Some Novel Probes for Chirality-Flip Interactions at Colliders

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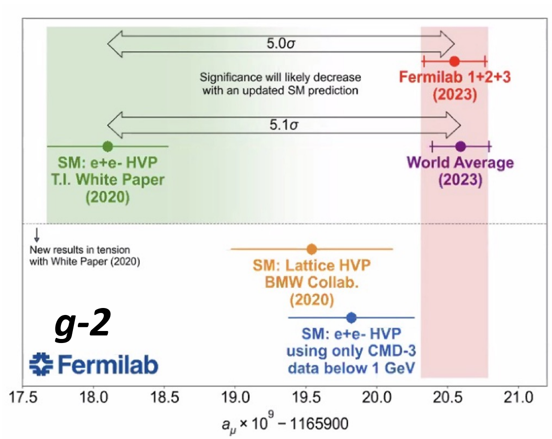
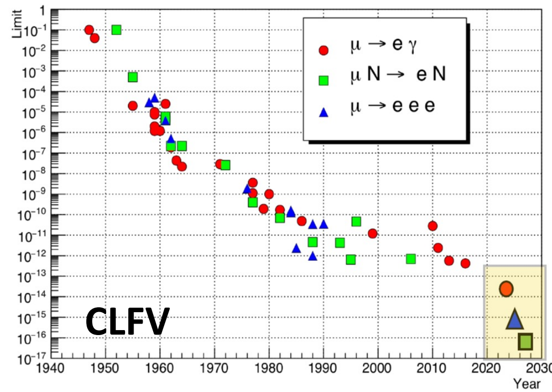
Phys.Rev.Lett. **131** (2023) 24, 241801
In collaboration with Hao-Lin Wang, Hongxi Xing and Bin Yan
Phys.Rev.D **109** (2024) 9, 095025
Works in Progress

2024/08/14 @ Qingdao

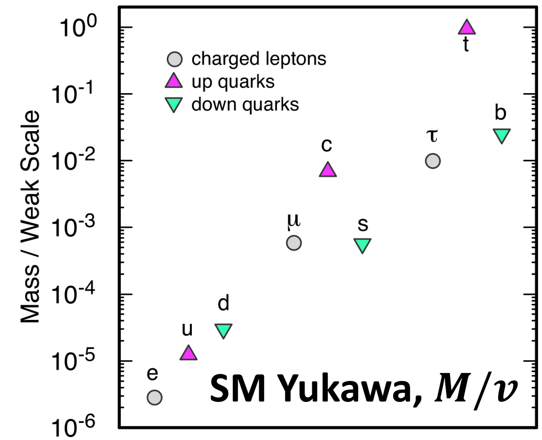
Chirality-Flip Interactions and New Physics



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

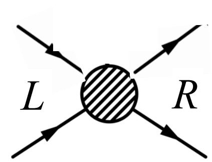


$$R_\pi = \frac{\Gamma(\pi^+ \to e^+\nu)}{\Gamma(\pi^+ \to \mu^+\nu)} \quad R_K, R_{D^{(*)}}$$

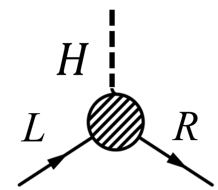


Chris Quigg, *Ann.Rev.Nucl.Part.Sci.* 59 (2009)

Dipole Operator



Scalar/Tensor
Four-Fermion operator



Yukawa operator

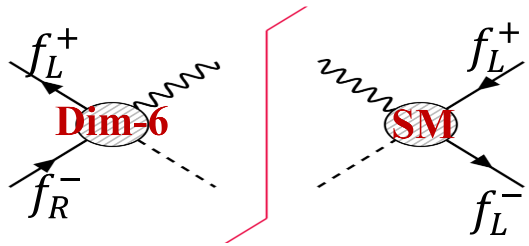
Fermion bilinear form: scalar and tensor currents

Due to heavy mass, Z and H can only be detected by colliders

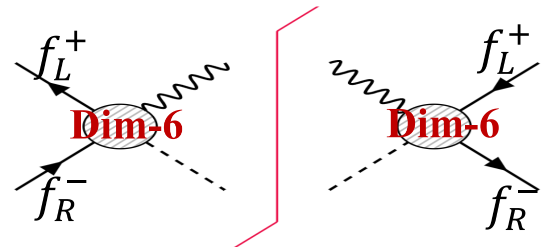
SMEFT Chirality-Flip Operator

$$|\mathcal{A}|^2 \sim \left| A_{\rm SM} + \frac{A_{\rm dim-6}}{\Lambda^2} + \frac{A_{\rm dim-8}}{\Lambda^4} + \ldots \right|^2 \sim |A_{\rm SM}|^2 + \frac{2}{\Lambda^2} A_{\rm dim-6} A_{\rm SM}^* + \frac{1}{\Lambda^4} |A_{\rm dim-6}|^2 + \frac{2}{\Lambda^4} A_{\rm dim-8} A_{\rm SM}^*$$

$\mathcal{O}(1/\Lambda^2)$ ✗



$\mathcal{O}(1/\Lambda^4)$ ✓



interference~**0** for tiny mass **← Chirality-Flip →** Non-interfering Leading effect

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

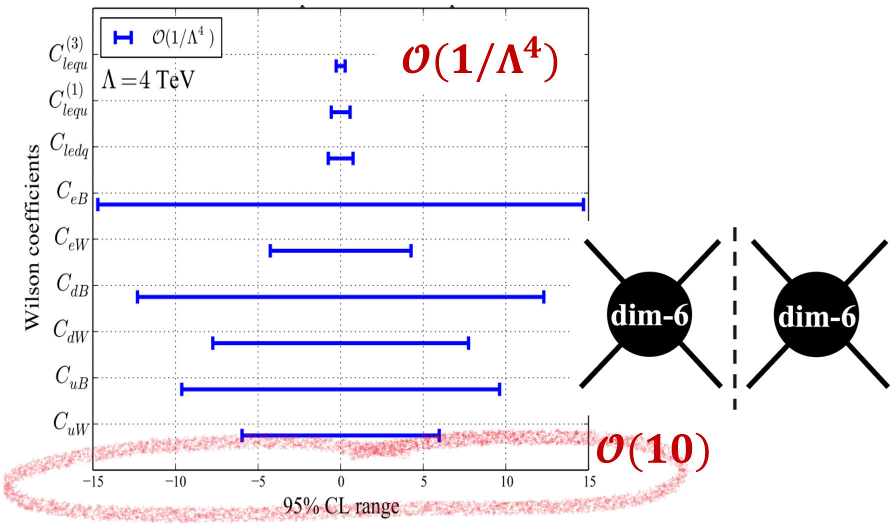
Table 2: Dimension-six operators other than the four-fermion ones.

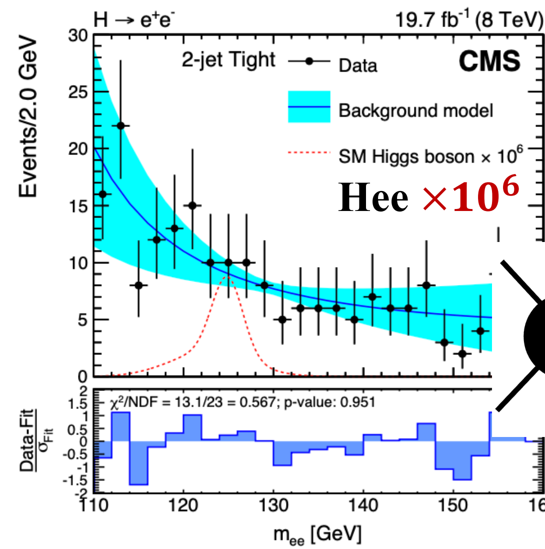
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

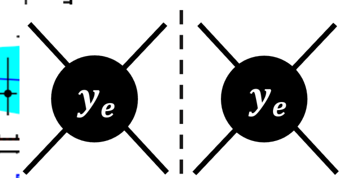
Table 3: Four-fermion operators.

Data for Chirality-Flip Operator

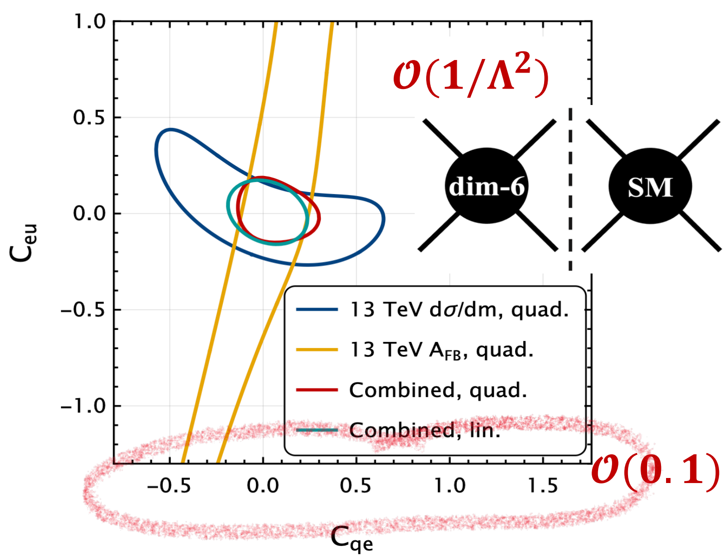
Constrained poorly in traditional rates of cross-section and width, suffer from contaminations







$$|y_e| \leq 260|y_e^{SM}| \text{ at } 95\% \text{ CL}$$



CMS Collaboration, *Phys.Lett.B* 744 (2015) 184-207
ATLAS Collaboration, *Phys. Lett. B* 801 (2020) 135148
R. Boughezal et al. *Phys.Rev.D* 104 (2021); *Phys.Rev.D* 108 (2023) 7

Single-Parameter-Analysis
Drell-Yan, Higgs boson decay @LHC

How to probe Chirality-Flip operators at $\mathcal{O}(1/\Lambda^2)$?

How to Probe Chirality-Flip Operator at $1/\Lambda^2$

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

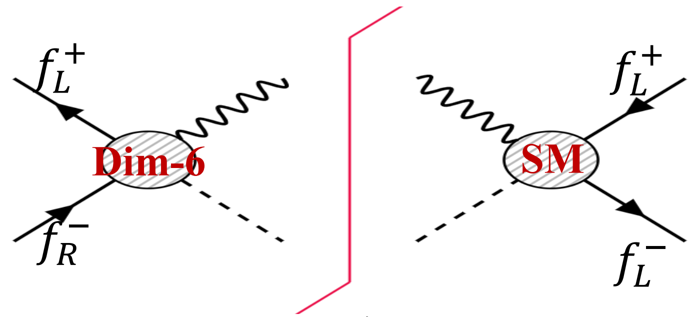
Our proposal:

- Transverse polarization effect of fermions

  Interference of the different helicity amplitudes

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

$$|\mathcal{M}|^2 = \rho_{\alpha_1\alpha_1'}(\boldsymbol{s})\rho_{\alpha_2\alpha_2'}(\bar{\boldsymbol{s}})\mathcal{M}_{\alpha_1\alpha_2}(\phi)\mathcal{M}^*_{\alpha_1'\alpha_2'}(\phi)$$



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

$\mathcal{O}(1/\Lambda^2)$ leading effect

- Allow chirality-flip NP, Forbid the others

  Single helicity-flip in fermion line

- **Transverse Spin Asymmetry**

  Nontrivial azimuthal behavior

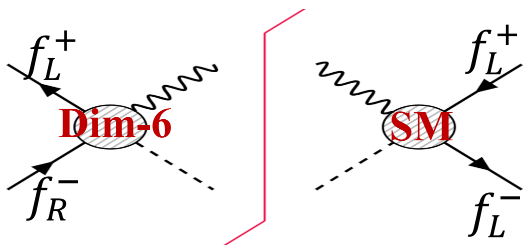
X.-K.W, BY, ZY, C.-P.Y, *Phys.Rev.Lett.* 131 (2023) 24
RB, DF, FP, WV, *Phys.Rev.D* 107 (2023) 07
H.-L.W, **X.-K.W**, HX, BY *Phys.Rev.D* **109** (2024) 9
RB, FP, KŞ, *arXiv:* 2407.12975
X.-K.W, BY, ZY, C.-P.Y, *arXiv:* 2408.xxxxxx, 2409.xxxxx
H.-L.W, **X.-K.W**, HX, BY, *arXiv:* 2409.xxxxx
J.-N. D, **X.-K.W**, BY, *work in progress*

Transverse Spin Induces Azimuthal Behavior

- Breaking rotational invariance

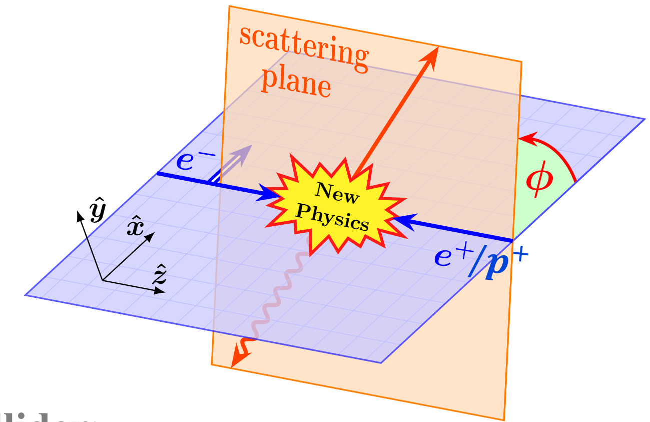
Nontrivial azimuthal behavior

$$\mathcal{M}_{\lambda_1,\lambda_2}(\theta,\phi) = e^{i(\lambda_1-\lambda_2)\phi}\mathcal{T}_{\lambda_1,\lambda_2}(\theta)$$



$e^{i\phi*0}$ $e^{i\phi*1}$

X.-K.W, BY, ZY, C.-P.Y, work in progress



STSAA@ee collider:

dipole operator → $\mathcal{M}_{\pm\pm}$, massless SM → $\mathcal{M}_{\pm\mp}$

DSA@eP collider:

Four-F operator → $\mathcal{M}_{-i,-j}$, massless SM → $\mathcal{M}_{ij}$

	U	L	T	
U	$\lvert\mathcal{M}\rvert^2_{UU} \to 1$	$\lvert\mathcal{M}\rvert^2_{UL} \to 1$	$\lvert\mathcal{M}\rvert^2_{UT} \to \cos\phi, \sin\phi$	→ **STSAA**
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	$\lvert\mathcal{M}\rvert^2_{TU} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TL} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TT} \to 1, \cos 2\phi, \sin 2\phi$	→ **DSA**

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

A New Probe of Dipole Operators @ ee collider

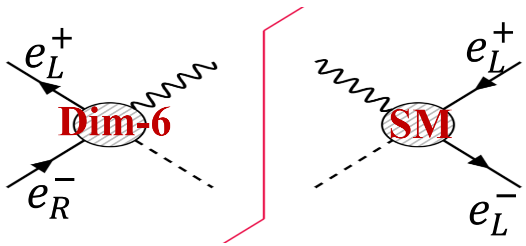
$$\frac{2\pi\, d\sigma^i}{\sigma^i\, d\phi} = 1 + A_R^i(b_T, \bar{b}_T)\cos\phi + A_I^i(b_T, \bar{b}_T)\sin\phi + b_T\,\bar{b}_T\, B^i \cos 2\phi + \mathcal{O}(1/\Lambda^4)$$

$\mathrm{Re}[\Gamma_f]$ — $\vec{s}\cdot\vec{p}_f \propto \cos\phi$ — CP-conserving

$\mathrm{Im}[\Gamma_f]$ — $\vec{s}\times\vec{p}_f \propto \sin\phi$ — CP-violation

SM & other NP

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



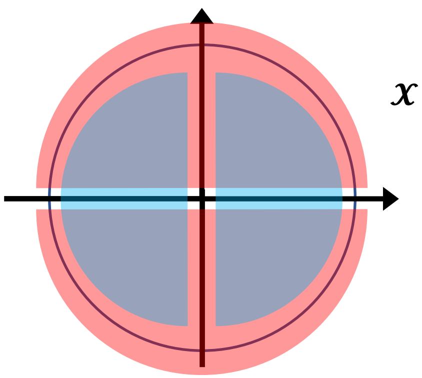
$$|\mathcal{M}|^2 \propto \mathrm{Re}[\Gamma_q\, e^{i(\phi_s - \phi_\ell)}]$$

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

Linearly dependent on the dipole couplings Γ_f and spin b_T

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

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



Without contaminations from other NP and SM

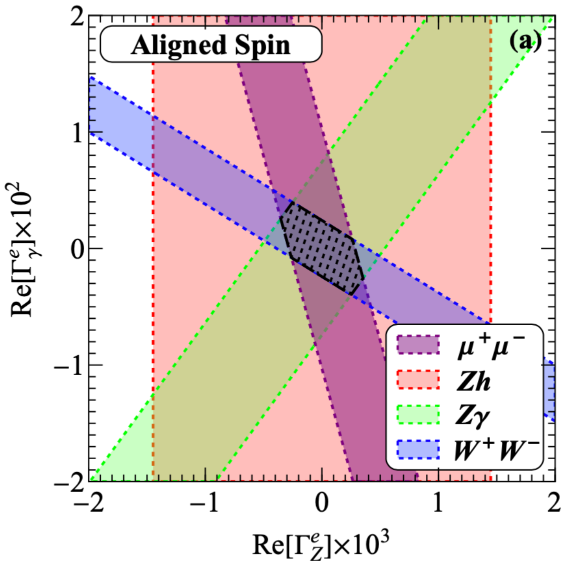
Pinning down Dipole Operators @ ee collider

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

$$\Gamma^e_\gamma = \Gamma^e_W - \Gamma^e_B$$

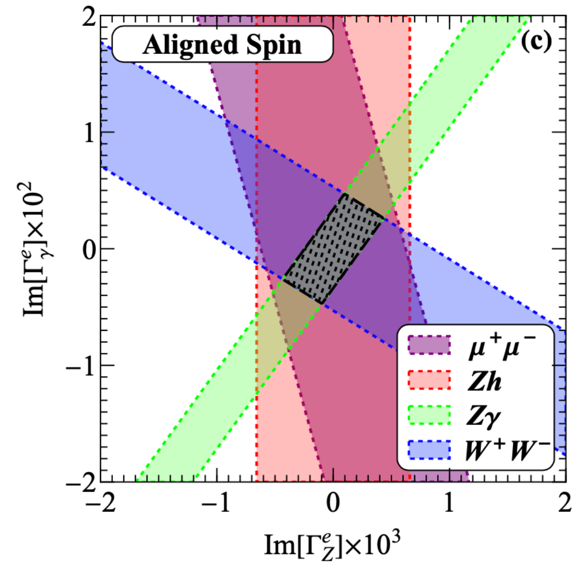
$$\Gamma^e_Z = c_W^2 \Gamma^e_W + s_W^2 \Gamma^e_B$$

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



$$(b_T, \bar{b}_T) = (0.8, 0.3)$$

$$\sqrt{s} = 250\ \text{GeV}, \mathcal{L} = 5\ \text{ab}^{-1}$$



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

Much stronger sensitivity than other approaches by 1~2 orders of magnitude

Our bounds: $\mathcal{O}(10^{-4}\sim10^{-3})$, LHC or LEP: $\mathcal{O}(10^{-2}\sim10^{-1})$

Offering a new opportunity for directly probing potential CP-violating effects

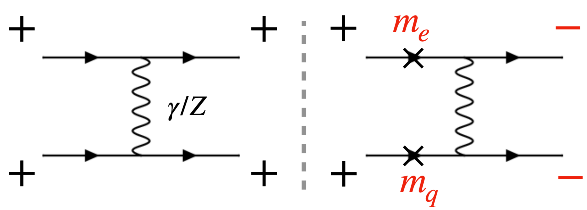
Transverse Double-Spin-Asymmetry @ EIC

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

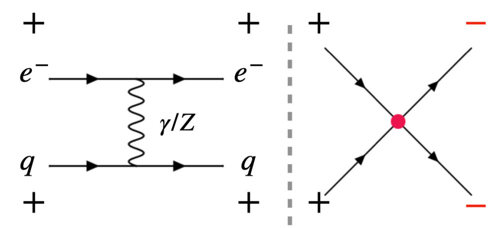
Polarized DIS (Transverse lepton and proton)

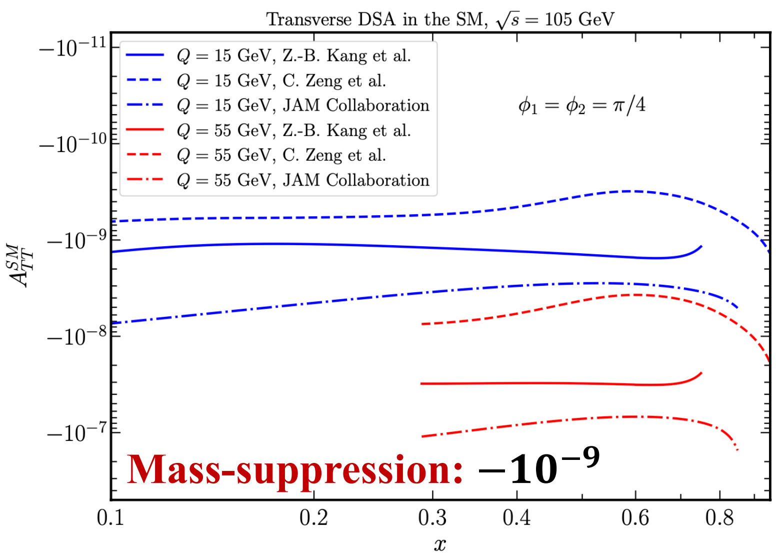
- **2ϕ** and **flat** shape

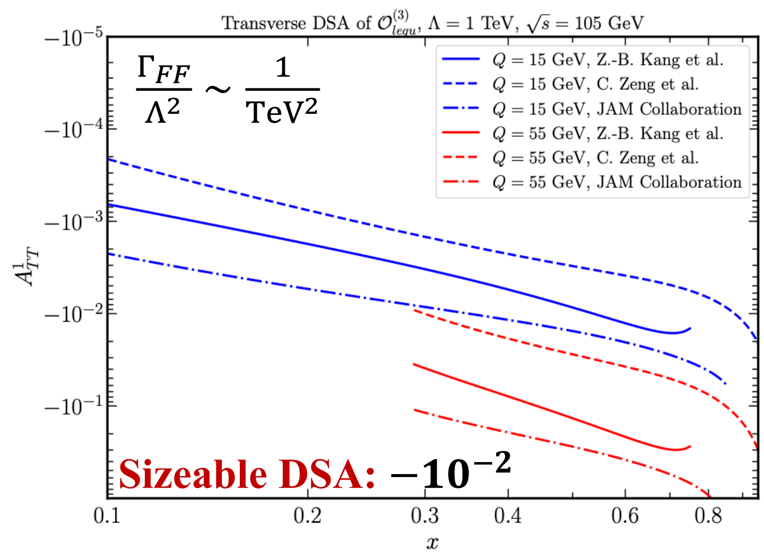
SM



Scalar/Tensor four-fermion operator







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

Without contamination from the SM and other NP

Probing four-fermion operators @EIC & EicC

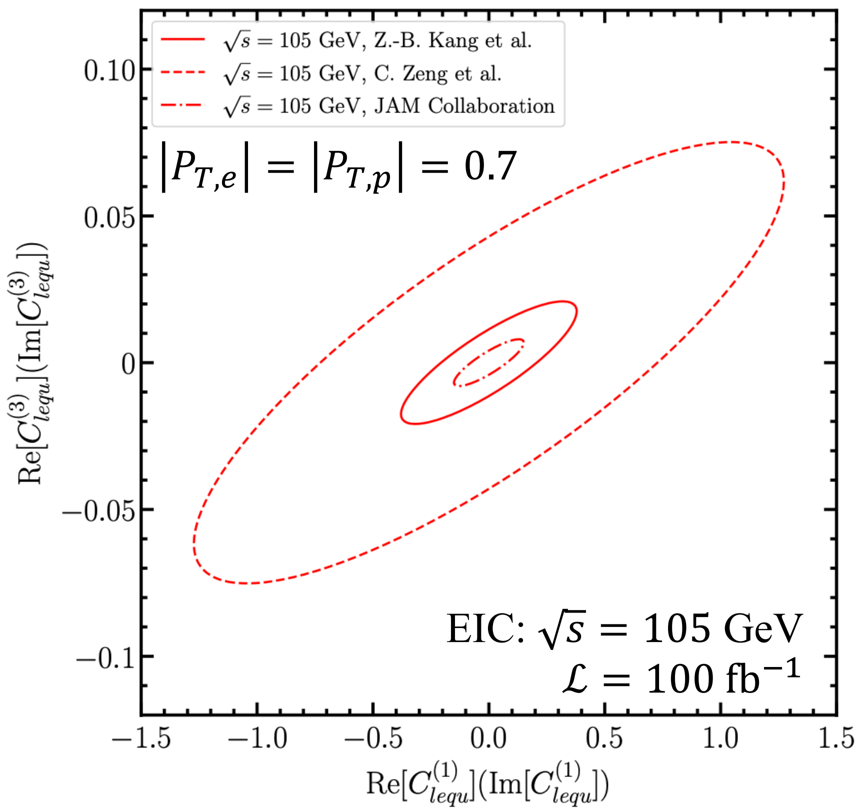
H.-L. Wang, **X.-K. Wen**, H. Xing and B. Yan, *Phys.Rev.D* **109** (2024) 9, 095025

scalar/tensor four-fermion operator

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

- highly depend on transversity $h(x,\mu)$

Z.-B. Kang et al., *Phys.Rev.D* 93 (2016) 1
C. Zeng et al., *Phys.Rev.D* 109 (2024) 5
JAM collaboration *Phys.Rev.D* 106 (2022) 3



- ✓ The bounds are *stronger* or *comparable* to other $\mathcal{O}(1/\Lambda^4)$-approaches
- ✓ Enabling direct study of potential CP-violating effects.

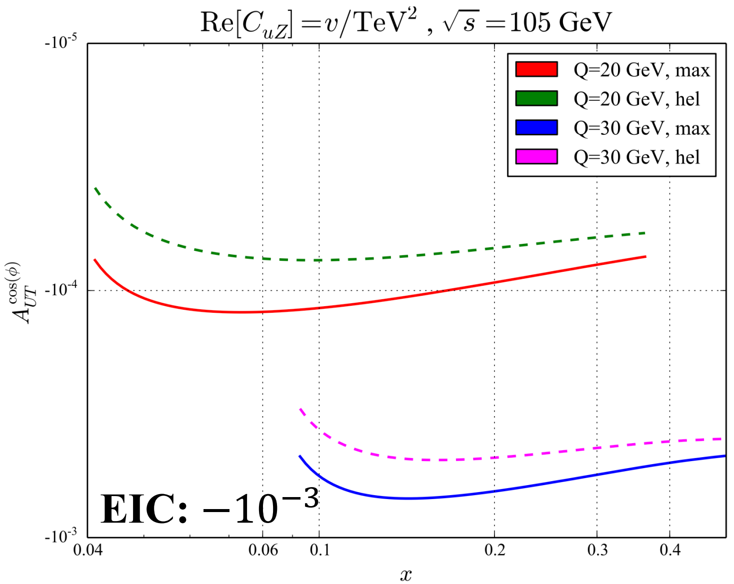
Transverse Spin Asymmetry @ EIC and FCC-ee

lepton or **quark** dipole operator

Polarized DIS (Transverse lepton or proton)

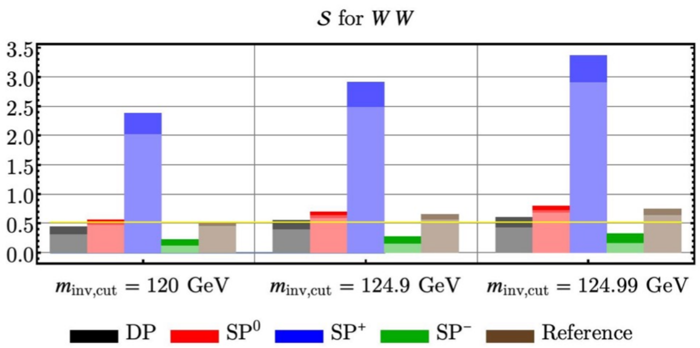
- single-ϕ shape

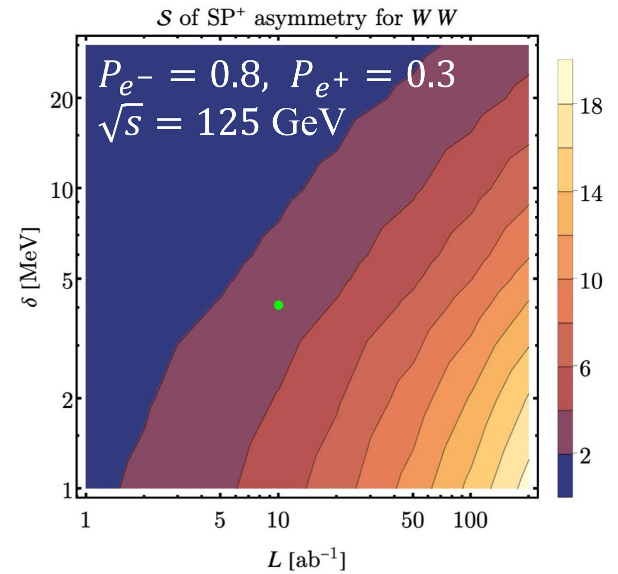
$$A_{TU} = \frac{\sigma(e^{\uparrow}) - \sigma(e^{\downarrow})}{\sigma(e^{\uparrow}) + \sigma(e^{\downarrow})} \qquad A_{UT} = \frac{\sigma\left(e^{U}p^{\uparrow}\right) - \sigma\left(e^{U}p^{\downarrow}\right)}{\sigma\left(e^{U}p^{\uparrow}\right) + \sigma\left(e^{U}p^{\downarrow}\right)}$$



R adja Boughezal, et al., *Phys.Rev.D* 107 (2023) 7

Hee **Yukawa** coupling





Frank Petriello, et al., *arXiv:* 2407.12975

✓ Spin asymmetry enhances the detection sensitivity to Chirality-Flip interactions

Dihadron Azimuthal Asymmetry @ EIC

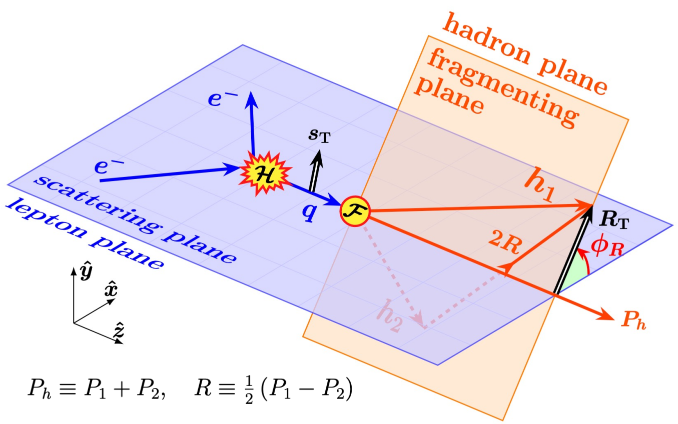
Dihadron azimuthal asymmetry probes **light-quark** dipole moments without hadron spin

Unpolarized DIS (at most longitudinal polarized electron)

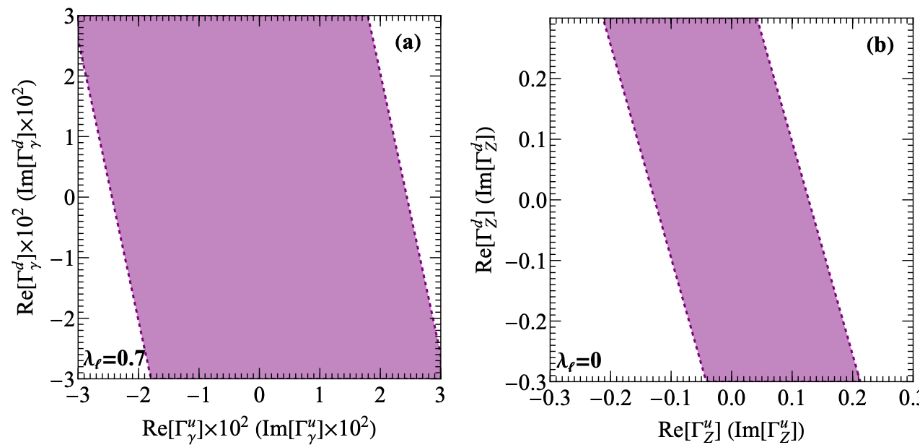
$$e^-(\ell) + p(p) \rightarrow e^-(\ell') + h_1(p_1) + h_2(p_2) + X$$

- single-ϕ_R shape

$$\boldsymbol{s}_{T,q} \cdot (\boldsymbol{p}_1 \times \boldsymbol{p}_2)$$



$P_h \equiv P_1 + P_2, \quad R \equiv \frac{1}{2}(P_1 - P_2)$



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

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, *arXiv:* 2408.xxxxx (announced tomorrow), 2409.xxxxx

Quark transverse spin transmitted into dihadron asymmetry within collinear factorization

Dipole interactions produce light-quark transverse spin ←→ Observables independent of hadron spin

Stronger bounds than other approaches by about one orders of magnitude

Summary

- ✓ The muon g-2 data and many NP models may hint Chirality-Flip interactions
- ✓ Chirality-Flip operators are difficult to be probed since their leading effects @$1/\Lambda^4$
- ✓ These operators can be linearly probed @$1/\Lambda^2$ via *transverse spin of fermions*
- ✓ Simultaneously constraining well both Re & Im parts
  - ➢ Without contamination from other NP and SM
  - ➢ Offering a new opportunity for directly probing potential CP-violating effects.
- ✓ The sensitivities are much stronger than other approaches by 1~2 orders of magnitude
- ✓ Transverse spin asymmetries enhance detection of Chirality-Flip interactions
- ✓ Future colliders (Z/Higgs/Top factory…)
  - ➢ Polarized Muon collider, Muon-Ion collider, Hadron colliders, Electron-Ion Collider…
  - ➢ More new transverse / linear spin polarization probes for New Physics

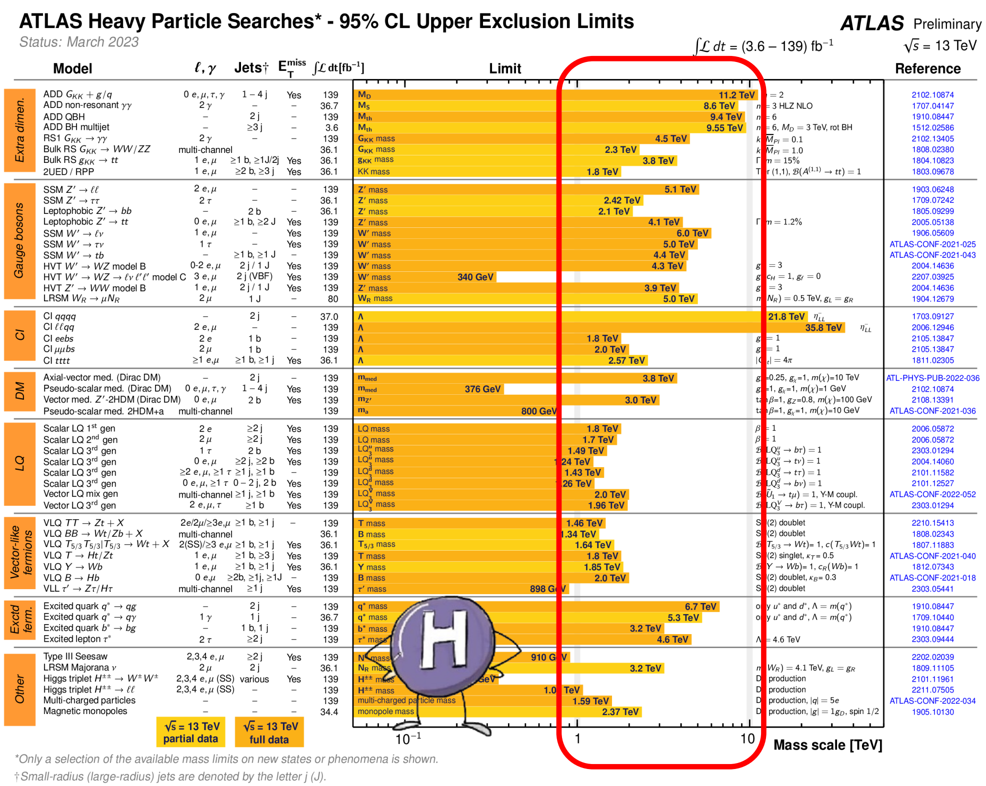
Thank you

Backup

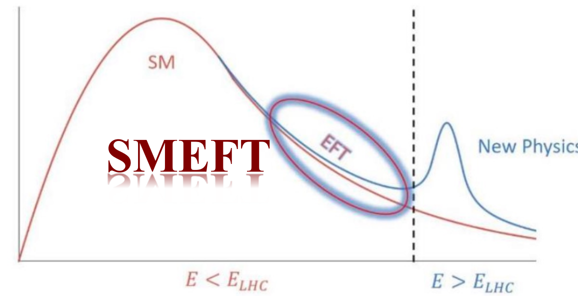
BACKUP

New Physics and SMEFT

SM is successful enough but there are still open questions requiring New Physics



Direct searches: Null !!



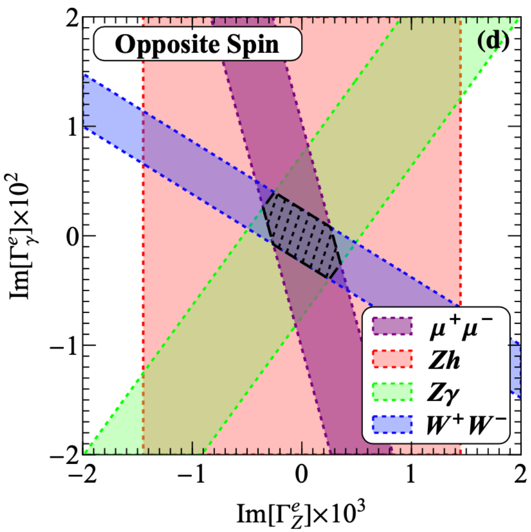
$$\mathcal{L} = \frac{C_6}{\Lambda^2}\mathcal{O}_6 + \frac{C_8}{\Lambda^4}\mathcal{O}_8 + \ldots$$

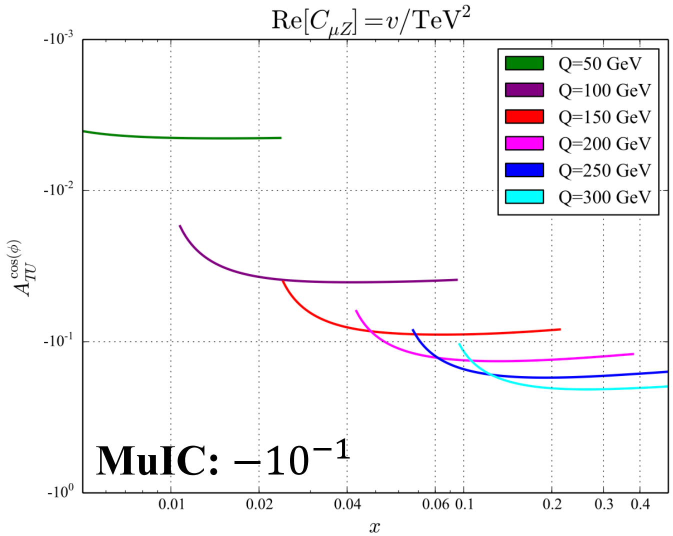
B. Grzadkowski, et al. *JHEP* 10 (2010)
W. Buchuller, D. wyler, 1986

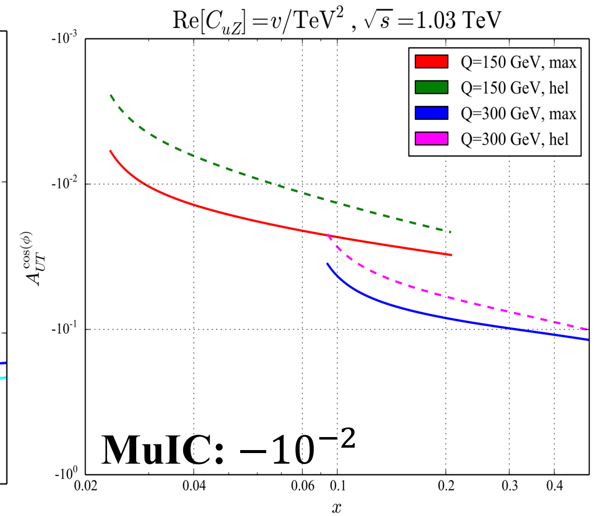
Precision measurements

New Physics excluded to **Multi-TeV** @ LHC ➡ $\boldsymbol{\Lambda \sim \mathcal{O}(\mathrm{TeV})}$

Backup







The sensitivity to Γ_Z^e is much stronger than Γ_γ^e ➢ Parity property of helicity amplitude

Why the limit difference between the Aligned Spin and the Opposite Spin? ➢ CP property

The asymmetry at MuIC is significantly larger than at EIC ➢ Energy enhancement

$$A_{TT}^w = \frac{1}{P_{T,e}P_{T,p}} \frac{1}{N_{\uparrow\uparrow}+N_{\downarrow\downarrow}+N_{\uparrow\downarrow}+N_{\downarrow\uparrow}} \times \int_0^{2\pi} d\phi\, w(\phi)\Big(N_{\uparrow\uparrow}(\phi)+N_{\downarrow\downarrow}(\phi)-N_{\uparrow\downarrow}(\phi)-N_{\downarrow\uparrow}(\phi)\Big)$$

$$\delta A_{TT}^w \simeq \frac{1/(P_{T,e}P_{T,p})}{\sqrt{4\mathcal{L}\sigma(P_{T,e(p)}=0)}} \cdot \sqrt{\frac{\int_0^{2\pi} d\phi\, w^2(\phi)}{2\pi}}$$

Backup: Some Formulae

$$|\Theta,\chi\rangle_1 = \cos\frac{\Theta}{2}|h=+\rangle + \sin\frac{\Theta}{2}e^{i\chi}|h=-\rangle$$

Superposition of the two helicity states along polarization $\vec{s}(\Theta,\chi)$

$$T_{h\bar{h}} = \langle\phi,\ldots|T|\chi,\bar{\chi}\rangle = \langle\phi=0,\ldots|T|\chi-\phi,\bar{\chi}-\phi\rangle$$

2-to-2 rotational invariance

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

$$|\mathcal{M}|^2(\boldsymbol{s},\bar{\boldsymbol{s}},\theta,\phi) = \sum_{\alpha_1,\alpha_2,\alpha_1',\alpha_2'} \rho_{\alpha_1,\alpha_1'}(\boldsymbol{s})\,\bar{\rho}_{\alpha_2,\alpha_2'}(\bar{\boldsymbol{s}})\,\mathcal{M}_{\alpha_1,\alpha_2}(i\to f;\theta,\phi)\,\mathcal{M}^\dagger_{\alpha_1',\alpha_2'}(i\to f;\theta,\phi)$$

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

$$\rho = \frac{1}{2}(1+\boldsymbol{\sigma}\cdot\boldsymbol{s})$$

$$\mathcal{M}_{\lambda_1,\lambda_2}(\theta,\phi) = e^{i(\lambda_1-\lambda_2)\phi}\mathcal{T}_{\lambda_1,\lambda_2}(\theta)$$

$$|\mathcal{M}|^2_{TU} = \frac{1}{2}b_\mathrm{T}\mathrm{Re}\left[e^{i(\phi-\phi_0)}\left(\mathcal{T}_{++}\mathcal{T}^\dagger_{-+} + \mathcal{T}_{+-}\mathcal{T}^\dagger_{--}\right)\right]$$

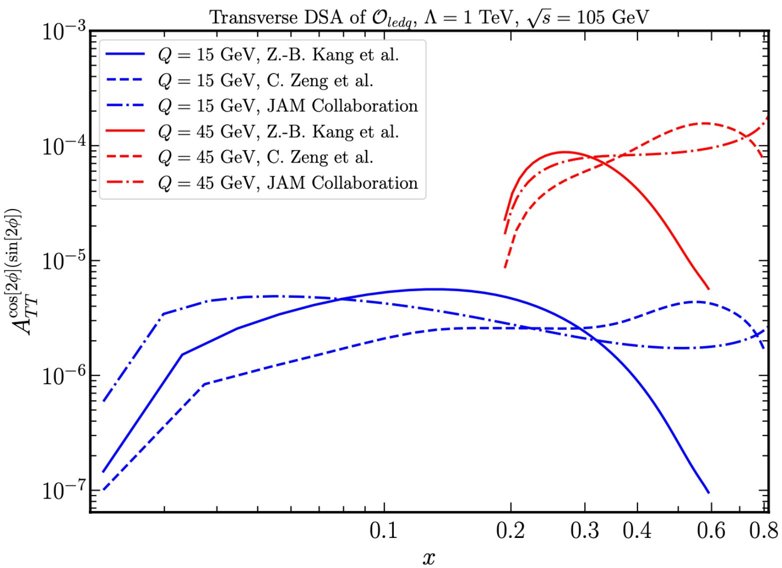
$$T_{-\lambda_a,-\lambda_b,-\lambda_c,-\lambda_d}(\theta) = \eta\cdot(-1)^{\lambda-\mu}\cdot T_{\lambda_a,\lambda_b,\lambda_c,\lambda_d}(\theta)$$

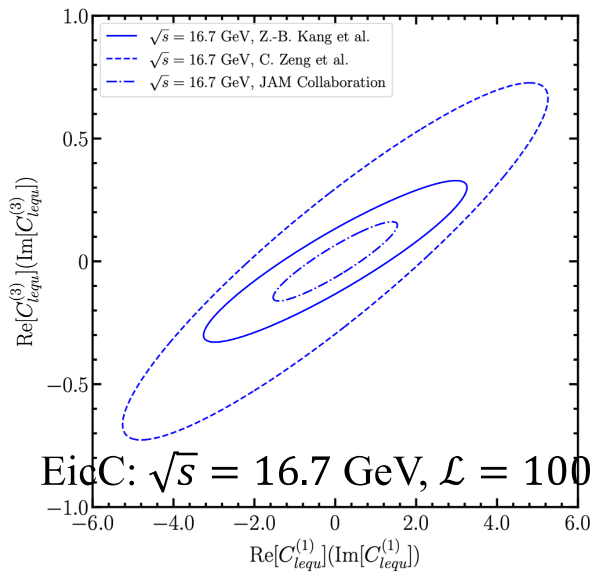
$$\eta = \frac{\eta_c\eta_d}{\eta_a\eta_b}\cdot(-1)^{s_a+s_b-s_c-s_d}$$

$$\begin{aligned}|M|^2 = |M|^2_{\mathrm{unpol}} &- \frac{1}{2}\lambda_T\bar{\lambda}_T\mathrm{Re}[T^*_{++}T_{--}] \\ &- \frac{1}{2}\lambda_T\bar{\lambda}_T\mathrm{Re}[e^{-2i\phi}T^*_{+-}T_{-+}] \\ &+ \frac{1}{2}\lambda_T\mathrm{Re}\left[e^{-i\phi}(T^*_{+-}T_{--}+T^*_{++}T_{-+})\right] \\ &- \frac{1}{2}\bar{\lambda}_T\mathrm{Re}\left[e^{-i\phi}(T^*_{+-}T_{++}+T^*_{--}T_{-+})\right]\end{aligned}$$

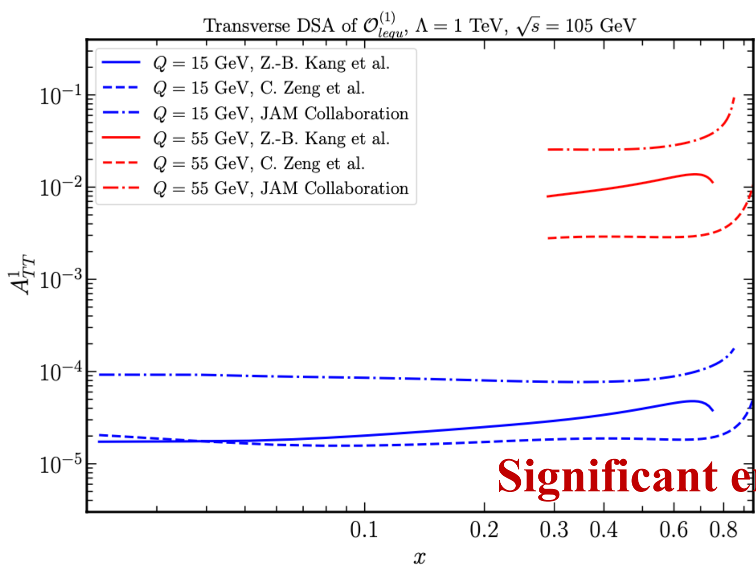
X.-K.W, BY, ZY, C.-P.Y, works in progress

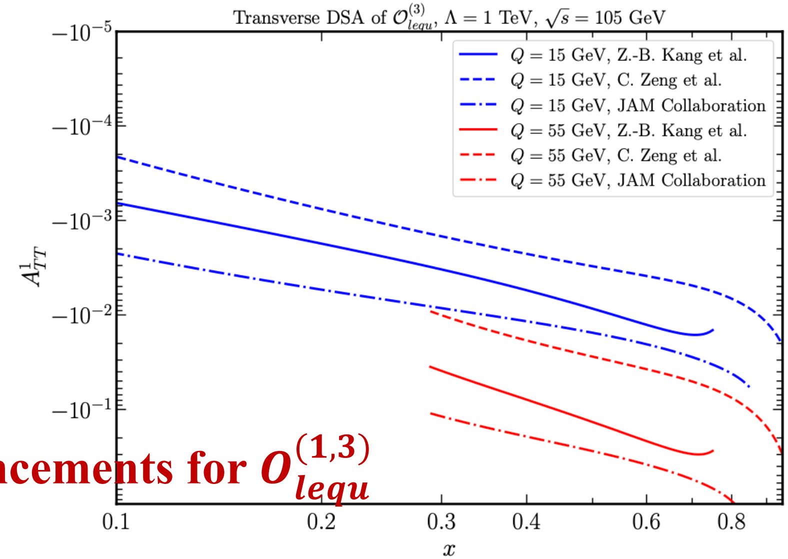
Backup





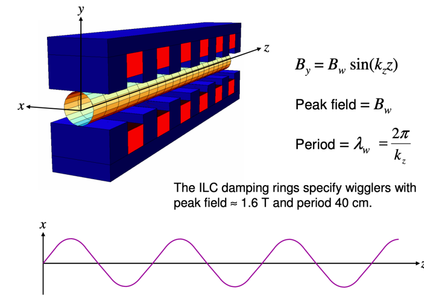
EicC: $\sqrt{s} = 16.7$ GeV, $\mathcal{L} = 100$ fb^{-1}





Significant enhancements for $O_{lequ}^{(1,3)}$

Backup: Polarized beam realization



Transverse polarization is more natural

Sokolov-Ternov effect (92.4%, minutes-hours, 50GeV)

Laser-assistant

Spin-precession

Photon-based scheme:

Polarized positrons are produced via pair production in a thin target from circularly-polarized photons with energy of multi-MeV (up to about 100 MeV). The cost difference between an polarized source and an upgrade from a unpolarized source is small (~ 1%). At 500 GeV, loss of polarization <1%, at IP <0.25%.

Polarized electron source consists of a polarized high-power laser beam and a high- voltage dc gun with a semiconductor photocathode.

Only polarization parallel or anti-parallel to the guide fields of the damping ring is preserved. Need to avoid spin-orbit coupling resonance depolarizing effects.

The spin rotator systems between the damping rings and the main linacs *permit the setting of arbitrary polarization vector orientations* at the IP.

Polarized-photons source:

I. a high-energy electron beam (>~ 150 GeV) passing through a short period, helical undulator. (E-166, SLAC)
II. Compton backscattering of laser light off a GeV energy-range electron beam. (KEK)

In both schemes a polarization of about |Pe+ | ≥ 90% is reported.

Muons produced from pion decays are naturally polarized. The level of polarization in the lab frame depends on the initial pion energy and decay angle.

G. Moortgat-Pick et al. *Phys.Rept.* 460 (2008), hep-ph/0507011

D. Acosta and W. Li, Nucl.Instrum.Meth.A 1027 (2022) 166334