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Inclusive and dijet jet production measured with the ATLAS detector

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Inclusive jet and dijet double differential cross sections have been measured in proton proton collisions at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV using the ATLAS detector. The dijet cross section has been measured up to a dijet invariant mass of 4.6 TeV. The cross sections have been measured using jets defined with the anti-k_T algorithm. The data are compared to predictions based on next-to-leading order QCD calculations corrected for non perturbative effects, as well as to Monte Carlo predictions at next-to-leading order using parton shower matching. Ratios of cross sections measured at different centre-of-mass energies allow for reduced experimental and/or theoretical uncertainties. A NLO QCD analysis of the data indicates constraining power for the gluon density in the proton.

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1. Introduction

The production of jets is an important process in high energy proton-proton collisions at the LHC. Precise measurements of jet production and the properties of jets provide a test of perturbative quantum chromodynamics (pQCD) calculations at next-to-leading order (NLO). Jet production is also an important background for many physics measurements and new physics searches and so accurate measurements of the jet cross section are important.

Dijet and inclusive jet cross sections measured with the ATLAS detector [1] are presented here. High mass dijet cross sections [2] have been measured at $\sqrt{s} = 7$ TeV with 4.8 fb^{-1} of data collected in 2011 with a range of dijet invariant mass from 260 GeV to 4.6 TeV and in different ranges of $y^* = |y_1 - y_2|/2$ where y_1 and y_2 are the rapidities of the two leading jets. The inclusive jet cross section was measured at $\sqrt{s} = 2.76$ TeV using 0.2 pb^{-1} of data from proton-proton collisions collected in 2011 [3]. The ratio of the inclusive jet cross section at $\sqrt{s} = 2.76$ TeV to that measured at $\sqrt{s} = 7$ TeV with 37 pb^{-1} of data collected in 2010 [4] is shown [3]. The jet cross sections at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV are also used for an analysis of parton distribution functions (PDFs). Constraining power is achieved due to the strong correlation of the dominant systematic uncertainty (due to the jet calibration) at the two different centre-of-mass energies.

2. Theoretical predictions

The results presented here are compared to NLO pQCD predictions. “Particle-level” jets are built from stable, interacting particles after detector simulation using the anti-k_T algorithm. Two generators are used for the hard scatter: NLOJET++ [5] and POWHEG with the POWHEGBOX package [6]. NLOJET++ uses fixed order pQCD calculations to predict the parton level cross sections. The predictions are then corrected for non-perturbative effects using multiplicative factors. These factors are derived using the ratio of cross sections from leading order Monte Carlo generators with a leading logarithmic parton shower with and without hadronisation and the underlying event. The baseline correction is derived using PYTHIA 6.425 [7] with the AUET2B CTEQ6L1 tune [8]. The uncertainty on these corrections is evaluated by taking the envelope of the correction factors derived from several different generators and tunes [3].

The POWHEG generator uses a matrix element calculation with parton shower matching. It can be interfaced to PYTHIA or HERWIG [9] for the hadronisation and the underlying event. This procedure is expected to give improved theoretical predictions although there are also additional uncertainties due to the matching procedure and tuning of the parton shower.

For the inclusive jet cross section predictions with NLOJET++ the renormalisation and factorisation scales are chosen to be $\mu = \mu_R = \mu_F = p_T^{max}(y_i)$ where $p_T^{max}(y_i)$ is the maximum jet p_T in rapidity bin y_i. For the dijet cross section predictions $\mu = p_T e^{0.3y^*}$. This choice gives a more stable cross section in the forward region [4]. The scale uncertainties were derived by varying the renormalisation and factorisation scales by a factor of 0.5 and 2 with respect to the nominal values. For POWHEG predictions $\mu = p_T^{Born}$ where p_T^{Born} is the maximum jet p_t at leading order.

The CT10 [10] NLO PDF set is used as the default PDF for both generators. NLOJET++ is also used with the MSTW2008, NNPDF 2.1, HERAPDF and ABM11 PDF sets. The uncertainties due to the PDF set and α_s are evaluated according to the recommendations of the PDF4LHC group [11].

3. Event selection and experimental uncertainties

Jets are reconstructed with the anti-k_T algorithm with a distance parameter of $R = 0.4$ and 0.6 from clusters of topologically connected calorimeter energy deposits [12] which are calibrated to the energy scale of an electromagnetic shower. A correction factor, the Jet Energy Scale (JES), is applied in order to correct for the non-compensation of the calorimeter, dead material in the detector and noise thresholds. At $\sqrt{s} = 7$ TeV the jet energy is corrected for additional energy deposits due to multiple proton-proton interactions whereas at $\sqrt{s} = 2.76$ TeV this correction was not needed due to the low number of proton-proton interactions in each bunch crossing.

The dijet cross section measurement covers the dijet invariant mass range from 260 GeV to 4.6 TeV. The leading and subleading jets are selected from jets within the range $|y| < 4.4$. The leading jet must have $p_T > 100$ GeV and the subleading jet $p_T > 50$ GeV. The leading and subleading jets are required to lie within $|y| < 2.8$. The cross section is measured as a function of the invariant mass of the leading and subleading jets, m_{12}, and binned in y^*, covering the range $y^* < 2.5$.

The inclusive jet cross section was measured within $|y| < 4.4$ and covers the transverse momentum range of $20 \leq p_T \leq 430$ GeV for the $\sqrt{s} = 2.76$ TeV results and $20 \leq p_T \leq 1500$ GeV for the $\sqrt{s} = 7$ TeV results.

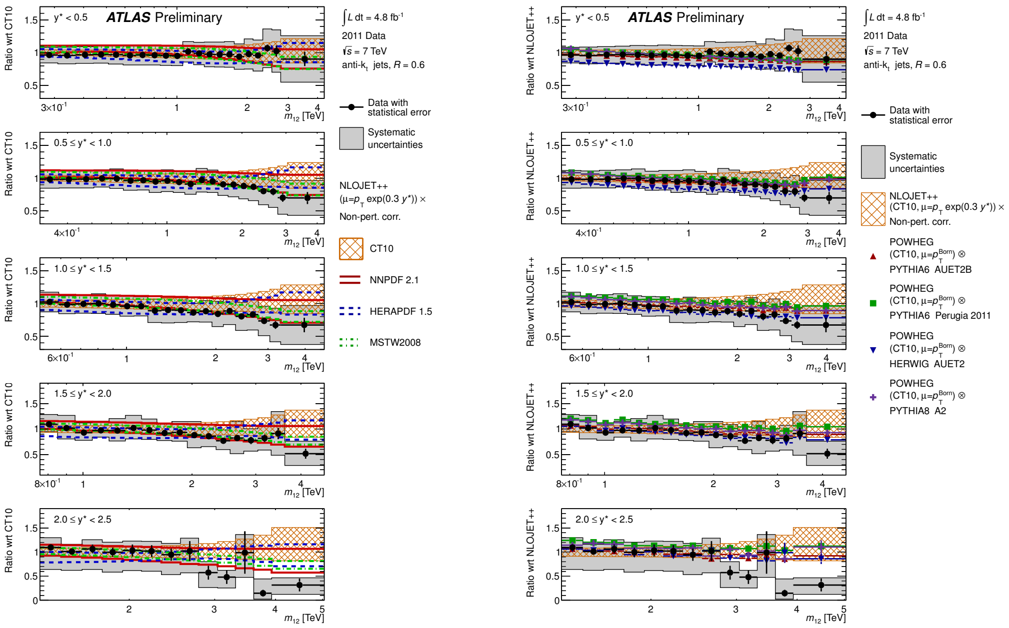
The distributions in data are unfolded to particle-level using an iterative dynamically stabilised unfolding method [13]. This method is based on a transfer matrix which relates the particle-level and reconstruction level observable and corrects for all detector and resolution effects except for the JES [2, 3].

Experimental uncertainties which are considered are the trigger efficiency, jet reconstruction and calibration, the uncertainty due to the unfolding procedure and the luminosity measurement. The dominant experimental uncertainty for the inclusive and dijet measurements is due to the JES calibration. The JES uncertainty is derived from single hadron response measurements and Monte Carlo simulations and is confirmed in-situ [12]. An uncertainty of $\sim$2.5 % for jets in the central calorimeter region is achieved over the range $60 \leq p_T \leq 800$ GeV. The uncertainty is larger for jets with lower p_T and for jets in the forward region. All the systematic uncertainties are propagated through the unfolding procedure in order to evaluate their effect on the measured jet cross section.

4. Results

The ratio of the measured dijet differential cross section as a function of m_{12} to the prediction of NLOJET++ using CT10 is shown in Figure 1 for $R = 0.6$ and different ranges of y^*. In Figure 1(a) the results are compared to the NLOJET++ predictions based on the CT10, NNPDF2.1, HERAPDF1.5 and MSTW2008 PDF sets. In Figure 1(b) the results are compared to the predictions of POWHEG with different generators and tunes. It is observed that the measured dijet cross section is in good agreement with the theoretical predictions from NLOJET++ and POWHEG within systematic uncertainties, although differences of up to 40 % can be seen at high m_{12} and large y^*. The data are better described by the predictions of POWHEG showered with PYTHIA 6 AUET2B than those of NLOJET++.

Inclusive jet cross sections with $R = 0.4$ and 0.6 at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV were compared to the NLOJET++ predictions. The data and the NLOJET++ predictions were found to



(a) (b)

Figure 1: The ratio of the measured dijet double differential cross section to the NLOJET++ prediction as a function of m_{12} for $R = 0.6$ and different ranges in y^* [2]. The ratios of the NLOJET++ prediction based on NNPDF 2.1, HERAPDF 1.5 and MSTW2008 to that based on CT10 are shown in (a). The ratios of the POWHEG prediction interfaced to PYTHIA 6, PYTHIA 8 and HERWIG parton showers to that of NLOJET++ with CT10 are shown in (b).

agree within systematic uncertainties. However, the data are seen to be systematically lower than the NLOJET++ prediction for $R = 0.4$ jets and in the forward region only for $R = 0.6$ jets [3].

At $\sqrt{s} = 7$ TeV significant differences were observed between the measured inclusive jet cross section and predictions from POWHEG interfaced to PYTHIA or HERWIG using different tunes [4]. For the $\sqrt{s} = 2.76$ TeV results revision 2169 of POWHEGBOX was used with a new option which avoids fluctuations in the final observables after the showering process [6]. As can be seen in Figure 2 very good agreement is now seen between the measured inclusive jet cross section and POWHEG interfaced to the AUET2B and the Perugia 2011 tunes. It is also observed that the measured jet cross section agrees equally well with the POWHEG prediction interfaced to PYTHIA for both $R = 0.4$ and 0.6 jets.

The ratio of the measured inclusive jet cross sections at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV were taken for the same ranges in y and p_T ($\rho(y, p_T)$) as well as for the same ranges in y and $x_T = \frac{2p_T}{\sqrt{s}}$ ($\rho(y, x_T)$) [3]:

$$\rho(y,x_T) = \left(\frac{2.76TeV}{7TeV}\right)^3 \frac{\sigma(y,x_T,2.76TeV)}{\sigma(y,x_T,7TeV)} \text{ and } \rho(y,p_T) = \frac{\sigma(y,p_T,2.76TeV)}{\sigma(y,p_T,7TeV)} \tag{4.1}$$

Due to correlations between the uncertainties at the two centre of mass energies the uncertainties on the ratio are reduced. In the quark parton model $\rho(y, x_T)$ is predicted to be unity, while

QCD introduces scaling violations which result in deviations from that prediction. The theoretical uncertainties on the ratio $\rho(y, x_T)$ are very small as can be seen in Figure 3 and the theoretical predictions from NLOJET++ and POWHEG agree well with the data. The measurements of $\rho(y, p_T)$ are shown in Figure 4 in comparison to NLOJET++ predictions with the MSTW 2008, NNPDF 2.1, HERAPDF 1.5 and ABM 11 NLO PDF sets. It is observed that the predictions are slightly lower in the central region and higher in the forward region compared to the data. None of the PDF sets used here follow this trend well with ABM11 showing the largest tension with the data.

For the ratio $\rho(y, p_T)$ the experimental uncertainties are significantly smaller than the theoretical uncertainties. This suggests that the jet cross sections at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV may be used to constrain the PDFs if the correlations between the two datasets are taken into account. An NLO pQCD analysis using the inclusive jet cross sections for $R = 0.6$ measured with the ATLAS detector at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV and HERA I data has been performed using the HERAFitter package [3]. The gluon distribution derived from this analysis is shown in Figure 5. Using data from HERA and the measurements of inclusive jet cross sections from ATLAS at both centre-of-mass energies and accounting properly for correlations between the systematic uncertainties results in a harder gluon distribution and a reduced uncertainty compared to the fit using HERA data alone.

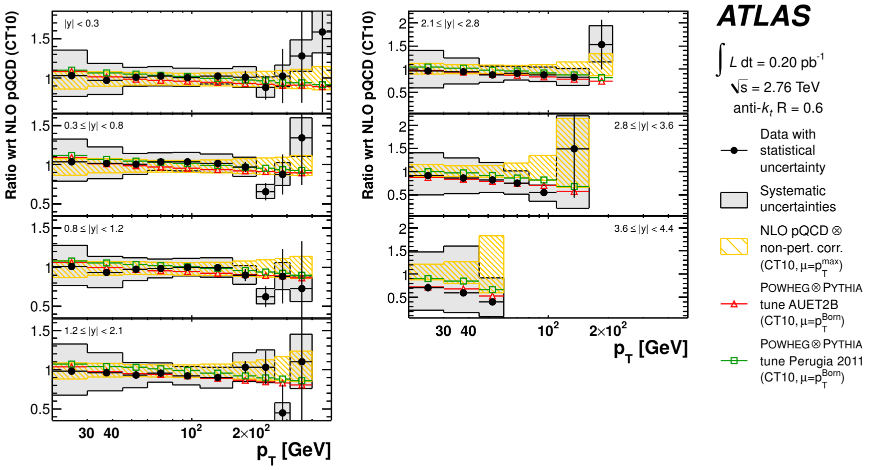


Figure 2: Ratio of the inclusive jet double differential cross section at $\sqrt{s} = 2.76$ TeV to the NLOJET++ prediction with the CT10 PDF set as a function of jet p_T for different ranges in jet rapidity [3]. The ratios of the data and the POWHEG prediction interfaced to PYTHIA with the AUET2B tune and the Perugia 2011 tune to that of NLOJET++ with the CT10 PDF set are also shown. Only the statistical uncertainty on the POWHEG prediction is shown. The 2.7 % uncertainty due to the luminosity measurement is omitted.

5. Conclusions

High mass dijet cross sections at $\sqrt{s} = 7$ TeV and inclusive jet cross sections at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV have been measured with the ATLAS detector for jets defined with the anti-k_T

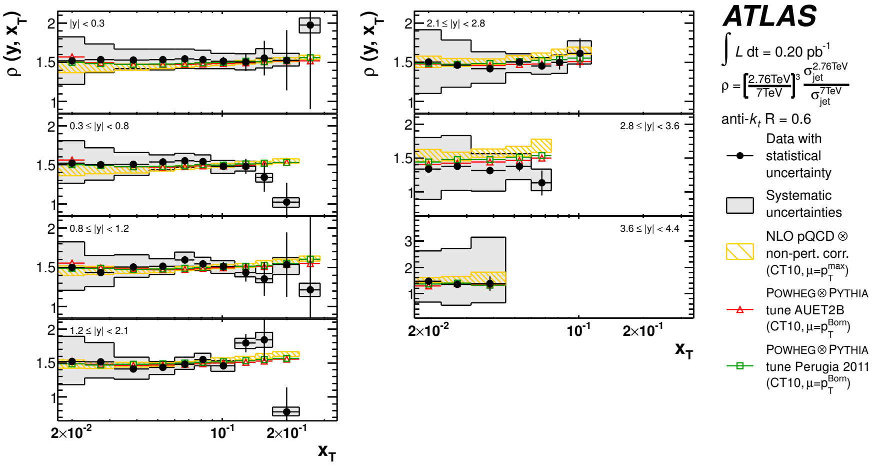


Figure 3: Measurements of $\rho(y,x_T)$ as a function of x_T for different ranges in jet rapidity [3]. The predictions of NLOJET++ with CT10 as well as those of POWHEG interfaced to PYTHIA with the AUET2B and Perugia 2011 tunes are also shown. Only the statistical uncertainty on the POWHEG prediction is shown. The 4.3 % uncertainty due to the luminosity measurement is omitted.

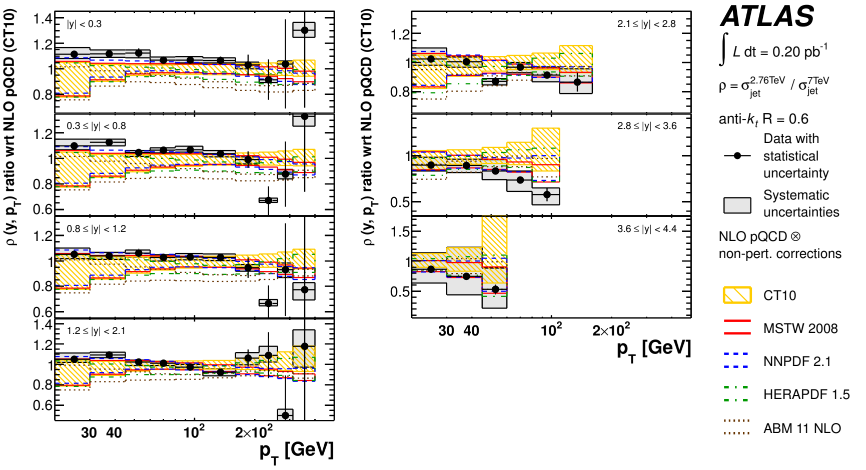


Figure 4: Ratio of the measured $\rho(y,p_T)$ to the NLOJET++ predictions as a function of p_T for different ranges in jet rapidity [3]. The ratios of the NLOJET++ prediction based on MSTW 2008, NNPDF 2.1, HERAPDF 1.5 and ABM 11 NLO to that on CT10 are also shown. The 4.3 % uncertainty due to the luminosity measurement is omitted.

algorithm with $R = 0.4$ and 0.6. The high mass dijet cross sections were measured up to a dijet invariant mass of 4.6 TeV and were found to be in good agreement with NLO pQCD predictions within systematic uncertainties with some differences of up to 40 % at high dijet mass and large y^*. In general, inclusive jet cross sections at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV, up to a jet p_T of 1.5 TeV and 430 GeV respectively, as well as the ratio of the inclusive jet cross section at the two centre-

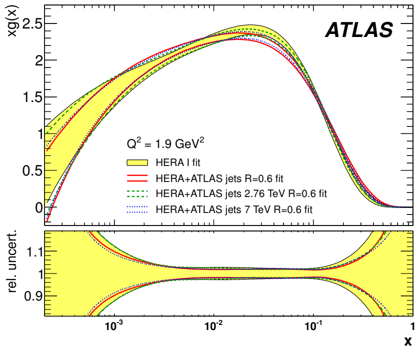


Figure 5: The momentum distribution of the gluon $xg(x)$ and the relative experimental uncertainty as a function of x for $Q^2 = 1.9$ GeV^2 [3]. The filled area indicates a fit to HERA data only. The bands show fits to HERA data in combination with both ATLAS jet datasets and the individual ATLAS jet datasets separately for jets with R = 0.6. The uncertainty on the PDF is centred on unity for each fit.

of-mass energies were found to agree with NLO pQCD predictions, confirming that perturbative QCD can describe jet production at high jet transverse momentum. The ATLAS inclusive jet cross section data were also used in combination with HERA data to perform fits of the proton PDFs resulting in a harder gluon distribution.

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