Probing Electroweak Phase Transition at CEPC via Exotic Higgs Decays in 4b Final States

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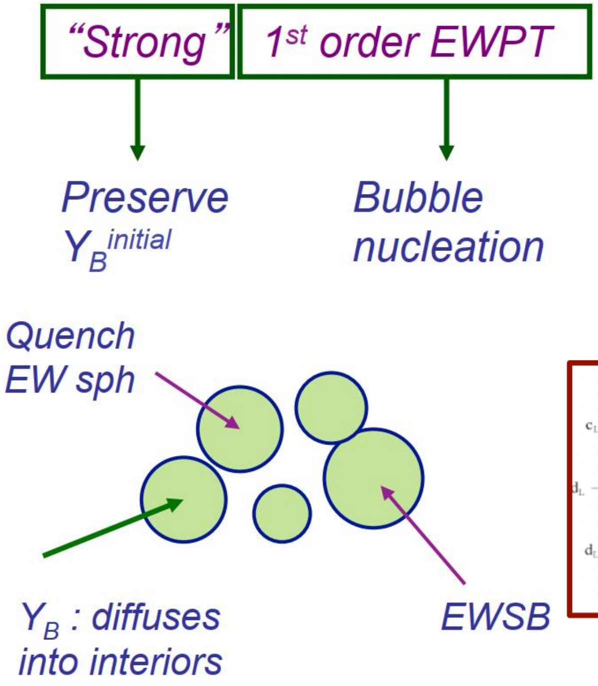
2024-10-25

Physics Motivation

- We are interested in the strong first-order electroweak phase transition in the "SM Higgs + **Light Real Singlet Scalar**" model:

$$V = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}a_1|H|^2S + \frac{1}{2}a_2|H|^2S^2 + b_1S + \frac{1}{2}b_2S^2 + \frac{1}{3}b_3S^3 + \frac{1}{4}b_4S^4$$

- Mass eigenstates: $h_1 = h\cos\theta + s\sin\theta$ (h_1 : singlet-like)
  $h_2 = -h\sin\theta + s\cos\theta$ (h_2 : SM-like Higgs)



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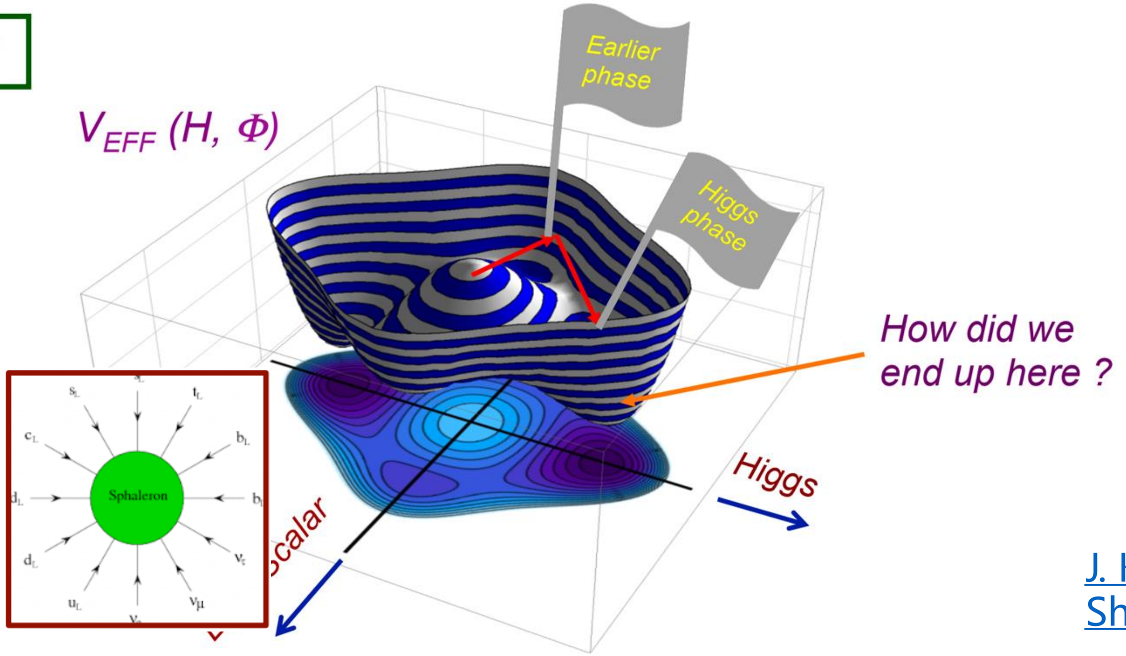
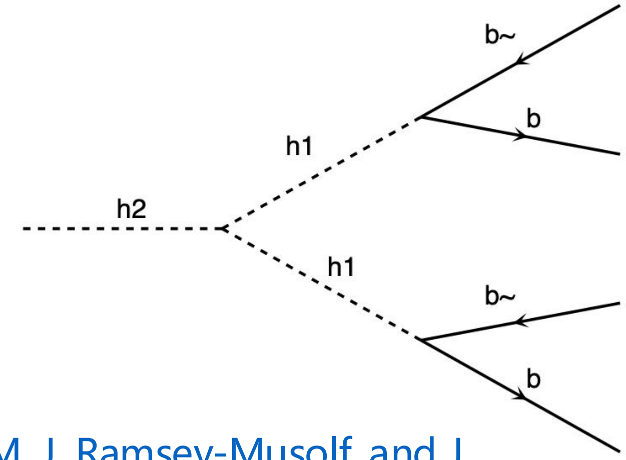




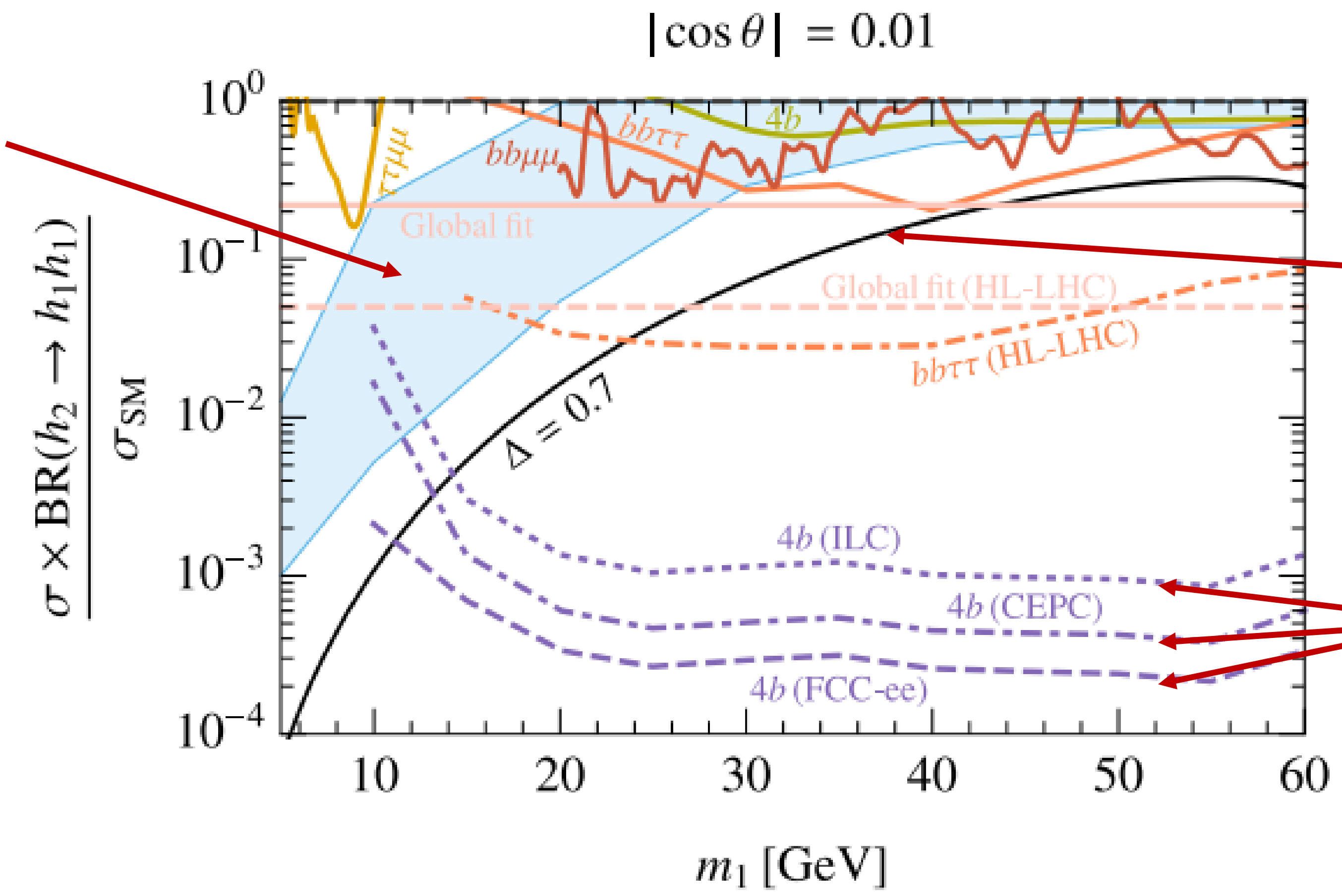
J. Kozaczuk, M. J. Ramsey-Musolf, and J. Shelton Phys. Rev. D **101**, 115035 (2020).

Extrema can evolve differently as T evolves →
Rich possibilities for symmetry breaking

Theoretical Prospects

$H \to ss \to 4b$

EWPT viable: numerical



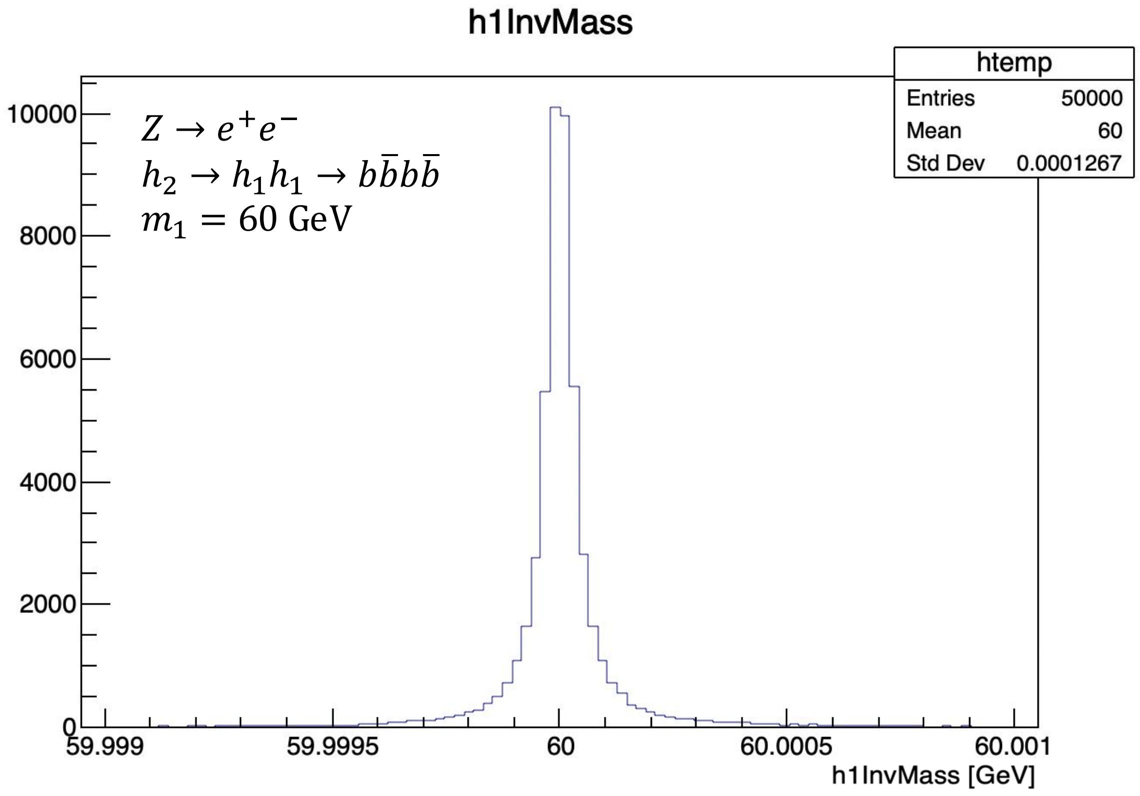
EWPT viable: semi analytic

Future e^+e^-

J. Kozaczuk, M. J. Ramsey-Musolf, and J. Shelton *Phys. Rev. D* **101**, 115035 (2020).
Z. Liu *et al.*, *Chinese Phys. C* **41**, 063102 (2017).

Sample Production

- **Signal:** The samples are generated at 240 GeV. 50000 events per mass point from 5 to 60 GeV for electron and muon channel separately
- **Generator:** Madgraph5 and Pythia8
- **Simulation and reconstruction:** cepcsoft 0.1.1 , CEPC_v4



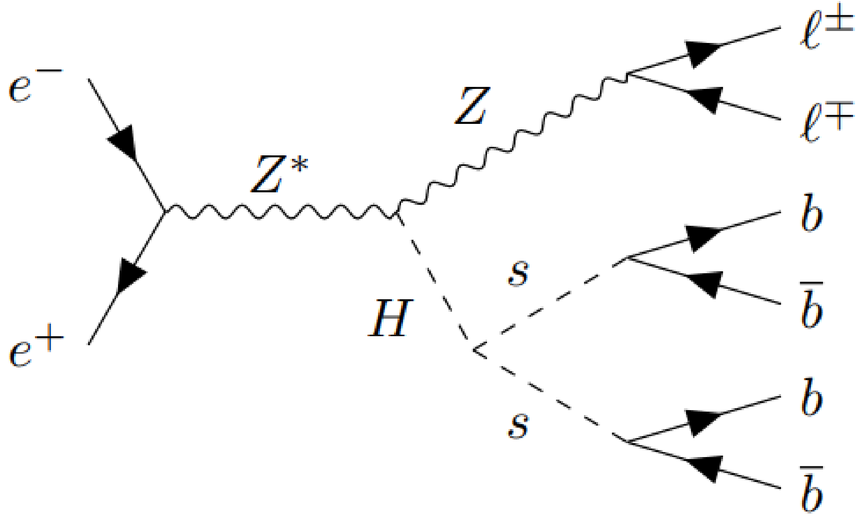


Fig. Mass distribution of h_1 when $m_1 = 60\text{GeV}$

Sample Production

- Background: **2-Fermion, 4-Fermion, eeH, $\mu\mu H$** as our background. Expect luminosity : $5\ \text{ab}^{-1}$ (also scaled to $\mathbf{20\ ab^{-1}}$).

Process	$\int L$	Final states	X-sections (fb)	Comments
	5 ab^{-1}	ffH	203.66	all signals
	5 ab^{-1}	e^+e^-H	7.04	including ZZ fusion
	5 ab^{-1}	$\mu^+\mu^-H$	6.77	
	5 ab^{-1}	$\tau^+\tau^-H$	6.75	
	5 ab^{-1}	$\nu\bar{\nu}H$	46.29	all neutrinos (ZH+WW fusion)
	5 ab^{-1}	$q\bar{q}H$	136.81	all quark pairs (Z→ $q\bar{q}$)

2 fermion backgounds

Process	$\int L$	Final states	X-sections (fb)	Comments
$e^+e^- \to e^+e^-$	5 ab^{-1}	e^+e^-	24770.90	

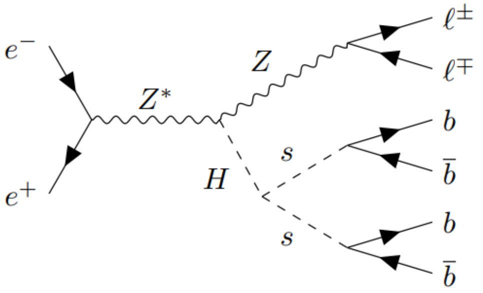
decay mode	branching ratio	relative uncertainty
$H \to b\bar{b}$	57.7%	+3.2%, −3.3%
$H \to c\bar{c}$	2.91%	+12%, −12%
$H \to \tau^+\tau^-$	6.32%	+5.7%, −5.7%
$H \to \mu^+\mu^-$	2.19×10^{-4}	+6.0%, −5.9%
$H \to WW^*$	21.5%	+4.3%, −4.2%
$H \to ZZ^*$	2.64%	+4.3%, −4.2%
$H \to \gamma\gamma$	2.28×10^{-3}	+5.0%, −4.9%
$H \to Z\gamma$	1.53×10^{-3}	+9.0%, −8.8%
$H \to gg$	8.57%	+10%, −10%
Γ_H	4.07 MeV	+4.0%, −4.0%

http://cepcsoft.ihep.ac.cn/guides/Generation/docs/ExistingSamples/#240-gev
https://iopscience.iop.org/article/10.1088/1674-1137/43/4/043002/pdf
lxslc7 : /cefs/data/DstData/CEPC240/CEPC_v4_update

Cut Based Approach

- **Same flavor opposite sign lepton pair** with energy larger than 20 GeV
- Invariant lepton pair mass should be within the **Z mass window [77.5,104.5] GeV**
- **Recoiled mass** of the lepton pair system should be within [124,140] GeV
- 4 jets are required to be reconstructed. **Reconstructed S particle** is decided by pairing them 2 by 2 and find the set with smallest mass difference.
- **Number of energetic particles**(energy > 0.4 GeV) in the 4jets should be larger than 40
- **B-inefficiency : GBDT-based b-jet tagging algorithm. $L_{b1}, L_{b2}, L_{b3}, L_{b4}$ should satisfy**

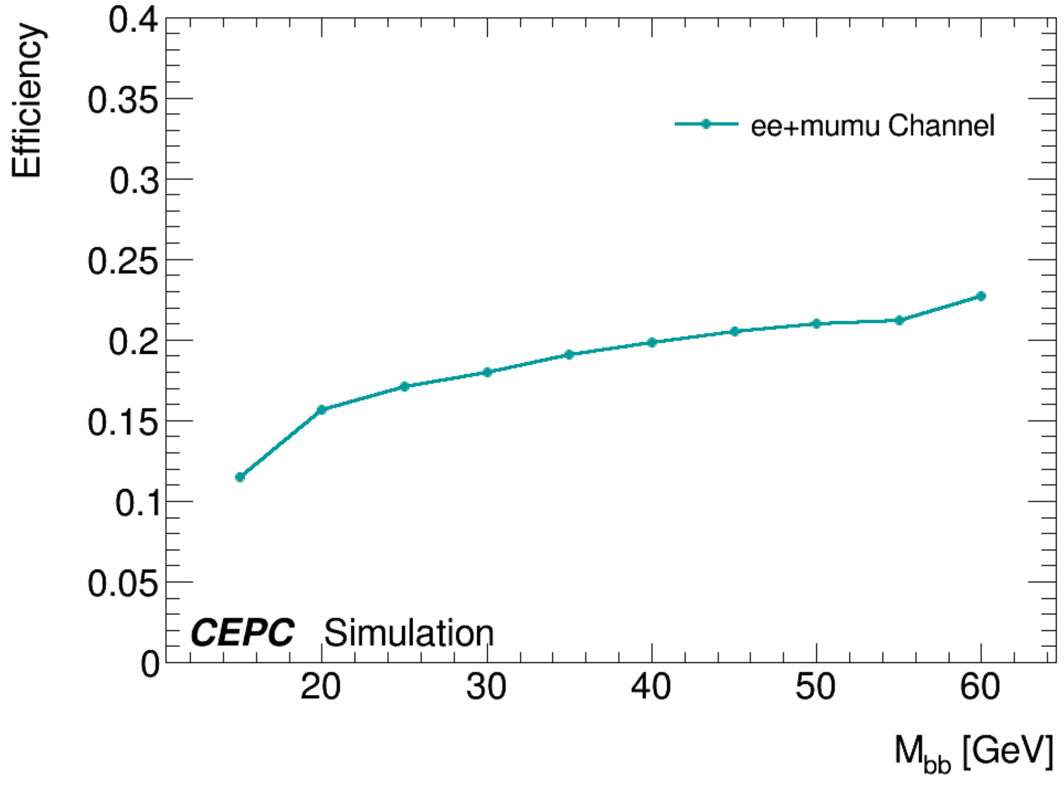
$$Log10\left(\frac{L_{b1}\times L_{b2}\times L_{b3}\times L_{b4}}{L_{b1}\times L_{b2}\times L_{b3}\times L_{b4}+(1-L_{b1})\times(1-L_{b2})\times(1-L_{b3})\times(1-L_{b4})}\right) < -4.0$$



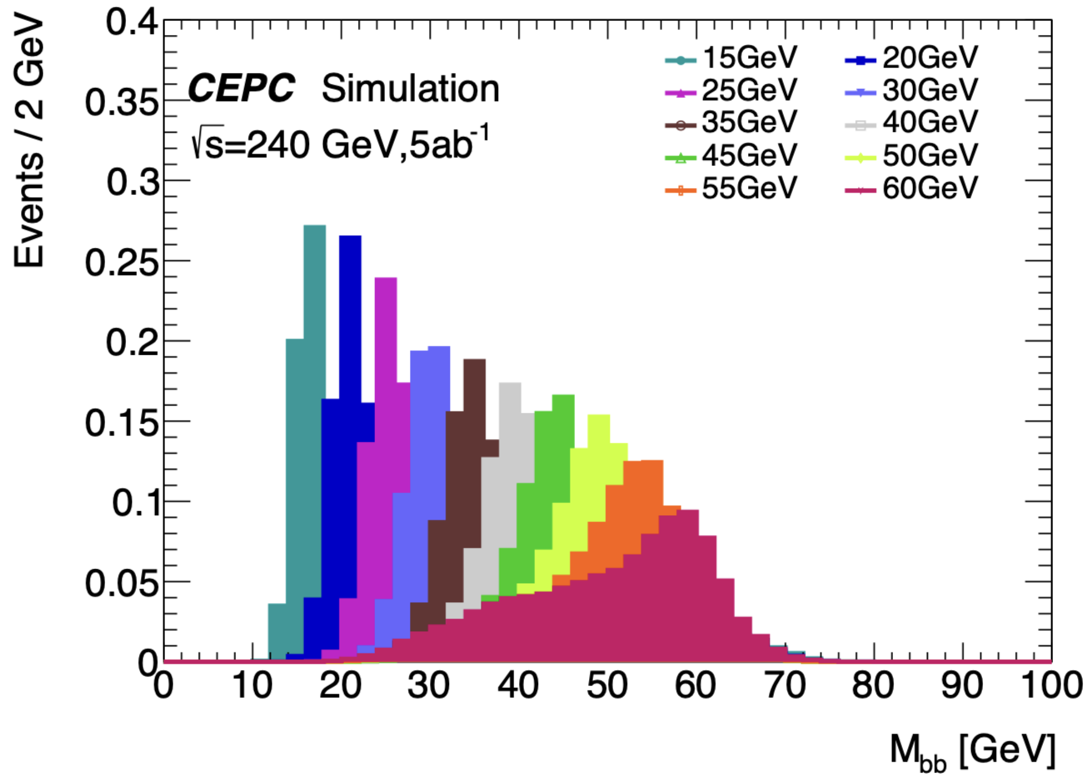
Thanks to Yu Bai.
Y. Bai *et al., Chinese Phys. C* **44**, 013001 (2020).

Cut Based Approach

- **Signal Selection Efficiencies:**



- **Signal Distribution:**

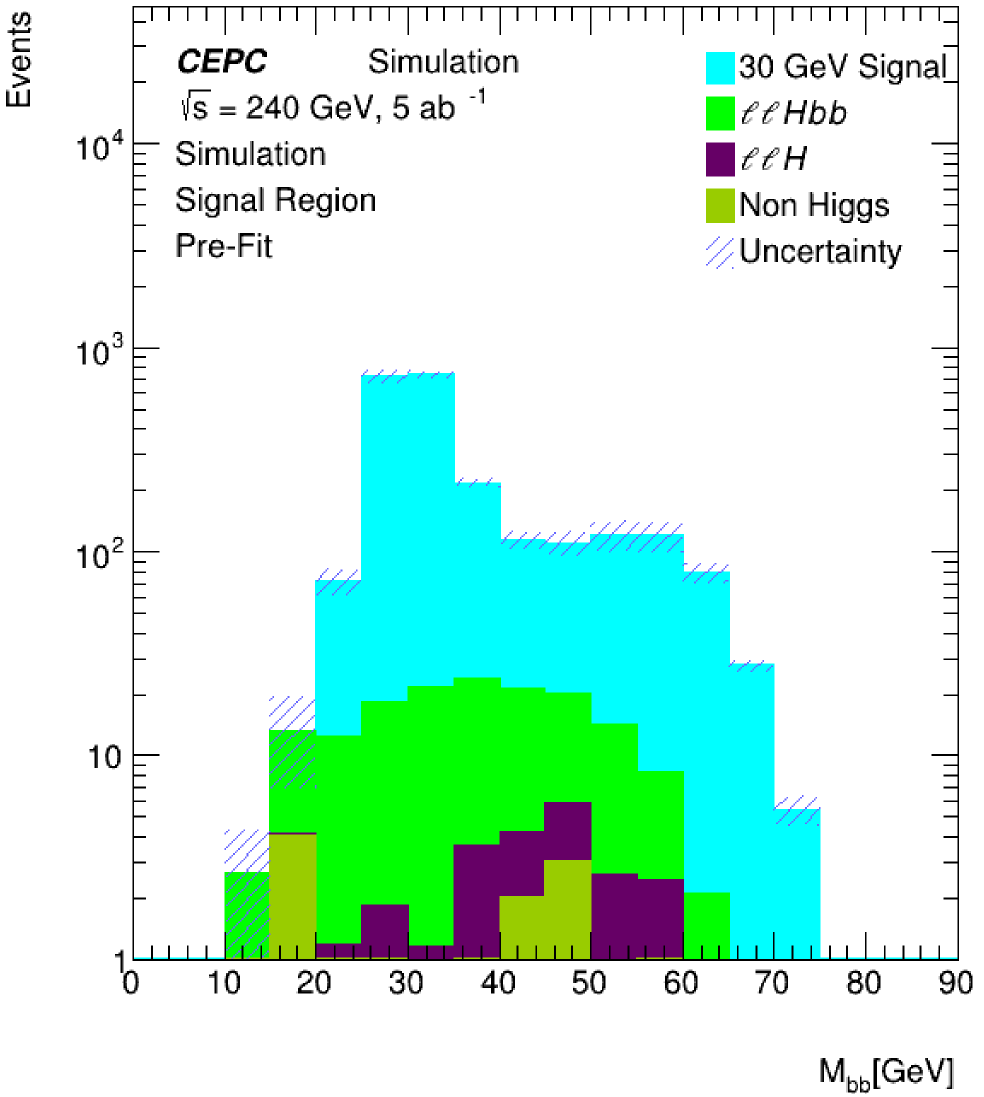


Cut Based Approach

- Signal:
  - Singlet mass at 30 GeV
- Background:
  - llH_bb (dominant)
  - Other llH process
  - Non Higgs process

Selection	Signal ($m_s = 30$ GeV)	$\ell\ell Hbb$	other $\ell\ell H$	non Higgs
Original	8865	2.92×10^4	2.41×10^4	3.79×10^7
Lepton pair selection	6042	1.83×10^4	1.20×10^4	1.32×10^6
Lepton pair mass	5537	1.65×10^4	1.07×10^4	6.17×10^5
Jet selection and pairing	4054	7947	4661	3698
B-inefficiency	2210	131	15	14

Cutflow Table



BDT Approach

- Trained the variables after some loose selections :
- **Same flavor opposite sign lepton pair** with energy larger than 20 GeV
- Invariant lepton pair mass should be within the **Z mass window [77.5,104.5] GeV**
- **Recoiled mass** of the lepton pair system should be within [124,140] GeV

10 BDTs are trained with 10 different mass points from 15GeV to 60 GeV

Variables used in training

- lep_pt
- jet_energy
- jet_inv_mass
- opening_angle
- jet_recoil_mass
- S_mass
- **btag_ineff**
- Y12
- Y23
- Y34
- Y45
- Y56
- jetcoshel
- sscosphi

Output of BDT classifier is used as the discriminant and used in the fitting and limit setting.

MARCH 21, 2012 BY UPAUDEL

Helicity angle calculations

A useful quantity in many analyses is the helicity angle. In the reaction Y -> X -> a + b, the helicity angle of particle a is the angle measured in the rest frame of the decaying parent particle, X, between the direction of the decay daughter a and the direction of the grandparent particle Y.

BDT Approach

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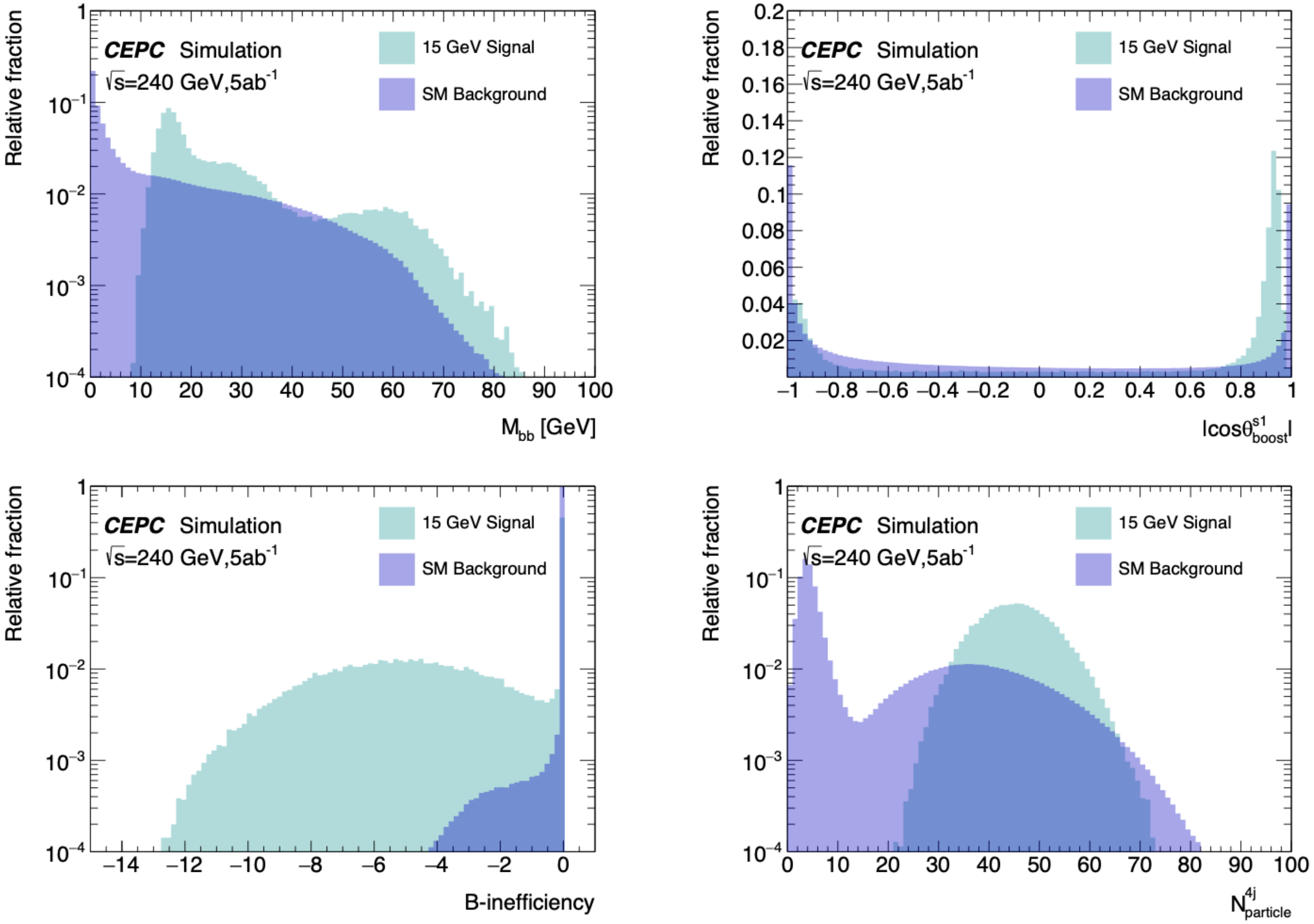
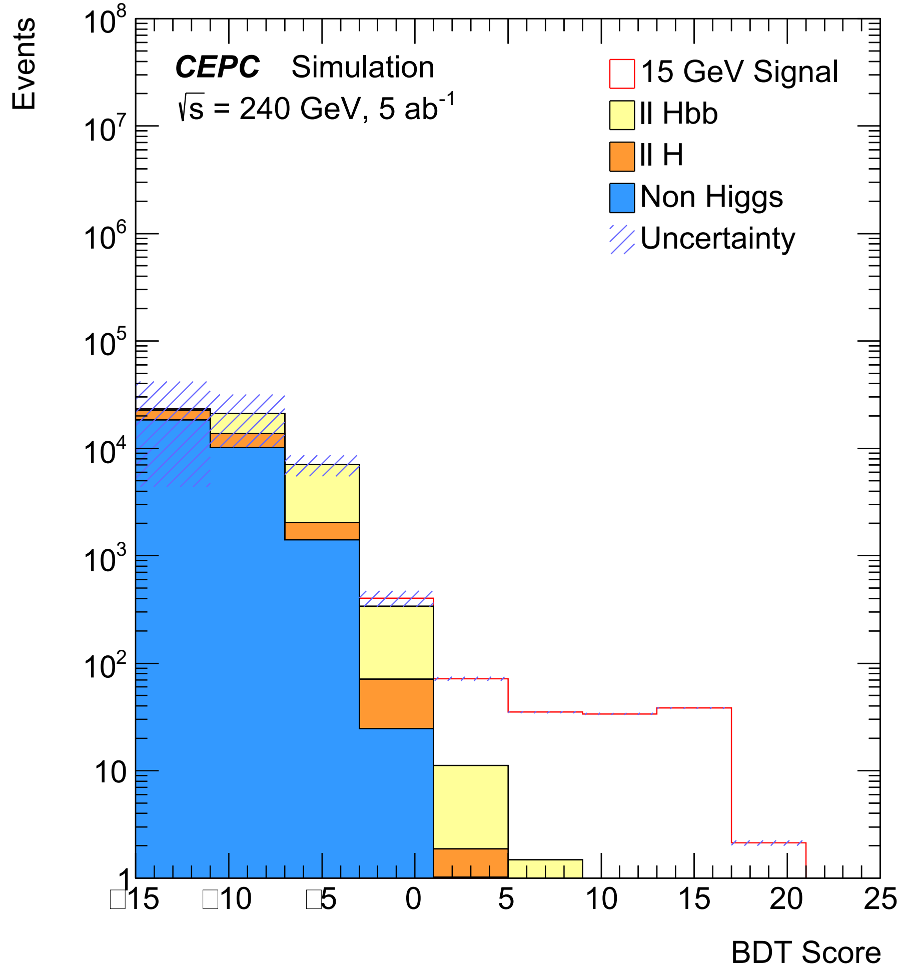
- Example of BDT inputs with 15 GeV signal





Systematic Uncertainty

- Systematic uncertainty from *luminosity and lepton identification* are considered to be small.

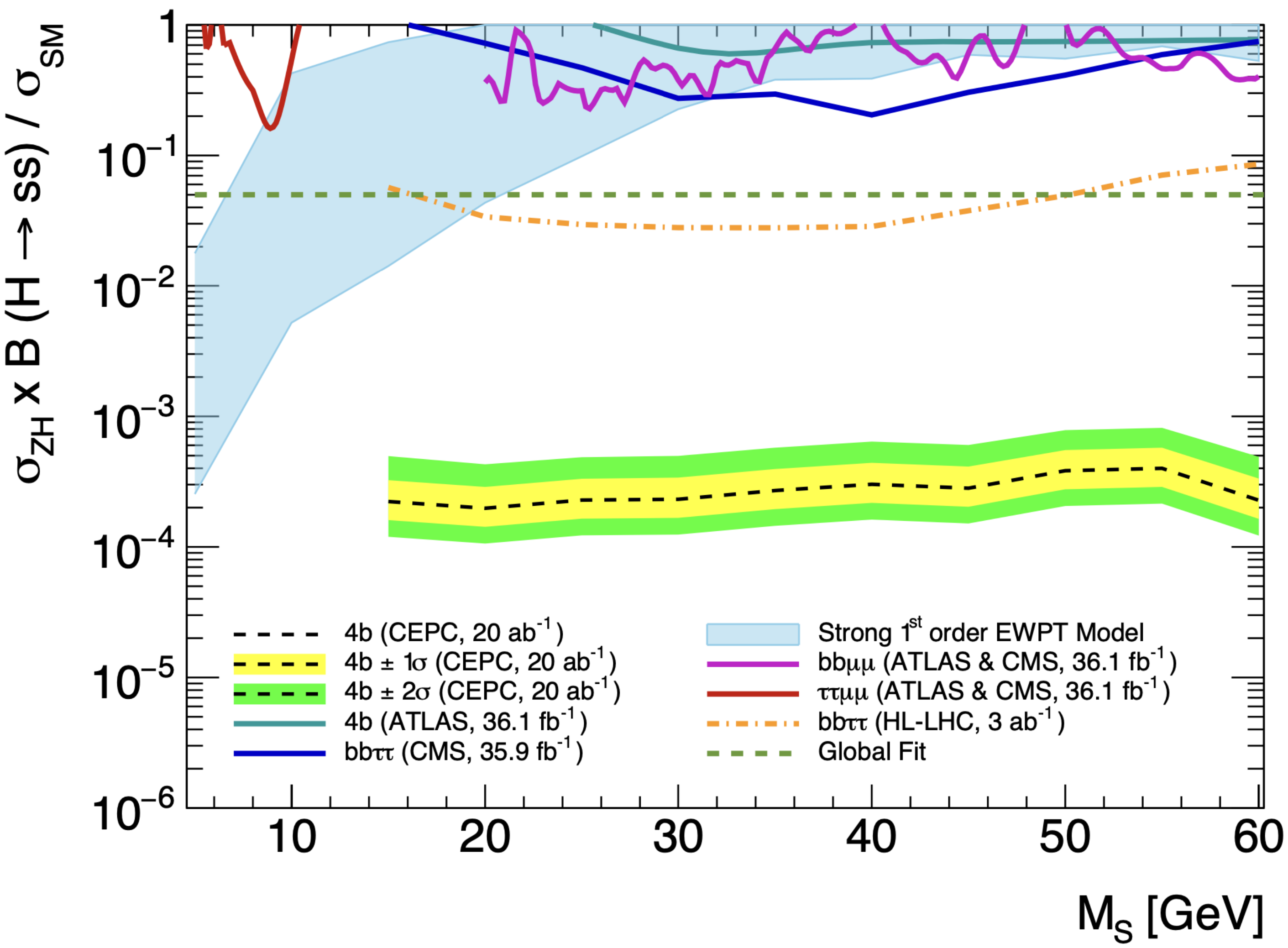
- **Event yield** of all kinds of backgrounds are conservatively considered by varying event yields by 5% for dominant process and 100% for other processes.

- **Flavor tagging uncertainty** is estimated on ZZ->qq+mumu control sample and yields 0.78% for 2jet analysis, we conservatively set this term to 1%.

- **Jet energy resolution** is estimated by MC samples.

Limit Setting

- Current limit of BDT approach.



Lepton collider does have advantages in sensitivity compared with hadronic colliders

arXiv:2203.10184

Summary

- A search for exotic decays of the Higgs boson into a pair of spin-zero singlet-like particles is done with 5 ab^{-1} simulation data with CEPC (also scaled to **20 ab^{-1}**).
- This realistic study yields a similar exclusion limit compared to the theoretical projections
- The study with 4b final states could conclusively test the possibility of an SFOEWPT in the extended-SM with a light singlet of mass as low as 15 GeV.

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

Danning Liu, Rui-Qing Xiao, Shu Li, Hong-Jian He, John Ellis, Rui Yuan

October, 2024 CEPC WP

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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 :

Phys.Rev.D 107 035005

Phys.Rev.D 108 L111704

Sci.China Phys.Mech.Astro 64 221062 (2021)

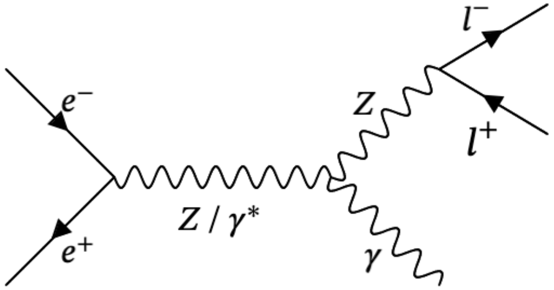
Introduction to nTGCs

- 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:

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

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

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



- Effective Vertex Approach:
  - We denote:

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

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

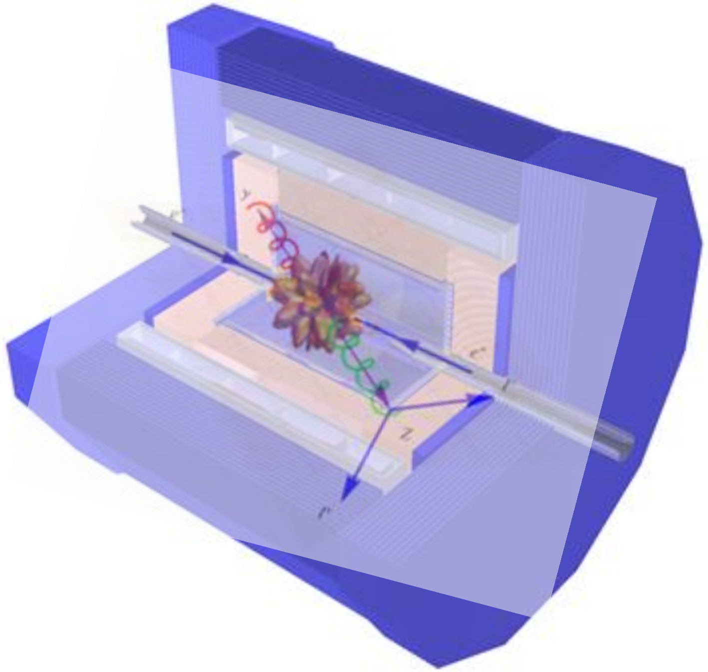
$$h_4 = -\frac{\text{sign}(\tilde{c}_{G+})}{\Lambda^4_{G+}} \frac{v^2 M_Z^2}{s_W c_W} \equiv \frac{r_4}{[\Lambda^4_{G+}]}, \qquad h_3^V = 0, \qquad \text{for } \mathcal{O}_{G+},$$

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

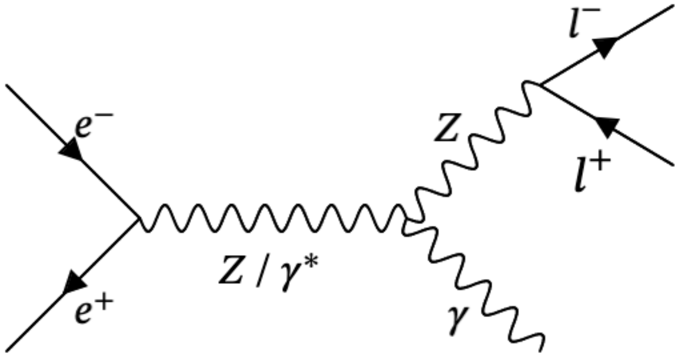
$$h_3^\gamma = -\frac{\text{sign}(\tilde{c}_{G-})}{\Lambda^4_{G-}} \frac{v^2 M_Z^2}{2 c_W^2} \equiv \frac{r_3^\gamma}{[\Lambda^4_{G-}]}. \qquad h_3^Z, h_4^V = 0, \qquad \text{for } \mathcal{O}_{G-},$$

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

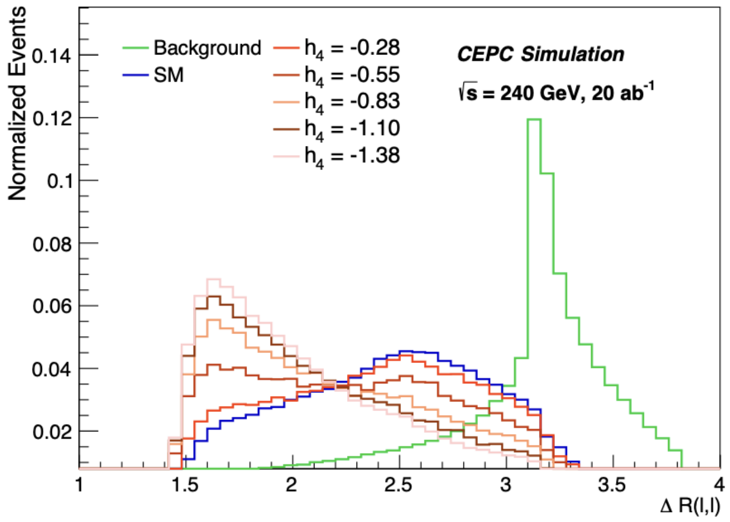
Remove jet-related background contributions

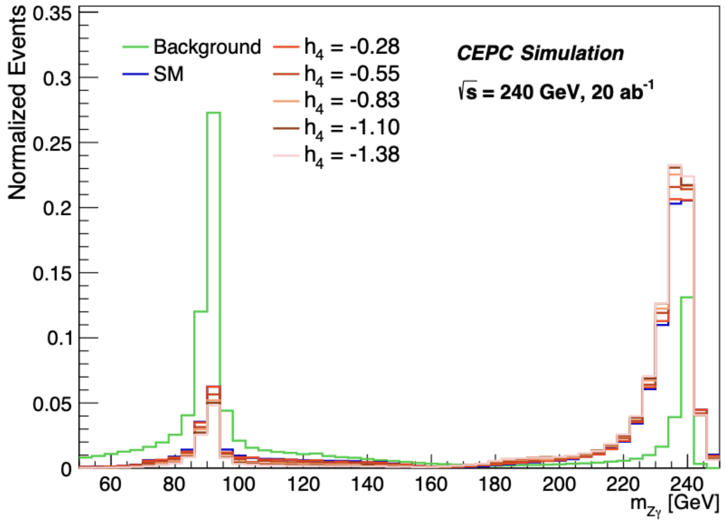
Remove higher-order corrections

Guarantee that the enhancement of cross section comes from nTGC effect

Invariant mass selection → Suppress Z plus final-state radiation photon scenario

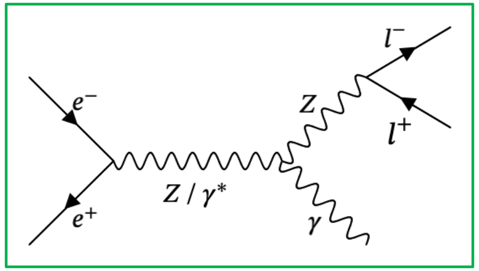
Ensure that final-state leptons decay from on-shell Z boson

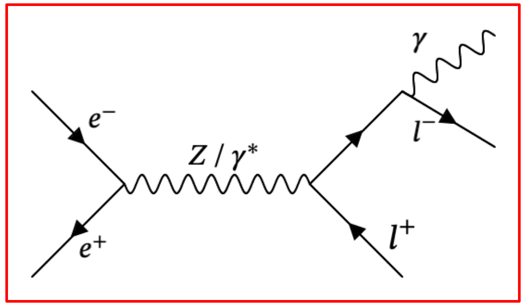


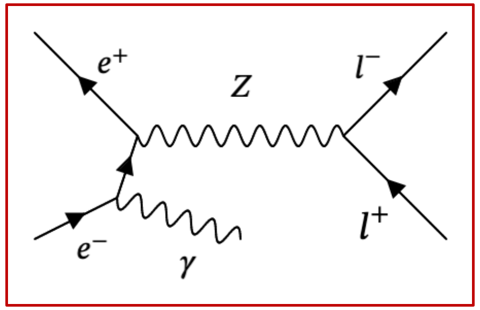


Analysis Strategy

- 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:

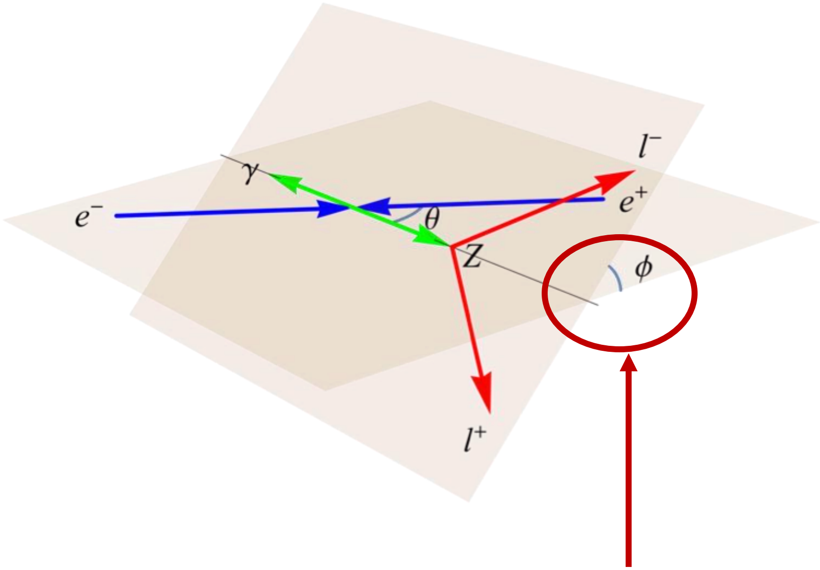
Variables	SM Backgrounds	SM $Z\gamma$	h_4	h_3^γ	h_3^Z
$N_{\text{pho}} \geqslant 1$	11712	1572	1629	1747	1710
$N_{\text{lep}} = 2$	1152	587	624	696	675
$N_{\text{jet}} = 0$	811	587	624	696	675
$\Delta R(\ell,\ell) < 3$	698	548	585	656	634
$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV	303	192	226	288	271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

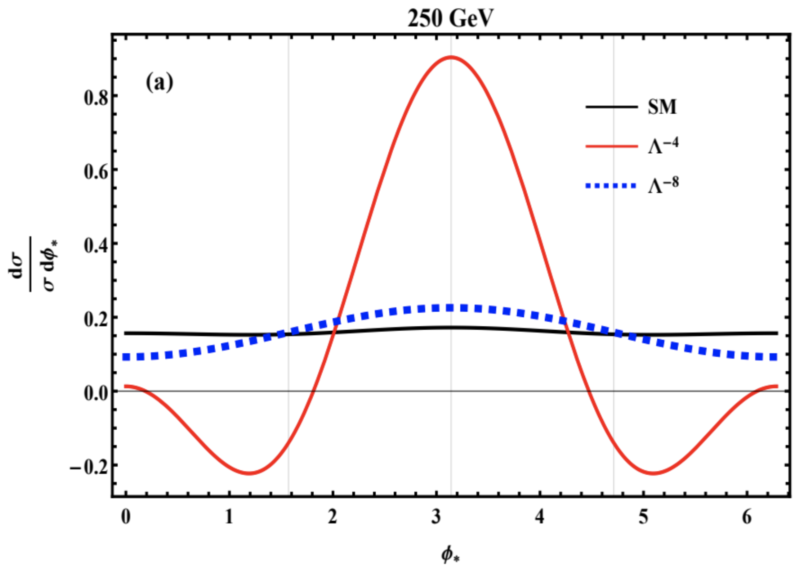
Cross section[fb] after applying sequential selections

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



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



Phys.Rev.D 107 035005

Phys.Rev.D 108 L111704

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Frontier of Physics 20 (2025) 12501, no.1

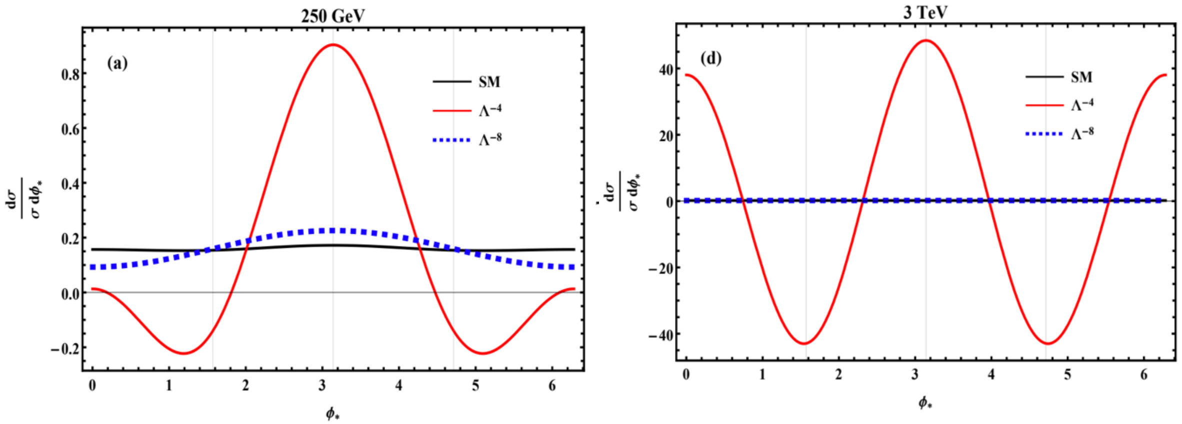
Analysis Optimization

- 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:

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

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

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



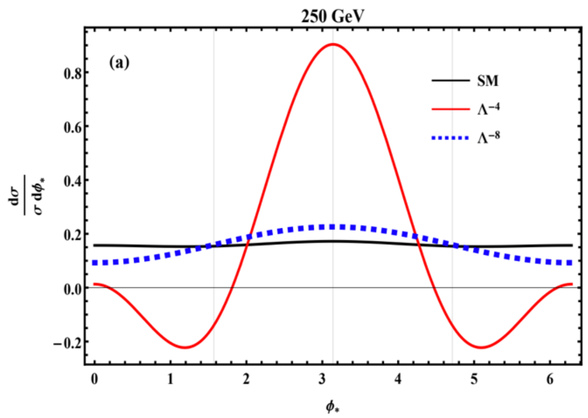
Interference term: dominated by $\cos2\phi$ term, significantly related to s/M_Z^2

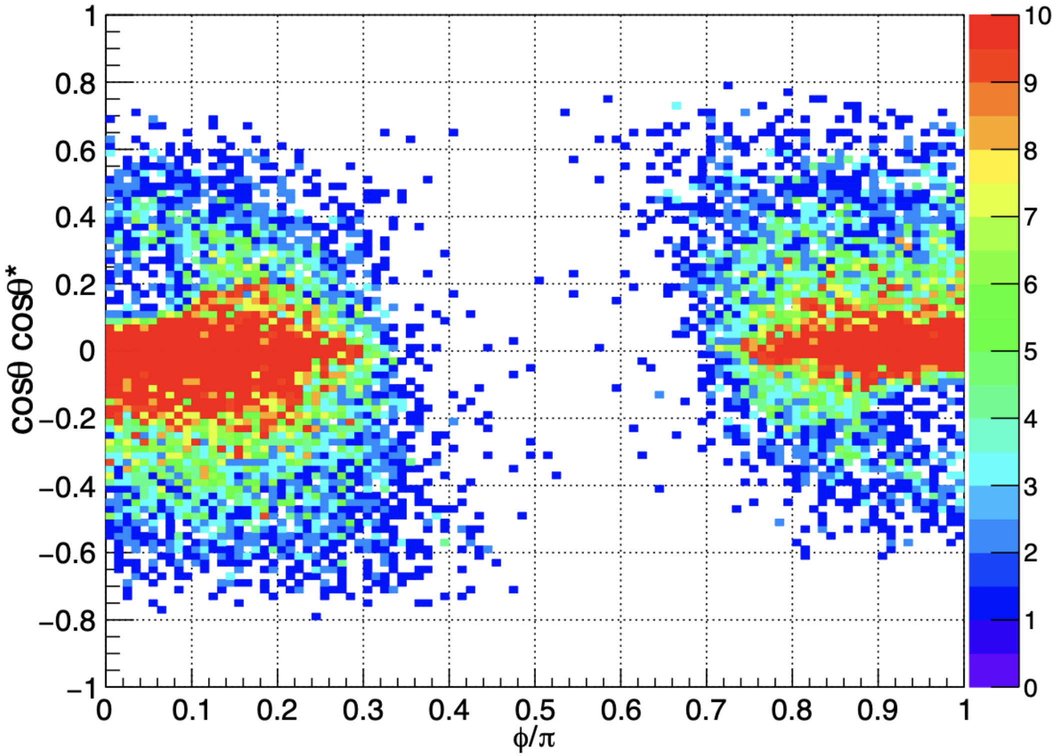
SM and Quadratic term: dominated by the constant term $\frac{1}{2\pi}$ and ϕ-dependent term which is suppressed by $M_Z^2/\sqrt{s}$

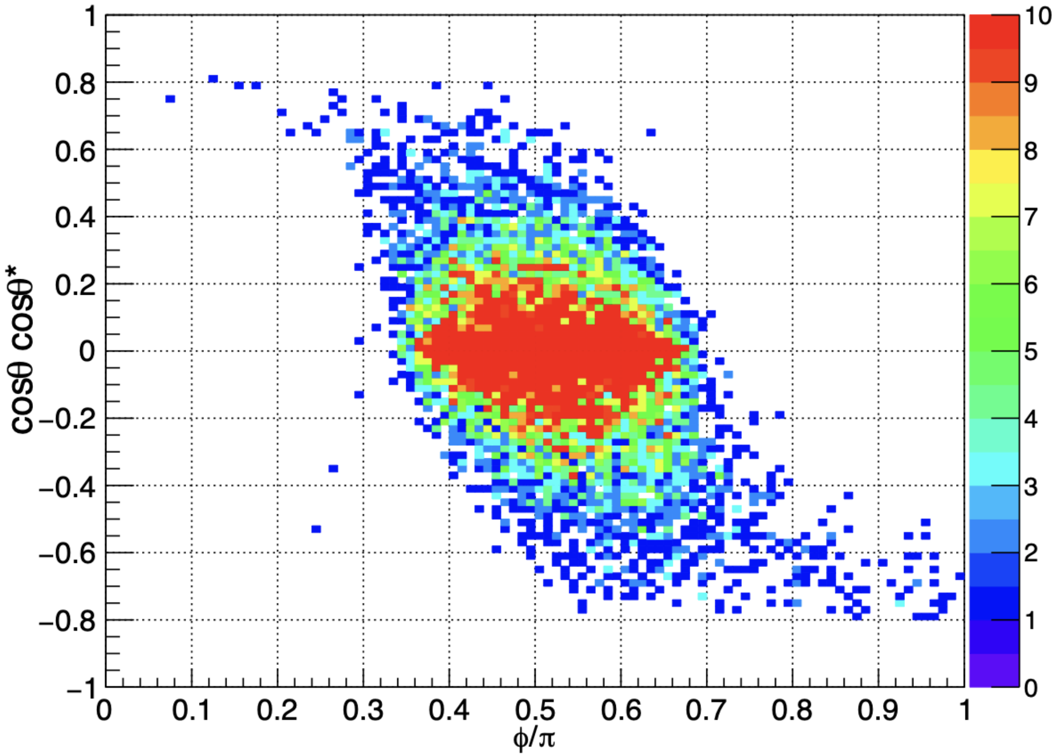
ϕ could be a good candidate to probe nTGCs

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

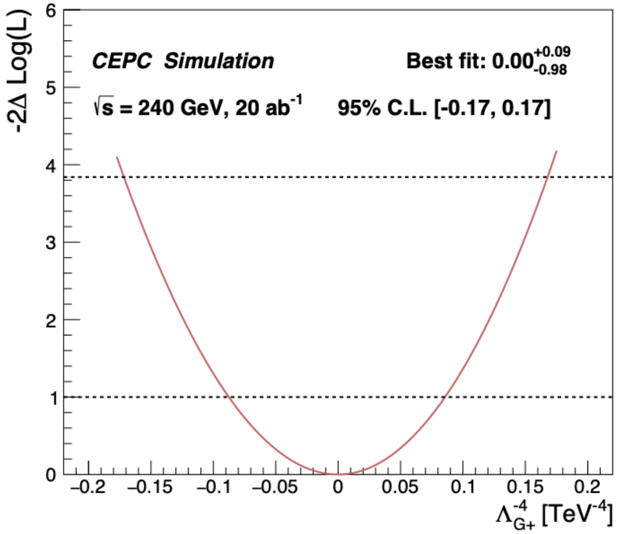
- Systematic uncertainties are categorised into two types :
  - Assigned on signal yields
    - Theoretical uncertainty : 0.5% uncertainty for modeling
    - Experimental uncertainty : luminosity, object identification, object reconstruction resolution, energy resolution, and detector acceptance
  -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

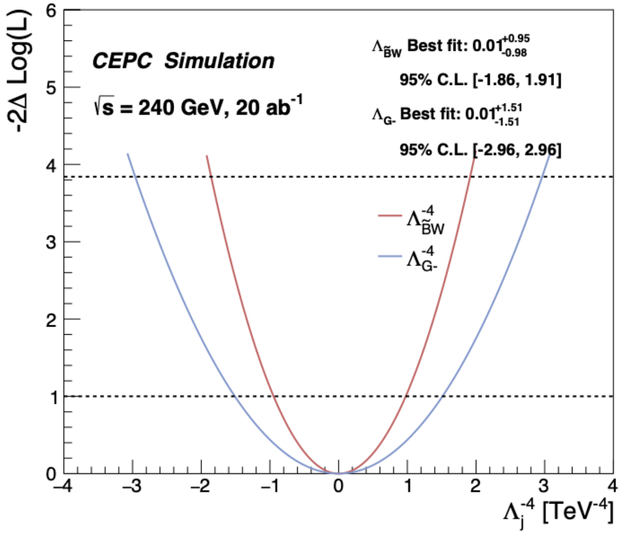
Processes	Statistical	Theoretical	Experimental
$Z\gamma$ production ($e^+e^- \to \ell^+\ell^-\gamma$)	0.52%	0.5%	(+2.96,-3.15)%
Fixed background	Dominant background: 5% Other backgrounds: 100%		

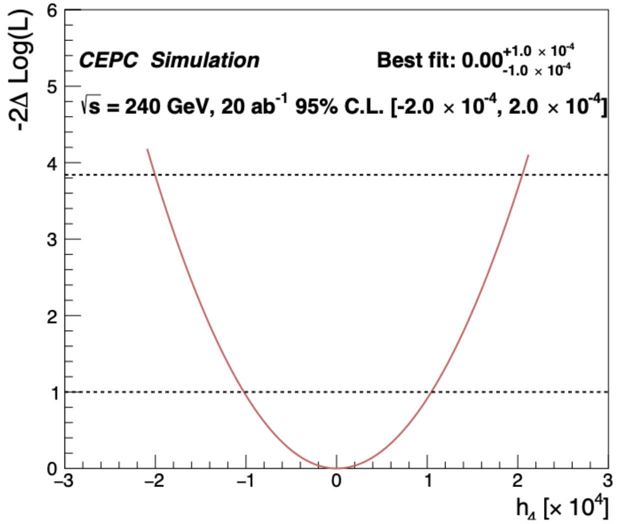
Results

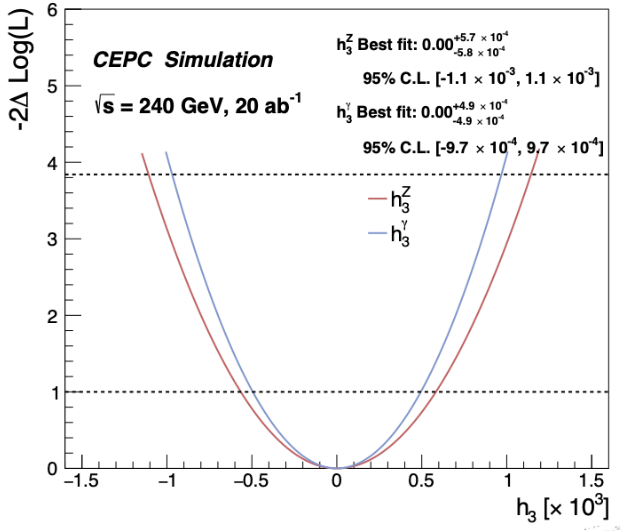
- Expected exclusion constraints acchieved from ϕ variable

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
		$\Lambda_{B\widetilde{W}}$	1.05



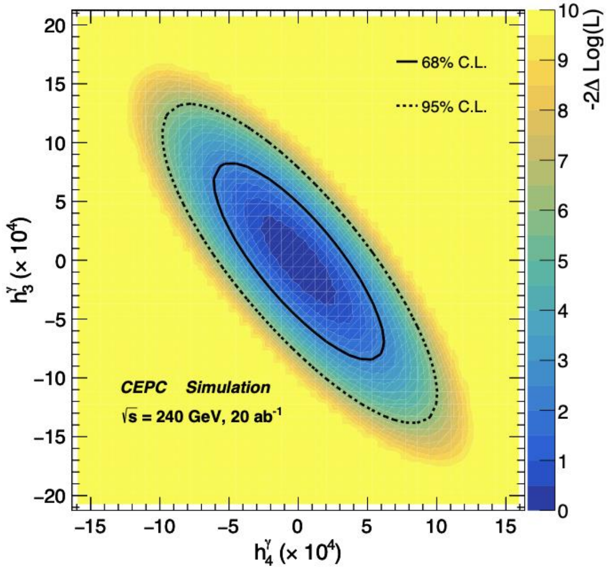


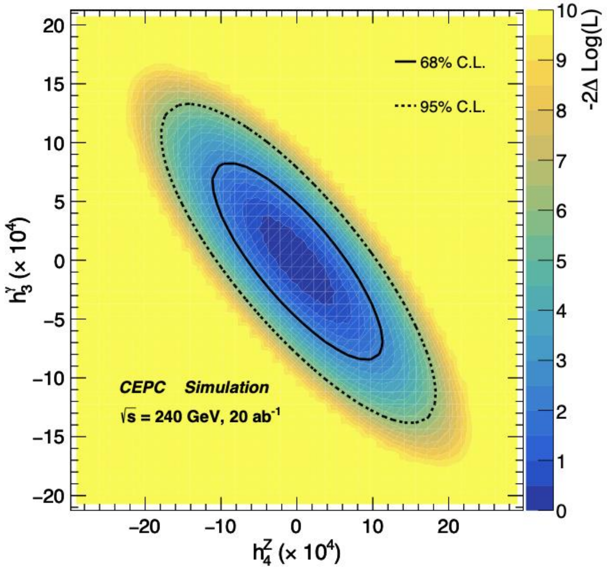


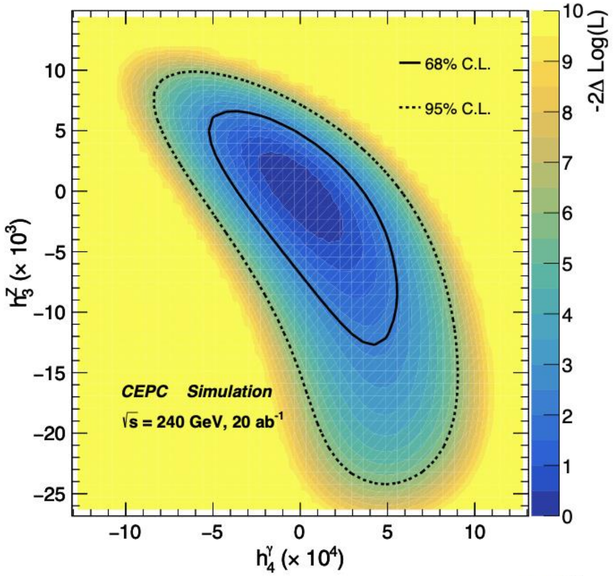


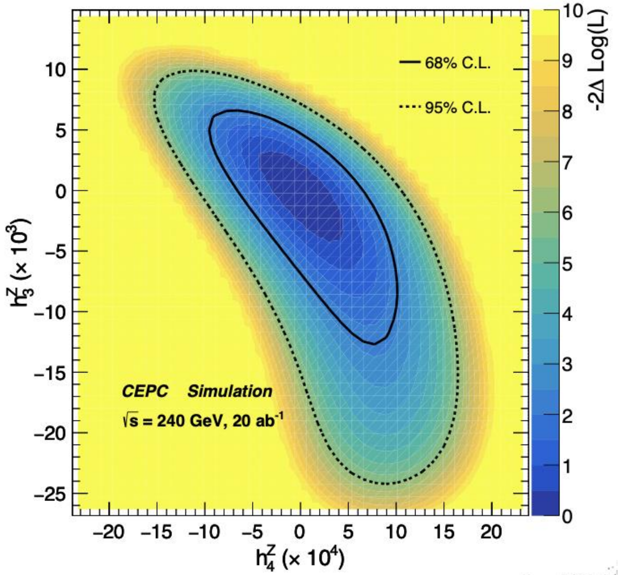
Results

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



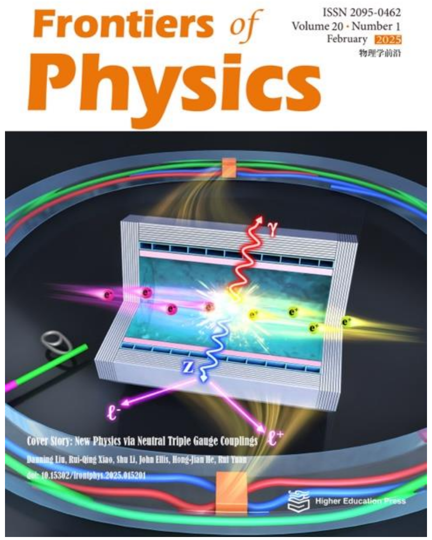




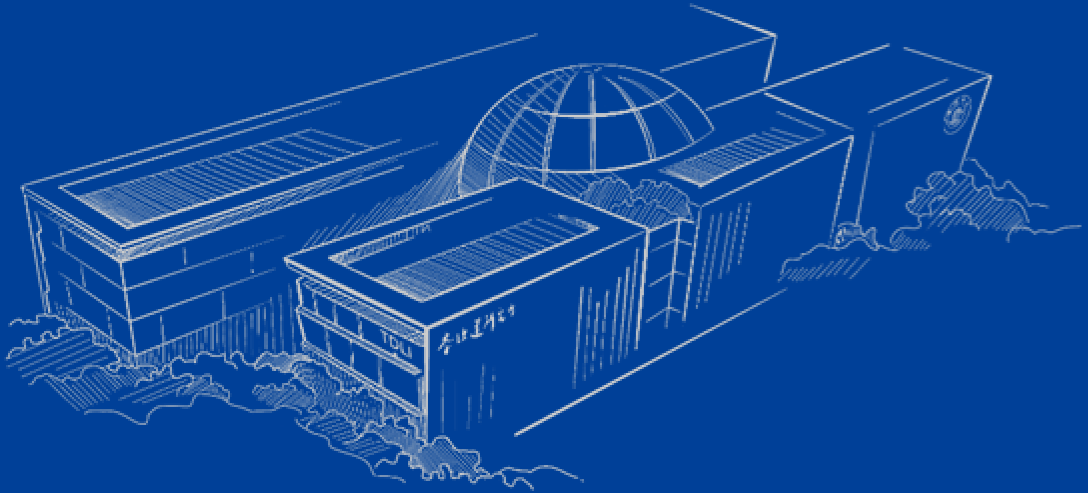


Summary

- 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"



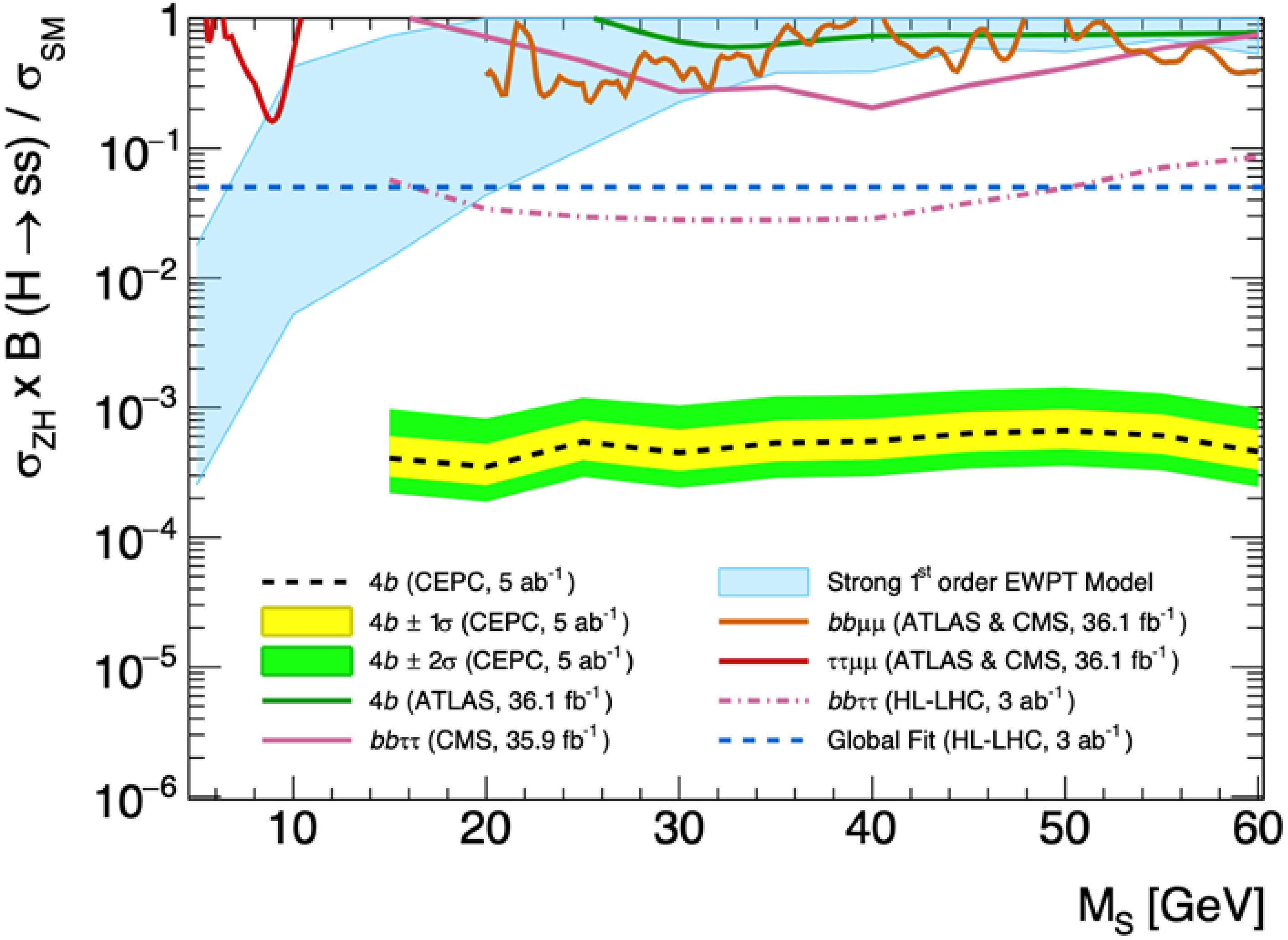
Thank You



Thanks!

Limit Setting

- Current limit of BDT approach. $(5\ \mathrm{ab}^{-1})$



arXiv:2203.10184

Backup

- Jet energy resolution

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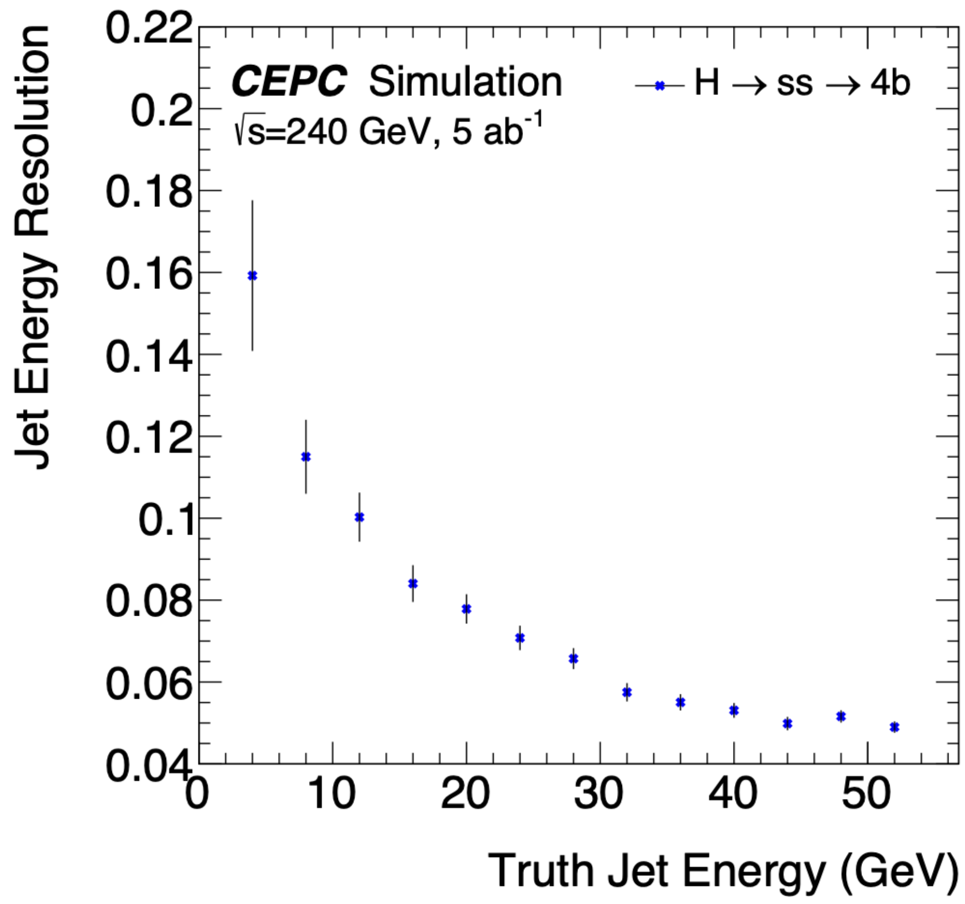
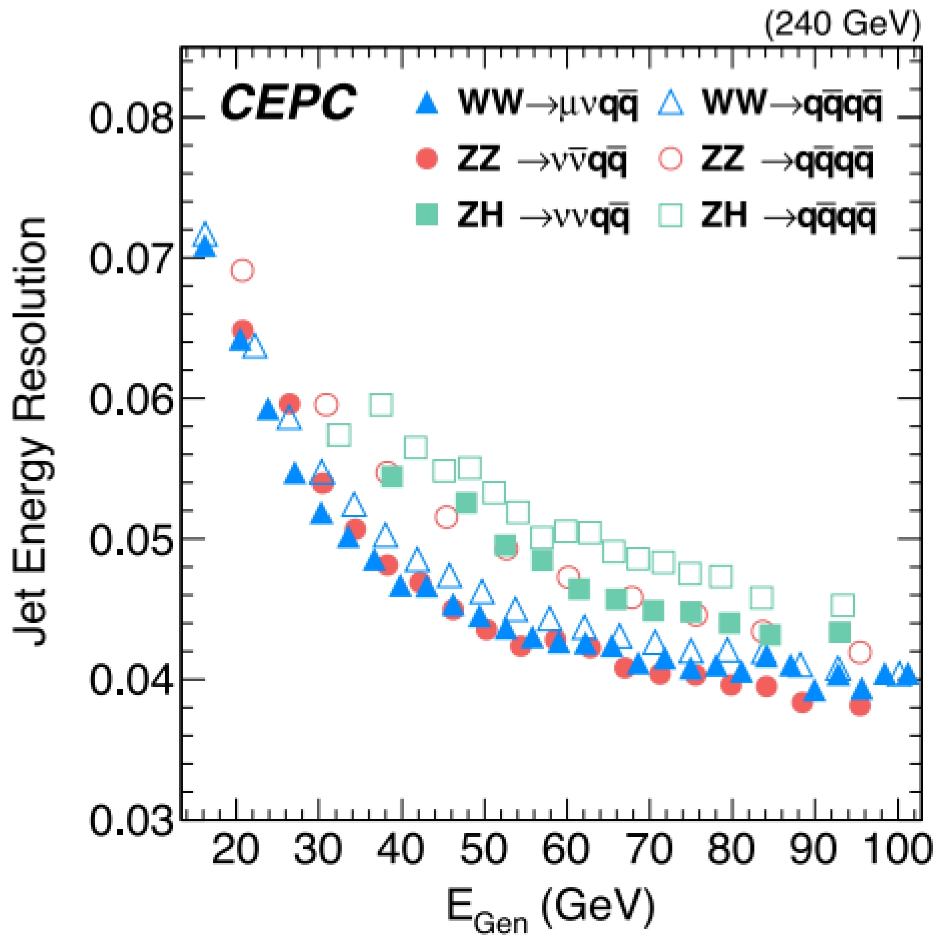




Backup

- Backup

$m_1[GeV]$	a_2	b_3	b_4	D_width	BR
5	0.00379269019	0.00087284094	3.16227766017e-05	7.3774e-05	0.01780479
	0.00033598183	0.00693322201	8.91250938133e-07	1.0348e-06	0.00025421
10	0.02511886432	0.01954047457	0.00125892541179	0.0030277	0.42627589
	0.00199526231	0.04908345294	1.58489319246e-05	2.1351e-05	0.00521904
15	0.05011872336	0.00389883725	0.00446683592151	0.011795	0.73632455
	0.00375837404	0.19540474574	7.94328234724e-05	5.9206e-05	0.01422012
20	0.00630957344	0.49083452948	0.00025118864315	0.0001866	0.04347394
25	0.01	0.97934363956	0.00063095734448	0.00044524	0.09859974
30	0.01678804018	1.55215506742	0.00125892541179	0.0011898	0.22613126
35	0.02511886432	2.46	0.00251188643151	0.0025006	0.38033656
40	0.02660725059	3.89883725345	0.00398107170553	0.0025799	0.38771480
45	0.04216965034	4.90834529482	0.00630957344480	0.0058611	0.58957125
50	0.04216965034	7.77920304401	0.01	0.0050107	0.55126677
55	0.06309573445	9.79343639562	0.01584893192461	0.0089054	0.68549957
60	0.05956621435	15.5215506742	0.02511886431509	0.0045989	0.53001523

Table. Parameters and related BRs that satisfy a strong 1-st order electroweak phase transition. The orange shading represent parameter when BR is at its upper bound, and blue shading represent the lower bound.

Mass	BDT Limits	Theory
20GeV	0.0005	0.0006
30GeV	0.0006	0.0005

Limits from BDT and Theory

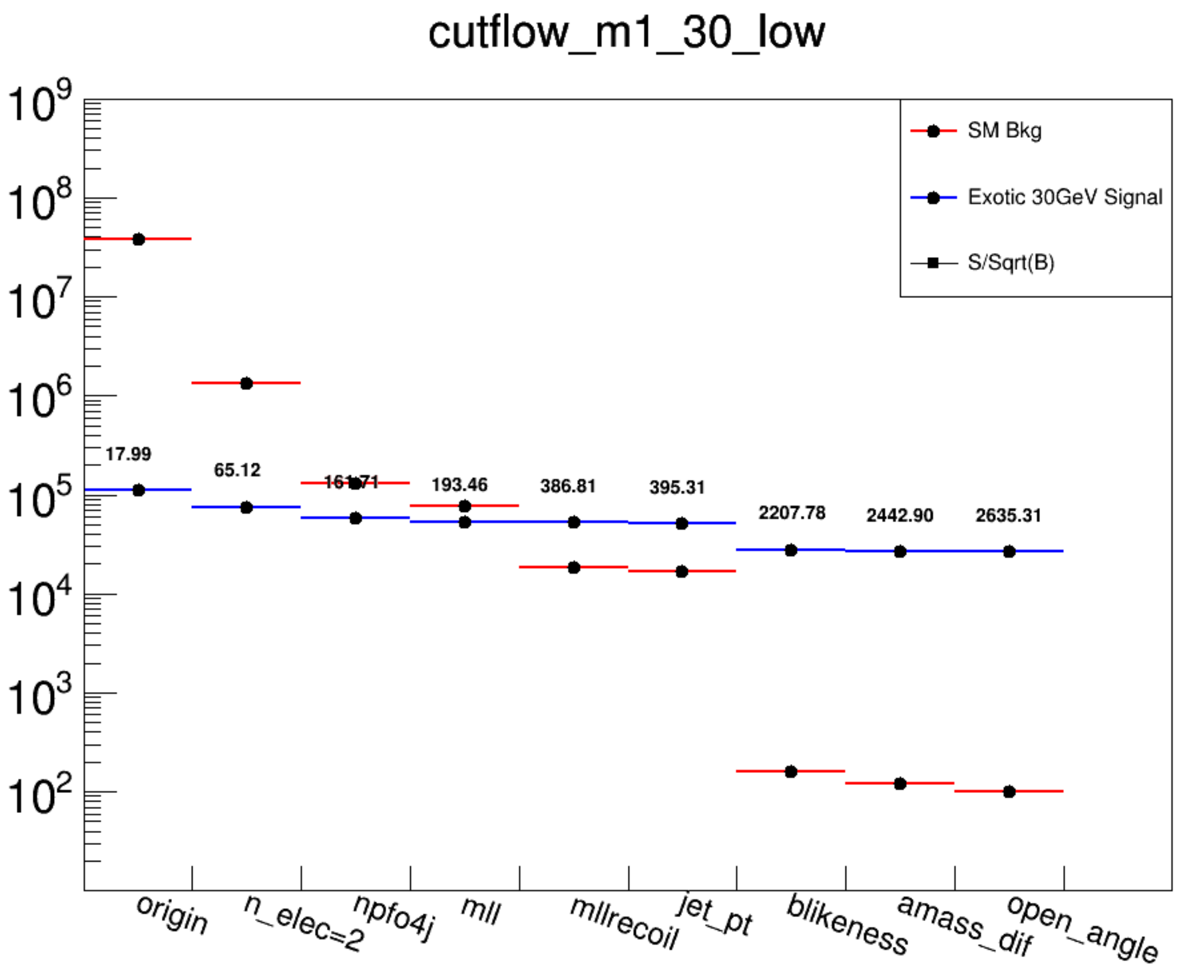
Backup

- Backup

10 BDTs are trained with 10 different signal samples from 15GeV to 60 GeV

Number of events in one training:

```
: Number of training and testing events
: ---------------------------------------------------
: Signal     -- training events              : 30000
: Signal     -- testing events               : 7806
: Signal     -- training and testing events: 37806
: Dataset[dataset] : Signal     -- due to the preselec
: Background -- training events              : 400000
: Background -- testing events               : 166345
: Background -- training and testing events: 566345
```


cutflow_m1_30_low
SM Bkg
Exotic 30GeV Signal
S/Sqrt(B)
17.99
65.12
161.71
193.46
386.81
395.31
2207.78
2442.90
2635.31
origin
n_elec=2
npfo4j
mll
mllrecoil
jet_pt
blikeness
amass_dif
open_angle
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9