Transverse spin asymmetry as a probe of new physics beyond the SM

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Institute of High Energy Physics

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Nov. 08-13 , 2024

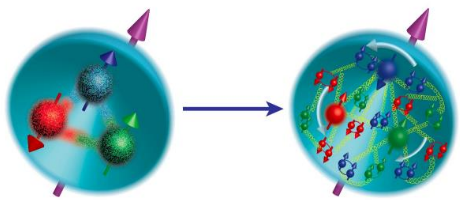
Based on Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255
Dingyu Shao, Bin Yan, Shu-Ruan Yuan, Cheng Zhang,
Sci. China Phys. Mech. Astron. 67 (2024) 281062
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801

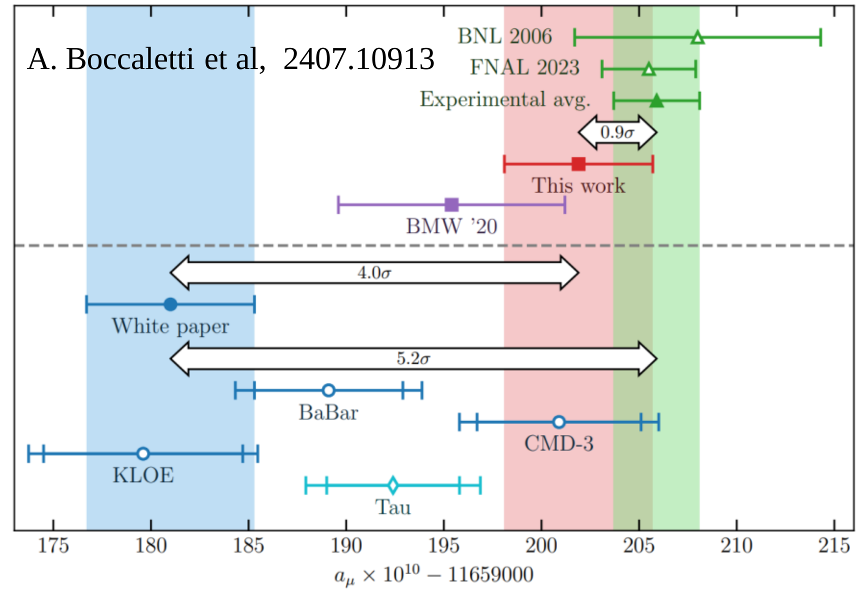
New physics and Dipole Operator

- 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..

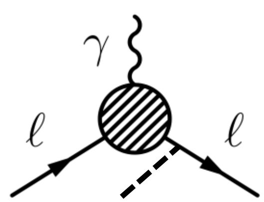




  - **Quarks: any internal structures?**

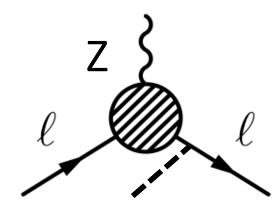
  - **From MDM and EDM to weak dipole moments?**

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



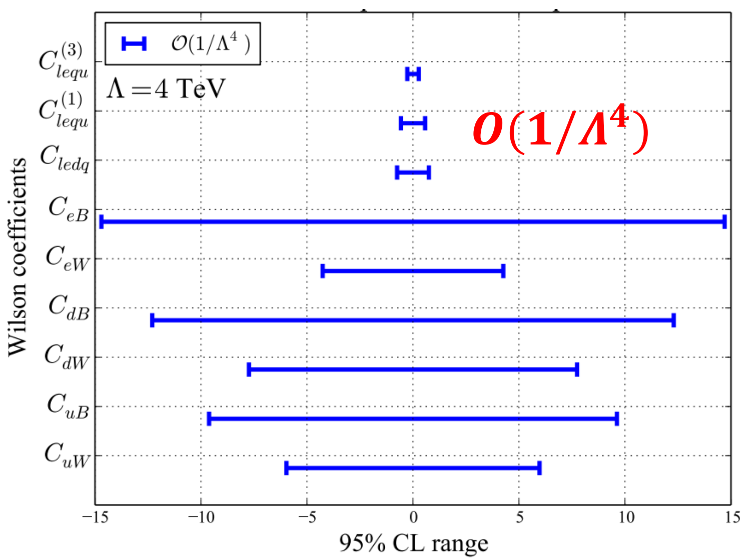
May have same physics source

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

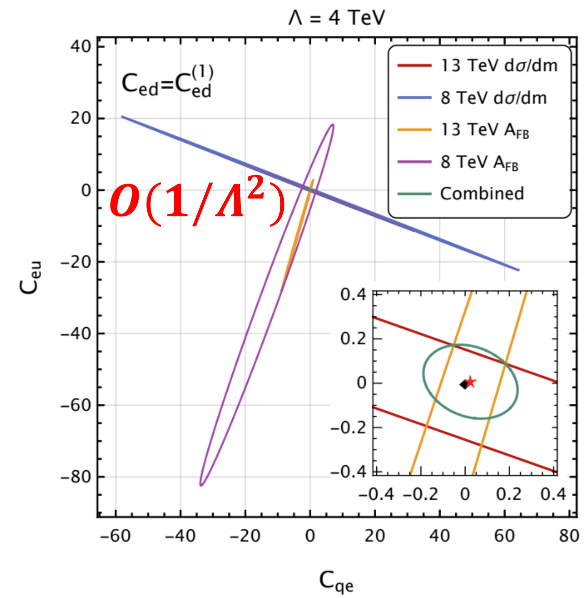


Example: Electroweak Dipole Operator

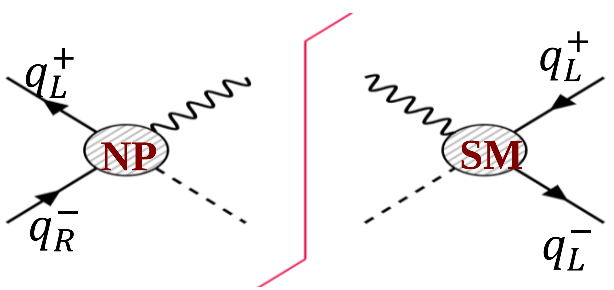
Single-Parameter-Analysis: EW dipole couplings are poorly constrained by Drell-Yan data



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



R. Boughezal et al, 2303.08257



=0 for the cross section

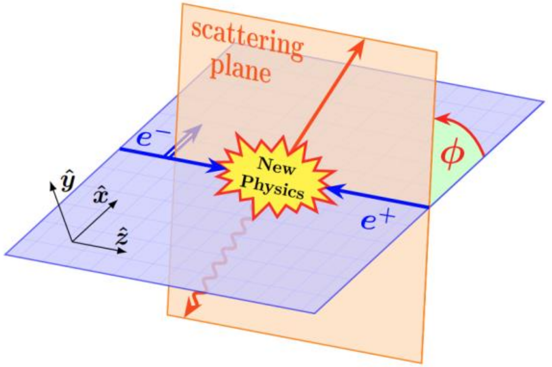
Leading contribution: $\left|\frac{c_{dipole}}{\Lambda^2}\right|^2$

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

Electroweak dipole moments of leptons

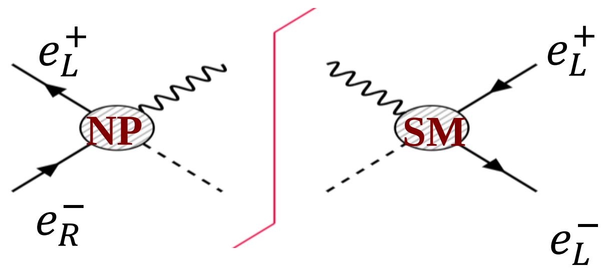
- Transversely polarized effect of beams @ lepton collider

The interference between the different helicity states



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

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



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

$$\bar{e}\sigma_{\mu\nu}eA^{\mu\nu}, \bar{e}\sigma_{\mu\nu}eZ^{\mu\nu}$$

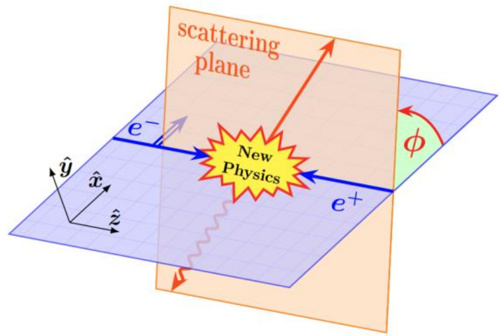
$$M \propto e^{i(\alpha 1 - \alpha 2)\phi} d(\theta)$$

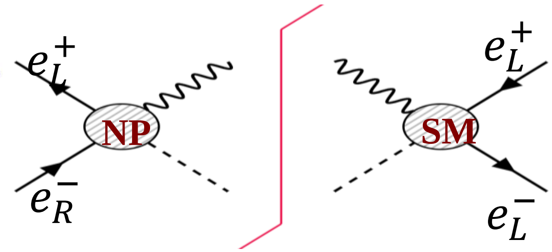
	U	L	T
U	$\lvert\mathcal{M}\rvert^2_{UU} \to 1$	$\lvert\mathcal{M}\rvert^2_{UL} \to 1$	$\lvert\mathcal{M}\rvert^2_{UT} \to \cos\phi, \sin\phi$
L	$\lvert\mathcal{M}\rvert^2_{LU} \to 1$	$\lvert\mathcal{M}\rvert^2_{LL} \to 1$	$\lvert\mathcal{M}\rvert^2_{LT} \to \cos\phi, \sin\phi$
T	$\lvert\mathcal{M}\rvert^2_{TU}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

Breaking the rotational invariance & A nontrivial azimuthal behavior

Electroweak dipole moments of leptons

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





$M \propto e^{i(\alpha 1-\alpha 2)\phi} d(\theta)$ $\quad e^{i\phi * 0}$ $\quad e^{i\phi}$

	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	$\lvert\mathcal{M}\rvert^2_{TU} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TL} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TT} \to 1, \cos 2\phi, \sin 2\phi$

$$\frac{2\pi\, d\sigma^i}{\sigma^i\, d\phi} = 1 + \underline{A_R^i(b_T, \bar{b}_T)}\cos\phi + \underline{A_I^i(b_T, \bar{b}_T)}\sin\phi + \underline{b_T\, \bar{b}_T\, B^i}\cos 2\phi + \mathcal{O}(1/\Lambda^4)$$

Re[C_{dipole}] Im[C_{dipole}] SM & other NP

CP-conserving CP-violation

- Linearly dependent on the dipole couplings C_{dipole} and spin b_T
- Without depending on other NP operators

Single Transverse Spin Asymmetries

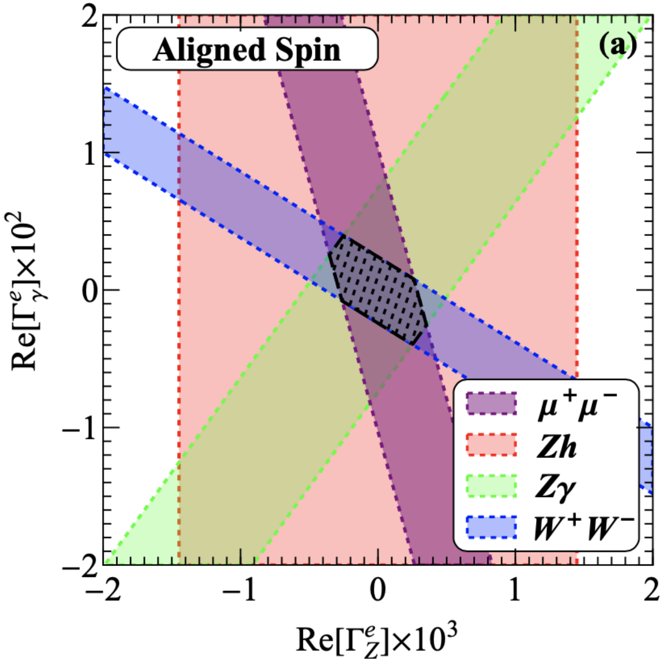
$$A_{LR}^i = \frac{\sigma^i(\cos\phi > 0) - \sigma^i(\cos\phi < 0)}{\sigma^i(\cos\phi > 0) + \sigma^i(\cos\phi < 0)} = \frac{2}{\pi} A_R^i$$

$$A_{UD}^i = \frac{\sigma^i(\sin\phi > 0) - \sigma^i(\sin\phi < 0)}{\sigma^i(\sin\phi > 0) + \sigma^i(\sin\phi < 0)} = \frac{2}{\pi} A_I^i,$$

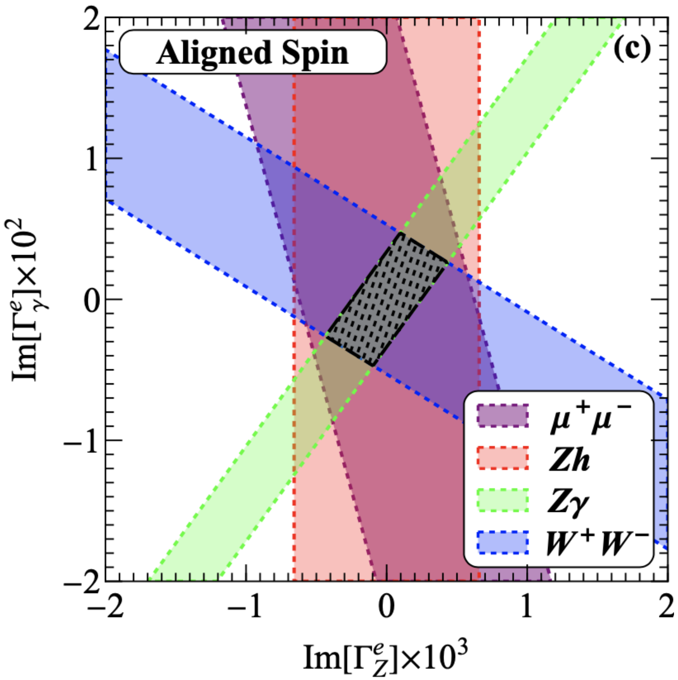
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan,

PRL 131 (2023) 241801

$\sqrt{s} = 250$ GeV, $\mathcal{L} = 5$ ab^{-1} $\quad (b_T, \bar{b}_T) = (0.8, 0.3)$



CP-conserved dipole operator



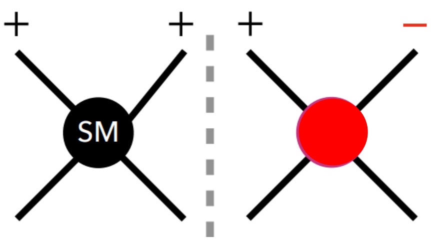
CP-violated dipole operator

- Our bounds are much stronger than other approaches by 1~2 orders of magnitude
- Weak dipole coupling, SSA: 0.01%, LHC: 1%

Transverse spin effects of electron @ EIC

- Electron dipole operators

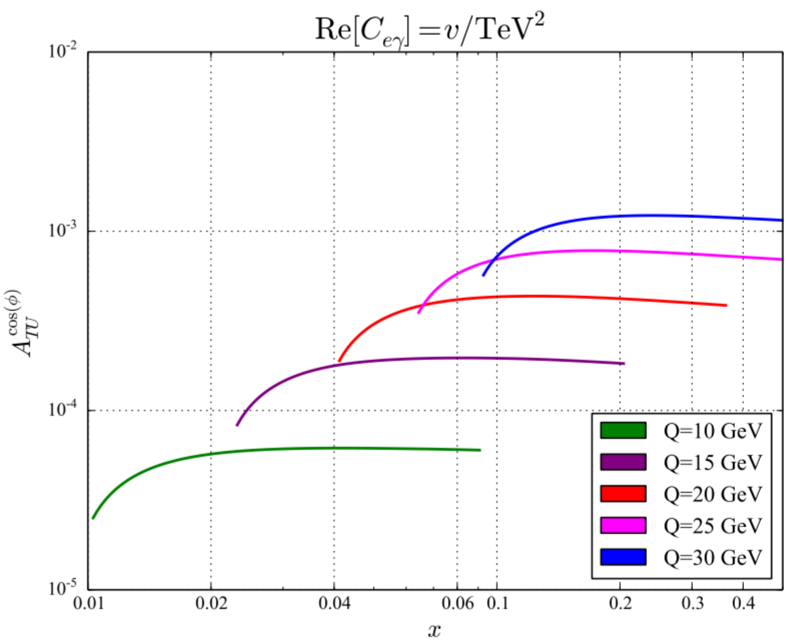
R. Boughezal, D. Florian, F. Petriello, W. Vogelsang,
PRD 107 (2023) 7, 075028

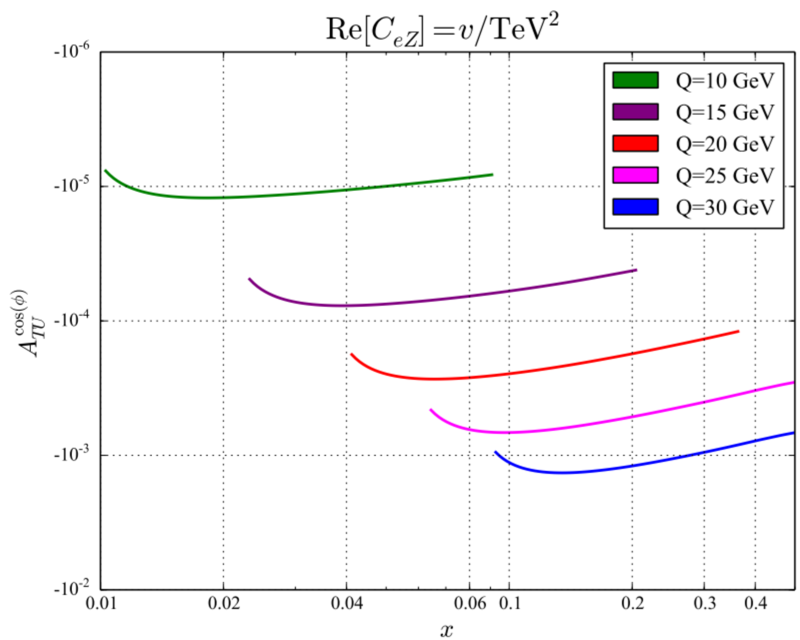


$$\sim \mathcal{O}(\frac{1}{\Lambda^2})$$

$$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu}e)\tau^I \varphi W^I_{\mu\nu},$$
$$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}e)\varphi B_{\mu\nu},$$

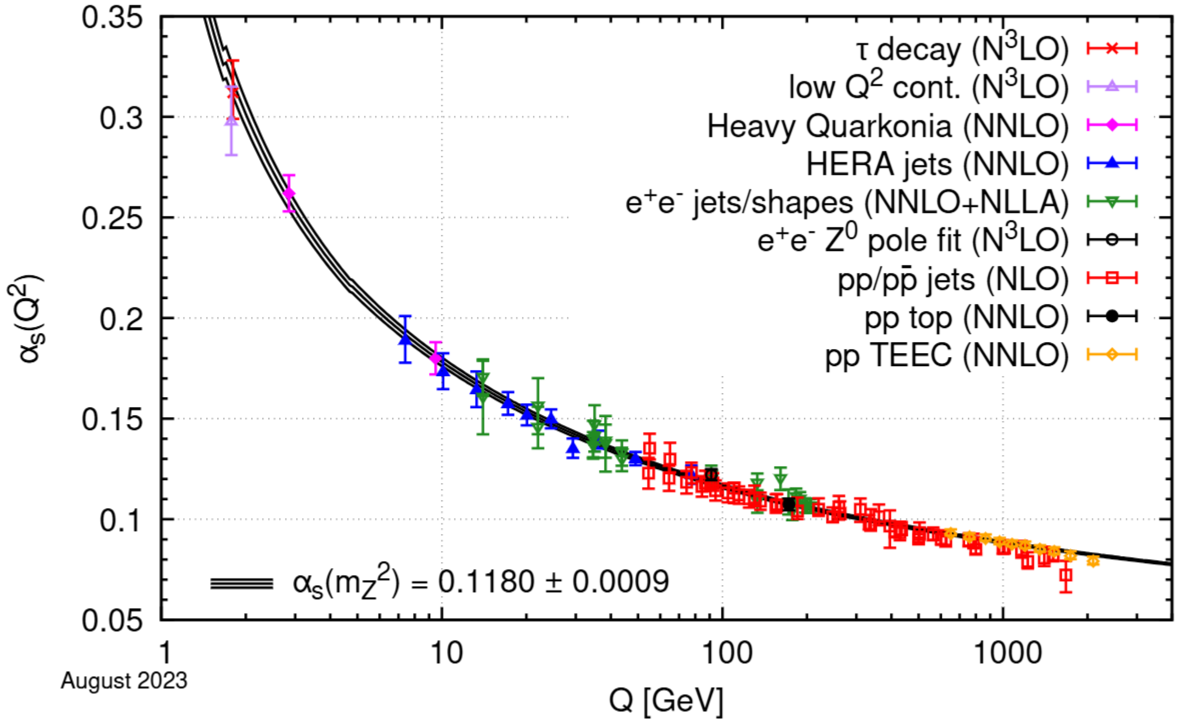
$$A_{TU} = \frac{\sigma(e^\uparrow p^U) - \sigma(e^\downarrow p^U)}{\sigma(e^\uparrow p^U) + \sigma(e^\downarrow p^U)}$$



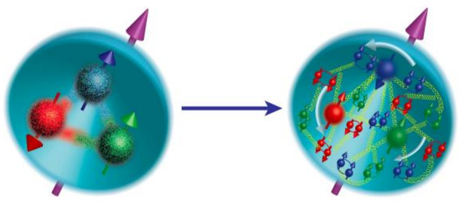


Electroweak dipole moments of quarks

➢ 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

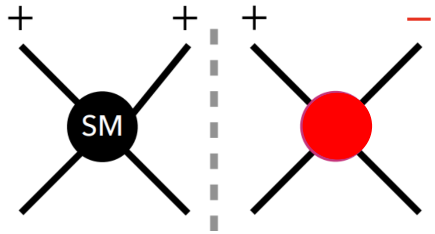
- Quark dipole operators

R. Boughezal, D. Florian, F. Petriello, W. Vogelsang, PRD 107 (2023) 7, 075028
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan, PRD 109 (2024) 095025

Leading Quark TMDPDFs — Nucleon Spin, Quark Spin

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

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



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

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

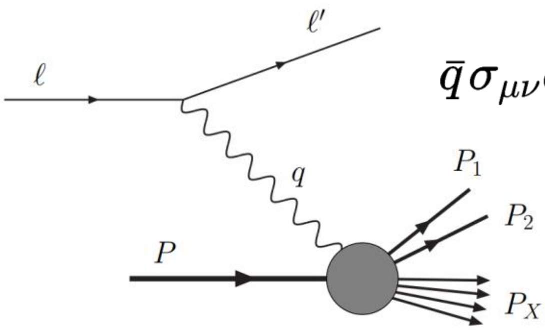
$$A_{UT} = \frac{\sigma(e^U p^\uparrow) - \sigma(e^U p^\downarrow)}{\sigma(e^U p^\uparrow) + \sigma(e^U p^\downarrow)}$$

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

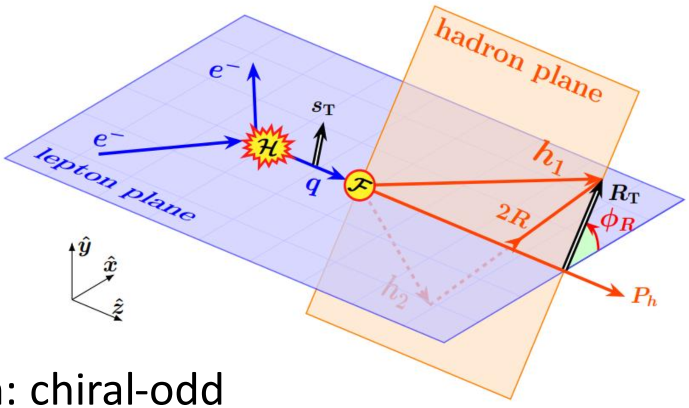
Kang, Prokudin, Sun, Yuan, PRD 93 (2016) 014009; Zeng, Dong, Liu, Sun, Zhao, PRD 109 (2024) 056002;
JAM Collaboration, PRD 106 (2022) 034014

Transverse spin effects of quark @ EIC

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



$$\bar{q}\sigma_{\mu\nu}qA^{\mu\nu}, \bar{q}\sigma_{\mu\nu}qZ^{\mu\nu}$$



- The interference dihadron fragmentation function: chiral-odd

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

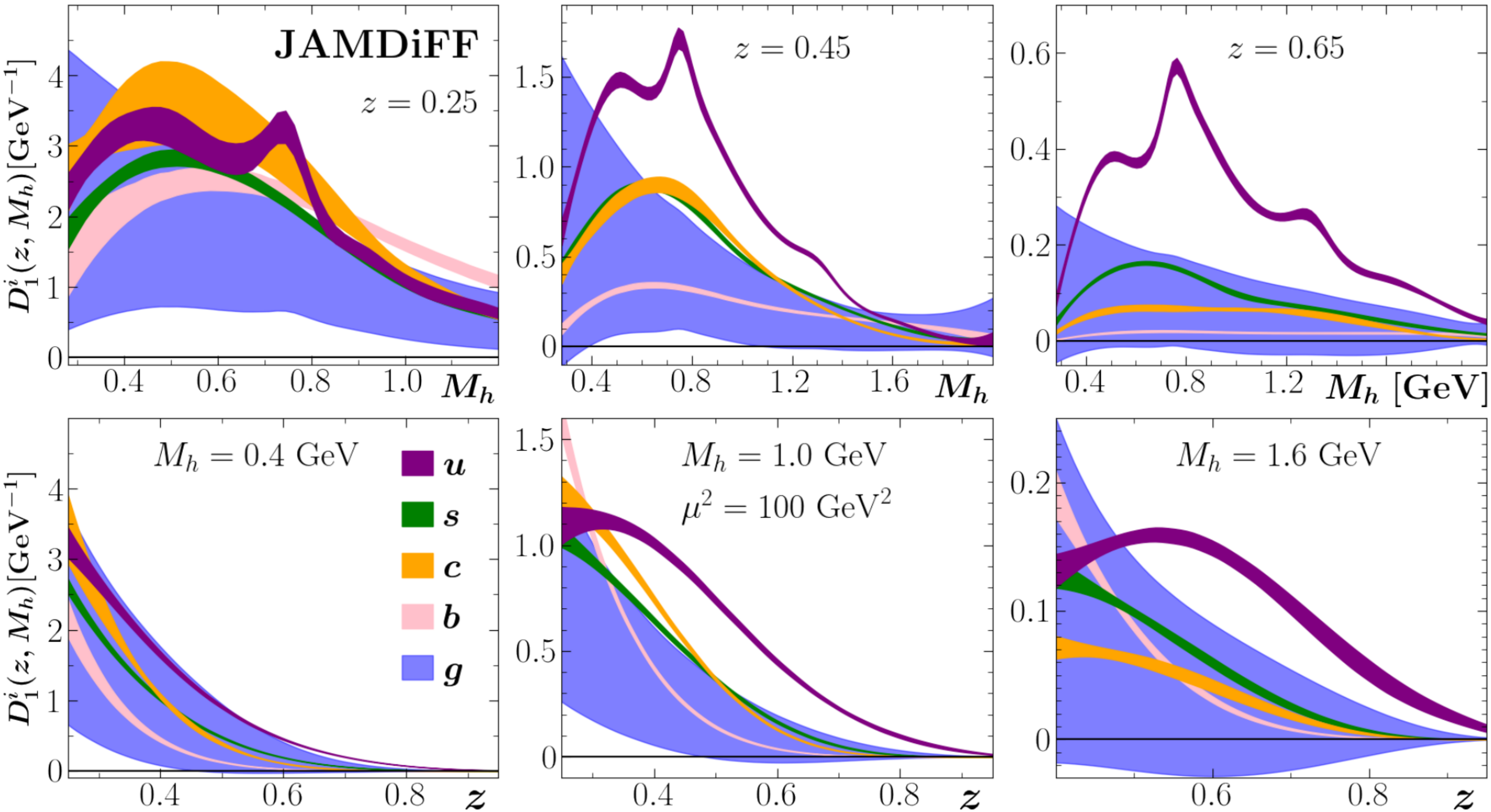
$$s_q^x = \frac{2}{C_q}\left(w_\gamma^q\,\mathrm{Re}\,\Gamma_\gamma^q + w_Z^q\,\mathrm{Re}\,\Gamma_Z^q\right)$$

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

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

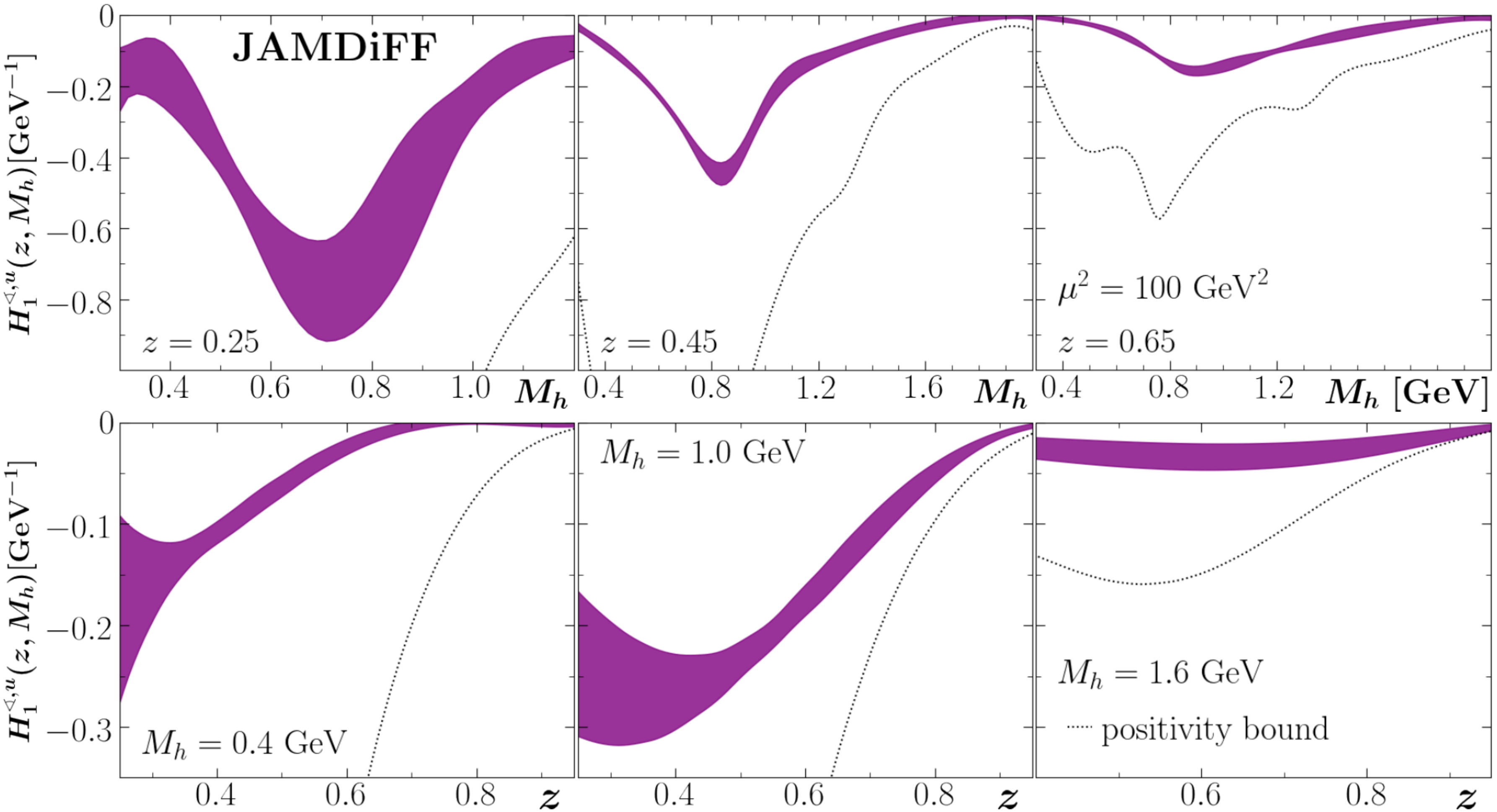
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255

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



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

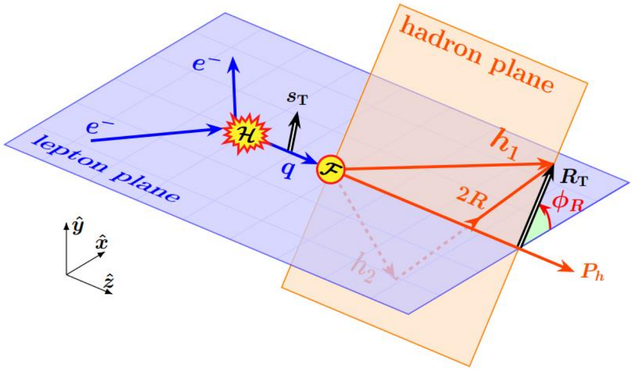
$\pi^+\pi^-$ Dihadron fragmentation functions



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

Transverse spin effects of quark @ EIC

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

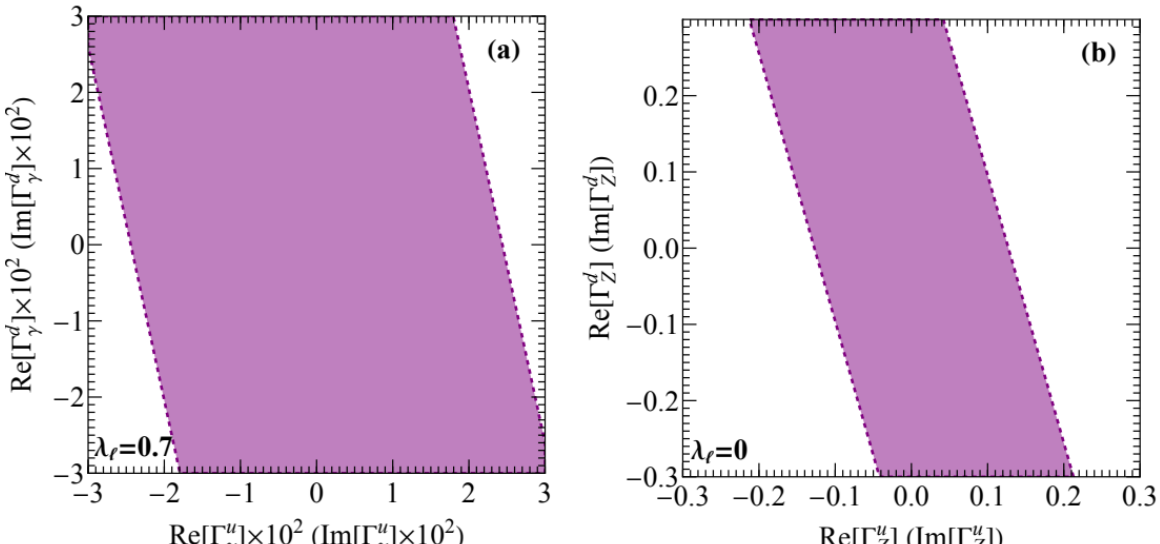


The non-trivial azimuthal distribution requires parity-violation effects:

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

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

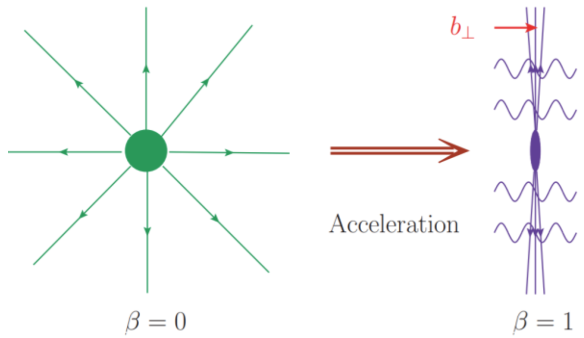
$$A_{LR} = \frac{\sigma(\cos\phi_R > 0) - \sigma(\cos\phi_R < 0)}{\sigma(\cos\phi_R > 0) + \sigma(\cos\phi_R < 0)} = \frac{2}{\pi} A_I \qquad A_{UD} = \frac{\sigma(\sin\phi_R > 0) - \sigma(\sin\phi_R < 0)}{\sigma(\sin\phi_R > 0) + \sigma(\sin\phi_R < 0)} = \frac{2}{\pi} A_R$$

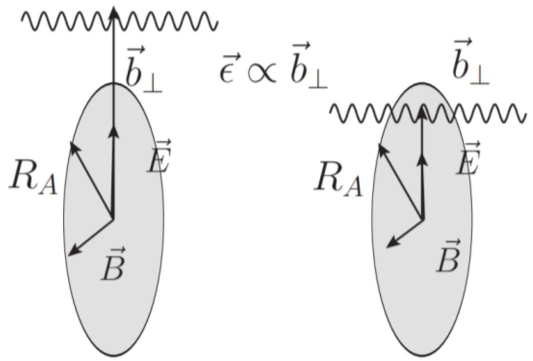


$\sqrt{s} = 105$ GeV, $\mathcal{L} = 1$ ab^{-1}

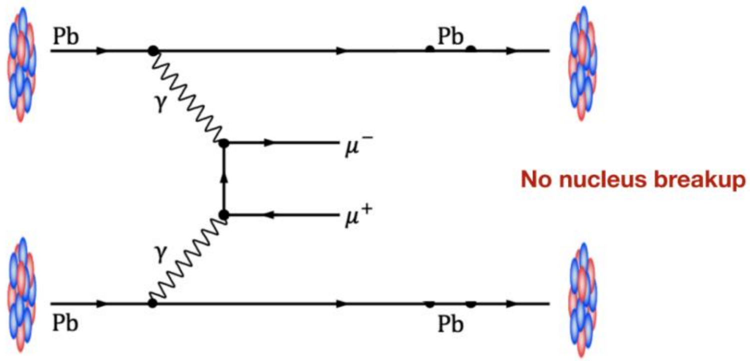
- Photon dipole: O(0.01)
- Z-boson dipole: O(0.1)

Linear polarization @ UPCs





C. Li, J. Zhou, Y. J. Zhou, Phys. Lett. B. 795, 576 (2019)



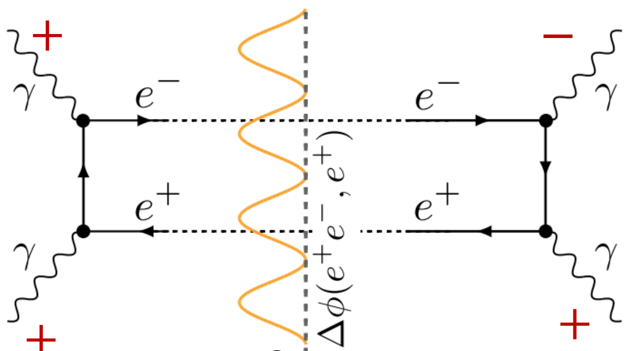
- Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic field
- Weizsacker-Williams equivalent photon approximation
- Photons are linearly polarized
- Large quasi-real photon flux $\propto Z^2$
- The impact parameter $b_\perp > 2R_A$

The linear polarization for gluons based on the NEEC:
Yuxun Guo, Xiaohui Liu, Feng Yuan, HuaXing Zhu, 2406.05880
Xiao Lin Li, Xiaohui Liu, Feng Yuan, HuaXing Zhu, PRD 108 (2023) L091502

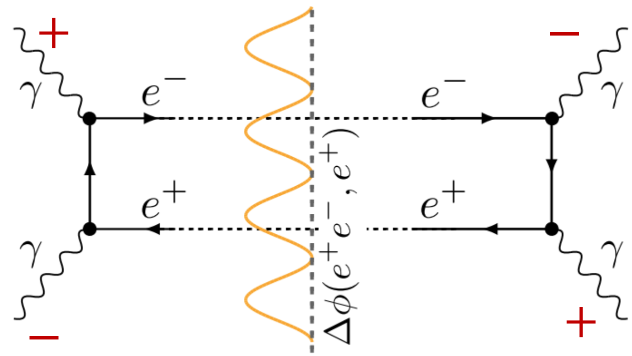
See Jian Zhou's talk

Linear polarization @ UPCs

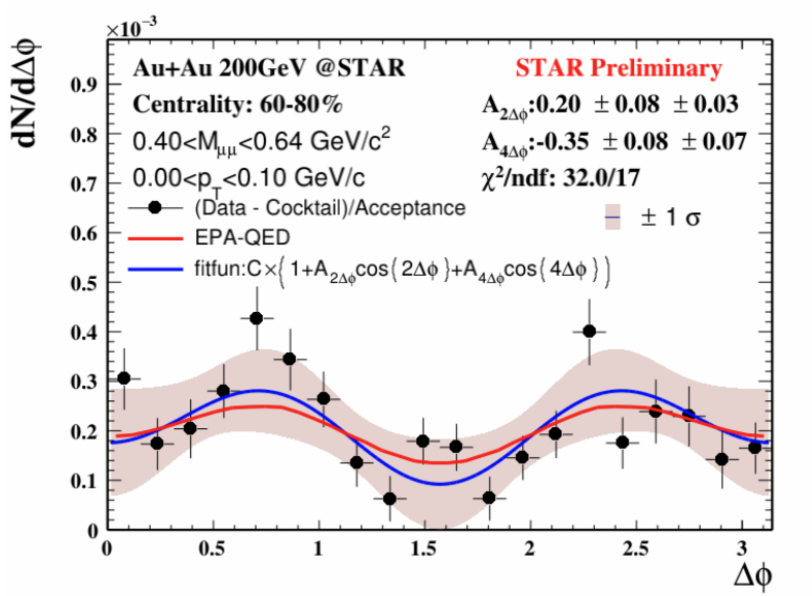
D. Y. Shao, C. Zhang, J. Zhou, Y. Zhou, PRD107 (2023) 3, 036020



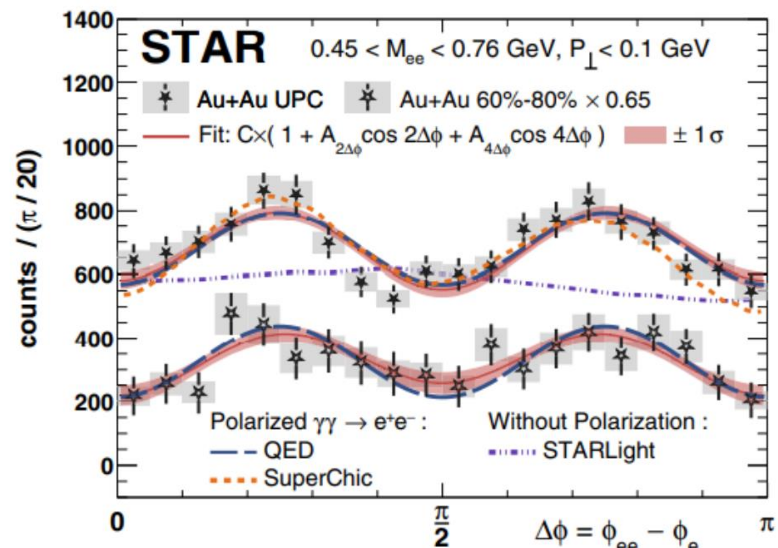
$$\frac{m_e^2}{p_T^2} cos2\Delta\phi$$



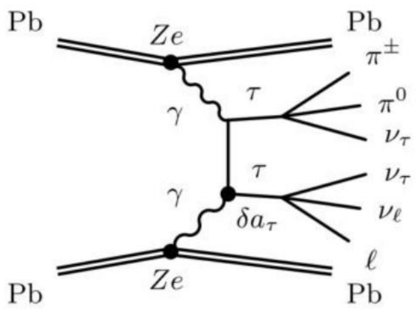
$$cos4\Delta\phi$$



PRL 127 (2021) 5, 052302

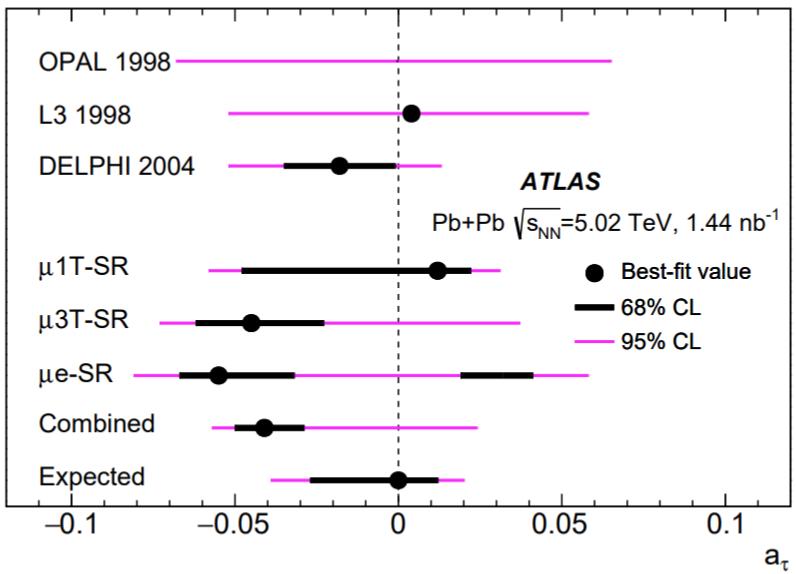


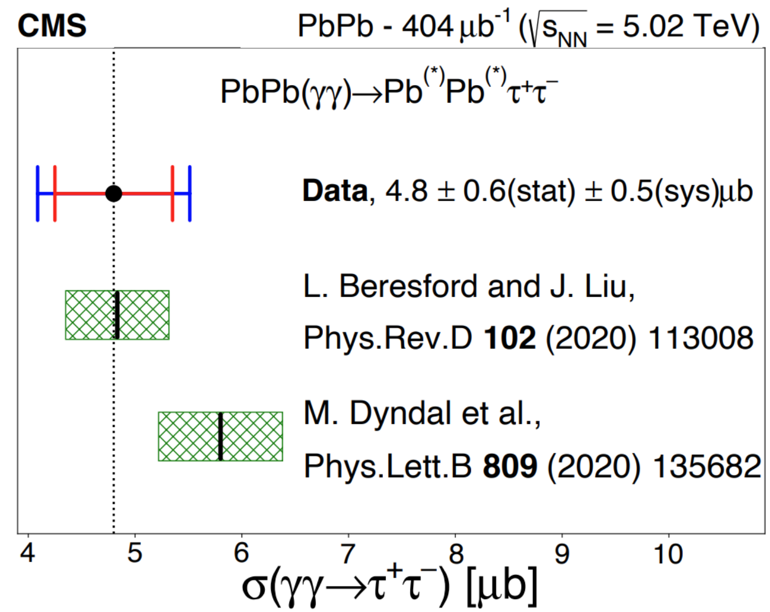
Tau pair production @ UPCs



$$\Gamma^{\mu}_{\text{eff.}}(q^2) = -ie\left[iF_2(q^2) + F_3(q^2)\gamma^5\right]\frac{\sigma^{\mu\nu}q_\nu}{2m_\tau}$$

$$F_2(0) = a_\tau, \quad F_3(0) = 2\frac{m_\tau d_\tau}{e}$$





Phys. Rev. Lett. 131 (2023) 15, 151802

Phys. Rev. Lett. 131 (2023) 151803

Linear polarization @ UPCs

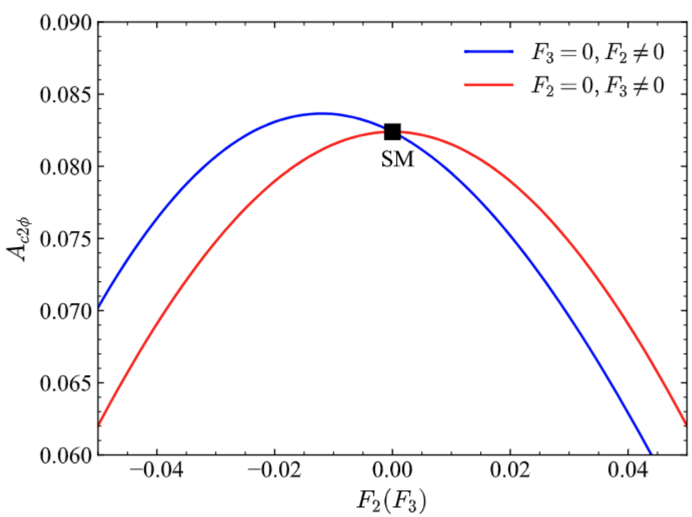
Dingyu Shao, Bin Yan, Shu-Ruan Yuan, Cheng Zhang,
Sci. China Phys. Mech. Astron. 67 (2024) 281062

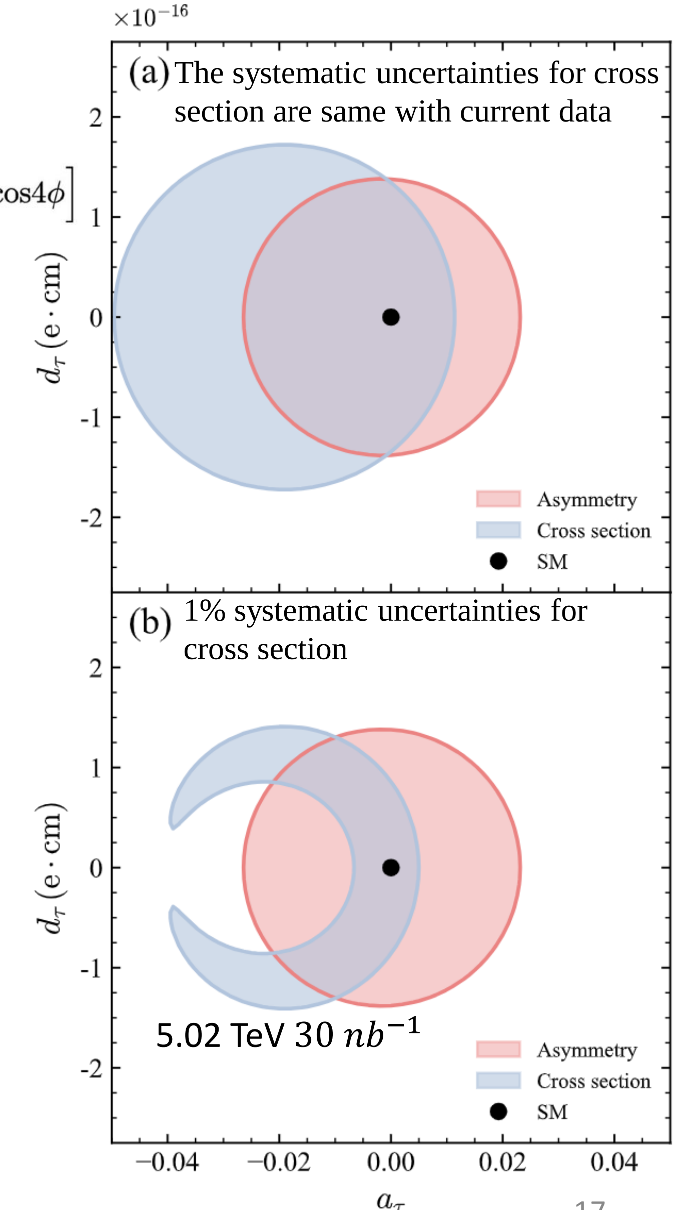
$$d\sigma \sim \left[A_0 + B_0^{(1)}F_2 + B_0^{(2)}F_2^2 + C_0^{(2)}F_3^2 + \left(A_2 + B_2^{(2)}F_2^2 + C_2^{(2)}F_3^2\right)\cos 2\phi + A_4 \cos 4\phi\right]$$

$$F_2(0) = a_\tau, \quad F_3(0) = 2\frac{m_\tau d_\tau}{e}$$

Suppressed by lepton mass

$$A_{c2\phi} = \frac{\sigma(\cos 2\phi > 0) - \sigma(\cos 2\phi < 0)}{\sigma(\cos 2\phi > 0) + \sigma(\cos 2\phi < 0)}$$





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
- The photons from UPCs are linearly polarized and can be used to probe the NP

Thank you