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Probing Neutral Triple Gauge Couplings via $Z(\ell^+\ell^-/\nu\bar{\nu})\gamma$ production at Future Lepton Collider

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SPCS2025: Precision Higgs Factory Physics: Theory Meets Experiment

上海交通大學
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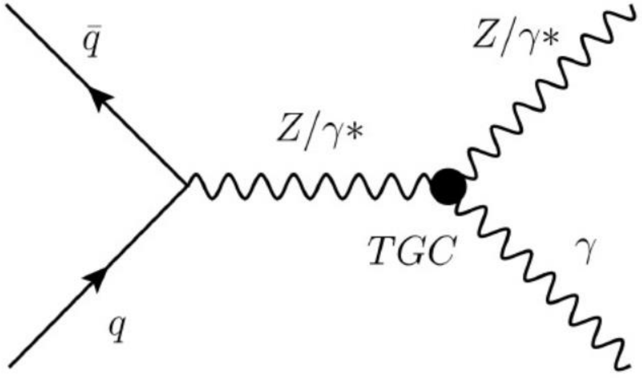
Introduction

- **Standard Model Effective Field theory**
  - Model-independent way to explore Beyond Standard Model (BSM) physics
  - High-dim operators constrained by SU(2)⊗U(1) symmetry, to describe new physics

$$\boxed{\Delta\mathcal{L}_{dim8} = \sum_i \frac{\tilde{c}_j}{\tilde{\Lambda}^4} O_i = \sum_i \frac{sign(\tilde{c}_j)}{\Lambda_j^4} O_j}$$

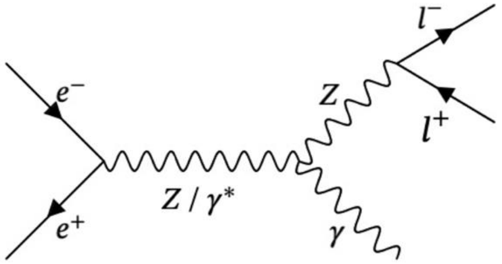
- **Neutral triple gauge couplings (nTGCs) : $ZZ\gamma$, $\gamma{*}Z\gamma$**
  - Part of anomalous TGCs (aTGCs), but absent in SM at tree level
  - First arise from dim-8 contributions
  - To provide a unique portal to BSM



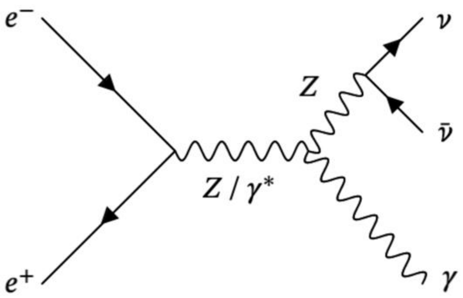
[PRD 107 (2023) 035005](#)
[PRD 108 (2023) L111704](#)
[Sci. Chin.-Phys. Mech. Astron. 64 221062 (2021)](#)

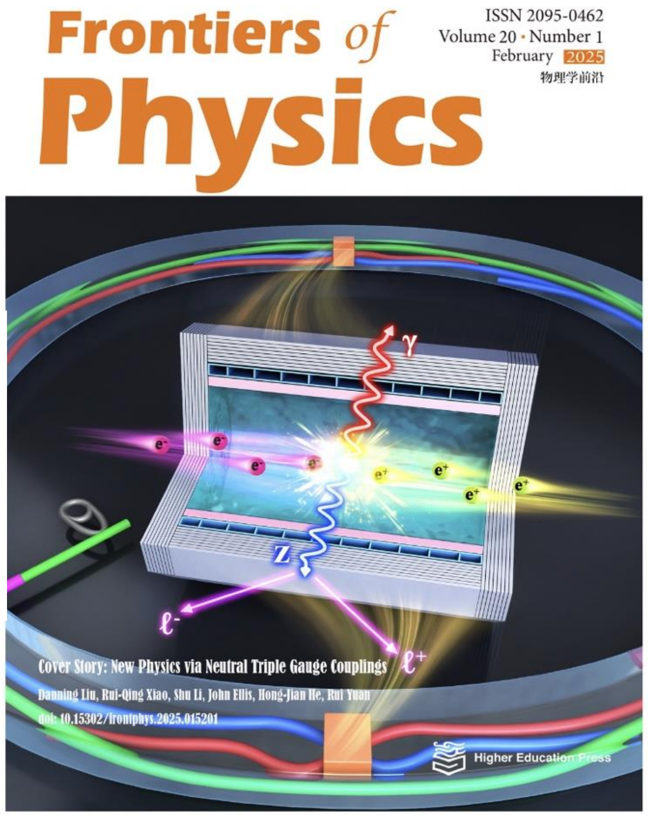
From Z(ℓℓ)γ to Z(νν)γ: Extending the nTGC Study

- $e^+e^- \to Z(\ell^+\ell^-)\gamma$
  - 1st SU(2)⊗U(1) fully gauge invariant nTGCs
    - Theo. Ref. **PRD 107 (2023) 035005**
  - Correct matching between the SMEFT and the form factor
  - Two extra dim-8 operators $\mathcal{O}_{G+}$, $\mathcal{O}_{G-}$ are added to makes the correct transformation
  - Designed for on-shell scenario
  - Work published: **Front. Phys. 20 (2025) 12501, no.1**



- $e^+e^- \to Z(\nu\bar{\nu})\gamma$
  - Still preserve SU(2)⊗U(1) fully gauge invariant treatment
  - Extends SMEFT to off-shell $Z^*\gamma V^*$ interactions
  - Includes both CPC and CPV dim-8 operators
    - Theo. Ref. **PRD 108 (2023) L111704**





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Theoretical Framework

- **CPC dim-8 nTGC operators** (both ℓℓγ and ννγ channels)

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

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

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

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

- **CPV dim-8 nTGC operators** (only ννγ channel)

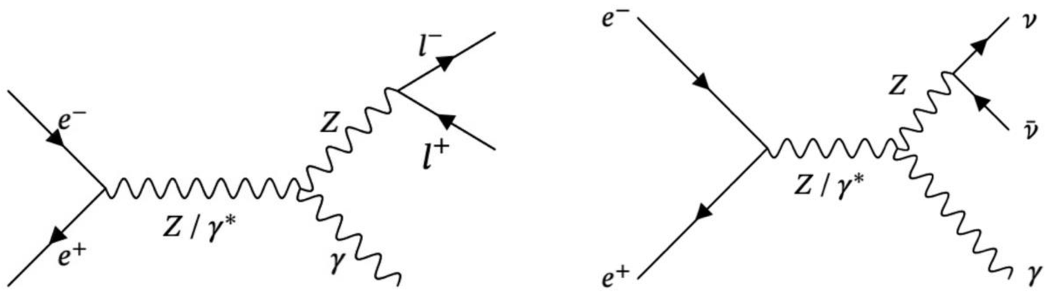
$$g\tilde{\mathcal{O}}_{G+} = B_{\mu\nu}W^{a\mu\rho}\left(D_{\rho}D_{\lambda}W^{a\nu\lambda} + D^{\nu}D^{\lambda}W^{a}_{\lambda\rho}\right)$$

$$g\tilde{\mathcal{O}}_{G-} = B_{\mu\nu}W^{a\mu\rho}\left(D_{\rho}D_{\lambda}W^{a\nu\lambda} - D^{\nu}D^{\lambda}W^{a}_{\lambda\rho}\right)$$

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

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

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



Phys.Rev.D 108 (2023) L111704

Theoretical Framework

- Transformation: **Form factors**
  - Convert constraints from SMEFT approach to Effective Vertex approach

$$\hat{h}_4 = \frac{\hat{r}_4}{[\Lambda_{G+}^4]} = -\frac{1}{[\Lambda_{G+}^4]}\frac{v^2 M_Z^2}{s_W c_W} \qquad \hat{h}_3^{\gamma} = \frac{\hat{r}_3^{\gamma}}{[\Lambda_{G-}^4]} = -\frac{1}{[\Lambda_{G-}^4]}\frac{v^2 M_Z^2}{2c_W^2}$$

$$\hat{h}_3^{Z} = \frac{\hat{r}_3^{Z}}{[\Lambda_{\tilde{B}W}^4]} = \frac{1}{[\Lambda_{\tilde{B}W}^4]}\frac{v^2 M_Z^2}{2 s_W c_W} \qquad \boxed{\hat{h}_{31}^{\gamma} = \frac{\hat{r}_{31}^{\gamma}}{[\Lambda_{\widetilde{BW}}^4]} = -\frac{1}{[\Lambda_{\widetilde{BW}}^4]}\frac{v^2 M_Z^2}{s_W c_W}}$$

newly considered in the ννγ channel, while the others are included in both channels

- Neutral Triple Gauge Vertices

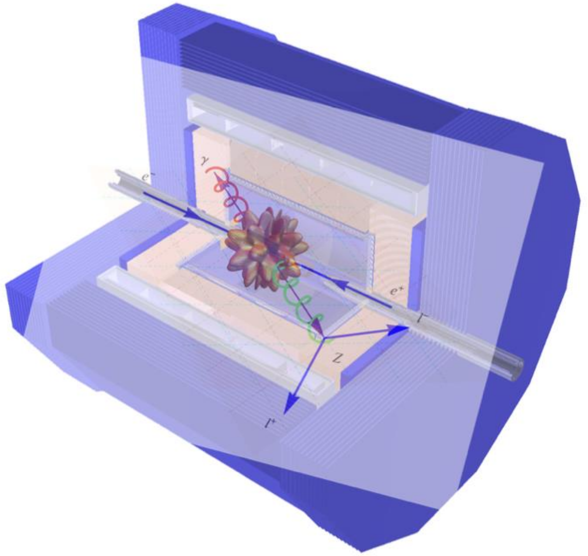
$$\Gamma_{Z^*\gamma Z^*}^{\alpha\beta\mu}(q_1,q_2,q_3) = \frac{e(q_3^2-q_1^2)}{M_Z^2}\left(\hat{h}_3^Z q_{2\nu}\epsilon^{\alpha\beta\mu\nu}\right) + \frac{\hat{h}_4}{2M_Z^2}\left(2q_2^{\alpha} q_{3\nu} q_{2\sigma}\epsilon^{\beta\mu\nu\sigma} + q_3^2 q_{2\nu}\epsilon^{\alpha\beta\mu\nu}\right)$$

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

PRD 108 (2023) L111704

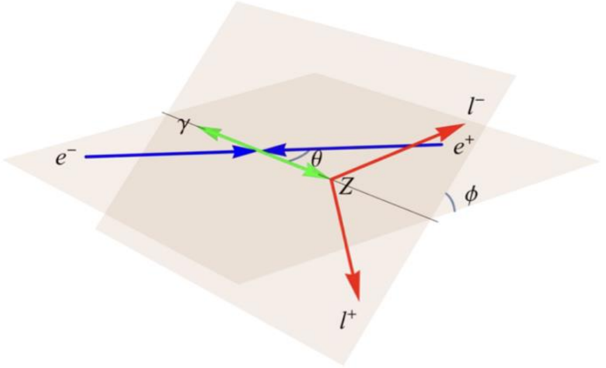
nTGC Search @ CEPC Experiment

- Circular Electron Positron Collider
  - High luminosity provides high statistics
  - Precise beam direction and energy
- Experiment configurations
  - Energy $\sqrt{s}$ = 240 GeV
  - Integrated luminosity : 20 ab^{-1}
  - Signal sample generated by MadGraph5 and showered by Pythia8



- $e^+e^- \to Z(\ell^+\ell^-)\gamma$
  - **Full simulation** with CEPC official software (V4)
  - Optimized with a newly defined variable ϕ

$$cos\phi = \frac{(\vec{p}_e \times \vec{p}_Z) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})}{|\vec{p}_e \times \vec{p}_Z||\vec{p}_{\ell^-} \times \vec{p}_{\ell^+}|}$$

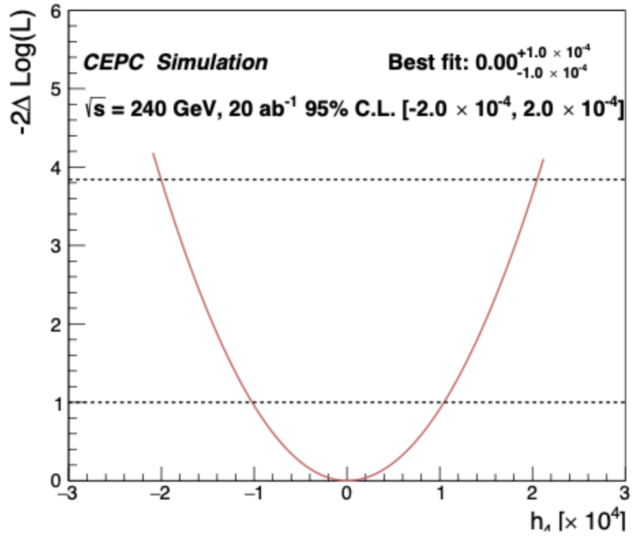


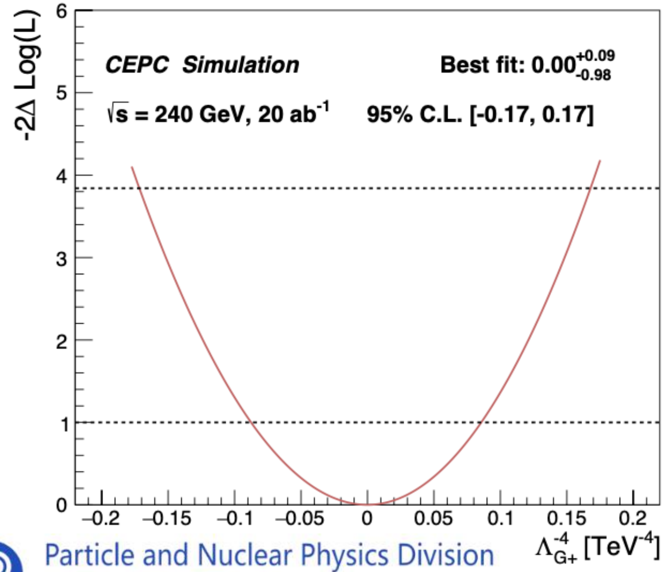
- $e^+e^- \to Z(\nu\bar{\nu})\gamma$
  - **Fast simulation** performed with **Delphes** using CEPC detector card (V4)

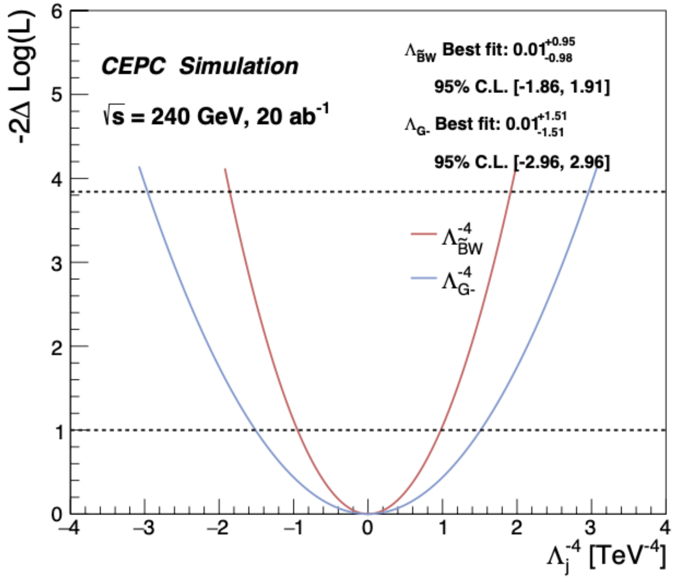
Results in Z(ℓℓ)γ Channel

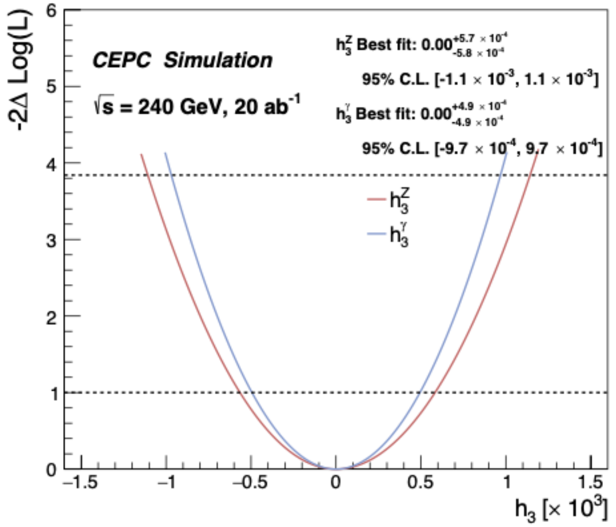
- Expected exclusion constraints achieved from ϕ variable

Expected limits			
Form factors (h_i^V)		New physics scale ($\Lambda_j[TeV]$)	
h_4	$[-2.0\times10^{-4}, 2.0\times10^{-4}]$	Λ_{G+}	1.55
h_3^Z	$[-9.7\times10^{-4}, 9.7\times10^{-4}]$	Λ_{G-}	0.76
h_3^γ	$[-1.1\times10^{-3}, 1.1\times10^{-3}]$	$\Lambda_{\tilde{B}W}$	0.85
		$\Lambda_{\widetilde{BW}}$	1.05









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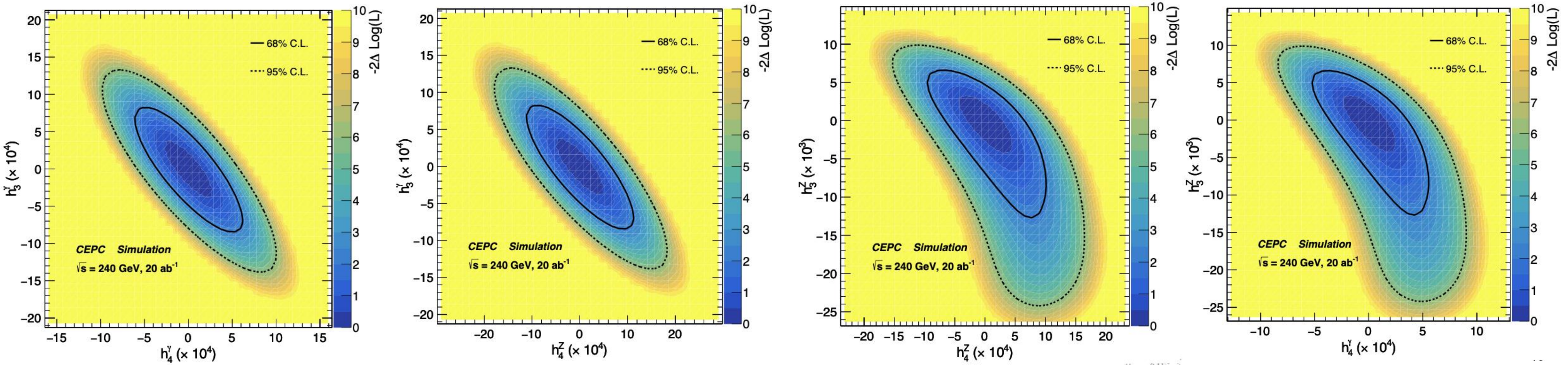
Results in Z(ℓℓ)γ Channel

- 2D constraints extracted by scanning pairs of nTGC operators simultaneously
- Study the correlation of sensitivity reaches between different pairs of nTGC operators

Conference Note: Highlight from ATLAS Real Data Analysis



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Analysis Strategy on $Z(\nu\bar{\nu})\gamma$ channel

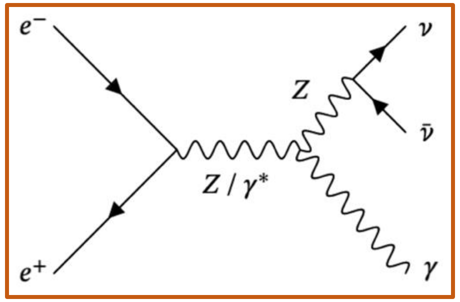
- Signal signature (Z$\nu\nu\gamma$ nTGC)
  - One signal photon
  - A pair of invisible neutrinos, reconstructed as **Missing Energy** $E_{miss} = 240GeV - \sum E_{visible}$
- Traditional selection-based analysis relies on the clear signal signature
  - One isolated signal photon
  - No charged leptons
  - Jet veto selection : to remove jet contributions or higher-order correction

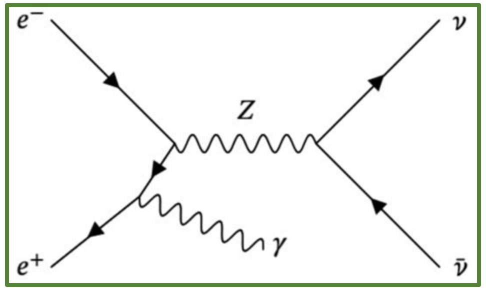
Variable	Cut
N_{pho}	≥ 1 signal photon with p_T^γ>35GeV
N_{lep}	0 no charged leptons
N_{jet}	0

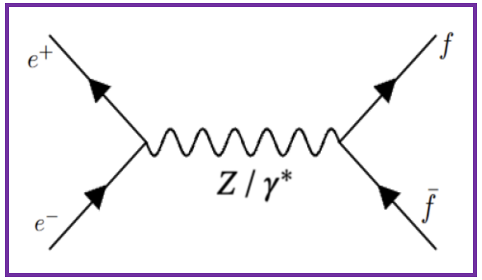
- Variables used in this study : p_T^γ and missing energy E_{miss}

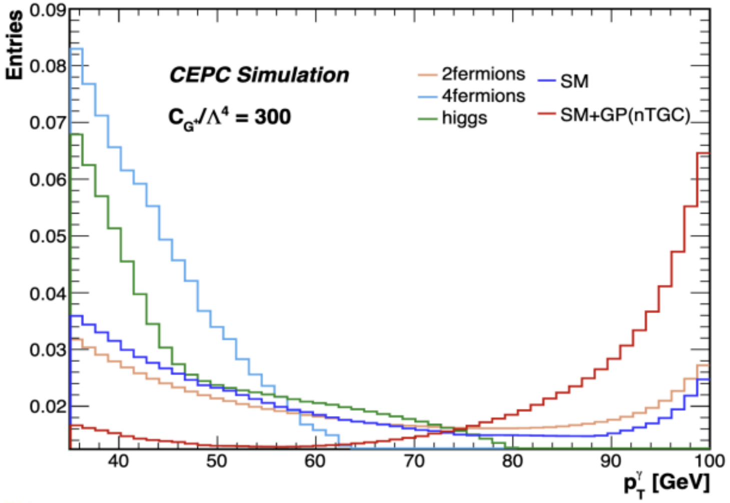
Signal and Backgrounds

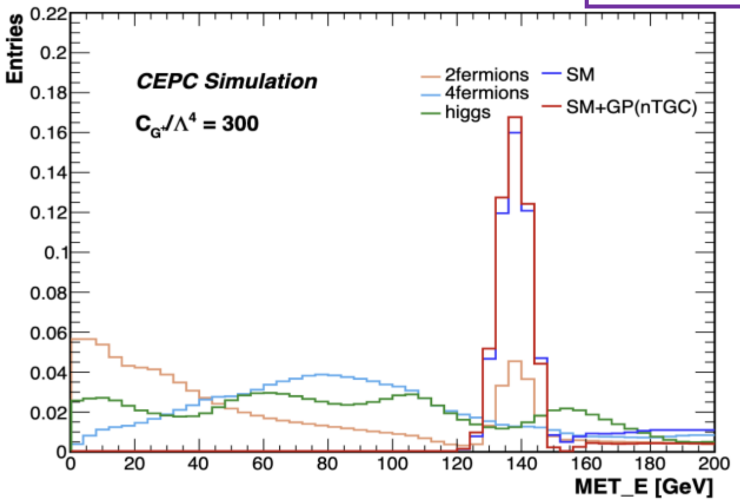
- The cut-based approach proposed previously has been applied to both signal and background samples
- Signal processes
  - Z(νν)γ nTGC (modeled w/ EFT)
- Background processes
  - irreducible background (SM Zννγ)
  - Other backgrounds : 2-fermions (dominant), 4-fermions and Higgs







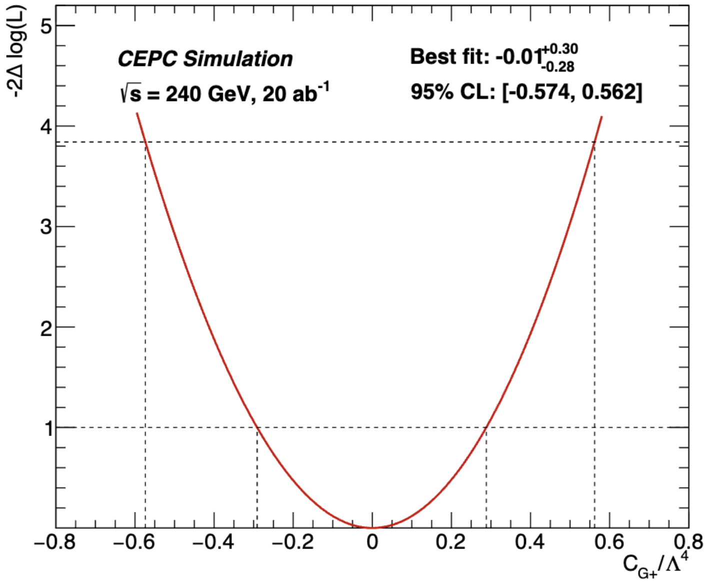




1D Exclusion Limits—New and Preliminary

- Expected limits extracted from the distribution with **higher sensitivity** b/w p_T^{γ} and E_{miss}
- Expected 95% C.L. limits on dim-8 operators from likelihood scans
- The outer range is **excluded at 95% C.L.**

New physics scale	Expected limits [TeV] (Zvvy, CEPC 240GeV, 20ab⁻¹)	Theoretical Reference (LHC 13 TeV, 0.3 ab⁻¹)
$\Lambda_{\tilde{B}W}$	0.6	1.4
$\Lambda_{\widetilde{BW}}$	1.36	1.6
Λ_{BW}	0.44	1.2
Λ_{WW}	0.37	0.98
Λ_{BB}	0.62	1.4
Λ_{G+}	1.14	3.5
Λ_{G-}	0.97	1.3
$\Lambda_{\tilde{G}+}$	0.56	2.9
$\Lambda_{\tilde{G}-}$	0.46	1.1

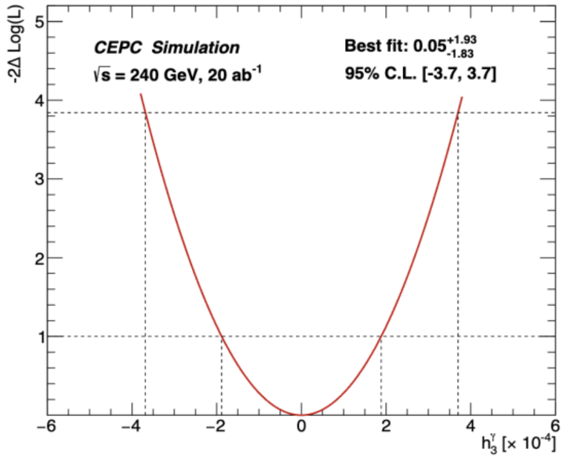


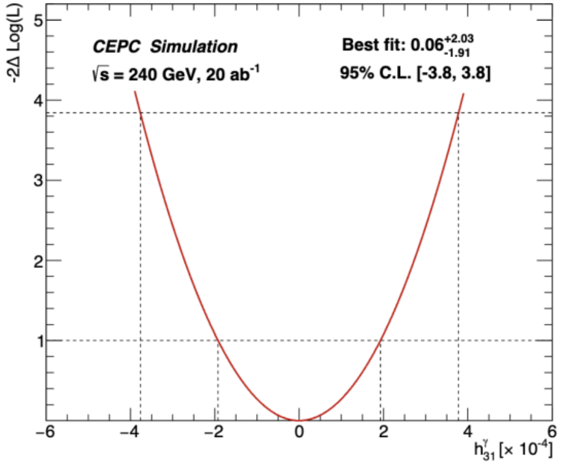
PRD 108 (2023) L111704

1D Exclusion Limits—New and Preliminary

- Expected 95% C.L. limits on **form factors**
- Converted from dim-8 operators limits via SMEFT form factor formulations [**SU(2)⊗U(1) preserved for 1st time!**]

Form Factors	Expected limits (Zllγ, CEPC 240GeV, 20ab⁻¹)	Expected limits (Zννγ, CEPC 240GeV, 20ab⁻¹)	Theoretical Reference (LHC 13 TeV, 0.3 ab⁻¹)
$\hat{h}_4$	2.0×10^{-4}	6.8×10^{-4}	8.5×10^{-6}
$\hat{h}_3^Z$	9.7×10^{-4}	4.5×10^{-4}	1.7×10^{-4}
$\hat{h}_3^\gamma$	1.1×10^{-3}	3.7×10^{-4}	1.3×10^{-4}
h_{31}^γ	-	3.8×10^{-4}	2.0×10^{-4}



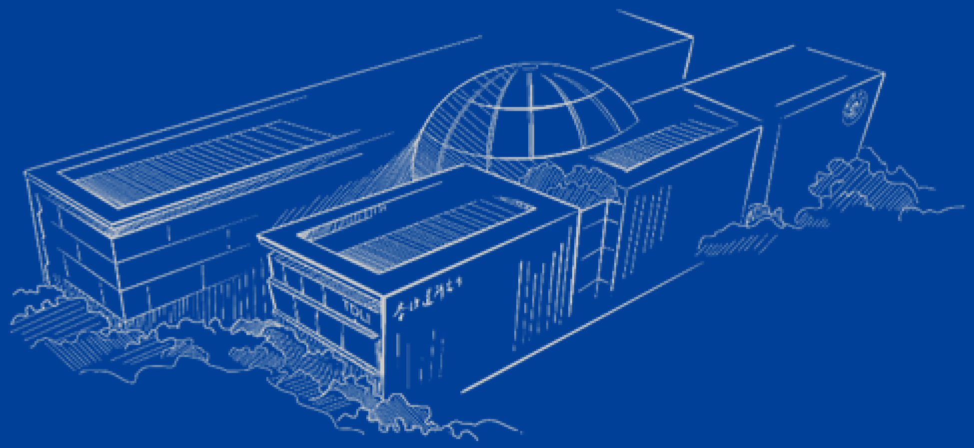


PRD 108 (2023) L111704

Summary

- nTGC provide a unique window to explore new physics beyond the SM
- A search for nTGC has been performed at CEPC using full simulation for the $\boldsymbol{Z(\ell^+\ell^-)\gamma}$ channel, published as a cover article in Frontiers of Physics
- A preliminary fast simulation study has been conducted for the $\boldsymbol{Z(\nu\bar{\nu})\gamma}$ channel with Delphes
- This study represents the 1st exploration incorporating the latest nTGC theoretical progress with SU(2)⊗U(1) gauge invariance, providing the 1st $\boldsymbol{Z(\nu\bar{\nu})\gamma}$ nTGC sensitivity estimation with detector fast simulation
- **Full simulation study** of $Z(\nu\bar{\nu})\gamma$ at **CEPC TDR geometry** is ongoing, please stay tuned for the updated results

Thank you!



Dim-8 operators in nTGC models

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- Pure dimension-8 operators

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

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

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

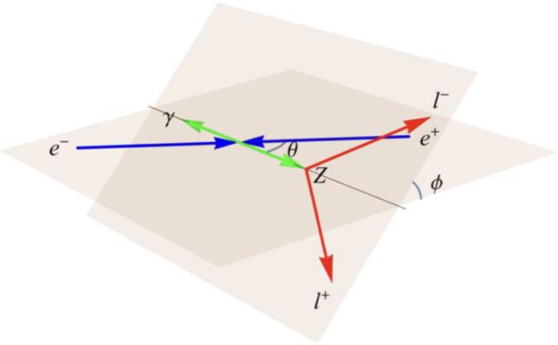
- Matching form factors to dimension-8 operators

$$h_4 = -\frac{sign(\tilde{c}_{G+})}{\Lambda^4_{G+}}\frac{v^2M_Z^2}{s_Wc_W} == \frac{r_4}{[\Lambda^4_{G+}]},$$

$$h_3^Z = \frac{sign(\tilde{c}_{\tilde{B}W})}{\Lambda^4_{\tilde{B}W}}\frac{v^2M_Z^2}{2s_Wc_W} == \frac{r_3^Z}{\Lambda^4_{\tilde{B}W}},$$

$$h_3^\gamma = -\frac{sign(\tilde{c}_{G-})}{\Lambda^4_{G-}}\frac{v^2M_Z^2}{2c_W^2} == \frac{h_3^\gamma}{[\Lambda^4_{G-}]}.$$

- Kinematic variables
  - Transverse momentum of leading photon
  - Angular variable ϕ (new defined in this study)



Event Selections

- Signal signature
  - Two opposite sign same flavour charged leptons
  - One signal photon

- Traditional selection-based analysis relies on the clear signal signature
  - Two OSSF leptons + one signal photon
  - Invariant mass selection : ensure that leptons decays from on- shell Z boson
  - Two isolated leptons
  - Jet veto selection : to remove jet contributions or higher- order correction

Variables	Cut
N_{lep}	2 signal OSSF leptons with leading lepton $p_T^{\text{lep}} > 30$ GeV
N_{pho}	≥ 1 signal photon with $p_T^{\gamma} > 35$ GeV
N_{jet}	0
$\Delta R(\ell, \ell)$	< 3
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV
$m_{\ell\ell} + m_{\ell\ell\gamma}$	> 182 GeV

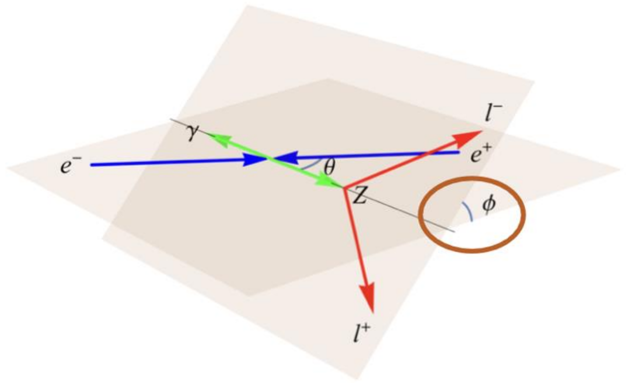
Systematics

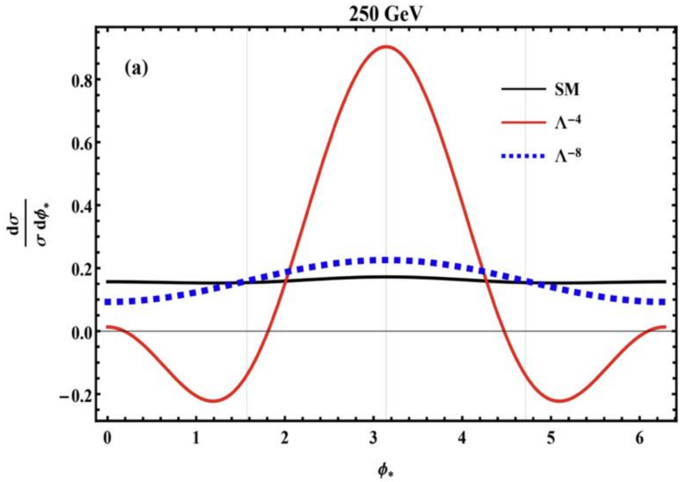
- Assigned on signal yields
  - Theoretical uncertainty : 0.5% uncertainty for modeling
  - Experimental uncertainty : luminosity, object identification, object reconstruction resolution, energy resolution, and detector acceptance

- Assigned on background yields
  - Floating event yields to account for background modeling
  - Dominant background: varied by 5% up/down
  - Other backgrounds : varied by 100% up/down

Optimaztion

- new special kinematic variables ϕ
  - Definition: Angle between scattering plane and decay plane
  - Direct evidence of interference between pure SM and BSM distributions





$$cos\phi = \frac{(\vec{p}_e \times \vec{p}_Z)\cdot(\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})}{|\vec{p}_e \times \vec{p}_Z||\vec{p}_{\ell^-} \times \vec{p}_{\ell^+}|}$$

CEPC background samples

Processes		Final States	σ (fb)
2 fermions	$\ell\ell$	$e^+e^-/\mu^+\mu^-/\tau^+\tau^-$	34856.50
	$\nu\nu$	$\nu_e\bar{\nu}_e/\nu_\mu\bar{\nu}_\mu/\nu_\tau\bar{\nu}_\tau$	50499.51
	qq	$u\bar{u}/d\bar{d}/c\bar{c}/s\bar{s}/b\bar{b}$	54106.86
4 fermions	WW (hadronic decay)		3825.46
	WW (leptonic decay)		403.66
	WW (semi-leptonic decay)		4846.99
	ZZ (hadronic decay)		516.67
	ZZ (leptonic decay)		67.81
	ZZ (semi-leptonic decay)		556.59
Higgs	e^+e^-H	e^+e^-+H	7.04
	$\mu^+\mu^-H$	$\mu^+\mu^-+H$	6.77
	$\tau^+\tau^-H$	$\tau^+\tau^-+H$	6.75
	$\nu\nu H$	$\nu_e\bar{\nu}_e/\nu_\mu\bar{\nu}_\mu/\nu_\tau\bar{\nu}_\tau+H$	46.29
	qqH	$u\bar{u}/d\bar{d}/c\bar{c}/s\bar{s}/b\bar{b}+H$	136.81

Results Comparison

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Parameters	Expected limits [TeV^{-4}]
$C_{\tilde{B}W}/\Lambda^4$	[-6.6,8.2]
$C_{\widetilde{BW}}/\Lambda^4$	[-0.3,0.3]
C_{BW}/Λ^4	[-29.7,29.4]
C_{WW}/Λ^4	[-74.6,71.8]
C_{BB}/Λ^4	[-6.6,6.4]
C_{G+}/Λ^4	[-0.57,0.56]
C_{G-}/Λ^4	[-1.1,1.1]
$C_{\tilde{G}+}/\Lambda^4$	[-11.1,10.9]
$C_{\tilde{G}-}/\Lambda^4$	[-24.3,23.4]

$\sqrt{s}$	13 TeV			100 TeV		
$\mathcal{L}\,(\mathrm{ab}^{-1})$	0.14	0.3	3	3	10	30
Λ_{G+}(CPC)	3.2	3.5	4.1	23	25	28
Λ_{G-}(CPC)	1.2	1.3	1.5	7.7	8.5	9.3
$\Lambda_{\tilde{B}W}$(CPC)	1.3	1.4	1.6	5.4	5.9	6.4
$\Lambda_{\widetilde{BW}}$(CPC)	1.5	1.6	1.8	6.2	6.8	7.4
$\Lambda_{\tilde{G}+}$(CPV)	2.7	2.9	3.5	19	21	23
$\Lambda_{\tilde{G}-}$(CPV)	1.0	1.1	1.3	6.5	7.2	7.8
Λ_{WW}(CPV)	0.93	0.98	1.2	3.9	4.3	4.6
Λ_{WB}(CPV)	1.1	1.2	1.4	4.6	5.1	5.5
Λ_{BB}(CPV)	1.3	1.4	1.7	5.6	6.2	6.8

Form Factors	Expected limits
$\hat{h}_4$	[-6.7,6.9] ×10^{-4}
$\hat{h}_3^Z$	[-4,4.9] ×10^{-4}
$\hat{h}_3^\gamma$	[-3.7,3.7] ×10^{-4}
h_{31}^γ	[-3.8,3.8] ×10^{-4}

$\sqrt{s}$	13 TeV				100 TeV		
$\mathcal{L}(\mathrm{ab}^{-1})$	0.14	0.3	3		3	10	30
$\lvert\hat{h}_{4,2}\rvert\times10^6$	11	8.5	4.2	$\lvert\hat{h}_{4,2}\rvert\times10^9$	4.5	2.9	2.0
$\lvert\hat{h}^Z_{3,1}\rvert\times10^4$	2.2	1.7	0.90	$\lvert\hat{h}^Z_{3,1}\rvert\times10^7$	7.0	4.8	3.4
$\lvert\hat{h}^\gamma_{3,1}\rvert\times10^4$	1.6	1.3	0.67	$\lvert\hat{h}^\gamma_{3,1}\rvert\times10^7$	0.94	0.62	0.44
$\lvert h^\gamma_{31,11}\rvert\times10^4$	2.5	2.0	1.0	$\lvert h^\gamma_{31,11}\rvert\times10^7$	8.3	5.7	4.0