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

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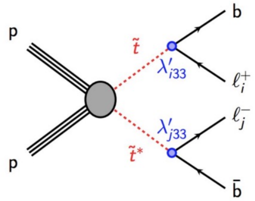
How to Probe New Physics

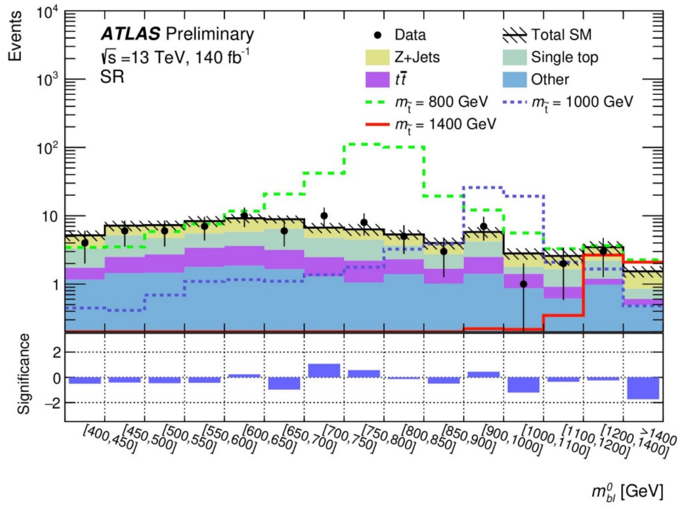
- Two general ways to probe new physics : new particles or new interactions

Model-dependent

New particles :
SUSY, 2HDM ···

Resonance peaks

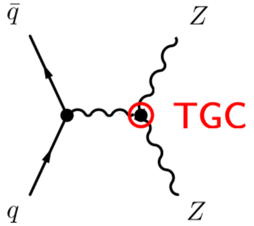


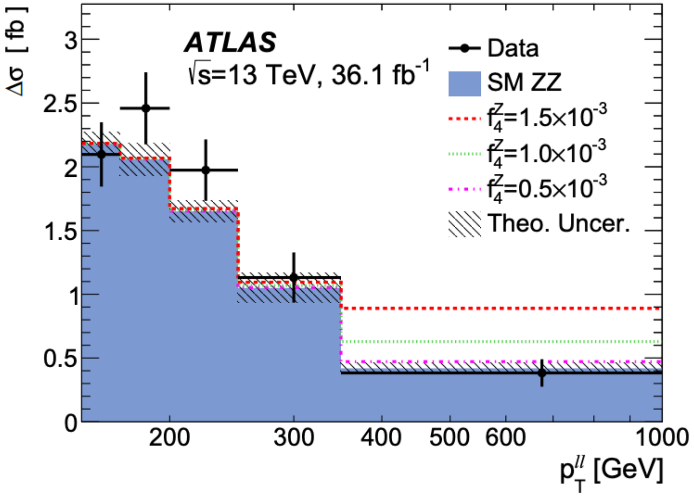


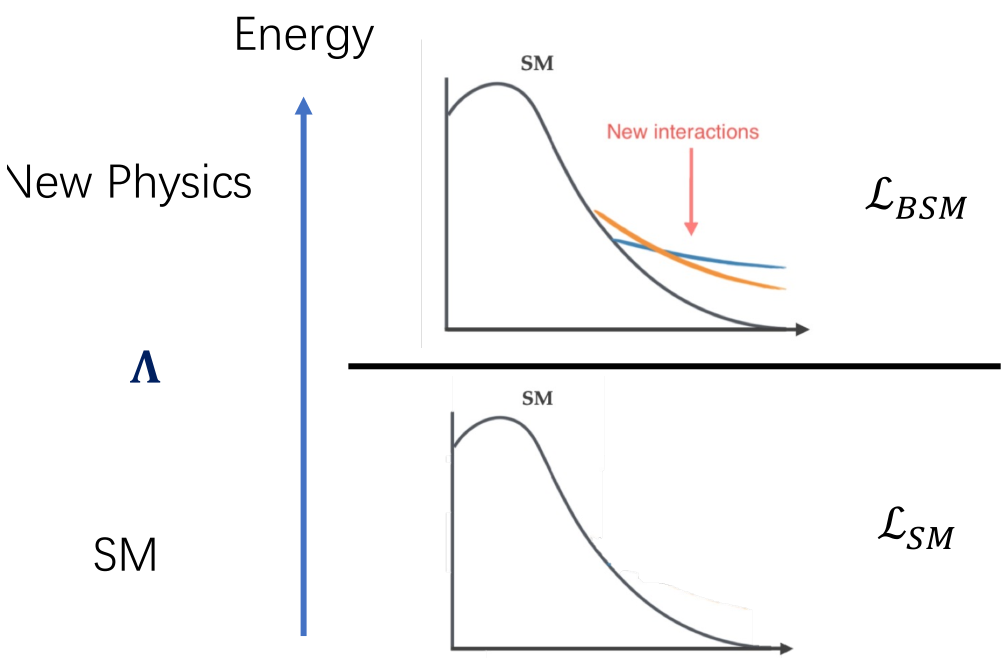
Model-independent

New interactions :
Anomalous coupings, EFT

Deviations in tails







Standard Model Effective Field Theory

- Standard Model Effective Field Theory – a model-independent way to explore new physics beyond the SM
  - Higher-dimensional operators constrained by SU(2) × U(1) symmetry, contributing to new physics :
    - Dimension-8 contributions scaled by quadratic power of new physics scale :

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

    - Neutral Triple Gauge Couplings (nTGCs) : $Z\gamma Z^*, Z\gamma\gamma^*$
  - Constrain Wilson coefficients with global analysis of experiment data
    - Non-zero c_i would indicate any BSM : Masses, spins, quantum number of new particles

Theoretical basis :

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Anomalous Couplings Beyond the Standard Model

- Anomalous coupling framework
  - EFT higher-dimension operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_i^d}{\Lambda^{d-4}} O_i^d$$

  - Vector approach by adding new degrees of freedom in the SM Lagrangian
    - Adding new interaction term to introduce anomalous triple gauge couplings
    - Comparable with different experimental results

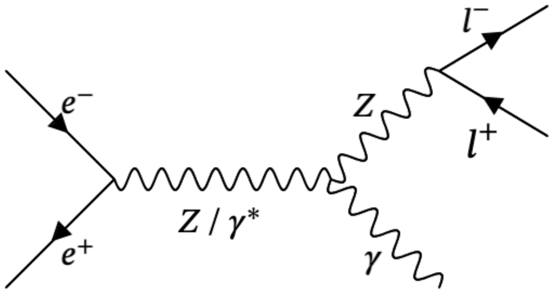
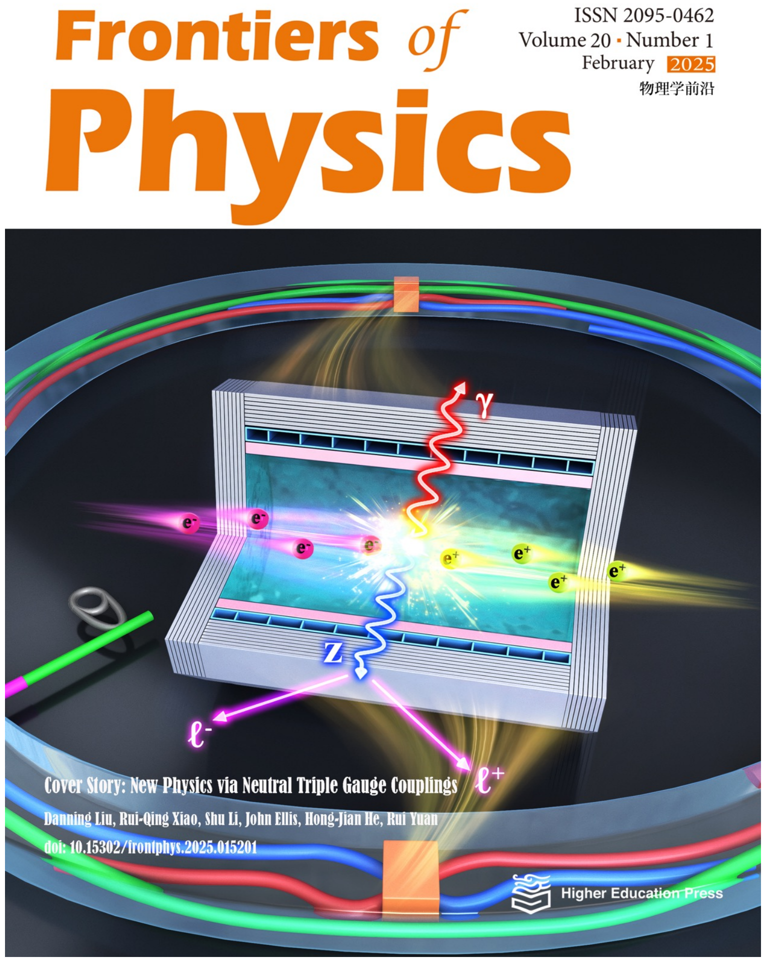


Diagram of $e^+e^- \to Z\gamma \to \ell^+\ell^-\gamma$: nTGC s-channel



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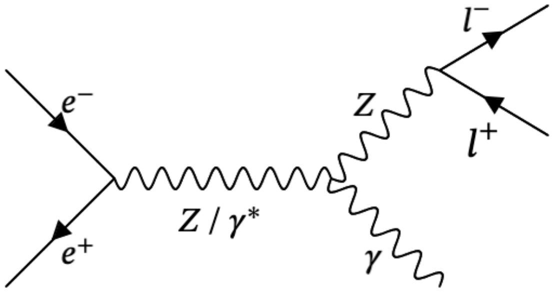
Introduction to nTGCs

- nTGCs: forbidden at SM tree level but first arise from dimension-8 contributions
- Effective Field Approach:
  - Definitions of pure gauge operators of dimension-8 that contribute to nTGCs:

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

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

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



- Effective Vertex Approach:
  - We denote:

$$h_4^V = 2h_5^V$$

$$h_4^Z = \frac{c_W}{s_W} h_4^\gamma$$

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

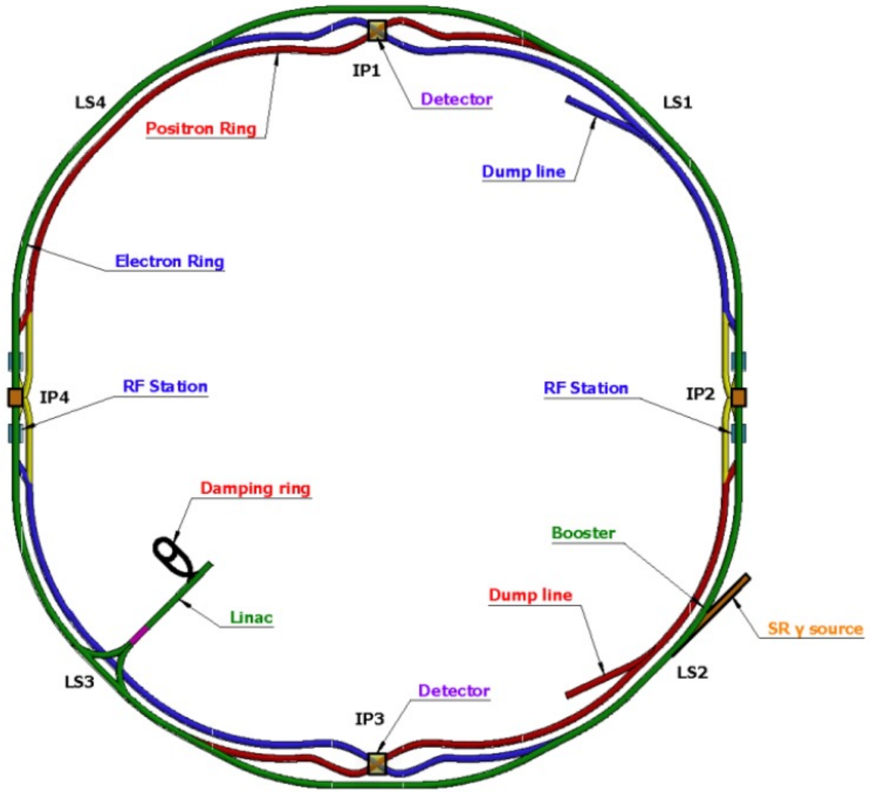
$$h_3^Z = \frac{\mathrm{sign}(\tilde{c}_{\widetilde{B}W})}{\Lambda^4_{\widetilde{B}W}} \frac{v^2 M_Z^2}{2 s_W c_W} \equiv \frac{r_3^Z}{[\Lambda^4_{\widetilde{B}W}]}, \qquad h_3^\gamma, h_4^V = 0, \qquad \text{for } \mathcal{O}_{\widetilde{B}W},$$

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

Circular Electron Positron Collider

- Circular Electron Positron Collider (CEPC)
  - First proposed by China in 2013
  - Higgs / W / Z factory
- Aiming to reach unpredecented accuracy
  - Higgs properties
  - Electroweak interaction parameters
  - QCD and Flavour physics
  - New physics beyond the Standard Model, such as anomalous gauge couplings

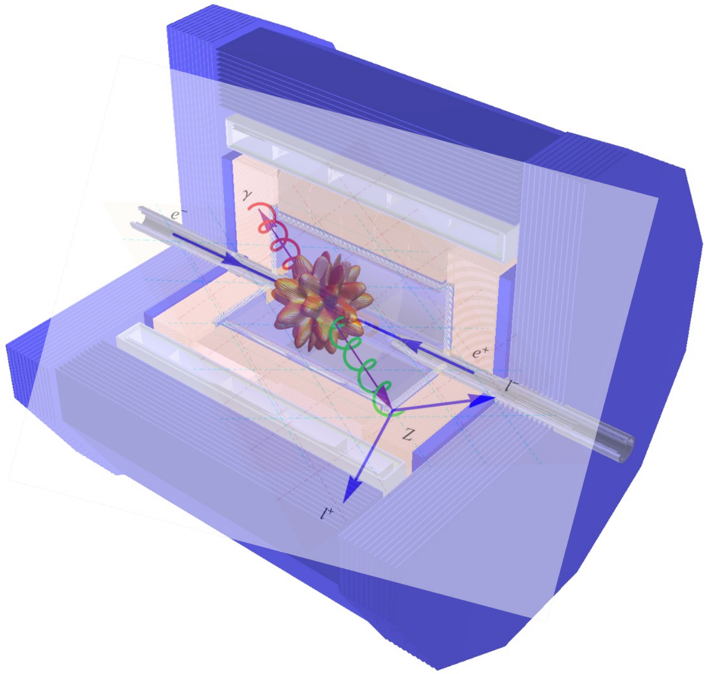
Our Focus !

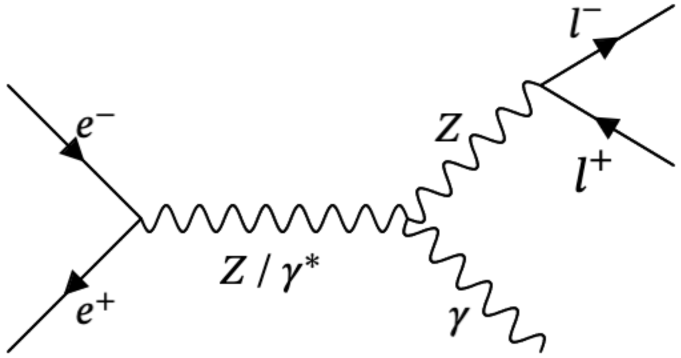


nTGC Searches at CEPC

- Experimental configurations:
  - **Full simulation** with CEPC official software (V4)
  - $\sqrt{s} = 240$ GeV, with an integrated luminosity of 20 ab^{-1}
  - Signal sample generated by MadGraph5 and showered by Pythia8

- General nTGC topology
  - $e^+e^- \to Z(\ell^+\ell^-)\gamma$, where Z decays to a pair of charged leptons
  - Two opposite sign same flavour charged leptons
  - One signal photon





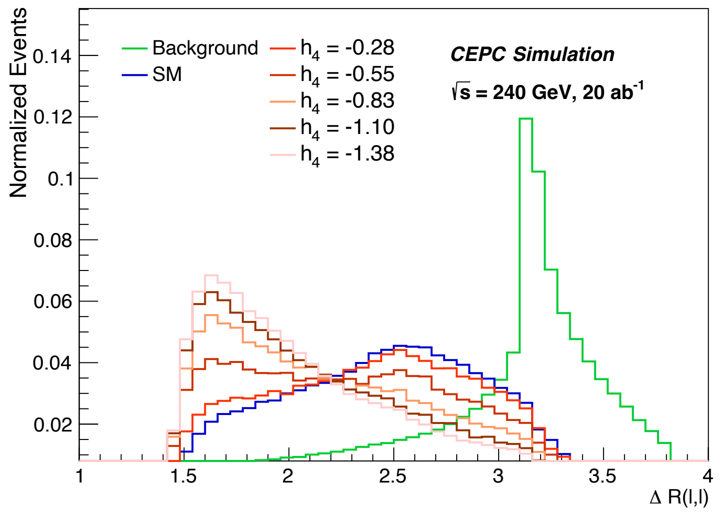
Analysis Strategy

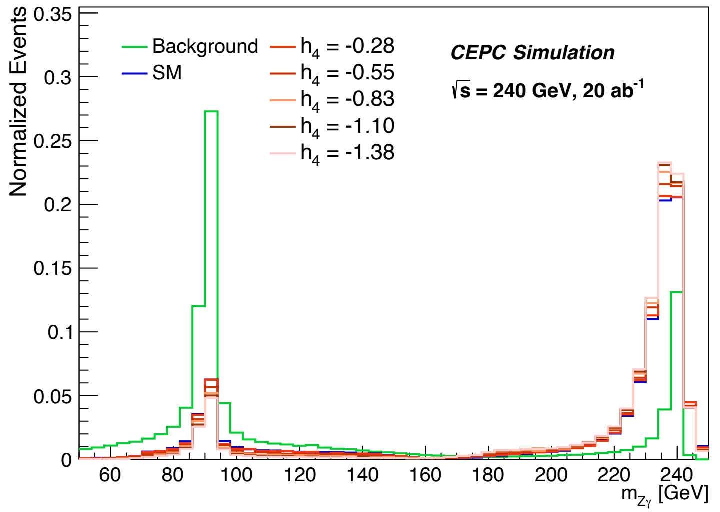
- Traditional selection-based analysis relies on the clear signal signature

Two isolated leptons → Strongly suppress possible background contributions

Jet veto selection
Remove jet-related background contributions
Remove higher-order corrections
Guarantee that the enhancement of cross section comes from nTGC effect

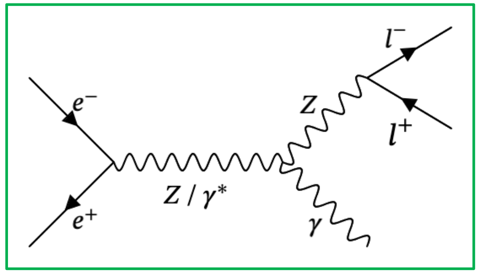
Invariant mass selection → Suppress Z plus final-state radiation photon scenario
Ensure that final-state leptons decay from on-shell Z boson

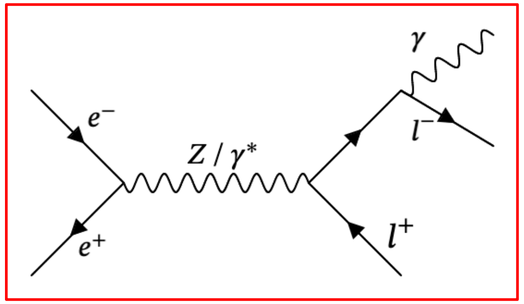


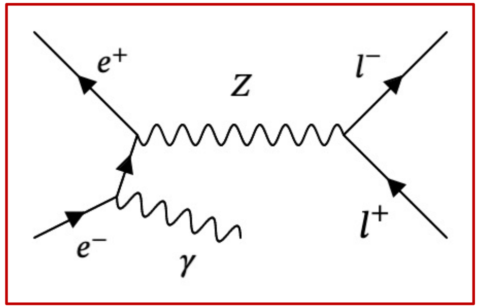


Analysis Strategy

- Contributions from possible processes:
  - Signal: nTGC contributions
  - Background :
    - Irreducible processes (Z with an initial or final state radiation photon)
    - Other processes
      - 2-fermions, 4-fermions
      - Higgs background







Cut-flow table:

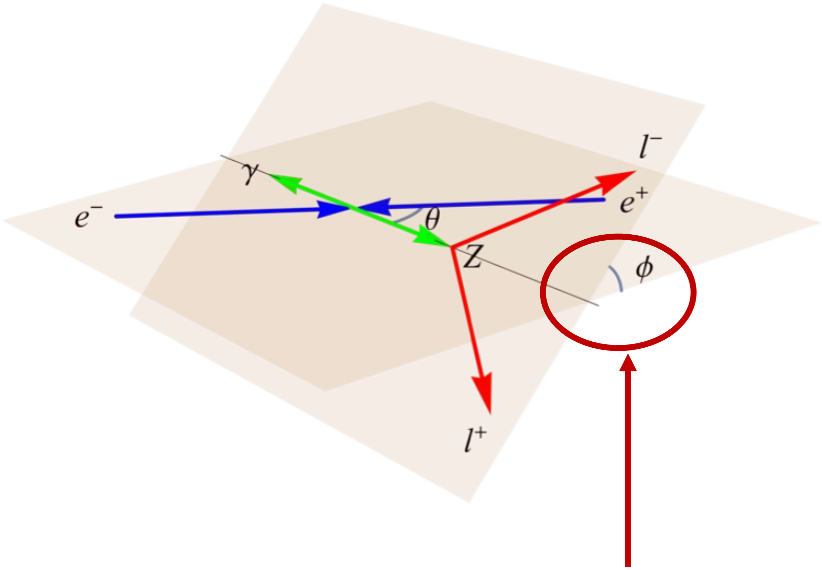
Variables	SM Backgrounds	SM $Z\gamma$	h_4	h_3^γ	h_3^Z
$N_{\text{pho}} \geqslant 1$	11712	1572	1629	1747	1710
$N_{\text{lep}} = 2$	1152	587	624	696	675
$N_{\text{jet}} = 0$	811	587	624	696	675
$\Delta R(\ell,\ell) < 3$	698	548	585	656	634
$\lvert m_{\ell\ell} - m_Z\rvert < 10\,\text{GeV}$	303	192	226	288	271
$(m_{\ell\ell} + m_{\ell\ell\gamma}) > 182\,\text{GeV}$	300	192	226	288	271

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

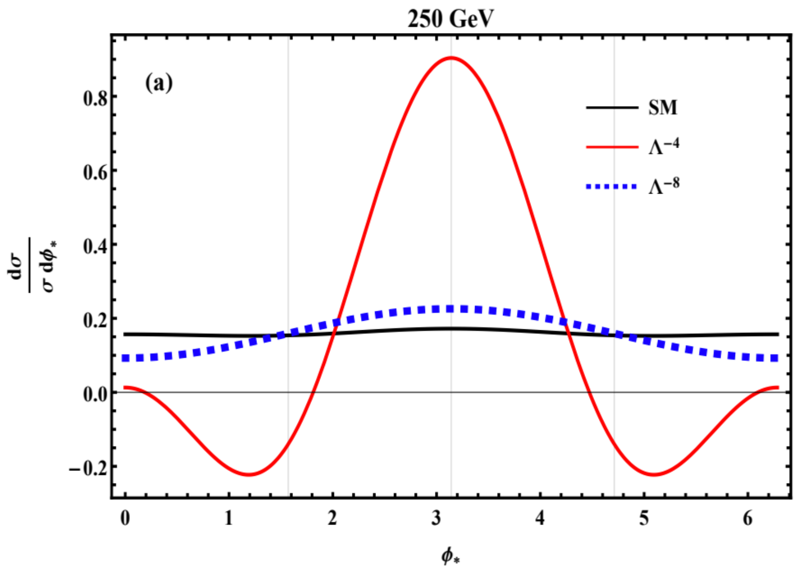
Cross section[fb] after applying sequential selections

Analysis Optimization

- Unlike traditional measurements, a special kinematic structure ϕ applied to reach better sensitivity
  - Defined as the angle between scattering plane and decay plane
  - Direct evidence of the interference between the SM and pure BSM effects



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



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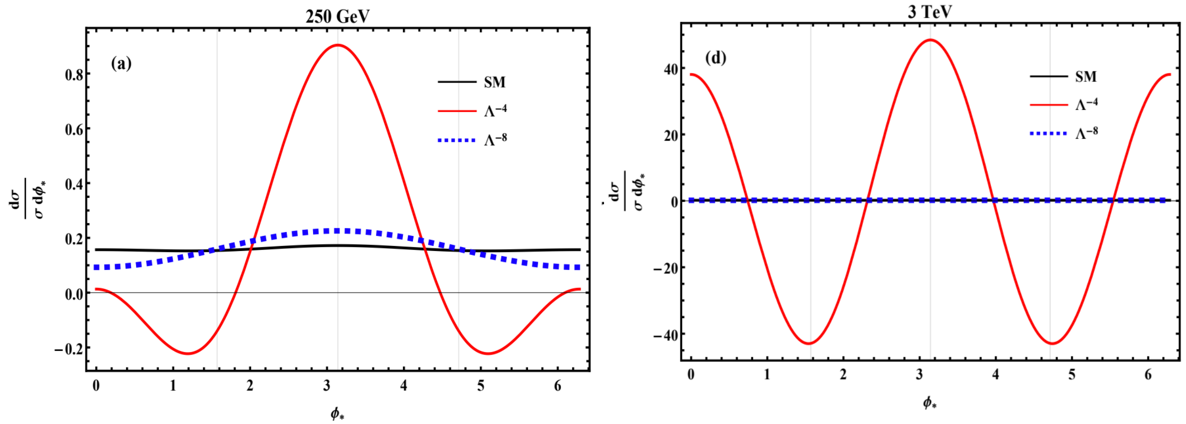
Analysis Optimization

- Parameterization of nTGCs: $\sigma = \sigma_0(\mathrm{SM}) + \sigma_1(\mathrm{SM}\times\mathrm{nTGC}) + \sigma_2(\mathrm{nTGC}^2)$
- Similarly, we define the normalized angular distribution function respectively:

$$f_\phi^{sm} = \frac{1}{2\pi} + \frac{3\pi^2(c_L^2 - c_R^2)^2 M_Z\sqrt{s}(s+M_Z^2)\cos\phi - 8(c_L^2+c_R^2)^2 M_Z^2 s\cos 2\phi}{16\pi(c_L^2+c_R^2)^2\left[(s-M_Z^2)^2 + 2(s^2+M_Z^4)\ln\sin\frac{\delta}{2}\right]} + O(\delta)$$

$$f_\phi^{int} = \frac{1}{2\pi} - \frac{3\pi(q_L^2 - q_R^2)(M_Z^2+5s)\cos\phi}{256(q_L^2+q_L^2)M_Z\sqrt{s}} + \frac{s\cos 2\phi}{8\pi M_Z^2}$$

$$f_\phi^{qua} = \frac{1}{2\pi} - \frac{9\pi(q_L^2-q_R^2)M_Z\sqrt{s}\cos\phi}{128(q_L^2+q_R^2)(s+M_Z^2)}$$



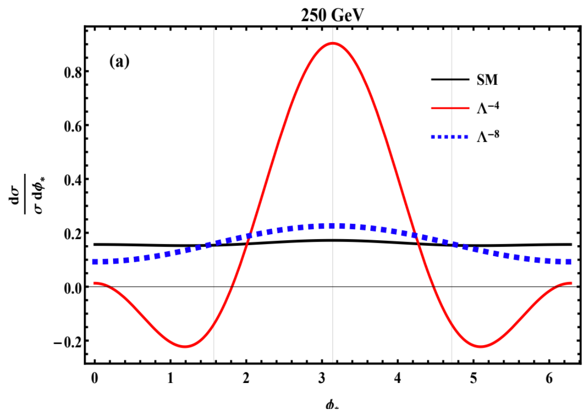
Interference term: dominated by $\cos 2\phi$ term, significantly related to s/M_Z^2

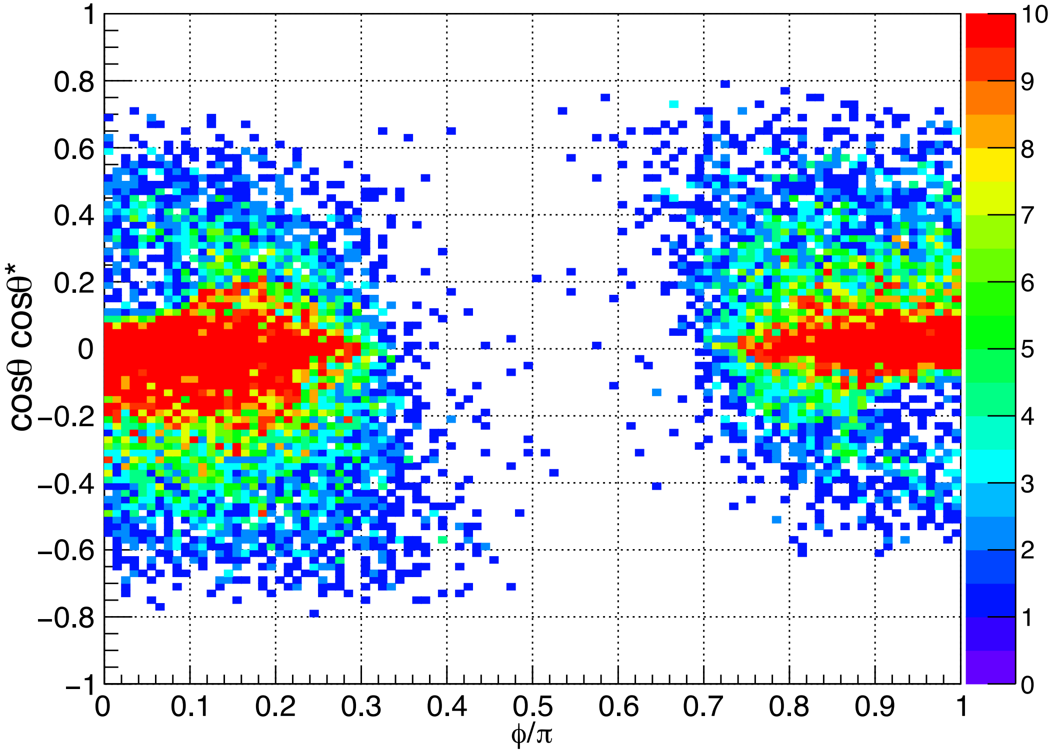
SM and Quadratic term: dominated by the constant term $\frac{1}{2\pi}$ and ϕ-dependent term which is suppressed by $M_Z^2/\sqrt{s}$

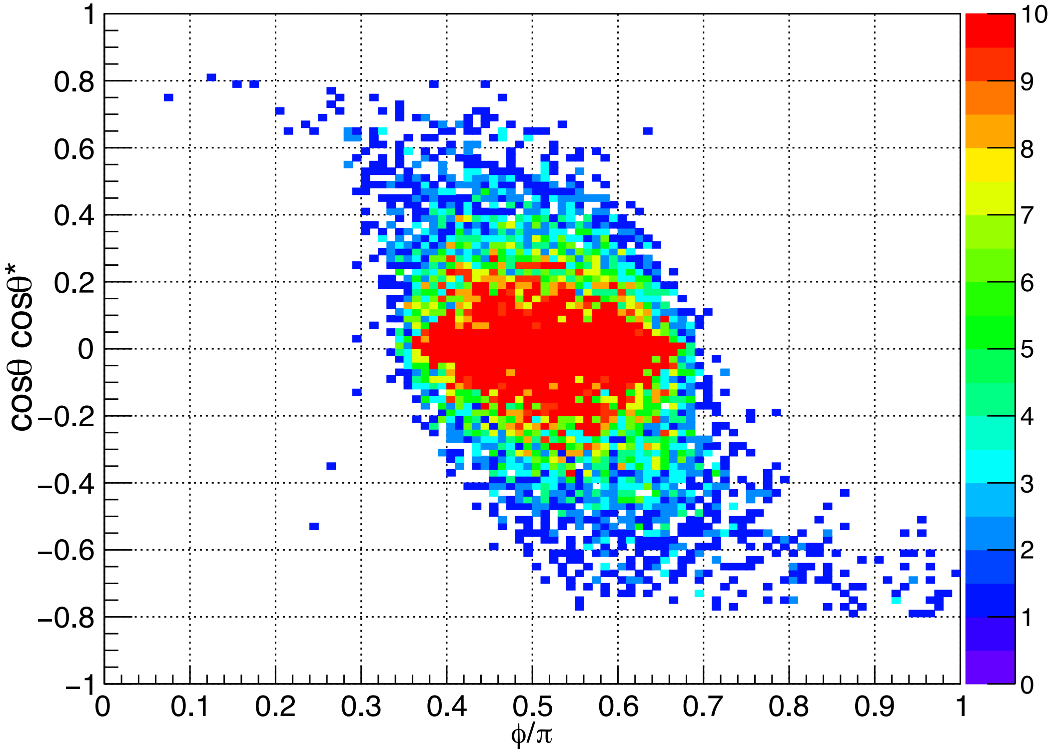
ϕ could be a good candidate to probe nTGCs

Analysis Optimization

- Optimization applied with net cross section for significance enhancement
  - Boudaries are set to distinguish events with positive or negative cross sections







Systematic Uncertainty

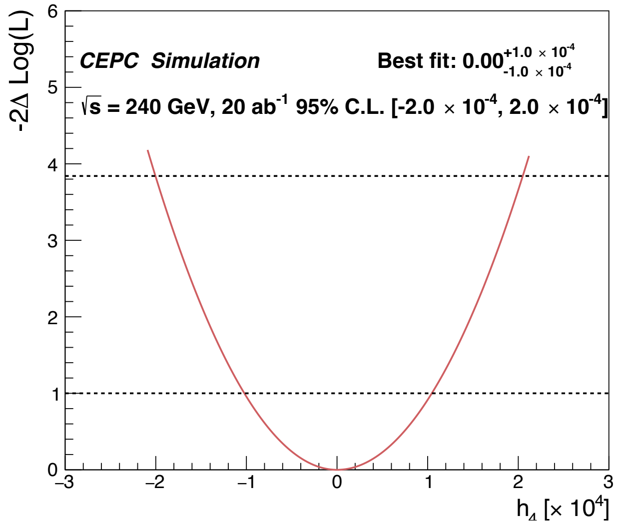
- Systematic uncertainties are categorised into two types :
  - Assigned on signal yields
    - Theoretical uncertainty : 0.5% uncertainty for modeling
    - Experimental uncertainty : luminosity, object identification, object reconstruction resolution, energy resolution, and detector acceptance
  - 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

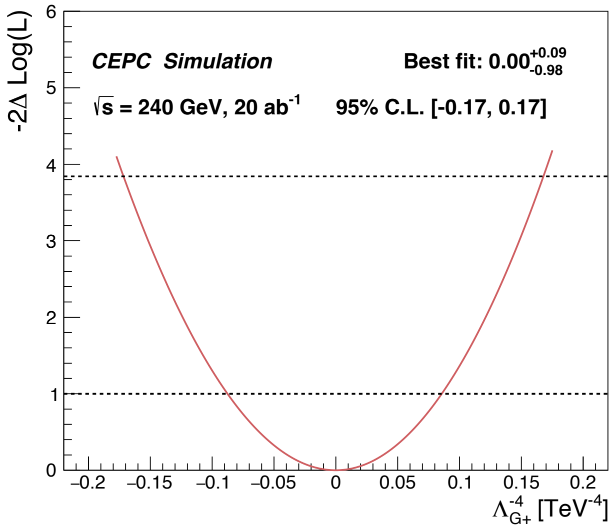
Processes	Statistical	Theoretical	Experimental
$Z\gamma$ production ($e^+e^- \to \ell^+\ell^-\gamma$)	0.52%	0.5%	(+2.96,-3.15)%
Fixed background	Dominant background: 5% Other backgrounds: 100%		

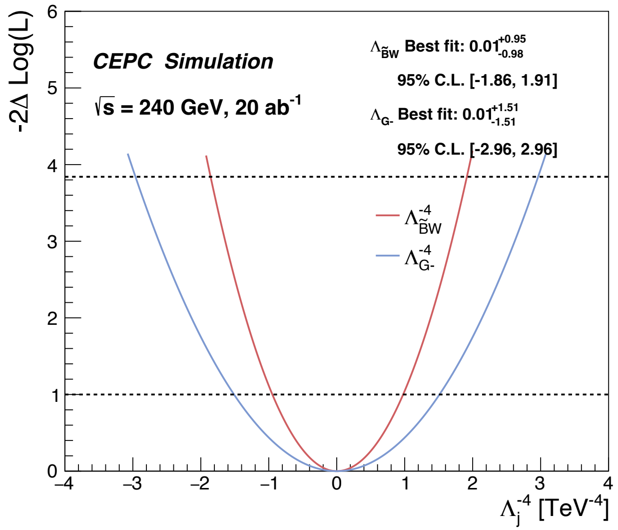
Results

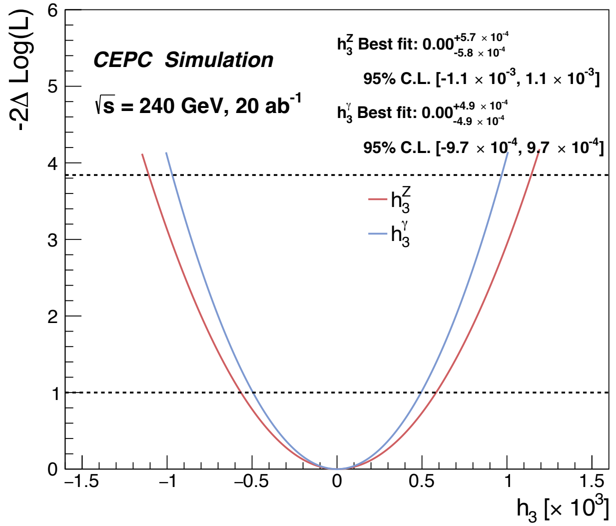
- Expected exclusion constraints acchieved from ϕ variable

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



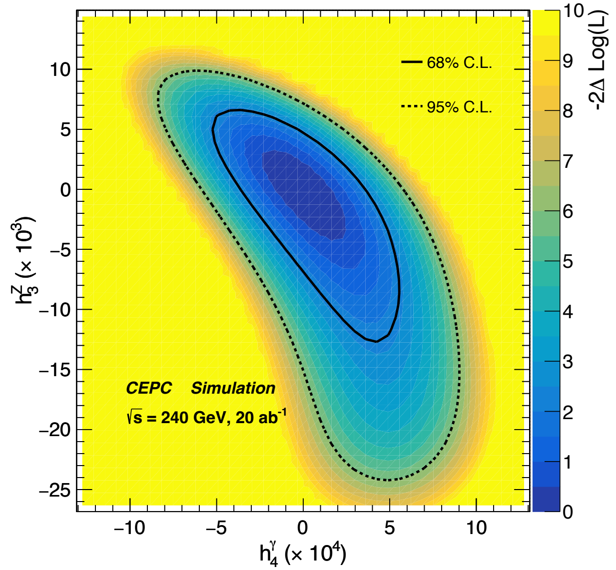


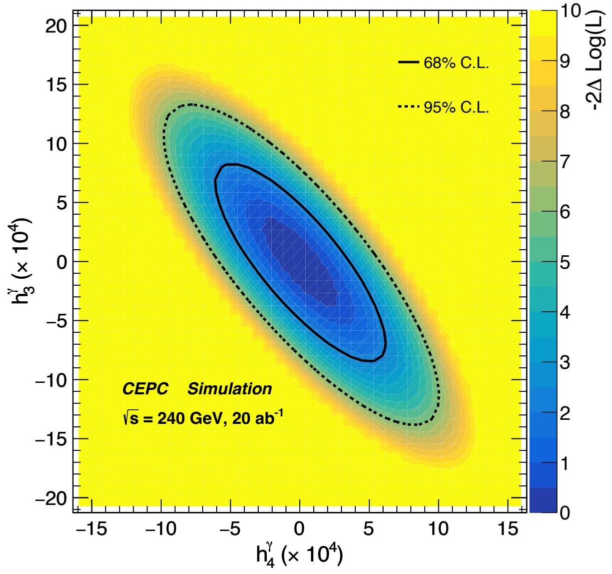


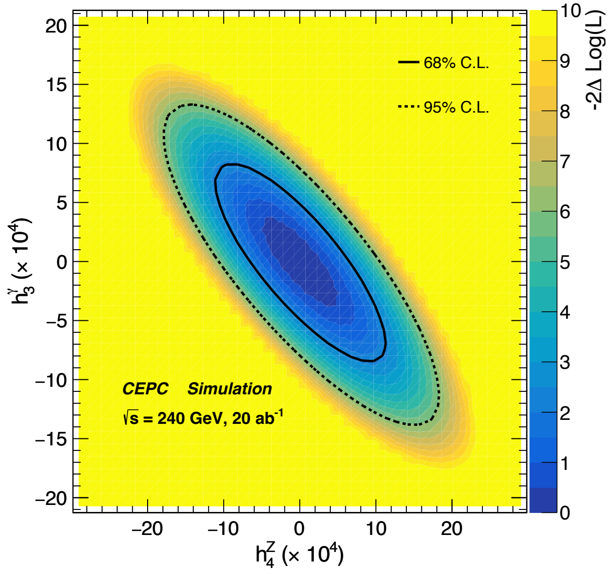


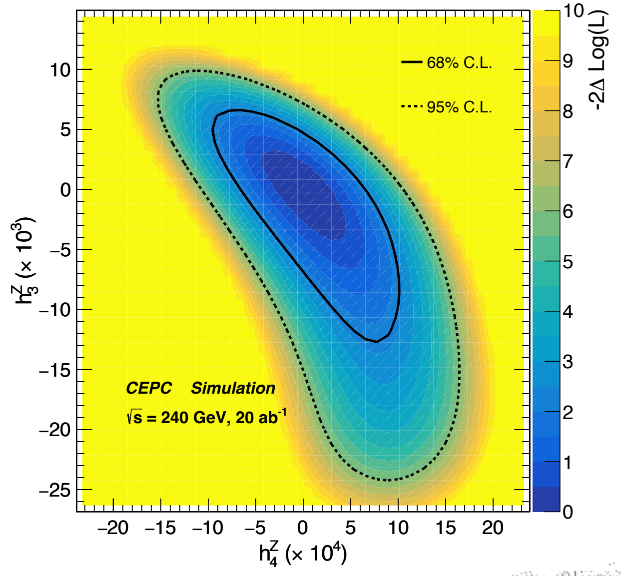
Results

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









Summary

- nTGCs provide unique probe of dimension-8 SMEFT operators, and serves as a new pathway to explore new physics beyond the SM
- We present the search for nTGCs at CEPC at $\sqrt{s} = 240$ GeV with an integrated luminosity of 20 ab^{-1}
- First exploration with a more realistic simulation in collaboration with the latest nTGC theoretical progress at lepton colliders
  - With SU(2)×U(1) invariant gauge symmetry applied
- Results acceptted by FOP journal as “Cover Article”

Thank You