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

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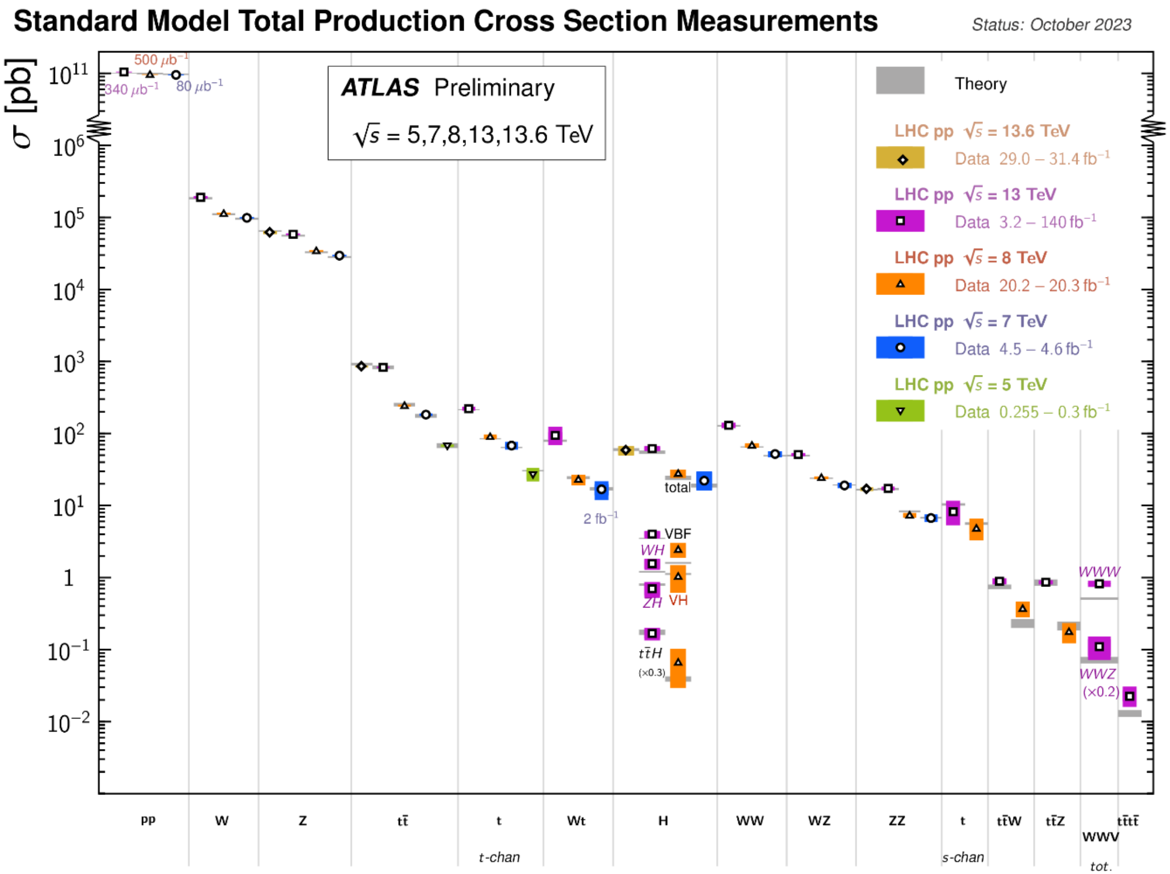
HENPIC seminar
Oct. 10 , 2024

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801, 2408.07255
Dingyu Shao, Bin Yan, Shu-Ruan Yuan, Cheng Zhang, Sci. China Phys. Mech. Astron. 67 (2024) 281062
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan, PRD 109 (2024) 095025
Xu Li, Bin Yan, C.-P. Yuan, 2405.04069

The status of SM



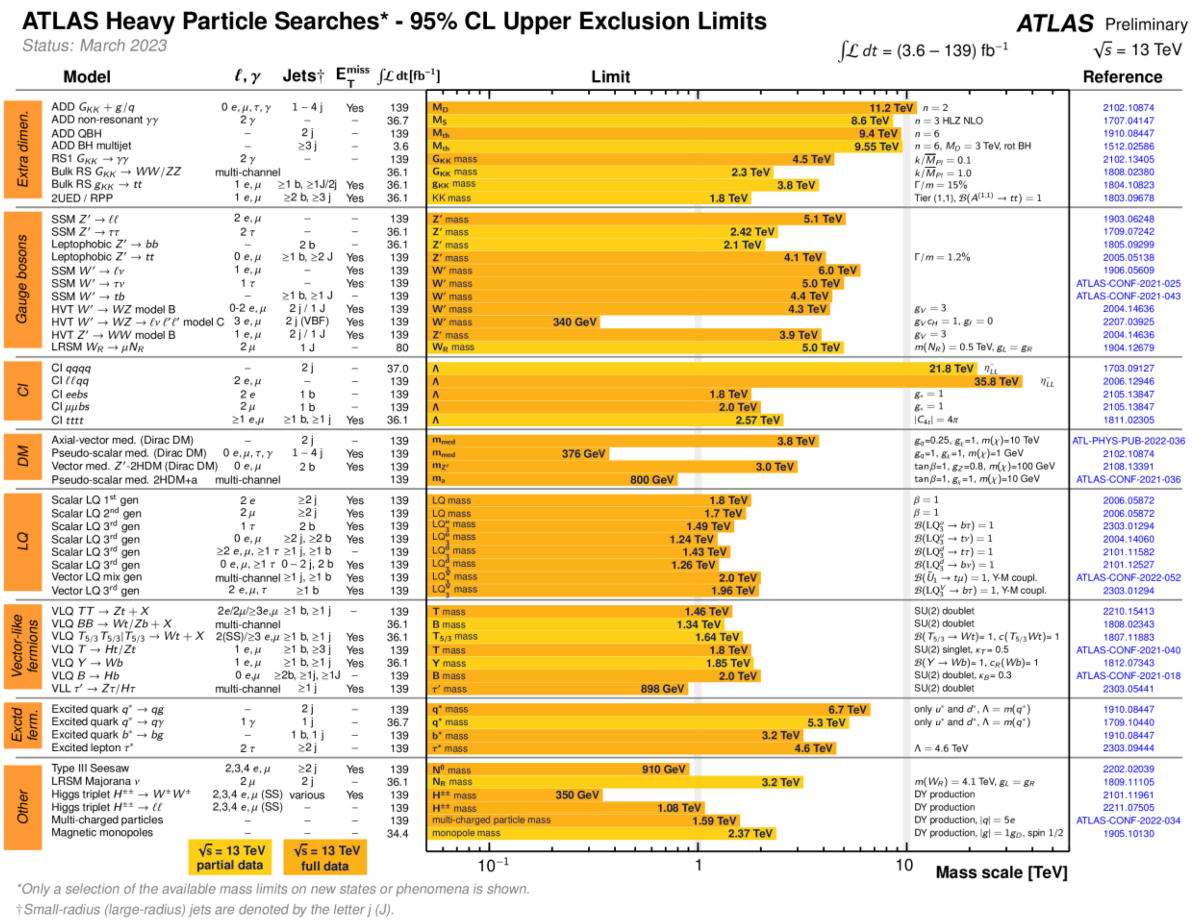
Open questions:

- Dark Matter ?
- neutrino mass?
- matter-antimatter asymmetry?
- W-mass anomaly, muon g-2
- electroweak symmetry breaking?
- Higgs boson (Composite or elementary particle)?
- …

Remarkable agreement between SM theory and data

New Physics beyond the SM
new measurements

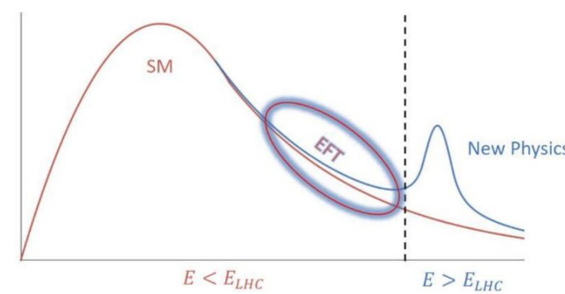
New Physics Searches @ LHC



Top-down approach

$\mathcal{O}(\mathrm{TeV})$

SMEFT



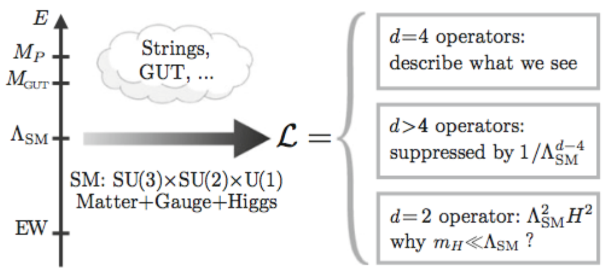
Bottom-up approach

New Physics and EFT

1. The κ framework for the couplings:

BSM physics is expected to affect the production modes and decay channels by a SM like interactions

2. The Standard Model Effective Field Theory



Linear realized EFT

Higgs is a fundamental particle

Weak interacting

W. Buchuller, D. wyler 1986

B. Grzadkowski et al, 2010

L. Lehman, A. Marin, 2015

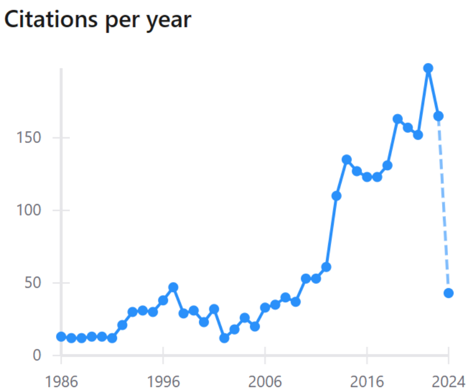
B. Henning et al, 2015

H-L. Li et al, 2020

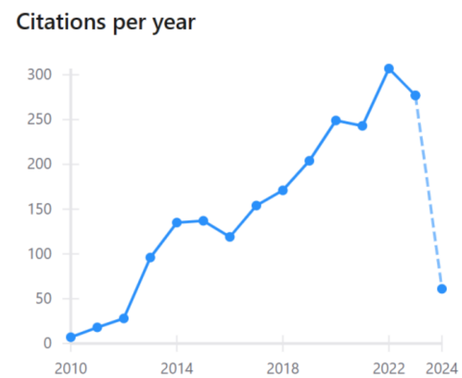
Murphy, 2020

$$\mathcal{L} = \frac{C_6}{\Lambda^2}\mathcal{O}_6 + \frac{C_8}{\Lambda^4}\mathcal{O}_8 + \ldots$$

W. Buchuller, D. wyler 1986



B. Grzadkowski et al, 2010



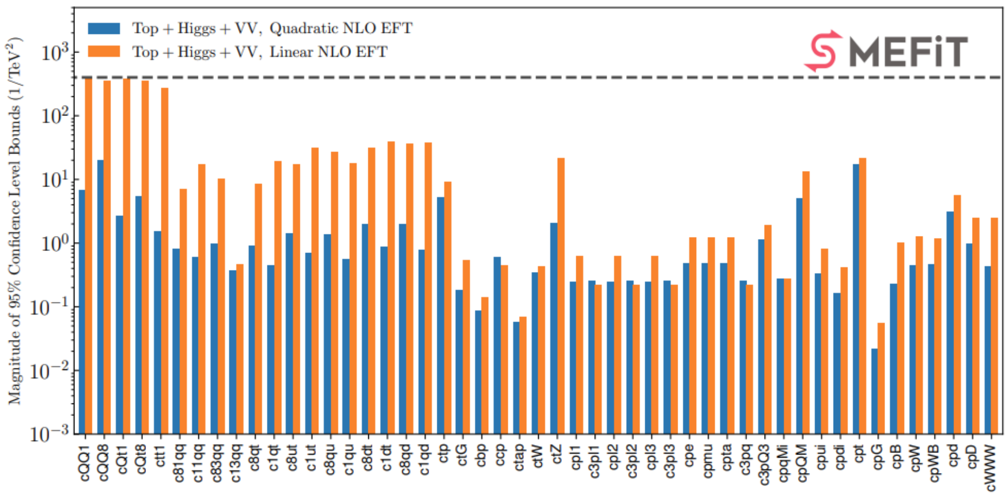
3. Higgs Effective Field Theory

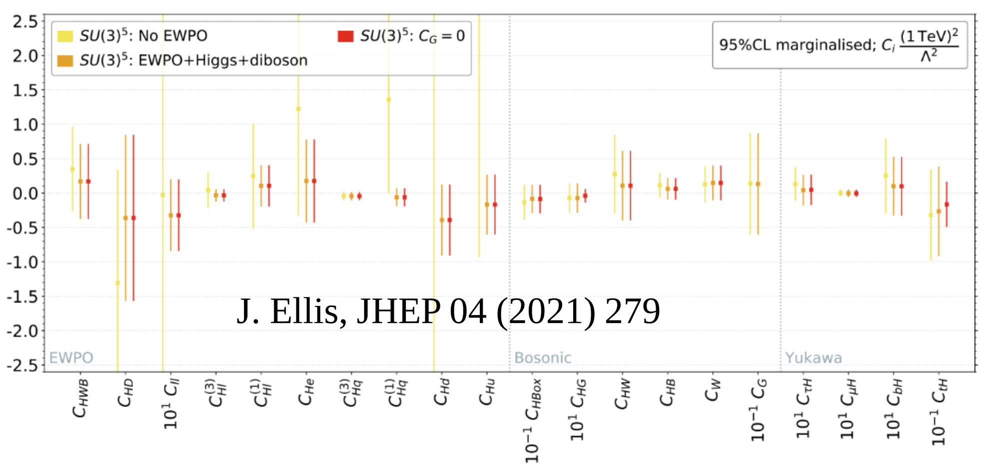
Callan, Coleman, Wess, Zumino, 1969

The electroweak chiral Lagrangian+light Higgs, A.C. Longhitano, 1980,….

Global analysis @ SMEFT

SMEFiT Collaboration, JHEP 11 (2021) 089





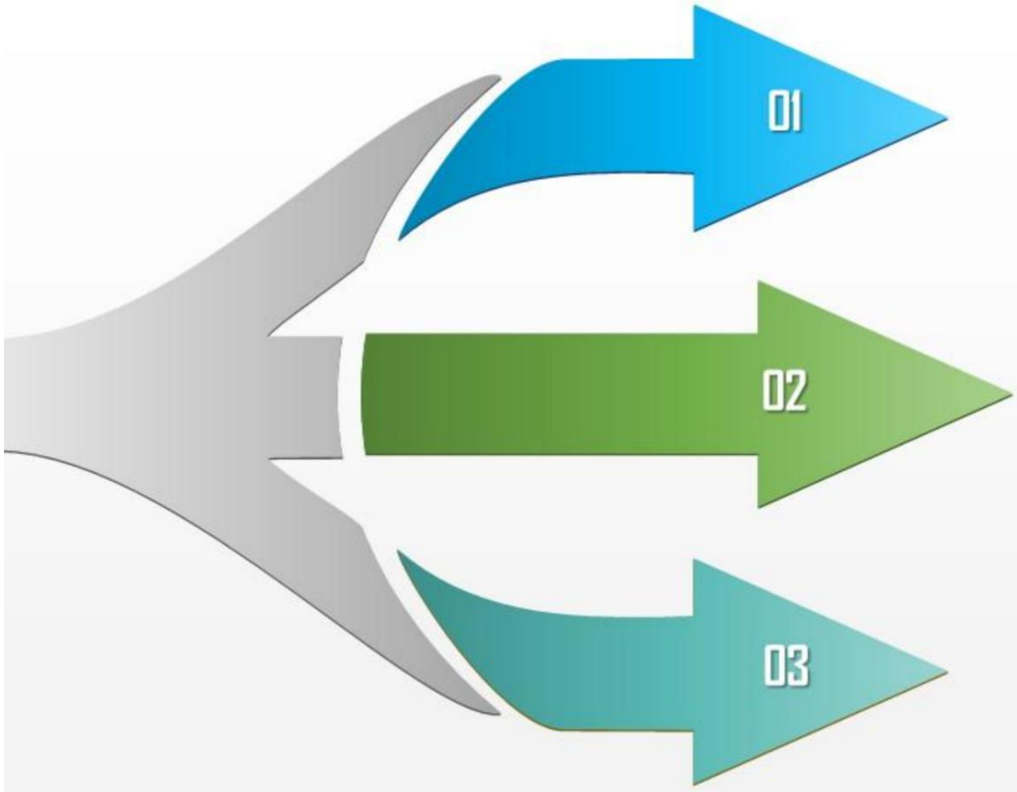
J. Ellis, JHEP 04 (2021) 279

The SMEFT approach allows for the combination

- Higgs data
- Electroweak precision observables
- Diboson production
- Top quark Physics
- ……

SMEFT is becoming one of the standard tool for the LHC experimental analysis

So, what's the next step for the new physics searches from the theoretical point of view?



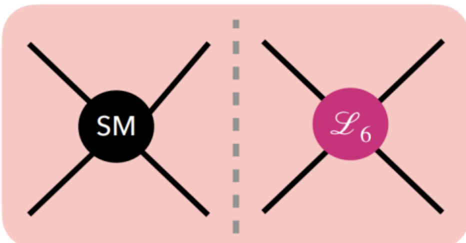
- Global analysis with more processes; the combination of low energy and high energy measurements
- QCD and EW correction to reduce the theoretical uncertainties
- New observables and new measurements

→ Transverse/linear polarization observables

New Physics and SMEFT

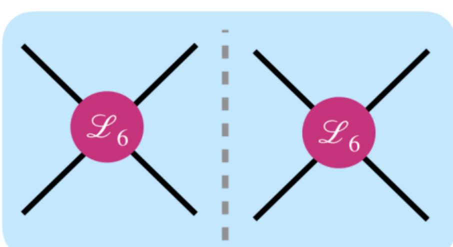
B. Grzadkowski et al, JHEP 10 (2010) 085

Interference effects



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

Chirality-flipped operators



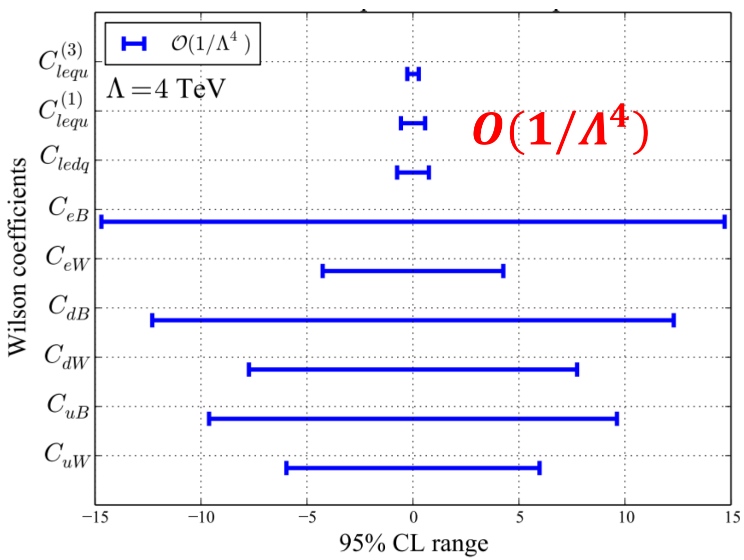
$\sim \mathcal{O}(\frac{1}{\Lambda^4})$

The constraints will be very weak

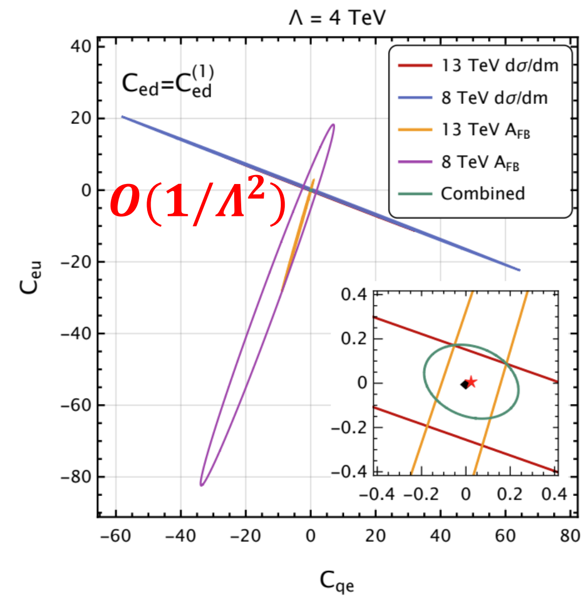
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) \varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

Example: Dipole Operator

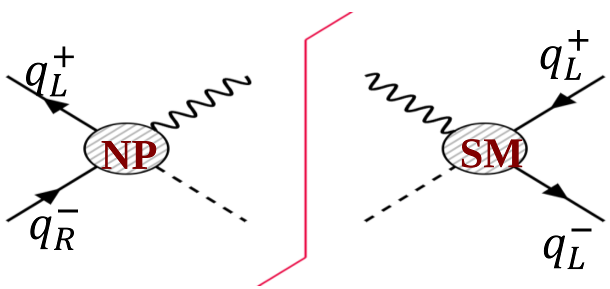
Single-Parameter-Analysis: EW dipole couplings are poorly constrained



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



R. Boughezal et al, 2303.08257



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

=0 for the cross section

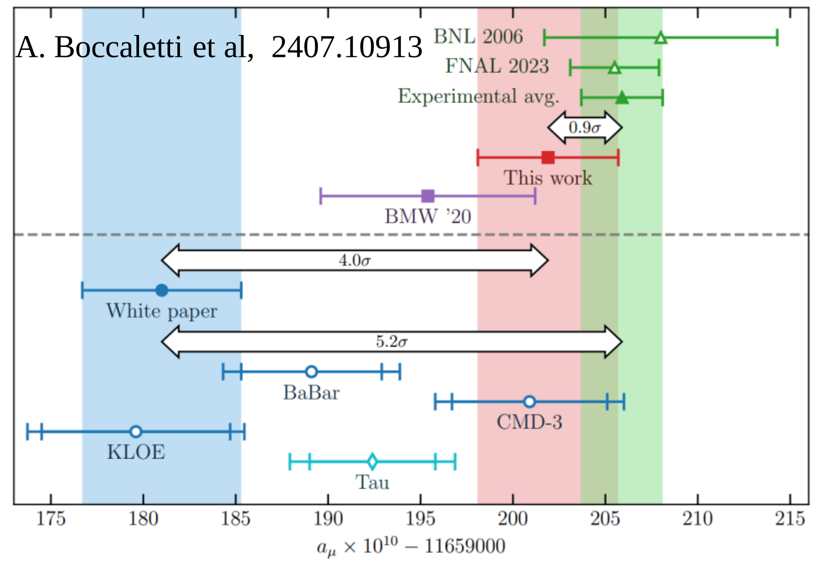
New physics and Dipole Operator

- Magnetic dipole moments: probing the internal structures of particles

  - Elementary particle:

    Electron: g/2=1.001159…

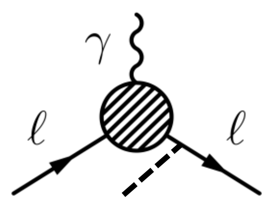
    Muon: g/2=1.0011659..



- The Lattice's results agree with data, but different from data-driven approach

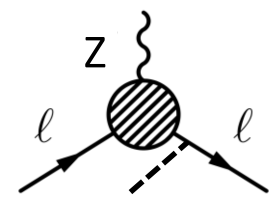
- New physics or non-perturbative issue?
  Loop-induced by the BSM

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



May have same physics source

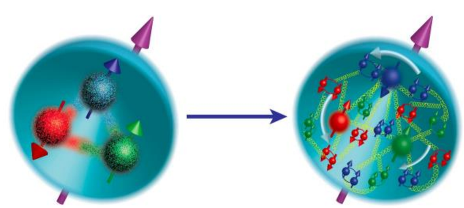
$$B_{\mu\nu}, W_{\mu\nu}$$



  - Composite particle:

    Proton: g/2=2.7928444..

    Neutron: g/2=-1.91394308..



New physics and Dipole Operator

- Magnetic dipole moments: probing the internal structures of particles

Elementary particle:

Electron: g/2=1.001159…

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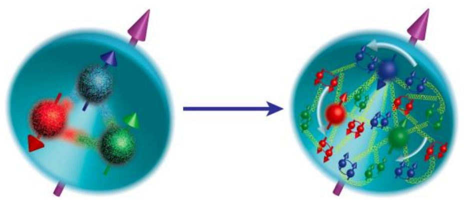
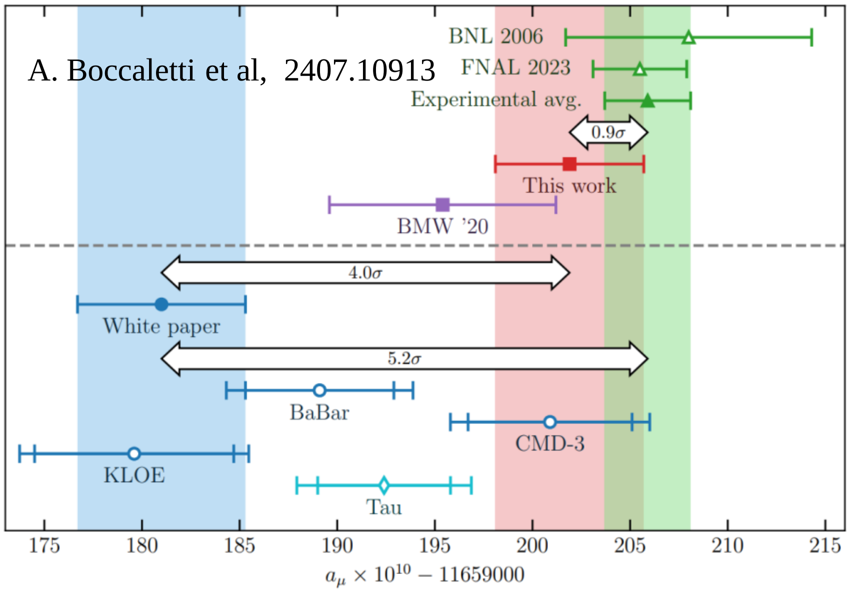
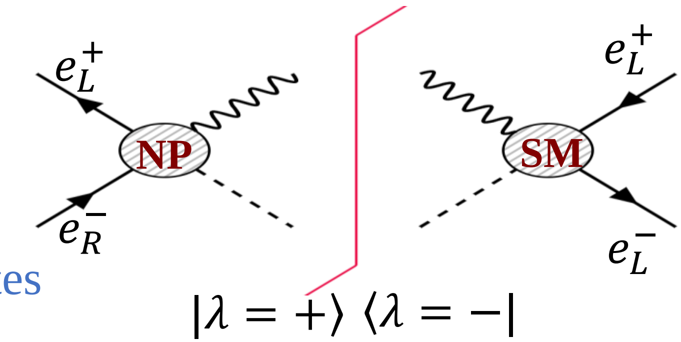




- How to probe the electroweak dipole interactions?
- Do quarks have any internal structures or probing quark dipole moments?

Electroweak dipole moments of leptons

Is it possible to probe the dipole operators at $o\left(\frac{1}{\Lambda^2}\right)$?

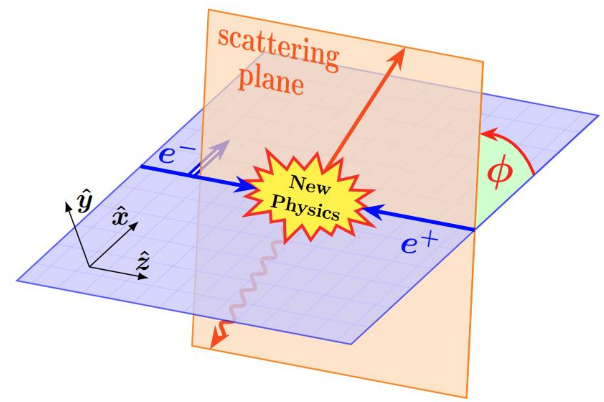


Transversely polarized effect of beams:

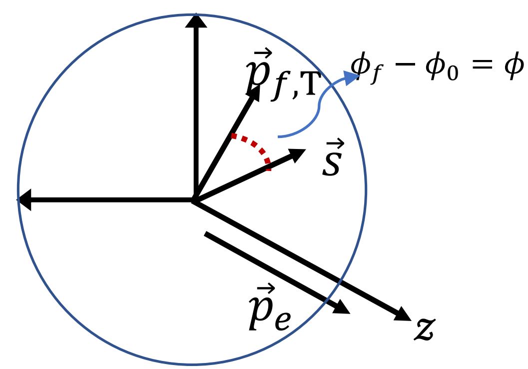
The interference between the different helicity states

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

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



Breaking the rotational invariance & A nontrivial azimuthal behavior



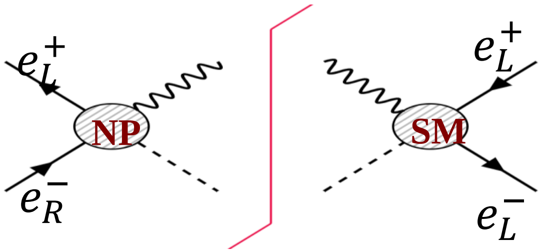
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan,
PRL 131 (2023) 241801

Transverse spin effects @ CEPC

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

Ken-ichi Hikasa, *Phys.Rev.D* 33 (1986) 3203, *PhysRevD*.38 (1988) 1439

G. Moortgat-Pick et al. *Phys.Rept*. 460 (2008), *JHEP* 01 (2006)



$e^{i\phi*0}$ $\qquad$ $e^{i\phi}$

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

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

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

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

CP-conserving $\qquad$ CP-violation

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

Single Transverse Spin Asymmetries

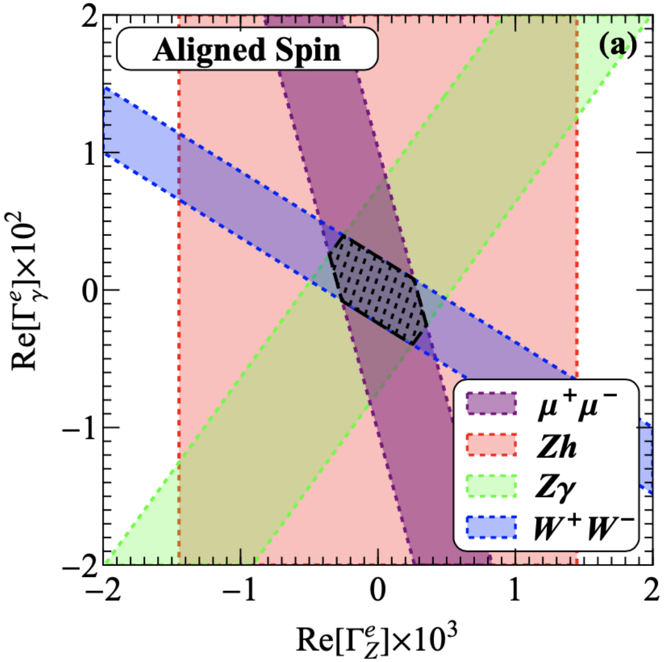
$$A^i_{LR} = \frac{\sigma^i(\cos\phi > 0) - \sigma^i(\cos\phi < 0)}{\sigma^i(\cos\phi > 0) + \sigma^i(\cos\phi < 0)} = \frac{2}{\pi} A^i_R$$

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

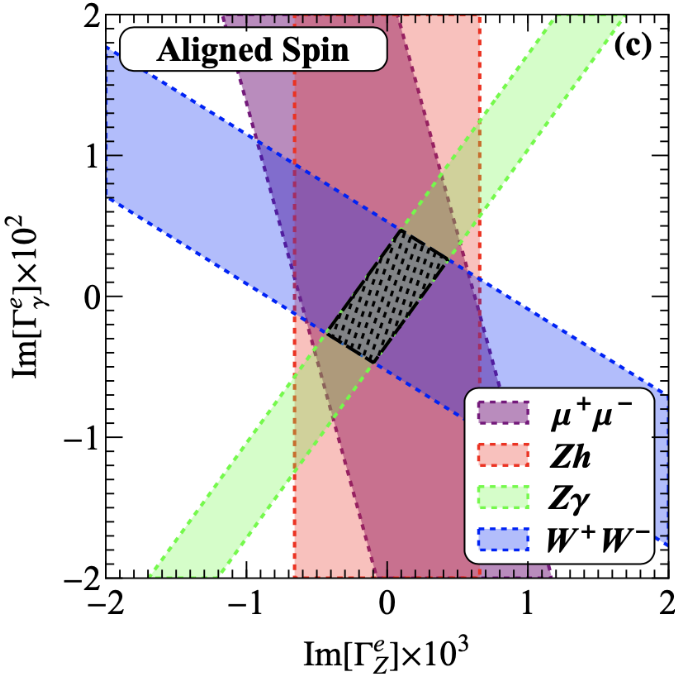
$\sqrt{s} = 250$ GeV, $\mathcal{L} = 5$ ab^{-1} $\quad (b_T, \bar{b}_T) = (0.8, 0.3)$

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

PRL 131 (2023) 241801



CP-conserved dipole operator



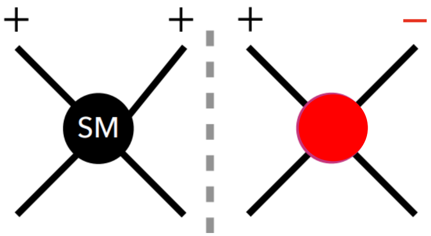
CP-violated dipole operator

- 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

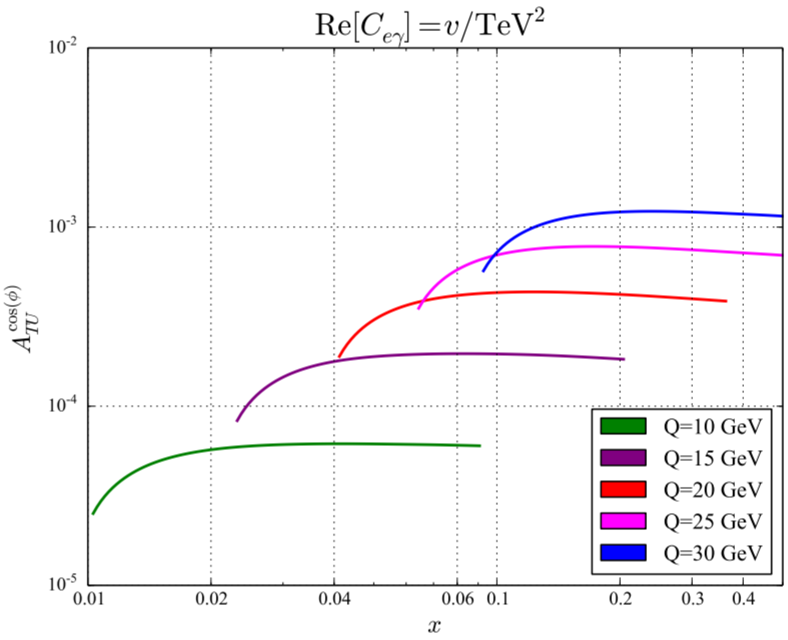
R. Boughezal, D. Florian, F. Petriello, W. Vogelsang, PRD 107 (2023) 7, 075028

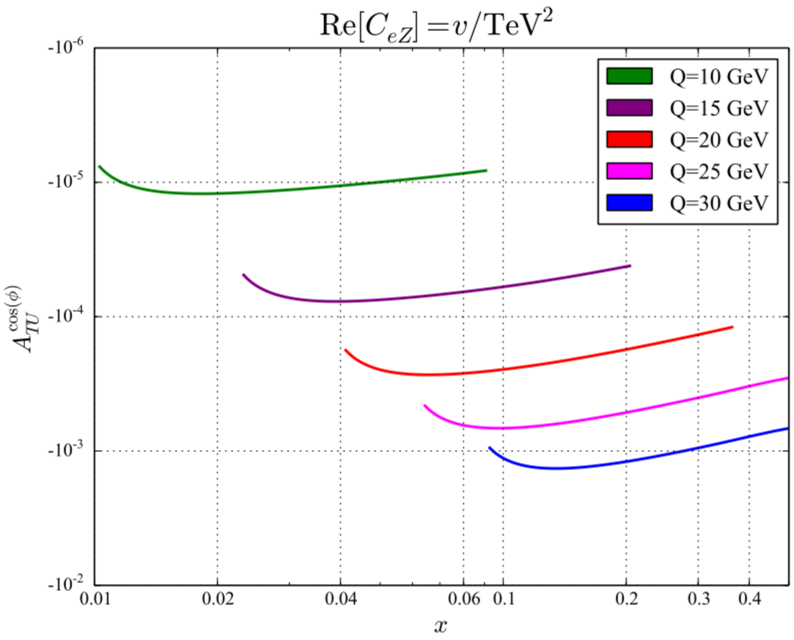


$$\sim \mathcal{O}(\frac{1}{\Lambda^2})$$

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

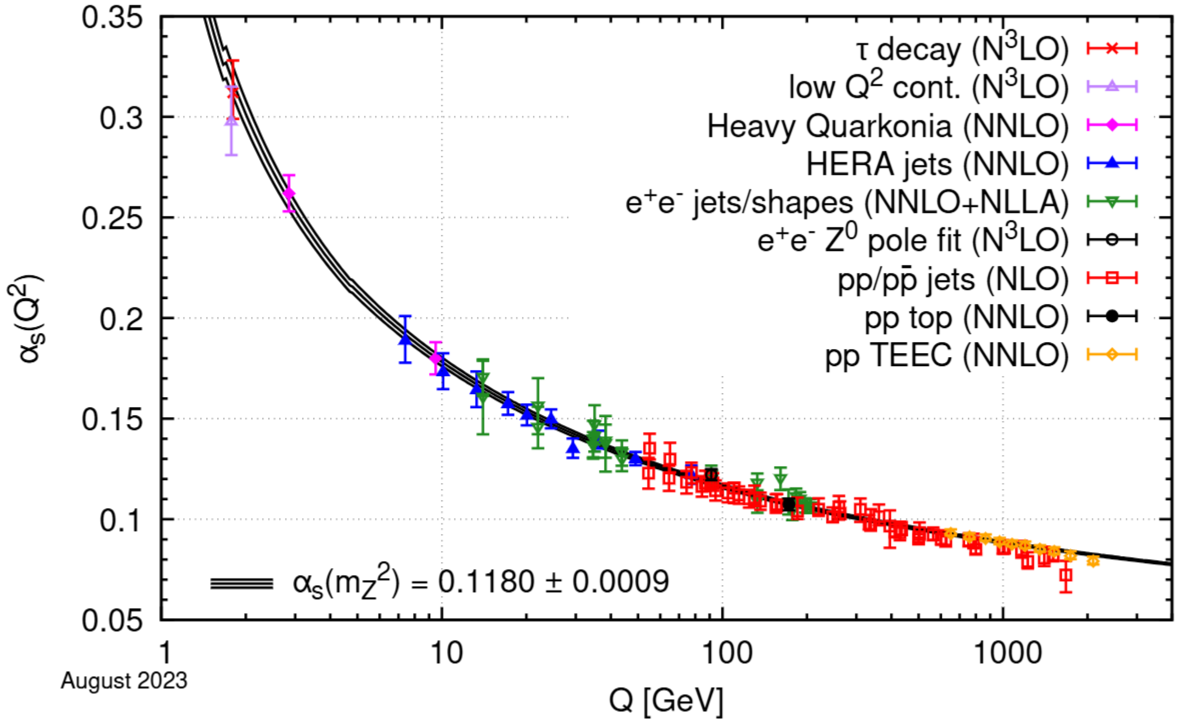
$$A_{TU} = \frac{\sigma\left(e^{\uparrow}p^{U}\right) - \sigma\left(e^{\downarrow}p^{U}\right)}{\sigma\left(e^{\uparrow}p^{U}\right) + \sigma\left(e^{\downarrow}p^{U}\right)}$$



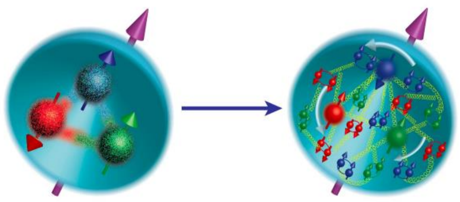


Electroweak dipole moments of quarks

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



Asymptotic freedom of QCD theory



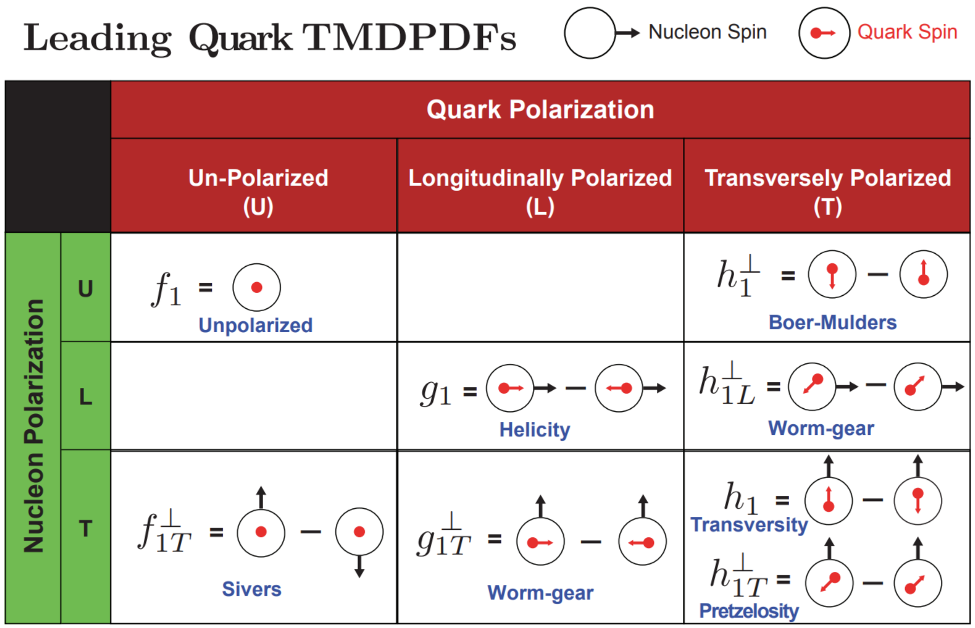
- How to probe the spin information of quarks?

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

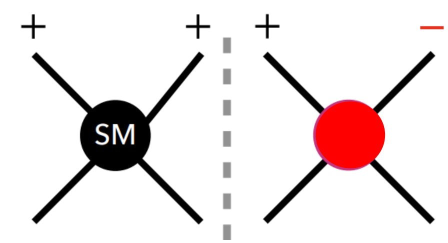
Transverse spin effects of quark @ EIC

- 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

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

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

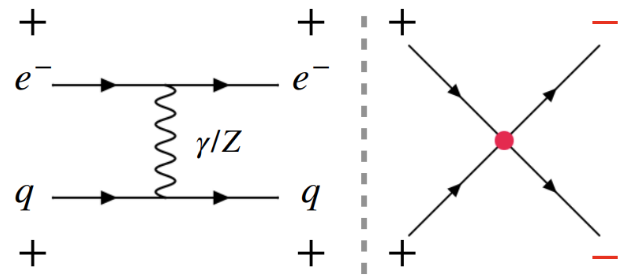
Kang, Prokudin, Sun, Yuan, PRD 93 (2016) 014009; Zeng, Dong, Liu, Sun, Zhao, PRD 109 (2024) 056002;
JAM Collaboration, PRD 106 (2022) 034014

Transverse spin effects @ EIC

- Scalar and tensor four fermion operators

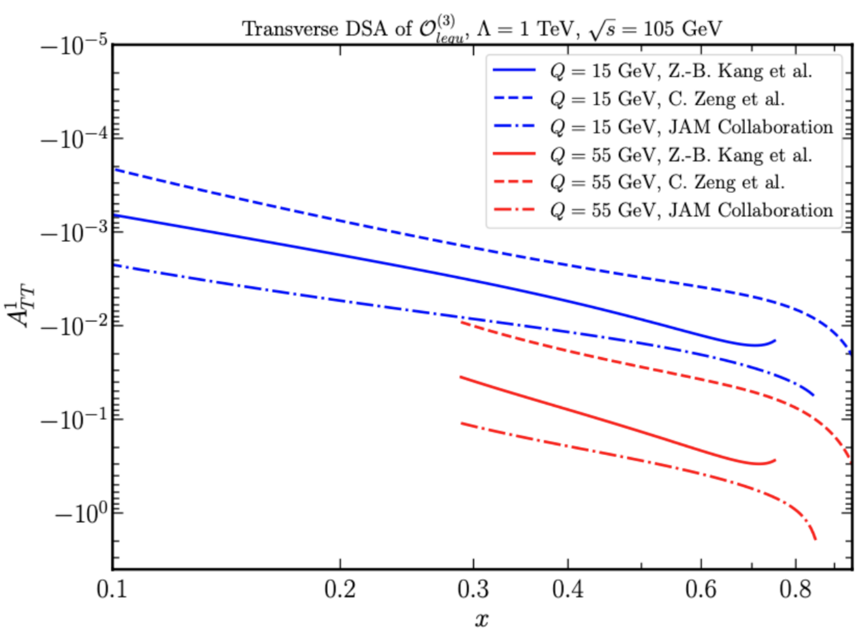
$$\mathcal{O}_{ledq} = (\bar{L}^j e)(\bar{d}Q^j),$$
$$\mathcal{O}^{(1)}_{lequ} = (\bar{L}^j e)\,\epsilon_{jk}\,(\bar{Q}^k u),$$
$$\mathcal{O}^{(3)}_{lequ} = (\bar{L}^j \sigma^{\mu\nu} e)\,\epsilon_{jk}\,(\bar{Q}^k \sigma_{\mu\nu} u),$$

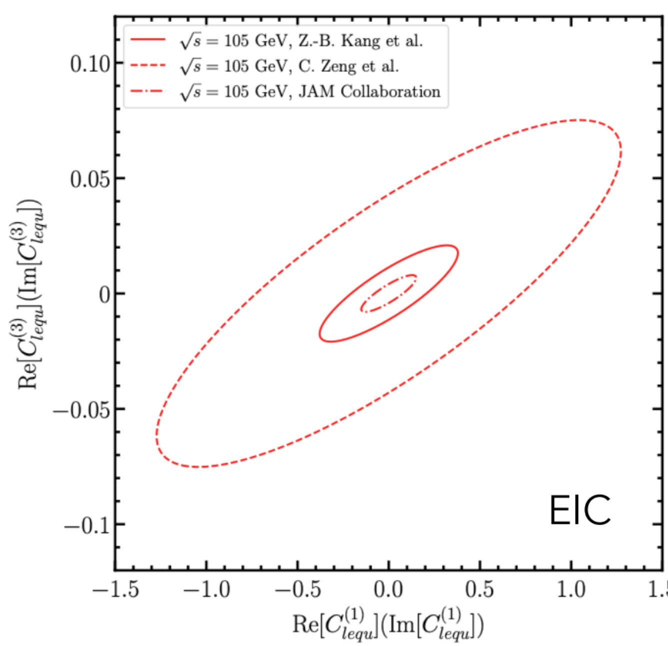
$$P_{T,e} = P_{T,p} = 0.7, \mathcal{L} = 100\ \text{fb}^{-1}$$



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

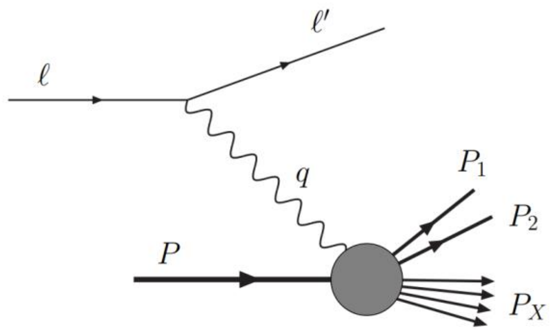
$$A_{TT} = \frac{\sigma(e^\uparrow p^\uparrow) + \sigma(e^\downarrow p^\downarrow) - \sigma(e^\uparrow p^\downarrow) - \sigma(e^\downarrow p^\uparrow)}{\sigma(e^\uparrow p^\uparrow) + \sigma(e^\downarrow p^\downarrow) + \sigma(e^\uparrow p^\downarrow) + \sigma(e^\downarrow p^\uparrow)}$$

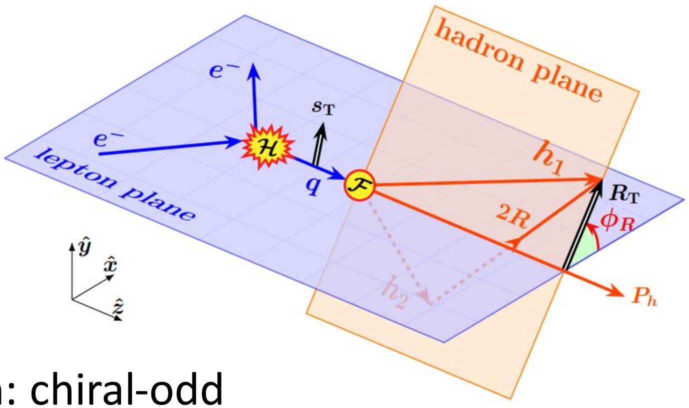




Transverse spin effects of quark @ EIC

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





- The interference dihadron fragmentation function: chiral-odd

$$\frac{d\sigma}{dx\,dy\,dz\,dM_h\,d\phi_R} = \frac{N}{2\pi}\sum_q f_q(x,Q)\big[D_{h_1h_2/q}(z,M_h;Q)$$

$$-\,(\boldsymbol{s}_{T,q}(x,Q)\times\hat{\boldsymbol{R}}_T)^z H_{h_1h_2/q}(z,M_h;Q)\big]C_q(x,Q)$$

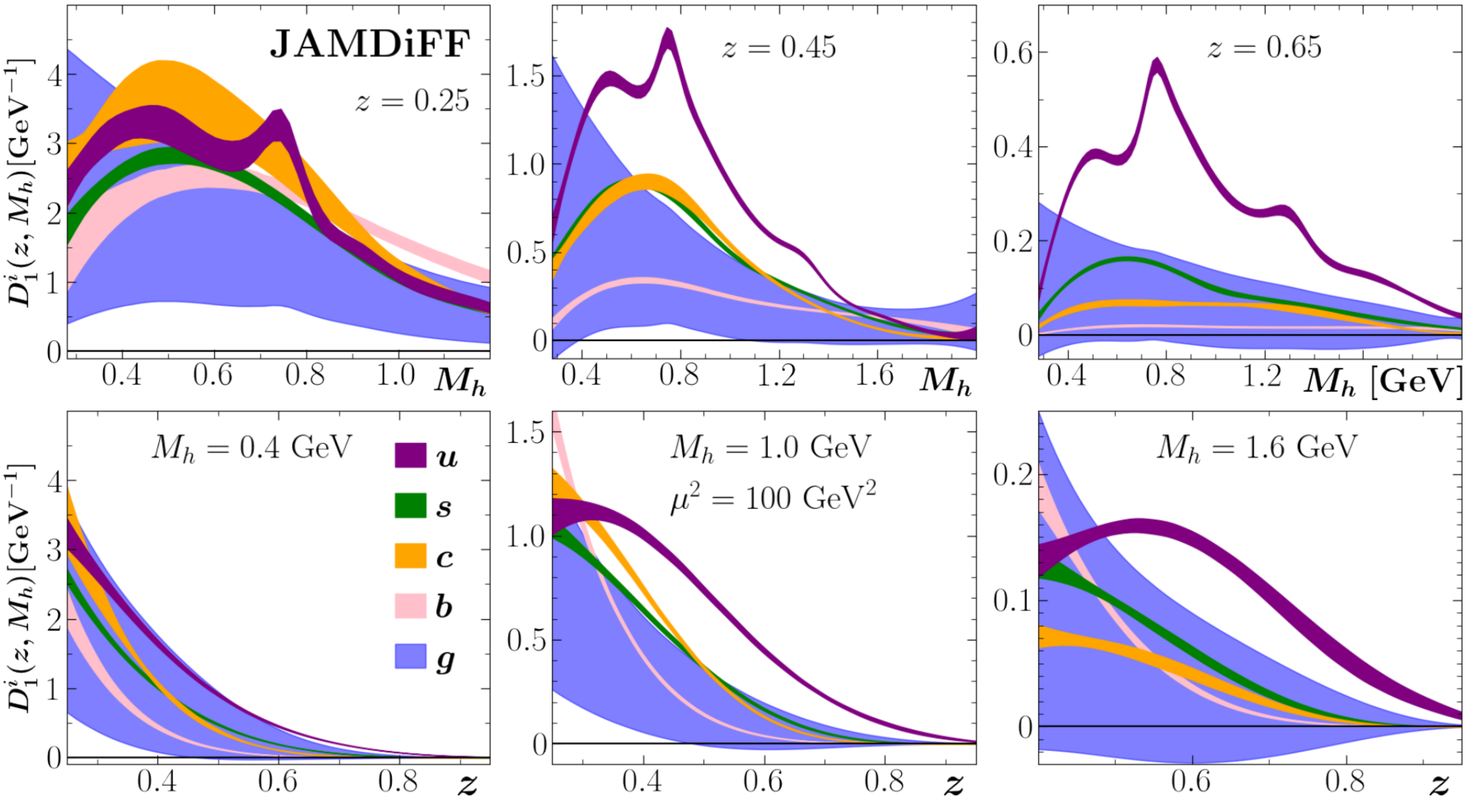
$$s_q^x = \frac{2}{C_q}\left(w_\gamma^q\ \mathrm{Re}\,\Gamma_\gamma^q + w_Z^q\ \mathrm{Re}\,\Gamma_Z^q\right)$$

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

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

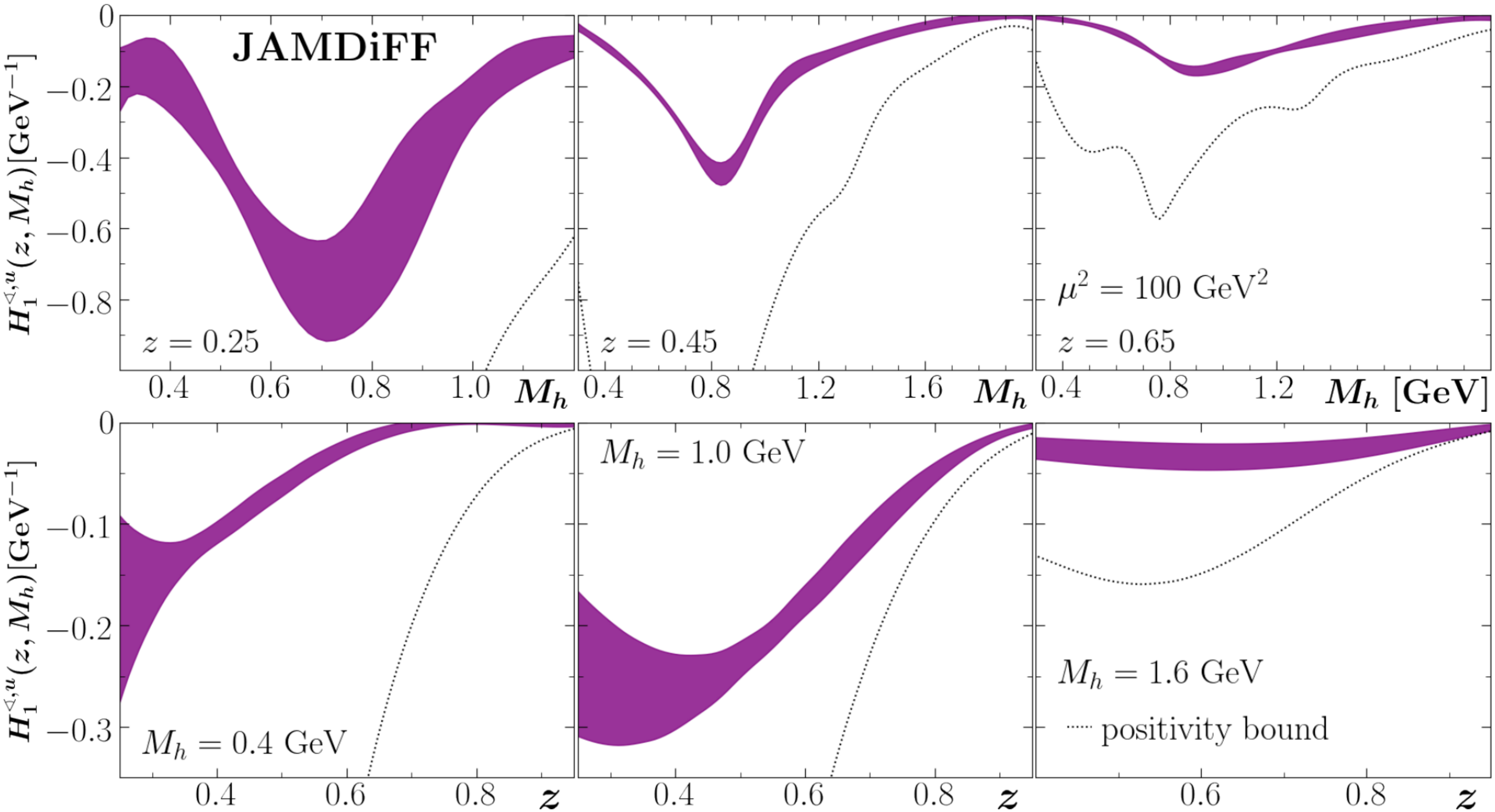
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255

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



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

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



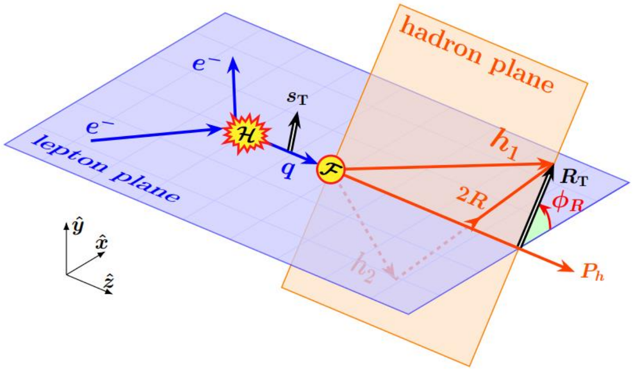
JAM Collaboration, PRL 132 (2024) 091901 , PRD 109 (2024) 034024

Transverse spin effects of quark @ EIC

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

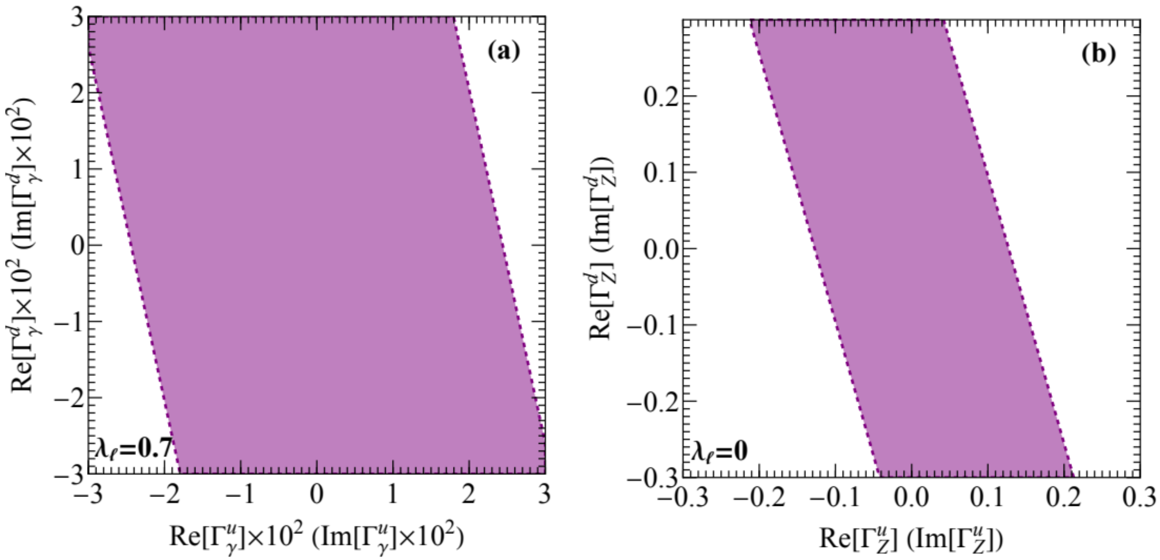
The non-trivial azimuthal distribution requires parity-violation effects:

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



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

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

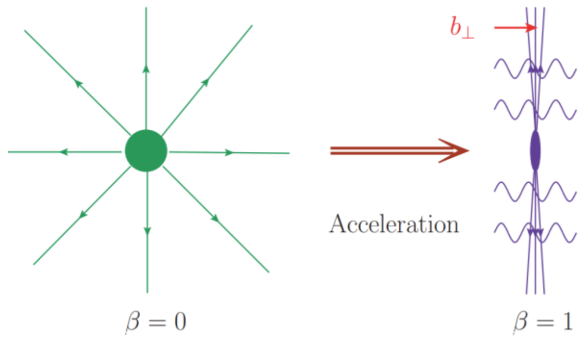


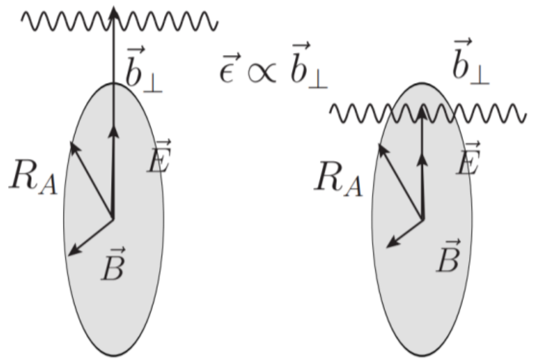
$\sqrt{s} = 105$ GeV, $\mathcal{L} = 1$ ab^{-1}

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

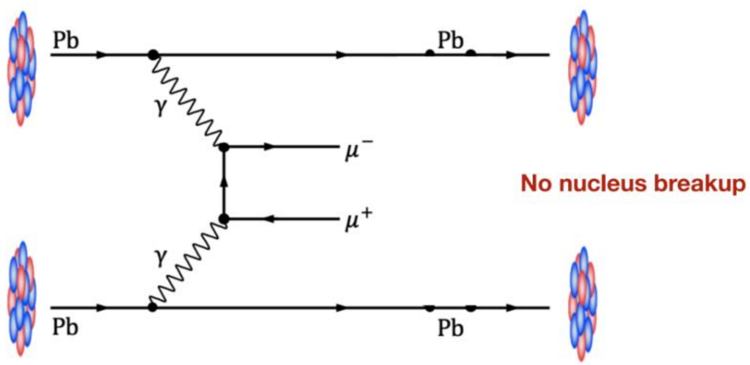
The flat direction in dipole couplings?

Linear polarization @ UPCs





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

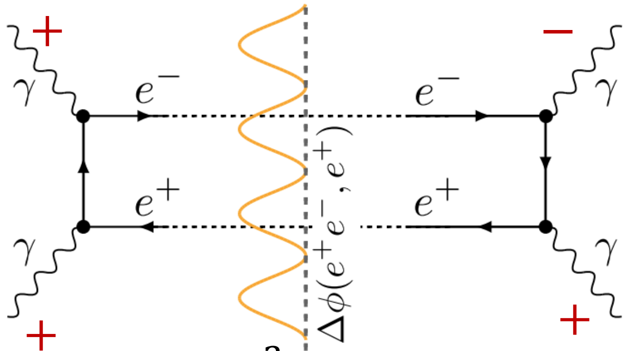


- Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic field
- Weizsacker-Williams equivalent photon approximation
- Photons are linearly polarized
- Large quasi-real photon flux $\propto Z^2$
- The impact parameter $b_\perp > 2R_A$

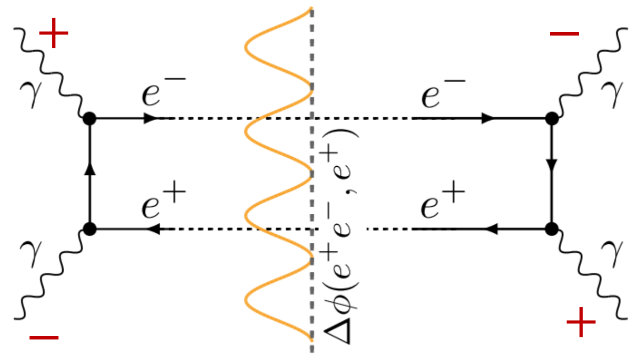
The linear polarization for gluons based on the NEEC:
Yuxun Guo, Xiaohui Liu, Feng Yuan, HuaXing Zhu, 2406.05880
Xiao Lin Li, Xiaohui Liu, Feng Yuan, HuaXing Zhu, PRD 108 (2023) L091502

Linear polarization @ UPCs

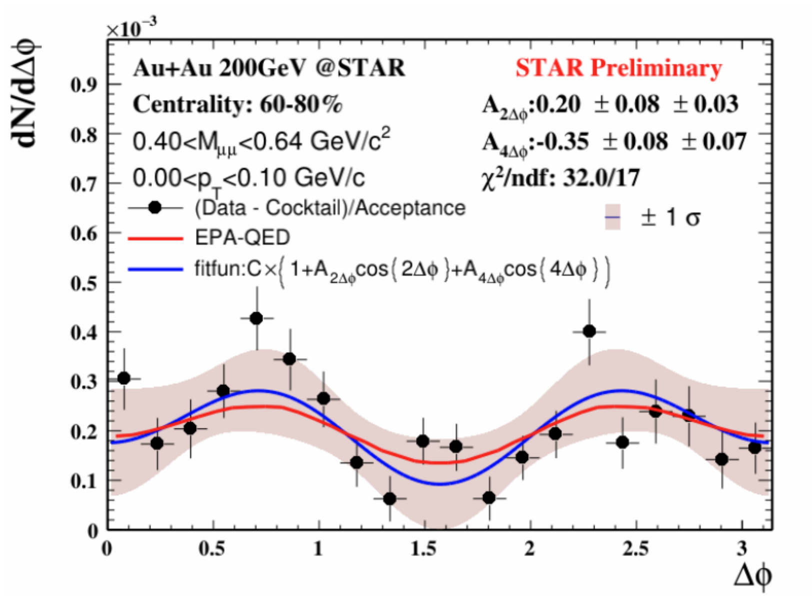
D. Y. Shao, C. Zhang, J. Zhou, Y. Zhou, PRD107 (2023) 3, 036020



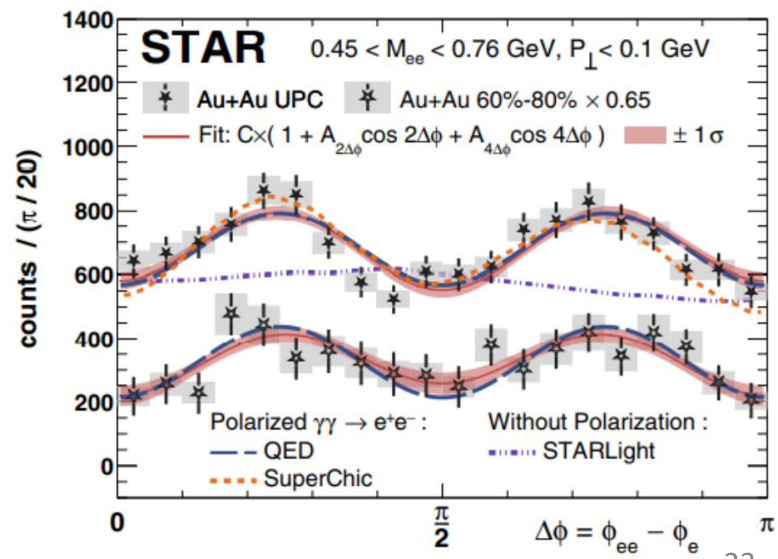
$$\frac{m_e^2}{p_T^2} cos2\Delta\phi$$



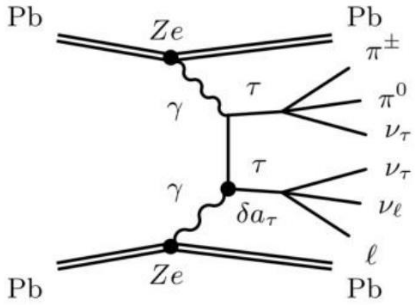
$$cos4\Delta\phi$$



PRL 127 (2021) 5, 052302

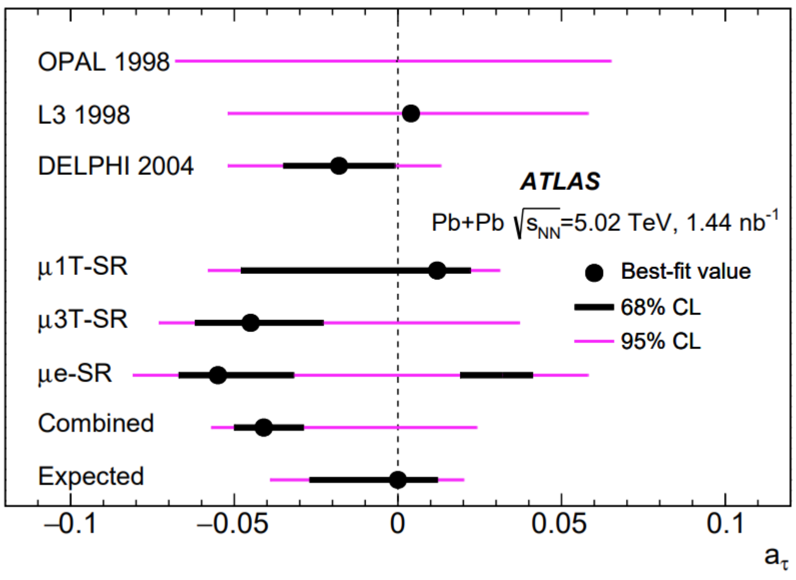


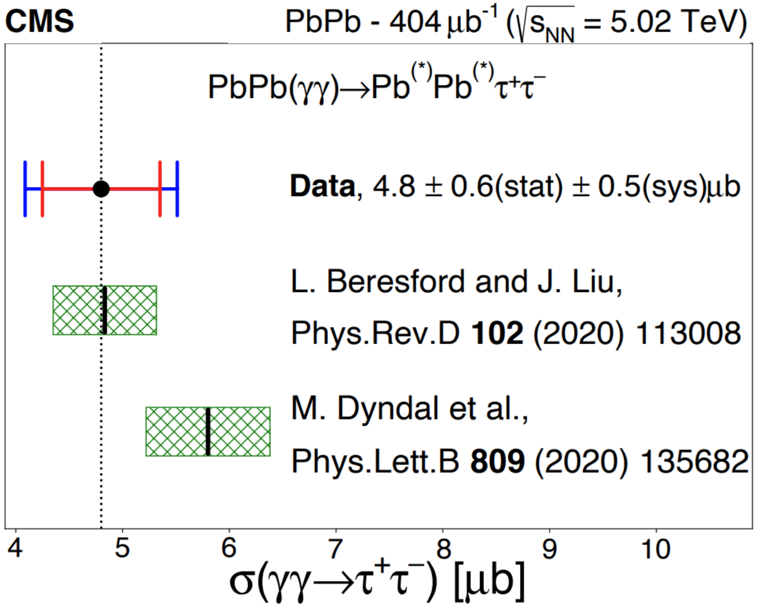
Tau pair production @ UPCs



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

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





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

Phys. Rev. Lett. 131 (2023) 151803

Linear polarization @ UPCs

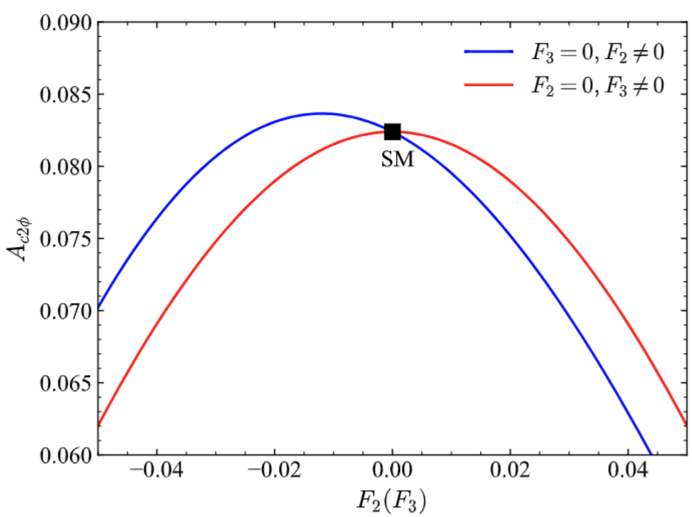
Dingyu Shao, Bin Yan, Shu-Ruan Yuan, Cheng Zhang,
Sci. China Phys. Mech. Astron. 67 (2024) 281062

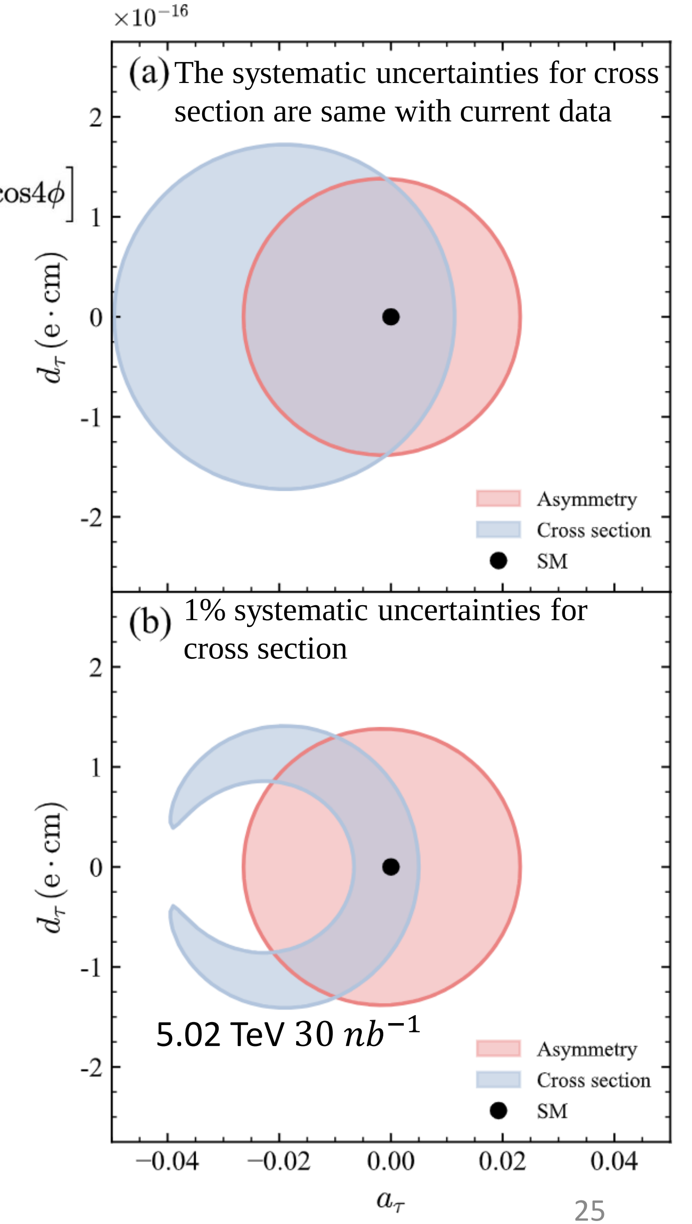
$$d\sigma \sim \left[A_0 + B_0^{(1)} F_2 + B_0^{(2)} F_2^2 + C_0^{(2)} F_3^2 + \left(A_2 + B_2^{(2)} F_2^2 + C_2^{(2)} F_3^2\right)\cos 2\phi + A_4 \cos 4\phi\right]$$

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

Suppressed by lepton mass

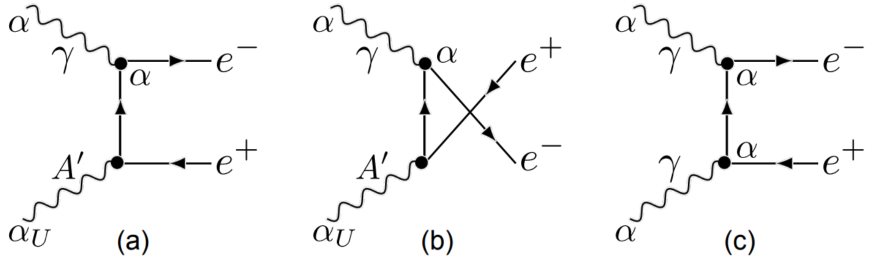
$$A_{c2\phi} = \frac{\sigma(\cos 2\phi > 0) - \sigma(\cos 2\phi < 0)}{\sigma(\cos 2\phi > 0) + \sigma(\cos 2\phi < 0)}$$

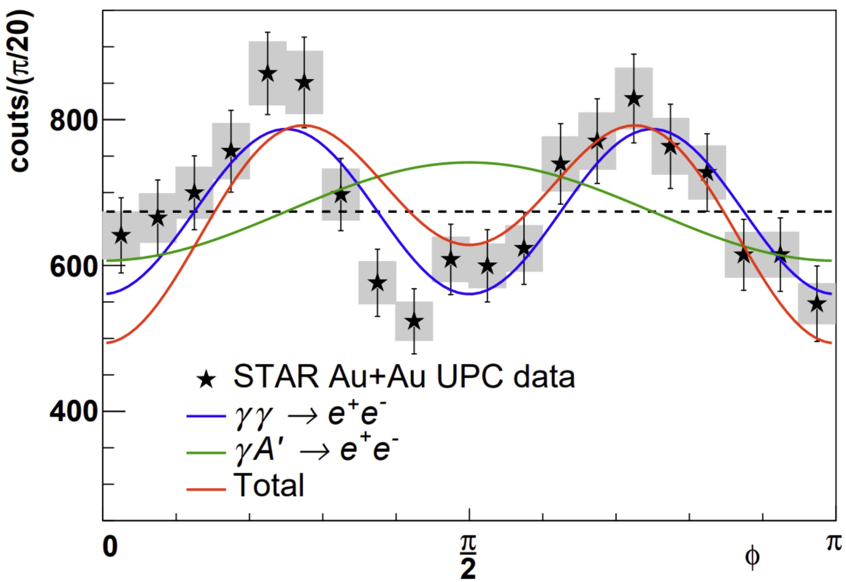




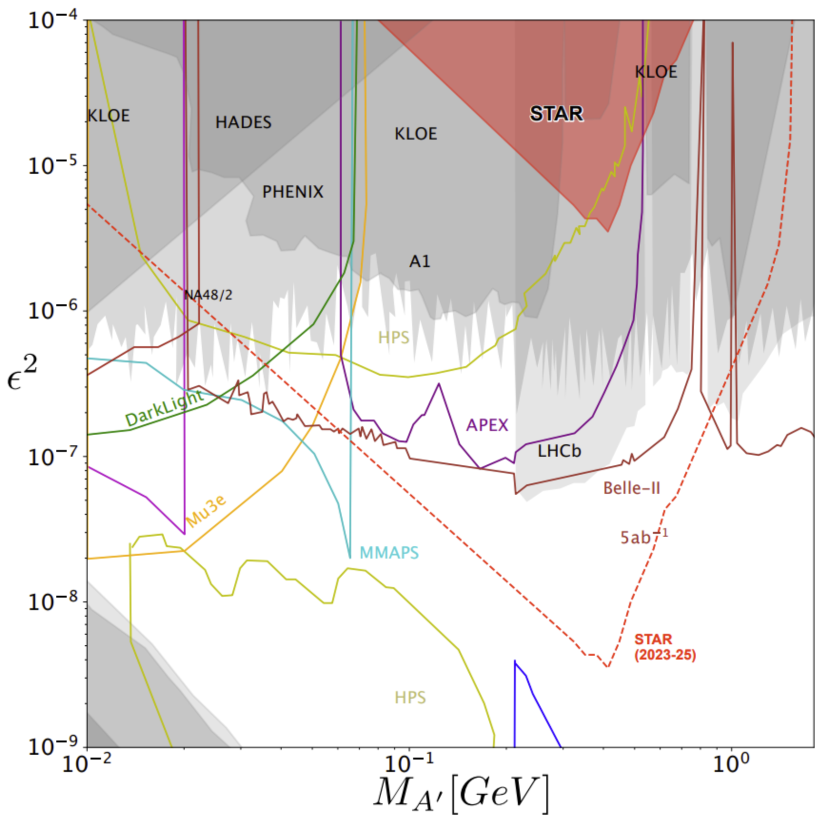
Linear polarization @ UPCs

Dingyu Shao, Yujie Tian, Bin Yan, Cheng Zhang, working in progress



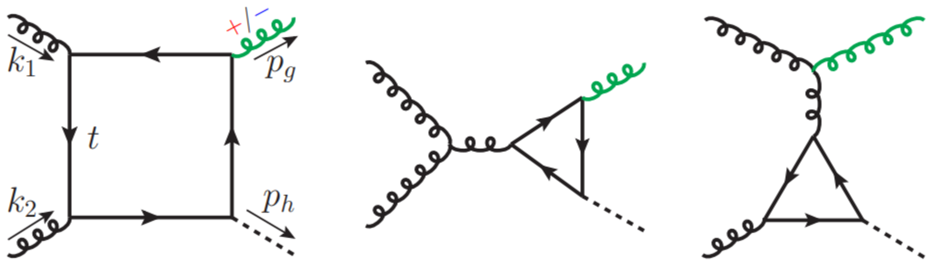


I. Xu et al, arXiv:2211.02132

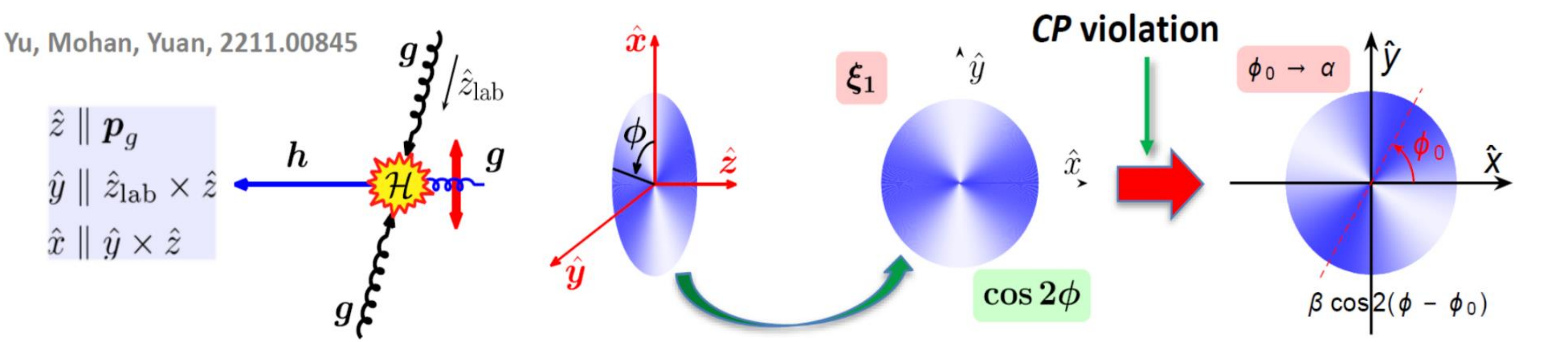


$$A_{2\phi}(\epsilon, M_{A'}) \simeq \left(\frac{\epsilon^2}{\alpha}\right)^{1/2} \left(2\frac{M_{A'}}{M_{ee}}\right)^2$$

Linear polarization of gluon



$$\rho_{\lambda\lambda'} = \frac{1}{2}(1+\boldsymbol{\xi}\cdot\boldsymbol{\sigma})_{\lambda\lambda'} = \frac{1}{2}\begin{pmatrix} 1+\xi_3 & \xi_1 - i\,\xi_2 \\ \xi_1 + i\,\xi_2 & 1-\xi_3 \end{pmatrix}$$



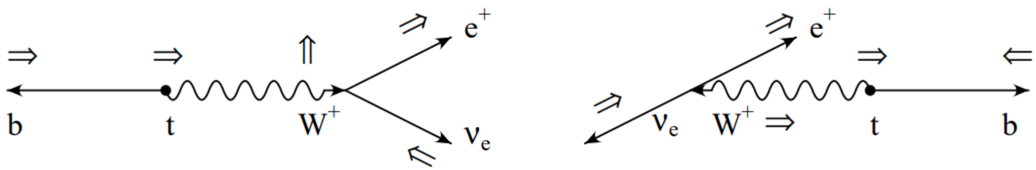
$\xi_1(\alpha)\cos 2\phi + \xi_2(\alpha)\sin 2\phi$

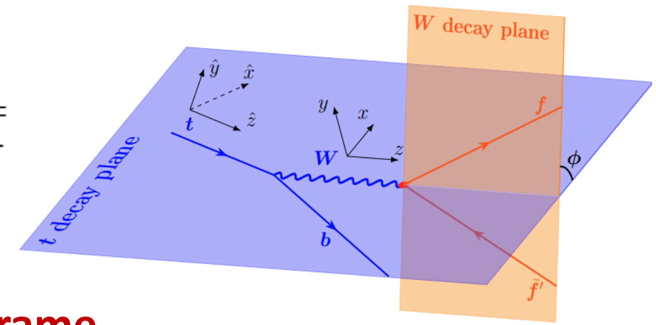
***CP* phase = rotation of anisotropy axis**

C.-P. Yuan's talk @ MBI 2023

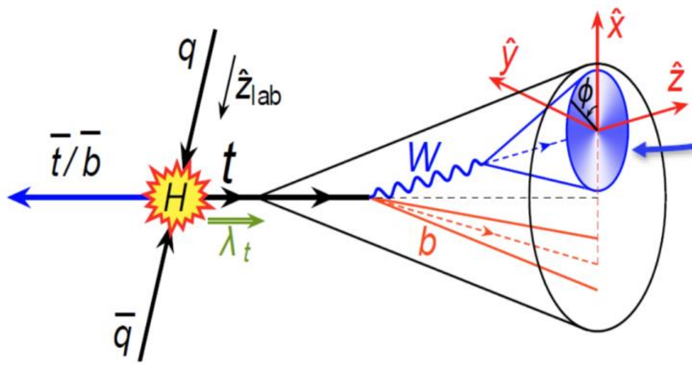
Linear polarization of W boson

Zhite Yu, C.-P. Yuan, PRL 129 (2022) 11,11





W boson is not linearly polarized in top quark rest frame



$$\frac{dE}{d\phi} = \frac{E_{\text{tot}}}{2\pi}\left[1 + \xi \cos 2\phi\right]$$ **Infrared safe**

Boosted limit: $\xi = \xi(\lambda_t) = 0.145(\lambda_t - 1)$

[Assuming SM tbW coupling]

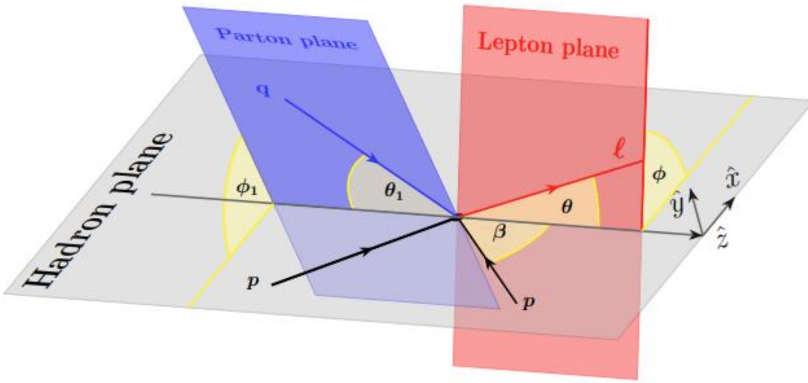
Azimuthal correlation → Boosted top polarization

- Measuring longitudinal polarization of boosted top
- New top tagger against QCD jets

→ A new tool to probe the NP effects, e.g. the CP violation in top quark decay

Qi Bi, Bin Yan, Zhite Yu, working in progress

Lam-Tung relation and polarization



Collins-Soper frame

$$\frac{d\sigma}{d^4q\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{d^4q}\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0\,(1-3\cos^2\theta) + A_1\,\sin(2\theta)\cos\phi + \frac{1}{2}A_2\,\sin^2\theta\,\cos(2\phi) + A_3\,\sin\theta\,\cos\phi + A_4\,\cos\theta + A_5\,\sin^2\theta\,\sin(2\phi) + A_6\,\sin(2\theta)\,\sin\phi + A_7\,\sin\theta\,\sin\phi\Big\},$$

$$\rho_{\lambda_Z\lambda'_Z} = \begin{pmatrix} \frac{1-\delta_L}{3}+\frac{J_3}{2} & \frac{J_1+2Q_{xz}-i(J_2+2Q_{yz})}{2\sqrt{2}} & \lambda_T - iQ_{xy} \\ \frac{J_1+2Q_{xz}+i(J_2+2Q_{yz})}{2\sqrt{2}} & \frac{1+2\delta_L}{3} & \frac{J_1-2Q_{xz}-i(J_2-2Q_{yz})}{2\sqrt{2}} \\ \lambda_T + iQ_{xy} & \frac{J_1-2Q_{xz}+i(J_2-2Q_{yz})}{2\sqrt{2}} & \frac{1-\delta_L}{3}-\frac{J_3}{2} \end{pmatrix}$$

$$\frac{\Gamma}{\Omega_f^*} \propto \frac{|B_+|^2+|B_-|^2}{2}\Big[\frac{2}{3}+\frac{\delta_L}{3}(1-3\cos^2\theta_f^*)+\lambda_T\sin^2\theta_f^*\cos 2\phi_f^* + Q_{yz}\sin 2\theta_f^*\sin\phi_f^* + Q_{xz}\sin 2\theta_f^*\cos\phi_f^* + Q_{xy}\sin^2\theta_f^*\sin 2\phi_f^*\Big] + \frac{|B_+|^2-|B_-|^2}{2}\left(J_1\sin\theta_f^*\cos\phi_f^* + J_2\sin\theta_f^*\sin\phi_f^* + J_3\cos\theta_f^*\right).$$

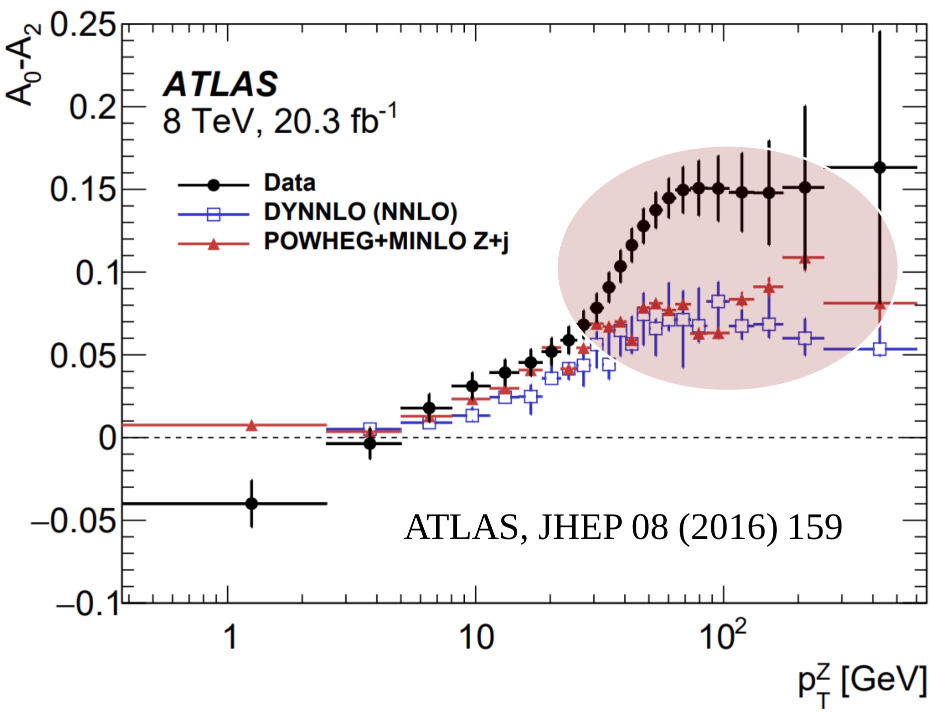
Lam-Tung relation: $A_0 = A_2$

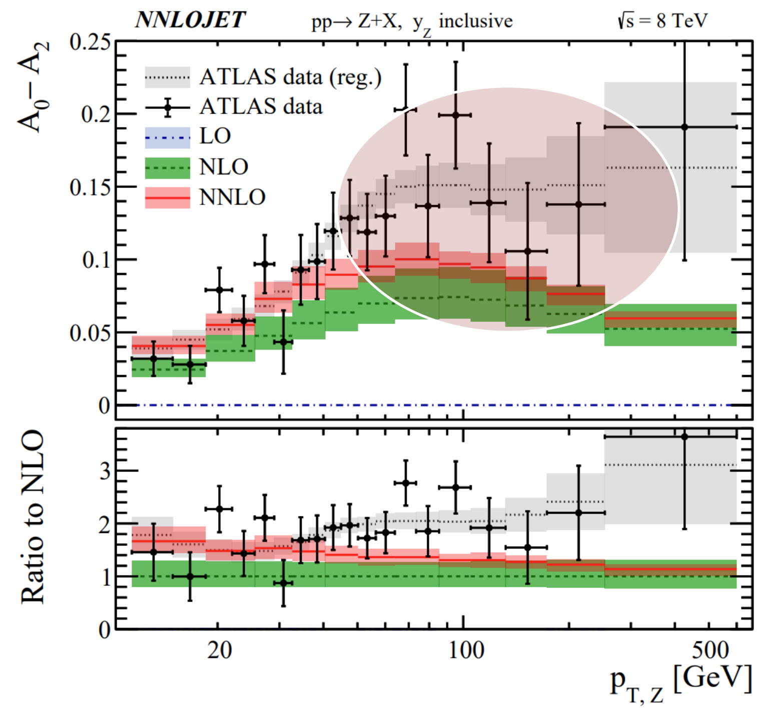
Linear and Longitudinal polarization of Z boson

$A_0 \neq A_2$ @ NNLO in QCD
non-coplanarity between the hadron and parton planes

J.C. Peng et al, PLB 758,384 (2016)

Lam-Tung relation and polarization





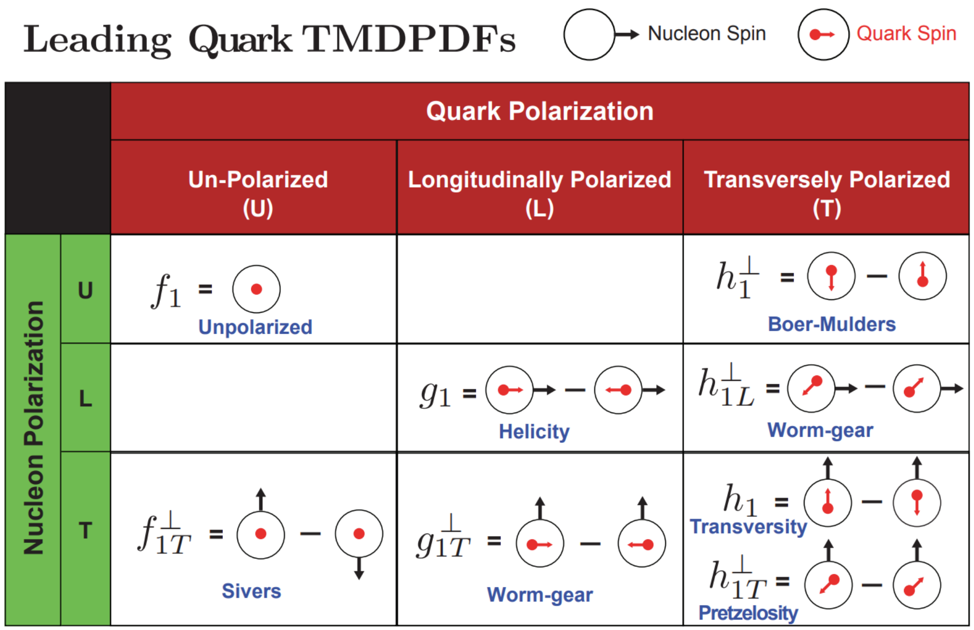
R. Gauld et al, JHEP 2017, N3LO

These results are confirmed by CMS (PLB750, 154 (2015)) and LHCb (PRL 129 (2022) 091801) collaborations

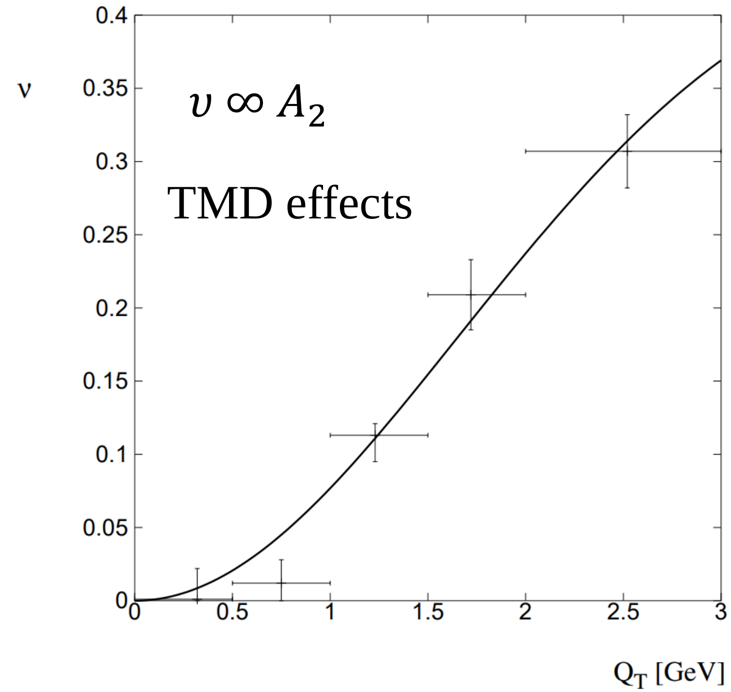
The discrepancy with the SM prediction
NP effects or non-perturbative effects ?

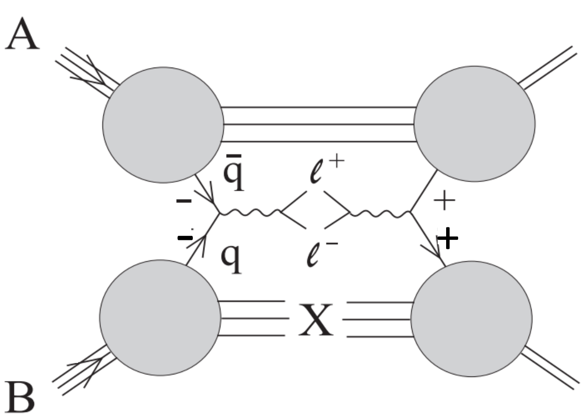
Boer-Mulders function

The $cos2\phi$ dependence can be induced by the Boer-Mulders function



Boer, PRD 60 (1999) 014012





Transversely polarized quark

Lam-Tung relation and NP

Center-of-mass frame:

$$\frac{d\sigma}{d\Omega} = a\cos\hat{\theta} + b\cos^2\hat{\theta} + c\cos^3\hat{\theta} + d$$

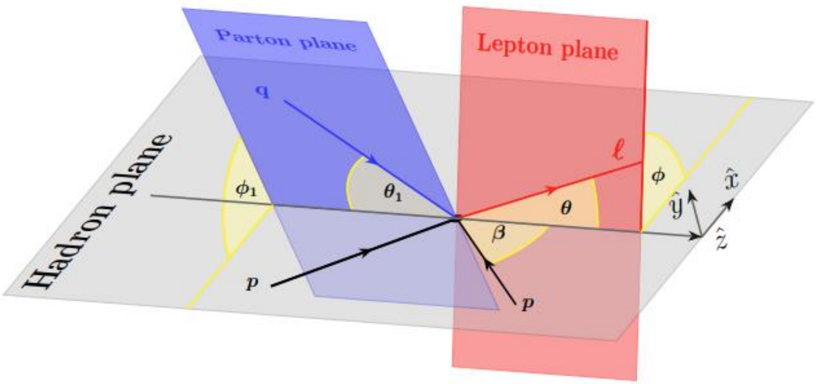
$$\cos\hat{\theta} = \cos\theta\cos\theta_1 + \sin\theta\sin\theta_1\cos(\phi-\phi_1)$$

$$A_0 = \left\langle \frac{2(d-b)+4b\sin^2\theta_1}{b+3d} \right\rangle,$$

$$A_2 = \left\langle \frac{4b\sin^2\theta_1\cos 2\phi_1}{b+3d} \right\rangle.$$

$$\langle P_l(\cos\theta,\phi)\rangle = \frac{\int P_l(\cos\theta,\phi)\, d\sigma d\cos\theta d\phi}{\int d\sigma d\cos\theta d\phi}$$

J.C. Peng et al, PLB 758,384 (2016)

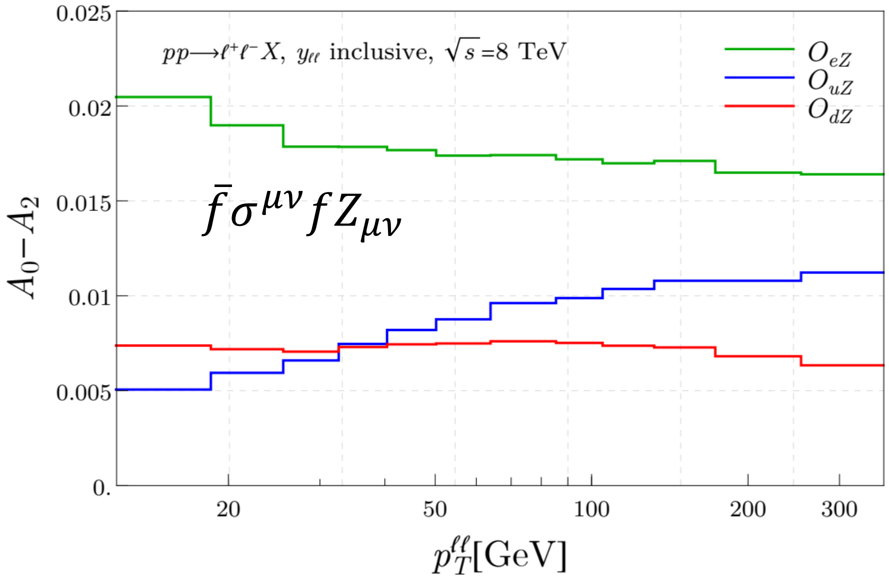


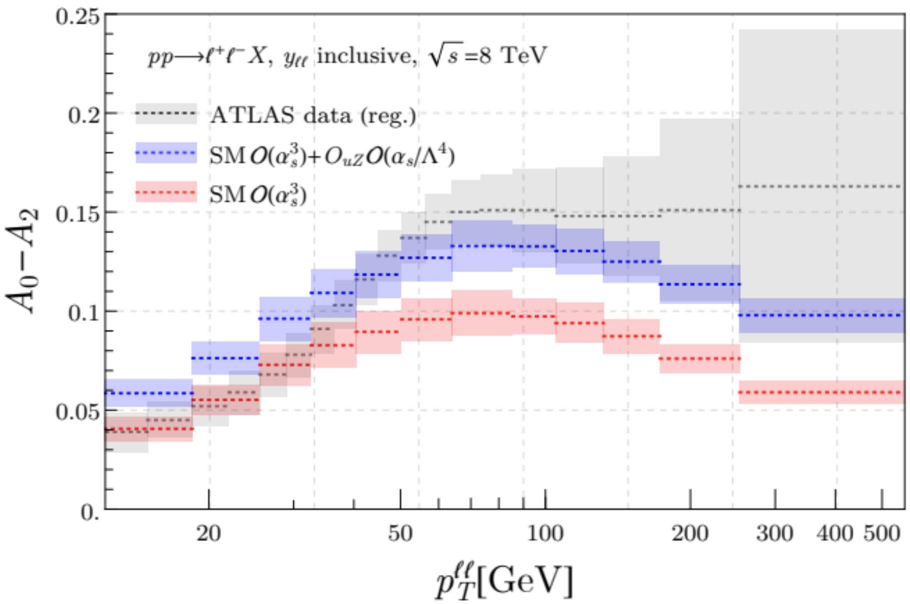
$A_0 \neq A_2$

- Coplanarity case: $b \neq d$, BSM effects
- Non-coplanarity case: $\phi_1 \neq 0$, NNLO and beyond or by the nonperturbative effects

Xu Li, Bin Yan, C.-P. Yuan, arxiv: 2405.04069

Lam-Tung relation and polarization

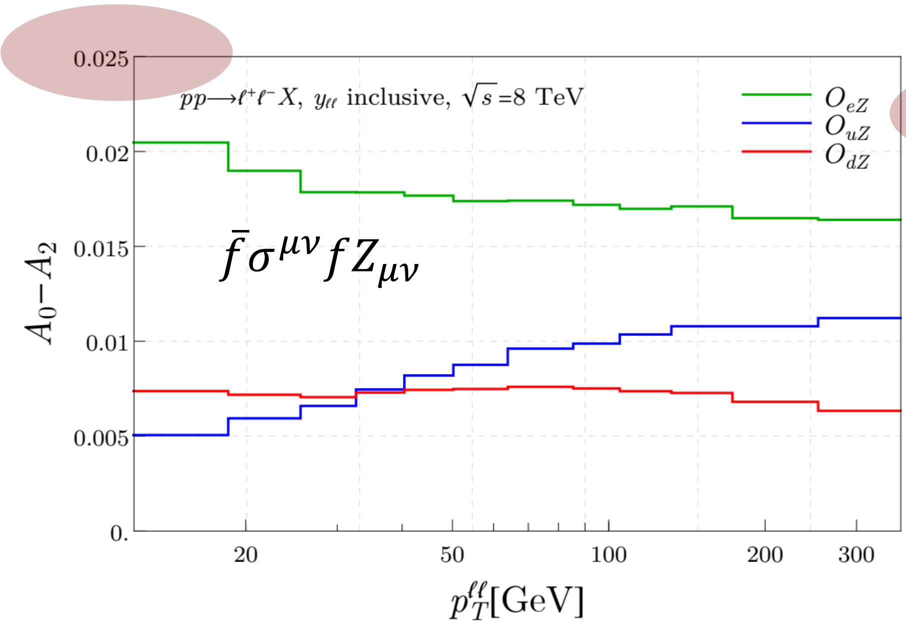


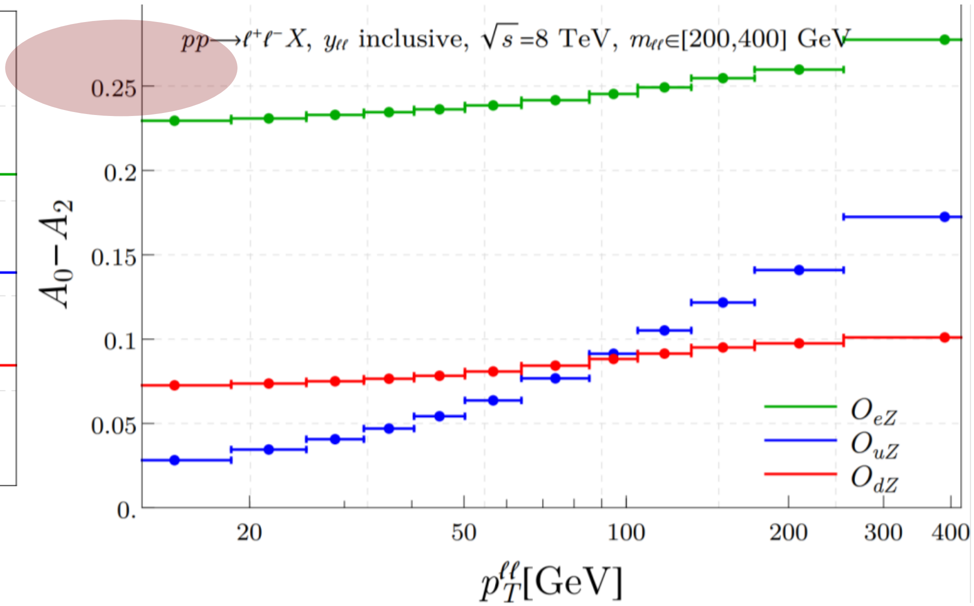


- The discrepancy in Lam-Tung relation could be explained by electroweak dipole interactions (transversely polarized quark or lepton)
- It could be more significant in high-invariant mass region

Xu Li, Bin Yan, C.-P. Yuan, arxiv: 2405.04069

Lam-Tung relation and polarization

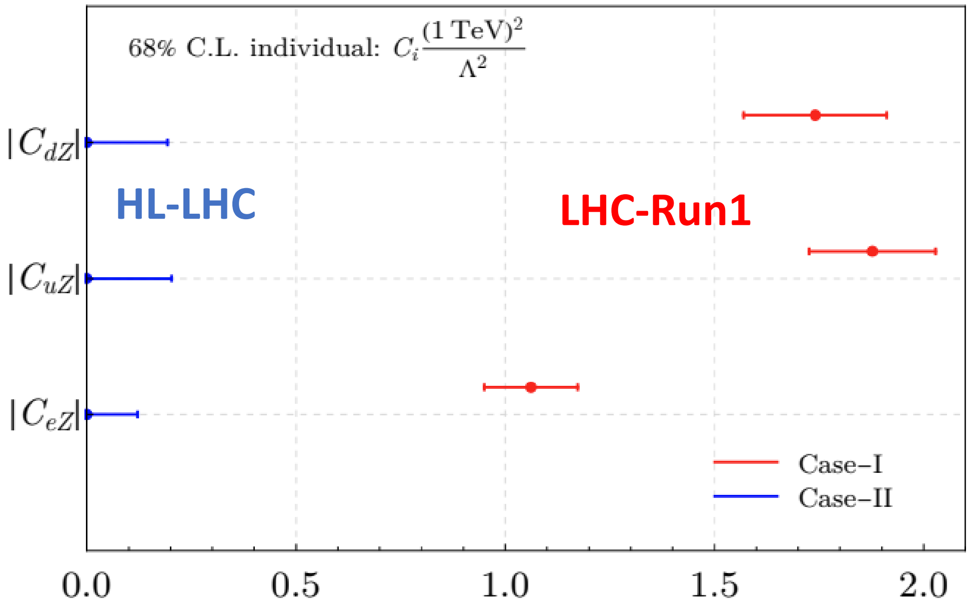


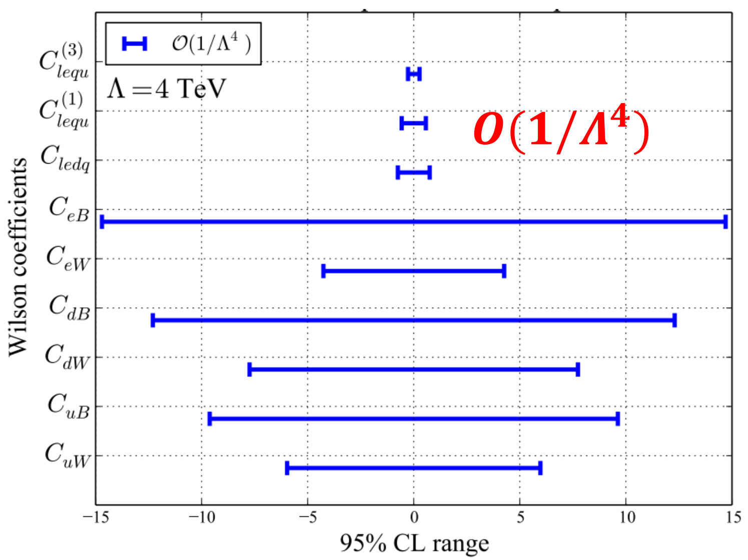


- The accuracy for the normalization of the angular coefficients in high invariant mass: $O(\alpha_s)$
- The breaking effects from the weak dipole interactions could be enhanced by one order of magnitude

Xu Li, Bin Yan, C.-P. Yuan, arxiv: 2405.04069

Lam-Tung relation and polarization





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

- The accuracy from A0-A2 would be comparable to the results from cross section, but the violation effects will dominantly depend on the dipole interactions.

Xu Li, Bin Yan, C.-P. Yuan, arxiv: 2405.04069

Summary

- The electroweak dipole operators are difficult to be probed at colliders since their leading effects are from $1/\Lambda^4$
- These operators can be probed at $1/\Lambda^2$ via transverse spin effects (beams or non-perturbative 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 by 1~2 orders of magnitude
- The photons from UPCs are linearly polarized and can be used to probe the NP
- Polarized Muon collider, hadron colliders, electron-Ion collider
- The linear polarization of the gauge bosons: photon, gluon and W/Z

Thank you