

Single Transverse Spin Asymmetry as a New Probe of SMEFT Dipole Operators

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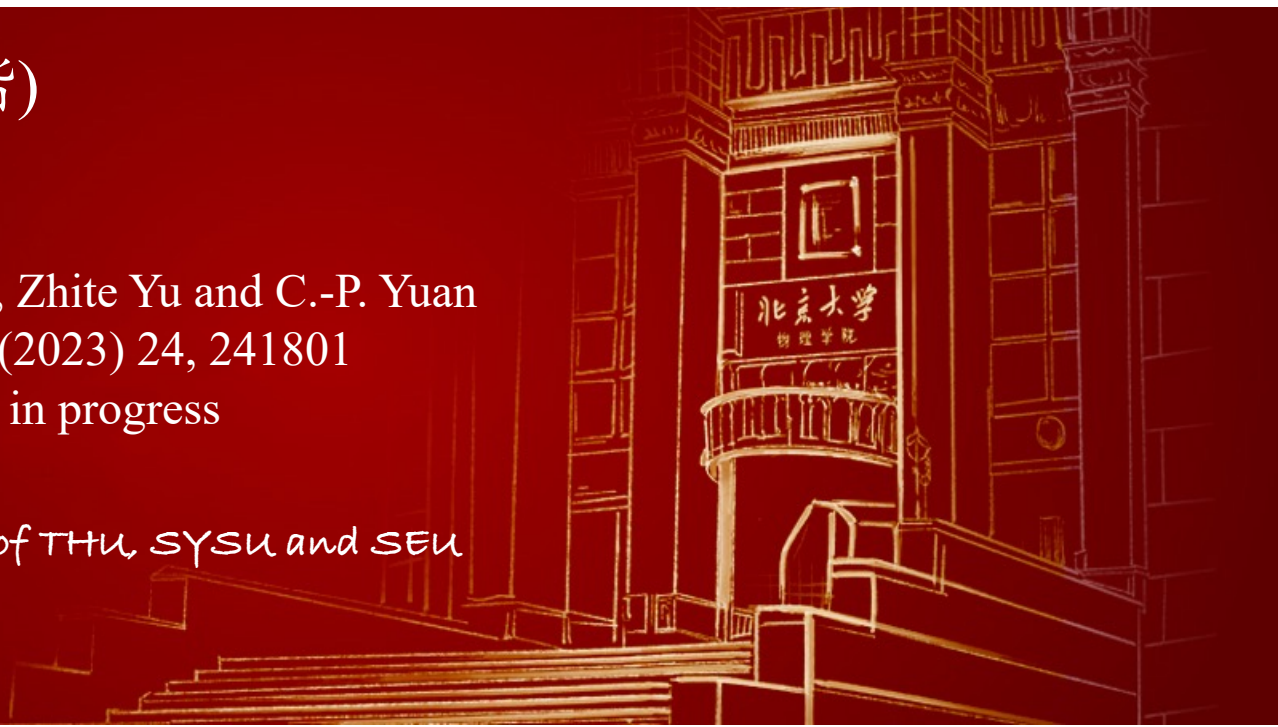
In collaboration with Bin Yan, Zhite Yu and C.-P. Yuan

Basing on *Phys.Rev.Lett.* **131** (2023) 24, 241801

arXiv: 2307.05236 and works in progress

Thanks a lot to the organizers of THU, SYSU and SEU
Nanjing, Jiangsu, China

2023/12/16



New Physics and SMEFT

None new fundamental resonance has been discovered.

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_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0, e, \mu, \tau, \gamma$	$1 - 4j$	Yes	139	M_{Pl} 11.2 eV $n=2$
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_s 8.6 TeV $n=3$ HLZ NLO
	ADD QBH	-	$2j$	-	139	M_{BH} 9.4 TeV $n=6$
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{BH} 9.55 TeV $n=6, M_{Pl} = 3 \text{TeV}$, rot BH
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	$k/\overline{M}_{Pl} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$k/\overline{M}_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow tt$	$1, e, \mu$	$\geq 1b, \geq 1J/2j$	Yes	36.1	$\Gamma/m = 15\%$
	2UED / RPP	$1, e, \mu$	$\geq 2b, \geq 3j$	Yes	36.1	Tier (1,1), $\mathcal{B}(A^{(1)} \rightarrow tt) = 1$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2, e, \mu$	-	-	139	Z' mass 1903.06248
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 1709.07242
	Leptophobic $Z' \rightarrow bb$	-	$2b$	-	36.1	Z' mass 2.42 TeV
	Leptophobic $Z' \rightarrow tt$	$0, e, \mu$	$\geq 1b, \geq 2j$	Yes	139	Z' mass 2.1 TeV
	SSM $W' \rightarrow \ell\nu$	$1, e, \mu$	-	-	Yes	W' mass 4.1 TeV
	SSM $W' \rightarrow \tau\nu$	1τ	-	-	Yes	W' mass 6.0 TeV
	SSM $W' \rightarrow tb$	-	$\geq 1b, \geq 1j$	-	Yes	W' mass 5.0 TeV
	HVT $W' \rightarrow WZ$ model B	$0, 2, e, \mu$	$2j(1j)$	Yes	139	W' mass 4.4 TeV
	HVT $W' \rightarrow WZ \rightarrow \ell\nu(\ell'\ell')$ model C	$3, e, \mu$	$2j(\text{VBF})$	Yes	139	W' mass 4.3 TeV
	HVT $Z' \rightarrow WW$ model B	$1, e, \mu$	$2j(1j)$	Yes	139	Z' mass 3.9 TeV
	LRSM $W_R \rightarrow \mu N_R$	2μ	$1j$	-	80	W_R mass 5.0 TeV
CI	Cl qqq	-	$2j$	-	37.0	A 21.8 TeV η_{LL}
	Cl ℓqq	$2, e, \mu$	-	-	139	A 35.8 TeV η_{LL}
	Cl ebs	$2, e$	$1b$	-	139	$g_s = 1$
	Cl μbs	$2, \mu$	$1b$	-	139	$g_s = 1$
	Cl $tttt$	$\geq 1, e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	$ C_{4\ell} = 4\pi$
DM	Axial-vector med. (Dirac DM)	-	$2j$	-	139	\tilde{m}_{med} 3.8 TeV
	Pseudo-scalar med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	$1 - 4j$	Yes	139	\tilde{m}_{med} 376 GeV
	Vector med. Z' -2HDM (Dirac DM)	$0, e, \mu$	$2b$	Yes	139	\tilde{m}_{med} 3.0 TeV
	Pseudo-scalar med. 2HDM+A	multi-channel	-	-	139	800 GeV
LQ	Scalar LQ 1 st gen	$2, e$	$\geq 2j$	Yes	139	LQ mass 1.8 TeV
	Scalar LQ 2 nd gen	$2, \mu$	$\geq 2j$	Yes	139	LQ mass 1.7 TeV
	Scalar LQ 3 rd gen	$0, \tau$	$2b$	Yes	139	LQ mass 49 TeV
	Scalar LQ 3 rd gen	$0, e, \mu$	$\geq 2j, \geq 2b$	Yes	139	LQ mass 1.2 TeV
	Scalar LQ 3 rd gen	$\geq 2, e, \mu$	$\geq 1\tau, \geq 1b$	-	139	LQ mass 1.93 TeV
	Scalar LQ 3 rd gen	$0, e, \mu$	$\geq 1\tau, 2j, 2b$	Yes	139	LQ mass 1.2 TeV
	Vector LQ mix gen	multi-channel	$\geq 1j, \geq 1b$	Yes	139	LQ mass 2.0 TeV
	Vector LQ 3 rd gen	$2, e, \mu, \tau$	$\geq 1b$	-	139	LQ mass 1.96 TeV
Vector-like fermions	VLO $TT \rightarrow Zt + X$	$2e/2\mu/\geq 3e, \mu$	$\geq 1b, \geq 1j$	-	139	T mass 146 TeV
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV
	VLO $T_{5/3} \rightarrow T_{5/3} + Wt + X$	$2(SS)/\geq 3, e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV
	VLO $T \rightarrow Ht/Zt$	$1, e, \mu$	$\geq 1b, \geq 3j$	Yes	139	T mass 1.8 TeV
	VLO $\gamma \rightarrow Wb$	$1, e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	Y mass 1.85 TeV
	VLO $B \rightarrow Hb$	$0, e, \mu$	$\geq 2b, \geq 1j, \geq 1j$	Yes	139	B mass 2.0 TeV
	VLL $\tau \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1j$	Yes	139	e' mass 898 GeV
Exotic ferm.	Excited quark $q^* \rightarrow qg$	-	$2j$	-	139	q^* mass 6.7 TeV
	Excited quark $q^* \rightarrow q\gamma$	1γ	-	-	139	q^* mass 5.3 TeV
	Excited quark $b^* \rightarrow b\gamma$	-	$1b, 1j$	-	139	b^* mass 3.2 TeV
	Excited lepton e^*	2τ	$\geq 2j$	-	139	e^* mass 4.6 TeV
Other	Type III Seesaw	$2, 3, 4, e, \mu$	$\geq 2j$	Yes	139	N^* mass 910 GeV
	LHGS Majorana ν	$2, 3, 4, e, \mu$	$2j$	Yes	36.1	N_s mass 2 μ
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$	$2, 3, 4, e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 3.2 TeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4, e, \mu$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV
	Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV

*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).

new physics
new measurements

	X^3	φ^6 and $\varphi^2 D^2$	$\varphi^2 \varphi^6$
Q_{φ^2}	$f^{ABC} G^A G^B G^C$	Q_{φ^2}	Q_{φ^2}
Q_{φ^4}	$f^{ABC} \tilde{G}^A \tilde{G}^B \tilde{G}^C$	Q_{φ^4}	Q_{φ^4}
Q_{φ^6}	$\tilde{f}^{ABC} \tilde{W}^A \tilde{W}^B \tilde{W}^C$	Q_{φ^6}	Q_{φ^6}
Q_{φ^8}	$\tilde{f}^{ABC} \tilde{W}^A \tilde{W}^B \tilde{W}^C$	Q_{φ^8}	Q_{φ^8}

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

- B. Grzadkowski, et al. *JHEP* 10 (2010)
- W. Buchmuller, D. Wyler, 1986
- B. Henning et al, 2015

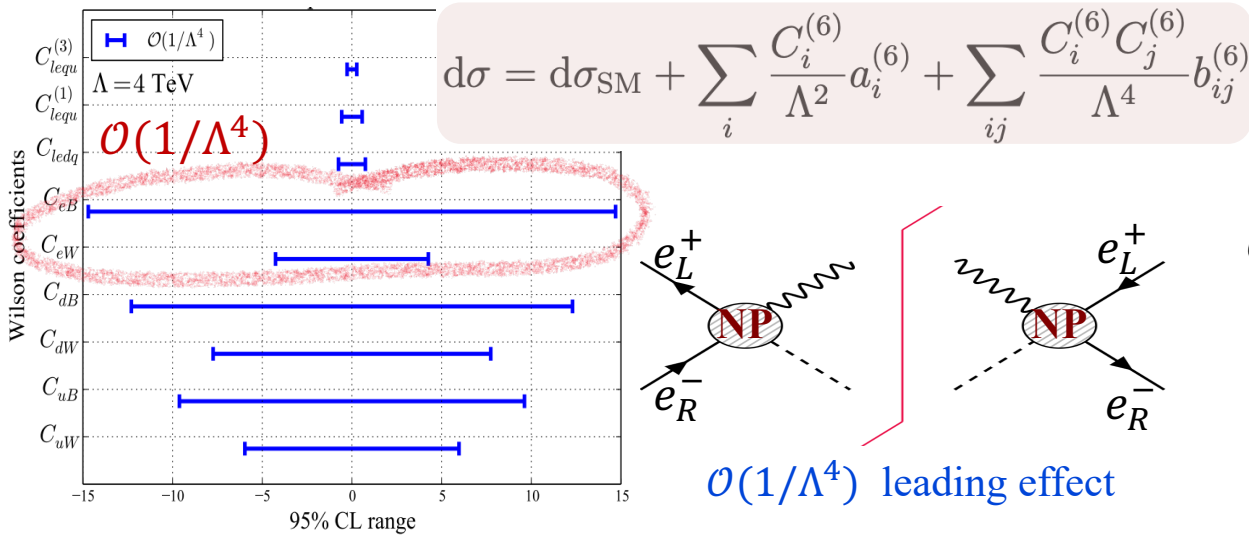
Powerful Tool @ EW
 $\{G, P\}_{SM}$, linear rep. H...

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

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

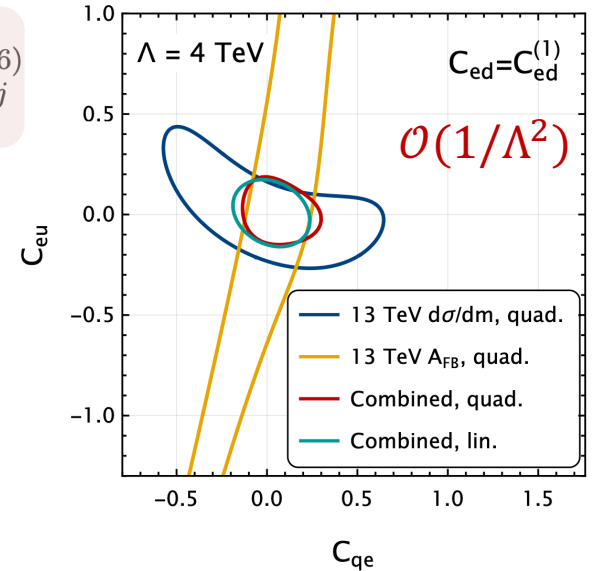
Data for Dipole Operator

EW dipole couplings constrained very poorly in traditional method via cross-section and width



Single-Parameter-Analysis @LHC

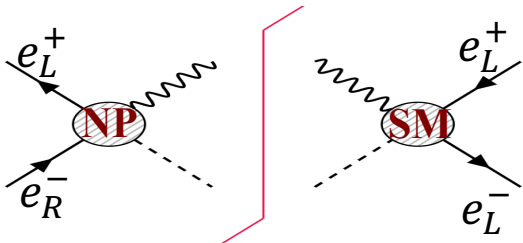
(R. Boughezal et al. *Phys.Rev.D* 104 (2021)...)



(R. Boughezal et al. *arXiv*: 2303.08257)

✓ Cause Chirality Flip of Fermion
(Disappear in massless SM)

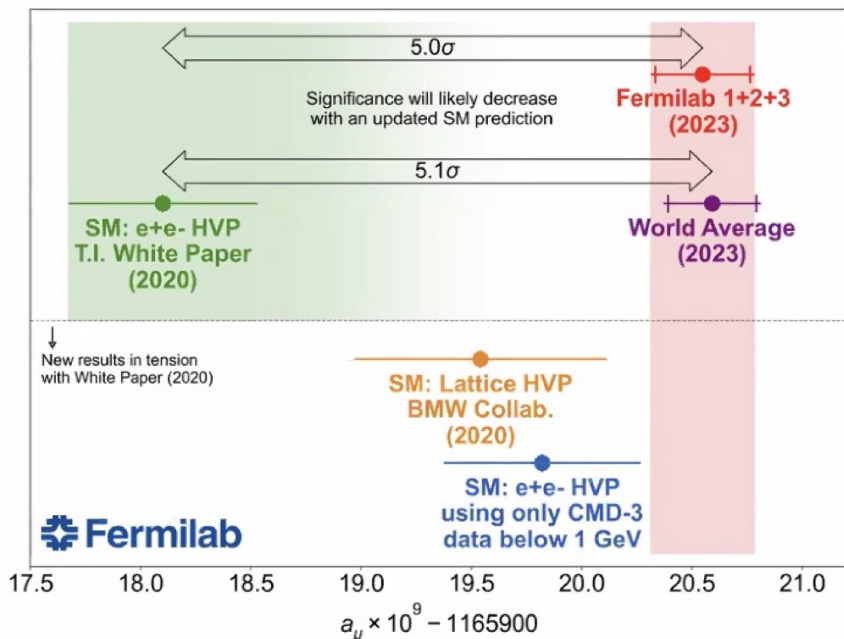
➔ Only small non-interfering effect with $\left| \frac{C_{\text{dipole}}}{\Lambda^2} \right|^2$



How to trigger
 $\mathcal{O}(1/\Lambda^2)$ interference?

New Physics with Dipole Operator

E/M Dipole Moment
Direct & Dominant Effect



Loop-induced by the BSM
Indirect probes of quantum effects of NP

Minimal models for muon g-2: 1 field extensions

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result for $\Delta a_\mu^{\text{BNL}}, \Delta a_\mu^{2021}$	
1	0	(1, 1, 1)	Excluded: $\Delta a_\mu < 0$	EXCLUDED
2	0	(1, 1, 2)	Excluded: $\Delta a_\mu < 0$	
3	0	(1, 2, -1/2)	Updated in Sec. 3.2	From: JHEP 09 (2021) 080, [PA, C.Balázs, D.H.J. Jacob, W. Kotlarski, D. Stöckinger, H. Stöckinger-Kim]
4	0	(1, 3, -1)	Excluded: $\Delta a_\mu < 0$	
5	0	($\bar{3}$, 1, 1/3)	Updated Sec. 3.3	
6	0	($\bar{3}$, 1, 4/3)	Excluded: LHC searches	
7	0	($\bar{3}$, 3, 1/3)	Excluded: LHC searches	
8	0	(3, 2, 7/6)	Updated Sec. 3.3	
9	0	(3, 2, 1/6)	Excluded: LHC searches	
10	1/2	(1, 1, 0)	Excluded: $\Delta a_\mu < 0$	
11	1/2	(1, 1, -1)	Excluded: Δa_μ too small	
12	1/2	(1, 2, -1/2)	Excluded: LEP lepton mixing	
13	1/2	(1, 2, -3/2)	Excluded: $\Delta a_\mu < 0$	
14	1/2	(1, 3, 0)	Excluded: $\Delta a_\mu < 0$	
15	1/2	(1, 3, -1)	Excluded: $\Delta a_\mu < 0$	
16	1	(1, 1, 0)	Special cases viable	
17	1	(1, 2, -3/2)	UV completion problems	
18	1	(1, 3, 0)	Excluded: LHC searches	
19	1	($\bar{3}$, 1, -2/3)	UV completion problems	
20	1	($\bar{3}$, 1, -5/3)	Excluded: LHC searches	
21	1	($\bar{3}$, 2, -5/6)	UV completion problems	
22	1	($\bar{3}$, 2, 1/6)	Excluded: $\Delta a_\mu < 0$	
23	1	($\bar{3}$, 3, -2/3)	Excluded: proton decay	

2HDM

Scalar leptoquarks

Dark photon

SUSY.....

Scalar extensions.....

Peter Athron et al., *JHEP* 09 (2021) 080



May have same physics source
but Z only detected by colliders

MUCH IMPORTANCE!

How to probe EW dipole operator at $\mathcal{O}(1/\Lambda^2)$?

How to Probe Dipole Operator at $1/\Lambda^2$

Traditional method via cross-section and width only leading @ $|C_{dipole}|^2/\Lambda^4$ and suffer from assumptions

Our proposal:

- ✓ Transverse polarization effect of beams

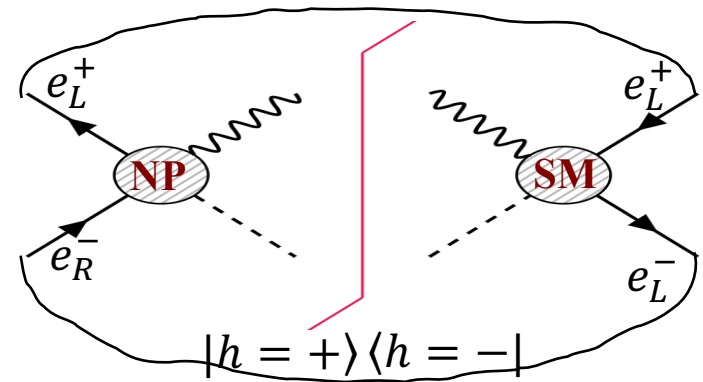
(Interference between the different helicity states)

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

- ✓ C_{dipole}/Λ^2 , interfering with the massless SM
- ✓ Without depending on other NP operators
- ✓ Non-trivial azimuthal angular distribution

Single Transverse Spin Azimuthal Asymmetries

In a word, transverse polarization effect triggers interference of helicity amplitudes and breaks the rotational invariance to induce nontrivial azimuthal behavior.

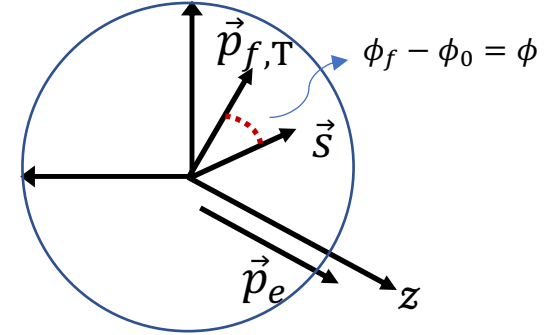


$\mathcal{O}(1/\Lambda^2)$ leading effect

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

Transverse Spin Polarization

Transverse spin effect → Interference of helicity amplitudes
 Breaking rotational invariance, Nontrivial azimuthal behavior



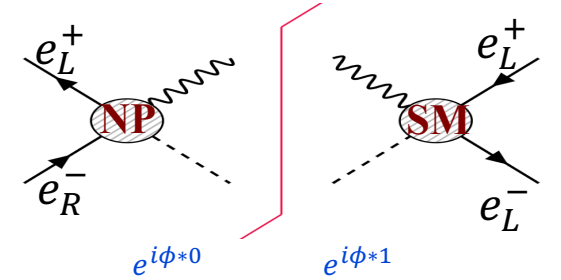
Spin dependent amplitude square:

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

$$\mathbf{s} = (b_1, b_2, \lambda) = (b_T \cos \phi_0, b_T \sin \phi_0, \lambda)$$

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

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



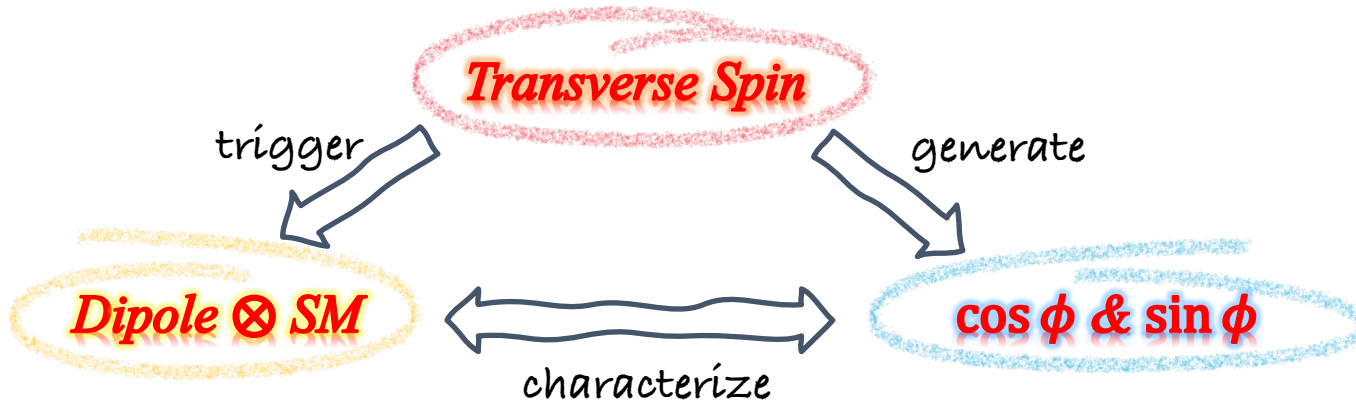
dipole operator → $\mathcal{M}_{\pm\pm}$, massless SM → $\mathcal{M}_{\pm\mp}$

	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$
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$

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

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

A New Probe of Dipole Operators



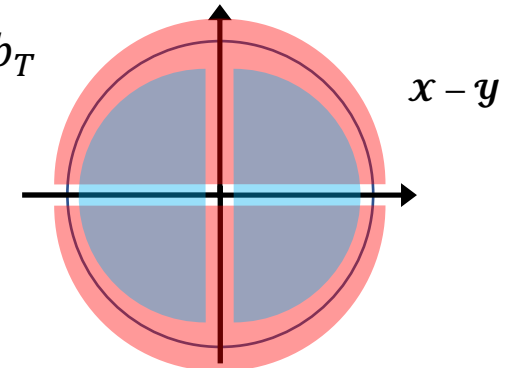
$$\frac{2\pi d\sigma^i}{\sigma^i d\phi} = 1 + \underbrace{A_R^i(b_T, \bar{b}_T)}_{\text{Re}[C_{dipole}]} \cos \phi + \underbrace{A_I^i(b_T, \bar{b}_T)}_{\text{Im}[C_{dipole}]} \sin \phi + \underbrace{b_T \bar{b}_T B^i}_{\text{SM \& other NP}} \cos 2\phi + \mathcal{O}(1/\Lambda^4)$$

$\vec{s} \cdot \vec{p}_f \propto \cos \phi$	$\vec{s} \times \vec{p}_f \propto \sin \phi$
CP-conserving	CP-violation

X.-K.W, BY, ZY, C.-P.Y, 2307.05236

Linearly dependent on the dipole couplings C_{dipole} and spin b_T

$$\begin{aligned} \text{Blue} \quad A_{LR}^i &= \frac{\sigma^i(\cos \phi > 0) - \sigma^i(\cos \phi < 0)}{\sigma^i(\cos \phi > 0) + \sigma^i(\cos \phi < 0)} = \frac{2}{\pi} A_R^i \\ \text{Red} \quad A_{UD}^i &= \frac{\sigma^i(\sin \phi > 0) - \sigma^i(\sin \phi < 0)}{\sigma^i(\sin \phi > 0) + \sigma^i(\sin \phi < 0)} = \frac{2}{\pi} A_I^i \end{aligned}$$



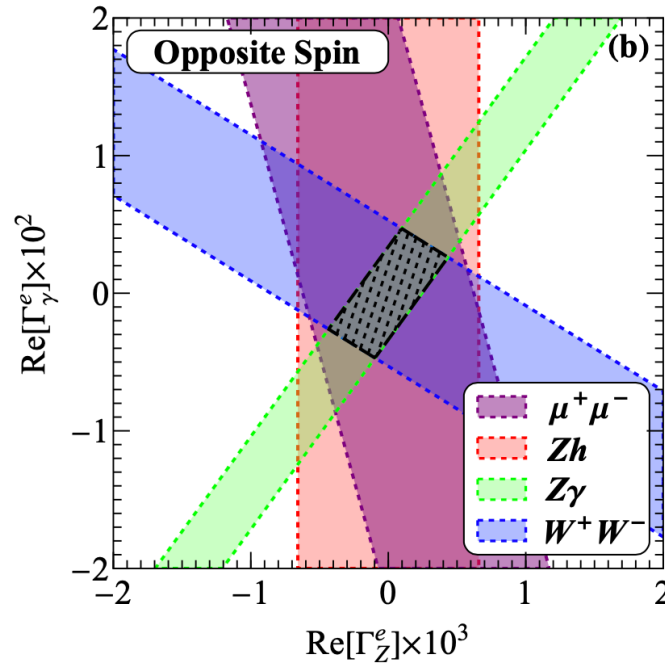
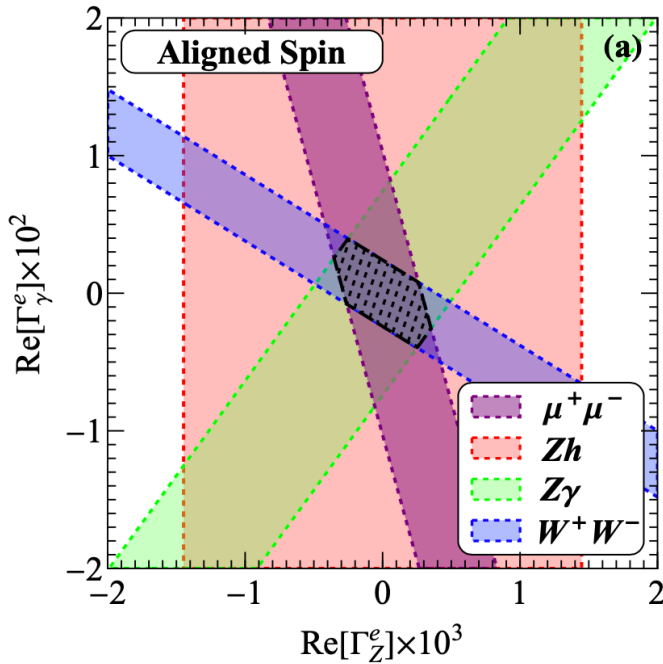
Pinning down Dipole Operators

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

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

Aligned Spin
 $\phi_0 = \bar{\phi}_0 = 0$
 Opposite Spin
 $(\phi_0, \bar{\phi}_0) = (0, \pi)$

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



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

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

Single spin
is
enough!!

Why the limit difference between the Aligned Spin and the Opposite Spin?

CP property

$$e^+e^- : |e^-(s)e^+(\bar{s})\rangle \xrightarrow{\mathcal{CP}} |e^-(\bar{s})e^+(s)\rangle$$

$$\mu^+\mu^- : |\phi, \theta\rangle \xrightarrow{\mathcal{CP}} |\phi, \theta\rangle \quad Z\gamma : |\phi, \theta\rangle \xrightarrow{\mathcal{CP}} |\phi + \pi, \pi - \theta\rangle \quad \rightarrow$$

$$A_R^{\mu\mu} \propto \mathbf{s}_T + \bar{\mathbf{s}}_T$$

$$A_R^{Z\gamma} \propto \mathbf{s}_T - \bar{\mathbf{s}}_T$$

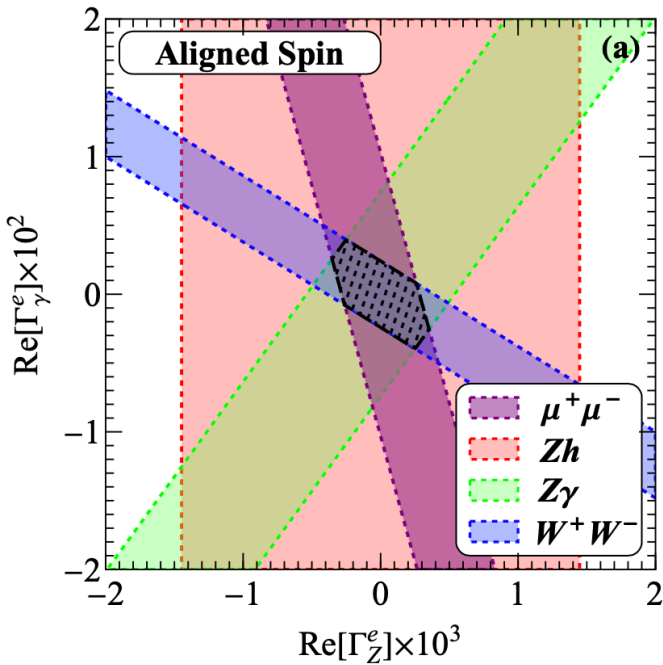
Pinning down Dipole Operators

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

Aligned Spin
 $\phi_0 = \bar{\phi}_0 = 0$
 Opposite Spin
 $(\phi_0, \bar{\phi}_0) = (0, \pi)$

The sensitivity to Γ_Z^e is much stronger than Γ_γ^e

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



$$A_{R\setminus I}(\Gamma_\gamma^e) < A_{R\setminus I}(\Gamma_Z^e)$$

Parity property

$$\mathcal{M}_{++}^*\mathcal{M}_{-+} = -\mathcal{M}_{+-}^*\mathcal{M}_{--}(g_L \leftrightarrow g_R)$$

$$|\mathcal{M}|_{1\phi}^2 \sim (g_L - g_R)[(g_L^e + g_R^e)\Gamma_\gamma^e + \Gamma_Z^e]$$

- SM $(g_L^e + g_R^e) = -\frac{1}{2} + 2 \sin^2 \theta_W \ll 1$
- SM $WW\gamma < WWZ$
- $\Gamma_W^e = \Gamma_Z^e + s_W^2 \Gamma_\gamma^e$

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

Pinning down Dipole Operators

For the imaginary parts of dipole couplings, things are similar

Aligned Spin

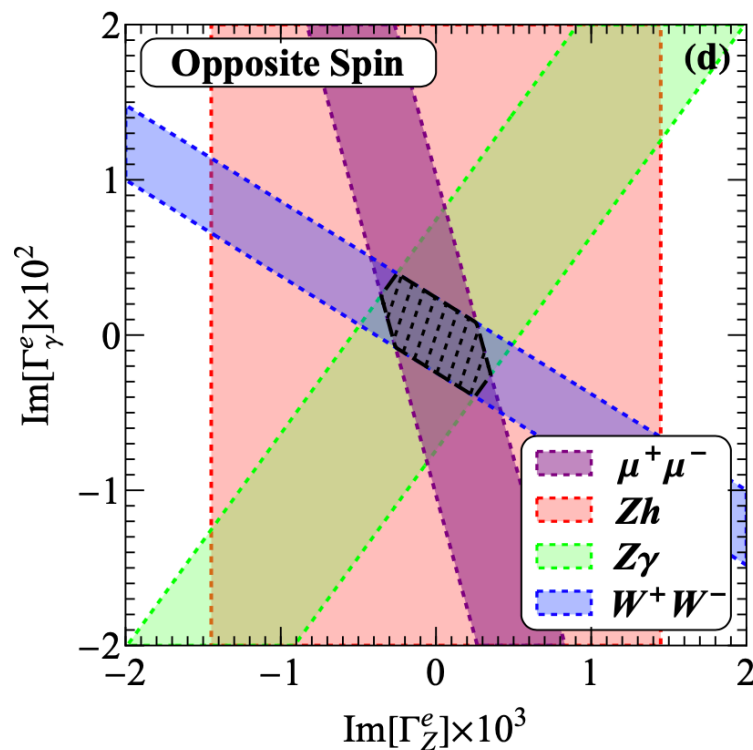
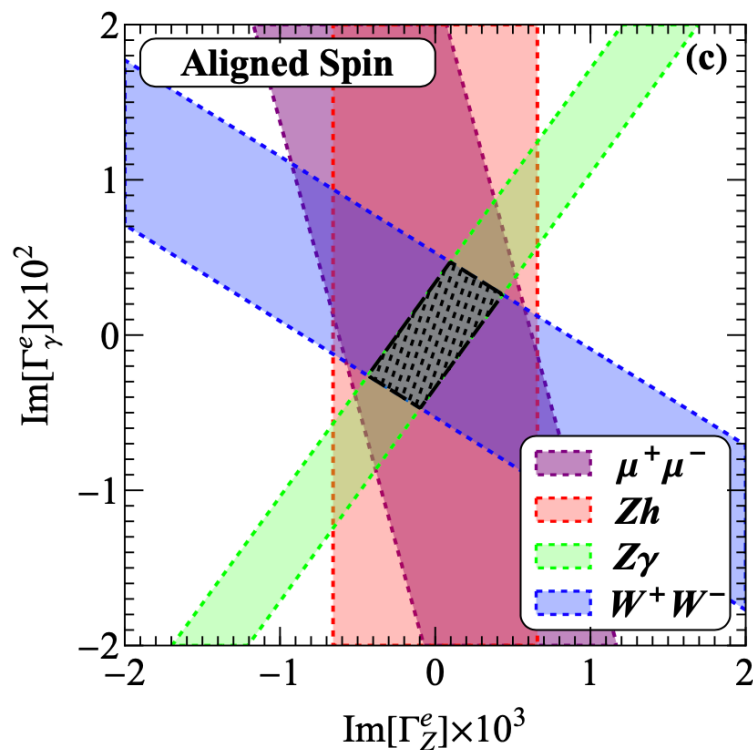
$$\phi_0 = \bar{\phi}_0 = 0$$

Opposite Spin

$$(\phi_0, \bar{\phi}_0) = (0, \pi)$$

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

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



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

Summary



- ✓ The muon $g-2$ data may hint the NP effects from the dipole operators, but their weak interactions are difficult to be probed since the leading effects are from $1/\Lambda^4$
- ✓ We propose a new method to **probe dipole operator at $1/\Lambda^2$** via *transverse polarized beams*

Single Transverse Spin Azimuthal Asymmetries

- ✓ STSAA simultaneously constrains well both Re & Im parts

without impact from other NP

offering a new opportunity for directly probing potential CP-violating effects.

- ✓ Our bound could be reached around $O(0.01\% \sim 0.1\%)$, much stronger sensitivity than other approaches by 1~2 orders of magnitude

- ✓ Future colliders (Z/Higgs/Top factory...)

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

	$ \Gamma_Z^e $	$ \Gamma_\gamma^e $
Our Study	0.0002	0.005
LHC Drell-Yan	0.0765	0.197
Z Partial Width	0.0582	0.093
$(g-2)_e$	10^{-2}	10^{-6}

➤ [DSA@Transversely Polarized DIS](#) ➤ [See Hao-Lin's talk](#)

Thank you