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QCD physics at ATLAS

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Summary. — Quantum Chromodynamics (QCD) measurements represent an extensive part of the early physics program of the ATLAS experiment at LHC. In this contribution a selection of the first ATLAS QCD measurements is presented. The results are based on a part of the data sets collected during 2010 at the centre of mass energy of $\sqrt{s} = 7\,\text{TeV}$. The contribution includes an overview of the underlying event studies. A large number of measurements involving jets is also illustrated. After the investigation of jet shapes, the measurements of the cross section of the inclusive, dijet, multi-jet and bosons plus jets processes are presented. The angular decorrelations results in dijet events are also discussed. Finally the measurement of the prompt photon cross section is shown. The measurements are compared to the predictions from different Monte Carlo (MC) generators implementing leading-order (LO) matrix elements supplemented by parton showers, and to next-to-leading order (NLO) perturbative QCD (pQCD) calculations.

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1. – Introduction

The LHC started colliding protons at a centre of mass energy of $\sqrt{s} = 7\,\text{TeV}$ early in 2010. The luminosity of the machine has grown roughly exponentially with running time. By the end of the 2010 run, a sample of integrated luminosity around $45\,\text{pb}^{-1}$ was collected, at a peak luminosity of around $10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$. The ATLAS detector [1] performed well throughout the 2010 run and its response was quickly understood.

The QCD measurements are one of the most important chapters of the ATLAS early physics program. They are interesting in their own right as tests of the phenomenology of the strong interaction at the previously unexplored energy domain probed by the LHC. The hard QCD measurements can be compared with the available NLO pQCD calculations, providing a validation of the theory in the new kinematic regime, whereas deviations from the pQCD predictions could translate into a hint of new physics. In addition the hard QCD processes, mainly constituted by jet physics, form important backgrounds for both Standard Model and Beyond Standard Model physics processes, therefore a detailed measurement of these processes represents already the first step of the ATLAS discovery program.

In order to perform precise physics measurements or searches for new physics phenomena at hadron colliders, it is essential to have a good understanding not only of the QCD hard scattering process but also of the accompanying beam-beam remnants and the multiple parton interactions, that are the main components of the underlying events. The MC event generators that include LO matrix elements supplemented by parton shower need to be tuned on the data to perform an adequate description of these phenomena. By measuring the observables sensitive to the underlying event, a deeper insight into different contributing processes can be gained and the MC models can be improved.

In this contribution a review of the first QCD measurements is presented including the underlying event results, many hard QCD measurements involving jets and finally prompt photons measurements. Most of the results presented here are based on small data sets ranging from integrated luminosities of $17\,\mathrm{nb}^{-1}$ to about $300\,\mathrm{nb}^{-1}$. Although the data sample is modest, the large cross section for QCD processes already allowed significant tests of this phenomenology, with an extension of the kinematical reach beyond the measurements from previous experiments.

2. – The underlying event

The underlying event is defined as everything in the event except the hard scatter itself, so it consists of the accompanying beam-beam remnants and the multiple parton interactions. It also receives contributions from initial and final state parton QCD radiation. The underlying event has been first investigated at ATLAS through the study of the charged particles reconstructed in the Inner Detector [2]. The charged particles in every event are categorized according to their azimuthal angles ϕ. A "toward" region is then defined by the ϕ value of the highest-p_T track, which strongly correlates with the ϕ of the hardest scattering in the event. A "transverse" region is then defined by $60^\circ < |\Delta\phi| < 120^\circ$, with $|\Delta\phi|$ measured relative to the leading track. Little activity associated with the hard scatter is expected in this region and it is thus the most sensitive to underlying event effects. The data are corrected back to the particle level and the distributions are compared with the predictions from different MC models. Figure 1 shows the average number of central charged particles ($|\eta| < 2.5$, $p_T > 0.5\,\mathrm{GeV}$) per event in the transverse region. The level of activity is larger than that predicted by the underlying event model implemented in the different MCs using pre-LHC tunings. An underlying event analysis has also been performed using calorimeter information with similar conclusions [3]. The new tunes of MCs obtained by attempting to fit the charged particle multiplicity distributions in a diffraction limited phase-space, and also using the plateau of the underlying event distributions shown here results in a significant improvement [4].

3. – The jet shapes

Jets are distinctive signature of short-distance (hard) interactions between partons, and probe different aspects of high-p_T physics. Most of the results presented here are based on jets which are reconstructed using the anti-kt algorithm [5] with a distance parameter $R = 0.6$. The inputs to the anti-kt jet algorithm are clusters of calorimeter cells seeded by cells with energy that is significantly above the measured noise [6].

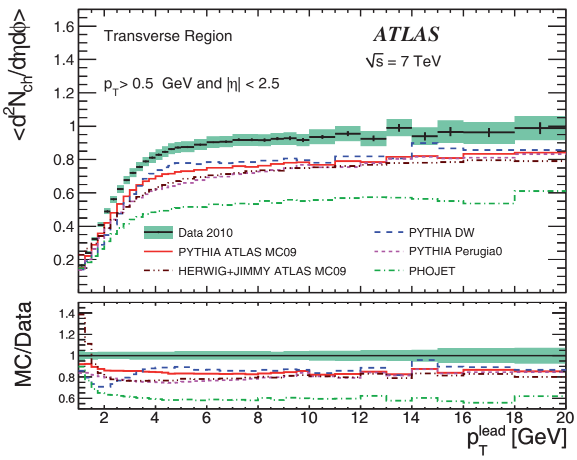

Fig. 1. – The charged particle multiplicity density as a function of the transverse momentum of the leading track restricted to azimuthal angles transverse to the leading particle. Data are compared with MC models.

The measured jet p_T is corrected to the particle level scale using an average correction, computed as a function of jet transverse momentum and pseudorapidity, and extracted from MC simulation. The main systematic uncertainty in the measurements presented here constitutes the jet energy scale uncertainty which, by the time of these studies, is determined to below 7% for central jets above 60 GeV transverse momentum [7].

The jet shapes [8] measurement tests the detailed modelling of jets in the MC generators. The shape of the jet depends on the type of partons (quark or gluon) that give rise to jets in the final state, and is also sensitive to non-perturbative fragmentation effects and underlying event contributions from the interaction between proton remnants. A proper modeling of the soft contributions is crucial for the understanding of jet production in p-p collisions and for the comparison of the jet cross section measurements with pQCD theoretical predictions. The differential jet shape $\rho(r)$ is defined as the average fraction of jet transverse momentum that lies inside an annulus of thickness $\Delta r = 0.1$ around the jet axis, normalized to the thickness. The measurements are carried out in the kinematic region with transverse momentum $30\,\text{GeV} < p_T < 600\,\text{GeV}$ and rapidity in the region $|y| < 2.8$ [9]. Figure 2 shows the measured differential jet shape corrected for detector effects separately for low-p_T (left) and high-p_T jets (right); the data are compared to several leading order QCD matrix element plus parton shower MC predictions, including different sets of tuning parameters. As expected, the measured jets become narrower with increasing jet transverse momentum. The jet shapes predicted by PYTHIA-Perugia2010 [10] provide a reasonable description of the data. HERWIG++ [11] predicts broader jets than the data at low and very high p_T, while ALPGEN [12] and PYTHIA-MC09 tend to produce narrower jets than the data.

4. – The inclusive jet, dijet and multijet cross sections

The first ATLAS inclusive jet and dijet data have been published using a data sample with an integrated luminosity of $17\,\text{nb}^{-1}$ [7]. The jet cross section measurements are

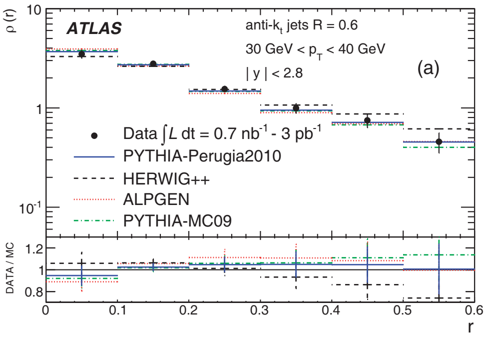

Fig. 2. – The measured differential jet shape, $\rho(r)$, in inclusive jet production for jets with $|y| < 2.8$ and $30\,\text{GeV} < p_T < 40\,\text{GeV}$ (left) and $500\,\text{GeV} < p_T < 600\,\text{GeV}$ (right) is shown in different p_T regions. Data are compared with MC models.

corrected for all experimental effects. They are performed in the kinematic region $p_T > 60\,\text{GeV}$ and $|y| < 2.8$ (in the dijet measurement the second leading jet should have $p_T > 30\,\text{GeV}$). This ensures that jets lie well within the high efficiency plateau region for the triggers used and that the jets are in a region where the jet energy scale is well understood. Figure 3 (left) shows the inclusive jet double-differential cross section measured as a function of the jet p_T in different rapidity regions. Figure 3 (right) shows the dijet differential cross section measured as a function of the invariant mass of the dijet system (m_{12}) binned in the maximum rapidity of the two leading jets. The cross sections extend into previously unmeasured kinematic regimes. For inclusive jets, the p_T

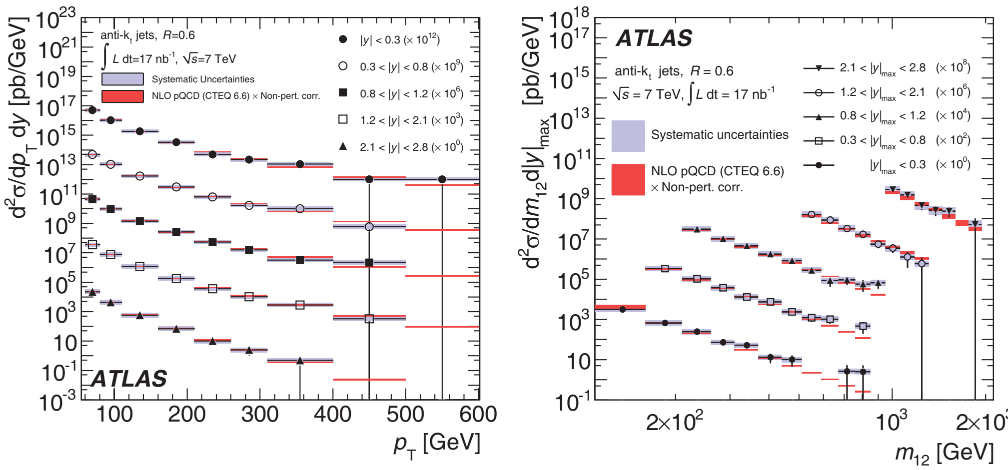

Fig. 3. – The inclusive jet differential cross section as a function of jet p_T in different rapidity regions (left). The dijet double-differential cross section as a function of dijet mass, binned in the maximum rapidity of the two leading jets ($|y|_{max}$) (right). In both cases, the results are shown for jets identified using the anti-kt algorithm with $R = 0.6$. the data are compared to NLO pQCD calculations to which soft QCD corrections have been applied.

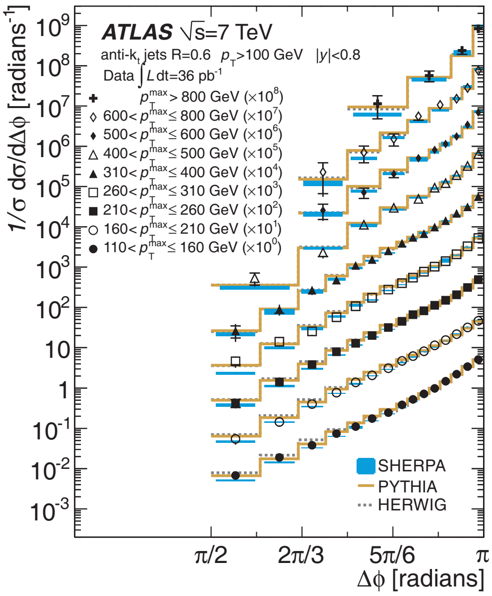

Fig. 4. – The differential cross section $(1/\sigma)(\mathrm{d}\sigma/\mathrm{d}\Delta\phi)$ binned in nine regions based on the p_T of the leading jet. The data are compared to various MC generators.

distribution extends up to 600 GeV. For dijet events, the dijet mass distribution extends up to nearly 2 TeV. The measurements have been compared to NLO pQCD calculations corrected for non perturbative effects. The theory agrees well with the data.

A particularly challenging class of jet production pertains to the study of events with more than two jets in the final state. Multijet events provide a particularly fertile testing ground for perturbative QCD at high energies. First ATLAS results are shown in [13]. The measurements are well described within uncertainties by the leading order matrix element calculation provided by ALPGEN, and PYTHIA describes the shapes of the distributions adequately.

5. – The dijet azimuthal decorrelation

The measurement of dijet angular decorrelations constitutes a very interesting method to access multi parton production using only the two hardest jets per event. In pure dijet signatures the two jets are back to back in the transverse plane due to energy momentum conservation. These events have small azimuthal decorrelations, $\Delta\phi = \pi$, while $\Delta\phi \ll \pi$ is typical of events with several high-p_T jets. QCD also describes the evolution of the shape of the $\Delta\phi$ distribution, which narrows with increasing leading jet p_T. A detailed understanding of events with large azimuthal decorrelations is important to searches for new physical phenomena with dijet signatures, such as supersymmetric extensions to the Standard Model. Figure 4 shows the measurement of the differential cross section binned in different regions based on the p_T of the leading jet [14]. The data are compared to various MC generators. A reasonable description is given by all MC generators within the measurement uncertainties.

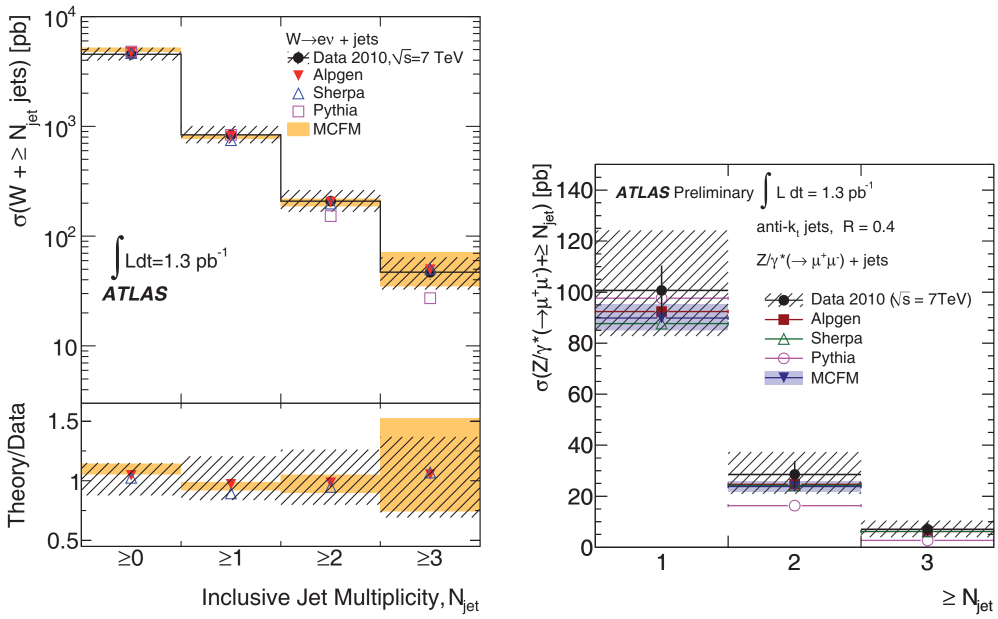

Fig. 5. – The W+jets cross section in the electron decay mode (left) and the Z+jets cross section in the muon decay mode (right) as a function of jet multiplicity. The cross sections are quoted in a limited and well-defined kinematic region, described in the text. Also shown are predictions from PYTHIA, ALPGEN, SHERPA, and MCFM. For the W+jets cross section the ratio of theoretical predictions to data is also shown.

6. – The boson plus jets cross section

The production of jets in association with W or Z bosons forms an important background for both Standard Model and Beyond Standard Model physics processes. A detailed measurement is needed to validate and tune the MCs. The first ATLAS measurement of the inclusive W+jets cross section [15] and of the inclusive Z+jets cross section [16] is based on an integrated luminosity of $1.3\,\text{pb}^{-1}$. Figure 5(left) shows the cross sections in the electron decay mode of the W boson as a function of jet multiplicity; the results have been corrected for all known detector effects and are quoted in a limited and well-defined range of jet and lepton kinematics: $p_T^j > 20\,\text{GeV}$ and $|\eta^j| < 2.8$, $E_T^e > 20\,\text{GeV}$, $|\eta^e| < 2.47$ (excluding $1.37 < |\eta^e| < 1.52$), $p_T^\nu > 25\,\text{GeV}$ $M_T > 40\,\text{GeV}$, $\Delta R^{e,j} > 0.5$, where e, j and ν denote the electron, the jet and the neutrino, respectively. The measured cross sections are compared to particle-level predictions based on perturbative QCD. Next-to-leading order calculations are found in good agreement with the data. Leading-order multi parton event generators, as ALPGEN and SHERPA [17], normalized to the NNLO total cross section, describe the data well for all measured jet multiplicities. PYTHIA underestimates the cross section.

Figure 5(right) shows the first ATLAS total Z+jets cross sections as a function of jet multiplicity, in a similar kinematic region to the W+jets measurement. In this case the data amount is reduced by a factor 10, due to the smaller Z production cross section compared to the W, but the general conclusions are similar to the W+jets measurement within the quite large statistical uncertainty.

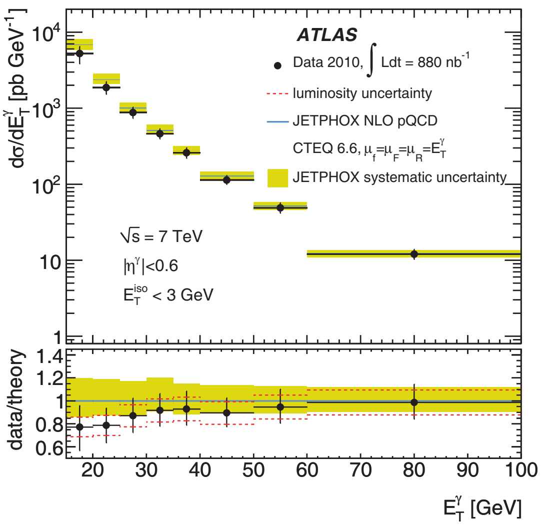

Fig. 6. – The measured and the expected inclusive prompt photon production cross section, for photons with transverse energies above 15 GeV and in the pseudorapidity range $|\eta| < 0.6$.

7. – The prompt photon cross section

The prompt photon production at hadron colliders probes perturbative QCD predictions [18]. They provide a colorless probe of quarks in the hard partonic interaction and the subsequent parton shower. Their production is directly sensitive to the gluon content of the proton through the qg process, which dominates at leading order (LO). The measurement of the prompt photon production cross section can thus be exploited to constrain the gluon density function. The first ATLAS measurement of the inclusive isolated prompt photon cross section is based on an integrated luminosity of 880 nb^{-1} [19]. Figure 6 shows the measured inclusive isolated prompt photon production cross sections as a function of the photon transverse energy in the pseudorapidity range $|\eta^\gamma| < 0.6$ and in the transverse energy range $15 < E_T^\gamma < 100$ GeV. The data are compared to NLO pQCD calculations done with JETPHOX [20]. The measured cross section is in agreement with the theoretical predictions for $E_T > 25$ GeV.

8. – Conclusions

In this contribution the first QCD measurements in p-p collisions at $\sqrt{s} = 7$ TeV have been presented using the data from the initial data taking phase of the ATLAS experiment at LHC. The data are corrected for detector effects and compared to different leading-order matrix elements plus parton shower MC predictions and to NLO calculations. Properties of hadronic jets have been determined and their cross sections have been measured.

The results for underlying event and jet shapes reported in this paper indicate the potential of these measurements at the LHC to constrain the current phenomenological models for soft gluon radiation, underlying event activity, and non-perturbative fragmentation processes in the final state. The new tunes of the MCs obtained using the underlying event distributions have been already implemented and show a significant improvements compared to the pre-LHC tunings.

The cross section measurements of the processes presented here show in general a good agreement with NLO QCD calculations and state of the art MC generators, including phase space regions not covered by earlier experiments. This is a decisive test of QCD itself and a very important prerequisite for searches for new physics.

At the time these proceedings are written, preliminary updates of these results with the full 2010 data set have been presented by the Collaboration [21]; the results in general confirm the conclusions of the measurements done with early data.

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