Composite effective field theory signal in case of searching for neutral triple gauge couplings with $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ production

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Motivation

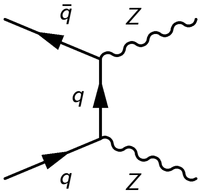
Anomalous couplings are manifestations of new physics.

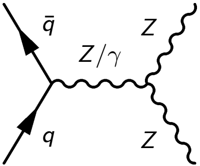
Effective field theory (EFT) model-independent parameterization of the Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \mathcal{L}_8 + \ldots = \mathcal{L}_{\mathrm{SM}} + \sum_i \sum_{d>4} \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}.$$

$C_i^{(d)}/\Lambda^{d-4}$ — Wilson coefficients that can be constrained experimentally and then converted into the limits on model-dependent parameters.

ZZ production is the process sensitive to neutral triple gauge couplings (nTGCs).





Considered decay: $ZZ \to \ell^+\ell^-\nu\bar{\nu}$.
Charged-lepton decay allows registering Z with high precision.
Neutrino decay provides higher statistics compared to charged-lepton decay and smaller QCD background compared to hadronic decay.

EFT framework

Basis of operators for studying nTGC:

$$\mathcal{O}_{\tilde{B}W} = i\Phi^\dagger \tilde{B}_{\mu\nu} \hat{W}^{\mu\rho} \{D_\rho, D^\nu\} \Phi$$
$$\mathcal{O}_{BW} = i\Phi^\dagger B_{\mu\nu} \hat{W}^{\mu\rho} \{D_\rho, D^\nu\} \Phi$$
$$\mathcal{O}_{WW} = i\Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\rho} \{D_\rho, D^\nu\} \Phi$$
$$\mathcal{O}_{BB} = i\Phi^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D^\nu\} \Phi$$

arXiv: 1308.6323

$$\mathcal{O}_{G\pm} = \frac{2}{g}\tilde{B}_{\mu\nu} \mathrm{Tr}\left[\hat{W}^{\mu\rho}\left(D_\rho D_\lambda \hat{W}^{\nu\lambda} \pm D^\nu D^\lambda \hat{W}_{\lambda\rho}\right)\right]$$

arXiv: 2206.11676

Operators $\mathcal{O}_{G+}$ and $\mathcal{O}_{G-}$ are new and have not been studied by ATLAS or CMS. Operators $\mathcal{O}_{BW}$, $\mathcal{O}_{BB}$ and $\mathcal{O}_{WW}$ are CP-breaking.

Squared amplitude in case of 1D parameterization includes SM term, interference (linear) term and quadratic (pure BSM) term:

$$|\mathcal{A}|^2 = \left|\mathcal{A}_{\text{SM}} + \frac{C}{\Lambda^4}\mathcal{A}_{\text{BSM}}\right|^2 = |\mathcal{A}_{\text{SM}}|^2 + \frac{C}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{A}_{\text{SM}}^\dagger \mathcal{A}_{\text{BSM}}\right) + \frac{C^2}{\Lambda^8}|\mathcal{A}_{\text{BSM}}|^2.$$

$O(\Lambda^{-8})$ expansion is considered since there are effects of SM-BSM interference suppression due to the polarizations for CP-even operators. For CP-odd operators SM-BSM interference is zero without accounting special CP-sensitive variables.

Composite anomalous signal, main backgrounds

Main idea: The conventional method for setting the limits is based on considering the BSM contributions only in the main (signal) process. However, in the general case, one or several background processes can also have a BSM part and contribute to the BSM yields. Changes in the BSM yields lead to corrections in the derived limits. In case of current experimental sensitivity corrections lead to tightening of the limits. arXiv: 2209.07906

Operator	ZZZ, $ZZ\gamma$, $Z\gamma\gamma$	WWZ	$WW\gamma$
$\mathcal{O}_{\tilde{B}W}$	○	○	○
$\mathcal{O}_{BW}$	○	○	○
$\mathcal{O}_{WW}$	○	○	
$\mathcal{O}_{BB}$	○		
$\mathcal{O}_{G\pm}$	○	○	○

Main backgrounds for $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ production:

- $WZ \to \ell\nu\ell^+\ell^-$
- $Z(e^+e^-)$+jets, $Z(\mu^+\mu^-)$+jets
- Wt, $t\bar{t}$, $Z(\tau^+\tau^-)$, $W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ (non-resonant)
- $ZZ \to \ell^+\ell^-\ell^+\ell^-$

EFT impact on backgrounds is studied in this work.

Modelling and selection

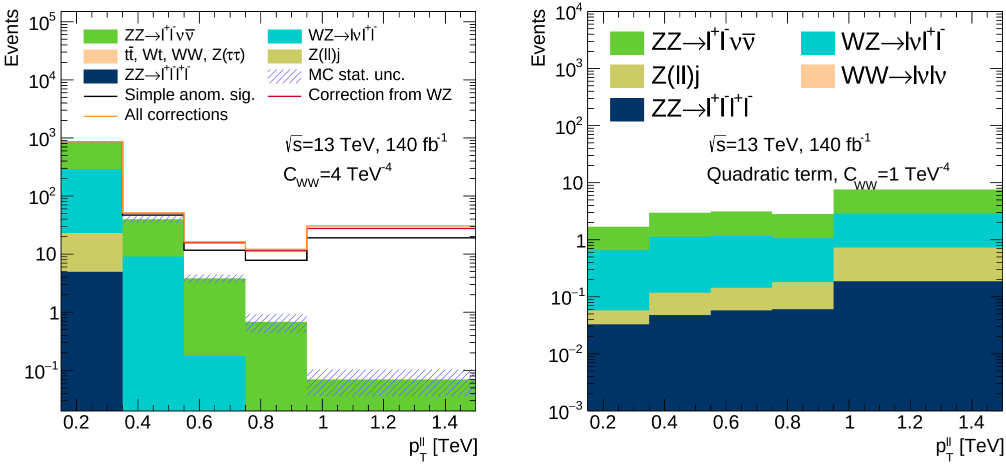
`MadGraph5` (arXiv: 1405.0301) was used for event generation, `Pythia8` (arXiv: 1410.3012) was used for hadronization and parton showering, `Delphes` (arXiv: 1307.6346) with the ATLAS detector geometry was used for detector simulation.

Event selection is based on the ATLAS study of *ZZ* production arXiv: 1905.07163

$N_\ell = 2$ (same flavour, opposite charge)
$p_\mathrm{T}^\ell > 30(20)$ GeV for leading (subleading) lepton
$76 < m_{\ell\ell} < 106$ GeV
$N_j \geq 0,\ N_{b\text{-jet}} = 0$
$E_\mathrm{T}^\mathrm{miss} > 110$ GeV, $\lvert \sum_{\ell,j} \vec{p}_\mathrm{T} \rvert / \sum_{\ell,j} p_\mathrm{T} > 0.65$
$\Delta R_{\ell\ell} < 1.9,\ \Delta\varphi(\vec{p}_\mathrm{T}^{\,\ell\ell}, \vec{p}_\mathrm{T}^{\,\mathrm{miss}}) > 2.2$

ATLAS Run II conditions are used in this work including integrated luminosity of 140 fb^{-1}.

Modelling results



1D results

In the limit-setting procedure frequentist statistical method was used. Test statistic based on the likelihood ratio and its asymptotic distribution (Wilks' theorem) was used.

Main correction: EFT impact only on main background, *WZ*, in accounted.

Coefficient	No corrections	Main correction	Improvement	All corrections	Improvement
C_{G+}/Λ^4	[-0.124; 0.123]	[-0.041; 0.041]	67.1%	[-0.037; 0.037]	70.2%
C_{G-}/Λ^4	[-0.412; 0.415]	[-0.399; 0.403]	3.1%	[-0.345; 0.347]	16.4%
$C_{\tilde{B}W}/\Lambda^4$	[-0.663; 0.671]	[-0.626; 0.639]	5.2%	[-0.604; 0.616]	8.5%
C_{BW}/Λ^4	[-1.53; 1.51]	[-1.42; 1.42]	6.4%	[-1.37; 1.37]	10.2%
C_{BB}/Λ^4	[-0.815; 0.819]	[-0.815; 0.819]	0	[-0.775; 0.779]	4.9%
C_{WW}/Λ^4	[-1.27; 1.25]	[-1.05; 1.04]	17.4%	[-1.00; 0.99]	21.1%

These corrections provide significant improvement. The most significant correction comes from *WZ* bakground, however for some coefficients correction from $Z(\ell^+\ell^-)$+jets background is alo significant.

Comparison of the limits from $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ and $Z\gamma \to \nu\bar{\nu}\gamma$ production

In case of $Z(\nu\bar{\nu})\gamma$ production the main correction comes from $W(\ell\nu)\gamma$ background.

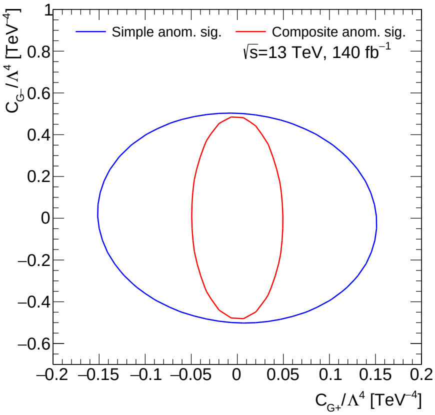
Limits after the main corrections are presented.

Coefficient	Limits from ZZ	Limits from $Z\gamma$
C_{G+}/Λ^4	[-0.041; 0.041]	[-0.00443; 0.00445]
C_{G-}/Λ^4	[-0.399; 0.403]	[-0.272; 0.286]
$C_{\tilde{B}W}/\Lambda^4$	[-0.626; 0.639]	[-0.244; 0.233]
C_{BW}/Λ^4	[-1.42; 1.42]	[-0.447; 0.450]
C_{BB}/Λ^4	[-0.815; 0.819]	[-0.223; 0.222]
C_{WW}/Λ^4	[-1.05; 1.04]	[-1.11; 1.12]

In general, limits from $Z\gamma$ production are more stringent. However the correction allow one to set more stringent limits on C_{WW}/Λ^4 from ZZ production then from $Z\gamma$ production.

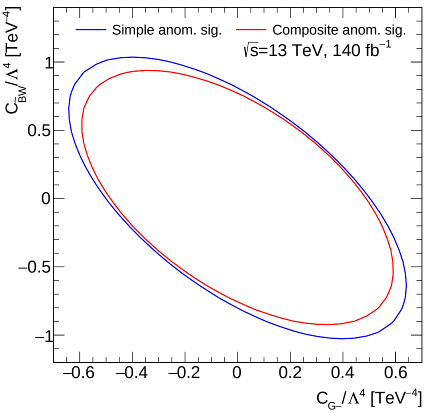
2D results [1]

C_{G+}/Λ^4 vs C_{G-}/Λ^4



Improvement: 68.5%

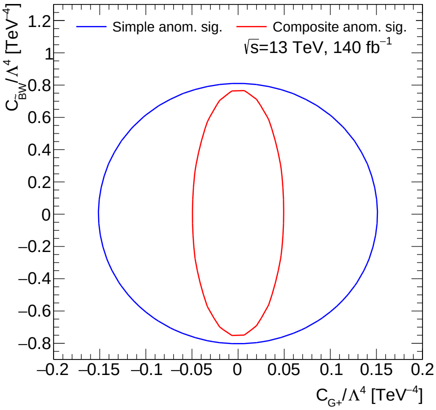
C_{G-}/Λ^4 vs $C_{\tilde{B}W}/\Lambda^4$



Improvement: 12.6%

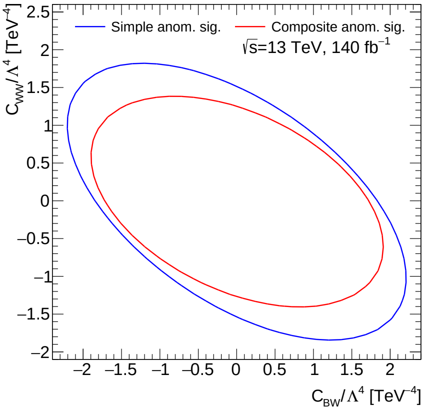
2D results [2]

C_{G+}/Λ^4 vs $C_{\tilde{B}W}/\Lambda^4$



Improvement: 69.2%

C_{BW}/Λ^4 vs C_{WW}/Λ^4



Improvement: 28.8%

Conclusion and plans

- Composite anomalous signal method leads to significant improvement of the limits on the Wilson coefficients in case of $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ production.
- The main correction comes from WZ background, however for some coefficients corrections from $Z(\ell^+\ell^-)$+jets are also significant.
- This method allow setting more stringent limits on C_{WW}/Λ^4 then from $Z(\nu\bar{\nu})\gamma$ production.

- Since nTGC operators affect charged triple gauge couplings, it is possible to improve limits by accounting EFT contributions in WZ control region.
- It is planned to consider combination of the limits from ZZ and $Z\gamma$ production with and without corrections.