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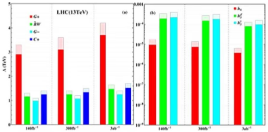
Probing Neutral Triple Gauge Couplings at the LHC, CEPC and SPPC

Rui-Qing Xiao



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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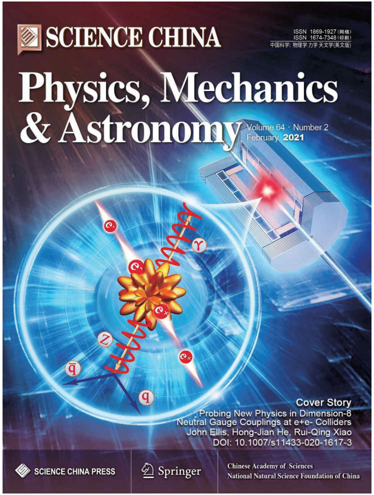

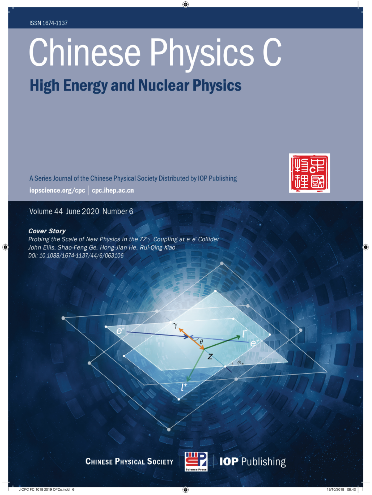

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John Ellis, Hong-Jian He, Rui-Qing Xiao, Phys.Rev.D(Letter) (2023), in Press [arXiv:2308.16887]

Standard Model Effective Field Theory

SMEFT is a model independent way to look for BSM physics

- Higher-dimensional operators as relics of higher energy physics, e.g., dimension-6:
  $\mathcal{L}_{eff} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i = \sum_i \frac{\text{sign}(c_j)}{\Lambda_j^2}\mathcal{O}_i$
- 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:
  $\Delta\mathcal{L}_{dim-8} = \sum_i \frac{\tilde{c}_i}{\tilde{\Lambda}^4}\mathcal{O}_i = \sum_i \frac{\text{sign}(\tilde{c}_i)}{\Lambda_i^4}\mathcal{O}_i$
- 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

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

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

$f^V_{4,5}$ and $h^V_{1,2,3,4}$ are function of q_i^2, but treated as constant in experimental analysis

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

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

Dimension-8 nTGC operators

The following CPC and CPV nTGC operators include Higgs doublets:

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

$$\mathcal{O}_{\widetilde{BW}}^{(\mathrm{CPC})} = \mathrm{i}\, H^{\dagger} (D_{\sigma} \widetilde{W}_{\mu\nu}^{a} W^{a\mu\sigma} + D_{\sigma} \widetilde{B}_{\mu\nu} B^{\mu\sigma}) D^{\nu} H + \text{h.c.},$$

$$\widetilde{\mathcal{O}}_{BW}^{(\mathrm{CPV})} = \mathrm{i}\, H^{\dagger} B_{\mu\nu} W^{\mu\rho} \left\{ D_{\rho}, D^{\nu} \right\} H + \text{h.c.}\,,$$

$$\widetilde{\mathcal{O}}_{WW}^{(\mathrm{CPV})} = \mathrm{i}\, H^{\dagger} W_{\mu\nu} W^{\mu\rho} \left\{ D_{\rho}, D^{\nu} \right\} H + \text{h.c.}\,,$$

$$\widetilde{\mathcal{O}}_{BB}^{(\mathrm{CPV})} = \mathrm{i}\, H^{\dagger} B_{\mu\nu} B^{\mu\rho} \left\{ D_{\rho}, D^{\nu} \right\} H + \text{h.c.}\,,$$

The dimension-8 nTGC operators containing pure gauge fields only:

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

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

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

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

Neutral Triple Gauge Vertices with on-shell $Z\gamma$

Dimension-8 SMEFT:

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

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:

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

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

$$\mathcal{T}_{(8)}[Z_L,\gamma_T]\;=\;\mathcal{T}_{(8)}[-\mathrm{i}\pi^0,\gamma_T]+B=\mathcal{O}(E^3)\,,$$

Doubly off-shell neutral gauge vertices $Z^*\gamma V^*$

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Why doubly off-shell?

At pp colliders $Z^* \to \nu\bar{\nu}$ cannot be separated from $Z \to \nu\bar{\nu}$.

CPC:

$$\Gamma^{\alpha\beta\mu}_{Z^*\gamma\gamma^*}(q_1,q_2,q_3) = \frac{e}{M_Z^2}\left(h_{31}^{\gamma} + \frac{\hat{h}_3^{\gamma} q_1^2}{M_Z^2}\right) q_3^2 q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + \frac{e s_W \hat{h}_4 q_3^2}{2 c_W M_Z^4}\left(2q_2^{\alpha} q_{3\nu} q_{2\sigma}\epsilon^{\beta\mu\nu\sigma} + q_3^2 q_{2\nu}\epsilon^{\alpha\beta\mu\nu}\right),$$

$$\Gamma^{\alpha\beta\mu}_{Z^*\gamma Z^*}(q_1,q_2,q_3) = \frac{e(q_3^2 - q_1^2)}{M_Z^2}\left[\hat{h}_3^{Z} q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + \frac{\hat{h}_4}{2M_Z^2}\left(2q_2^{\alpha} q_{3\nu} q_{2\sigma}\epsilon^{\beta\mu\nu\sigma} + q_3^2 q_{2\nu}\epsilon^{\alpha\beta\mu\nu}\right)\right].$$

CPV:

$$\Gamma^{\alpha\beta\mu}_{Z^*\gamma\gamma^*}(q_1,q_2,q_3) = \frac{e}{M_Z^2}\left(h_{11}^{\gamma} + \frac{\hat{h}_1^{\gamma} q_1^2}{M_Z^2}\right) q_3^2 \left(q_2^{\alpha} g^{\mu\beta} - q_2^{\mu} g^{\alpha\beta}\right) + \frac{e s_W \hat{h}_2 q_3^2}{2 c_W M_Z^4}\left(q_1^2 q_2^{\alpha} g^{\mu\beta} - q_3^2 q_2^{\mu} g^{\alpha\beta}\right),$$

$$\Gamma^{\alpha\beta\mu}_{Z^*\gamma Z^*}(q_1,q_2,q_3) = \frac{e(q_3^2 - q_1^2)}{M_Z^2}\left[\hat{h}_1^{Z}\left(q_2^{\alpha} g^{\mu\beta} - q_2^{\mu} g^{\alpha\beta}\right) + \frac{\hat{h}_2}{2M_Z^2}\left(q_1^2 q_2^{\alpha} g^{\mu\beta} - q_3^2 q_2^{\mu} g^{\alpha\beta}\right)\right],$$

Matching Form Factors to Dimension-8 Operators

$$\hat{h}_4 = -\frac{v^2 M_Z^2}{s_W c_W [\Lambda_{G+}^4]}, \quad \hat{h}_3^{Z} = \frac{v^2 M_Z^2}{2 s_W c_W [\Lambda_{\widetilde{B}W}^4]},$$

$$\hat{h}_3^{\gamma} = -\frac{v^2 M_Z^2}{2 c_W^2 [\Lambda_{G-}^4]}, \quad h_{31}^{\gamma} = -\frac{v^2 M_Z^2}{s_W c_W [\Lambda_{\widetilde{BW}}^4]},$$

$$\hat{h}_1^{Z} = \frac{v^2 M_Z^2}{4 c_W s_W}\left(\frac{c_W^2 - s_W^2}{[\Lambda_{WB}^4]} - \frac{c_W s_W}{[\Lambda_{WW}^4]} + \frac{4 c_W s_W}{[\Lambda_{BB}^4]}\right),$$

$$h_{11}^{\gamma} = \frac{v^2 M_Z^2}{4 c_W s_W}\left(\frac{2 c_W s_W}{[\Lambda_{WB}^4]} - \frac{s_W^2}{[\Lambda_{WW}^4]} - \frac{4 c_W^2}{[\Lambda_{BB}^4]}\right),$$

$$\hat{h}_1^{\gamma} = \frac{v^2 M_Z^2}{4 c_W^2 [\Lambda_{\widetilde{G}-}^4]}, \quad \hat{h}_2 = -\frac{v^2 M_Z^2}{2 s_W c_W [\Lambda_{\widetilde{G}+}^4]}.$$

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

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

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

$$\sigma_1 = \frac{e^2 c_L Q T_3 M_Z^2\left(s-M_Z^2\right)}{4\pi s_W c_W s}\frac{1}{[\Lambda_{G+}^4]} - \frac{e^2 Q(c_L x_L - c_R x_R)M_Z^2\left(s-M_Z^2\right)\left(s+M_Z^2\right)}{8\pi s_W c_W\, s^2}\frac{1}{[\Lambda_j^4]},$$

$$= \frac{e^2 c_L Q T_3 M_Z^2\left(s-M_Z^2\right)}{4\pi s_W c_W s}\frac{h_4}{r^4} - \frac{e^2 Q(c_L x_L - c_R x_R)M_Z^2\left(s-M_Z^2\right)\left(s+M_Z^2\right)}{8\pi s_W c_W\, s^2}\frac{h_3^V}{r_3^V} = h_4\mathcal{O}(s^0) + h_3^V\mathcal{O}(s^0),$$

$$\sigma_2 = \frac{T_3^2\,(s+M_Z^2)\left(s-M_Z^2\right)^3}{48\pi\, s}\frac{1}{\Lambda_{G+}^8} + \frac{(x_L^2+x_R^2)M_Z^2\left(s+M_Z^2\right)\left(s-M_Z^2\right)^3}{48\pi\, s^2}\frac{1}{\Lambda_j^8} + \text{cross terms}$$

$$= \frac{T_3^2\,(s+M_Z^2)\left(s-M_Z^2\right)^3}{48\pi\, s}\left(\frac{h_4}{r_4}\right)^2 + \frac{(x_L^2+x_R^2)M_Z^2\left(s+M_Z^2\right)\left(s-M_Z^2\right)^3}{48\pi\, s^2}\left(\frac{h_3^V}{r_3^V}\right)^2 + \text{cross terms} = (h_4)^2\mathcal{O}(s^3) + (h_3^V)^2\mathcal{O}(s^2) + \text{cross terms},$$

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

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

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

Contribution of CPV nTGC to σ_1 vanish
Contribution of CPV nTGC to σ_2 has the same structure as that of the corresponding CPC nTGC

Kinematical structure

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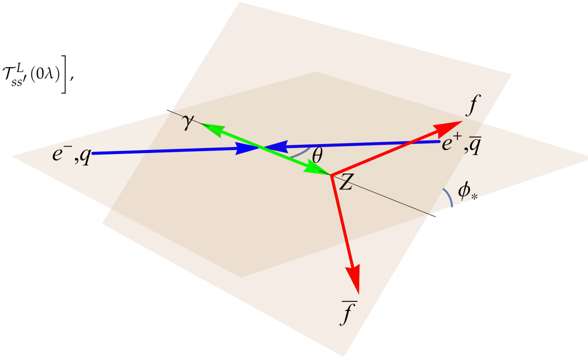
The full amplitude $\mathcal{T}^{ss'}_{\sigma\sigma'\lambda}$ can be expressed as combination of $\mathcal{T}_{ss'}(\lambda_Z\lambda_\gamma)$
ss': helicities of initial state fermions
$\sigma\sigma'$: helicities of final state fermions
$\lambda_Z\lambda_\gamma$: polarizations of $Z\gamma$

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

$(f^\sigma_L, f^\sigma_R) = ((T_3 - Qs^2_W)\delta_{\sigma,-\frac{1}{2}}, -Qs^2_W\delta_{\sigma,\frac{1}{2}})$ 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 $\rightarrow \cos\phi_*$ terms cancel out, $\cos(2\phi_*) = 2\cos^2\phi_* - 1$ are not affected

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

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

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

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

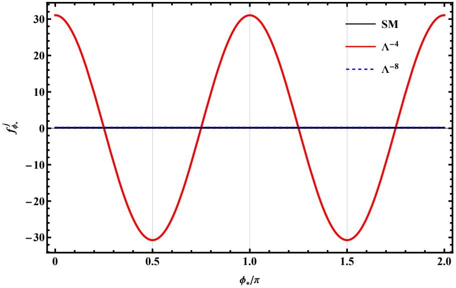
$$f^2_{\phi_*} = \frac{1}{2\pi} - \frac{9\pi(f_L^2-f_R^2)M_Z\sqrt{s}\cos\phi_*}{128(f_L^2+f_R^2)(s+M_Z^2)},$$

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

Define

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

to get leading energy dependence of interference term.



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

ϕ_* Distribution of $\mathcal{O}_{\widetilde{B}W}$&$h_3^Z$

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

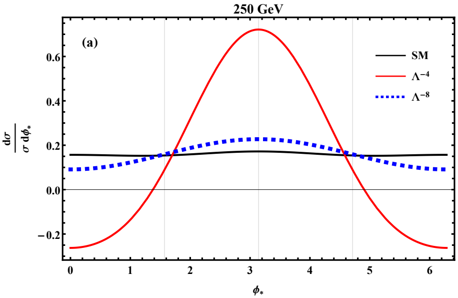
$$f^1_{\phi_*} = \frac{1}{2\pi} - \frac{9\pi(c_L x_L + c_R x_R)(f_L^2 - f_R^2)\sqrt{s}\,\cos\phi_*}{128(c_L x_L - c_R x_R)(f_L^2+f_R^2)M_Z} + \frac{s\cos 2\phi_*}{4\pi(s+M_Z^2)},$$

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

Define

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

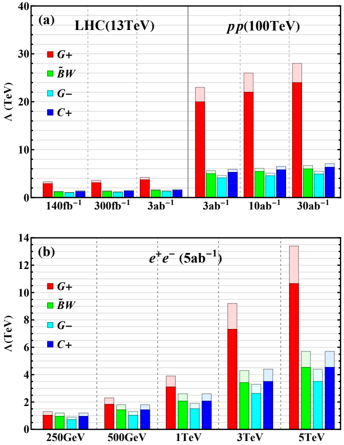
to get leading energy dependence of interference term.



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

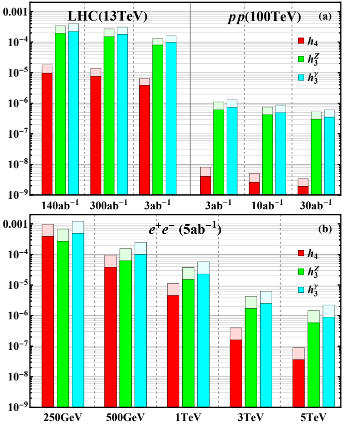
Sensitivities of new physics scale (on-shell)

$\sqrt{s}$ (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 (on-shell)

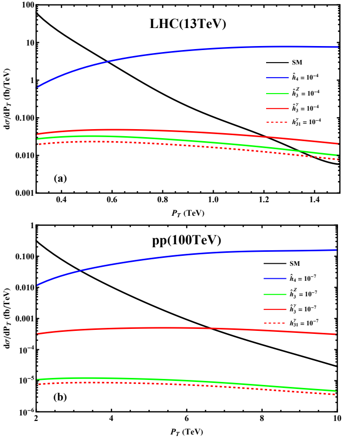
$\sqrt{s}$ (TeV)	$\mathcal{L}$ (ab^{-1})	$\lvert h_4 \rvert$	$\lvert h_3^Z \rvert$	$\lvert h_3^\gamma \rvert$
e^+e^- (0.25)	5	$(3.9, 2.0)\times10^{-4}$	$(2.7, 2.3)\times10^{-4}$	$(4.9, 1.6)\times10^{-4}$
e^+e^- (0.5)	5	$(3.8, 1.9)\times10^{-5}$	$(6.2, 5.2)\times10^{-5}$	$(10, 3.7)\times10^{-5}$
e^+e^- (1)	5	$(4.5, 2.3)\times10^{-6}$	$(1.5, 1.2)\times10^{-5}$	$(2.3, 1.0)\times10^{-5}$
e^+e^- (3)	5	$(1.6, 0.84)\times10^{-7}$	$(1.7, 1.4)\times10^{-6}$	$(2.5, 1.0)\times10^{-6}$
e^+e^- (5)	5	$(3.6, 1.8)\times10^{-8}$	$(5.8, 4.9)\times10^{-7}$	$(8.9, 3.4)\times10^{-7}$
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}



Sensitivity reaches via $pp(q\bar{q}) \to Z^*\gamma \to \nu\bar{\nu}\gamma$

$\sqrt{s}$	13 TeV				100 TeV		
$\mathcal{L}\,(\text{ab}^{-1})$	0.14	0.3	3		3	10	30
$\lvert\hat{h}_{4,2}\rvert \times 10^6$	11	8.5	4.2	$\lvert\hat{h}_{4,2}\rvert \times 10^9$	4.5	2.9	2.0
$\lvert\hat{h}^{Z}_{3,1}\rvert \times 10^4$	2.2	1.7	0.90	$\lvert\hat{h}^{Z}_{3,1}\rvert \times 10^7$	7.0	4.8	3.4
$\lvert\hat{h}^{\gamma}_{3,1}\rvert \times 10^4$	1.6	1.3	0.67	$\lvert\hat{h}^{\gamma}_{3,1}\rvert \times 10^7$	0.94	0.62	0.44
$\lvert h^{\gamma}_{31,11}\rvert \times 10^4$	2.5	2.0	1.0	$\lvert h^{\gamma}_{31,11}\rvert \times 10^7$	8.3	5.7	4.0

$\sqrt{s}$	13 TeV			100 TeV		
$\mathcal{L}\,(\text{ab}^{-1})$	0.14	0.3	3	3	10	30
Λ_{G+}	3.2	3.5	4.1	23	25	28
Λ_{G-}	1.2	1.3	1.5	7.7	8.5	9.3
$\Lambda_{\widetilde{B}W}$	1.3	1.4	1.6	5.4	5.9	6.4
$\Lambda_{\widetilde{BW}}$	1.5	1.6	1.8	6.2	6.8	7.4
$\Lambda_{\widetilde{G}+}$	2.7	2.9	3.5	19	21	23
$\Lambda_{\widetilde{G}-}$	1.0	1.1	1.3	6.5	7.2	7.8
Λ_{WW}	0.93	1.0	1.2	3.9	4.3	4.6
Λ_{WB}	1.1	1.2	1.4	4.6	5.1	5.5
Λ_{BB}	1.3	1.4	1.7	5.6	6.2	6.8



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

Backup

CP-conserving Dimension-8 nTGC operators

上海交通大学 SHANGHAI JIAO TONG UNIVERSITY

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 $\psi_R\bar{\psi}_R \to Z\gamma$

Unitary Bounds

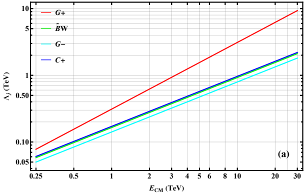
$$\Lambda_{G+} > \frac{\sqrt{s}}{(24\sqrt{2}\,\pi)^{1/4}} \simeq 0.311\sqrt{s}\,,$$

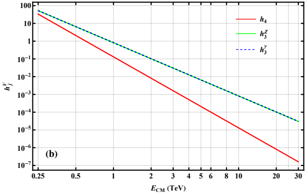
$$\Lambda_j > \left(\frac{c'_{L,R} M_Z}{12\sqrt{2}\,\pi}\right)^{\frac{1}{4}} (\sqrt{s}\,)^{\frac{3}{4}} \simeq 0.203\,\left(c'_{L,R}\right)^{\frac{1}{4}} \left(\text{TeV}\sqrt{s^3}\right)^{\frac{1}{4}},$$

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

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

$\sqrt{s}$ (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}

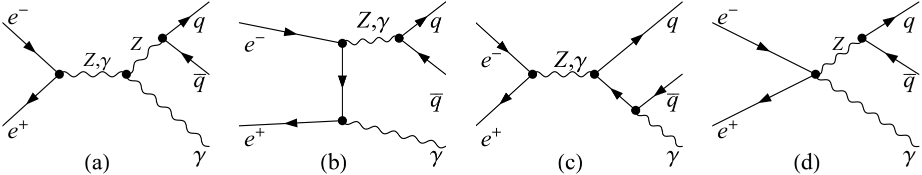




Unitary bounds($f\bar{f} \to Z\gamma$) are much weaker than our sensitivity bounds!

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

Sensitivity reaches at Lepton colliders

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

$\sqrt{s}$ (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 $(P_L^e, P_R^{\bar{e}}) = (0.9, 0.65)$.