PROCEEDINGS OF SCIENCE

Multiboson production at the LHC

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Production of multiple electroweak vector bosons in proton collisions at LHC allows testing the Standard Model in both electroweak and QCD domains, extracting properties of Standard Model particles, and testing theories beyond the Standard Model. This report presents selected ATLAS and CMS measurements of inclusive diboson and triboson production performed using data sets collected between 2015 and 2018.

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Introduction

Multiboson production – inclusive production of two or more electroweak bosons W, Z, γ – provides a rich area for Standard Model (SM) studies and searches for effects beyond the Standard Model (BSM). The latter are often concentrated on potential new physics effects leading to anomalous triple (aTGC) and quartic (aQGC) gauge couplings of electroweak bosons, though other effects are also checked for. A common way to look for deviations from the SM is to put constraints on coefficients of effective field theory (EFT) operators of mass dimension greater than four. This note presents a summary of selected inclusive diboson and triboson measurements by the ATLAS [1] and CMS [2] experiments. Unless stated otherwise, the decays of W and Z bosons to leptons are considered, and the full LHC Run 2 pp collision data, corresponding to an integrated luminosity of around 140 fb^{-1} per experiment, at the centre-of-mass energy $\sqrt{s} = 13$ TeV, are used.

1. Inclusive diboson measurements

The measurement of $\boldsymbol{W^+W^-}$ **+** $\boldsymbol{\geq}$ **1 jet production** [3] was performed by the ATLAS experiment, considering opposite-charge dilepton electron-muon $e\mu$ events, with lepton transverse momenta $p_{\mathrm{T}} > 27$ GeV and the dilepton invariant mass $M_{\ell\ell} > 85$ GeV, at least one hadronic jet with $p_{\mathrm{T}}^{\mathrm{jet}} > 30$ GeV, and a b-jet veto. The background from $t\bar{t}$ events, dominating the event yield in the signal region, was estimated using a data-driven b-tag counting method [4]. This method significantly reduced the dependence of the $t\bar{t}$ background estimate on the Monte Carlo (MC) modelling, as well as led to a reduction to the uncertainty in the background estimate by a factor of 4 compared to the MC based estimate. The dominant systematic uncertainty of the fiducial cross section measurement is coming from the jet calibration and resolution uncertainties. Differential cross sections were measured as a function of several variables, also in the region with high $p_{\mathrm{T}}^{\mathrm{lead.\,jet}} > 200$ GeV. Limits on the Wilson coefficient c_W of the EFT dimension-6 operator Q_W defined in [5], which modifies the W boson self-coupling, were set. The limits obtained in the high-$p_{\mathrm{T}}^{\mathrm{lead.\,jet}}$ region were found to be tighter compared to those with the nominal $p_{\mathrm{T}}^{\mathrm{jet}}$ threshold for the case when the SM + linear-only term in c_W/Λ^2 was considered in the expansion of the SM+EFT cross section. This was not the case for the linear + quadratic fit, which implies that the overall sensitivity to c_W is driven by the pure EFT term.

Inclusive $\boldsymbol{WZ}$ production [6] was measured and extensively studied by the CMS experiment. The three-lepton events ($l = e, \mu$) are considered, where two leptons with the same flavour and opposite electric charge are required to be consistent with the Z-boson decay products, based on the dilepton invariant mass requirement $|m_{\ell\ell} - m_Z| < 15$ GeV. A further condition on the missing transverse momentum, $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV, is imposed. The relatively small background of 16% is dominated by ZZ events and events with non-prompt leptons. Fiducial and differential cross section measurements were performed, as well as an interpretation of results from different perspectives. The charge asymmetry, defined as the cross section ratio $\sigma_{\mathrm{fid}}(pp \to W^+Z)/\sigma_{\mathrm{fid}}(pp \to W^-Z)$, is sensitive to the relative contribution of u- and d-quark parton density functions (PDF). The measured value of the charge asymmetry was found to be in agreement with the theory prediction and was used to reduce the PDF-related uncertainty of the latter by about 10%, by applying a Bayesian reweighting procedure to the PDF replicas of the NNPDF30_nlo_as_118 PDF set [7]. In addition, measurements of boson polarisation fractions were performed, separately for W and Z

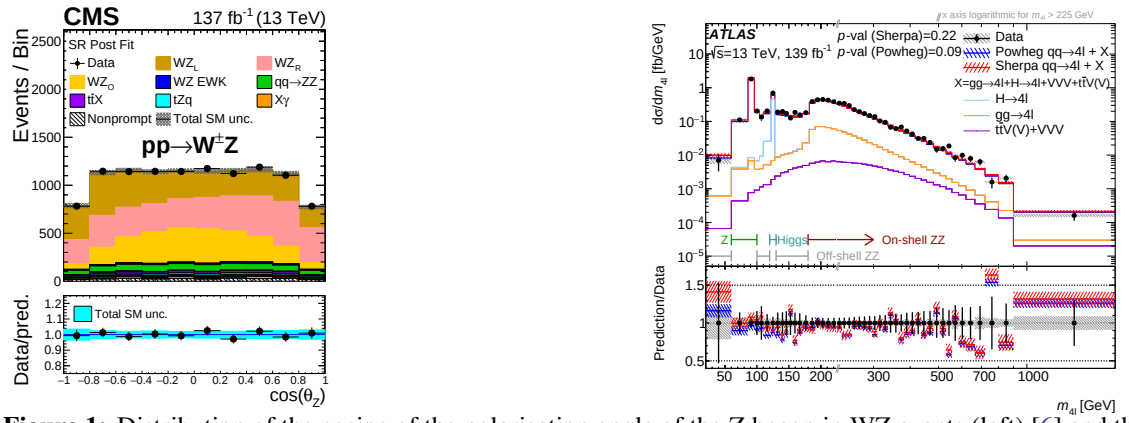

Figure 1: Distribution of the cosine of the polarisation angle of the Z boson in WZ events (left) [6] and the differential cross section of inclusive four-lepton production as a function of the invariant four-lepton mass, m_{4l} (right) [8].

boson polarisations (see Figure 1, left). Finally, the distribution of the W and Z invariant mass, $M(WZ)$, was used to set limits on Wilson coefficients of five EFT dimension-6 operators affecting the WZ process. The limits were obtained for both linear and linear+quadratic EFT contributions, and for different values of the cutoff energy scale, setting an upper threshold for the presence of EFT effects. The limits were found to be a factor of 2 tighter than for the previous measurement based on 36 fb^{-1}.

Inclusive four-lepton final states [8] were comprehensively studied by the ATLAS Collaboration in the four-lepton mass range $20 < m_{4l} < 2000$ GeV. All processes contributing to the prompt production of four lepton were considered signal, while the background originates from events with at least one non-prompt lepton. Such a choice of the signal processes is beneficial for later reinterpretations of the four-lepton cross sections, since no SM assumptions are made for their estimate (except for the unfolding to the particle level, though here BSM injection tests were performed which showed very little to no sensitivity of the unfolded results to the presence of BSM effects). The differential cross sections in four regions of m_{4l} were measured, corresponding to dominant processes in these regions, as shown in Figure 1 (right). The branching ratio of the Z-boson decay to four leptons was measured to be $\mathcal{B}_{Z\to 4l} = (4.41 \pm 0.30) \times 10^{-6}$, with the best precision to date. Constraints on coefficients of 22 EFT operators affecting four-lepton final states were derived. In addition, limits on a $(B-L)$ model with a spontaneously broken symmetry of the baryon-number-minus-lepton-number, with a second Higgs boson and a Z' boson [9], were set.

Cross sections of **inclusive WW, WZ, and ZZ diboson production** at $\sqrt{s} = 5.02$ TeV [10] were measured at CMS, using low-pileup pp run, serving as a reference run for heavy ions. The integrated luminosity of the dataset used is 302 pb^{-1}. The measurements agree with the theoretical predictions at next-to-next-to-leading order (NNLO) in QCD with next-to-leading order (NLO) EW corrections. Differential cross section measurements were not possible due to limited data statistics.

Fiducial and differential cross section measurements of the **inclusive $Z\gamma$ production** [11] were performed by the ATLAS experiment, for $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ final states. The phase space of the measurement is targeting photons from the initial state radiation, with $p_{\mathrm{T}}^{\gamma} > 30$ GeV. Since neutral TGC vertices are not allowed in SM, this process (as well as inclusive diphoton production) is not sensitive to weak boson self-couplings at the leading order, and can be used to test perturbative QCD predictions. A good description of the data was found for Sherpa [12] NLO+PS and NNLO (+NLO EW) predictions by Matrix [13], where the latter is corrected from parton to particle level

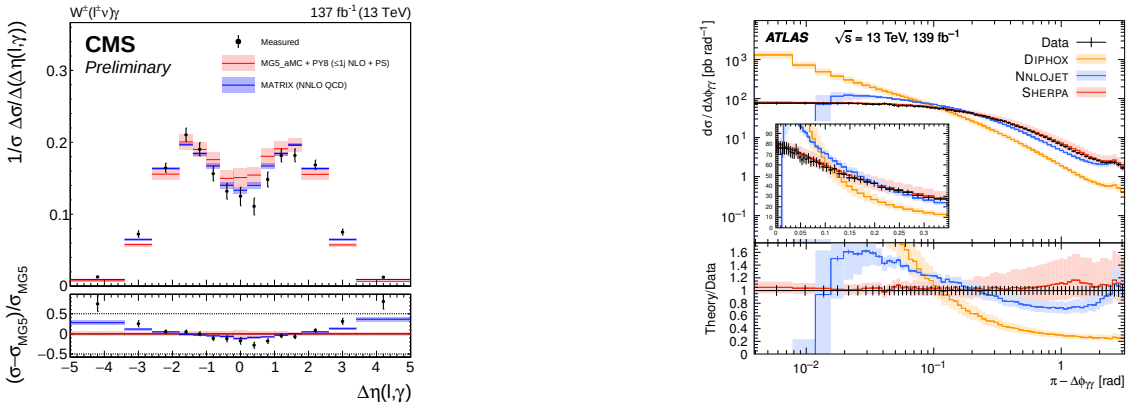

Figure 2: Normalised differential cross section of inclusive $W\gamma$ production as a function of the rapidity separation between the charged lepton and the photon (left) [14]. Differential cross section as a function of $\pi - \Delta\phi_{\gamma\gamma}$ of inclusive diphoton production (right) [16].

with coefficients obtained from the SHERPA MC.

The CMS experiment measured the **inclusive production of $W\gamma$** [14], which probes the $WW\gamma$ vertex. At leading order (LO) in QCD, the cross section at 0 pseudorapidity difference between the lepton and photon, $\Delta\eta(\ell, \gamma) = 0$, vanishes due to an interference effect ("radiation amplitude zero") [15]. The presence of new physics effects can alter the behaviour of the cross section at the minimum, though a satisfactory agreement was found by the MATRIX NNLO predictions, as shown in Figure 2 (left). The interpretation of the cross sections within the EFT dimension-6 framework was performed, setting limits on the coefficient C_{3W} of an operator from [5] modifying the $WW\gamma$ TGC. The limits when including the linear term in C_{3W}/Λ^2 only were shown to improve by a factor 10 when adding the distribution of ϕ, the azimuthal angle of the final-state fermion from the $W^{\pm}$ boson decay with a positive helicity in a special reference frame, to the interpretation based on the p_{T}^{γ} cross section.

An **inclusive diphoton ($\gamma\gamma$)** cross section measurement [16] was performed by ATLAS, with cuts on the transverse momenta of the leading (subleading) photon $p_{\mathrm{T},\gamma_{1(2)}} > 40\,(30)$ GeV. Signal events include direct photons emitted from the quark lines, and fragmentation photons, while non-prompt photons coming from hadron decays were treated as background. The signal purity in the signal region was found to be around 60%, with main backgrounds produced by events with jets misidentified as photons. The pileup background, with photons coming from separate pp interactions within the same bunch crossing, was estimated to be 0.6%, using the distribution of the longitudinal impact parameter of electron tracks in events with converted photons. The measured cross sections at the particle level were compared to SHERPA NLO+PS predictions and to a number of fixed-order theory predictions. It was shown (see Figure 2, right) that to describe the soft or collinear regions of the phase space, QCD resummation through the parton shower is essential. The fixed-order predictions at LO and at NNLO in QCD differ by a factor of 6, showing the importance of the higher-order QCD corrections.

2. Inclusive triboson measurements

The first **observation of the inclusive WWW triboson production** [17] was made by ATLAS, using events with two charged leptons and two jets, or with three charged leptons, excluding events with same-flavour opposite-sign leptons. The signal events include on-shell WWW production as well as off-shell W's from the associated production of the Higgs H and W bosons, WH, $H \to WW^*$.

Boosted decision trees (BDT) were trained in 2- and 3-lepton regions to separate the signal from the background. The signal strength $\mu(WWW)$ with respect to the SM expectation was obtained from the fit of the BDT output score distribution, and was found to be $\mu(WWW) = 1.66 \pm 0.28$. The corresponding inclusive production cross section was measured to be $\sigma(pp \to WWW) = 850 \pm 100\,(\text{stat.}) \pm 80\,(\text{syst.})$ fb. The predicted MC and fixed-order values are $\sigma_{\text{MC}} = 511$ fb and $\sigma_{\text{FO}} = 505$ fb, with an uncertainty below 50 and 30 fb, respectively. The observed (expected) signal significance is 8.2 (5.4) standard deviations.

An **observation of the inclusive $V\gamma\gamma$ process, $V = W, Z$** [18], was made by the CMS experiment, with the signal significance of 3.1 and 4.8 standard deviations for $W\gamma\gamma$ and $Z\gamma\gamma$, respectively. This process is sensitive to anomalous QGC that can be generated by dimension-6 or dimension-8 EFT operators. However because of the available statistics, the sensitivity to dimension-6 operators is expected to be lower than those of the diboson measurements. Therefore, the distribution of the transverse momentum of the diphoton system, $p_{\text{T}}^{\gamma\gamma}$, was used to constrain 10 (8) coefficients of EFT dimension-8 operators from [19] for the $W\gamma\gamma$ ($Z\gamma\gamma$) process.

Summary

Selected measurements of diboson and triboson processes by ATLAS and CMS experiments are presented. The diboson cross sections are generally well described by state-of-the-art fixed-order predictions at NNLO in QCD, with NLO EW corrections. Neither in EFT interpretations nor in direct searches any deviations from the Standard Model are found.

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