29th Mini-Workshop on the Frontier of LHC, Fuzhou, Dec. 13-16, 2024

Center for High Energy Physics, PKU

Transverse spin effects of light-quark dipole moments at colliders

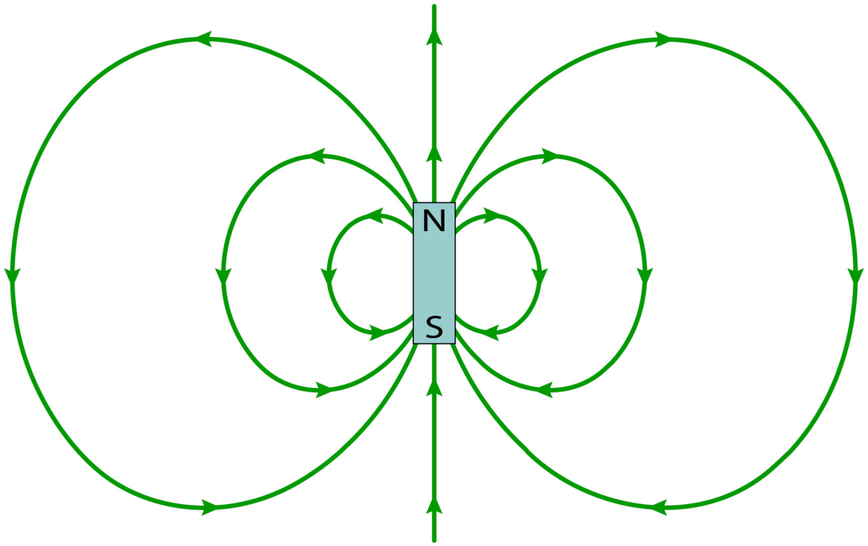
Xin-Kai Wen (文新锴)
(xinkaiwen@pku.edu.cn)
Peking University

Base on: **Xin-Kai Wen**, Bin Yan, Zhite Yu and C.-P. Yuan
arXiv: 2411.13845, 2408.07255, 2307.05236 (*Phys.Rev.Lett.* **131** (2023) 24, 241801)

2024/12/15 @ FZU, Fuzhou, Fujian

Dipole Moments

Its investigation is essential for internal structure and intrinsic property of particles



Elementary	$\mu_e = +2.002319\,\mu_B$
	$\mu_\mu = +2.002332\,\mu_B$
Composite	$\mu_p = +2.792847\,\mu_N$
	$\mu_n = -1.913043\,\mu_N$

How about:

Electroweak (Weak) dipole moments?

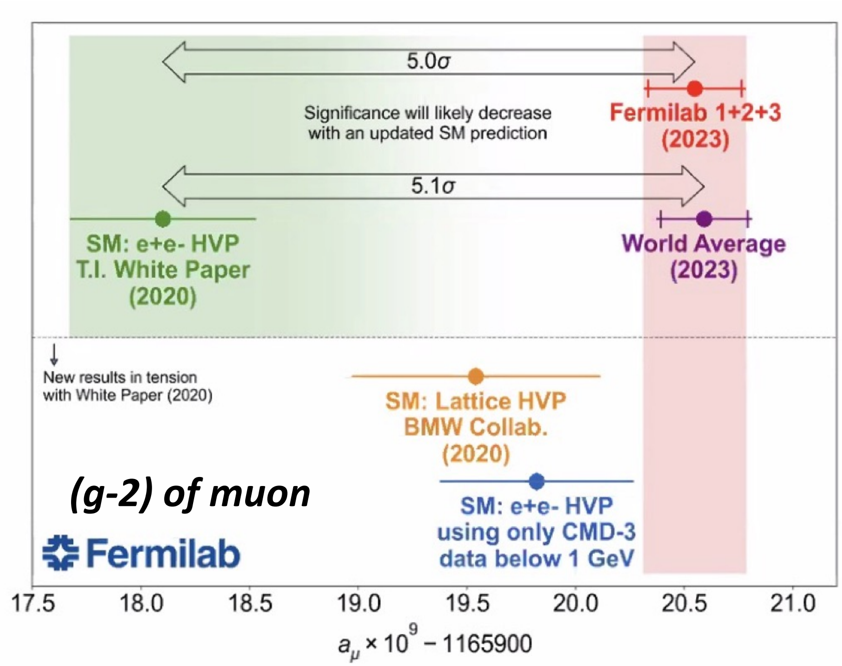
Light-quark dipole moments?

$$-\mu_f \frac{\vec{S}}{|\vec{S}|}\cdot\vec{B} \Leftrightarrow Q_f\, e\left(\bar{f}\,\gamma_\mu\, f\right) A^\mu + a_f \frac{Q_f\, e}{4\, m_f}\left(\bar{f}\,\sigma_{\mu\nu}\, f\right) F^{\mu\nu}$$

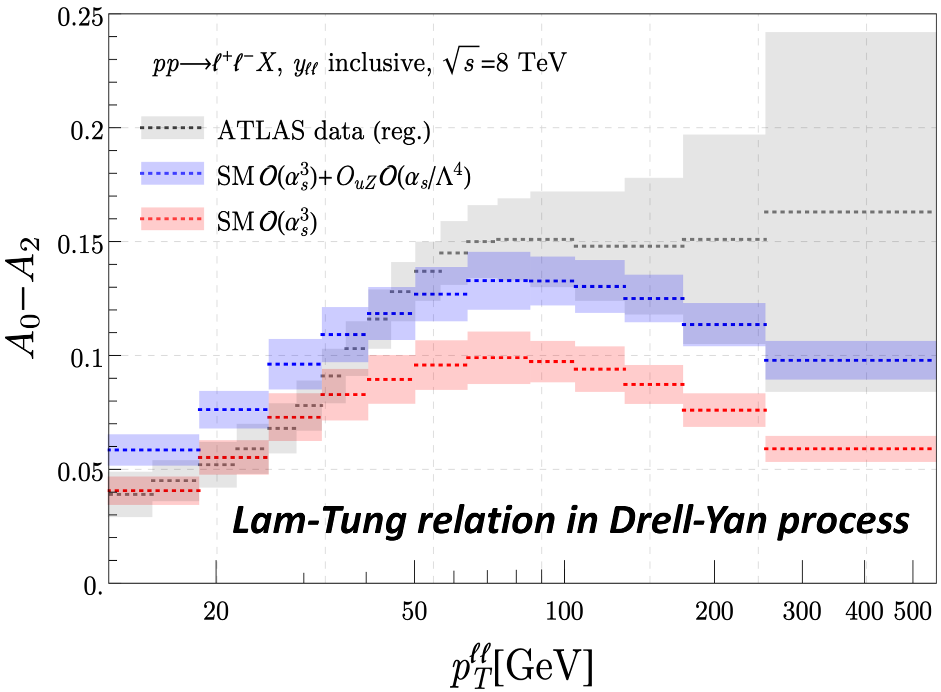
$$-d_f \frac{\vec{S}}{|\vec{S}|}\cdot\vec{E} \Leftrightarrow \qquad + d_f \frac{i}{2}\left(\bar{f}\,\sigma_{\mu\nu}\,\gamma_5\, f\right) F^{\mu\nu}$$

$$\mu_f = g_f \frac{Q_f\, e}{2\, m_f} \qquad \left(g_f - 2\right) = 2\, a_f$$

Dipole Moments



D.P. Aguillard et al., (Muon g-2), *Phys.Rev.Lett.* 131 (2023) 16

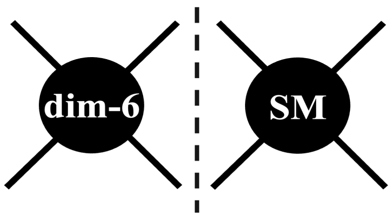


X. Li, B. Yan, C.-P. Yuan, *arXiv:* 2405.04069

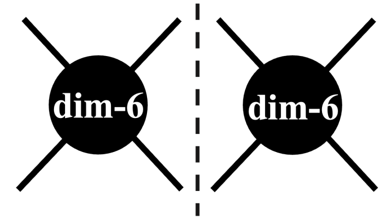
Its measurement is crucial for testing the Standard Model and probing New Physics

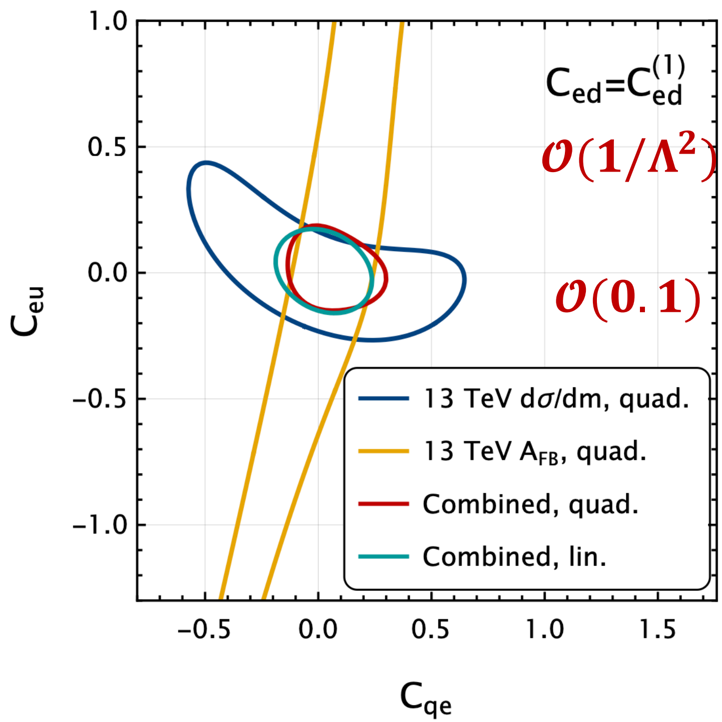
Dipole Moments

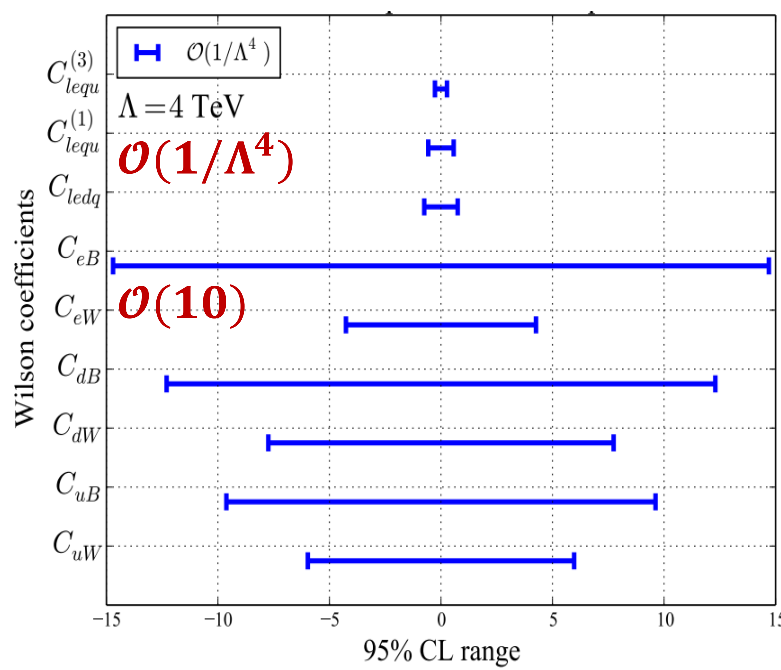
Chirality-flip of fermion ⟹ Difficult to probe at colliders



- Lack interference
- Poor constraint
- Much contamination



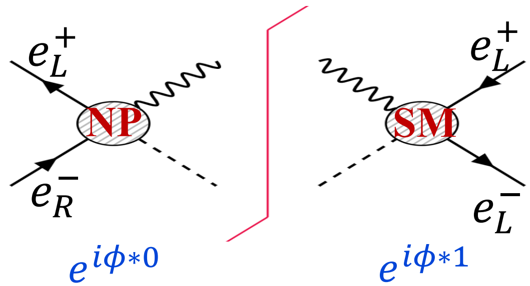


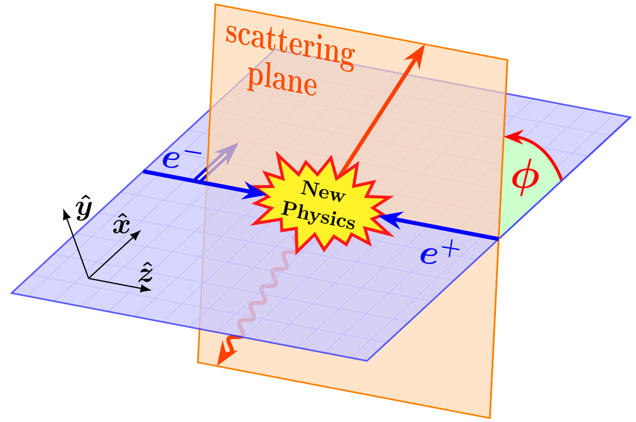


R. Boughezal et al. *Phys.Rev.D* 104 (2021), 9, 095022 *Phys.Rev.D* 108 (2023) 7, 076008

Lepton Dipole Moments

Transverse spin effect of initial leptons ⟹ Interference of the different helicity amplitudes

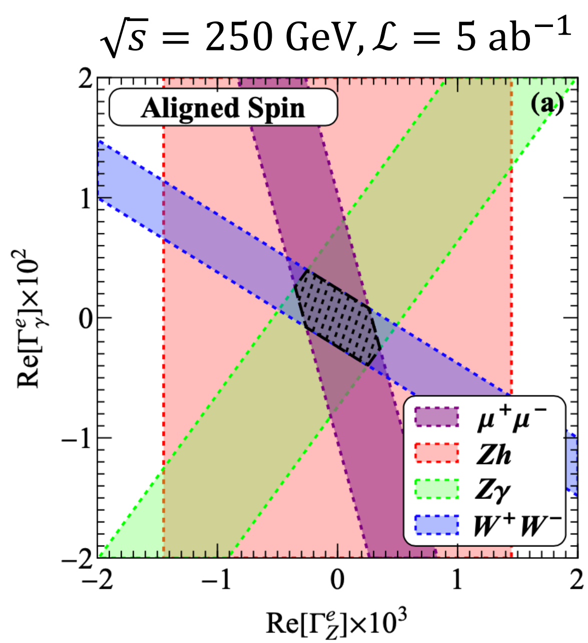




$$\frac{2\pi \, d\sigma^i}{\sigma^i \, d\phi} = 1 + A_R^i(b_T, \bar{b}_T)\cos\phi + A_I^i(b_T, \bar{b}_T)\sin\phi$$

$\mathrm{Re}[\Gamma_f]$ — CP-conserving

$\mathrm{Im}[\Gamma_f]$ — CP-violating



Transverse Spin Asymmetry

Much stronger sensitivity: $\mathcal{O}(10^{-4}\sim 10^{-3})$, others: $\mathcal{O}(10^{-2}\sim 10^{-1})$

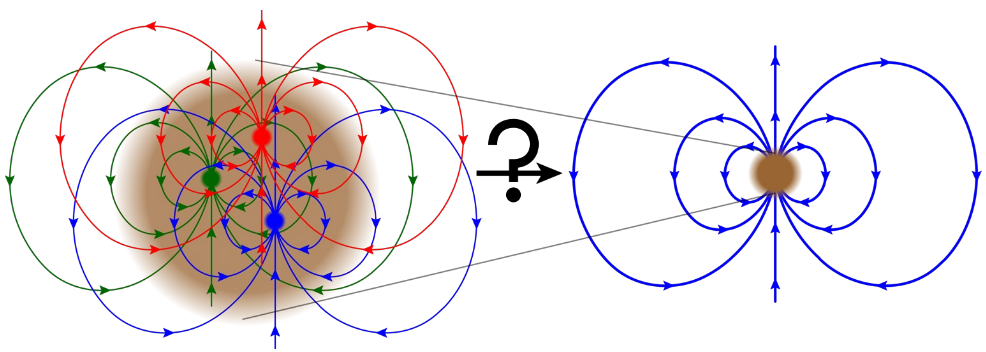
Probing potential CP-violating effects

Without contaminations

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

Light-quark Dipole Moments

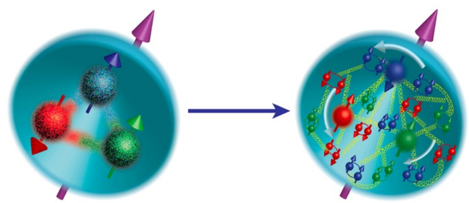
QCD color confinement prevents a direct measurement of the quark dipole moments

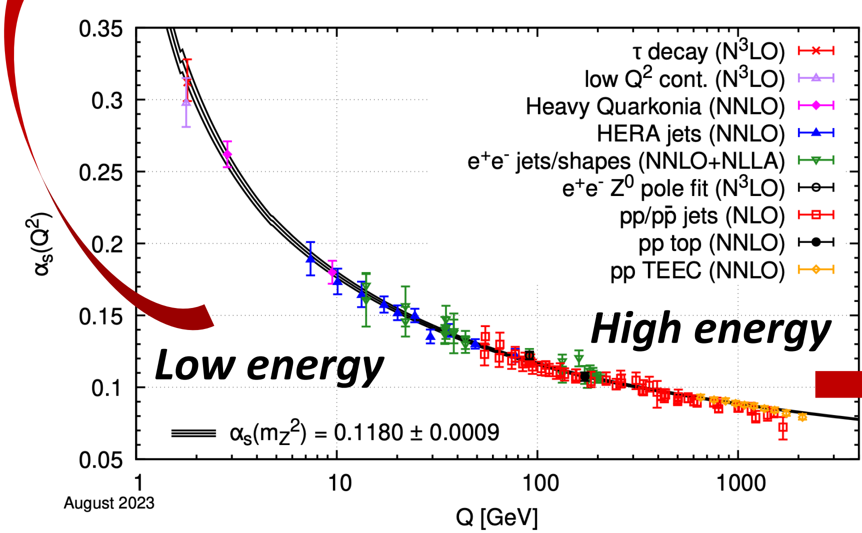


S. Blundell, J. Griffith, J. Sapirstein, *Phys. Rev. D* 86 (2012) 2, 025023

Nucleon dipole moment measurements?

nonperturbative input of nucleon spin structure!





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

Asymptotic freedom

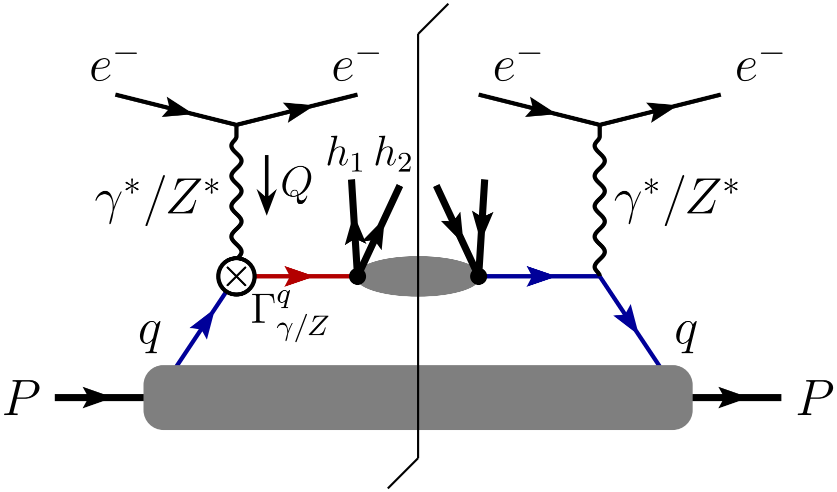
Transversity PDFs or FFs

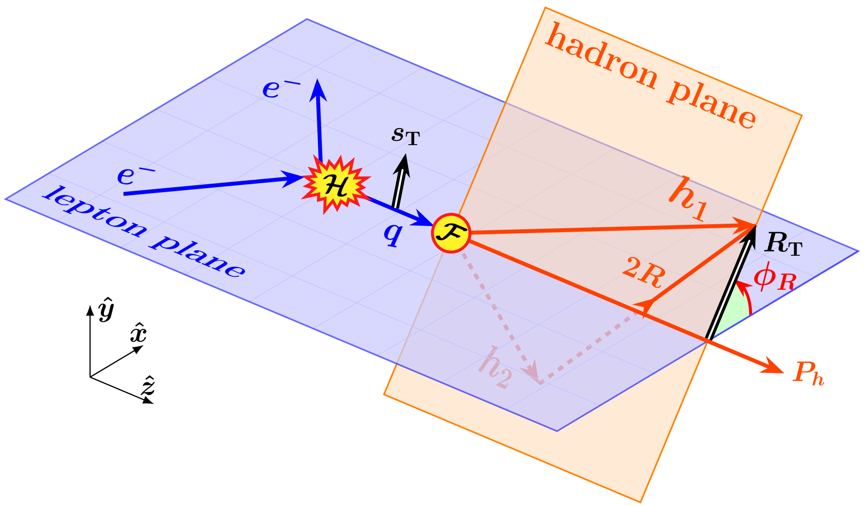
H.-L. Wang, **X.-K. Wen**, H. Xing and B. Yan, *Phys.Rev.D* **109** (2024) 9, 095025

Independent of hadron spin? Dihadron!

Light-quark Dipole Moments @ EIC

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





$$\frac{d\sigma}{dx\,dy\,dz\,dM_h\,d\phi_R} = \frac{N}{2\pi}\sum_q f_q(x,Q)\big[D_{h_1h_2/q}(z,M_h;Q) - (\boldsymbol{s}_{T,q}(x,Q)\times\hat{\boldsymbol{R}}_T)^z H_{h_1h_2/q}(z,M_h;Q)\big]C_q(x,Q)$$

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

Dihadron chiral-odd interference fragmentation function projects out transverse spin of quarks with azimuthal asymmetry

Xin-Kai Wen, Bin Yan, Zhite Yu and C.-P. Yuan, *arXiv:* 2408.07255

Light-quark Dipole Moments @ EIC

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

$$s_q^x = \frac{2}{C_q}\left(w_\gamma^q \,\mathrm{Re}\,\Gamma_\gamma^q + w_Z^q \,\mathrm{Re}\,\Gamma_Z^q\right)$$

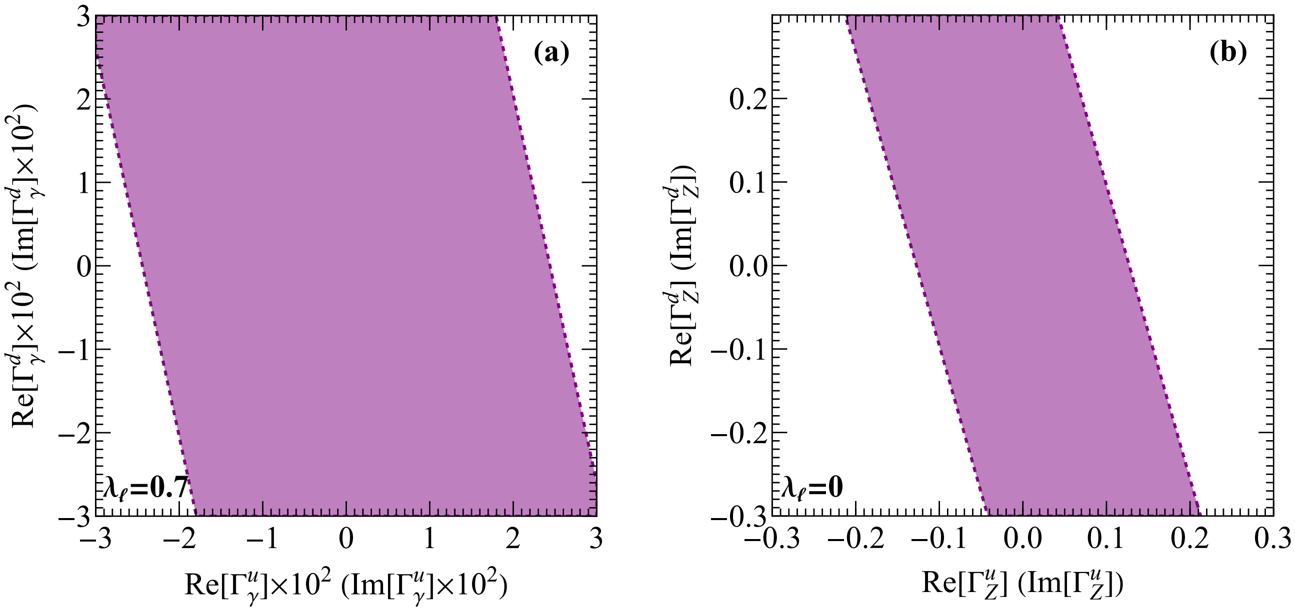
$$s_q^y = \frac{2}{C_q}\left(w_\gamma^q \,\mathrm{Im}\,\Gamma_\gamma^q + w_Z^q \,\mathrm{Im}\,\Gamma_Z^q\right)$$

$$\frac{2\pi}{\sigma_{\mathrm{tot}}}\frac{d\sigma}{d\phi_R} = 1 + A_R \sin\phi_R + A_I \cos\phi_R$$

Requiring parity-violation effects

- the electron longitudinal polarization
- the Z boson axial couplings

$\sqrt{s} = 105$ GeV, $\mathcal{L} = 1000\ \mathrm{fb}^{-1}$



$\mathcal{O}(10^{-2})$ for $\Gamma_\gamma^{u,d}$

$\mathcal{O}(10^{-1})$ for $\Gamma_Z^{u,d}$

Exclusive for quark dipole moments and independent of hadron spin but flat direction ?

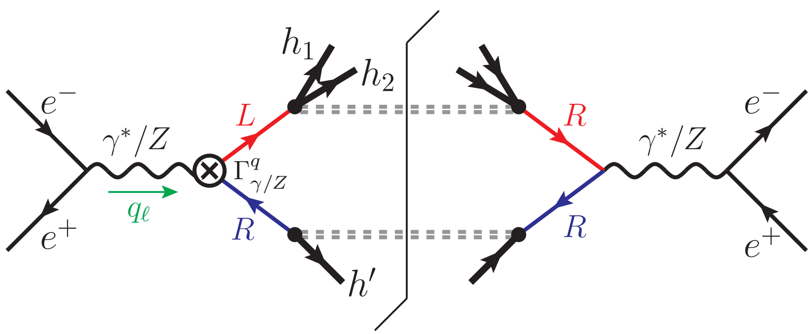
Light-quark Dipole Moments @ e^+e^- colliders

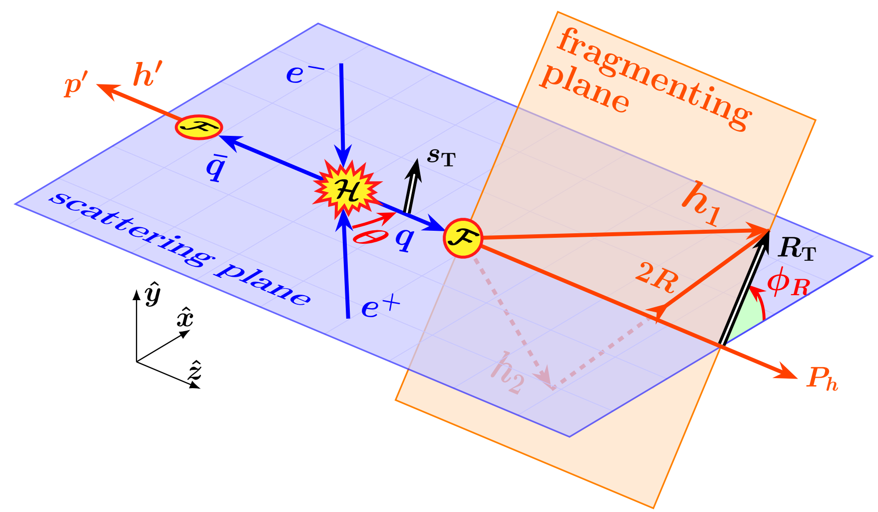
dihadron-hadron pairs disentangle the up and down quark dipole moments exclusively, giving individual and stronger constraints.

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

$$C_q\, s_q^x = 2\left(w_\gamma^q\, \mathrm{Re}\,\Gamma_\gamma^q + w_Z^q\, \mathrm{Re}\,\Gamma_Z^q\right)$$
$$C_q\, s_q^y = 2\left(w_\gamma^q\, \mathrm{Im}\,\Gamma_\gamma^q + w_Z^q\, \mathrm{Im}\,\Gamma_Z^q\right)$$

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

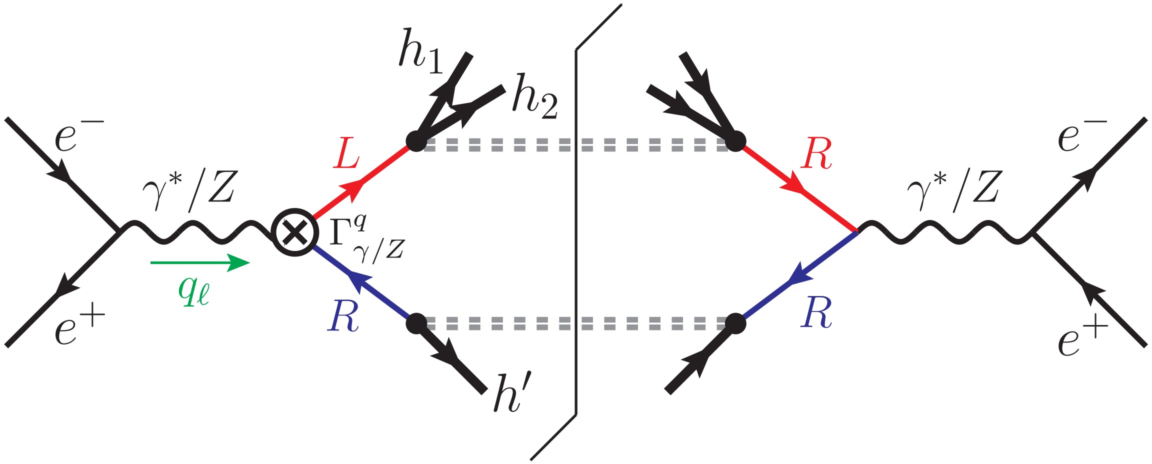




Xin-Kai Wen, Bin Yan, Zhite Yu and C.-P. Yuan, *arXiv:* 2411.13845

Light-quark Dipole Moments @ e^+e^- colliders

Requiring parity-violation effects, the electron longitudinal polarization and C.M. energy effectively distinguish the photon and Z-boson dipole moments separately



$$C_q\, s_q^x = 2\left(w_\gamma^q\, \mathrm{Re}\,\Gamma_\gamma^q + w_Z^q\, \mathrm{Re}\,\Gamma_Z^q\right)$$

$$C_q\, s_q^y = 2\left(w_\gamma^q\, \mathrm{Im}\,\Gamma_\gamma^q + w_Z^q\, \mathrm{Im}\,\Gamma_Z^q\right)$$

Photon dipole:

- Low energy
- Electron longitudinal polarization

Z-boson dipole:

- Z-pole energy
- Z boson axial vector couplings

Light-quark Dipole Moments @ e^+e^- colliders

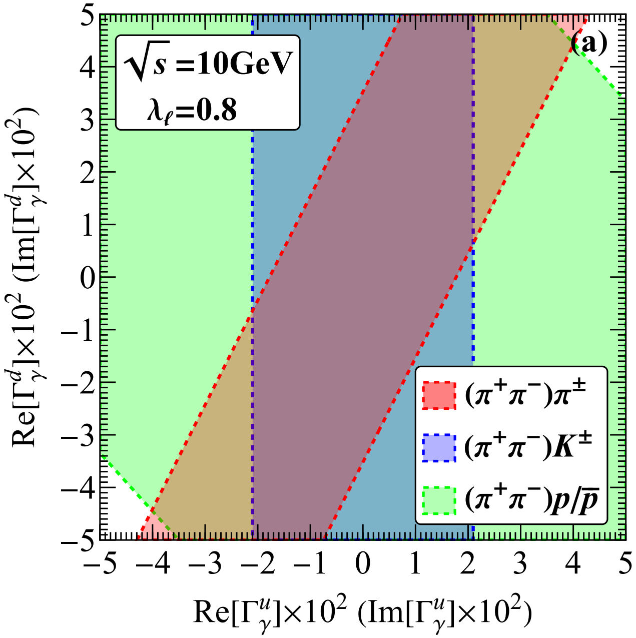
Flavor relations due to SM couplings, isospin and charge conjugation symmetries

different channels provide different constraints, enabling them to be separately constrained

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

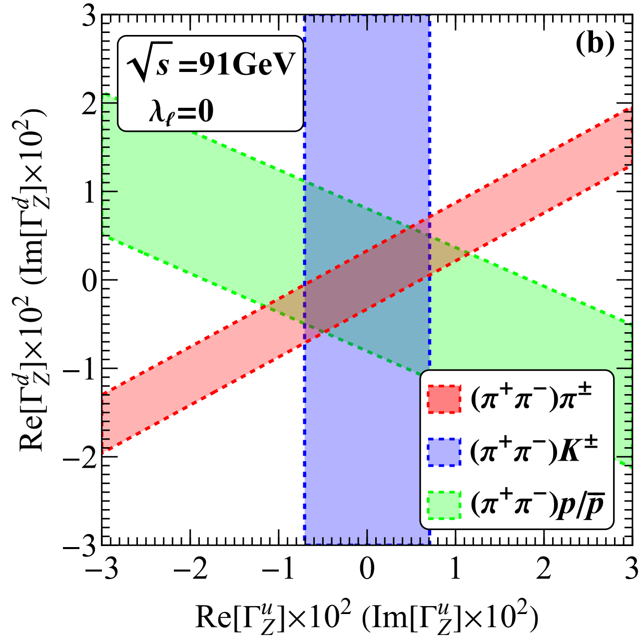
$$B^i = H_u^{\pi^+\pi^-} \left[\langle S_u^i \rangle \left(D_{\bar{u}}^{h'} - D_u^{h'} \right) - \langle S_d^i \rangle \left(D_{\bar{d}}^{h'} - D_d^{h'} \right) \right]$$

- $(\pi^+\pi^-)\pi^\pm$ $\left(\langle S_u^i \rangle + \langle S_d^i \rangle \right)$
- $(\pi^+\pi^-)K^\pm$ $D_d^{K^\pm} = D_{\bar{d}}^{K^\pm}$
- $(\pi^+\pi^-)p/\bar{p}$ $\left(\langle S_u^i \rangle - \langle S_d^i \rangle / 2 \right)$



$\mathcal{O}(10^{-2})$ for $\Gamma_\gamma^{u,d}$

$\mathcal{O}(10^{-3})$ for $\Gamma_Z^{u,d}$



Summary

- ✓ Measuring light-quark dipole moments is crucial for testing the Standard Model and probing New Physics, but quark cannot be directly seen due to QCD confinement
- ✓ Rate observables are difficult to bound them since their leading effect is from $1/\Lambda^4$
- ✓ Light-quark dipole moments linearly produce transverse spin effect of quarks
- ✓ Dihadron azimuthal asymmetry projects out transverse spin of quarks via interference fragmentation function, exclusively probe light-quark dipole moments from $1/\Lambda^2$, independent of hadron spin and without impact from other NP
- ✓ By combining all possible channels of hadron-dihadron, we resolve the degeneracy issue of the up and down quark dipole moments, giving individual constraints
- ✓ Both real and imaginary parts can be well constrained, offering a new opportunity for directly probing potential CP-violating effects.
- ✓ Our bounds are much stronger than other approaches by 1~2 orders of magnitude

Thank you