Probing Neutral Triple Gauge Couplings via $Z\gamma$ production at e+e- colliders

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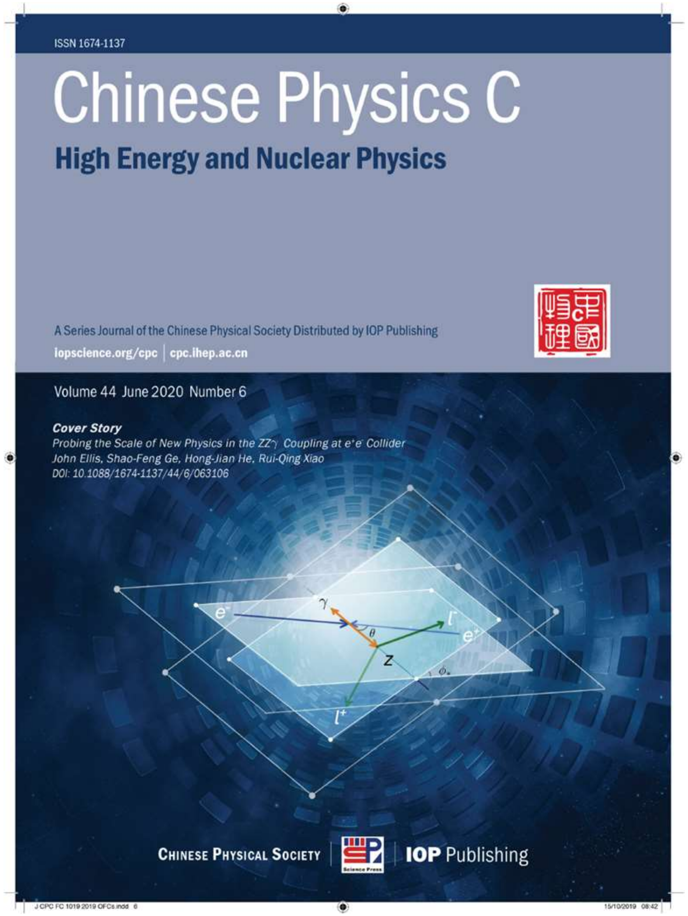
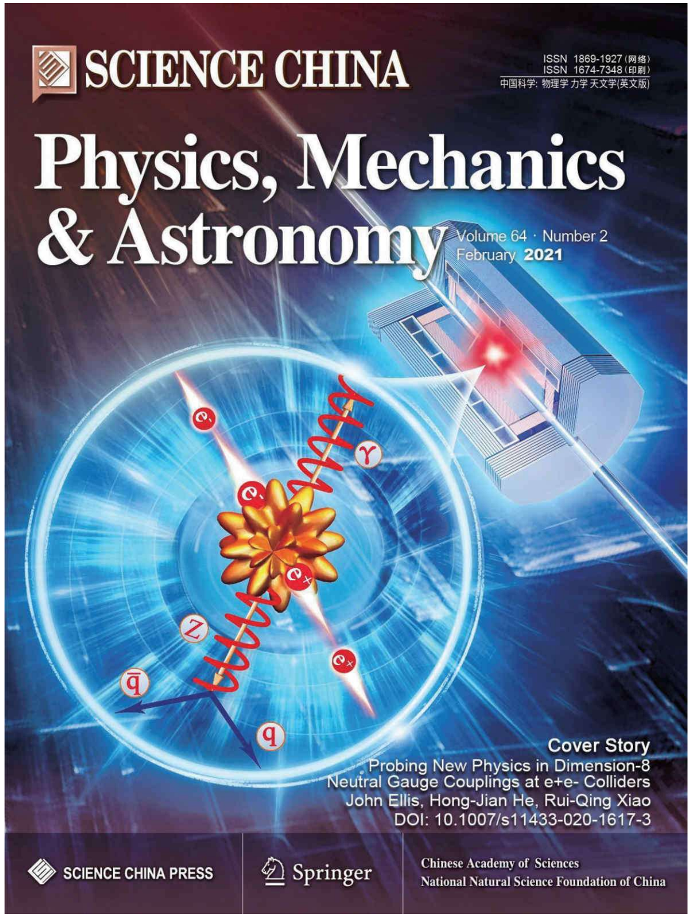
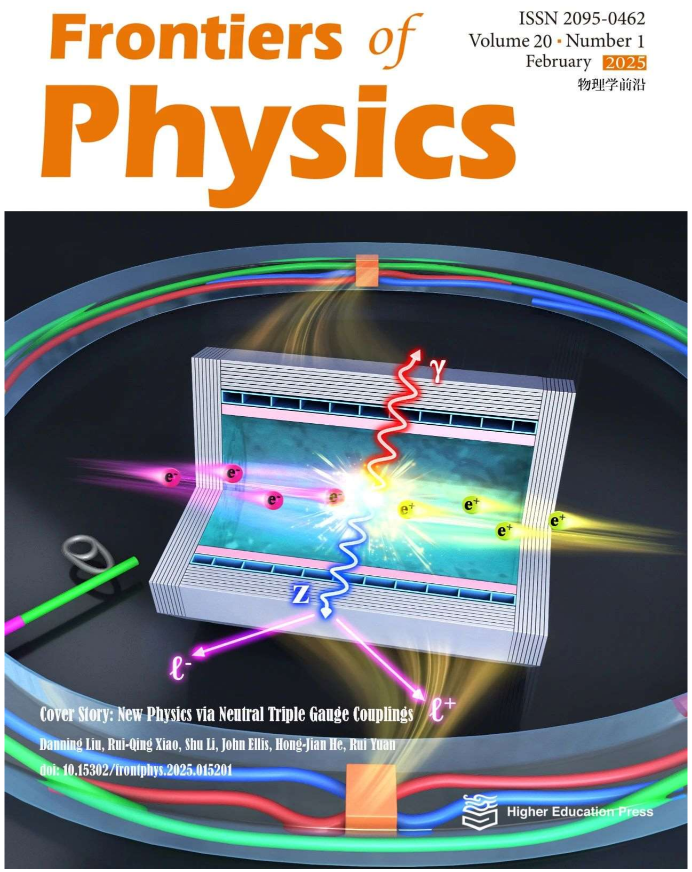
Our studies



Leptonic channel
Chin.Phys.C 44 (2020) 6, 063106



Hadronic channel
Sci.China Phys.Mech.Astron. 64 (2021) 2, 221062



Detector-level simulation at CEPC
Front.Phys. 20 (2025) 15201

UV completion 2408.12508
CP Violating nTGC To be published

Leptonic channel at pp collider Phys.Rev.D 107 (2023) 3, 035005
Invisible channel at pp collider Phys.Rev.D-Letter 108 (2023) 11, L111704

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, dimension-6:** $\mathcal{L}_{dim-6} = \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i = \sum_i \frac{\text{sign}(c_i)}{\Lambda_i^2} \mathcal{O}_i$
- **Operators constrained by SU(2)xU(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:** $\mathcal{L}_{dim-8} = \sum_i \frac{c_i}{\Lambda^4} \mathcal{O}_i = \sum_i \frac{\text{sign}(c_i)}{\Lambda_i^4} \mathcal{O}_i$
- **Study processes without dimension-6 contributions:** $q\bar{q} \to V^* \to Z\gamma,\ e^+e^- \to V^* \to Z\gamma$
- **Neutral Triple Gauge Couplings $Z\gamma Z^*, Z\gamma\gamma^*$ are unique window to probe high dimension new physics**

nTGC SMEFT Operators

nTGC operators with Higgs fields:

$$\mathcal{O}_{\tilde{B}W}^{(\mathrm{CPC})} = iH^{\dagger}\tilde{B}_{\mu\nu}W^{\mu\rho}\{D_\rho, D^\nu\}H + \mathrm{h.c.}$$

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

$$\widetilde{\mathcal{O}}_{\tilde{B}W}^{(\mathrm{CPV})} = iH^{\dagger}B_{\mu\nu}W^{\mu\rho}\{D_\rho, D^\nu\}H + \mathrm{h.c.}$$

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

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

nTGC operators with pure gauge fields:

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

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

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

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

They can be connected by Eqution of Motion:

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

$$\mathcal{O}_{G+}^{(\mathrm{CPC})} - \{iH^{\dagger}\tilde{B}_{\mu\nu}W^{\mu\rho}[D_\rho, D^\nu]H + i\,2(D_\rho H)^{\dagger}\tilde{B}_{\mu\nu}W^{\mu\rho}D^\nu H + \mathrm{h.c.}\} = \mathcal{O}_{C-}^{(\mathrm{CPC})} = \tilde{B}_{\mu\nu}W^{a\mu\rho}\left[D_\rho(\overline{\psi_L}T^a\gamma^\nu\psi_L) - D^\nu(\overline{\psi_L}T^a\gamma_\rho\psi_L)\right]$$

Both sides of equal sign have same effect in physical process

Phys.Rev.D 107 (2023) 3, 035005
Phys.Rev.D-Letter 108 (2023) 11, L111704
Sci.China Phys.Mech.Astron. 64 (2021) 2, 221062
Chin.Phys.C 44 (2020) 6, 063106

nTGC Form Factor

Conventional nTGC form factors only Lorentz and U(1) gauge invariance

Phys.Rev.D 61 (2000) 073013

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

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V^*}(q_1,q_2,q_3) = \frac{-e(q_3^2-m_V^2)}{M_Z^2}\{h_1^V(q_2^\mu g^{\alpha\beta}-q_2^\alpha g^{\mu\beta})+\frac{h_2^V}{M_Z^2}q_3^\alpha\left[(q_2q_3)g^{\mu\beta}-q_2^\mu q_3^\beta\right]-h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho}-\frac{h_4^V}{M_Z^2}q_2^\alpha q_{3\nu}q_{2\sigma}\,\epsilon^{\beta\mu\nu\sigma}\}$$

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

$f_4^V, h_{1,2}^V$ are CP-violating, $f_5^V, h_{3,4}^V$ are CP-conserving

Conventional nTGC form factors do not respect SU(2)×U(1) symmetry. They are adopted for 23 years. LHC ATLAS+CMS used them in nTGC analysis and obtain unreliable strong bounds.

Matching SMEFT **We propose form factor with SU(2)×U(1) symmtry**

Phys.Rev.D (2023)

APS Editors' Suggestion

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

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V^*}(q_1,q_2,q_3) = \frac{e(q_3^2-M_V^2)}{M_Z^2}\left[(h_1^V+h_6^V\frac{q_3^2}{M_Z^2})\,(q_2^\alpha g^{\mu\beta}-q_2^\mu g^{\alpha\beta})+\frac{h_2^V}{M_Z^2}q_2^\alpha(q_2q_3g^{\mu\beta}-q_2^\mu q_3^\beta)\right]$$

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

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

$$\mathcal{T}[f\bar{f}\to Z_L\gamma] = h_1^V\mathcal{O}(E^3)+h_2^V\mathcal{O}(E^5)+h_6^V\mathcal{O}(E^5) = \Lambda_j^{-4}\mathcal{O}(E^3)$$

$h_4^V = 2h_5^V$, $h_2^V = 2h_6^V$

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

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

Relations between form factor coefficients

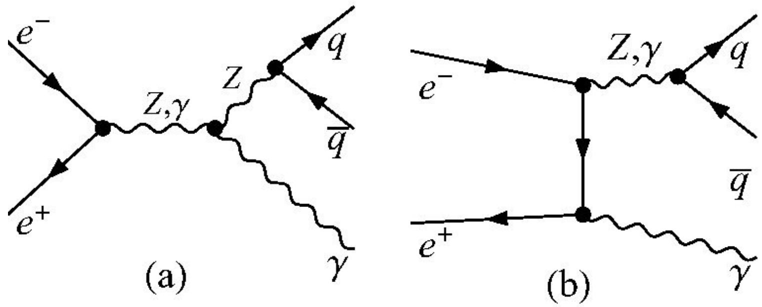
$$h_4 = -\frac{1}{[\Lambda_{G+}^4]}\frac{v^2M_Z^2}{c_Ws_W} \qquad h_3^Z = \frac{1}{[\Lambda_{\tilde{B}W}^4]}\frac{v^2M_Z^2}{2c_Ws_W} \qquad h_3^\gamma = -\frac{1}{[\Lambda_{G-}^4]}\frac{v^2M_Z^2}{2c_W^2} - \frac{1}{[\Lambda_{\widetilde{BW}}^4]}\frac{v^2M_Z^2}{c_Ws_W}$$

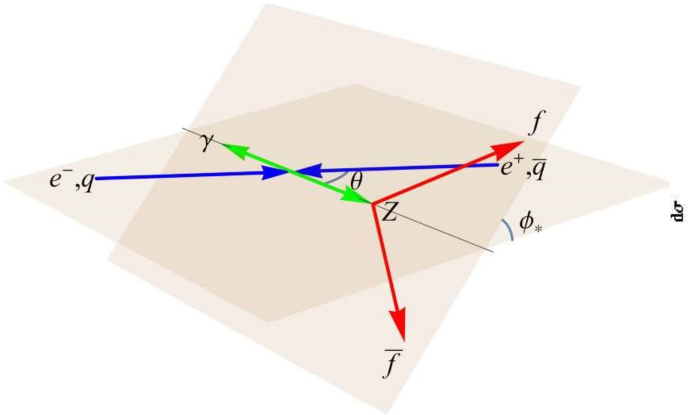
$$h_2 = -\frac{1}{[\Lambda_{\tilde{G}+}^4]}\frac{v^2M_Z^2}{c_Ws_W} \qquad h_1^Z = \frac{v^2M_Z^2}{4c_Ws_W}\left(\frac{c_W^2-s_W^2}{[\Lambda_{WB}^4]}-\frac{c_Ws_W}{[\Lambda_{WW}^4]}+\frac{4c_Ws_W}{[\Lambda_{BB}^4]}\right) \qquad h_1^\gamma = \frac{v^2M_Z^2}{4c_Ws_W}\left(\frac{2c_Ws_W}{[\Lambda_{WB}^4]}-\frac{s_W^2}{[\Lambda_{WW}^4]}+\frac{4c_W^2}{[\Lambda_{BB}^4]}\right)-\frac{1}{[\Lambda_{\tilde{G}-}^4]}\frac{v^2M_Z^2}{4c_W^2}$$

$$[\Lambda_i^4] = \Lambda_i^4\ \mathrm{sign}(c_i) \qquad h_4 = h_4^Z = \frac{c_W}{s_W}h_4^\gamma,\ h_2 = h_2^Z = \frac{c_W}{s_W}h_2^\gamma$$

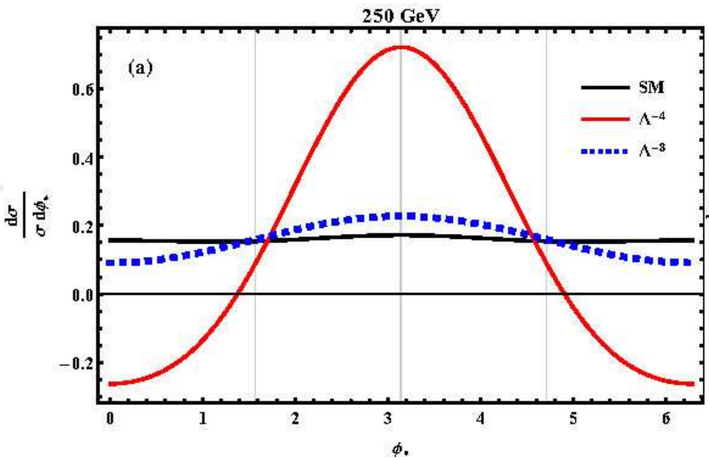
Probing CPC nTGC at colliders

$Z\gamma$ production and decay: $e^+e^- \to V^* \to Z\gamma \to f\bar{f}\gamma$

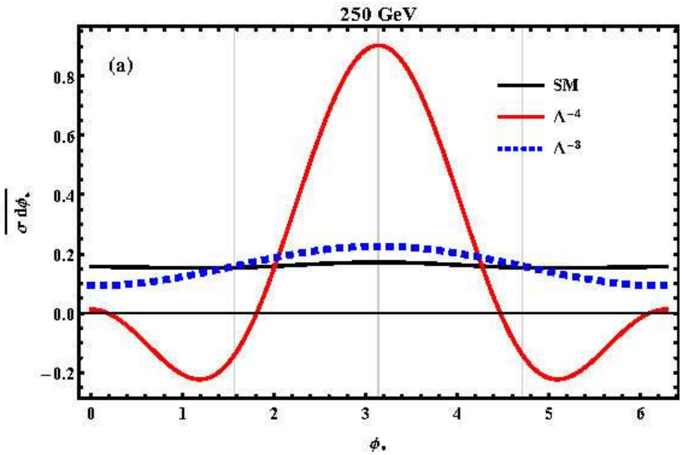




Kinematical structure



Distribution of $e^+e^- \to Z\gamma \to d\bar{d}\gamma$ at CEPC($\mathcal{O}_{\tilde{B}W}, h_3^Z$)



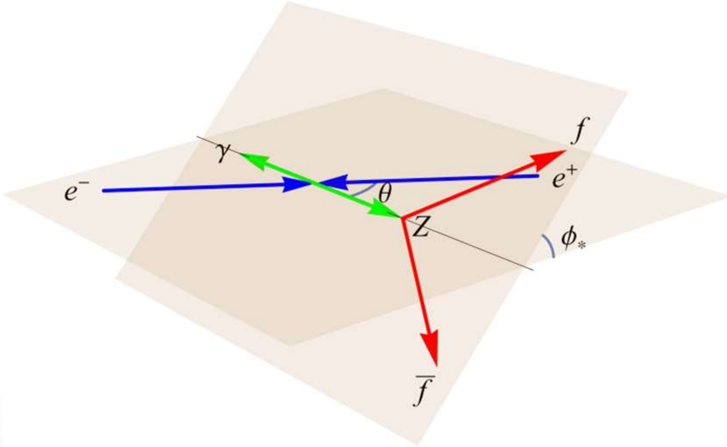
Distribution of $e^+e^- \to Z\gamma \to d\bar{d}\gamma$ at CEPC ($\mathcal{O}_{G+}, h_4$)

$$\frac{d\sigma}{d\phi_*} \propto \mathcal{O}(E^{-2}) + h_3^V\mathcal{O}(E)\cos\phi_* + h_4\mathcal{O}(E^2)\cos 2\phi_* + (h_3^V)^2\mathcal{O}(E^2) + (h_4)^2\mathcal{O}(E^6)$$

$$\sigma \propto \mathcal{O}(E^{-2}) + h_3^V\mathcal{O}(E^0) + h_4\mathcal{O}(E^0) + (h_3^V)^2\mathcal{O}(E^2) + (h_4)^2\mathcal{O}(E^6)$$

We need separate positive and negative contribution via ϕ_* distribution

Probing CPV nTGC at colliders



Amplitude of $e^+e^- \to Z\gamma$
CPV nTGC:

$$\mathcal{T}^{ss',\mathrm{T}}_{(8),\mathrm{F}}\begin{pmatrix} -- & -+ \\ +- & ++ \end{pmatrix} = \frac{ie^2\sin(\theta)\left(c_L^V+c_R^V\right)\left(M_Z^2-s\right)\left(2h_1^V M_Z^2+h_2^V s\right)}{4M_Z^4}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix},$$

$$\mathcal{T}^{ss',\mathrm{L}}_{(8),\mathrm{F}}(0-,0+) = -\frac{ie^2\left(2h_1^V+h_2^V\right)\sqrt{s}\,(s-M_Z^2)}{2\sqrt{2}M_Z^3}\left(c_L^V\sin^2\frac{\theta}{2}-c_R^V\cos^2\frac{\theta}{2}, c_L^V\cos^2\frac{\theta}{2}-c_R^V\sin^2\frac{\theta}{2}\right)$$

SM:

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

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

CPV amplitude and SM amplitude always have different phase i, so there is no interference term between SM and CPV nTGC!

However, interference terms of $e^+e^- \to Z\gamma \to f\bar{f}\gamma$ exist and are odd function of ϕ_* :

$$\frac{d^3\sigma_1}{\mathrm{d}\theta d\theta_* d\phi_*} = c_1(\theta,\theta_*)\sin\phi_* + c_2(\theta,\theta_*)\sin 2\phi_*$$

ϕ_* distributions for CPV nTGC

Define ϕ_* distribution for $e^+e^- \to Z\gamma$

$$\tilde{\sigma}_i \equiv \frac{d\sigma_i(e^+e^- \to Z\gamma \to f\bar{f}\gamma)}{\text{Br}(f\bar{f})d\phi_*}$$

$$\tilde{\sigma}_1 = \frac{e^4 h_1^V Q \sin\phi_*(M_Z^2 - s)}{c_W s_W M_Z^2}\left(\frac{3(f_L^2 - f_R^2)(M_Z^2 + 3s)(c_L^V c_L + c_R^V c_R)}{2048(f_L^2 + f_R^2)s^{3/2}M_Z} - \frac{\cos\phi_*(c_L^V c_L - c_R^V c_R)}{32\pi^2 s}\right)$$
$$+\frac{e^4 h_2^V Q \sin\phi_*(s - M_Z^2)}{c_W s_W M_Z^3}\left(\frac{3(f_L^2 - f_R^2)(M_Z^2 - 5s)(c_L^V c_L + c_R^V c_R)}{4096(f_L^2 + f_R^2)s^{3/2}} + \frac{\cos\phi_*(c_L^V c_L - c_R^V c_R)}{64\pi^2 M_Z}\right)$$

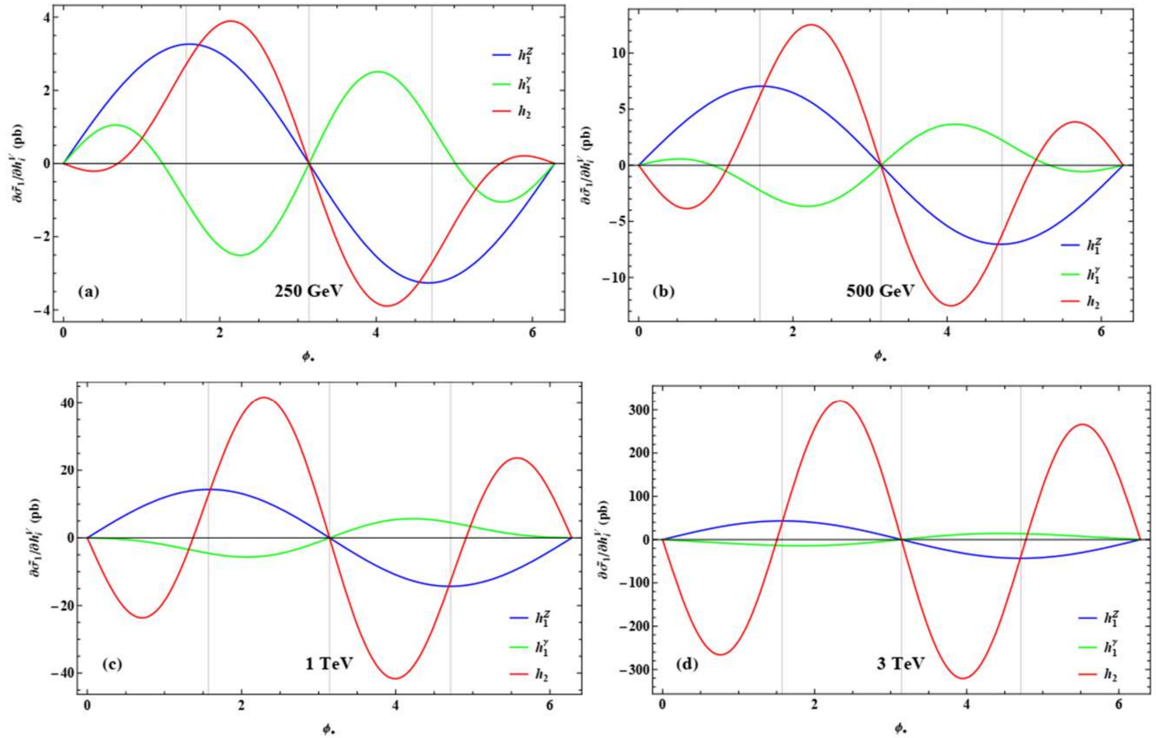


Figure 2: *Angular distributions in ϕ_* for $e^+e^- \to Z\gamma$ followed by $Z \to d\bar{d}$, as generated by the form factors h_1^Z, h_1^γ and h_2 at e^+e^- colliders with $\sqrt{s}$=250 GeV, 500 GeV, 1 TeV and 3 TeV.*

Multidimensional distributions for CPV nTGC

To separate the positive and negative regions of the interference term, we can exploit their multidimensional distribution.

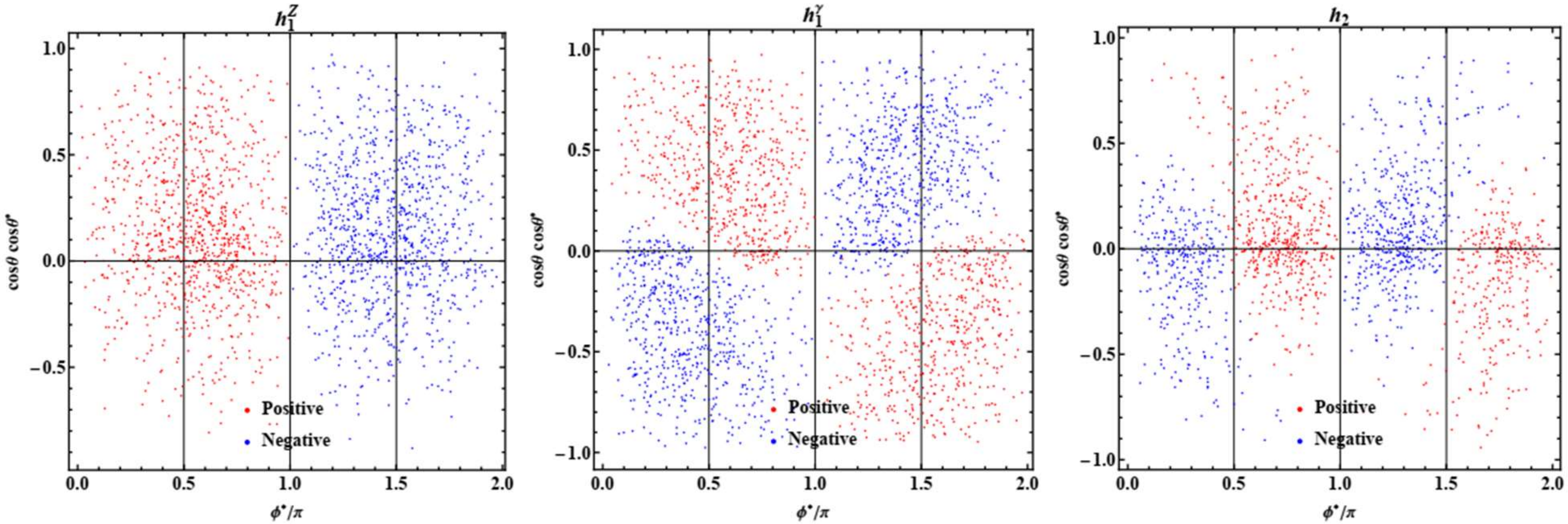
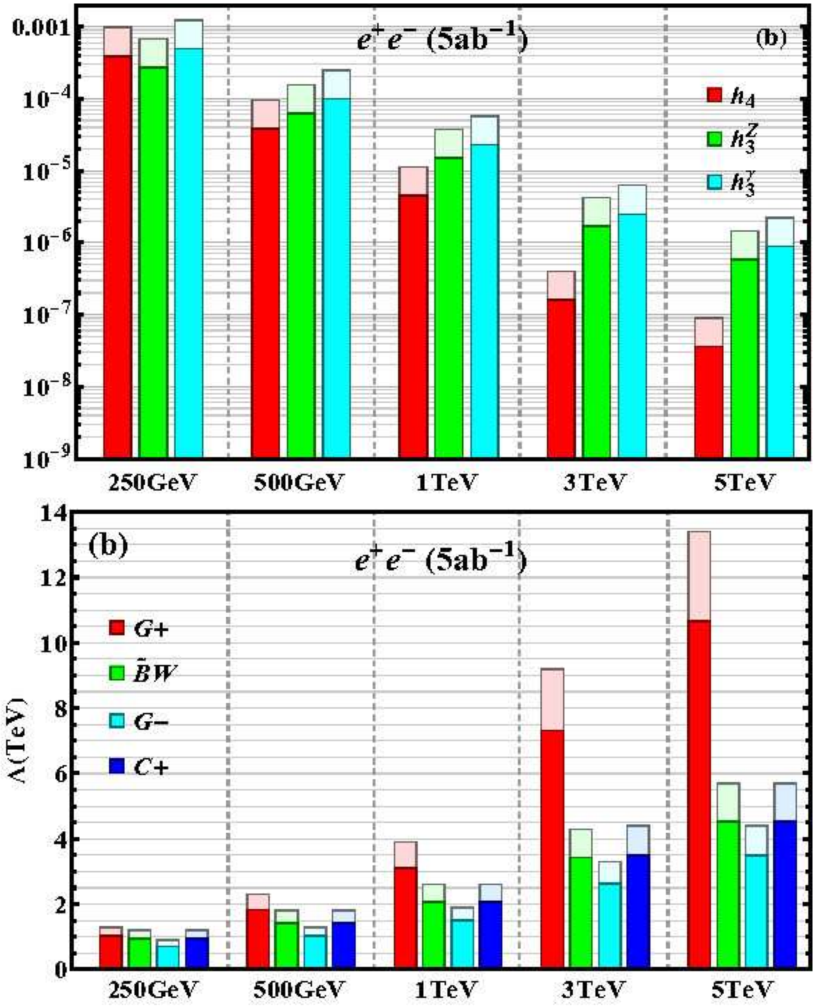


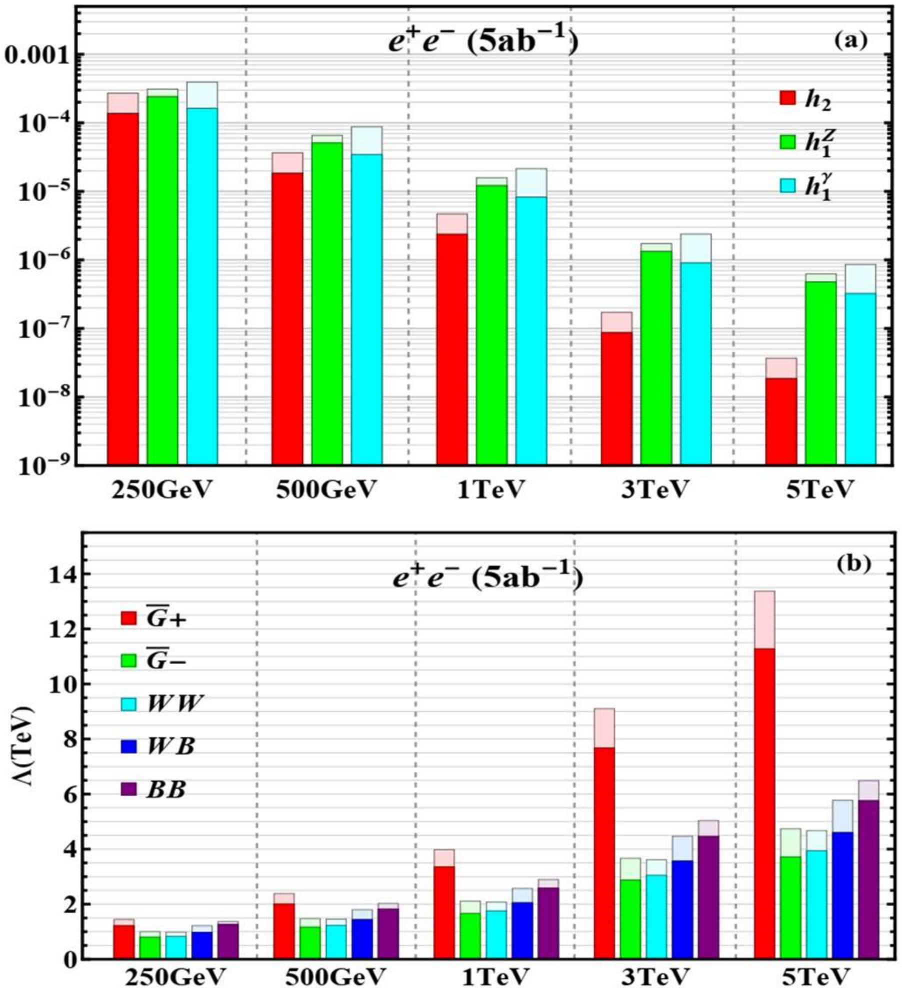
Figure 6: *The distribution of simulated events in the* $(\phi^*, \cos\theta\cos\theta^*)$ *plane for* $e^+e^- \to Z\gamma \to l^-l^+\gamma$ *at* e^+e^- *colliders with* $\sqrt{s}=250\ GeV$ *showing clear separation between events with different signs for* h_1^Z, h_1^γ *and* h_2.

Positive and negative contributions are clearly separated in the plane!

Probing sensitivities of nTGC

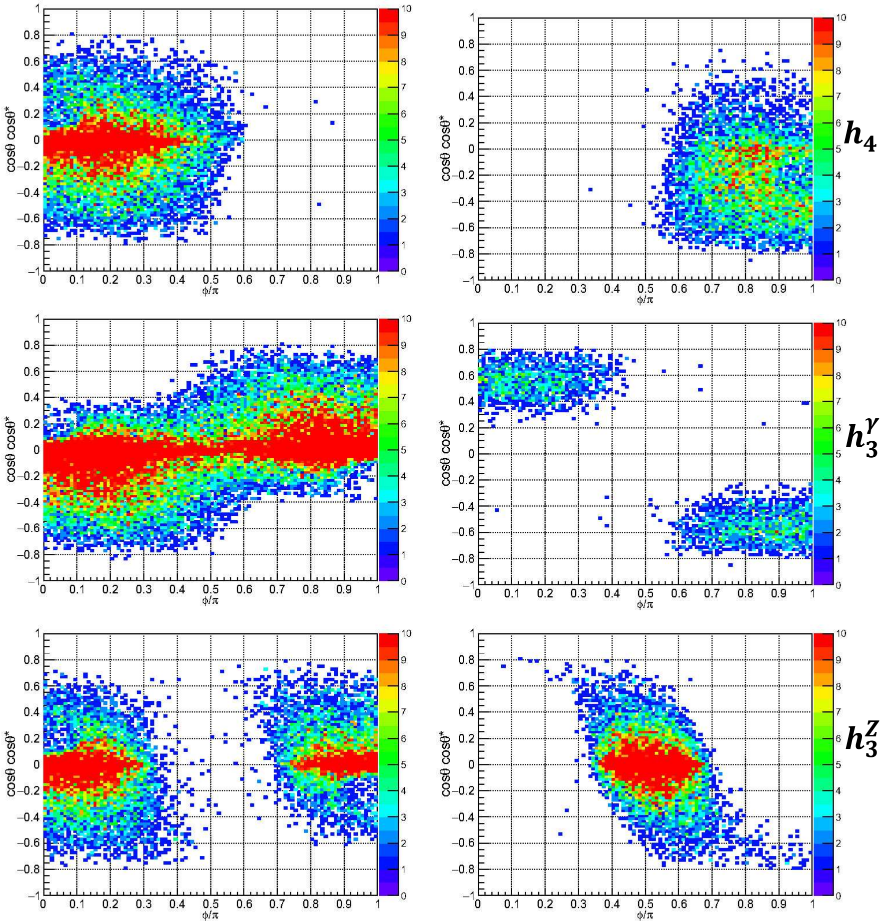


CPC



CPV

Detector-level simulation at CEPC



$\bar{\sigma}_1 > 0$ $\bar{\sigma}_1 < 0$

Analyze $l^+l^-\gamma$ with CEPC detector configuration (CEPC TDR, [arXiv:2312.14363])
E=240GeV L=20ab^{-1}

Cross section: $\sigma = \sigma_0 + \bar{\sigma}_1 h_i^V + \bar{\sigma}_2 (h_i^V)^2$
$\bar{\sigma}_1$ has both positive and negative contribution, as shown in the plots
Positive events and negative events are separated on this 2d parameter space
We can find the boundaries via Multivariate Analysis

Form Factors	Expected limits	New Physics Scales	Expected limits (TeV)
h_4	$[-2.0,2.0] \times 10^{-4}$	Λ_{G+}	1.55
h_3^γ	$[-9.7,9.7] \times 10^{-4}$	Λ_{G-}	0.76
h_3^Z	$[-1.1,1.1] \times 10^{-3}$	$\Lambda_{\tilde{B}W}$	0.85
		$\Lambda_{\widetilde{BW}}$	1.05

Probing sensitivities for nTGC form factors and new physics scales

Probed new physics scale can be 6 times of CEPC collision energy

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UV Completion of Neutral Triple Gauge Couplings

CPC nTGC operators with Higgs fields

$$
\begin{aligned}
O_{\tilde{W}W} &= \mathrm{i}H^\dagger \tilde{W}_{\mu\nu} W^{\nu\rho}\{D_\rho, D_\mu\}H\,,\\
O'_{\tilde{W}W} &= \mathrm{i}H^\dagger \tilde{W}_{\mu\nu}(D_\rho W^{\nu\rho})D_\mu H\,,\\
O_{\tilde{B}B} &= \mathrm{i}H^\dagger \tilde{B}_{\mu\nu} B^{\nu\rho}\{D_\rho, D_\mu\}H\,,\\
O'_{\tilde{B}B} &= \mathrm{i}H^\dagger \tilde{B}_{\mu\nu}(D_\rho B^{\nu\rho})D_\mu H\,,
\end{aligned}
$$

$$
\begin{aligned}
O_{\tilde{B}W} &= \mathrm{i}H^\dagger \tilde{B}_{\mu\nu} W^{\nu\rho}\{D_\rho, D^\mu\}H\,,\\
O'_{\tilde{B}W} &= \mathrm{i}H^\dagger \tilde{B}_{\mu\nu}(D_\rho W^{\nu\rho})D^\mu H\,,\\
O_{\tilde{W}B} &= \mathrm{i}H^\dagger \tilde{W}_{\mu\nu} B^{\nu\rho}\{D_\rho, D^\mu\}H\,,
\end{aligned}
$$

triple gauge boson vertex $W^\mu(-p_1-p_2)$-$W^\nu(p_1)$-$W^\rho(p_2)$

$$
\left[-p_2^2 p_{1\sigma} + p_1^2 p_{2\sigma} - 2p_1\cdot p_2\,(p_2-p_1)_\sigma - 2p_2^2 p_{2\sigma} + 2p_1^2 p_{1\sigma}\right]\epsilon^{\mu\nu\rho\sigma}\,,
$$

$$
\left[(p_1+p_2)^\mu \epsilon^{\nu\rho\alpha\beta} + p_1^\nu \epsilon^{\mu\rho\alpha\beta} - p_2^\rho \epsilon^{\mu\nu\alpha\beta}\right] p_{2\alpha} p_{1\beta}\,,
$$

W-B-B vertex

$$
\begin{aligned}
&\left(p_1^2 p_{1\sigma} - p_2^2 p_{2\sigma}\right)\epsilon^{\mu\nu\rho\sigma}\,,\\
&(p_1-p_2)^\mu\,\epsilon^{\nu\rho\alpha\beta} p_{2\alpha} p_{1\beta}\,,\\
&\left(p_1^\nu \epsilon^{\mu\rho\alpha\beta} - p_2^\rho \epsilon^{\mu\nu\alpha\beta}\right) p_{2\alpha} p_{1\beta}\,,\\
&\left(p_1^\rho \epsilon^{\mu\nu\alpha\beta} - p_2^\nu \epsilon^{\mu\rho\alpha\beta}\right) p_{2\alpha} p_{1\beta}\,,\\
&(p_1\cdot p_2)\,\epsilon^{\mu\nu\rho\sigma}\,(p_{2\sigma} - p_{1\sigma})\,,
\end{aligned}
$$

7 general form factors

From factors for on-shell VV production

$$
\Gamma^{\mu\nu\alpha}_{V^*\gamma Z}(q,p_1,p_2) = \frac{c_{V^*\gamma Z}}{m_Z^2}(q^2-m_V^2)p_{1\beta}\epsilon^{\mu\nu\alpha\beta}\,,
$$

$$
\Gamma^{\mu\nu\alpha}_{V^*ZZ}(q,p_1,p_2) = \frac{c_{V^*ZZ}}{m_Z^2}(q^2-m_V^2)(p_1-p_2)_\beta\,\epsilon^{\mu\nu\alpha\beta}\,.
$$

4 on-shell form factors

$$
\begin{aligned}
\Delta c_{\gamma^*\gamma Z} &= \tfrac{1}{4}m_Z^3 v\left[-\sin(2\theta_W)c'_{\tilde{B}W} + 4\cos^2\theta_W c'_{\tilde{B}B} + \sin^2\theta_W c'_{\tilde{W}W}\right],\\
\Delta c_{Z^*\gamma Z} &= \tfrac{1}{8}m_Z^3 v\left[4c_{\tilde{B}W} - 4c_{\tilde{W}B} - 4\cos^2\theta_W c'_{\tilde{B}W} - 4\sin(2\theta_W)c'_{\tilde{B}B} + \sin(2\theta_W)c'_{\tilde{W}W}\right],\\
\Delta c_{\gamma^*ZZ} &= \tfrac{1}{8}m_Z^3 v\left[-4c_{\tilde{B}W} + 4c_{\tilde{W}B} + 4\sin^2\theta_W c'_{\tilde{B}W} - 4\sin(2\theta_W)c'_{\tilde{B}B} + \sin(2\theta_W)c'_{\tilde{W}W}\right],\\
\Delta c_{Z^*ZZ} &= \tfrac{1}{4}m_Z^3 v\left[\sin(2\theta_W)c'_{\tilde{B}W} + 4\sin^2\theta_W c'_{\tilde{B}B} + \cos^2\theta_W c'_{\tilde{W}W}\right].
\end{aligned}
$$

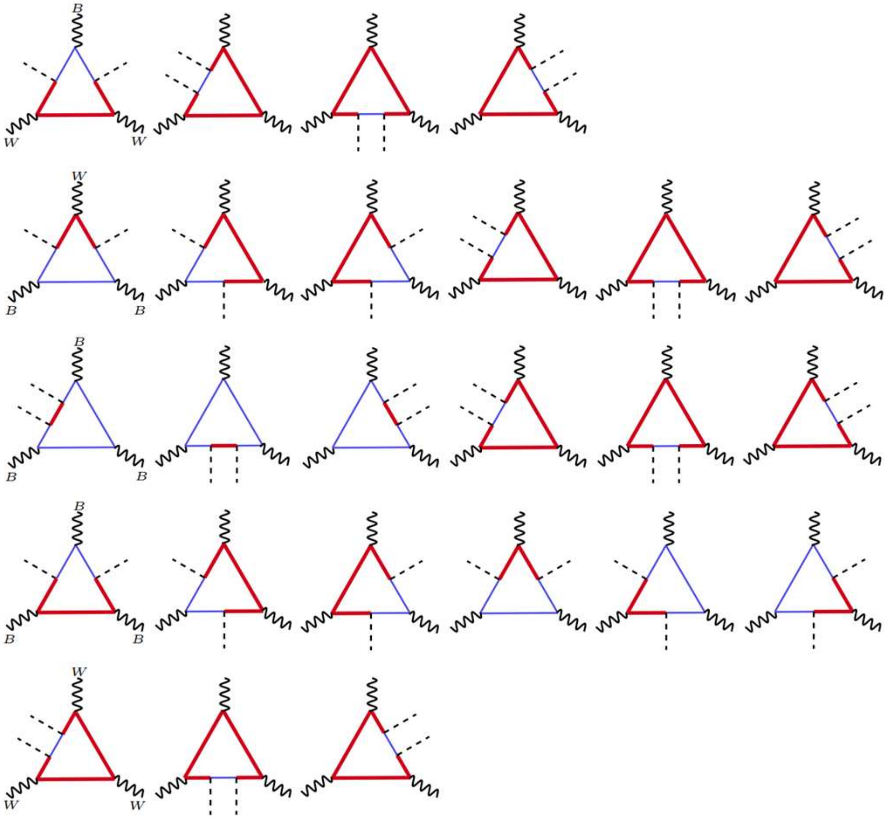
2408.12508

Structure of Heavy Fermion Loop Contributions to nTGCs

Yukawa interaction between a fermionic weak doublet N and a fermionic weak singlet E

$$\bar{N}H(c_V + c_A\gamma_5)E + \text{h.c.}$$

(1) All heavy: Both ***N*** and ***E*** are heavy with mass scale ***M***
(2) Heavy-light: Only one of ***N*** or ***E*** is heavy with mass scale ***M***



Pure gauge operators cannot obtained from one-loop
However, they can be generated at two-loop level

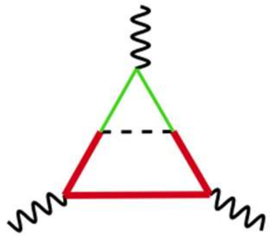


Figure 3: A sample two-loop diagram containing internal fields of heavy fermions and Higgs doublet that contribute to the nTGCs. Here a sum over directions of the fermion loop flows is implied.

Results for Induced nTGCs

All heavy $\mathcal{L} \supset \bar{\mathcal{N}}(\mathrm{i}\not{D}-M_{\mathcal{N}})\mathcal{N}+\bar{\mathcal{E}}(\mathrm{i}\not{D}-M_{\mathcal{E}})\mathcal{E}+\bar{\mathcal{N}}H(c_V+c_A\gamma_5)\mathcal{E}+\text{h.c.}$

$$c_{\tilde{W}W} = -\frac{g^2 c_{VA}^2}{240\pi^2 M^4}, \quad c'_{\tilde{W}W} = \frac{g^2 c_{VA}^2}{160\pi^2 M^4},$$

$$c_{\tilde{B}B} = -\frac{g'^2(1-5Y_{\mathcal{N}}+10Y_{\mathcal{N}}^2)c_{VA}^2}{960\pi^2 M^4}, \quad c'_{\tilde{B}B} = \frac{g'^2(3-20Y_{\mathcal{N}}+40Y_{\mathcal{N}}^2)c_{VA}^2}{1920\pi^2 M^4},$$

$$c_{\tilde{B}W} = -\frac{gg' c_{VA}^2}{1920\pi^2 M^4}, \quad c'_{\tilde{B}W} = -\frac{gg'(1-5Y_{\mathcal{N}})c_{VA}^2}{240\pi^2 M^4}, \quad c_{\tilde{W}B} = \frac{gg'(3-20Y_{\mathcal{N}})c_{VA}^2}{1920\pi^2 M^4},$$

$$c_{\gamma^* ZZ} = \frac{m_Z^5 c_{VA}}{192\pi^2 v M^4}\sin(2\theta_W)(2Y_{\mathcal{N}}-1)\big[(2Y_{\mathcal{N}}-1)\cos(2\theta_W)-2Y_{\mathcal{N}}\big],$$

$$c_{Z^* ZZ} = \frac{m_Z^5 c_{VA}}{1920\pi^2 v M^4}\big[5(2Y_{\mathcal{N}}-1)^2\cos(4\theta_W)-40(2Y_{\mathcal{N}}-1)\cos(2\theta_W)+60Y_{\mathcal{N}}^2-20Y_{\mathcal{N}}+7\big],$$

$$c_{\gamma^*\gamma Z} = \frac{m_Z^5 c_{VA}}{192\pi^2 v M^4}\sin^2(2\theta_W)(2Y_{\mathcal{N}}-1)^2,$$

$$c_{Z^*\gamma Z} = \frac{m_Z^5 c_{VA}}{192\pi^2 v M^4}\sin(2\theta_W)(2Y_{\mathcal{N}}-1)\big[(2Y_{\mathcal{N}}-1)\cos(2\theta_W)-2Y_{\mathcal{N}}\big],$$

Heavy-light $\mathcal{L} \supset \bar{F}(\mathrm{i}\not{D}-M)F+(y\bar{F}He_R+\text{h.c.}).$

$$c_{\tilde{W}W} = -\frac{g^2 y^2}{192\pi^2 M^4}, \quad c'_{\tilde{W}W} = \frac{g^2 y^2}{144\pi^2 M^4},$$

$$c_{\tilde{B}B} = \frac{11 g'^2 y^2}{768\pi^2 M^4}, \quad c'_{\tilde{B}B} = \frac{g'^2 y^2}{576\pi^2 M^4}\left(1+6\log\frac{\mu^2}{M^2}\right),$$

$$c_{\tilde{B}W} = \frac{g' g y^2}{1152\pi^2 M^4}\left(35+12\log\frac{\mu^2}{M^2}\right),$$

$$c'_{\tilde{B}W} = \frac{g' g y^2}{144\pi^2 M^4}\left(4+3\log\frac{\mu^2}{M^2}\right),$$

$$c_{\tilde{W}B} = -\frac{g' g y^2}{1152\pi^2 M^4}\left(17+12\log\frac{\mu^2}{M^2}\right).$$

$$c'_{\gamma^* ZZ}(q_{\gamma^*}) = \frac{m_Z^5 y^2}{288\pi^2 v M^4}\sin(2\theta_W)\left[-3\cos(2\theta_W)+1+6\log\frac{M^2}{-q_{\gamma^*}^2}\right],$$

$$c'_{Z^* ZZ}(q_{Z^*}) = -\frac{m_Z^5 y^2}{576\pi^2 v M^4}\left[3\cos(4\theta_W)-20\cos(2\theta_W)+13+24\sin^2\theta_W\log\frac{M^2}{-q_{Z^*}^2}\right],$$

$$c'_{\gamma^*\gamma Z} = -\frac{m_Z^5 y^2}{96\pi^2 v M^4}\sin^2(2\theta_W),$$

$$c'_{Z^*\gamma Z} = \frac{m_Z^5 y^2}{96\pi^2 v M^4}\sin(2\theta_W)\big[-\cos(2\theta_W)+3\big].$$

Summary

- **We accomplished series of nTGC studies：**
- **These papers open up new direction for international research on SMEFT nTGC**
- **We propose new nTGC form factor formalism which match Dimension-8 SMEFT**
  - **Conventional nTGC form factor formalism disregards SU(2)×U(1) of SM**
  - **ATLAS and CMS are redoing the analysis**
- **We study collider phenomenon for both CPC and CPV nTGCs**
- **We perform a dedicated simulation with a realistic detector configuration of CEPC**
- **Our studies show measurements of nTGCs at CEPC and other Higgs factories have the potential to probe energy scales well beyond their center-of-mass energies, even exceeding 1 TeV**
- **We explore UV completion of nTGCs and show how nTGCs may be generated by loop diagrams involving vector-like heavy fermions**

感谢聆听