Studies of vector boson+jet production with the ATLAS detector

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The production of jets or b-jets in association with a W or Z boson in proton-proton collisions at 7 TeV at the LHC is an important test of quantum chromodynamics (QCD). Electron and muon decay channels of the Z and W bosons are studied. Cross sections have been measured up to high jet multiplicities with the ATLAS detector on data samples with integrated luminosities between 33 pb^{-1} and 37 pb^{-1}. These measurements were compared to new higher-order QCD calculations. The ratio of (W + a single jet)/(Z + a single jet) has also been measured. Overall, the cross sections demonstrate the need for the inclusion of higher-multiplicity matrix elements in the calculations.

1 Introduction and motivation

Measurements of the production of jets in association with a W or Z boson constitute a stringent set of tests of our understanding of the Standard Model and quantum chromodynamics (QCD). It is particularly interesting to perform such measurements in the high energy regime of the LHC and compare them to both leading-order (LO) and next-to-leading-order (NLO) predictions. Measurements of vector boson+jets cross sections with improved precision also benefit other measurements for which they are important backgrounds, such as measurements in the top sector and searches for new phenomena beyond the Standard Model.

2 Data and Monte Carlo event samples

The data used for all measurements discussed here was collected with the ATLAS detector [1] in 2010. In all cases here, the vector bosons decay via leptonic channels, where "lepton" is taken to mean electron or muon. The data event samples were collected via single lepton triggers in the ATLAS trigger system. Electrons are chosen to have transverse momentum $p_T > 20$ GeV and pseudorapidity ($|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$) to avoid the calorimeter transition region. Muons are chosen to have $p_T > 20$ GeV and $|\eta| < 2.4$. Jet candidates are reconstructed using an anti-k_T algorithm with radius parameter R=0.4 and are chosen to have $p_T > 30$ GeV and rapidity $|y| < 4.4$. A minimal distance requirement given by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ >0.5 or 0.6, according to the analysis, is applied between the jets and the leptons. In cases with a Z boson decaying to a lepton pair, the invariant mass of the pair of leptons is restricted to a mass window around the Z mass of 66 GeV $< m_{ll} <$ 116 GeV. In cases with a W boson decaying to a lepton l and a neutrino ν, events are further required to have missing transverse energy $E_T^{miss} > 25$ GeV and a transverse mass $m_T = \sqrt{2p_T^l p_T^\nu (1 - \cos(\phi^l - \phi^\nu))} > 40$ GeV.

Results are compared to the predictions at LO from Monte Carlo event generators PYTHIA [2], SHERPA [3] and ALPGEN [4] and at NLO from Monte Carlo generators BlackHat(+SHERPA)[5] and MCFM [6], as well as calculations in the 5 flavour number scheme (5FNS) [7].

3 Z+jets and W+jets cross sections

Cross section measurements of the production of jets in association with Z and W bosons were performed as a function of many variables [8, 9]. The experimental cross section measured as a function of any one of many variables, here denoted generically as ξ, is given by

$$\frac{d\sigma}{d\xi} = \frac{1}{\mathcal{L}}\frac{1}{\Delta\xi}(N_{data} - N_{backg}) \times U(\xi),$$

where $\mathcal{L}$ is the integrated luminosity of the data sample, N_{data} is the number of observed events in an interval $\Delta\xi$, N_{backg} is the estimated number of background events in this interval and $U(\xi)$ is an unfolding factor. Background contributions from Standard Model processes are estimated using a combination of LO Monte Carlo event samples with the exception of the multijet background from QCD, which is estimated from data. The cross section measurements are unfolded bin-by-bin to particle level, using LO Monte Carlo signal samples to derive the values of the correction factors $U(\xi)$. These factors range in value from 0.9 to 1.5. Dominant systematic uncertainties on these measurements come from the jet energy scale and resolution (10-20%) and the uncertainty on the unfolding factor, which goes up to 5% at high jet p_T and multiplicity.

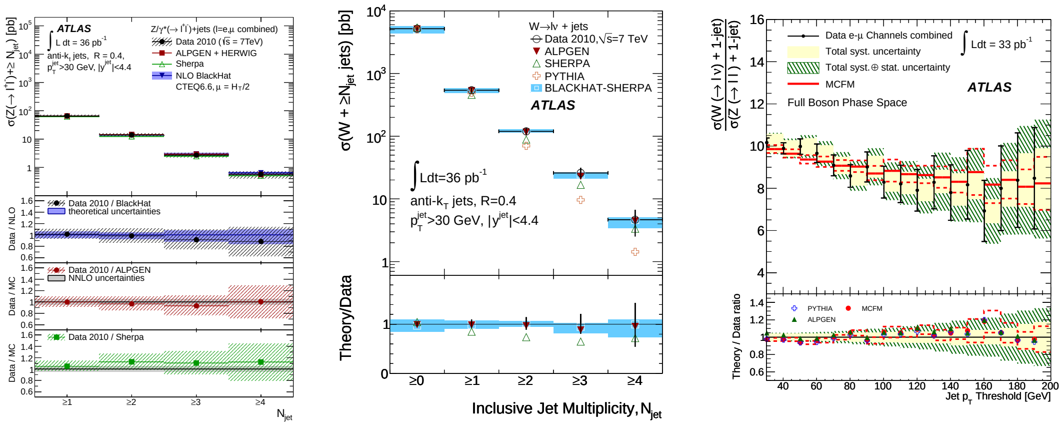

Figure 1: (left) Measured cross section $\sigma_{N_{jet}}$ for Z/gamma* $(\to l^+l^-)$+jets production as a function of the inclusive jet multiplicity for the combined electron and muon channels [8]. (centre) W+jets cross section for the combined electron and muon channels as a function of corrected jet multiplicity [9]. (right) Ratio of the vector boson + 1 jet cross sections extrapolated to the total phase space [10]. All the measurements are compared to theoretical predictions.

In Figure 1 (left), the measured cross section $\sigma_{N_{jet}}$ for Z/gamma* ($\rightarrow l^+l^-$)+jets production as a function of the inclusive jet multiplicity is compared to predictions. It is well-matched by all the theoretical predictions from Monte Carlo generators. Cross sections with respect to other variables such as jet transverse momenta and rapidities are also well-described by Monte Carlo models, in particular BlackHat.

In Figure 1 (centre), the measured W+jets cross section for the combined electron and muon channels as a function of corrected jet multiplicity is compared to predictions. BlackHat-SHERPA and ALPGEN provide good descriptions of the behaviour of the data while SHERPA and PYTHIA fall off more steeply than data.

4 Ratio of vector boson + single jet cross sections

The ratio of (W+single jet) cross section to the (Z+single jet) cross section was measured as a function of the jet p_T threshold [10]. This measurement is designed to maximize the cancellation of experimental systematic uncertainties. Here, the jet pseudorapidity is limited to the region $|\eta| < 2.8$ and the range of allowed dilepton invariant masses is 71 GeV $< m_{ll} <$ 111 GeV. Estimated background event yields are subtracted from the observed event counts to obtain the signal estimate $N^{l,V}_{sig}$ for each lepton l and each boson V. The particle level event count $N^{l,V}_{part}$, is obtained by applying a correction that accounts for the trigger, lepton reconstruction and boson reconstruction efficiencies, and the boson resolution. The cross section ratio is then given by $R_{jet} = (N^{l,W}_{part}/N^{l,Z}_{part}) \times C^l_{jet}$ where C^l_{jet} is a correction factor accounting for all remaining non-cancelling effects related to lepton and jet selection criteria. Systematic uncertainties on the measurement of the ratio range from 4% at low jet p_T to 15% at high p_T. The main contribution comes from systematic uncertainties on the boson reconstruction.

The measurement of the cross section ratio as a function of jet p_T threshold, extrapolated to the full boson phase space, is shown in Figure 1 (right). It is compared to an NLO prediction from MCFM. The prediction is found to be in good agreement with data over the range of jet p_T thresholds investigated.

5 Z+b jets and W+b jets cross sections

Cross sections were also measured in the particular case of the production of a Z or W boson in association with b-jets [11, 12], of particular interest as probes into the heavy sector. To perform these measurements, in addition to the data selection highlighted above for leptons, events were required to contain at least one jet with $p_T > 25$ GeV in the rapidity region $|y| < 2.1$, tagged as a b-jet by a secondary vertex tagger (SV0) [13], calibrated to give 50% b-tagging efficiency. The b-jet signal yield is extracted from template fits to the behaviour of the tagger. The systematic uncertainty associated to the b-tagging efficiency, approximately ±10%, is a dominant systematic uncertainty for the measurements in both the Z and W cases. Acceptance and/or unfolding factors were extracted from leading-order signal Monte Carlo samples. The uncertainty on the model dependence of the correction factors is the other dominant systematic uncertainty in the Z boson case, while in the W boson case the systematic uncertainty on the background estimate forms the other dominant systematic uncertainty.

The measurements of the inclusive cross section for the production of a Z boson in association with b-jets as well as the average number of b-jets produced per Z boson (i.e. the ratio of this cross section to the inclusive Z+jets cross section) are given in Table 1. The measurements are

	Cross section (pb)	Number of b-jets per Z boson
Experiment	$3.55^{+0.82}_{-0.74}$(stat)$^{+0.73}_{-0.55}$(syst)±0.12(lumi)	$(7.6^{+1.8}_{-1.6}$(stat)$^{+1.5}_{-1.2}$(syst)) $\times 10^{-3}$
MCFM	3.88± 0.58	(8.8± 1.1)$\times 10^{-3}$
ALPGEN	2.23± 0.01(stat only)	(6.2± 0.1(stat only))$\times 10^{-3}$
SHERPA	3.29± 0.04(stat only)	(9.3± 0.1(stat only))$\times 10^{-3}$

Table 1: Experimental measurement and predictions of σ_b, the fiducial cross section for inclusive b-jet production in association with a Z boson and of the average number of b-jets produced per Z boson [11].

	Experiment (pb)	NLO 5FNS (pb)
1 b-jet	4.5 ± 1.3(stat)±1.3(syst)	$2.9^{+0.4}_{-0.8}$(scale)$^{+0.2}_{-0.0}$(PDF)$^{+0.2}_{-0.1}m_b \pm 0.2$ NP
2 b-jet	5.7 ± 1.3(stat)±1.4(syst)	$1.9^{+0.8}_{-0.4}$(scale)$^{+0.1}_{-0.0}$(PDF)$^{+0.1}_{-0.1}m_b \pm 0.1$ NP

Table 2: Experimental measurement and predictions of the fiducial cross section for the production of a W boson in association with b-jets, converted to one lepton flavour. The uncertainties on the prediction arise from the choice of factorization and renormalisation scales (scale), parton distribution functions (PDF) and b-quark mass (m_b), and from non-perturbative corrections (NP) [12].

compared to NLO predictions from MCFM and LO predictions from ALPGEN and SHERPA. MCFM provides predictions that are compatible with the experimental measurements whereas the LO predictions, being also compatible within the uncertainties of the measurement, differ significantly from each other.

The measurements of the cross section for the production of a W boson in association with 1 or with 2 b-jets are presented in Table 2 and compared to 5FNS NLO predictions. The predictions fall below the observed cross section, but are compatible within the uncertainty.

6 Summary and conclusions

The ATLAS experiment has performed many measurements of the production of jets in association with vector bosons. These constitute a series of precision tests of the Standard Model. Overall, these measurements show good agreement with LO predictions and improved agreement when higher-order matrix elements are included in the calculation of these predictions.

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