HEAVY ION PHYSICS WITH THE ATLAS DETECTOR*

Iwona Grabowska-Bołd

for the ATLAS Collaboration

University of California, Irvine, USA
and
AGH University of Science and Technology, Kraków, Poland

(Received April 29, 2011)

The heavy-ion program at the Large Hadron Collider has been commenced in November 2010 by three experiments including ATLAS, a multipurpose detector. It was originally constructed to study high-energy proton–proton collisions but now it also proves to be an excellent tool for studying nuclear interactions. In these proceedings results from the lead–lead run at $\sqrt{s_{NN}} = 2.76$ TeV based on the minimum-bias data sample are reviewed. In particular, an observation of the centrality-dependent di-jet asymmetry is reported. Also a centrality-dependent suppression in the yield of J/ψ mesons decaying to $\mu^+\mu^-$ pairs is discussed along with an observation of the Z boson production. These evidences may bring new insight to the dynamics of heavy-ion collisions.

DOI:10.5506/APhysPolB.42.1393
PACS numbers: 25.75.Nq, 25.75.Bh, 25.75.Cj

1. Introduction

Heavy-ion data collected by the experiments at the Relativistic Heavy Ion Collider (RHIC) provided insight into what can be expected at the Large Hadron Collider (LHC). RHIC results suggest that in heavy-ion collisions at $\sqrt{s_{NN}} = 200$ GeV an equilibrated, strongly-coupled partonic system is formed. There is a strong evidence that this dense partonic medium is highly interactive, perhaps best described as a quark–gluon fluid, and is also almost opaque to fast partons. In addition, many surprisingly simple empirical relationships describing the global characteristics of particle production have been found. An extrapolation to the LHC energies suggests that the heavy-ion program has significant potential for major discoveries. Similar to the expectations for high energy physics, heavy-ion studies at the LHC will

* Presented at the Cracow Epiphany Conference on the First Year of the LHC, Cracow, Poland, January 10–12, 2011.

either confirm and extend the theoretical picture emerging from lower-beam energies or challenge and redirect our understanding of strongly interacting matter at extreme densities. This will be accomplished both by extending existing studies over a dramatic increase in energy and also by bringing to bear a broad range of novel probes with high-p_{T} jets, photons and Z^0 bosons among them, which are accessible only at LHC energies.

The LHC commenced a heavy-ion program in fall 2010 with a first lead–lead run at $\sqrt{s_{NN}} = 2.76$ TeV per colliding nucleon pair. In these proceedings a report on early jet and di-muon measurements will be given. They already provide the first insight into the dynamics of the hot and dense medium created at the LHC.

2. Experimental setup

The ATLAS detector is a multi-purpose detector described in details elsewhere [1].

The Inner Detector (ID) surrounds the interaction point. It measures trajectories of charged particles in the pseudorapidity region $|\eta| < 2.5$. Its volume is within the 2 T magnetic field of a superconducting solenoid. A charged particle typically traverses three layers of silicon pixel detectors, eight silicon strip sensors (SCT detector) arranged in four layers of double-sided modules, and a transition radiation tracker composed of straw tubes. Liquid argon (LAr) technology providing excellent energy and position resolution is used in the electromagnetic calorimeter that covers the pseudorapidity range $|\eta| < 3.2$. The hadronic calorimetry in the range $|\eta| < 1.7$ is provided by a sampling calorimeter made of steel and scintillating tiles. In the end-caps ($1.5 < |\eta| < 3.2$), LAr technology is also used for the hadronic calorimeters. To complete the η coverage, the LAr forward calorimeters provide both electromagnetic and hadronic energy measurements, extending the coverage up to $\eta = 4.9$. The Muon Spectrometer (MS) surrounds the calorimeters and provides tracking for muons with $|\eta| < 2.7$ and triggering in the range $|\eta| < 2.4$. The muon momentum determination is based on three stations of precision drift chambers that measure a trajectory of each muon in a toroidal magnetic field produced by three air-core toroids.

In studies reported here, events were triggered using minimum-bias devices such as Minimum Bias Trigger Scintillator (MBTS) counters covering $2.1 < |\eta| < 3.9$ on each side of the experiment, or the two Zero Degree Calorimeters (ZDC), each positioned at 140 m from the collision point, detecting neutrons and photons with $|\eta| > 8.3$. They are 100% efficient for measurements presented here.

Event centrality is defined using the total transverse energy ($\sum E_{\mathrm{T}}$) deposited in the forward calorimeters, which cover $3.2 < |\eta| < 4.9$. Centrality bins are determined according to fractions of the total lead–lead cross-section

selected by the trigger and are expressed in terms of percentiles (0–10%, 10–20%, *etc.*) with 0% representing the upper end of the $\sum E_{\mathrm{T}}$ distribution. The forward $\sum E_{\mathrm{T}}$ is used in measurements reported here to avoid biasing the centrality measurements with particles reconstructed at mid-rapidity.

The data sample has been collected in the course of the 2010 lead–lead run, which accumulated 9.17 $\mu\mathrm{b}^{-1}$ of statistics with data recording efficiency above 95% as summarized in Fig. 1.

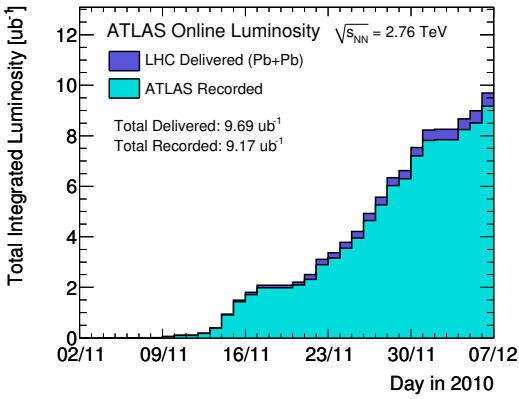


Fig. 1. Cumulative integrated luminosity *versus* day, delivered to (dark gray/dark blue) and recorded by (light gray/light blue) ATLAS for lead–lead collisions during stable beams and for 2.76 TeV center-of-mass energy per nucleon pair.

3. Dijet asymmetry

Collisions of heavy ions at ultra-relativistic energies are expected to produce a hot and dense state, in which the relevant degrees of freedom are not hadrons, but quarks and gluons. In this medium, high-energy quarks and gluons are expected to transfer energy to the medium by multiple interactions with the ambient plasma. Large transverse momentum jets, among many other hard processes in ultra-relativistic heavy-ion collisions, have been proposed as effective probes of the transient hot and dense matter. It was suggested that one should search for jet quenching effects which could manifest themselves by an observation of highly unbalanced dijets when one jet is produced at the periphery of the collision overlap zone while the second jet is produced in the dense medium.

High-p_{T} hadron measurements made by RHIC experiments showed a clear suppression of back-to-back hadron production in central heavy-ion collisions [2]. However, the limited rapidity coverage of the experiments, and jet energies comparable to the underlying event energy, prevented a stronger conclusion being drawn from those data. At energies achieved at the LHC, next-to-leading-order QCD calculations predict substantial rates

of jets above 100 GeV produced in the pseudorapidity region $|\eta| < 4.5$, which is within the ATLAS acceptance. This opens perspective for dijet measurements at the LHC experiments.

3.1. Data analysis

In the first dijet studies at ATLAS [3] the focus was on the balance between the highest transverse energy pair of jets in events. Jets have been reconstructed using the infrared-safe anti-k_t jet clustering algorithm [4] with the radius parameter $R = 0.4$. Input cells were weighted using energy-density dependent factors to account for calorimeter non-compensation and other energy losses. A background from an underlying event was calculated based on the average transverse energy density in bins of width $\Delta\eta = 0.1$, and averaged over azimuth. Then these average values were subtracted layer-by-layer from cells which built each signal jet, scaling appropriately for the cell area.

Events with at least one jet with transverse energy $E_{T,1} > 100$ GeV in $|\eta| < 2.8$ were considered. The highest-E_T jet was called a leading jet, while a sub-leading one was defined as a second most energetic jet in an event with $E_{T,2} > 25$ GeV. A requirement was imposed on an azimuthal angle separation between two jets $\Delta\phi = |\phi_1 - \phi_2| > \pi/2$ to reduce contributions from multi-jet final states. A sample of 1693 events have been selected in 1.7 μb^{-1} of data. The jet energy imbalance was quantified in terms of the asymmetry A_J

$$A_J = \frac{E_{T,1} - E_{T,2}}{E_{T,1} + E_{T,2}} \,. \tag{1}$$

Dijet events are expected to have A_J near zero with some spread due to gluon radiation falling outside the jet cone, as well as from instrumental effects. Eventual energy loss in the medium could lead to much stronger deviations in the reconstructed energy balance.

3.2. Results

The dijet asymmetry and a difference in azimuthal angle between two most energetic jets are shown in four centrality bins in Fig. 2, where they are compared with proton–proton data at $\sqrt{s} = 7$ TeV and with fully reconstructed HIJING [5] lead–lead events with embedded PYTHIA [6] dijet events. The simulated events are intended to illustrate the effect of the heavy-ion background on jet reconstruction, not any underlying physics process. The dijet asymmetry in peripheral lead–lead events is similar to that in both proton–proton and in simulated events. However, as the events become more central, the lead–lead data develop different characteristics,

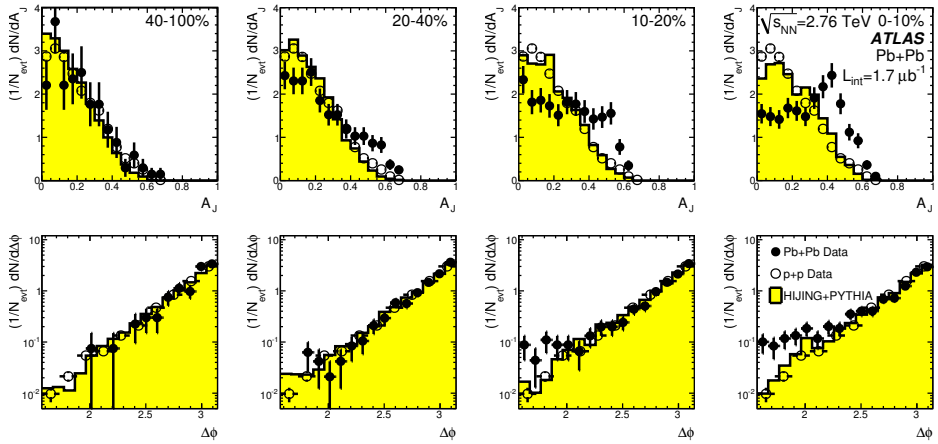


Fig. 2. Top: Dijet asymmetry distribution A_J for lead–lead data (solid points) and unquenched HIJING with superimposed PYTHIA dijets (solid gray (yellow) histograms), as a function of collision centrality (left to right from peripheral to central ones). Proton–proton data at $\sqrt{s} = 7$ TeV, analyzed with the same jet selection, is shown as open circles. Bottom: Distribution of the azimuthal angle separation $\Delta\phi$ between two jets, for data and HIJING + PYTHIA, also as a function of centrality.

indicating an increased rate of highly asymmetric dijet events. The asymmetry distribution broadens, the mean shifts to higher values. For most central events the peak at zero asymmetry is no longer visible while for the most central events a peak at higher asymmetry values becomes evident. At the same time the $\Delta\phi$ distribution is examined. It shows that both leading and sub-leading jets are primarily back-to-back in all centrality bins. However, a systematic increase in the rate of sub-leading jets at large angles with respect to the recoil direction is observed as events become more central.

To confirm the effect, numerous systematic studies have been performed to verify that events with the large asymmetry are not produced by energy fluctuations, background, or detector effects.

4. Di-muon final states

Measurements of quarkonia production in ultra-relativistic heavy-ion collisions provide a powerful tool for studying properties of the hot and dense matter created in these collisions. If deconfined matter is indeed formed, then color screening is expected to prevent the formation of quarkonia states when the screening length becomes shorter than the quarkonium size [7]. Since this length is directly related to the temperature of the system, a measurement of a suppressed quarkonia yield may provide direct experimental sensitivity to the temperature of the medium created in high energy nuclear collisions.

Production of Z bosons, only available in heavy-ion collisions at the LHC energies, can serve as a reference process for J/ψ production. Zs are not expected to be affected by the hot and dense medium, although modifications to the nuclear parton distribution functions must be taken into account [8].

4.1. Event selection

In the first di-muon studies in ATLAS [9], muons were reconstructed by combining independent measurements of trajectories from the ID and MS, resulting in relative momentum resolution ranging from about 2% at low momentum up to about 3% at $p_{\mathrm{T}} \approx 50$ GeV. Opposite sign muons were selected with a minimum transverse momentum p_{T} of 3 (20) GeV to reconstruct particles from J/ψ (Z) final states. Both muons were required to be within the region $|\eta| < 2.5$. With the chosen transverse momentum cuts on the J/ψ decay muons, 80% of the reconstructed J/ψ have $p_{\mathrm{T}} > 6.5$ GeV. A total data sample analyzed in searches for J/ψ and Zs corresponds to about 6.7 $\mu\mathrm{b}^{-1}$.

J/ψ and Z yields were extracted from invariant mass spectra in the signal region and corrected for muon reconstruction inefficiency and other instrumental effects. Those corrections were derived from Monte Carlo events which have been produced superimposing J/ψ and Z events from PYTHIA into simulated lead–lead events generated with HIJING. A background in the J/ψ analysis was subtracted based on a sideband technique. In the Z boson searches a simple counting in the signal window was applied without any background subtraction due to limited statistics.

Yields were computed in four centrality bins: 40–80%, 20–40%, 10–20% and 0–10%. The most peripheral bin (100–80%) was dropped in these studies due to large systematic uncertainties. The J/ψ yields were not corrected for feed-down from other charmonium states and B decays.

A *relative yield* is defined by normalizing a corrected number of J/ψ or Zs to the yield found in the 40–80% centrality bin. While a *normalized yield* is defined by scaling the relative yield by the ratio of the mean number of binary collisions in each centrality bin to that for the most peripheral one. The mean number of binary nucleon–nucleon collisions in each centrality bin was calculated using a Glauber Monte Carlo package which was extensively used at the RHIC energies [10].

4.2. Results

The relative J/ψ yield derived from data is compared to the expected yield values in the left panel of Fig. 3. The yield errors are computed by adding the statistical and systematic uncertainties in quadrature. A clear difference is observed as a function of centrality between the measured relative J/ψ yield and the prediction, indicating a deviation from the expecta-

tion based on QCD factorization. A ratio of these two values is shown as a function of centrality in the right panel of Fig. 3. A significant decrease of the J/ψ yield as a function of centrality is observed.

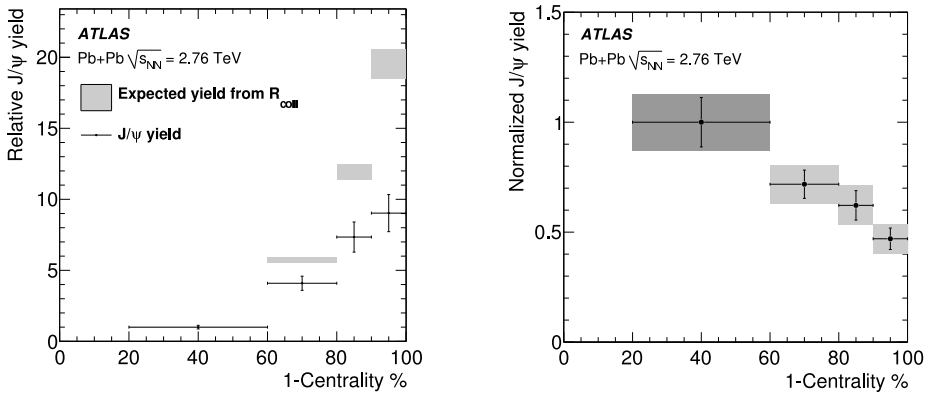


Fig. 3. Left: Relative J/ψ yield as a function of centrality normalized to the most peripheral bin shown as black dots with errors. The expected relative yields, obtained assuming a scaling with a number of binary collisions, are also shown as boxes reflecting 1σ systematic uncertainties. Right: Normalized J/ψ yield as a function of centrality. The statistical errors are shown as vertical bars while the gray boxes also include the combined systematic errors. Uncertainties from the most peripheral bin are not propagated to higher centrality bins.

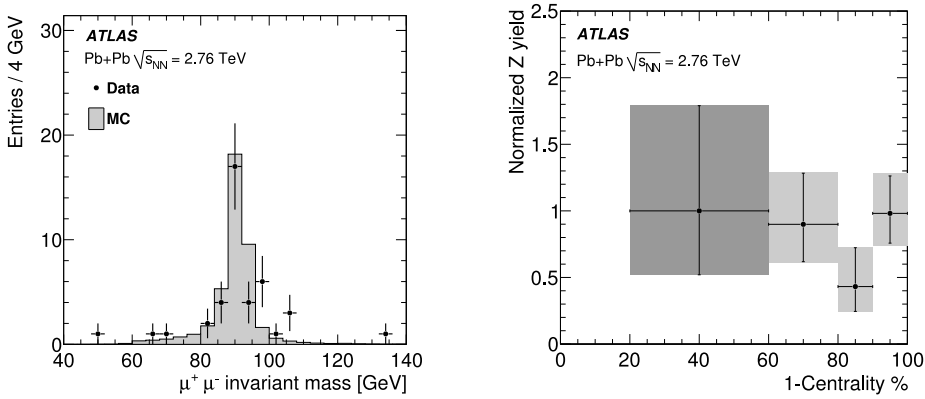


Fig. 4. Left: Di-muon invariant mass distribution after the selection described in the text. Right: Normalized Z yield as a function of centrality for 38 selected Z candidates. The statistical errors are shown as vertical bars while the gray boxes also include the combined systematic errors. The uncertainties in the most peripheral bin are not propagated to higher centrality bins.

The left panel of Fig. 4 shows a Z mass peak. With the selection described in the previous subsection, 38 candidates of Z particles are retained in the signal mass window between 66–116 GeV. The background after this selection is expected to be below 2% and is not corrected for in the result.

A normalized Z yield as a function of centrality is shown in the right panel of Fig. 4. Although, within the large statistical uncertainty, it appears to be compatible with a linear scaling with the number of binary collisions, the low statistics preclude drawing any strong conclusion.

5. Summary

In these proceedings, first results are presented on dijet and di-muon measurements in lead–lead collisions at a center-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV per nucleon pair, with the ATLAS detector at the LHC. In a sample of events with a reconstructed jet with transverse energy above 100 GeV an asymmetry is observed between the transverse energies of the leading and sub-leading jets that increases with centrality of the collisions. In a sample of opposite sign muon pairs J/ψ and Z final states have been reconstructed. A centrality dependent suppression is observed in the normalized J/ψ yield. The relative yields of 38 observed Z candidates as a function of centrality have also been presented, although no conclusion can be inferred about their scaling with the number of binary collisions due to limited statistics. These measurements are the first evidences of such large dijet asymmetries and J/ψ suppression in central lead–lead collisions at the LHC energy.

REFERENCES

[1] [ATLAS Collaboration] G. Aad *et al.*, `arXiv:0901.0512v4 [hep-ex]`.
[2] [STAR Collaboration] C. Adler *et al.*, *Phys. Rev. Lett.* **89**, 202301 (2002).
[3] [ATLAS Collaboration] G. Aad *et al.*, *Phys. Rev. Lett.* **105**, 252303 (2010).
[4] M. Cacciari, G. Salam, G. Soyez, *J. High Energy Phys.* **0804**, 063 (2008).
[5] X.-N. Wang, M. Gyulassy, *Phys. Rev.* **D44**, 3501 (1991).
[6] T. Sjostrand, S. Mrenna, P. Skands, *J. High Energy Phys.* **0605**, 026 (2006).
[7] T. Matsui, H. Satz, *Phys. Lett.* **B178**, 416 (1986).
[8] R. Vogt, *Phys. Rev.* **C64**, 044901 (2001).
[9] [ATLAS Collaboration] G. Aad *et al.*, *Phys Lett.* **B697**, 294 (2011).
[10] M.L. Miller *et al.*, *Annu. Rev. Nucl. Part. Sci.* **57**, 205 (2007).