



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

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In collaboration with Bin Yan, Zhite Yu and C.-P. Yuan

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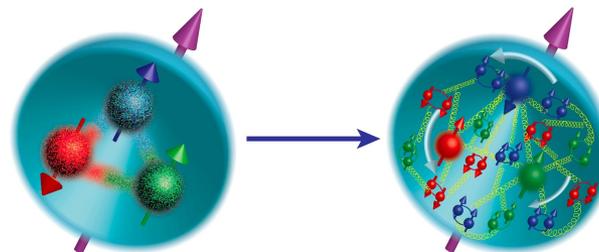
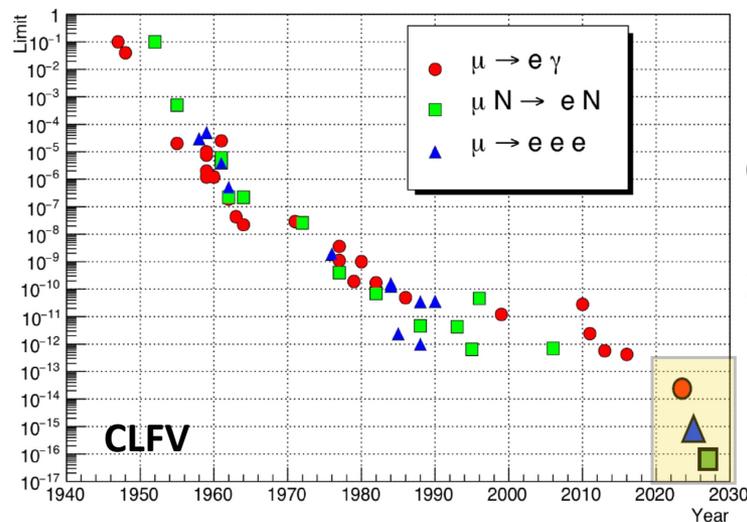
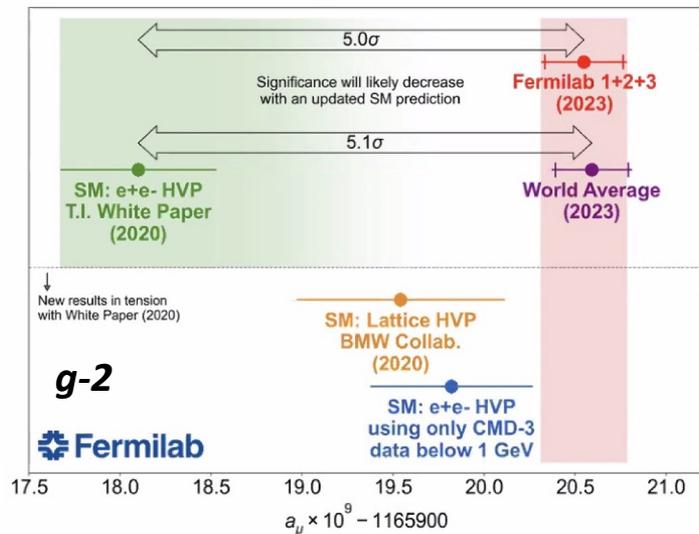
In collaboration with Hao-Lin Wang, Hongxi Xing and Bin Yan

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

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

$\sqrt{s} = 13 \text{ TeV}$

Model	ℓ, γ	Jets†	$E_{\text{miss}}^{\dagger}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1 - 4 j$	Yes	139	$M_0 = 11.2 \text{ TeV}$
	ADD non-resonant $\gamma\gamma$	2γ	-	-	139	$M_s = 8.6 \text{ TeV}$
	ADD GBH	-	$2 j$	-	139	$M_{\text{th}} = 9.4 \text{ TeV}$
	ADD BH multijet	-	$\geq 3 j$	-	316	$M_{\text{th}} = 6, M_0 = 3 \text{ TeV, rot BH}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	$G_{KK} \text{ mass} = 4.5 \text{ TeV}$
Gauge bosons	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$M_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2$	Yes	36.1	$\Gamma = 15\%$
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	$\text{Tr}(1,1), \text{Tr}(A^{(1,1)} \rightarrow tt) = 1$
	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	$Z' \text{ mass} = 2.42 \text{ TeV}$
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	$Z' \text{ mass} = 2.1 \text{ TeV}$
CI	Leptophobic $Z' \rightarrow bb$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$Z' \text{ mass} = 4.1 \text{ TeV}$
	Leptophobic $Z' \rightarrow \tau\tau$	$1 e, \mu$	-	-	139	$Z' \text{ mass} = 6.0 \text{ TeV}$
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	-	139	$W' \text{ mass} = 5.0 \text{ TeV}$
	SSM $W' \rightarrow \tau\nu$	1τ	-	-	139	$W' \text{ mass} = 4.4 \text{ TeV}$
	SSM $W' \rightarrow tb$	-	$\geq 1 b, \geq 1 J$	-	139	$W' \text{ mass} = 4.3 \text{ TeV}$
DM	HVT $W' \rightarrow WZ$ model B	$0-2 e, \mu$	$2 j / 1 J$	Yes	139	$W' \text{ mass} = 340 \text{ GeV}$
	HVT $W' \rightarrow WZ$ model C	$0-2 e, \mu$	$2 j / 1 J$	Yes	139	$W' \text{ mass} = 3.9 \text{ TeV}$
	HVT $Z' \rightarrow WW$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	$W_R \text{ mass} = 5.0 \text{ TeV}$
	LRSM $W_R \rightarrow \mu N_R$	2μ	$1 J$	-	80	$W_R \text{ mass} = 5.0 \text{ TeV}$
	CI $q\bar{q}q\bar{q}$	-	$2 j$	-	37.0	$A = 21.8 \text{ TeV}$
LQ	CI $\ell\ell q\bar{q}$	$2 e, \mu$	-	-	139	$A = 35.8 \text{ TeV}$
	CI $e\bar{e}b\bar{b}$	$2 e$	$1 b$	-	139	$A = 1.8 \text{ TeV}$
	CI $\mu\bar{\mu}b\bar{b}$	2μ	$1 b$	-	139	$A = 2.0 \text{ TeV}$
	CI $t\bar{t}t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$A = 2.57 \text{ TeV}$
	Scalar LQ 1^{st} gen	$2 e$	$\geq 2 j$	Yes	139	$LQ \text{ mass} = 1.8 \text{ TeV}$
Vector-like fermions	Scalar LQ 2^{nd} gen	2μ	$\geq 2 j$	Yes	139	$LQ \text{ mass} = 1.7 \text{ TeV}$
	Scalar LQ 3^{rd} gen	1τ	$2 b$	Yes	139	$LQ \text{ mass} = 1.49 \text{ TeV}$
	Scalar LQ 3^{rd} gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	$LQ \text{ mass} = 1.24 \text{ TeV}$
	Scalar LQ 3^{rd} gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 j, \geq 1 b$	-	-	139	$LQ \text{ mass} = 1.43 \text{ TeV}$
	Scalar LQ 3^{rd} gen	$0 e, \mu, \geq 1 \tau, 0-2 j, 2 b$	-	-	139	$LQ \text{ mass} = 26 \text{ TeV}$
Excited fermions	Vector LQ mix gen	multi-channel	$\geq 1 j, \geq 1 b$	Yes	139	$LQ \text{ mass} = 2.0 \text{ TeV}$
	Vector LQ 3^{rd} gen	$2 e, \mu, \tau$	$\geq 1 b$	Yes	139	$LQ \text{ mass} = 1.95 \text{ TeV}$
	VLO $TT \rightarrow Zt + X$	$2e2\mu/23e\mu$	$\geq 1 b, \geq 1 j$	-	139	$T \text{ mass} = 1.46 \text{ TeV}$
	VLO $BB \rightarrow WtZb + X$	multi-channel	-	-	36.1	$B \text{ mass} = 1.34 \text{ TeV}$
	VLO $T_{32} T_{33} \rightarrow Wt + X$	$2(SS)/23 e\mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{32} \text{ mass} = 1.64 \text{ TeV}$
Other	VLO $Y \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	$T \text{ mass} = 1.8 \text{ TeV}$
	VLO $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$Y \text{ mass} = 1.85 \text{ TeV}$
	VLO $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1 j, \geq 1 J$	Yes	139	$B \text{ mass} = 2.0 \text{ TeV}$
	VLL $\tau^+ \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	$\tau \text{ mass} = 898 \text{ GeV}$
	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	139	$\Lambda = 6.7 \text{ TeV}$
Other	Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	-	36.7	$\Lambda = 5.3 \text{ TeV}$
	Excited quark $q^* \rightarrow b\bar{g}$	-	$1 b, 1 j$	-	139	$\Lambda = 3.2 \text{ TeV}$
	Excited lepton τ^*	2τ	$\geq 2 j$	-	139	$\Lambda = 4.6 \text{ TeV}$
	Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2 j$	Yes	139	$\Lambda = 910 \text{ GeV}$
	LRSM Majorana ν	2μ	$2 j$	-	36.1	$M(\nu) = 350 \text{ GeV}$
Other	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	$2, 3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm} \text{ mass} = 1.0 \text{ TeV}$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	139	$H^{\pm\pm} \text{ mass} = 1.59 \text{ TeV}$
	Multi-charged particles	-	-	-	139	$\text{multi-charged particle mass} = 2.37 \text{ TeV}$
	Magnetic monopoles	-	-	-	34.4	magnetic mass

$\sqrt{s} = 13 \text{ TeV}$
partial data

$\sqrt{s} = 13 \text{ TeV}$
full data

*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

	X^3	ψ^4 and $\psi^2 D^2$	$\psi^2 \psi^2$
Q_{G_2}	$f^{ABC} G^A G^B G^C$	Q_{G_2}	Q_{G_2}
$Q_{SU(3)_C}$	$f^{ABC} G^A G^B G^C$	$Q_{SU(3)_C}$	$Q_{SU(3)_C}$
$Q_{SU(2)_L}$	$f^{ABC} G^A G^B G^C$	$Q_{SU(2)_L}$	$Q_{SU(2)_L}$
$Q_{U(1)_Y}$	$f^{ABC} G^A G^B G^C$	$Q_{U(1)_Y}$	$Q_{U(1)_Y}$

SMEFT

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

B. Grzadkowski, et al. *JHEP* 10 (2010)
W. Buchmuller, D. Wyler, 1986

Powerful Tool @ EW to confront with NP effects

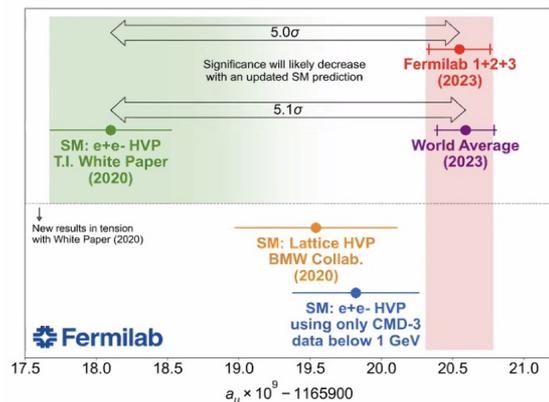
New Physics models excluded to **Multi-TeV @ LHC.**

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

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

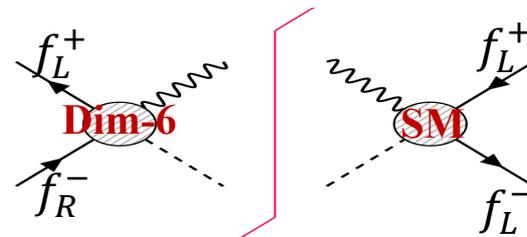


same NP source ?

Z only detected by colliders

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

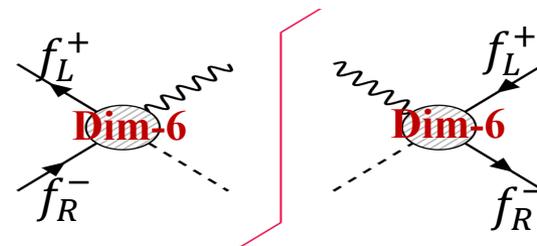
X



interference ~ 0 for tiny mass

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

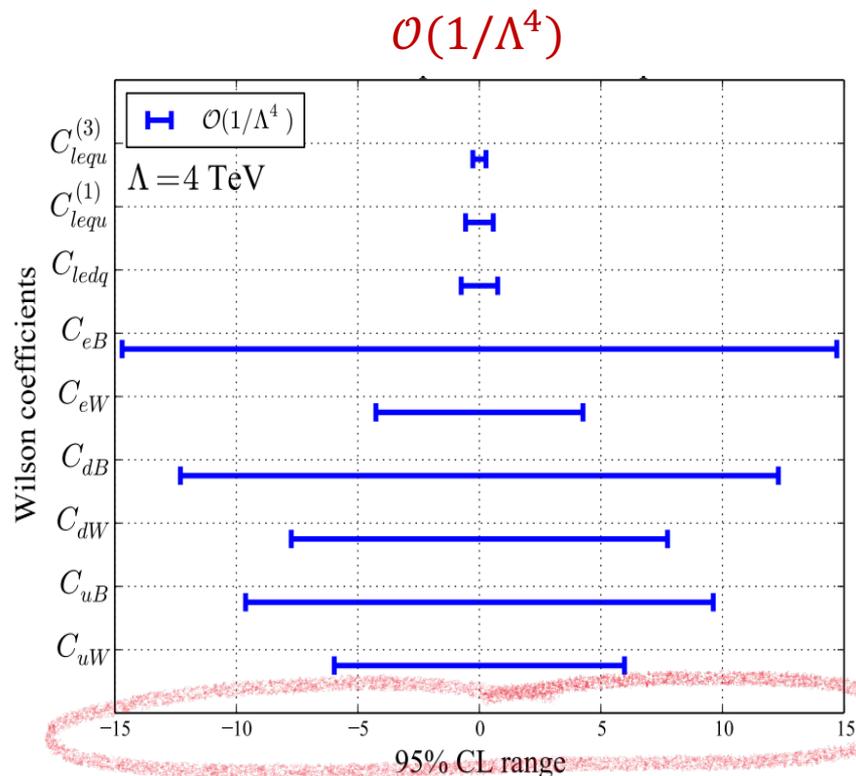
✓



Non-interfering Leading effect

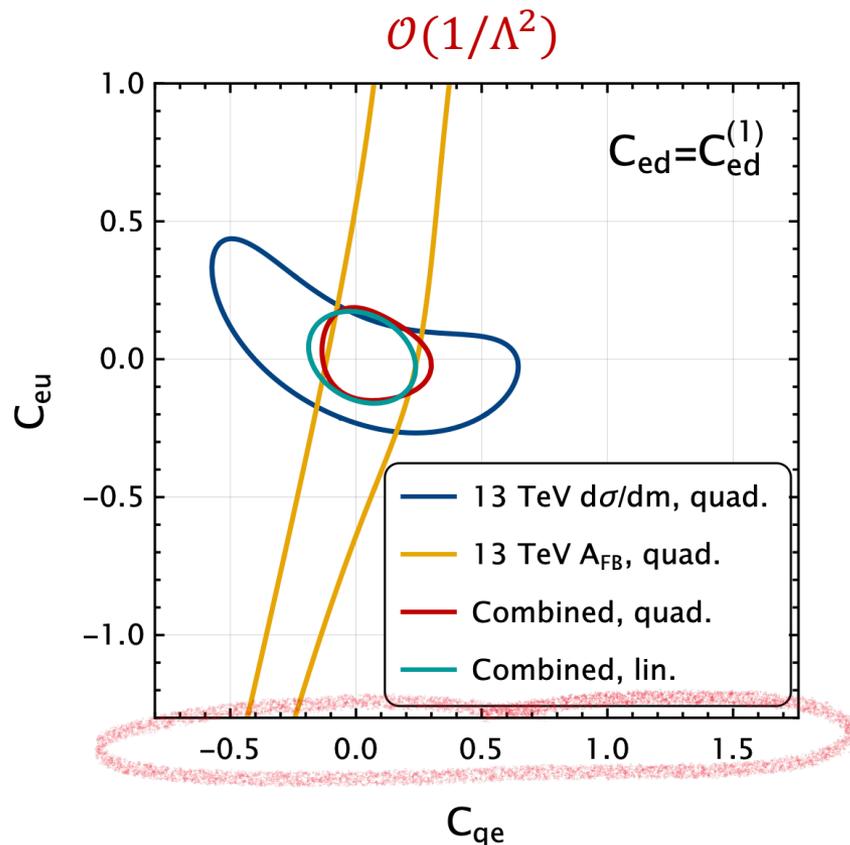
Data for Chirality-Flip Operator

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



Single-Parameter-Analysis Drell-Yan @LHC

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



(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

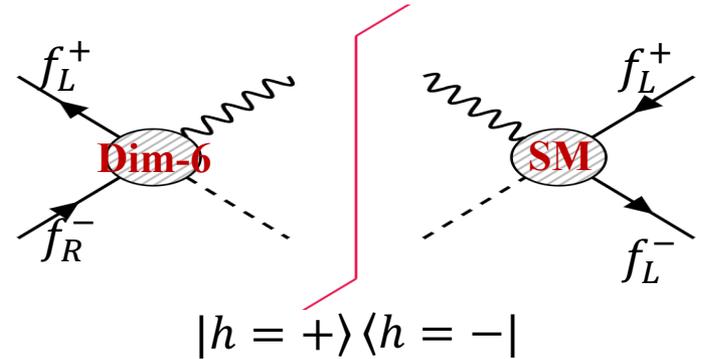
Our proposal:

- Transverse polarization effect of fermions

Interference of the different helicity amplitudes

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

$$|\mathcal{M}|^2 = \rho_{\alpha_1 \alpha'_1}(\mathbf{s}) \rho_{\alpha_2 \alpha'_2}(\bar{\mathbf{s}}) \mathcal{M}_{\alpha_1 \alpha_2}(\phi) \mathcal{M}_{\alpha'_1 \alpha'_2}^*(\phi)$$



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

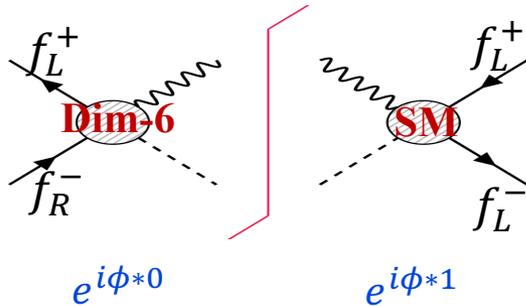
H.-L.W, X.-K.W, HX, BY *Phys.Rev.D* 109 (2024) 9

Transverse Spin Induces Azimuthal Behavior

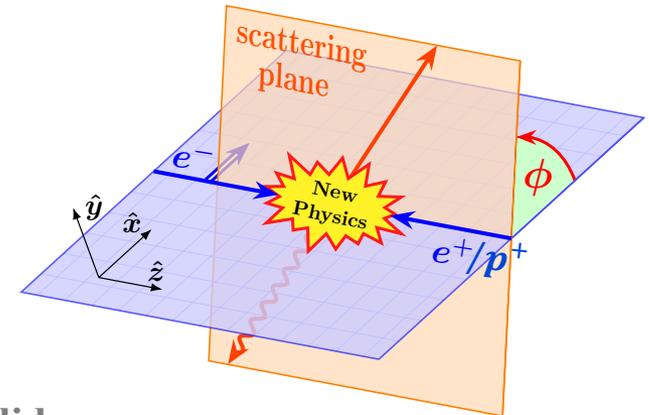
➤ Breaking rotational invariance

Nontrivial azimuthal behavior

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



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



STSAA@ee collider:

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

DSA@eP collider:

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

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

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

A New Probe of Dipole Operators @ee collider

$$\frac{2\pi d\sigma^i}{\sigma^i d\phi} = 1 + \underbrace{A_R^i(b_T, \bar{b}_T)}_{\text{Re}[\Gamma_f]} \cos \phi + \underbrace{A_I^i(b_T, \bar{b}_T)}_{\text{Im}[\Gamma_f]} \sin \phi + \underbrace{b_T \bar{b}_T B^i}_{\text{SM \& other NP}} \cos 2\phi + \mathcal{O}(1/\Lambda^4)$$

$\text{Re}[\Gamma_f]$

$\text{Im}[\Gamma_f]$

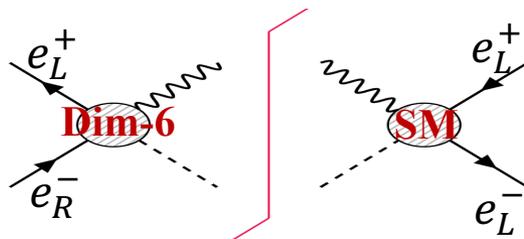
SM & other NP

$$\vec{s} \cdot \vec{p}_f \propto \cos \phi$$

$$\vec{s} \times \vec{p}_f \propto \sin \phi$$

CP-conserving

CP-violation



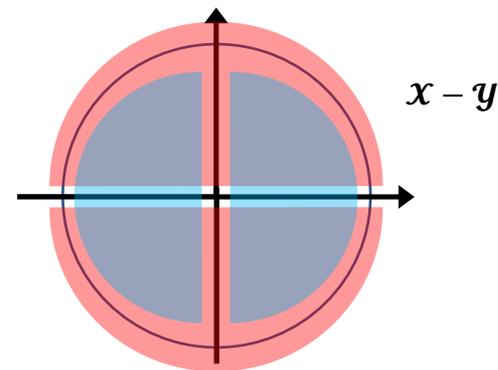
$$|\mathcal{M}|^2 \propto \text{Re}[\Gamma_q e^{i(\phi_s - \phi_\ell)}]$$

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

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

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



Pinning down Dipole Operators @ee collider

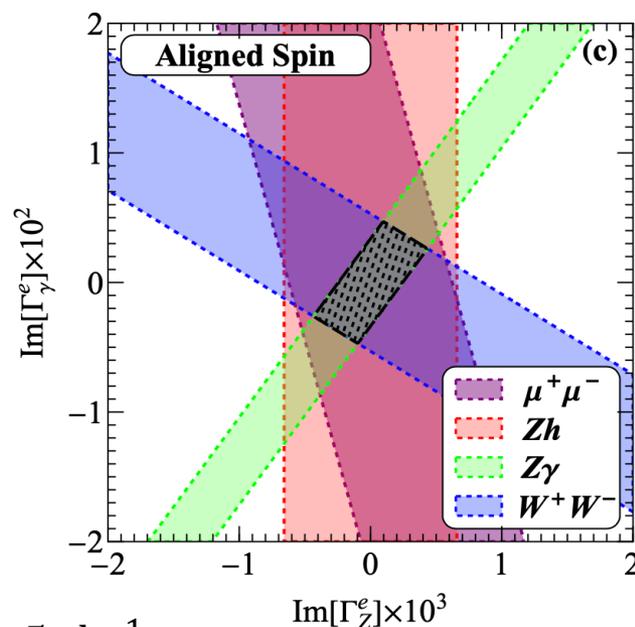
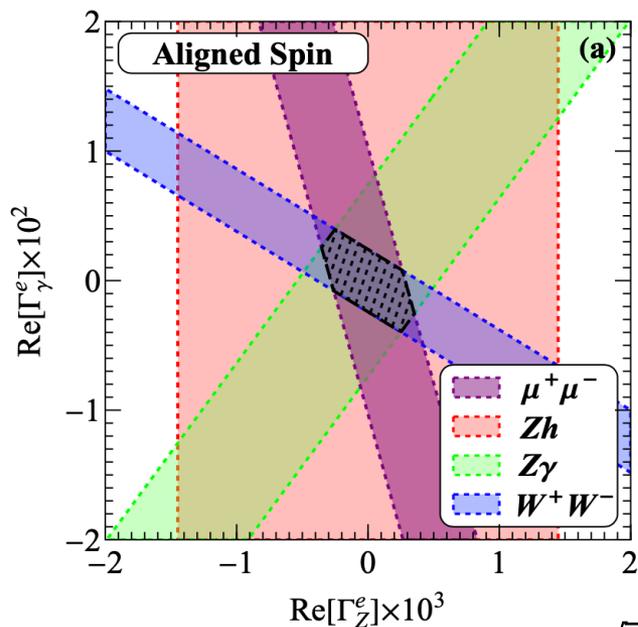
$$\mathcal{L}_{\text{eff}} = -\frac{1}{\sqrt{2}} \bar{\ell}_L \sigma^{\mu\nu} (g_1 \Gamma_B^e B_{\mu\nu} + g_2 \Gamma_W^e \sigma^a W_{\mu\nu}^a) \frac{H}{v^2} e_R + \text{h.c.}$$

$$\Gamma_\gamma^e = \Gamma_W^e - \Gamma_B^e$$

$$\Gamma_Z^e = c_W^2 \Gamma_W^e + s_W^2 \Gamma_B^e$$

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

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



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

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

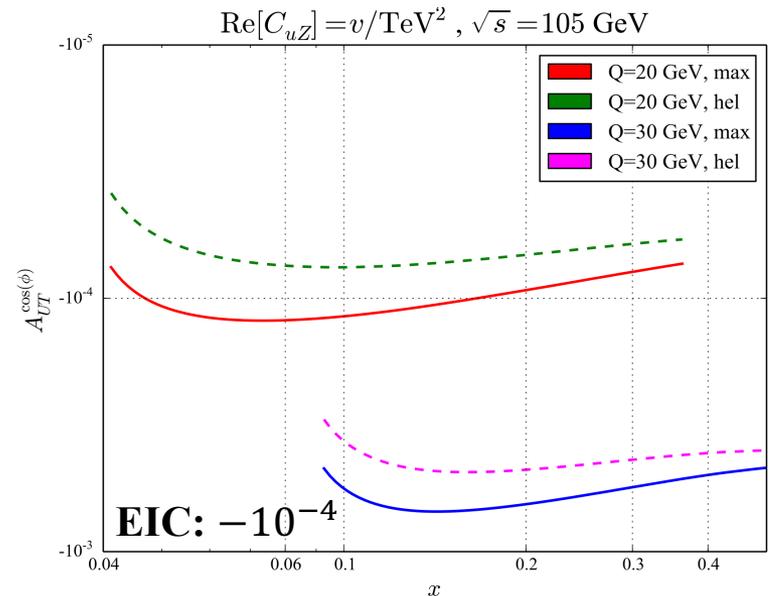
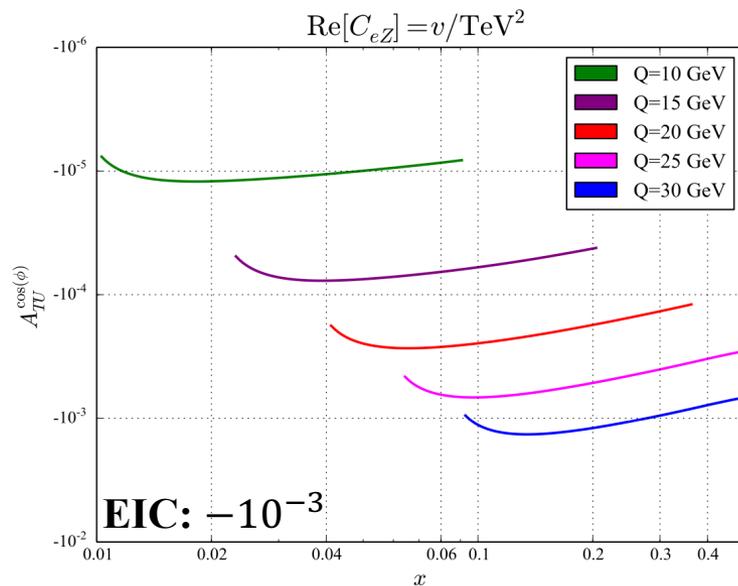
To probe lepton or quark dipole operator at $\mathcal{O}(1/\Lambda^2)$

➤ Polarized DIS (Transverse lepton/ transverse PDF)

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

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

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

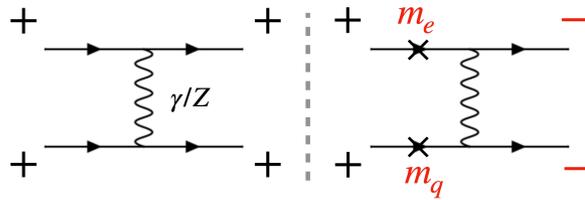


Transverse Double-Spin-Asymmetry(DSA)_@EIC

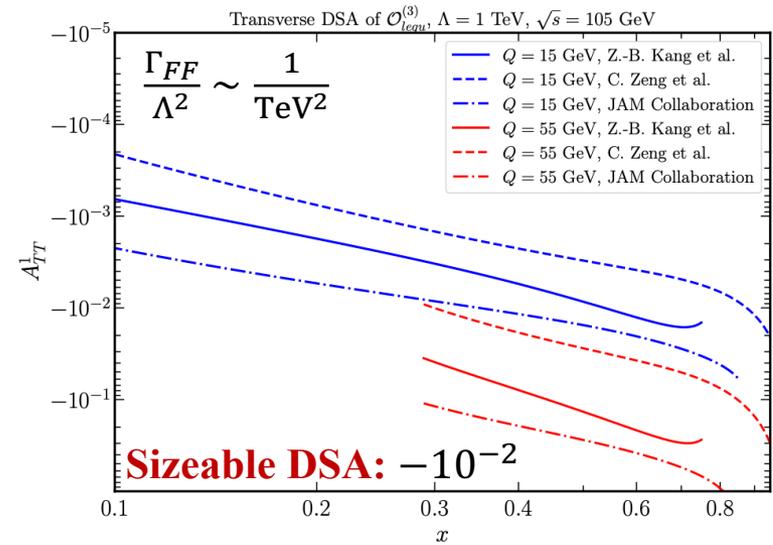
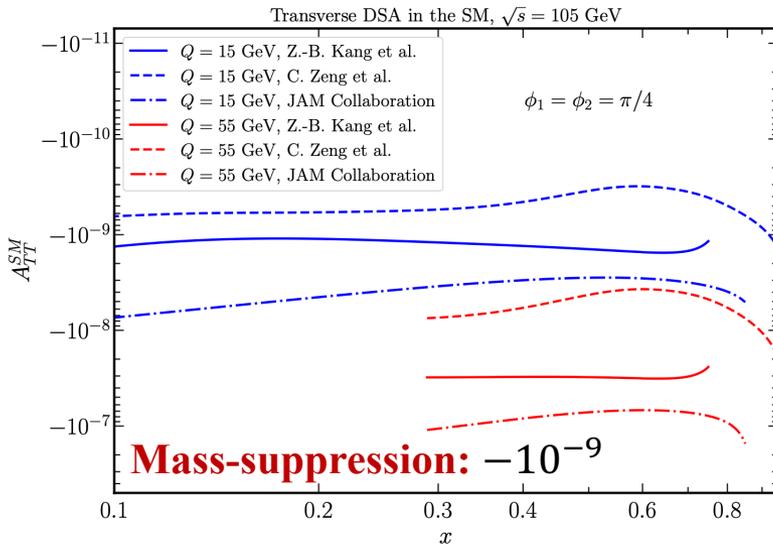
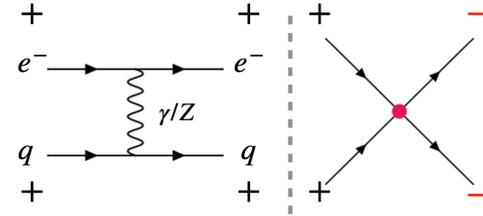
$$A_{TT} = \frac{\sigma(e^\uparrow p^\uparrow) + \sigma(e^\downarrow p^\downarrow) - \sigma(e^\uparrow p^\downarrow) - \sigma(e^\downarrow p^\uparrow)}{\sigma(e^\uparrow p^\uparrow) + \sigma(e^\downarrow p^\downarrow) + \sigma(e^\uparrow p^\downarrow) + \sigma(e^\downarrow p^\uparrow)}$$

➤ **2 ϕ** 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

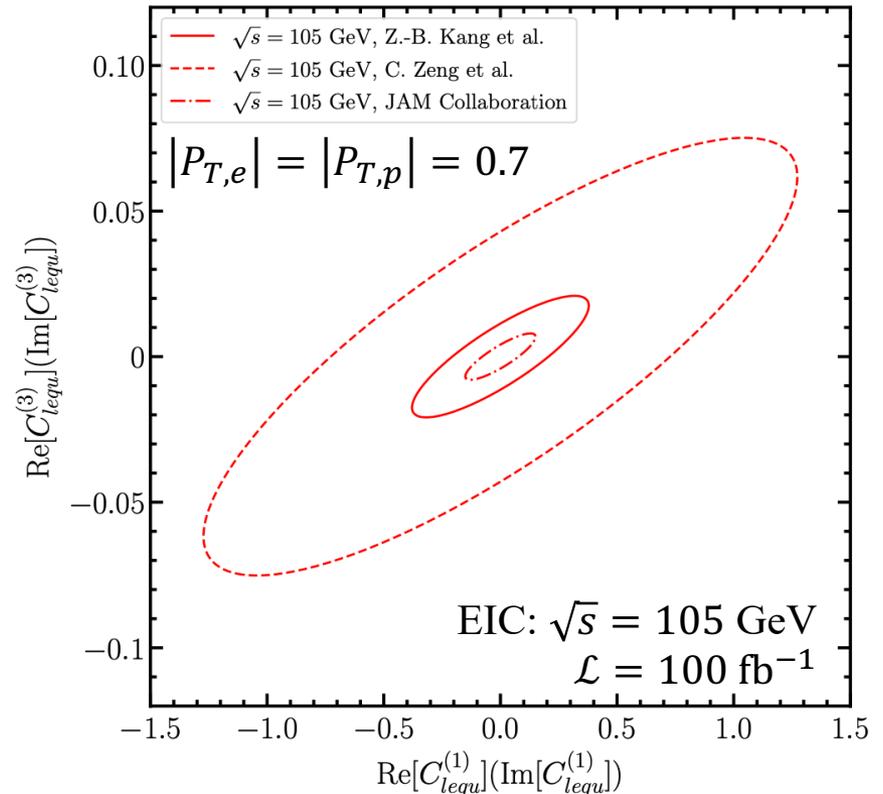
H.-L. Wang, X.-K. Wen, H. Xing and B. Yan, *Phys.Rev.D* **109** (2024) 9 , 095025

scalar/tensor four-fermion operator

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

➤ 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



- ✓ 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 $\sim 1/\Lambda^4$
- ✓ We propose a new method to linearly probe them $\sim 1/\Lambda^2$ 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 $\vec{s}(\Theta, \chi)$

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

2-to-2 rotational invariance

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

$$|\mathcal{M}|^2(\mathbf{s}, \bar{\mathbf{s}}, \theta, \phi) = \sum_{\alpha_1, \alpha_2, \alpha'_1, \alpha'_2} \rho_{\alpha_1, \alpha'_1}(\mathbf{s}) \bar{\rho}_{\alpha_2, \alpha'_2}(\bar{\mathbf{s}}) \mathcal{M}_{\alpha_1, \alpha_2}(i \rightarrow f; \theta, \phi) \mathcal{M}_{\alpha'_1, \alpha'_2}^\dagger(i \rightarrow f; \theta, \phi)$$

$$\mathbf{s} = (b_1, b_2, \lambda) = (b_T \cos \phi_0, b_T \sin \phi_0, \lambda) \quad \rho = \frac{1}{2} (1 + \boldsymbol{\sigma} \cdot \mathbf{s})$$

$$\mathcal{M}_{\lambda_1, \lambda_2}(\theta, \phi) = e^{i(\lambda_1 - \lambda_2)\phi} \mathcal{T}_{\lambda_1, \lambda_2}(\theta) \quad |M|^2 = |M|_{\text{unpol}}^2 - \frac{1}{2} \lambda_T \bar{\lambda}_T \text{Re}[T_{++}^* T_{--}]$$

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

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

$$- \frac{1}{2} \lambda_T \bar{\lambda}_T \text{Re}[e^{-2i\phi} T_{+-}^* T_{-+}]$$

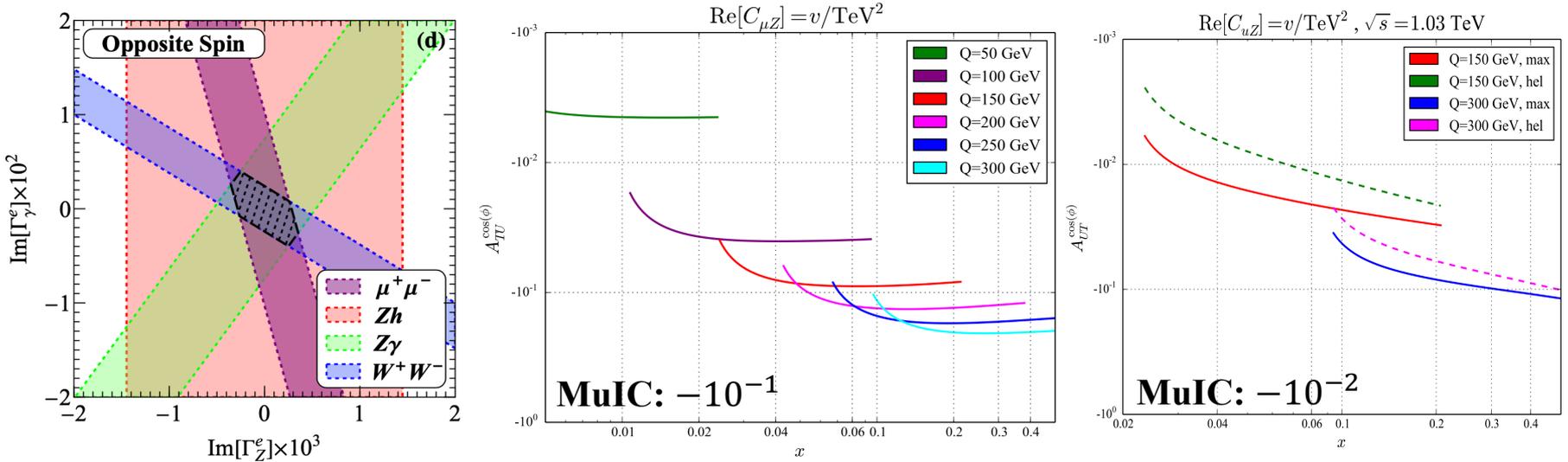
$$+ \frac{1}{2} \lambda_T \text{Re} [e^{-i\phi} (T_{+-}^* T_{--} + T_{++}^* T_{-+})]$$

$$- \frac{1}{2} \bar{\lambda}_T \text{Re} [e^{-i\phi} (T_{+-}^* T_{++} + T_{--}^* T_{-+})]$$

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

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

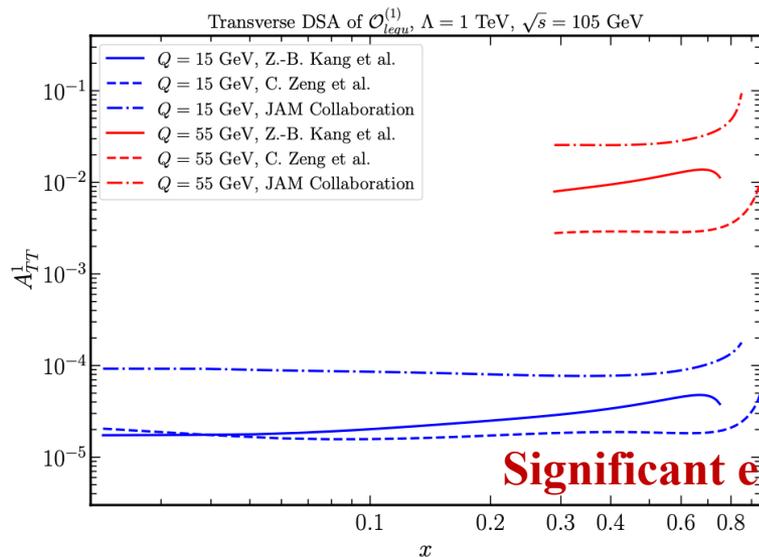
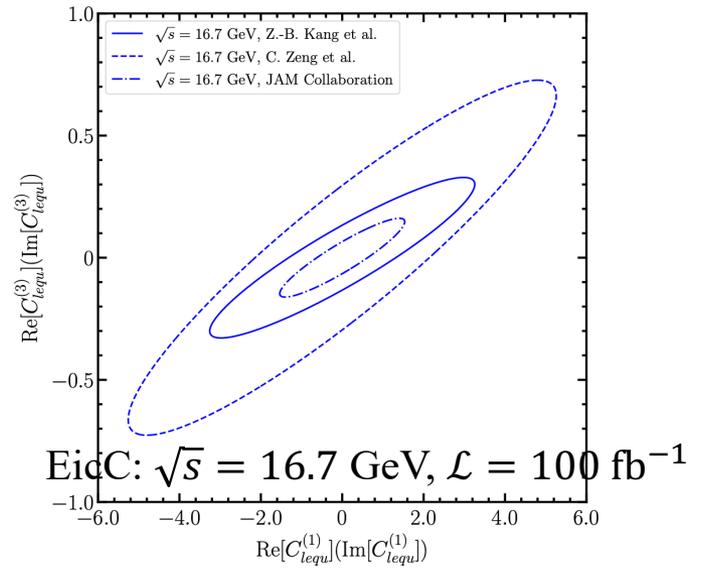
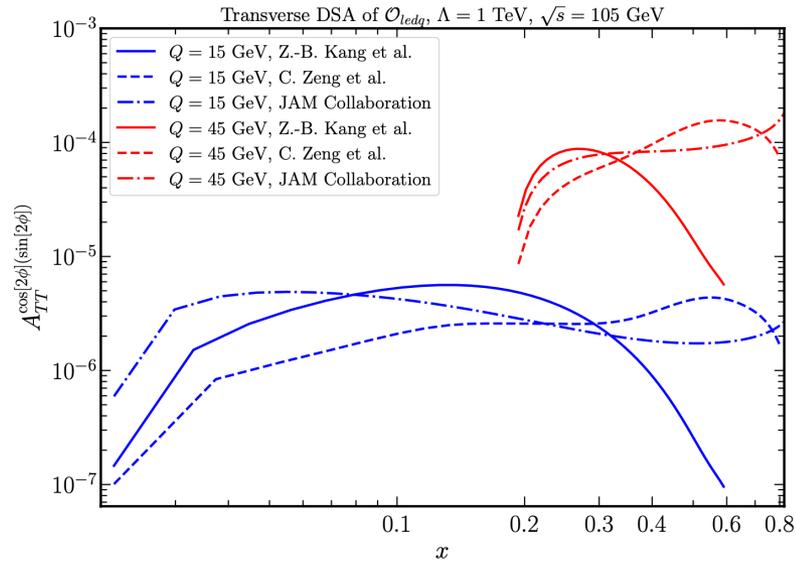
The asymmetry at MuIC is significantly larger than at EIC ➤ Energy enhancement

$$A_{TT}^w = \frac{1}{P_{T,e} P_{T,p}} \frac{1}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

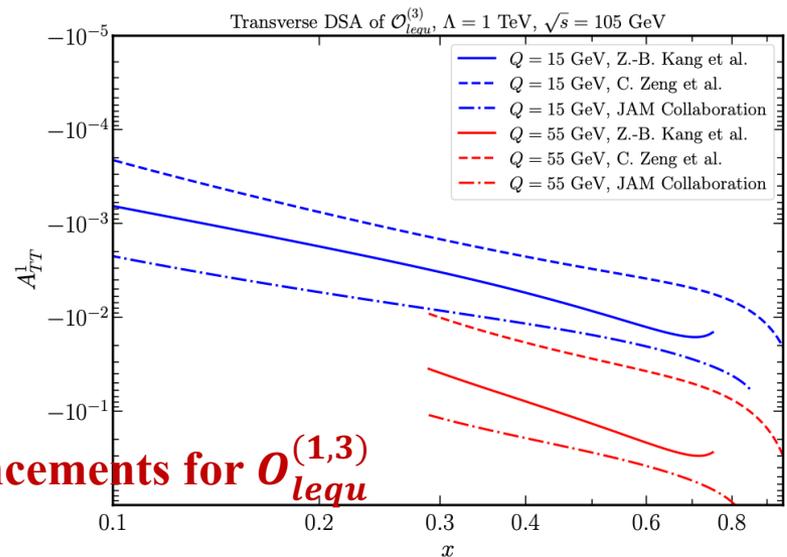
$$\times \int_0^{2\pi} d\phi w(\phi) (N_{\uparrow\uparrow}(\phi) + N_{\downarrow\downarrow}(\phi) - N_{\uparrow\downarrow}(\phi) - N_{\downarrow\uparrow}(\phi))$$

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

Backup



Significant enhancements for $\mathcal{O}_{lequ}^{(1,3)}$

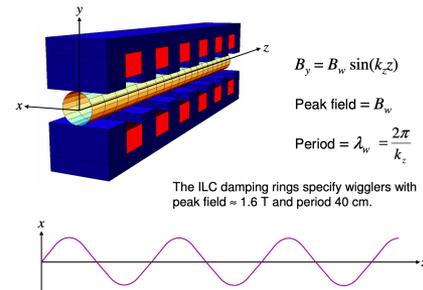


Backup: Polarized beam realization

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 ($\sim 1\%$). 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 ($>\sim 150$ 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 $|P_{e^+}| \geq 90\%$ 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.