Dimension-8 SMEFT Study of Neutral Triple Gauge Couplings at LHC and future colliders

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Standard Model Effective Field Theory and Dimension-8 Operators

SMEFT is a model independent way to look for BSM physics

- Higher-dimensional operators as relics of higher energy physics
- Constrain operator coefficients with global analysis of experimental data;
- Non-zero c_i would indicate BSM:
  Masses($\sim \Lambda$), spins, quantum numbers of new particles?
- Most analyses focus on dimension-6:
  $\mathcal{L}_{eff} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i = \sum_i \frac{\text{sign}(c_j)}{\Lambda_j^2}\mathcal{O}_i$
- Dimension-8 contributions scaled by quartic power of new physics scale:
  $\mathcal{L}_{eff} = \sum_i \frac{c_i}{\Lambda^4}\mathcal{O}_i = \sum_i \frac{\text{sign}(c_j)}{\Lambda_j^4}\mathcal{O}_i$
- Study processes without dimension-6 contributions
- Neutral triple-gauge couplings (nTGCs): $Z\gamma Z^*$, $Z\gamma\gamma^*$

Dimension-8 Operators Contributing to nTGCs

$$
\begin{aligned}
g\mathcal{O}_{G+} &= \widetilde{B}_{\mu\nu} W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda} + D^\nu D^\lambda W^a_{\lambda\rho}), \\
g\mathcal{O}_{G-} &= \widetilde{B}_{\mu\nu} W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda} - D^\nu D^\lambda W^a_{\lambda\rho}), \\
\mathcal{O}_{\widetilde{B}W} &= \mathrm{i}\, H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho}\{D_\rho, D^\nu\}H + \text{h.c.}, \\
\mathcal{O}_{C+} &= \widetilde{B}_{\mu\nu} W^{a\mu\rho}\Big[D_\rho(\overline{\psi_L} T^a \gamma^\nu \psi_L) + D^\nu(\overline{\psi_L} T^a \gamma_\rho \psi_L)\Big], \\
\mathcal{O}_{C-} &= \widetilde{B}_{\mu\nu} W^{a\mu\rho}\Big[D_\rho(\overline{\psi_L} T^a \gamma^\nu \psi_L) - D^\nu(\overline{\psi_L} T^a \gamma_\rho \psi_L)\Big].
\end{aligned}
$$

$\mathcal{O}_{C+}$ and $\mathcal{O}_{C-}$ are connected to $(\mathcal{O}_{G+}, \mathcal{O}_{G-}, \mathcal{O}_{\widetilde{B}W})$ by the equation of motion:

$$
\begin{aligned}
\mathcal{O}_{C+} &= \mathcal{O}_{G-} - \mathcal{O}_{\widetilde{B}W}, \\
\mathcal{O}_{C-} &= \mathcal{O}_{G+} - \{\mathrm{i} H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho}[D_\rho, D^\nu]H + \mathrm{i}\,2(D_\rho H)^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} D^\nu H + \text{h.c.}\}.
\end{aligned}
$$

3 independent nTGC operators

Only ψ_L in $\mathcal{O}_{C-}$ $\rightarrow$ $\mathcal{O}_{G+}$ can not contribute to $\psi_R \bar{\psi}_R \rightarrow Z\gamma$

nTGCs

Dimension-8:

$$\Gamma^{\alpha\beta\mu}_{Z\gamma Z^*(G+)}(q_1,q_2,q_3) \;=\; -\frac{v(q_3^2-M_Z^2)}{M_Z\,[\Lambda^4_{G+}]}\left(q_3^2\, q_{2\nu}\epsilon^{\alpha\beta\mu\nu}+2q_2^\alpha q_{3\nu} q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right),$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma\gamma^*(G+)}(q_1,q_2,q_3) \;=\; -\frac{s_W\, v\, q_3^2}{c_W M_Z\,[\Lambda^4_{G+}]}\left(q_3^2\, q_{2\nu}\epsilon^{\alpha\beta\mu\nu}+2q_2^\alpha q_{3\nu} q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right),$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma Z^*(\widetilde{B}W)}(q_1,q_2,q_3) \;=\; \frac{v\, M_Z\,(q_3^2-M_Z^2)}{[\Lambda^4_{\widetilde{B}W}]}\epsilon^{\alpha\beta\mu\nu} q_{2\nu}\,,$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma\gamma^*(G-)}(q_1,q_2,q_3) \;=\; -\frac{s_W\, v\, M_Z}{c_W\,[\Lambda^4_{G-}]}\epsilon^{\alpha\beta\mu\nu} q_{2\nu} q_3^2\,.$$

Conventional form factor parameterization(arXiv:hep-ph/9910395):

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V^*}(q_1,q_2,q_3) \;=\; \frac{e\,(q_3^2-M_V^2)}{M_Z^2}\left(h_3^V\, q_{2\nu}\epsilon^{\alpha\beta\mu\nu}+\frac{h_4^V}{M_Z^2}\, q_2^\alpha\, q_{3\nu}\, q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right),$$

Full SU(2)×U(1) gauge constraints:

$$\Gamma^{\alpha\beta\mu(8)}_{Z\gamma V^*}(q_1,q_2,q_3) \;=\; \frac{e\,(q_3^2-M_V^2)}{M_Z^2}\left[\left(h_3^V+h_5^V\,\frac{q_3^2}{M_Z^2}\right) q_{2\nu}\epsilon^{\alpha\beta\mu\nu}+\frac{h_4^V}{M_Z^2}\, q_2^\alpha\, q_{3\nu}\, q_{2\sigma}\,\epsilon^{\beta\mu\nu\sigma}\right],$$

$\mathcal{O}(E^5)$ terms must cancel each other in amplitude with longitudinal Z:

$$\mathcal{T}[f\bar{f}\to Z_L\gamma] = h_3^V\, O(E^3)+h_4^V\, O(E^5)+h_5^V\, O(E^5) = \Lambda_j^{-4}\, O(E^3)\,.$$

Matching Form Factors to Dimension-8 Operators

$\mathcal{T}[f\bar{f} \to Z_L\gamma]$ as contributed by the gauge-invariant dimension-8 nTGC operators must obey the equivalence theorem (ET):

$$\mathcal{T}_{(8)}[Z_L, \gamma_T] \;=\; \mathcal{T}_{(8)}[-\mathrm{i}\pi^0, \gamma_T] + B\,,$$

The residual term $B = \mathcal{T}_{(8)}[v^\mu Z_\mu, \gamma_T]$ is suppressed by the relation
$v^\mu \equiv \epsilon_L^\mu - q_Z^\mu / M_Z = O(M_Z/E_Z)$.
Only $\mathcal{O}_{\widetilde{B}W}$ could give a nonzero contribution to $\mathcal{T}_{(8)}[-\mathrm{i}\pi^0, \gamma_T] = \mathcal{O}(E^3)$
$\mathcal{O}_{G_+}$ does not contribute to $\mathcal{T}_{(8)}[-\mathrm{i}\pi^0, \gamma_T]$, but can contribute $B = \mathcal{O}(E^3)$.

h_4^Z / h_4^γ must be fixed to cancel their contributions to
$\mathcal{T}[f\bar{f} \to Z^* \to Z\gamma] + \mathcal{T}[f\bar{f} \to \gamma^* \to Z\gamma]$ via right-handed fermions.

Relations between form factor coefficients $h_4^V = 2\,h_5^V$, $h_4^Z = \frac{c_W}{s_W}\,h_4^\gamma$ and :

$$h_4 = -\frac{\mathrm{sign}(\tilde{c}_{G+})}{\Lambda_{G+}^4}\frac{v^2 M_Z^2}{s_W c_W} \equiv \frac{r_4}{[\Lambda_{G+}^4]}\,,\; h_3^V = 0\,, \quad \text{for } \mathcal{O}_{G+}\,,$$

$$h_3^Z = \frac{\mathrm{sign}(\tilde{c}_{\widetilde{B}W})}{\Lambda_{\widetilde{B}W}^4}\frac{v^2 M_Z^2}{2 s_W c_W} \equiv \frac{r_3^Z}{[\Lambda_{\widetilde{B}W}^4]}\,,\; h_3^\gamma, h_4^V = 0 \text{ for } \mathcal{O}_{\widetilde{B}W}\,,$$

$$h_3^\gamma = -\frac{\mathrm{sign}(\tilde{c}_{G-})}{\Lambda_{G-}^4}\frac{v^2 M_Z^2}{2 c_W^2} \equiv \frac{r_3^\gamma}{[\Lambda_{G-}^4]}\,. \quad h_3^Z, h_4^V = 0 \text{ for } \mathcal{O}_{G-}\,,$$

nTGC Contributions to $q\bar{q} \to Z\gamma$

$$\sigma = \sigma_0 + \sigma_1 + \sigma_2$$

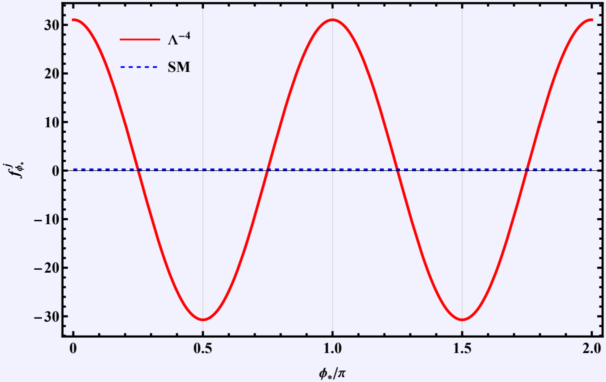
$$\sigma_0 = \frac{e^4(q_L^2+q_R^2)\,Q^2\left[-(s-M_Z^2)^2-2(s^2+M_Z^4)\ln\sin\frac{\delta}{2}\right]}{8\pi s_W^2 c_W^2 (s-M_Z^2)s^2} = \mathcal{O}(s^{-1}),$$

$$\begin{aligned}
\sigma_1 &= \frac{e^2 q_L Q\, T_3 M_Z^2 (s-M_Z^2)}{4\pi s_W c_W s}\frac{1}{[\Lambda_{G+}^4]} - \frac{e^2 Q(q_L x_L - q_R x_R) M_Z^2 (s-M_Z^2)(s+M_Z^2)}{8\pi s_W c_W\, s^2}\frac{1}{[\Lambda_j^4]}, \\
&= \frac{e^2 q_L Q\, T_3 M_Z^2 (s-M_Z^2)}{4\pi s_W c_W s}\frac{h_4}{r^4} - \frac{e^2 Q(q_L x_L - q_R x_R) M_Z^2 (s-M_Z^2)(s+M_Z^2)}{8\pi s_W c_W\, s^2}\frac{h_3^V}{r_3^V} \\
&= h_4\mathcal{O}(s^0) + h_3^V\mathcal{O}(s^0),
\end{aligned}$$

$$\begin{aligned}
\sigma_2 &= \frac{T_3^2(s+M_Z^2)(s-M_Z^2)^3}{48\pi s}\frac{1}{\Lambda_{G+}^8} + \frac{(x_L^2+x_R^2)M_Z^2(s+M_Z^2)(s-M_Z^2)^3}{48\pi s^2}\frac{1}{\Lambda_j^8} + \text{cross terms} \\
&= \frac{T_3^2(s+M_Z^2)(s-M_Z^2)^3}{48\pi s}\left(\frac{h_4}{r_4}\right)^2 + \frac{(x_L^2+x_R^2)M_Z^2(s+M_Z^2)(s-M_Z^2)^3}{48\pi s^2}\left(\frac{h_3^V}{r_3^V}\right)^2 + \text{cross terms} \\
&= (h_4)^2\mathcal{O}(s^3) + (h_3^V)^2\mathcal{O}(s^2) + \text{cross terms},
\end{aligned}$$

$$\begin{aligned}
(x_L, x_R) &= -Q s_W^2(1, 1), && (\text{for } \mathcal{O}_j = \mathcal{O}_{G-}), \\
(x_L, x_R) &= \left(T_3 - Q s_W^2, -Q s_W^2\right), && (\text{for } \mathcal{O}_j = \mathcal{O}_{\widetilde{B}W}), \\
(x_L, x_R) &= -(T_3, 0), && (\text{for } \mathcal{O}_j = \mathcal{O}_{C+}).
\end{aligned}$$

Azimuthal Angle Distribution of $\mathcal{O}_{G+}$ & h_4

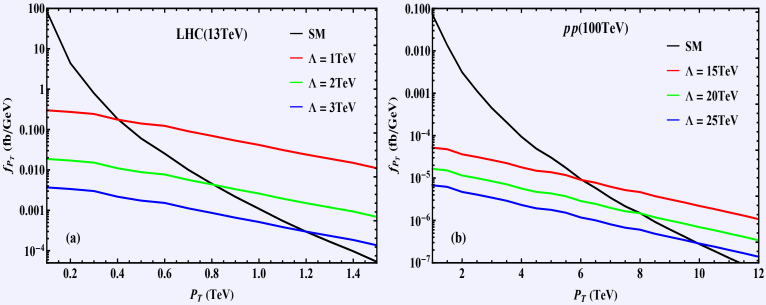


$$f^0_{\phi_*} = \frac{1}{2\pi} + \frac{3\pi^2(q_L^2-q_R^2)(f_L^2-f_R^2)M_Z\sqrt{s}\,(s+M_Z^2)\cos\phi_* - 8(q_L^2+q_R^2)(f_L^2+f_R^2)M_Z^2\, s\cos 2\phi_*}{16\pi(q_L^2+q_R^2)(f_L^2+f_R^2)\left[(s-M_Z^2)^2+2(s^2+M_Z^4)\ln\sin\frac{\delta}{2}\right]} + O(\delta),$$

$$f^1_{\phi_*} = \frac{1}{2\pi} - \frac{3\pi(f_L^2-f_R^2)(M_Z^2+5\,s)\cos\phi_*}{256(f_L^2+f_R^2)M_Z\sqrt{s}} + \frac{s\cos 2\phi_*}{8\pi M_Z^2},$$

$$f^2_{\phi_*} = \frac{1}{2\pi} - \frac{9\pi(f_L^2-f_R^2)M_Z\sqrt{s}\,\cos\phi_*}{128(f_L^2+f_R^2)(s+M_Z^2)},$$

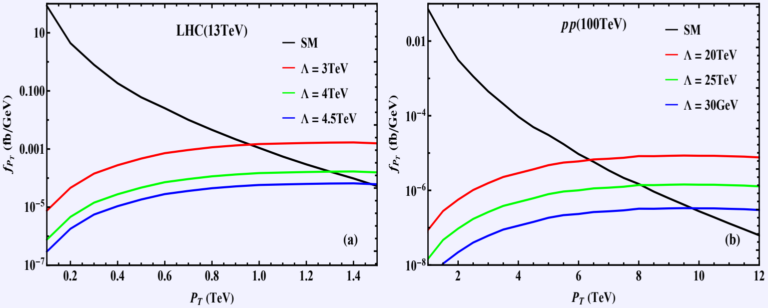
Photon Transverse Momentum Distribution at $\mathcal{O}(1/\Lambda^4)$



SM ϕ_* distribution $f^0_{\phi_*}$ is nearly flat
Maximum of the nTGC contribution $f^1_{\phi_*}$ is at $\phi_* = 0$

$$f^j_{P_T} = \left.\frac{2\pi d^2\sigma_j}{dP_T\, d\phi_*}\right|_{\phi_*=0} .$$

Photon Transverse Momentum Distribution at $\mathcal{O}(1/\Lambda^8)$



Sensitivity Estimates

$$\mathcal{Z} = \sqrt{2\left(B \ln \frac{B}{B+S} + S\right)} = \sqrt{2\left(\sigma_0 \ln \frac{\sigma_0}{\sigma_0+\Delta\sigma} + \Delta\sigma\right)} \times \sqrt{\mathcal{L} \times \epsilon}\,,$$

$\mathcal{L}$ is the integrated luminosity, and ϵ is the detection efficiency

$$\Lambda \propto (\mathcal{L}\times\epsilon)^{1/16}, \qquad (\text{for } B \gg S),$$
$$\Lambda \propto (\mathcal{L}\times\epsilon)^{1/8}, \qquad (\text{for } S \gg B).$$

Sensitivities for $Z \to ll$

$\sqrt{s}$	LHC (13 TeV)			pp (100 TeV)		
$\mathcal{L}$ (ab^{-1})	0.14	0.3	3	3	10	30
$\Lambda_{G+}^{2\sigma}$ (TeV)	3.2	3.4	4.1	22	25	27
$\Lambda_{G+}^{5\sigma}$ (TeV)	2.7	2.9	3.6	19	21	23

Including $Z \to \nu\nu$

$\sqrt{s}$	LHC (13 TeV)			pp (100 TeV)		
$\mathcal{L}$ (ab^{-1})	0.14	0.3	3	3	10	30
$\Lambda_{G+}^{2\sigma}$ (TeV)	3.5	3.8	4.4	25	27	30
$\Lambda_{G+}^{5\sigma}$ (TeV)	3.0	3.2	3.9	21	23	26

SMEFT Form Factor Sensitivities

$\sqrt{s}$	13 TeV ($\ell\bar{\ell}$)			13 TeV ($\ell\bar{\ell}, \nu\bar{\nu}$)		
$\mathcal{L}(\mathrm{ab}^{-1})$	0.14	0.3	3	0.14	0.3	3
$\lvert h_4 \rvert \times 10^6$	11 (21)	8.5 (16)	4.3 (7.3)	7.6 (14)	6.0 (11)	3.1 (5.3)
$\lvert h_3^Z \rvert \times 10^4$	2.2 (3.9)	1.7 (3.0)	0.89 (1.5)	1.5 (2.7)	1.2 (2.2)	0.67 (1.1)
$\lvert h_3^\gamma \rvert \times 10^4$	2.5 (4.5)	2.0 (3.5)	1.0 (1.7)	1.8 (3.1)	1.4 (2.5)	0.77 (1.3)
$\sqrt{s}$	100 TeV ($\ell\bar{\ell}$)			100 TeV ($\ell\bar{\ell}, \nu\bar{\nu}$)		
$\mathcal{L}(\mathrm{ab}^{-1})$	3	10	30	3	10	30
$\lvert h_4 \rvert \times 10^9$	4.7 (9.6)	3.0 (5.9)	2.1 (3.9)	3.1 (6.2)	2.1 (3.9)	1.5 (2.7)
$\lvert h_3^Z \rvert \times 10^7$	7.0 (1.3)	4.7 (8.6)	3.4 (6.0)	4.9 (8.9)	3.4 (6.0)	2.5 (4.2)
$\lvert h_3^\gamma \rvert \times 10^7$	8.0 (15)	5.5 (10)	3.9 (6.9)	5.6 (10)	3.9 (6.9)	2.9 (4.9)

2σ, 5σ

With same integrated luminosity, bounds at 100TeV pp colliders is around $\mathcal{O}(10^{-3})$ of bounds at LHC.
Bounds of h_4 is $\mathcal{O}(10^{-2})$ of bounds of h_3^V.

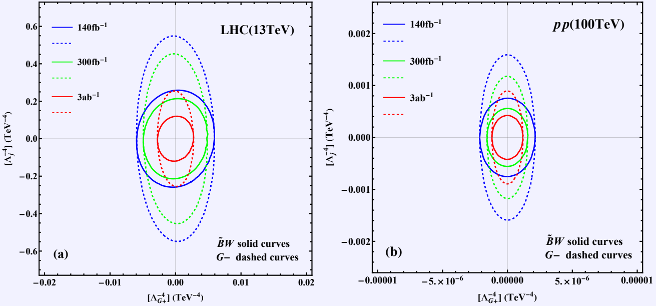
Comparison of SMEFT and Naive Form Factor Sensitivities

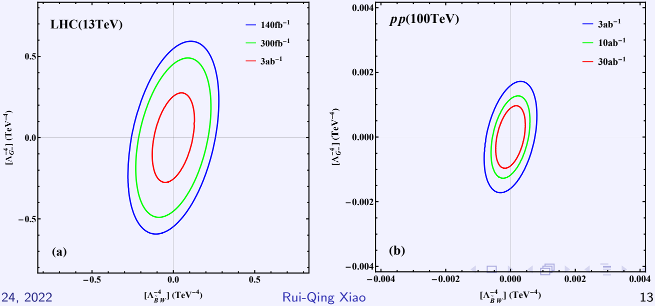
$\sqrt{s}$	13 TeV $(\ell\bar{\ell},\nu\bar{\nu})$			$\sqrt{s}$	100 TeV $(\ell\bar{\ell},\nu\bar{\nu})$		
$\mathcal{L}\,(\mathrm{ab}^{-1})$	0.14	0.3	3	$\mathcal{L}\,(\mathrm{ab}^{-1})$	3	10	30
$\lvert h_4\rvert\times 10^6$	7.6	6.0	3.1	$\lvert h_4\rvert\times 10^9$	3.1	2.1	1.5
$\lvert h_4^Z\rvert\times 10^7$	4.1	3.2	1.7	$\lvert h_4^Z\rvert\times 10^{11}$	2.2	1.5	1.0
$\lvert h_4^\gamma\rvert\times 10^7$	4.8	3 .8	2.0	$\lvert h_4^\gamma\rvert\times 10^{11}$	2.5	1.7	1.2

h_4 is much weaker than conventional form factors h_4^V
$\mathcal{O}(20)$ at LHC and $\mathcal{O}(100)$ at 100TeV pp colliders

Correlations between Sensitivities

$$\rho(x,y) = -\frac{\sigma_2(xy)}{2\sqrt{\sigma_2(x^2)\sigma_2(y^2)}}, \qquad \rho(\Lambda_{G+}^{-4},\Lambda_j^{-4}) \propto s^{-1/2}, \qquad \rho(\Lambda_{\widetilde{B}W}^{-4},\Lambda_{G-}^{-4}) \propto s^0$$





Comparison with Experimental Analysis($Z \to \nu\bar{\nu}$)

CMS Run-I(arXiv:1602.07152): $\sqrt{s}$=8TeV $\mathcal{L}$=19.6fb^{-1}
ATLAS Run-II(arXiv:1810.04995): $\sqrt{s}$=13TeV $\mathcal{L}$=36.1fb^{-1}

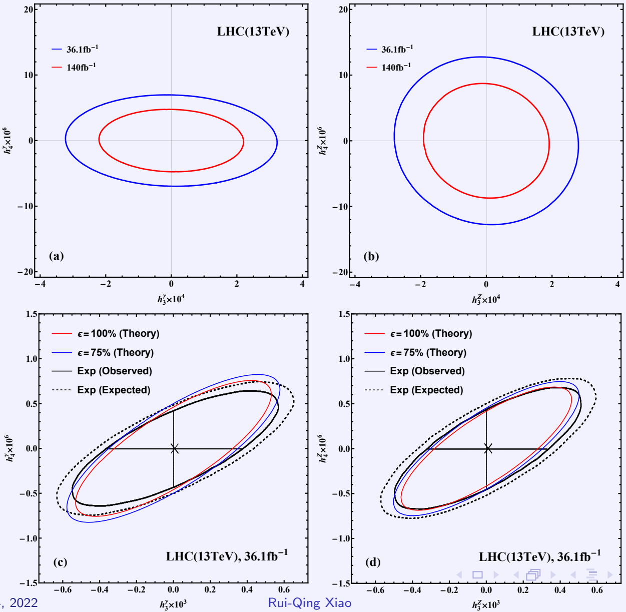
$$\begin{aligned} \text{CMS:} \quad & h_3^Z \in (-1.5,\, 1.6)\times 10^{-3}, \quad && h_3^\gamma \in (-1.1,\, 0.9)\times 10^{-3}, \\ & h_4^Z \in (-3.9,\, 4.5)\times 10^{-6}, && h_4^\gamma \in (-3.8,\, 4.3)\times 10^{-6}; \\ \text{ATLAS:} \quad & h_3^Z \in (-3.2,\, 3.3)\times 10^{-4}, && h_3^\gamma \in (-3.7,\, 3.7)\times 10^{-4}, \\ & h_4^Z \in (-4.5,\, 4.4)\times 10^{-7}, && h_4^\gamma \in (-4.4,\, 4.3)\times 10^{-7}. \end{aligned}$$

For ATLAS inputs(13TeV, 36.1fb^{-1}, assuming $\epsilon = 0.75$), we use conventional form factors to derive the bounds:

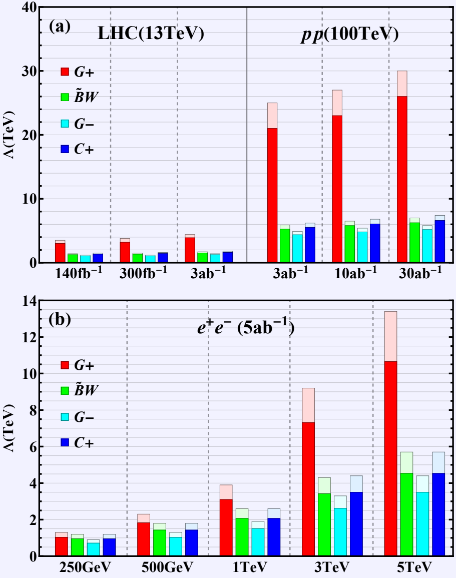
$$|h_3^Z| < 2.7\times 10^{-4}, \quad |h_3^\gamma| < 3.1\times 10^{-4}, \quad |h_4^Z| < 4.1\times 10^{-7}, \quad |h_4^\gamma| < 4.5\times 10^{-7},$$

Comparison of Correlainons

$$\rho(h_4, h_3^V) \propto s^{-1/2}, \qquad \rho(h_4^V, h_3^V) \propto s^0$$



Operator Sensitivities



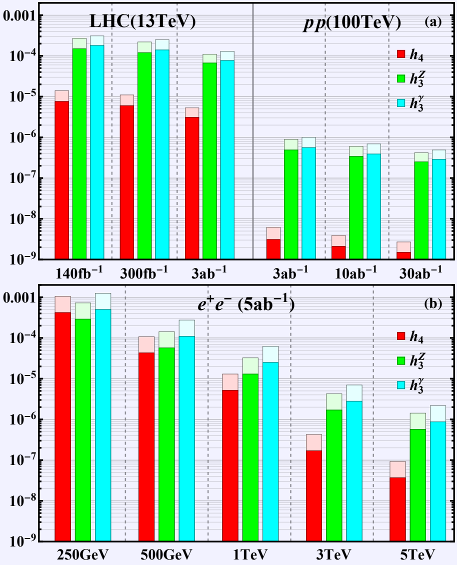
2σ(light color), 5σ(heavy color)

Comparison of e^+e^-, pp Colliders

$\sqrt{s}$ (TeV)	$\mathcal{L}$ (ab^{-1})	Λ_{G+}	Λ_{G-}	$\Lambda_{\widetilde{B}W}$	Λ_{C+}
e^+e^- (0.25)	5	(1.3, 1.6)	(0.9, 1.1)	(1.2, 1.3)	(1.2, 1.6)
e^+e^- (0.5)	5	(2.3, 2.7)	(1.3, 1.7)	(1.8, 1.9)	(1.8, 2.2)
e^+e^- (1)	5	(3.9, 4.7)	(1.9, 2.4)	(2.6, 2.6)	(2.6, 2.9)
e^+e^- (3)	5	(9.2, 11.0)	(3.3, 4.2)	(4.3, 4.5)	(4.4, 5.2)
e^+e^- (5)	5	(13.4, 15.9)	(4.4, 5.5)	(5.7, 5.9)	(5.7, 6.8)
LHC (13)	0.14	3.5	1.2	1.4	1.5
	0.3	3.8	1.2	1.5	1.6
	3	4.4	1.4	1.7	1.8
pp (100)	3	25	4.9	5.9	6.2
	10	27	5.4	6.5	6.8
	30	30	5.8	7.0	7.4

arXiv:2206.11676

Form Factor Sensitivities



2σ(heavy color), 5σ(light color)

Comparison of e^+e^-, pp Colliders

$\sqrt{s}$ (TeV)	$\mathcal{L}$ (ab^{-1})	$\lvert h_4 \rvert$	$\lvert h_3^Z \rvert$	$\lvert h_3^\gamma \rvert$
e^+e^- (0.25)	5	$(4.2, 1.8)\times10^{-4}$	$(2.9, 2.1)\times10^{-4}$	$(5.0, 2.2)\times10^{-4}$
e^+e^- (0.5)	5	$(4.3, 2.2)\times10^{-5}$	$(5.7, 4.5)\times10^{-5}$	$(11, 3.9)\times10^{-5}$
e^+e^- (1)	5	$(5.2, 2.4)\times10^{-6}$	$(1.3, 1.2)\times10^{-5}$	$(2.5, 1.0)\times10^{-5}$
e^+e^- (3)	5	$(1.7, 0.82)\times10^{-7}$	$(1.7, 1.4)\times10^{-6}$	$(2.8, 1.0)\times10^{-6}$
e^+e^- (5)	5	$(3.7, 1.9)\times10^{-8}$	$(5.7, 4.9)\times10^{-7}$	$(8.7, 3.6)\times10^{-7}$
LHC (13)	0.14	7.6×10^{-6}	4.1×10^{-4}	4.8×10^{-4}
	0.3	6.0×10^{-6}	3.2×10^{-4}	3.8×10^{-4}
	3	3.1×10^{-6}	1.7×10^{-4}	2.0×10^{-4}
pp (100)	3	3.1×10^{-9}	4.9×10^{-7}	5.6×10^{-7}
	10	2.1×10^{-9}	3.4×10^{-7}	3.9×10^{-7}
	30	1.5×10^{-9}	2.5×10^{-7}	2.9×10^{-7}

arXiv:2206.11676

Unitarity Bounds

$\sqrt{s}$ (TeV)	0.25	0.5	1	3	5	23
Λ_{G+} (TeV)	0.078	0.16	0.31	0.93	1.6	7.2
$\Lambda_{\widetilde{B}W}$ (TeV)	0.058	0.098	0.16	0.37	0.55	1.7
Λ_{G-} (TeV)	0.050	0.084	0.14	0.32	0.47	1.5
Λ_{C+} (TeV)	0.060	0.10	0.17	0.39	0.57	1.8
$\lvert h_4 \rvert$	33	2.1	0.13	0.0016	2.1×10^{-4}	4.6×10^{-7}
$\lvert h_3^Z \rvert$	53	6.6	0.83	0.031	6.7×10^{-3}	6.8×10^{-5}
$\lvert h_3^\gamma \rvert$	54	6.7	0.84	0.031	6.7×10^{-3}	6.9×10^{-5}

Unitary bounds($f\bar{f} \to Z\gamma$) are much weaker than our sensitivity bounds!

Summary

- nTGCs provide unique probe of dimension-8 SMEFT operators
- We propose new nTGC form factor formalism which match Dimension-8 SMEFT
  Conventional nTGC form factor formalism disregards $SU(2)\times U(1)$ of SM
  We encourage experimental colleagues to redo the analysis
- Sensitivity in 3-4TeV range at LHC
  comparable to sensitivity of ILC(1TeV e^+e^- collider)
- Sensitivity can reach $\mathcal{O}(20-30)$TeV at pp (100TeV) colliders
  higher than sensitivity of CLIC (3-5TeV e^+e^- collider)