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CMS LHC Run 1 Multiboson Interactions Review

Senka Duric[*] **(on behalf of CMS collaboration) University of Wisconsin-Madison**

E-mail: senka.duric@cern.ch

We present the multiboson interaction measurements performed by the CMS collaboration using Run 1 data taking period at LHC. Anomalous triple and quartic gauge couplings are measured in diboson and triboson production channels at the center-of-mass energy of 7 and 8 TeV. Resulting limits on anomalous neutral triple and anomalous quartic gauge couplings are the best world limits, while limits on anomalous charged triple gauge couplings are competitive with results from LEP experiments.

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[*] Speaker.

1. Vector boson couplings and beyond

The existence of triple (TGC) and quartic (QGC) vector boson couplings are a fundamental prediction of the Standard Model (SM). These couplings are a direct consequence of non-Abelian nature of the SU(2)×U(1) gauge theory and are uniquely predicted. Only self-couplings involving charged vector bosons are allowed, while vertices with only neutral gauge bosons attached are forbidden in the SM. Diboson and triboson production processes are direct probes of TGC and QGC.

If the particle spectrum of the SM had to be enlarged with new particles beyond SM with mass values above 1 TeV, these particles would manifest themselves at the LHC center-of-mass energies generating anomalous couplings. Many extensions of the SM predict additional processes with multiple bosons in the final state. A measurement of vector boson couplings can thus be sensitive to new phenomena at high energies that would require higher energy or luminosity to be observed directly. Any deviation can be quantified in terms of anomalous couplings (aTGC, aQGC).

There are two general ways to look for deviations from the SM: either assuming a specific model of new physics (SUSY scenario, dark matter, ...) or searching for model independent deviations and measuring the size of the deviation from SM. Deviations may appear both in the form of a peak in some kinematic observable distribution, or as deviations in tails. The search for anomalous couplings belongs to the second category. Even though model independent, deviations still have to be parameterized to perform a measurement.

Different frameworks exist to extend the SM Lagrangian with new operators in a generic way to accommodate physics beyond the SM. The Effective Lagrangian approach (“phenomenological Lagrangian”) [1] is used for all charged aTGC measurements. except in the WW analysis, where Effective Field Theory (EFT) [2] is used. A translation between these two parameterizations [3] is used to provide results in both. EFT parameterization is also used for aQGC measurements. Neutral aTGC are measured in Effective vertex parameterization [4].

2. Anomalous couplings limit setting in CMS experiment

Anomalous couplings result in an increase of the cross section at high values of the vector bosons system. Therefore, the mass of the multiboson system and the transverse momenta of the bosons are particularly sensitive observables. Couplings are measured (or limits are set) by performing binned fits of a single sensitive observable. Different observables are found to give the best sensitivity to anomalous couplings in different multiboson channels.

Bins with highest invariant mass or transverse momentum are the most sensitive to anomalous couplings signal. In order to use all available events, the last bin always includes the overflow contribution. Sensitivity to anomalous couplings depends on the absolute size of anomalous couplings signal, the absolute size of background processes, and the corresponding uncertainties. The expected limit increases with the increase of background processes yield, and with the decrease of signal yield and increase of uncertainties.

A limiting factor for the sensitivity is low statistics in the tail of observable distribution, as having less than one expected signal event in a given bin does not give an extra sensitivity. Binning is optimized to reach the highest expected sensitivity. Systematic and statistical uncertainties on the expected signal and background yields have secondary effects on the sensitivity. In many analyses a fit of anomalous coupling parameters is performed simultanaously in both electron and muon boson decay channels.

The anomalous couplings signal model is built as a binned model. The Lagrangian is linear in anomalous couplings parameters, therefore, cross sections depend quadratically. Since the signal contribution depends on the value of the observable, the signal modelling needs to reflect this dependency.

For parameter measurements the signal model has to be continuous. Expected signal distributions for many different values of anomalous couplings are generated with Monte Carlo techniques, using dedicated software toolkits for the simulation of the passage of particles through the CMS detector. For some analyses reweighting techniques are used to reweight SM distributions to different points in anomalous coupling parameter space, for others a full generation and simulation of events is performed for different points. A continuous signal model is build by means of quadratic fits of the expected number of signal events in every observable bin as a function of parameters. Many analyses perform a measurement varying one or two parameters at a time. All other parameters are fixed to SM value. Therefore, a signal model is build with one or two dimensional quadratic fits.

Limits are set using the profile likelihood ratio as test statistic with the use of Wilks theorem or modified frequentist CLs methods [5]. Limits are set at 95% confidence level (CL).

3. Anomalous triple gauge couplings results

No significant deviation from the SM expectation is observed in any multiboson production channel with CMS detector. All anomalous couplings limits are mainly dictated by the statistical uncertainty.

Limits on anomalous triple gauge couplings are derived from many diboson production channels in CMS, this discussed in the following are only the most recent results. All results are summarized, and compared to results from other experiments, in Figure 1 [6, 7].

3.1 Measurement with pp→WW→lνlν

WW→lνlν analysis [8] is performed using the full 8 TeV center-of-mass energy dataset. Events are required to have exactly two leptons with transverse momentum $p_T(l)$>20 GeV, $p_T(ll)$> 30/45 GeV for different/same flavor leptons, with dilepton mass $M(ll)$>12 GeV, and significant missing transverse energy (MET>20 GeV). To reduce the background from Z boson production, the dilepton mass must be outside the Z mass window ($|M(ll)-M(Z)|$>15 GeV).

The most significant background contribution comes from W+jets and top processes. Their contributions is estimated from data using a fake rate method and estimation using inverted top veto region, respectively.

In the aTGC analysis a zero jet requirement is used, asking that no jet with p_T>30GeV and $|\eta|$<4.7 in present in the event. Allowing the presence of a jet significantly decreases the signal over background ratio due to a large top quark background. Since aTGC operators do not modify initial-state radiation emission, using events with a jet would only populate with background sources a phase space that is signal dominated otherwise. WZ and ZZ processes also contribute to the background. Since they contribute little to the total yield, it is assumed they have no effect from aTGC.

The Higgs-induced part of the process is considered as a part of the SM WW signal.

The aTGC signal is generated using LO Madgraph [9] generator with the reweighting option. Limits on aTGC parameters are set through a binned fit to M(ll) distribution.

3.2 Combination of measurements with pp→ZZ→4l and pp→ZZ→2l2ν

A combination of two leptonic decay channels of the ZZ boson pair, ZZ→4l [10, 11] and ZZ→2l2ν [12], is performed using full datasets at 7 and 8 TeV center-of-mass energy.

Since ZZ→4l has a very clean signature with small background contribution only basic selection criteria on 4 leptons are requested. But the ZZ→2l2ν signature also collects significant contributions from background processes: other diboson final states, Z+jets, W+jets and top. Contribution from the WZ process is estimated from simulation while others are estimated from data using distribution side-bands. To control the background level, a zero jet requirement is used. Other selection requirements are an opposite-sign same-flavor pair of leptons in a Z mass window with no additional leptons, $p_T(l)$>20 GeV, $p_T(ll)$>45 GeV, and large MET balanced with dilepton transverse momentum.

The aTGC signal is modelled with the Sherpa generator [13] and limits are derived from a binned fit to $M(4l)/p_T(ll)$ distribution in ZZ→4l/ZZ→2l2ν channels.

This result includes contribution from NLO QED corrections [14]. As a consequence, $p_T(ll)$ and $M(4l)$ expected distributions fall more rapidly and the overall cross section decreases by about 4%. This correction is only applied to SM ZZ, not to aTGC contributions. Therefore, expected limits are tighter then without applying corrections.

Limits with 8 TeV data are around a factor of 2 better than limits with 7 TeV data. Combining the two channels improves limits by 20%.

3.3 Measurement with pp→Zγ→2$\nu\gamma$

Analysis of the Zγ→2$\nu\gamma$ [15] production process is performed using the full dataset at 8 TeV center-of-mass energy. Unlike the Zγ→2lγ process, the Zγ→2$\nu\gamma$ process does not get contributions from photons radiated from the final state lepton. An additional advantage for anomalous coupling searches is the significantly higher branching ratio and the access to an higher $E_T(\gamma)$ tail. The selection requires MET>140 GeV, a photon with E_T>145 GeV and no additional lepton. The main background source is the Wγ→l$\nu\gamma$ process where a lepton is not reconstructed. Its contribution is estimated from data in a control region. Several additional processes contribute to the background and they are mostly derived from data with different methods.

The aTGC signal is modelled with Sherpa MC [13] and limits are derived from a binned fit to $E_T(\gamma)$ distribution. As expected, limits are significantly better then limits derived from Zγ→2lγ [16]. Improvements are larger for h_4^γ and h_4^Z than for h_3^γ and h_3^Z parameters. This can be explained with a faster increase of aTGC effect with energy for h_4^γ and h_4^Z parameters.

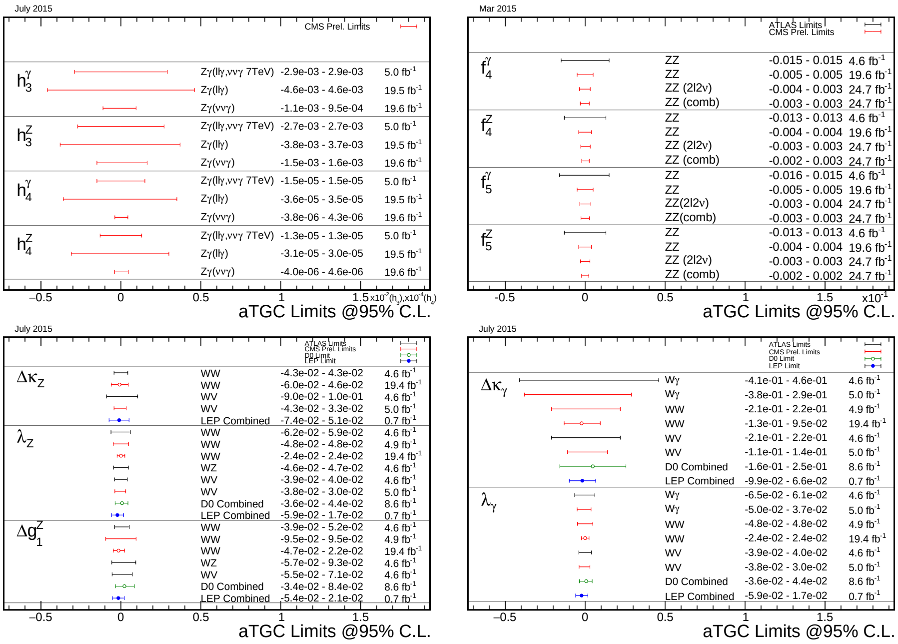

Figure 1: Summary of one parameter observed limits on aTGC parameters by CMS in comparison with results from other experiments [7].

4. Anomalous quartic gauge couplings results

Quartic gauge couplings can be probed in triboson production or vector boson scattering (VBS) diboson production. Measurements in CMS are performed in WVγ triboson [17] and W$^{\pm}$W$^{\pm}$ VBS production [18].

The WVγ triboson production is studied in semileptonic decay modes, WV$\gamma \rightarrow$lνjjγ. Event selection requires MET>35 GeV, an isolated lepton with $p_T(l)$>25/30 GeV for muon/electron, at least two jets and an isolated photon with $E_T(\gamma)$>30 GeV. Mass of two jets is required to be within the W and Z mass range 70<$M(jj)$<100 GeV. This channel suffers from very large background from $W\gamma$+2jets process. A correction factor on the MC estimated contribution is obtained from data using a fit on a dijet invariant mass distribution outside of signal region. The aTGC signal is modelled with the aMC@NLO MC generator [19] and limits are derived from a binned fit to $E_T(\gamma)$ distribution. Anomalous quartic couplings can be parameterized in two ways: the non-linear formalism resulting from assumption of spontaneous symmetry breaking without a Higgs boson, and the linear formalism resulting from symmetry breaking with a Higgs boson. A conversion between these approaches is used [20] to provide results in both parameterizations. The non-linear formalism was used at LEP and it is included here to be able to compare results.

W$^{\pm}$W$^{\pm}$ VBS (EWK) production includes a vertex with four W bosons attached. Only W bosons of the same sign are used to reduce the background. Event selection requires exactly two isolated leptons with $p_T(l)$>20 GeV, MET>40 GeV, and at least two jets with a op jet veto. Standard VBS topology requirements ($M(jj)$>500 GeV, $|\Delta\eta(j,j)|$>2.5) reduce the QCD production background. The aQGC signal is modelled with LO Madgraph generator [9] and limits are derived from binned fit to $M(ll)$ distribution. WZ EWK production is part of the background sources, however, effects of possible aQGC on the WZ process in the signal region are negligible. Therefore, aQGC is assumed to have an effect only on $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$ EWK production. Among $pp \to \mathrm{W}^{\pm}\mathrm{W}^{\pm}$ production diagrams, processes including TGC vertices are also present. As in other similar measurements here we assume no anomalous TGC. This assumption is justified since aTGCs are measured more precisely in QCD diboson production than they could be measured in VBS production.

Results are summarized, and compared to results from other experiments, in Figure 2 [6, 7].

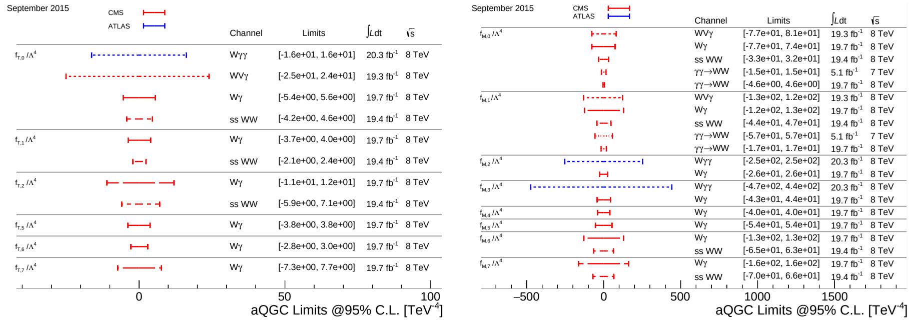

Figure 2: Summary of one parameter observed limits on aQGC parameters by CMS in comparison with results from ATLAS experiment [7].

5. Question of unitarity

Any non-zero value for anomalous couplings will lead to a tree-level unitarity violation at sufficiently high energy. At these high energies the effective theory (that we see at energies where we perform the measurement) has to be replaced by a new physics model conserving unitarity. To preserve unitarity an arbitrary form-factor is usually applied. Unitarity violation is not an observable, however, a measurement of limits can be "over-sensitive" if using models that break the unitarity for signal model building. In CMS limits are set without the use of a form-factor. Calculations of unitarity bounds in comparison with CMS results show that for neutral aTGC results are in unitarity non-violating regime for limits from $\mathrm{Z}\gamma \to 2\nu\gamma$ measurements. For charged aTGCs observed limits are two orders of magnitude smaller then the unitarity bound, so results are also in the unitarity non-violating regime. For aQGC limits are in the unitarity violating regime.

6. Conclusion

Diboson and triboson production channels are very good indirect probes of new physics through anomalous couplings measurement. Being a model independent kind of search, these measurements allow us to study various new physics scenarios. Depending on the vertex and channel effective Lagrangian, vertex function and EFT approaches are used to parameterize anomalous couplings dependence . Sensitivity to anomalous couplings is in high p_T or multiboson system mass tail, therefore, all results are statistically limited. Vector boson anomalous triple and quartic coupling limits are measured in many diboson and triboson channels with the CMS detector [6].

None of them shows any significant deviation in the high p_T or mass tail. Parameter limits are best, or close to, best world results. Since an anomalous coupling signal increases with energy a new CMS data at center-of-mass energy of 13 TeV should provide even better results with lower luminosity.

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