PROCEEDINGS OF SCIENCE

Measurement of W/Z boson + heavy quark production at ATLAS

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Measurement of vector boson + heavy quark production is an important test of QCD, providing probes of higher order QCD processes and measurements of the heavy flavour content of the proton. Cross-sections are measured for Z+b and W+b production. For W+b they are also presented differentially as a function of jet multiplicity and transverse momentum of the leading b-jet. The results are compared to the QCD predictions at NLO.

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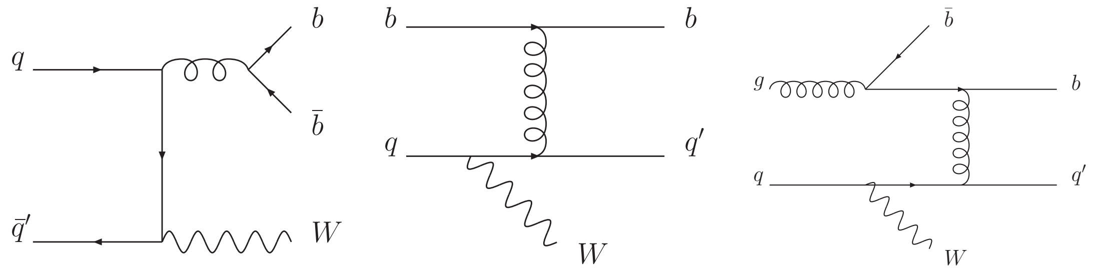


Figure 1: (a) and (b): Leading-order parton-level processes for the production of a W boson and one or two jets with at least one b jet, and (c) example of Wbj production appearing at NLO. [3]

1. Introduction

The measurement of vector boson (V) plus heavy quark production is an important test of perturbative quantum chromodynamics (QCD). Several processes contribute significantly at next-to-leading order (NLO) allowing the study of the content of parton distribution functions (PDFs). Example Feynman diagrams for the production of W+b production are shown in Fig. 1. With the results of these measurements the different flavour number schemes and calculation approaches can be tested [1]. Furthermore, V + heavy quark production is an important background to Higgs, top quark and beyond Standard Model measurements.

NLO calculations are available for W+b production in Monte Carlo (MC) simulations at parton level and enhanced with parton shower models (see [2] and references therein). The presence of b-quarks in the initial state which is theoretically described by a five-flavour number scheme plays a significant role at LHC energies. Double-parton interactions (DPI), in which the vector boson and b-jets are produced from different parton-parton interactions within the same pp collision, are also expected to contribute to the observed total cross-section.

In the following, measurements of W and Z + heavy quark production performed in pp collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV using the ATLAS experiment [4] are summarised. The cross-section measurements are presented, for the W+b result also differentially, and compared to theoretical predictions.

2. Experimental challenges

The ATLAS experiment is a multi-purpose particle detector at the Large Hadron Collider (LHC) at CERN. Particularly important for the identification of V + heavy quark processes is the identification of heavy quark jets. This is achieved by exploiting the long lifetime and mass of B-hadrons. These can experimentally be accessed by identifying particles from secondary vertices and measuring their impact parameter with respect to the primary vertex. The ATLAS pixel detector is crucial for this task. The technique used to identify b-jets is referred to as b-tagging. For the measurements presented here b-jets are identified with efficiencies around 50% for light-quark jet rejection rates of about 1000.

3. Analysis approach and event selection

Both the Z + heavy quark [5] and the W + heavy quark measurement [2] are performed within a fiducial volume. The Z+b analysis uses the 2010 ATLAS dataset with an integrated luminosity of $\mathscr{L} = 35$ pb^{-1} whereas the W+b analysis uses the 2011 dataset with $\mathscr{L} = 4.6$ fb^{-1}. The multi-jet background coming from hadronic jets identified as leptons (only electrons and muons are considered here) are completely determined from data. The shapes of all other backgrounds are taken from simulation, the normalisation obtained from sideband regions for the W+b measurement and from theory for the Z+b measurement due to limited data statistics. The heavy quark contribution in the W/Z sample is estimated fitting the b-tagging probability distribution for the W+b analysis and the secondary vertex mass distribution for the Z+b analysis.

For both analyses only jets in the central rapidity region, $|y| < 2.1$[1], with transverse momentum of $p_T > 25$ GeV are considered. Jets are reconstructed using the anti-k_T algorithm with a cut-off parameter $R = 0.4$. Leptons are required to have an absolute pseudo-rapidity $|\eta| < 2.5$. For the W+b analysis exactly one b-tagged jet is required while for the Z+b at least one b-tagged jet has to be selected. Additionally, each analysis applies cuts to reject background processes. In order to restrict the comparison to theory to the experimentally accessible region a selection as close as possible to the sensitive volume of the detector is implemented by a particle level selection, i.e. the Monte Carlo generator level closest to the measured objects. Based on MC studies this selection follows the reconstructed objects selection and defines the fiducial volume. Particle jets are considered to be b-tagged if a b-hadron is found within $\Delta R = 0.3$ of the jet axis.

4. Cross-section extraction and systematic uncertainties

In order to extract the cross-section, Bayesian unfolding to the particle level is performed with respect to the fiducial region accounting for trigger and object reconstruction efficiencies. AlpGEN Monte Carlo samples are used to obtain correction factors for events passing particle level selection but not reconstruction level and vice versa. In this way the measurement becomes largely independent of the underlying theory.

Many systematic uncertainties that might affect signal and background processes are taken into account. They are evaluated in pseudo-experiments. The dominant systematic uncertainties are related to the jet energy scale and resolution as well as b-tagging efficiencies and initial and final state radiation modelling. The Z+b measurement is statistically limited due to the rather small data sample analysed, the statistical uncertainty amounting to 22% and the systematic uncertainties to around 19%. The W+b measurement is systematically limited with a total uncertainty of about 20%.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y axis points upward. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe, referred to the x-axis. The pseudorapidity is defined in terms of the polar angle θ with respect to the beamline as $\eta = -\ln\tan(\theta/2)$. When dealing with massive jets and particles, the rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$ is used, where E is the jet energy and p_z is the z-component of the jet momentum.

Experiment	$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})$ pb
MCFM	3.88 ± 0.58 pb
AlpGEN	2.23 ± 0.01 (stat only) pb
SHERPA	3.29 ± 0.04 (stat only) pb

Table 1: Experimental measurement and Monte Carlo predictions of σ_b, the fiducial cross-section per lepton channel for inclusive b-jet production in association with a Z boson as described in the text. [5]

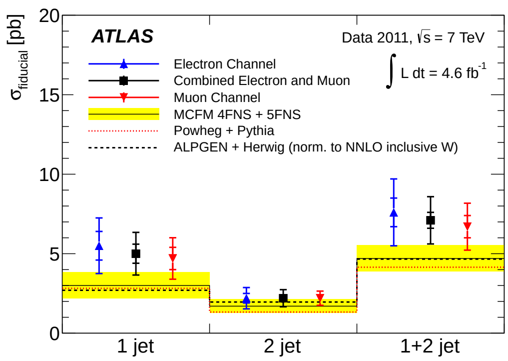


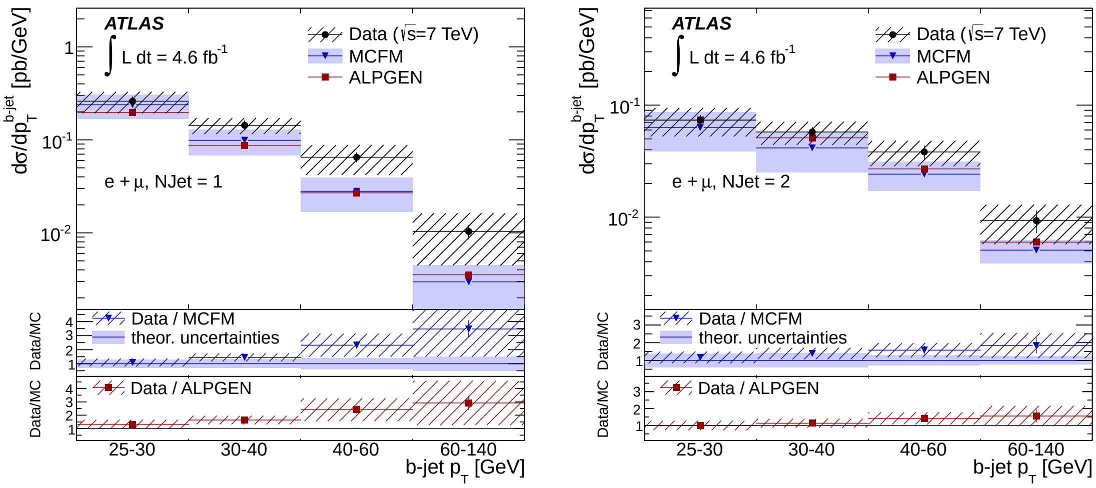
Figure 2: Measured fiducial W+b cross-sections with the statistical (inner error bar) and statistical plus systematic (outer error bar) uncertainties in the electron, muon, and combined electron and muon channels. The cross-sections are given in the 1-jet, 2-jet, and 1+2-jet exclusive final states. The measurements are compared with theory and corrected for hadronisation and DPI effects. [2]

5. Results

The results of the Z+b analysis are shown in Table 1. Apart from the intrinsic measurement uncertainties one can observe significant theoretical uncertainties quoted for MCFM only obtained from scale, PDF, and α_s variations as well as non-perturbative corrections. In addition to the cross-section result an additional measurement of the average number of b-jets produced in association with a Z boson has been performed, where again theory predictions differ significantly, but are in agreement with data (not shown here).

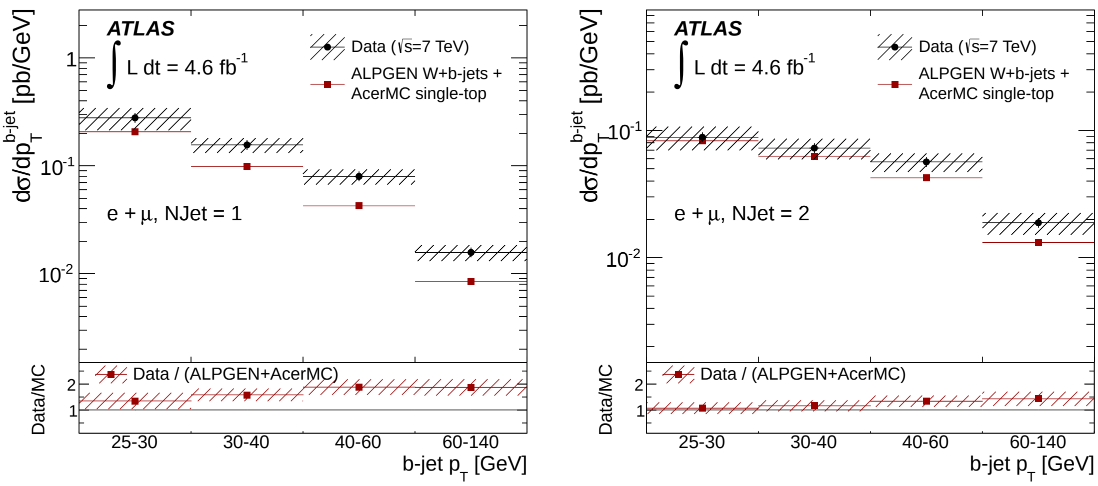
The results of the W+b measurement are shown in Fig. 2 and Table 2, where comparisons to different theory predictions are given. Data and MC agree within uncertainties but only after large double-parton interaction (DPI) corrections which increase predicted event yields by about 30% for events with 1 jet and 20% for events with 2 jets.

The measurement of the W+b differential cross-section, $d\sigma/dp_T$, is shown in Fig. 3. One can observe a small discrepancy at large p_T between data and prediction, which is, however, still covered by the uncertainties. The relatively large uncertainties in the plots are due to the subtraction of all expected background contributions. The measurement of the differential cross-section without subtracting single top prediction is shown in Fig. 4 and gives higher experimental precision demanding more precise theoretical predictions.



(a) (b)

Figure 3: Measured differential W+b-jets cross-sections with the statistical plus systematic uncertainties as a function of $p_T^{b-\mathrm{jet}}$ in the 1-jet (a) and 2-jet (b) fiducial regions. The measurements are compared to the MCFM predictions and to the AlpGEN predictions interfaced to Herwig and Jimmy and scaled by the NNLO inclusive W normalisation factor. The ratios between measured and predicted cross-sections are also shown. [2]



(a) (b)

Figure 4: Measured differential W +b-jets cross-section without single-top subtraction as a function of $p_T^{b-\mathrm{jet}}$ in the 1-jet (a) and 2-jet (b) samples, obtained by combining the electron and muon channels. The measurements are compared to the W+b-jets plus single-top predictions obtained using Alpgen interfaced to Herwig and Jimmy and scaled by the NNLO inclusive W normalisation factor plus AcerMC interfaced to Pythia and scaled to the NLO single-top cross-section. The ratios between measured and predicted cross-sections are also shown. [2]

Experiment 1 jet	5.0 ± 0.5 (stat) ± 1.2 (syst)
MCFM 1 jet	3.01 ± 0.07 (stat) $^{+0.72}_{-0.54}$ (scale) ± 0.04 (PDF) ± 0.08 (non-pert) $^{+0.40}_{-0.29}$ (DPI)
Experiment 2 jets	2.2 ± 0.2 (stat) ± 0.5 (syst)
MCFM 2 jets	1.69 ± 0.06 (stat) $^{+0.40}_{-0.23}$ (scale) ± 0.04 (PDF) ± 0.08 (non-pert) $^{+0.12}_{-0.09}$ (DPI)
Experiment 1+2 jets	7.1 ± 0.5 (stat) ± 1.4 (syst)
MCFM 1+2 jets	4.70 ± 0.09 (stat) $^{+0.60}_{-0.49}$ (scale) ± 0.06 (PDF) ± 0.16 (non-pert) $^{+0.52}_{-0.38}$ (DPI)

Table 2: Experimental measurement and NLO predictions for the $W+b$-jets fiducial cross-section in pb for one lepton flavour calculated with the MCFM program, corrected for non-perturbative effects and DPI contributions as described in the text. [2]

6. Conclusions

Measurements of W and Z + heavy quark production are presented, in which the heavy quark jets are identified using b-tagging techniques. All measurements are in agreement with theory predictions. The Z+b measurements promise smaller systematic uncertainties, but are currently statistics limited. For the W+b measurement using a larger data set a differential measurement of W+b $d\sigma/dp_T$ is also performed. The measurement of W+b plus single top reduces experimental uncertainties, but needs more input from theory.

References

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