PROCEEDINGS OF SCIENCE

Measurements of quartic coupling and vector boson scattering in ATLAS

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Measurements of multiboson production at the LHC probe the electroweak gauge structure of the Standard Model for contributions from anomalous couplings. Vector boson scattering and triboson production provide the opportunity to directly access the quartic gauge-boson couplings. This report presents the recent ATLAS results on the measurement of electroweak production of $Z(\nu\bar{\nu})\gamma$ in association with two jets and the first observation of the associated production of three W bosons.

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1. Introduction

Spontaneous breaking of the $SU(2)_L \times U(1)_Y$ electroweak (EW) symmetry of the Standard Model (SM) sets the constraints on the allowed vector-boson self-interaction vertices. Thus, measurement of multiboson production in the pp collisions allows to directly probe the SM predictions and perform indirect searches of physics beyond the SM (BSM). Among them, vector boson scattering (VBS) [1] and triboson production are of particular interest due to the sensitivity to the quartic gauge-boson couplings (QGCs). Such measurements become accessible in the ATLAS [2] and CMS [3] experiments at the LHC due to the high luminosity of data collected by these experiments.

BSM searches are performed in the model independent framework of Effective Field Theory (EFT) [4]. It extends the SM Lagrangian of mass dimension-4 with the operators of mass dimension $d > 4$ which are constructed with the SM fields and suppressed by the energy scale of the BSM physics Λ. The strength of each operator O_i^d is given by a dimensionless (Wilson) coefficient f_i^d and the full operator coupling f_i^d/Λ^{d-4} can be measured in the experiment. Dimension-8 operators O_i^8 are the lowest dimension operators that conserve lepton number and only include QGCs without triple gauge-boson vertices [5]. The values of these operator couplings are expected to grow with the increasing momentum transfer between the incoming partons making the final states with high values of boson p_T more sensitive to the couplings deviation from zero.

Two studies that use ATLAS $\sqrt{s} = 13\,\mathrm{TeV}$ pp collision data corresponding to $139\,\mathrm{fb}^{-1}$ are presented: WWW production [6] and EW production of $Z(\nu\bar{\nu})\gamma$ in association with two jets [7].

2. WWW production

Evidence for the $pp \to WWW$ process was previously provided by the ATLAS experiment [8] and the CMS experiment observed the combined production of three massive vector bosons (WWW, WWZ, WZZ and ZZZ) [9]. Two decay channels are considered in the reported ATLAS analysis [6]: $\ell^\pm\nu\ell^\pm\nu qq$ and $\ell^\pm\nu\ell^\pm\nu\ell^\mp\nu$ ($\ell = e$ or μ) denoted as 2ℓ and 3ℓ, respectively. The 2ℓ final state is exactly two same-sign charged leptons ($e^\pm e^\pm/\mu^\pm e^\pm/\mu^\pm\mu^\pm$), at least two hadronic jets and missing transverse momentum $E_\mathrm{T}^\mathrm{miss}$. The 3ℓ final state is exactly three charged leptons with no same-flavor opposite-sign lepton pairs ($e^\pm e^\pm\mu^\mp/\mu^\pm\mu^\pm e^\mp$). The dominant background contributions are the $WZ(\ell\nu\ell\ell)$+jets process and processes with non-prompt leptons (leptons from hadron decays and jet $\to \gamma$ misidentification). The non-prompt processes are estimated using data-driven techniques and the binned maximum-likelihood fit is performed to estimate the WZ background and to measure the cross section. The fit uses trilepton invariant mass $m_{\ell\ell\ell}$ in the control regions (CRs) and the response of the boosted decision tree (BDT) classifier distributions in the signal regions (SRs) presented in Figure 1.

The $pp \to WWW$ production cross section is measured to be $820 \pm 100(\mathrm{stat.}) \pm 80(\mathrm{syst.})$ fb, approximately 2.6 standard deviations from the predicted cross section of 511 ± 18 fb calculated at next-to-leading-order (NLO) QCD and leading order (LO) EW accuracy. The SM background-only hypothesis is rejected with an observed (expected) significance of 8.0σ (5.4σ) resulting in the first observation of the $pp \to WWW$ process.

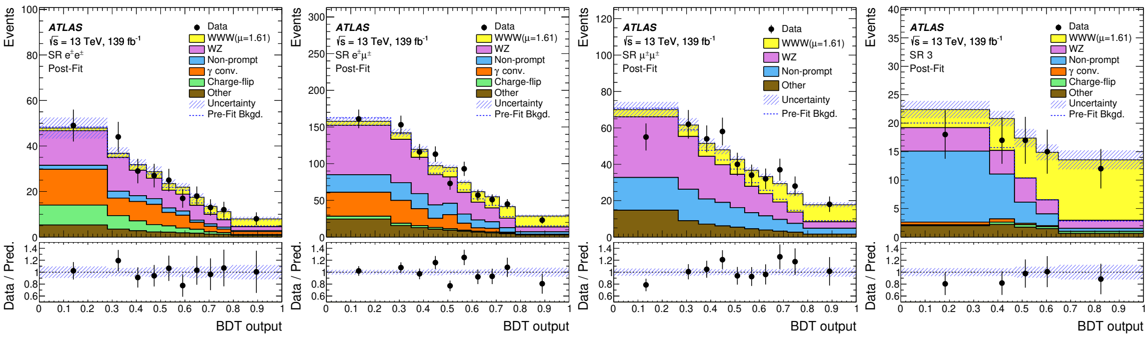

Figure 1: Post-fit BDT classifier output distributions in the signal regions of the maximum-likelihood fit used to extract the $pp \to WWW$ production cross section [6].

3. $Z(\nu\bar{\nu})\gamma jj$ production

The EW $pp \to Z\gamma jj$ process was previously observed by the CMS experiment in the $Z \to \ell^-\ell^+$ decay channel [11]. The ATLAS experiment has studied this process in the $Z \to \nu\bar{\nu}$ decay channel [10] exploiting high signal event yield in the final state with low values of photon transverse energy $E_{\mathrm{T}}^{\gamma} < 110$ GeV, that provided the opportunity to make an observation but had negligible sensitivity for the BSM searches. The reported ATLAS analysis [7] is aimed at the anomalous QGC measurement and studies the events with a photon with $E_{\mathrm{T}}^{\gamma} > 150$ GeV, high $E_{\mathrm{T}}^{\mathrm{miss}}$ and at least two hadronic jets. The main challenge in this measurement comes from the high event yield of the dominant background contributions: the QCD production of the same final state $Z(\nu\bar{\nu})\gamma jj$ and the $W(\ell\nu)\gamma jj$ production. It is addressed by performing binned maximum-likelihood fit that uses dijet invariant mass m_{jj} in the CRs and the response of the BDT classifier distribution in the SR to measure the cross section. The aQGC limits are set in the high E_{T}^{γ} part of the SR using the correction factors from the binned fit.

The $Z(\nu\bar{\nu})\gamma jj$ production cross section is measured to be $0.77^{+0.34}_{-0.30}$ fb with the predicted cross section of 0.98 ± 0.02 (stat.) ± 0.09 (scale) ± 0.02 (PDF) fb calculated at NLO QCD and LO EW accuracy. The SM background-only hypothesis is rejected with an observed (expected) significance of 3.2σ (3.7σ) which becomes 6.3σ (6.8σ) when combined with the results from Ref. [10]. Both non-unitarised and unitarised one-dimension limits on the couplings f_i^8/Λ^4 for the set of the dimension-8 EFT operators $O_{T,j}^8$ and $O_{M,j}^8$ are obtained with the non-unitarised limits presented in Table 1. Unitarisation is achieved using the clipping method, i.e. by setting the anomalous contribution to zero for the mass of Z boson and photon system $m_{Z\gamma}$ (estimated at particle level) greater than the cutoff scale calculated from the partial wave unitarity constraints [12]. The limits on $O_{M,j}^8$ couplings are competitive with those previously published with the limits on $O_{T,j}^8$ couplings being the most stringent ones.

Coefficient	Observed limit, TeV^{-4}	Expected limit, TeV^{-4}
$f_{T,0}/\Lambda^4$	$[-9.4, 8.4] \times 10^{-2}$	$[-1.3, 1.2] \times 10^{-1}$
$f_{T,5}/\Lambda^4$	$[-8.8, 9.9] \times 10^{-2}$	$[-1.2, 1.3] \times 10^{-1}$
$f_{T,8}/\Lambda^4$	$[-5.9, 5.9] \times 10^{-2}$	$[-8.1, 8.0] \times 10^{-2}$
$f_{T,9}/\Lambda^4$	$[-1.3, 1.3] \times 10^{-1}$	$[-1.7, 1.7] \times 10^{-1}$
$f_{M,0}/\Lambda^4$	$[-4.6, 4.6]$	$[-6.2, 6.2]$
$f_{M,1}/\Lambda^4$	$[-7.7, 7.7]$	$[-1.0, 1.0] \times 10^{1}$
$f_{M,2}/\Lambda^4$	$[-1.9, 1.9]$	$[-2.6, 2.6]$

Table 1: Observed and expected one-dimensional limits on dimension-8 operator couplings. Limits are obtained by setting all operator couplings except one to zero [7].

4. Conclusion

Two new measurements of multiboson production — WWW and EW $Z(\nu\bar{\nu})\gamma jj$ — in 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data are reported by the ATLAS experiment at the LHC. The $pp \to WWW$ process is observed for the first time. EW $Z(\nu\bar{\nu})\gamma jj$ production is used to obtain the most stringent up do date limits on the $O^8_{T,j}$ couplings with and without unitarisation. Results of cross section measurements of both WWW and EW $Z(\nu\bar{\nu})\gamma jj$ production are in agreement with the SM predictions.

References

[1] R. Covarelli et al, *Int. J. Mod. Phys. A* **36** (2021) 2130009 [2102.10991].

[2] ATLAS Collaboration, *JINST* **3** (2008) S08003.

[3] CMS Collaboration, *JINST* **3** (2008) S08004.

[4] C. Degrande et al., *Annals Phys.* **335** (2013) 21 [1205.4231].

[5] O.J.P. Éboli and M.C. Gonzalez–Garcia, *Phys. Rev. D* **93** (2016) 093013 [1604.03555].

[6] ATLAS Collaboration, *Phys. Rev. Lett.* **129** (2022) 061803 [2201.13045].

[7] ATLAS Collaboration, Aug., 2022, arXiv:2208.12741.

[8] ATLAS Collaboration, *Phys. Lett. B* **798** (2019) 134913 [1903.10415].

[9] CMS Collaboration, *Phys. Rev. Lett.* **125** (2020) 151802 [2006.11191].

[10] ATLAS Collaboration, *Eur. Phys. J. C* **82** (2022) 105 [2109.00925].

[11] CMS Collaboration, *Phys. Rev. D* **104** (2021) 072001 [2106.11082].

[12] E.d.S. Almeida et al, *Phys. Rev. D* **101** (2020) 113003 [2004.05174].