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LHC and Future High Energy Colliders: Probing the nTGC New Physics *

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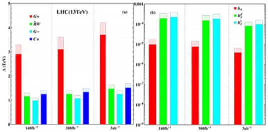

EDITORS' SUGGESTION

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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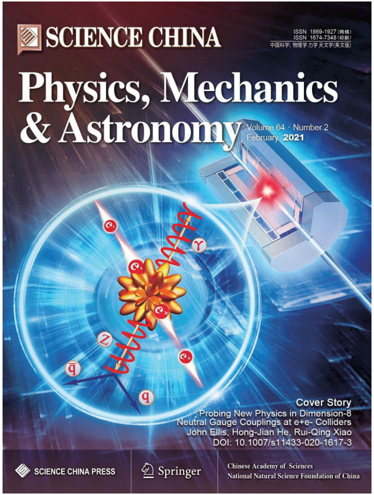

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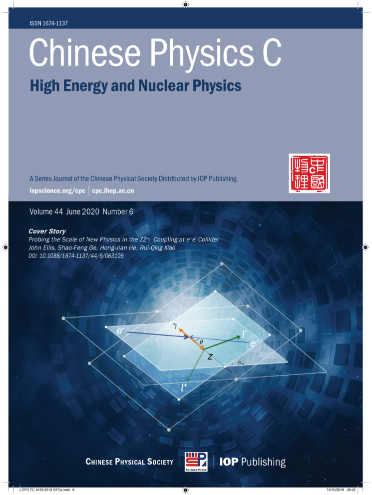

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Standard Model Effective Field Theory

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., light-by-light scanering, $gg \to \gamma\gamma$...
- Neutral triple-gauge couplings (nTGCs): $Z\gamma Z^*$, $Z\gamma\gamma^*$

Previous nTGC studies†

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

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

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

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

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

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

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

Dimension-8 nTGC operators with Higgs[‡]

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CP breaking(C odd, P even)

$$\mathcal{O}_{BW} = i\, H^\dagger B_{\mu\nu} W^{\mu\rho} \left\{D_\rho, D^\nu\right\} H,$$
$$\mathcal{O}_{WW} = i\, H^\dagger W_{\mu\nu} W^{\mu\rho} \left\{D_\rho, D^\nu\right\} H,$$
$$\mathcal{O}_{BB} = i\, H^\dagger B_{\mu\nu} B^{\mu\rho} \left\{D_\rho, D^\nu\right\} H.$$

CP conserving(C odd, P odd)

$$\mathcal{O}_{\widetilde{B}W} = i\, H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} \left\{D_\rho, D^\nu\right\} H,$$
$$\mathcal{O}_{B\widetilde{W}} = i\, H^\dagger B^{\mu\nu} \widetilde{W}_{\mu\rho} \left\{D_\rho, D^\nu\right\} H,$$
$$\mathcal{O}_{\widetilde{W}W} = i\, H^\dagger \widetilde{W}_{\mu\nu} W^{\mu\rho} \left\{D_\rho, D^\nu\right\} H,$$
$$\mathcal{O}_{\widetilde{B}B} = i\, H^\dagger \widetilde{B}_{\mu\nu} B^{\mu\rho} \left\{D_\rho, D^\nu\right\} H.$$

Matching form factors to SMEFT operators

$$h_3^Z = \frac{v^2 M_Z^2}{4 c_w s_w} \frac{C_{\widetilde{B}W}}{\Lambda^4}$$

$$h_1^Z = \frac{M_Z^2 v^2 \left(-c_w s_w \frac{C_{WW}}{\Lambda^4} + \frac{C_{BW}}{\Lambda^4}\left({c_w}^2 - {s_w}^2\right) + 4 c_w s_w \frac{C_{BB}}{\Lambda^4}\right)}{4 c_w s_w}$$

$$h_1^\gamma = -\frac{M_Z^2 v^2 \left({s_w}^2 \frac{C_{WW}}{\Lambda^4} - 2 c_w s_w \frac{C_{BW}}{\Lambda^4} + 4 {c_w}^2 \frac{C_{BB}}{\Lambda^4}\right)}{4 c_w s_w}$$

h_2^V and h_4^V are absent!

[‡] C. Degrande, JHEP 1402 (2014) 101

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

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:

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

Matching Form Factors to Dimension-8 Operators

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$\mathcal{T}[f\bar{f} \to Z_L\gamma]$ 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 :

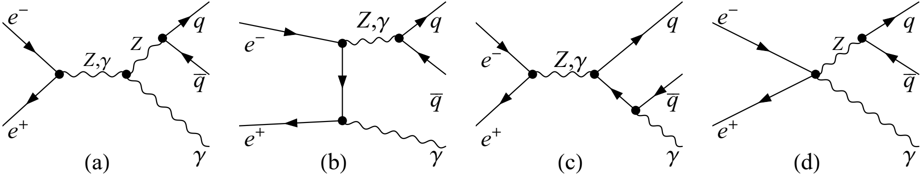
$$h_4 = -\frac{\mathrm{sign}(\tilde{c}_{G+})}{\Lambda_{G+}^4}\frac{v^2 M_Z^2}{s_W c_W} \equiv \frac{r_4}{[\Lambda_{G+}^4]}\,, \qquad h_3^V = 0\,, \qquad \text{for } \mathcal{O}_{G+}\,,$$

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

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

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 helicity combinations $\lambda_Z\lambda_\gamma = (--,-+,+-,++,0-,0+)$

$$\mathcal{T}^{ss',\mathrm{T}}_{\mathrm{sm}}\begin{pmatrix} -- & -+ \\ +- & ++ \end{pmatrix} = \frac{-2e^2Q}{s_Wc_W(s-M_Z^2)}\begin{bmatrix} \left(c'_L\cot\frac{\theta}{2} - c'_R\tan\frac{\theta}{2}\right)M_Z^2 & \left(-c'_L\cot\frac{\theta}{2} + c'_R\tan\frac{\theta}{2}\right)s \\ \left(c'_L\tan\frac{\theta}{2} - c'_R\cot\frac{\theta}{2}\right)s & \left(-c_L\tan\frac{\theta}{2} + c_R\cot\frac{\theta}{2}\right)M_Z^2 \end{bmatrix},$$

SM leading enegy dependence: s^0 $(-+,+-)$

$$\mathcal{T}^{ss',\mathrm{L}}_{\mathrm{sm}}(0-,0+) = \frac{-2\sqrt{2}e^2Q\,(c'_L+c'_R)\,M_Z\sqrt{s}}{s_Wc_W(s-M_Z^2)}\,(1,\,-1)\,,$$

$$(c'_L,\,c'_R) = ((T_3 - Qs_W^2)\delta_{s,-\frac{1}{2}},\,-Qs_W^2\delta_{s,\frac{1}{2}})$$

$$\mathcal{T}^{ss',\mathrm{T}}_{(8),\mathrm{F}}\begin{pmatrix} -- & -+ \\ +- & ++ \end{pmatrix} = \frac{(c_L^V+c_R^V)e^2(2h_3^VM_Z^2+h_4^Vs)(s-M_Z^2)\sin\theta}{4M_Z^4c_Ws_W}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix},$$

h_4^V leading enegy dependence: s^2 $(++,--)$

$$\mathcal{T}^{ss',\mathrm{L}}_{(8),\mathrm{F}}(0-,0+) = \frac{\sqrt{2}\,e^2(s-M_Z^2)\sqrt{s}}{4M_Z^3c_Ws_W}(2h_3^V+h_4^V)\left(c_L^V\sin^2\frac{\theta}{2} - c_R^V\cos^2\frac{\theta}{2},\; c_R^V\sin^2\frac{\theta}{2} - c_L^V\cos^2\frac{\theta}{2}\right),$$

h_3^V leading enegy dependence: $s^{3/2}$ $(0+,0-)$

$(c_L^Z,\,c_R^Z) = ((T_3 - Qs_W^2)\delta_{s,-\frac{1}{2}},\,-Qs_W^2\delta_{s,\frac{1}{2}})$ and $c_L^A = c_R^A = Qc_Ws_W(\delta_{s,-\frac{1}{2}},\delta_{s,\frac{1}{2}})$
denote the couplings of initial states fermions

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

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

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

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

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

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

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

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

Kinematical structure

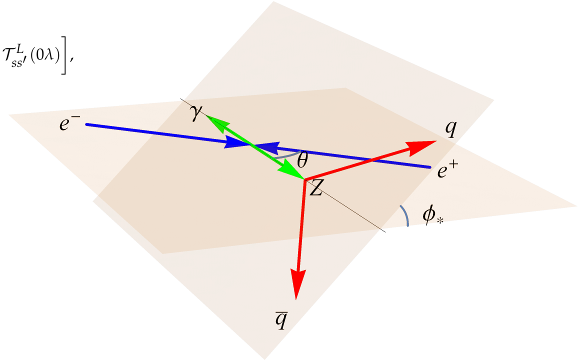
The full amplitude $\mathcal{T}^{ss'}_{\sigma\sigma'\lambda}$ can be expressed as combination of $\mathcal{T}_{ss'}(\lambda_Z\lambda_\gamma)$

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

$(f^\sigma_L, f^\sigma_R) = ((T_3 - Qs^2_W)\delta_{\sigma,-\frac{1}{2}}, -Qs^2_W\delta_{\sigma,\frac{1}{2}})$ 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

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

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

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

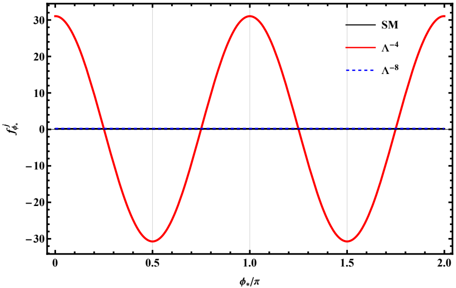
$$f^2_{\phi_*} = \frac{1}{2\pi} - \frac{9\pi(f_L^2-f_R^2)M_Z\sqrt{s}\cos\phi_*}{128(f_L^2+f_R^2)(s+M_Z^2)},$$

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

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

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

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

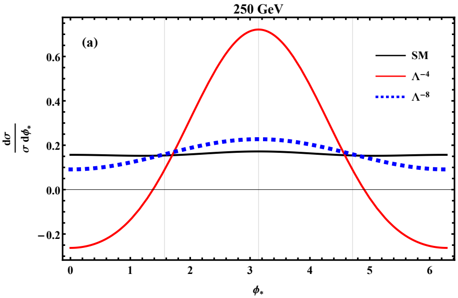
$$f^1_{\phi*} = \frac{1}{2\pi} - \frac{9\pi(c_L x_L + c_R x_R)(f_L^2 - f_R^2)\sqrt{s}\,\cos\phi_*}{128(c_L x_L - c_R x_R)(f_L^2+f_R^2)M_Z} + \frac{s\cos 2\phi_*}{4\pi(s+M_Z^2)},$$

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

Define

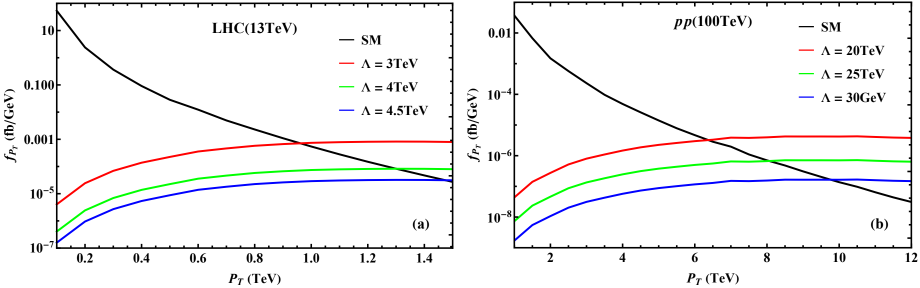
$$\mathbb{O}_1 = \left|\sigma_1 \int d\phi_*\, f^1_{\phi_*} \times \mathrm{sign}(\cos\phi_*)\right| = \mathcal{O}(s^{1/2}),$$

to get leading energy dependence of interference term.



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

Photon P_T Distribution at $\mathcal{O}(1/\Lambda_{G+}^8)$



- Distribution function of SM decreases with P_T
- Distribution function of $\mathcal{O}_{G+}$ increases with P_T

Sensitivity Estimates

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

$\mathcal{L}$ is the integrated luminosity, and ϵ is the detection efficiency.
In order to maximize the detection sensitivity, we divide events into bins of $P_T(\gamma)$ and construct the following significance measure:

$\mathcal{Z}_{\text{total}} = \sqrt{\sum \mathcal{Z}^2_{\text{bin}}}$.

at $\mathcal{O}(\Lambda^{-4})$

$$\Lambda \propto (\mathcal{L}\times\epsilon)^{1/8}, \qquad (\text{for } B \gg S),$$
$$\Lambda \propto (\mathcal{L}\times\epsilon)^{1/4}, \qquad (\text{for } S \gg B).$$

at $\mathcal{O}(\Lambda^{-8})$

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

Sensitivities of Λ_{G+} at $\mathcal{O}(\Lambda^{-4})$, $Z \to ll$

$\sqrt{s}$	LHC (13 TeV)			pp (100 TeV)		
$\mathcal{L}$ (ab^{-1})	0.14	0.3	3	3	10	30
$\Lambda^{2\sigma}_{G+}$ (TeV)	2.1	2.4	3.3	14	17	19
$\Lambda^{5\sigma}_{G+}$ (TeV)	1.6	1.8	2.6	10	12	15

Sensitivities of Λ_{G+} at $\mathcal{O}(\Lambda^{-8})$, $Z \to ll$

$\sqrt{s}$	LHC (13 TeV)			pp (100 TeV)		
$\mathcal{L}$ (ab^{-1})	0.14	0.3	3	3	10	30
$\Lambda^{2\sigma}_{G+}$ (TeV)	3.0	3.2	3.9	21	24	26
$\Lambda^{5\sigma}_{G+}$ (TeV)	2.6	2.8	3.4	17	20	22

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
$\Lambda^{2\sigma}_{G+}$ (TeV)	3.3	3.6	4.2	23	26	28
$\Lambda^{5\sigma}_{G+}$ (TeV)	2.9	3.1	3.7	20	22	24

SMEFT Form Factor Sensitivities

$\sqrt{s}$	13 TeV ($\ell\bar{\ell}$)			13 TeV ($\ell\bar{\ell},\nu\bar{\nu}$)		
$\mathcal{L}(\text{ab}^{-1})$	0.14	0.3	3	0.14	0.3	3
$\lvert h_4(\mathbb{O}_1)\rvert\times10^5$	5.8 (18)	3.7 (11)	1.0 (2.8)	5.8 (18)	3.7 (11)	1.0 (2.8)
$\lvert h_4\rvert\times10^6$	14 (28)	11 (21)	5.2 (9.1)	9.6 (18)	7.5 (14)	3.8 (6.4)
$\lvert h_3^Z\rvert\times10^4$	2.7 (5.0)	2.1 (3.8)	1.1 (1.8)	1.9 (3.4)	1.5 (2.7)	0.80 (1.3)
$\lvert h_3^\gamma\rvert\times10^4$	3.1 (5.8)	2.5 (4.5)	1.3 (2.1)	2.2 (4.0)	1.8 (3.1)	0.97 (1.6)
$\sqrt{s}$	100 TeV ($\ell\bar{\ell}$)			100 TeV ($\ell\bar{\ell},\nu\bar{\nu}$)		
$\mathcal{L}(\text{ab}^{-1})$	3	10	30	3	10	30
$\lvert h_4(\mathbb{O}_1)\rvert\times10^8$	3.4 (11)	1.6 (5.0)	0.85 (2.6)	3.4 (11)	1.6 (5.0)	0.85 (2.6)
$\lvert h_4\rvert\times10^9$	6.1 (13)	3.9 (7.8)	2.6 (5.1)	4.0 (8.1)	2.6 (5.1)	1.9 (3.4)
$\lvert h_3^Z\rvert\times10^7$	8.9 (17)	6.0 (11)	4.2 (7.5)	6.1 (11)	4.2 (7.5)	3.0 (5.2)
$\lvert h_3^\gamma\rvert\times10^7$	10 (20)	6.8 (13)	4.9 (8.7)	7.2 (13)	4.9 (8.7)	3.5 (6.1)

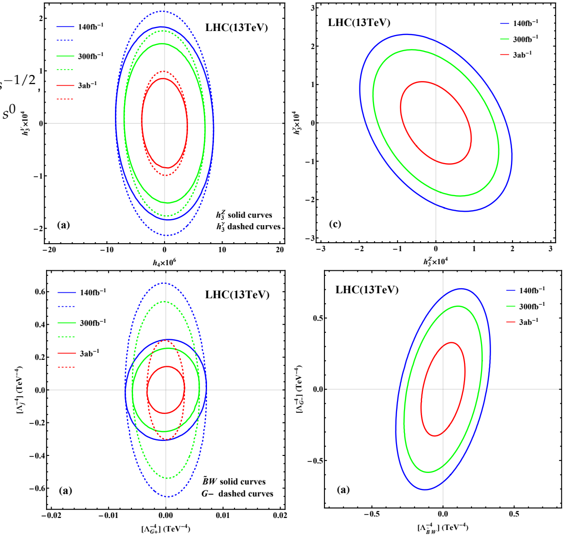
2σ, 5σ

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.

Correlations between Sensitivities

$$\sigma_2 = Ax^2 + By^2 + Cxy$$
$$\rho(x,y) = -\frac{C}{2\sqrt{AB}}$$
$$\rho(\Lambda_{G+}^{-4}, \Lambda_{j}^{-4}) = \text{sign}(r_3^V r_4)\rho(h_4, h_3^V) \propto s^{-1/2},$$
$$\rho(\Lambda_{\tilde{B}W}^{-4}, \Lambda_{G-}^{-4}) = \text{sign}(r_3^Z r_3^\gamma)\rho(h_3^Z, h_3^\gamma) \propto s^0$$



SMEFT vs Naive Form Factor Sensitivities

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$\sqrt{s}$	13 TeV $(\ell\bar{\ell},\nu\bar{\nu})$			$\sqrt{s}$	100 TeV $(\ell\bar{\ell},\nu\bar{\nu})$		
$\mathcal{L}$(ab^{-1})	0.14	0.3	3	$\mathcal{L}$(ab^{-1})	3	10	30
$\lvert h_4\rvert\times10^6$	9.6	7.5	3.8	$\lvert h_4\rvert\times10^9$	4.0	2.6	1.9
$\lvert h_4^Z\rvert\times10^7$	5.2	4.0	2.0	$\lvert h_4^Z\rvert\times10^{11}$	2.8	1.9	1.3
$\lvert h_4^\gamma\rvert\times10^7$	5.9	4.7	2.4	$\lvert h_4^\gamma\rvert\times10^{11}$	3.3	2.1	1.5

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

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}

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

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

$$
|h_3^Z| < 3.0\times 10^{-4}, \quad |h_3^\gamma| < 3.4\times 10^{-4}, \quad |h_4^Z| < 4.4\times 10^{-7}, \quad |h_4^\gamma| < 4.9\times 10^{-7},
$$

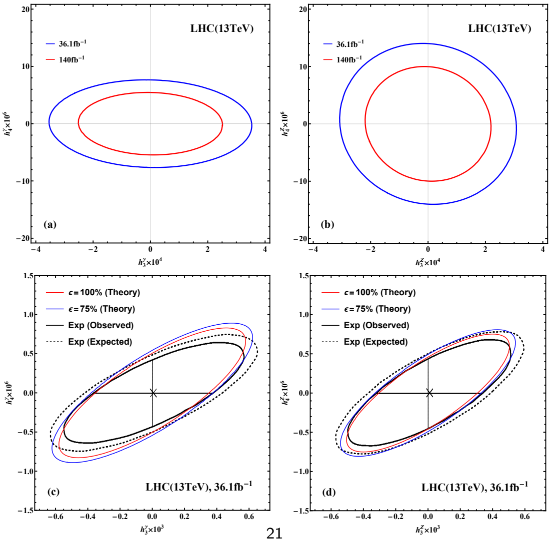
Comparison of Correlainons

SMEFT form factor:

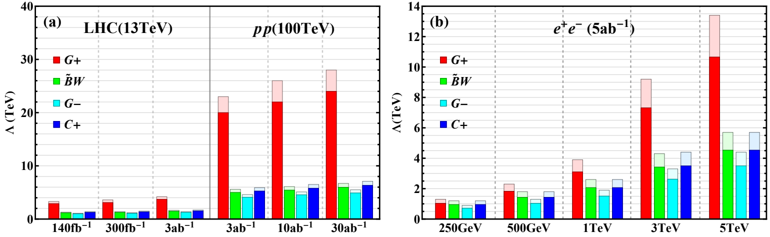
$\rho(h_4, h_3^V) \propto s^{-1/2}$

Naïve form factor:

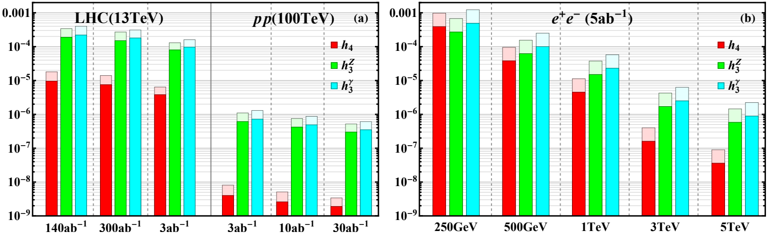
$\rho(h_4^V, h_3^V) \propto s^0$



Comparison of e^+e^-, pp Colliders



2σ(light color), 5σ(heavy color)



2σ(heavy color), 5σ(light color)

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 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)