Prospects of search for CP-violating effects of neutral triple gauge couplings at the LHC

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Introduction to EFT and nTGCs

- The Standard Model (SM) is expected to be extended to a more general theory.

- Indirect search for new physics is prospective and may help to constrain SM extensions.

- Effective field theory (EFT) parameterizes the Lagrangian using operators of higher dimensions:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \dots, \qquad \mathcal{L}^{(d)} = \sum_i \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}.$$

  - $C_i^{(d)}/\Lambda^{d-4}$ are the Wilson coefficients, which are to be constrained experimentally.
  - Λ is the new physics energy scale.

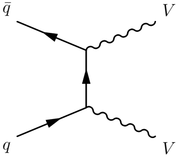
- EFT is often used by the ATLAS and CMS collaborations, e.g. in 1503.05467, 1810.04995, 2208.12741, etc.

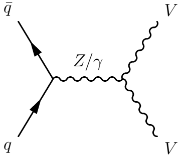
- More stringent limits allows constraining the SM extensions more strictly.

Neutral triple gauge couplings (nTGCs)

- This work uses EFT to parameterize neutral triple gauge couplings (nTGCs), which arise starting at dimension-8 operators. Basis: 1308.6323, 2308.16887.

- NTGCs are triple interactions between Z and γ. Experimentally, they are searched for using production of two neutral bosons.





- Signal process squared matrix element:

$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{\text{SM}}|^2}_{\text{SM}} + \underbrace{(C/\Lambda^4)2\text{Re}\,\mathcal{M}^\dagger_{\text{SM}}\mathcal{M}_{\text{BSM}}}_{\text{SM-BSM interference term}} + \underbrace{(C/\Lambda^4)^2|\mathcal{M}_{\text{BSM}}|^2}_{\text{quadratic term}}.$$

- Quadratic term is dropped in this study, since CP violation can exist only in the interference term.

CP violation in nTGCs

- There are five CP-violating operators classified:

$$\mathcal{O}_{BB} = i\Phi^\dagger B_{\mu\nu} B^{\mu\rho} \left\{D_\rho, D^\nu\right\} \Phi + \text{h.c.},$$
$$\mathcal{O}_{BW} = i\Phi^\dagger B_{\mu\nu} \hat{W}^{\mu\rho} \left\{D_\rho, D^\nu\right\} \Phi + \text{h.c.},$$
$$\mathcal{O}_{WW} = i\Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\rho} \left\{D_\rho, D^\nu\right\} \Phi + \text{h.c.},$$
$$\mathcal{O}_{\tilde{G}+} = g^{-1} B_{\mu\nu} W^{a\mu\rho} \left(D_\rho D_\lambda W^{a\nu\lambda} + D^\nu D^\lambda W^a_{\lambda\rho}\right),$$
$$\mathcal{O}_{\tilde{G}+} = g^{-1} B_{\mu\nu} W^{a\mu\rho} \left(D_\rho D_\lambda W^{a\nu\lambda} - D^\nu D^\lambda W^a_{\lambda\rho}\right).$$

- Usually LHC analyses do not probe CP violation in nTGCs, basing their analyses on the CP-conserving contributions: 1503.05467, 1709.07703, 1810.04995, 1905.07163, etc.

- However, CP violation can be probed using some diboson final states.

- The aim of this work is to find CP-sensitive variables and to study their experimental sensitivity to CP-violating nTGCs.

- $Z(\ell\ell)\gamma$ production at the LHC experiments is used as an example.

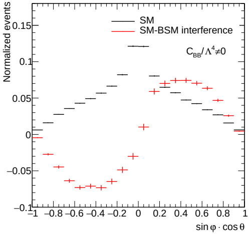
Angular CP-sensitive variable

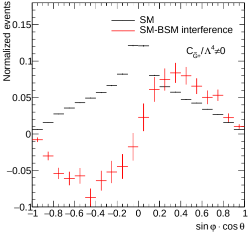
- The simplest variable can be constructed out of angles of the decay products: $\sin\varphi\cos\theta$. It has been used in $ZZ(4\ell)$ ATLAS analysis ATLAS-CONF-2023-038.

- The angles are measured for the lepton of negative charge in a special system:
  - Simulation of Z decay in rest: boost to the system of $\ell\ell$ rest.
  - Special axes are defined for each event separately:
    - z axis: direction of $\ell\ell$ in $\ell\ell\gamma$ rest system,
    - x axis: lies in the reaction plane so that initial z axis is located between new z and x axes,
    - y axis: cross product of z and x ones.

- Advantages: good CP sensitivity in nTGC sector, analyticity. • Disadvantages: necessity of additional optimization in energetic variable, different sensitivity to different Wilson coefficients.

- The largest sensitivity is at $|\sin\varphi\cos\theta| \gtrsim 0.2$.





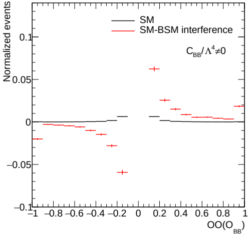
CP-sensitive optimal observable

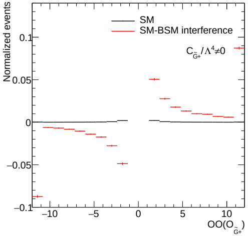
- Usual definition: $OO = \dfrac{2\mathrm{Re}\,\mathcal{M}^{\dagger}_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM}}}{|\mathcal{M}_{\mathrm{SM}}|^2}$ 1602.04516.

- Components of the squared matrix elements for the LHC are defined using PDFs:
  - $2\mathrm{Re}\,\mathcal{M}^{\dagger}_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM}} = \sum_{i,j} f_i(x_1)f_j(x_2)2\mathrm{Re}\,\mathcal{M}^{ij\,\dagger}_{\mathrm{SM}}\mathcal{M}^{ij}_{\mathrm{BSM}}$
  - $|\mathcal{M}_{\mathrm{SM}}|^2 = \sum_{i,j} f_i(x_1)f_j(x_2)|\mathcal{M}^{ij}_{\mathrm{SM}}|^2$
  - i, j — partons from the proton coming from positive, negative z axis direction.
  - $x_1 = \dfrac{m_{\ell\ell\gamma}}{\sqrt{s}}e^{y_{\ell\ell\gamma}}$, $x_2 = \dfrac{m_{\ell\ell\gamma}}{\sqrt{s}}e^{-y_{\ell\ell\gamma}}$.

- Advantage: perfect sensitivity.
- Disadvantage: different observables for different coefficients.

- The largest sensitivity is at the last bins.

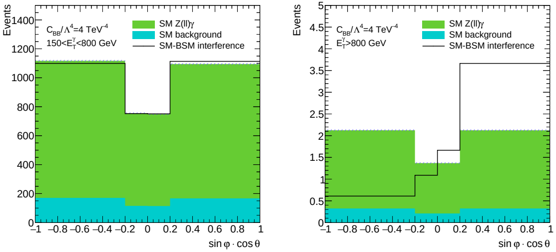




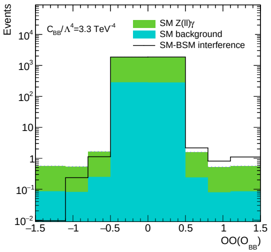
Model for the sensitivity study

- Object and event selection is taken from the ATLAS Run II study 1911.04813.
- Fraction of the background events is taken from the same work.
- MC modelling: `MadGraph5_aMC@NLO` + `Pythia8` + `Delphes3`.
- Binning in CP-sensitive variables is optimized so that to reach the best sensitivity but to stay in the experimental sensitivity regime.

Angular variable



Optimal observable

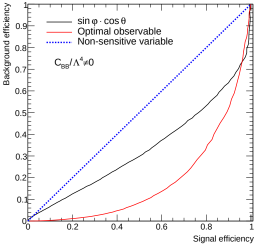


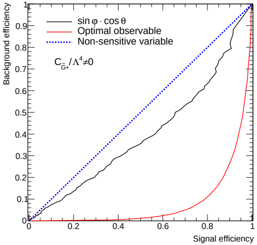
- Two categories splitted by E_T^γ are used to increase the sensitivity.
- Threshold of 800 GeV is set after the optimization.

Sensitivity study

- Profile likelihood fit has been used to set the limits on Wilson coefficients.
- Systematic of 10% has been applied.
- $L_{\text{int}} = 140 \text{ fb}^{-1}$

Coef.	Angular	Optimal
C_{BB}/Λ^4	[-4.0; 4.0]	[-3.4; 3.3]
C_{BW}/Λ^4	[-9.6; 8.4]	[-7.3; 6.4]
C_{WW}/Λ^4	[-24; 24]	[-17; 17]
$C_{\tilde{G}+}/\Lambda^4$	[-3.8; 3.0]	[-0.081; 0.081]
$C_{\tilde{G}-}/\Lambda^4$	[-29; 31]	[-8.8; 8.9]





Conclusion

- Two CP-sensitive variables has been considered in the nTGC sector.
- Sensitivity of the variables to the CP-violating nTGCs has been probed in $Z(\ell\ell)\gamma$ channel.
- Optimal observables show better performance than typical angular variable (the limits are 16%-98% better).
- Despite the fact that limits based on CP-conserving effects are more stringent, such study can provide additional independent probe of the anomalous couplings and CP violation.
- Optimal observable performance is to be compared to the ML approaches.
- First checks show that the final state $ZZ \to \ell\ell\nu\nu$ is also CP-sensitive despite the fact that the final state cannot be fully identified.

BACK-UP

MC modelling summary

Numbers of generated events:

1. SM term: 1.2M, splitted by E_T^γ:
- 400k for $140 < E_\mathrm{T}^\gamma < 300$ GeV,
- 400k for $300 < E_\mathrm{T}^\gamma < 600$ GeV,
- 400k for $E_\mathrm{T}^\gamma > 600$ GeV.

2. Interference terms: 300k per coefficient, splitted by E_T^γ:
- 100k for $140 < E_\mathrm{T}^\gamma < 300$ GeV,
- 100k for $300 < E_\mathrm{T}^\gamma < 600$ GeV,
- 100k for $E_\mathrm{T}^\gamma > 600$ GeV.

Sensitivity for projected Run III luminosity

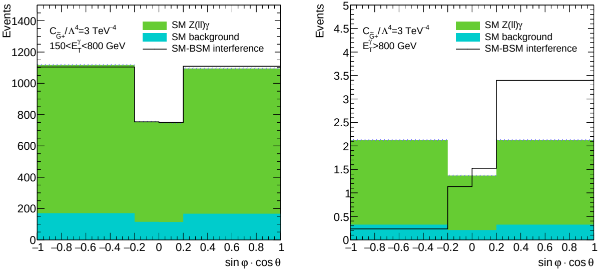
$L_{\text{int}} = 300\ \text{fb}^{-1}$

Coef.	Angular	Optimal
C_{BB}/Λ^4	[-2.6; 2.2]	[-2.7,2.7]
C_{BW}/Λ^4	[-7.0; 6.3]	[-5.7; 5.3]
C_{WW}/Λ^4	[-18; 18]	[-14; 14]
$C_{\tilde{G}+}/\Lambda^4$	[-3.8; 3.0]	[-0.071; 0.071]
$C_{\tilde{G}-}/\Lambda^4$	[-21; 22]	[-7.3; 7.3]

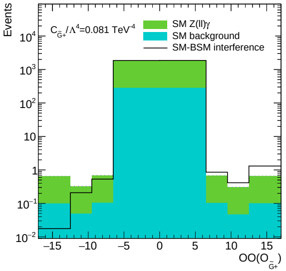
Model for $C_{\tilde{G}+}/\Lambda^4$

- Object and event selection is taken from the ATLAS Run II study 1911.04813.
- Fraction of the background events is taken from the same work.
- Binning in CP-sensitive variables is optimized so that to reach the best sensitivity but to stay in the experimental sensitivity regime.

Angular variable



Optimal observable



- ▶ Two categories splitted by E_T^γ are used to increase the sensitivity.
- ▶ Threshold of 800 GeV is set after the optimization.