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

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第十七届粒子物理、核物理和宇宙学交叉研讨会
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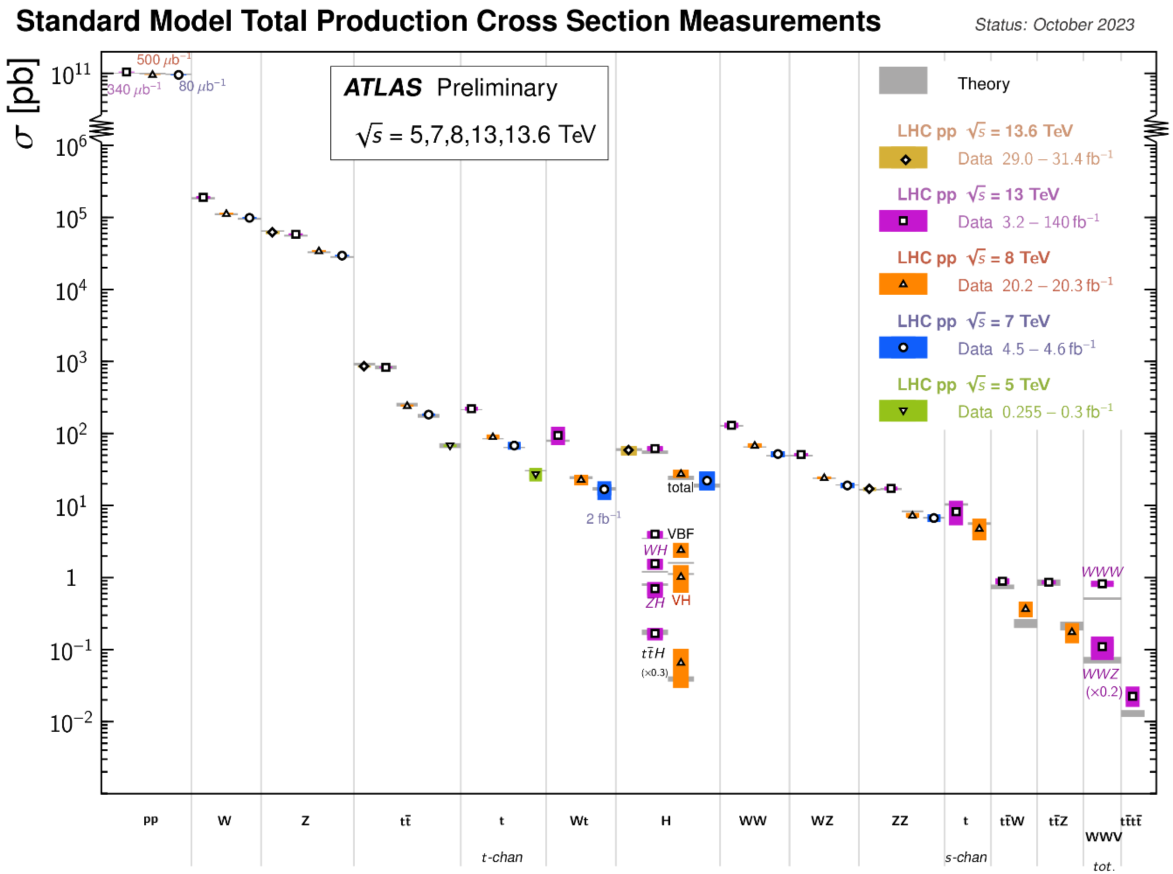
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801
Dingyu Shao, Bin Yan, Shu-Ruan Yuan, Cheng Zhang, 2310.14153
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan, PRD 109 (2024) 095025
Xu Li, Bin Yan, C.-P. Yuan, 2405.04069

The status of SM



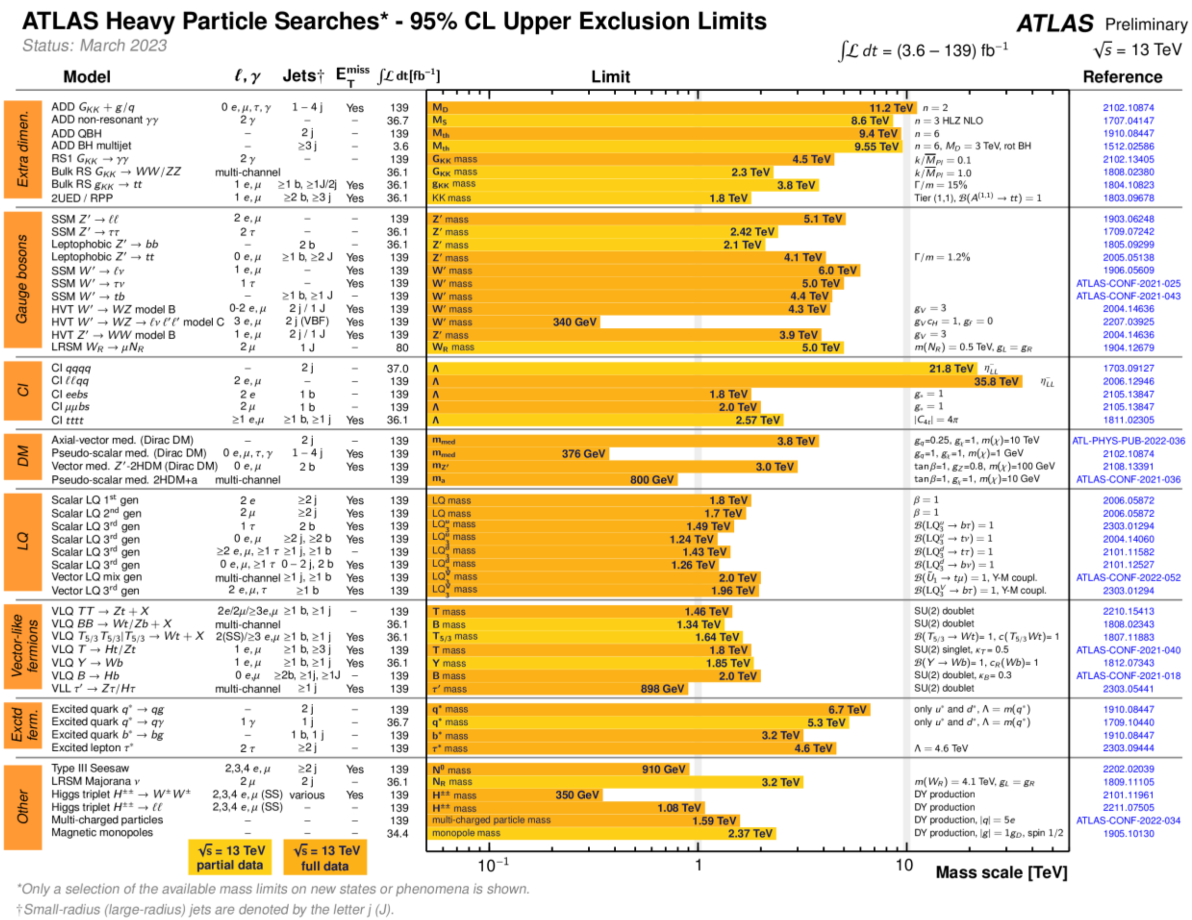
Open questions:

- 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

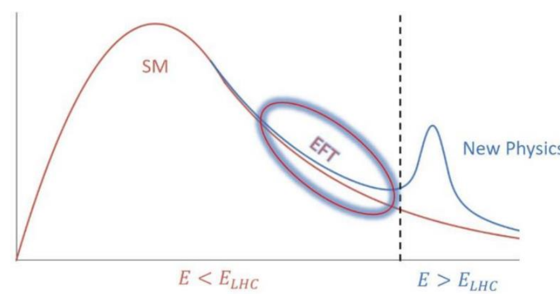
New Physics beyond the SM new measurements

New Physics Searches @ LHC



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

SMEFT



Top-down approach

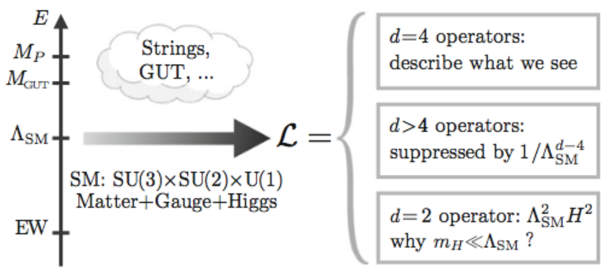
Bottom-up approach

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

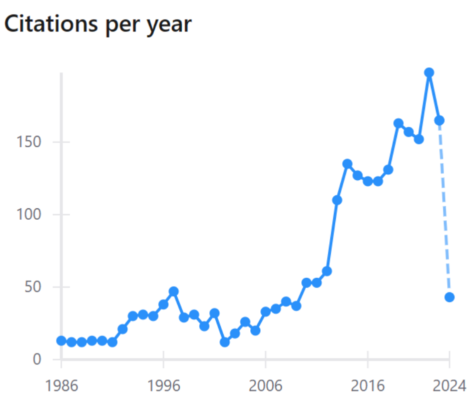


Linear realized EFT

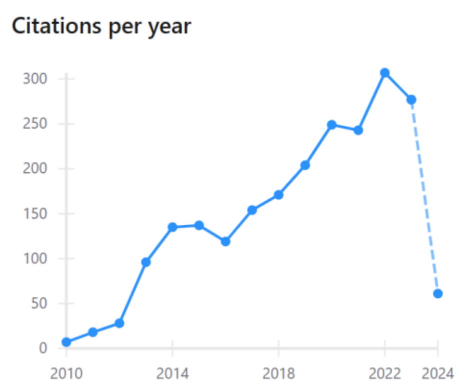
Higgs is a fundamental particle

Weak interacting

W. Buchuller, D. wyler 1986



B. Grzadkowski et al, 2010



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

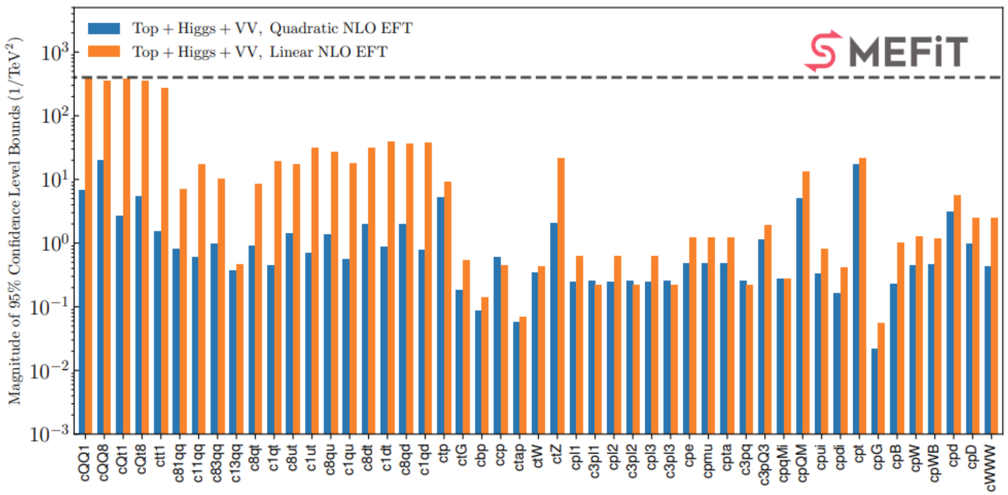
$$\mathcal{L} = \frac{C_6}{\Lambda^2}\mathcal{O}_6 + \frac{C_8}{\Lambda^4}\mathcal{O}_8 + \ldots$$

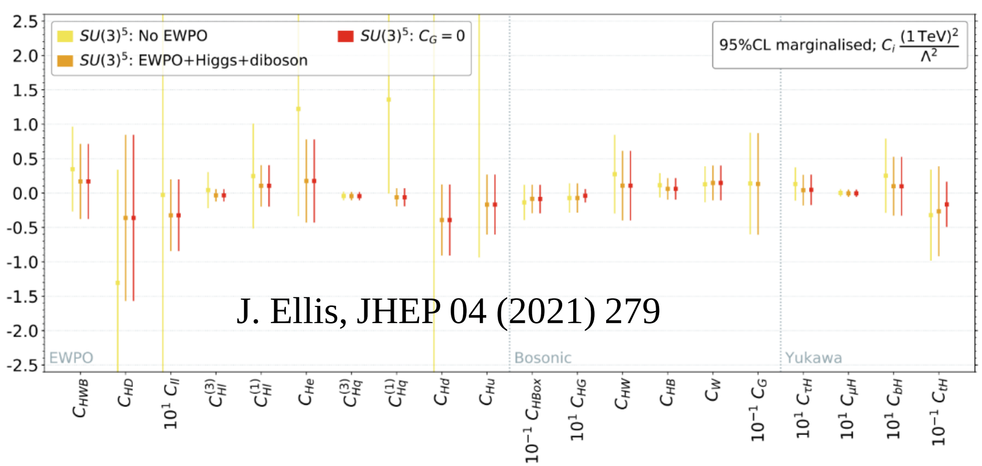
3. Higgs Effective Field Theory

Callan, Coleman, Wess, Zumino, 1969
The electroweak chiral Lagrangian+light Higgs, A.C. Longhitano, 1980,….

Global analysis @ SMEFT

SMEFiT Collaboration, JHEP 11 (2021) 089





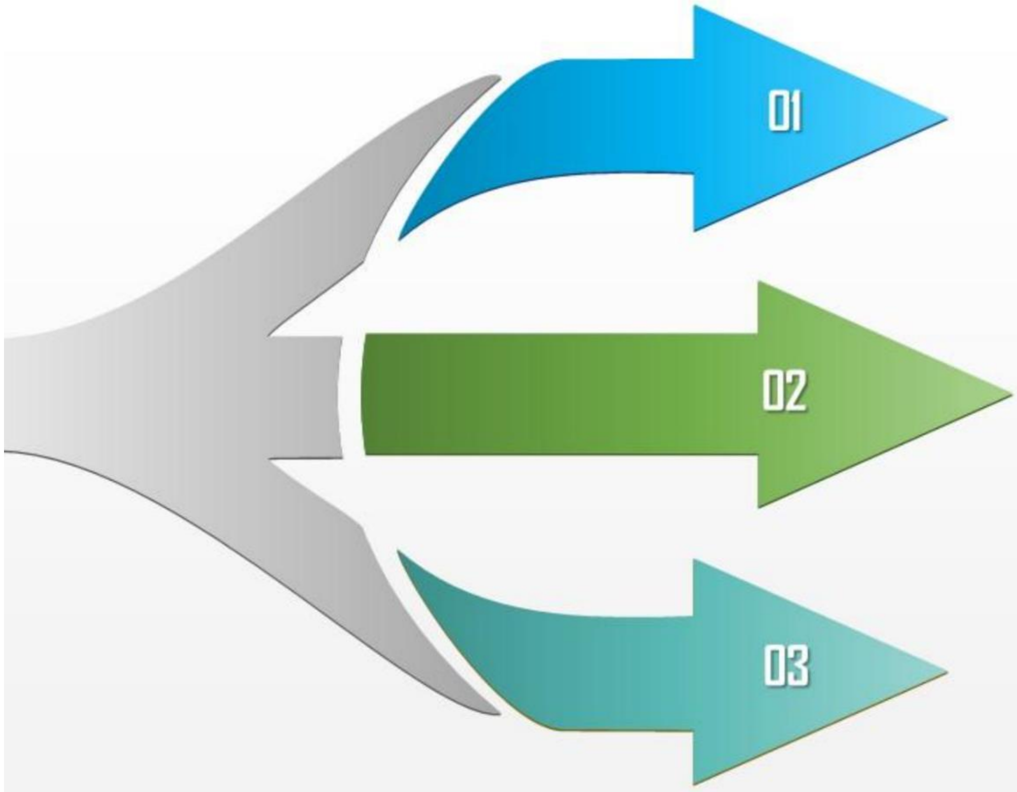
J. Ellis, JHEP 04 (2021) 279

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 beyond the SM from the theoretical point of view?



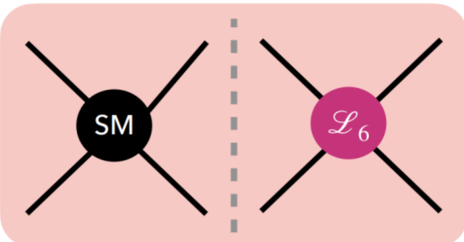
- Global analysis with more processes; the combination of low energy and high energy measurements
- QCD and EW correction to reduce the theoretical uncertainties
- New observables and new measurements

→ New polarization observables

New Physics and SMEFT

B. Grzadkowski et al, 2010

Interference effects

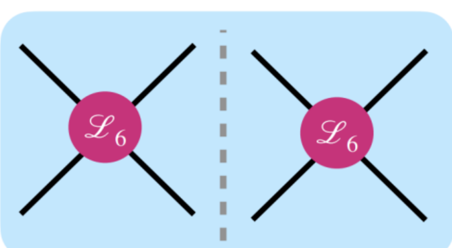


$\sim \mathcal{O}(\frac{1}{\Lambda^2})$

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

Chirality-flipped operators

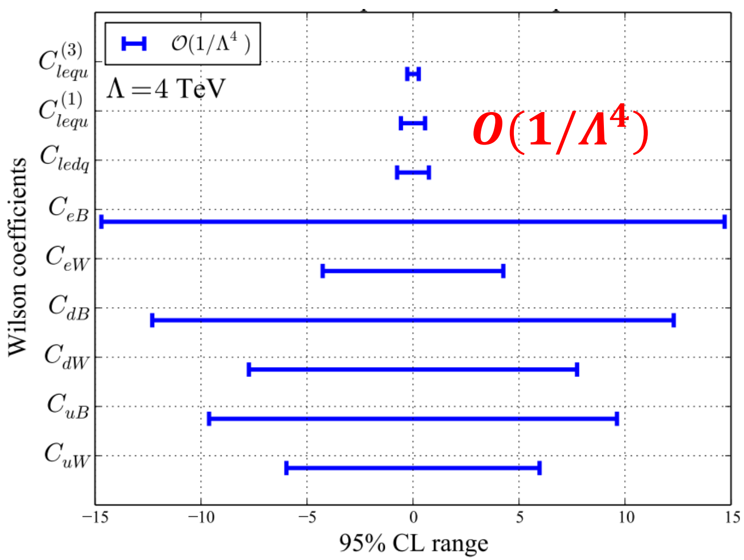


$\sim \mathcal{O}(\frac{1}{\Lambda^4})$

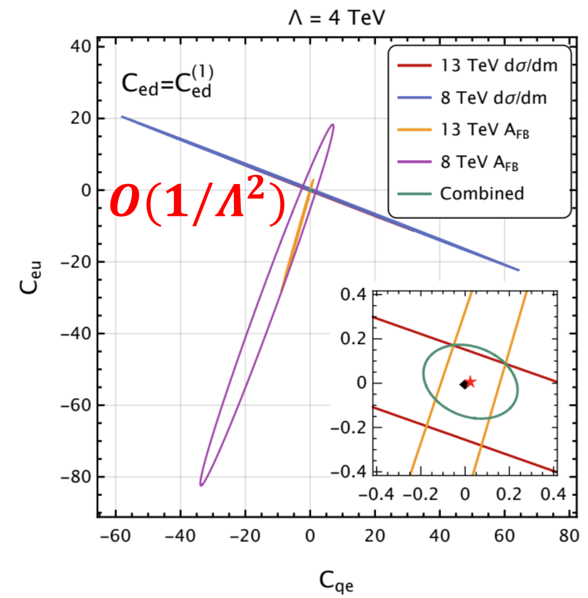
The constraints will be very weak

Example: Dipole Operator

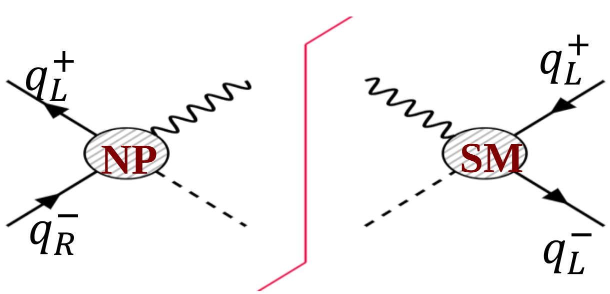
Single-Parameter-Analysis: EW dipole couplings are poorly constrained



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



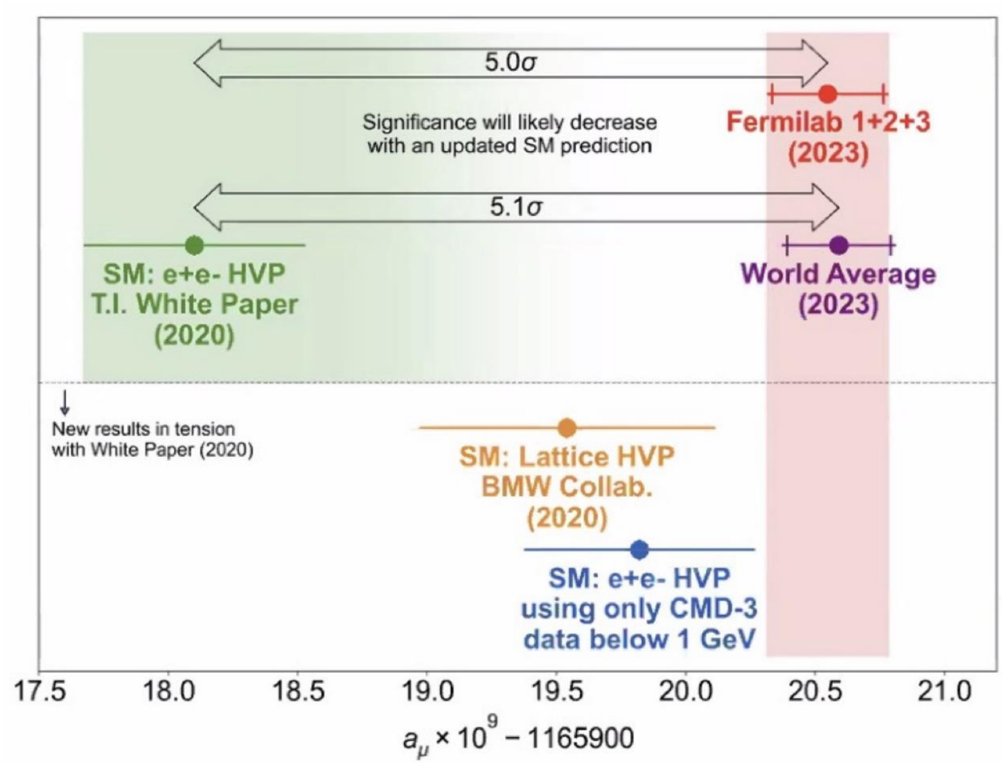
R. Boughezal et al, 2303.08257



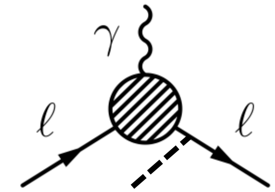
=0 for the cross section

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

New Physics and Dipole Operator

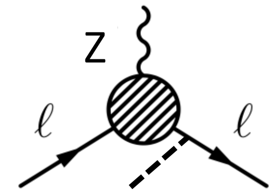


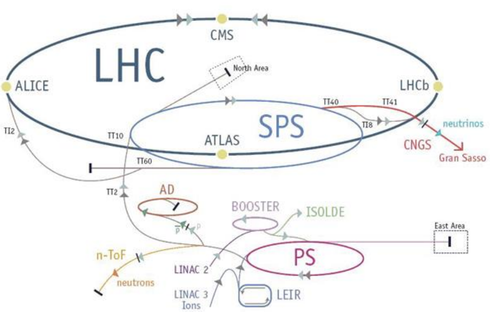
Loop-induced by the BSM

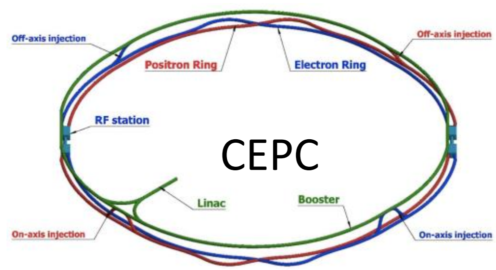


May have same physics source

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



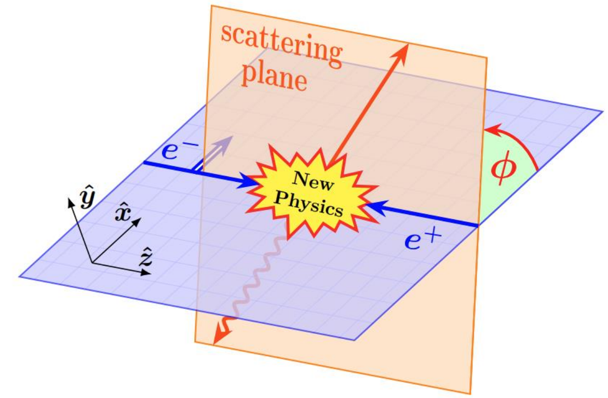




How to probe the electroweak dipole operators?

How to Probe Dipole Operator

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

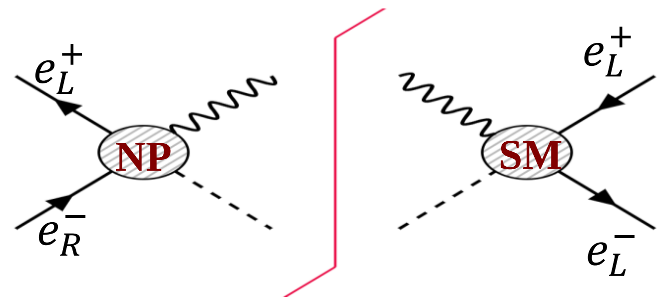


Transversely polarized effect of beams:

The interference between the different helicity states

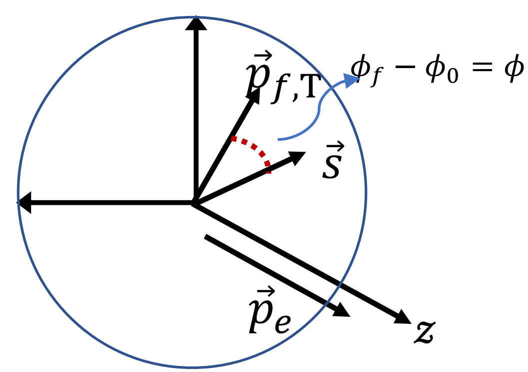
$$\boldsymbol{s} = (b_1, b_2, \lambda) = (b_{\rm T}\cos\phi_0, b_{\rm T}\sin\phi_0, \lambda)$$

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



$$|\lambda = +\rangle\langle\lambda = -|$$

Breaking the rotational invariance & A nontrivial azimuthal behavior



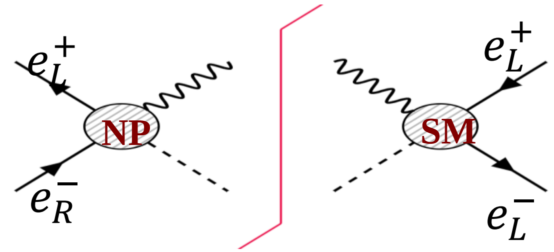
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan,
PRL 131 (2023) 241801

Transverse Spin Polarization

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)



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

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

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

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

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

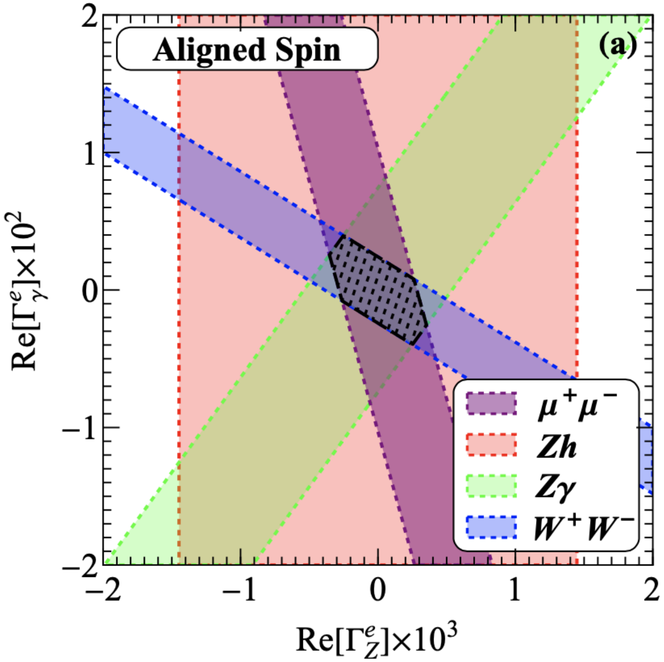
$$A^i_{LR} = \frac{\sigma^i(\cos\phi > 0) - \sigma^i(\cos\phi < 0)}{\sigma^i(\cos\phi > 0) + \sigma^i(\cos\phi < 0)} = \frac{2}{\pi} A^i_R$$

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

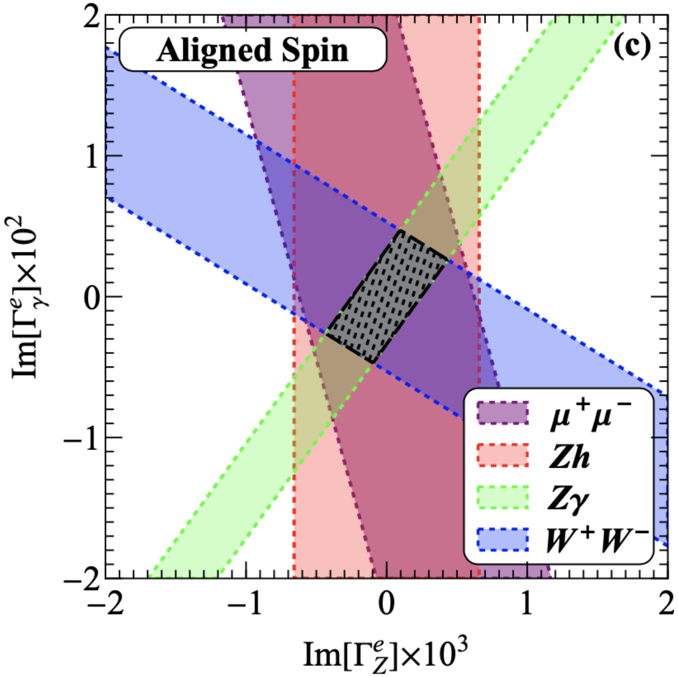
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan,

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

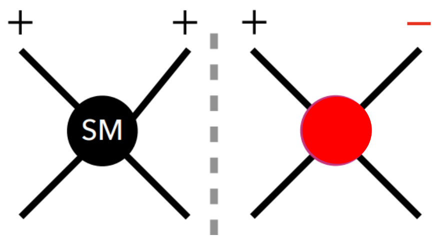
- Our bounds are much stronger than other approaches by 1~2 orders of magnitude

Transverse spin effects@ EIC

- Dipole operators

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

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



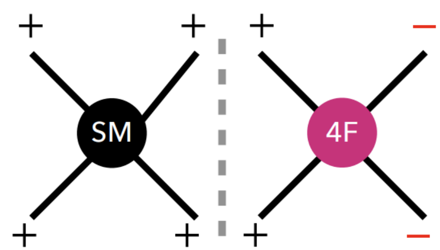
$\sim \mathcal{O}(\frac{1}{\Lambda^2})$

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

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

- Scalar and tensor four fermion operators

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

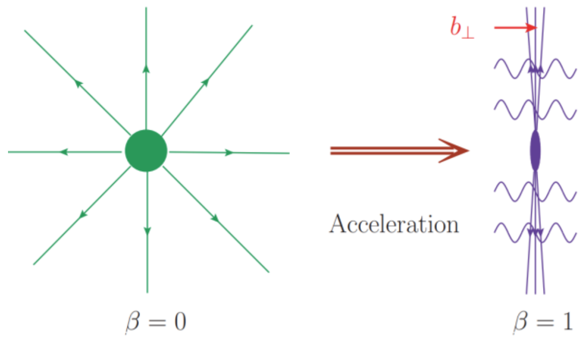


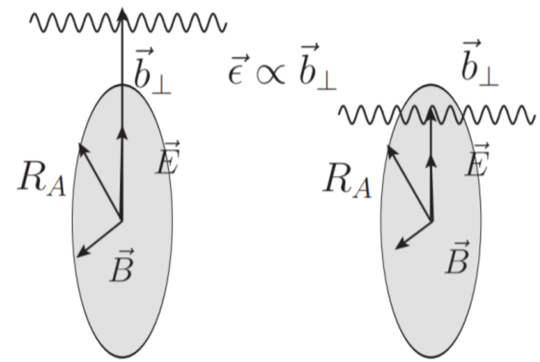
$\sim \mathcal{O}(\frac{1}{\Lambda^2})$

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

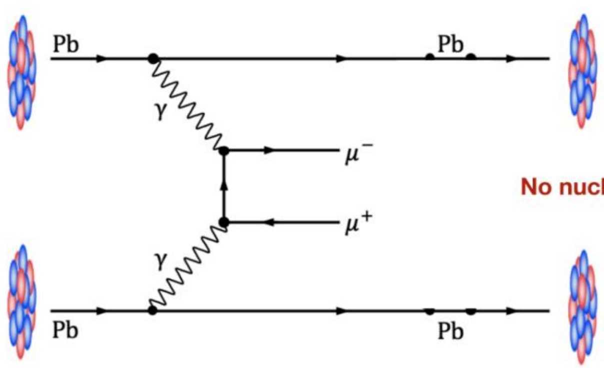
$$A_{TT} = \frac{\sigma\left(e^{\uparrow}p^{\uparrow}\right) + \sigma\left(e^{\downarrow}p^{\downarrow}\right) - \sigma\left(e^{\uparrow}p^{\downarrow}\right) - \sigma\left(e^{\downarrow}p^{\uparrow}\right)}{\sigma\left(e^{\uparrow}p^{\uparrow}\right) + \sigma\left(e^{\downarrow}p^{\downarrow}\right)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

Linear polarization @ UPCs





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

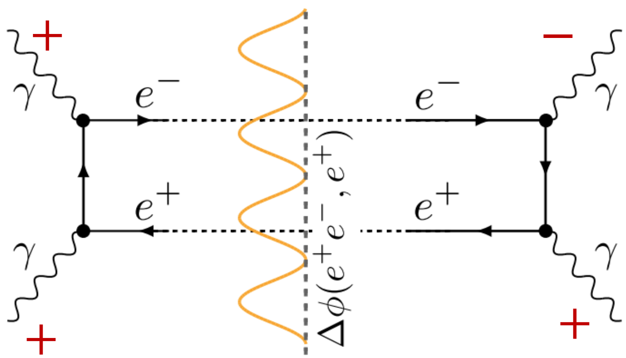


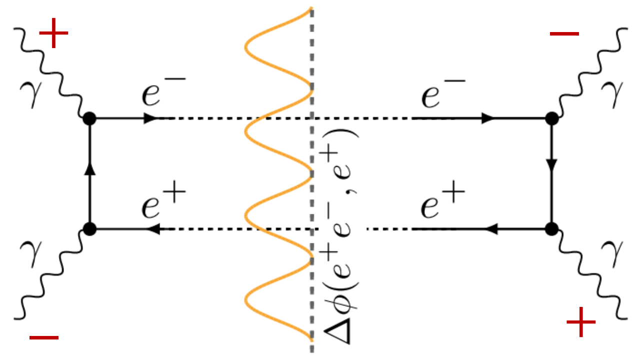
No nucleus breakup

- 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 $b_\perp > 2R_A$

Linear polarization @ UPCs

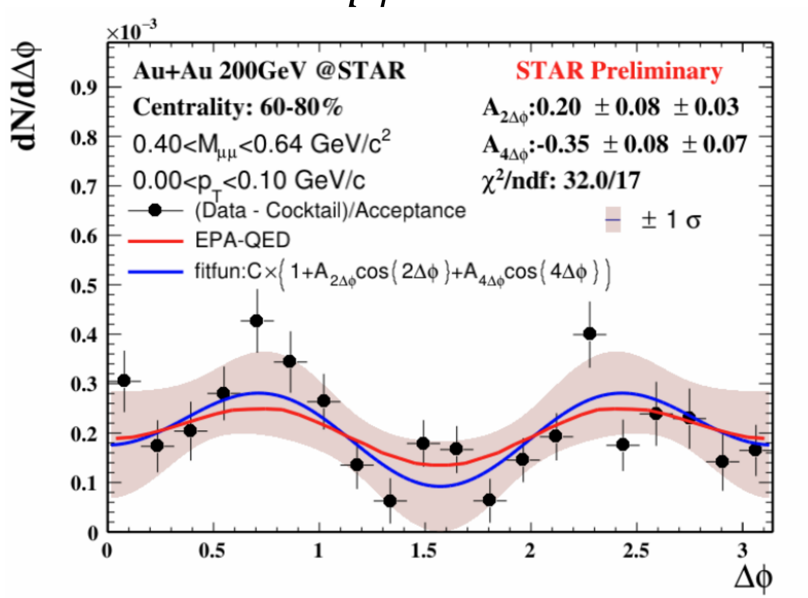
D. Y. Shao, C. Zhang, J. Zhou, Y. Zhou, PRD107 (2023) 3, 036020

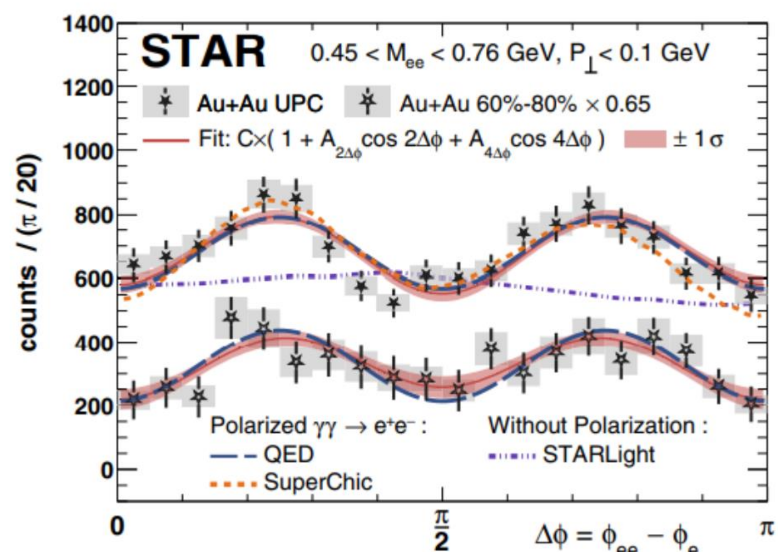




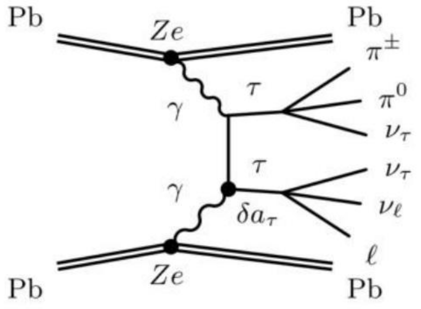
$$\frac{m_e^2}{p_T^2} cos2\Delta\phi$$

$$cos4\Delta\phi$$



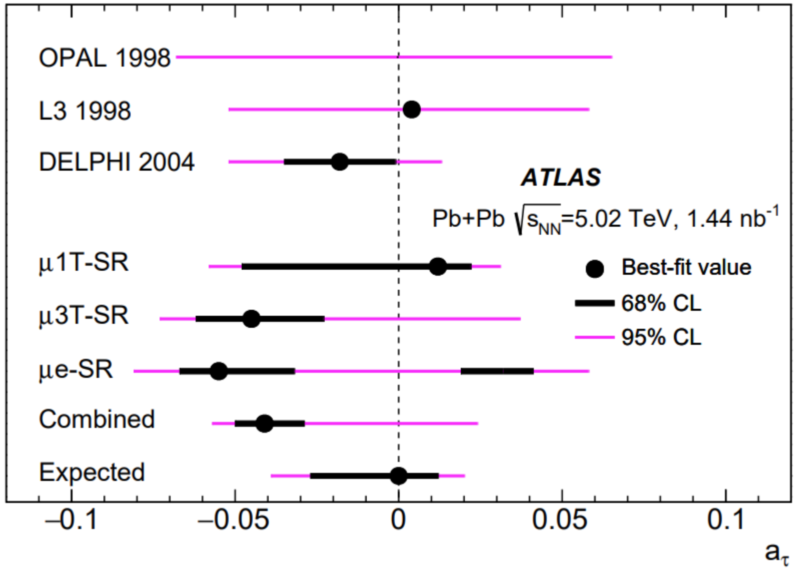


Tau pair production @ UPCs

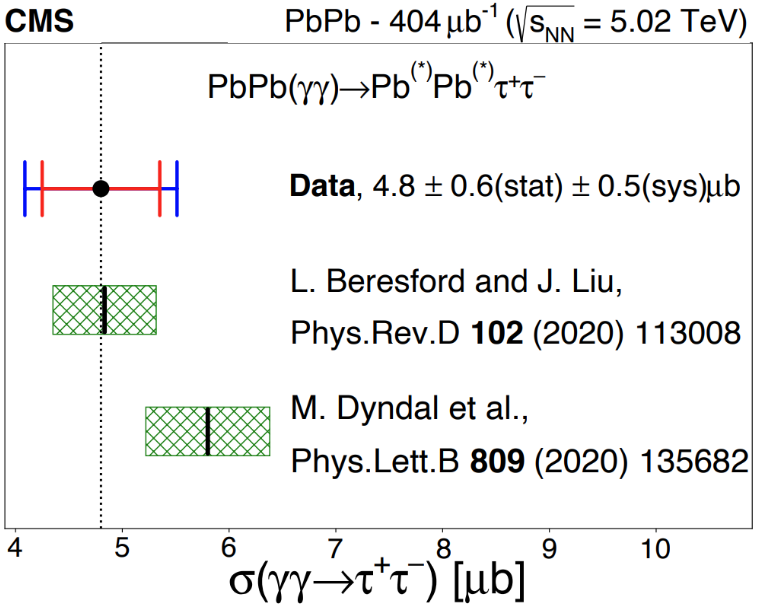


$$\Gamma^{\mu}_{\text{eff.}}(q^2) = -ie\left[iF_2(q^2) + F_3(q^2)\gamma^5\right]\frac{\sigma^{\mu\nu}q_\nu}{2m_\tau}$$

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



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



Phys. Rev. Lett. 131 (2023) 151803

Linear polarization @ UPCs

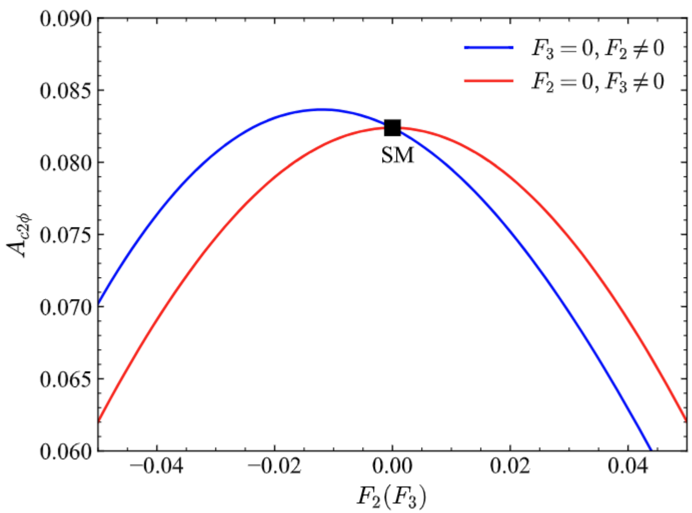
Dingyu Shao, Bin Yan, Shu-Ruan Yuan, Cheng Zhang, 2310.14153

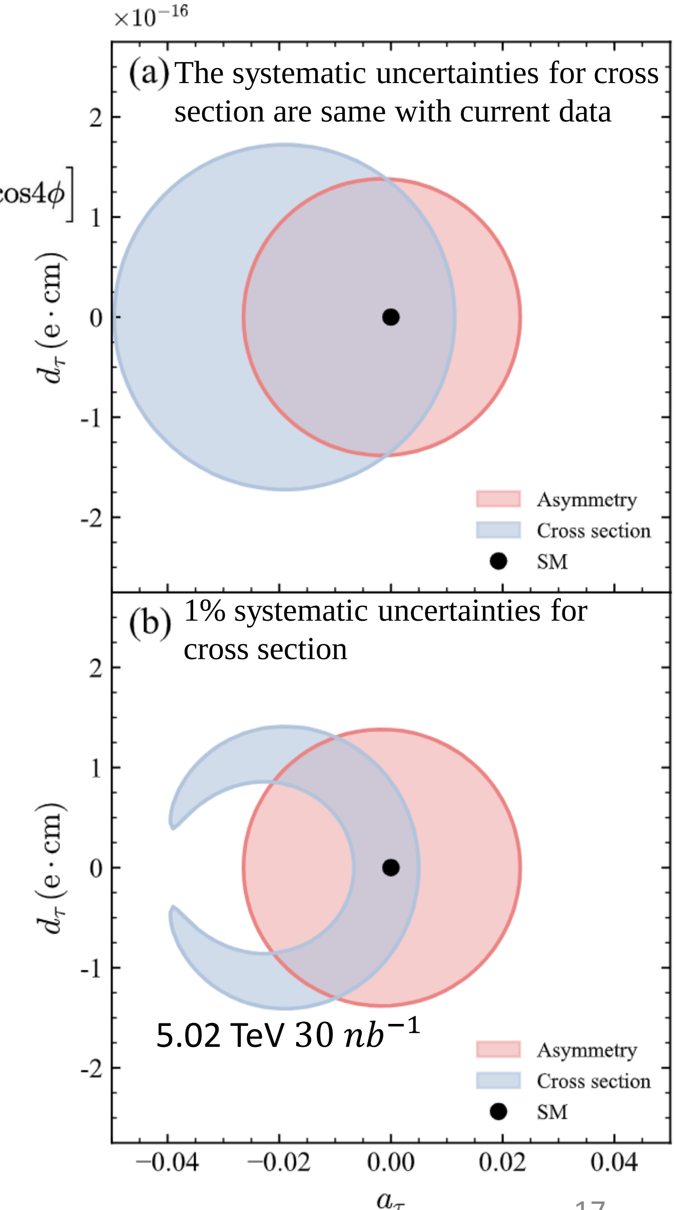
$$d\sigma \sim \left[A_0 + B_0^{(1)} F_2 + B_0^{(2)} F_2^2 + C_0^{(2)} F_3^2 + \left(A_2 + B_2^{(2)} F_2^2 + C_2^{(2)} F_3^2\right) \cos 2\phi + A_4 \cos 4\phi\right]$$

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

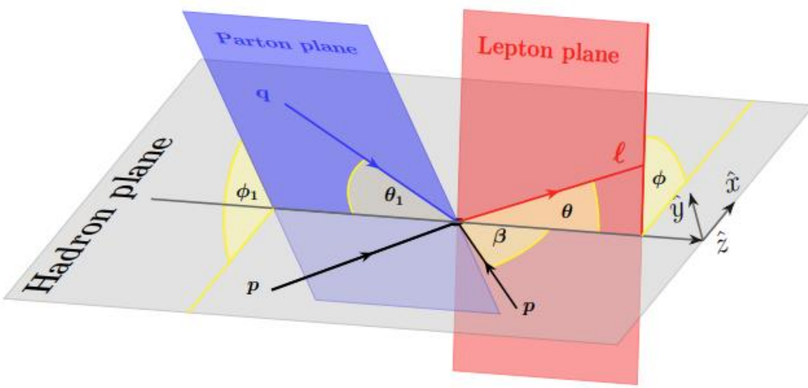
Suppressed by lepton mass

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





Lam-Tung relation and polarization



Collins-Soper frame

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

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

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

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

Center-of-mass frame:

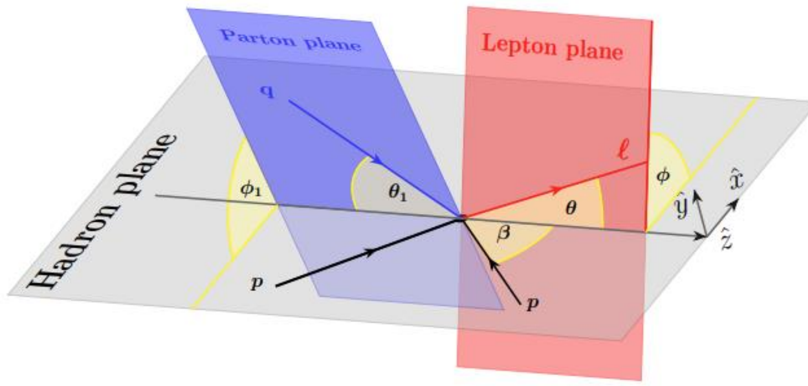
$$\frac{d\sigma}{d\Omega} = a\cos\hat{\theta} + b\cos^2\hat{\theta} + c\cos^3\hat{\theta} + d$$

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

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

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

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



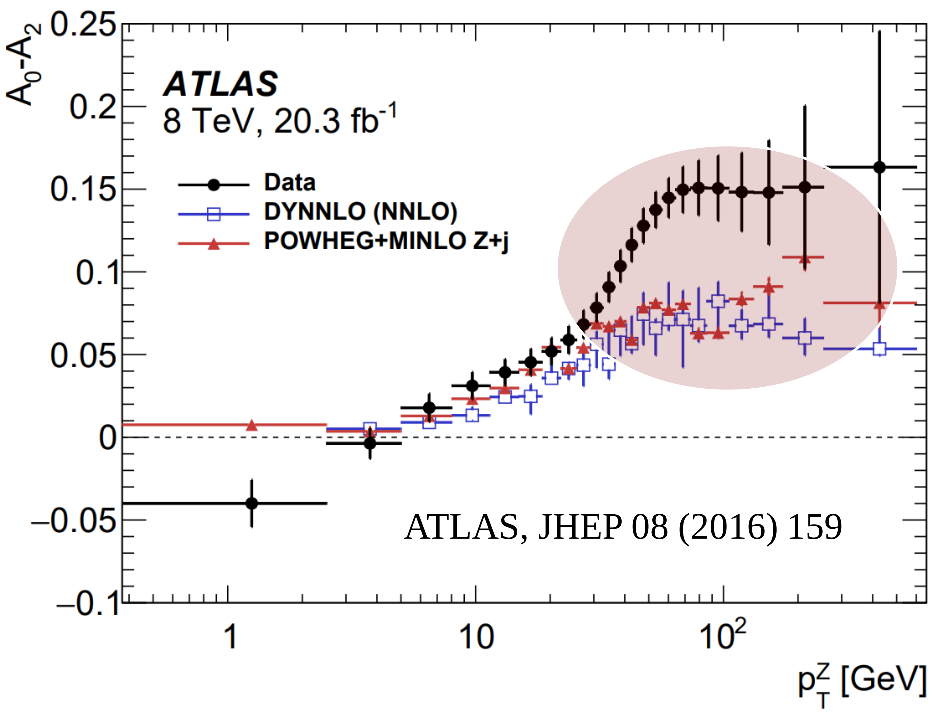
$A_0 \neq A_2$

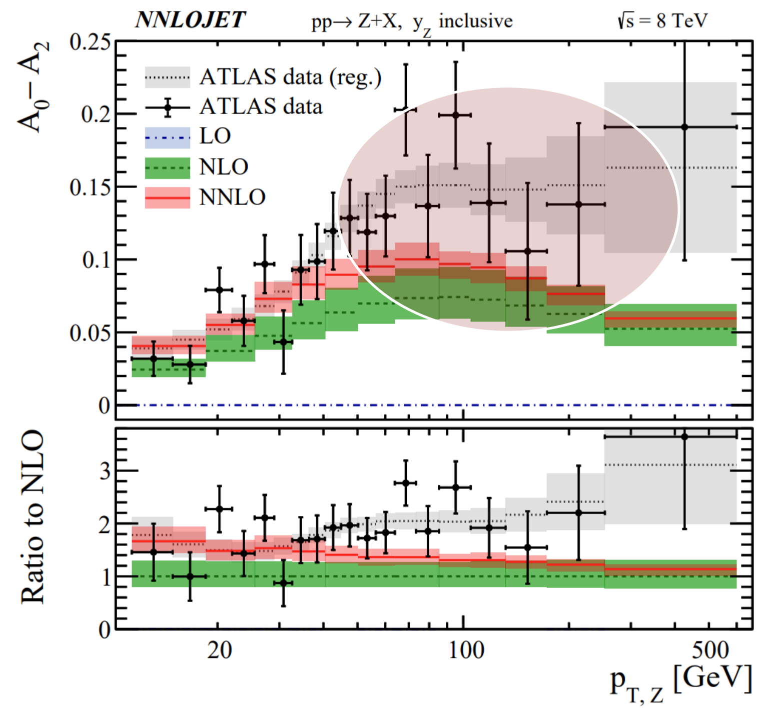
- Coplanarity case: $b \neq d$
- Non-coplanarity case: $\phi_1 \neq 0$, NNLO and beyond or by the nonperturbative effects

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

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

Lam-Tung relation and polarization





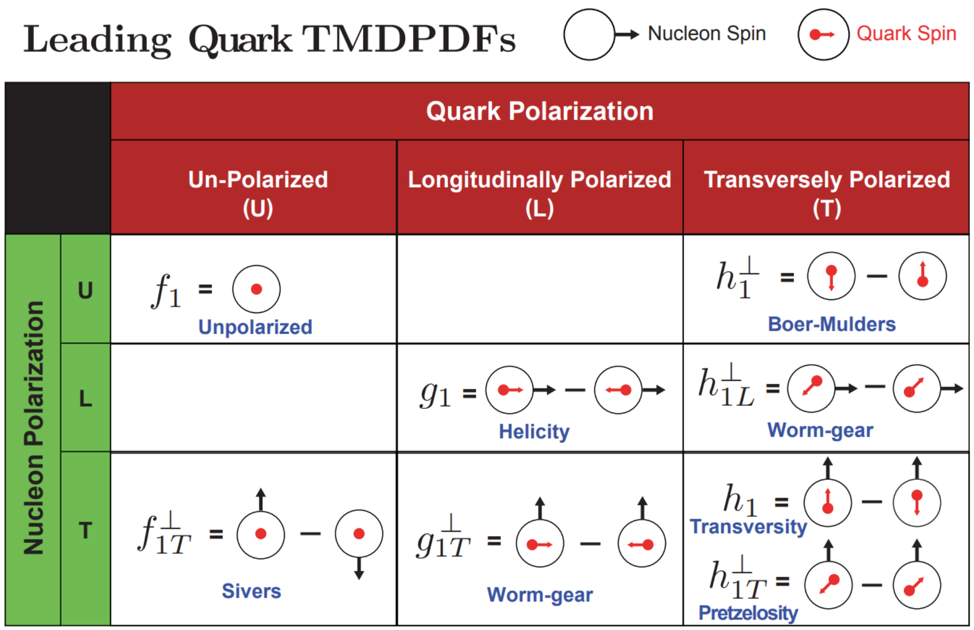
R. Gauld et al, JHEP 2017, N3LO

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

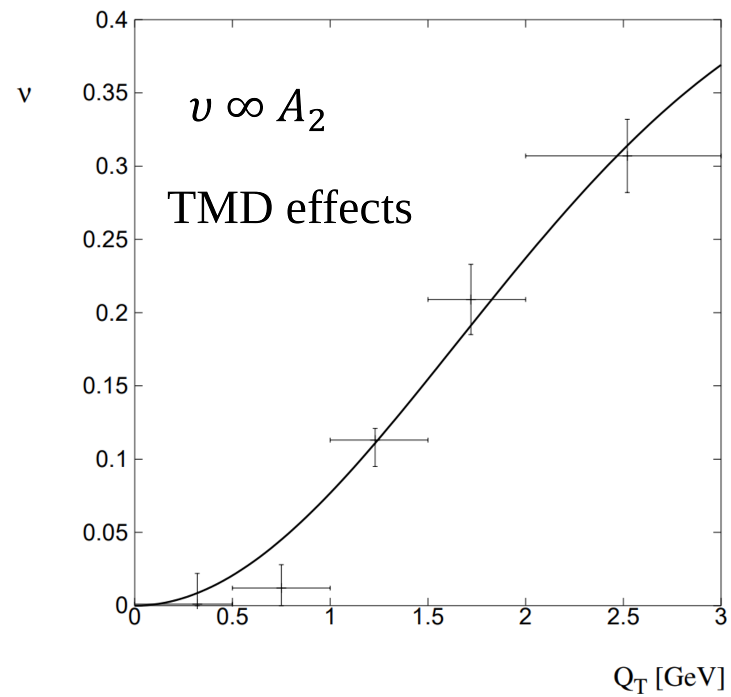
The discrepancy with the SM prediction
NP effects or non-perturbative effects ?

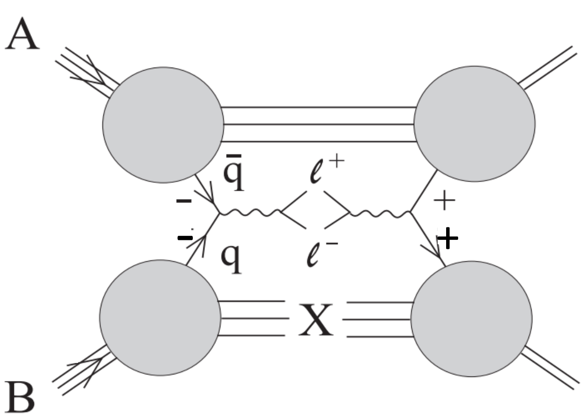
Boer-Mulders function

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



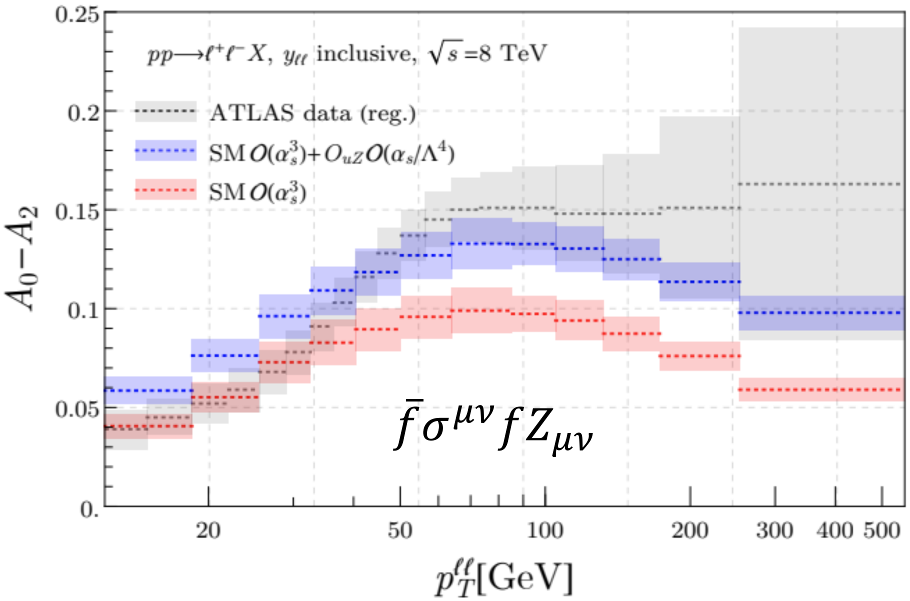
Boer, PRD 60 (1999) 014012

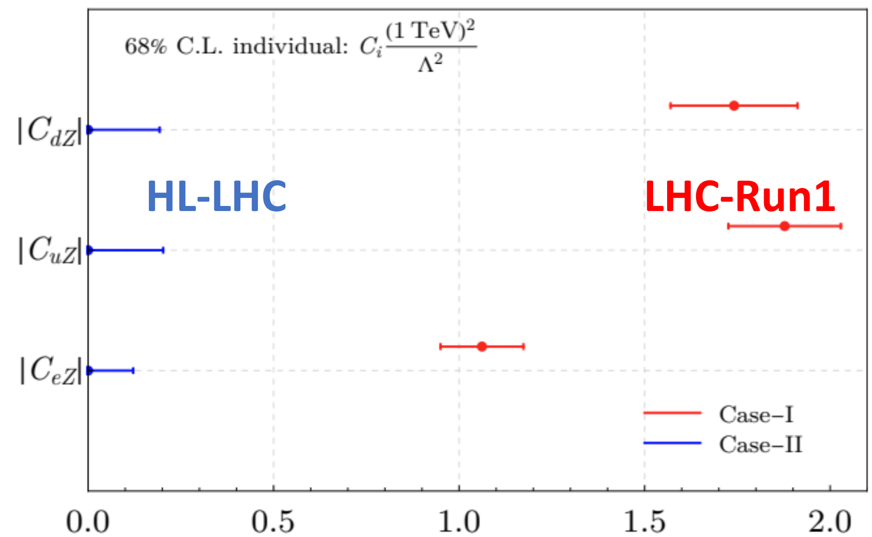




Transversely polarized quark

Lam-Tung relation and 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

Summary

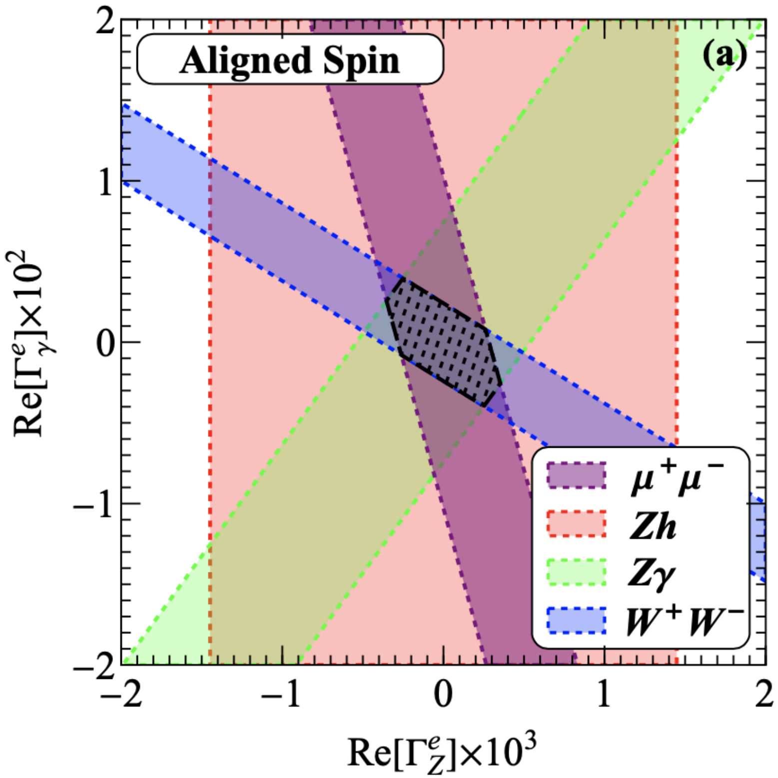
- The Chirality-flipped operators are difficult to be probed at colliders since their leading effects are from $1/\Lambda^4$
- These operators can be probed at $1/\Lambda^2$ via transverse spin effects of beams
- Both Re & Im parts can be well constrained, *without impact from other NP and* offering 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

Pinning down Dipole Operators

$$\mathcal{L}_{\rm eff} = -\frac{1}{\sqrt{2}}\bar{\ell}_L \sigma^{\mu\nu}\left(g_1 \Gamma^e_B B_{\mu\nu} + g_2 \Gamma^e_W \sigma^a W^a_{\mu\nu}\right)\frac{H}{v^2} e_R + \text{h.c.}$$

The sensitivity to Γ^e_Z is much stronger than Γ^e_γ



Parity property

$$\mathcal{M}^*_{++}\mathcal{M}_{-+} = -\mathcal{M}^*_{+-}\mathcal{M}_{--}(g^e_L \leftrightarrow g^e_R)$$

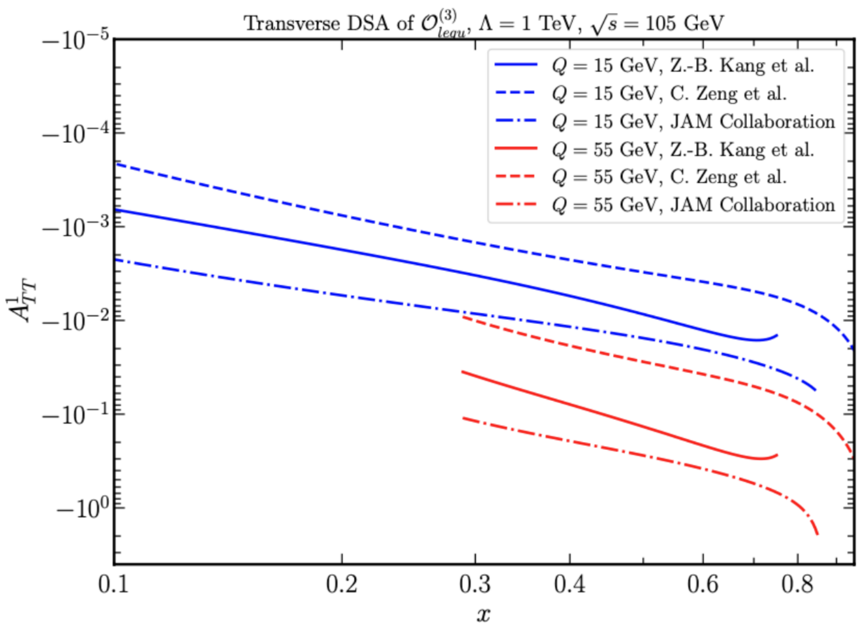
$$|\mathcal{M}|^2 \sim (g^e_L - g^e_R)[(g^e_L + g^e_R)\Gamma^e_\gamma + \Gamma^e_Z]$$

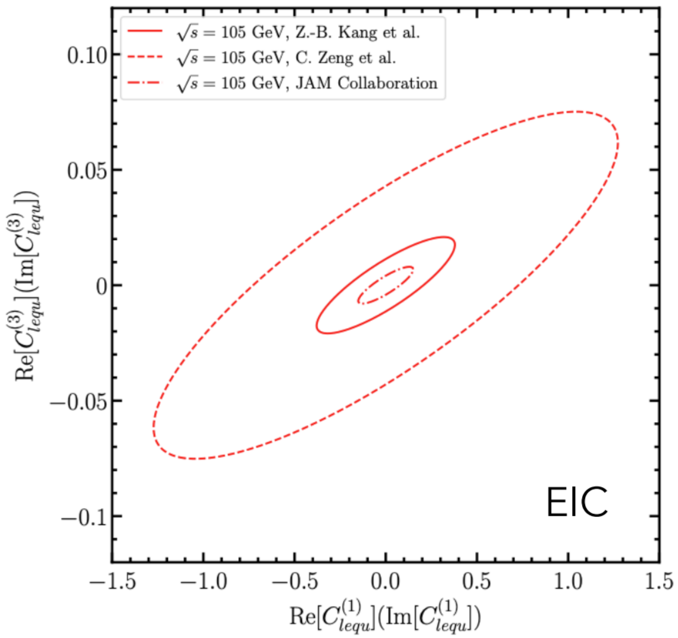
- SM $(g^e_L + g^e_R) = -1/2 + 2s^2_W \ll 1$
- SM $WW\gamma < WWZ$
- $\Gamma^e_W = \Gamma^e_Z + s^2_W \Gamma^e_\gamma$

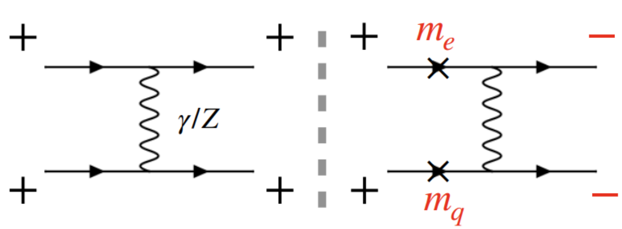
Transverse spin effects@ EIC

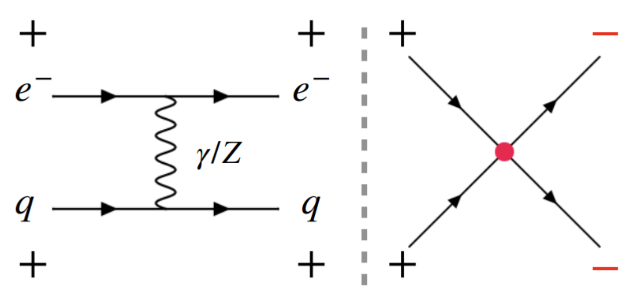
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan, PRD 109 (2024) 095025

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



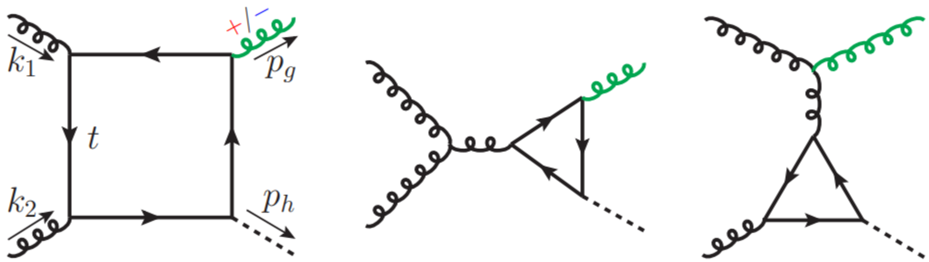




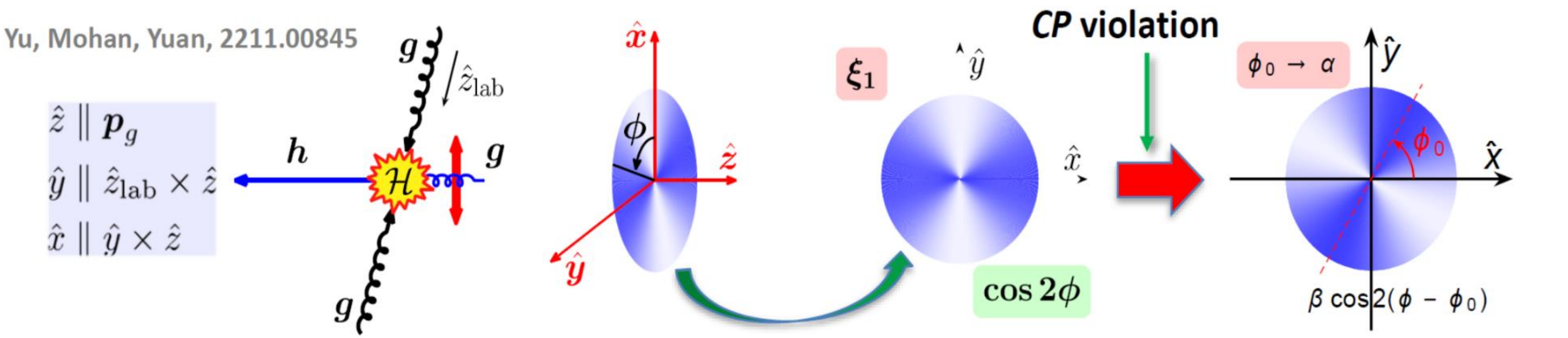


DSA in SM will be suppressed by electron and quark masses $O(10^{-7} \sim 10^{-9})$

Linear polarization of gluon



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

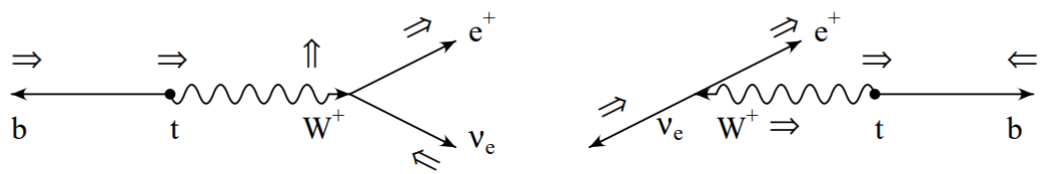


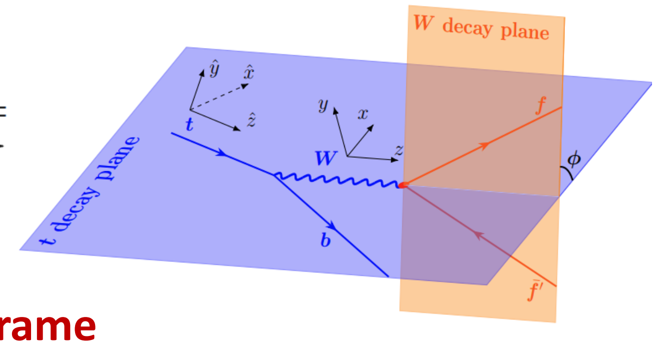
CP phase = rotation of anisotropy axis

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

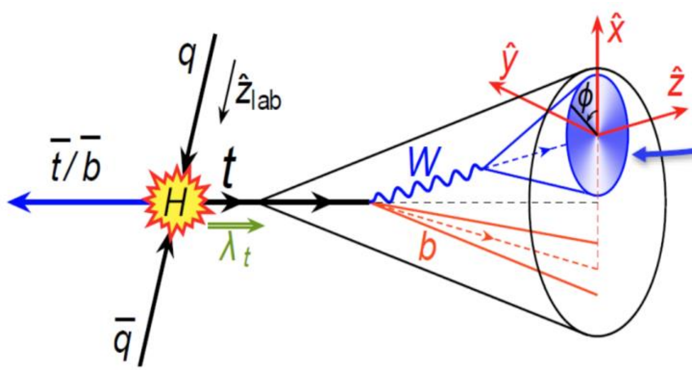
Linear polarization of W boson

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





W boson is not linearly polarized in top quark rest frame



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

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

[Assuming SM tbW coupling]

Azimuthal correlation

➡ Boosted top polarization

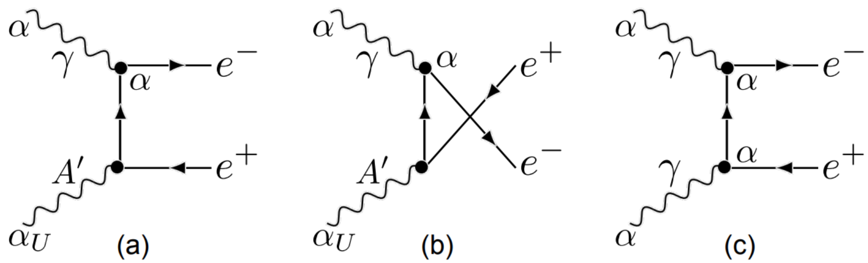
- Measuring longitudinal polarization of boosted top
- New top tagger against QCD jets

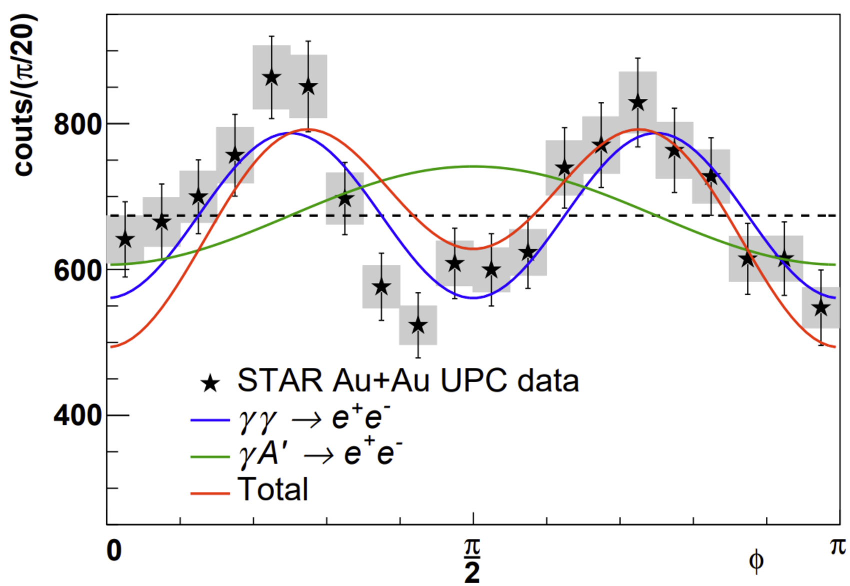
➡ A new tool to probe the NP effects,
e.g. the CP violation in top quark decay

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

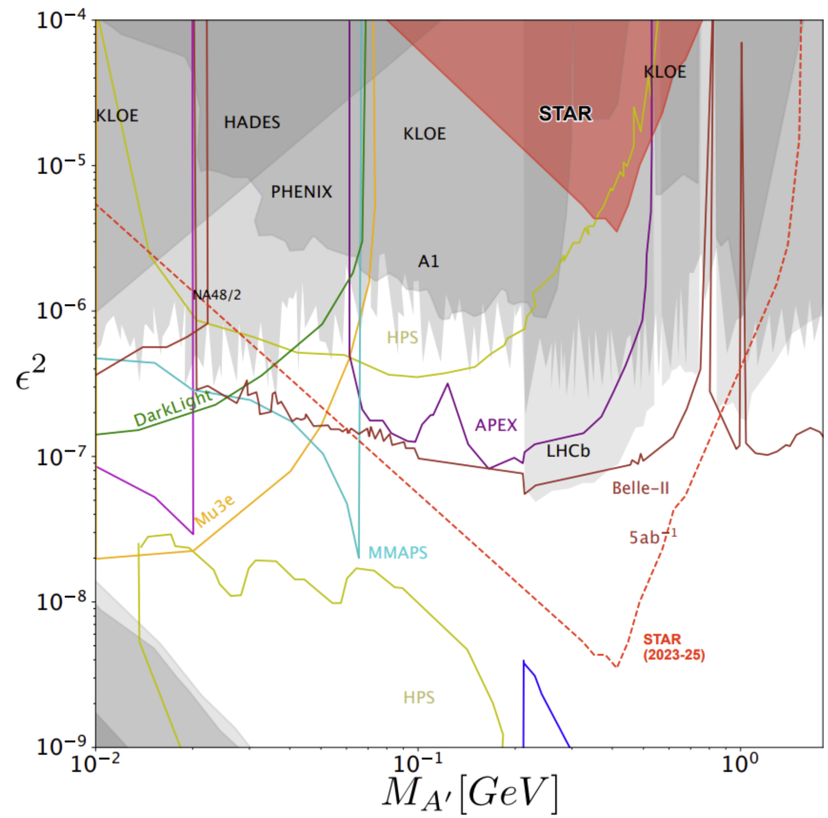
Linear polarization @ UPCs

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





I. Xu et al, arXiv:2211.02132



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