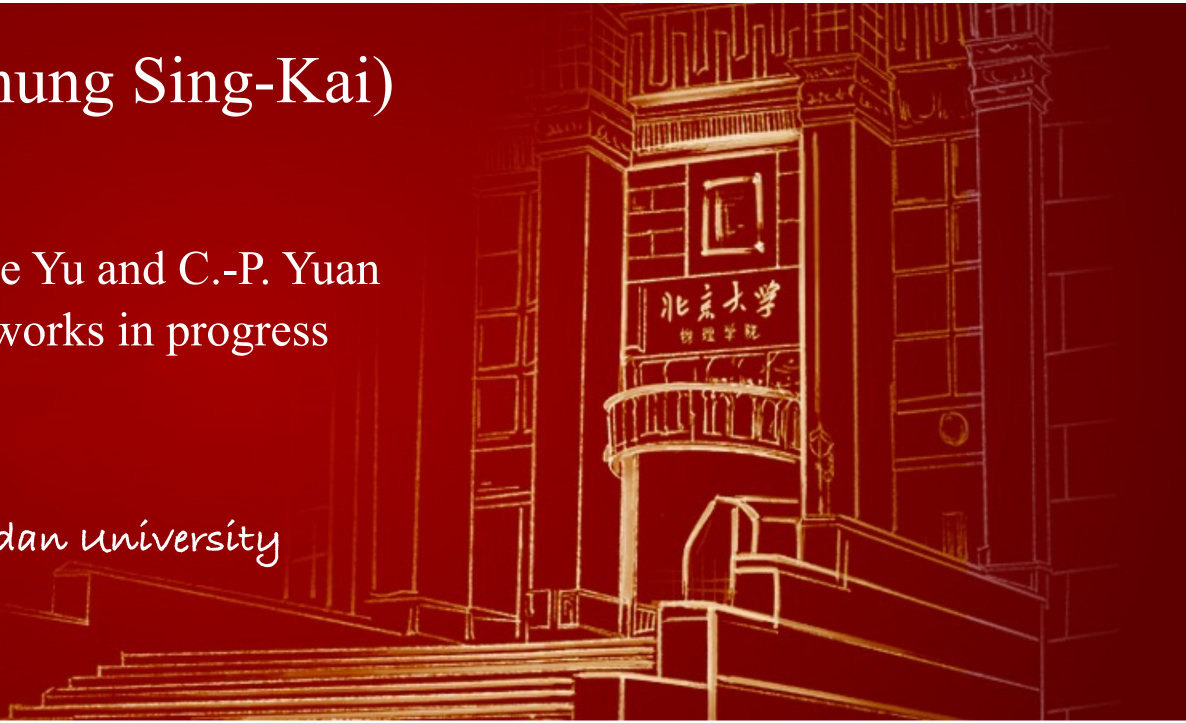
CEPC 味物理-新物理和相关探测技术研讨会
The CEPC Workshop on Flavor Physics, New Physics and Detector Technologies
中国上海，August 13-18, 2023

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

Xin-Kai Wen (文新锴 Bhung Sing-Kai)
Peking University

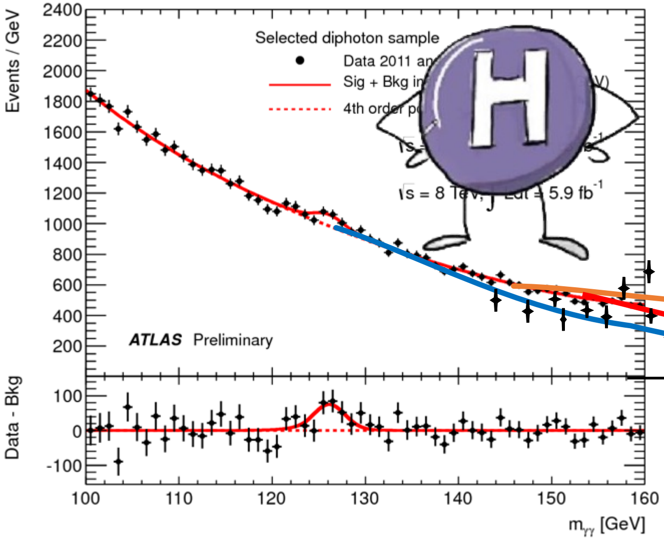
In collaboration with Bin Yan, Zhite Yu and C.-P. Yuan
Basing on arXiv: 2307.05236 and works in progress



Thanks a lot to the organizers of Fudan University
Shanghai, China
2023/08/18

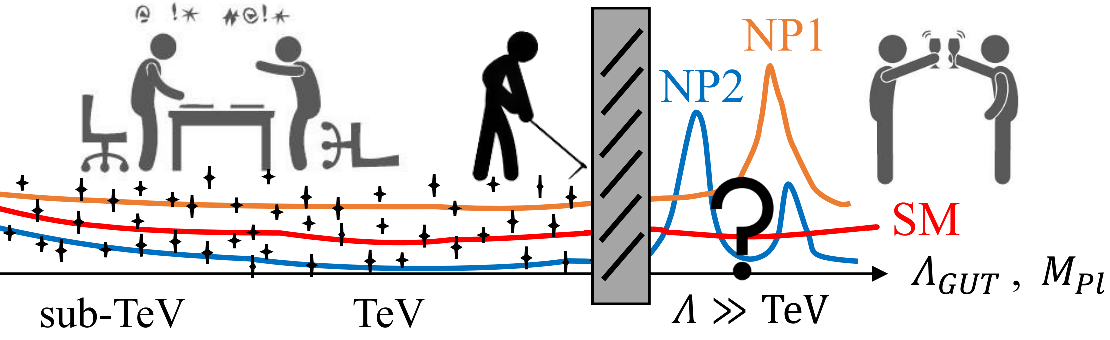
New Physics and SMEFT

None new fundamental resonance since 2012 but anomalies bursting



“5W1H”: Where, What, Why, When, Who, How ***NP***

NP might hide within the current scale



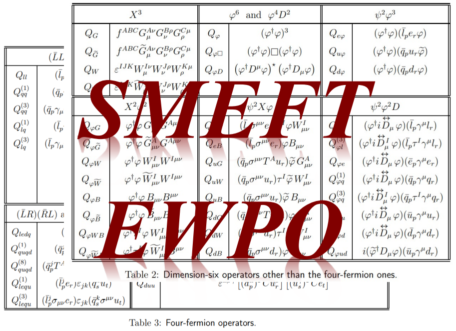


Table 2: Dimension-six operators other than the four-fermion ones.

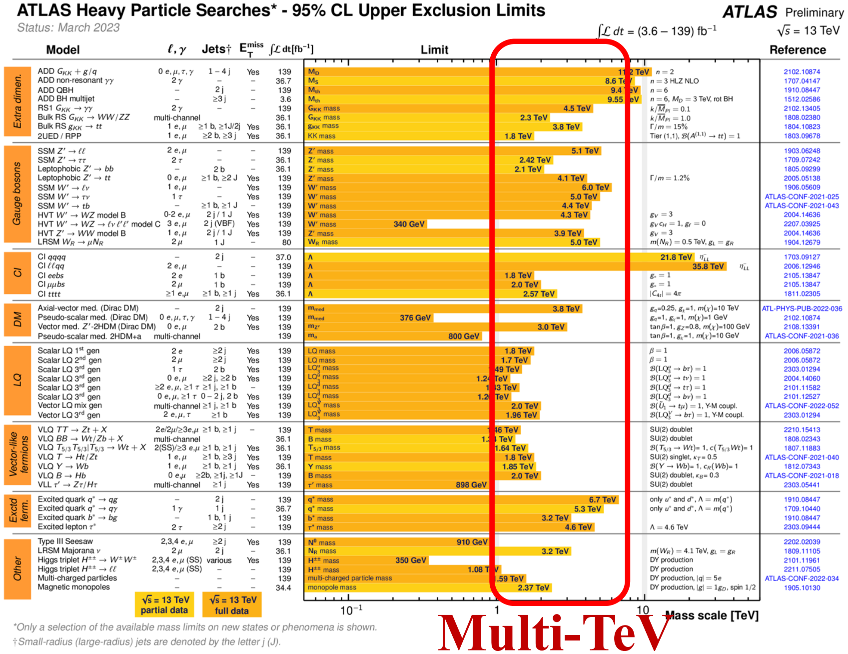
Table 3: Four-fermion operators.

B. Grzadkowski, et al. *JHEP* 10 (2010).

→ Global Fitting

Many excellent works

See talks of Jiayin Gu, Yong Du, Peter Athron and so on



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

Status: March 2023

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 13$ TeV

	Model	ℓ,γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimen.	ADD $G_{KK}+g/q$	0 e,μ,τ,γ	1 – 4 j	Yes	139	M_D	11.2 TeV	$n=2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S	8.6 TeV	$n=3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th}	9.4 TeV	$n=6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th}	9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK}\to\gamma\gamma$	2 γ	–	–	139	G_{KK} mass	4.5 TeV	$k/\overline{M}_{Pl}=0.1$	2102.13405
	Bulk RS $G_{KK}\to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl}=1.0$	1808.02380
	Bulk RS $g_{KK}\to tt$	1 e,μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m=15\%$	1804.10823
	2UED / RPP	1 e,μ	≥2 b, ≥3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)}\to tt)=1$	1803.09678
Gauge bosons	SSM $Z'\to\ell\ell$	2 e,μ	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z'\to\tau\tau$	2 τ	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z'\to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z'\to tt$	0 e,μ	≥1 b, ≥2 J	Yes	139	Z' mass	4.1 TeV	$\Gamma/m=1.2\%$	2005.05138
	SSM $W'\to\ell\nu$	1 e,μ	–	Yes	139	W' mass	6.0 TeV		1906.05609
	SSM $W'\to\tau\nu$	1 τ	–	Yes	139	W' mass	5.0 TeV		ATLAS-CONF-2021-025
	SSM $W'\to tb$	–	≥1 b, ≥1 J	–	139	W' mass	4.4 TeV		ATLAS-CONF-2021-043
	HVT $W'\to WZ$ model B	0-2 e,μ	2 j / 1 J	Yes	139	W' mass	4.3 TeV	$g_V=3$	2004.14636
	HVT $W'\to WZ\to\ell\nu\,\ell'\ell'$ model C	3 e,μ	2 j (VBF)	Yes	139	W' mass	340 GeV	$g_V c_H=1$, $g_f=0$	2207.03925
	HVT $Z'\to WW$ model B	1 e,μ	2 j / 1 J	Yes	139	Z' mass	3.9 TeV	$g_V=3$	2004.14636
	LRSM $W_R\to\mu N_R$	2 μ	1 J	–	80	W_R mass	5.0 TeV	$m(N_R)=0.5$ TeV, $g_L=g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e,μ	–	–	139	Λ	35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ	1.8 TeV	$g_*=1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ	2.0 TeV	$g_*=1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t}\rvert=4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	–	2 j	–	139	m_{med}	3.8 TeV	g_q=0.25, g_χ=1, $m(\chi)$=10 TeV	ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	0 e,μ,τ,γ	1 – 4 j	Yes	139	m_{med}	376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e,μ	2 b	Yes	139	$m_{Z'}$	3.0 TeV	tanβ=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_a	800 GeV	tanβ=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass	1.8 TeV	$\beta=1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass	1.7 TeV	$\beta=1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass	[illegible]49 TeV	$\mathcal{B}(LQ_3^u\to b\tau)=1$	2303.01294
	Scalar LQ 3rd gen	0 e,μ	≥2 j, ≥2 b	Yes	139	LQ_3^u mass	1.24 TeV	$\mathcal{B}(LQ_3^u\to t\nu)=1$	2004.14060
	Scalar LQ 3rd gen	≥2 e,μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass	1.43 TeV	$\mathcal{B}(LQ_3^d\to t\tau)=1$	2101.11582
	Scalar LQ 3rd gen	0 e,μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass	1.2[illegible] TeV	$\mathcal{B}(LQ_3^d\to b\nu)=1$	2101.12527
	Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	LQ_3^V mass	2.0 TeV	$\mathcal{B}(\tilde{U}_1\to t\mu)=1$, Y-M coupl.	ATLAS-CONF-2022-052
	Vector LQ 3rd gen	2 e,μ,τ	≥1 b	Yes	139	LQ_3^V mass	1.96 TeV	$\mathcal{B}(LQ_3^V\to b\tau)=1$, Y-M coupl.	2303.01294
Vector-like fermions	VLQ $TT\to Zt+X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass	1.46 TeV	SU(2) doublet	2210.15413
	VLQ $BB\to Wt/Zb+X$	multi-channel			36.1	B mass	1.3[illegible] TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3}\to Wt+X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3}\to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T\to Ht/Zt$	1 e,μ	≥1 b, ≥3 j	Yes	139	T mass	1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y\to Wb$	1 e,μ	≥1 b, ≥1 j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y\to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B\to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass	2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
	VLL $\tau'\to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass	898 GeV	SU(2) doublet	2303.05441
Exctd ferm.	Excited quark $q^*\to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1910.08447
	Excited quark $q^*\to q\gamma$	1 γ	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1709.10440
	Excited quark $b^*\to bg$	–	1 b, 1 j	–	139	b^* mass	3.2 TeV		1910.08447
	Excited lepton τ^*	2 τ	≥2 j	–	139	τ^* mass	4.6 TeV	$\Lambda=4.6$ TeV	2303.09444
Other	Type III Seesaw	2,3,4 e,μ	≥2 j	Yes	139	N^0 mass	910 GeV		2202.02039
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R)=4.1$ TeV, $g_L=g_R$	1809.11105
	Higgs triplet $H^{\pm\pm}\to W^\pm W^\pm$	2,3,4 e,μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass	350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm}\to\ell\ell$	2,3,4 e,μ (SS)	–	–	139	$H^{\pm\pm}$ mass	1.08 TeV	DY production	2211.07505
	Multi-charged particles	–	–	–	139	multi-charged particle mass	[illegible].59 TeV	DY production, $\lvert q\rvert=5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\lvert g\rvert=1g_D$, spin 1/2	1905.10130

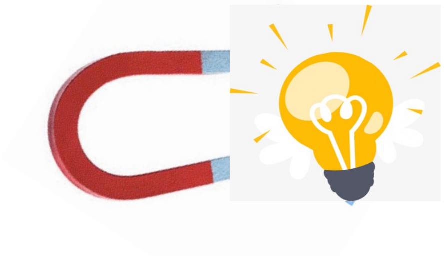
*Only a selection of the available mass limits on new states or phenomena is shown.

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

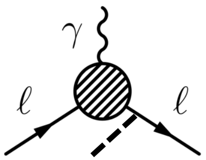
Multi-TeV

but some constrained poorly
because of non-interference effect

Dipole Operator

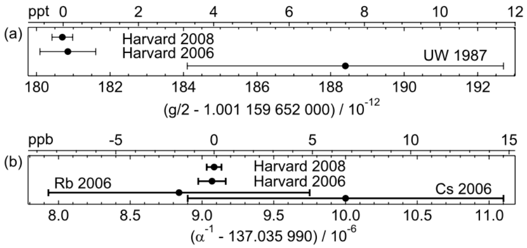


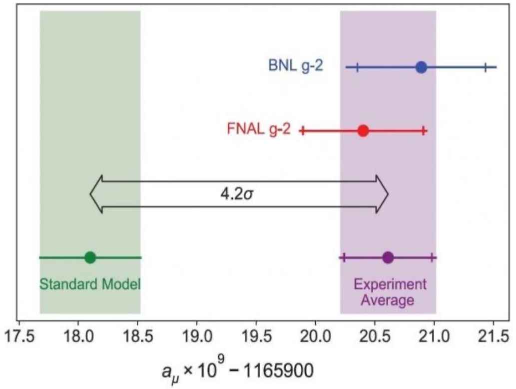
- ✓ Connect Mass and E/M Dipole Moment
- ✓ Loop-induced by the UV BSM
- ✓ Cause Chirality Flip



especially for the "4.2$\boldsymbol{\sigma}$"

Direct & Dominant





D. Hanneke et al., *Phys.Rev.Lett.* 100,(2008)
G.W. Bennett et al. *Phys.Rept.* 887 (2020)
B. Abi et al. *Phys.Rev.Lett.* 126 (2021)

New results from Muon g-2 *Liang Li*

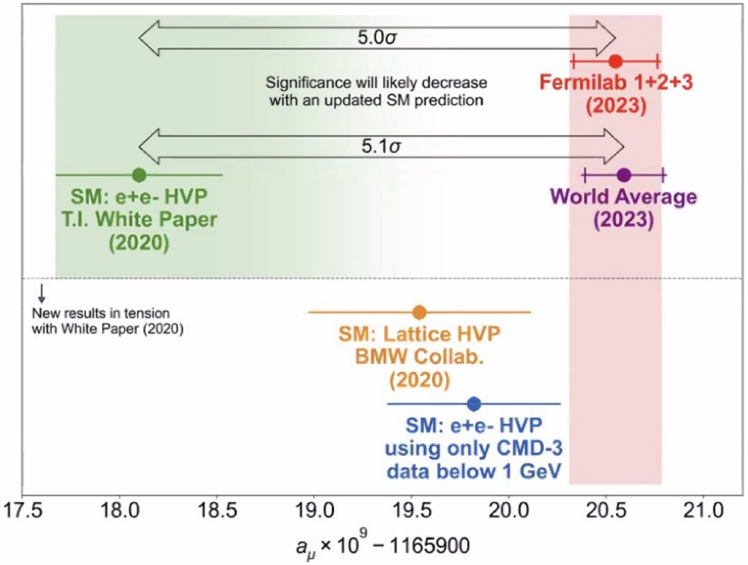
C108, 物理楼 09:40 - 10:05

Experiment vs Theory Comparison

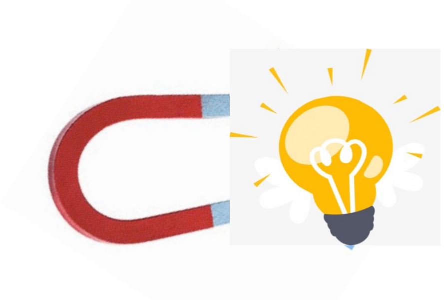
- Theory prediction is less clear now, but we can still compare

See talks of Liang Li and Fermilab papers and so on

Fermilab



Dipole Operator



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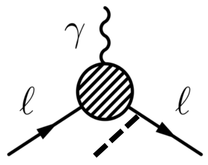
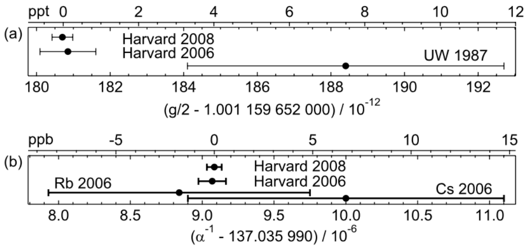
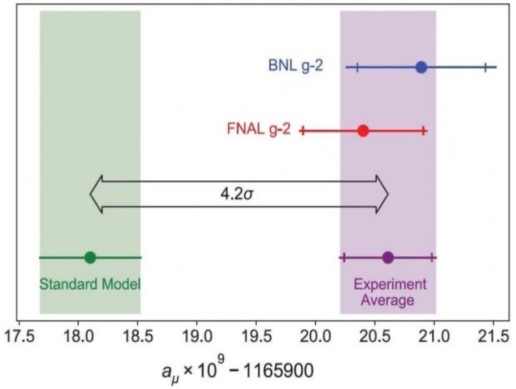


especially for the “4.2σ”

Direct & Dominant





D. Hanneke et al., *Phys.Rev.Lett.* 100,(2008)
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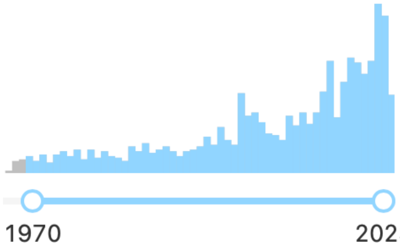
Loop-induced by the BSM

- Encode information about heavy particle interactions
- Indirect probes of quantum effects of NP



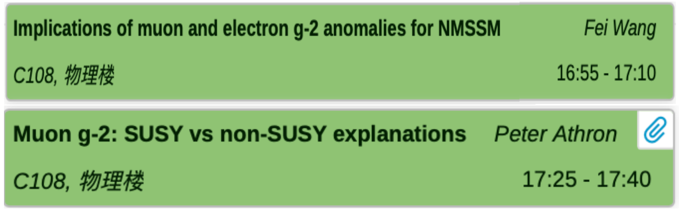
Z' and dark photon model

NMSSM (SUSY)

Scalar extension……

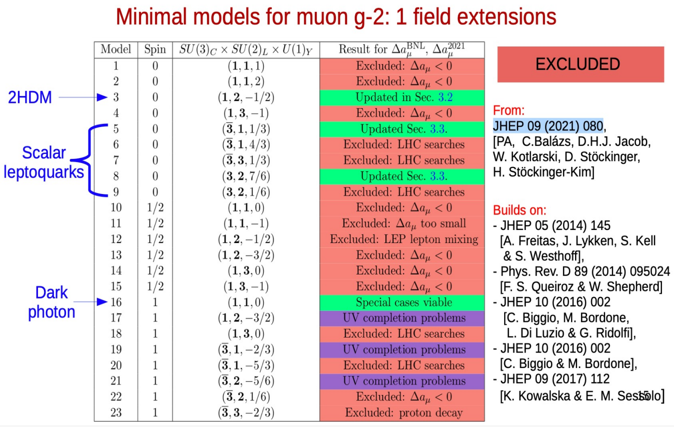
F. Wang et al. *Universe* 9 (2023), 2305.04623
J. Cao et al., 2306.06854
J. Liu et al., *JHEP* 03 (2019), 1810.11028

See talks of Fei Wang, Peter Athron and so on



Implications of muon and electron g-2 anomalies for NMSSM *Fei Wang*
C108, 物理楼 16:55 - 17:10

Muon g-2: SUSY vs non-SUSY explanations *Peter Athron*
C108, 物理楼 17:25 - 17:40



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

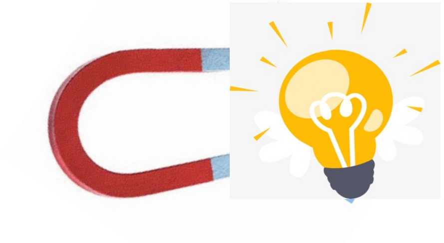
EXCLUDED

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

Builds on:
- JHEP 05 (2014) 145
  [A. Freitas, J. Lykken, S. Kell
  & S. Westhoff],
- Phys. Rev. D 89 (2014) 095024
  [F. S. Queiroz & W. Shepherd]
- JHEP 10 (2016) 002
  [C. Biggio, M. Bordone,
  L. Di Luzio & G. Ridolfi],
- JHEP 10 (2016) 002
  [C. Biggio & M. Bordone],
- JHEP 09 (2017) 112
  [K. Kowalska & E. M. Sessolo]

F. Wang et al. *Nucl.Phys.B* 970 (2021)
Peter Athron et al., *JHEP* 09 (2021) 080
……

Dipole Operator



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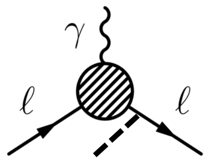

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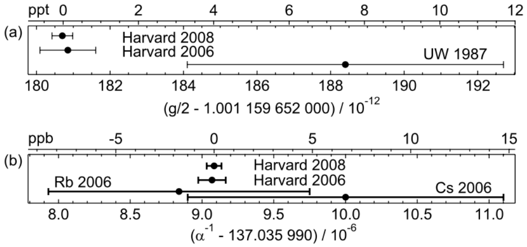

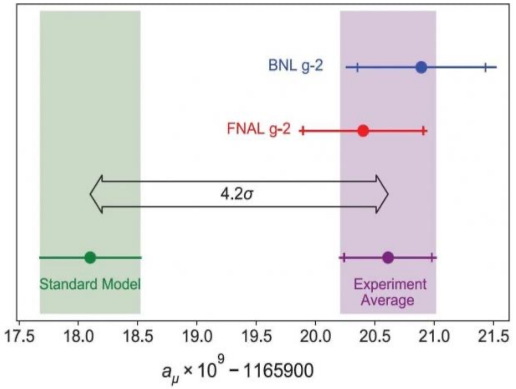

D. Hanneke et al., *Phys.Rev.Lett.* 100,(2008)
G.W. Bennett et al. *Phys.Rept.* 887 (2020)
B. Abi et al. *Phys.Rev.Lett.* 126 (2021)

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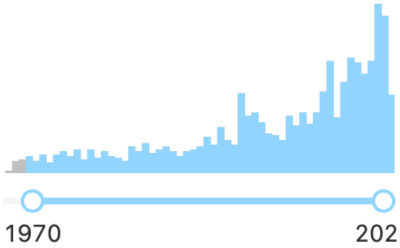

Z' and dark photon model
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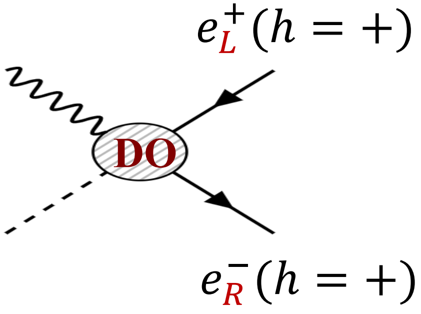
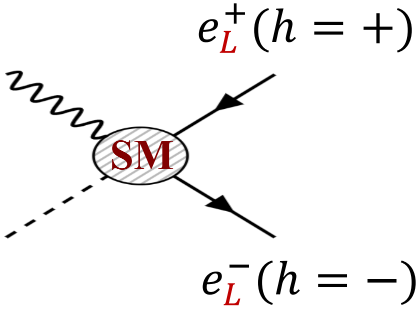
F. Wang et al. *Universe* 9 (2023), 2305.04623
Peter Athron et al., *JHEP* 09 (2021) 080
J. Liu et al., *JHEP* 03 (2019), 1810.11028

Chirality flip

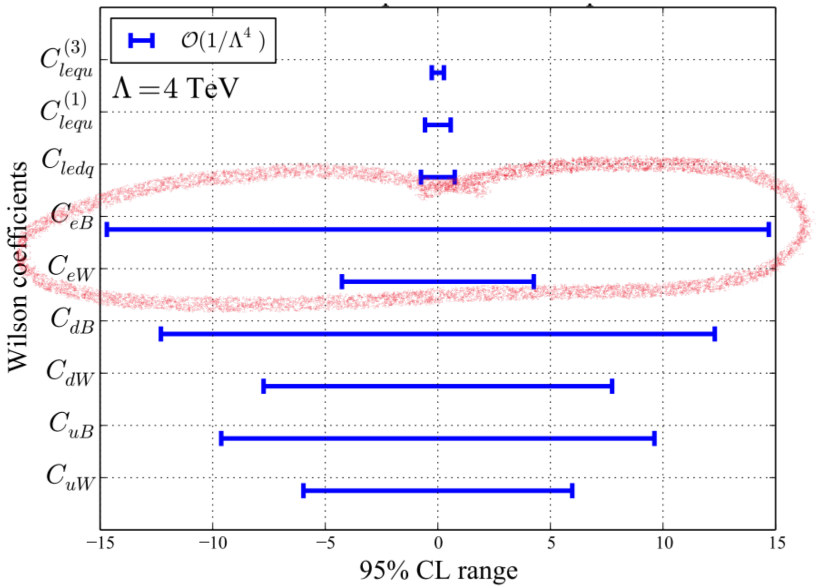
Disappear in massless SM





Proposal and Data for Dipole Operator

In Global Analyses, EW dipole couplings constrained poorly



Single-Parameter-Analysis from recent Drell-Yan Data at LHC

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

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

LHC Drell-Yan: $O(10^{-2} \sim 10^{-1})$

(R. Boughezal et al. *Phys.Rev.D* 104 (2021)…) Even if HL-LHC, lifting at most five times better

LEP Z-boson partial width: $O(10^{-2} \sim 10^{-1})$

(R. Escribano et al. *Nucl.Phys.B* 429 (1994), S. Schael et al. *Phys.Rept.* 427 (2006)…)

EFT running for interpretation $(g-2)_e$: $O(10^{-6} \sim 10^{-2})$

(A. V. Manohar et al. *JHEP* 07 (2021), T. Giani et al. 2302.06660, J. J. Ethier et al. *JHEP* 11 (2021)…)

How to Probe Dipole Operator

Our proposal:

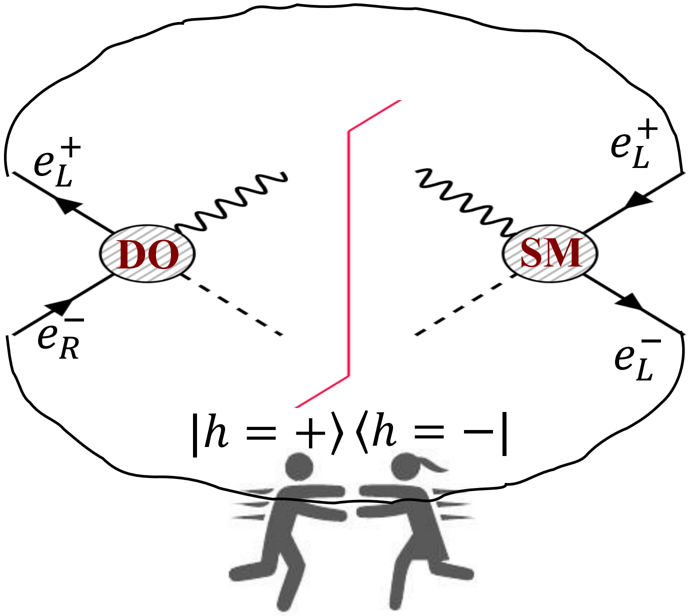
✓ C_{dipole}/Λ^2, interfering with the massless SM

✓ Without depending on other NP operators

✓ Transverse polarization effect

✓ Non-trivial azimuthal angular distribution

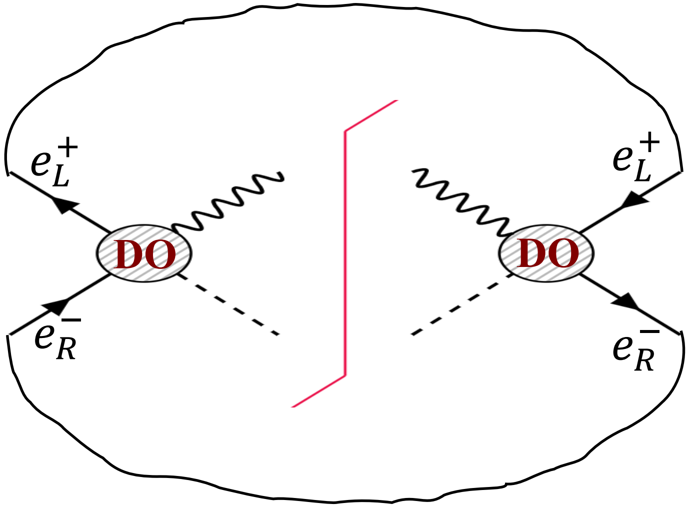
Single Transverse Spin Azimuthal Asymmetries



Traditional method via cross section and width

➢ $|C_{dipole}|^2/\Lambda^4$, small effect from non-interference

➢ Bothered by other operators and assumptions



Transverse Spin Polarization

Transverse polarization effect → Interference of helicity amplitudes

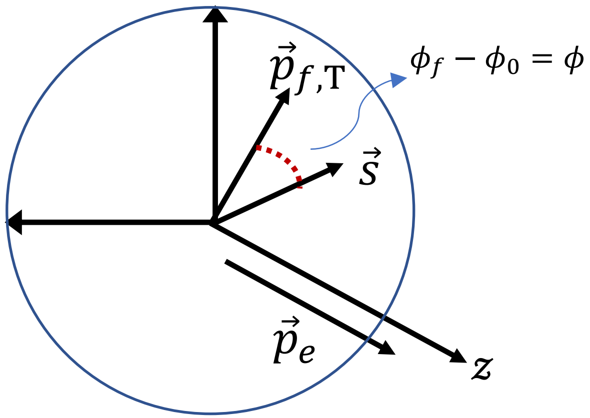
Breaking the rotational invariance & A nontrivial azimuthal behavior

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

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

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

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



Only the azimuthal difference between initial $\vec{s}$ and finial $\vec{p}_f$ physical meaningful

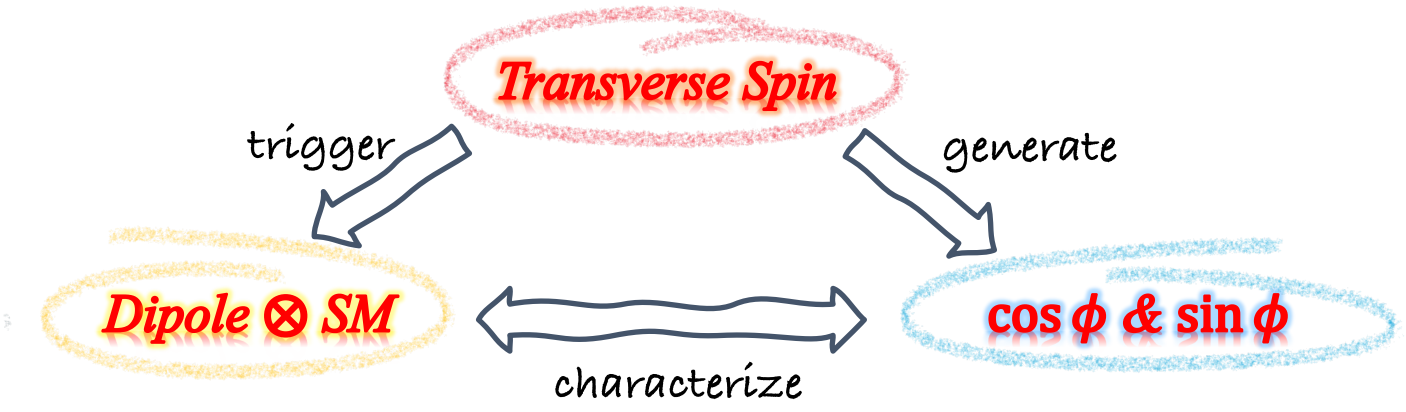
Only dipole operator contribute to $\mathcal{M}_{\pm\pm}$ while $\mathcal{M}^{\mathrm{SM}}_{\pm\pm} = 0$, massless SM only $\mathcal{M}_{\pm\mp} \neq 0$

	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



Transverse Spin

trigger

generate

Dipole ⊗ SM

characterize

$\cos\phi$ & $\sin\phi$

Aligned Spin

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

Opposite Spin

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

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

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

CP-conserving $\qquad$ CP-violation

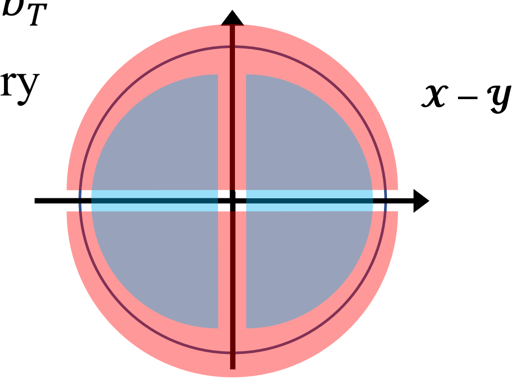
X.-K.W, BY, ZY, C.-P.Y, 2307.05236

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

Using azimuthal asymmetry instead of polarization asymmetry

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

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



Pinning down Dipole Operators

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

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

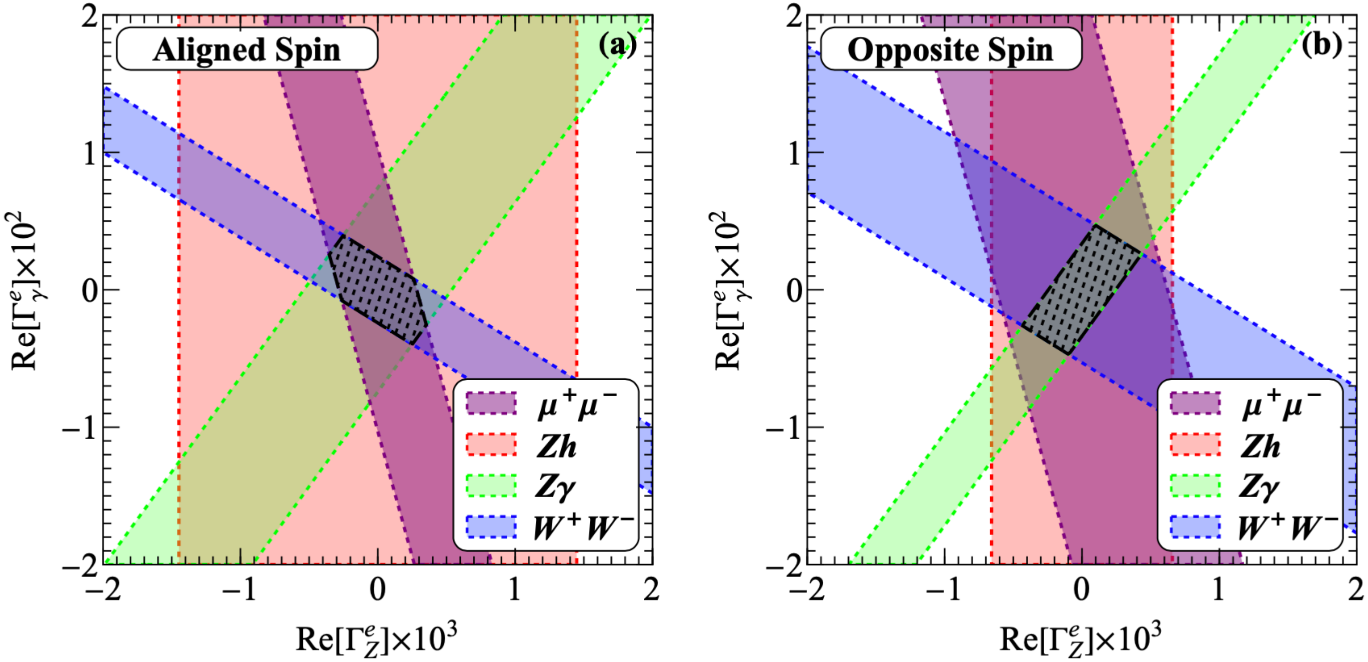
Aligned Spin

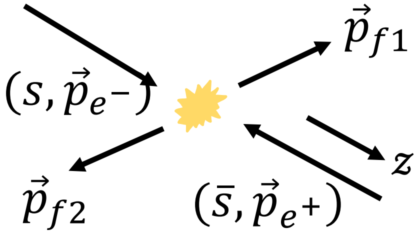
$$\phi_0 = \bar{\phi}_0 = 0$$

Opposite Spin

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

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





CP property

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

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

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

$$A^i(\boldsymbol{s}_T, \bar{\boldsymbol{s}}_T; \Gamma^e_{Z,\gamma}) = \pm A^i(\bar{\boldsymbol{s}}_T, \boldsymbol{s}_T; \Gamma^{e*}_{Z,\gamma})$$

$$(A^{WW,\,\mu\mu}_R,\ A^{Zh,\,Z\gamma}_I) \propto \boldsymbol{s}_T + \bar{\boldsymbol{s}}_T$$

$$(A^{WW,\,\mu\mu}_I,\ A^{Zh,\,Z\gamma}_R) \propto \boldsymbol{s}_T - \bar{\boldsymbol{s}}_T$$

Pinning down Dipole Operators

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

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

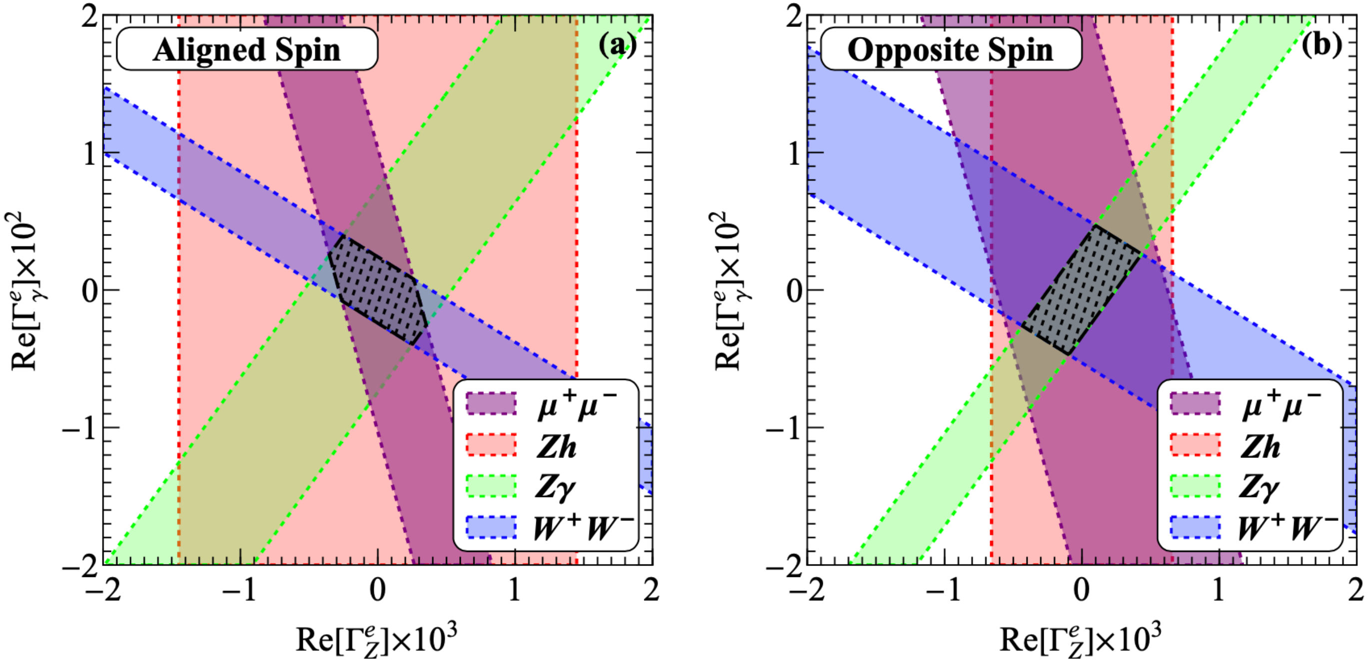
Aligned Spin

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

Opposite Spin

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

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



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

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

Parity property

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

Pinning down Dipole Operators

For the imaginary parts of dipole couplings, things are similar

Aligned Spin

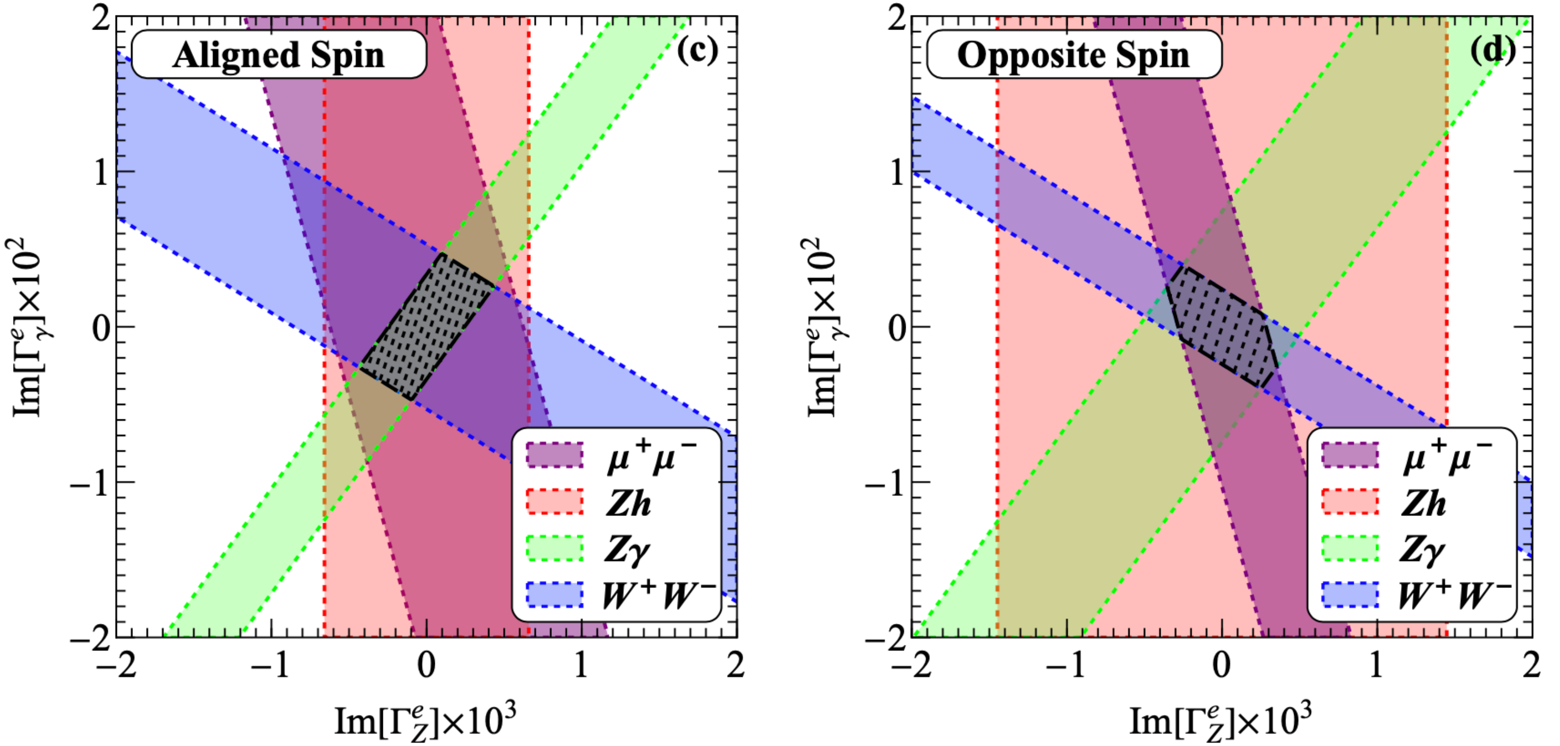
$$\phi_0 = \bar{\phi}_0 = 0$$

Opposite Spin

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

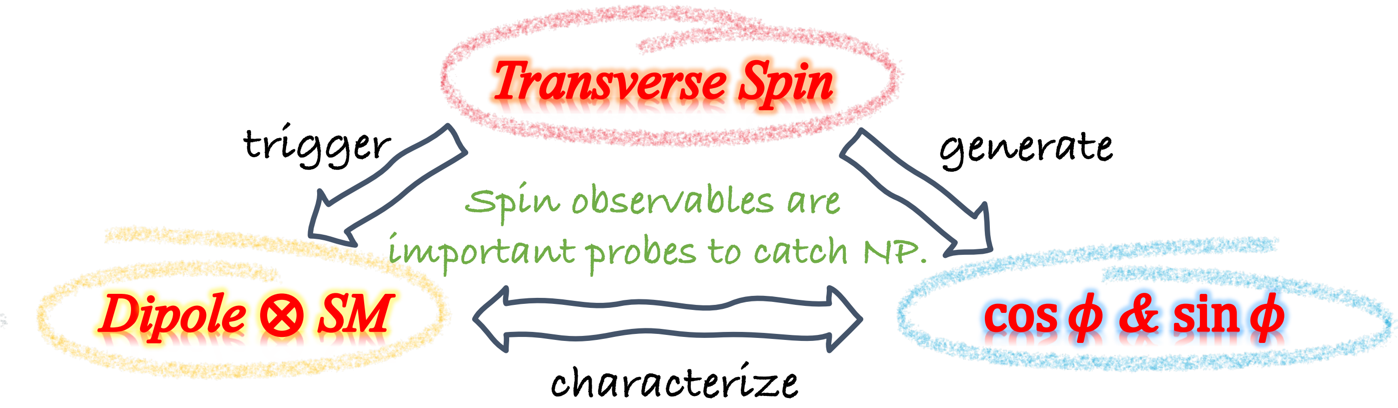
$$\sqrt{s} = 250\ \mathrm{GeV}, \mathcal{L} = 5\ \mathrm{ab}^{-1}$$

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



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

Summary



- ✓ Dipole operators flip fermion helicities being ideally studied at $1/\Lambda^2$ through--

Single Transverse Spin Azimuthal Asymmetries

- ✓ STSAA simultaneously determining 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

	$\lvert\Gamma_Z^e\rvert$	$\lvert\Gamma_A^e\rvert$
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 $\vec{s}(\Theta,\chi)$

$$T_{h\bar{h}} = \langle\phi,\ldots|T|\chi,\bar{\chi}\rangle = \langle\phi=0,\ldots|T|\chi-\phi,\bar{\chi}-\phi\rangle$$

2-to-2 rotational invariance

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

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

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

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

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

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

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

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

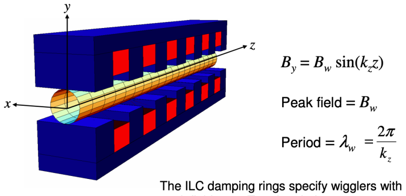
$$\begin{aligned}|M|^2 = |M|^2_{\mathrm{unpol}} &- \frac{1}{2}\lambda_T\bar{\lambda}_T\mathrm{Re}[T^*_{++}T_{--}]\\ &- \frac{1}{2}\lambda_T\bar{\lambda}_T\mathrm{Re}[e^{-2i\phi}T^*_{+-}T_{-+}]\\ &+ \frac{1}{2}\lambda_T\mathrm{Re}\left[e^{-i\phi}(T^*_{+-}T_{--}+T^*_{++}T_{-+})\right]\\ &- \frac{1}{2}\bar{\lambda}_T\mathrm{Re}\left[e^{-i\phi}(T^*_{+-}T_{++}+T^*_{-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

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

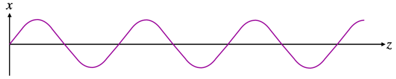
Backup: Polarized beam realization

Transverse polarization is more natural

Sokolov-Ternov effect (92.4%, minutes-hours, 50GeV)
Laser-assistant
Spin-precession



The ILC damping rings specify wigglers with peak field ≈ 1.6 T and period 40 cm.



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