HEAVY ION PHYSICS WITH THE ATLAS DETECTOR*

Barbara Wosiek

On behalf of the ATLAS Collaboration

H. Niewodniczański Institute of Nuclear Physics PAN
Radzikowskiego 152, 31-342 Kraków, Poland

(Received November 15, 2006)

The Large Hadron Collider will provide an opportunity to study Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5\,\mathrm{TeV}$ as well as other nucleus–nucleus collision systems including proton–nucleus collisions. The ATLAS apparatus with its hermetic calorimetry, a precise silicon inner detector and a background-free standalone muon spectrometer is well suited to study a wide range of phenomena in nucleus–nucleus collisions at LHC. This talk reports on the studies of the ATLAS experiment capabilities for heavy ion physics at LHC. These studies show a very good potential of the ATLAS detector for measuring global properties of nucleus–nucleus collisions such as charged particle multiplicities and azimuthal anisotropies as well as heavy quark and quarkonia production and jet quenching. The results from the first round of studies based on the full simulations of the detector response are presented. Ongoing activities are also briefly summarized.

PACS numbers: 25.75.Nq, 25.75.Dw

1. Introduction

The Large Hadron Collider (LHC) at CERN will allow to study heavy ion collisions at the center-of-mass energy 30 times larger that the one reached at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. The fascinating results obtained by the RHIC experiments [1,2], in particular a discovery of a new form of matter with the properties resembling those of an ideal fluid, make the study of nucleus–nucleus collisions at still higher energies even more attractive and interesting. At the LHC energy, the initial state is expected to be in a fully saturated regime of the Color Glass Condensate [3] and the system produced in heavy ion collisions will be hotter, denser, longer lived and possibly more weakly coupled.

* Presented at the "Physics at LHC" Conference, Kraków, Poland, July 3–8, 2006.

The ATLAS detector has been designed to study high-transverse momentum (p_{T}) physics in pp collisions at the center-of-mass energy of 14 TeV [4]. Several features of the detector are well suited and important for heavy ion physics [5]. With the ATLAS detector we can study the properties of the produced system by detailed measurements of high-p_{T} phenomena, heavy quark and quark–antiquark production complemented with the detailed information on the global properties of the collision event, including centrality of the collision, charged particle multiplicity and collective flow effects. All of these measurements were crucial for obtaining the interesting results from RHIC experiments and can be studied in more details at LHC energy thanks to the significant increase in the cross-sections for jet and quarkonia production. For the first time the weakly interacting probes, like $W^{\pm}$ and Z^0 will become available. It should also be noted that the calorimetric system of the ATLAS detector, capable of measuring a variety of high-p_{T} phenomena including jet quenching, significantly surpasses the calorimetry used in RHIC experiments.

2. Simulations of the detector response

The ATLAS apparatus [4] consists of the inner detector with silicon pixels, silicon strips (SCT) and a transition radiation tracker(TRT) with acceptance spanning over five units in pseudorapidity ($|\eta| < 2.5$) and a full azimuth range. The inner detector is placed in a 2 T solenoid magnet. It is surrounded by the electromagnetic and hadronic calorimeters. The calorimetric system has a hermetic coverage over 10 units of η ($|\eta| < 4.9$) and fine segmentation both in the longitudinal and transversal direction. Outermost, a standalone muon spectrometer placed in a toroidal field covers $|\eta| < 2.7$

The detector performance for the heavy ion collisions is studied based on the HIJING event generator [6] and the GEANT3 [7] simulation package, folding in the signal response for all detector elements. HIJING model with the jet quenching switched off is used giving the charged particle density at midrapidity, $dN_{\mathrm{ch}}/d\eta$, of about 3200 for central Pb–Pb collisions. This density is much higher than compared to about 1200 obtained by extrapolating RHIC data, but allows the studies of the worst-case scenario with the large density environment. Even with this largely overestimated particle density, the occupancy of the silicon pixel detector was found to be below 2%, and of the silicon strip detectors below 20%. The occupancy of the TRT detector was too high and, therefore, it has not been considered in the present study.

3. Global event characterization

Measurements of charged particle multiplicity and transverse energy distributions (N_{ch}, $dN_{\mathrm{ch}}/d\eta$, E_{T}, $dE_{\mathrm{T}}/d\eta$) as well as of azimuthal anisotropies can be obtained with the low-statistics event samples, collected during few seconds of data taking at the nominal luminosity of 4×10^{26} cm^{-2} s^{-1} for heavy ion running. These basic measurements provide information on the initial energy density, the entropy production during the system evolution and are sensitive to a variety of physics processes responsible for multiparticle production. They are important for constraining model predictions and are indispensable for understanding and estimating the accuracy of the more detailed measurements of *e.g.* jet or quarkonia production. It is important to note that for the measurements of global event properties, the time consuming reconstruction of tracks or jets in the high density environment is not needed. They can be derived from recorded hits or hit clusters in the inner detector and the position and energy of calorimetric cells.

The initial conditions of heavy ion collisions are determined by the energy and the overlap of the two nuclei *i.e.* centrality of the collision. The collision centrality is given by the impact parameter, b, which, however, is not directly measurable. Yet, the estimate of the impact parameter is possible by using experimentally accessible variables which are strongly and monotonically correlated with b. It has been shown [5] that using the total number of hits in the silicon detectors or total transverse energy deposited in the calorimeters, and accuracy of about 1 fm for the estimate of the impact parameter can be achieved.

The reconstruction of the charged particle pseudorapidity distributions is based on a simple clustering algorithm using hits in the pixel barrel detector. For illustration we show in Fig. 1 (Fig. 2) the comparison of the

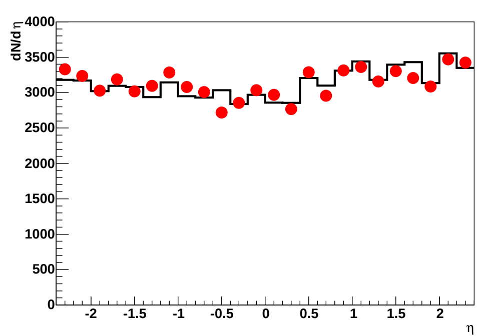

Fig. 1. Comparison of the reconstructed charged particle density distribution (•) with the true distribution (histogram) for one central HIJING event with jet quenching turned off.

reconstructed and true $dN_{ch}/d\eta$ distributions for a central HIJING event with jet quenching switched off (on). One can see an excellent agreement in both cases demonstrating our sensitivity to the details of the underlying dynamics.

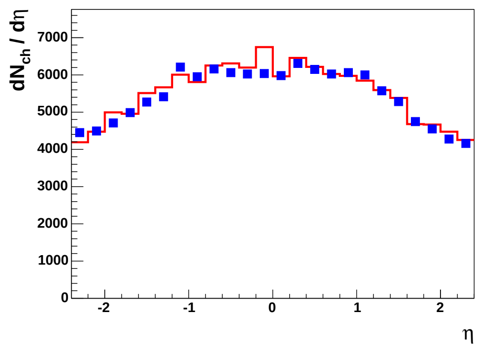

Fig. 2. The same as in Fig. 1, but for the HIJING event with jet quenching turned on.

The characterization of the collective flow of produced particles by their azimuthal anisotropy has proven to be one of the best probes of the dynamics of heavy ion collisions at RHIC [1, 2]. Flow effects are sensitive to the early

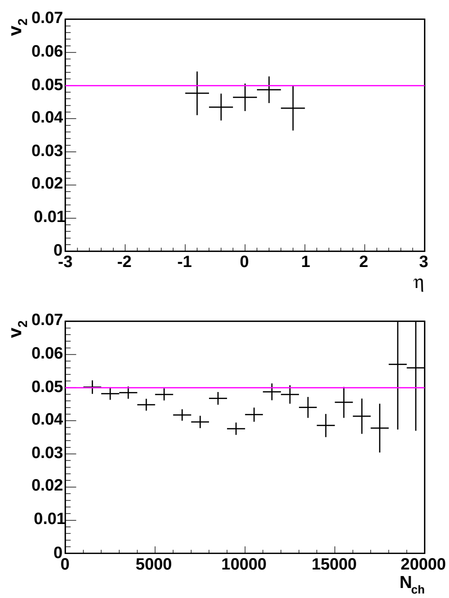

Fig. 3. Reconstructed elliptic flow v_2 as a function of pseudorapidity, η (top panel) and charged particle multiplicity, N_{ch} (bottom panel). The lines correspond to the input v_2 value.

stages of the system evolution and provide information on the properties of the hot, dense matter that is produced. Here, we report on the capability of measuring the strength of the elliptic flow, v_2, defined by the second harmonic in the Fourier expansion of the particle azimuthal angle distribution relative to the reaction plane. The study is based on the HIJING simulations with the implemented constant flow, $v_2 = 0.05$. The analysis method uses the estimate of the reaction plane as described in [8]. Elliptic flow signal is measured using azimuthal angles of hit clusters in pixel barrel detector, while the reaction plane is estimated from the energy depositions in forward calorimeters. Fig. 3 shows the reconstructed flow signal compared to the input value. One can see that we can reasonably well measure the flow effects. The observed small dilution (less than 10%) of the flow signal is due to hits not correlated with the reaction plane and will be accounted for by Monte Carlo corrections.

4. Track reconstruction

The ability to track particles gives an efficient tool for studying heavy quark and quarkonia production as well as the jet fragmentation function. Tracking in high multiplicity heavy ion collision events is a difficult task. As mentioned before, the transition radiation tracker is not used in this study due to too high detector occupancy. This limits the number of hits per track to a maximum of 11 (13) in the barrel (end-caps) region of silicon pixel and strip layers. Tracks were reconstructed with the standard XKALMAN algorithm [4] with small adjustments to the high-multiplicity environment [5]. For central Pb–Pb collisions with impact parameter $b < 1$ fm and charged particle density of $dN_{\mathrm{ch}}/d\eta \approx 3200$, the tracking efficiency is $\sim 70\%$ with the fraction of fake tracks $\sim 5\%$ for $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ (see Fig. 4). The overall momentum resolution of about 3% is obtained over $|\eta| < 2.5$.

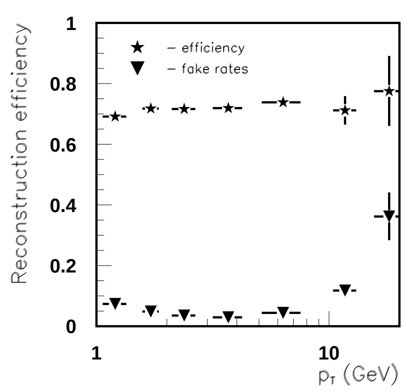

Fig. 4. Reconstruction efficiency (★) and percentage of fake tracks (▼) as a function of particle p_{T}.

This tracking efficiency allows to tag on b-jets via searching for a displaced vertex in the silicon inner detector. For a preliminary study of the b-tagging performance we use a sample of $pp \to WH \to l\nu b\overline{b}$ events and a sample of $pp \to WH \to l\nu u\overline{u}$ events overlaid on central HIJING Pb–Pb events. The rejection factor against u-jets of ~ 100 can be obtained for a b-tagging efficiency of 25%. This performance can be improved by using optimized algorithms and tagging on soft muons in the muon spectrometer. The study of the heavy quark production is interesting since it is expected that the radiative energy loss in a dense medium is smaller for heavy quarks due to the dead-cone effect than for the light quarks [9].

5. Jet reconstruction

With the ATLAS detector we can study jets in a broad range of jet momenta, both at the moderate p_{T} (40–60 GeV) where quenching is still strong and at very high p_{T} where quenching is expected [10] to disappear. In addition a variety of observables related to jet studies, from jet inclusive cross sections, jet rates through the measurements of the jet fragmentation functions and jet shapes, is accessible.

The sample of dijet events generated with PYTHIA and embedded in the HIJING central events is used to evaluate the jet reconstruction capability. Jets are reconstructed with a sliding window algorithm. The reconstruction is preceded by the average background subtraction. The jet reconstruction efficiency, shown in Fig. 5, reaches 95% for jets with $E_{\mathrm{T}} > 75$ GeV, and

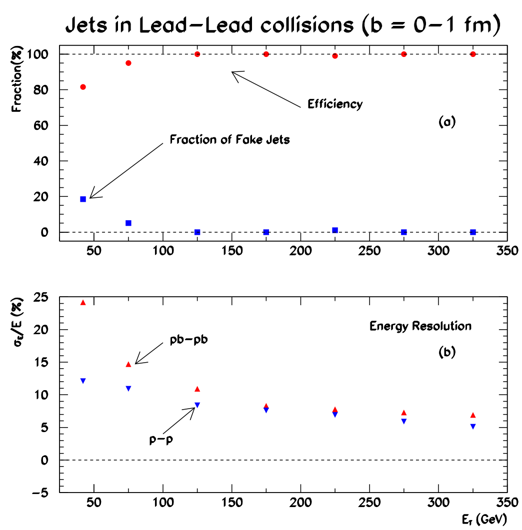

Fig. 5. Reconstruction efficiency and percentage of fake jets (top panel) and energy resolution (bottom panel) as a function of jet transverse energy, E_{T}.

drops to about 80% for $E_{\mathrm{T}} \sim 40\,\mathrm{GeV}$. The fraction of fake jets is negligible at high jet energies, and rises to about 20% for $E_{\mathrm{T}} \sim 40\,\mathrm{GeV}$. The jet energy resolution, obtained after applying jet calibration procedures described in [4], is compared to that for *pp* collisions in Fig. 5, bottom panel. One can see that, above $E_{\mathrm{T}} \approx 150$ GeV, the energy resolution is at the same level as in *pp* collisions. Thanks to the fine granularity of calorimetric system, the jet direction can be reconstructed with a good angular resolution [5].

6. Quarkonia detection

At the high center-of-mass energy reached at LHC, the abundant production of $c\bar{c}$ and $b\bar{b}$ pairs is expected. The production of these quarkonium states is expected to be suppressed in a deconfined medium, when the Debye screening length becomes smaller than the size of the quark–antiquark bound states [11]. Therefore, the study of quarkonium production provides a powerful probe of the medium produced in heavy ion collisions and is considered as a most promising signature of the quark–gluon plasma.

The ATLAS detector offers a possibility to study the production of Υ and J/ψ resonances via their decay into $\mu^+\mu^-$. The dimuon invariant mass resolution should be sufficient to separate different states of the Υ and J/ψ families, which dissolve at different temperatures. To achieve such good mass resolution, the measurements from the standalone muon spectrometer are combined with the tracking in the inner detector. The resolution of 145 MeV, sufficient to separate Υ and Υ' states, is obtained for $|\eta| < 2$, with a combined acceptance and efficiency of 12.5%, and a signal to background ratio of 0.2 (see Fig. 6).

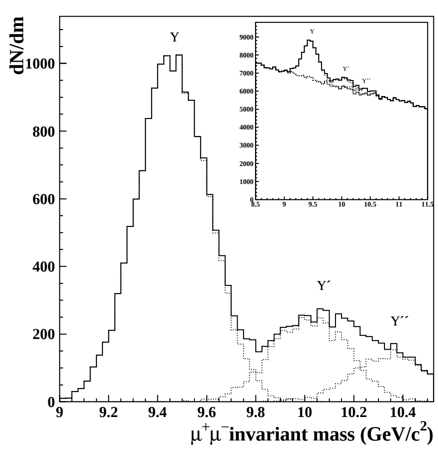

Fig. 6. Reconstructed $\mu^+\mu^-$ invariant mass distribution in the region of Υ state, with and without background.

A very good mass resolution of 68 MeV can be achieved for the J/ψ family. Due to the $\mu - p_{\rm T}$ cut of 3 GeV at small η, the acceptance is only for $|\eta| > 1.5$ and the low-$p_{\rm T}$ range of J/ψ is not accessible. However, lowering the $\mu - p_{\rm T}$ cut to 1.5 GeV, a full $p_{\rm T}$ range of J/ψ can be accessed. For more details on the capability of J/ψ detection see [12].

7. Ongoing activities

The initial studies of the ATLAS capability for heavy ion physics show that the detector will perform very well without any hardware modifications. The current activities are focused on the preparation of the Physics Performance Report and on the readiness for data taking when the LHC starts operation in 2008. Studies are being carried out on several fronts. The optimization of the tracking algorithms is in progress. We are also considering a partial use of the transition radiation tracker with higher signal threshold. This will improve the tracking performance and the dimuon mass resolution. Jet reconstruction algorithm is being optimized and alternative reconstruction codes are developed. The aim is to improve the efficiency at low $E_{\rm T}$ and reduce background by exploiting longitudinal segmentation of the calorimeters. Studies of $\gamma+$ jet and Z^0+ jet events are also going on. We are developing analysis of pp minimum bias events and improving the reconstruction of global properties in heavy ion collisions. These efforts should be completed before the LHC start up. The research programs for proton–nucleus and ultra-peripheral nucleus–nucleus collisions are also developed. It has to be noted that pp and pA data will provide baseline references which will be used to calibrate and interpret AA data. Several dedicated studies are concentrated on the triggering on minimum bias pp and Pb–Pb collisions, on low-$p_{\rm T}$ muons and on jets. The goal of these studies is to get high efficiency and small rate of background events. The work on the design and integration of the Zero Degree Calorimeters (ZDC) is progressing. Installation of ZDC will provide efficient triggering on minimum bias and ultra-peripheral AA collisions, and will allow measurements of the reaction plane and centrality of the collision. Last but not least, all heavy ion algorithms are being integrated with the official ATLAS software framework.

8. Summary

The simulation studies of the ATLAS detector performance for heavy ion physics studies are presented. The results of these studies show a good capability of the ATLAS experiment for measuring global characteristics of Pb–Pb collisions including charged particle multiplicities and collective flow effects as well as high transverse momentum phenomena and heavy quark and quarkonia production. These measurements will provide information crucial for understanding the properties of the strongly interacting matter produced with unprecedented energy densities, greater than $30\,\mathrm{GeV\,fm^{-3}}$. Thus, the ATLAS experiment can provide a significant contribution to the LHC heavy ion research program.

REFERENCES

[1] For experimental review of RHIC results see *Nucl. Phys.* **A757** (2005).
[2] For theoretical review of RHIC results see *Nucl. Phys.* **A750** (2005).
[3] D. Kharzeev, E. Levin, M. Nardi, *Nucl. Phys.* **A747**, 609 (2005).
[4] ATLAS Collaboration, Technical Design Report, CERN/LHCC 99-14.
[5] ATLAS Collaboration, Letter of Intent, CERN/LHCC 2004-009.
[6] M. Gyulassy, X.N. Wang, *Phys. Rev.* **D44**, 3501 (1991).
[7] GEANT3, CERN Program Library.
[8] A.M. Poskanzer, S.A. Voloshin, *Phys. Rev.* **C58**, 1671 (1998).
[9] Y.L. Dokshitzer, D.E. Kharzeev, *Phys. Lett.* **B519**, 199 (2001).
[10] I. Vitev, M.Gyulassy, *Phys. Rev. Lett.* **89**, 252301 (2002).
[11] T. Matsui, H. Satz, *Phys. Lett.* **B178**, 416 (1986).
[12] L. Rosselet, ATLAS Collaboration, *Springer Proc. Phys.* **108**, 206 (2006).