Measurement of multi-jet cross-sections in proton-proton collisions at 7 TeV center-of-mass energy in ATLAS

Zinonas Zinonos - on behalf of the ATLAS Collaboration
Università di Pisa & INFN Sezione di Pisa, Italia
E-mail: zenon@cern.ch

Abstract. Inclusive multi-jet production is studied using the ATLAS detector for proton-proton collisions with a center-of-mass energy of 7 TeV at the Large Hadron Collider at CERN. The data sample corresponds to an integrated luminosity of 2.4 pb$^{-1}$, using the first proton-proton data collected by the ATLAS detector in 2010. Results on multi-jet cross sections are presented and compared to both leading-order plus parton-shower Monte Carlo predictions and next-to-leading-order QCD calculations.

1. Introduction

Multi-jet cross sections serve as one of the main observables in high-energy particle physics. Events containing multiple jets in the final state are prolific and provide a good testing ground for the theory of the strong interaction, quantum chromodynamics (QCD). At high transverse momentum (high $p_T$), the production of jets is modeled by QCD as the hard scattering of partons and the subsequent parton showering, followed by a hadronization process. Within the framework of QCD, the jet energy is related to the energy of partons produced in the hadron collisions. Consequentially, the study of energy distributions for multi-jet events provides a fundamental and direct test of QCD at hadron colliders.

This is the first study [2] performed of multi-jet events from proton-proton collisions at 7 TeV center-of-mass energy, using the ATLAS detector at the Large Hadron Collider (LHC) at CERN. The data sample used for the analysis was collected between April 10 and August 30 of 2010 and represents a total integrated luminosity of 2.4 pb$^{-1}$ [1]. Approximately half a million events with at least two jets in the final state are selected using this data sample.

Two primary motivations for the multi-jet study are to evaluate how robust leading-order (LO) QCD calculations are in representing the high jet multiplicity events, relevant as backgrounds in high-energy searches, and to test next-to-leading-order perturbative QCD (NLO pQCD) calculations. For the leading-order comparisons, events with up to six jets in the final state are studied, and for the next-to-leading-order perturbative QCD study the focus is on three-jet events and their comparison to two-jet events.

2. The ATLAS Detector

ATLAS is a general-purpose detector surrounding Interaction Point 1 of the LHC and its architecture is based on a system of solenoidal and toroidal magnets [3].

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High-energy particles produced in collisions initially pass through an inner tracking system embedded in a strong solenoidal magnetic field. The inner tracker covers a pseudorapidity $|\eta| < 2.5$ and has full coverage in azimuth. In the barrel region, it is made of three main components arranged in concentric layers, all of which are immersed in a 2 Tesla field provided by the inner solenoid magnet. Three layers of silicon pixel detectors provide a two-dimensional hit position very close to the interaction point. Silicon microstrip detectors are then used in the next four layers, providing excellent position resolution for charged particles. A transition-radiation detector is the outermost component of the tracker, with coarser position resolution with respect to the silicon, but giving a large lever-arm for track reconstruction in addition to particle identification capabilities. The ATLAS calorimeter is also composed of many subdetectors. The electromagnetic calorimeter ($|\eta| < 3.2$) is a high-granularity sampling detector in which the sensitive medium is liquid argon (LAr). The hadronic calorimeters are divided into three sections: a tile scintillator/steel calorimeter in used in both the barrel ($|\eta| < 1.0$) and extended barrel cylinders ($0.8 < |\eta| < 1.7$); the hadronic endcap covers the region $1.5 < |\eta| < 3.2$ and consists of LAr/copper calorimeter modules. Finally the forward calorimeter measures both electromagnetic and hadronic energy in the range $3.2 < |\eta| < 4.9$ using LAr/copper and LAr/tungsten modules. The total coverage of the ATLAS calorimeters is therefore $|\eta| < 4.9$. A muon spectrometer, which is designed to identify muons and measure both their trajectories and momenta with high accuracy: the design momentum resolution is 10% at momenta transverse to the beam line ($p_T$) of 1 TeV. The muon spectrometer, comprises three toroidal magnet systems consisting of eight coils each with a bending power $f B dl = 1 - 7.5$ Tm.

The ATLAS trigger system employs three trigger levels, of which only the hardware-based first level trigger is used in this analysis. Events are selected using the calorimeter-based jet trigger. The first level jet trigger [4] uses coarse detector information to identify areas in the calorimeter where energy deposits above a certain threshold occur. A simplified jet finding algorithm based on a sliding window of size $\Delta \phi \times \Delta \eta = 0.8 \times 0.8$ is used to identify these areas. This algorithm uses coarse calorimeter towers with a granularity of $\Delta \phi \times \Delta \eta = 0.2 \times 0.2$ as inputs.

3. Cross Section Definitions and Kinematics
The anti-$k_t$ algorithm [5, 6] with full four-momentum recombination is used to identify jets.

For high multiplicity studies, namely up to six jets in an event, the resolution parameter in the jet reconstruction is fixed to $R = 0.4$ to contend with the limited phase space and to reduce the impact of the underlying event [7] in the jet energy determination. For testing NLO pQCD calculations, where the study focuses on three-jet events, a resolution parameter of $R = 0.6$ is preferred, since a larger value of $R$ is less sensitive to theoretical scale uncertainties. The anti-$k_t$ algorithm was chosen because it can be implemented in the NLO pQCD calculation, is infra-red safe to all orders and produces jets with a simple geometrical shape.

Jet measurements are corrected for all experimental effects and refer to the particle-level final state. At the particle level, jets are built using all final-state particles with a proper lifetime longer than 10 ps, including muons and neutrinos from hadronic decays.

Cross sections are calculated in bins of inclusive jet multiplicity, meaning that an event is recorded in a jet multiplicity bin if it contains a number of jets that is equal to or greater than that multiplicity. For example, an event with three reconstructed jets will be counted both in the two-jet and three-jet multiplicity bin. Inclusive multiplicity bins are used because they are stable in the pQCD fixed-order calculation, unlike exclusive bins. Only jets with $p_T \geq 60$ GeV and $|y| \leq 2.8$ are counted in the measurement. These cuts are chosen to ensure that the jets are reconstructed with high efficiency. The leading jet is further required to have $p_T \geq 80$ GeV to stabilize the NLO pQCD calculations [8].
4. Theoretical Predictions

Measurements are compared to pQCD calculations at leading order and next-to-leading order. The different predictions are all normalized to the measured inclusive two-jet cross section and then used for shape comparisons.

For the leading-order analysis, ALPGEN [9] is used to generate events with up to six partons in the final state using the leading-order set of proton PDFs CTEQ6L1 [10]. ALPGEN is interfaced to HERWIG/JIMMY [12, 13] or PYTHIA [11] Monte Carlo generators in order to sum leading logarithms to all orders in the parton-shower approximation and to include non-perturbative effects such as hadronization and the underlying event. This was done by evaluating the ratio of the cross-section with and without hadronisation and underlying event simulation using different leading-logarithmic parton-shower Monte Carlo programs and then multiplying the NLO theory distributions by this correcting factor.

SHERPA [14] with its default parameters and renormalization scale scheme from version 1.2.3 is also used to generate events with up to six partons in the final state. This provides an independent matrix-element calculation with a different matching scheme between the matrix element and the parton shower.

The PYTHIA 6.421 [15] event generator is also compared to the data to study the limitations of leading-order $2 \to 2$ matrix-element calculations. This generator implements a leading-order matrix-element calculation for $2 \to 2$ processes, $p_T$-ordered parton showers, an underlying-event model for multiple-parton interactions and the Lund string model for hadronization.

For the purpose of understanding detector effects, the particles generated in the leading-order Monte Carlo generators are passed through a full simulation of the ATLAS detector and trigger [16] based on GEANT4 [17]. Additional proton-proton collisions are added to the hard scatter in the simulation process to reproduce realistic LHC running conditions. Events and jets are selected using the same criteria in data and Monte Carlo simulations.

For the next-to-leading-order pQCD study, the calculation implemented in NLOJet++ [18] is used. The renormalization and factorization scales are varied independently by a factor of two in order to estimate the impact of higher order terms not included in the calculation. An additional requirement that the ratio of the renormalization and factorization scales did not differ by more than a factor of two was imposed.

The NLOJet++ program implements only a matrix-element calculation, lacking a parton-shower interface. Therefore, it does not account for non-perturbative effects such as the hadronization and underlying event. To compare to particle-level measurements, a correction factor is applied which takes the next-to-leading-order pQCD calculations to the particle level.

5. Jet Reconstruction and Calibration

Jets are reconstructed at the electromagnetic scale using the anti-$k_T$ algorithm. The input objects to the jet algorithm are three-dimensional topological clusters [19] built from calorimeter cells. The four-momentum of the uncalibrated, EM-scale jet is defined as the sum of the four-momenta of its constituent calorimeter energy clusters. Additional energy due to multiple proton-proton interactions within the same bunch crossing (pile-up) is subtracted by applying a correction derived using minimum bias data. The energy and the position of the jet are corrected for instrumental effects such as dead material and non-compensation. This jet energy scale (JES) correction is calculated using isolated jets in the Monte Carlo simulation as a function of the transverse momentum and pseudorapidity of the reconstructed jet [20].

6. Offline Selection

6.1. Trigger

A set of ATLAS first level (level-1) multi-jet triggers is used to select events for the analysis. Multi-jet triggers require several jets reconstructed with a level-1 sliding window algorithm. All
multi-jet triggers are symmetric, meaning that each trigger had one particular energy threshold that applied equally to all jets in an event. Only two-jet and three-jet triggers were needed for the analysis.

The trigger efficiencies have been calculated using a bootstrap technique in data as well in Monte Carlo simulated events. Figure 1 shows the efficiency for the third leading jet to fire the three-jet trigger as a function of the reconstructed jet $p_T$ for jets of $R = 0.4$. The trigger becomes fully efficient when at least one jet with offline $p_T > 60$ GeV is found in the fired event.

The event-level efficiency as a function of the closest distance between two selected $R = 0.4$ offline jets for events selected using the three-jet trigger is also shown in Figure 2, to probe possible topological dependences in the trigger. A dependence at low $\Delta R$ is observed, where $\Delta R = \sqrt{\Delta \phi^2 + \Delta y^2}$ represents the minimum separation between selected jets in the event. The dependence on $\Delta R$ is well described by the Monte Carlo simulation. Such an inefficiency due to the nearby jet activity is taken into account in the data correction (Section 7). However, this effect is not observed in the analysis of jets reconstructed using the anti-$k_t$ algorithm with resolution parameter $R = 0.6$.

![Figure 1](image1.png) **Figure 1.** Jet trigger efficiency for the third leading jet as a function of $p_T$ for anti-$k_t$ jets with $R = 0.4$.

![Figure 2](image2.png) **Figure 2.** Jet trigger efficiency as a function of the minimum separation $\Delta R$ between the two closest jets.

All events falling in the three-jet inclusive multiplicity bin or higher are selected using the three-jet trigger with a jet threshold of 10 GeV on the level-1 jet objects. In order to select events in the two-jet inclusive multiplicity bin, several two-jet triggers were used. Three two-jet triggers with symmetric transverse energy thresholds of 10, 15 and 30 GeV were combined independently, weighted by the luminosity associated with each trigger. More specifically, the three triggers with thresholds of 10, 15 and 30 GeV covered the ranges of second leading jet $p_T$ of 60-80 GeV, 80-110 GeV and greater than 110 GeV, respectively.

6.2. Event Selection

To reject events due to cosmic-ray muons and other non-collision backgrounds, events are required to have at least one primary vertex that is consistent with the beam spot position and that has at least five tracks associated to it. The efficiency for collision events to pass these vertex requirements, as measured in a sample of events passing all selections of this analysis, is well over 99%.
6.3. Jet Selection Criteria

Jets considered in the analysis are selected using the following kinematic and data quality selection criteria:

(i) An event must contain at least one jet with $|y| \leq 2.8$ and a $p_T$ greater than or equal to 80 GeV.

(ii) Jets are required to have $|y| \leq 2.8$ and $p_T \geq 60$ GeV in order to be counted.

(iii) Jets are only accepted if at least 70% of the total $p_T$ of the associated charged tracks comes from the event vertex. Overall, this cut reduces the two-jet cross section by 0.4%, and its effect increases with jet multiplicity. The cut reduces the six-jet cross section by 3.4%. All observables show a negligible dependence on the number of reconstructed primary vertices when this cut is applied. Jets with no charged particle content are accepted.

(iv) Only events with a minimum of two selected jets are used in the analysis.

For a total integrated luminosity of 2.4 pb$^{-1}$, approximately 500,000 multi-jet events survived the selection cuts.

7. Data Correction

A correction is needed to compare the measurements to theoretical predictions. The correction, which accounts for trigger inefficiencies, detector resolutions and other detector effects that affect the jet counting, is performed in a single step using a bin-by-bin unfolding method calculated from Monte Carlo simulations. For each measured distribution, the corresponding Monte Carlo simulation cross section using truth jets, as defined in Section 5, is evaluated in the relevant bins, along with the equivalent distributions obtained after the application of detector simulation and analysis cuts. The ratio of the true to the simulated distributions provides the multiplicative correction factor (unfolding factor) to be applied to the measured distributions.

8. Uncertainty on the Jet Energy Scale

The uncertainty in the jet energy scale is the dominant systematic uncertainty for most of the measurements performed in analysis. The rather steeply falling cross sections as a function of jet $p_T$ implies that even a relatively small uncertainty in the determination of the jet $p_T$ translates into a substantial change in the cross sections as events migrate up or down the steeply falling curve.

The standard jet energy scale (JES) uncertainty in ATLAS [21] has been calculated using jets from a dijet sample without near-by activity in the calorimeter. The JES uncertainty in the central calorimeter region ($\eta < 0.8$) is lower than 2.5% for jets with transverse momentum $60 < p_T < 800$ GeV, and less than 4.6% for the full $p_T$-range $p_T > 20$ GeV. In the endcap ($0.8 < |\eta| < 2.8$) and forward ($2.8 < |\eta| < 4.5$) regions, the uncertainty for jets with $p_T > 50$ GeV is below 4% and 6% respectively.

For a multi-jet analysis, a set of additional systematic uncertainties are considered. The uncertainties arise from the different calorimeter response to jets of different flavors as well as effects that are sensitive to the available phase space for multi-jet events. These different effects are taken into account in the overall uncertainty of the JES.

9. Results

Figure 3 shows the results for the cross section as a function of the inclusive jet multiplicity. The data are compared to leading-order Monte Carlo simulations (ALPGEN+HERWIG with AUET1 tune, ALPGEN+PYTHIA tuned with MC09, PYTHIA with AMBT1 tune and SHERPA with its default settings) normalized to the measured inclusive two-jet cross section. The measurement systematics are dominated by the jet energy scale uncertainty and range from 10-20% at low
multiplicities to almost 30-40% at high multiplicities. The Monte Carlo simulation predictions fall on the measured results across the full inclusive multiplicity spectrum.

A study that reduces significantly the impact of systematic uncertainties is the ratio of the \( n \)-jet to \((n-1)\)-jet cross section as a function of multiplicity. Figure 4 shows the results for such a study. Both the unfolding and the jet energy scale uncertainties contribute comparably to the total systematic uncertainty, whereas the statistical uncertainties are smaller than the systematic uncertainties, and negligible in most bins. All Monte Carlo simulations agree well with the data, yet there is a noticeable spread in their predictions. Differences at the level of 15% are observed between PYTHIA AMBT1 and ALPGEN+PYTHIA MC09 [22] ATLAS tunes in the first bin. These differences most likely arise from the difference between the ME+PS and the pure parton-shower Monte Carlo simulations.

The differential cross section for multi-jet events as a function of the jet \( p_T \) is useful for characterizing the kinematic features. Figures 5-6 present the \( p_T \)-dependent differential cross sections for the leading and second leading jet in multi-jet events. The systematic uncertainty in the measurement is 10-20% across \( p_T \) and increasing up to 30% for the fourth leading jet differential cross section. The jet energy scale systematic uncertainty remains the dominant uncertainty in the measurement. All Monte Carlo simulations agree reasonably well with the data. The PYTHIA AMBT1 Monte Carlo simulation predicts a somewhat steeper slope, compared to the data, as a function of the leading jet \( p_T \) and of the second leading jet \( p_T \). The effect is most noticeable in the highest \( p_T \) range.

NLO pQCD calculations of the three-to-two-jet cross section ratio were performed as a function of the sum of the \( p_T \) of the two leading jets, \( H_T^{(2)} \). The NLO pQCD calculation for the ratio as a function of this specific observable was found to give the smallest theoretical scale uncertainty and is, therefore, most sensitive to input parameters such as the \( \alpha_S \) fit.

Figure 7 shows a comparison of the measurement to NLO pQCD calculations with the MSTW 2008 NLO PDF [23] set for \( R = 0.6 \) jets. Scale uncertainties of the NLO pQCD calculations are found to be larger for jets with \( R = 0.4 \) than with \( R = 0.6 \) [2]. The theoretical uncertainty of the
Figure 5. Differential cross section as a function of leading jet $p_T$ for events with $N_{\text{jets}} \geq 2$ jets.

Figure 6. Differential cross section as a function of sub-leading jet $p_T$ for events with $N_{\text{jets}} \geq 2$ jets.

NLO pQCD calculations is comparable to the measurement uncertainties of data. A comparison of the same measurement to leading-order Monte Carlo simulations is given in Figure 8 showing a very good agreement.

Figure 7. Three-to-two-jet differential cross-section ratio as a function of the sum of the $p_T$ of the two leading jets using $R = 0.6$. The data results are compared to NLO pQCD calculations.

Figure 8. Three-to-two-jet differential cross-section ratio as a function of $H_T^{(2)}$ for jet with a resolution parameter $R = 0.6$. Data measurements are compared to several leading-order Monte Carlo simulations.
10. Conclusions
A first dedicated study of multi-jet events has been performed using the ATLAS detector at a center-of-mass energy of 7 TeV with an integrated luminosity of 2.4 pb$^{-1}$ [2].

For events containing two or more jets, good agreement is found between data and leading-order Monte Carlo simulations with parton-shower tunes that describe adequately the ATLAS $\sqrt{s} = 7$ TeV underlying-event data.

All models reproduce the main features of the multi-jet data. ALPGEN, which contains higher multiplicity tree-level matrix elements matched to parton showers, generally describes the shapes well, whether the HERWIG or PYTHIA parton showers are used. Similarly, SHERPA describes the data well. However, PYTHIA, which contains a $2 \to 2$ leading-order matrix element augmented by parton showers, shows only a marginal agreement with the data.

A measurement of the three-to-two-jet cross section ratio as a function of the sum of the two leading jet $p_T$s has also been performed and is described by ALPGEN, SHERPA and a NLO pQCD calculation. Comparisons with NLO pQCD calculations may be useful for constraining parameters, such as parton distribution functions or the value of the strong coupling constant, $\alpha_S$, given that the systematic uncertainties from the measurement are comparable to the theoretical uncertainties.

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