

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



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 $\int \int dt = (3.6 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 13 \text{ TeV}$

Мос	lel ℓ, γ	Jets†	E_{T}^{miss}	∫£ dt[fb	-1]	Lim	it	J~	0 41 - (0	.0 100/10	Reference
ADD <i>G_K</i> ADD on ADD on ADD OE ADD BH RS1 <i>G_K</i> Bulk RS Bulk RS 2UED / I	$\begin{array}{c c} \kappa + g/q & 0 \ e, \mu, \tau \\ r-resonant \gamma \gamma & 2 \gamma \\ H & - \\ multijet & - \\ \kappa \rightarrow \gamma \gamma & 2 \gamma \\ G_{KK} \rightarrow WW/ZZ & multi-cha \\ g_{KK} \rightarrow tt & 1 \ e, \mu \\ PP & 1 \ e, \mu \end{array}$	γ 1 - 4 j 2 j ≥ 3 j - nnel $2 \geq 1$ b, ≥ 1 J/ $2 \geq 2$ b, ≥ 3	Yes - - - 2j Yes j Yes	139 36.7 139 3.6 139 36.1 36.1 36.1 36.1	Mp Ms Mth Mth Grkr mass Grkr mass KK mass			4.5 TeV 2.3 TeV 3.8 TeV 1.8 TeV	11.2 TeV 8.6 TeV 9.4 TeV 9.55 TeV		2102.10874 1707.04147 1910.08447 1512.02586 2102.13405 1808.02380 1804.10823 1803.09678
SSM Z' SSM Z' Leptoph SSM W SSM W SSM W SSM W HVT W HVT W HVT Z' LRSM V		$\begin{array}{cccc} & & - & & & \\ & & & 2 b, \geq 2 \\ & & & - & \\ & & & - & \\ & & & 2 1 b, \geq 1 \\ & & & 2 j (1 J \\ & & & 2 j (VBF) \\ & & & 2 j (VBF) \\ & & & 2 j (J J \\ & & & 1 J \end{array}$	- - Yes Yes J - Yes Yes Yes -	139 36.1 36.1 139 139 139 139 139 139 139 139 80	Z' mass Z' mass Z' mass W' mass W' mass W' mass W' mass W' mass W' mass W, mass	340 GeV		5.1 TeV 2.42 TeV 2.1 TeV 4.1 TeV 5.0 TeV 4.4 TeV 4.3 TeV 3.9 TeV 5.0 TeV 5.0 TeV	V	$\Gamma/m = 1.2\%$ $g_V = 3$ $g_V c_H = 1, g_T = 0$ $g_V = 3$ $m(N_R) = 0.5$ TeV, $g_L = g_R$	1903.06248 1709.07242 1805.08299 2005.05138 1906.05609 ATLAS-CONF-2021-043 2004.14636 2207.03925 2004.14636 1904.12679
CI qqqq CI ℓℓqq CI eebs CI μμbs CI tttt	_ 2 e,μ 2 e 2 μ ≥1 e,	2 j 1 b 1 b 4 ≥1 b, ≥1	- - - j Yes	37.0 139 139 139 36.1	Λ Λ Λ Λ			1.8 TeV 2.0 TeV 2.57 TeV		21.8 TeV η_{LL}^- 35.8 TeV η_{LL}^- $g_* = 1$ $g_* = 1$ $ C_{4t} = 4\pi$	1703.09127 2006.12946 2105.13847 2105.13847 1811.02305
Axial-ver Pseudo- Vector m Pseudo-	tor med. (Dirac DM) – scalar med. (Dirac DM) 0 e, μ, τ ed. Z'-2HDM (Dirac DM) 0 e, μ scalar med. 2HDM+a multi-cha	2j γ 1-4j 2b nnel	- Yes Yes	139 139 139 139	m _{med} m _{med} m _Z , m _a	376 GeV	800 GeV	3.8 TeV 3.0 TeV		$\begin{array}{l} g_q = 0.25, \ g_{\chi} = 1, \ m(\chi) = 10 \ {\rm TeV} \\ g_q = 1, \ g_{\chi} = 1, \ m(\chi) = 1 \ {\rm GeV} \\ \tan\beta = 1, \ g_{\chi} = 0.8, \ m(\chi) = 100 \ {\rm GeV} \\ \tan\beta = 1, \ g_{\chi} = 1, \ m(\chi) = 10 \ {\rm GeV} \end{array}$	ATL-PHYS-PUB-2022-036 2102.10874 2108.13391 ATLAS-CONF-2021-036
Calar L Scalar L Scalar L Scalar L Scalar L Scalar L Vector L	$\begin{array}{llllllllllllllllllllllllllllllllllll$	$ \begin{array}{c} \geq 2j \\ \geq 2j \\ 2b \\ \geq 1 \\ \tau \geq 1j, \geq 1l \\ 1 \\ \tau \\ 0 - 2j, 2 \\ nnel \geq 1j, \geq 1l \\ \tau \\ \geq 1 b \end{array} $	Yes Yes Yes Yes Yes Yes Yes	139 139 139 139 139 139 139 139	LQ mass LQ mass LQ" mass LQ" mass LQ" mass LQ" mass LQ" mass LQ" mass		1.49 1.24 Te 1.43 1.26 Te	1.8 TeV 1.7 TeV 9 TeV 9 TeV 20 2.0 TeV 1.96 TeV		$\begin{array}{l} \beta = 1 \\ \beta = 1 \\ \mathcal{B}(\mathrm{LQ}_3^u \to \mathrm{br}) = 1 \\ \mathcal{B}(\mathrm{LQ}_3^u \to \mathrm{tr}) = 1 \\ \mathcal{B}(\mathrm{LQ}_3^d \to \mathrm{tr}) = 1 \\ \mathcal{B}(\mathrm{LQ}_3^d \to \mathrm{br}) = 1 \\ \mathcal{B}(\tilde{U}_i \to \mathrm{tr}) = 1 \\ \mathcal{B}(\tilde{U}_i \to \mathrm{tr}) = 1, \text{Y-M coupl.} \end{array}$	2006.05872 2006.05872 2303.01294 2004.14060 2101.11582 2101.12527 ATLAS-CONF-2022-052 2303.01294
VLQ TT VLQ BB VLQ T5, VLQ T VLQ T VLQ T VLQ T VLQ T	$\begin{array}{lll} \hline \rightarrow Zt + X & 2e/2\mu \leq t \\ \rightarrow Wt/Zb + X & multi-cha \\ 3 \rightarrow Tb/3 T_{5/3} T_{5/3} + X & 2(SS) \geq 3 \\ 4 + L/2t & 1 & e, \mu \\ \rightarrow Wb & 1 & e, \mu \\ \rightarrow Wb & 0 & e, \mu \\ \rightarrow Z\tau/H\tau & multi-cha \end{array}$	$\begin{array}{llllllllllllllllllllllllllllllllllll$	j – j Yes j Yes j Yes 1J – Yes	139 36.1 36.1 139 36.1 139 139	T mass B mass T _{5/3} mass T mass Y mass B mass r' mass		1.46 1.34 1. 1. 898 GeV	5 TeV TeV 64 TeV 1.8 TeV 1.85 TeV 2.0 TeV		$\begin{array}{l} {\rm SU(2) \ doublet} \\ {\rm SU(2) \ doublet} \\ {\rm SU(2) \ doublet} \\ {\rm SU(2) \ singlet, } \kappa_{T} = 0.5 \\ {\rm SU(2) \ singlet, } \kappa_{T} = 0.5 \\ {\rm SU(2) \ singlet, } \kappa_{R} = 0.3 \\ {\rm SU(2) \ doublet} \\ {\rm sU(2) \ doublet} \\ {\rm supp} \end{array}$	2210.15413 1808.02343 1807.11883 ATLAS-CONF-2021-040 1812.07343 ATLAS-CONF-2021-018 2303.05441
Excited Excited Excited Excited Excited	$\begin{array}{lll} \mbox{uark} q^* \to qg & - \\ \mbox{quark} q^* \to q\gamma & 1 \ \gamma \\ \mbox{quark} b^* \to bg & - \\ \mbox{epton} \ \tau^* & 2 \ \tau \end{array}$	2j 1j 1b,1j ≥2j	_ _ _	139 36.7 139 139	q* mass q* mass b* mass τ* mass			6.7 1 5.3 TeV 3.2 TeV 4.6 TeV	ſeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 4.6 \text{ TeV}$	1910.08447 1709.10440 1910.08447 2303.09444
Type III 3 LRSM M Higgs tri Higgs tri Multi-ch. Magneti	Seesaw 2,3,4 e ajorana v 2 μ polet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ 2,3,4 e, μ arged particles - to monopoles - $\sqrt{s} = 13 \text{ Term}^{+}$,μ ≥2j 2j (SS) various (SS) - - - - - - - - - - - - - - - - - - -	Yes Yes - 3 TeV lata	139 36.1 139 139 139 34.4	Nº mass N _R mass H ^{±±} mass H ^{±±} mass multi-charged partic monopole mass 10 ⁻¹	350 GeV e mass	910 GeV 1.08 TeV 1.3	3.2 TeV 59 TeV 2.37 TeV	<u></u> 10	$m(W_R) = 4.1$ TeV, $g_L = g_R$ DY production DY production DY production, $ q = 5e$ DY production, $ g = 1g_D$, spin 1/2 Mass scale [TeV]	2202.02039 1809.11105 2101.11961 2211.07505 ATLAS-CONF-2022-034 1905.10130

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



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



W. Buchuller, D. wyler 1986

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

.

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



SMEFT Analysis:

B. Grzadkowski et al, 2010

Citations per year





Data for Dipole Operator



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

New Physics and Dipole Operator



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 $o\left(\frac{1}{\Lambda^2}\right)$?

Transverse polarization effect of beams:

The interference between the different helicity states

$$\boldsymbol{s} = (b_1, b_2, \lambda) = (b_{\mathrm{T}} \cos \phi_0, b_{\mathrm{T}} \sin \phi_0, \lambda)$$
$$\rho = \frac{1}{2} (1 + \boldsymbol{\sigma} \cdot \boldsymbol{s}) = \frac{1}{2} \begin{pmatrix} 1 + \lambda & b_{\mathrm{T}} e^{-i\phi_0} \\ b_{\mathrm{T}} e^{i\phi_0} & 1 - \lambda \end{pmatrix}$$

✓ Without depending on other NP operators



Transverse Spin Polarization



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

Single Transverse Spin Asymmetries



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

$$A_{LR}^{i} = \frac{\sigma^{i}(\cos\phi > 0) - \sigma^{i}(\cos\phi < 0)}{\sigma^{i}(\cos\phi > 0) + \sigma^{i}(\cos\phi < 0)} = \frac{2}{\pi}A_{R}^{i}$$
$$A_{UD}^{i} = \frac{\sigma^{i}(\sin\phi > 0) - \sigma^{i}(\sin\phi < 0)}{\sigma^{i}(\sin\phi > 0) + \sigma^{i}(\sin\phi < 0)} = \frac{2}{\pi}A_{I}^{i},$$





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



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

The sensitivity to Γ_Z^e is much stronger than Γ_{γ}^e



Parity property

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

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

• SM
$$(g_L^e + g_R^e) = -1/2 + 2s_W^2 \ll 1$$

• SM $WW\gamma < WWZ$

•
$$\Gamma^e_W = \Gamma^e_Z + s^2_W \Gamma^e_\gamma$$

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
- $\checkmark\,$ 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