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

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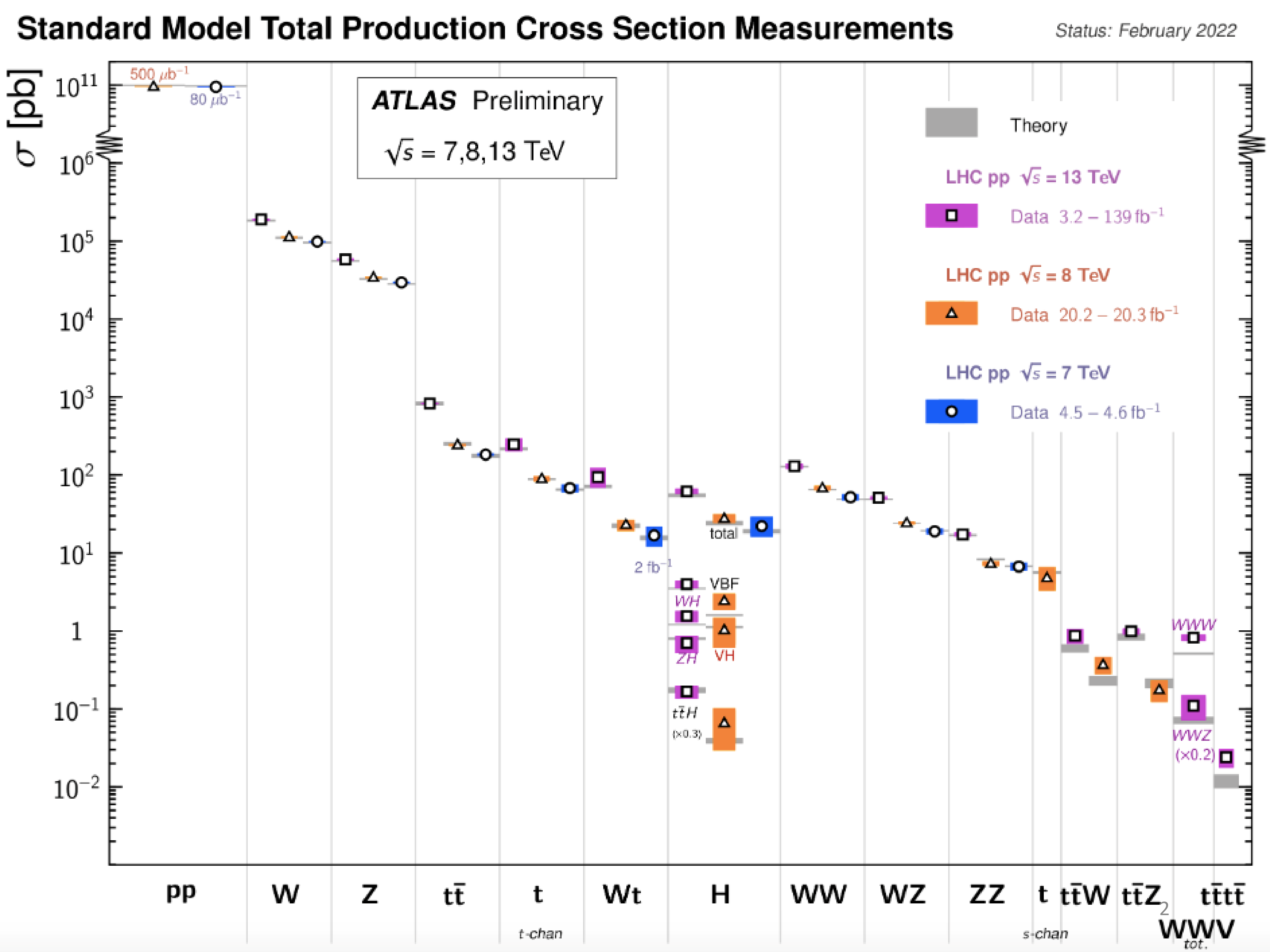


Standard Model Total Production Cross Section Measurements
Status: February 2022
ATLAS Preliminary
√s = 7,8,13 TeV
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.6 fb⁻¹
σ [pb]
500 μb⁻¹
80 μb⁻¹
2 fb⁻¹
total
VBF
WH
ZH
VH
tt̄H
(×0.3)
WWW
WWZ
(×0.2)
pp
W
Z
tt̄
t
t-chan
Wt
H
WW
WZ
ZZ
t
s-chan
tt̄W
tt̄Z
tt̄tt̄
WWV
tot.

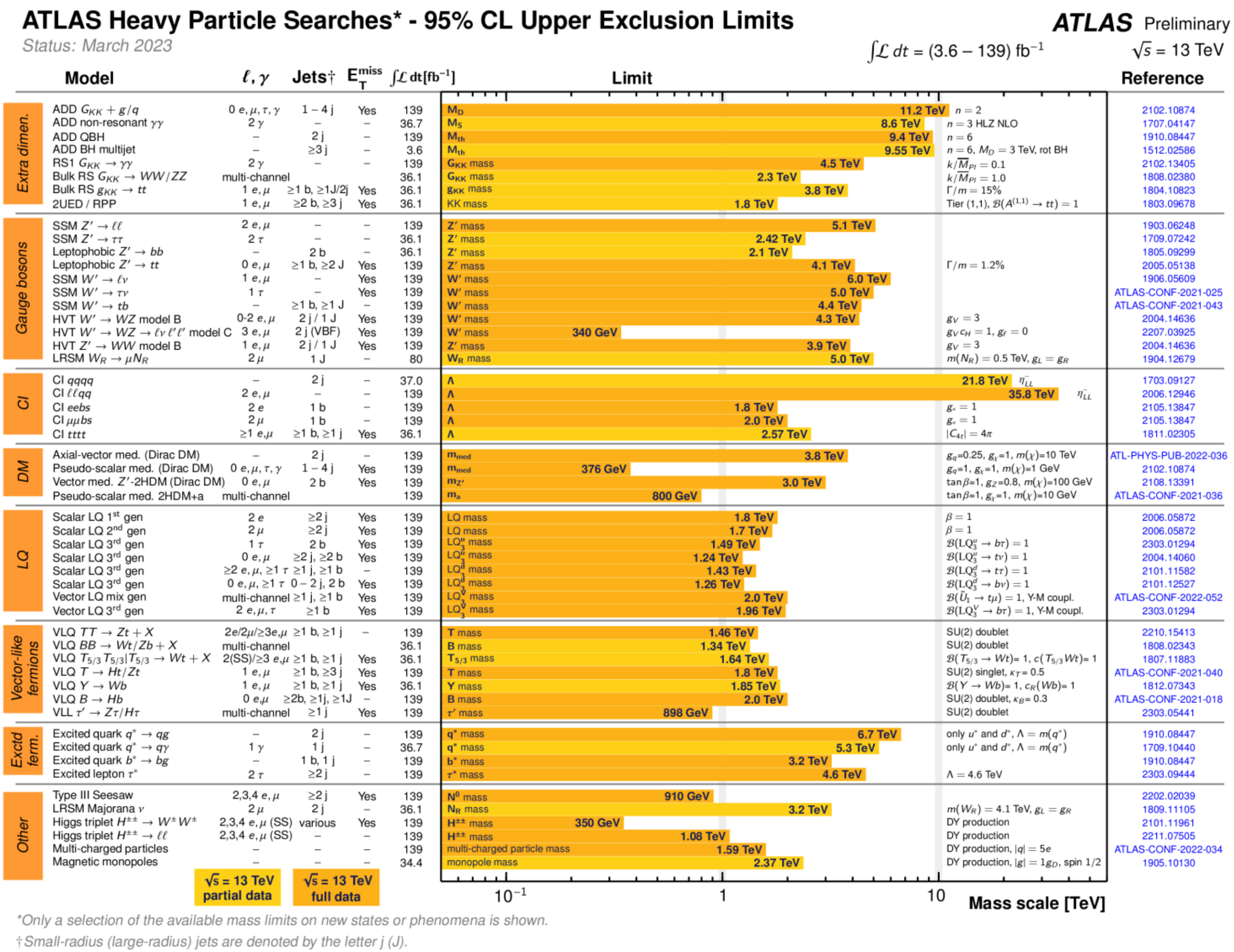
Why we need the New Physics

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



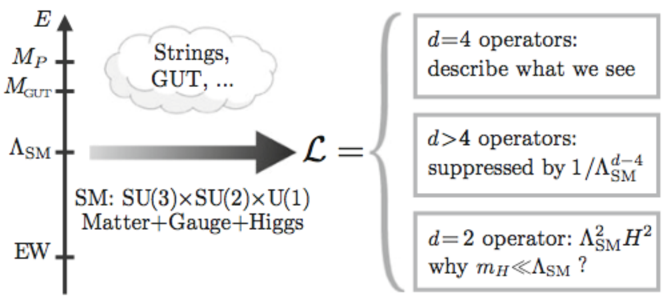
$\mathcal{O}$(TeV)

SMEFT

New Physics and SMEFT

Linear realized EFT

Higgs is a fundamental particle
Weak interacting

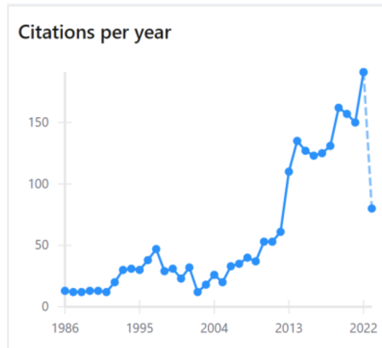


W. Buchuller, D. wyler 1986
B. Grzadkowski et al, 2010
L. Lehman, A. Marin, 2015
B. Henning et al, 2015
H-L. Li et al, 2020
……

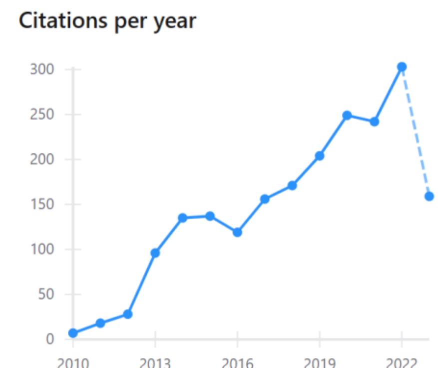
$$\mathcal{L} = \frac{C_6}{\Lambda^2}\mathcal{O}_6 + \frac{C_8}{\Lambda^4}\mathcal{O}_8 + \ldots$$

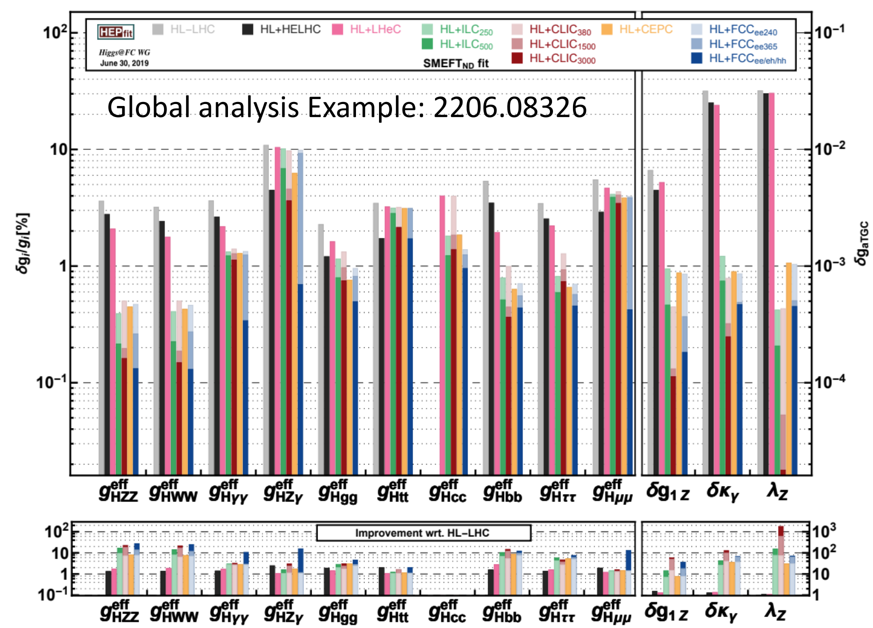
SMEFT Analysis:

W. Buchuller, D. wyler 1986



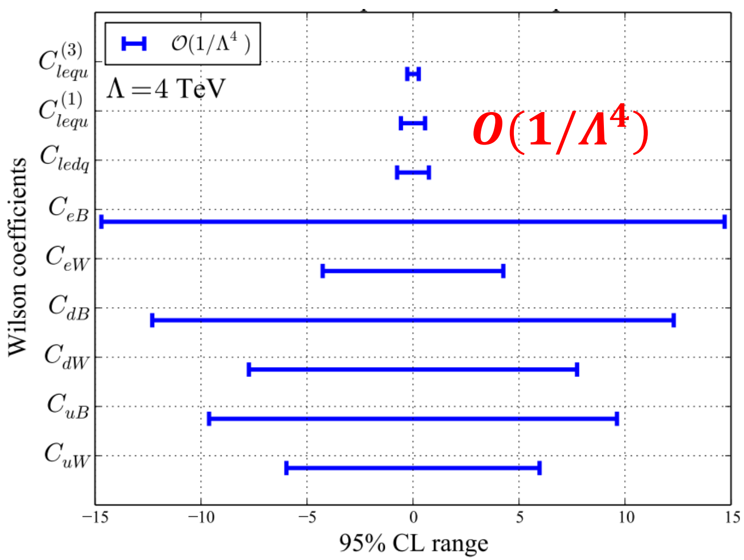
B. Grzadkowski et al, 2010



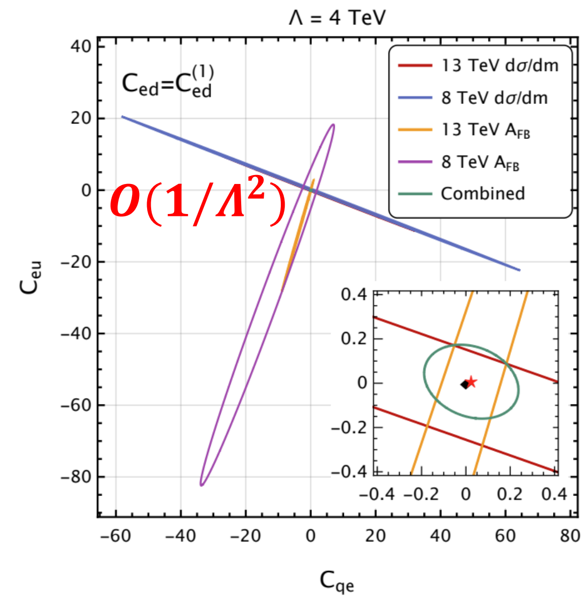


Data for Dipole Operator

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

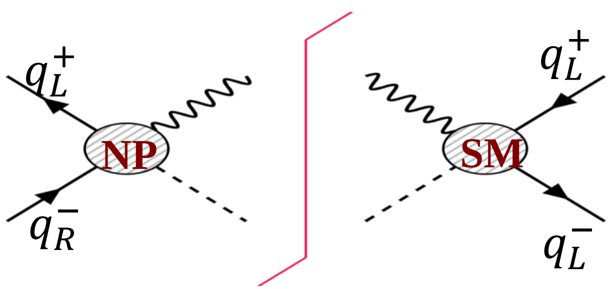


R. Boughezal et al. *Phys.Rev.D* 104 (2021) 9, 095022



R. Boughezal et al, 2303.08257

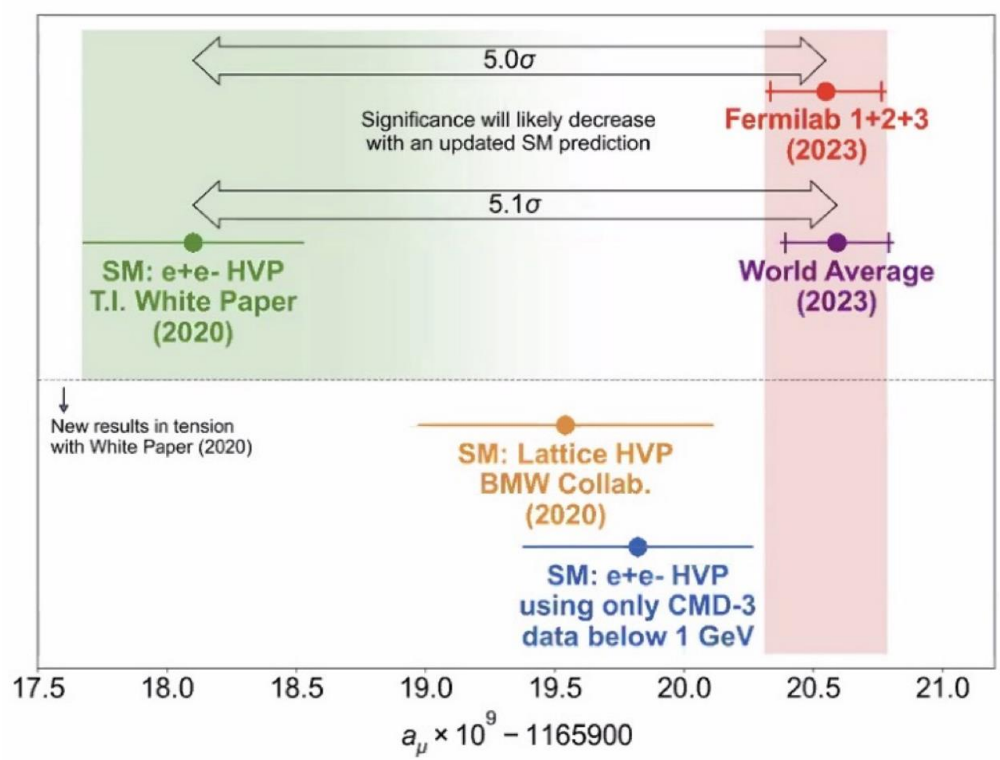
The interfering effect between the SM and Dipole operators can be ignored



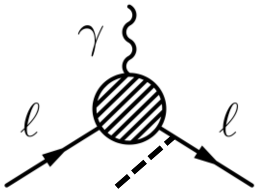
Leading contribution: $\left|\frac{c_{dipole}}{\Lambda^2}\right|^2$

=0 for the cross section

New Physics and Dipole Operator

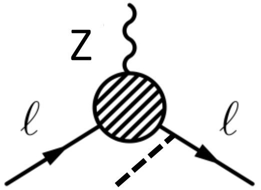


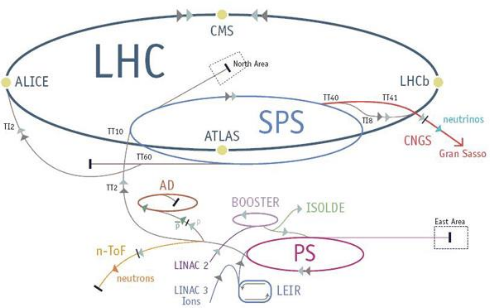
Loop-induced by the BSM

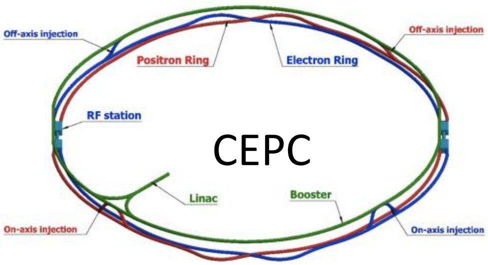


May have same physics source

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





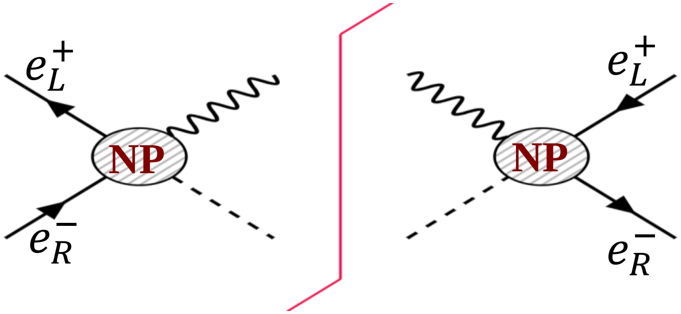


How to probe the electroweak dipole operators?

How to Probe Dipole Operator

Traditional method via cross section and width

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



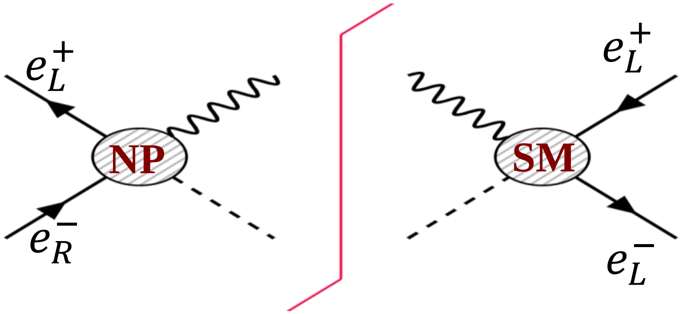
Is it possible to probe the dipole operators at $o\left(\frac{1}{\Lambda^2}\right)$?

Transverse polarization effect of beams:

The interference between the different helicity states

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

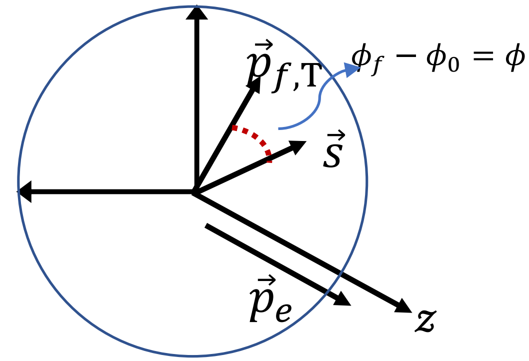
$$\rho = \frac{1}{2}(1 + \boldsymbol{\sigma}\cdot\boldsymbol{s}) = \frac{1}{2}\begin{pmatrix} 1+\lambda & b_{\mathrm{T}}e^{-i\phi_0} \\ b_{\mathrm{T}}e^{i\phi_0} & 1-\lambda \end{pmatrix}$$



$|\lambda = +\rangle\langle\lambda = -|$

✓ Without depending on other NP operators

Transverse Spin Polarization



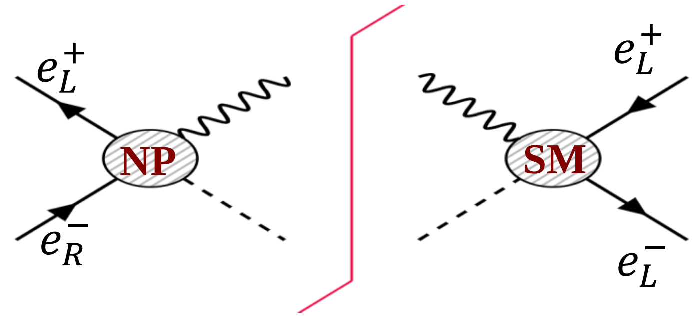
Transverse spin polarization of beams

Breaking the rotational invariance & A nontrivial azimuthal behavior

Spin dependent amplitude square:

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

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



$M \propto e^{i(\alpha 1 - \alpha 2)\phi}$ $e^{i\phi * 0}$ $e^{i\phi}$

	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	$\lvert\mathcal{M}\rvert^2_{TU} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TL} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TT} \to 1, \cos 2\phi, \sin 2\phi$

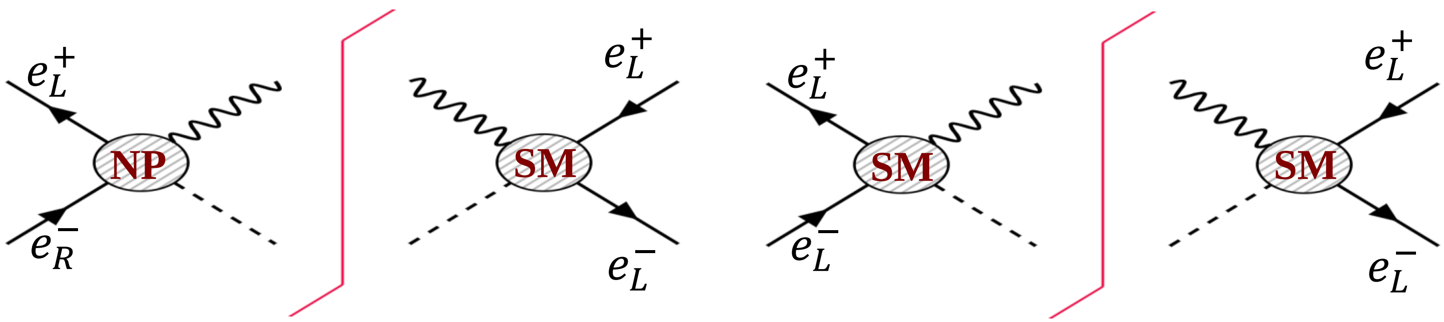
G. Moortgat-Pick et al. *Phys.Rept.* 460 (2008), *JHEP* 01 (2006)

Single Transverse Spin Asymmetries

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

Re[C_{dipole}]   Im[C_{dipole}]   SM & other NP

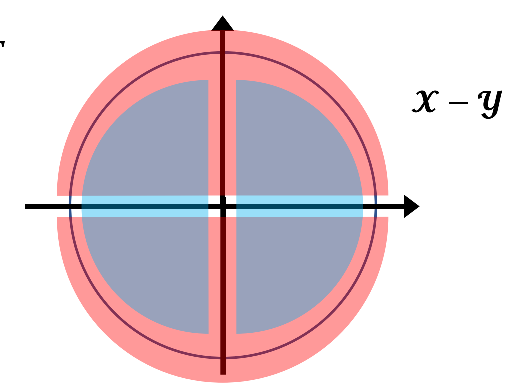
CP-conserving   CP-violation



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

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

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



Pinning down Dipole Operators

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

$$\Gamma^e_\gamma = \Gamma^e_W - \Gamma^e_B \qquad \Gamma^e_Z = c^2_W\Gamma^e_W + s^2_W\Gamma^e_B$$

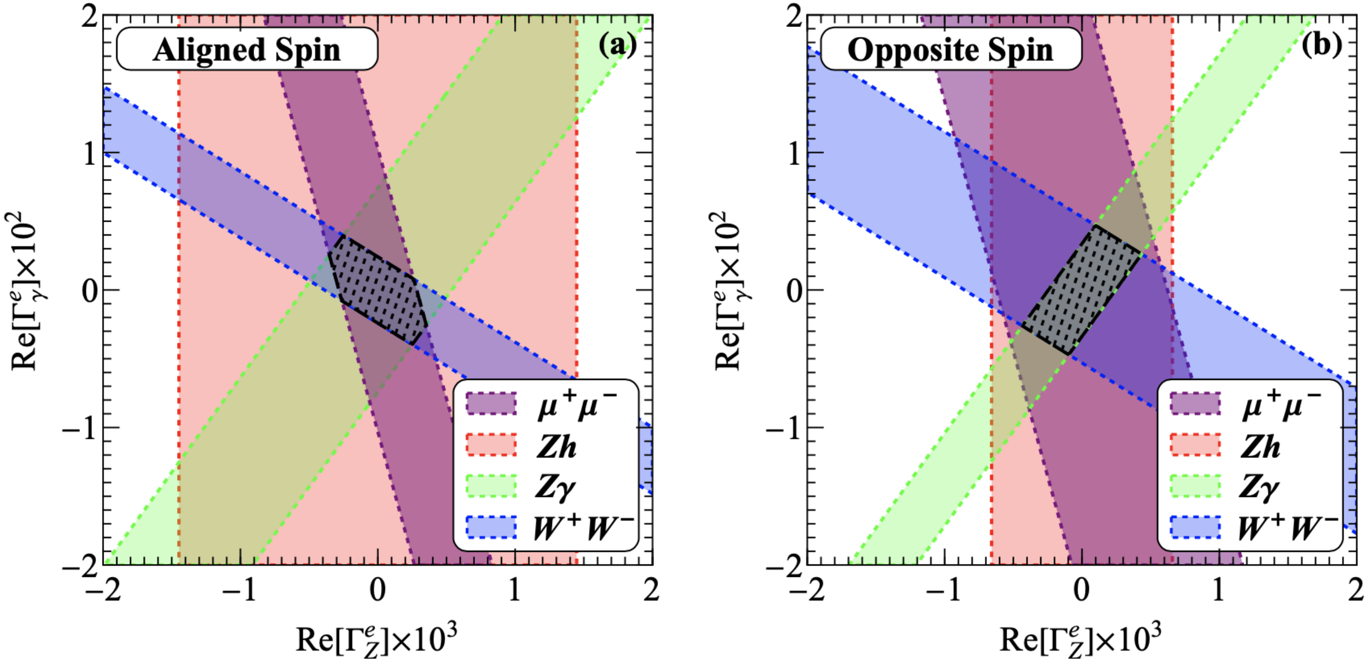
Aligned Spin

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

Opposite Spin

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

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



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

Pinning down Dipole Operators

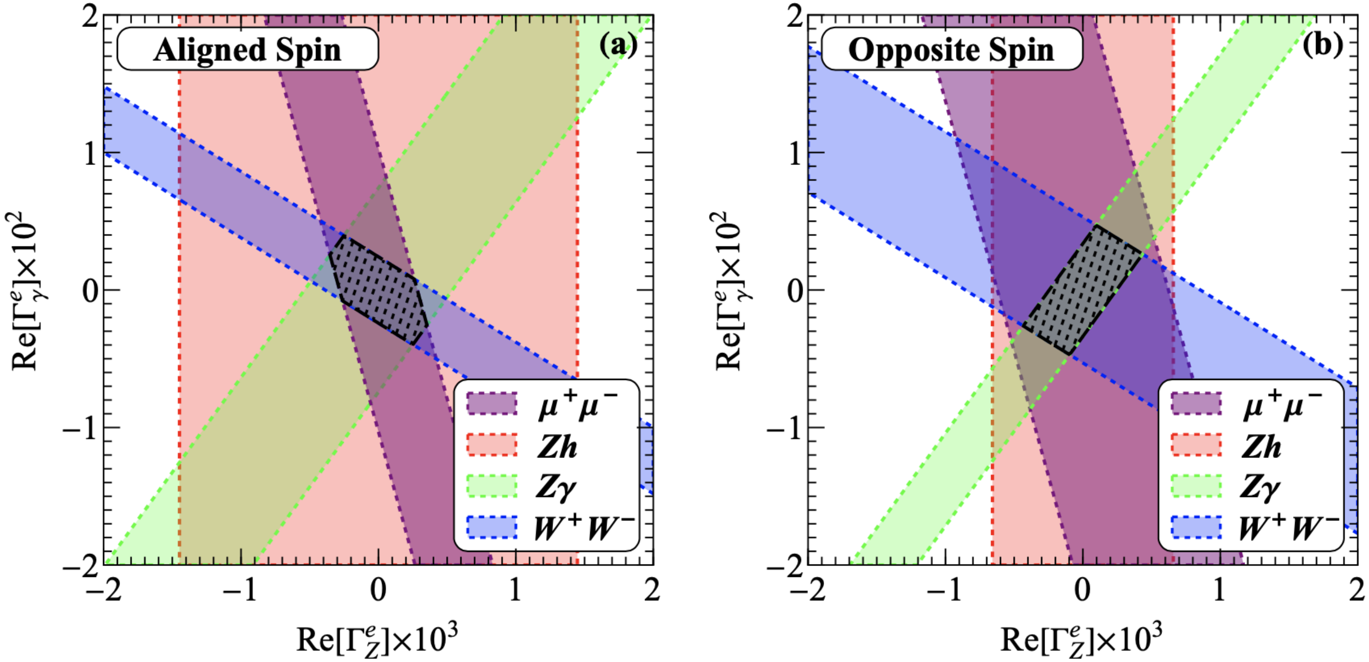
$$\mathcal{L}_{\text{eff}} = -\frac{1}{\sqrt{2}}\bar{\ell}_L \sigma^{\mu\nu}\left(g_1 \Gamma_B^e B_{\mu\nu} + g_2 \Gamma_W^e \sigma^a W_{\mu\nu}^a\right)\frac{H}{v^2} e_R + \text{h.c.}$$

Aligned Spin

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

Opposite Spin

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



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

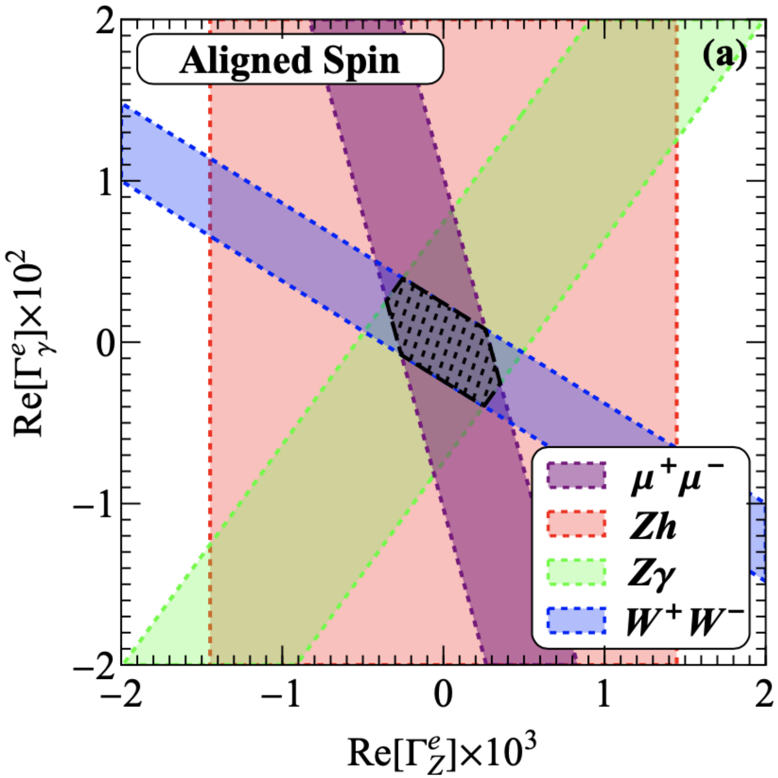
$$\mu^+\mu^- : |\phi, \theta\rangle \xrightarrow{\mathcal{CP}} |\phi, \theta\rangle$$

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

Pinning down Dipole Operators

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

The sensitivity to Γ^e_Z is much stronger than Γ^e_γ



Parity property

$$\mathcal{M}^*_{++}\mathcal{M}_{-+} = -\mathcal{M}^*_{+-}\mathcal{M}_{--}(g^e_L \leftrightarrow g^e_R)$$

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

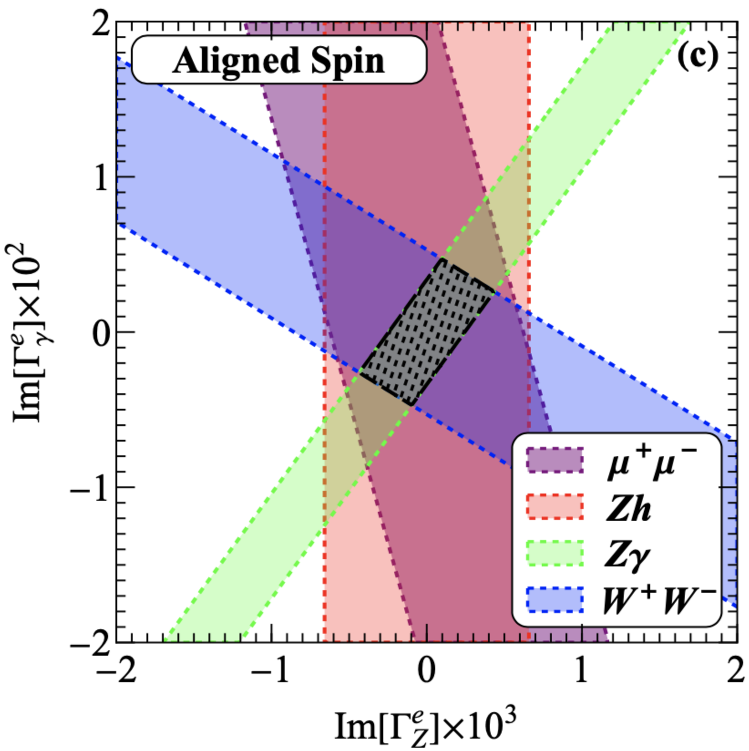
- SM $(g^e_L + g^e_R) = -1/2 + 2s^2_W \ll 1$
- SM $WW\gamma < WWZ$
- $\Gamma^e_W = \Gamma^e_Z + s^2_W\Gamma^e_\gamma$

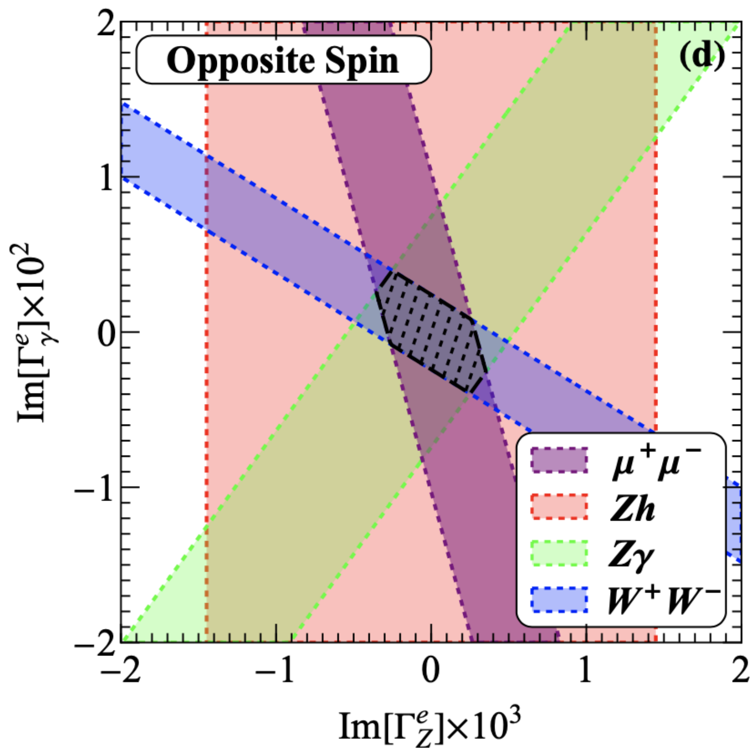
Pinning down Dipole Operators

For the imaginary parts of dipole couplings, things are similar

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

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 $1/\Lambda^4$
- ✓ 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

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