

Production of Jets in Association with W and Z at ATLAS

Maria Fiascaris^a on behalf of the ATLAS collaboration

^aParticle Physics Department, University of Oxford,
Keble Road, Oxford - United Kingdom

The study of final states with hadronic jets accompanying a W or Z boson is of high importance at hadronic colliders both to understand Standard Model processes and measure background contribution to Beyond the Standard Model searches. In view of the imminent start up of the LHC, we present the ATLAS prospects for the cross-section measurement of $W/Z + \text{jets}$ events in proton-proton collisions at 14 TeV centre of mass energy. The statistical and systematic limitations are discussed in terms of probing perturbative QCD predictions and Monte Carlo generators.

1. Introduction

The Large Hadron Collider (LHC) will shortly start colliding protons at a centre of mass energy of 14 TeV and will offer unprecedented opportunities to explore unknown kinematic regions and discover new physics. Its discovery capabilities, however, strongly depend on our understanding of the Standard Model (SM), in particular on precise predictions in Quantum Chromodynamics (QCD), the gauge theory of strong interactions which dominates much of the LHC physics.

Processes with $W/Z + \text{jets}$ in the final state are good candidates for testing QCD. The gauge boson mass ensures that the interaction scale is sufficiently large for applying perturbative calculations and the high production rate ensures abundant statistics for precise measurements. These studies are particularly important in view of new physics searches since hadronic jets with the leptonic decays of W and Z bosons are background to both SM and Beyond the SM searches, like top production and supersymmetry.

In this note we present a feasibility study for the $W/Z + \text{jets}$ cross-section measurement at ATLAS with 1 fb^{-1} of data, an integrated luminosity that should be accumulated within the first two years of running. The primary end-results are hadron-level cross-sections, which are compared to fixed order calculations at leading (LO) and next-to-leading order (NLO) in QCD and to parton shower Monte Carlo models. We concen-

trate on channels with decays into electrons and muons and use simulated signal and background Monte Carlo samples. After a description of the available tools to calculate the $W/Z + \text{jets}$ cross-section, data analysis techniques are presented. Event selection, backgrounds and major sources of systematic uncertainties are discussed. Finally a comparison between measurement and theoretical predictions is made.

2. Theoretical Predictions for $W/Z + \text{jets}$

At present NLO calculations for $W/Z + n$ jets can only be performed up to $n = 2$ jets, although calculations for $n = 3$ are underway. NLO is the first order at which the $W/Z + n$ jets production cross-sections have a reliable normalization [1]. Cross-sections for $W/Z + 0, 1$ and 2 (3) jet final states can be conveniently calculated at LO and NLO (LO only for $W/Z + 3$ jets) using the MCFM [2] program, and it is from this program that we determine our reference cross-sections. The MCFM cross-sections were generated using the CTEQ6.1 PDFs and a renormalization/factorization scale of $m_V^2 + p_{T,V}^2$ ($V = W, Z$), where $p_{T,V}$ is the transverse momentum of the vector boson.

The Monte Carlo datasets used as pseudo-data for the signal processes are generated with ALPGEN [3] interfaced with HERWIG [4] using the leading order PDF set CTEQ6LL [5]. The cross-sections are calculated using the same scheme



as for MCFM. The full datasets are obtained by merging samples of $W(Z) + 0$ up to 5 partons, weighted according to the expected cross-sections, using the MLM [3] prescription. W/Z production and background samples are produced with PYTHIA.

3. W and Z Event Selection

W and Z boson final states are selected through their leptonic decays. Events are triggered by requiring one (for W) or two (for Z) isolated leptons with transverse momentum p_T above a threshold (typically 15-25 GeV). For the Z offline selection the di-lepton invariant mass is required to be close to the Z mass peak, whereas the W selection requires a single electron/muon and transverse missing energy above 25 GeV. More details on electron and muon reconstruction algorithms at ATLAS can be found in [6].

Jets are reconstructed using the seeded cone algorithm with a radius of $\Delta R = 0.4$, built from calorimeter towers and calibrated to the hadron level.

3.1. Lepton Triggering and Reconstruction

The performance of trigger and reconstruction algorithms is extracted using the tag and probe method on $Z \rightarrow ll$ and its dependence on jet multiplicity and overall hadronic activity is investigated. In the presence of additional jets in the event, leptons are more boosted and the distance between leptons and jets becomes smaller. As a result, the larger acceptance deriving from the boost of leptons in a multi-jet environment almost balances the drop in efficiency caused by trigger isolation requirements. The total reconstruction (trigger + offline) efficiency is therefore stable with respect to both the jet multiplicity and the transverse momentum of the leading jet and it is overall only 1 – 2% lower than in the inclusive sample.

3.2. Backgrounds

The major source of background to W/Z +jets events is the production of QCD multi-jet final states where one or two jets fake a lepton candidate and, in the case of the W boson, a significant mismeasurement of the jet energy results

in large missing transverse energy. Other backgrounds are processes with real leptons, such as top production and $W \rightarrow l\nu$, $Z \rightarrow \tau\tau$ (for Z) or $W \rightarrow \tau\nu$, $Z \rightarrow ll$ (for W), where l is an electron or a muon.

The background contamination is at the level of 5 – 10% in the Z sample and slightly higher in the W sample. In both cases it varies with jet multiplicity, as shown in Fig.1 for $W \rightarrow e\nu$. At low multiplicity QCD multi-jets are the dominant background whereas $t\bar{t}$ takes over at high multiplicity.

Whereas the leptonic backgrounds can be reliably estimated by Monte Carlo techniques, jet production cross-section and fragmentation suffer from large theoretical uncertainties. Thus multi-jet background can only be estimated using data-driven techniques as explained in [7].

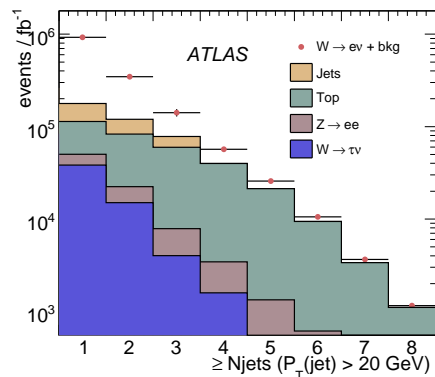


Figure 1. Inclusive jet multiplicity distribution for $W \rightarrow e\nu$ and backgrounds for jets with transverse momentum $p_T > 20$ GeV.

4. Systematic Uncertainties

The main sources of theoretical and experimental systematic uncertainties on the determination of W/Z + jets cross-section are parton distribution functions (PDFs) and jet energy scale

(JES) respectively. Additional sources of systematic errors are background subtraction, lepton/jet reconstruction efficiencies and energy resolution and non-perturbative effects (fragmentation and underlying event).

4.1. PDF Uncertainties

PDFs affect any cross-section calculation at the LHC, therefore their knowledge is vital for precise predictions of both SM and beyond the SM processes.

The effect of PDF uncertainties on physical distributions is investigated applying the PDF re-weighting technique. The ALPGEN datasets generated with the PDF set CTEQ6LL are re-weighted to the central value of CTEQ6M and the 40 error sets corresponding to the upper and lower uncertainty on each of the 20 eigenvectors. PDF uncertainties vary between 3% and 6% and exhibit a dependence on jet p_T and multiplicity, increasing at very low and very high transverse momentum and at high multiplicity.

4.2. Jet Energy Scale Uncertainties

ATLAS expects a limited precision of the jet energy scale in the first years, starting at the level of 10% and converging eventually to 1%. Three benchmark scenarios are obtained by propagating jet energy scale uncertainties of 1%, 5% and 10% into the measured cross-sections.

Figure 2 shows the relative uncertainties on the cross section as a function of cumulative jet multiplicity. As for the PDFs, jet scale uncertainties show a tendency to increase with the multiplicity. When the jet energy is miscalibrated by 1%, the experimental systematic uncertainties on the cross section remain within 5%, but they increase significantly with higher miscalibrations.

5. Method to Compare Theoretical Predictions with Data

One of the goals of this study is to evaluate the statistical and systematic precision of the $W/Z + \text{jets}$ cross-section measurement and compare this precision with the differences in the predictions of LO and NLO QCD calculations and with the predictions from matrix element and parton-shower generators. In this section we first

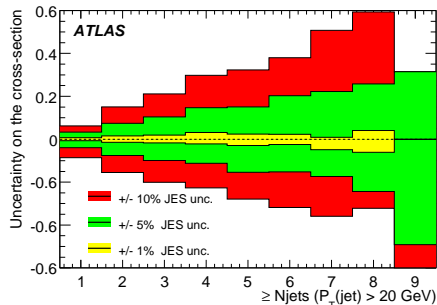


Figure 2. Uncertainties due to the jet energy scale on the $W \rightarrow e\nu$ cross-section as a function jet multiplicity.

compare MCFM predictions with ALPGEN and PYTHIA generators and then we compare these predictions to pseudo-data. We will focus here on the $Z + \text{jets}$ cross-section measurement.

5.1. Generator Comparison

Predictions for the inclusive jet cross-sections from the Monte Carlo Generators PYTHIA and ALPGEN are compared to fixed-order LO and NLO calculations from MCFM partonic level generator. The two Monte Carlo samples are normalized to the inclusive NLO Z cross-section, as determined in MCFM.

The effect of higher order corrections, extracted comparing NLO to LO MCFM predictions for $Z + 1, 2$ partons, are of the order of 20% – 30%. The difference between the predictions of PYTHIA and ALPGEN and between both generators and MCFM amounts to 10–60% depending on the jet multiplicity. Both Monte Carlo generators predict a lower cross-section than the NLO MCFM calculation for final states with more than one jet. PYTHIA predicts a larger $Z + 1$ jets cross-section than ALPGEN, but a lower average jet multiplicity. The difference between ALPGEN and PYTHIA depends on the shape of the jet p_T spectrum. While the jet p_T distribution predicted by ALPGEN agrees well with NLO MCFM predictions, PYTHIA generates a clearly softer spectrum.

5.2. Comparison Pseudo-Data to Theory

Fully simulated ALPGEN Z + jets samples equivalent to 1 fb^{-1} of integrated luminosity are treated as data for the cross-section measurement which is compared to fixed order calculations, such as MCFM. Comparison is performed at hadron-level, hence reconstructed data have to be unfolded for efficiency, resolution and non-linearities in electron and jet reconstruction. Systematic uncertainties stemming from unfolding corrections, background subtraction and jet energy scale are included in data, while errors from PDF uncertainties and non-perturbative effects are included in the MCFM predictions.

The uncertainty on the theoretical predictions and on the measured cross section are propagated to the data/theory ratio. Figure 3 shows the resulting uncertainty on a ratio of 1 for the inclusive cross-section. The systematic uncertainty from a jet energy scale uncertainty of 5% is twice as large as the sum of other systematic and statistical uncertainties. In this case the overall precision on the data to theory ratio expected with the first fb^{-1} is at the level of 8 – 15% for events with 1-3 jets. A jet energy scale uncertainty of 10% results in a total uncertainty of 15 – 30%, which is of the same order as the difference between LO and NLO predictions or between predictions from different generators.

6. Conclusions

Final states containing W/Z + jets will serve as a Standard Model benchmark at the LHC. We have considered cross-section measurements for theoretically well-defined quantities with the aim of probing perturbative QCD predictions and testing the performance of parton shower Monte Carlo models. Data analysis techniques, statistical and systematic errors on the cross-section measurements and on the ratio data/theory have been discussed. The dominant systematic error is expected to be the uncertainty on the jet energy scale. If ATLAS is successful at its goal of keeping the jet energy scale uncertainty within 1 – 2%, uncertainties on the cross-section would remain within 5%. However if the energy scale uncertainty is higher (for example at the level

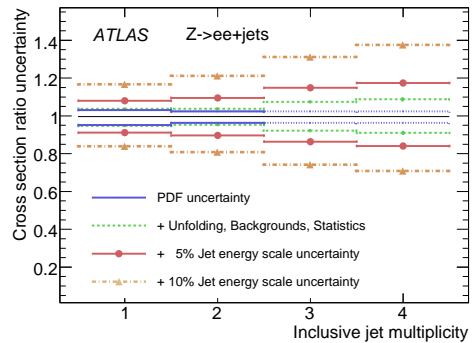


Figure 3. Uncertainty on the ratio between measurement and theory for the inclusive jet cross-section for $Z \rightarrow ee$.

of 5 – 10%), as it has to be expected with early data, uncertainties could be as large as 20 – 30%. This would limit the possibility of probing LO and NLO predictions and improving Monte Carlo generators and could hence deteriorate the ATLAS potentials for new physics discoveries at this early running phase.

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