

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



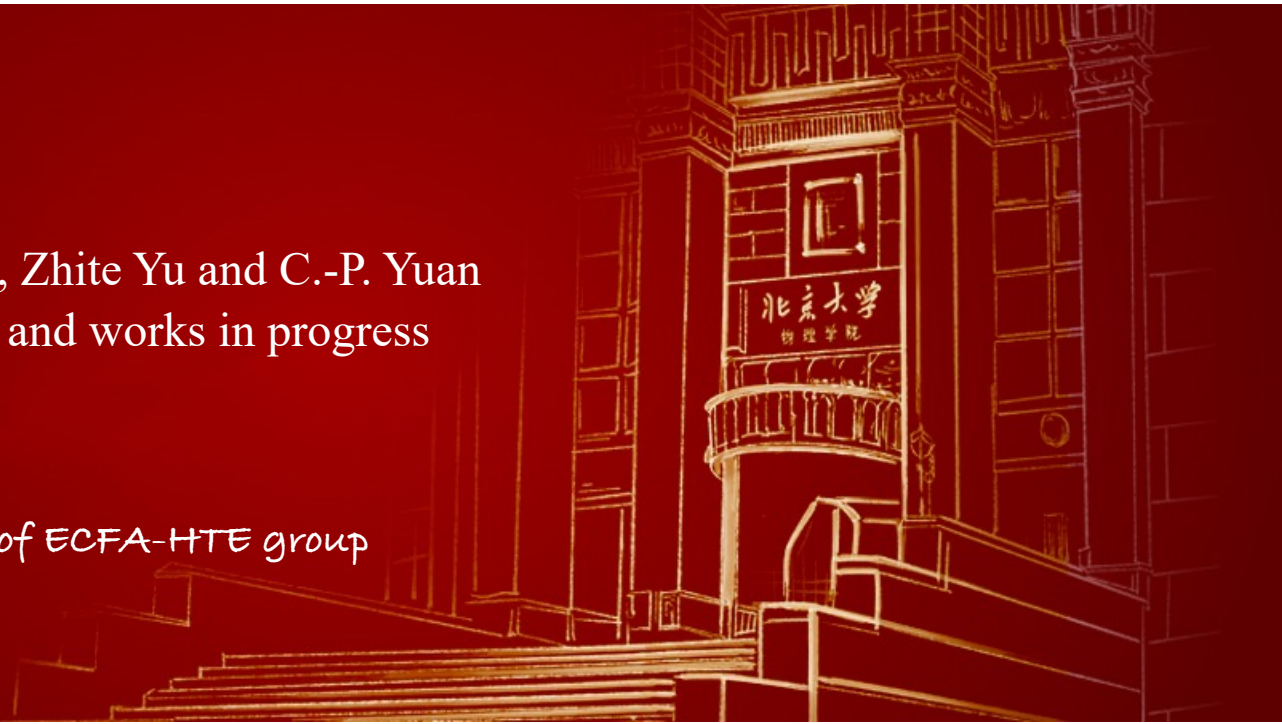
Single Transverse Spin Asymmetry as a New Probe of SMEFT Dipole Operators

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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*

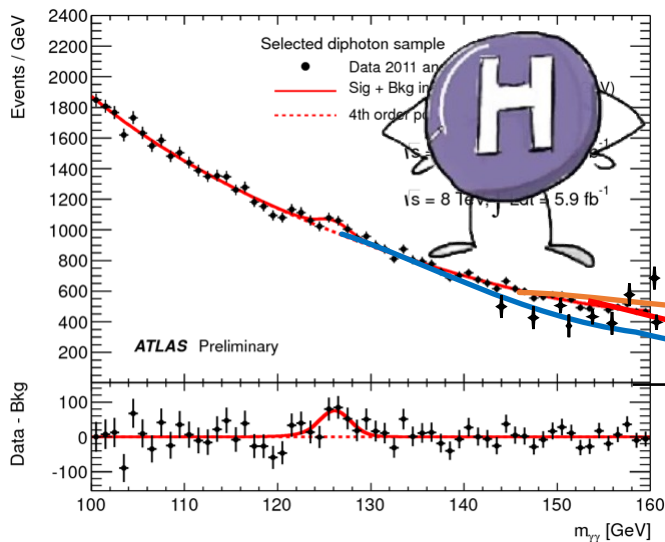


New Physics and SMEFT

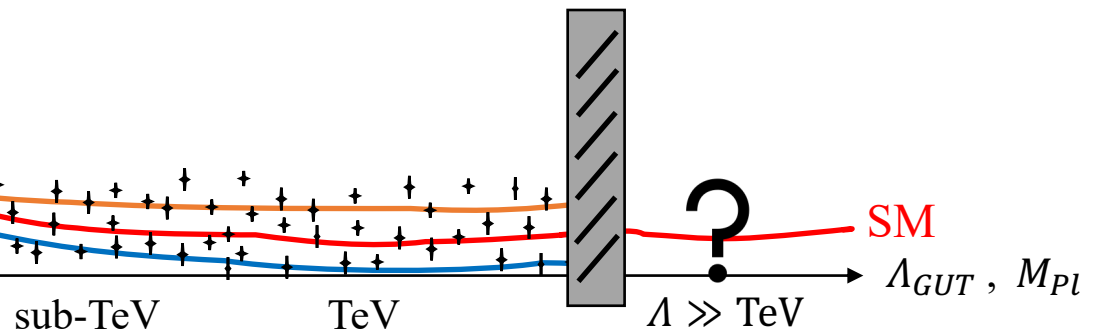
We need **new physics** and **new measurements** to answer open questions:

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



Digging out NP within the current scale



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 \dagger	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 TeV, $n=2$
	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
	RSt $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	$k/\overline{M}_{Pl} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$k/\overline{M}_{Pl} = 1.0$
Gauge bosons	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	$\Gamma/m = 15\%$
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3j$	Yes	36.1	Tier (1,1), $\mathcal{B}(A^{(1)} \rightarrow tt) = 1$
	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 2.42 TeV, 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 2.1 TeV
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	36.1	Z' mass 4.1 TeV
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2J$	Yes	139	Z' mass 6.0 TeV
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	-	139	W' mass 5.0 TeV
	SSM $W' \rightarrow \tau\nu$	1τ	-	-	139	W' mass 5.0 TeV
	SSM $W' \rightarrow tb$	-	$\geq 1 b, \geq 1J$	-	139	W' mass 4.4 TeV
	HVT $W' \rightarrow WZ$ model B	$0, 2 e, \mu$	$2j/1, 1j$	Yes	139	W' mass 4.3 TeV
CI	HVT $Z' \rightarrow WZ$ model C	$3 e, \mu$	$2j$ [VBF]	Yes	139	W' mass 340 GeV
	HVT $Z' \rightarrow WW$ model B	$1 e, \mu$	$2j/1, 1j$	Yes	139	Z' mass 3.9 TeV
	LRSM $W_R \rightarrow \mu N_R$	2μ	$1J$	-	80	W_R mass 5.0 TeV
DM	Cl $q\bar{q}q$	-	$2j$	-	37.0	$\tilde{m}_{\tilde{L}}$ 21.8 TeV, $\tilde{m}_{\tilde{U}}$ 35.8 TeV
	Cl $\ell\ell q$	$2 e, \mu$	-	-	139	$\tilde{m}_{\tilde{L}}$
	Cl $e\bar{e}b$	$2 e$	$1 b$	-	139	$\tilde{m}_{\tilde{L}}$
	Cl $\mu\mu b$	2μ	$1 b$	-	139	$\tilde{m}_{\tilde{L}}$
DM	Cl $t\bar{t}t$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	$ \mathcal{C}_{4\ell} = 4\pi$
	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	376 GeV
	Vector med. Z' -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	\tilde{m}_{H^\pm} 3.0 TeV
LQ	Pseudo-scalar med. 2HDM+A	multi-channel	-	-	139	800 GeV
	Scalar LQ 1 st gen	$2 e$	$\geq 2j$	Yes	139	LQ mass 1.8 TeV
	Scalar LQ 2 nd gen	2μ	$\geq 2j$	Yes	139	LQ mass 1.7 TeV
	Scalar LQ 3 rd gen	$0, 1\tau$	$2 b$	Yes	139	LQ mass 49 TeV
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2j, \geq 2 b$	Yes	139	LQ mass 1.2 TeV
	Scalar LQ 3 rd gen	$\geq 2 e, \mu$	$\geq 1\tau, \geq 1j, \geq 1 b$	-	139	LQ mass 1.93 TeV
Vector-like fermions	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 1\tau, \geq 2j, 2 b$	Yes	139	LQ mass 1.2 TeV
	Vector LQ mix gen	multi-channel	$\geq 1j, \geq 1 b$	Yes	139	LQ mass 2.0 TeV
	Vector LQ 3 rd gen	$2 e, \mu, \tau$	$\geq 1 b$	-	139	LQ mass 1.96 TeV
	VLO $T\bar{T} \rightarrow Zt + X$	$2e/2\mu/\geq 3e, \mu$	$\geq 1 b, \geq 1j$	-	139	T mass 1.46 TeV
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV
	VLO $T\bar{T}_{5/3} \rightarrow T\bar{T}_{5/3} + Wt + X$	$2(SS)/\geq 3 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1$
Excited ferm.	VLO $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3j$	Yes	139	T mass 1.8 TeV
	VLO $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	Y mass 1.85 TeV
	VLO $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1j, \geq 1 b$	Yes	139	B mass 1.93 TeV
	VLL $\tau \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1j$	Yes	139	τ' mass 898 GeV
	Excited quark $q^* \rightarrow qg$	-	$2j$	-	139	q^* mass 6.7 TeV
	Excited quark $q^* \rightarrow q\gamma$	1γ	-	-	36.7	q^* mass 5.3 TeV
Other	Excited quark $b^* \rightarrow b\bar{g}$	-	$1 b, 1j$	-	139	b^* mass 3.2 TeV
	Excited lepton $\tau^* \rightarrow b\bar{g}$	2τ	$\geq 2j$	-	139	τ^* mass 4.6 TeV
	Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2j$	Yes	139	N^c mass 910 GeV
	Higgs Majorana ν	$2j$	-	-	36.1	N_h mass 2.1 TeV
	Liggs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$	$2, 3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV
	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).

EWPO

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

Global Fitting

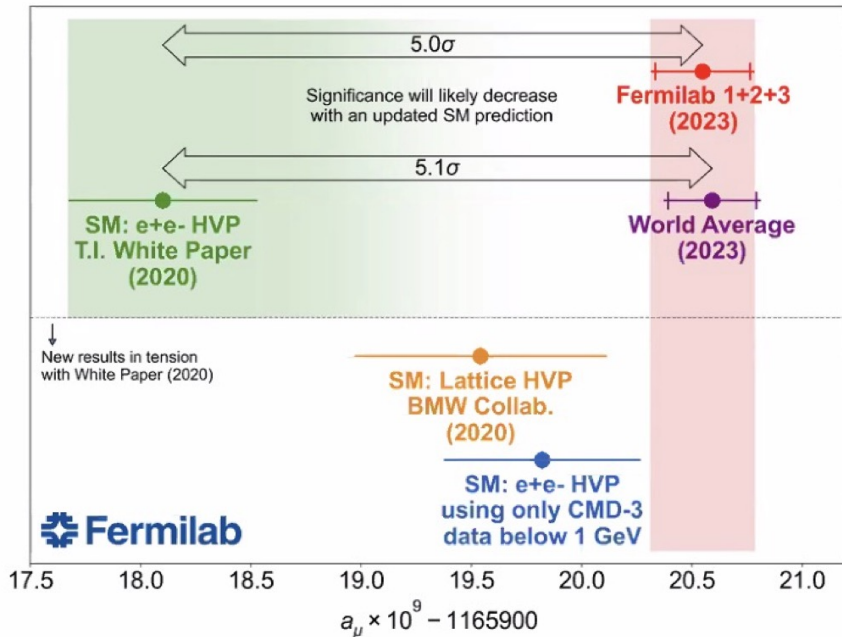
- F. Maltoni et al., SMEFT, 2021
- P. Athron et al., GAMBIT, 2017
- J.Y. Gu, Y. Du et al., 2022



	X^3	ψ^3 and $\psi^2 D^2$	$\psi^3 \psi^3$
Q_6	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_6	$(\psi^3 \psi^3)$
Q_7	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_7	$(\psi^3 \psi^3)$
Q_8	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_8	$(\psi^3 \psi^3)$
Q_9	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_9	$(\psi^3 \psi^3)$
Q_{10}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{10}	$(\psi^3 \psi^3)$
Q_{11}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{11}	$(\psi^3 \psi^3)$
Q_{12}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{12}	$(\psi^3 \psi^3)$
Q_{13}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{13}	$(\psi^3 \psi^3)$
Q_{14}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{14}	$(\psi^3 \psi^3)$
Q_{15}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{15}	$(\psi^3 \psi^3)$
Q_{16}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{16}	$(\psi^3 \psi^3)$
Q_{17}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{17}	$(\psi^3 \psi^3)$
Q_{18}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{18}	$(\psi^3 \psi^3)$
Q_{19}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{19}	$(\psi^3 \psi^3)$
Q_{20}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{20}	$(\psi^3 \psi^3)$
Q_{21}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{21}	$(\psi^3 \psi^3)$
Q_{22}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{22}	$(\psi^3 \psi^3)$
Q_{23}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{23}	$(\psi^3 \psi^3)$
Q_{24}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{24}	$(\psi^3 \psi^3)$
Q_{25}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{25}	$(\psi^3 \psi^3)$
Q_{26}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{26}	$(\psi^3 \psi^3)$
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Q_{28}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{28}	$(\psi^3 \psi^3)$
Q_{29}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{29}	$(\psi^3 \psi^3)$
Q_{30}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{30}	$(\psi^3 \psi^3)$
Q_{31}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{31}	$(\psi^3 \psi^3)$
Q_{32}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{32}	$(\psi^3 \psi^3)$
Q_{33}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{33}	$(\psi^3 \psi^3)$
Q_{34}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{34}	$(\psi^3 \psi^3)$
Q_{35}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{35}	$(\psi^3 \psi^3)$
Q_{36}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{36}	$(\psi^3 \psi^3)$
Q_{37}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{37}	$(\psi^3 \psi^3)$
Q_{38}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{38}	$(\psi^3 \psi^3)$
Q_{39}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{39}	$(\psi^3 \psi^3)$
Q_{40}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{40}	$(\psi^3 \psi^3)$
Q_{41}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{41}	$(\psi^3 \psi^3)$
Q_{42}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{42}	$(\psi^3 \psi^3)$
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Q_{46}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{46}	$(\psi^3 \psi^3)$
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Q_{49}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{49}	$(\psi^3 \psi^3)$
Q_{50}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{50}	$(\psi^3 \psi^3)$
Q_{51}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{51}	$(\psi^3 \psi^3)$
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Q_{56}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{56}	$(\psi^3 \psi^3)$
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Q_{58}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{58}	$(\psi^3 \psi^3)$
Q_{59}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{59}	$(\psi^3 \psi^3)$
Q_{60}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{60}	$(\psi^3 \psi^3)$
Q_{61}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{61}	$(\psi^3 \psi^3)$
Q_{62}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{62}	$(\psi^3 \psi^3)$
Q_{63}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{63}	$(\psi^3 \psi^3)$
Q_{64}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{64}	$(\psi^3 \psi^3)$
Q_{65}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{65}	$(\psi^3 \psi^3)$
Q_{66}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{66}	$(\psi^3 \psi^3)$
Q_{67}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{67}	$(\psi^3 \psi^3)$
Q_{68}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{68}	$(\psi^3 \psi^3)$
Q_{69}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{69}	$(\psi^3 \psi^3)$
Q_{70}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{70}	$(\psi^3 \psi^3)$
Q_{71}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{71}	$(\psi^3 \psi^3)$
Q_{72}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{72}	$(\psi^3 \psi^3)$
Q_{73}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{73}	$(\psi^3 \psi^3)$
Q_{74}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{74}	$(\psi^3 \psi^3)$
Q_{75}	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	Q_{75}	$(\psi^3 \psi^3)$
$$			

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 $\Delta a_\mu^{\text{BNL}}, \Delta a_\mu^{2021}$	EXCLUDED
1	0	(1, 1, 1)	Excluded: $\Delta a_\mu < 0$	<div style="border: 1px solid black; padding: 5px;"> <p>From:</p> <p>JHEP 09 (2021) 080, [PA, C. Balázs, D.H.J. Jacob, W. Kotlarski, D. Stöckinger, H. Stöckinger-Kim]</p> </div>
2	0	(1, 1, 2)	Excluded: $\Delta a_\mu < 0$	
3	0	(1, 2, -1/2)	Updated in Sec. 3.2	
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 → Model 3
Scalar leptoquarks → Models 4-9
Dark photon → Model 16

SUSY.....
Scalar extensions.....

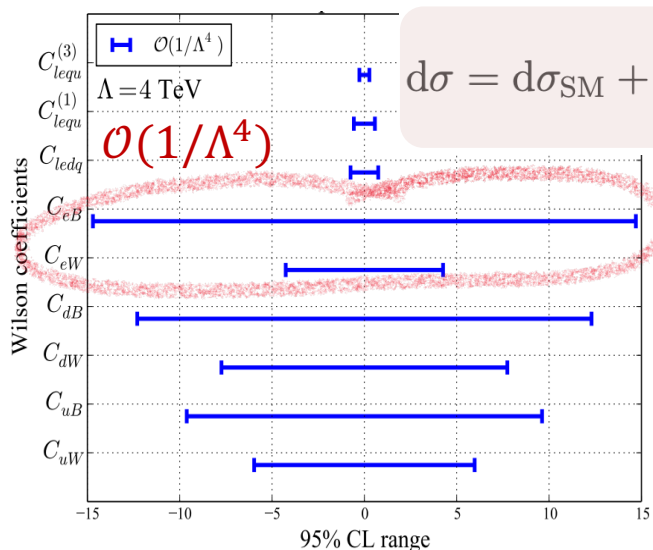
Peter Athron et al., *JHEP* 09 (2021) 080



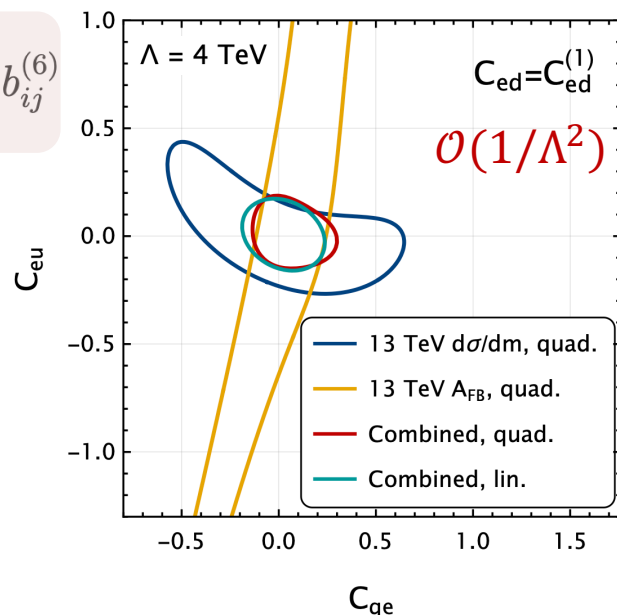
May have same physics source
but Z only detected by colliders

Data for Dipole Operator

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



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



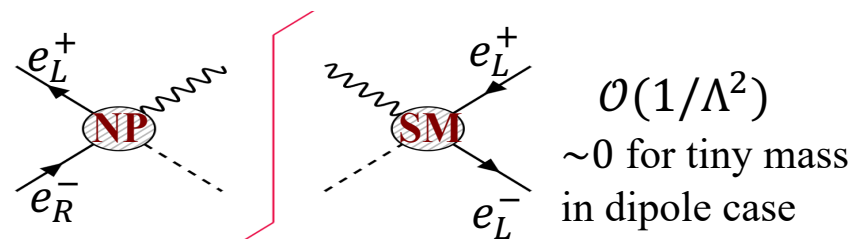
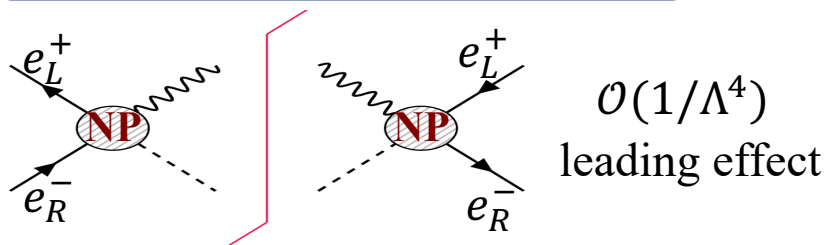
Single-Parameter-Analysis @LHC

(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)

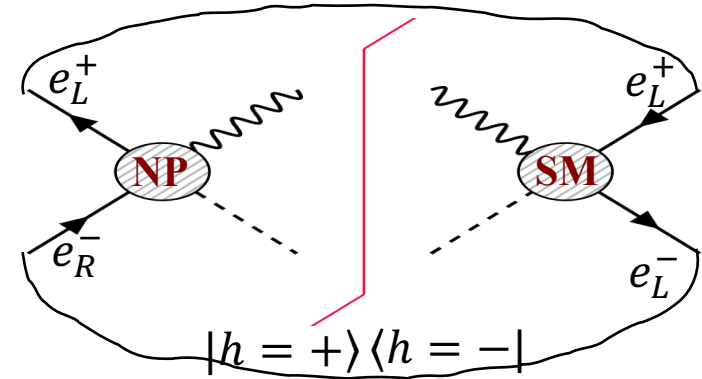
➔ Only small non-interfering effect with $\left| \frac{c_{dipole}}{\Lambda^2} \right|^2$



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

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

Transverse polarization effect \rightarrow Interference of helicity amplitudes

Breaking the rotational invariance \rightarrow A nontrivial azimuthal behavior

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

Transverse Spin Polarization

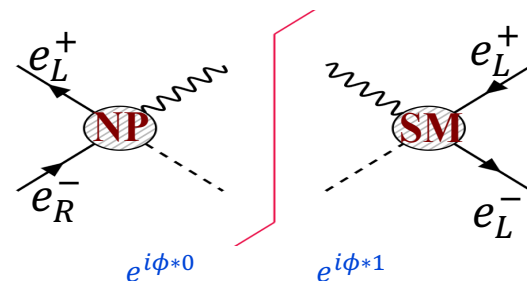
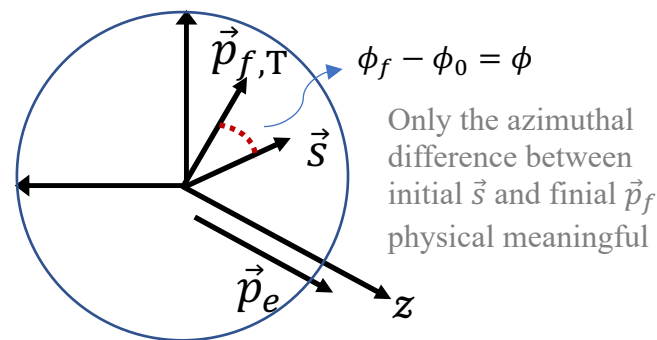
Spin dependent amplitude square:

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

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

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

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



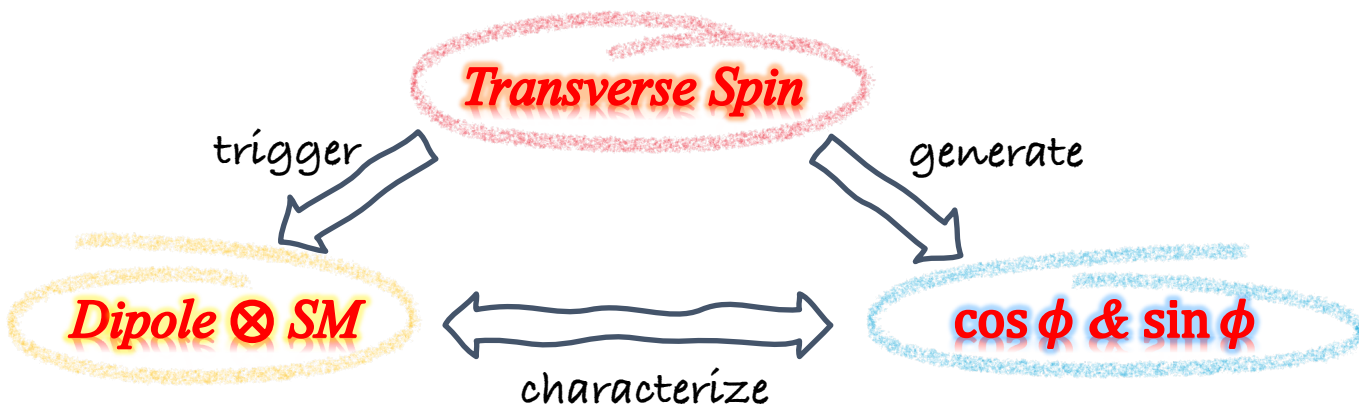
dipole operator $\rightarrow \mathcal{M}_{\pm\pm}$, massless SM $\rightarrow \mathcal{M}_{\pm\mp}$

	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



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

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

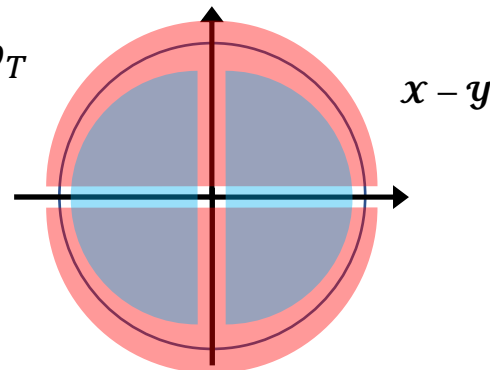
$\vec{s} \times \vec{p}_f \propto \sin \phi$
 CP-violation

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

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

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

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



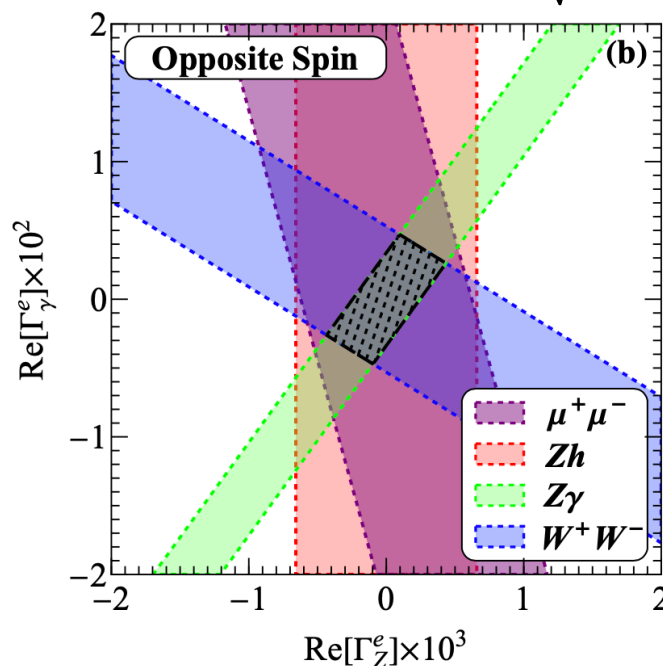
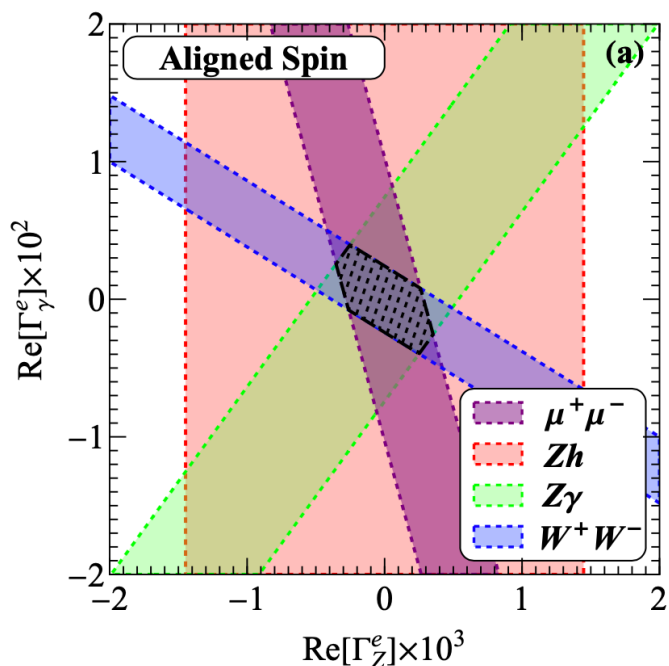
Pinning down Dipole Operators

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

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

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

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



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

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

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

CP property

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

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

$$\rightarrow \begin{aligned} A_R^{\mu\mu} &\propto \mathbf{s}_T + \bar{\mathbf{s}}_T \\ A_R^{Z\gamma} &\propto \mathbf{s}_T - \bar{\mathbf{s}}_T \end{aligned}$$

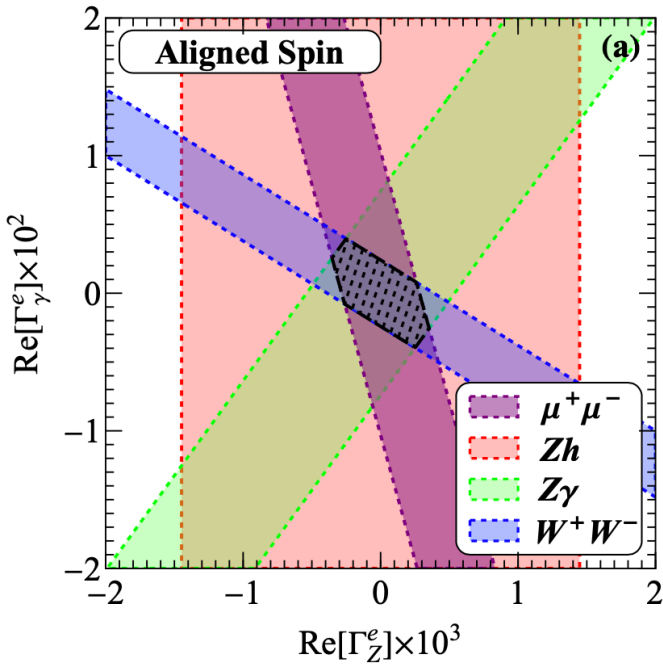
Pinning down Dipole Operators

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

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

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

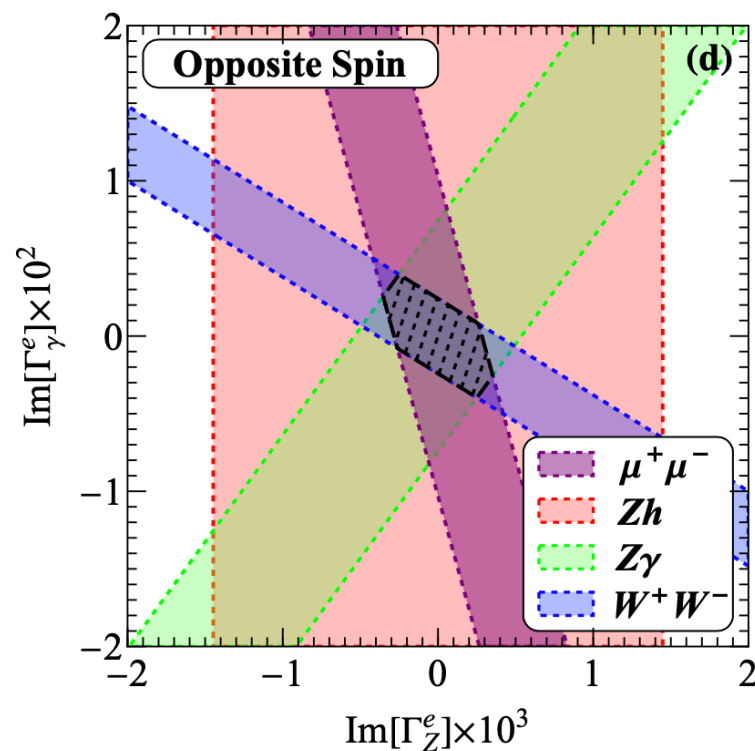
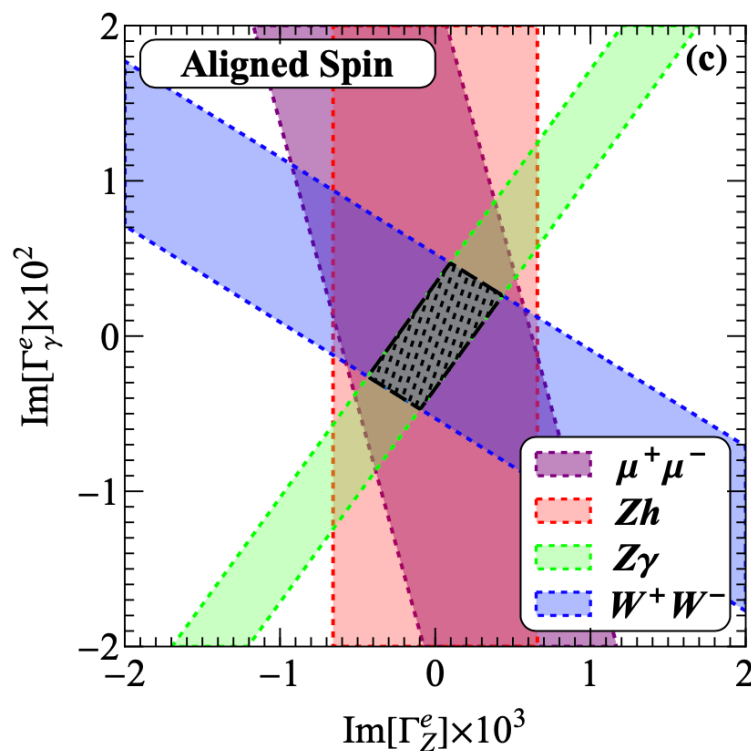
Aligned Spin

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

Opposite Spin

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

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



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



- ✓ 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

	$ \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

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

$$|\mathcal{M}|^2(\mathbf{s}, \bar{\mathbf{s}}, \theta, \phi) = \sum_{\alpha_1, \alpha_2, \alpha'_1, \alpha'_2} \rho_{\alpha_1, \alpha'_1}(\mathbf{s}) \bar{\rho}_{\alpha_2, \alpha'_2}(\bar{\mathbf{s}}) \mathcal{M}_{\alpha_1, \alpha_2}(i \rightarrow f; \theta, \phi) \mathcal{M}_{\alpha'_1, \alpha'_2}^\dagger(i \rightarrow f; \theta, \phi)$$

$$\mathbf{s} = (b_1, b_2, \lambda) = (b_T \cos \phi_0, b_T \sin \phi_0, \lambda) \quad \rho = \frac{1}{2} (1 + \boldsymbol{\sigma} \cdot \mathbf{s})$$

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

$$|M|^2 = |M|_{\text{unpol}}^2 - \frac{1}{2} \lambda_T \bar{\lambda}_T \text{Re}[T_{++}^* T_{--}]$$

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

$$- \frac{1}{2} \lambda_T \bar{\lambda}_T \text{Re}[e^{-2i\phi} T_{+-}^* T_{-+}]$$

$$+ \frac{1}{2} \lambda_T \text{Re} [e^{-i\phi} (T_{+-}^* T_{--} + T_{++}^* T_{-+})]$$

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

$$- \frac{1}{2} \bar{\lambda}_T \text{Re} [e^{-i\phi} (T_{+-}^* T_{++} + T_{--}^* T_{-+})]$$

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

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

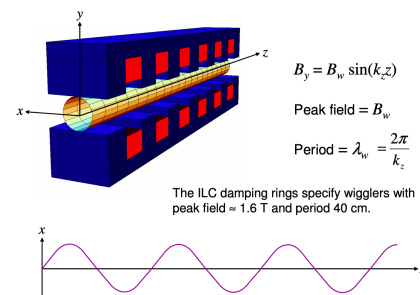
Backup: Polarized beam realization

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 ($\sim 1\%$). 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 ($>\sim 150$ 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 $|\text{Pe}^+| \geq 90\%$ is reported.