The study of nTGCs in Z+photon at the CEPC

CEPC Workshop 2023 @ Nanjing

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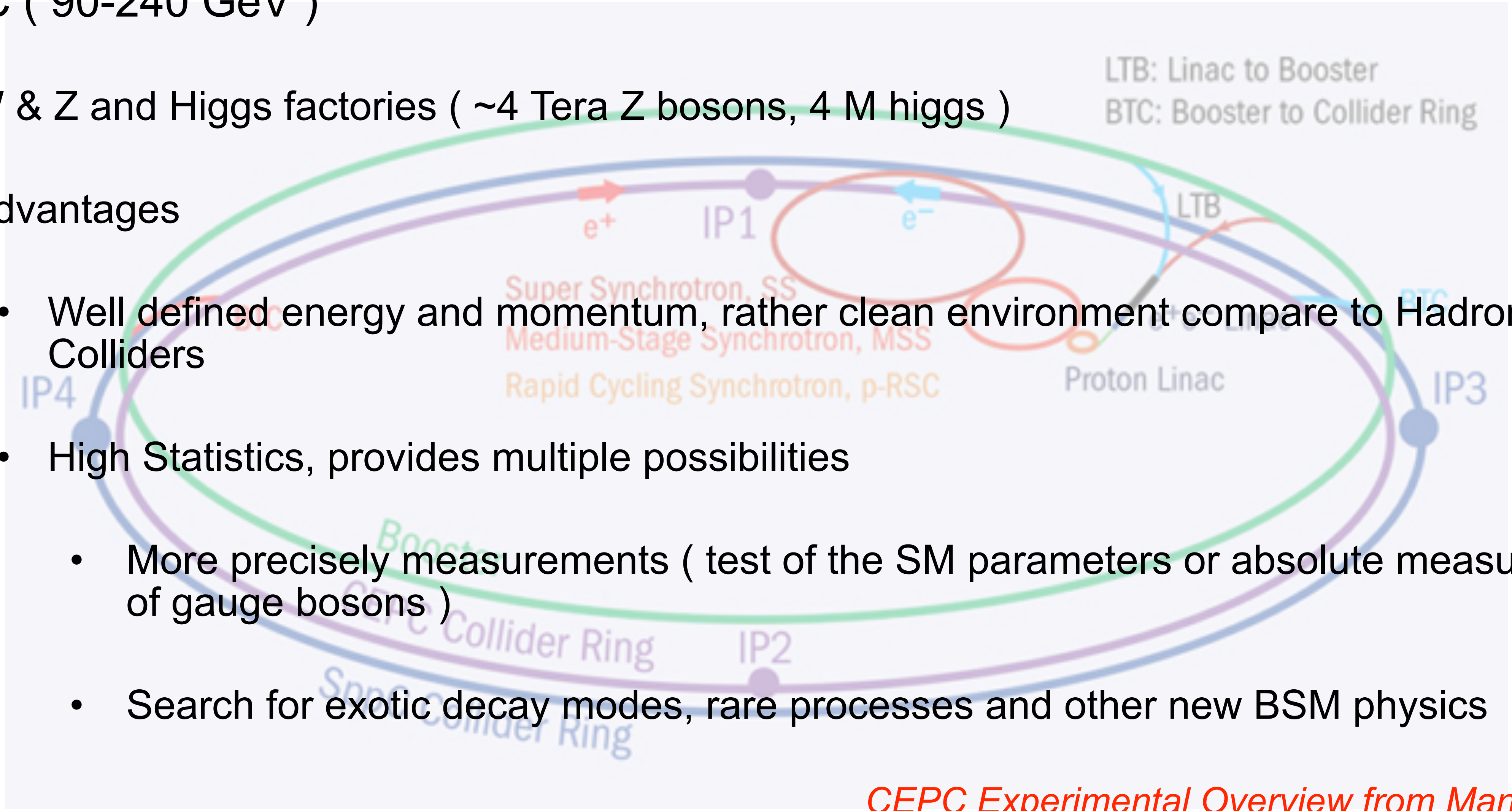
Outline

- CEPC detector
- Neutral Triple Gauge Couplings
- Monte Carlo Samples
- Signal Extraction
- Systematics
- Results
- Additional Materials

- CEPC (90-240 GeV)
  - W & Z and Higgs factories (~4 Tera Z bosons, 4 M higgs)
  - Advantages
    - Well defined energy and momentum, rather clean environment compare to Hadron Colliders
    - High Statistics, provides multiple possibilities
      - More precisely measurements (test of the SM parameters or absolute measurement of gauge bosons)
      - Search for exotic decay modes, rare processes and other new BSM physics



CEPC Experimental Overview from Manqi Ruan

Neutral Triple Gauge Couplings

- Neutral Triple Gauge Couplings (nTGCs)

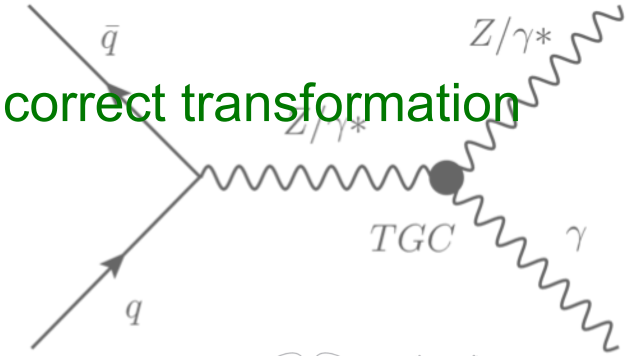
  Chinese Phys. C 44 063106

  - Don't appear in the SM Lagrangian, nor in the dimension-6 Lagrangian of the SMEFT
  - First appear through the gauge-invariant dimension-8 operators in the SMEFT

$$\Delta L(dim-8) = \sum_j \frac{\tilde{c}_j}{\tilde{\Lambda}^4}\mathcal{O}_j = \sum_j \frac{sign(\tilde{c}_j)}{\Lambda_j^4}\mathcal{O}_j = \sum_j \frac{1}{[\Lambda_j^4]}\mathcal{O}_j$$

General dimension-8 SMEFT Lagrangian

- Highlight of nTGCs
  - Based on the latest formulation proposed by Prof. John Ellis, Prof. Hong-Jian He and Dr. Rui-Qing Xiao with fully gauged invariant treatment SU(2)×U(1)
  - Designed for on-shell scenario
  - Two extra dimension-8 operators O_{G+}, O_{G-} are needed to make correct transformation
  - A unique window to explore new physics beyond the SM,



See more details in *Ruiqing's talk*

Operators in nTGC model

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

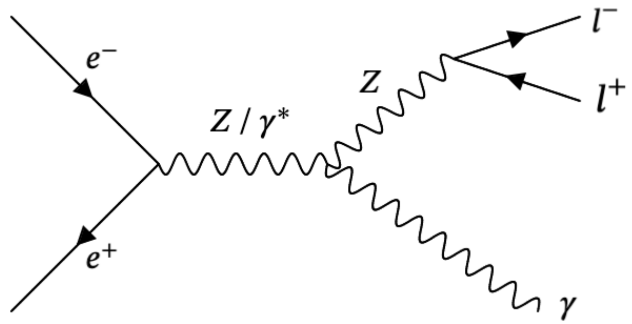
JE, GE, HE & Xiao, arXiv : 1902.06631
JE, HE & Xiao, arXiv : 2008.04298
JE, HE & Xiao, arXiv : 2206.11676
Phys. Rev. D 107 035005 (2023) with "Editor's suggestion"
John's talk at the LHC EWK-MB meeting

- Dimension-8 operators : $O_{G+}, O_{G-}, O_{\tilde{B}W}$ (CP-conserving)

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

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

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



- Transformation

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

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

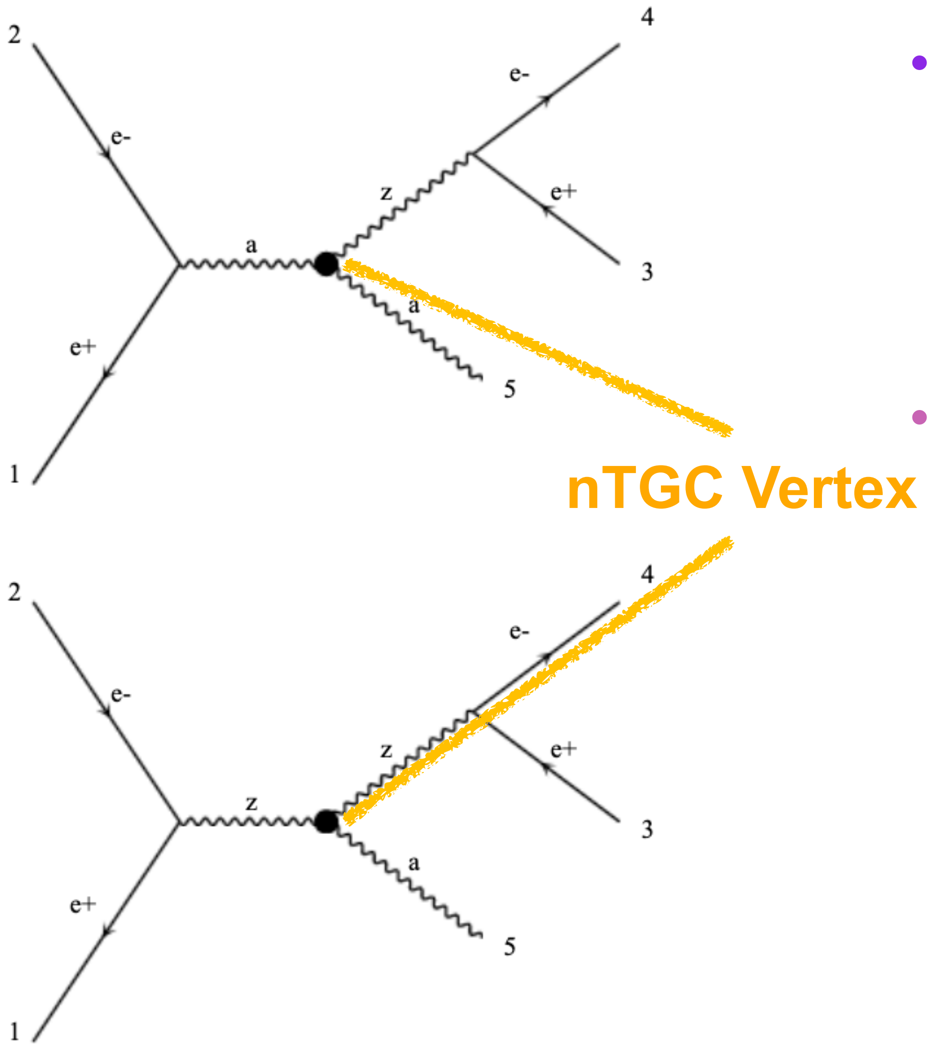
$$h_3^\gamma=-\frac{\text{sign}(\tilde{c}_{G-})}{\Lambda^4_{G-}}\frac{v^2M_Z^2}{2c_W^2}$$

Conversion

Convert constraints from SMEFT approach to Effective Vertex approach

See more theory details in *Ruiqing's talk*

nTGCs searches at CEPC

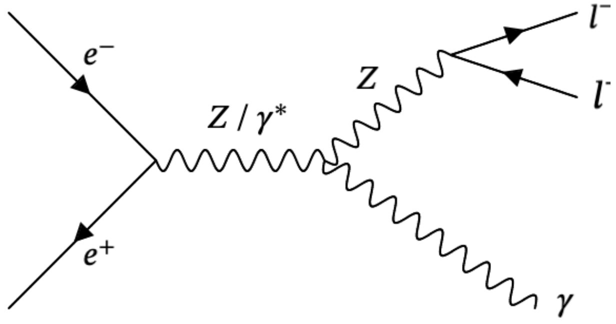


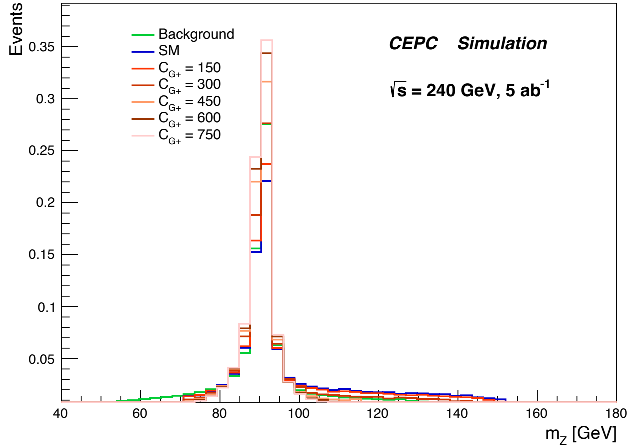
- Target of this study :
  - $e^+e^- \to Z\gamma, (Z \to l^+l^-, l = e, \mu)$
  - Cleanest channel : Z decay to two leptons

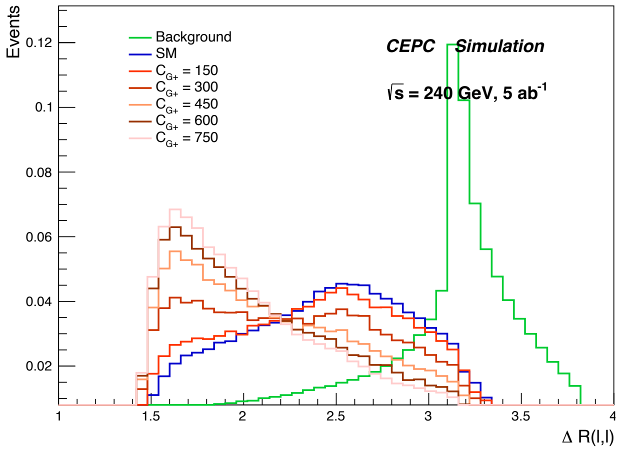
- Basic setups
  - Energy : 240 GeV
  - Beam : electron and positron
  - Luminosity : 5 ab^{-1}
  - Generator : MadGraph5 and Pythia8
  - Detector simulation with GEANT4 (CEPC_V4)

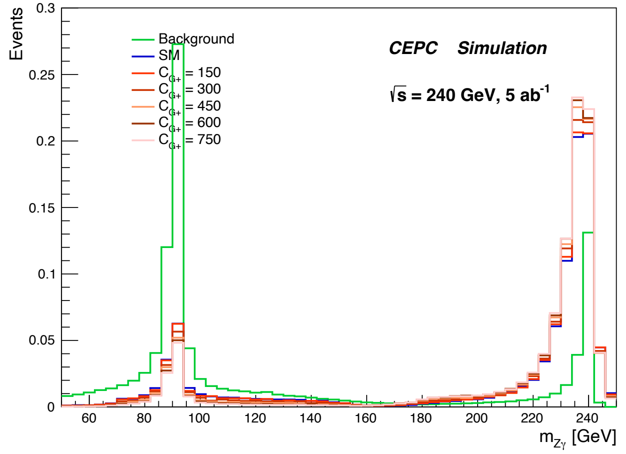
Signal Extraction

- Signal signatures : 2 Opposite Sign Same Flavour leptons and at least one signal photon
- Other requirements :
  - At least 1 selected photon
    - $p_T^{\gamma} > 35$ GeV
  - Two isolated leptons
    - $\Delta R(l, l) < 3$
  - Leptons decayed from Z bosons
    - $|m_{ll} - m_Z| < 10$ GeV
  - Low mass resonance suppressed
    - $(m_{ll} + m_{ll\gamma}) > 182$ GeV
  - Higher order contribution suppressed
    - $N_{jet} = 0$



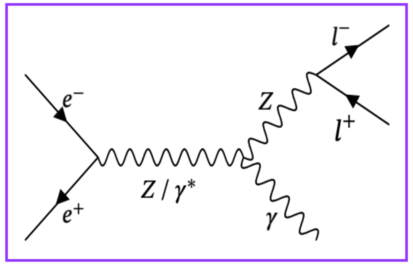


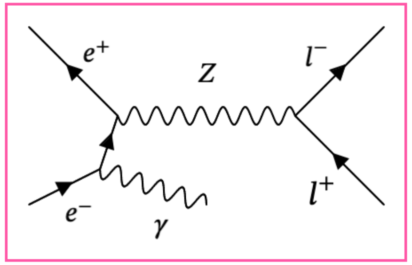


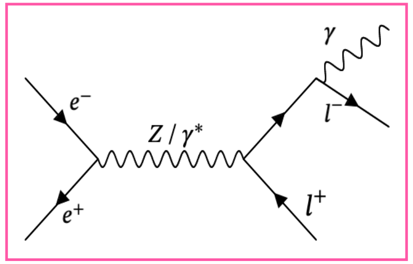


Signal Extraction

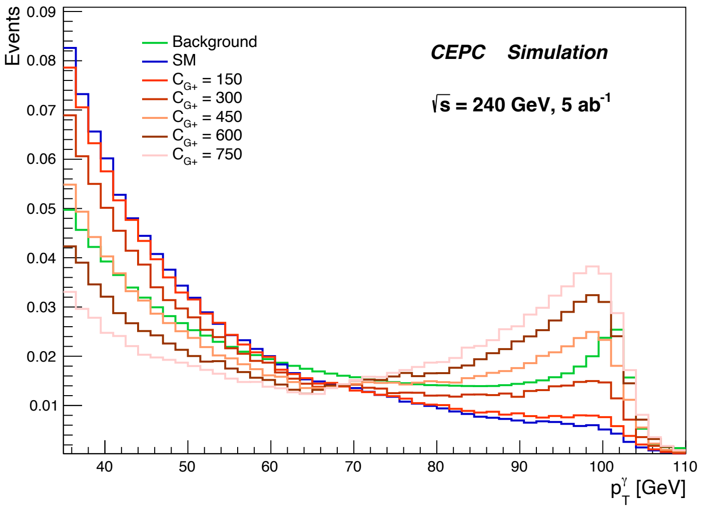
- The cut-based approach proposed previously has been applied to both signal and background samples
  - Cross-sections [fb] of different processes are listed after each cut
  - Signal : EFT $Z+\gamma$ ($O_{G+}, O_{G-}, O_{\tilde{B}W}$)
  - Background
    - SM $Z+\gamma$
    - Other background : 2 fermions (dominant), 4 fermions and Higgs backgrounds







Variables	SM Backgrounds	SM $Z+\gamma$	O_{G+}	O_{G-}	$O_{\tilde{B}W}$
$N_{pho} \geq 1$	11712.2	1571.54	1629.2	1746.7	1710.19
$N_{lep} = 2$	1151.58	587.08	623.96	696.10	675.12
$N_{jet} = 0$	810.95	586.65	623.51	695.54	674.63
$\Delta R(l,l) < 3$	698.00	548.39	585.07	656.23	634.47
$\lvert m_{ll} - m_Z \rvert < 10$ GeV	302.80	192.28	225.77	287.94	271.16
$(m_{ll} + m_{ll\gamma} > 182)$ GeV	299.99	192.28	225.77	287.94	271.16

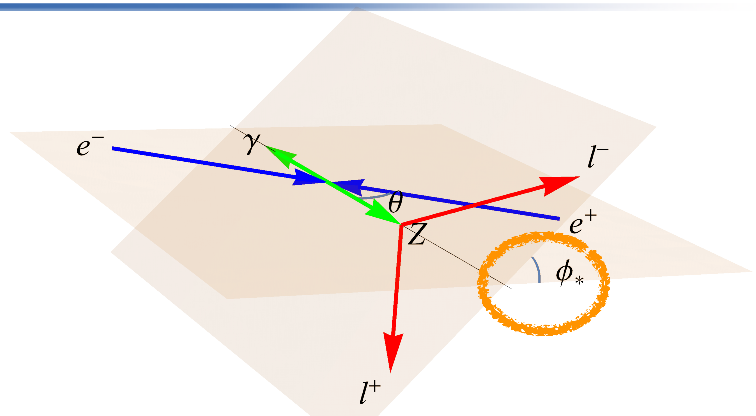


Systematic Uncertainty

- Systematic uncertainty are categorised into two types
- Assigned on **signal** yields
  - Theoretical uncertainty : Assume a 0.5% uncertainty on the signal yields for modelling (Chinese Phys. C 47 043002)
  - Experimental uncertainty : (Chinese Phys. C 47 043002 and Chinese Phys. C 44 013001)
    - Uncertainties from both luminosity, lepton identification and detector acceptance are considered to be small
    - Uncertainties from object reconstruction, identification and energy scale/resolution are assigned by assuming 1% for photon, and for leptons are estimated by varying m_{ll} selection up/down by 1 GeV
- Assigned on **background** yields
  - Event yields of all kinds of backgrounds are conservatively considered by varying 5% up/down for dominant process and 50% for other process (Chinese Phys. C 44 013001)

Limit setting with *EFTFitter*

- The expected limits for both SMEFT and Effective Vertex approaches are shown here :
  - The expected limits are extracted from $\phi*$ distribution
  - Defined as the value of nTGCs that demarcate the central 95% of the integral of the likelihood distribution
  - The outer range is excluded



$\phi*$: appeared due to the interference between pure SM and BSM

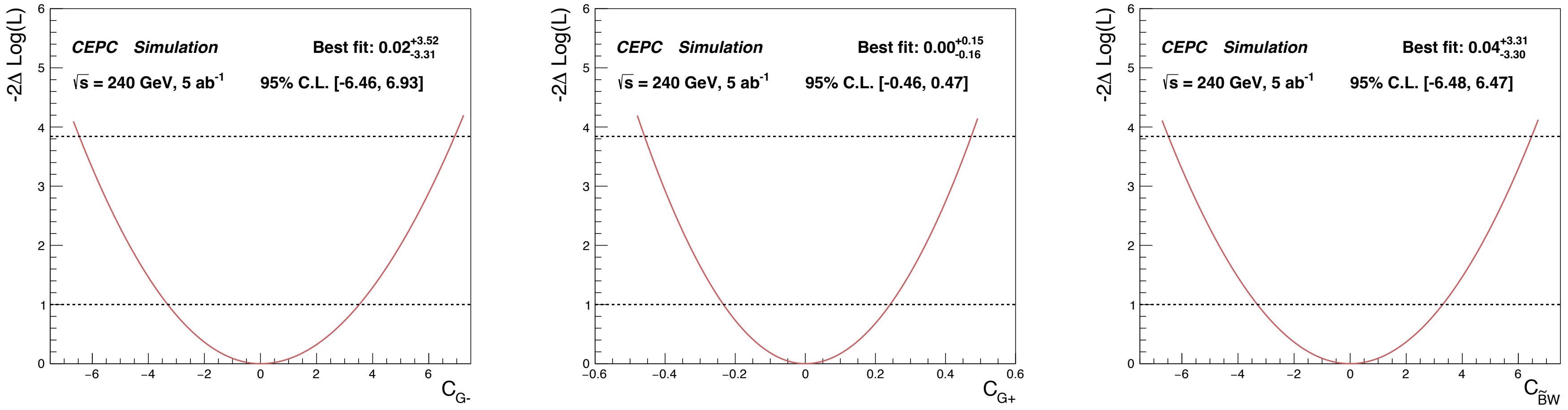
SMEFT	Expected Limits [TeV-4]	Form Factor	Expected Limits [TeV-4]
O_{G+}	[-1.30, 1.34]	h_4^γ	$[-8.7\times10^{-4}, 8.5\times10^{-4}]$
		h_4^Z	$[-1.6\times10^{-3}, 1.6\times10^{-3}]$
O_{G-}	[-5.95, 5.93]	h_3^γ	$[-1.9\times10^{-3}, 1.9\times10^{-3}]$
$O_{\tilde{B}W}$	[-21.41, 21.36]	h_3^Z	$[-1.3\times10^{-2}, 1.3\times10^{-2}]$

$$h_4 = -\frac{\text{sign}(\tilde{c}_{G+})}{\Lambda_{G+}^4}\frac{v^2M_Z^2}{s_Wc_W}$$

$$h_3^Z = \frac{\text{sign}(\tilde{c}_{BW})}{\Lambda_{\tilde{B}W}^4}\frac{v^2M_Z^2}{2s_Wc_W}$$

$$h_3^\gamma = -\frac{\text{sign}(\tilde{c}_{G-})}{\Lambda_{G-}^4}\frac{v^2M_Z^2}{2c_W^2}$$

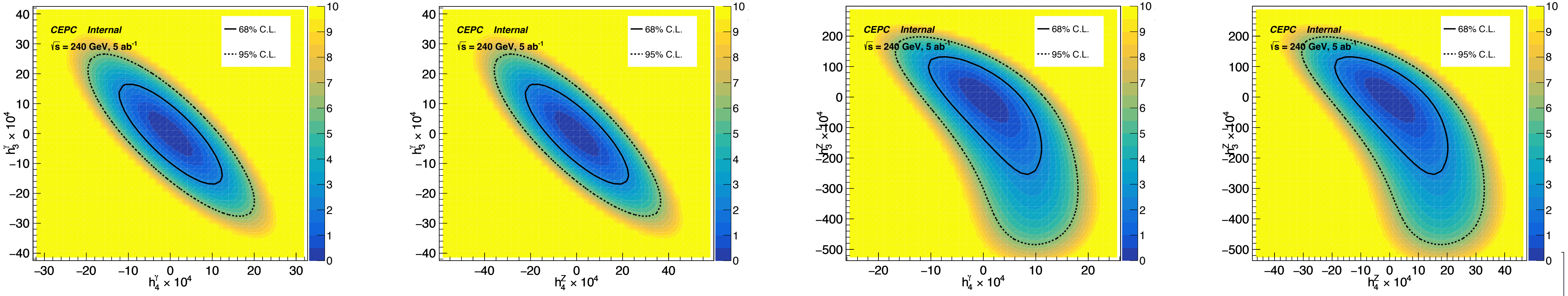
Limit setting with *EFTFitter*



Extracted experimental constraints from CEPC for dimension-8 operators for 1D scenario

Outer range is excluded @ 95% C.L.

- 2D limits are also extracted for pairs of dimension-8 operators to study the correlation of sensitivity reaches between pairs of dimension-8 operators, constraints are displayed as format of contour plots and converted to limits of form factors



Summary

- A search for Neutral Triple Gauge Couplings in $Z+\gamma$ channel with Z leptonic decays is performed with 5 ab^{-1} simulation data with CEPC
- Cut-based approach applied and optimised to get better sensitivity
- A more realistic study is carried out with a weaker exclusion limit compared to the theoretical predictions
- This study with 2 charged lepton plus 1 photon could help to understand the electroweak symmetry mechanism and also provide an experimental test for new formulation

- Future plan
  - Finish journal submission at the end of this year
  - More possibilities ? off-shell ?

Thank you for attention !

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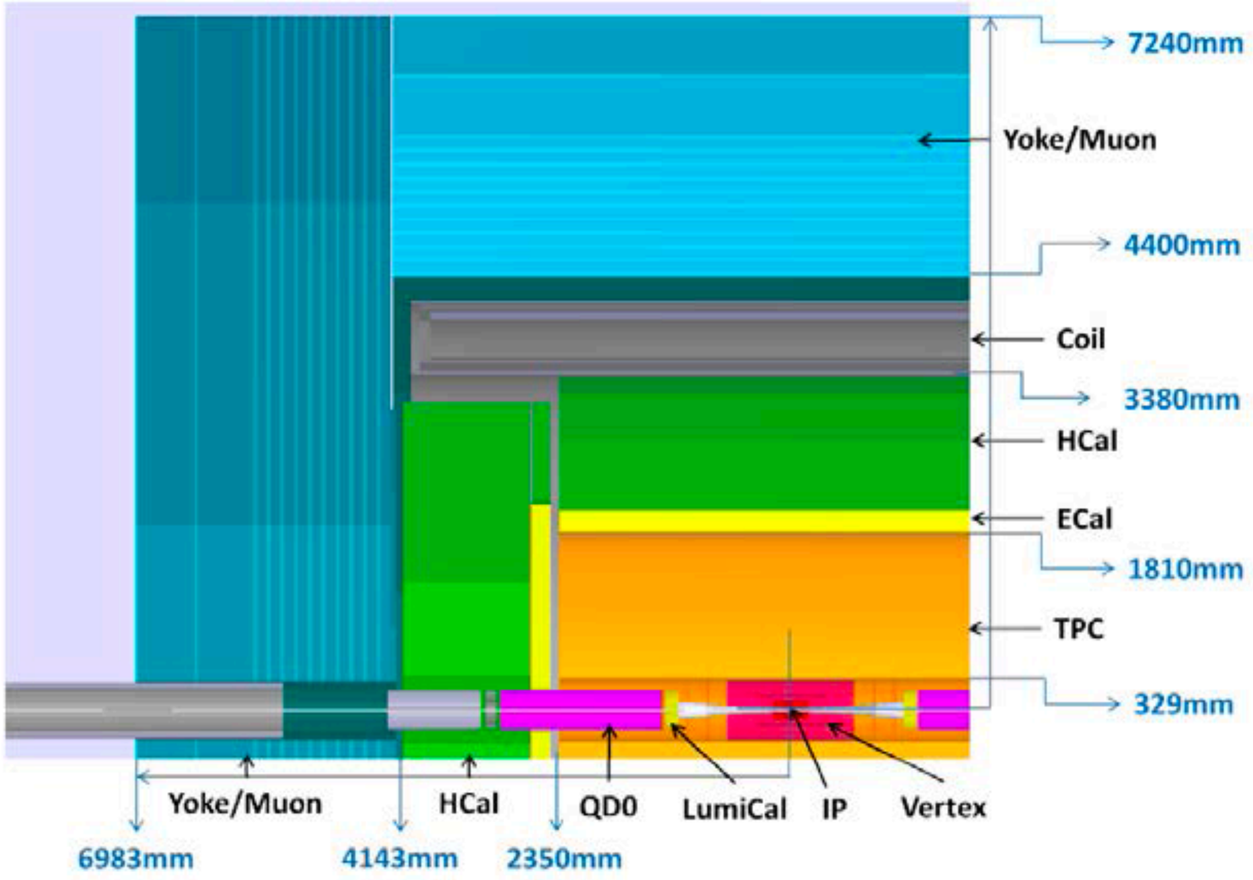
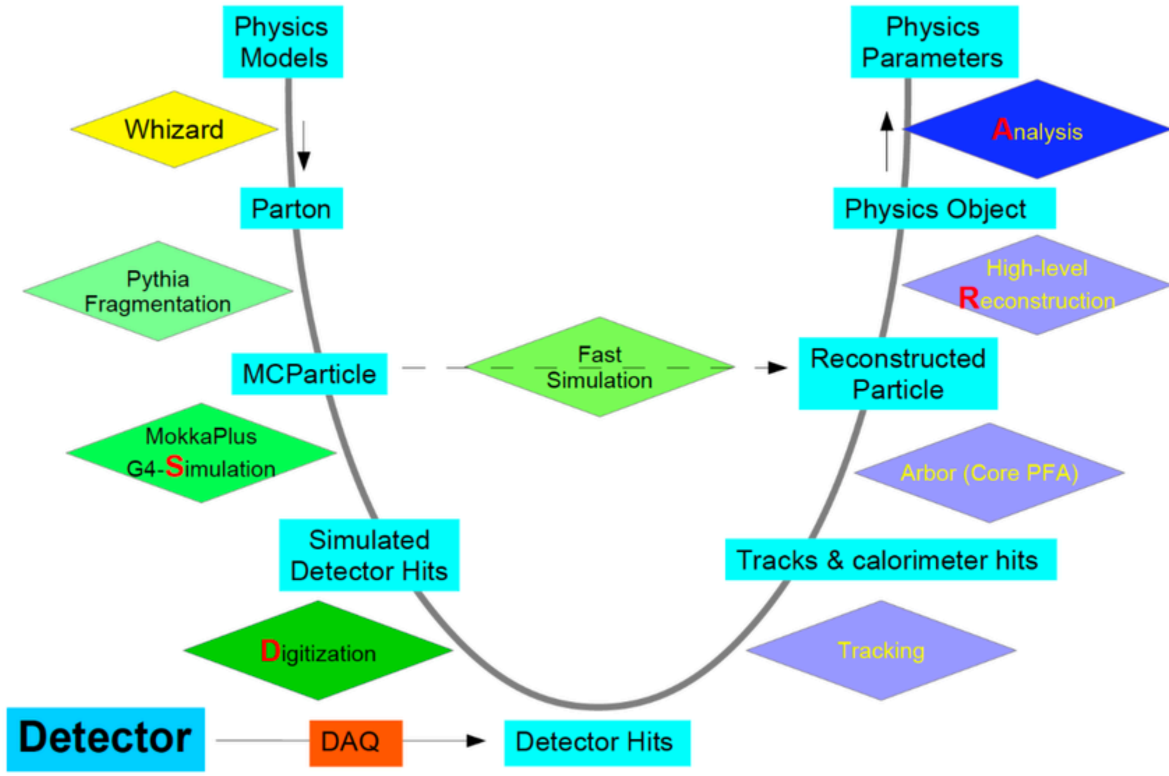
Additional Materials

Detector and Reconstruction

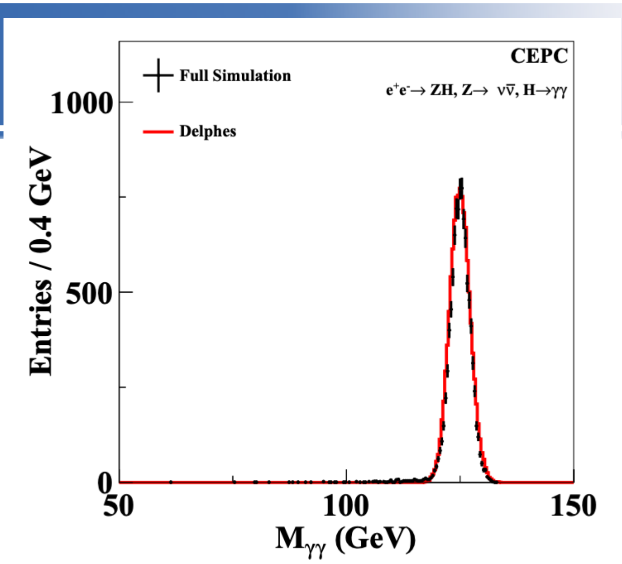




CEPC Figure

CEPC Experimental Overview from Manqi Ruan

Monte Carlo Samples



- Signal samples
  - $O_{G+}, O_{G-}, O_{\tilde{B}W}$ (CP-conserving)
  - Generated with MadGraph5 and Pythia8
  - Simulated with CEPC_V4 framework based on GEANT4

- Background samples
  - 2 fermions (dominant)
  - 4 fermions
  - Higgs
  - Fast simulated with Delphes

arXiv : 1712.09517

	Processes	Final States	σ [fb]
2 fermions	ll	$e^+e^-/\mu^+\mu^-/\tau^+\tau^-$	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	e1e1h	$e^+e^- + H$	7.04
	e2e2h	$\mu^+\mu^- + H$	6.77
	e3e3h	$\tau^+\tau^- + H$	6.75
	nnh	$\nu_e\bar{\nu}_e/\nu_\mu\bar{\nu}_\mu/\nu_\tau\bar{\nu}_\tau$ + H	46.29
	qqh	$u\bar{u}/d\bar{d}/c\bar{c}/s\bar{s}/b\bar{b}$ + H	136.81

Decomposition Closure

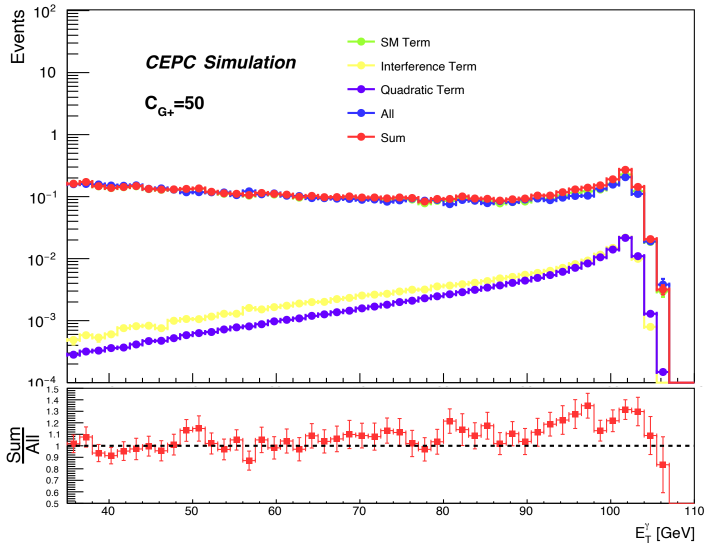
- Decomposition (parameterisation)

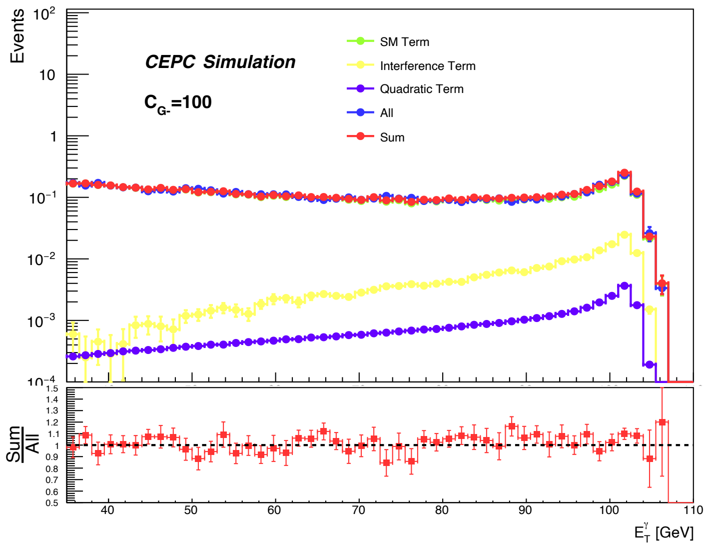
$$|A|^2 = |A_{SM} + (C/\Lambda^4)A_{BSM}|^2$$

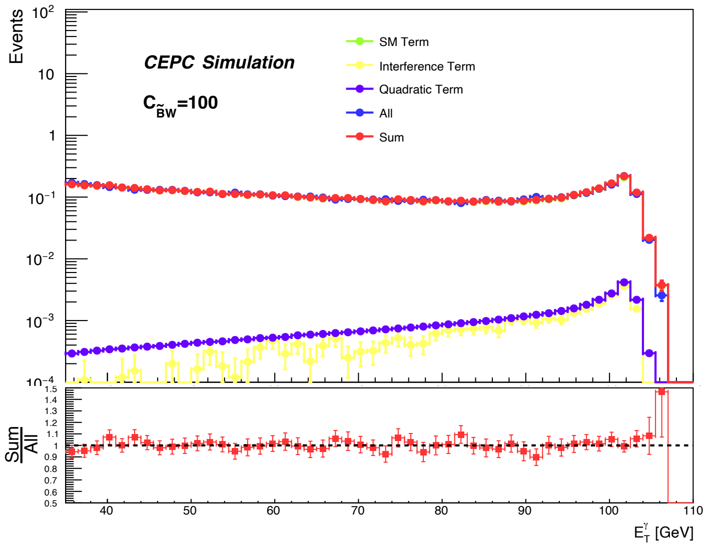
$$= \underbrace{|A_{SM}|^2}_{\text{SM term}} + \underbrace{(C/\Lambda^4)2Re(A_{SM}^{\dagger}A_{BSM})}_{\text{Interference Term}} + \underbrace{(C^2/\Lambda^8)|A_{BSM}|^2}_{\text{Quadratic Term}}$$

Decomposition controlled by NP

- $NP^2 = 1$: Interference Term
- $NP = 1$: Quadratic Term





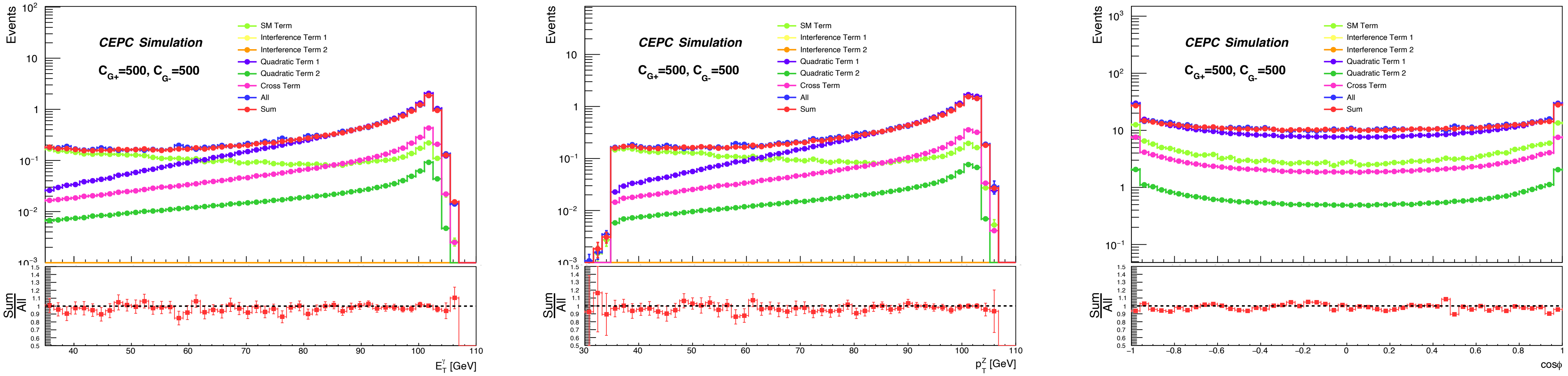


- Good agreement observed !

- To study the correlation of sensitivity reaches between pairs of dimension-8 operators

Variables	SM Backgrounds	SM $Z+\gamma$	$[O_{G+}, O_{G-}]$	$[O_{G-}, O_{\tilde{B}W}]$	$[O_{G-}, O_{\tilde{B}W}]$
$N_{pho} \geq 1$	11712.2	1571.54	2614.01	2505.51	3811.12
$N_{lep} = 2$	1151.58	587.08	1224.99	1177.15	1998.57
$N_{jet} = 0$	810.95	586.65	1223.71	1176.05	1995.92
$\Delta R(l,l) < 3$	698.00	548.39	1178.57	1125.87	1929.37
$\lvert m_{ll} - m_Z \rvert < 10$ GeV	302.80	192.28	750.50	717.212	1441.24
$(m_{ll} + m_{ll\gamma} > 182)$ GeV	299.99	192.28	750.50	717.212	1441.24

Cut-flow table



Limits setting

- This study is a more realistic search compared to theoretical predictions
  - With detector simulation, response added
  - With object reconstruction, identification, resolution effect/efficiencies added
  - With different sources of systematic uncertainties added
  - ……
  - A weaker exclusion limit extracted

Theory	Expected Limits	Experiment	Expected Limits
$\Lambda^{2\sigma}_{C_{G+}}/TeV$	—	$\Lambda^{2\sigma}_{C_{G+}}/TeV$	0.96
$\Lambda^{2\sigma}_{C_{G-}}/TeV$	—	$\Lambda^{2\sigma}_{C_{G-}}/TeV$	0.64
$\Lambda^{2\sigma}_{C_{\tilde{B}W}}/TeV$	0.60	$\Lambda^{2\sigma}_{C_{\tilde{B}W}}/TeV$	0.47

Chinese Phys. C 44 063106