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

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

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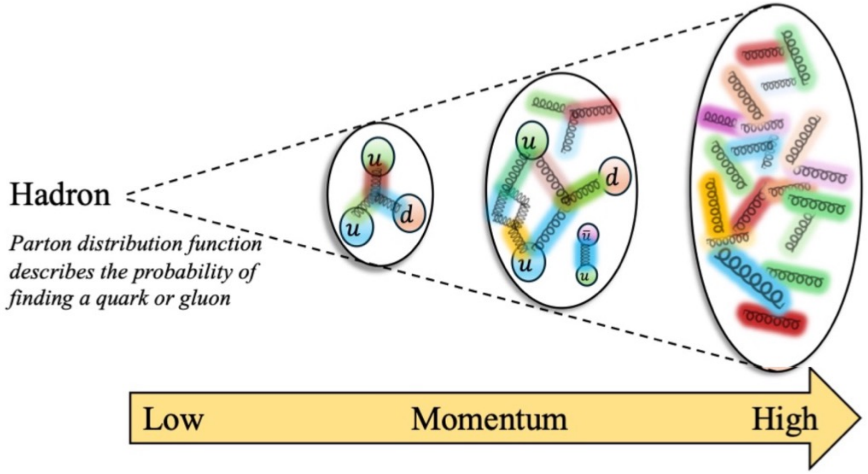
QCD factorization and Fragmentation Functions

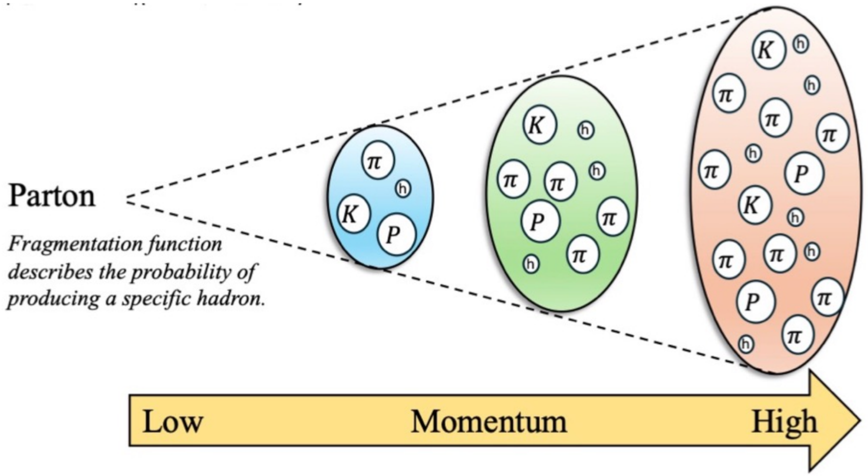
QCD factorization:

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

f : parton distribution functions



D : fragmentation functions

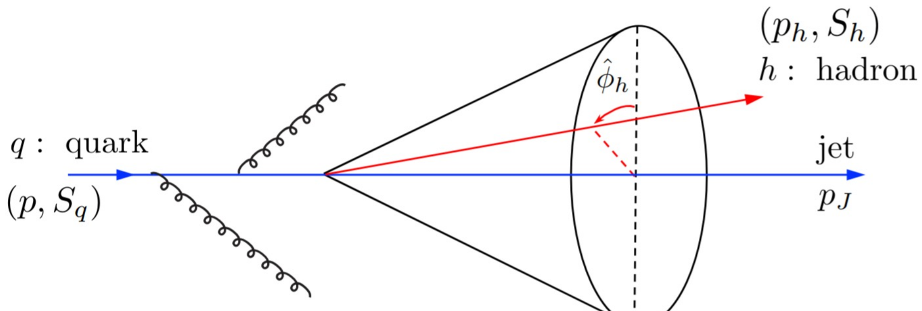


J. Datta et al, PRL 134 (2025) 111902

The process from partons to hadrons can be described with un-perturbative **fragmentation functions**. 👍

Spin Effect in QCD and Interference Fragmentation Functions

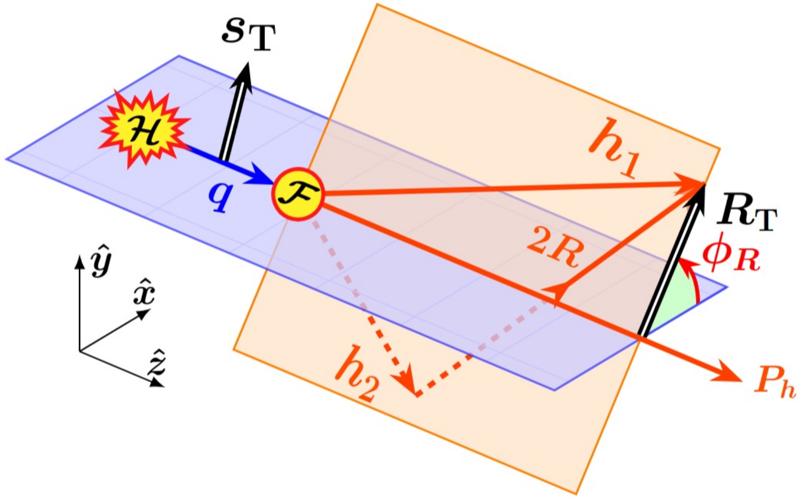
TMD fragmentation:

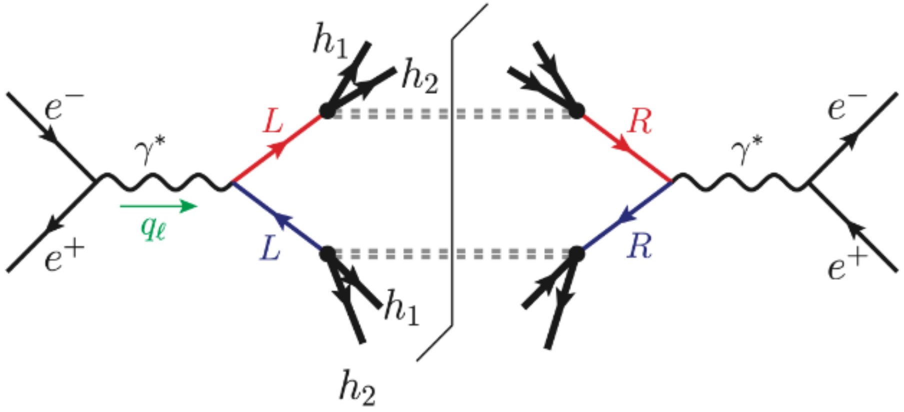


Leading Quark TMDFFs — Hadron Spin — Quark Spin

	Quark Polarization: Un-Polarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: 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 $H_{1T}^\perp$ = −

Di-hadron fragmentation:

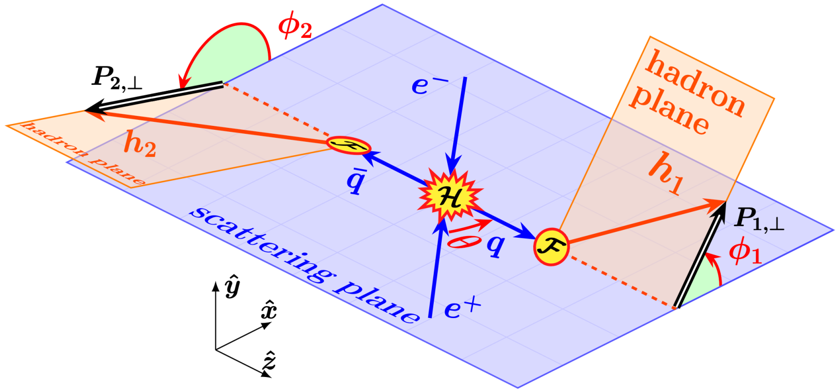




Kang, Prokudin, Sun, Yuan, *Phys.Rev.D* **93** (2016) 014009;
Zeng, Dong, Liu, Sun, Zhao, *Phys.Rev.D* **109** (2024) 056002;
TMD Handbook, *arXiv:* 2304.03302; ......

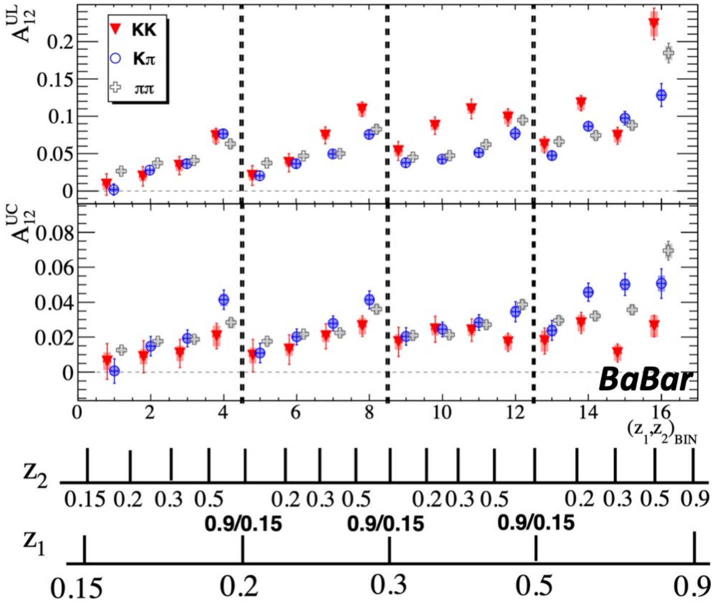
Azimuthal Angle Asymmetry and Spin Correlation

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



$$A_{12} = 2\langle\cos(\phi_1+\phi_2)\rangle$$

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



quark pair spin density matrix: $$\rho = \frac{I_2\otimes I_2 + B_i\sigma_i\otimes I_2 + \bar{B}_i I_2\otimes\sigma_i + C_{ij}\sigma_i\otimes\sigma_j}{4}$$

Asymmetry:

$$\langle\cos(\phi_1\pm\phi_2)\rangle \propto \langle S_{1x}S_{2x}\rangle \mp \langle S_{1y}S_{2y}\rangle = \frac{1}{4}(C_{xx}\mp C_{yy})$$

$$\langle\sin(\phi_1\pm\phi_2)\rangle \propto \langle S_{1x}S_{2y}\rangle \pm \langle S_{1y}S_{2x}\rangle = \frac{1}{4}(C_{xy}\pm C_{yx})$$

at SM, only $C_{xx}-C_{yy}$ nonzero 🤨

Spin Correlation within SMEFT

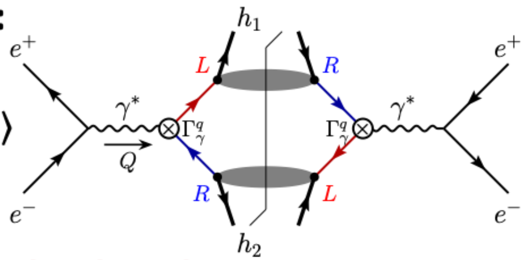
Chirality-Flip operators in SMEFT provide unique spin structure:

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

MDM, EDM:

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

$d^1_{1,0}$

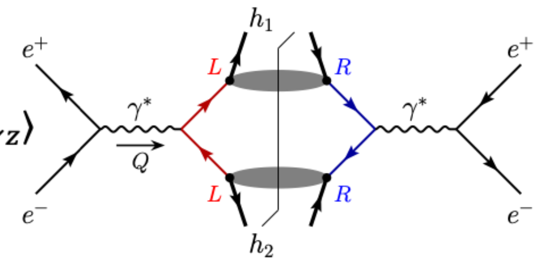


Chirality-Flip

SM:

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

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



Chirality-Conserve

up to $\mathcal{O}(1/\Lambda^4)$,

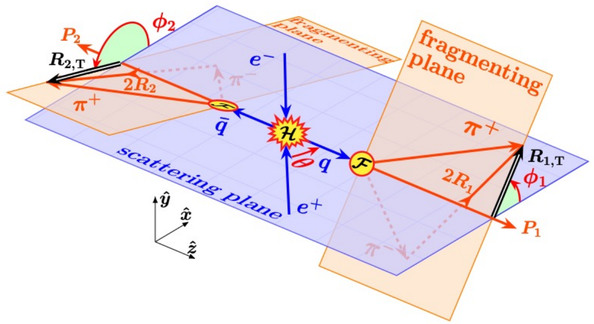
$$C_{xx} + C_{yy} = \frac{\sin^2\theta}{1+\cos^2\theta}\frac{sv^2}{\pi\alpha\Lambda^4 Q_q^2}([\mathrm{Re}C_\gamma^q]^2 - [\mathrm{Im}C_\gamma^q]^2),$$

$$C_{xx} - C_{yy} = \frac{\sin^2\theta}{1+\cos^2\theta}(2 + \frac{1}{\Lambda^2}\mathcal{F}_1 + \frac{1}{\Lambda^4}\mathcal{F}_2),$$

$$C_{xy} = -C_{yx} = -\frac{\sin^2\theta}{1+\cos^2\theta}\frac{sv^2}{\pi\alpha\Lambda^4 Q_q^2}[\mathrm{Re}C_\gamma^q][\mathrm{Im}C_\gamma^q],$$

Observables

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



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

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

Unpolarized DiFFs

Interference DiFFs (transverse polarized)

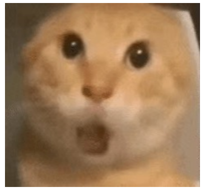
where, $\mathcal{B}_\pm = C_{xx} \pm C_{yy}$

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

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

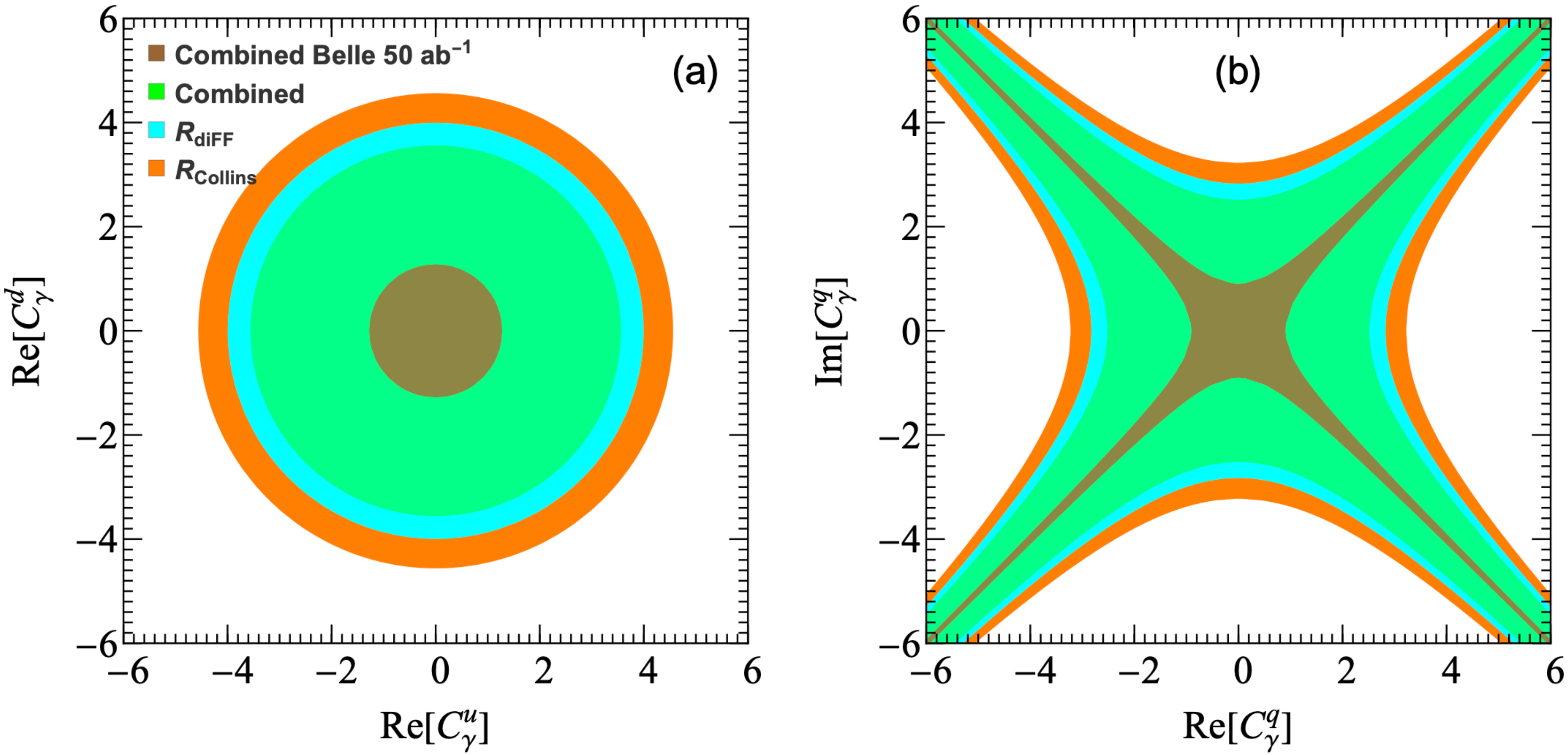
$$H_1^{\sphericalangle,u} = -H_1^{\sphericalangle,d},\ H_1^{\sphericalangle,s,\bar{s},c,\bar{c},b,\bar{b}} = 0,$$
$$H_1^{\sphericalangle,q} = -H_1^{\sphericalangle,\bar{q}}$$

independent of FFs values !



Sensitivity

We proposed revisiting existing data at Belle and BaBar within both the collinear and TMD factorization frameworks to constrain light-quark dipole couplings.



SUMMARY

👍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**.

Thank you