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Measurement of the cross sections for the production of W and Z bosons in association with jets and heavy flavours in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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Preliminary measurements are presented of the cross sections for the production of W and Z bosons in association with jets in pp collisions at $\sqrt{s} = 7$ TeV. The measurements are based on 35 pb^{-1} of data collected with the ATLAS detector at the LHC. The cross sections are measured for the electron and muon decay channels of the W and Z bosons, and for jets reconstructed with the anti-k_t clustering algorithm. Jets containing b-hadrons are identified and measured. Inclusive and differential results are presented as a function of jet multiplicity and kinematics. A measurement of the ratio of the W and Z plus one jet production cross section is also presented. The results are compared with leading and next-to-leading order QCD predictions.

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The measurement of the cross sections for the production of electroweak bosons accompanied with hadronic jets is a fundamental ingredient for reestablishing the Standard Model (SM) in pp collisions at $\sqrt{s} = 7$ TeV. The higher centre-of-mass energy compared with previous experiments allows more jets in the final state with a wider kinematic reach. In addition, compared with the Tevatron, at the LHC processes initiated by qg and gg scattering give an more important contribution to the cross section. This is relevant for the production of heavy flavour where their presence in the initial state becomes important. For these reasons the measurements of $W/Z+$jets cross sections is a compelling test of perturbative quantum-chromodynamics (pQCD). $W/Z+$jets final states are the dominant signatures for the identification of a number of heavy particles produced at high energy, both in the SM and in models beyond the SM. For example, the top quark, both single- and pair-produced, is reconstructed from a final state with at least a W boson and a number of jets; and many signatures for the Higgs boson searches have a W or Z plus jets in the final state. The identification of these particles and the measurements of their properties requires an accurate description of the SM $W/Z+$jets production. Direct measurements of the $W/Z+$jets production rates are therefore important and will provide a better understanding of the SM background to new physics.

In this contribution, measurements are presented of the cross sections for the production of W and Z bosons in association with jets in pp collisions at $\sqrt{s} = 7$ TeV. The cross sections are measured for the electron and muon decay channels of the W and Z bosons, and for jets reconstructed with the anti-k_t clustering algorithm. The measurements are based on data collected during 2010 with the ATLAS detector at the LHC.

The ATLAS detector [1] consists of an inner detector tracking system (ID) ($|\eta| < 2.5$) surrounded by a superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters (η<4.9), and a muon spectrometer ($|\eta| < 2.7$). The dataset used corresponds to about 35 pb^{-1} with on average about 2 interactions per bunch crossing. The uncertainty on the integrated luminosity is 3.4% [2]. The events are collected using a single electron or muon high p_T trigger, with the offline selection lying well within the trigger efficiency plateau. All measurements presented here share a similar selection which is briefly described below. Additional details on the specific analyses can be found in the individual publications [3, 4, 5, 6, 7]. All events are required to have at least one primary vertex. Events are requested to have exactly one (for the W) or two (for the Z) isolated lepton with $E_T > 20$ GeV in the central region of the detector. The W boson is selected by requiring the missing transverse energy of the event to satisfy $E_T^{miss} > 25$ GeV, and the W transverse mass $m_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos(\phi^l - \phi^\nu))} > 40\ \mathrm{GeV}/c^2$. The Z boson is selected by requiring 2 leptons with opposite charge with their invariant mass satisfying $66 < m_{\ell\ell} < 116\ \mathrm{GeV}/c^2$. Jets are reconstructed using the anti-k_t clustering algorithm with a resolution parameter $R = 0.4$. Only central jets with $|y| < 2.8$ and $p_T > 20\ \mathrm{GeV}/c$ are considered. All jets with an angular separation $\Delta R < 0.5$ from a selected lepton are removed. All known instrumental effects are corrected for using Monte Carlo (MC) simulated events with full detector simulation [8] based on the GEANT4 [9] program. Differences between data and detector simulation are accounted for by applying scale factors to the MC events. The dominant correction factors to the $W/Z+$jets flavour-inclusive measurements come from the lepton trigger and identification efficiencies, which are measured in data using $Z \to \ell\ell$ [10]; and the E_T^{miss} and jet energy scale (JES), which is calibrated using simulated events [11]. All measurements are given in a phase space that is well covered by the detector acceptance and they are defined such to correspond to particle level cross sections. All stable particles ($\tau > 10$ ps) are used by the jet clustering algorithm with the exception of the W and Z decay products. b-jets are defined by the presence of a b hadron with $p_T > 5$ GeV$/c$ associated to the jet requiring ΔR(jet, b hadron)<0.3. Charged leptons are defined by including the energy of all radiated photons within a cone of radius $R = 0.1$ around the lepton. The neutrino p_T is used as the event missing transverse energy.

The dominant source of background to the $W/Z+$jets production is represented by multi-jet final states in the electron channel and by electroweak backgrounds in the the muon channel. The multi-jet background consists of events where one or more jets are incorrectly reconstructed in the detector as leptons, and, in the case of the W, have mis-measured energy, resulting in large event E_T^{miss}. The leptonic background consists of events which contain real leptons and/or neutrinos from boson decay and include single- and pair-produced top quark, di-boson (WW, WZ, ZZ), $W \to \ell\nu$, $Z \to \tau\tau$ (for Z) or $W \to \tau\nu$, $Z \to \ell\ell$ (for W). The total background contamination is within 5-10% in the Z+jets sample [4] and 10-20% in the W+jets sample [3]. In both cases it varies with the jet multiplicity and p_T. At low multiplicity the multi-jet background dominates, whereas the top background become important at high jet multiplicity. The electroweak backgrounds are evaluated with simulated events normalised to their next-to-leading (NLO) production cross section. The multi-jet background is estimated on data with techniques that vary for different channels. For $W \to e\nu$ channel, where the multi-jet background is higher, it proceeds as follows. A multi-jet background enriched sample is constructed by removing the E_T^{miss} requirement. Multi-jet, leptonic, and signal E_T^{miss} distributions are then fit to the data. The multi-jet sample is modeled using the analysis dataset by requiring that some of the electron identification criteria fail [3, 10].

The $W/Z+$jets production cross section is measured as a function of a number of variables including jet multiplicity, jet p_T, jet rapidity, and the sum E_T of all reconstructed objects in the event [3, 4]. The dominant systematic uncertainty arises form the JES which accounts for 8(26)% of the total uncertainty to the cross section for W with at least 1(4) jets. Additional sources of systematic effects, each accounting for about 2% or less, are the background subtraction, the lepton/jet reconstruction efficiency and energy resolution, and the modeling of the signal in the unfolding procedure. The results are in very good agreement with NLO pQCD prediction from MCFM [12]. The leading order calculations from ALPGEN [13] and SHERPA [14] reproduce within the uncertainties the shape of all differential cross sections, whereas PYTHIA [15] does not describe well the high jet multiplicity measurements.

Many of the experimental and theoretical uncertainties that affect individual $W/Z+$jets measurements are not present in their ratio. For the first time a measurement is presented of the ratio R_{jet} of the production cross sections of W and Z in association with exactly one jet [5]. The measurement is performed requiring exactly one jet with $|\eta| < 2.5$ as a function of the minimum p_T of the jet (p_T^{cut}) starting from 30 GeV$/c$. The results for the lowest $p_T^{cut} = 30$ GeV$/c$ in the electron and muon channels are:

$$R_{jet}(e) = 8.73 \pm 0.30(\text{stat}) \pm 0.40(\text{syst}); \quad R_{jet}(\mu) = 8.49 \pm 0.23(\text{stat}) \pm 0.33(\text{syst})$$

The measurements have a comparable statistical and systematic uncertainties of about 5% at the lowest $p_T^{cut} = 30$ GeV$/c$, whereas at the highest $p_T^{cut} = 200$ GeV$/c$ they become statistically limited whereas the systematic uncertainty remains at about 14%. Figure 1 (left) shows very good agreement of the NLO prediction from MCFM with the measurement along the whole p_T^{cut} range. LO predictions from ALPGEN and PYTHIA are also in good agreement with the measurement.

The b-jet content in $W/Z+$jets events has been measured and presented for the first time at this conference [6, 7]. Jets originating from b-quarks are identified by exploiting the long lifetime ($\sim$1.5 ps) and the large mass of b hadrons ($\sim$5 GeV). The algorithm used to tag b-jets (SV0) [16] is based on the decay length significance between the primary vertex and the displaced secondary vertex reconstructed in the jet. To ensure the jets are well within the tracking volume only jets with $|y| < 2.1$ are considered. In addition, jets are requred to have p_T>25 GeV$/c$. The selection efficiency for b-jets in the $W/Z+$jets sample is about 35% with a mistag rate of about 0.3% and 8% for light- and c-jets, respectively. The b-tagging efficiency and its systematic uncertainties are estimated by studying semi-leptonic B decays in QCD multi-jet events and top events [17]. The requirement of at least one jet to be b-tagged changes the composition of the backgrounds with respect to the $W/Z+$jets flavour inclusive measurements. In particular, the heavy-flavour jet production becomes the dominant process contributing to the multi-jet background, and the top events become the dominant background source at high jet multiplicity. These changes have a limited impact on the $Z+b$-jets where $S/B > 10$, whereas on $W+b$-jets the effect is very important, bringing $S/B \sim 0.5$. To cope with such backgrounds new techniques have been developed for the $W+b$-jets measurement. To reduce the multi-jet fraction to about 30% a very tight requirement is applied on the lepton isolation [6]. To mitigate the impact of the top production the measurement is performed separately requiring exactly one or two jets, one of which has to be b-tagged. The top background is then estimated in data requiring at least one b-tag and measuring the top yield in event with at least 4 jets (purity $\sim$ 95%). The top yield is then projected into the signal region using MC simulation. This method has the advantage to be almost independent of the b-tagging uncertainty. For both the W and Z analyses, a maximum likelihood fit to the secondary vertex mass m_{SV} is used to separate b-, c-, and light-jets and extract flavour fraction on a statistical basis. The m_{SV} templates are modeled with MC simulated events, and the systematic uncertainty associated to their shapes is evaluated comparing data and MC in multi-jet event samples enriched in light-, c- and b-jets. The fit is performed for all b-tagged jets in the electron and muon sample for the $Z+b$-jets measurement (Fig. 2 left), whereas it is separated for each lepton flavour and jet multiplicity bin for the $W+b$-jet measurement (Fig. 2 right).

The inclusive b-jet production cross section in association with a Z boson is measured to be:

$$\sigma(Z+b-\text{jets}) = 3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})\ \text{pb}$$

The dominant systematic uncertainties include the b-tagging and m_{SV} template ($\sim$ 10%), the $Z+b$-jet modeling ($\sim$ 10%), and the jet energy scale ($\sim$ 4%). The NLO MCFM prediction of 3.40 ± 0.44 pb is in good agreement with the measurement.

The cross section for the production of a W boson in association with b-jets is shown in figure 1 (right) in the 1, 2, and 1+2 jet exclusive bins. The dominant systematic uncertainties include those associated to the b-tagging and m_{SV} template ($\sim$ 16%), the top ($\sim$ 12%) and multi-jet ($\sim$ 7%) backgrounds, the $W+b$-jet modeling ($\sim$ 10%), and the jet energy scale ($\sim$ 7%). The measurements are compared with the NLO prediction obtained in the 5 flavour number scheme (5FNS) described in [18]. This calculation requires the combination of two contributions. The first contribution has a bb pair in the final state, and the b quarks are considered massive (4FNS). The second one has a b quark in the initial state and is treated in a scheme based on b quark PDFs where the b quark is assumed to be massless. The measurements, consistent with the NLO prediction within 1.5 σ, lie above the expectation.

In conclusion, with the first 35 pb^{-1} of data ATLAS has characterized the $W/Z+$jets physics in pp collisions at 7 TeV performing an extensive set of measurements. These measurements have been found to be well described by NLO pQCD predictions, and their differential behavior appropriately modeled in shape by LO event generators. The measurements with heavy flavours have a significant uncertainty, and will benefit from the high statistics dataset collected during 2011.

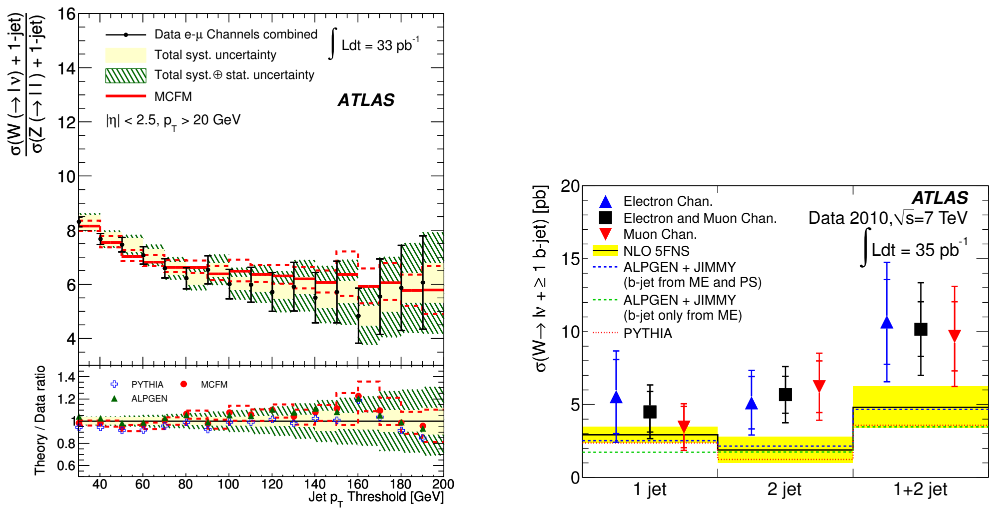

Figure 1: (left) The ratio R_{jets} of $W+1$ jet to Z+1 jet in the electron and muon combined channels as a function of p_T. The measurement (black points) is compared to prediction from MCFM (red line). The error bars on data represent the statistical error, the yellow band shows the systematic uncertainties, and the hashed green band represents the statistical and systematic uncertainties added in quadrature. The theory uncertainty (dashed red line) includes contributions from the parton density functions, the renormalization and factorization scale uncertainties [5]. (right) Measured cross section with the statistical (inner error bar) and statistical plus systematic (outer error bar) uncertainty in the electron, muon, and combined electron plus muon channel. The cross section is given in the 1, 2, and 1+2 jet exclusive bins. The measurements are compared with a NLO [19] predictions and with LO event generators. The yellow (shaded) band represents the total uncertainty on the prediction obtained by combining in quadrature the renormalisation and factorization scale, PDF set, and non-perturbative correction uncertainties [6].

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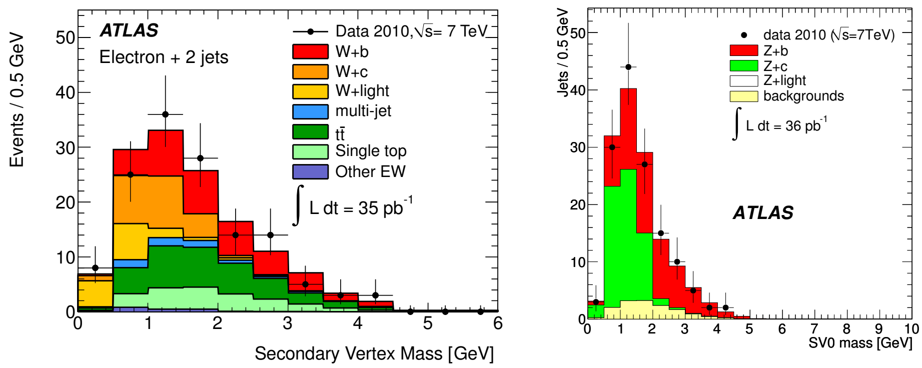

Figure 2: Secondary vertex mass distribution for b-tagged jets in the $W \to e\nu$+2 jets (left) [6] and in $Z \to \ell\ell + b$-jets (right) [7] selected events.

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