Probing Neutral Triple Gauge Couplings via $Z\gamma(\ell^+\ell^-\gamma)$ Production at LHC-ATLAS and future Collider

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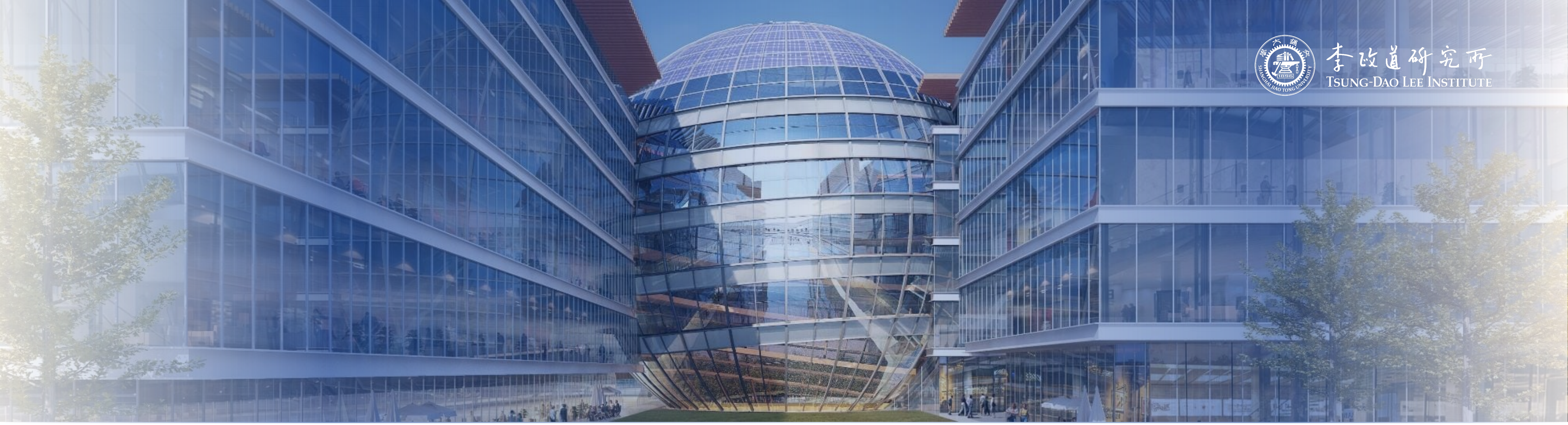


OUTLINE

- Motivation of nTGC searches
- nTGC search @ ATLAS
- nTGC search @ CEPC
- Summary and Prospect

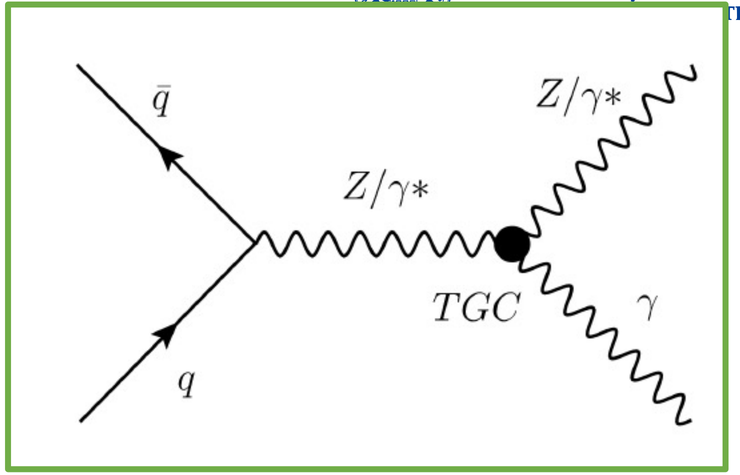
Neutral Triple Gauge Couplings

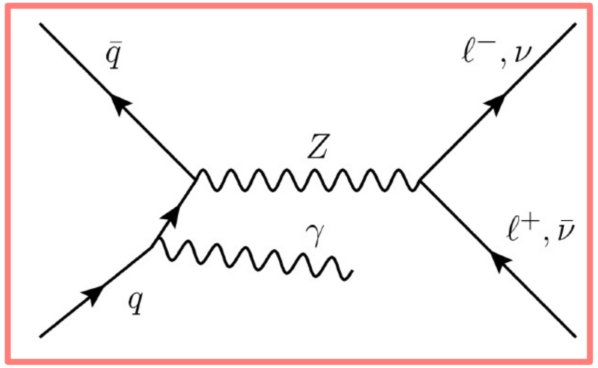
- New interaction ($ZZ\gamma, \gamma^{*}Z\gamma$) – beyond the Standard Model
  - Forbidden at the SM tree level
  - First arise from dimension-8 contributions
  - A model-independent pathway to uncover new physics
- nTGC formulation

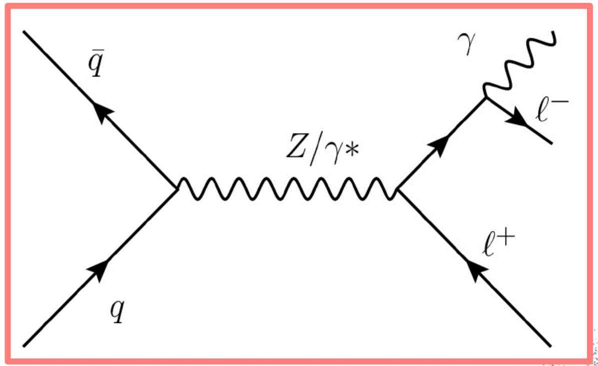
$$\Delta\mathcal{L}_{dim8} = \sum_i \frac{\tilde{c}_j}{\tilde{\Lambda}^4} O_i = \sum_i \frac{sign(\tilde{c}_j)}{\Lambda_j^4} O_j$$

  - Incorporate with fully gauge invariant $SU(2)\times U(1)$ symmetry
  - Several new operators first proposed, interpreted, and presented in this talk

nTGC







SM $Z\gamma$

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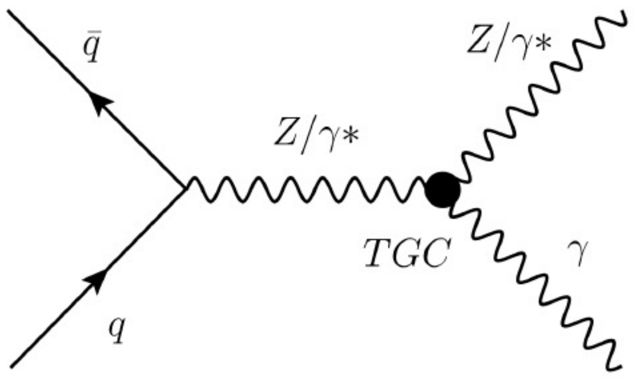
Highlights of nTGC Studies

- Pure dimension-8 operators

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

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

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



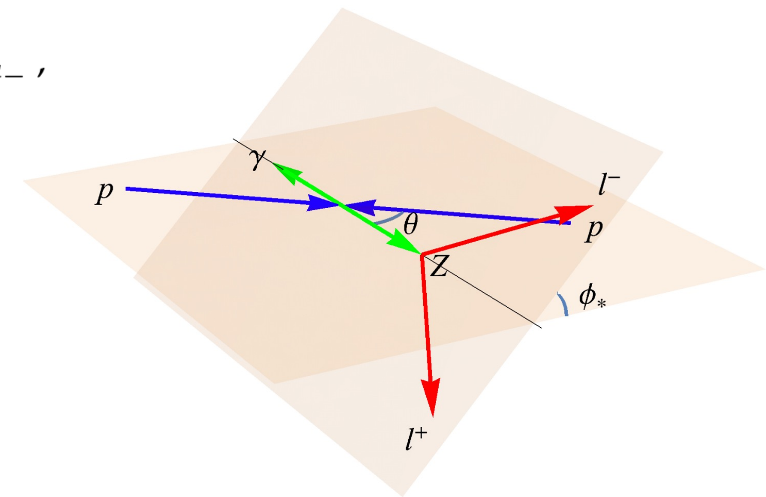
- Form factors

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

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

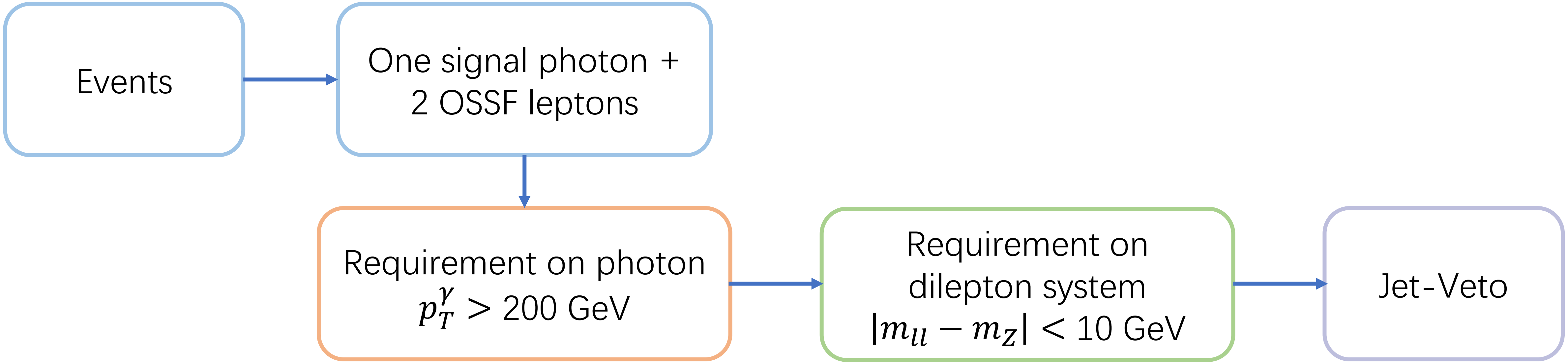
$$h_3^\gamma = -\frac{\text{sign}(\tilde{c}_{G-})}{\Lambda^4_{G-}} \frac{v^2 M_Z^2}{2 c_W^2} \equiv \frac{r_3^\gamma}{[\Lambda^4_{G-}]}. \qquad h_3^Z, h_4^V = 0, \qquad \text{for } \mathcal{O}_{G-},$$

- Variables
  - Transverse momentum of leading photon
  - Angular variable ϕ



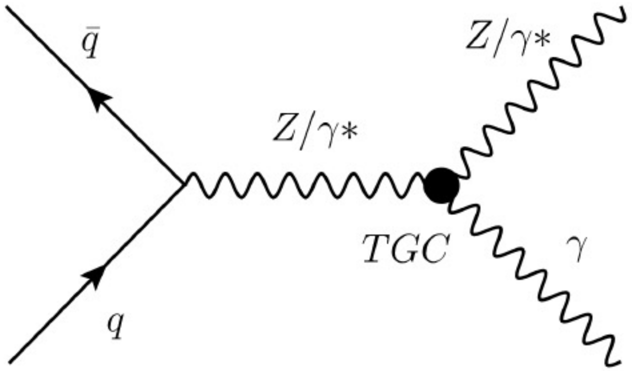
nTGC Selections

- Traditional selection-based analysis relies on the clear signal signature
- Selections are optimized to tailor the requirements of nTGC formulation and to reach a more physically meaningful result



- Suppress SM background, and make sure dilepton decay from on-shell Z boson
- Remove higher order correction, or jet-background contribution

nTGC Search at ATLAS Experiment



- ATLAS experiment
  - Energy frontier and large statistics
- MC samples

	Process	Generator	DSID
Signal (SM $Z\gamma$) sample	$Z\gamma$ 0,1j @ NLO + 2,3,4j @LO	Sherpa 2.2.11	700398 - 700399
Background samples	Z+jets 0j @ NLO	PowhegBox	361106 - 361107
	Pile-up (data-driven)	--	--
	$t\bar{t}\gamma/tW\gamma$ LO	MadGraph5_aMc@NLO	410389 / 412120
	$ZZ \rightarrow llll/W^{\pm}Z \rightarrow lllv$ 0,1j	Sherpa 2.2.2	364739-364742 / 364250/364253
	$llv\gamma, llvv\gamma$ 0j @NLO + 1,2,3j @ LO	Sherpa 2.2.11	700356 / 700204
EFT samples	$O_{G+}, O_{G-}, O_{\tilde{B}W}, O_{BB}, O_{BW}, O_{WW}$ 0j @ LO	MadGraph5_aMc@NLO	512493 – 512517, 515544 - 515548

Object Definitions and Event Selections

Property	Requirements
Electrons	
Kinematics	p_T >25 GeV & $\|\eta\|$ <2.47, (excl. 1.37< $\|\eta\|$ <1.52)
Identification	Medium
Isolation	FCLoose
Impact parameter	$\|d_0/\sigma(d_0)\| < 5$, $\|z_0 sin\theta\| < 0.5$ mm
Muons	
Kinematics	p_T >25 GeV & $\|\eta\|$ <2.5
Identification	Medium
Isolation	PflowLoose_FixedRadIso
Impact parameter	$\|d_0/\sigma(d_0)\| < 3$, $\|z_0 sin\theta\| < 0.5$ mm
Photons	
Kinematics (baseline)	p_T >150 GeV & $\|\eta\|$ <2.37, (excl. 1.37< $\|\eta\|$ <1.52)
Identification (baseline)	Loose
Kinematics (signal)	p_T >200 GeV & $\|\eta\|$ <2.37, (excl. 1.37< $\|\eta\|$ <1.52)
Identification (signal)	Tight
Isolation (signal)	FixedCutLoose
Jets	
Algorithm	anti-k_T ($R = 0.4$, PFlow)
Kinematics (basline)	p_T >25 GeV, & $\|\eta\|$ <4.5
Kinematics (signal)	p_T >30 GeV if $\|\eta\|$ <2.5 $\|\|$ p_T >50 GeV if 2.5< $\|\eta\|$ <4.5
Pileup Mitigation	JVT Medium for p_T <120 GeV & $\|\eta\|$ <2.5

- List of object definitions
- List of signal region definitions

Signal Region Definition	
Variables	Cut
Trigger	single lepton trigger
N_{lepton}	$\geq$ 2 signal leptons (OSSF for nTGC region)
Leading Lepton	p_T > 30GeV
Photon	$\geq$ 1 signal photon with p_T > 200GeV
Jet	exclusive, N_{jet}=0
m_{ll}	$\|m_{ll} - m_Z\|$ <10GeV
$m_{ll} + m_{ll\gamma}$	>182GeV

Background and Systematic Estimation

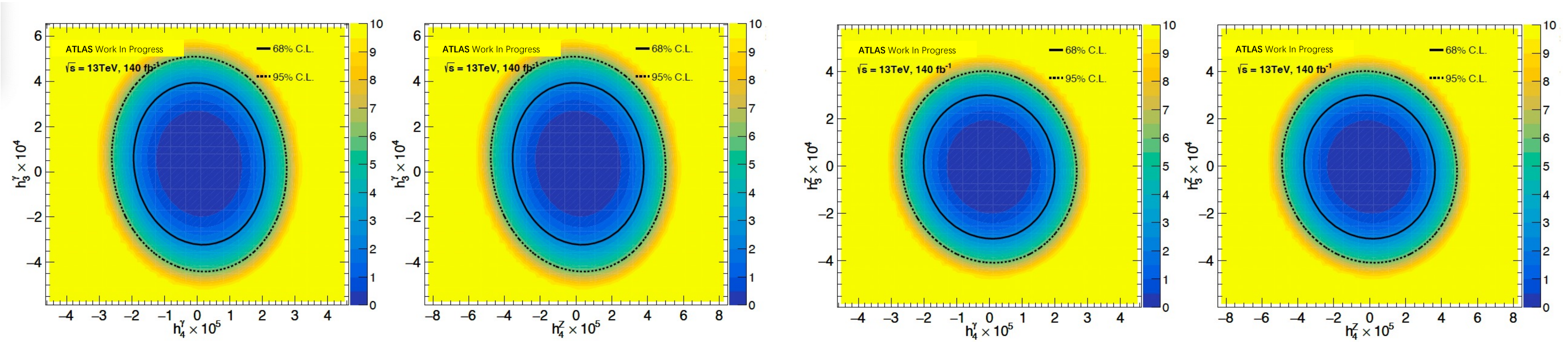
- Background estimation
  - Dominant background
    - Z+jets background, estimated through a two-dimensional side-band method
  - Other background
    - Pileup photon background, where Z boson and the photon come from different vertices, is estimated through data-driven method
    - $t\bar{t}\gamma$ process, where top quark leptonical decay, is estimated in a $e\mu\gamma$ control region
    - Multi-boson background, where lepton is misidentified as a photon, is estimated from MC
- Systematic ucertainty estimation
  - Modelling, finite resolution of object recontruction, and etc.

Results

- Exclusive constraints derived from p_T^{γ} variable

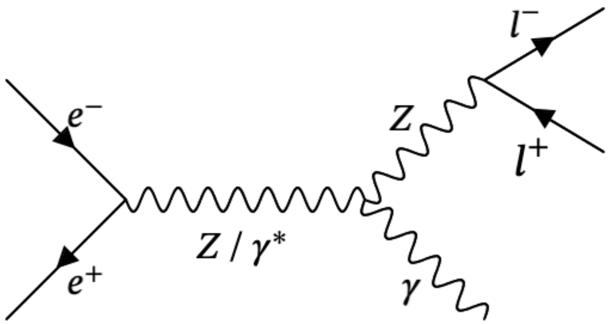
Expected Limits			
Form Factors (h_i^V)		Wilson coefficient (Λ_j [TeV])	
h_4	$[-4.1\times10^{-5}, 4.1\times10^{-5}]$	Λ_{G+}	2.40
h_3^{γ}	$[-3.5\times10^{-4}, 3.7\times10^{-4}]$	Λ_{G-}	0.97
h_3^{Z}	$[-3.6\times10^{-3}, 3.5\times10^{-3}]$	$\Lambda_{\tilde{B}W}$	1.14
		$\Lambda_{\widetilde{BW}}$	1.34

- 2D constraints are also extracted by scanning pairs of nTGC operators simultaneously

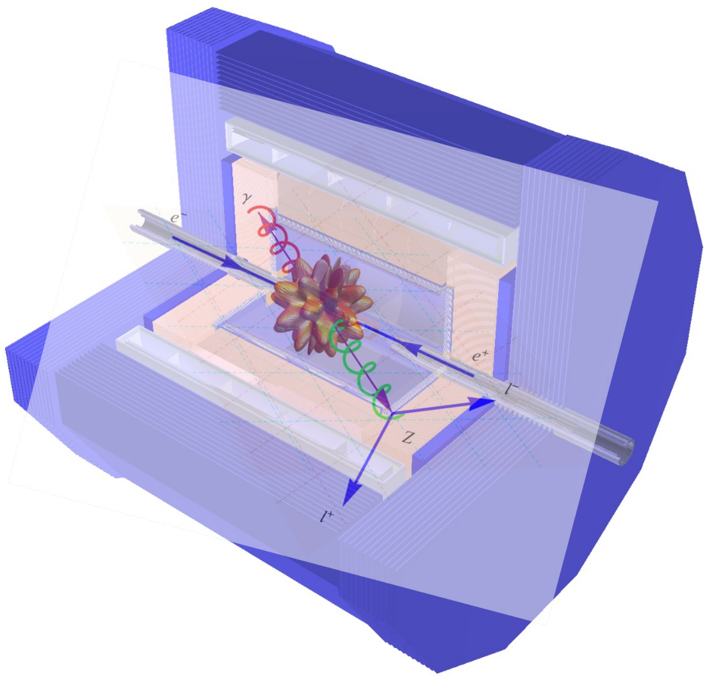


nTGC Search at CEPC Experiment

- Circular Electron Positron Collider
  - High luminosity
  - Precise beam direction and energy
  - Perfect angular reconstruction



- 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
- Topology
  - $e^+e^- \to Z(\ell^+\ell^-)\gamma$, where Z decays to a pair of charged leptons



Selection Efficiencies

- Summary table of selections

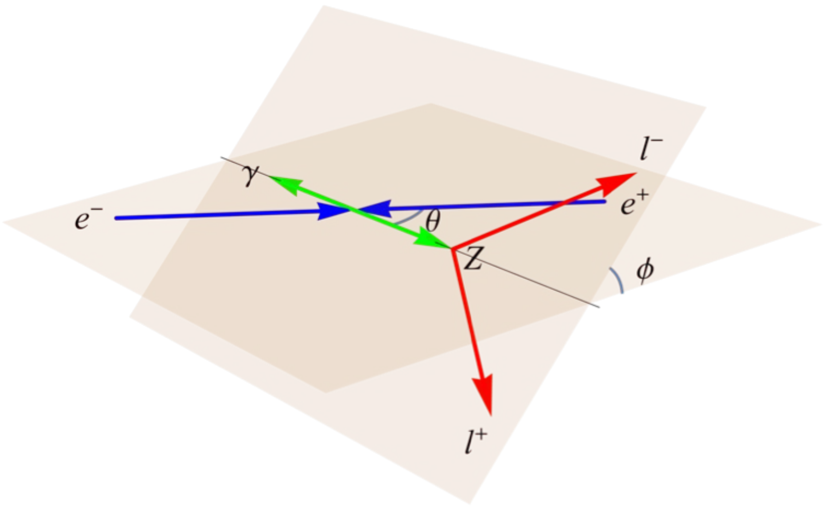
Variables	Cut
N_{lep}	2 signal OSSF leptons with leading lepton $p_T^{\text{lep}} > 30$ GeV
N_{pho}	≥ 1 signal photon with $p_T^{\gamma} > 35$ GeV
N_{jet}	0
$\Delta R(\ell,\ell)$	< 3
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV
$m_{\ell\ell} + m_{\ell\ell\gamma}$	> 182 GeV

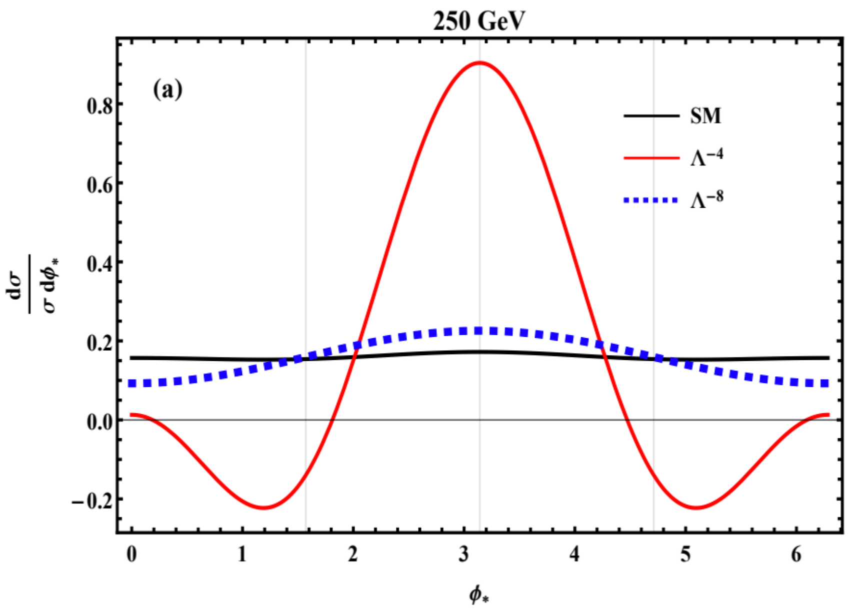
- Cutflow table: Cross section[fb] after applying sequential selections

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
$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV	303	192	226	288	271
$(m_{\ell\ell} + m_{\ell\ell\gamma}) > 182$ GeV	300	192	226	288	271

Kinematic Optimization

- Thanks to the well-defined beam direction and energy, angular variable is able to be reconstructed precisely
  - A special kinematic variable applied in this study
  - ϕ : Direct reflect of the interference between SM and pure BSM terms, defined as the angle between the scattering plane and the decay plane





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Systematic Uncertainty

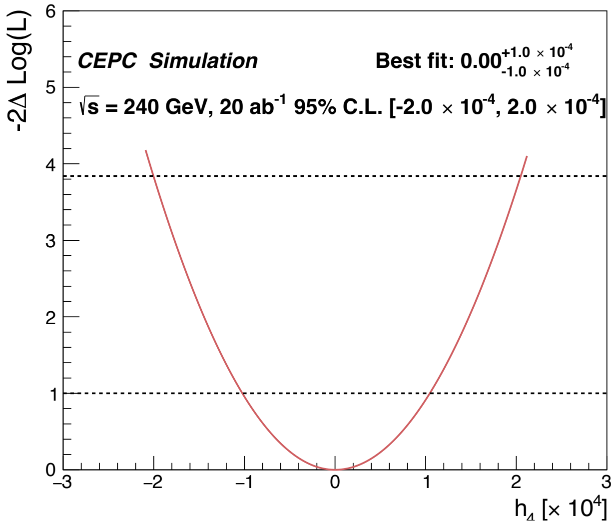
- Systematic uncertainties are categorised into two types :
  - Assigned on signal yields
    - Theoretical uncertainty : 0.5% uncertainty for modeling
    - Experimental uncertainty : luminosity, object identification, object reconstruction resolution, energy resolution, and detector acceptance
  -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

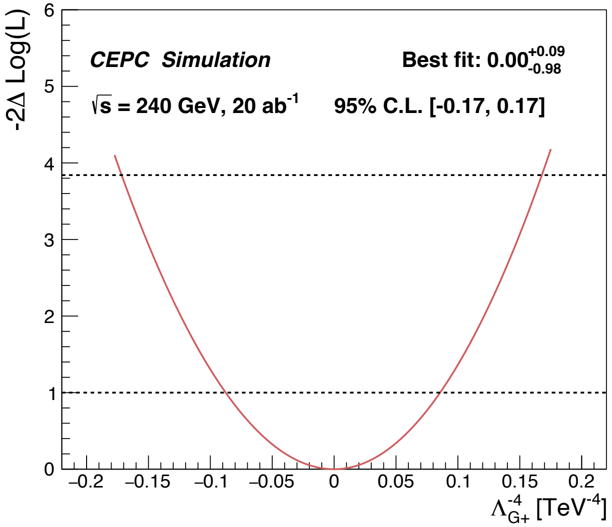
Processes	Statistical	Theoretical	Experimental
$Z\gamma$ production ($e^+e^- \to \ell^+\ell^-\gamma$)	0.52%	0.5%	(+2.96,-3.15)%
Fixed background	Dominant background: 5% Other backgrounds: 100%		

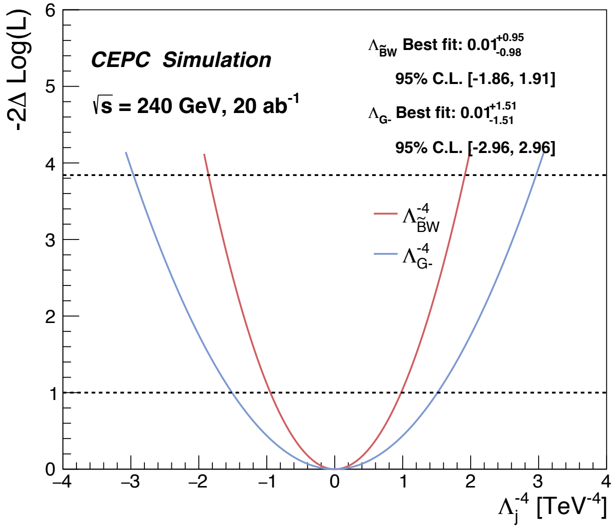
Results

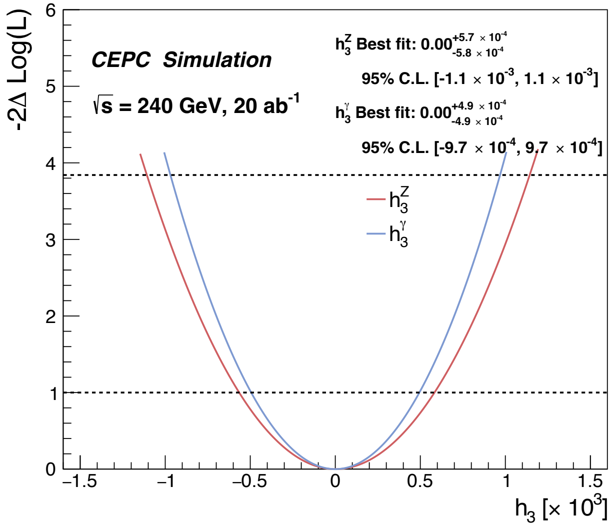
- Expected exclusion constraints achieved from ϕ variable

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



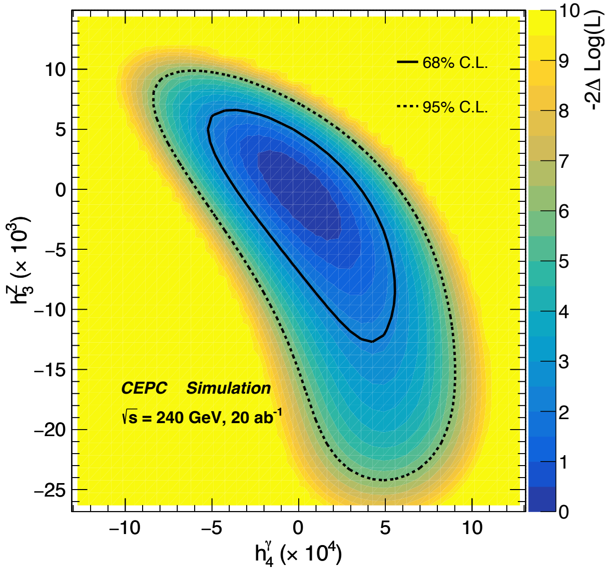


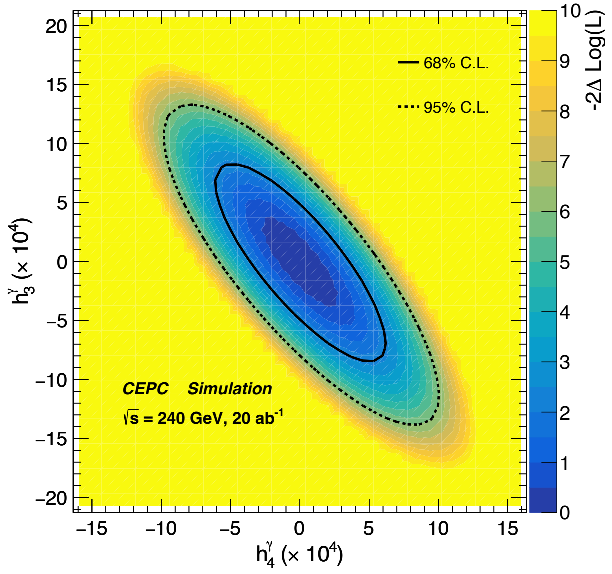


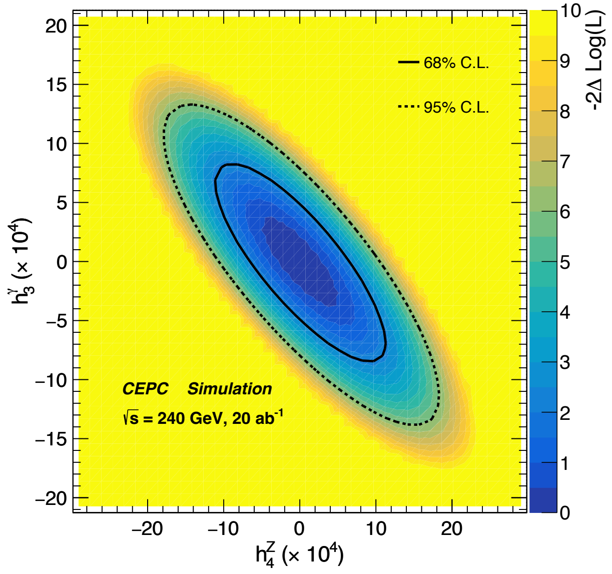


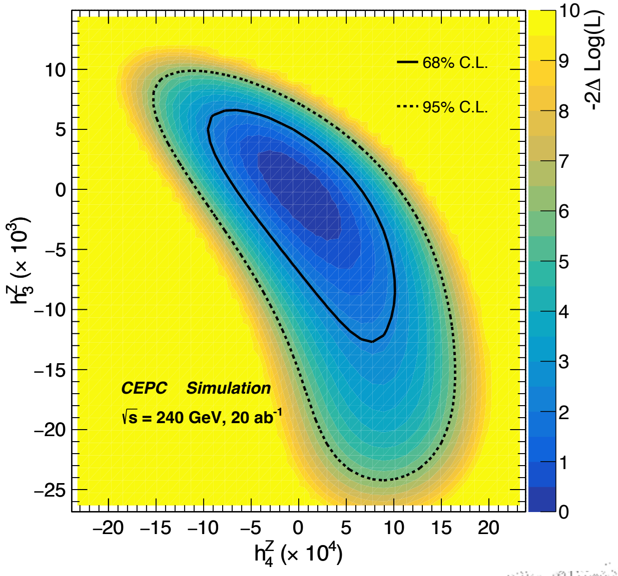
Results

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



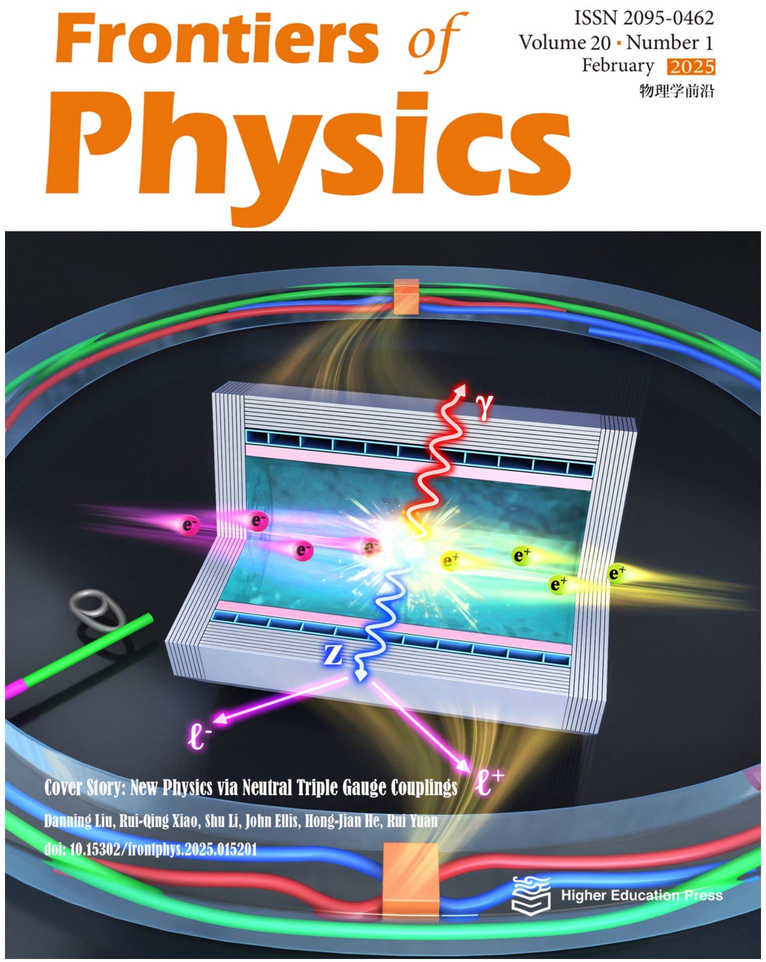






Summary

- nTGCs provide unique probe of dimension-8 SMEFT operators, and serves as a new pathway to explore new physics beyond the SM
- First exploration with a more realistic simulation in collaboration with the latest nTGC theoretical progress
  - With SU(2)×U(1) invariant gauge symmetry applied
- We present the searches for nTGCs at both ATLAS and CEPC
  - ATLAS results: under EB review
  - CEPC results: acceptted by FOP journal as "Cover Article"



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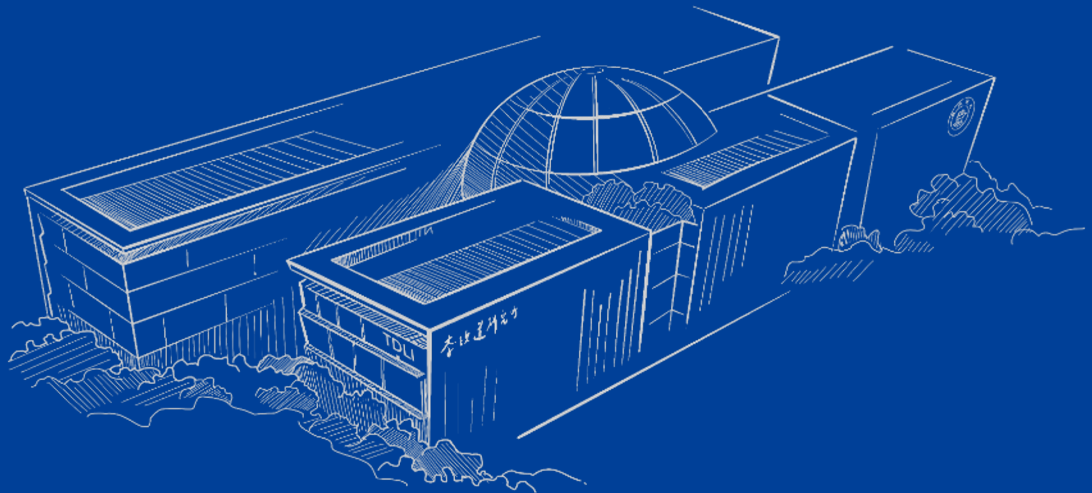
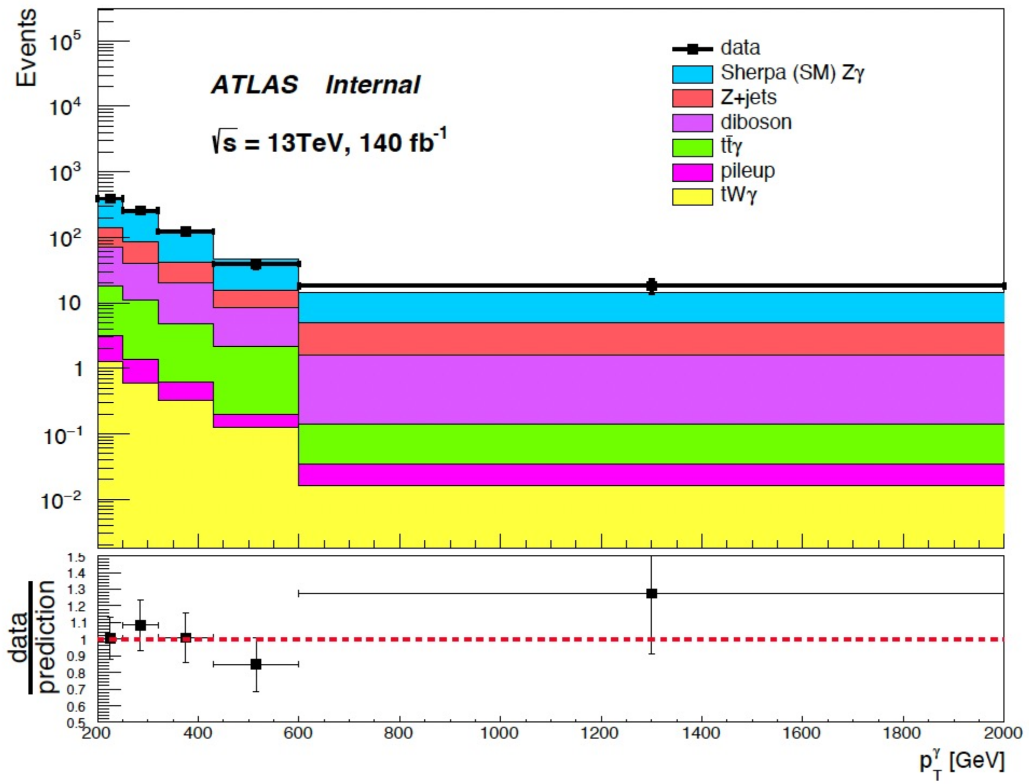
Thank You



Backup: ATLAS – Background Estimation

- A validation region is defined by reversing jet-veto selection, to check the estimation of various background, with good agreement observed

Variables	Cut
Trigger	single lepton trigger
N_{lepton}	$\geq$ 2 signal leptons (OSSF for nTGC region)
Leading Lepton	p_T > 30GeV
Photon	$\geq$ 1 signal photon with p_T > 200GeV
Jet	$N_{jet} > 0$
m_{ll}	$\|m_{ll} - m_Z\|$ <10GeV
$m_{ll} + m_{ll\gamma}$	>182GeV



Backup: CEPC – Background Samples

- List of 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

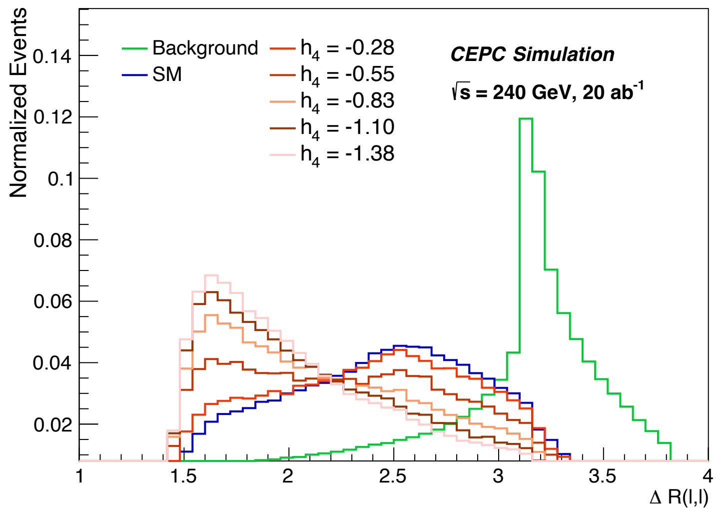
Backup: CEPC – Analysis Strategy

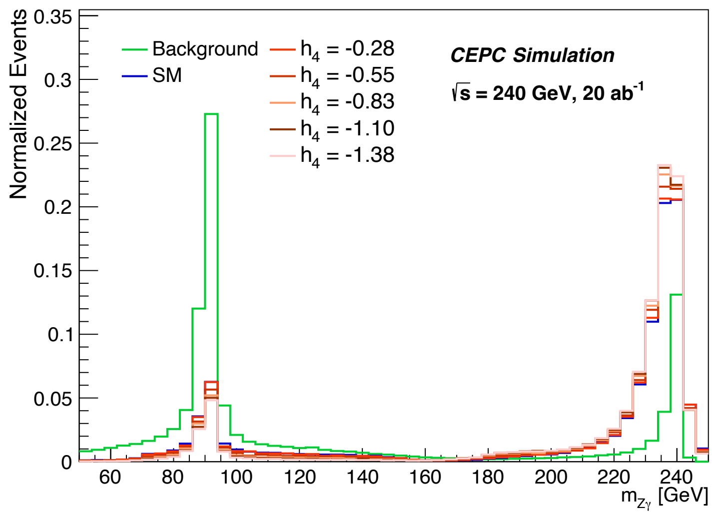
- Traditional selection-based analysis relies on the clear signal signature

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

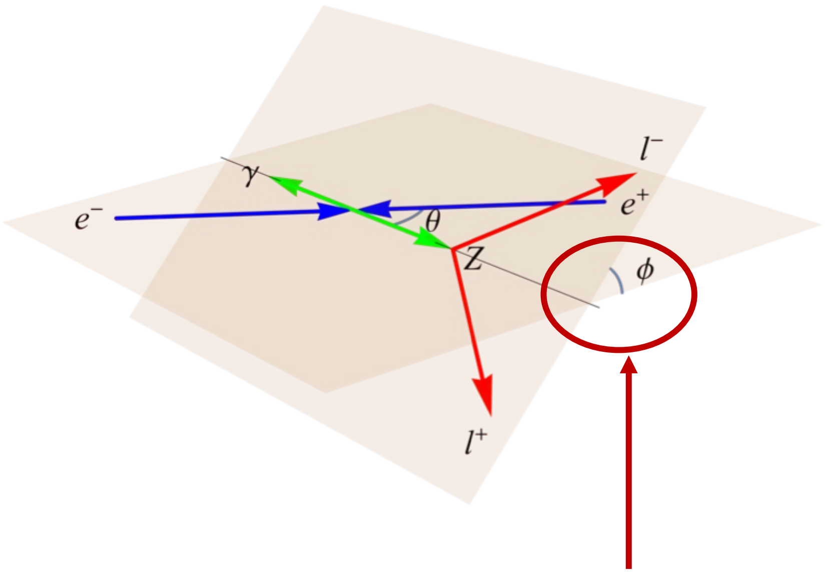
Invariant mass selection → Suppress Z plus final-state radiation photon scenario
Ensure that final-state leptons decay from on-shell Z boson





Backup: CEPC – 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



- Unlike traditional measurements, a special kinematic structure ϕ applied to reach better sensitivity
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$$\cos\phi = \frac{(\vec{p}_e \times \vec{p}_Z) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})}{|\vec{p}_e \times \vec{p}_Z||\vec{p}_{\ell^-} \times \vec{p}_{\ell^+}|}$$

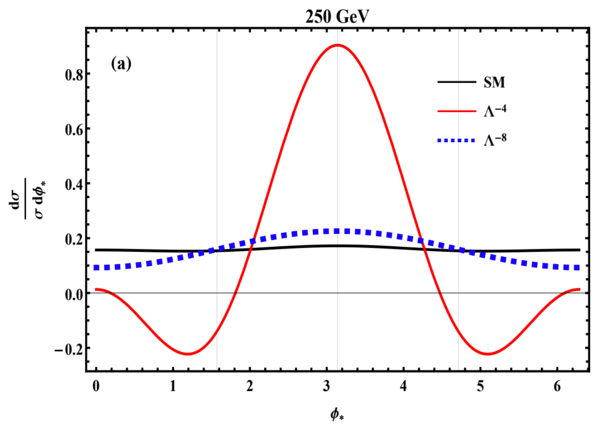
Backup: CEPC – Analysis Optimization

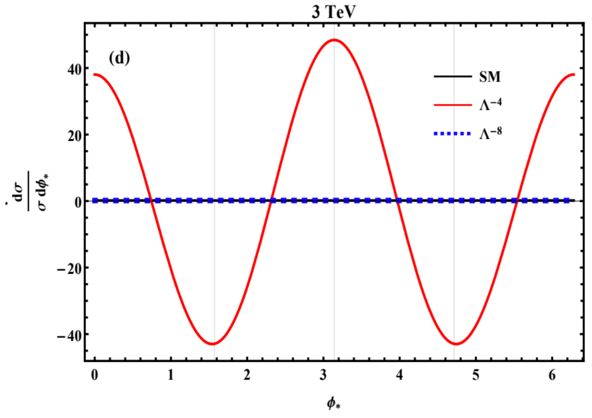
- Parameterization of nTGCs: $\sigma = \sigma_0(\mathrm{SM}) + \sigma_1(\mathrm{SM}\times\mathrm{nTGC}) + \sigma_2(\mathrm{nTGC}^2)$
- Similarly, we define the normalized angular distribution function respectively:

$$f_\phi^{sm} = \frac{1}{2\pi} + \frac{3\pi^2(c_L^2 - c_R^2)^2 M_Z\sqrt{s}(s+M_Z^2)\cos\phi - 8(c_L^2+c_R^2)^2 M_Z^2 s\cos2\phi}{16\pi(c_L^2+c_R^2)^2\left[(s-M_Z^2)^2 + 2(s^2+M_Z^4)\ln\sin\frac{\delta}{2}\right]} + O(\delta)$$

$$f_\phi^{int} = \frac{1}{2\pi} - \frac{3\pi(q_L^2 - q_R^2)(M_Z^2+5s)\cos\phi}{256(q_L^2+q_L^2)M_Z\sqrt{s}} + \frac{s\cos2\phi}{8\pi M_Z^2}$$

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



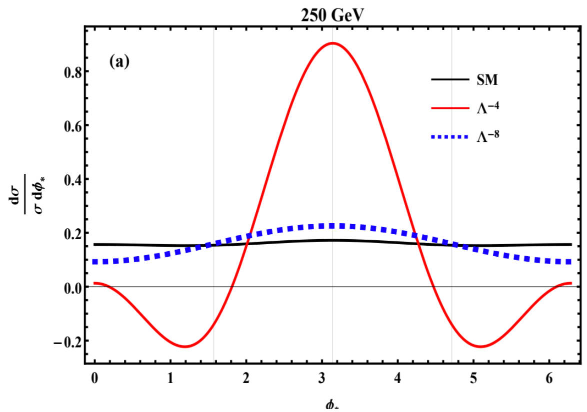


Interference term: dominated by cos2ϕ term, significantly related to s/M_Z^2

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

Backup: CEPC – Analysis Optimization



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