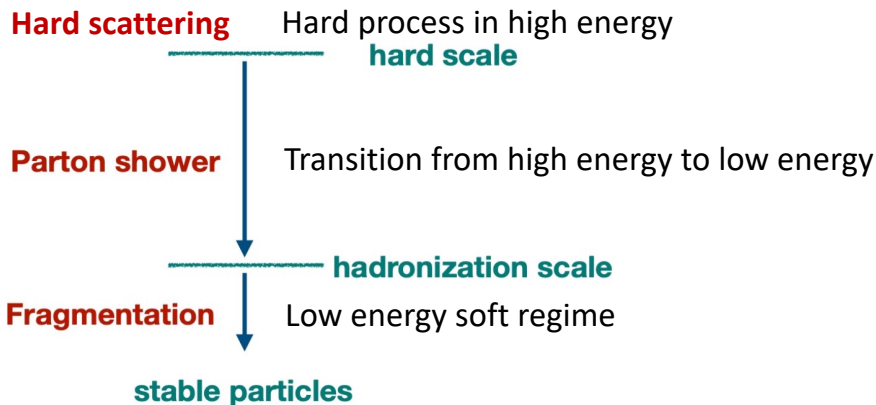
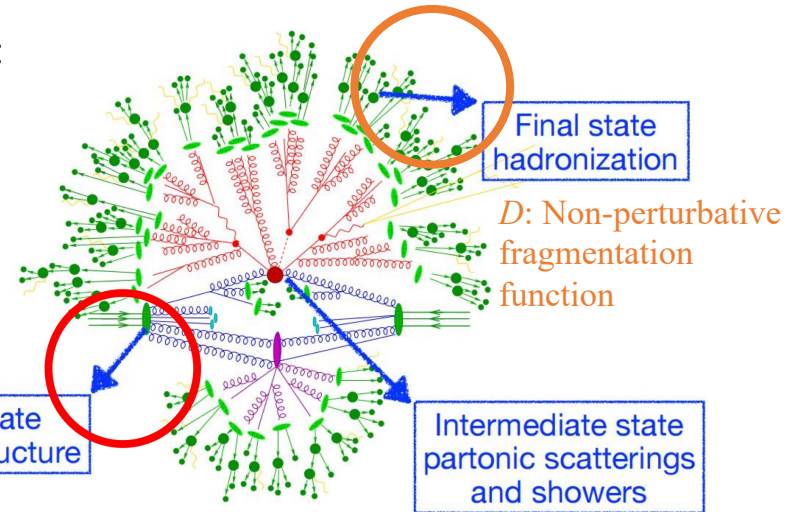
QCD asymptotic freedom and factorization pave an avenue to study quarks and gluons



QCD factorization:

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

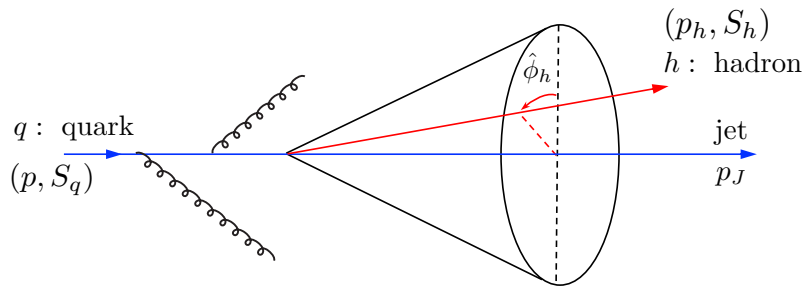
f : Non-perturbative parton distribution function



Lepton Collider: A Clean QCD Spin Probe

Collins FF and Dihadron FF: **light quark spin information transferring to the hadrons**

➤ TMD Fragmentation Functions

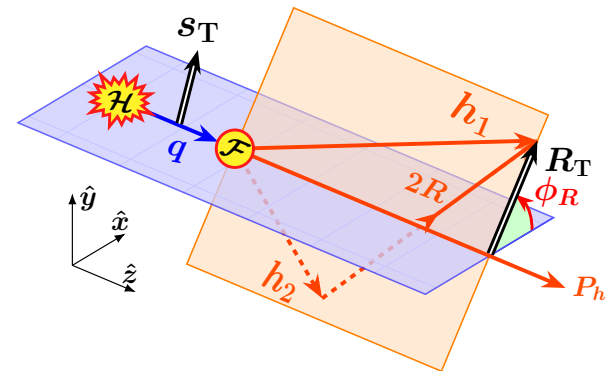


Leading Quark TMDFFs

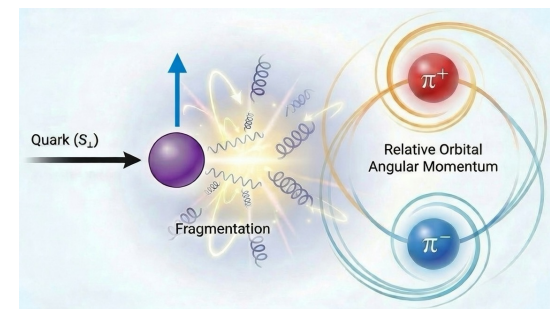


		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		$D_1 = \text{Unpolarized}$		$H_1^\perp = \text{Collins}$
Polarized Hadrons	L		$G_1 = \text{Helicity}$	$H_{1L}^\perp$
	T	$D_{1T}^\perp = \text{Polarizing FF}$	$G_{1T}^\perp$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

➤ Dihadron Fragmentation Functions



spin transfer



New Global fitting

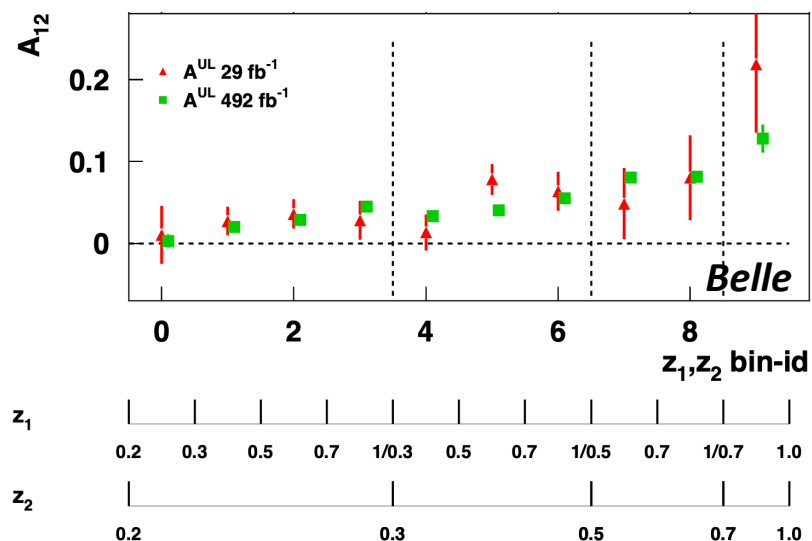
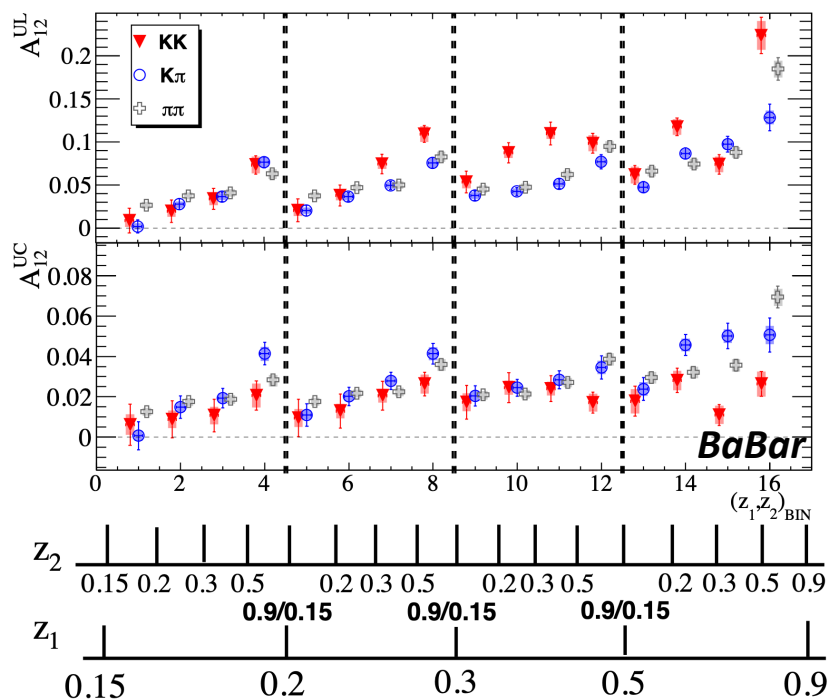
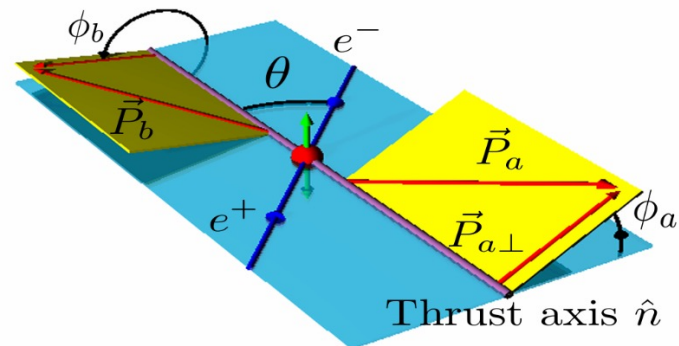
JAM Collaboration, MAP Collaboration, ...

Collins Effects and Asymmetry

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

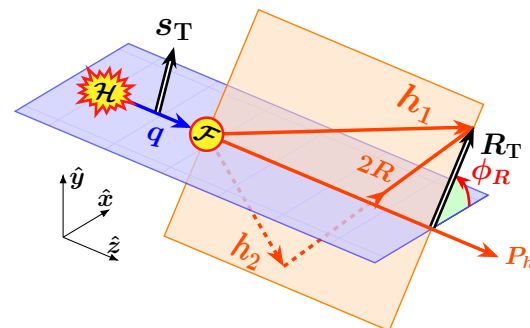
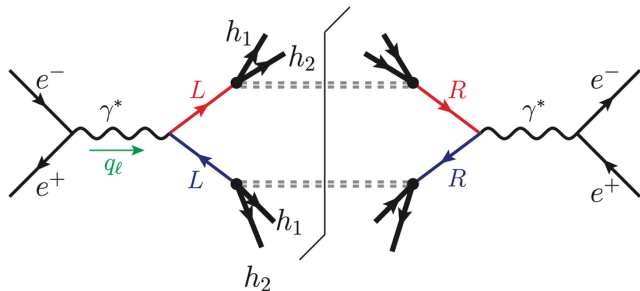
Belle Collaboration, *Phys. Rev. D* **78** (2008) 032011

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



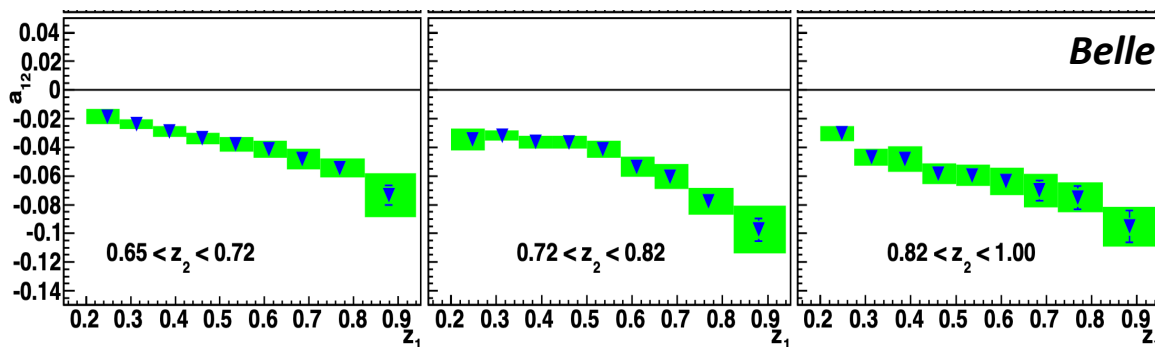
Artru-Collins Asymmetry and Dihadron

The transverse spin effects have been observed in dihadron pair production and SIDIS



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

$$A_{UT}^{\text{SIDIS}} = c(y) \frac{\sum_q e_q^2 h_1^q(x) H_1^{\triangleleft, q}(z, M_h)}{\sum_q e_q^2 f_1^q(x) D_1^q(z, M_h)}$$



Collaboration	Observable	Process
Belle	$d\sigma/dz\,dM_h$	$e^+e^- \rightarrow (\pi^+\pi^-) X$
Belle	$A^{e^+e^-}$	$e^+e^- \rightarrow (\pi^+\pi^-)(\pi^+\pi^-) X$
HERMES	A_{UT}^{SIDIS}	$e p^\uparrow \rightarrow e'(\pi^+\pi^-) X$
COMPASS	A_{UT}^{SIDIS}	$\mu\{p, D\}^\uparrow \rightarrow \mu'(\pi^+\pi^-) X$
STAR	A_{UT}^{pp}	$p^\uparrow p \rightarrow (\pi^+\pi^-) X$

Belle Collaboration, *Phys. Rev. Lett.* **107** (2011) 072004

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

Spin correlation in QCD

Spin correlation effects are essential for accessing chiral-odd nonperturbative functions in the nucleon structure

Leading Quark TMDPDFs  Nucleon Spin  Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \text{Unpolarized}$		$h_1^\perp = \text{Boer-Mulders}$
	L		$g_1 = \text{Helicity}$	$h_{1L}^\perp = \text{Worm-gear}$
	T	$f_{1T}^\perp = \text{Sivers}$	$g_{1T}^\perp = \text{Worm-gear}$	$h_1 = \text{Transversity}$ $h_{1T}^\perp = \text{Pretzelosity}$

Leading Quark TMDFFs  Hadron Spin  Quark Spin

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

Nonperturbative functions **for transversely polarized quarks are chiral-odd.**

Physical observables must be chiral-even: **require pairing of two chiral-odd functions**

- Collins Azimuthal Asymmetries in SIDIS: Collins function + Transversity function
- Hadron-pair production in lepton colliders: Two Collins functions
- Dihadron production in SIDIS: Interference dihadron fragmentation + Transversity function

Spin Correlation of Entangled Light Quarks

Quantum entanglement of light-quark system can be studied through **transverse spin correlations**: Dihadron interference FFs (collinear) or Collins functions (TMD)

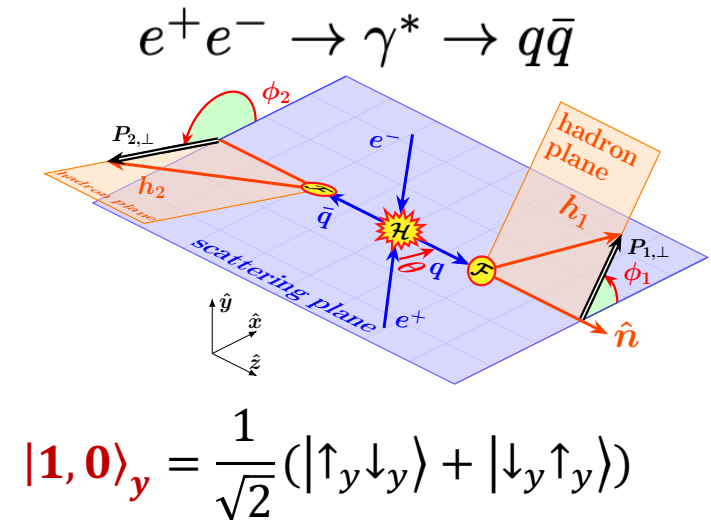
$$\mathcal{B}_{\pm} \equiv C_{xx} \pm C_{yy} \quad \Leftrightarrow \quad \cos(\phi_1 \mp \phi_2)$$

➤ In the SM

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

$$\mathcal{B}_+ = 0$$

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



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

$\mathcal{B}_+ = 0$ is a result of the chiral symmetry of SM (massless quarks)

➤ Light-quark pair exhibit **100% transverse spin correlation** forming a **maximally entangled Bell state** (triplet) **along $\hat{y}$ -direction** in the central scattering region

What type of physics effect would exhibit sensitivity to $\mathcal{B}_+$?

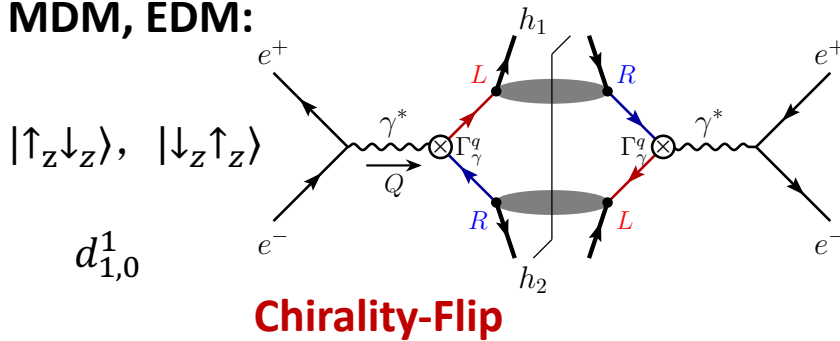
Any nonzero $\mathcal{B}_+$ would hint the New Physics, free from SM contamination

Spin Correlation of Entangled Light Quarks

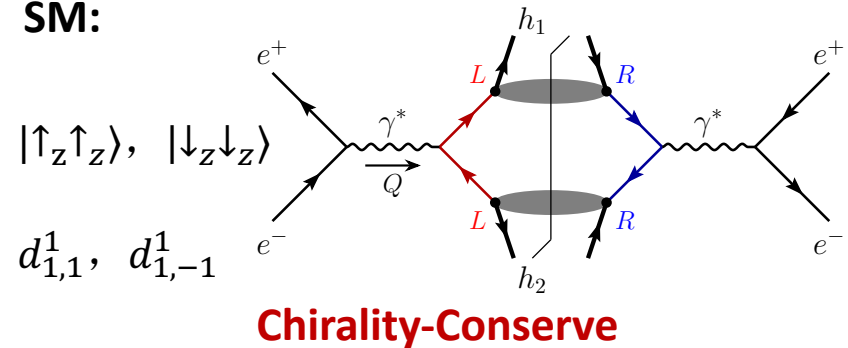
- **Beyond the SM** (up to $O(1/\Lambda^4)$ operators), new spin structure $\mathcal{B}_+$ from chiral symmetry breaking uniquely sensitive to **quark dipole couplings**

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

MDM, EDM:



SM:



- **New spin patterns distinct from SM:** Chiral symmetry breaking
- **Spin patterns distinct between MDM and EDM:** CP symmetry and CP transformation

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

$$|1,0\rangle_z = \frac{1}{\sqrt{2}} (|\uparrow_z \downarrow_z\rangle + |\downarrow_z \uparrow_z\rangle)$$

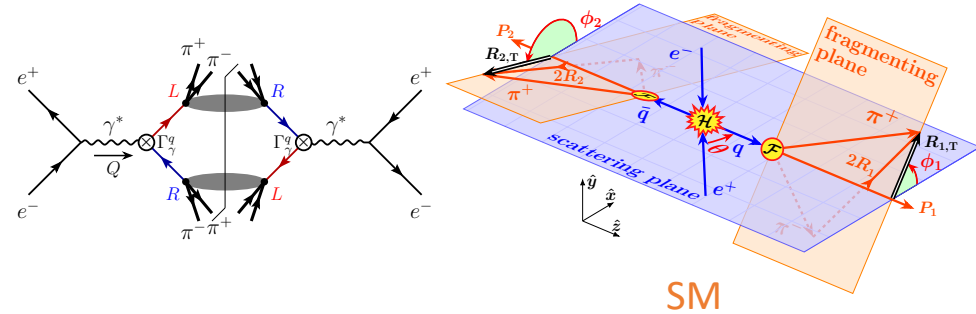
$$C_{ij}^{\text{Re}} = \text{diag}(1, 1, -1)$$

$$|0,0\rangle = \frac{1}{\sqrt{2}} (|\uparrow_z \downarrow_z\rangle - |\downarrow_z \uparrow_z\rangle)$$

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

Spin Transfer from Quarks to Hadrons

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



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

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

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

- New $\cos(\phi_1 - \phi_2)$ to hint the presence of light-quark dipole couplings (MDM, EDM)

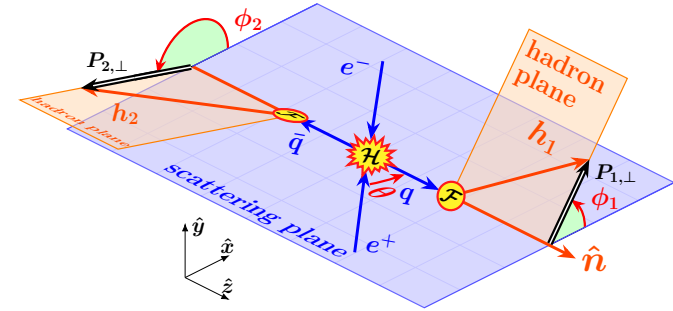
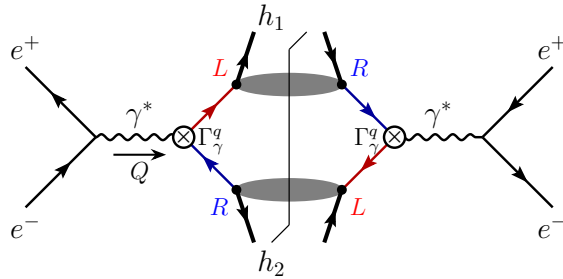
$$R_{\text{diFF}} = \frac{A_-}{A_+} \simeq -\frac{sv^2}{2\pi\alpha\Lambda^4} \frac{\sum_{q=u,d} ([\text{Re}C_\gamma^q]^2 - [\text{Im}C_\gamma^q]^2)}{\sum_{q=u,d} Q_q^2}$$

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

- The ratios of $\cos(\phi_1 - \phi_2)$ and $\cos(\phi_1 + \phi_2)$ to constrain dipole couplings, reducing dependence on nonperturbative DiFFs

Spin Transfer from Quarks to Hadrons

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



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

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

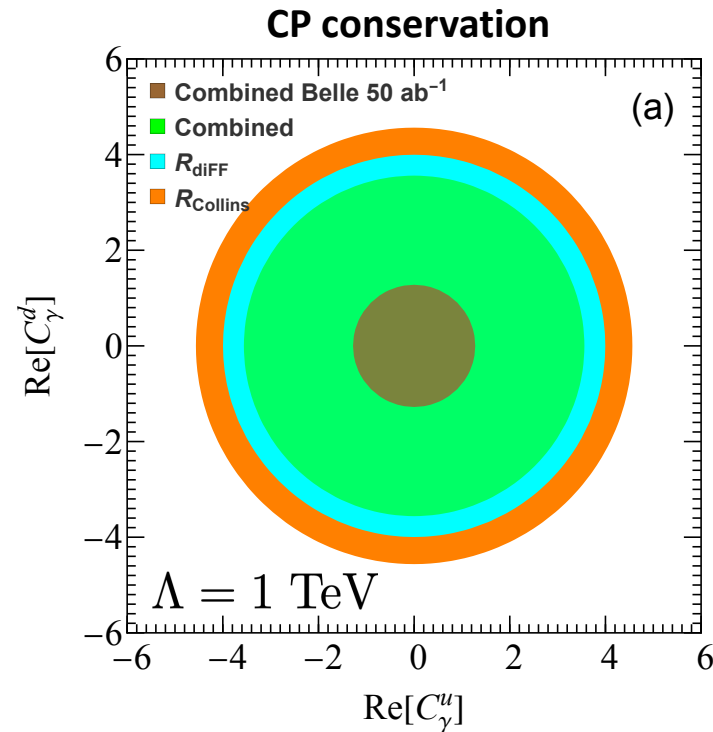
$$\frac{N_U}{N_L} \simeq 1 + \sum_q \mathcal{F}_{UL}^q [\mathcal{B}_- \cos(\phi_1 + \phi_2) - \mathcal{B}_+ \cos(\phi_1 - \phi_2)]$$

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

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* with the collinear dihadron FFs and TMD Collins FFs to constrain quark EM dipole couplings

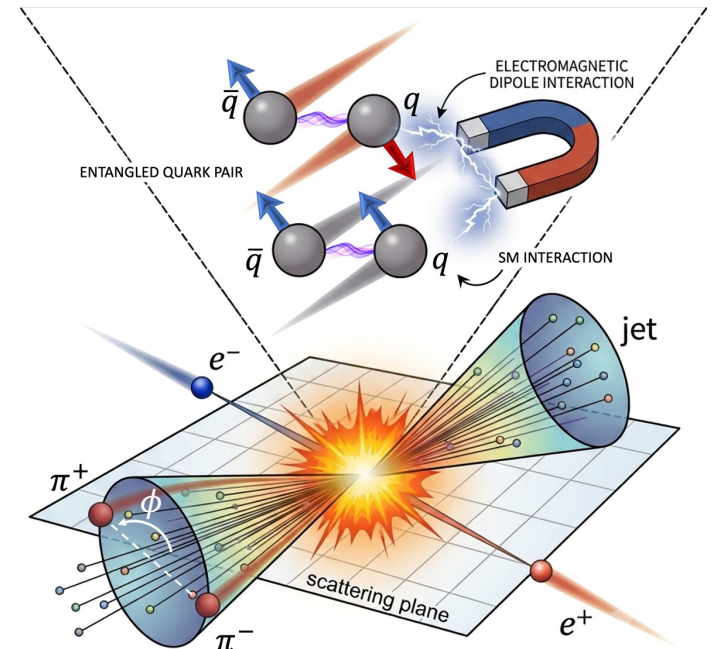
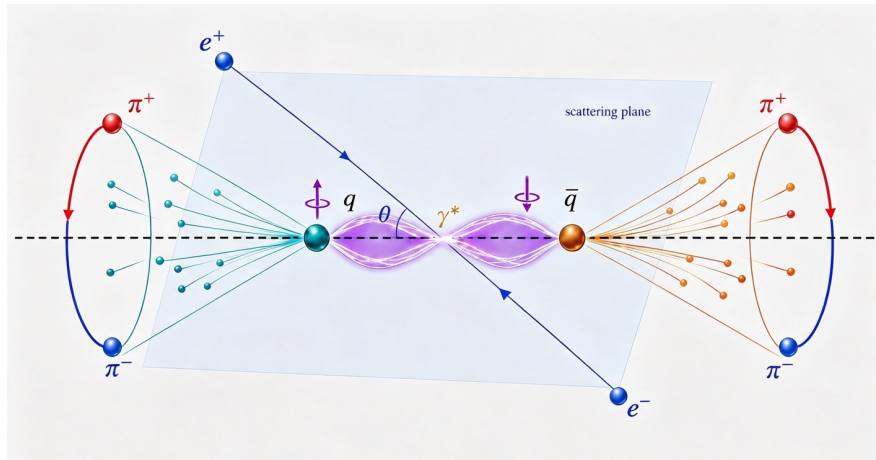


- Current data yield bounds on light-quark MDM and EDM, without ad hoc assumptions
- New spin structure unique to light quark dipole, free from contamination of other NP

A direct connection between entanglement, QCD spin correlations in hadronization, and probes of BSM

Summary

- ✓ 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**
- **QCD Spin Effect** and **New Polarization Observables** are crucial for testing the Standard Model and searching for New Physics
- **Spin Entanglement** also highlights the New Physics effect with distinct entanglement pattern from the SM



Thank you