PROCEEDINGS OF SCIENCE

QCD Results from ATLAS

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ATLAS results of both soft- and hard-QCD measurements are presented for the first data produced by the LHC. Distributions of jets reconstructed using either calorimeter or Inner Detector information are compared to the Monte Carlo simulation. The calorimeter response to isolated hadrons is shown to be described by the simulation to within 5%.

The first measurements of the properties of proton-proton interactions are presented. The charged-particle density, its dependence on transverse momentum and pseudorapidity, and the relationship between transverse momentum and charged-particle multiplicity are measured for events with at least one charged particle in the kinematic range $|\eta| < 2.5$ and $p_T > 500$ MeV at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. The measurements are compared to minimum bias Monte Carlo model predictions. This was the first presentation by ATLAS of charged particle multiplicities at 7 TeV.

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1. Introduction

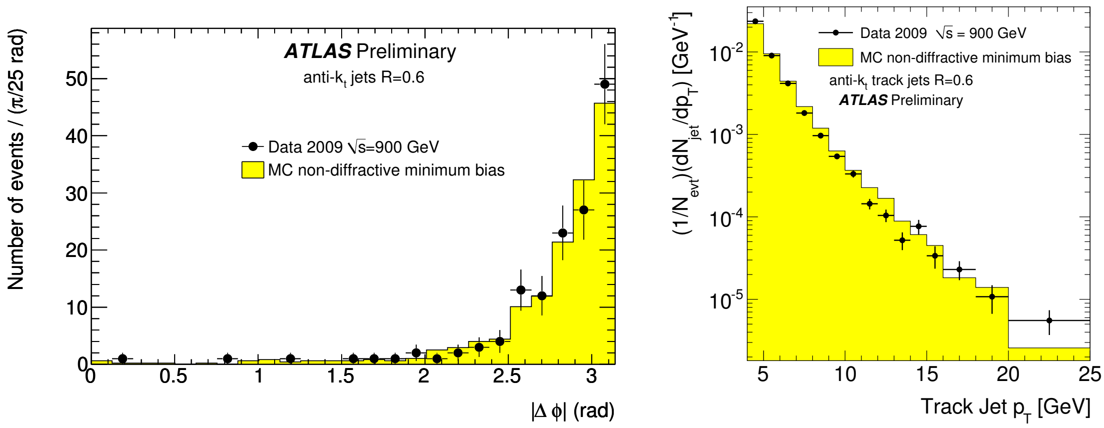
The ATLAS experiment [1] recorded the first LHC collision data on the 23rd of November 2009. In December, $12\mu b^{-1}$ of proton-proton collisions at a centre-of-mass energy of $\sqrt{s} =$ 900 GeV were recorded. On the 30th of March 2010, collisions at $\sqrt{s} = 7$ TeV were recorded, which made the LHC the highest energy proton-proton collider in the world. This paper discusses QCD results from ATLAS from analyses using the data taken at $\sqrt{s} = 900$ GeV and 7 TeV. It includes a comparison of basic properties of calorimeter and track jets and the response to isolated hadrons between data and simulation. The measurement of charged particle multiplicities in the kinematic range $p_T > 500$ MeV and $|\eta| < 2.5$ by ATLAS at 900 GeV [2] and 7 TeV are discussed. This was the first presentation of charged particle multiplicity measurements at 7 TeV by ATLAS [3].

Measurements are made using tracks reconstructed in the Inner Detector (ID) and jets reconstructed in either the ID or the calorimeters. The ID consists of a silicon pixel detector, a silicon microstrip detector (SCT) and a transition radiation tracker (TRT). It has full coverage in ϕ and covers the pseudorapidity range $|\eta| < 2.5$. The calorimetry consists of a high-granularity liquid-argon (LAr) electromagnetic sampling calorimeter ($|\eta| < 3.2$), a scintillator-tile hadronic calorimeter ($|\eta| < 1.7$) and a LAr hadronic calorimeter ($1.5 < |\eta| < 3.2$). Events are triggered by the Minimum Bias Trigger Scintillators (MBTS) mounted on the end of the calorimeter cryostats, which provide a pseudorapidity coverage of $2.09 < |\eta| < 3.84$. See [1] for further details of the ATLAS detector.

2. Early Jet Physics

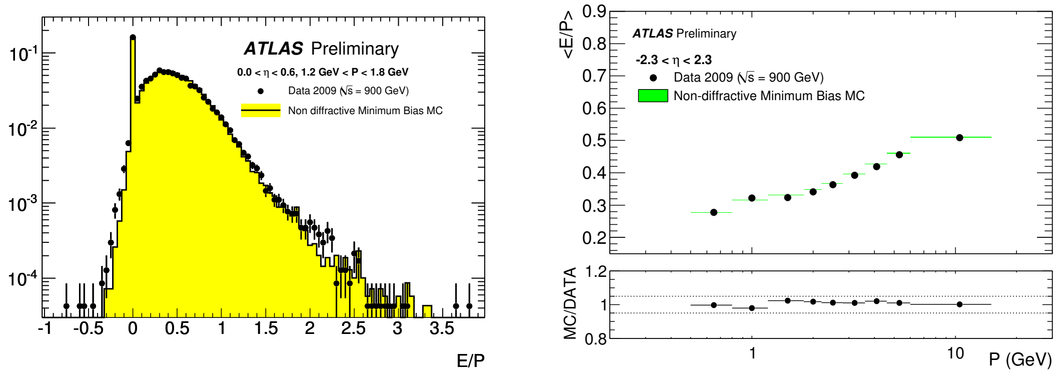
In the 2009 data, 1165 calorimeter jets were reconstructed with $p_T^{EM} > 7$ GeV within $|\eta| <$ 2.6 by the default ATLAS jet reconstruction algorithm, the anti-k_T algorithm with $R = 0.6$. The transverse momentum, p_T^{EM}, is at the electromagnetic scale. No correction was made for energy loss in dead material before the calorimeter or the non-compensation of the calorimeters. There were 143 events containing at least two jets. Figure 1 (a) shows the difference in the azimuthal angle of the two highest p_T jets ($\Delta\phi$) [4]. Jets were also reconstructed from tracks [5] to complement the calorimeter-based measurements. The tracks were selected according to criteria in [2] and jets were also reconstructed with the anti-k_T algorithm with $R = 0.6$. Figure 1 (b) shows the transverse momentum distribution of 13364 track jets with $p_T > 4$ GeV and $|\eta| < 1.9$. Both distributions show good agreement between data and simulation.

The calorimeter response to hadrons was studied by comparing the energy in calorimeter clusters to the track momentum of isolated tracks [6]. Figure 2 (a) shows an example of the E/p distribution in data and simulation. The entries with E/p exactly zero are isolated tracks for which no cluster was found largely due to hadronic interactions in the material before the calorimeter. The dependence of the mean value of E/p on the track momentum is shown in Fig. 2 (b), with the data shown as points and the simulation as green bands. The increase in $\langle E/p \rangle$ with momentum is because the fraction of hadron energy measured by the calorimeter increases with momentum. The value of $\langle E/p \rangle$ agrees to within 5% between data and simulation for particles with momenta between 0.5 MeV and 10 GeV.



(a) (b)

Figure 1: Azimuthal angle distribution for anti-k_T jets with R=0.6 reconstructed with topological clusters, satisfying the requirements: p_T^{EMScale} >7 GeV and $|\eta|$ <2.6. The Monte-Carlo simulation distribution is normalized to the number of jets in data (left) The transverse momentum distribution of track jets: one entry per jet. The jets are required to have $|\eta| < 1.9$, which corresponds to tracks with $|\eta| < 2.5$. The PYTHIA Monte Carlo (MC) simulation prediction shows the raw value after detector simulation, and is normalized to the same area as the data. (right)



(a) (b)

Figure 2: E/p distribution for isolated tracks with an impact point in the region at the 2nd layer of the EM calorimeter with $|\eta| = [0, 0.6]$ and $p = [1.2, 1.8]$ GeV. (left) Mean value of E/p as a function of the track momentum in whole region, $\eta = [-2.3, 2.3]$. The black dots represent the collision data while the green rectangles represent the MC prediction (right,upper) . Ratio between MC and collision data as a function of the track momentum (lower).

3. Minimum Bias Physics

Inclusive charged particle distributions measured in pp and $p\bar{p}$ collisions at a range of different centre-of-mass energies [7–14] have been used to characterise inelastic hadron-hadron collisions and to constrain phenomenological models of soft QCD interactions. The results presented here study primary charged particles with transverse momentum, $p_T > 500$ MeV within the pseudorapidity range $|\eta| < 2.5$. Primary charged particles are defined as charged particles with a mean lifetime $\tau > 3 \times 10^{-11}$s directly produced in pp interaction or from the decays of particles with a shorter lifetime. Four particle-level distributions are measured:

$$\frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}, \frac{1}{N_{\mathrm{ev}}} \cdot \frac{1}{2\pi p_{\mathrm{T}}} \cdot \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}, \frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ev}}}{\mathrm{d}n_{\mathrm{ch}}} \text{ and} \langle p_{\mathrm{T}} \rangle \text{ vs. } n_{\mathrm{ch}} \tag{3.1}$$

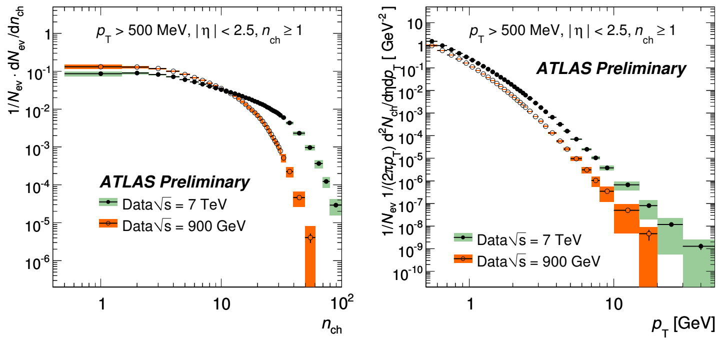
where N_{ev} is the number of events with at least one charged-particle in the kinematic acceptance, N_{ch} is the total number of charged particles, n_{ch} is the number of charged particles in an event and $\langle p_{\mathrm{T}} \rangle$ is the average p_T of events with a specific multiplicity.

A total of 455,593 events at 900 GeV and 369,673 events at 7 TeV were selected by the MBTS trigger. Tracks were reconstructed using a silicon-seeded algorithm in the Inner Detector. Events were required to contain a primary vertex reconstructed from at least three (two) tracks with $p_T >$ 150 MeV with a transverse impact parameter with respect to the beam-spot position $d_0^{BS} < 4$ mm at 900 GeV (7 TeV). A more sophisticated vertex reconstruction algorithm was used at 7 TeV capable of reconstructing multiple primary vertices per event and the beam spot position was used as a constraint in the vertex fix, which allowed the requirement on the number of tracks to be reduced. The tracks used to measure the charged particle multiplicity were required to have $p_T > 500$ MeV and at least one pixel and six SCT hits. The tracks were also required to have impact parameters calculated with respect to the primary vertex within $d_0 < 1.5$ mm and $z_0 \cdot \sin\theta < 1.5$ mm. Events were required to contain at least one selected track.

The distributions were corrected to the particle level by weighting each track by the reciprocal of each efficiency component. The trigger and vertex efficiency were measured in data as a function of the number of selected tracks without cuts on the impact parameters, but with $d_0^{BS} < 4$ mm. The trigger efficiency was independent of p_T and the small dependence of the vertex efficiency on η for events with a single selected track was corrected. Events containing a second primary vertex with at least four tracks were rejected in the 7 TeV analysis to remove pile-up, which was estimated to be present in 0.1% of events. The contribution from pile-up at 900 GeV was negligible. The track reconstruction efficiency was determined from a simulation based on Geant 4 [15] and parametrised as a function of p_T and η. The distributions were corrected for secondaries and bin migration due to track parameter resolution.

The charged particle multiplicity from an event-by-event Bayesian unfolding [16]. Events with $n_{ch} \geq 1$ but no reconstructed tracks were corrected for using: $1/(1-(1-\langle\varepsilon\rangle)^{n_{ch}})$ where $\langle\varepsilon\rangle$ is the average track reconstruction efficiency. The largest systematic uncertainty is 3.8% because the track reconstruction efficiency is estimated from the simulation. This is dominated by the uncertainty on the material budget of the ID, which was estimated from the tails of the impact parameter distribution, the length of tracks and a study of the reconstructed K_S^0 mass [17].

The charged particle multiplicity distributions measured at 7 TeV are compared to the predictions from Monte Carlo models in Fig. 4. The ATLAS MC09 [18] tune is found to best describe the data, however discrepancies are observed for higher values of p_T and n_{ch}. Figure 3 (a) and (b) compares the measured charged particle multiplicity and p_T spectra between 900 GeV and 7 TeV. The dependence of the average multiplicity at central rapidity on the centre-of-mass energy is compared in Fig. 3 (c), where the measured values are observed to be higher than the predictions from



(a) (b) (c)

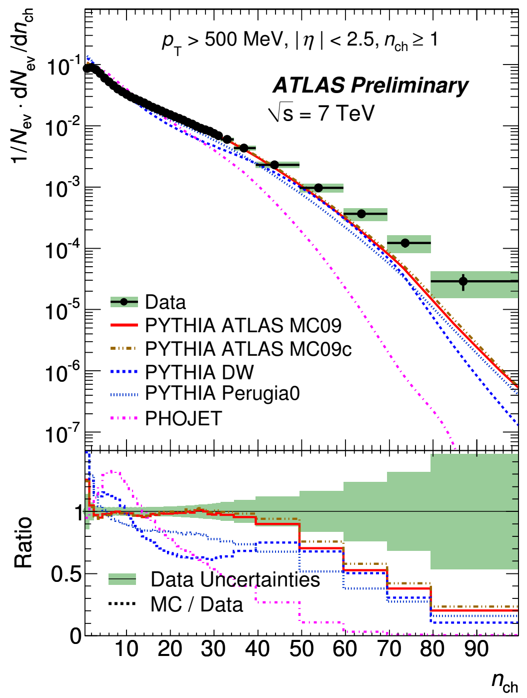
Figure 3: Charged-particle multiplicities for events with $n_{ch} \geq 1$ within the kinematic range $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. The panels compare the charged-particle multiplicity (a) and as a function of pseudo-rapidity of the transverse momentum (b). The closed and open dots represent the data at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 900$ GeV, respectively. The vertical bars represent the statistical uncertainties, while the shaded areas show the statistical and systematic uncertainties added in quadrature. The average charged particle multiplicity per unit of rapidity for $\eta = 0$ for events with $n_{ch} \geq 1$ within the kinematic range $p_T > 500$ MeV and $|\eta| < 2.5$ as a function of the centre of mass energy.

the different Monte Carlo tunes. The average multiplicity per unit event and unit of pseudorapidity at 7 TeV is measured to be $2.418 \pm 0.004(\text{stat.}) \pm 0.076(\text{syst.})$ for $|\eta| < 0.2$.

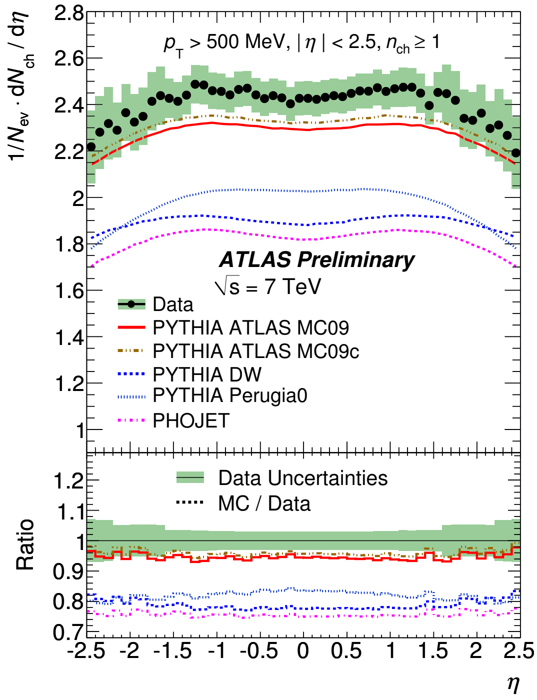
4. Conclusion

Early QCD results from the ATLAS experiment using data taken at 900 GeV and 7 TeV have been presented. The Monte Carlo simulation has been shown to provide a good description of both the Inner Detector and calorimeter. Basic kinematic properties of jets reconstructed using either calorimeter or Inner Detector information were shown. The average calorimeter response to isolated hadrons was shown to be described by the simulation to the 5% level.

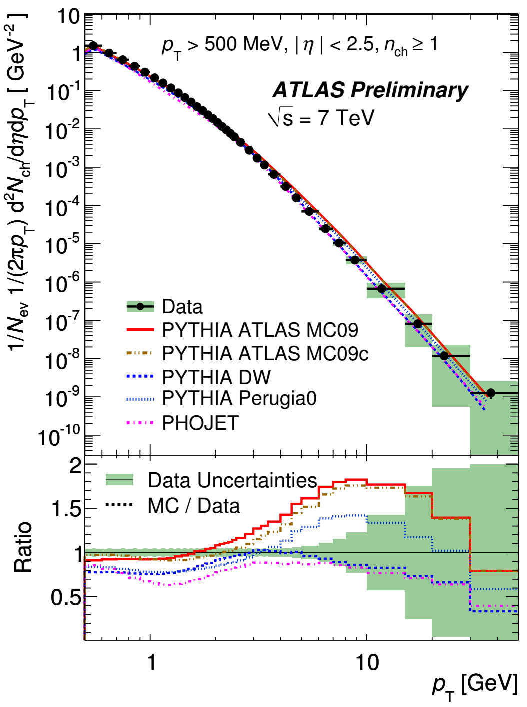
Results of the first ATLAS measurement of charged particle multiplicities at $\sqrt{s} = 7$ TeV were presented and compared predictions from Monte Carlo models and previous measurements at 900 GeV. These are presented as inclusive inelastic distributions measured at the particle level within the kinematic range $p_T > 500$ MeV and $|\eta| < 2.5$ for events containing at least one charged particle. The average multiplicity per unit event and unit of pseudorapidity at 7 TeV was measured to be $2.418 \pm 0.004(\text{stat.}) \pm 0.076(\text{syst.})$ for $|\eta| < 0.2$, which is larger than the predictions from the Monte Carlo models studied.



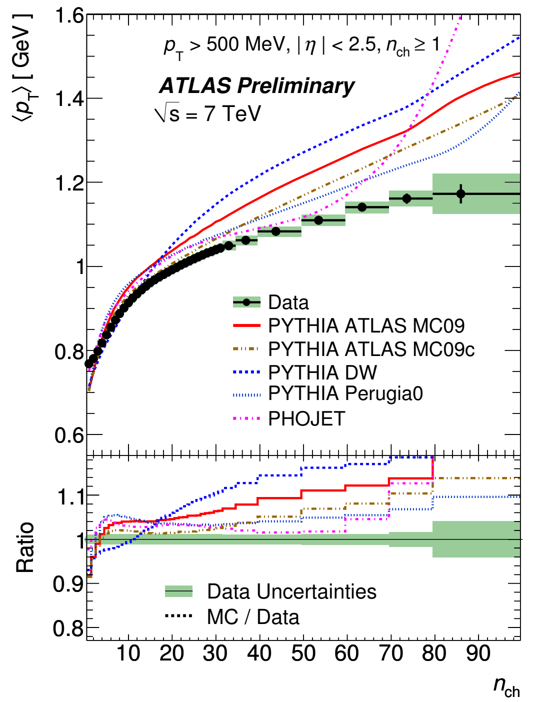
(a)



(b)



(c)



(d)

Figure 4: Charged-particle multiplicities for events with $n_{ch} \geq 1$ within the kinematic range $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s} = 7$ TeV. The panels show the charged particle multiplicity (a) as a function of the pseudo-rapidity (b), transverse momentum (c) and the average transverse momentum as a function of the number of charged particles in the event (d). The dots represent the data and the curves the predictions from different Monte Carlo models. The vertical bars represent the statistical uncertainties, while the shaded areas show the statistical and systematic uncertainties added in quadrature. The values of the ratio histograms refer to the bin centroids.

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