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PHYSICS CAPABILITIES OF THE ATLAS EXPERIMENT IN Pb+Pb COLLISIONS AT THE LHC*

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Relativistic heavy ion collisions at the LHC will uncover properties of a hot and dense medium formed at a collision energy thirty times larger than the energy presently available at RHIC. ATLAS is one of the three experiments participating in the heavy ion program at the LHC. A brief overview of the variety of observables which will be measured by ATLAS to study soft and hard QCD phenomena in heavy ion environment is presented. In particular the detector will measure global observables like charged particle multiplicity, azimuthal anisotropy and energy flow. The detector provides also an excellent capability to probe the quark gluon plasma by measurement of high energy jets and photons as well as quarkonia states. Performance of a high granularity calorimeter, silicon tracking detector and muon spectrometer in heavy ion collisions is reported. The unique ATLAS potential to study Pb+Pb interactions is discussed.

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1. Introduction

The new form of matter, the quark gluon plasma (QGP), is well established by many relativistic heavy ion experiments conducted at SPS and RHIC accelerators. In particular, RHIC results provide solid evidence that the QGP is strongly interacting and behaves like a nearly-perfect fluid [1]. At the LHC, in Pb+Pb collisions, much higher energy densities and temperatures of the medium will be obtained. At this new energy scale, basic properties of the medium will be determined by measurements of global observables including charged particles multiplicity (N_{ch}), transverse energy

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density ($dE_{\mathrm{T}}/d\eta$) and elliptic flow (v_2). These variables provide valuable information for theoretical models describing evolution of the system from initial state to the final freeze-out. More detailed information about the QGP will be provided by measurements of high energy jets and photons. The interaction of hard scattered partons within dense and colored medium leads to the jet quenching phenomena [2], which can be used as a tomographic probe of the QGP. Additionally, the measurement of quarkonia states suppression provides an excellent tool to study quark and gluon deconfinement [3]. All these key observables for heavy ion physics will be measured in a wide acceptance range by the ATLAS detector [4] which will collect the first Pb+Pb data already at the end of 2010.

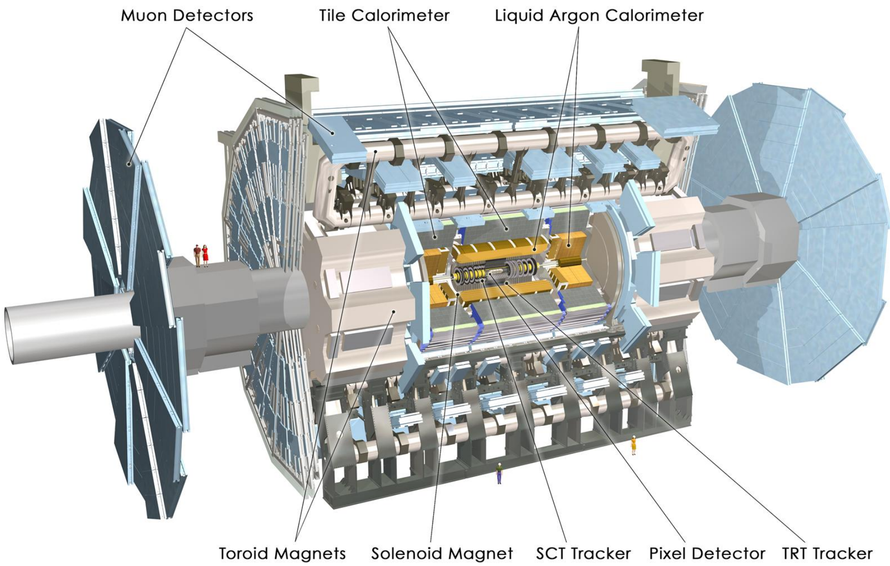

Fig. 1. General overview of the ATLAS detector.

2. The ATLAS experiment

ATLAS (A Toroidal LHC ApparatuS) [4] is the biggest detector ever built at accelerators. It is 44 meters long and 25 meters in diameter. The detector has a uniquely large coverage in pseudorapidity (η), fully surrounding the interaction point in azimuthal angle (ϕ). ATLAS consists of 3 major subsystems (Fig. 1): the inner tracking detector, the calorimeters and the muon spectrometer. Tracking detectors, located in solenoidal magnetic field of 2 T, can measure charged particles with $|\eta| < 2.5$. Calorimeters coverage for jet measurements spans over almost ten units of pseudorapidity

($|\eta| < 5$), while photons are reconstructed within the high granularity (of $\Delta\eta \sim 0.003$) liquid argon calorimeter in a pseudorapidity range from -3.2 to 3.2. The muon spectrometer can measure muons with $|\eta| < 2.5$. Additionally, several ATLAS subdetectors, located at large η, like LUCID, ZDC and ALFA, will be used to measure luminosity and forward physics studies. The ATLAS apparatus have been extensively tested with test beams as well as, after installing in cavern pit, during long cosmic runs and with proton-beams available since 2008. Commissioning proved good understanding of data and Monte Carlo detector simulations as well as readiness of the detector for the long physics run. Near 100% operational efficiency for all subsystems has been achieved.

3. Global observables in heavy ion collisions

Global observables like charged particle multiplicity, total transverse energy and elliptic flow are of prime interest as they are sensitive to the dynamics of colliding system. Based on AGS, SPS and RHIC results several divergent predictions for particle multiplicity at LHC energies have been made [5]. In ATLAS these predictions will be validated by measurement of particle multiplicity with various techniques [6].

The hit counting method is based on an assumption that the number of signals (clusters) in the pixel silicon detector is proportional to the number of primary charged particles. Fig. 2 (left) shows that with this method the input particle multiplicity is well reproduced on an event-by-event level.

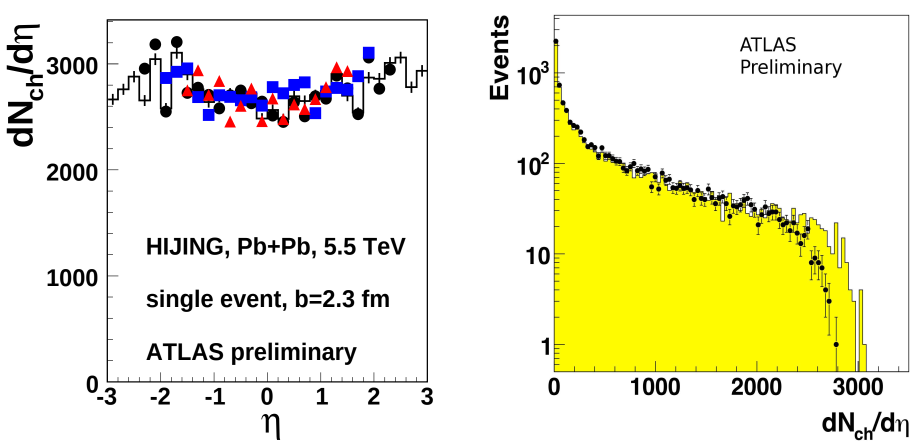

Fig. 2. Left: Distribution of $dN_{\rm ch}/d\eta$ for simulated (histogram) and reconstructed single Pb+Pb event obtained with pixel cluster counting method for the first (points), second (squares) and third (triangles) layer. Right: $dN_{\rm ch}/d\eta$ distribution for minimum bias Pb+Pb from HIJING generator (histogram) and the reconstructed one with tracklet method (points).

In another approach charged particle multiplicity is measured with help of the "tracklet" method. Tracklets are built from the vertex and pixel clusters from the two position layers closest to the beam pipe. As one can see in Fig. 2 (right), the HIJING generated charged particle multiplicity distribution for minimum bias Pb+Pb collisions and the reconstructed one agree quite well. The large acceptance ATLAS calorimeter system provides a unique possibility to measure the transverse energy as a function of pseudorapidity in heavy ion collisions which can be used to estimate the energy density of the medium [7]. A method was developed to measure $dE_{\mathrm{T}}/d\eta$ directly from energy deposits in electromagnetic and hadronic cells. To obtain the total transverse energy, the MC based corrections for different detector effects (like energy losses in dead material) have to be applied. The capability of transverse energy reconstruction for a single central Pb+Pb event is depicted in Fig. 3. An excellent agreement between the input and reconstructed $dE_{\mathrm{T}}/d\eta$ distributions is observed.

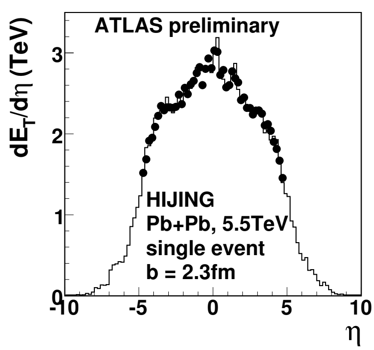

Fig. 3. Comparison of the reconstructed (points) and the true (solid line) $dE_{\mathrm{T}}/d\eta$ distribution for a single central Pb+Pb collision.

One of the most prominent RHIC discoveries was observation of large azimuthal anisotropy in particle production [8] which manifests strong collective behavior of the OGP. The anisotropy called elliptic flow, in the common approach is quantified by second Fourier coefficient (v_2), of the particle azimuthal angle distribution measured with respect to the reaction plane. Special MC simulations of the elliptic flow effects were used to study ATLAS sensitivity to measure this phenomena. Fig. 4 shows the reconstructed flow signal compared to the input implemented in the HIJING generator. As we can see, the v_2 dependence on the transverse momentum and collision centrality is well reproduced with different methods using various reconstructed objects, including tracks and signals in calorimeters. An approach of applying several methods to study elliptic flow allows for determination of systematics and control of non-flow effects in Pb+Pb collisions.

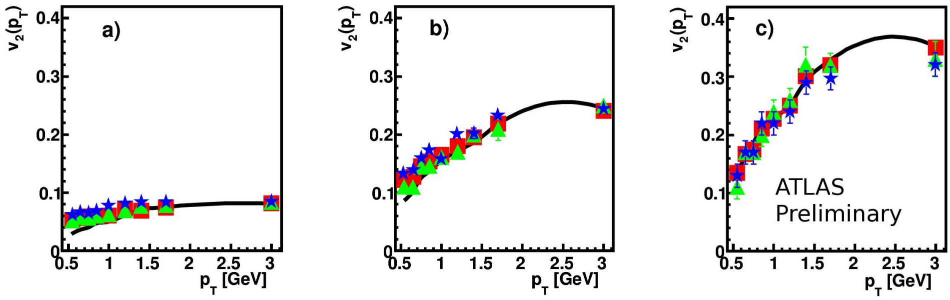

Fig. 4. Transverse momentum dependence of the reconstructed v_2 by event plane method (squares), two-particle correlations (stars), Lee–Yang Zeros method (triangles) for Pb+Pb collisions with (a) $b = 2.3$ fm, (b) $b = 7$ fm, (c) $b = 10.7$ fm [6]. Lines denote the input flow.

4. Jet measurements

One of the major goals of the ATLAS heavy ion program is gaining an understanding of QGP properties by means of hard probes, specifically, high energy jets. The strong suppression in relative production of high $p_{\rm T}$-hadrons in central AA and pp collisions observed at RHIC [9] indicates that fast partons traversing the medium lose a significant amount of their energy. These observations of energy loss make jet quenching phenomena a valuable probe of properties of the medium.To evaluate the heavy ion jet reconstruction performance, PYTHIA di-jet events were embedded in Pb+Pb HIJING events [10]. These events were reconstructed using the full simulation and response of the ATLAS detector. The seeded cone algorithm was used to reconstruct jets with a cone size of $R = 0.4$ and seed tower energy threshold equal to 5 GeV. Fig. 5(a) shows a comparison of the reconstructed jet spectrum with the input distribution. Even without correcting for efficiency and energy resolution, the reconstructed spectrum already matches the input spectrum quite well for jet energies above 80 GeV. Additionally, thanks to the fine granularity of calorimeter system, the jet direction can be reconstructed with a good angular resolution ($\sigma_\phi = 0.036$ rad and $\sigma_\eta = 0.045$). It is expected that about 20 M of jets with $E_{\rm T} > 50$ GeV will be measured in Pb+Pb collisions at integrated luminosity of $0.5\,{\rm nb}^{-1}$. The high rate provides unprecedented opportunity to study jet physics in heavy ion collisions.

In ATLAS, simultaneous reconstruction of jets in calorimeters and tracks in the inner detector allows to study the jet fragmentation function $D(z)$, where z is defined as a fraction of jet momentum carried by a jet fragment. It is expected that the jet fragmentation function will be modified due to in-medium partonic energy loss. In Fig. 5(b) reconstructed $D(z)$ is shown

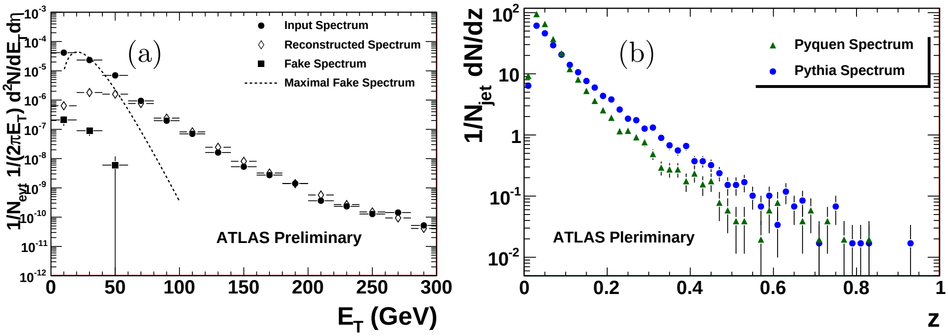

Fig. 5. (a) Jet spectra in central ($dN_{\rm ch}/d\eta$=2650) Pb+Pb collisions; input (circles), reconstructed (diamonds) and not matching generated jets fake spectra (squares). (b) Reconstructed [11] fragmentation function for PYTHIA and PYQUEN di-jets events.

for PYTHIA (no jet quenching) and PYQUEN (with jet quenching). Clear separation of z distribution in Fig. 5(b) indicates that ATLAS is sensitive to quenching effects predicted by PYQUEN.

5. Photons in heavy ion environment

Another useful tool to study energy loss process in the QGP is measurement of photon-jet events. Photons passing through the QGP are unaffected by the medium and they can be used to measure the original energy and direction of the away side jets.

Fine segmentation of the first layer of the ATLAS electromagnetic calorimeter allows for the separation of photons and neutral hadrons only on the basis of their shower shape, without an isolation cut [12]. To study the performance of photon identification in high density heavy ion environment,

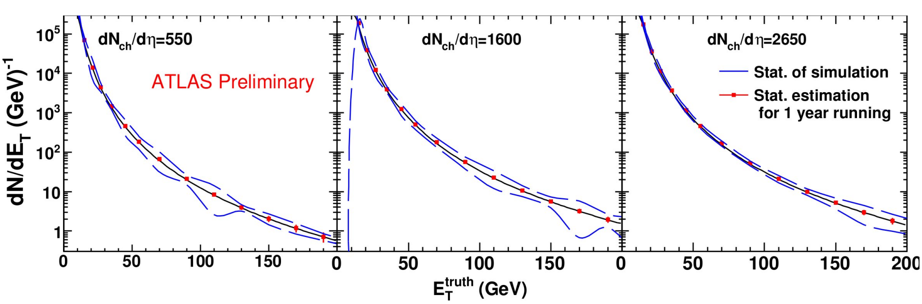

Fig. 6. Reconstructed photon spectrum for peripheral (left panel), mid-central (middle panel), and central (right panel) Pb+Pb collisions. Distributions are obtained after applying cuts which separate photons from neutral hadrons.

single γ's, π^0s and ηs have been embedded into events simulated with HIJING and then processed with official ATLAS software. The results proved that the shape of the shower in calorimeter is not affected by background from Pb+Pb collisions. Expected rate of direct photons in Pb+Pb collision for integrated luminosity of 0.5 nb^{-1}, is about 200 k photons with transverse energy above 30 GeV and S/B (signal to background) ratio larger than 1. For $E_{\mathrm{T}} > 70$ GeV, about 10 k photons is expected to be measured with S/B > 4. Fig. 6 shows photon spectra for different centrality ranges, after neutral hadron background subtraction.

6. Quarkonia suppression

Suppression of quarkonia states is an important signature of the QGP. Color screening prevents various quarkonia states from being formed when the color screening length becomes smaller than the quarkonium size. Color screening length is related to the temperature of the matter created in heavy ion collisions. Therefore, precise measurement of the suppression level provides information about medium temperature [13]. Fig. 7 presents reconstructed di-muon invariant mass distribution (crosses), for muons from the barrel region ($|\eta| < 1$) in the mass range of Υ. The reconstruction takes into account various sources of backgrounds including muons from hadronic decays or calorimeter "leakage". Mass resolution of 120 MeV was achieved which easily allows to distinguish Υ and Υ'.

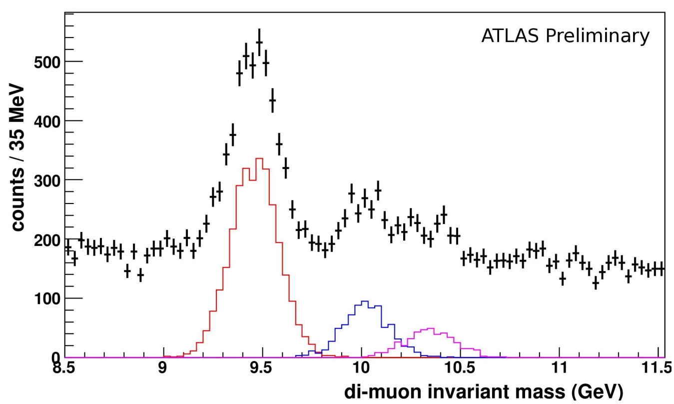

Fig. 7. Di-muon invariant mass distribution in 0.25 nb^{-1} Pb+Pb collisions for muons from barrel region only ($\eta < 1$). Solid lines represent contributions from different Υ states.

7. Summary

Thanks to hermetic and fine granularity of tracking and calorimeter systems, ATLAS has a great potential to perform comprehensive measurements for heavy ion collisions. With the ATLAS silicon inner detector, calorimeters and muon spectrometer we will be able to study various observables including global variables, high energy jets and photons, quarkonia suppression. Early analysis of $p+p$ shows that detector performance agrees very well with the expectations from Monte Carlo simulations of the detector response [14]. The $p+p$ data will be used for preparation to Pb+Pb run and will serve as a baseline for Pb+Pb measurements.

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