

LATEST QCD RESULTS IN pp AND PbPb COLLISIONS FROM ATLAS*

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The ATLAS experiment is measuring both pp and PbPb collisions at the largest energies available in laboratory delivered by the Large Hadron Collider. Tests of the Standard Model and searches for exotic phenomena require precise information on QCD processes, which are responsible for the background present in pp interactions. In the heavy ion collisions, the QCD processes are determining the properties of the quark-gluon plasma which is created in the conditions of the extreme energy density. In this contribution, selected recent pp results from the ATLAS experiment are presented, including studies of jet properties and correlations in the multi-particle production. The effects of strong interactions in the dense matter created in PbPb collisions observed as the jet suppression and the collective flow are discussed in more detail.

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1. Introduction

The ATLAS experiment is collecting data since the start of the Large Hadron Collider (LHC) in 2009, with a continuous increase of the energy of the colliding proton beams from the initial $\sqrt{s} = 900$ GeV to $\sqrt{s} = 8$ TeV in 2012. The collisions of lead nuclei were registered in 2010 and in 2011 at the energy $\sqrt{s_{NN}} = 2.76$ TeV, while p Pb collisions at similar energy are planned for the end of 2012. The ATLAS detector [1] has a complete coverage in the azimuthal angle, allows charged particle tracks reconstruction in the $|\eta| < 2.5$ range and provides calorimetric measurements in the $|\eta| < 4.9$ range.

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The earlier studies of particle production in pp collisions at lower energies and parallel development of Monte Carlo models based on the Quantum Chromodynamics (QCD) allowed to obtain various extrapolations to the new, much larger energy of pp collisions at the LHC. The models like Pythia6, Pythia8 and Phojet were tuned to describe the pp and $p\bar{p}$ collisions at the centre-of-mass energies from 200 GeV to 1.96 TeV. In several analyses, their predictions were systematically compared to ATLAS results obtained for pp collisions at $\sqrt{s} = 0.9$ TeV, $\sqrt{s} = 2.36$ TeV and $\sqrt{s} = 7$ TeV.

In addition to the beams of protons, LHC accelerates also lead nuclei and collides them at the centre-of-mass of a nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV. Such collisions are characterized by centrality, denoted as percentage ranges with 0–10% as the most central events class. It is connected with the impact parameter (closest distance between colliding nuclei), the overlap area of the nuclei during collision, and the number of nucleons participating in the collision, N_{part} .

2. Results from pp collisions

The global characteristics of minimum bias pp collisions are studied in Ref. [2]. MC models approximately reproduce them, however, the measured charged particle multiplicity is higher than predicted by the MC models, with differences up to 20% for the pseudorapidity distribution and even larger in the tails of multiplicity or transverse momentum distributions [2].

The study of two-particle angular correlations [3] reveals a complex structure in pseudorapidity and azimuth. A strong correlation at small $|\Delta\eta|$ (Fig. 1(a)) is observed. It is, partially, due to the jets which induce also the correlation at $|\Delta\phi|$ near zero and at $|\Delta\phi| \approx \pi$ (Fig. 1(b)). However, the correlation at $|\Delta\phi| \approx \pi$ is present also for the particles distant in pseu-

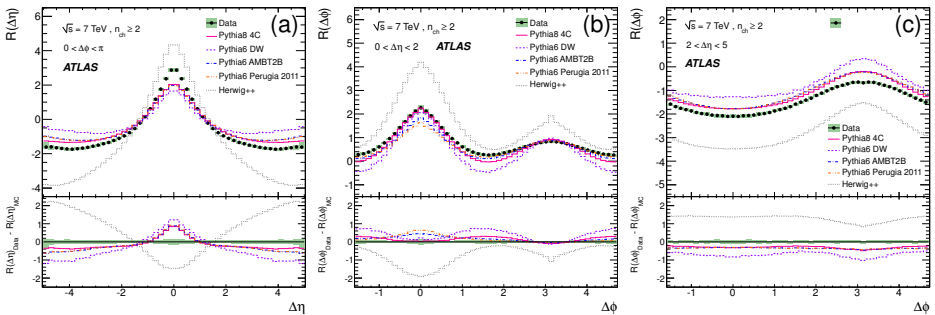


Fig. 1. Two-particle correlation functions $R(\Delta\eta)$ (a) and $R(\Delta\phi)$ obtained by integrating $\Delta\eta$ between 0 and 2 (b) or between 2 and 5 (c). Results measured at 7 TeV are compared with several model predictions [3].

dorapidity (Fig. 1(c)). Two-particle correlations increase with the energy of the collisions [3]. The models considered in this analysis reproduce the shape of the correlation, but not the magnitude of it. Similar conclusions are also reported in the study of forward-backward multiplicity correlations [4] in which the correlations between the number of particles in pseudorapidity bins symmetric with respect to $\eta = 0$ are shown. These correlations decrease with the distance between particles in η and are stronger at larger collision energy. The MC models in most cases reproduce these trends, but none of them fully describes the data.

While the previously presented studies are related to the soft QCD, the analysis of dijet azimuthal decorrelations [6] can be described by the perturbative QCD. The theoretical calculations reasonably well predict the distributions of the azimuthal angle $\Delta\phi$ between the two most energetic jets (Fig. 2). This distribution changes for the events with more than two high- p_T jets — the original maximum at π moves to $5\pi/6$ and the width of the $\Delta\phi$ distribution increases with the number of additional jets.

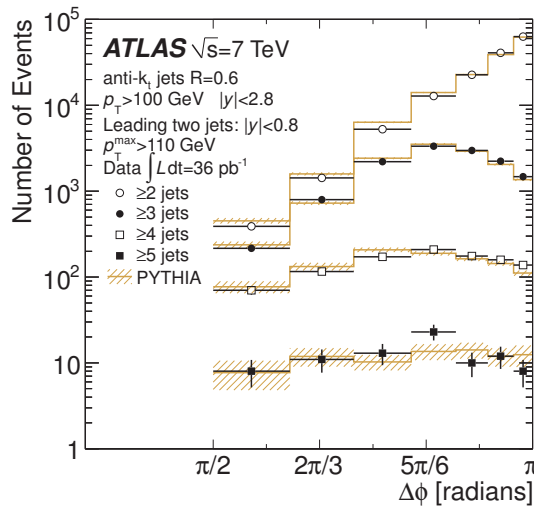


Fig. 2. The measured distribution of the azimuthal angle between the two most energetic jets, $\Delta\phi$, for events with ≥ 2 , ≥ 3 , ≥ 4 , and ≥ 5 jets with $p_T > 100$ GeV (points). Overlaid are results from Pythia [5] processed through the detector simulation (lines) [6].

3. Results from PbPb collisions

In the PbPb collisions, interactions of many nucleons result in a high energy density released in a small volume of the overlap of the colliding nuclei. In these conditions, the quark-gluon plasma (QGP) is created and

its properties and evolution determine the production of particles. The strong interactions in this matter were observed at the Relativistic Heavy Ion Collider (RHIC) as suppression of the particles with high momenta and anisotropy in particle production caused by collective phenomena. In the ATLAS experiment, these effects are even more pronounced and are observed also for the most energetic partons producing jets [7]. The jet suppression is studied using the asymmetry parameter A_J

$$A_J = (E_{T,1} - E_{T,2}) / (E_{T,1} + E_{T,2}) ,$$

calculated for the transverse energies, $E_{T,1}$ and $E_{T,2}$, of two the most energetic jets. In Fig. 3, the distributions of A_J for several centrality intervals are shown [8]. The asymmetry is the largest for the most central collisions, in which suppression is expected to be the largest, while the A_J distribution in the most peripheral events is very similar to that measured in pp collisions. The effects of underlying event cannot explain measured asymmetries, they cause only moderate widening of the A_J distribution, as can be seen in Fig. 3, for Monte Carlo simulations using PbPb collisions from the Hijing [9] generator (as an underlying event) with embedded high- p_T dijets from Pythia [5].

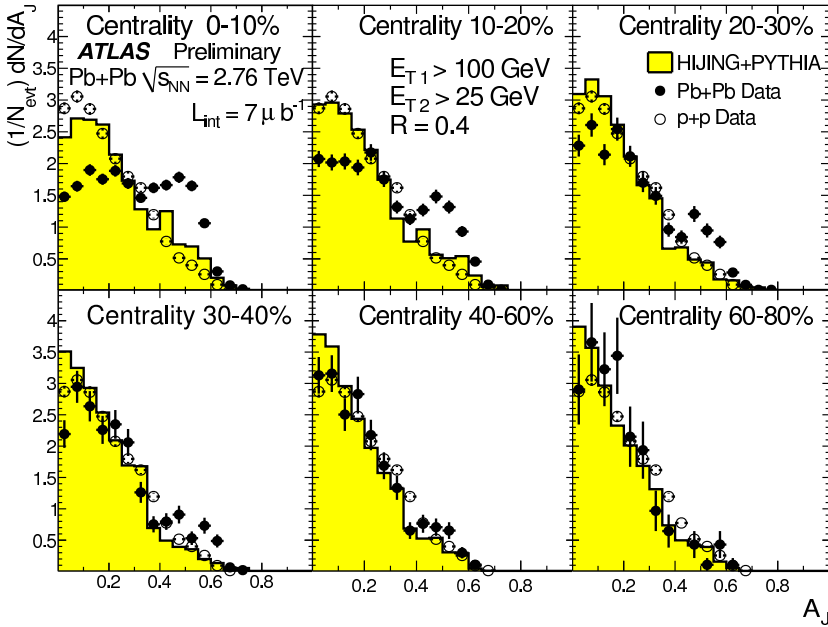


Fig. 3. Dijet asymmetry A_J in six centrality bins in events with a leading jet with $E_T > 100$ GeV. A comparison to Hijing with embedded Pythia dijet events (grey/yellow) and ATLAS $\sqrt{s} = 7$ TeV pp data (open circles) is shown [8].

The observed asymmetry of the energy of jets prompts a question: where is this energy transferred? In Fig. 4, the distributions of two parameters of the jet shape are shown

$$j_T = p_{T,\text{part}} \sin \Delta R$$

and

$$z = (p_{T,\text{part}}/E_{T,\text{jet}}) \cos \Delta R,$$

where $p_{T,\text{part}}$ is the transverse momentum of a particle belonging to the jet and $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is the angular distance between the jet axis and the particle in the η, ϕ space. The first parameter, j_T , measures the transverse momentum of particles relative to the jet axis while the second, z , is the longitudinal fraction of the jet momentum carried by the particle. Jet shapes for the most central and peripheral collisions are compared to see if they are affected by the energy loss. The transverse structure of jets is unchanged as within the statistical errors the ratio of j_T distributions is consistent with one. We do not observe a significant modification of the fragmentation function at large z . This is consistent with a picture in which the energy lost by a parton is distributed among many particles at large angles relative to the jet axis.

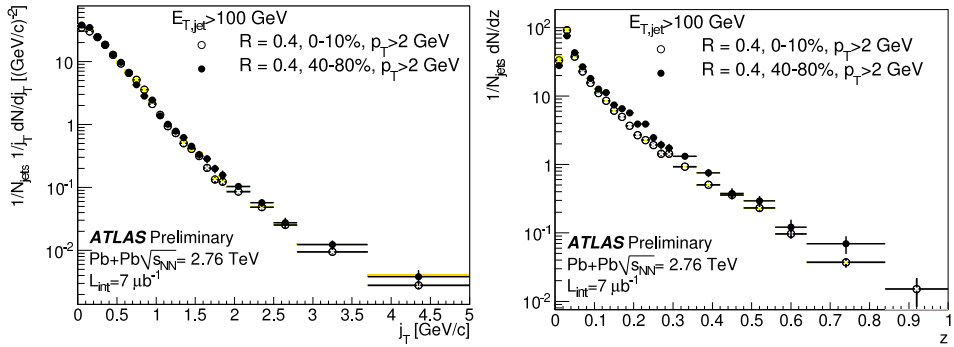


Fig. 4. The distributions of jet shape parameters: transverse (left) and longitudinal (right) for the most energetic jets in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [8].

The energy loss in QGP is observed also as a suppression of particle yields in central PbPb collisions relative to the pp yield (R_{AA}) or to the yield in peripheral PbPb collisions (R_{CP}). ATLAS has measured R_{CP} values for charged particles up to $p_T = 30$ GeV [10], which are always smaller than one and decrease with centrality. As a function of p_T , R_{CP} is decreasing in the interval 2–7 GeV and slowly increasing for $p_T > 7$ GeV, without approaching unity. The inclusive measurements were also performed for J/ψ , Z^0 and W^\pm [11, 12]. While a centrality dependent suppression of J/ψ

is observed, R_{CP} values for Z and W bosons are consistent with one. This confirms expectations that the production and decays of bosons carrying the weak force do not change in the events in which QGP is formed.

The measurements of azimuthal anisotropy resulting from the collective flow were performed in ATLAS experiment [13, 14] using two methods. In the event-plane method, the distribution of the azimuthal angle of particles, ϕ , relative to the reconstructed reaction plane angle, Ψ , is expressed by the Fourier series

$$E \frac{d^2 N}{dp^3} = \frac{d^2 N}{2\pi p_T dp_T d\eta} \left(1 + 2 \sum_{n=1}^{\infty} v_n(p_T, \eta) \cos n(\phi - \Psi_n) \right),$$

where the v_n is the n^{th} -order harmonics and independent estimates Ψ_n are used for different values of n . Alternatively, in the two-particle correlation method, the azimuthal angle difference between pairs of particles are used to obtain coefficients $v_{n,n}$, which are related to single-particle v_n by $v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a) v_n(p_T^b)$ (factorization valid for $n > 1$ and large $\Delta\eta$). Flow harmonics are non-zero up to $n = 6$ and weakly depend on η . In Fig. 5, their dependence on p_T is shown. All harmonics have a maximum at $p_T \approx 3$ and their values are the largest for 30–50% centrality. The elliptic flow v_2 is the largest (with exception of the very central events 0–5%) and

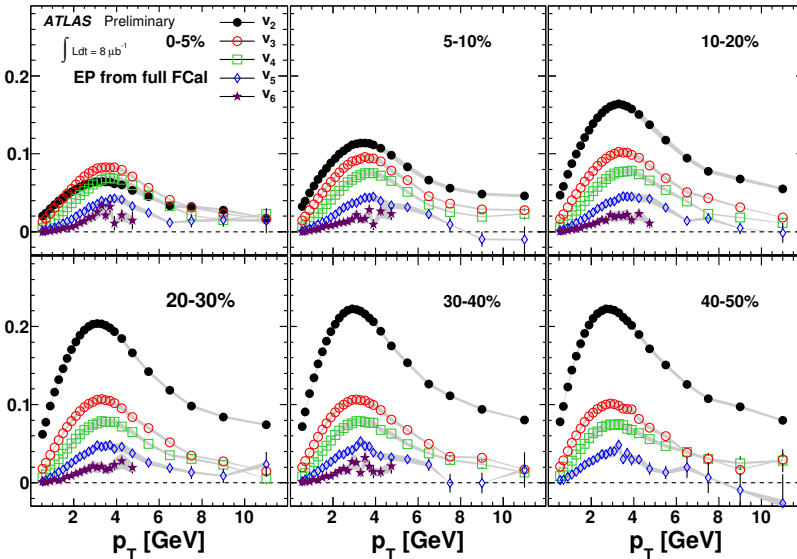


Fig. 5. Harmonic coefficients v_n ($2 \leq n \leq 6$) of azimuthal anisotropy of produced charged particles as a function of transverse momentum for several centrality intervals. The values of v_n were obtained using event-plane method [14].

the values of v_n decrease with n . These results reflect the asymmetry of the overlap of the nuclei for different collision centralities and the magnitude of the fluctuations in the positions of nucleons during collisions.

REFERENCES

- [1] ATLAS Collaboration, *JINST* **3**, S08003 (2008).
- [2] ATLAS Collaboration, *New J. Phys.* **13**, 053033 (2011).
- [3] ATLAS Collaboration, [arXiv:1203.3549v1](#) [hep-ex].
- [4] ATLAS Collaboration, [arXiv:1203.3100v1](#) [hep-ex].
- [5] T. Sjostrand, S. Mrenna, P. Skands, *J. High Energy Phys.* **0605**, 026 (2006).
- [6] ATLAS Collaboration, *Phys. Rev. Lett.* **106**, 172002 (2011).
- [7] ATLAS Collaboration, *Phys. Rev. Lett.* **105**, 252303 (2010).
- [8] ATLAS Collaboration, ATLAS-CONF-2011-075.
- [9] X.-N. Wang, M. Gyulassy, *Phys. Rev.* **D44**, 3501 (1991).
- [10] ATLAS Collaboration, ATLAS-CONF-2011-079.
- [11] ATLAS Collaboration, *Phys. Lett.* **B697**, 294 (2011).
- [12] ATLAS Collaboration, ATLAS-CONF-2011-078.
- [13] ATLAS Collaboration, *Phys. Lett.* **B707**, 330 (2012).
- [14] ATLAS Collaboration, [arXiv:1203.3087v2](#) [hep-ex].