Transverse Spin Asymmetry as a New Probe of SMEFT Chirality-Flip Operators

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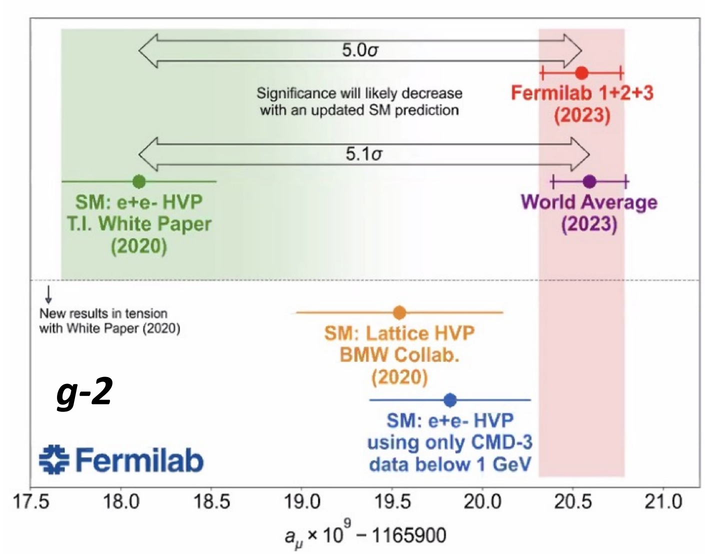
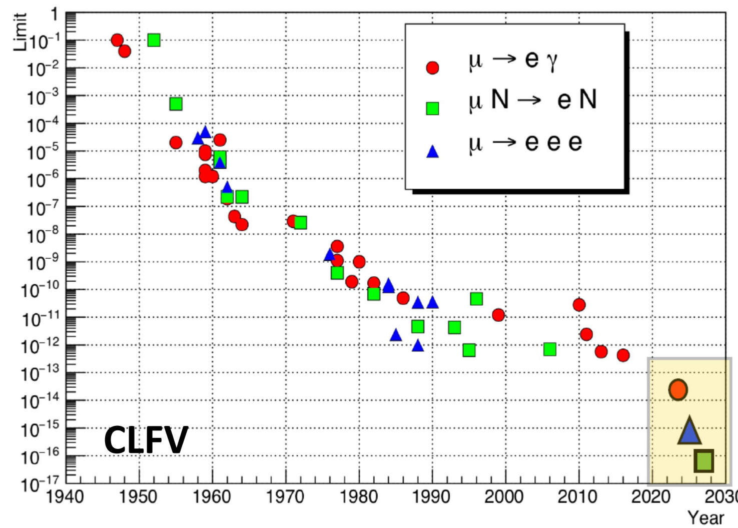
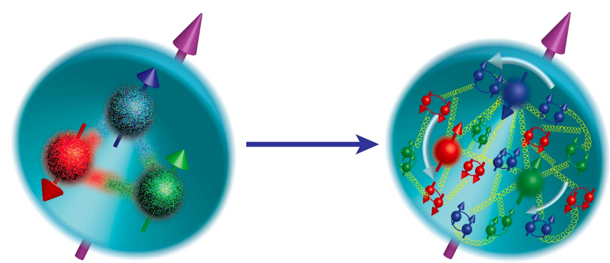
In collaboration with Hao-Lin Wang, Hongxi Xing and Bin Yan
Phys.Rev.D **109** (2024) 9, 095025
Works in Progress

2024/07/09, THNU @ Tonghua, Jilin

New Physics

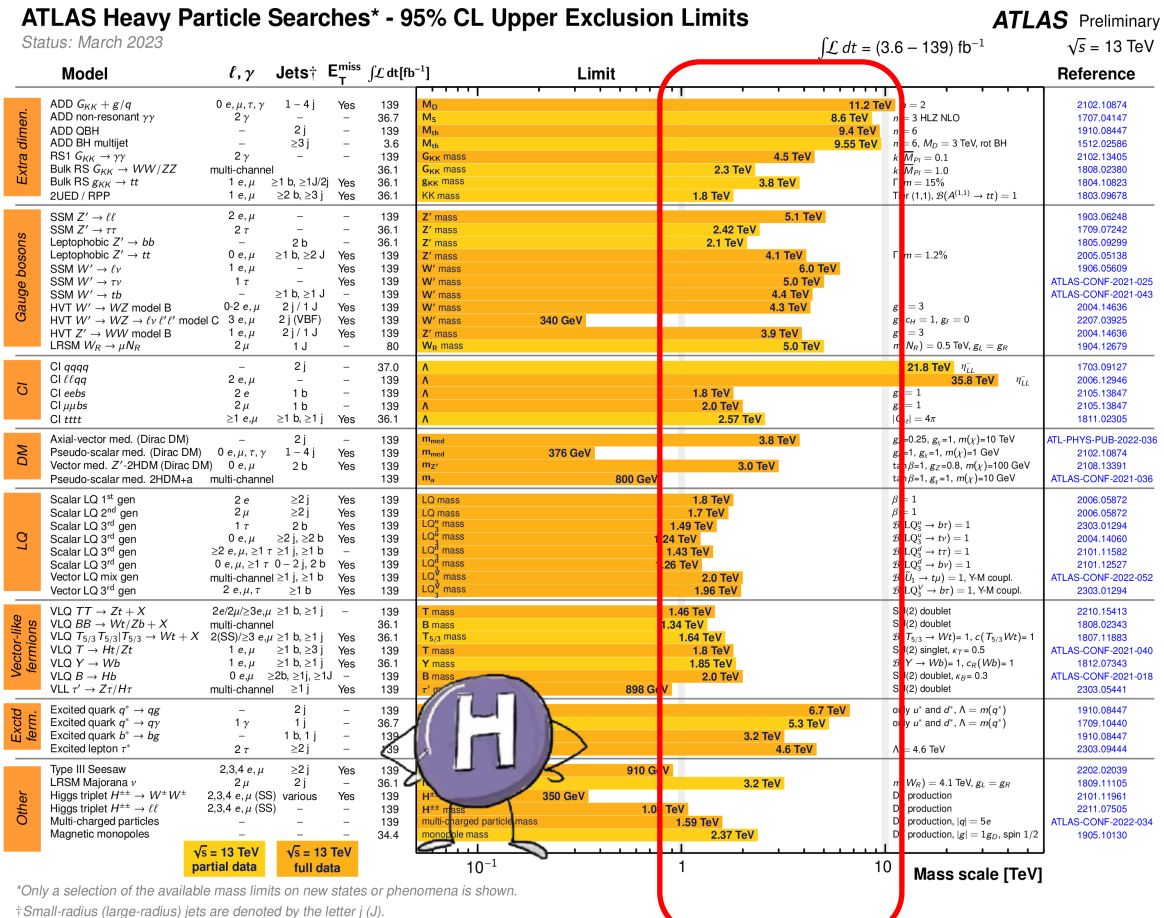


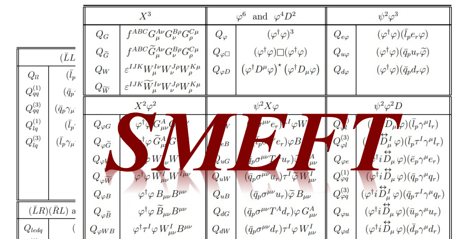




Lots of Open Questions

New Physics and SMEFT





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

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

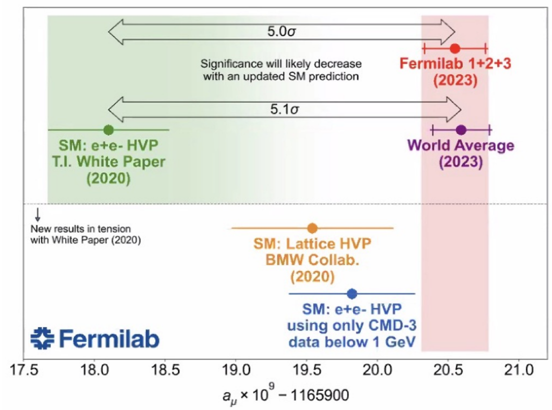
Powerful Tool @ EW to confront with NP effects

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

SMEFT Chirality-Flip Operator

Direct effect & Indirect probes of NP quantum effects

Dipole Operator: $(g-2)$? EDM ?

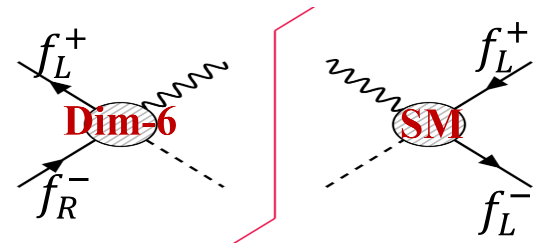


D.P. Aguillard et al., (Muon g-2), *Phys.Rev.Lett.* 131 (2023) 16

same NP source ?

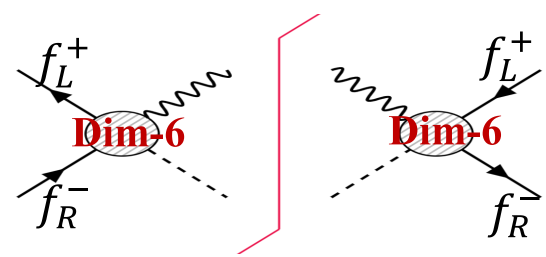
Z only detected by colliders

$\mathcal{O}(1/\Lambda^2)$ ✗



interference~**0** for tiny mass

$\mathcal{O}(1/\Lambda^4)$ ✓

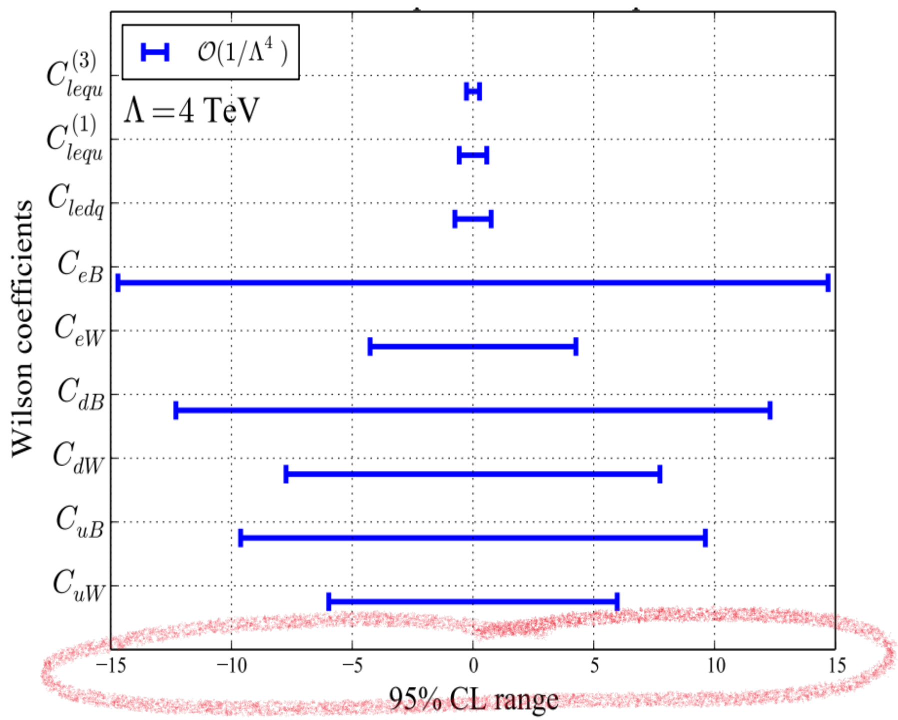


Non-interfering Leading effect

Data for Chirality-Flip Operator

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

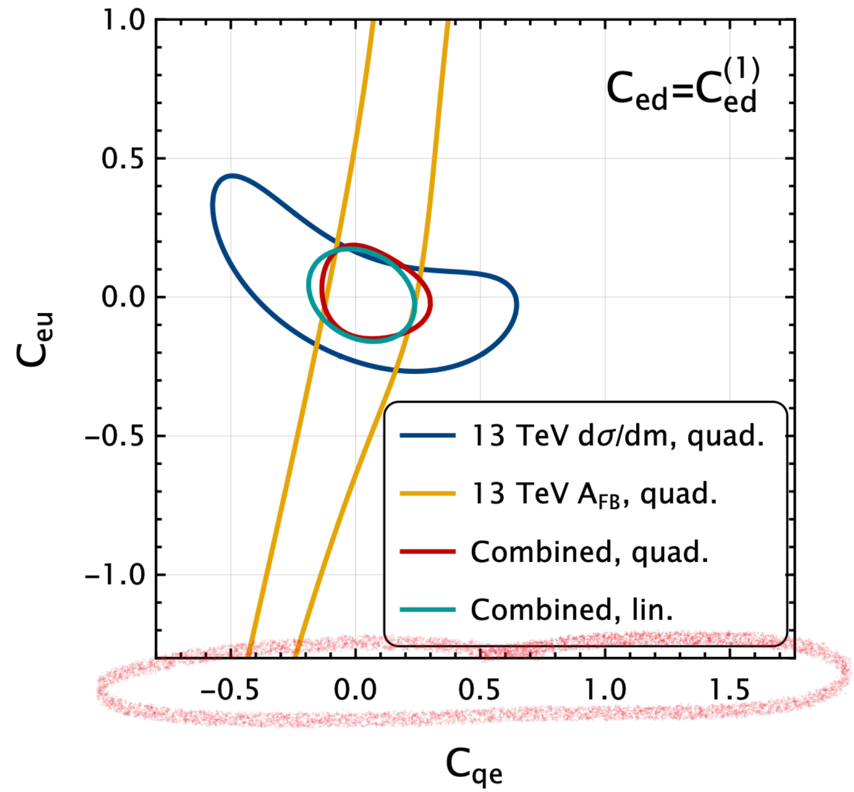
$\mathcal{O}(1/\Lambda^4)$



Single-Parameter-Analysis Drell-Yan @LHC

(R. Boughezal et al. *Phys.Rev.D* 104 (2021)…)

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



(R. Boughezal et al., *Phys.Rev.D* 108 (2023) 7)

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

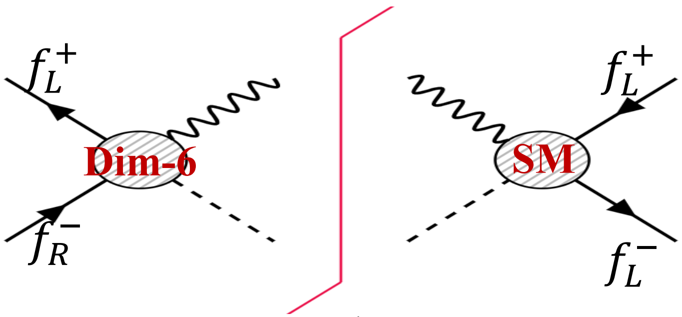
Our proposal:

- 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

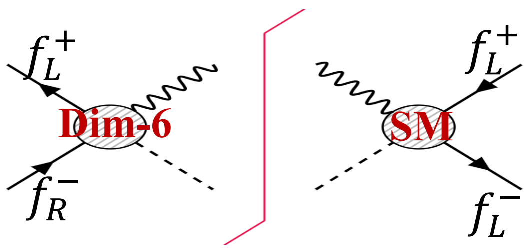
H.-L.W, **X.-K.W**, HX, BY *Phys.Rev.D* **109** (2024) 9

Transverse Spin Induces Azimuthal Behavior

- Breaking rotational invariance

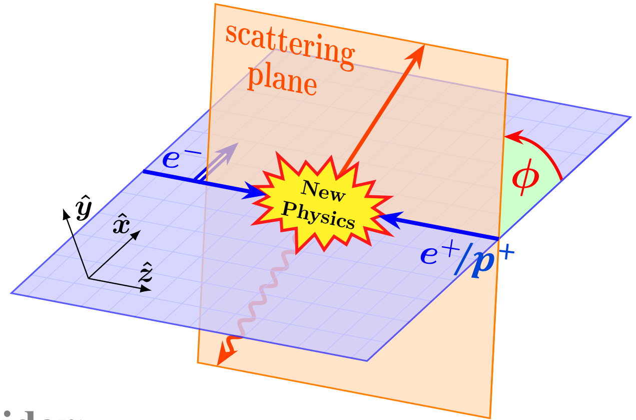
Nontrivial azimuthal behavior

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



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

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 → $\mathcal{M}_{ij}$

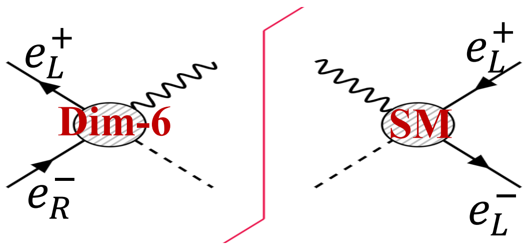
	U	L	T	
U	$\lvert\mathcal{M}\rvert^2_{UU} \to 1$	$\lvert\mathcal{M}\rvert^2_{UL} \to 1$	$\lvert\mathcal{M}\rvert^2_{UT} \to \cos\phi, \sin\phi$	→ **STSAA**
L	$\lvert\mathcal{M}\rvert^2_{LU} \to 1$	$\lvert\mathcal{M}\rvert^2_{LL} \to 1$	$\lvert\mathcal{M}\rvert^2_{LT} \to \cos\phi, \sin\phi$	
T	$\lvert\mathcal{M}\rvert^2_{TU}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

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

A New Probe of Dipole Operators @ee collider

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

$\mathrm{Re}[\Gamma_f]$	$\mathrm{Im}[\Gamma_f]$	SM & other NP
$\vec{s}\cdot\vec{p}_f \propto \cos\phi$	$\vec{s}\times\vec{p}_f \propto \sin\phi$	
CP-conserving	CP-violation	



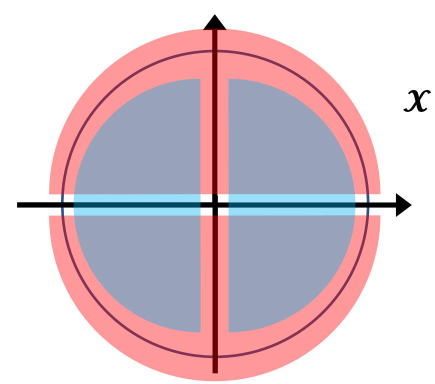
$$|\mathcal{M}|^2 \propto \mathrm{Re}[\Gamma_q\, e^{i(\phi_s - \phi_\ell)}]$$

X.-K.W, BY, ZY, C.-P.Y, *Phys.Rev.Lett.* 131 (2023) 24

Linearly dependent on the dipole couplings Γ_f and spin b_T

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

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



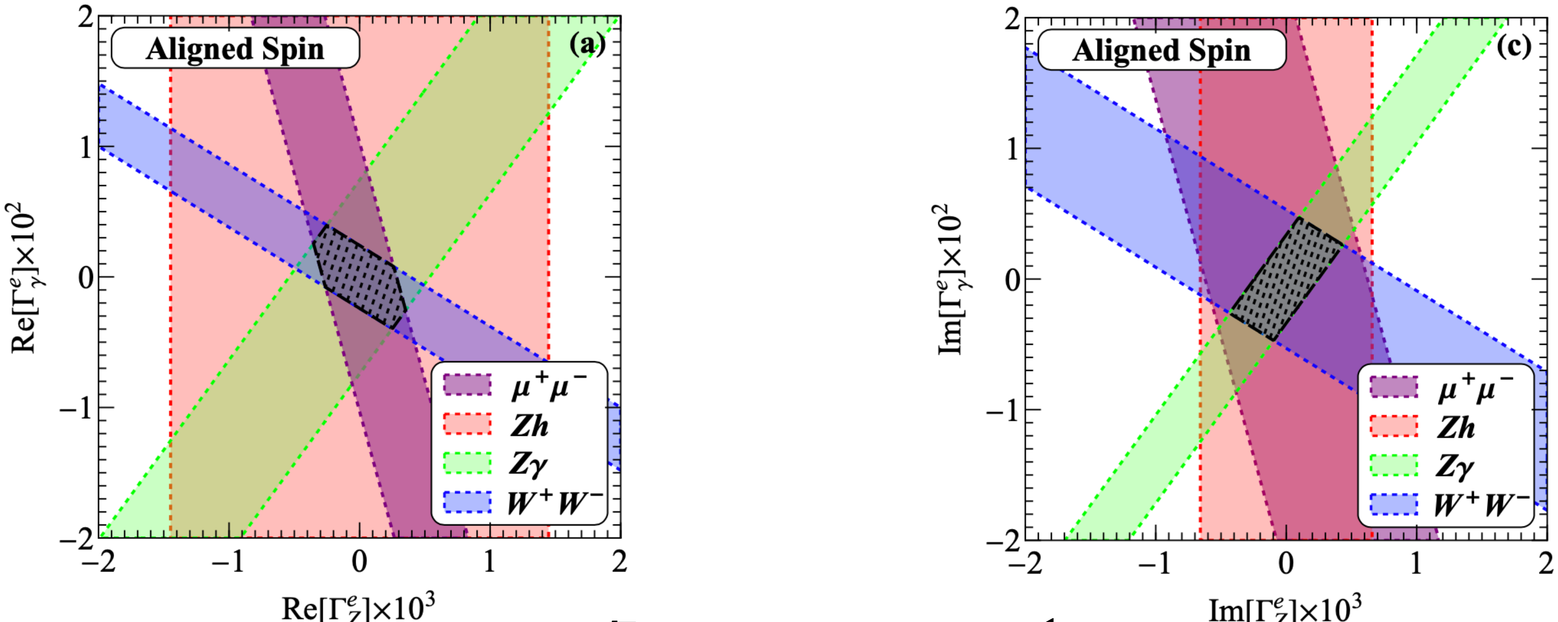
Pinning down Dipole Operators @ee collider

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

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

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

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



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

Much stronger sensitivity than other approaches by 1~2 orders

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

Transverse Beam- and Target-SSA @ EIC

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

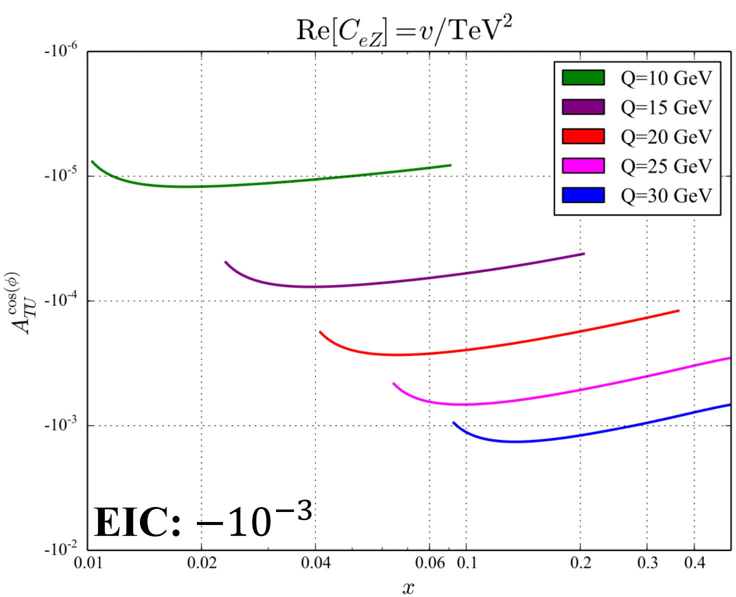
To probe **lepton** or **quark** dipole operator **at $\mathcal{O}(1/\Lambda^2)$**

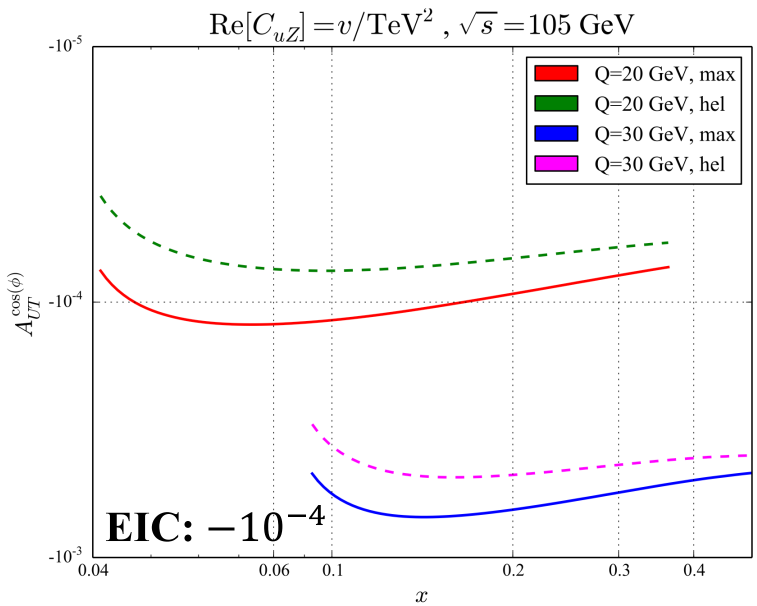
- Polarized DIS (Transverse lepton/ transverse PDF)

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

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

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



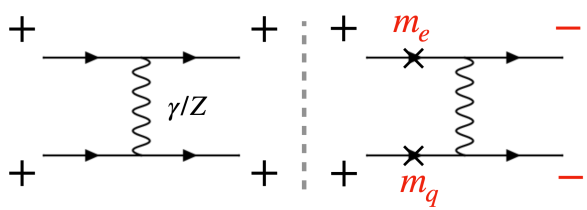


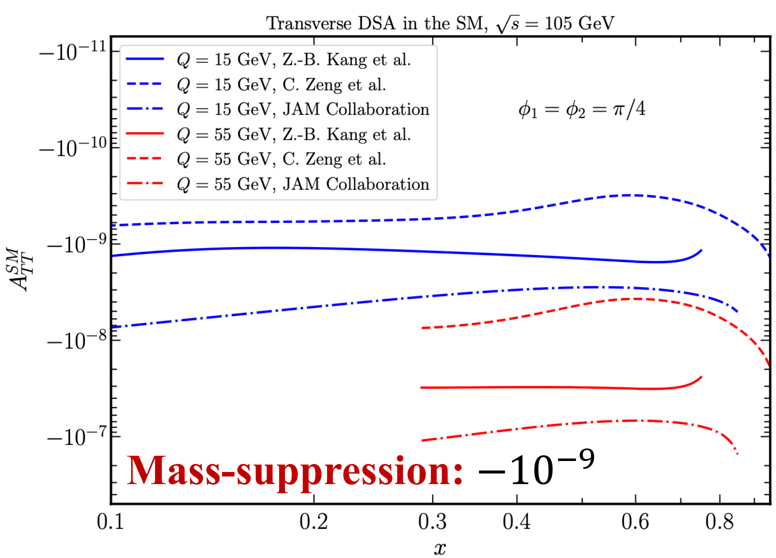
Transverse Double-Spin-Asymmetry(DSA)@EIC

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

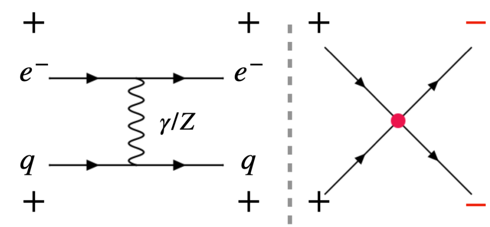
- **2ϕ** and **flat** shape

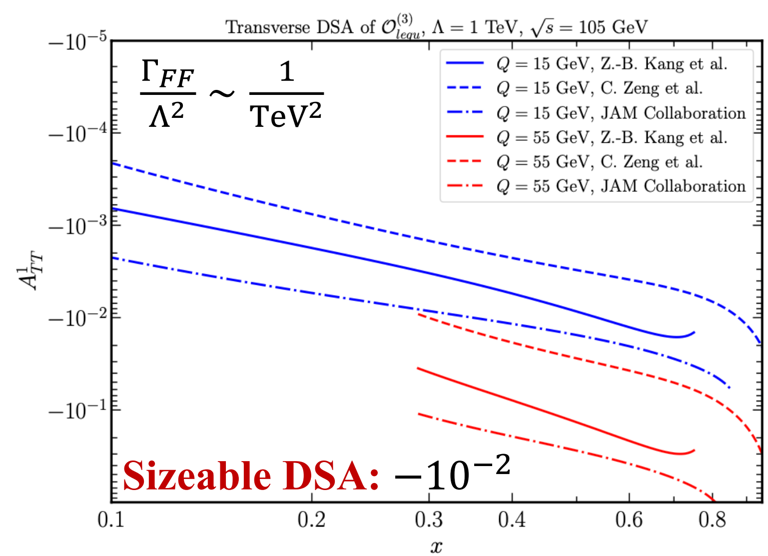
SM





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

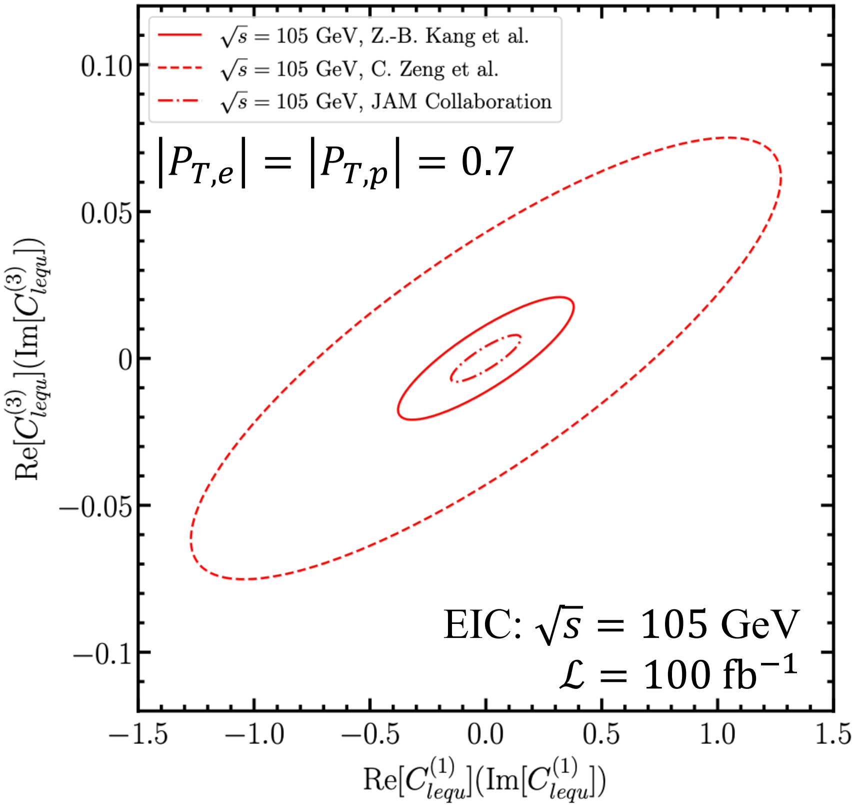
H.-L. Wang, **X.-K. Wen**, H. Xing and B. Yan, *Phys.Rev.D* **109** (2024) 9 , 095025

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 $\boldsymbol{h(x,\mu)}$

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



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

Summary

- ✓ The muon g-2 data and many NP models may hint SMEFT chirality-flip operators
- ✓ Chirality-flip operators are difficult to be probed since the leading effects $@1/\Lambda^4$
- ✓ We propose a new method to linearly probe them $@1/\Lambda^2$ via *transverse fermions*
  - ➢ Interference of the different helicity amplitudes with single helicity-flip
  - ➢ Nontrivial azimuthal behavior
- ✓ Simultaneously constraining well both Re & Im parts
  - ➢ Without contaminations from other NP and SM, without mass-suppression
  - ➢ Offering a new opportunity for directly probing potential CP-violating effects.
- ✓ Our bound have much stronger sensitivity than other approaches by 1~2 orders
- ✓ Future colliders (Z/Higgs/Top factory…)

  Polarized Muon collider, Muon-Ion collider, hadron colliders, Electron-Ion Collider…

Thank you

Backup

BACKUP

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

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

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

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

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

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

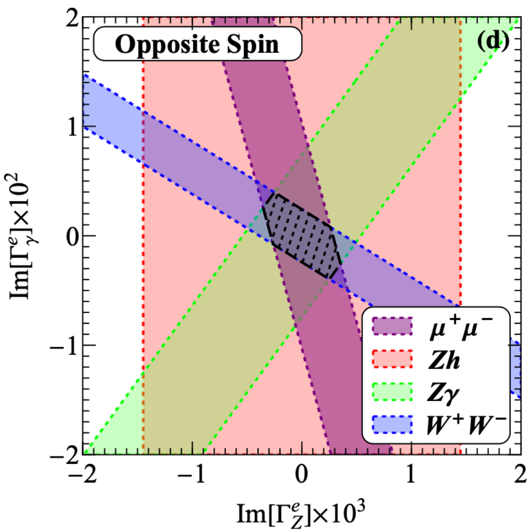
$$T_{-\lambda_a,-\lambda_b,-\lambda_c,-\lambda_d}(\theta) = \eta\cdot(-1)^{\lambda-\mu}\cdot T_{\lambda_a,\lambda_b,\lambda_c,\lambda_d}(\theta)$$

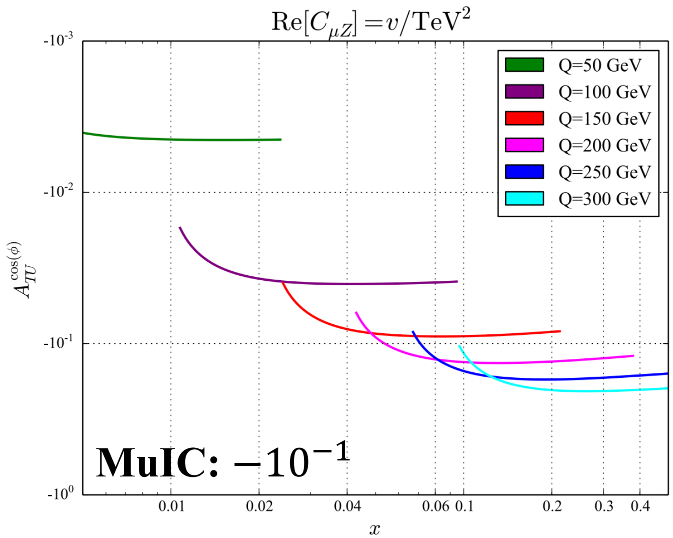
$$\eta = \frac{\eta_c\eta_d}{\eta_a\eta_b}\cdot(-1)^{s_a+s_b-s_c-s_d}$$

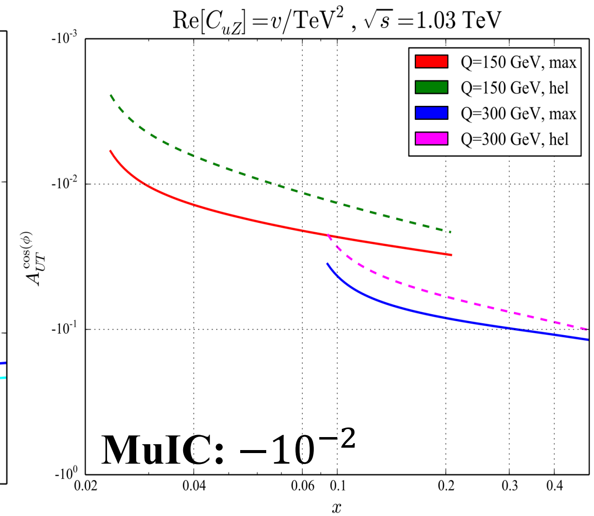
$$\begin{aligned}|M|^2 = {} & |M|^2_{\mathrm{unpol}} - \frac{1}{2}\lambda_T\bar{\lambda}_T\mathrm{Re}[T^*_{++}T_{--}] \\ & - \frac{1}{2}\lambda_T\bar{\lambda}_T\mathrm{Re}[e^{-2i\phi}T^*_{+-}T_{-+}] \\ & + \frac{1}{2}\lambda_T\mathrm{Re}\left[e^{-i\phi}(T^*_{+-}T_{--}+T^*_{++}T_{-+})\right] \\ & - \frac{1}{2}\bar{\lambda}_T\mathrm{Re}\left[e^{-i\phi}(T^*_{+-}T_{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

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

Backup







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

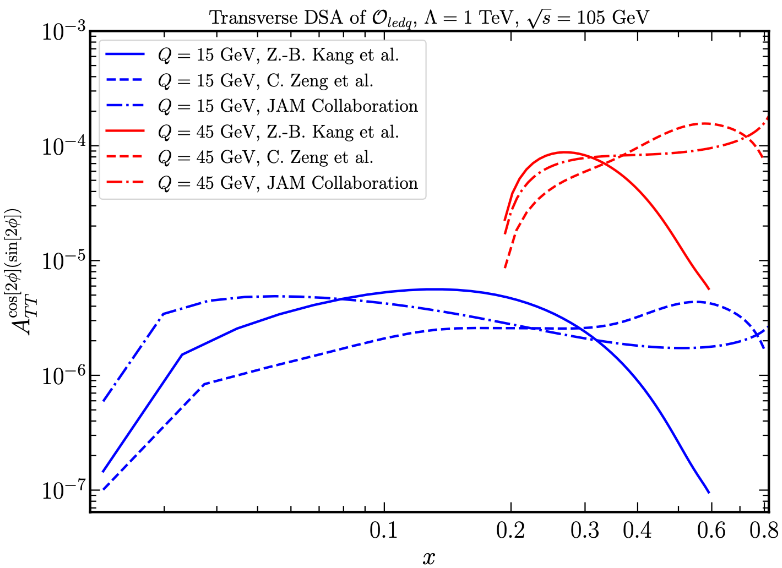
Why the limit difference between the Aligned Spin and the Opposite Spin? ➢ CP property

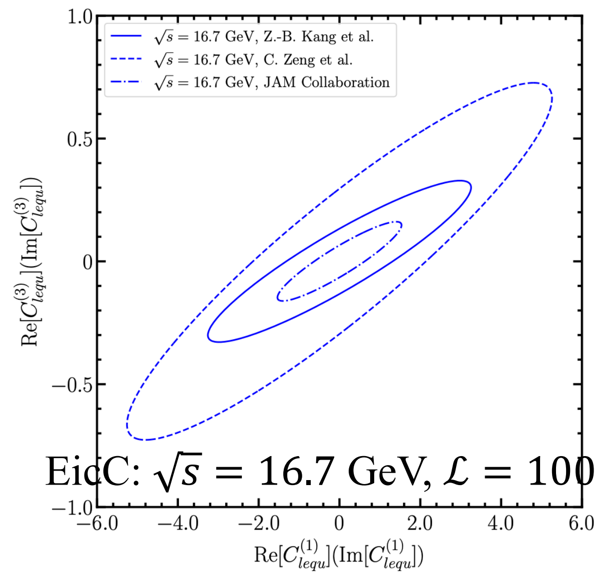
The asymmetry at MuIC is significantly larger than at EIC ➢ Energy enhancement

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

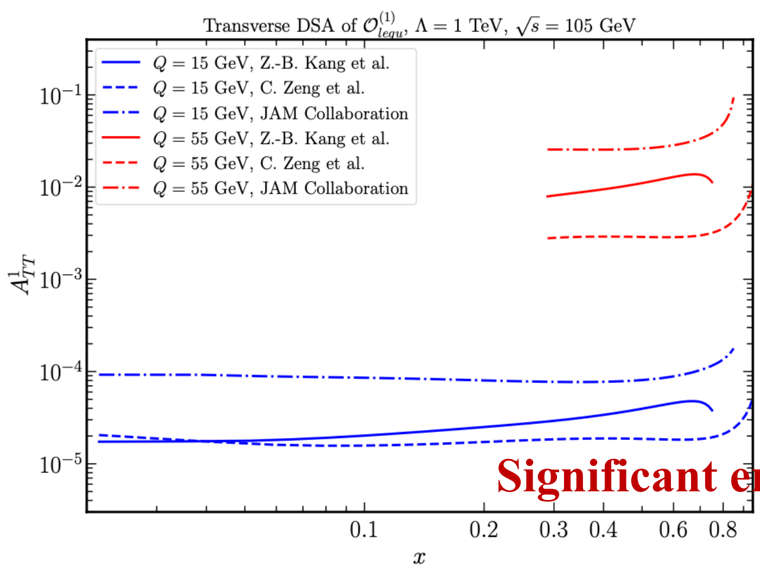
$$\delta A_{TT}^w \simeq \frac{1/(P_{T,e}P_{T,p})}{\sqrt{4\mathcal{L}\sigma(P_{T,e(p)} = 0)}} \cdot \sqrt{\frac{\int_0^{2\pi} d\phi w^2(\phi)}{2\pi}}$$

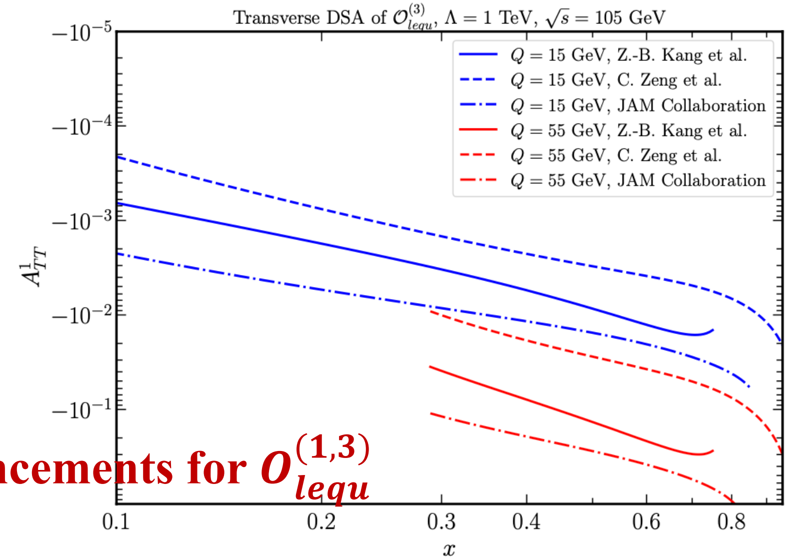
Backup





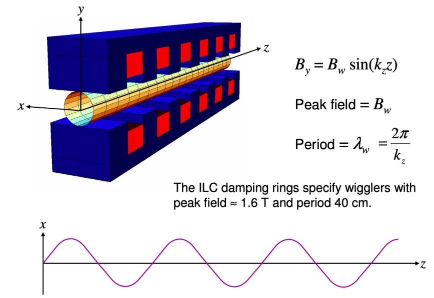
EicC: $\sqrt{s} = 16.7$ GeV, $\mathcal{L} = 100\ \mathrm{fb}^{-1}$





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