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Probing Neutral Triple Gauge Couplings at the LHC, CEPC and SPPC *

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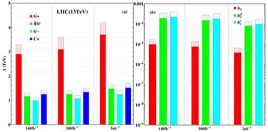

EDITORS' SUGGESTION

Probing neutral triple gauge couplings at the LHC and future hadron colliders

Many searches for new physics can be parameterized by higher-dimension operators in effective field theories. In this work, the authors show a consistent translation of dimension-8 operators into triple gauge boson form factors and analyze the expected experimental reach. Incorporating the full Standard Model symmetry requires an additional term which has been neglected in earlier work, leading to significantly different results.

John Ellis, Hong-Jian He, and Rui-Qing Xiao
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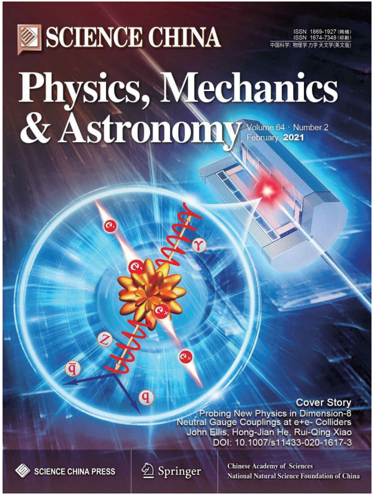

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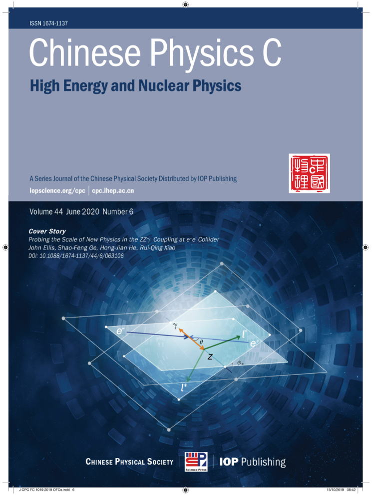

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SMEFT is a model independent way to look for BSM physics

- Higher-dimensional operators as relics of higher energy physics, e.g., dimension-6: $\mathcal{L}_{eff} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i = \sum_i \frac{\mathrm{sign}(c_j)}{\Lambda_j^2}\mathcal{O}_i$
- Operators constrained by SU(2)×U(1) symmetry, assuming usual quantum numbers for SM particles
- Constrain operator coefficients with global analysis of experimental data;
- Non-zero c_i would indicate BSM: Masses, spins, quantum numbers of new particles?
- Dimension-8 contributions scaled by quartic power of new physics scale: $\Delta\mathcal{L}_{dim-8} = \sum_i \frac{\tilde{c}_i}{\tilde{\Lambda}^4}\mathcal{O}_i = \sum_i \frac{\mathrm{sign}(\tilde{c}_i)}{\Lambda_i^4}\mathcal{O}_i$
- Study processes without dimension-6 contributions, e.g., $\gamma\gamma \to \gamma\gamma$, $gg \to \gamma\gamma$...
- Neutral triple-gauge couplings (nTGCs): $Z\gamma Z^*$, $Z\gamma\gamma^*$

Previous nTGC studies[†]

Assuming only Lorentz and $U(1)_{em}$ gauge invariance

$$\Gamma^{\alpha\beta\mu}_{ZZV}(q_1,q_2,q_3) = \frac{(q_3^2-m_V^2)}{m_Z^2}\left[f_4^V(q_3^\alpha g^{\mu\beta}+q_3^\beta g^{\mu\alpha}) - f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho\right],$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,q_3) = \frac{(q_3^2-m_V^2)}{m_Z^2}\Big\{h_1^V(q_2^\mu g^{\alpha\beta}-q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{m_Z^2}q_3^\alpha[(q_2q_3)g^{\mu\beta}-q_2^\mu q_3^\beta] - h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{m_Z^2}q_3^\alpha\epsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}\Big\}.$$

$f_{4,5}^V$ and $h_{1,2,3,4}^V$ are function of q_i^2, but treated as constant in experimental analysis

$$\begin{aligned}\mathcal{L}_{NP} = \frac{e}{m_Z^2}\Big[& -[f_4^\gamma(\partial_\mu F^{\mu\beta})+f_4^Z(\partial_\mu Z^{\mu\beta})]Z_\alpha(\partial^\alpha Z_\beta)+[f_5^\gamma(\partial^\sigma F_{\sigma\mu})+f_5^Z(\partial^\sigma Z_{\sigma\mu})]\widetilde{Z}^{\mu\beta}Z_\beta \\ & - [h_1^\gamma(\partial^\sigma F_{\sigma\mu})+h_1^Z(\partial^\sigma Z_{\sigma\mu})]Z_\beta F^{\mu\beta} - [h_3^\gamma(\partial_\sigma F^{\sigma\rho})+h_3^Z(\partial_\sigma Z^{\sigma\rho})]Z^\alpha\widetilde{F}_{\rho\alpha} \\ & - \left\{\frac{h_2^\gamma}{m_Z^2}[\partial_\alpha\partial_\beta\partial^\rho F_{\rho\mu}]+\frac{h_2^Z}{m_Z^2}[\partial_\alpha\partial_\beta(\Box+m_Z^2)Z_\mu]\right\}Z^\alpha F^{\mu\beta} \\ & + \left\{\frac{h_4^\gamma}{2m_Z^2}[\Box\partial^\sigma F^{\rho\alpha}]+\frac{h_4^Z}{2m_Z^2}[(\Box+m_Z^2)\partial^\sigma Z^{\rho\alpha}]\right\}Z_\sigma\widetilde{F}_{\rho\alpha}\Big],\end{aligned}$$

The conventional nTGC form factor formalism was adopt by previous LHC experimental analysis, but it disregards SU(2)×U(1) of SM!

† G. J. Gounaris, J. Layssac, and F. M. Renard, Phys. Rev. D 61 (2000) 073013

CP-conserving Dimension-8 nTGC operators

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We propose the pure gauge operators of dimension-8 ($\mathcal{O}_{G+}, \mathcal{O}_{G-}$) that contribute to nTGCs and are independent of the dimension-8 operator involving the Higgs doublet.

$$g\mathcal{O}_{G+} = \widetilde{B}_{\mu\nu} W^{a\mu\rho} (D_\rho D_\lambda W^{a\nu\lambda} + D^\nu D^\lambda W^a_{\lambda\rho}),$$

$$g\mathcal{O}_{G-} = \widetilde{B}_{\mu\nu} W^{a\mu\rho} (D_\rho D_\lambda W^{a\nu\lambda} - D^\nu D^\lambda W^a_{\lambda\rho}),$$

$$\mathcal{O}_{\widetilde{B}W} = \mathrm{i}\, H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H + \text{h.c.},$$

$$\mathcal{O}_{C+} = \widetilde{B}_{\mu\nu} W^{a\mu\rho} \left[D_\rho (\overline{\psi_L} T^a \gamma^\nu \psi_L) + D^\nu (\overline{\psi_L} T^a \gamma_\rho \psi_L) \right],$$

$$\mathcal{O}_{C-} = \widetilde{B}_{\mu\nu} W^{a\mu\rho} \left[D_\rho (\overline{\psi_L} T^a \gamma^\nu \psi_L) - D^\nu (\overline{\psi_L} T^a \gamma_\rho \psi_L) \right].$$

$\mathcal{O}_{C+}$ and $\mathcal{O}_{C-}$ are connected to ($\mathcal{O}_{G+}$, $\mathcal{O}_{G-}$, $\mathcal{O}_{\widetilde{B}W}$) by the equation of motion: $D^\nu W^a_{\mu\nu} = \mathrm{i}g \left[H^\dagger T^a D_\mu H - (D_\mu H)^\dagger T^a H \right] + g\, \overline{\psi_L} T^a \gamma_\mu \psi_L$

$$\mathcal{O}_{C+} = \mathcal{O}_{G-} - \mathcal{O}_{\widetilde{B}W},$$

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

Left side and right side have the same contribution to $\psi\bar{\psi} \to Z\gamma$
3 independent nTGC operators
Only ψ_L in $\mathcal{O}_{C-}$ $\rightarrow$ $\mathcal{O}_{G+}$ can not contribute to $\psi_R \bar{\psi}_R \to Z\gamma$

Neutral Triple Gauge Vertices

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Dimension-8 SMEFT:

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

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

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

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

Conventional form factor parameterization:

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

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 $h_4^V = 2h_5^V$, $h_4^Z = \frac{c_W}{s_W} h_4^\gamma$ and :

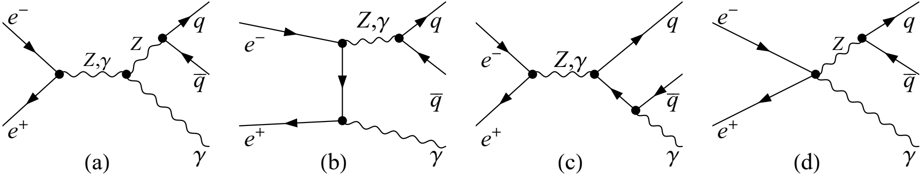
$$h_4 = -\frac{\text{sign}(\tilde{c}_{G+})}{\Lambda_{G+}^4} \frac{v^2 M_Z^2}{s_W c_W} \equiv \frac{r_4}{[\Lambda_{G+}^4]}, \qquad h_3^V = 0, \qquad \text{for } \mathcal{O}_{G+},$$

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

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

Feynman Diagrams

$$e^-e^+ \to q\bar{q}\gamma$$



- (a) nTGC s channel $Z\gamma$
- (b) SM t and u channel $Z\gamma$
- (c) Reducible SM backgrounds
- (d) $\mathcal{O}_{C+}, \mathcal{O}_{C-}$ contribution

Diagrams of $q\bar{q} \to l^- l^+ \gamma$ have the same structure

Cross section of $f\bar{f} \to Z\gamma$

$\sigma = \sigma_0(\text{SM}^2) + \sigma_1(\text{SM} \times \text{nTGC}) + \sigma_2(\text{nTGC}^2)$

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

$$\begin{aligned}
\sigma_1 &= \frac{e^2 c_L Q T_3 M_Z^2\left(s-M_Z^2\right)}{4\pi s_W c_W s}\frac{1}{[\Lambda_{G+}^4]} - \frac{e^2 Q(c_L x_L - c_R x_R)M_Z^2\left(s-M_Z^2\right)\left(s+M_Z^2\right)}{8\pi s_W c_W\, s^2}\frac{1}{[\Lambda_j^4]},\\
&= \frac{e^2 c_L Q T_3 M_Z^2\left(s-M_Z^2\right)}{4\pi s_W c_W s}\frac{h_4}{r^4} - \frac{e^2 Q(c_L x_L - c_R x_R)M_Z^2\left(s-M_Z^2\right)\left(s+M_Z^2\right)}{8\pi s_W c_W\, s^2}\frac{h_3^V}{r_3^V}\\
&= h_4\mathcal{O}(s^0) + h_3^V\mathcal{O}(s^0),\\
\sigma_2 &= \frac{T_3^2(s+M_Z^2)\left(s-M_Z^2\right)^3}{48\pi s}\frac{1}{\Lambda_{G+}^8} + \frac{(x_L^2+x_R^2)M_Z^2\left(s+M_Z^2\right)\left(s-M_Z^2\right)^3}{48\pi s^2}\frac{1}{\Lambda_j^8} + \text{cross terms}\\
&= \frac{T_3^2(s+M_Z^2)\left(s-M_Z^2\right)^3}{48\pi s}\left(\frac{h_4}{r_4}\right)^2 + \frac{(x_L^2+x_R^2)M_Z^2\left(s+M_Z^2\right)\left(s-M_Z^2\right)^3}{48\pi s^2}\left(\frac{h_3^V}{r_3^V}\right)^2 + \text{cross terms}\\
&= (h_4)^2\mathcal{O}(s^3) + (h_3^V)^2\mathcal{O}(s^2) + \text{cross terms},
\end{aligned}$$

$(x_L, x_R) = -Qs_W^2(1,1),$ (for $\mathcal{O}_j = \mathcal{O}_{G-}$),

$(x_L, x_R) = \left(T_3 - Qs_W^2, -Qs_W^2\right),$ (for $\mathcal{O}_j = \mathcal{O}_{\widetilde{B}W}$),

$(x_L, x_R) = -(T_3, 0),$ (for $\mathcal{O}_j = \mathcal{O}_{C+}$).

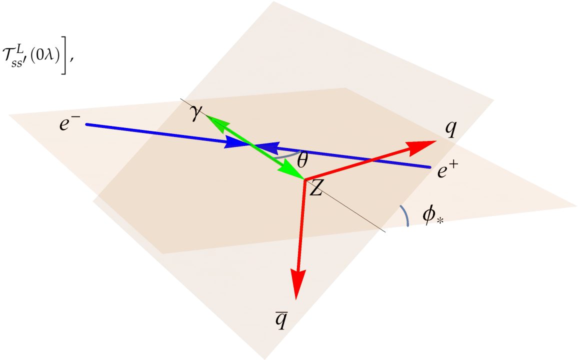
Kinematical structure

The full amplitude $\mathcal{T}^{ss'}_{\sigma\sigma'\lambda}$ can be expressed as combination of $\mathcal{T}_{ss'}(\lambda_Z\lambda_\gamma)$

$$\mathcal{T}^{ss'}_{\sigma\sigma'\lambda}(f\bar{f}\gamma) = \frac{eM_Z\mathcal{D}_Z}{s_W c_W}\Big[\sqrt{2}\,e^{i\phi_*}\Big(f^\sigma_R\cos^2\frac{\theta_*}{2} - f^\sigma_L\sin^2\frac{\theta_*}{2}\Big)\mathcal{T}^T_{ss'}(+\lambda)$$
$$+\sqrt{2}\,e^{-i\phi_*}\Big(f^\sigma_R\sin^2\frac{\theta_*}{2} - f^\sigma_L\cos^2\frac{\theta_*}{2}\Big)\mathcal{T}^T_{ss'}(-\lambda) + (f^\sigma_R + f^\sigma_L)\sin\theta_*\,\mathcal{T}^L_{ss'}(0\lambda)\Big],$$

$(f^\sigma_L, f^\sigma_R) = ((T_3 - Qs^2_W)\delta_{\sigma,-\frac{1}{2}}, -Qs^2_W\delta_{\sigma,\frac{1}{2}})$ denote the couplings of final states fermions

$$\cos\phi_* = \frac{(\mathbf{p}_{q,e^-}\times\mathbf{p}_Z)\cdot(\mathbf{p}_f\times\mathbf{p}_{\bar{f}})}{|\mathbf{p}_{q,e^-}\times\mathbf{p}_Z|\,|\mathbf{p}_f\times\mathbf{p}_{\bar{f}}|}\,.$$



At LHC, q can be emitted from either proton beam $\to$ $\cos\phi_*$ terms cancel out, $\cos(2\phi_*) = 2\cos^2\phi_* - 1$ are not affected

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

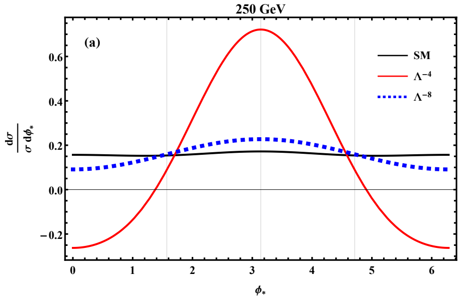
$$f^1_{\phi*} = \frac{1}{2\pi} - \frac{9\pi(c_L x_L + c_R x_R)(f_L^2 - f_R^2)\sqrt{s}\,\cos\phi_*}{128(c_L x_L - c_R x_R)(f_L^2+f_R^2)M_Z} + \frac{s\cos 2\phi_*}{4\pi(s+M_Z^2)},$$

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

Define

$$\mathbb{O}_1 = \left|\sigma_1\int d\phi_*\, f^1_{\phi_*}\times \mathrm{sign}(\cos\phi_*)\right| = \mathcal{O}(s^{1/2}),$$

to get leading energy dependence of interference term.



$$e^-e^+ \to Z\gamma \to d\bar{d}\gamma$$

ϕ_* Distribution of $\mathcal{O}_{G+}$&h_4

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Normalized angular distribution function at $\mathcal{O}(1/\Lambda^0), \mathcal{O}(1/\Lambda^4), \mathcal{O}(1/\Lambda^8)$

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

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

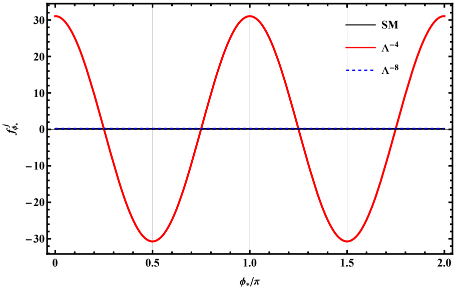
$$f^2_{\phi_*} = \frac{1}{2\pi} - \frac{9\pi(f_L^2-f_R^2)M_Z\sqrt{s}\cos\phi_*}{128(f_L^2+f_R^2)(s+M_Z^2)},$$

$$(c_\pm^2, f_\pm^2) = (c_L^2 \pm c_R^2, f_L^2 \pm f_R^2)$$

Define

$$\mathbb{O}_1 = \left|\sigma_1 \int d\phi_*\, f^1_{\phi_*} \times \text{sign}(\cos 2\phi_*)\right| = \mathcal{O}(s),$$

to get leading energy dependence of interference term.



$q\bar{q} \to Z\gamma \to l^- l^+ \gamma$ at LHC

Sensitivity reaches at Lepton colliders

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$\sqrt{s}$ (energy)	$\mathcal{L}$ (ab^{-1})	$\Lambda_{G+}^{\ell,2\sigma}$ (unpol, pol)	$\Lambda_{G+}^{\ell,5\sigma}$ (unpol, pol)	$\Lambda_{\widetilde{B}W}^{\ell,2\sigma}$ (unpol, pol)	$\Lambda_{\widetilde{B}W}^{\ell,5\sigma}$ (unpol, pol)
250 GeV	2	(0.93, 1.1)	(0.74, 0.87)	(0.56, 0.65)	(0.44, 0.51)
	5	(1.0, 1.2)	(0.83, 0.97)	(0.63, 0.73)	(0.49, 0.57)
500 GeV	2	(1.7, 2.0)	(1.3, 1.5)	(0.8, 1.0)	(0.64, 0.78)
	5	(1.9, 2.2)	(1.4, 1.7)	(0.90, 1.1)	(0.72, 0.87)
1 TeV	2	(2.8, 3.3)	(2.3, 2.7)	(1.2, 1.4)	(0.91, 1.1)
	5	(3.1, 3.7)	(2.6, 3.0)	(1.3, 1.6)	(1.0, 1.2)
3 TeV	2	(6.5, 7.7)	(5.1, 6.0)	(2.0, 2.5)	(1.6, 2.0)
	5	(7.3, 8.6)	(5.7, 6.7)	(2.2, 2.8)	(1.8, 2.2)
5 TeV	2	(9.5, 11.2)	(7.5, 8.8)	(2.6, 3.2)	(2.0, 2.6)
	5	(10.6, 12.5)	(8.4, 9.9)	(2.9, 3.6)	(2.2, 2.9)

$e^-e^+ \to Z\gamma \to l^-l^+\gamma$

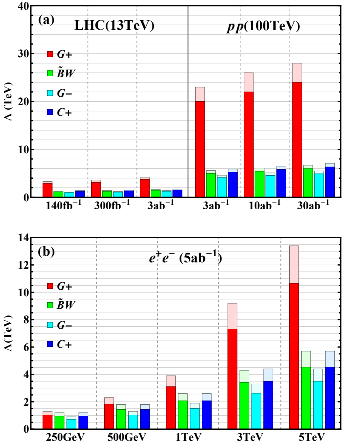
$\sqrt{s}$	$\Lambda_{G+}^{2\sigma}$	$\Lambda_{G+}^{5\sigma}$	$\Lambda_{G-}^{2\sigma}$	$\Lambda_{G-}^{5\sigma}$	$\Lambda_{\widetilde{B}W}^{2\sigma}$	$\Lambda_{\widetilde{B}W}^{5\sigma}$	$\Lambda_{C+}^{2\sigma}$	$\Lambda_{C+}^{5\sigma}$
0.25	(1.3, 1.6)	(1.0, 1.2)	(0.9, 1.1)	(0.72, 0.89)	(1.2, 1.3)	(0.97, 1.0)	(1.2, 1.6)	(0.97, 1.2)
0.5	(2.3, 2.7)	(1.9, 2.2)	(1.3, 1.7)	(1.1, 1.3)	(1.8, 1.9)	(1.4, 1.4)	(1.8, 2.2)	(1.4, 1.7)
1	(3.9, 4.7)	(3.2, 3.7)	(1.9, 2.4)	(1.6, 1.9)	(2.6, 2.6)	(2.0, 2.1)	(2.6, 2.9)	(2.0, 2.4)
3	(9.2, 11.0)	(7.2, 8.6)	(3.3, 4.2)	(2.7, 3.3)	(4.3, 4.5)	(3.5, 3.6)	(4.4, 5.2)	(3.4, 4.1)
5	(13.4, 15.9)	(10.8, 12.7)	(4.4, 5.5)	(3.4, 4.4)	(5.7, 5.9)	(4.5, 4.7)	(5.7, 6.8)	(4.5, 5.5)

$e^-e^+ \to Z\gamma \to q\bar{q}\gamma$

The sensitivity limits on Λ are shown in pair inside the parentheses of each entry and correspond to the cases with (unpolarized, polarized) $e^{\mp}$ beams, which are marked with (blue, red) colors. We choose a sample integrated luminosity $\mathcal{L} = 5\,\mathrm{ab}^{-1}$ and the $e^{\mp}$ beam polarizations $(P_L^e, P_R^{\bar{e}}) = (0.9, 0.65)$.

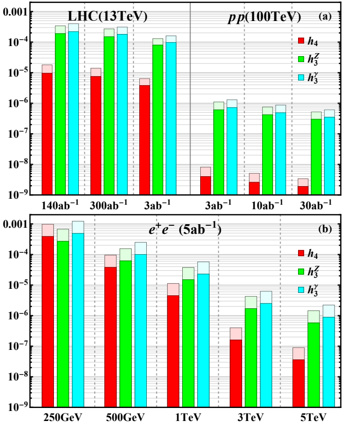
Sensitivities of new physics scale at e^+e^-, pp Colliders

$\sqrt{s}$ (TeV)	$\mathcal{L}$ (ab^{-1})	Λ_{G+}	Λ_{G-}	$\Lambda_{\tilde{B}W}$	Λ_{C+}
e^+e^- (0.25)	5	(1.3, 1.6)	(0.90, 1.2)	(1.2, 1.3)	(1.2, 1.6)
e^+e^- (0.5)	5	(2.3, 2.7)	(1.4, 1.7)	(1.8, 1.9)	(1.8, 2.2)
e^+e^- (1)	5	(3.9, 4.7)	(1.9, 2.5)	(2.5, 2.6)	(2.6, 2.9)
e^+e^- (3)	5	(9.2, 11.0)	(3.4, 4.3)	(4.3, 4.5)	(4.4, 5.2)
e^+e^- (5)	5	(13.4, 15.9)	(4.4, 5.6)	(5.7, 5.9)	(5.7, 6.8)
LHC (13)	0.14	3.3	1.1	1.3	1.4
	0.3	3.6	1.2	1.4	1.5
	3	4.2	1.4	1.7	1.7
pp (100)	3	23	4.6	5.6	5.9
	10	26	5.1	6.1	6.5
	30	28	5.5	6.7	7.1



Sensitivities of form factors at 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	$(3.9, 2.0)\times 10^{-4}$	$(2.7, 2.3)\times 10^{-4}$	$(4.9, 1.6)\times 10^{-4}$
e^+e^- (0.5)	5	$(3.8, 1.9)\times 10^{-5}$	$(6.2, 5.2)\times 10^{-5}$	$(10, 3.7)\times 10^{-5}$
e^+e^- (1)	5	$(4.5, 2.3)\times 10^{-6}$	$(1.5, 1.2)\times 10^{-5}$	$(2.3, 1.0)\times 10^{-5}$
e^+e^- (3)	5	$(1.6, 0.84)\times 10^{-7}$	$(1.7, 1.4)\times 10^{-6}$	$(2.5, 1.0)\times 10^{-6}$
e^+e^- (5)	5	$(3.6, 1.8)\times 10^{-8}$	$(5.8, 4.9)\times 10^{-7}$	$(8.9, 3.4)\times 10^{-7}$
LHC (13)	0.14	9.6×10^{-6}	1.9×10^{-4}	2.2×10^{-4}
	0.3	7.5×10^{-6}	1.5×10^{-4}	1.8×10^{-4}
	3	3.8×10^{-6}	0.80×10^{-4}	0.97×10^{-4}
pp (100)	3	4.0×10^{-9}	6.1×10^{-7}	7.2×10^{-7}
	10	2.6×10^{-9}	4.2×10^{-7}	4.9×10^{-7}
	30	1.9×10^{-9}	3.0×10^{-7}	3.5×10^{-7}



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
  ATLAS and CMS are redoing the analysis
- Sensitivity can reach 1TeV at CEPC
- Sensitivity in 3-4TeV range at LHC
- Sensitivity can reach $\mathcal{O}(20-30)$TeV at SPPC

Backup

Unitary Bounds

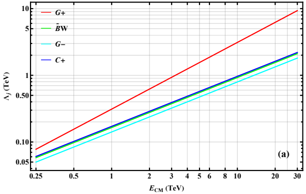
$$\Lambda_{G+} > \frac{\sqrt{s}}{(24\sqrt{2}\,\pi)^{1/4}} \simeq 0.311\sqrt{s}\,,$$

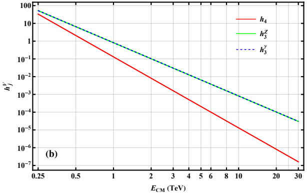
$$\Lambda_j > \left(\frac{c'_{L,R} M_Z}{12\sqrt{2}\,\pi}\right)^{\frac{1}{4}} (\sqrt{s}\,)^{\frac{3}{4}} \simeq 0.203\,\left(c'_{L,R}\right)^{\frac{1}{4}} \left(\mathrm{TeV}\sqrt{s^3}\right)^{\frac{1}{4}}\,,$$

$$|h_4| < \frac{24\sqrt{2}\,\pi v^2 M_Z^2}{s_W c_W s^2} \simeq \left(\frac{0.597\,\mathrm{TeV}}{\sqrt{s}}\right)^4,$$

$$|h_3^V| < \frac{6\sqrt{2}\,\pi\,\bar{r}_3^V}{s_W c_W c'_{L,R}} \frac{v^2 M_Z}{\sqrt{s^3}} \simeq \frac{0.350\,\bar{r}_3^V}{c'_{L,R}} \left(\frac{\mathrm{TeV}}{\sqrt{s}}\right)^3,$$

$\sqrt{s}$ (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!