The Heavy–Ion Physics Programme with the ATLAS Detector

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Abstract. The CERN LHC will collide lead ions at $\sqrt{s} = 5.5$ TeV per nucleon pair and will provide crucial information about the formation of a quark–gluon plasma at the highest temperatures and densities ever created in the laboratory. We report on an updated evaluation of the ATLAS potential to study heavy–ion physics. The ATLAS detector will perform especially well for high p_T phenomena even in the presence of the high–multiplicity soft background expected from lead-lead collisions, and most of the detector subsystems retain their nearly full capability. ATLAS will study a full range of observables which characterize the hot and dense medium formed in heavy–ion collisions. In addition to global measurements such as particle multiplicities and collective flow, heavy–quarkonia suppression, jet quenching and the modification of jets passing in the dense medium will be accessible. ATLAS will also study forward physics and ultraperipheral collisions using Zero Degree Calorimeters.

1. Introduction and simulation

In a very near future, in addition to proton beams, Pb beams will be run in the CERN LHC at $\sqrt{s} = 5.5$ TeV per colliding nucleon pair. At these energies, central collisions produce an enormous number of virtual partons, largely dominated by gluons, which are deconfined and form a new phase of QCD matter, often referred to as the quark–gluon plasma (QGP), with a phase transition expected to coincide with a partial restoration of chiral symmetry, according to lattice QCD simulations. The outstanding results obtained by the SPS and the RHIC experiments, in particular the evidence for a new form of matter with unexpected properties resembling those of a "perfect liquid" [1], make the study of heavy-ion collisions at still higher energies very promising. At the LHC energy, thirty times larger than achievable presently at the RHIC, Pb collisions should result in the creation of a larger volume of deconfined matter which will last longer, making easier the study of deconfined states and the exploration of the phase diagram of strongly interacting matter.

The ATLAS detector [2] contains an inner detector with silicon pixels, silicon strips and a transition radiation tracker (TRT) inside a 2 T solenoid magnet. It is surrounded by electromagnetic and hadronic calorimeters, and, outermost, by a stand–alone μ–spectrometer in a toroidal field with $\int B\,dl = 4$ Tm. The calorimeters have a hermetic coverage over 10 units of pseudorapidity ($|\eta| < 4.9$), a fine granularity and longitudinal segmentation with 3 layers both in the electromagnetic and hadronic part. The inner detector ($|\eta| < 2.5$) and the μ–spectrometer ($|\eta| < 2.7$) have a large coverage with a full azimuth range.

The simulation was done with the HIJING 1.38 [3] event generator and the GEANT simulation package. The maximum charged particle pseudorapidity density $dN_{ch}/d\eta$ reaches

about 3200 for central Pb+Pb collisions. This density is high when compared to the multiplicity of 2000 predicted by the saturation model [4] or to the 1200 charged particles expected from extrapolation of RHIC data [5], but allows to study the worst-case scenario with a large density environment. Most of produced particles have a low E_T and range out in the first longitudinal layer of 4 radiation lengths of the electromagnetic calorimeter [2]. When switching from proton to Pb beams, due to the higher occupancy, limitations might occur concerning the inner detector and in particular the TRT which cannot be fully exploited in central Pb collisions [6]. The partial usage of the TRT is the subject of ongoing studies. Even with this overestimated particle multiplicity, the occupancy in central Pb collisions of the silicon pixel detector, below 2%, and of the strip detector, below 20% (10%) in the innermost (outermost) layer, allows track reconstruction with an efficiency of 60 to 70% for p_T in the range 1–10 GeV and with a fake rate below 1%, as shown in Fig. 1. These results were obtained with the standard $xKalman$ reconstruction algorithm [2] with small adjustments to the high–multiplicity environment, using only the pixel and strip silicon detectors (no TRT). The p_T resolution ranges from about 4% in the end–cap region to 2% at $\eta = 0$ for $p_T > 1$ GeV and is limited by multiple scattering.

The studies presented here are based mainly on modified versions of the ATLAS production software release 11.0.41, and 7.5.0 with a partial cross check using release 12.0.6 in section 3.

2. Global observables

The first measurements concern global observables, such as charged particle and transverse energy distributions (N_{ch}, $dN_{ch}/d\eta$, E_T, $dE_T/d\eta$), azimuthal anisotropies and collective flow effects. These basic variables, which are accessible with low-statistics event samples, reflect all physics processes happening during the collision and provide information on fundamental event properties. Several of these global variables, e.g. the charged particle multiplicity, can be inferred from the total number of hit clusters in the silicon pixel and strip detectors, without a full track reconstruction in the inner detector. This is also the case for the estimate on an event–by–event basis of the collision centrality, given by the impact parameter b, obtained with an accuracy of the order of 1 fm, or the estimate of the charged particle pseudorapidity density $dN_{ch}/d\eta$ with an accuracy of about 5% for central collisions, as can be seen in Fig. 2. Similarly, the strength of elliptic flow can be measured from the angular distribution of hit clusters in pixel detectors, using the forward calorimeters to reconstruct the reaction plane. Moreover, it is the comparison of elliptic flow measurements with predictions of the hydrodynamical model which has revealed the unexpected fluid–like properties of the matter observed at RHIC [1]. The accessibility of this global variable in ATLAS without a full reconstruction of the event is therefore very promising.

3. Heavy–quarkonia

The study of the suppression of heavy–flavour bosons, when the color screening length in a dense hot deconfined medium becomes smaller than the size of the bosons, provides crucial tests of the long–range confining potential of QCD [7]. As each quark–antiquark bound state is characterized by a different dissociation temperature, the systematic measurement of the suppression of these resonances should provide some sort of thermometer for the early stage of the system evolution, even if the observed suppression results from a complex interplay between suppression and regeneration scenarios [8]. The possibility of observing states of the Υ and J/ψ families via their decay into μ's have first been studied. As the stand–alone μ–spectrometer gives poor mass resolution for low p_T μ–pairs, several algorithms have been developed to associate μ candidates with tracks in the inner detector. A first algorithm matches through a global fit tracks fully traversing the μ–spectrometer with inner detector tracks. A second algorithm uses a tagging method selecting inner detector tracks whose extrapolation coincides with a track segment in the μ–spectrometer. The choice of very strict cuts in the matching algorithms reduces the
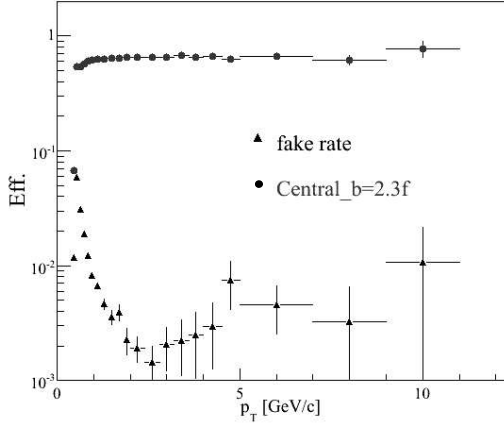
Figure 1. Reconstruction efficiency and percentage of fake tracks as a function of the reconstructed particle p_T, for tracks with $|\eta| < 1$ in central Pb collisions (preliminary).
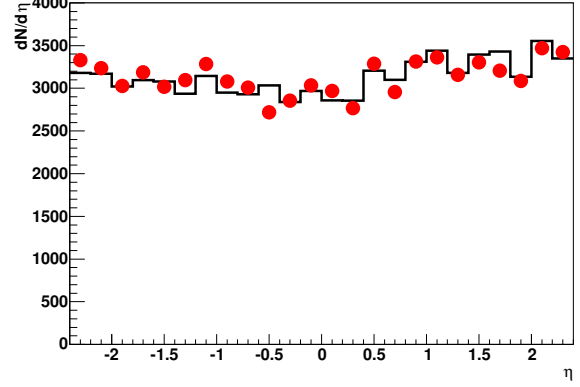

Figure 2. Comparison between the charged particle density distribution estimated from pixel information (dots) and the true distribution (histogram) for one central Pb+Pb event.
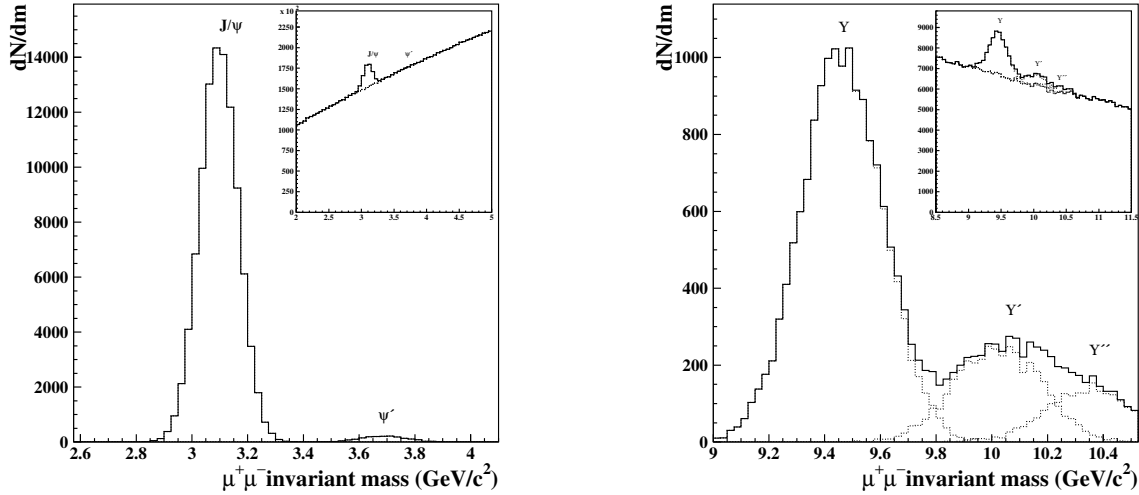

Figure 3. Reconstructed $\mu^+\mu^-$ invariant mass distribution in the J/ψ region (left), and in the Υ region for muons with $|\eta| < 2$ (right) without background, and with background in the inset.

background from hadron decays to an acceptable level. In one strategy ("Global fit"), only di-muons reconstructed with the first method are used, whereas another strategy ("Global+tag") considers also μ–pairs with at most one of the μ's reconstructed with the tagging method in order to increase statistics. An additional way to improve the heavy quarkonia acceptance is to reduce the toroidal field of the μ–spectrometer, e.g. of a factor 2. Finally, 4 strategies have been considered: the "Global fit" and the "Global+tag" methods with full field ($\int B\,dl = 4$ Tm) or half field (B/2 mode). Using tagging is basically a trade off between statistics and purity whereas reducing the field is a trade off between statistics and mass resolution. The best scenario will depend in large part on the real charged particle multiplicity, which is difficult to predict for Pb collisions at the LHC energy, and on the TRT capability to improve track reconstruction. Thus all possibilities are kept open. At the Υ peak, without the TRT, the mass resolution ranges from 110 MeV to 160 MeV depending on the η cut applied on the decay μ's, and a compromise has to be found to clearly separate Υ states with maximum statistics. Typically, a resolution below

150 MeV, sufficient to separate Υ and Υ' states, with a combined acceptance and efficiency of 12.5% and a signal to background ratio of 0.2, is obtained when limiting the μ acceptance $|\eta| < 2$ with the "Global+tag" selection, a μ–$p_T > 3$ GeV, and the full field (Fig. 3). The number of $\Upsilon \to \mu^+\mu^-$ events accumulated in one month of Pb+Pb running (0.4 nb^{-1}) is expected to be 1.5×10^4. Contrary to the J/ψ case, the B/2 mode doesn't bring a significant improvement because keeping a similar mass resolution to well separate the Υ states requires more severe cuts which annihilate the gain in statistics.

In the J/ψ region, the mass resolution is 70 MeV, which allows a clear separation of the ψ states (Fig. 3). Due to the low mass of the J/ψ, the acceptance is mainly for $|\eta| > 1.5$, and a μ–p_T cut down to 1.5 GeV is needed to measure the J/ψ from $p_T = 0$. Thus, the possibility of a trigger based on a low μ–p_T cut for $|\eta| > 1.5$ is investigated. With the "Global+tag" strategy and a μ–$p_T > 1.5$ GeV, the acceptance and efficiency is 0.53%, the signal to background 0.2. The number of J/$\psi \to \mu^+\mu^-$ events expected per month of 0.4 nb^{-1} is 10^5 and even 2×10^5 with the B/2 mode. The use of the TRT to identify low p_T electrons in Pb collisions is being evaluated and a study of Υ and J/$\psi \to e^+e^-$ is under way. The possibility of measuring χ_c decaying into J/ψ is also investigated.
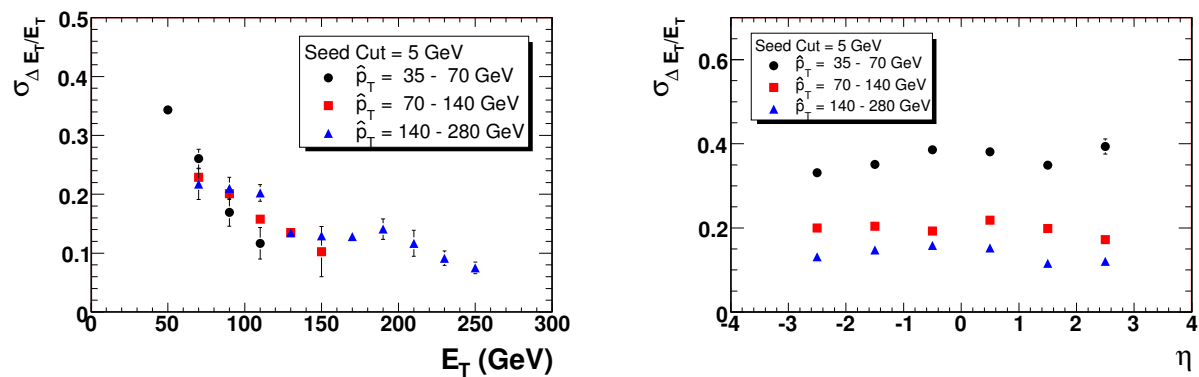

Figure 4. Jet energy resolution as a function of input PYTHIA jet E_T and η (preliminary).

4. Jet quenching

Jet quenching is due to the energy loss by gluon radiation of the hard-scattered partons at the origin of jets while traversing the dense partonic medium produced in heavy-ion collisions [9, 10]. This induced gluon radiation is expected to broaden the jet by increasing the amount of low–momentum hadrons produced with a broader angular distribution and by suppressing high–z ($z = p^{had}/p^{jet}$) particles from the jet fragmentation. This should result in an apparent reduction of the jet cross section when measured for a fixed cone size. Measurements at RHIC have shown a decrease of high–p_T hadrons in single–particle spectra [11, 12], a suppression of the back–to–back correlation between high–p_T hadrons and a double peak structure in central Au+Au collisions [12], which can be related to jet quenching phenomena. It is therefore of utmost importance to measure in the ATLAS detector as many jet properties as possible including the jet profile.

The expected jet rate per month of 0.4 nb^{-1} ranges from 30×10^6 events with a jet p_T larger than 50 GeV down to 4.4×10^4 for a jet $p_T > 200$ GeV. It should be noted that every accepted jet event is a jet–jet event because the calorimeters have a nearly complete phase space coverage. Jet studies were made with PYTHIA di–jets embedded into Pb+Pb HIJING central events. The first attempts of reconstruction was done using the standard ATLAS cone algorithm with a cone of size R=0.4, with a splitting/merging procedure and a multi-step background subtraction [6]. Fig. 4 shows the jet energy resolution as a function of E_T and η for different samples. The E_T threshold for jet finding and energy measurement is 40 GeV in Pb collisions (cf. 15 GeV in pp)

and the jet energy resolution is comparable to what is expected in pp collisions above 150 GeV. Another jet algorithm under evaluation is the "Fast k_T Jet Finder" [13] which doesn't use a fixed cone size and seems to suffer less from soft background fluctuations. It is also fast enough to be applied before background subtraction. In another reconstruction procedure, both a jet profile and a background around the jet axis are fitted. The sensitivity to profile can then be illustrated by the difference of the first radial moment between jets initiated by u– and b–quarks, and averaged on a few hundreds events [14]. In addition to jet profile fitting in the calorimeters, we can also measure the fragmentation function, dN/dz, obtained for charged particle tracks with $p_T > 3$ GeV and associated to the jet. The distribution of reconstructed tracks from jets in HIJING Pb+Pb events is similar to the distribution in pp events [6], which will be used as reference sample. This agreement indicates that the fragmentation function can be measured in the dense heavy–ion environment, and that the not quenched partons look similar in pp and Pb+Pb reactions.

5. Summary and conclusions

ATLAS is preparing intensely for heavy–ion data taking in 2008 and beyond. The simulation studies show that the detector should perform well in the dense heavy–ion environment, with some limitations concerning the TRT. Efficient tracking is possible using only the precision layers of the silicon inner detector. Global observables, such as charged particle multiplicities and collective flow effects, can be measured accurately, even without track reconstruction in the inner detector. Heavy–quarkonia physics is promising. J/ψ, ψ', Υ and $\Upsilon' \rightarrow \mu^+\mu^-$ events can be measured using a specially developed tagging method. Studies of J/ψ and Υ resonances decaying into e^+e^- as well as χ_c decaying into J/ψ are also under way. Despite the additional soft background, jet reconstruction is possible with a good efficiency even at relatively low jet E_T. In addition to di–jets, γ–jet and Z^0–jet events will be investigated. It is also possible to study separately jets initiated by light and heavy quarks. Consequently, heavy–quarkonia suppression and jet quenching, which are good probes to study the QGP, are well accessible in ATLAS. These measurements represent a substantial addition to the physics potential of the experiment and can provide a significant contribution to the LHC heavy–ion research programme.

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