Dihadron azimuthal asymmetry and light-quark dipole moments at the EIC

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Based on Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255

New physics and Dipole Operator

- Magnetic dipole moments: probing the internal structures of particles

◻ Elementary particle:

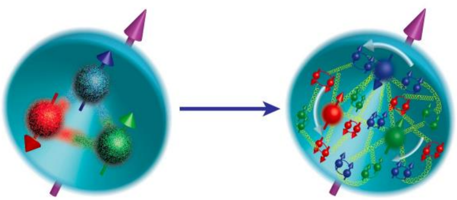
Electron: g/2=1.001159…

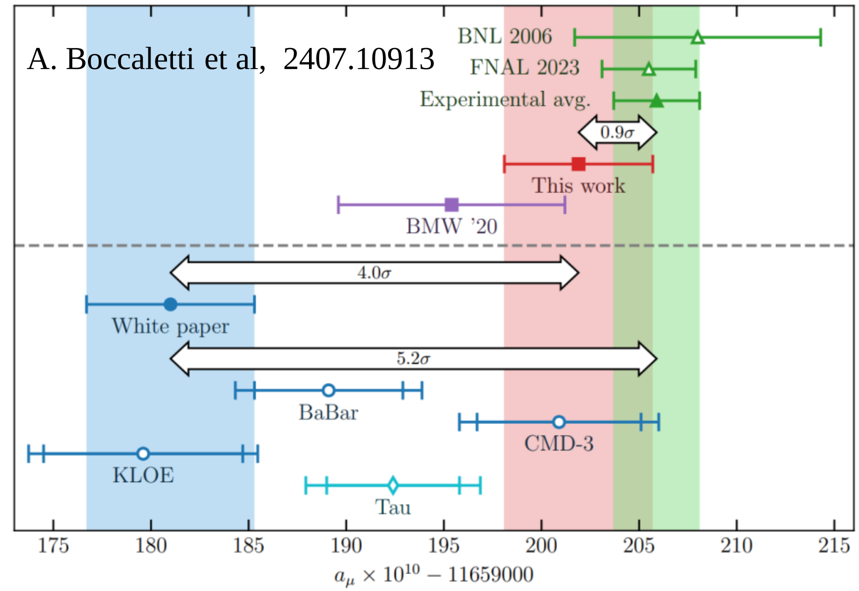
Muon: g/2=1.0011659..

◻ Composite particle:

Proton: g/2=2.7928444..

Neutron: g/2=-1.91394308..

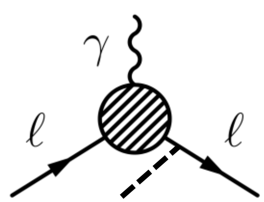




◻ Quarks: any internal structures?

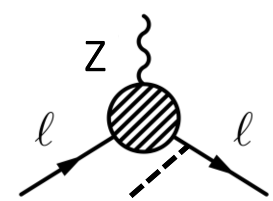
◻ From MDM and EDM to weak dipole moments

$$\bar{\ell}\,\sigma^{\mu\nu} e \tau^I \varphi W^I_{\mu\nu}\,,\ \bar{\ell}\,\sigma^{\mu\nu} e \varphi B_{\mu\nu}$$



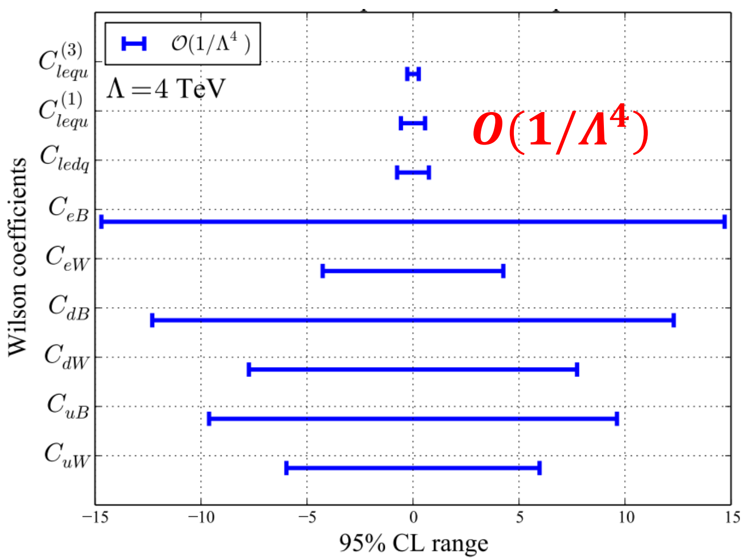
May have same physics source

$B_{\mu\nu}, W_{\mu\nu}$

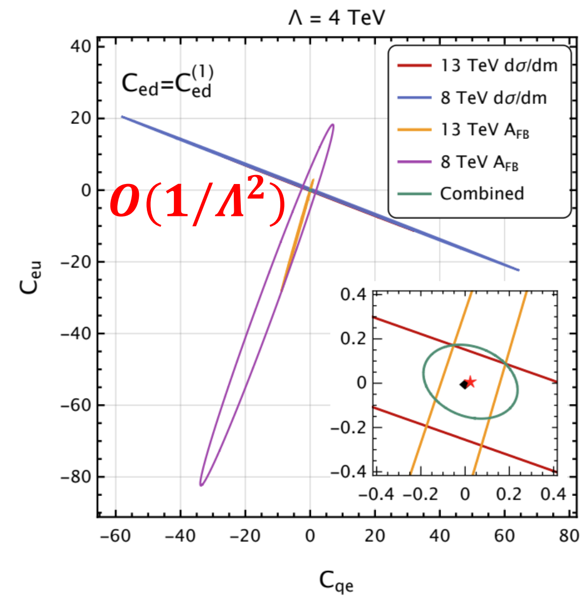


Example: Electroweak Dipole Operator

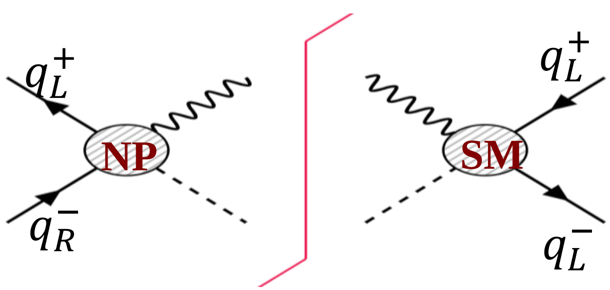
Single-Parameter-Analysis: EW dipole couplings are poorly constrained



R. Boughezal et al, PRD 104 (2021) 095022



R. Boughezal et al, 2303.08257



=0 for the cross section

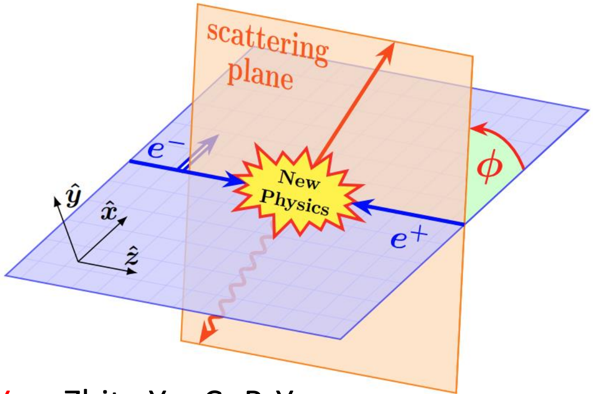
Leading contribution: $\left|\frac{c_{dipole}}{\Lambda^2}\right|^2$

➢ It is difficult to probe the electroweak dipole interactions at colliders

Electroweak dipole moments of leptons

- Transversely polarized effect of beams @ lepton collider

The interference between the different helicity states



$$\boldsymbol{s} = (b_1, b_2, \lambda) = \underline{(b_{\mathrm{T}} \cos\phi_0, b_{\mathrm{T}} \sin\phi_0, \lambda)}$$

$$\rho = \frac{1}{2}(1 + \boldsymbol{\sigma}\cdot\boldsymbol{s}) = \frac{1}{2}\begin{pmatrix} 1+\lambda & b_{\mathrm{T}} e^{-i\phi_0} \\ b_{\mathrm{T}} e^{i\phi_0} & 1-\lambda \end{pmatrix}$$

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan,
PRL 131 (2023) 241801

$$M \infty e^{i(\alpha 1 - \alpha 2)\phi}$$

	U	L	T
U	$\lvert\mathcal{M}\rvert^2_{UU} \to 1$	$\lvert\mathcal{M}\rvert^2_{UL} \to 1$	$\lvert\mathcal{M}\rvert^2_{UT} \to \cos\phi, \sin\phi$
L	$\lvert\mathcal{M}\rvert^2_{LU} \to 1$	$\lvert\mathcal{M}\rvert^2_{LL} \to 1$	$\lvert\mathcal{M}\rvert^2_{LT} \to \cos\phi, \sin\phi$
T	$\lvert\mathcal{M}\rvert^2_{TU} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TL} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TT} \to 1, \cos 2\phi, \sin 2\phi$

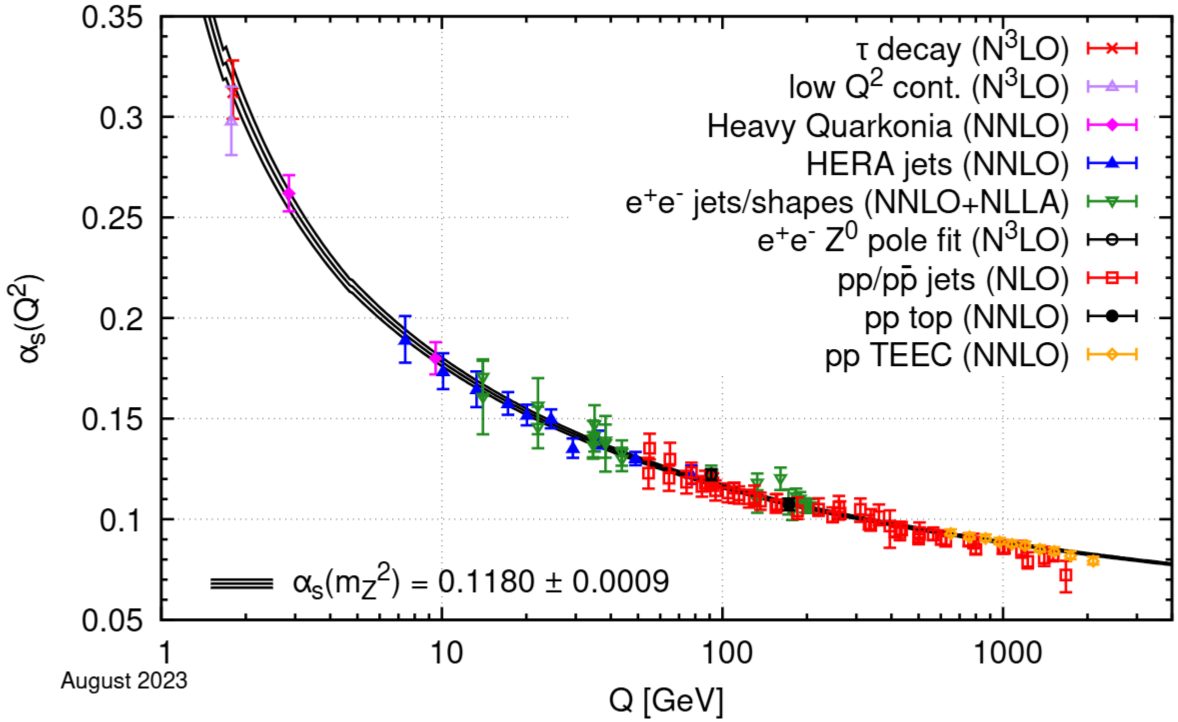
Breaking the rotational invariance & A nontrivial azimuthal behavior

- Transversely polarized effect of beams @ EIC

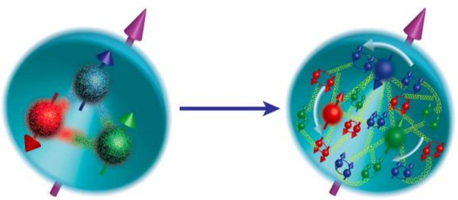
R. Boughezal, D. Florian, F. Petriello, W. Vogelsang, PRD 107 (2023) 7, 075028

Electroweak dipole moments of quarks

- The quark can not be a free particle due to the QCD confinement



Asymptotic freedom of QCD theory



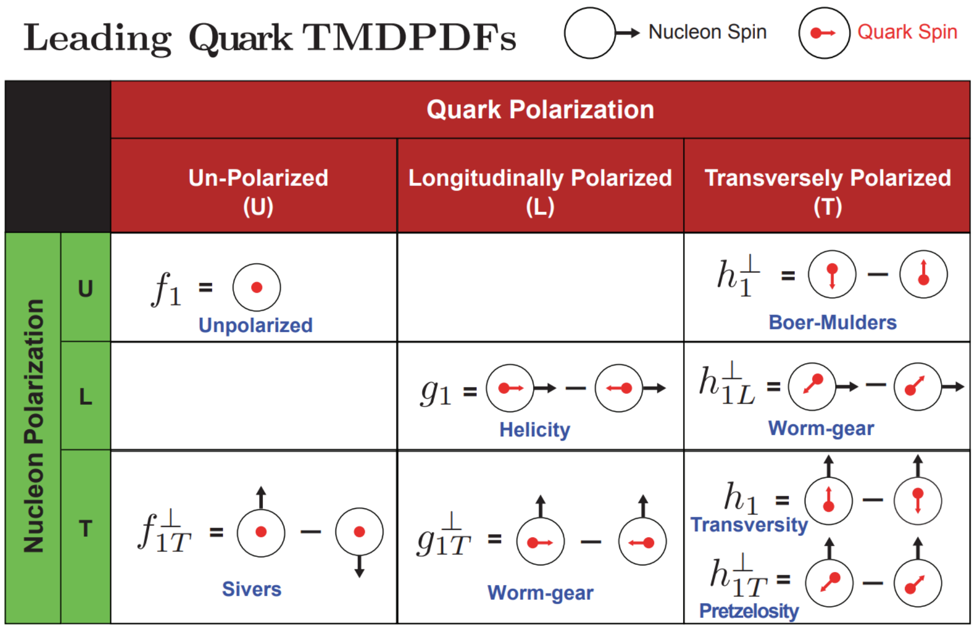
- How to probe the spin information of quarks?

The non-perturbative functions, i.e., the parton distirbuion functions and the fragmentation functions

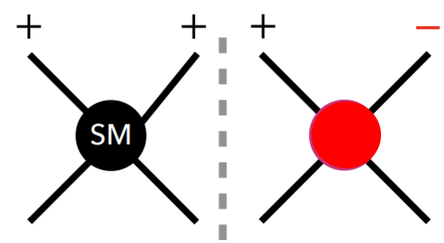
Transverse spin effects of quark @ EIC

- Quark dipole operators

R. Boughezal, D. Florian, F. Petriello, W. Vogelsang, PRD 107 (2023) 7, 075028



$$
\begin{aligned}
\mathcal{O}_{uW} &= (\bar{q}\sigma^{\mu\nu}u)\tau^I\varphi W^I_{\mu\nu},\\
\mathcal{O}_{uB} &= (\bar{q}\sigma^{\mu\nu}u)\varphi B_{\mu\nu},\\
\mathcal{O}_{dW} &= (\bar{q}\sigma^{\mu\nu}d)\tau^I\varphi W^I_{\mu\nu},\\
\mathcal{O}_{dB} &= (\bar{q}\sigma^{\mu\nu}d)\varphi B_{\mu\nu}.
\end{aligned}
$$



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

- The transversity is difficult to be constrained: chiral-odd

$$
A_{UT} = \frac{\sigma(e^U p^\uparrow) - \sigma(e^U p^\downarrow)}{\sigma(e^U p^\uparrow) + \sigma(e^U p^\downarrow)}
$$

  - Collins Azimuthal Asymmetries in SIDIS, Collins function
  - Low energy Drell-Yan process
  - Dihadron production in SIDIS, Interference dihadron fragmentation

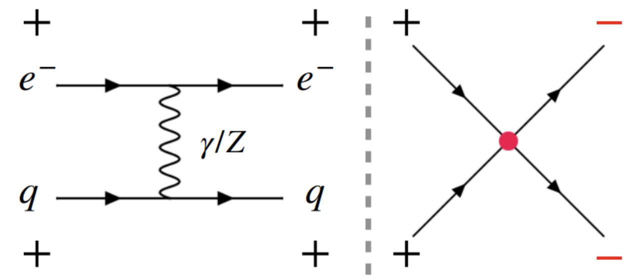
Kang, Prokudin, Sun, Yuan, PRD 93 (2016) 014009; Zeng, Dong, Liu, Sun, Zhao, PRD 109 (2024) 056002;
JAM Collaboration, PRD 106 (2022) 034014

Transverse spin effects @ EIC

- Scalar and tensor four fermion operators

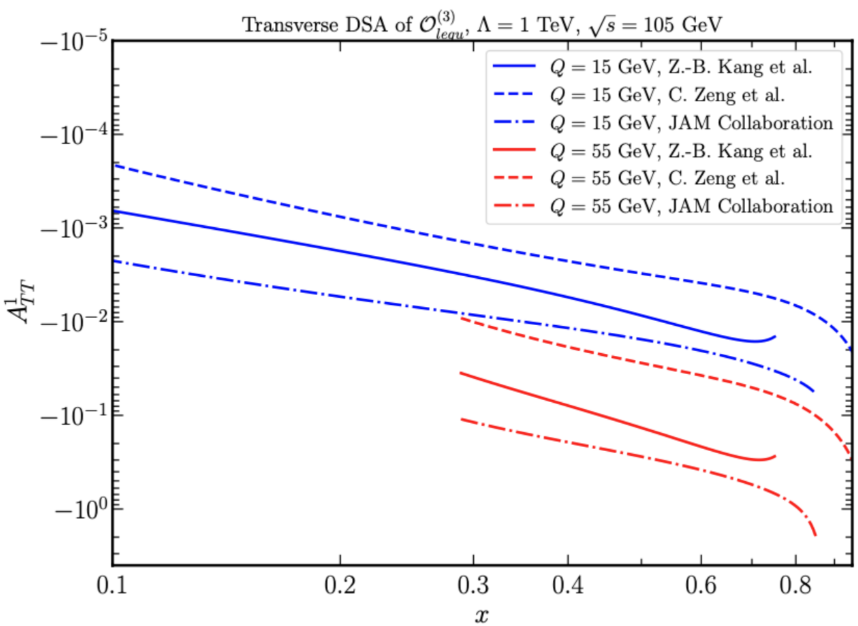
$$P_{T,e} = P_{T,p} = 0.7, \mathcal{L} = 100\ \mathrm{fb}^{-1}$$

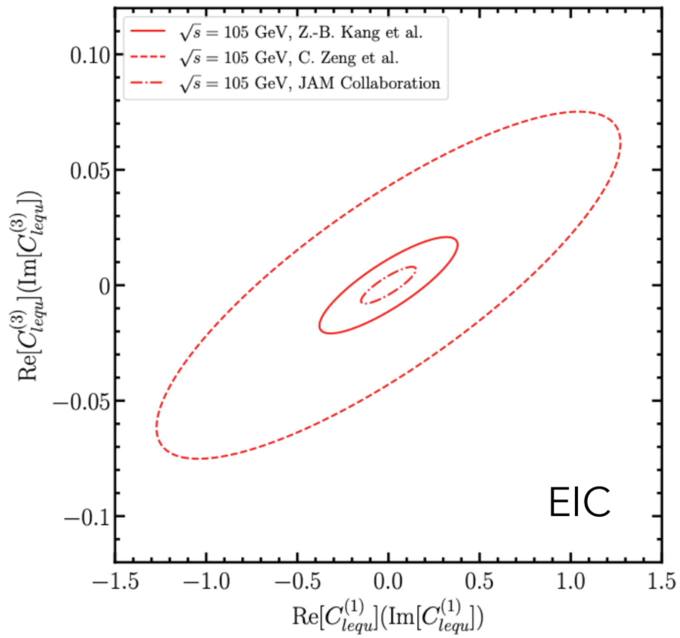
$$\begin{aligned} \mathcal{O}_{ledq} &= (\bar{L}^j e)(\bar{d}Q^j), \\ \mathcal{O}^{(1)}_{lequ} &= (\bar{L}^j e)\,\epsilon_{jk}\,(\bar{Q}^k u), \\ \mathcal{O}^{(3)}_{lequ} &= (\bar{L}^j \sigma^{\mu\nu} e)\,\epsilon_{jk}\,(\bar{Q}^k \sigma_{\mu\nu} u), \end{aligned}$$



Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan,
PRD 109 (2024) 095025

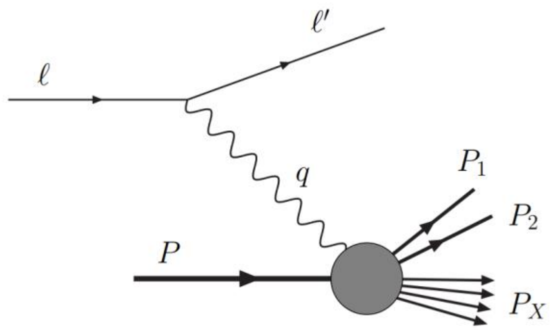
$$A_{TT} = \frac{\sigma(e^\uparrow p^\uparrow) + \sigma(e^\downarrow p^\downarrow) - \sigma(e^\uparrow p^\downarrow) - \sigma(e^\downarrow p^\uparrow)}{\sigma(e^\uparrow p^\uparrow) + \sigma(e^\downarrow p^\downarrow) + \sigma(e^\uparrow p^\downarrow) + \sigma(e^\downarrow p^\uparrow)}$$

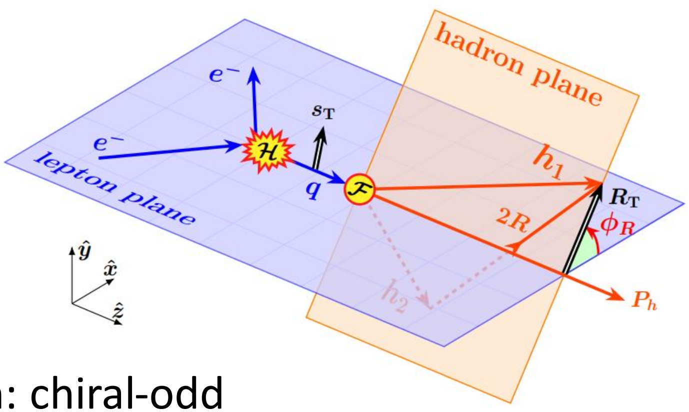




Transverse spin effects of quark @ EIC

- The transverse spin of quarks can be generated by the quark dipole moments





- The interference dihadron fragmentation function: chiral-odd

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

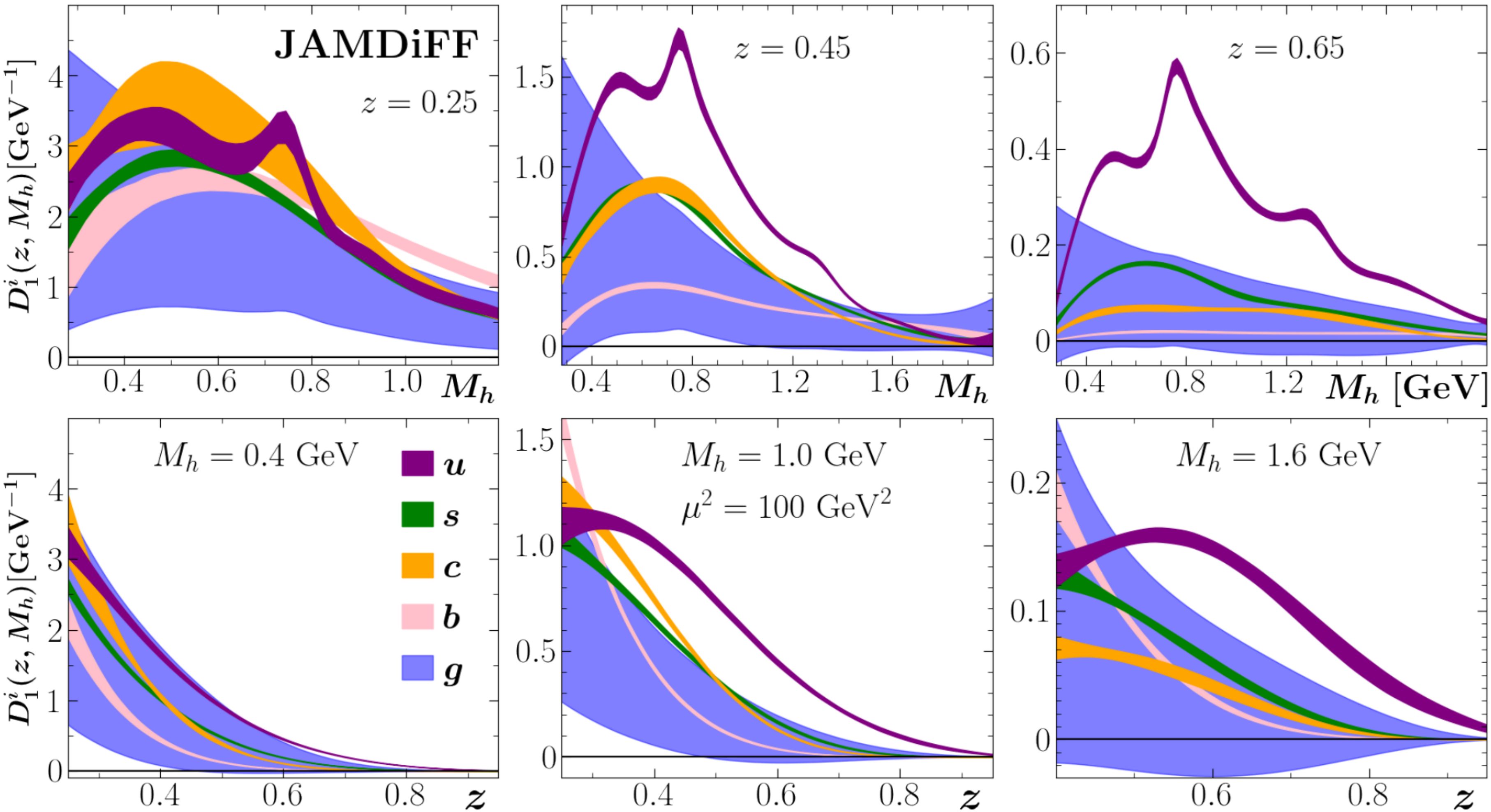
$$s_q^x = \frac{2}{C_q}\left(w_\gamma^q\ \mathrm{Re}\,\Gamma_\gamma^q + w_Z^q\ \mathrm{Re}\,\Gamma_Z^q\right)$$

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

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

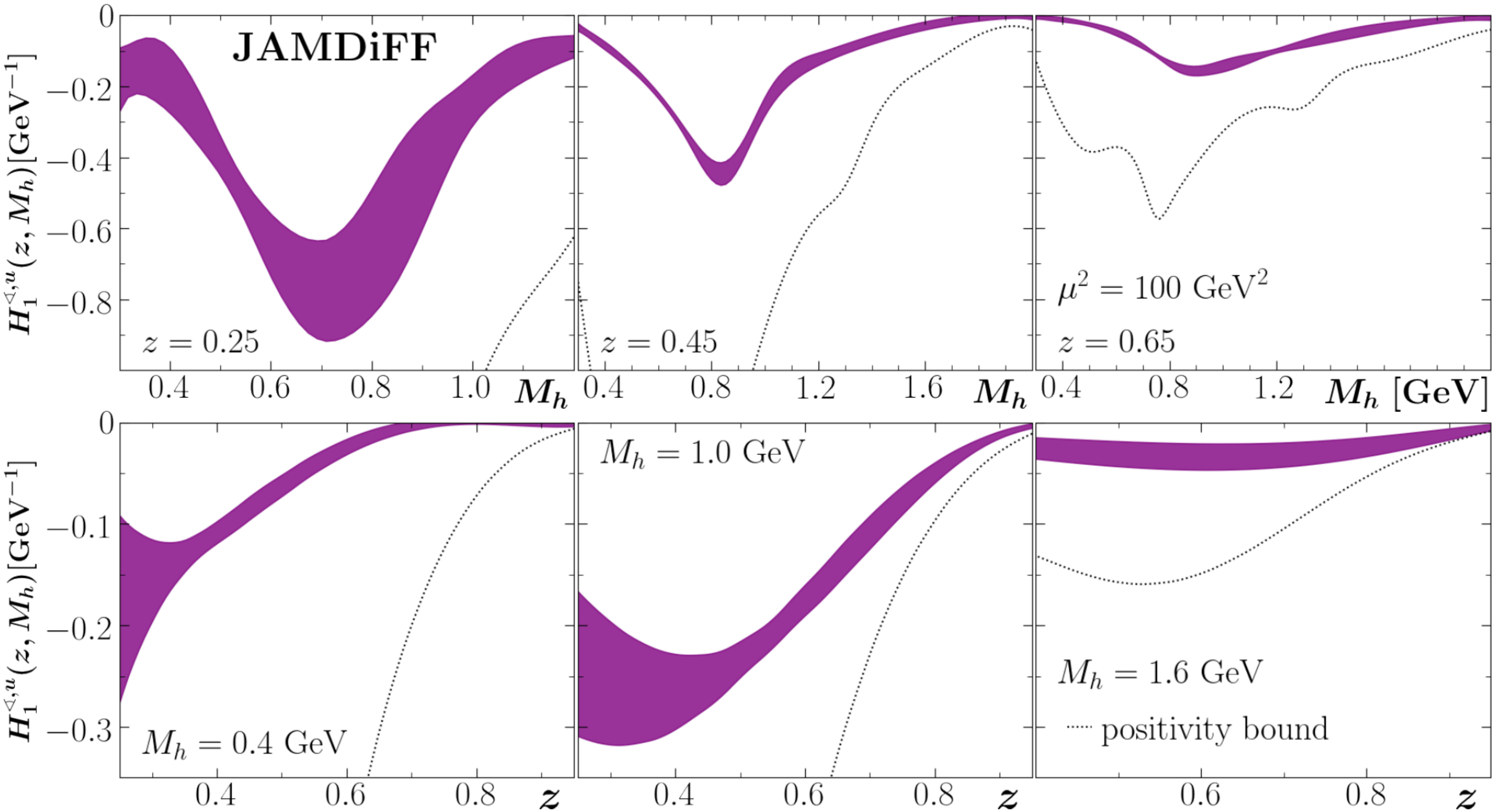
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255

$\pi^+\pi^-$ Dihadron fragmentation functions



JAM Collaboration, PRL 132 (2024) 091901 , PRD 109 (2024) 034024

$\pi^+\pi^-$ Dihadron fragmentation functions



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Transverse spin effects of quark @ EIC

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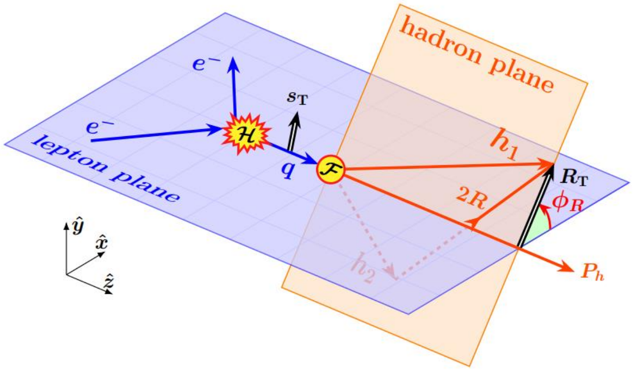
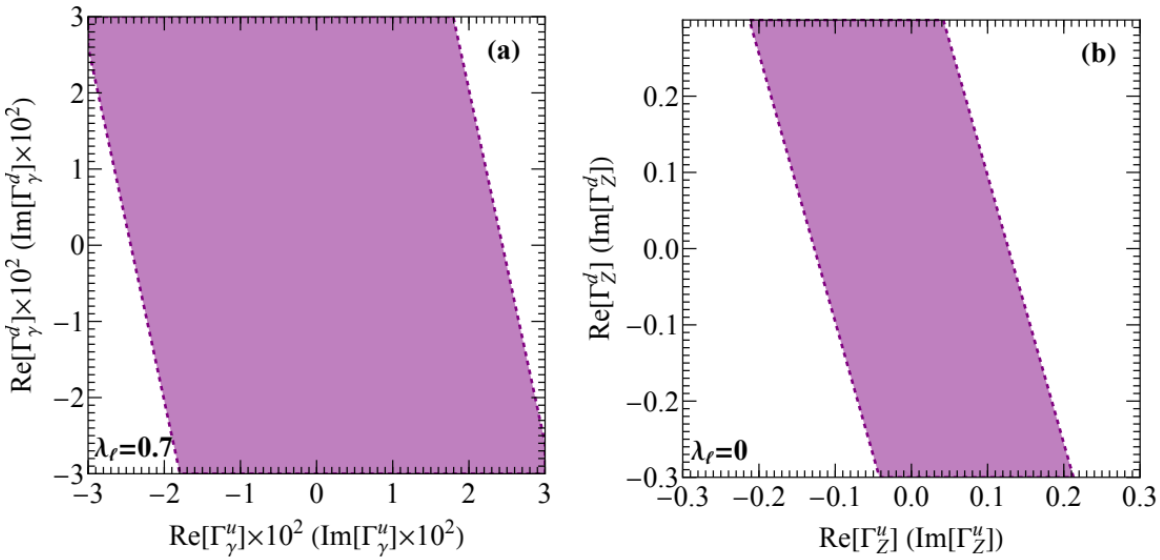


The non-trivial azimuthal distribution requires parity-violation effects:

- the longitudinal polarization of the electron
- the parity-violating Z interactions

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

$$A_{LR} = \frac{\sigma(\cos\phi_R > 0) - \sigma(\cos\phi_R < 0)}{\sigma(\cos\phi_R > 0) + \sigma(\cos\phi_R < 0)} = \frac{2}{\pi} A_I \qquad A_{UD} = \frac{\sigma(\sin\phi_R > 0) - \sigma(\sin\phi_R < 0)}{\sigma(\sin\phi_R > 0) + \sigma(\sin\phi_R < 0)} = \frac{2}{\pi} A_R$$



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

- Photon: O(0.01)
- Z-boson: O(0.1)

Summary

- The quark dipole moments is crucial for probing the internal structure of quarks
- The electroweak dipole operators are difficult to be probed at colliders since their leading effects are from $1/\Lambda^4$
- They can be probed at $1/\Lambda^2$ via transverse spin effects from non-perturbative functions: transversity and interference dihadron fragmentation functions
- Both Re & Im parts can be well constrained, *without impact from other NP and* offering a new opportunity for directly probing potential CP-violating effects.
- Our bounds are much stronger than other approaches, such as LHC and LEP

Thank you