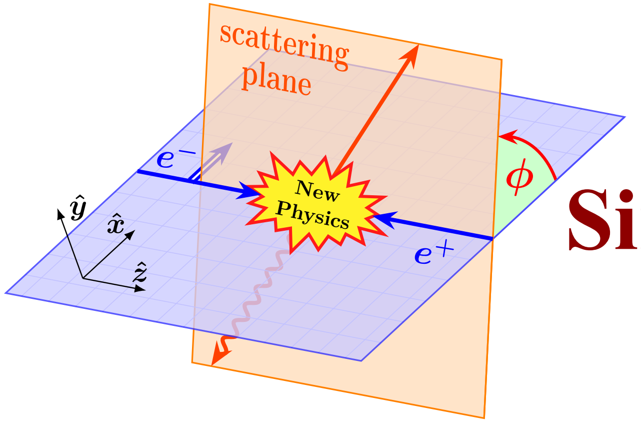
17th TeV-Phycics Working Group Workshop, Nanjing, Dec. 15-19, 2023
第十七届 TeV 物理工作组学术研讨会，中国南京



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

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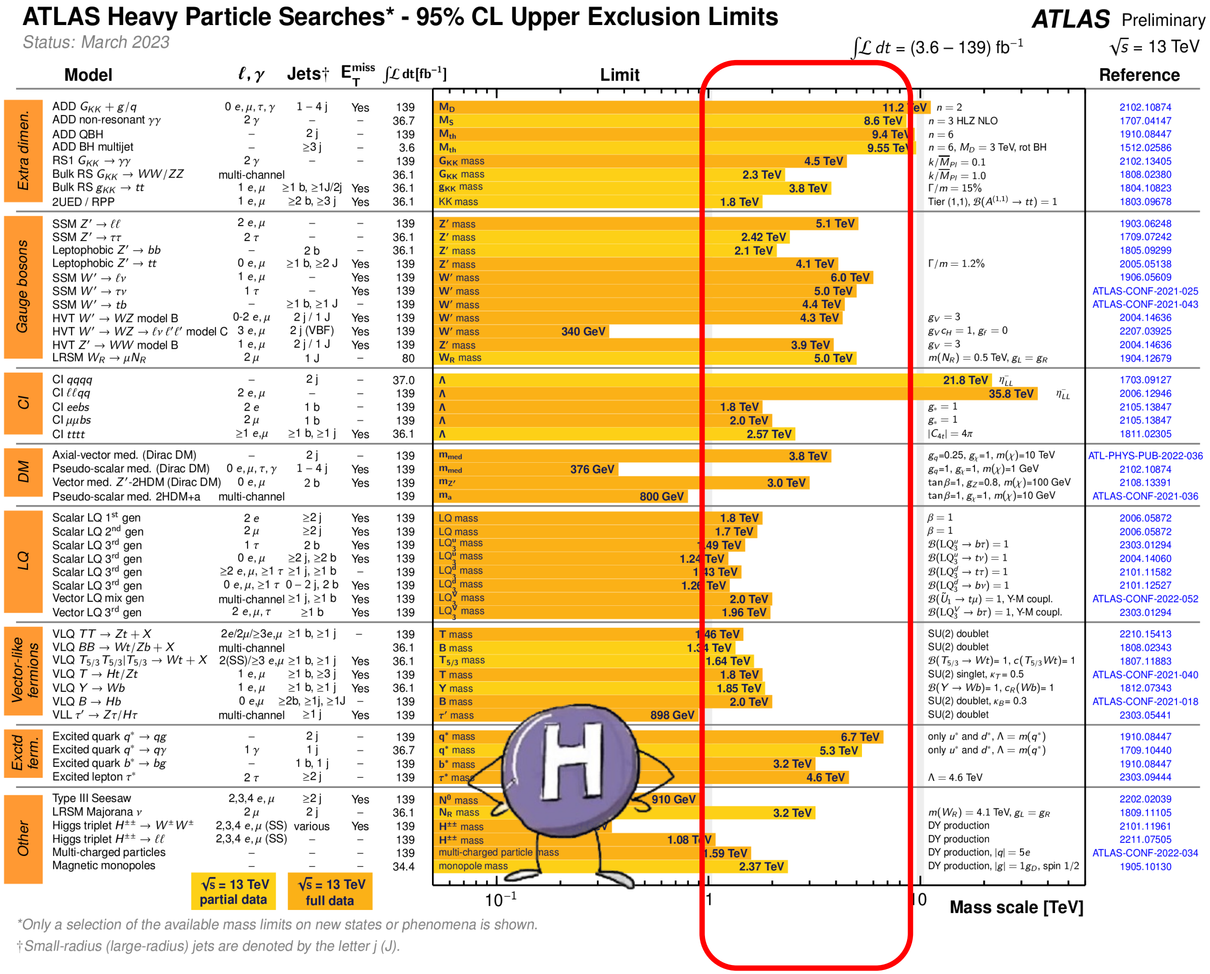
Peking University

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.

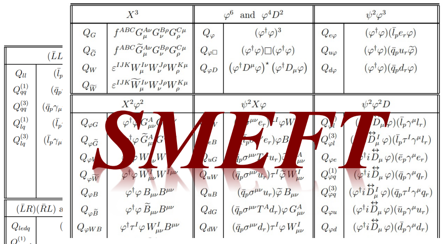


*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

new physics

new measurements



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

B. Grzadkowski, et al. *JHEP* 10 (2010)
W. Buchuller, D. wyler, 1986
B. Henning et al, 2015

Powerful Tool @ EW

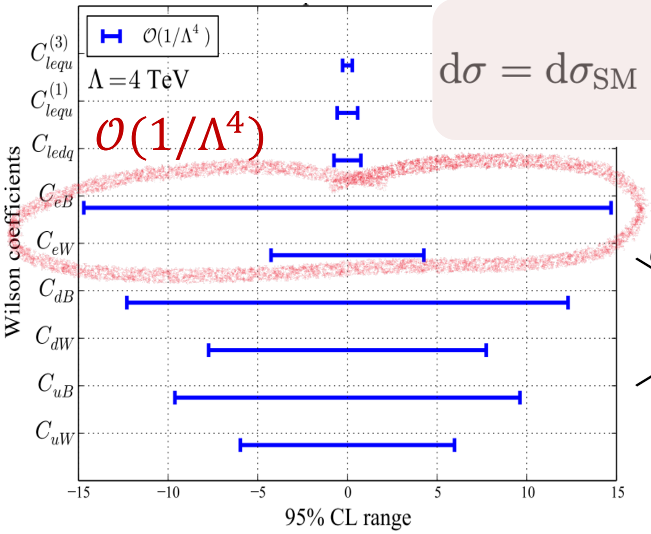
$\{G, P\}_{SM}$, linear rep. H…

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

Data for Dipole Operator

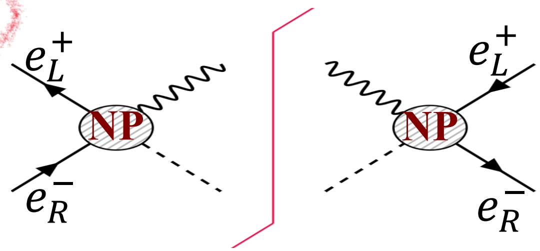
EW dipole couplings constrained very poorly in traditional method via cross-section and width

$$d\sigma = d\sigma_{\rm SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} a_i^{(6)} + \sum_{ij} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} b_{ij}^{(6)}$$

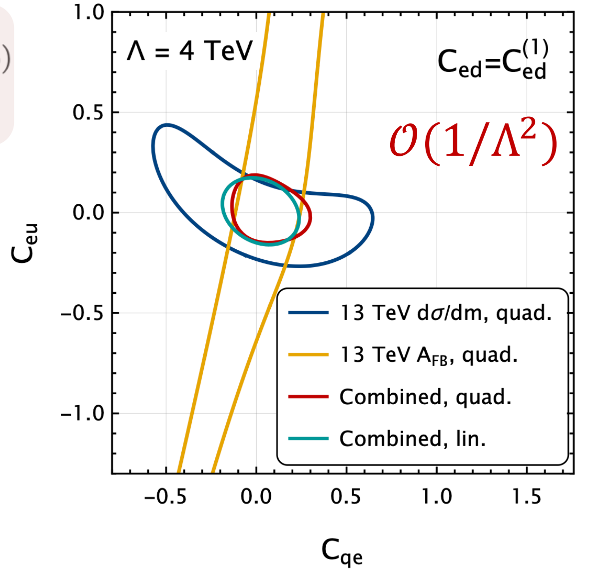


Single-Parameter-Analysis @LHC

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



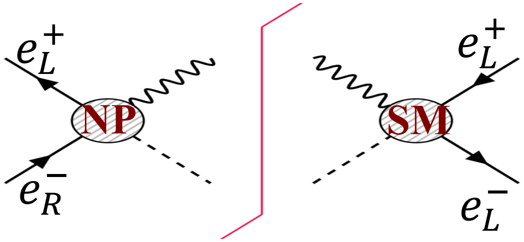
$\mathcal{O}(1/\Lambda^4)$ leading effect



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

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

➡ Only small non-interfering effect with $\left|\frac{c_{dipole}}{\Lambda^2}\right|^2$

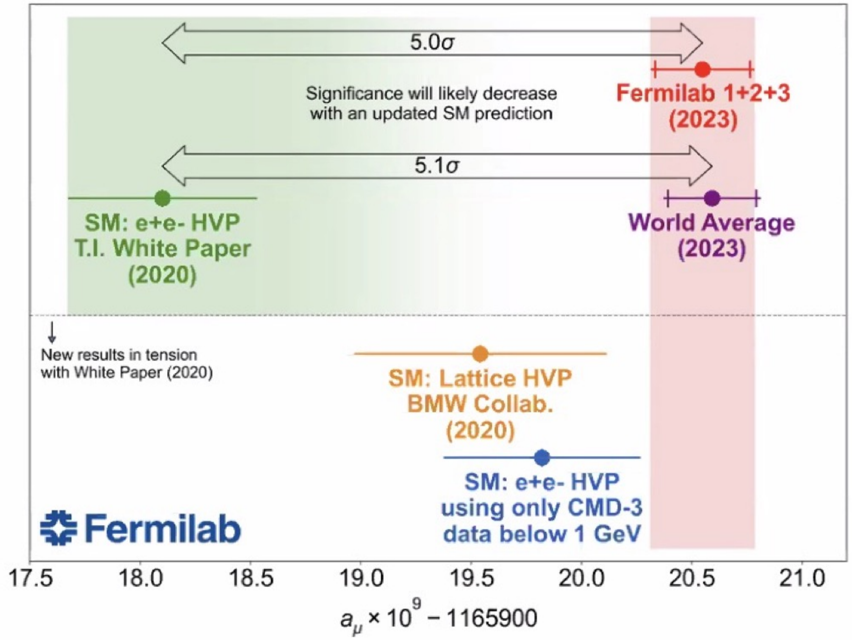


$\mathcal{O}(1/\Lambda^2)$
~0 for tiny mass
in dipole case

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

New Physics with Dipole Operator

E/M Dipole Moment
Direct & Dominant Effect



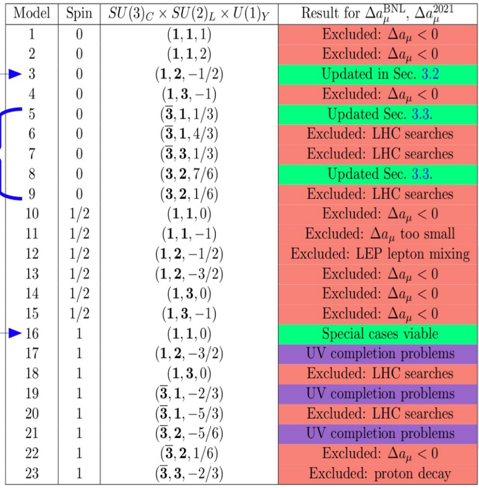
Loop-induced by the BSM
Indirect probes of quantum effects of NP

Minimal models for muon g-2: 1 field extensions

2HDM

Scalar leptoquarks

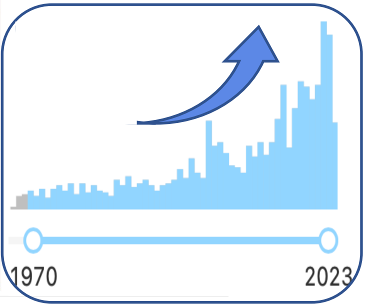
Dark photon



Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result for $\Delta a_\mu^{\mathrm{BNL}}$, Δa_μ^{2021}
1	0	$(\mathbf{1}, \mathbf{1}, 1)$	Excluded: $\Delta a_\mu < 0$
2	0	$(\mathbf{1}, \mathbf{1}, 2)$	Excluded: $\Delta a_\mu < 0$
3	0	$(\mathbf{1}, \mathbf{2}, -1/2)$	Updated in Sec. 3.2
4	0	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
5	0	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	Updated Sec. 3.3.
6	0	$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	Excluded: LHC searches
7	0	$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	Excluded: LHC searches
8	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	Updated Sec. 3.3.
9	0	$(\mathbf{3}, \mathbf{2}, 1/6)$	Excluded: LHC searches
10	1/2	$(\mathbf{1}, \mathbf{1}, 0)$	Excluded: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1}, \mathbf{1}, -1)$	Excluded: Δa_μ too small
12	1/2	$(\mathbf{1}, \mathbf{2}, -1/2)$	Excluded: LEP lepton mixing
13	1/2	$(\mathbf{1}, \mathbf{2}, -3/2)$	Excluded: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
16	1	$(\mathbf{1}, \mathbf{1}, 0)$	Special cases viable
17	1	$(\mathbf{1}, \mathbf{2}, -3/2)$	UV completion problems
18	1	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: LHC searches
19	1	$(\overline{\mathbf{3}}, \mathbf{1}, -2/3)$	UV completion problems
20	1	$(\overline{\mathbf{3}}, \mathbf{1}, -5/3)$	Excluded: LHC searches
21	1	$(\overline{\mathbf{3}}, \mathbf{2}, -5/6)$	UV completion problems
22	1	$(\overline{\mathbf{3}}, \mathbf{2}, 1/6)$	Excluded: $\Delta a_\mu < 0$
23	1	$(\overline{\mathbf{3}}, \mathbf{3}, -2/3)$	Excluded: proton decay

EXCLUDED

From:
JHEP 09 (2021) 080,
[PA, C.Balázs, D.H.J. Jacob,
W. Kotlarski, D. Stöckinger,
H. Stöckinger-Kim]



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 $1/\Lambda^2$

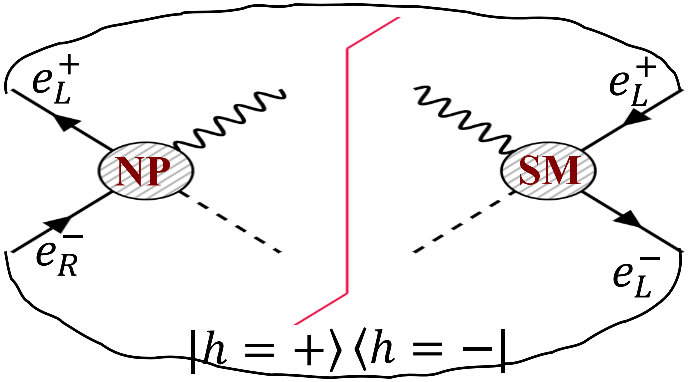
Traditional method via cross-section and width only leading @ $\left|C_{dipole}\right|^2/\Lambda^4$ and suffer from assumptions

Our proposal:

✓ Transverse polarization effect of beams

(Interference between the different helicity states)

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



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

✓ 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

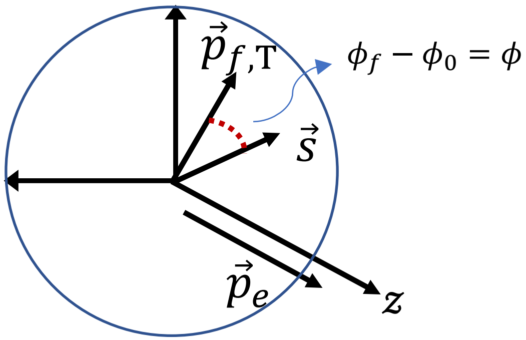
In a word, transverse polarization effect triggers interference of helicity amplitudes and breaks the rotational invariance to induce nontrivial azimuthal behavior.

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



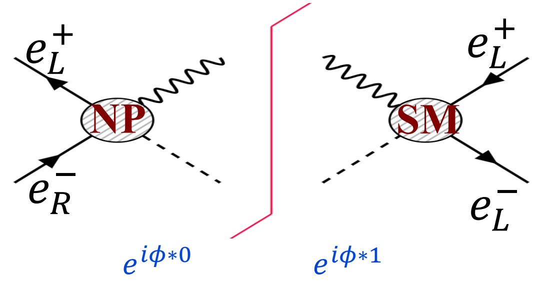
Spin dependent amplitude square:

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

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

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

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



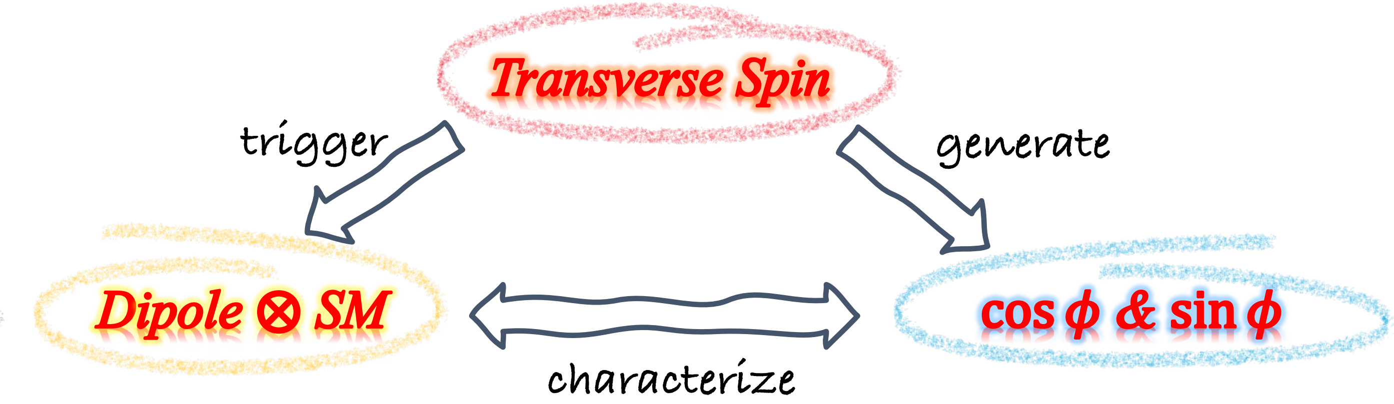
dipole operator → $\mathcal{M}_{\pm\pm}$, massless SM → $\mathcal{M}_{\pm\mp}$

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

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



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

Re[C_{dipole}]

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

CP-conserving

Im[C_{dipole}]

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

CP-violation

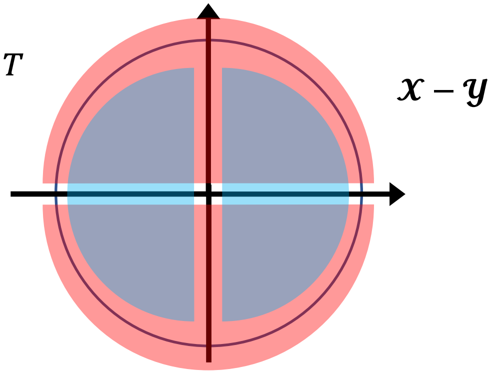
SM & other NP

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

Linearly dependent on the dipole couplings C_{dipole} 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

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

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

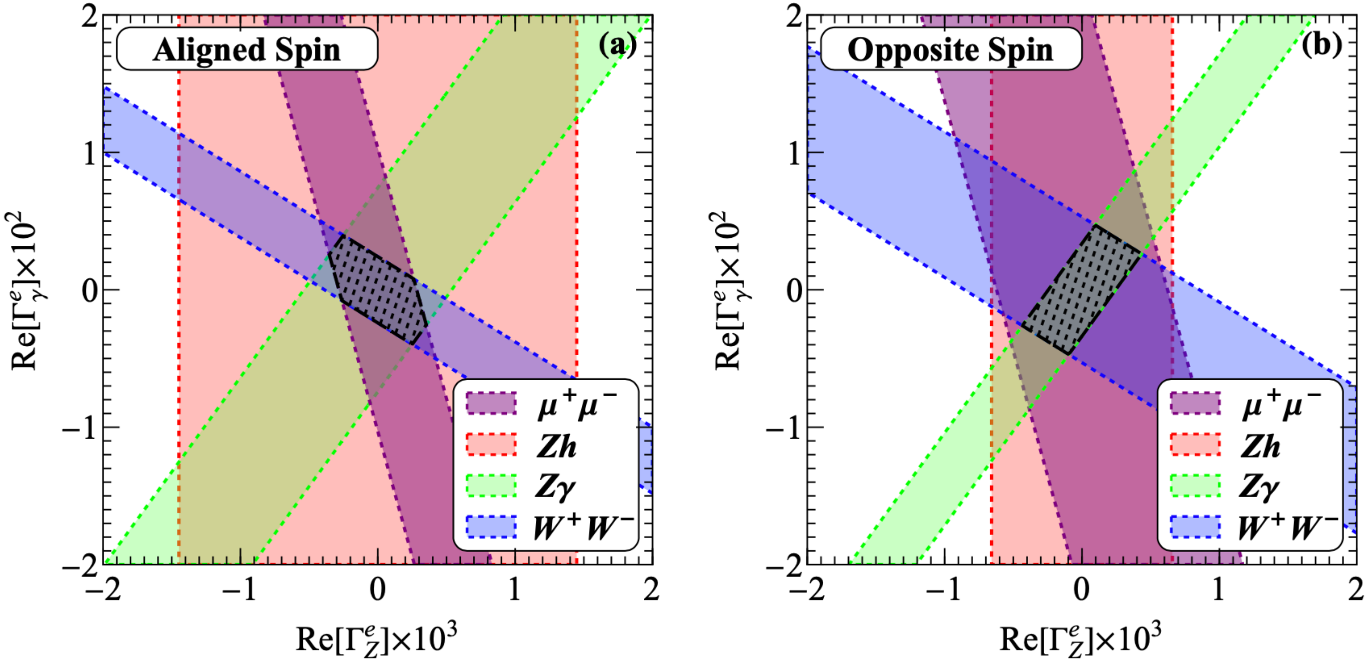
Aligned Spin

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

Opposite Spin

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

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



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

$$\Gamma^e_Z = c^2_W\Gamma^e_W + s^2_W\Gamma^e_B$$

Single spin is enough!!

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

CP property

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

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

→

$$A^{\mu\mu}_R \propto \boldsymbol{s}_T + \bar{\boldsymbol{s}}_T$$

$$A^{Z\gamma}_R \propto \boldsymbol{s}_T - \bar{\boldsymbol{s}}_T$$

Pinning down Dipole Operators

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

Aligned Spin

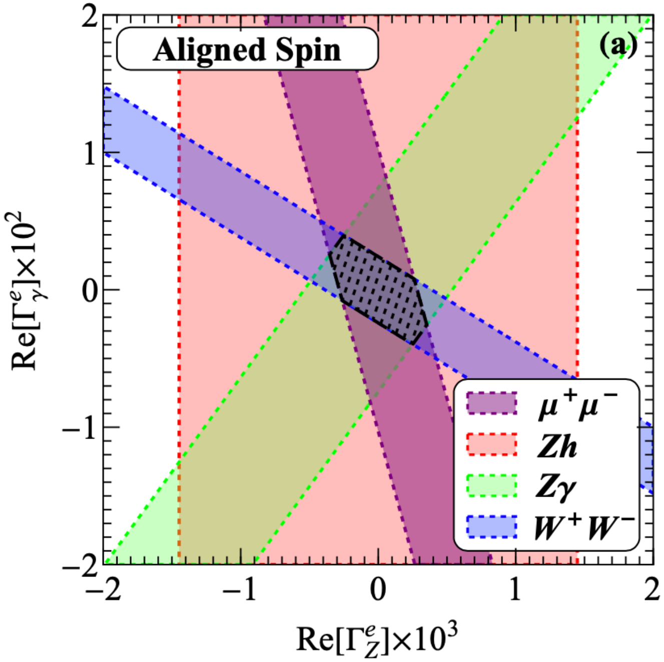
$$\phi_0 = \bar{\phi}_0 = 0$$

Opposite Spin

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

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

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



$$A_{R\backslash I}(\Gamma^e_\gamma) < A_{R\backslash I}(\Gamma^e_Z)$$

Parity property

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

$$|\mathcal{M}|^2_{1\phi} \sim (g_L - g_R)[(g^e_L + g^e_R)\Gamma^e_\gamma + \Gamma^e_Z]$$

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

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

Pinning down Dipole Operators

For the imaginary parts of dipole couplings, things are similar

Aligned Spin

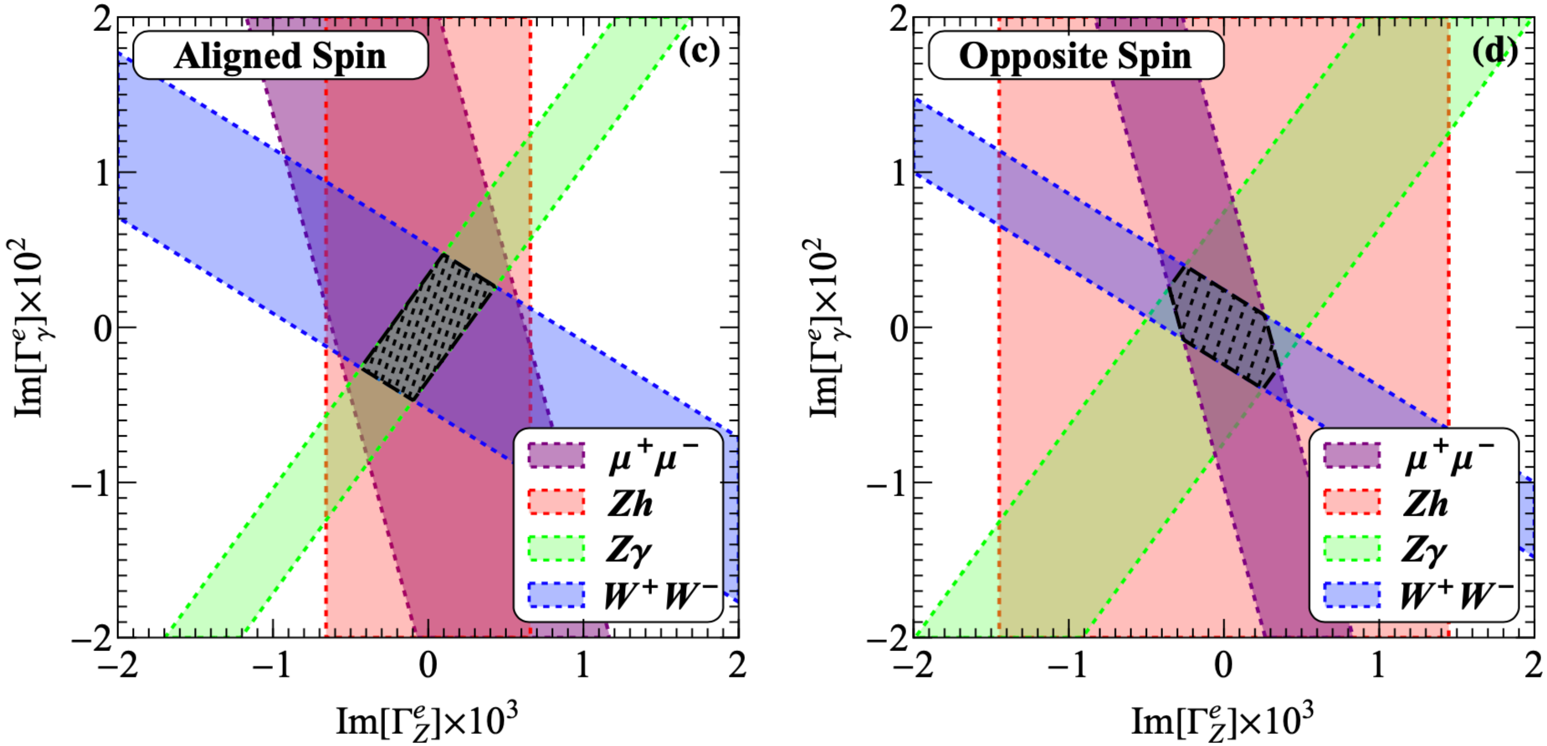
$$\phi_0 = \bar{\phi}_0 = 0$$

Opposite Spin

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

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

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



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%~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**

➢ DSA@Transversely Polarized DIS ➢ See Hao-Lin's talk

	$\lvert\Gamma_Z^e\rvert$	$\lvert\Gamma_\gamma^e\rvert$
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}

Thank you