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# Measurements of $W/Z$ vector bosons with associated jet production and ratios of cross sections with ATLAS

**Rhys Edward Owen*** **on behalf of the ATLAS collaboration**
*University of Birmingham (UK), Rutherford Appleton Laboratory (UK)*
*E-mail:* rhys.owen@cern.ch

Measurement results for vector boson with associated jet production cross sections and cross section ratios are presented, including results from both 7 and 13 TeV centre of mass energies. The data is also compared with predictions from Monte Carlo generators in preparation for Run 2 analyses.

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## 1. Introduction

Measurements of vector boson with associated jet production provide an important benchmark for performance at a hadron collider covering the reconstruction or electrons and muons as well as hadronic jets and missing transverse energy.

The vector boson decays are well understood in electroweak theory and measured at several experiments. For the $Z$ boson especially the leptonic decay into two electrons or muons provides a clear signal in the detector with which to select the events. The number of jets produced in association with the boson as well as their kinematic properties can then be measured. These measurements provide a powerful test of perturbative QCD calculations and can be used as a benchmark for various Monte Carlo generators.

These analyses follow a similar strategy identifying the leptons produced from the vector boson decay then also selecting the jets present in the event.

For the $Z$ boson leptons are selected with a $p_T$ greater than 20 GeV for the $\sqrt{s} = 7$ TeV analysis [1] and $p_T$ greater than 25 GeV at $\sqrt{s} = 13$ TeV [2]. The leptons are further required to fall within pseudo rapidity $|\eta| < 1.37$ or $1.52 < |\eta| < 2.4$ for electrons and $|\eta| < 2.4$ for muons. Additional requirements are placed on the selected leptons: that they have the opposite charge, have a separation[1] $\Delta R_{\ell\ell} > 0.2$ and have an invariant mass in the region of the $Z$ mass $66\ \text{GeV} \leq m_{\ell\ell} \leq 116$ GeV.

The selection for the $W$ boson requires a single lepton with $p_T > 25$ GeV in the same $|\eta|$ range [3]. The events are then required to have $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV. The transverse mass[2] between the lepton and the missing transverse energy is required to be greater than 40 GeV.

Once the vector boson has been selected the jets present in the event are selected. These are required to have $p_T > 30$ GeV be within the rapidity range $|y^{jet}| < 4.4$ and to have a separation of $\Delta R_{\ell j} > 0.5$ from any leptons passing the selection criteria.

Once the events have been selected the results are then unfolded to the particle level. This allows the data to be easily compared with several predictions both from direct calculations as well as Monte Carlo generators.

## 2. 13 TeV Results

For this analysis ATLAS [4] has collected 85 pb$^{-1}$ of data at $\sqrt{s} = 13$ TeV which provides an opportunity to study these vector boson processes at a higher energy than previously studied.

### 2.1 $Z$ boson production with associated jets

The analysis selection is described above and was performed alongside the inclusive cross-section measurement.

Figure 1 shows the fiducial cross section as a function of the inclusive jet count. Predictions are shown from SHERPA v2.1.1 [5] and MADGRAPH5_aMC@NLO v2.2.2 [6] . The results for the electon and muon channels are combined using the HERAVERAGER [7, 8] program.

[1] $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

[2] $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$

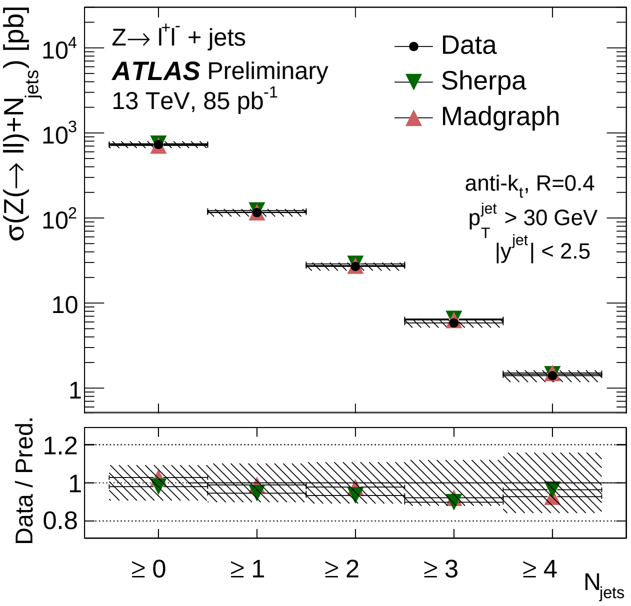


**Figure 1:** Fiducial cross sections for $Z \to \ell^+\ell^-$ production associated with at least $N$ jets. Results for both electron and muon channels have been combined. [2]. Below the plot the ratio of the prediction divided by the data value is shown.

## 3. 7 TeV Results

Vector boson production with associated jets has also been measured using the available 7 TeV dataset of 4.6 fb$^{-1}$. This dataset provides much greater statistics than the inital 13 TeV results and the opportunity for more detailed studies.

### 3.1 *Z* boson production with associated jets

With much higher statistics provided by this dataset the analysis of the $Z$ boson production cross section also performed measurements of several kinematic variables of the events as a function of the number of jets.

These variables are important as they hint at the underlying reasons for the differences between predictions and data as well as between different predictions themselves.

The data were unfolded to the particle level and then compared with three different predictions. Two Monte Carlo generators were used: SHERPA 1.4.1 [5] and ALPGEN v2.13 [9] which provide a leading order (LO) matrix element for $Z$+up to 3 jets and further jets are generated by the parton shower. A fixed order next to leading order (NLO) calculation is also compared from the BLACKHAT + SHERPA [10, 11, 12] tool.

The third jet in a given event can be important for the selection of vector boson fusion (VBF) produced Higgs events where $Z$+ jets can be a significant background reduced by placing a veto on a third central jet after the two forward jets associated with the VBF production [13]. Good modelling of the kinematic variables for the third jet can be used to improve the rejection of these events from such analyses as shown in Figure 2.

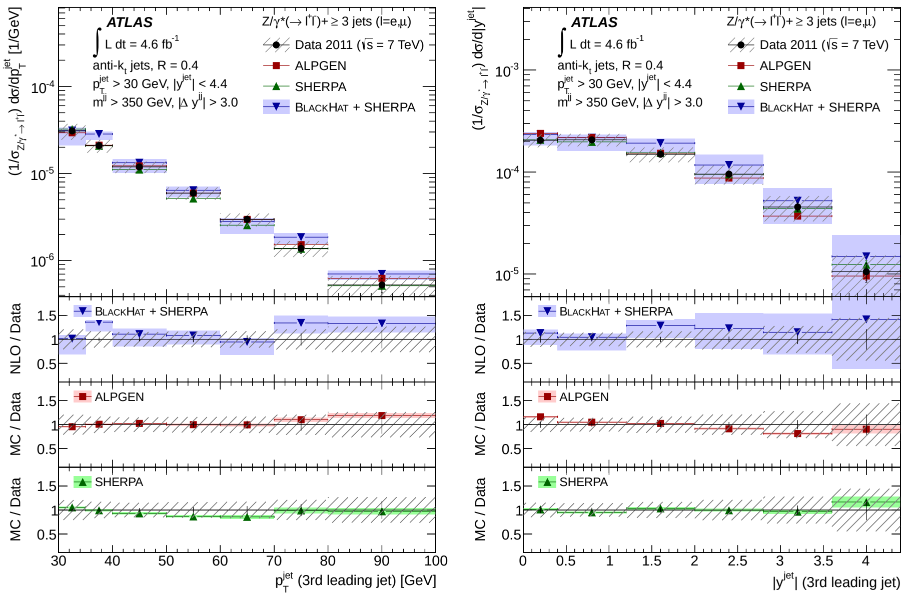


**Figure 2:** Measured cross section for $Z \to \ell\ell$ in association with jets as a function of the transverse momentum of the third jet (left) and as a function of the absolute value of the rapidity of the third jet (right) [1]. Below each plot the ratio of the prediction divided by the data value is shown.

### 3.2 $W$ boson production with associated jets

A similar analysis was also performed using the $W$ boson instead of $Z$ boson. This leads to a much more challenging analysis, without the clear tag of two leptons in the final state there is a much larger number of background events in the signal region.

Reflecting this more challenging analysis the measurement has a larger systematic uncertainty ranging from 8% to 25% for events containing $W$ boson production in association with 1 to 4 jets respectively.

This analysis used the same sources of predictions as the 7 TeV $Z$+jets analysis, SHERPA, ALPGEN and BLACKHAT + SHERPA. Two additional predictions were obtained from MEPS@NLO [14] and HEJ [15, 16]. MEPS@NLO provides a NLO prediction for up to two jets with LO matrix elements for up to four. HEJ is based on a perturbative calculation for $W$ boson production with at least 2, 3 or 4 jets. The resulting cross sections and comparisons with the predictions can be seen in Figure 3.

### 3.3 Ratio of production cross sections of $W$ bosons and $Z$ bosons with associated jets

Some of the experimental uncertainties from the $W$ boson and $Z$ boson with associated jets analyses can be cancelled by taking the ratio of the two measurements. Doing so produces an overall uncertainty of 1.2% to 18% for vector boson production with 1 to 4 associated jets. This comparison can be done both for the cross sections as well as for the kinematic variables within specific bins of jet multiplicity as shown in Figure 4.

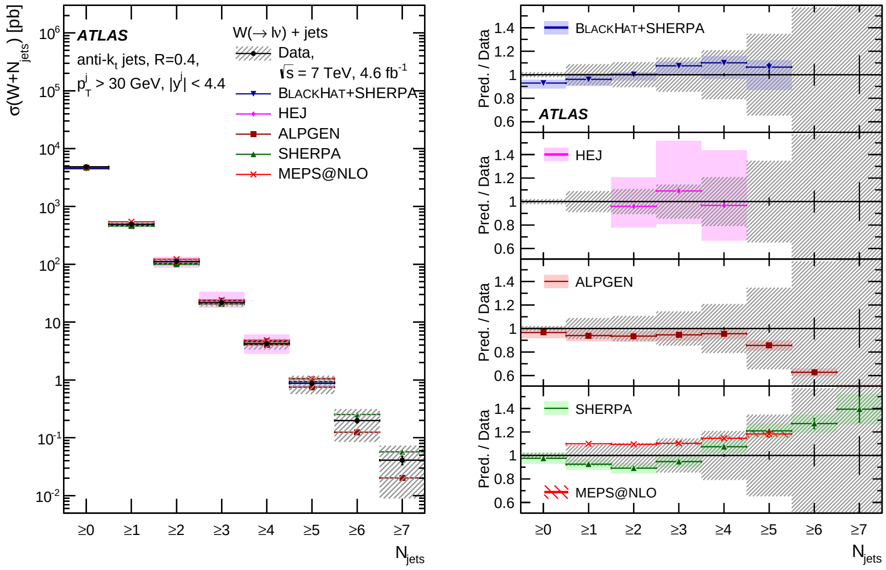


**Figure 3:** Cross section for the production of $W \to \ell\nu$ associated with N jets as a function of the inclusive jet multiplicity [3]. The absolute value of the cross section is shown (left) as well as ratios of the predicted divided by the measured cross sections (right)

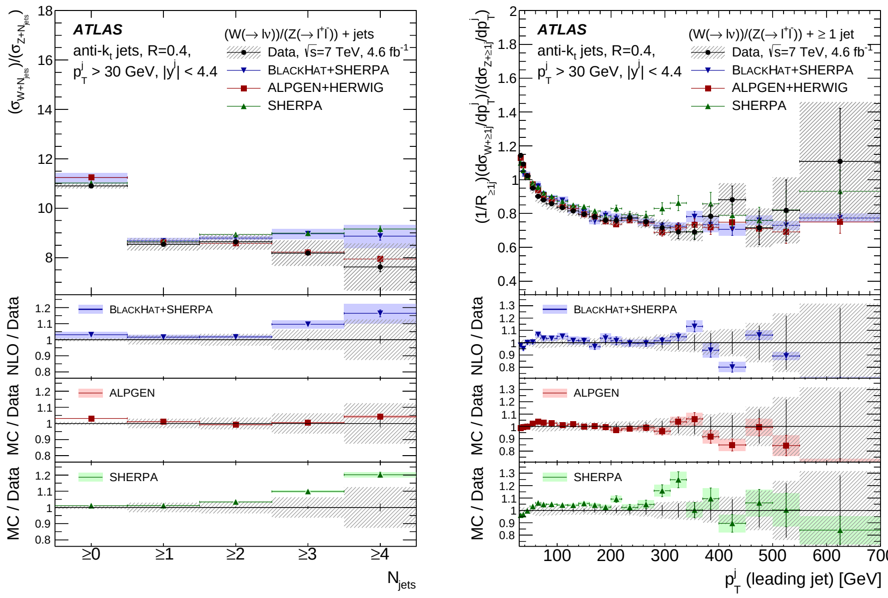


**Figure 4:** The ratio of $Z$ boson and $W$ boson production cross sections in association with jets as a function of inclusive jet multiplicity (left) and leading jet $p_T$ (right) [17]. Below each plot the ratio of the prediction divided by the data value is shown.

## 4. Data Comparison with Monte Carlo Generators for Run 2

Due to the unfolded nature of the data used in these analyses it is possible to perform updated comparisons to investigate the performance of the latest Monte Carlo generators for use in new analyses at Run 2 of the LHC.

In order to do this the unfolded data from the 7 and 13 TeV $Z$+ jets analyses were taken and compared with a new set of generators.

SHERPA 2.1 and 2.2 are used; these provide NLO matrix elements for up to two jets and LO matrix elements for up to four jets with higher multiplicities generated using the SHERPA model of the parton shower. Double counting between the matrix elements and the parton shower is avoided using the CKKW-L procedure [18] with a merging scale of 20 GeV. Version 2.2 represents a change of parton distribution function (pdf) set from NLO CT10 to NNLO NNPDF 3.0 [19] as well as redefined tuning of final state radiation and hadronisation parameters to better match LHC data.

MADGRAPH5_AMC@NLO+PYTHIA8 CKKW-L samples were produced using Madgraph5_aMC@NLO v2.2.2 interfaced with Pythia v8.186. LO matrix elements are used for up to four jets. The CKKW-L matching and merging scheme is again used but with the merging scale set to 30 GeV. Two tunes of this setup are used, firstly using the NNPDF v2.3 LO pdf set referred to as the A tune. The second B tune includes updates to Madgraph5_aMC@NLO v2.2.3, Pythia v8.210 as well as moving to the NNPDF 3.0 [19] NLO pdf set.

MADGRAPH5_AMC@NLO with FxFx merging[20] were generated using Madgraph5_aMC@NLO to generate vector boson with up to 2 jets at NLO accuracy with fixed jet multiplicities. The different multiplicities are then merged using the FxFx prescription which merges events from the matrix elements with one fewer and greater matrix elements to retain the NLO accuracy of the calculations though to the inclusive merged sample.

Selected results of this comparison can be seen in Figure 5 for two variables measuring the separation of the leading two jets of an event. These distributions show clear differences between the different Monte Carlo samples described above.

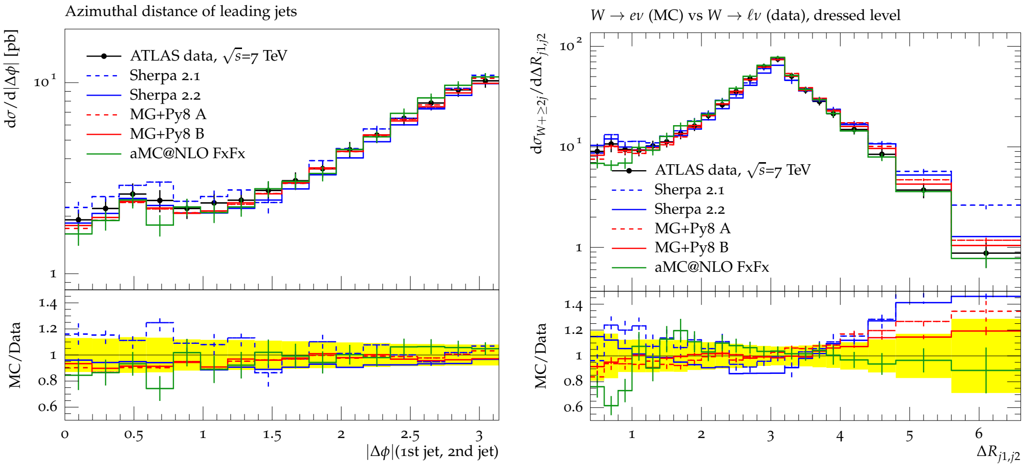


**Figure 5:** Separation of the two leading jets in azimuthal angle for the 7 TeV $Z$ boson analysis (left) and in $\Delta R$ for the 7 TeV $W$ boson analysis (right) [21] Below each plot the ratio of the prediction divided by the data value is shown.

## 5. Conclusions

Vector boson with associated jet measurements are an important tool at hadron colliders for testing perturbative QCD. The ATLAS experiment has a wide range of results from new measurements at 13 TeV to comprehensive studies and ratios of cross sections from the 7 TeV data. All of this information continues to be useful for analyses across the experiment in benchmarking the accuracy of different Monte Carlo generators.

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