ATLAS measurements of multi-boson production

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ABSTRACT

Measurements of electroweak gauge-boson pair-production in $\sqrt{s} = 7$ and 8 TeV $pp$ collisions at the LHC probe self-couplings and interference effects to an accuracy of $O(10\%)$ or better. ATLAS measurements of $ZZ$ and $WZ$ production at both center of mass energies, and of $WW$, $Z\gamma$ and $W\gamma$ production at $\sqrt{s} = 7$ TeV, are presented. Total, fiducial, and differential cross sections are given, along with limits on anomalous triple-gauge couplings.

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1 Introduction

The study of vector-boson pair-production at the LHC provides important information on gauge-boson self-couplings and on QCD corrections, which are particularly relevant for Higgs boson measurements in these final states. Measurements of diboson (VV) production at ATLAS generally include a cross section measured in the selected fiducial region, an extrapolation to a total production cross section, a cross section measured differentially in relevant variables, and limits on anomalous couplings.

The fiducial cross section is defined as

$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bd}}}{L_{VV}},$$

where $N_{\text{data}}$ is the number of observed events, $N_{\text{bd}}$ is the number of events expected from background, $L$ is the integrated luminosity, and $C_{VV}$ is the expected ratio of all selected events to the generated events in a relevant fiducial region. To extrapolate to the total cross section, the fiducial cross section is divided by $A_{VV}$, the ratio of events in the fiducial region to all generated events, and $B$, the relevant branching ratios.

Diboson measurements probe triple-gauge couplings, which contain a charged current in the SM. The general Lagrangian terms that conserve $C$ and $P$ for these couplings are

$$\mathcal{L}_{VVV} = ig_1^V(W_{\mu\nu}W^{\mu\nu}V^\nu - W_{\mu}V^\mu W^{\nu\nu}) + i\kappa_V W_{\mu}V^{\mu\nu} + \frac{i}{m_W^2} W_{\nu}V^\nu V_{\mu\lambda},$$

where $g_1^{V\text{SM}} = \kappa_V^{\text{SM}} = 1$ and $\lambda_V^{\text{SM}} = 0$ in the standard model (SM). The parameter $g_1$ is fixed to 1 by electromagnetic gauge invariance. Anomalous coupling limits are set in three scenarios: “LEP”, where $\Delta\kappa = (\cos^2\theta_W/\sin^2\theta_W)(\Delta\gamma^2 - \Delta\kappa Z)$ and $\lambda_Z = \lambda_G$, leaving three parameters; “HISZ”, where $\Delta\gamma^2 = \Delta\kappa Z/(\cos^2\theta_W - \sin^2\theta_W)$, $\Delta\kappa = 2\Delta\kappa Z\cos^2\theta_W/(\cos^2\theta_W - \sin^2\theta_W)$, and $\lambda_Z = \lambda_G$, leaving two parameters; and “equal couplings”, where $\Delta\kappa = \Delta\kappa Z$, $g_1^2 = 1$, and $\lambda = \lambda_G$, leaving two parameters. Generally the anomalous couplings lead to a violation of unitarity, so a suppression factor of, e.g., $\lambda(s) = (1 + \hat{s}/\Lambda^2)^2$ is applied.

In order of increasing rate, ATLAS has measured $ZZ$ production in four-lepton data in 7 and 8 TeV collisions; $WZ$ production in three-lepton data at both energies; $WW$ production in dilepton and monophoton data at 7 TeV; $Z\gamma$ production in dilepton-plus-photon and monophoton data at 7 TeV; $W\gamma$ production in lepton-plus-photon data at 7 TeV; and $\gamma\gamma$ production at 7 TeV.

2 ZZ cross sections

For the $ZZ$ cross section measurements at $\sqrt{s} = 8$ TeV, candidate events are selected with two pairs of opposite-charge electrons or muons with invariant mass consistent with $m_Z$ (66 < $m_{ll}$ < 116 GeV). Figure shows the distribution of the invariant mass of the pair with the highest dilepton $p_T$ (the “leading” pair) versus the invariant mass of the “subleading” pair with lower dilepton $p_T$.

This selection provides > 90% purity, with 292.5 ± 10.6 expected $ZZ$ events compared to a background of 20.4 ± 5.8 events in 20.3 ± 0.6 fb$^{-1}$ of integrated luminosity. With 305 observed events, the measured total cross section $\sigma_{\text{tot}}(ZZ) = 7.1^{+0.4}_{-0.5}$ (stat.) ± 0.8 (sys.) ± 0.2 (lum.) pb is consistent with the SM prediction (7.2$^{+0.3}_{-0.2}$ pb). The measured fiducial cross section is $\sigma_{\text{fid}}(ZZ \rightarrow llll) = 20.7^{+1.3}_{-1.2}$ (stat.) ± 0.8 (sys.) ± 0.6 (lum.) fb.

Including prior measurements, there is good agreement with SM predictions for $ZZ$ production in hadron collisions at center of mass energies ranging from 2 to 8 TeV (Fig. 1). Measurements in $pp$ collisions have been somewhat higher than the expectation, but not significantly so.

3 WZ cross sections

Using data corresponding to 13 fb$^{-1}$ of integrated luminosity at $\sqrt{s} = 8$ TeV, candidate $WZ$ events are selected by requiring: an opposite-charge electron or muon pair with invariant mass near $m_Z$ (81 < $m_{ll}$ < 101 GeV); an additional electron or muon; and significant missing transverse momentum ($E_T^{\text{miss}} >$...
25 GeV) in a direction that is not collinear with the additional lepton ($m_T > 20$ GeV, where $m_T = \sqrt{2(E_T^l E_T^{l'} - p_T^l p_T^{l'})}$). With this selection, the sample is 75% pure in WZ events, with 819 ± 34 expected signal events and 277 ± 26 background events. The 1094 observed events are consistent with the expectation for WZ production, as demonstrated with the $m_T$ distribution in Fig. 2. Combining all lepton channels, the measured fiducial cross section has 7% precision, $\sigma_{fid}(WZ \rightarrow l) = 99.2^{+3.8}_{-3.0} \text{ (stat.)}^{+5.1}_{-3.6} \text{ (sys.)}^{+3.3}_{-3.3} \text{ (lum.) \ fb}$, and is equal to the SM expectation (99.2 ± 3.6 fb). The total measured cross section is $\sigma_{tot}(WZ) = 20.3^{+0.8}_{-0.7} \text{ (stat.)}^{+1.2}_{-1.1} \text{ (sys.)}^{+0.7}_{-0.6} \text{ (lum.) \ pb}$, again equal to the SM expectation (20.3 ± 0.8 pb). As with the ZZ cross section measurements, the WZ measurements are consistent with SM predictions for $\sqrt{s}$ ranging from 2-8 TeV for $p\bar{p}$ and $pp$ collisions (Fig. 2).

Figure 1: Left: Invariant masses of the leading and subleading lepton pairs in events with two pairs of opposite-charge electrons or muons. The leading lepton pair has higher $p_T$ [3]. Right: The measured ZZ cross section as a function of center of mass energy for $p\bar{p}$ and $pp$ collisions [3].

Figure 2: Left: Transverse mass $m_T$ calculated using the lepton not associated with the Z-boson decay, and the reconstructed missing transverse momentum [3]. Right: The measured WZ cross section as a function of center of mass energy for $p\bar{p}$ and $pp$ collisions [4].
4 WW measurements

In 4.6 fb$^{-1}$ of $\sqrt{s} = 7$ TeV data, ATLAS has measured WW cross sections both inclusively and differentially as a function of the $p_T$ of the highest momentum lepton in the event [5]. Events are selected with two opposite-charge leptons (electron or muon); same-flavor leptons must have invariant mass inconsistent with $Z$-boson production. The top-quark background is suppressed by requiring events to have zero jets, and Drell-Yan processes are reduced by requiring significant $E_T^{miss}$, defined as $E_T^{miss}$ multiplied by the sine of the smallest $\Delta \phi(p_T^\ell, p_T^{\nu})$ when $\Delta \phi < \pi/2$.

The WW selection results in $824 \pm 69$ expected signal WW events and $369 \pm 61$ background events, for a purity of nearly 70%. Because of the reduced Drell-Yan background in events with different-flavor leptons, these events contain nearly two-thirds of the signal acceptance. The measured fiducial cross section in this final state is $\sigma_{fid}(WW \to e\nu\mu\nu) = 262.3 \pm 12.3$ (stat.) $\pm 20.7$ (sys.) $\pm 10.2$ (lum.) fb. Combining with same-flavor final states, the total cross section is $51.9 \pm 2.0$ (stat.) $\pm 3.9$ (sys.) $\pm 2.0$ (lum.) pb, which is a little more than 1σ higher than the prediction of $44.7^{+3.0}_{-2.1}$ pb.

The $p_T$ of the lepton with the highest $p_T$ (the "leading" lepton) probes the $Q^2$ of the event, and is sensitive to anomalous gauge couplings. The cross section is measured differentially as a function of leading lepton $p_T$, with results shown in Fig. 3. The reconstructed leading lepton $p_T$ is fit for the presence of anomalous gauge couplings and limits are set in the absence of evidence for these couplings. Figure 3 shows the resulting limits for $\Lambda = 6$ TeV, which preserves unitarity for coupling values that are not excluded, and for $\Lambda = \infty$. Limits from prior measurements are shown for comparison.

5 $Z\gamma$ measurements

Measurements of $Z\gamma$ production have been performed by ATLAS for both $Z \rightarrow \ell\ell$ and $Z \rightarrow \nu\nu$ decays, using 4.6 fb of integrated luminosity from $\sqrt{s} = 7$ TeV collisions [6]. Events from the decay to charged leptons are selected by requiring two same-flavor leptons (electrons or muons) with invariant mass larger than 40 GeV and a photon with $p_T > 15$ GeV. The selection yields 3990 expected signal events (with $\approx 5\%$ uncertainty) and 677 background events (with $\approx 30\%$ uncertainty), for a purity of 85%. For decays to neutrinos, the large background from photon plus jet jet production is suppressed by requiring a photon with $p_T > 100$ GeV and $E_T^{miss} > 90$ GeV. The direction of $E_T^{miss}$ must be opposite the photon $[\Delta \phi(E_T^{miss}, \gamma) > 2.6]$ and not in the direction of a jet $[\Delta \phi(E_T^{miss}, jet) > 0.4]$. Background from W-boson production is suppressed by removing
The highest rate of diboson production is $W\gamma$, producing more than 10000 signal events after event selection. The selection requires an electron or muon, a photon, and large $E_{T}^{miss}$, giving a purity of ≈ 60%. As with the $Z\gamma$ measurements, fiducial cross sections are measured inclusively in jets and in events with no reconstructed jets (Table 2). The measured inclusive cross section is more than 2σ higher than the MCFM prediction, due to the upper limit of one additional parton produced by MCFM. The agreement with MCFM is improved in events with no reconstructed jets, though the cross section measurement is still higher than the prediction. The differential cross section with respect to photon $E_{T}$ (Fig. 5) shows a discrepancy with MCFM that increases with increasing photon $E_{T}$, as with the $Z\gamma$ measurement.

### Table 1: The measured and predicted $Z\gamma$ cross sections in the $\ell\ell\gamma$ and $\nu\nu\gamma$ final states, for events inclusive in jets and events with no jets

| Final state                  | Measured $\sigma_{fid}$ (pb) | $\sigma_{fid}^{SM}$ (pb) |
|-----------------------------|-------------------------------|--------------------------|
| $\ell\ell\gamma$ (≥ 0 jets) | $1.30 \pm 0.03$ (stat.) ± 0.11 (sys.) ± 0.05 (lum.) | $1.18 \pm 0.05$ |
| $\ell\ell\gamma$ (0 jets)  | $1.05 \pm 0.02$ (stat.) ± 0.10 (sys.) ± 0.04 (lum.) | $1.06 \pm 0.05$ |
| $\nu\nu\gamma$ (≥ 0 jets) | $0.133 \pm 0.013$ (stat.) ± 0.020 (sys.) ± 0.005 (lum.) | $0.156 \pm 0.012$ |
| $\nu\nu\gamma$ (0 jets)   | $0.133 \pm 0.013$ (stat.) ± 0.020 (sys.) ± 0.005 (lum.) | $0.115 \pm 0.009$ |

Events with an identified electron or muon. This selection yields 420 signal events (with ≈ 15% uncertainty) and 670 background events (with ≈ 10% uncertainty), for a purity of just under 40%. The purity is increased to 55% by requiring the events to have no reconstructed jets. The $Z\gamma$ measurements are performed both inclusively in jets and exclusively using events with no jets.

The measured $Z\gamma$ fiducial cross sections are consistent with the MCFM predictions, as shown in Table 1. In the $\ell\ell\gamma$ final state, the cross section is measured differentially in jet multiplicity, photon $E_{T}$, and invariant mass of the $\ell\ell\gamma$ system. Figure 4 shows good agreement between the measurement and the predictions of MCFM or Sherpa, though MCFM tends to underestimate the rate of events with photons at high $E_{T}$. These can arise from higher-order production of quarks that radiate a high-momentum photon. Sherpa is generated with tree-level diagrams of up to three additional quarks or gluons (partons), whereas MCFM has at most one additional parton in this distribution.

Events with a reconstructed photon with $E_{T} > 100$ GeV are used to set limits on anomalous $ZZ\gamma$ or $Z\gamma\gamma$ vertices, with limits significantly improved over those of CDF and D0 at the Tevatron.

### 6 Wγ measurements

Figure 4: The differential cross sections for $Z\gamma \rightarrow \ell\ell\gamma$ production as functions of photon $E_{T}$ (left) and jet multiplicity (right).

The highest rate of diboson production is $W\gamma$, producing more than 10000 signal events after event selection. The selection requires an electron or muon, a photon, and large $E_{T}^{miss}$, giving a purity of ≈ 60%. As with the $Z\gamma$ measurements, fiducial cross sections are measured inclusively in jets and in events with no reconstructed jets (Table 2). The measured inclusive cross section is more than 2σ higher than the MCFM prediction, due to the upper limit of one additional partons produced by MCFM. The agreement with MCFM is improved in events with no reconstructed jets, though the cross section measurement is still higher than the prediction. The differential cross section with respect to photon $E_{T}$ (Fig. 5) shows a discrepancy with MCFM that increases with increasing photon $E_{T}$, as with the $Z\gamma$ measurement.
Table 2: The measured and predicted $W\gamma$ cross sections in the $\ell \nu \gamma$ final state, for events inclusive in jets and events with no jets [6].

| Final state | Measured $\sigma_{fid}$ (pb) | $\sigma_{SM}^{fid}$ (pb) |
|-------------|------------------------------|--------------------------|
| $\ell \nu \gamma$ (≥ 0 jets) | $2.77 \pm 0.03$ (stat.) $\pm 0.33$ (sys.) $\pm 0.14$ (lum.) | $1.96 \pm 0.17$ |
| $\ell \nu \gamma$ (0 jets) | $1.76 \pm 0.03$ (stat.) $\pm 0.21$ (sys.) $\pm 0.08$ (lum.) | $1.39 \pm 0.13$ |

Figure 5: Left: The differential $W\gamma \rightarrow \ell \nu \gamma$ cross section as a function of photon $E_T$ [6]. Right: Limits on anomalous couplings compared to those from D0 and LEP [6].

Anomalous couplings are probed using events with photon $E_T > 100$ GeV. The resulting limits on $\lambda_\gamma$ and $\Delta \kappa_\gamma$ are shown in Fig. 5 for $\Lambda = 6$ TeV and $\Lambda = \infty$, assuming all other couplings have their SM values.

7 Summary

ATLAS has measured diboson cross sections in $\sqrt{s} = 7$ and 8 TeV, including a number of unfolded differential cross sections. The cross sections are sensitive to higher order perturbative QCD predictions, and demonstrate the importance of including multiple partons in the predictions. Anomalous coupling limits have been set using the results from $\sqrt{s} = 7$ TeV data.

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