Production of Jets in Association with Z Bosons

The ATLAS collaboration

Abstract

We simulate a measurement of the inclusive $Z(\rightarrow e^+e^-/\mu^+\mu^-) + \text{jets}$ cross-section with the ATLAS experiment in pp collisions at 14 TeV for an integrated luminosity of 1 fb$^{-1}$ using fully-simulated signal and background Monte Carlo data sets. The reconstruction of leptons and of missing transverse energy becomes more complex in the presence of a multi-jet final state. We quantify the reconstruction differences with respect to those observed for inclusive Z production. We derive statistical and systematic limitations in terms of probing the perturbative QCD predictions and discriminating between predictions of different event generators.
1 Introduction

The production of $W/Z + \text{jets}$ in pp collisions at 14 TeV is an important part of the physics program at ATLAS. The processes are interesting in their own right as tests of perturbative QCD at the LHC, as well as forming important backgrounds for both Standard Model and Beyond Standard Model physics processes. The results of the measurements can be compared directly with fixed-order predictions at leading order (LO) and next-to-leading order (NLO) in QCD and the gauge boson mass provides a large scale for the perturbative calculations. In addition, the measurements can be used to test the performance of Monte Carlo event generators that will also be used to simulate the backgrounds for other physics processes.

In this analysis we present a feasibility study of the cross-section measurements for data corresponding to an integrated luminosity of 1 fb$^{-1}$ performed with fully-simulated signal and background Monte Carlo samples. The goal of the analysis is to test the performance of the lepton and jet triggering and reconstruction algorithms in high jet multiplicity events, to develop the necessary analysis techniques (unfolding, background subtraction) and to evaluate the statistical and systematic limitations of the data, in terms of probing the fixed-order QCD predictions and of discriminating between predictions of different Monte Carlo event generators. The primary end-result of the analysis with real ATLAS data will be hadron-level cross-sections. In this note we will concentrate on $Z + \text{jets}$ in final states with electrons and muons, but with techniques applicable to the case of $W + \text{jets}$ as well. Much of the effort on the triggering and reconstruction of leptons is in common with the inclusive $W/Z$ note [1]; thus, we do not reproduce all of the details from that note, but rather comment on the impact of a multi-jet environment on these issues.

2 Reference Cross-Sections and Monte Carlo Datasets

Reference cross-sections are collected in [2], but we briefly discuss here the cross-sections relevant for this note. NLO is the first order at which the $Z + \text{jets}$ cross-sections have a realistic normalization (and realistic shape for some kinematic distributions) [3]. The current state of the art for NLO calculations is for $Z + 2$ jets, although there is ongoing work for the calculation of $3$ jet final states. Cross-sections for $Z + 0,1$ and $2 (3)$ jet final states can be conveniently calculated at LO and NLO (LO only) using the parton-level MCFM [4] program (version 5.1, interfaced with LHAPDF 5.2.3 [5]), and it is from this program that we determine our reference cross-sections. We use the CTEQ6.1 parton distribution functions (PDFs) [6] and a dynamic renormalization/factorization scale of $m_Z^2 + p_T^2$. We apply similar kinematic cuts on the leptons and jets and the same jet algorithm on the partons as will be described in Section 3. The error on the cross-section stemming from the PDF uncertainty is calculated using the complete set of error PDFs in the CTEQ6.1 set.

2.1 Monte Carlo Datasets

The most important Monte Carlo data sets for the signal processes ($Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$) used in these studies are generated with ALPGEN [7] (v 2.05), interfaced with HERWIG [8] and using the leading order PDF set CTEQ6LL [9]. (Hereafter, when we refer to ALPGEN it is understood that it is interfaced with HERWIG.) The generation is done with a renormalization/factorization scale of $m_Z^2 + p_T^2$ and a MLM matching cut at $p_T > 20$ GeV (jets below this cut are generated by the parton shower and not by the matrix element) and $|\eta| < 6$. A discussion of the uncertainty in predictions for $Z + \text{jets}$ final states using different matrix element + Monte Carlo calculations and different matching cuts is beyond the scope of this study, but is given in Ref. [10].
The final Monte Carlo data sets are obtained following the standard prescription [7], by merging the samples of Z + n partons (where n=0-5), each sample weighted with the product of the respective sample cross-section, the MLM matching efficiency and the efficiency of the generator-level filter. All but the highest jet multiplicity sample are exclusive, i.e. events are only kept if all jets with \( p_T > 20 \text{ GeV} \) and \( |\eta| < 6 \) are matched to a matrix element parton. The highest multiplicity sample, Z + 5 partons, is inclusive; events with additional jets softer than the partons from the matrix element are not discarded. Thus, there can be more than 5 jets in this sample. The di-lepton mass is required to be larger than 40 GeV and lower than 200 GeV. A generator-level filter requires one seeded-cone jet, with a radius of \( R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4 \), with \( p_T > 20 \text{ GeV} \) and \( |\eta| < 5.0 \), and two electrons/muons with \( p_T > 10 \text{ GeV} \) and \( |\eta| < 2.7 \) in the event.

For the comparison with the fixed-order theoretical predictions, the merged data sets are normalized to the NLO inclusive \( Z \to e^+e^- \) and \( Z \to \mu^+\mu^- \) cross-sections. Because of the jet filter used in their generation, the fully-simulated data sets can not be used to derive the global normalization factor. For this purpose, we use additional \( Z \to e^+e^- \) and \( Z \to \mu^+\mu^- \) ALPGEN data sets which are produced with the same conditions, but without the generator-level filter applied.

PYTHIA [12] signal and background samples are generated with version 6.323 (\( Z \to e^+e^- \), \( Z \to \mu^+\mu^- \), \( Z \to \tau\tau \), and \( W \to e\nu \)) or 6.403 (\( t\bar{t} \), filtered QCD multi-jet) using the corresponding ATLAS underlying-event tune [11]. PYTHIA \( Z \to e^+e^- \) and \( W \to e\nu \) events are preselected with a generator-level filter requiring one electron with \( p_T > 10 \text{ GeV} \) and \( |\eta| < 2.7 \). The filter for the corresponding processes with muon final states requires one muon with \( p_T > 5 \text{ GeV} \) and \( |\eta| < 2.8 \). PYTHIA \( Z \to \tau\tau \) events are generated with a filter requiring two electrons/muons with \( p_T > 5 \text{ GeV} \) and \( |\eta| < 2.8 \). For each of the \( Z \to \ell\ell \) samples, the di-electron (di-muon, di-tau) mass is required to be larger than 60 GeV. The jet background for the electron channel is simulated with a PYTHIA QCD multi-jet sample with a minimum hard-scattering transverse momentum of 15 GeV. A generator-level filter requires a jet of \( p_T = 17 \text{ GeV} \) clustered in a narrow region of \( \Delta \eta/\Delta \phi = 0.06 \), a size similar to an electron cluster. The QCD multi-jet background for the muon channel is estimated with a PYTHIA \( b\bar{b} \) sample. Two muons with \( p_T > 4 \text{ GeV} \) and 6 GeV, respectively, are required in the final state.

### 2.2 Corrections from Parton to Hadron Level

Comparisons of data cross-section measurements and LO/NLO predictions are to be made at the hadron level (particle level). Hence, the MCFM predictions for the observables have to be corrected with respect to the non-perturbative effects resulting from jet fragmentation and from the underlying event. The impact of the underlying event correction is to add energy to the MCFM jets, while the jet fragmentation correction subtracts energy. Both corrections are expected to decrease with increasing jet \( p_T \). The non-perturbative corrections are determined from the current ATLAS PYTHIA tune by comparing the multiplicity and the \( p_T \) distribution of jets with a cone radius of 0.4 clustered on the final-state particles in \( Z \to \mu^+\mu^- \) Monte Carlo samples generated with PYTHIA 6.403 (a) using the standard ATLAS PYTHIA tune and (b) with fragmentation and multiple-particle interactions switched off. To the extent to which the two partons that can comprise a jet in MCFM mimic the effects of the parton shower in PYTHIA, the corrections derived from the above procedure can be applied to the MCFM output [3]. For jets with cone radius 0.4 with \( p_T > 40 \text{ GeV} \), the effects of fragmentation and underlying event cancel up to a residual correction at the percent level, which is then applied to the MCFM predictions. These corrections are expected to be re-done with the underlying event measurements determined from ATLAS data.
3 Particle Identification and Trigger

We adopt as much as possible definitions and cuts in common with the other analyses, and in particular with the inclusive $W/Z$ study [1].

3.1 Particle Identification

The electron candidates are required to have $p_T > 25$ GeV, and to lie in the range $|\eta| < 2.4$, excluding the barrel-to-endcap calorimeter crack region ($1.37 < |\eta| < 1.52$). The electrons are required to fulfill the medium electron-identification signature [13], which consists of requirements on the calorimeter shower-shape and the matched track. The $Z$ selection requires two electron candidates with an invariant mass of $81 < m_{ee} < 101$ GeV and $\Delta R > 0.2$ between the electrons. No calorimeter isolation cuts are applied for this analysis, although they will be applied for actual data analysis. There is an implicit isolation cut, however, present in the trigger [14].

A muon candidate requires the combined reconstruction of an inner detector track and a track in the muon spectrometer [15]. Muons are required to have $p_T > 15$ GeV and $|\eta| < 2.4$, with the range $1.2 < |\eta| < 1.3$ being excluded. Isolation is applied by requiring the energy deposition in the calorimeter to be less than 15 GeV in a cone of $\Delta R = 0.2$ around the extrapolation of the muon track. The $Z$ selection requires that there be two muon candidates with an invariant mass of $81 < m_{\mu\mu} < 101$ GeV.

For the analyses in this study, we use jets clustered with the standard ATLAS seeded-cone algorithm with a radius of $R = 0.4$, built from either calorimeter towers ($Z \rightarrow e^+e^- + \text{jets}$ analysis) or topological clusters [16] ($Z \rightarrow \mu^+\mu^- + \text{jets}$ analysis), and calibrated to the hadron level. The lepton and jet candidates must be separated by $\Delta R_{l,j} > 0.4$. It is required that the jet transverse momentum be larger than 40 GeV and that the jet be in the range $|\eta| < 3.0$.

3.2 Trigger Selection

The trigger selection used here is the same as that used in the inclusive analyses [1]. In the electron channel, $Z \rightarrow e^+e^- + \text{jets}$ events are required to pass the isolated di-electron trigger or the isolated single-electron trigger. In the muon channel, $Z \rightarrow \mu^+\mu^- + \text{jets}$ events are required to pass the isolated di-muon trigger. The trigger efficiencies at the first, second and event filter levels are evaluated as a function of the jet multiplicity, the $p_T$ of the leading jet and the $Z$ transverse momentum. For this purpose, the generated Monte Carlo information and the data driven tag-and-probe method are compared. Good agreement between the two methods is found. The efficiency for an electron to pass the isolated single-electron trigger is found to decrease with increasing jet multiplicity, $p_T$ of the leading jet and with decreasing distance to the closest jet.

4 Measurement of $Z + \text{jets}$ Cross-Sections

We study the comparison of theory and measurement for quantities suited to compare with a fixed-order NLO calculation: the inclusive cross-section for $Z \rightarrow \ell\ell'$ with at least 1 jet, 2 jets and 3 jets and the differential cross-sections with respect to the $p_T$ of the leading and the next-to-leading jets.
<table>
<thead>
<tr>
<th>Process</th>
<th>$Z \to \ell \ell^+ \geq 1$jet</th>
<th>$Z \to \ell \ell^+ \geq 2$jets</th>
<th>$Z \to \ell \ell^+ \geq 3$jets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma$ (fb)</td>
<td>fraction (%)</td>
<td>$\sigma$ (fb)</td>
</tr>
<tr>
<td>$Z \to e^+e^-$</td>
<td>23520±145</td>
<td>91.9±0.8</td>
<td>4894±45</td>
</tr>
<tr>
<td>QCD jets</td>
<td>1545±89</td>
<td>6.0±0.4</td>
<td>336±42</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>496±28</td>
<td>1.9±0.1</td>
<td>333±23</td>
</tr>
<tr>
<td>$W \to ev$</td>
<td>(28±13)</td>
<td>(0.1±0.05)</td>
<td>(5.9±2.6)</td>
</tr>
<tr>
<td>$Z \to \tau^+\tau^-$</td>
<td>3.2±1.2</td>
<td>0.01±0.01</td>
<td>(6.7±0.25)</td>
</tr>
</tbody>
</table>

| $Z \to \mu^+\mu^-$     | 59400±650     | 96.2±1.0     | 12600±300     | 90.1±1.9     | 2450±100     | 89.7±3.7     |
| QCD($b\bar{b}$)        | 1230±550      | 2.0±0.9      | 600±300       | 4.3±2.2      | 0±110        | 0.0±4.0      |
| $t\bar{t}$             | 1140±110      | 1.8±1.8      | 790±90        | 5.7±0.2      | 275±50       | 10.2±1.9     |
| $W \to \mu\nu$         | 0±180         | 0.0±0.3      | 0±30          | 0.0±0.2      | 0±5          | 0.0±0.2      |

Table 1: The accepted cross-sections ($\sigma$, in fb) and the corresponding fraction of the total sample (in %) for signal and for the background channels in the $Z \to e^+e^- +$jets and the $Z \to \mu^+\mu^- +$jets analyses, after applying the cuts outlined in Section 3. The numbers in brackets are extrapolated from results obtained for a lower jet multiplicity.

### 4.1 Lepton Reconstruction in a Multi-jet Environment

The presence of additional jets in the event has an impact on the kinematics of both the leptons and jets: the leptons are more boosted (larger $p_T$ and lower $\Delta \phi$ between leptons) in events with jets and the distance between leptons and jets becomes smaller in high-multiplicity events. The average jet $p_T$ increases with the number of jets. Due to the OR of the single electron and di-electron trigger channels used in this analysis and due to the boost of the electrons with large jet activity, the efficiency loss of the isolated electron triggers for large jet multiplicities has only a negligible impact. The total $Z$ reconstruction efficiency (offline+trigger) is stable with respect to both the jet multiplicity and the transverse momentum of the leading jet.

Muon reconstruction efficiencies and rejections for QCD multi-jet background are investigated for different isolation requirements. The isolation requirement for this analysis (see Section 3.1) is chosen such that it presents no significant bias for events with large jet multiplicities and large jet $p_T$, while at the same time providing a sufficiently large rejection for the QCD multi-jet background.

### 4.2 Background Estimation

For the evaluation of backgrounds to the $Z \to e^+e^- +$jets signal we consider processes with real electrons ($t\bar{t}, W \to ev, Z \to \tau^+\tau^-$) and QCD multi-jet production. Statistics of the multi-jet background sample are increased by applying a very loose electron selection and then reweighting the events with the rejection from the final electron identification cuts. For the $Z \to \mu^+\mu^-$ analysis the background is dominated by processes with real muons ($t\bar{t}, W \to \mu\nu$, and QCD multi-jets). QCD multi-jet backgrounds for isolated highly-energetic muons result mainly from decays of $b\bar{b}$ mesons. We thus use a $b\bar{b}(\to \mu^+\mu^-)$ sample to evaluate this background. For both analyses, all backgrounds are estimated from fully-simulated Monte Carlo samples, generated with PYTHIA. They are compared with the signal distributions, derived from the respective ALPGEN $Z +$ jets data sets.
Table 1 provides an overview of the accepted cross-section and the corresponding signal and background fractions within the selected event sample, for several jet multiplicities and for the electron and the muon channel respectively. The uncertainties displayed in the table are of statistical nature only. The total background is at the level of 5-15% depending on the jet multiplicity. With increasing jet multiplicity, $t\bar{t}$ replaces QCD multi-jet production as the dominant background source in both analysis channels. Due to the larger acceptance and the larger lepton reconstruction efficiency, we obtain more than twice as many signal events in the muon channel. Since the dominant ($t\bar{t}$) background also contains two real leptons, the signal-to-background ratio is comparable in both analyses.

![Figure 1](image1.png)

Figure 1: The distribution of the di-muon mass (a) and the inclusive jet multiplicity (b) for signal and backgrounds in the muon channel. In order to provide higher statistics for the background determination, background events in an invariant mass window of 51 - 131 GeV, are scaled down for an invariant mass window of 81 - 101 GeV. Also shown is the distribution of $p_T$ of the leading (c) and the next-to-leading (d) jet in the electron channel for $\int Ldt = 1$ fb$^{-1}$.

Figures 1(a+b) show the combined distribution of the di-muon mass and the jet multiplicity for events with at least one jet for signal and background events in the $Z \rightarrow \mu^+\mu^-$ + jets channel. Figures 1(c+d) show the distribution of signal and backgrounds for the $p_T$ of the leading and the next-to-leading jet in the $Z \rightarrow e^+e^- +$ jets channel. The jets from the QCD multi-jet background have a similar $p_T$ distribution as the jets from the signal events, while the jets from the $t\bar{t}$ background tend to be harder.
4.2.1 Background Subtraction

The $Z \rightarrow \tau^+\tau^-$, $t\bar{t}$ and $W \rightarrow e\nu$ backgrounds are subtracted using the Monte Carlo estimates. The systematic uncertainty from the limited background statistics is propagated into the systematic uncertainty of the cross-section measurement. Special care will be needed in validating against data the differential cross-section for the $t\bar{t}$ process, since it is the dominant background for large jet multiplicities. The QCD multi-jet background is expected to be determined with data-driven methods. From the simulations we expect a multi-jet background fraction independent of the jet $p_T$ such that it can be subtracted by applying a global factor. We assume in the following an uncertainty of 20% on the measurement of the QCD multi-jet fraction. The error is propagated into the systematic error on the measured cross-section.

4.3 Unfolding of Detector Effects

The reconstructed data have to be unfolded from the detector level to the hadron level, correcting for efficiency, resolution and non-linearities in electron and jet reconstruction. In this study, the individual unfolding corrections are assumed to factorize in leading approximation, and the individual contributions are investigated and corrected for separately. The corrections are detailed in the following for the case of the $Z \rightarrow e^+e^-$ channel. Unfolding of the $Z \rightarrow \mu^+\mu^-$ final state is done in a similar way. All corrections are derived with fully-simulated ALPGEN Monte Carlo samples.

The dominant correction on the inclusive cross-section for the $Z \rightarrow e^+e^-$ channel stems from the electron reconstruction. For each of the two electrons, the cross-section is corrected for the electron reconstruction efficiency, given as a function of the electron pseudo-rapidity and transverse momentum. The cross-section is also corrected for the trigger efficiency with respect to the offline selection. Corrections from jet reconstruction have a comparably small impact on the overall cross-section but bias the jet $p_T$ spectrum since, in general, the detector effects are greater for low $p_T$ jets. The reconstructed jet $p_T$ is corrected for the non-linearity of the jet energy scale, and for each jet in the required selection, the cross-section is corrected for the reconstruction efficiency and for the effect of the jet energy resolution. The uncertainties on deriving these corrections, stemming from the limited Monte Carlo statistics, are taken into account as systematic uncertainties on the cross-section measurement.

Figure 2 compares the distributions of the $p_T$ of the leading jet and the next-to-leading jet, in different unfolding stages, with the $p_T$ distribution of the original (hadron-level) Monte Carlo jets. Within the statistical and systematic errors, the $p_T$ distributions of the Monte Carlo jets and the corrected reconstructed jets are in agreement, thus providing a consistency check for the unfolding corrections.

4.4 Comparison of Event Generator and MCFM Predictions at the Hadron Level

One of the goals of our study is to evaluate the statistical and systematic precision of the $Z +$ jets cross-section measurement and to compare this precision with the size of the uncertainties that are expected in the first inverse femtobarn of data. Since this study deals with the measurements from the first data, we compare the precision of the measurement with the differences in the predictions of our LO and NLO QCD calculations and with the predictions from matrix element and parton-shower generators.

4.4.1 Generator Comparisons

In this section we compare the prediction for the inclusive jet cross-section from the generators PYTHIA and ALPGEN with those from the MCFM partonic level event generator. In order to sep-
Figure 2: Comparison of the distribution of the $p_T$ of the leading jet (a) and the next-to-leading jet (b) for the generated (hadron-level) Monte Carlo and for the reconstructed quantities without any correction, after the corrections for electron triggering and reconstruction and after applying in addition the jet-related corrections.

arate the reconstruction from the generation effects we use only Monte Carlo hadron-level generator information.

Figures 3(a)-(c) show the comparison of the distribution of the jet multiplicities and the $p_T$ of the leading and next-to leading jets for ALPGEN and PYTHIA $Z\rightarrow\mu^+\mu^-+\text{jets}$ samples with the NLO (LO) calculations from MCFM. The errors on the generator distributions are purely Monte Carlo statistics whereas the errors on the MCFM cross-section correspond to the PDF uncertainties and to the error from the unfolding to the hadron level. MCFM predictions are corrected to the hadron level as specified in section 2.2. The two Monte Carlo samples are normalized to the inclusive NLO $Z$ cross-section, as determined in MCFM.

The NLO MCFM predictions for the $Z+1$ jet and $Z+2$ jets cross-sections are, in general, greater than the LO predictions by 20 to 30%. PYTHIA predicts a larger $Z+1$ jet cross-section than ALPGEN, but also predicts a lower average jet multiplicity. Both Monte Carlo generators predict a lower cross-section than the NLO MCFM calculation for final states with more than one jet. The difference between the predictions of PYTHIA and ALPGEN, and between both generators and MCFM, amounts to 10-60% depending on the jet multiplicity. A comparison of the differential cross-section as a function of the jet $p_T$ indicates that the inclusive cross-sections shown in Figure 3(a) depend very much on the minimum jet $p_T$ required by the selection. PYTHIA predicts larger cross-sections than even NLO MCFM for low jet $p_T$. But, while the shape of the jet $p_T$ distribution predicted by ALPGEN agrees well with the NLO MCFM prediction, PYTHIA generates a clearly softer $p_T$ spectrum, as expected.

4.4.2 Statistical and Systematic Errors

In order to determine the expected precision of the analysis, the cross-section measurement is performed on the fully-simulated ALPGEN $Z+\text{jets}$ data sets, which are corrected to the hadron level, following the prescription of Section 4.3. Systematic errors from the corrections are included. In the next step we evaluate the impact of the uncertainties expected for real ATLAS data taking. ATLAS expects a limited precision of the jet energy scale in the first years, starting from uncertainties at the level of 10% and converging eventually towards 1%. We obtain two benchmark scenarios by propagating
Figure 3: Comparison of the inclusive jet cross-section (a) and the $p_T$ of the leading jet (b) and of the next-to-leading jet (c) for the $Z \rightarrow \mu^+ \mu^- + \text{jets}$ channel from PYTHIA and ALPGEN Monte Carlo with NLO (LO) MCFM predictions.

jet energy scale uncertainties of 5% and 10% into the measured cross-sections. Several backgrounds will be estimated with data-driven methods, introducing additional systematic errors. We account for that in a first approach by adding an error of 20% on the fraction of the multi-jet background for each jet multiplicity. The statistical uncertainties in the samples are scaled to the number of events expected to be selected for an integrated luminosity of 1 fb$^{-1}$.

Figure 4 compares, for the $Z \rightarrow e^+ e^- + \text{jets}$ channel, the inclusive jet multiplicity (a) and the $p_T$ of the leading jet (b) for MCFM and the fully-simulated corrected ALPGEN sample. The errors on the MCFM predictions result from the PDF uncertainty and from the errors from the correction for the non-perturbative effects. The errors on the ALPGEN Monte Carlo data include all the statistical and systematic uncertainties described in this section with the jet energy scale uncertainty set to 5%.

An additional systematic uncertainty is introduced on the unfolding correction for the jet resolution due to the uncertainty on the jet resolution measurement and to the uncertainty on the shape of the $p_T$ distribution which we use to derive the corrections. Using corrections from different event generators and varying the jet resolution within its uncertainty results in a systematic error on the cross section at the percent level.

The uncertainty on the theoretical predictions and on the measured cross section, as shown in
Figure 4: The inclusive jet cross-section (a) and the distribution of the $p_T$ of the leading jet (b), as predicted by NLO MCFM (corrected to the hadron-level) and by ALPGEN for the $Z \rightarrow e^+e^- + \text{jets}$ process.

Figure 4, are propagated on the data/theory ratio. Figure 5 shows the resulting uncertainty on a ratio of 1 for the inclusive cross-section and for the $p_T$ of the leading jet. The systematic uncertainty on the inclusive cross-section from a jet energy scale uncertainty of 5% is twice as large as as the sum of all the other statistical and systematic uncertainties. In this case, the overall precision on the data/theory ratio expected with the first $fb^{-1}$ of data is at the level of 8-15% for topologies with 1-3 jets. A jet energy scale uncertainty of 10% results in the dominant error on the cross-section. In this case, the total uncertainty on the cross section is at the level of 15-30%, which is at the same order as the typical differences expected between LO and NLO predictions, or between predictions from PYTHIA, ALPGEN and MCFM. Statistical limitations become sizable for large jet $p_T$ ($>200$ GeV).

Figure 5: Uncertainty on the ratio of measurement and theory for the inclusive jet cross-section (a) and the $p_T$ of the leading jet (b) for the $Z \rightarrow e^+e^- + \text{jets}$ process.
5 Conclusions

Final states containing $Z + \text{jets}$ will serve as one of the Standard Model benchmarks for physics analyses at the LHC. We have simulated cross-section measurements for theoretically well-defined quantities such as the inclusive $Z + \text{jets}$ cross-section, and the jet transverse momentum for the leading and next-to-leading jets. An unfolding technique from the detector to the hadron level has been developed, and results are presented at the hadron level. Theoretical corrections from parton to hadron level, necessary for comparisons of data to parton level predictions, are determined.

The main background sources are found to be QCD multi-jet processes for low jet multiplicities and $t\bar{t}$ for large jet multiplicities and amount to the level of 5-20%, depending on the jet multiplicity. Predictions from the Monte Carlo generators PYTHIA and ALPGEN have been compared with MCFM NLO (LO) calculations. The inclusive cross-section predictions differ by 10-60%, with larger discrepancies for the PYTHIA parton shower prediction (with respect to MCFM and ALPGEN) with increasing jet $p_T$. Statistical and systematic uncertainties on the ratio data/theory have been determined. A jet energy scale uncertainty of 5% would be the dominant systematic uncertainty on the measured cross section, resulting in a total uncertainty of 8-15% for final states with 1-3 jets. A jet energy scale uncertainty of 10% results in an overall precision at the level of 15-30% which is at the same order as the typical differences expected between LO and NLO predictions or between predictions from PYTHIA, ALPGEN and MCFM.

References


