ECFA HTE mini-workshop on e+e- physics at 240-350 GeV
CERN, Sept. 25th, 2023

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

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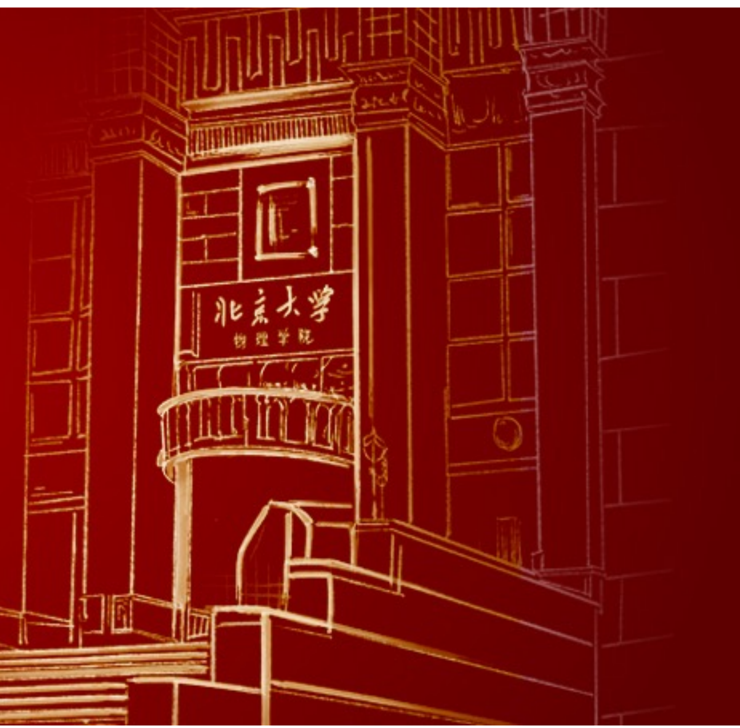
In collaboration with Bin Yan, Zhite Yu and C.-P. Yuan
Basing on arXiv: 2307.05236 and works in progress



Thanks a lot to the organizers of ECFA-HTE group

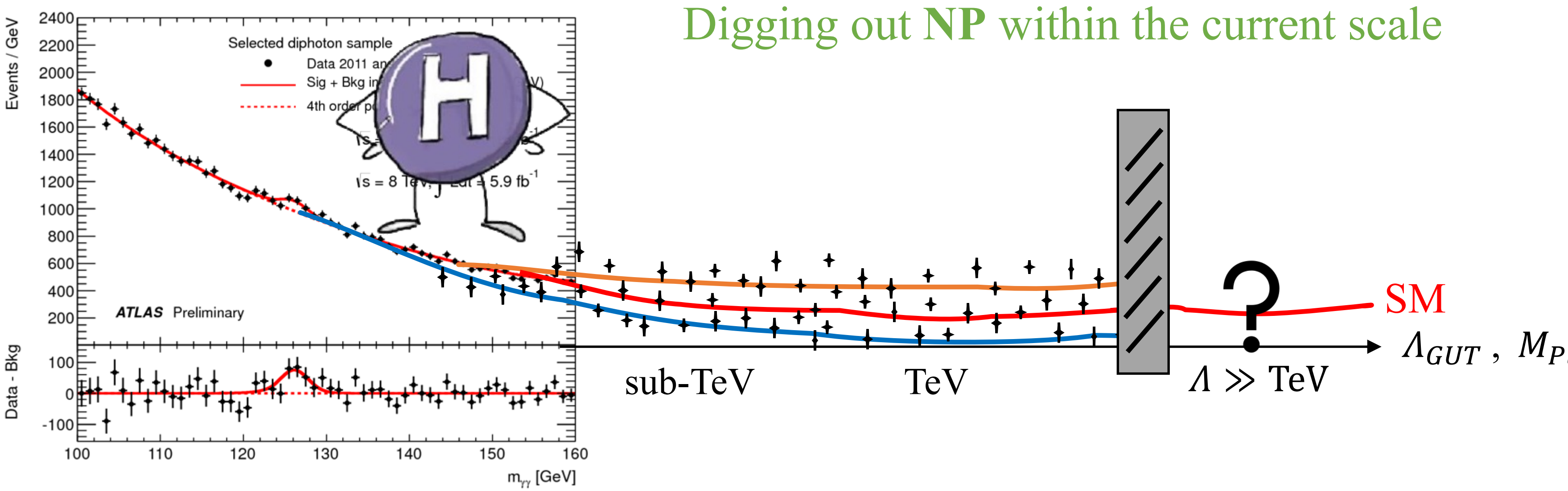
Remote online, CERN
2023/09/25

New Physics and SMEFT

We need new physics and new measurements to answer open questions:

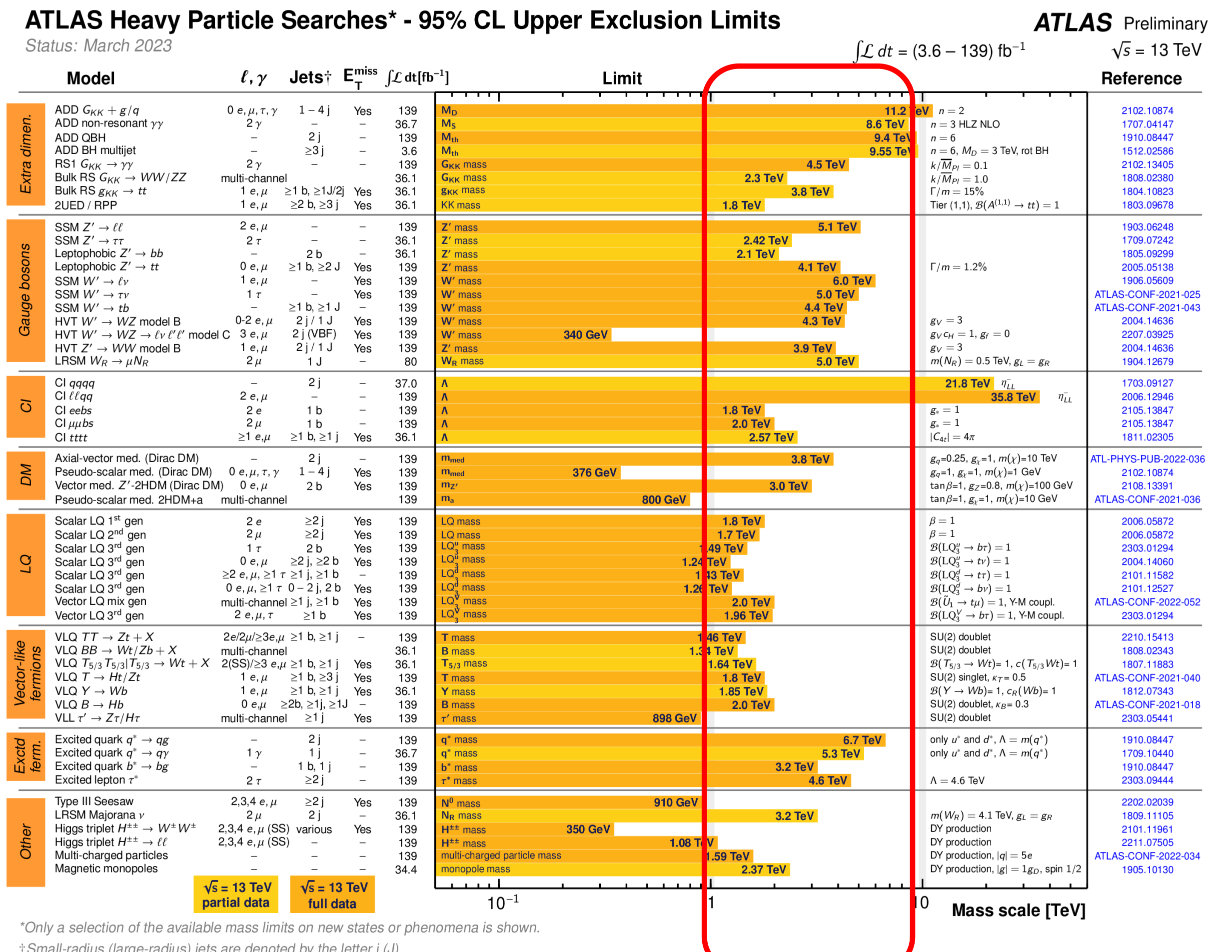
1. What is Dark Matter ?
2. What is the origin of the neutrino mass?
3. What is the source of matter-antimatter asymmetry?
4. What is the nature of the electroweak symmetry breaking?
5. What is the nature of the Higgs boson (Composite or elementary particle)?
6. ....

None new fundamental resonance since 2012 but anomalies bursting → NP



New Physics and SMEFT

None new fundamental resonance has been discovered.

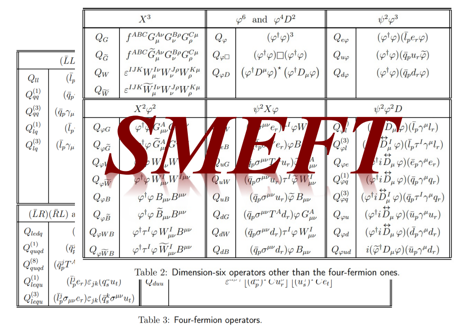


EWPO

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

Global Fitting

F. Maltoni et al., SMEFiT, 2021
P. Athron et al., GAMBIT, 2017
J.Y. Gu, Y. Du et al., 2022



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

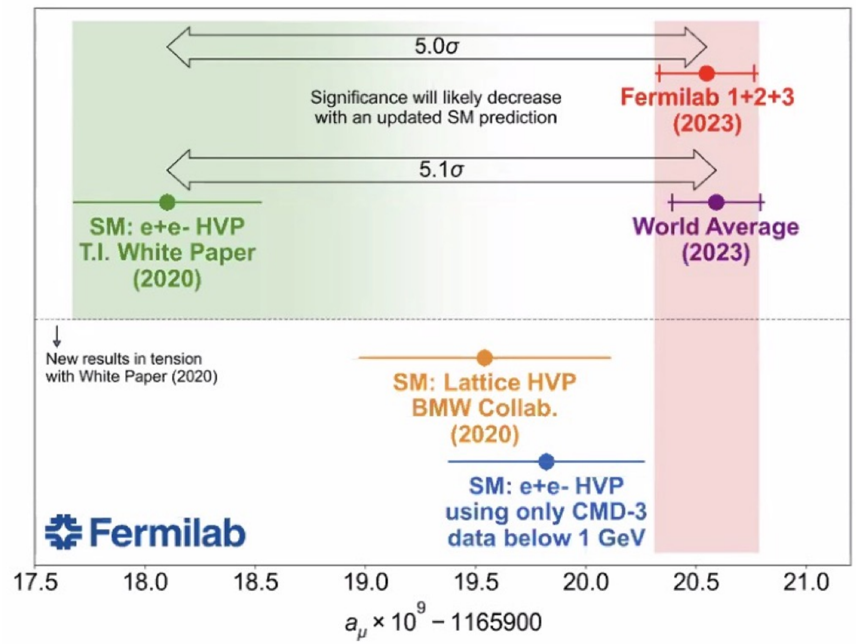
Powerful Tool @EW

$\{G, P\}_{SM}$, linear rep. H…

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

Dipole Operator

E/M Dipole Moment
Direct & Dominant Effect



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

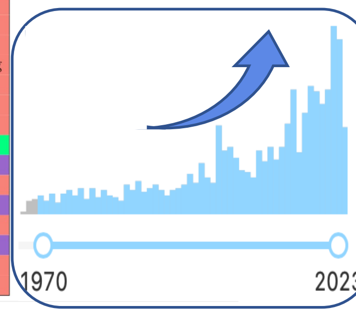
Minimal models for muon g-2: 1 field extensions

2HDM → 3; Scalar leptoquarks: 5–9; Dark photon → 16

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result for $\Delta a_\mu^{\rm BNL}$, 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……

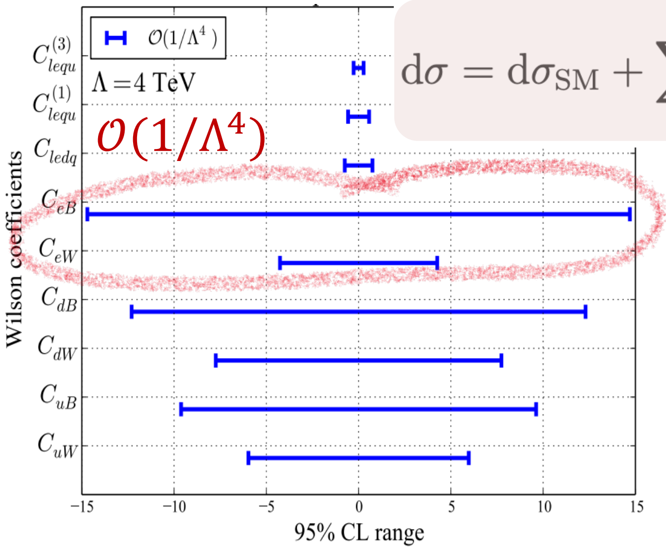
Peter Athron et al., *JHEP* 09 (2021) 080

May have same physics source
but *Z* only detected by colliders

Data for Dipole Operator

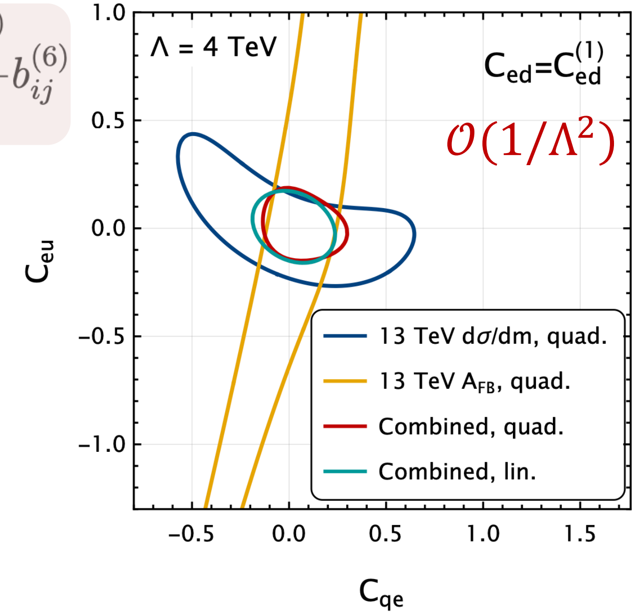
EW dipole couplings constrained poorly in traditional method via cross-section and width

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



Single-Parameter-Analysis @LHC

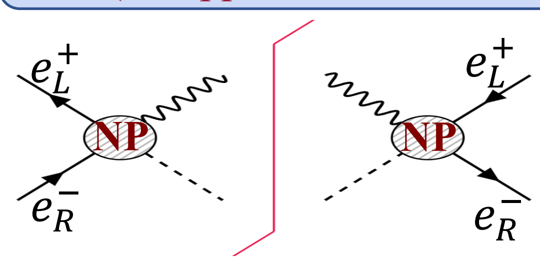
(R. Boughezal et al. *Phys.Rev.D* 104 (2021)…)



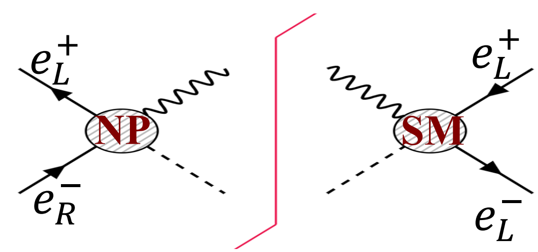
(R. Boughezal et al. *arXiv:* 2303.08257)

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

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



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



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

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

Our proposal:

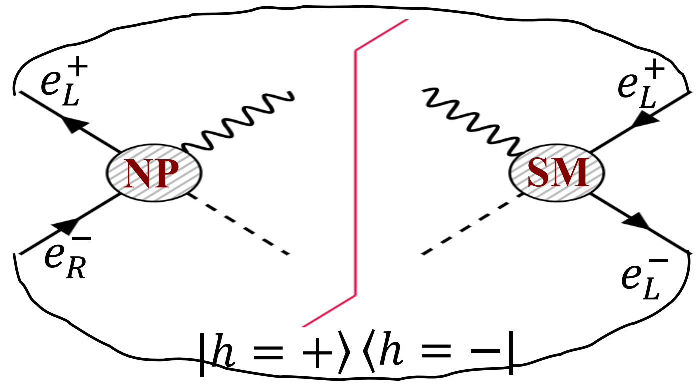
✓ Transverse polarization effect of beams

(Interference between the different helicity states)

✓ 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

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

Transverse polarization effect → Interference of helicity amplitudes

Breaking the rotational invariance → A nontrivial azimuthal behavior

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

Transverse Spin Polarization

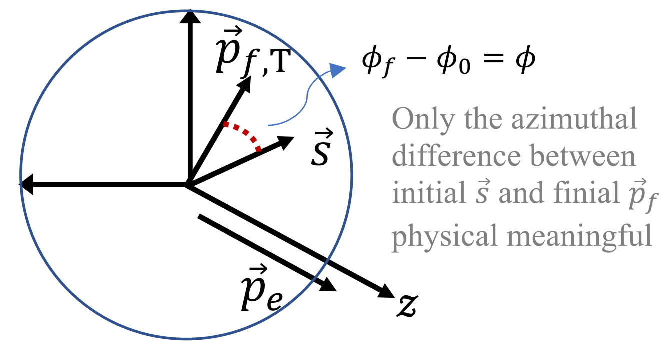
Spin dependent amplitude square:

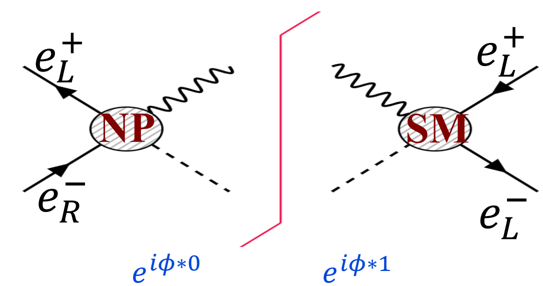
$$|\mathcal{M}|^2 = \rho_{\alpha_1\alpha_1'}(\boldsymbol{s})\rho_{\alpha_2\alpha_2'}(\bar{\boldsymbol{s}})\mathcal{M}_{\alpha_1\alpha_2}(\phi)\mathcal{M}^*_{\alpha_1'\alpha_2'}(\phi)$$

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

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

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





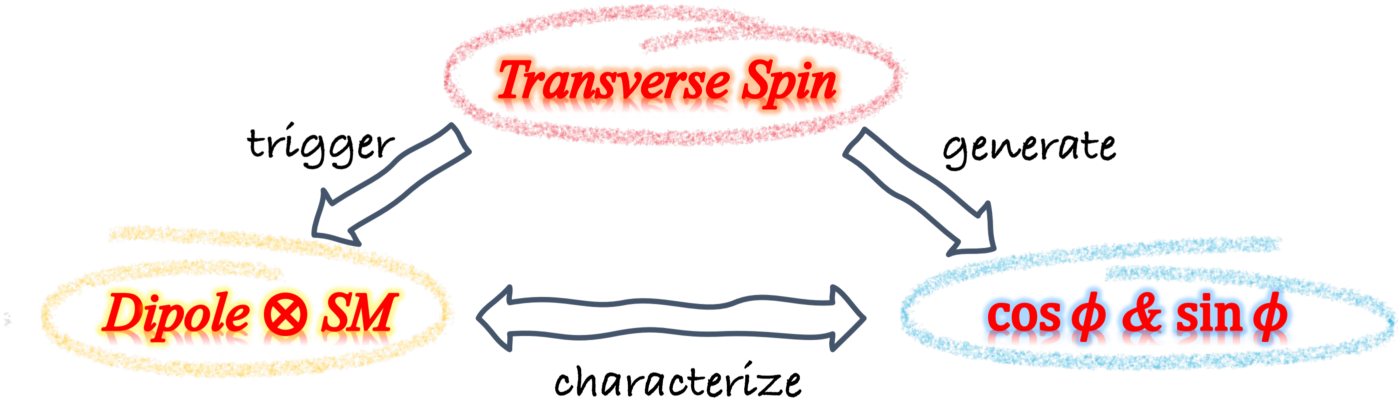
dipole operator → $\mathcal{M}_{\pm\pm}$, massless SM → $\mathcal{M}_{\pm\mp}$

	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



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

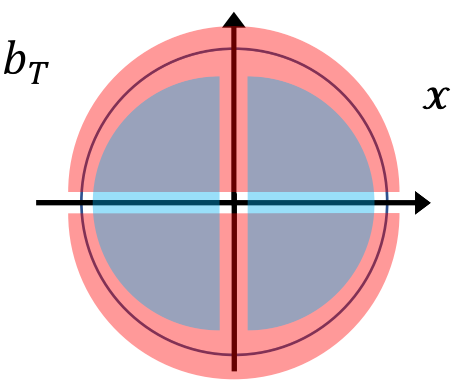
$A_R^i(b_T, \bar{b}_T)$	$A_I^i(b_T, \bar{b}_T)$	$b_T\,\bar{b}_T\,B^i$
$\mathrm{Re}[C_{dipole}]$	$\mathrm{Im}[C_{dipole}]$	SM & other NP
$\vec{s}\cdot\vec{p}_f \propto \cos\phi$	$\vec{s}\times\vec{p}_f \propto \sin\phi$	
CP-conserving	CP-violation	

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

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

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

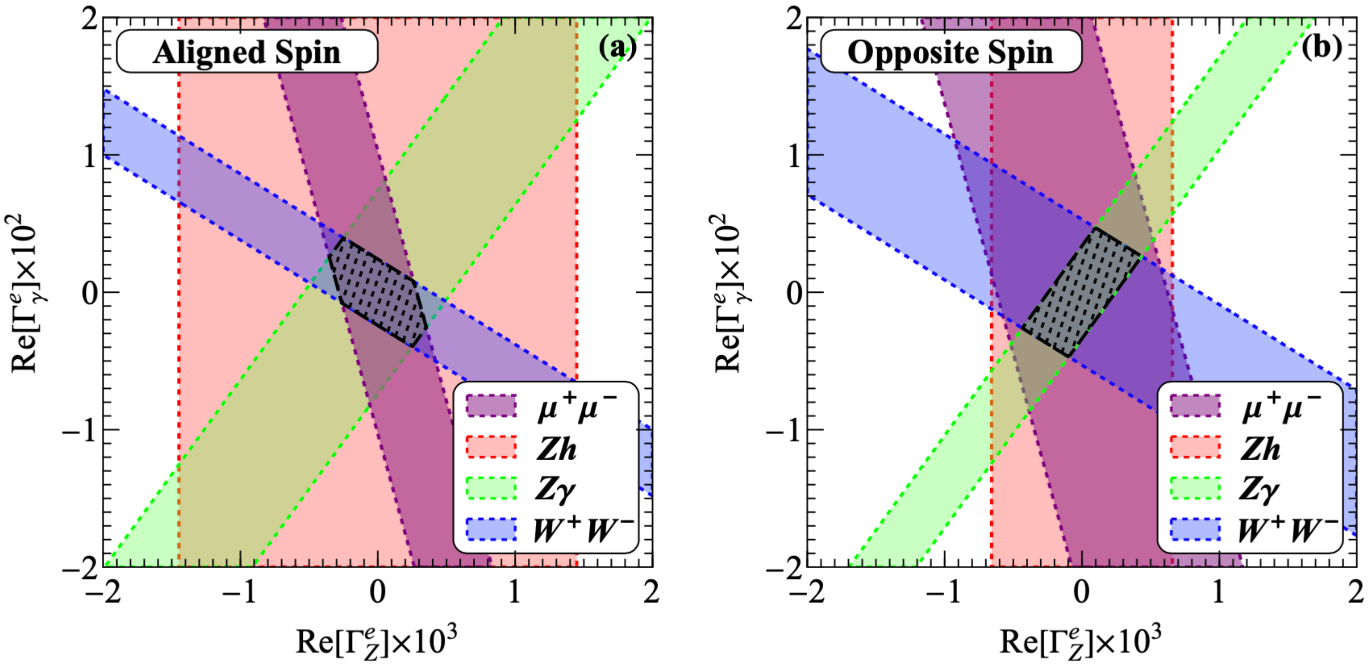
Aligned Spin

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

Opposite Spin

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

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



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

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

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

CP property

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

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

→

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

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

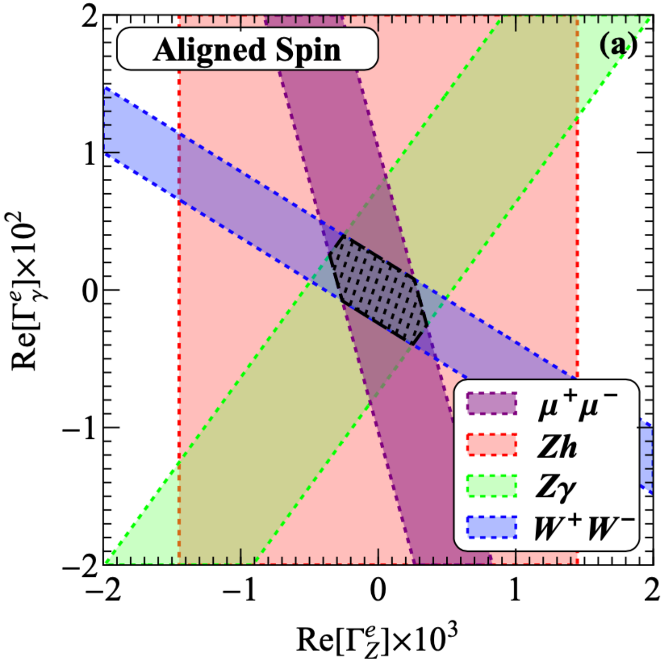
Pinning down Dipole Operators

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

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

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



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

Parity property

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

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

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

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

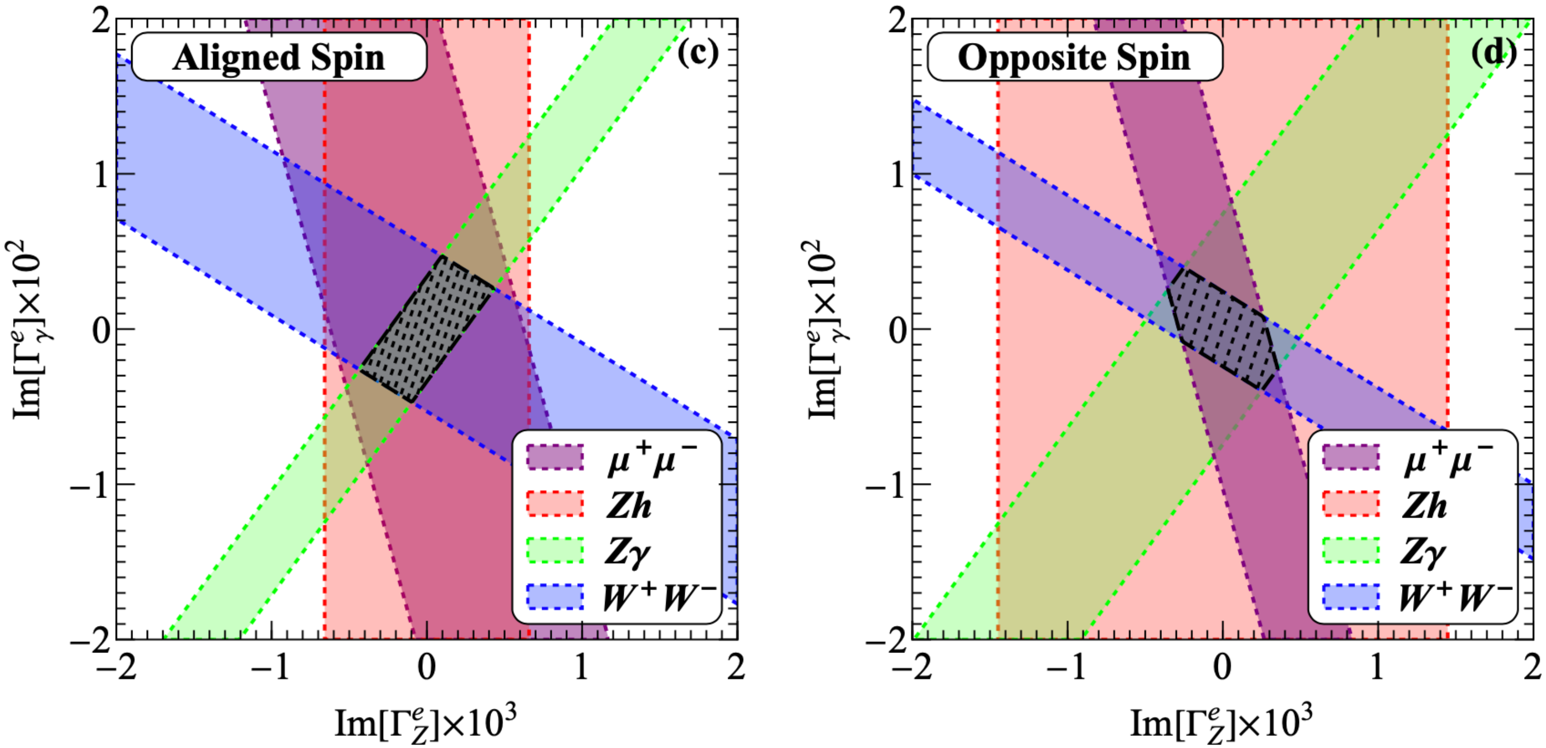
Pinning down Dipole Operators

For the imaginary parts of dipole couplings, things are similar

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

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

$\sqrt{s} = 250$ 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

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

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

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

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

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

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

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

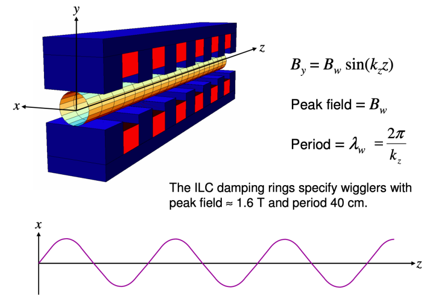
$$T_{-\lambda_a,-\lambda_b,-\lambda_c,-\lambda_d}(\theta) = \eta\cdot(-1)^{\lambda-\mu}\cdot T_{\lambda_a,\lambda_b,\lambda_c,\lambda_d}(\theta)$$

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

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

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

Backup: 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.

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