Probing Neutral Triple Gauge Couplings via $Z\gamma(\ell^+\ell^-\gamma)$ Production at e^+e^- Colliders

——paper study report

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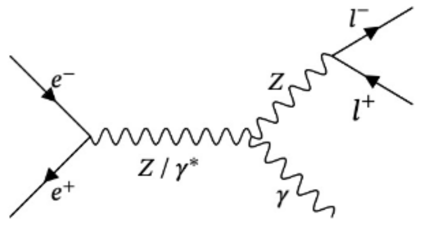
Outline

- Introduction
- The simulation and analysis at CEPC
- Systematic Uncentanties
- Results

Introduction

- Standard Model Effective Field Theory
  - A powerful framework for studying model-independently possible new physics beyond the Standard Model.
  - Introduce higher-dimensional operators to describe new physics effects.

- Neutral Triple Gauge Couplings(nTGCs)
  - Absent in the SM and at the level of dimension-6 operators in the SMEFT, but arising first at the level of dimension-8 operators.
  - It refers to new interactions between $Z\gamma V^* \ (V = Z, \gamma)$
  - Measure the corresponding nTGC form factors in the reaction $e^+e^- \to Z\gamma$ process with $Z \to \ell^+\ell^- \ (\ell = e, \mu)$ decays at CEPC detector.



Introduction-Theoretical framework

- The dimension-8 SMEFT effective Lagrangian takes the following form：

$$\mathcal{L}_{\text{SMEFT}} = \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_j = \sum_j \frac{\text{sign}(c_j)}{\Lambda_j^4}\mathcal{O}_j$$

- Effective Field approach

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

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

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

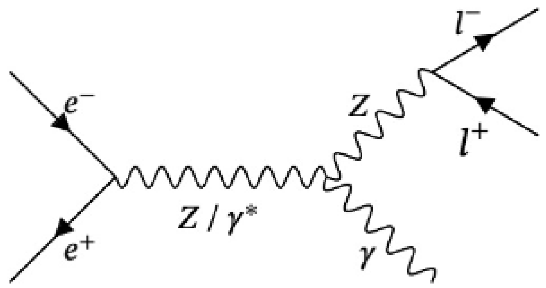
- Effective Vertex approach

$$\Gamma^{\alpha\beta\mu(8)}_{Z\gamma V^*}(q_1, q_2, q_3) = \frac{e(q_3^2 - M_V^2)}{M_Z^2}\left[\left(h_3^V + h_5^V \frac{q_3^2}{M_Z^2}\right) q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + \frac{h_4^V}{M_Z^2} q_2^\alpha q_{3\nu} q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right]$$

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

$$h_3^Z = \frac{\text{sign}(\tilde{c}_{\widetilde{B}W})}{\Lambda^4_{\widetilde{B}W}} \frac{v^2 M_Z^2}{2 s_W c_W} \equiv \frac{r_3^Z}{[\Lambda^4_{\widetilde{B}W}]},$$

$$h_3^\gamma = -\frac{\text{sign}(\tilde{c}_{G-})}{\Lambda^4_{G-}} \frac{v^2 M_Z^2}{2 c_W^2} \equiv \frac{r_3^\gamma}{[\Lambda^4_{G-}]}.$$



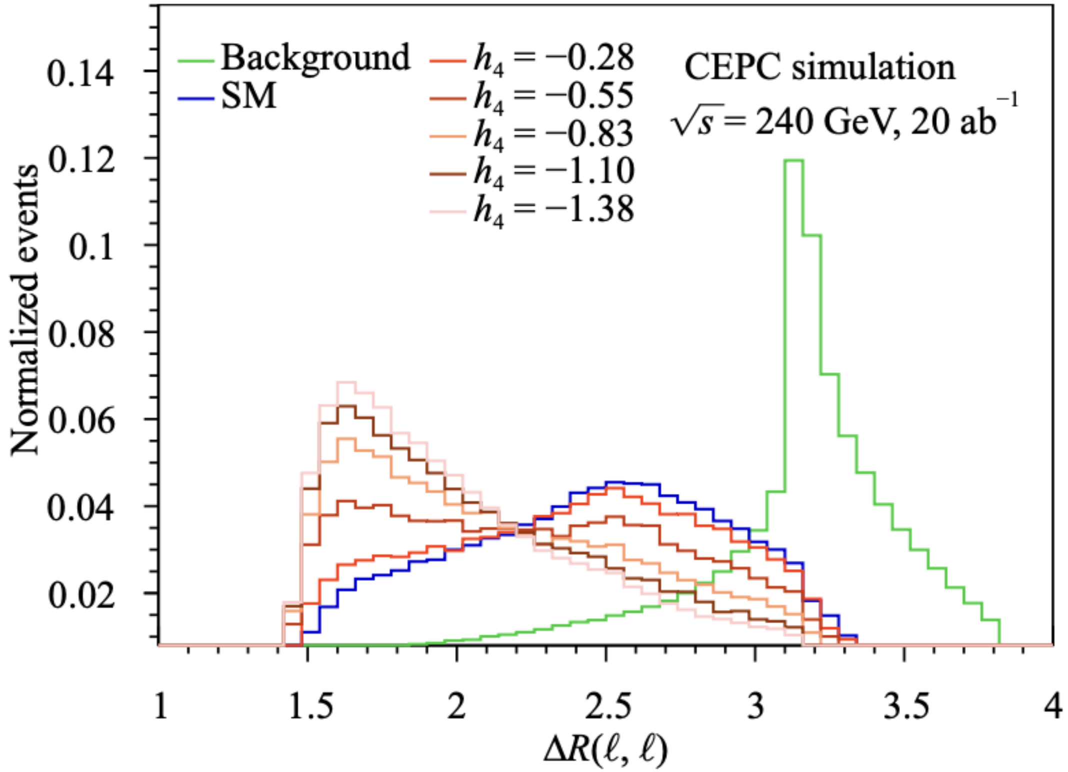
Simulation at CEPC

- Circular Electron Positron Collider
  - Aiming to meet the various physics studies, especially precision measurements.
  - $\sqrt{s}$ 240 GeV, with an integrated luminosity of 20 ab^{-1}
  - The angular resolution is set to be less than 0.1 mrad.

- Simulation
  - Signal Events：Generated by MadGraph5 and showered by Pythia8.
  - Background Events：Generated by WHIZARD
    divided into three categories:
    2-fermion background、4-fermion background、Resonant Higgs backgrounds
  - Full simulation with CEPC official software（V4）

Analysis Strategies

- Normalized distribution of the separation， has clear signal signature.
- Variations in the form factors lead to a significant deviation of the signal event distribution from the background. This indicates that nTGCs indeed play a role in the process.
- Set selection cuts （Two isolated leptons） to suppress possible background contributions.



Analysis Strategies

- Signal: nTGC contributions

- Background:
  - Irreducible processes (Z with an initial or final state radiation photon)

  - Other processes:
    - 2-fermions
    - 4-fermions
    - higgs background

Events selection cuts

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

Suppress background events through a series of selection cuts to improve the significance of the nTGC effect.

Systematic uncentanties

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

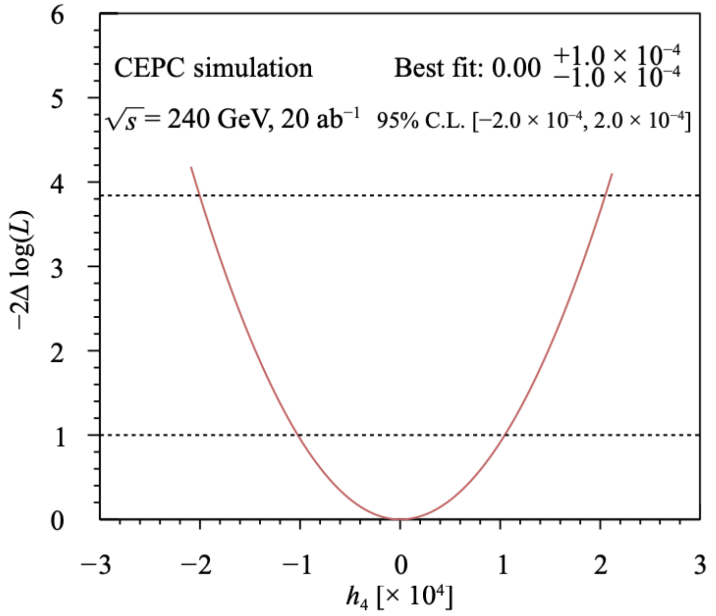
- Assigned on background yields
  - Floationg event yields to account for background modeling
  - Dominant background : varied by 5% up/down
  - Other backgrounds : varied by 100% up/down

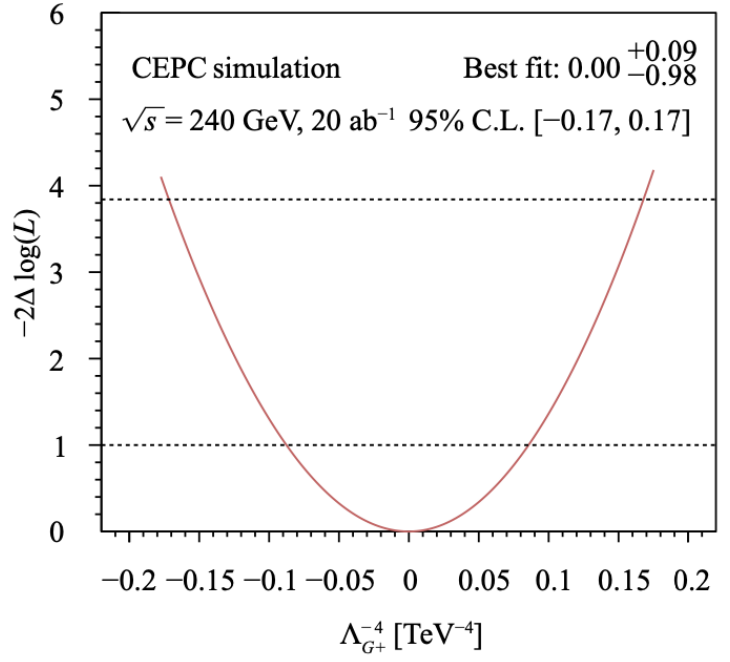
Results

The sensitivity reaches at the 95% CL for the new physics scales Λ_i as obtained from the expected constraints on the associated form factors derived from the SMEFT dimension-8 coefficients.

Highlight the central 95%C.L. range of the integral over the likelihood distribution, while values outside this range are excluded at this level.

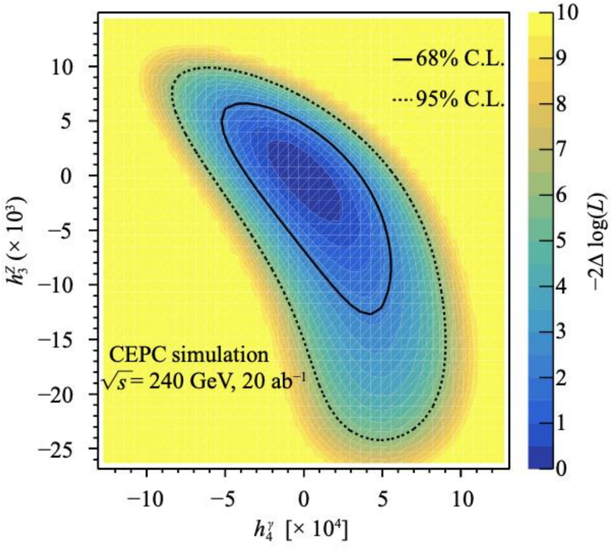
Form factors	Expected limits	New physics scales	Expected limits (TeV)
h_4	$[-2.0,\ 2.0]\times10^{-4}$	Λ_{G+}	1.55
h_3^{γ}	$[-9.7,\ 9.7]\times10^{-4}$	Λ_{G-}	0.76
h_3^{Z}	$[-1.1,\ 1.1]\times10^{-3}$	$\Lambda_{\tilde{B}W}$	0.85
		$\Lambda_{\widetilde{BW}}$	1.05

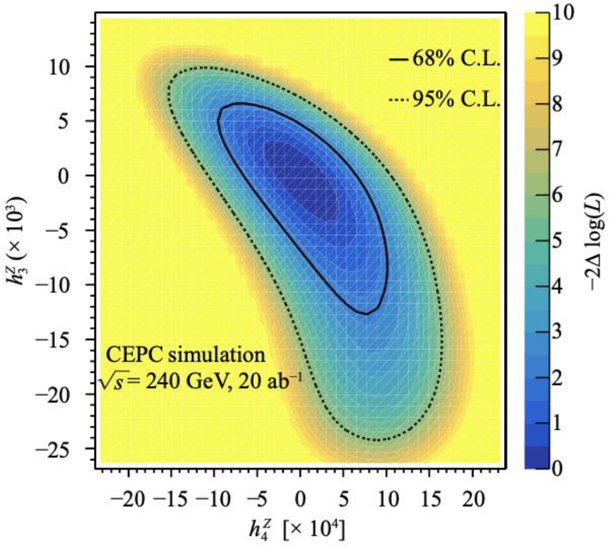


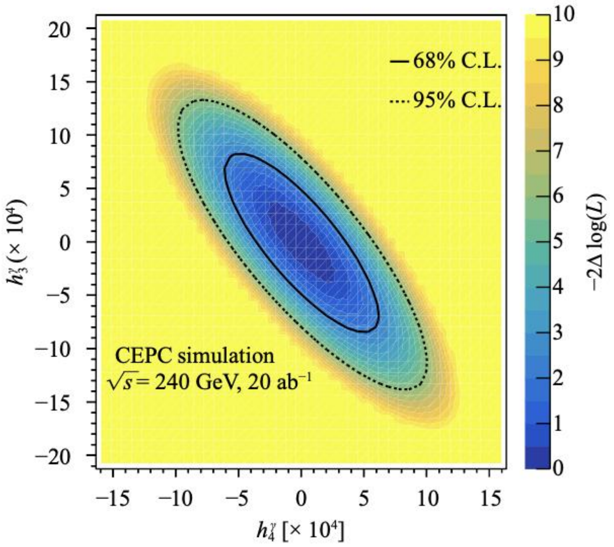


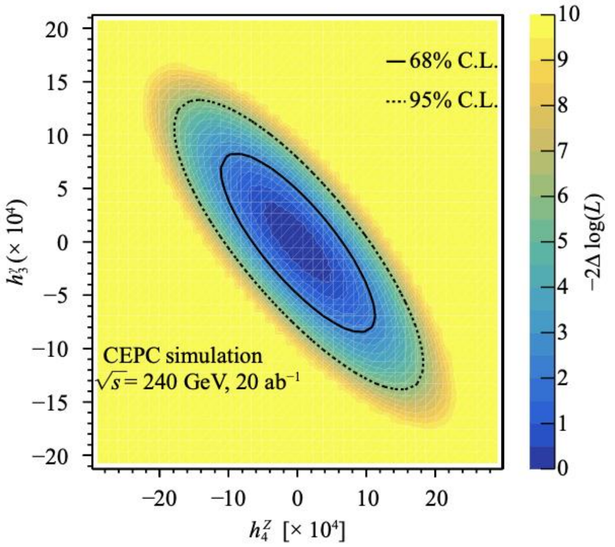
Results

- 2D constrains are also extracted by scanning pairs of nTGC operators simultaneously
  - To understand the correlation of sensitivity reaches between pairs of nTGC operators









Summary

- Focus on understanding the work on nTGC in the paper

- Replicate some of the results from the paper

- Next steps
  - Simulate the signal using Monte Carlo（MC)
  - Decompose closure test： We achieve accurate sample production by decomposing the Zγ cross section into these three terms and generating each term independently.