PROCEEDINGS OF SCIENCE

Measurements of the production of jets in association with a W or Z boson with the ATLAS detector

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The production of jets in association with vector bosons is an important process to study QCD in a multi-scale environment. The ATLAS collaboration has performed measurements of vector boson+jets cross sections, differential in several kinematic variables, in proton-proton collision data taken at center-of-mass energies of 8 TeV and 13 TeV. The measurements are compared to state-of-the art theory predictions and can be used to constrain the gluon PDF.
In data collected at 8 TeV, the collaboration has measured the production of W boson+jets with a large transverse momentum of the leading jet, which enriches the collinear production of the gauge boson and a jet. The measurements are compared to state-of-the-art QCD calculations and Monte Carlo simulations.

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1. Introduction

The measurement of the production of vector bosons in association with jets provides an excellent test of pertubative Quantum Chromodynamics (pQCD) and electroweak (EW) calculations. In addition, these processes constitute non-negligible backgrounds for many beyond Standard Model (SM) searches and Higgs boson studies. Usually these backgrounds are estimated using Monte Carlo (MC) predictions, which must be tuned and validated using corresponding data measurements. Predictions from the most recent MC generators combine next-to-leading order (NLO) matrix elements (ME) with parton showers and hadronization models. Fixed order calculations at next-to-next-to-leading order (NNLO) are also available for Z+jets and W+jets processes.

The measurements shown here are performed by the ATLAS experiment [1]. Differential cross-sections of the Z+jets production measured at the centre-of-mass energy $\sqrt{s}$ = 13 TeV are presented in Section 2. A measurement of the collinear W+jets production using data collected at the centre-of-mass energy $\sqrt{s}$ = 8 TeV is described in Section 3. Results of a measurement of the splitting scales occurring in the k_T jet-clustering algorithm for final states containing Z boson using 8 TeV data are presented in Section 4.

2. Z+jets production at 13 TeV

Differential cross-sections of the Z boson production in association with jets using 3.16 fb^{-1} of data collected by the ATLAS detector at the centre-of-mass energy 13 TeV are measured as a function of different variables, namely jet multiplicities, jet p_T for exclusive Z + 1 jet events, leading jet p_T for $Z+\geq 1$, 2, 3, 4 jet events, leading jet rapidity for $Z+\geq 1$ jet events, H_T, $\Delta\phi_{jj}$ and m_{jj} [2]. The Z boson is identified using its decays to electron or muon pairs ($Z \to e^+e^-$, $Z \to \mu^+\mu^-$). The results in these two channels are combined for better precision, taking into account the correlations of the systematic uncertainties. The measured cross-sections are compared to the fixed order calculations at NLO from BlackHat+Sherpa and at NNLO from the $Z+\geq 1$ jet N_{jetti} calculation, and to predictions from the MC generators Sherpa 2.2, Alpgen+Py6, MC_aMC+Py8 CKKWL and MG5_aMC+Py8 FxFx.

The differential cross-sections as a function of the inclusive jet multiplicity and the leading jet p_T for inclusive $Z+\geq 1$, 2, 3, 4 jet events are shown in Figure 1. The jet multiplicity is measured up to 7 jets and is well described by predictions, except for LO Alpgen+Py6 and NLO Sherpa 2.2, MG5_aMC+Py8 FxFx at high jet multiplicities, where a large fraction of the jets is coming from the parton shower. The leading jet p_T in $Z+\geq 1$, 2, 3, 4 jet events is measured in a range up to 700 GeV. Data agrees with NLO BlackHat+Sherpa, Sherpa 2.2, and MG5_aMC+Py8 FxFx and with LO Alpgen+Py6 predictions within systematic uncertainties. The LO generator MG5_aMC+Py8 CKKWL models a too-hard jet p_T spectrum for p_T > 200 GeV, this can be interpreted as the indication that the dynamic factorization and renormalization scales used in the generation are not appropriate for the full jet p_T range.

3. Collinear W+jets production at 8 TeV

At high energies real emissions of W bosons in dijet events can contribute significantly to the W+jet process. These contributions have a collinear enhancement in the angular distance between

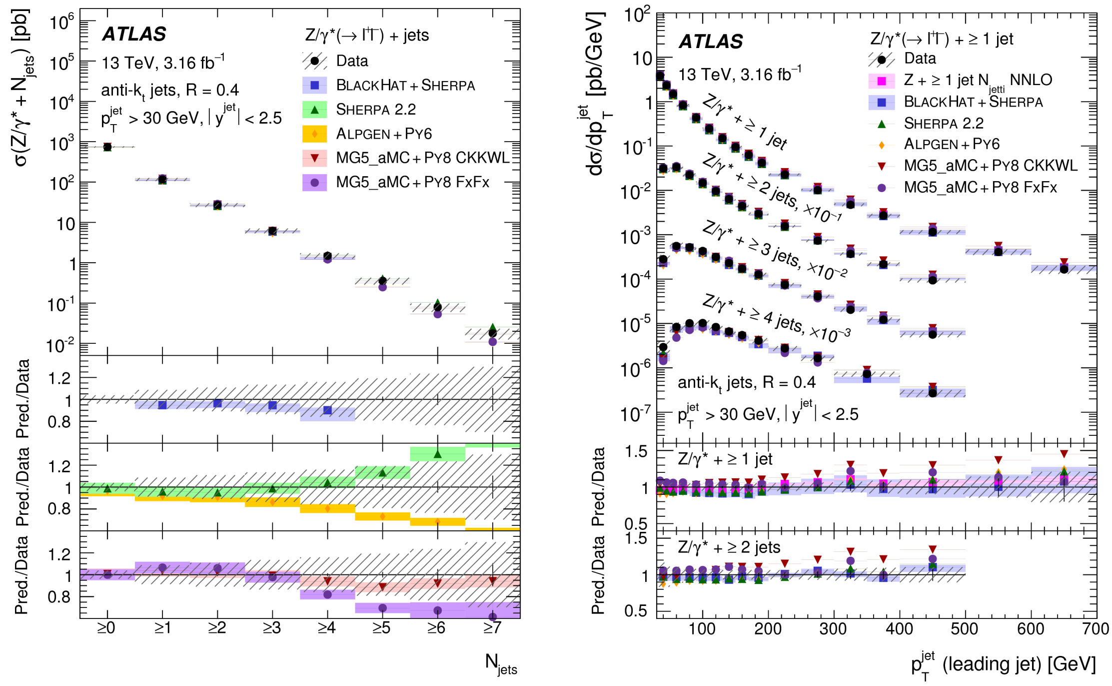

Figure 1: Measured cross section as a function of the inclusive jet multiplicity (left) and the leading jet p_T for inclusive $Z+\geq 1, 2, 3, 4$ jet events (right). Data are compared to the predictions from $Z+\geq 1$ jet N_{jetti} NNLO (leading jet p_T distribution), BlackHat+Sherpa, Sherpa 2.2, Alpgen+Py6, MG5_aMC+Py8 CKKWL, and MG5_aMC+Py8 FxFx.

the W and the closest jet. Since directions of the initial W boson and a muon from its decay are highly correlated, real W emissions can be probed by studying the region of small angular separation between a muon and a jet, $\Delta R(\mu, jet) = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 2.4$. In $\Delta R(\mu, jet) > 2.4$ region the W boson is balanced by a hadronic recoil that consists of one or more jets.

The differential cross-section of the production of a W boson in association with at least one high-p_T jet is measured using 20.3 fb^{-1} data collected at $\sqrt{s}$ = 8 TeV as a function of the distance between the muon from the W decay and the closest jet, $\Delta R(\mu, jet)$ [3]. In order to enrich the collinear production of W+jets the leading jet is required to have p_T > 500 GeV. The measured distribution of $\Delta R(\mu, jet)$ together with the predictions from Alpgen+Pythia6, Pythia8, Sherpa+OpenLoops and $W+\geq 1$ jet N_{jetti} NNLO are shown in Figure 2 (left). LO Alpgen+Pythia6 describes a shape of the $\Delta R(\mu, jet)$ distribution well but overestimates the total cross section. Pythia8 predictions, which include also dijet+weak shower, underestimate data at low $\Delta R(\mu, jet)$. NLO Sherpa+OpenLoops $W + j$ and $W + jj$ calculation, which incorporates NLO QCD and NLO EW corrections, and $W+\geq 1$ jet N_{jetti} NNLO calculation agree with data within uncertainties.

The selected W+jets events are divided into two categories depending on the leading jet p_T: 500 GeV < p_T(leading jet) < 600 GeV and p_T(leading jet) > 650 GeV. The measured $\Delta R(\mu, jet)$ data distributions for these two categories are shown in Figure 2 (right). The fraction of events in the collinear region increases with increasing jet p_T, and, thus, also with centre-of-mass energy. Therefore, good understanding of the real W emission process is important for W+jets measure-

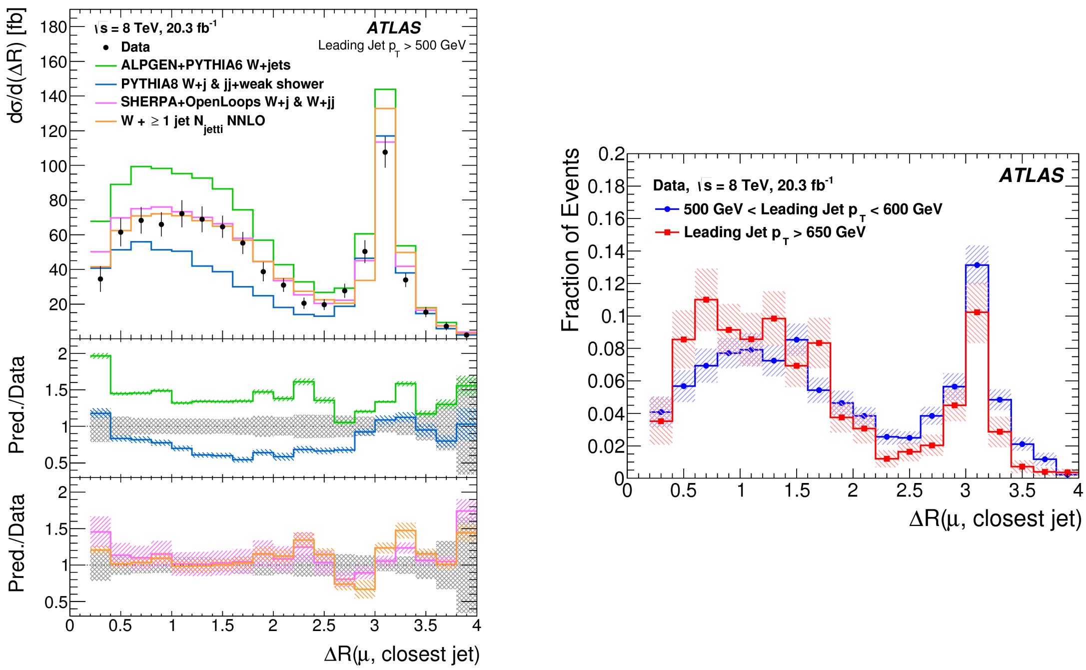

Figure 2: Unfolded distribution from background-subtracted data of the angular separation between the muon and the closest jet for events with p_T(leading jet) > 500 GeV (left) and for events with 500 GeV < p_T(leading jet) < 600 GeV and p_T(leading jet) > 650 GeV (right). The distribution for the inclusive p_T(leading jet) is compared to the predictions from Alpgen+Pythia6, Pythia8 ($W+j$ & dijet+weak showers), Sherpa+OpenLoops ($W+j$ & $W+jj$) and $W+\geq 1$ jet N_{jetti} NNLO.

ments at high p_T, vector boson scattering measurements and also for QCD multijets measurements at high m_{jj}. In addition, this process has a high potential to mimic the highly Lorentz-boosted top quark production, which makes it important also for New Physics searches.

4. k_T splittings in Z+jets events at 8 TeV

In addition to direct studies of the jet properties, a complementary approach by studying the jet production rates at different resolution scales can be used. The splitting scales of jets are constructed using an infrared-safe clustering algorithm based on a sequential combination of the input momenta, which approximates QCD evolution. The splitting scale d_k is defined for a given iteration of the algorithm at which a number of the input momenta drops from $k+1$ to k, i.e. the zeroth-order splitting scale, d_0, in the k_T clustering algorithm corresponds to the p_T of the leading k_T-jet.

The differential cross-sections of the Z+jets production are measured using 20.2 fb^{-1} data collected by the ATLAS detector at $\sqrt{s}$ = 8 TeV as functions of the splitting scales $d_{0...7}$ occurring in the k_T clustering algorithm using charged-particle tracks as inputs [4] . This measurement is sensitive to the hard perturbative modeling at high scales and to soft hadronic activity at lower scales. The measurement is performed in both $Z\to ee$ and $Z\to\mu\mu$ channels, for the jet-radius parameters R 0.4 and 1.0. All distributions shown here correspond to the electron channel and R=0.4.

The distributions of the second and seventh orders splitting scales are shown in Figure 3. Data are compared to predictions from Sherpa ("MEPS@NLO") and DY@NNLO+Powheg+Pythia8 ("NNLOPS"). As shown in Figure 3, neither of these generators provide a good description of data for the low-order splitting scales such as d_2, both of them underestimate data by 10-20 % in the peak region at around 3 GeV. At high scales values, which correspond to the hard perturbative region, NNLOPS overestimates cross section, while MEPS@NLO provides good description of data. For the higher-order splitting scales such as d_7, NNLOPS description improved significantly in the soft region.

In these comparisons the generator uncertainties are estimated only for perturbative aspects of the MC generators. Discrepancies observed in the soft region of the splitting scales distributions, where other aspects such as hadronization become relevant, demonstrate that these results can provide a valuable input for the non-perturbative parameters tuning.

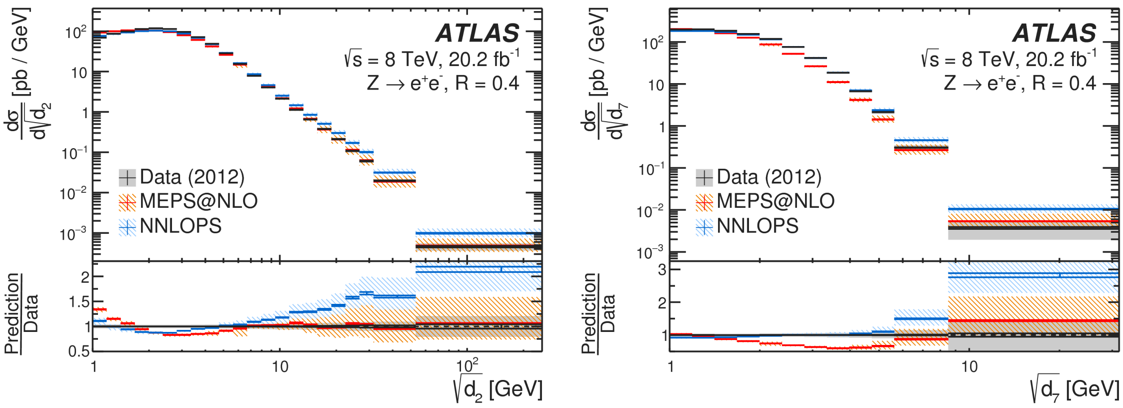

Figure 3: Charged-only distributions for the second and seventh order splitting scales in the electron channel using the jet-radius parameter $R = 0.4$. Data are compared to theoretical predictions from Sherpa with NLO multijet merging (MEPS@NLO) and from Powheg+Pythia8 with NNLO matching (NNLOPS).

For the benefit of theoretical calculations, the results are extrapolated from the nominal charged-particle-level to a particle-level including all particles using the unfolding procedure. The uncertainty increase for the extrapolated results, in particular for low values of the lower-order splitting scales such as $\sqrt{d_1}$, as shown in Figure 4.

5. Summary

An overview of vector boson production in association with jets measurements based on ATLAS Run I and Run II data is presented. Differential cross-sections of the Z+jet production are measured using 13 TeV data as a function of different key variables, providing an excellent test of pQCD predictions. The cross-section for W+jets boson in association with at least one very high transverse momentum jet is measured as a function of the angular distance between the muon from the W boson decay and the closest jet. This measurement allows to probe real W emissions, good understanding of which is especially important for measurements of processes with high p_T

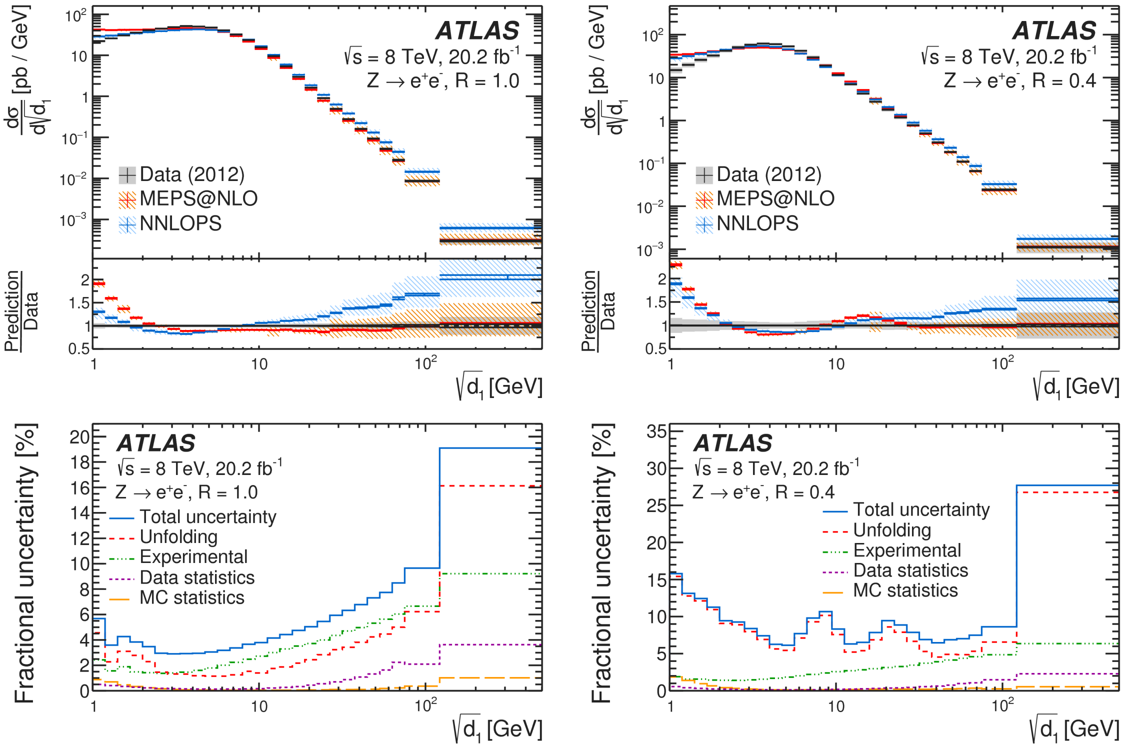

Figure 4: The upper panels show distributions for the first order splitting scale in the electron channel using the jet-radius parameter R = 0.4 for the nominal charged-particle-level (left) and the particle-level including all particles (right). The lower panels show breakdowns of the total systematic uncertainty in data.

jets and also for New Physics searches. Differential cross sections are measured as a function of the splitting scales in the k_T algorithm applied to the hadronic activity in events with a Z boson. These results are sensitive to the hard perturbative modelling as well as to soft hadronic activity and provide a valuable input for the MC generators tuning complementary to the standard jet measurements.

References

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