

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

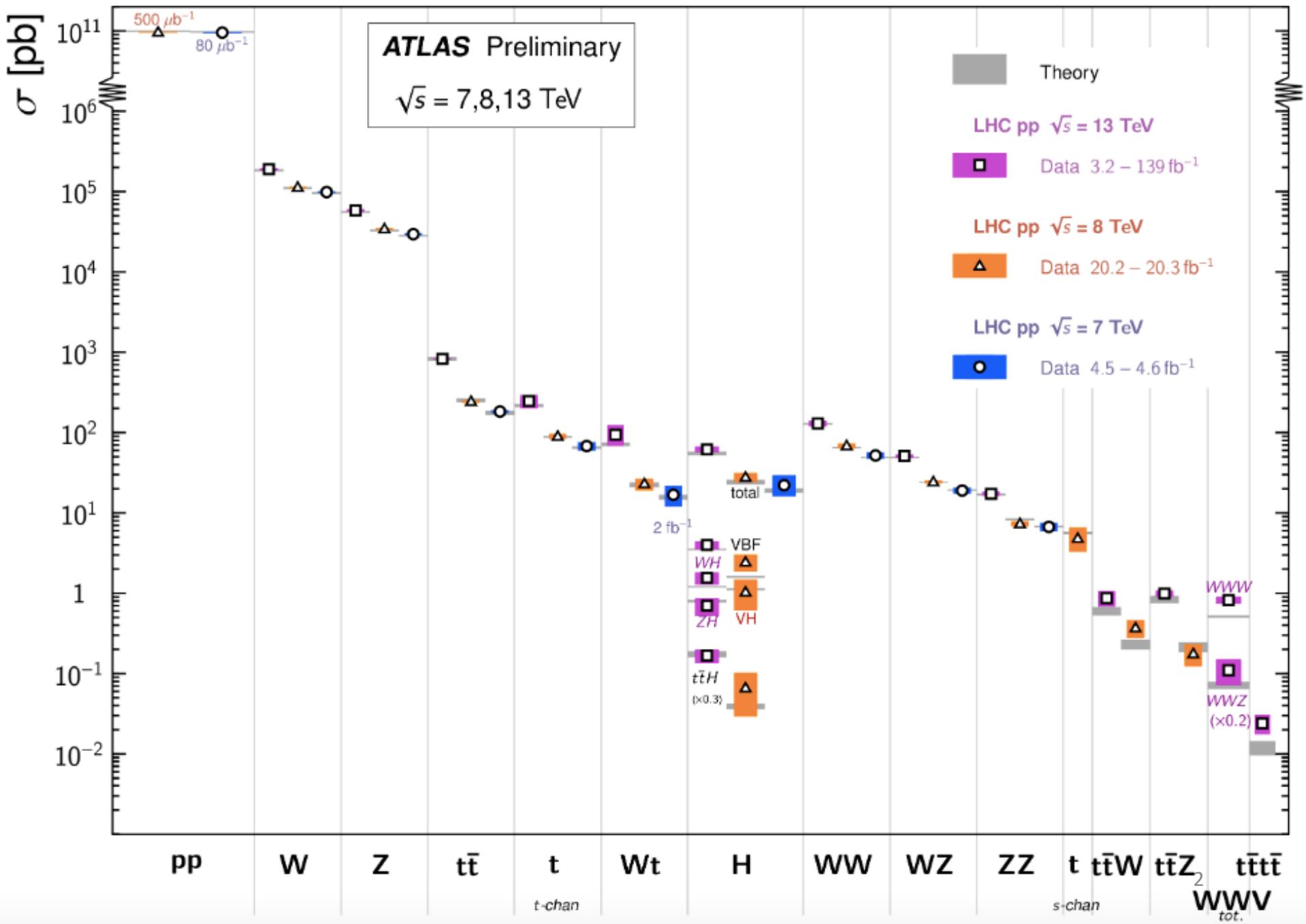
Bin Yan
Institute of High Energy Physics

CEPC 2023 @ Nanjing
Oct. 23-27, 2023

In cooperation with Xin-Kai Wen, Zhite Yu, C.-P. Yuan, arXiv: 2307.05236

Standard Model Total Production Cross Section Measurements

Status: February 2022



Why we need the New Physics

Some open questions:

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

New Physics Models and new measurements to answer these questions

New Physics Searches @ LHC

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

Status: March 2023

ATLAS Preliminary

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

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

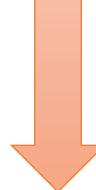
Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimen.						
ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1 – 4 j	Yes	139	M_D 11.2 TeV	2102.10874
ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	1707.04147
ADD QBH	–	2 j	–	139	M_{bh} 9.4 TeV	1910.08447
ADD BH multijet	–	$\geq 3 j$	–	3.6	M_{bh} 9.55 TeV	1512.02586
RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	139	G_{KK} mass 4.5 TeV	2102.13405
Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	–	–	36.1	G_{KK} mass 2.3 TeV	1808.02380
Bulk RS $g_{KK} \rightarrow tt$	1 e, μ	$\geq 1 b, \geq 1 J[2]$	Yes	36.1	B_{KK} mass 3.8 TeV	1804.10823
ZUED / RPP	1 e, μ	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV	1803.09678
Gauge bosons						
SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV	1903.06248
SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV	1709.07242
Lepto-phobic $Z' \rightarrow bb$	–	2 b	–	36.1	Z' mass 2.1 TeV	1805.09299
Lepto-phobic $Z' \rightarrow tt$	0 e, μ	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass 4.1 TeV	2005.05138
SSM $W' \rightarrow \ell\nu$	1 e, μ	–	–	139	W' mass 6.0 TeV	1906.05609
SSM $W' \rightarrow \tau\nu$	1 τ	–	–	139	W' mass 5.0 TeV	ATLAS-CONF-2021-025
SSM $W' \rightarrow tb$	–	$\geq 1 b, \geq 1 J$	–	139	W' mass 4.4 TeV	ATLAS-CONF-2021-043
HVT $W' \rightarrow WZ$ model B	0-2 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	2004.14636
HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell''$ model C	3 e, μ	2 j (VBF)	Yes	139	340 GeV	2207.03925
HVT $Z' \rightarrow WW$ model B	1 e, μ	2 j / 1 J	Yes	139	Z' mass 3.9 TeV	2004.14636
LRSM $W_R \rightarrow \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	1904.12679
C1						
C1 $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	1703.09127
C1 $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	2006.12946
C1 $eebs$	2 e	1 b	–	139	Λ 1.8 TeV	2105.13847
C1 $\mu\mu bs$	2 μ	1 b	–	139	Λ 2.0 TeV	2105.13847
C1 $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Λ 2.57 TeV	1811.02305
DM						
Axial-vector med. (Dirac DM)	–	2 j	–	139	m_{med} 3.8 TeV	ATL-PHYS-2022-036
Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med} 376 GeV	2102.10874
Vector med. Z' -2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	$m_{Z'}$ 3.0 TeV	2108.13391
Pseudo-scalar med. 2HDM+a	multi-channel	–	–	139	m_a 800 GeV	ATLAS-CONF-2021-036
LQ						
Scalar LQ 1 st gen	2 e	$\geq 2 j$	Yes	139	LO mass 1.8 TeV	2006.05872
Scalar LQ 2 nd gen	2 μ	$\geq 2 j$	Yes	139	LO mass 1.7 TeV	2006.05872
Scalar LQ 3 rd gen	1 τ	2 b	Yes	139	LO_3 mass 1.49 TeV	2303.01294
Scalar LQ 3 rd gen	0 e, μ	$\geq 2 j, \geq 2 b$	Yes	139	LO_3 mass 1.24 TeV	2004.14060
Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau$	$\geq 1 j, \geq 1 b$	–	139	LO_3 mass 1.43 TeV	2101.11582
Scalar LQ 3 rd gen	0 e, $\mu, \geq 1 \tau$	0 – 2 j, 2 b	Yes	139	LO_3 mass 1.26 TeV	2101.12527
Vector LQ mix gen	multi-channel	$\geq 1 j, \geq 1 b$	Yes	139	LO_3^ψ mass 2.0 TeV	ATLAS-CONF-2022-052
Vector LQ 3 rd gen	2 e, μ, τ	$\geq 1 b$	Yes	139	LO_3^ψ mass 1.96 TeV	2303.01294
Vector-like fermions						
VLO $TT \rightarrow Zt + X$	2 e/2 $\mu/2\tau, \mu$	$\geq 1 b, \geq 1 j$	–	139	T mass 1.46 TeV	2210.15413
VLO $BB \rightarrow Wt/Zb + X$	multi-channel	–	–	36.1	B mass 1.34 TeV	1808.02343
VLO $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	(SS) $\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	1807.11883
VLO $T \rightarrow Ht/Zt$	1 e, μ	$\geq 1 b, \geq 3 j$	Yes	139	T mass 1.6 TeV	ATLAS-CONF-2021-040
VLO $Y \rightarrow Wb$	1 e, μ	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV	1812.07343
VLO $B \rightarrow Hb$	0 e, μ	$\geq 2 b, \geq 1 j, \geq 1 J$	–	139	B mass 2.0 TeV	ATLAS-CONF-2021-018
VLL $\tau' \rightarrow Zt/Ht$	multi-channel	$\geq 1 j$	Yes	139	r' mass 898 GeV	2303.05441
Exotic ferm.						
Excited quark $q^* \rightarrow qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^* , $\Lambda = m(q^*)$
Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	1910.08447
Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	139	b^* mass 3.2 TeV	1709.10440
Excited lepton τ^*	2 τ	$\geq 2 j$	–	139	τ^* mass 4.6 TeV	1910.08447
Other						
Type III Seesaw	2,3,4 e, μ	$\geq 2 j$	Yes	139	N^0 mass 910 GeV	2202.02039
LRSM Majorana v	2 μ	2 j	–	36.1	N_ν mass 3.2 TeV	1809.11105
Higgs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	2101.11961
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV	2211.07055
Multi-charged particles	–	–	–	139	multi-charged particle mass 1.59 TeV	ATLAS-CONF-2022-034
Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	1905.10130

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

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

Mass scale [TeV]

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



SMEFT

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

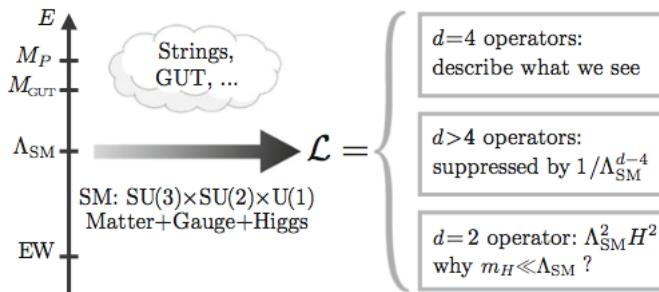
†Small-radius (large-radius) jets are denoted by the letter j (J).

New Physics and SMEFT

Linear realized EFT



Higgs is a fundamental particle
Weak interacting



W. Buchuller, D. wyler 1986

B. Grzadkowski et al, 2010

L. Lehman, A. Marin, 2015

B. Henning et al, 2015

H-L. Li et al, 2020

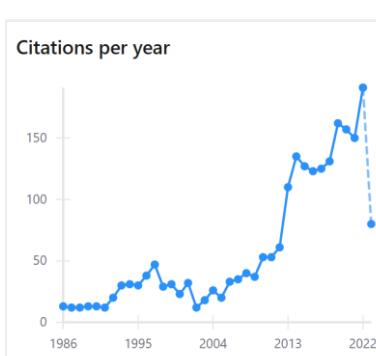
.....

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

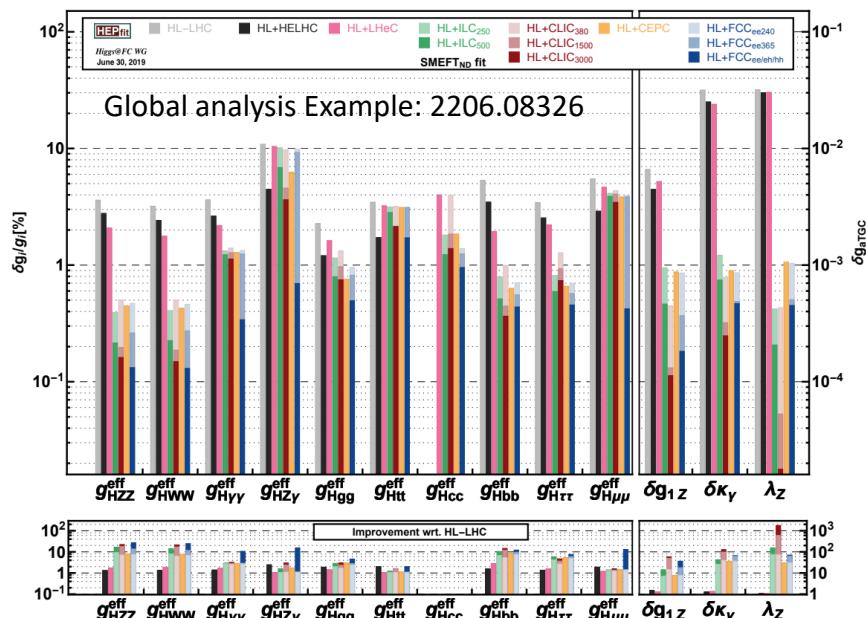
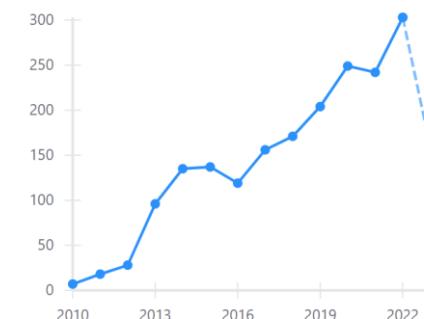
SMEFT Analysis:

W. Buchuller, D. wyler 1986

B. Grzadkowski et al, 2010

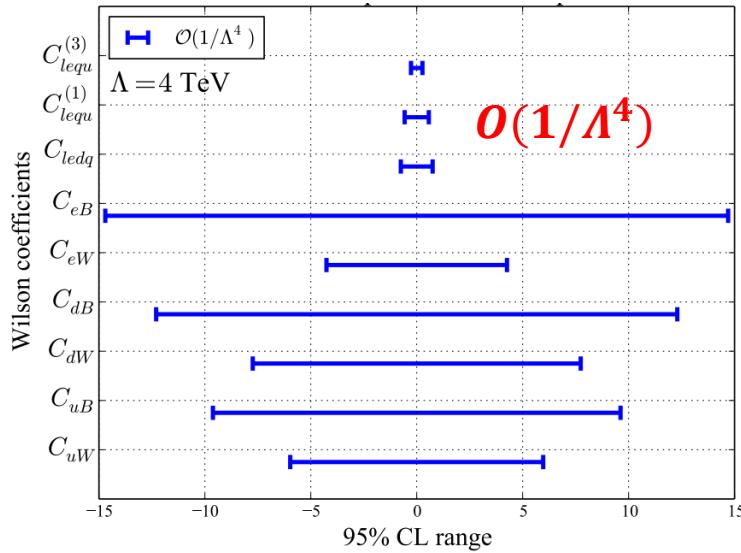


Citations per year

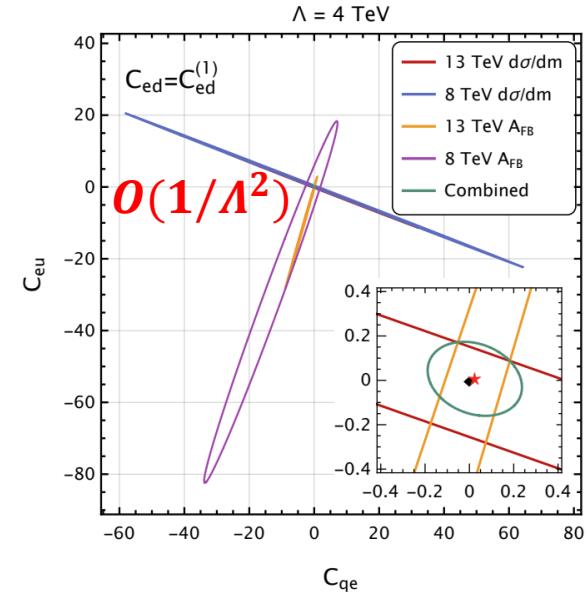


Data for Dipole Operator

Single-Parameter-Analysis: EW dipole couplings constrained very poorly

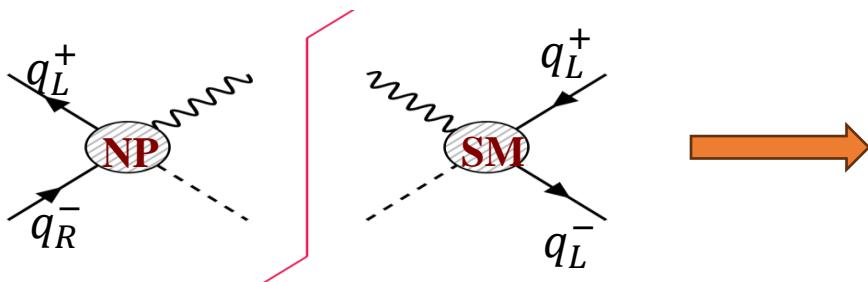


R. Boughezal et al. *Phys.Rev.D* 104 (2021) 9, 095022



R. Boughezal et al, 2303.08257

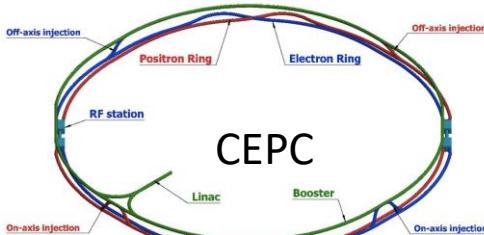
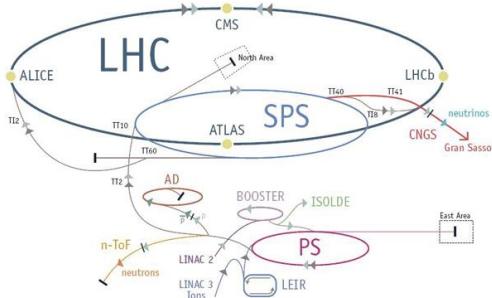
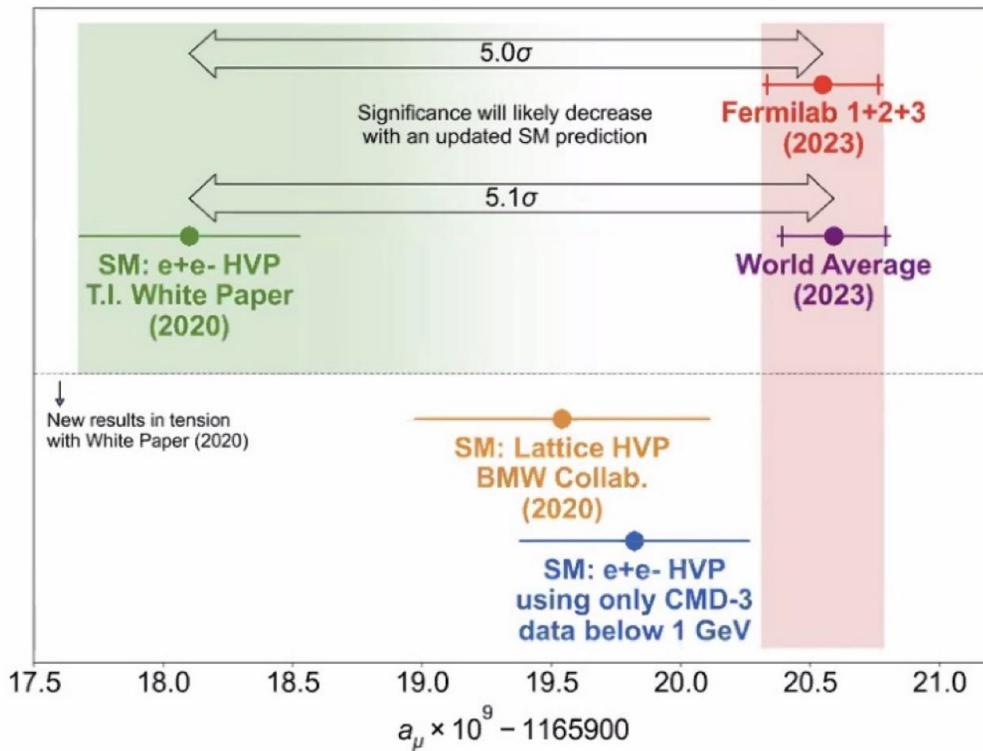
The interfering effect between the SM and Dipole operators can be ignored



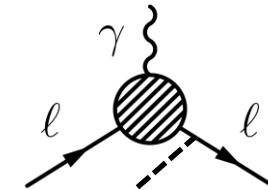
=0 for the cross section

Leading contribution: $\left| \frac{c_{dipole}}{\Lambda^2} \right|^2$

New Physics and Dipole Operator

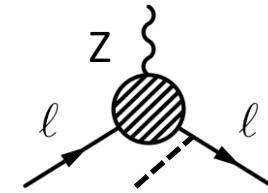


Loop-induced by the BSM



May have same physics source

$$B_{\mu\nu}, W_{\mu\nu}$$

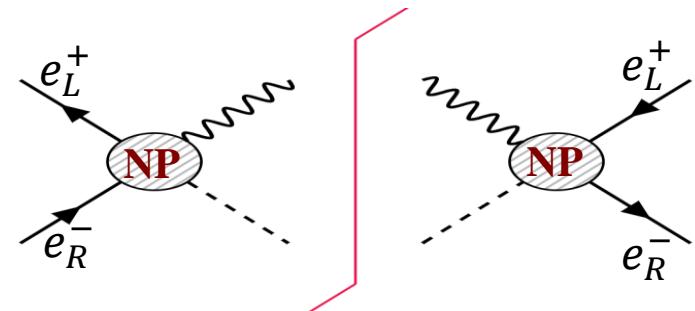


How to probe the electroweak dipole operators?

How to Probe Dipole Operator

Traditional method via cross section and width

- The leading effect is from $|C_{dipole}|^2/\Lambda^4$
- Bothered by other operators and assumptions
(Interference with SM)



Is it possible to probe the dipole operators at $\mathcal{O}\left(\frac{1}{\Lambda^2}\right)$?

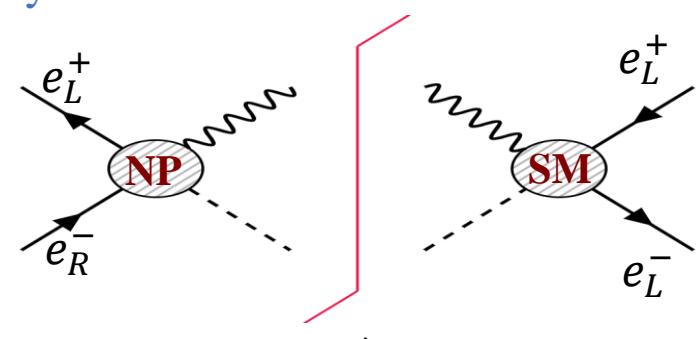
→ Transverse polarization effect of beams:

The interference between the different helicity states

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

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

- ✓ Without depending on other NP operators



Transverse Spin Polarization

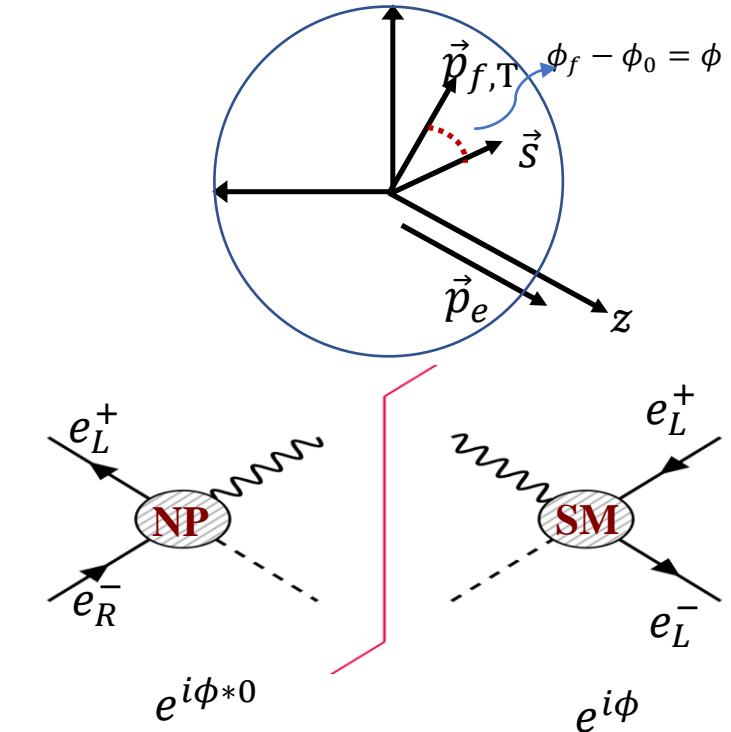
Transverse spin polarization of beams

Breaking the rotational invariance & A nontrivial azimuthal behavior

Spin dependent amplitude square:

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

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



	<i>U</i>	<i>L</i>	<i>T</i>
<i>U</i>	$ \mathcal{M} _{UU}^2 \rightarrow 1$	$ \mathcal{M} _{UL}^2 \rightarrow 1$	$ \mathcal{M} _{UT}^2 \rightarrow \cos \phi, \sin \phi$
<i>L</i>	$ \mathcal{M} _{LU}^2 \rightarrow 1$	$ \mathcal{M} _{LL}^2 \rightarrow 1$	$ \mathcal{M} _{LT}^2 \rightarrow \cos \phi, \sin \phi$
<i>T</i>	$ \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$

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

Single Transverse Spin Asymmetries

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

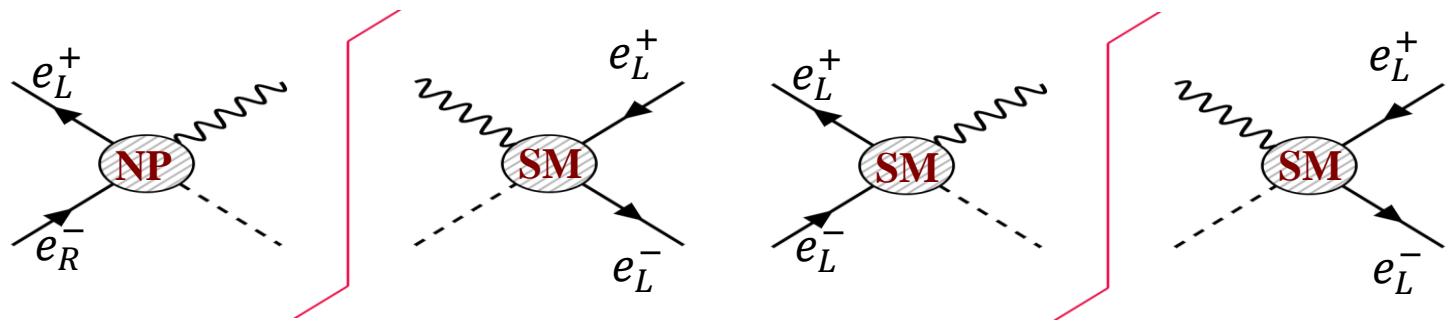
$\overline{\text{Re}[C_{dipole}]}$

$\overline{\text{Im}[C_{dipole}]}$

$\overline{\text{SM \& other NP}}$

CP-conserving

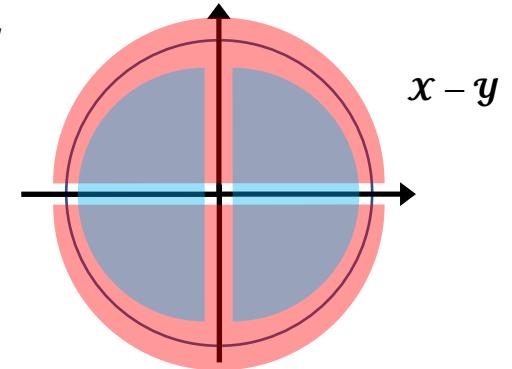
CP-violation



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

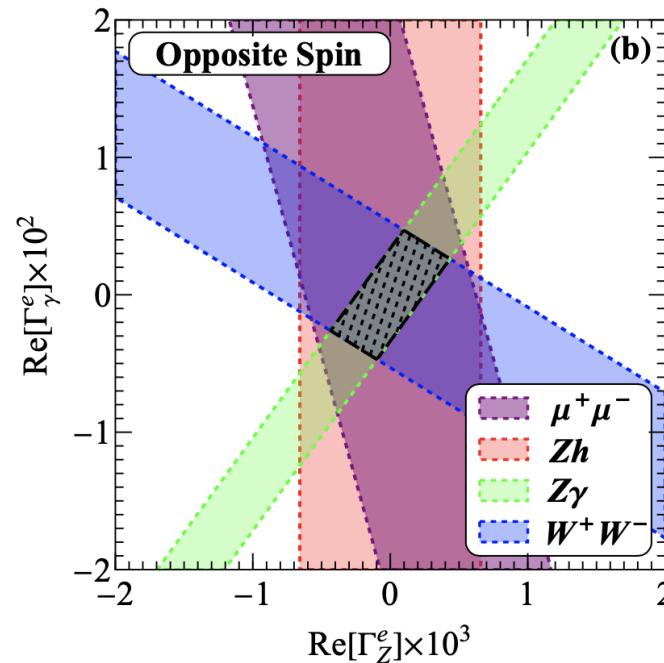
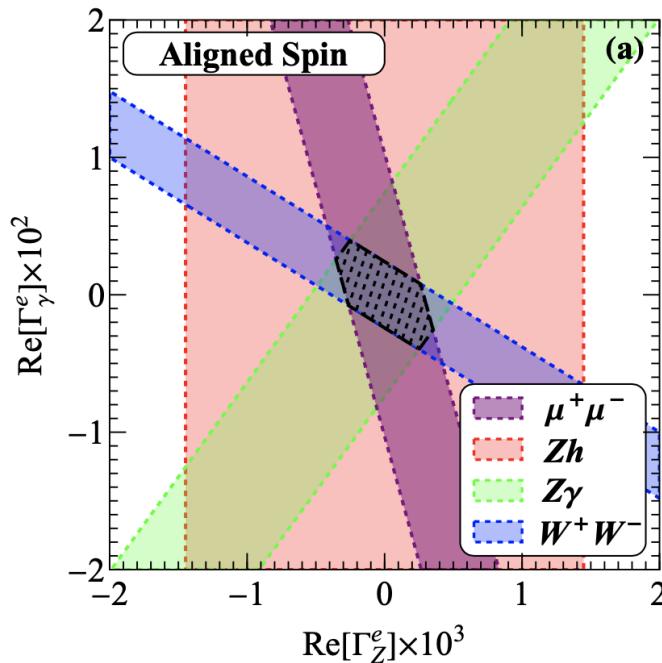
$$\mathcal{L}_{\text{eff}} = -\frac{1}{\sqrt{2}} \bar{\ell}_L \sigma^{\mu\nu} (g_1 \Gamma_B^e B_{\mu\nu} + g_2 \Gamma_W^e \sigma^a W_{\mu\nu}^a) \frac{H}{v^2} e_R + \text{h.c.}$$

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

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

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

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

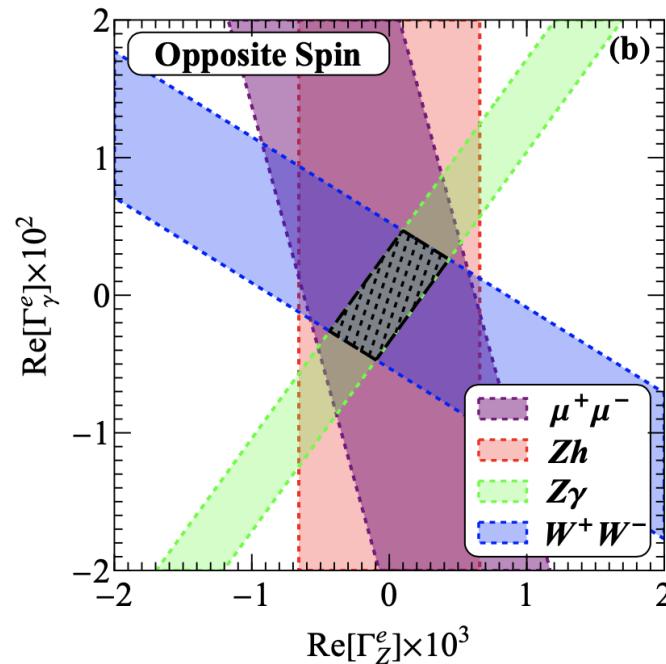
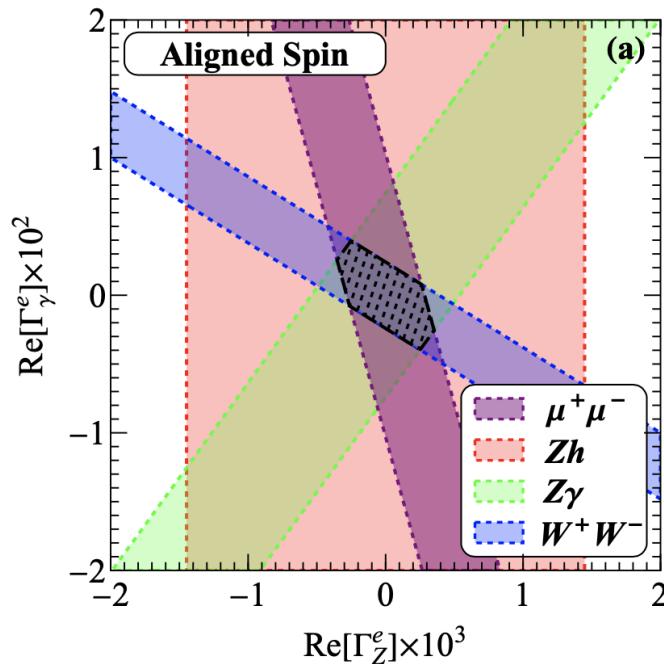


Why the limit from the Aligned Spin would be stronger than the Opposite Spin?

Pinning down Dipole Operators

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

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



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

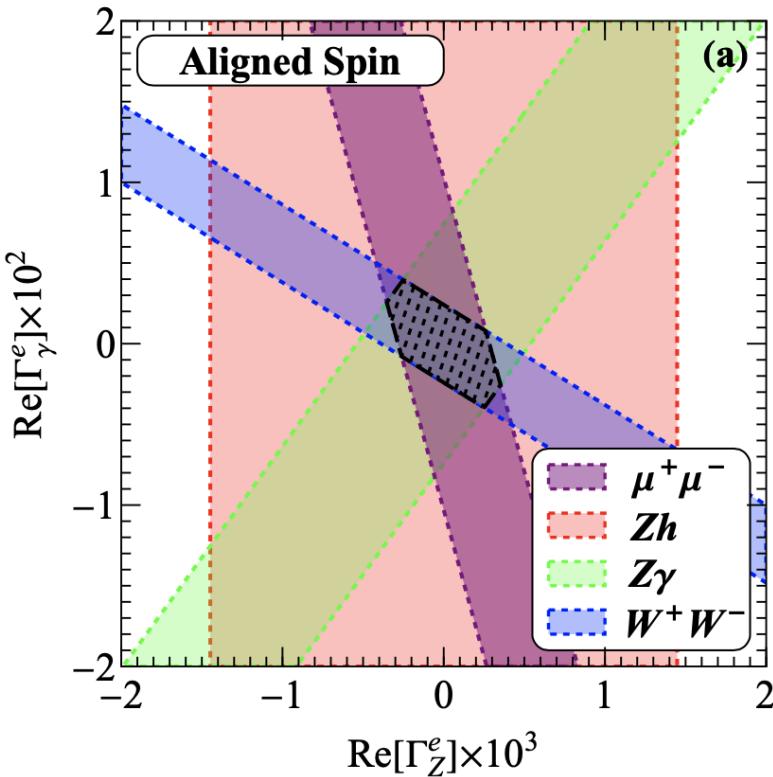
$$\mu^+ \mu^- : |\phi, \theta\rangle \xrightarrow{\mathcal{CP}} |\phi, \theta\rangle$$

→ $A_{LR}^{\mu\mu} \propto s_T + \bar{s}_T$

Pinning down Dipole Operators

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

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



Parity property

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

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

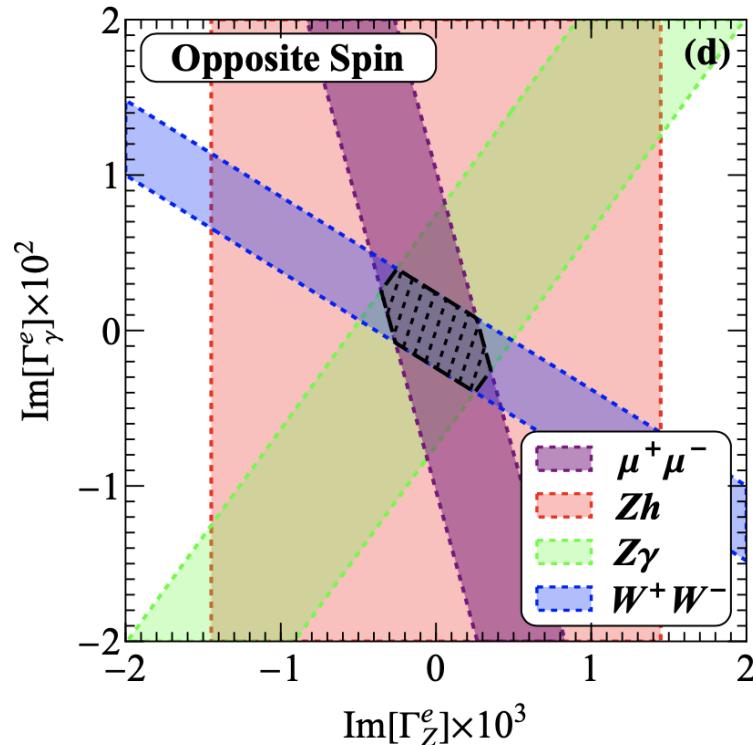
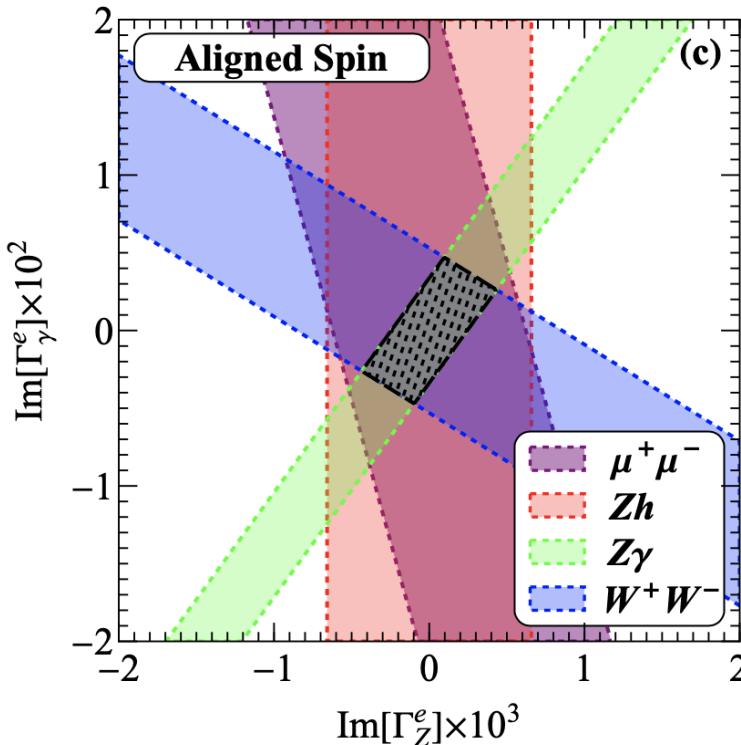
- SM $(g_L^e + g_R^e) = -1/2 + 2s_W^2 \ll 1$
- SM $WW\gamma < WWZ$
- $\Gamma_W^e = \Gamma_Z^e + s_W^2 \Gamma_\gamma^e$

Pinning down Dipole Operators

For the imaginary parts of dipole couplings, things are similar

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

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



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 $1/\Lambda^4$
- ✓ Dipole operators can be probed at $1/\Lambda^2$ via **transverse spin effects of beams**
- ✓ Both Re & Im parts can be well constrained, *without impact from other NP and offering a new opportunity for directly probing potential CP-violating effects.*
- ✓ Our bounds are much stronger than other approaches by 1~2 orders of magnitude
- ✓ 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}

Thank you