IL NUOVO CIMENTO **40 C** (2017) 202
DOI 10.1393/ncc/i2017-17202-7

COLLOQUIA: Physics in Collision 2017

Triple and quartic gauge boson couplings at the LHC

A. KUPCO

Institute of Physics of the Czech Academy of Sciences - Na Slovance 2, Prague, Czech Republic

received 6 April 2018

Summary. — This report presented at the conference Physics in Collision 2017 reviews recent results from the ATLAS and CMS experiments on production of gauge boson pairs, triples, and vector boson scattering (VBS) processes. Large datasets from LHC proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV allowed the first observations of rare processes: triboson production in channel $Z\gamma\gamma$ at $\sqrt{s} = 8$ TeV and VBS of the same sign WW at $\sqrt{s} = 13$ TeV. Both experiments observe a good agreement with the Standard model (SM) predictions. The data were used to set new limits on anomalous triple and quartic gauge couplings not present in the SM.

The electroweak (EWK) gauge boson couplings are defined uniquely by the underlying $SU(2) \times U(1)$ gauge symmetry in the Standard model (SM) of EWK interactions. An interplay between triple gauge couplings (TGC), quartic gauge couplings (QGC) and vector boson couplings to Higgs boson gives the theory a proper behavior at high energy. Multi-boson processes provide a direct experimental probe of this mechanism.

The delicate role played by gauge couplings makes these processes a natural place to look for new physics beyond the SM. In both ATLAS and CMS experiments, this search is made in a general framework, not coupled to a specific model, by looking at possible anomalous gauge couplings not present in the SM. Beside the traditional anomalous coupling approach used at LEP [1], the experiments adopted the effective field theory (EFT) framework to provide more coherent treatment of physics beyond the SM [2]. Although more challenging, both for experiment and theory, this approach allows to perform combined searches in Higgs and vector boson sectors.

Charged anomalous triple gauge couplings (aTGC) receive the first contribution from dimension six operators in the EFT approach and they are suppressed by square of the energy scale of the theory $1/\Lambda^2$. Neutral aTGC arise from dimension-eight operators and are suppressed by a factor of $1/\Lambda^4$. Searches of anomalous quartic gauge couplings (aQGC) always assume that there are no aTGC. The first operators leading to aQGC, but not to aTGC, are of dimension eight with the couplings suppressed by $1/\Lambda^4$ as well.

The presented results are based on proton-proton collision data from LHC collected by the ATLAS [3] and CMS [4] experiments during Run 1 (integrated luminosity per experiment of 5 fb^{-1} at center-of-mass energy of $\sqrt{s} = 7$ TeV, and 20 fb^{-1} at $\sqrt{s} = 8$ TeV),

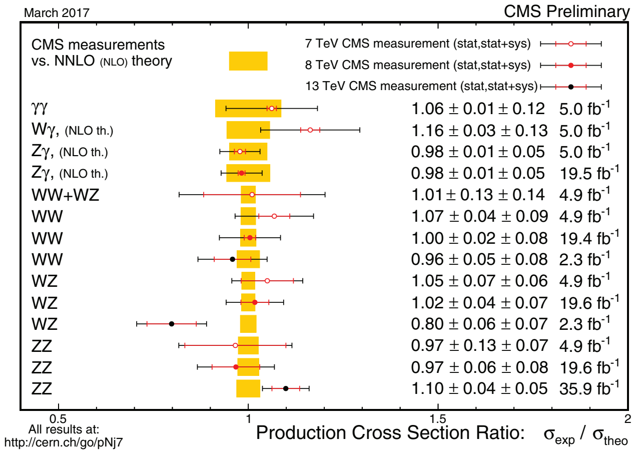

Fig. 1. – Compilation of the latest di-boson cross section measurements from CMS [8].

and part of Run 2 data collected at $\sqrt{s} = 13\,\mathrm{TeV}$ with luminosities up to $36\,\mathrm{fb}^{-1}$, corresponding to the data collected until the end of 2016. During LHC Run 2, the aim is to collect about $100\,\mathrm{fb}^{-1}$ per experiment at 13 TeV.

LHC high luminosity environment, at present with 33 interactions on average per bunch crossing, imposes challenges for triggering, data acquisition and event reconstruction. General strategy for multi-boson final states is to use leptonic decays of W and Z. The branching ratio is low; however, the isolated high-transverse-momentum (p_T) leptons from such decays provide an effective signal for trigger. In addition, leptonic channels do not suffer from large backgrounds induced by strong interactions. The multi-boson analyses are facing two types of background. Irreducible backgrounds, *i.e.* processes which lead to the same final-state signature as signal, are estimated from theory using Monte Carlo generators. Instrumental backgrounds arise due to detector imperfection. For the presented measurements, these are typically jets misidentified as electrons or photons and non-prompt leptons from heavy-quark decays. Instrumental backgrounds are estimated with data driven methods using control regions.

Vector boson pair production, sensitive to TGC, is discussed first, followed by Triple gauge boson production and vector boson scattering (VBS), processes relevant to QGC.

1. – Vector boson pair production

The most precise results on vector-boson pair production are obtained in leptonic channels. The main advantage is the low contamination with background. In case of $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ channel ($\ell, \ell' = e, \mu$), the background is below 5%, rising to 30% for $WW \to e\nu\mu\nu$. In this case, the different final-state lepton flavors were important for suppressing the background. The resulting precision on the cross section is at the level of 5% in the case of the ZZ measurement performed by both experiments on the $36\,\mathrm{fb}^{-1}$ Run 2 dataset at 13 TeV [5], rising to 10% in the case of WZ and WW measurements on the smaller 2.3–13.3 fb^{-1} Run 2 datasets [6, 7].

Measured diboson cross sections are consistent between the two experiments, and are in good agreement with the most accurate theoretical calculations available. These are typically at next-to-next-to-leading order (NNLO) for processes induced by strong force described by Quantum Chromodynamics (QCD), and at NLO for EWK processes, fig. 1.

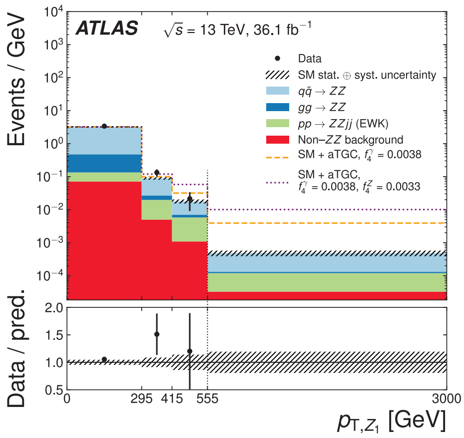

Fig. 2. – ATLAS data and SM prediction as a function of the transverse momentum of the leading-p_T Z boson candidate in ZZ leptonic final states [5]. Also shown is the SM plus aTGC signal prediction with $f_4^\gamma = 3.8 \times 10^{-4}$ as well as $f_4^\gamma = 3.8 \times 10^{-4}$ and $f_4^Z = 3.3 \times 10^{-4}$. In both cases, all other aTGC coupling strengths are set to zero. For better visualization, the last bin is shown using a different x-axis scale. The scale change is indicated by the dashed vertical line.

The data were used to set limits on aTGC by looking at high transverse momentum or high mass tails, like the leading Z p_T distribution in fig. 2. Limits on neutral aTGC obtained from the 13 TeV data are the most stringent up to today. They reach values of $\Lambda/\sqrt[4]{f} \sim$0.6–0.7 TeV, where f is the coupling of the particular EFT operator.

The charged aTGC searches benefit significantly from including the semi-leptonic channels $WV \to \ell\nu q\bar{q}$, where one W decays leptonically while the second vector boson V, either W or Z, decays hadronically to a quark-antiquark pair. At low V transverse momenta, the two quarks are reconstructed as two separated jets (resolved topology), while at higher transverse momenta, roughly above 200 GeV, the two jets merge into one large-radius jet (boosted topology). These final states exhibit large background, and the cross section measurements suffer from the large systematics connected with the background modeling. However, higher values of vector boson p_T are probed in semi-leptonic channels due to larger production rates. For example, the hadronic branching ratio of Z boson is about six times larger than the leptonic one. As a result, the sensitivity to aTQC is significantly increased with respect to the fully leptonic decays.

Both experiments analyzed the full 8 TeV Run 1 dataset [9] and CMS presented the first 13 TeV semi-leptonic results on the smaller 2.3 fb^{-1} dataset [10]. The obtained limits on aTGC were significantly better, in particular for the boosted topology, where ATLAS observed about 2.2 times larger sensitivity with respect to the fully leptonic case. LHC limits on aTQC are now better than LEP and Tevatron ones and they typically reach the value $\Lambda/\sqrt{f} \sim 0.6$ TeV.

2. – Triple gauge boson production

EWK triboson production involves an interplay between boson-radiation and three and four boson interactions. It is experimentally very challenging due to low leptonic branching ratios. Asking for at least one photon in the final state helps with reducing the penalty.

The easiest channel to study is a heavy vector boson produced in association with two photons $W\gamma\gamma$ or $Z\gamma\gamma$. Both experiments analyzed the full 8 TeV Run 1 dataset looking at the leptonic decay channels $W \to \ell\nu$ and $Z \to \ell\ell$ [11]. ATLAS included also $Z \to \nu\nu$. Both experiments observed $Z\gamma\gamma$ channel with large significance (6.3σ for ATLAS and 5.9σ for CMS) and ATLAS found an evidence for $W\gamma\gamma$ production with 3.0σ significance (2.6σ for CMS).

One-photon final states $WV\gamma$ are more challenging. Upper limits on production rates could only be derived for the semi-leptonic case using the full 8 TeV Run 1 dataset [12]. In the fully leptonic case, ATLAS measured the production cross section for channel $WW\gamma \to e\nu\mu\nu\gamma$, albeit with low statistical significance of 1.4σ.

3. – Vector boson scattering

In VBS, the incoming quarks act as sources of colliding boson beams. These processes are sensitive to TQG and QGC. The experimental signature is: two vector bosons VV plus two tagging high-p_{T} jets in the forward regions separated by a large rapidity gap with low hadronic activity due to the vector boson colourless nature. Unfortunately, the EWK scattering is not the only way to produce two gauge bosons and two jets in the final state. There is huge background from processes induced by strong interactions where both gauge bosons are coming from initial- and final-state radiation in $2 \to 2$ parton scattering.

Separating the EWK part from QCD background is the largest experimental challenge in the case of VBS. There are several strategies: either look in clean final states, like $Z\gamma jj$ and $ZZjj$, or use the cleanest channels with the highest EWK/QCD ratio, like the same-sign $W^{\pm}W^{\pm}jj$.

In the case of $Z\gamma jj$, both experiments analyzed the full 8 TeV Run 1 dataset, looking at fully leptonic channels $Z \to \ell^+\ell^-$ [13]. For the first time ATLAS made use of the $Z \to \nu\nu$ channel to provide better constraints on neutral aQGC via $Z\gamma$ VBS. CMS found 3σ evidence for the EWK $Z\gamma jj$ production, while ATLAS saw this channel with 2σ significance. The obtained neutral aQGC limits are much more stringent than the limits from triple boson $W\gamma\gamma$ and $WV\gamma$ channels.

In the case of $ZZjj$, CMS analyzed 36 fb^{-1} of 13 TeV data looking at fully leptonic channels [14]. Advance multivariate analysis techniques, involving boosted decision tree, were used to fight large QCD background. CMS observed the EWK part with 2.7σ significance and measured the fiducial cross section, which was found in good agreement with the SM prediciton. The aQGC limits, obtained from the high-mass tail in the ZZ invariant mass spectrum, are the most stringent limits on the dimension-eight operator couplings $f_{T,8}$ ($\Lambda/\sqrt[4]{f_{T,8}} \sim 1.0$ TeV) and $f_{T,9}$ ($\Lambda/\sqrt[4]{f_{T,9}} \sim 0.86$ TeV), which are accessible only via neutral gauge bosons final states. The limits are well within the unitarity violation bound.

CMS analyzed the 36 fb^{-1} dataset at 13 TeV also in the case of the same-sign $W^{\pm}W^{\pm}jj$ channel looking at the fully leptonic modes $W \to \ell\nu$, including τ decaying into e and μ [15]. As the same-sign WW cannot be produced by inital- and final-state radiation in $2 \to 2$ QCD processes whenever gluons are involved, this channel exhibits relatively small background. The dominant background is coming from non-prompt leptons, as shown in fig. 3, and it was constrained from control regions.

The EWK $W^{\pm}W^{\pm}jj$ cross section was obtained from 2D-fit in the (m_{jj}, m_{ll})-plane. The observed value in the fiducial region of $\sigma_{\mathrm{fid}} = 3.83 \pm 0.66(\mathrm{stat}) \pm 0.35(\mathrm{syst})$ fb is in agreement with the LO prediction of 4.25 ± 0.21 fb. This channel was observed with statistical significance of 5.7σ which makes this measurement the first ever observed signa-

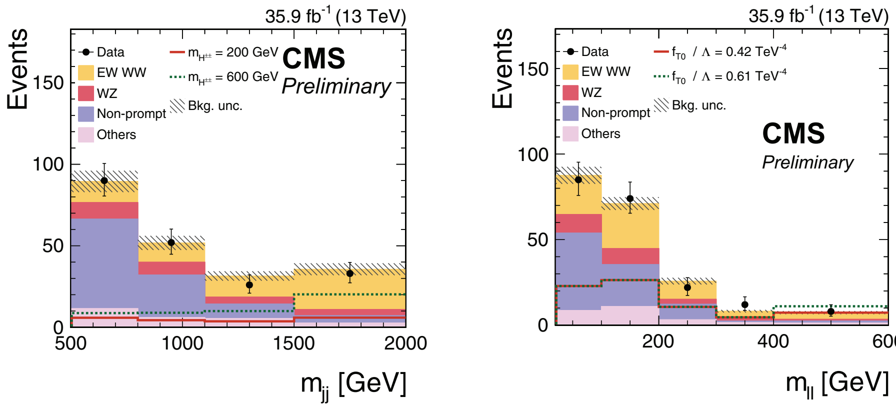

Fig. 3. – Dijet m_{jj} (left) and dilepton $m_{\rm ll}$ invariant-mass spectra in the signal region as measured by CMS experiment in the same-sign $W^{\pm}W^{\pm}jj$ channel [15]. The normalization of the predicted signal and background distributions corresponds to the result of the fit. The hatched bars include statistical and systematic uncertainties. For illustration, the doubly charged Higgs boson signal normalized to a cross section of 0.1 pb (left) and the distribution with aQGCs (right) are shown.

ture of vector boson scattering. The derived limits on aQGC are the best for the majority of relevant dimension-eight operators, reaching the scale $\Lambda > 1\,\text{TeV}$ (assuming the relevant couplings to be one). Improvements are expected from other VBS channels such as $\gamma\gamma \to WW$ responsible for the exclusive production of WW. In Run 1 dataset, this channel already gave better limits on some parameters than the same-signed $W^{\pm}W^{\pm}jj$ channel at 13 TeV [16].

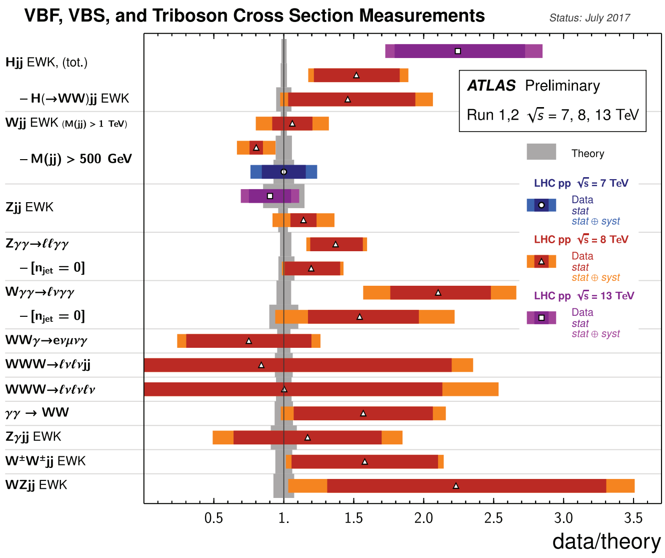

Fig. 4. – The data/theory ratios from ATLAS experiment [17] for several vector boson fusion, vector boson scattering, and triboson fiducial cross section measurements, corrected for leptonic branching fractions. All theoretical expectations were calculated at NLO. So far not all measurements are statistically significant.

4. – Conclusion

Challenging multi-boson measurements are possible thanks to the excellent LHC performance. These measurements are precision tests of the SM as they probe the gauge structure of the theory, being sensitive to possible anomalous TGC and QGC. Both experiments performed a wide range of measurements covered here only partially. The results as shown in fig. 4 are in good agreement with the SM predictions. Analysis of full Run 1 dataset at 8 TeV brought the first observation of triple boson production ($Z\gamma\gamma$) and the evidence of $W\gamma\gamma$ process. The 13 TeV Run 2 data in the same-signed $W^{\pm}W^{\pm}jj$ channel brought the first observation of the vector boson scattering process. The data were used to derive limits on anomalous gauge couplings, reaching and in some cases exceeding the energy scale of 1 TeV in the effective field theory approach (assuming the couplings to be $f = 1$).

REFERENCES

[1] Hagiwara K., Hikasa K., Peccei R.D. and Zeppenfeld D., *Nucl. Phys. B*, **282** (1987) 253; Hagiwara K., Ishihara S., Szalapski R. and Zeppenfeld D., *Phys. Rev. D*, **48** (1993) 2182.
[2] Degrande C., Greiner N., Kilian W., Mattelaer O., Mebane H., Stelzer T., Willenbrock S. and Zhang C., *Ann. Phys.*, **335** (2013) 21.
[3] ATLAS Collaboration, *J. Instrum.*, **3** (2008) S08003.
[4] CMS Collaboration, *J. Instrum.*, **3** (2008) S08004.
[5] ATLAS Collaboration, *Phys. Rev. D*, **97** (2018) 032005; CMS Collaboration, *Eur. Phys. J. C*, **78** (2018) 165.
[6] ATLAS Collaboration, ATLAS-CONF-2016-043, 2016; CMS Collaboration, *Phys. Lett. B*, **766** (2017) 268.
[7] ATLAS Collaboration, *Phys. Lett. B*, **773** (2017) 354; CMS Collaboration, CMS-PAS-SMP-16-006, 2016.
[8] CMS Collaboration, public results available at `https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined`, version of October 3, 2017.
[9] ATLAS Collaboration, *Eur. Phys. J. C*, **77** (2017) 563; CMS Collaboration, *Phys. Lett. B*, **772** (2017) 21.
[10] CMS Collaboration, CMS-PAS-SMP-16-012, 2016.
[11] ATLAS Collaboration, *Phys. Rev. D*, **93** (2016) 112002; ATLAS Collaboration, *Phys. Rev. Lett.*, **115** (2015) 031802; CMS Collaboration, *JHEP*, **10** (2017) 072.
[12] ATLAS Collaboration, *Eur. Phys. J. C*, **77** (2017) 646; CMS Collaboration, *Phys. Rev. D*, **90** (2014) 032008.
[13] ATLAS Collaboration, *JHEP*, **07** (2017) 107; CMS Collaboration, *Phys. Lett. B*, **770** (2017) 380.
[14] CMS Collaboration, CMS-PAS-SMP-16-019, 2017.
[15] CMS Collaboration, CMS-PAS-SMP-17-004, 2017.
[16] ATLAS Collaboration, *Phys. Rev. D*, **94** (2016) 032011; CMS Collaboration, *JHEP*, **08** (2016) 119.
[17] ATLAS Collaboration, public results available at `https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/`, version of October 3, 2017.