UFO models for neutral triple gauge couplings

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09.10.2023

Introduction to neutral triple gauge couplings

EFT parameterization of the Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \mathcal{L}^{(8)} + \ldots, \qquad \mathcal{L}^{(d)} = \sum_i \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Neutral triple gauge couplings (nTGCs) are zero in the SM at the tree level. They are described in the EFT with operators of eight or more dimensions.

Mixed Higgs-gauge operators are classified in 1308.6323:

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

New pure gauge operators was proposed in 2008.04298:

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

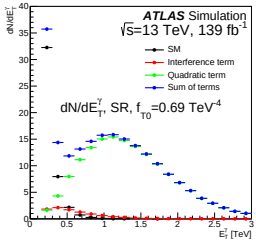
All the operators break C parity. $\mathcal{O}_{BW}$, $\mathcal{O}_{BB}$ and $\mathcal{O}_{WW}$ break CP parity.

Decomposition

One-dimensional parameterization:
$|\mathcal{A}|^2 = |\mathcal{A}_{SM} + (C/\Lambda^4)\mathcal{A}_{BSM}|^2 = |\mathcal{A}_{SM}|^2 +$
$+(C/\Lambda^4)\, 2\mathrm{Re}(\mathcal{A}^\dagger_{SM}\mathcal{A}_{BSM}) + (C^2/\Lambda^8)|\mathcal{A}_{BSM}|^2$

Two-dimensional parameterization:
$|\mathcal{A}|^2 = |\mathcal{A}_{SM} + (C_1/\Lambda^4)\mathcal{A}_{BSM,1} + (C_2/\Lambda^4)\mathcal{A}_{BSM,2}|^2 = |\mathcal{A}_{SM}|^2 +$
$+(C_1/\Lambda^4)\, 2\mathrm{Re}(\mathcal{A}^\dagger_{SM}\mathcal{A}_{BSM,1}) + (C_2/\Lambda^4)\, 2\mathrm{Re}(\mathcal{A}^\dagger_{SM}\mathcal{A}_{BSM,2}) +$
$+(C_1^2/\Lambda^8)|\mathcal{A}_{BSM,1}|^2 + (C_2^2/\Lambda^8)|\mathcal{A}_{BSM,2}|^2 +$
$+(C_1 C_2/\Lambda^8)\, 2\mathrm{Re}(\mathcal{A}^\dagger_{BSM,1}\mathcal{A}_{BSM,2})$

Plot from 2208.12741.



Two-dimensional parameterization contains cross term, that can significantly change the limits.

EFT@$O(\Lambda^{-8})$ is used here since:
- interference (linear) term of some CP-conserving operators is strongly suppressed by final-state helicities,
- interference (linear) term of CP-violating operators is zero (at least if one does not take into account CP-sensitive variables).

Sometimes it is impossible or difficult to reduce interference suppression or to use CP-sensitive variables, e.g. in $Z(\nu\bar{\nu})\gamma$ channel.

Separate modelling of the terms

It is convenient to use `MadGraph5_aMC@NLO` to generate different terms of $|\mathcal{A}|^2$ separately. Universal FeynRules output (UFO) model is needed.

Let `NP` be a single new physics `MadGraph5_aMC@NLO` coupling (one for all operators).

`NP^2==1` with one non-zero coefficient generates corresponding interference term.
`NP==1` with one non-zero coefficient generates corresponding quadratic term.
`NP==1` with two non-zero coefficients generates sum of corresponding quadratic terms and cross term
$\rightarrow$ direct modelling of cross term is impossible in case of a single new physics `MadGraph5_aMC@NLO` coupling.

In case of separate new physics `MadGraph5_aMC@NLO` couplings (e.g. `GP` and `GM`) it is possible to generate cross term directly via `GP^2==1 GM^2==1`.

Such separate couplings are used e.g. in UFO model for anomalous quartic gauge couplings (aQGCs, paper: 2004.05174, model: link to the model database).

Outline of previous UFO models for nTGCs in EFT formalism

Previously we had two UFO models:
1. Model created by the author of the paper 1308.6323, link to the model database. Operators covered: $\mathcal{O}_{\tilde{B}W}$, $\mathcal{O}_{BW}$, $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$. Separate couplings: no.
2. Model created by our ATLAS colleague. Operators covered: $\mathcal{O}_{\tilde{B}W}$, $\mathcal{O}_{G+}$, $\mathcal{O}_{G-}$. Separate couplings: yes.

Problems:
1. Having two models for one study is inconvenient.
2. There is no possibility to generate cross terms for CP-violating operators.
3. Models have different parameters. Model 1: diagonal CKM, no masses of fermions excepting the third generation. Model 2: Cabibbo-only CKM, all fermions masses.

Outline of the new model

New model was created using FeynRules to be used in $Z(\nu\bar{\nu})\gamma$ ATLAS analysis.
Operators covered: all six.
Separate couplings: yes, couplings names: `GP`, `GM`, `BTW`, `BW`, `BB`, `WW`.
Parameters: Cabbibo-only CKM, no masses of fermions excepting the third generation.

Validation strategy: for each operator cross sections for processes $pp \to \gamma\gamma$, $pp \to ZZ$, $pp \to W^+W^-$, $pp \to \nu\bar{\nu}\gamma$ was validated basing on previous models, all the results are the same.

In previous models definitions of all operators excepting $\mathcal{O}_{G-}$ differ from the definitions in the baseline papers by a factor of -1. It was corrected and results in changing the sign of the interference terms.

All the changed was agreed with the authors of the baseline papers.

New model was uploaded to the ATLAS model database and was successfully used for the sample request for $Z(\nu\bar{\nu})\gamma$ analysis.

UFO models for nTGCs in VF formalism

It is possible to use the decomposition in `MadGraph5_aMC@NLO` working with nTGCs in the vertex function formalism (basing on the parameterization of the Lagrangian).

Currently existing model contains 8 coefficients for $Z\gamma V^*$ vertex (h_i^V, $i = 1..4$, $V = Z, \gamma$) and 4 coefficients for ZZV^* vertex (f_i^V, $i = 4, 5$, $V = Z, \gamma$) presented in 1308.6323. Couplings are not separate.

In $Z(\nu\bar{\nu})\gamma$ analysis we also plan to probe these coefficients. New model with separate couplings and new published in 2206.11676 and 2308.16887 coefficients h_5^V, h_6^V was created. It is planned to validate it and agree with the authors.

Conclusion

- New UFO model, developed for the ATLAS $Z(\nu\bar{\nu})\gamma$ analysis, is presented in this report.
- Main advantages: possibility to generate any cross term directly and all operators in a single model.
- Basis of six operators is not complete. In the recent paper 2308.16887 three new EFT operators and new vertex function parameters are introduced. We consider them for probing in the analysis and, therefore, for adding to the UFO models.