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THE HEAVY-ION PHYSICS PROGRAMME WITH THE ATLAS DETECTOR

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Поздняков В. Н., Вертоградова Ю. Л. E1-2008-98
Физика взаимодействий тяжелых ионов на установке АТЛАС

Сооружаемый в ЦЕРН большой адронный коллайдер (Large Hadron Collider, LHC) будет работать с ускоренными до 5,5 ТэВ/нуклон пучками ионов свинца. Детектор АТЛАС, спроектированный для изучения физических процессов при больших поперечных импульсах частиц, рожденных в протон-протонных столкновениях, обладает потенциалом для изучения ультрарелятивистских столкновений тяжелых ионов во всем спектре наблюдаемых переменных, которые характеризуют предельно плотную ядерную материю и образование так называемой кварк-глюонной плазмы. Программа физических исследований на установке АТЛАС включает в себя измерение глобальных переменных (множественность рожденных частиц, распределения поперечного импульса и т. п.), измерение сечения образования тяжелых кваркониев, изучение эффекта «гашения струй» и изучение ультрапериферических взаимодействий.

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The Heavy-Ion Physics Programme with the ATLAS Detector

The CERN LHC collider will operate with lead ions at $\sqrt{s}$ of 5.5 TeV/nucleon. The ATLAS detector, designed to study high-p_T physics in pp mode of the LHC, has potential to study ultrarelativistic heavy-ion collisions in a full range of observables characterizing the extremely dense matter and the formation of a quark–gluon plasma. The ATLAS physics programme includes global event measurements (particle multiplicities, transverse momentum), suppression of heavy-quarkonia production, jet quenching and study of ultraperipheral collisions.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energy Physics, JINR.

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INTRODUCTION

The ultrarelativistic heavy-ion central collisions at the LHC will create hot and dense matter with enormous number of virtual deconfined partons. This new phase of QCD matter, called the quark–gluon plasma (QGP), is characterized by deconfined partons and by a partial restoration of chiral symmetry. The study of produced jets, direct photons and heavy quarks will probe earliest stage of collisions [1]. Modification of these processes compared to proton–proton collisions will allow one to learn about QCD in dense medium [2]. Analysis of particle multiplicities, transverse momentum and monojets intents to study of parton structure of the nucleus with models based on parton saturation (color glass condensate) [3]. The gluon radiation by partons moving the dense matter, often referred to as jet quenching [4], should reflect to properties of produced jets.

The ATLAS detector [5] includes different systems. The inner detector intends for precise measurements of charged particles. It is located inside a 2 T solenoid magnet and covers pseudorapidity domain $|\eta| < 2.5$. Finely granu-

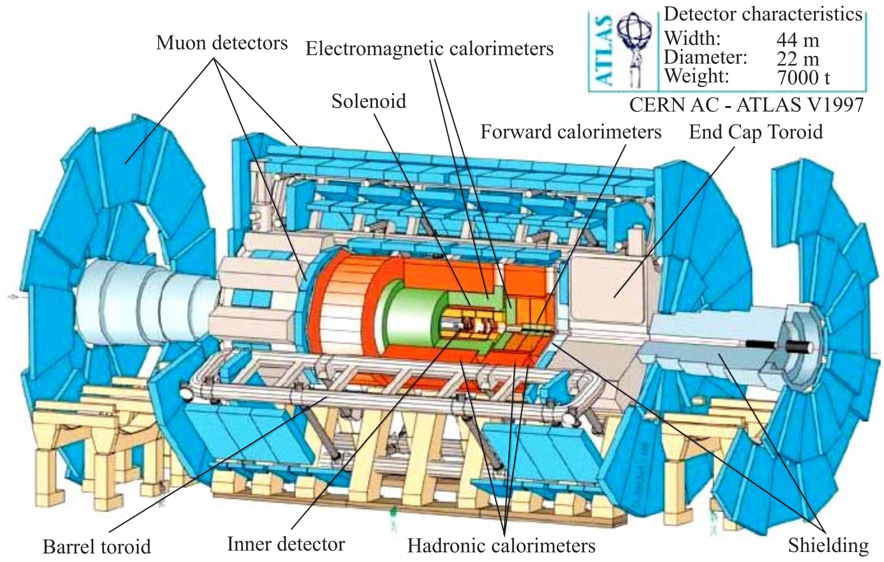

Fig. 1. The ATLAS detector

lated longitudinal segmented and azimuthal hermetic electromagnetic ($\eta < 3$) and hadronic ($|\eta| < 4.9$) calorimeters provide high energy and spacial resolutions. Stand-alone muon spectrometer ($|\eta| < 2.7$) is inside of a strong toroidal field. Two detectors, important for heavy-ion physics studies, extent the ATLAS acceptance into the forward region — zero degree calorimeter [6] intended for detection of forward neutrons and as an estimator of the event «centrality», and the LUCID detector [7] for the detection of primary charged particle around the beam-pipe. A view of the ATLAS setup is shown in Fig. 1. The main detectors are illustrated.

Basic parameters of the setup are mentioned. The characteristics (efficiency, resolution, etc.) of the ATLAS detector will be illustrated below in parts relevant to the specific physics tasks. The ATLAS detector is well suited to address many theoretical questions via precise experimental measurements using tools developed in the context of RHIC studies [8].

OBSERVABLES

The heavy-ion simulation was done with the HIJING 1.38 event generator [9] and with the GEANT simulation package [10].

It is worth-while to mention that the simulation probably overestimates the detector occupancy since extrapolated RHIC data [11] shown that particle densities should be by factor of 2–3 lower as compared to the HIJING expectation of around 3000 particles per unit of pseudorapidity for central Pb–Pb interactions. So we realized a «pessimistic» scenario and values of detector occupancies and reconstruction efficiency, given below, are to be improved. The occupancy of the inner detector varies from few percents for its pixel part up to 20% for strip detectors. The standard ATLAS reconstruction software (xKalman filter, [5]) already provides charged particle reconstruction efficiency on the level of 70% for the particle momenta above 1 GeV. Decreased detector occupancy (especially for the strip part) definitely increases the efficiency and also suppresses fake rate which is now of order of one percent.

The transverse energy deposited in towers of size $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ is between 1 and 3 GeV (depending on pseudorapidity) in the electromagnetic calorimeter and around 0.5 GeV in the hadronic calorimeter. This energy deposition is obtained with minbias HIJING events and it is a «pedestal» for jet search.

First days at the LHC will allow one to measure *global characteristics* of heavy-ion collisions such as charged and neutral particle yield and densities ($N_{\rm cha}$, $N_{\rm neu}$, $dN/d\eta$, p_T, $dp_T/d\eta$, etc.). These basic measurements provide information about initial conditions — energy and parton densities. These measurements will allow one to learn about initial-state entropy of produced system. They are also sensitive to the details of the nuclear structure functions and to the display of nuclear shadowing and jet quenching. The charged multiplicity measurement together with information coming from forward calorimeters is a way to estimate on an event-by-event basis of the collision centrality and to evaluate the impact parameter b of colliding ions with an accuracy of the order of 1 fm. The measurement of these global characteristics will be used for the model tuning as well. Charged particle multiplicities and densities will be measured within $|\eta| < 2.5$ with the precision layers of the inner detector while the neutral component of an event is studied with hermetic coverage of the ATLAS calorimeters. It is worth-while to mention that the charged multiplicity can be measured on an event-by-event basis even without complete event reconstruction. It was found that the relation between the number of signal hits in the inner detector correlates with the charged particle multiplicity via approximately linear dependence.

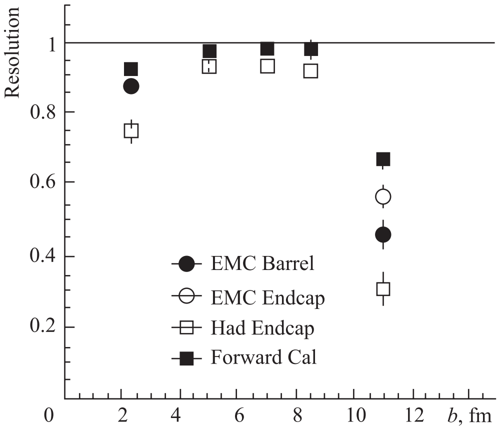

Fig. 2. Reaction plane resolution as a function of impact parameter

Collective phenomena in heavy-ion interactions are to be studied via *anisotropic flow* (direct and elliptic) measurements. Results on anisotropic flow have been obtained in several experiments [12]. The flow is important part of dynamics of heavy-ion collisions [13]. The measurement involves event-by-event estimation of the «reaction plane» determined by the beam axis and the impact parameter of colliding ions. Thus the key role plays an accuracy of its measurement. The reaction plane resolution* is obtained with the measurement of two subevents: one with particles in positive z direction and another — in negative direction. The expected resolution, expressed via cosine of true and reconstructed angle

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[*] The resolution is determined as $< \cos(2 \cdot (\Psi_{\rm rec} - \Psi_{\rm true})) >$, where $\Psi_{\rm rec}$ and $\Psi_{\rm true}$ are reconstructed and true azimuthal angles, respectively.

values, is shown in Fig. 2 as a function of the impact parameter b. The resolution in semicentral collisions (with b between 4 and 10 fm) is near to unit. The figure presents results of the calculations using different ATLAS calorimeters — ElectroMagnetic Barrel (EMC Barrel), ElectroMagnetic Endcap (EMC Endcap), hadronic endcap and forward calorimeters.

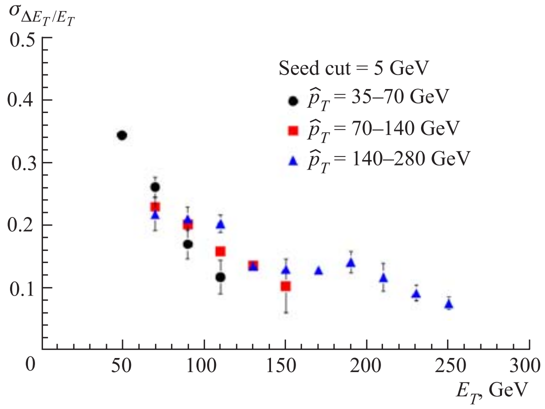

Fig. 3. Jet energy resolution vs jet finder threshold E_T

Partons, produced by hard scattering processes in ions interactions, traversed through and hadronized within dense quark–parton medium. This influences jet production cross section and properties of high-p_T jets. Such traversing results in enhanced particle multiplicities of produced jets and lowering particle transverse momentum (due to gluon radiation) and also broaden jets (due to rescattering off medium constituents). The effect is called *«jet quenching»*. Signatures of such an energy loss are a suppression of pairs of high-p_T jets [14] and an enhancement of monojet to the dijet cross section [15]. Jet rate at the LHC with Pb beams is evaluated to be of the order of 10^7 events with jet p_T more than 50 GeV for one-month heavy-ion LHC run at nominal luminosity.

Large acceptance and fine longitudinal segmentation of the electromagnetic calorimeter enhance ATLAS's ability to measure jets including the jet profile and direct photons. The jet energy resolution is shown in Fig. 3 as a function of the threshold for jet finder E_T. The standard ATLAS cone algorithm with splitting/merging and background subtraction procedures [16] was used. Investigation of jet properties in γ-jet and Z-jet events is simplified by ability to handle E_T scale with boson measurements. These events involve tagging the hard jet opposite the particle (γ^*/Z^0 decayed into e^+e^- or $\mu^+\mu^-$ pairs) that does not interact strongly with the produced dense matter. The jet finding efficiency is higher due to a back-to-back configuration between γ/Z and jet in the transverse plane (Fig. 4).

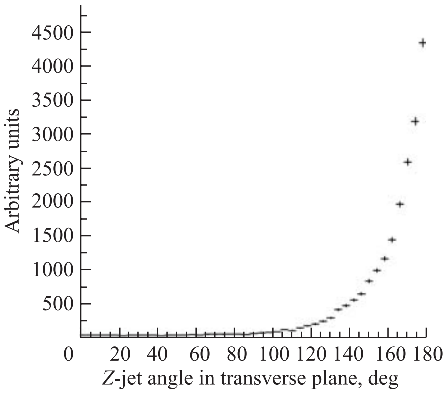

Fig. 4. Distribution of Z^0-jet angle in the transverse plane

The rate of produced quark–antiquark bound states depends on the color screening length in the medium. When this length becomes smaller than the size of quarkonia, their production is suppressed. Suppression of the J/ψ and ψ' states has been observed in nucleus–nucleus interactions [17]. The study of *quarkonia suppression* provides tests of QCD confining potential [18]. Since the Υ resonance has smaller radii than other $c\overline{c}$ and $b\overline{b}$ states, a much higher temperature is needed to dissociate this resonance. The study of Υ production provides a valuable tool to learn the characteristics of the plasma [19]. It is necessary to resolve different states of Υ family.

The possibility to reconstruct muon decays of charmonium and bottomonium states with the ATLAS muon spectrometer was studied. Several approaches were used in order to improve the mass resolution provided by the stand-alone muon spectrometer. The main idea is to develop algorithms for effective muon track association with a track in inner detector of the setup. Large track multiplicity in heavy-ion collisions makes such an association to be much more complicated than in *pp* interactions. The expected statistics of selected events should be increased for a price of worse purity in the selected sample. Other ways to increase statistics of reconstructed events are a reduce the magnetic field of the spectrometer and the use of a tagging method. The later means the use of track segment in the spectrometer (without full reconstruction) as a muon tag for soft decayed muons. The details of different approaches proposed to select events are presented in [20]. The obtained mass resolution at Υ peak is 110 MeV. Figure 5 illustrates invariant mass of reconstructed muon pairs without (with) background (in the inset).

In the case of large spatial separation between the projectile and target nuclei, the interactions are mediated by the electromagnetic fields coming from nuclei. The flux of such quasi-real photons is scaled as Z^2 and the cross sec-

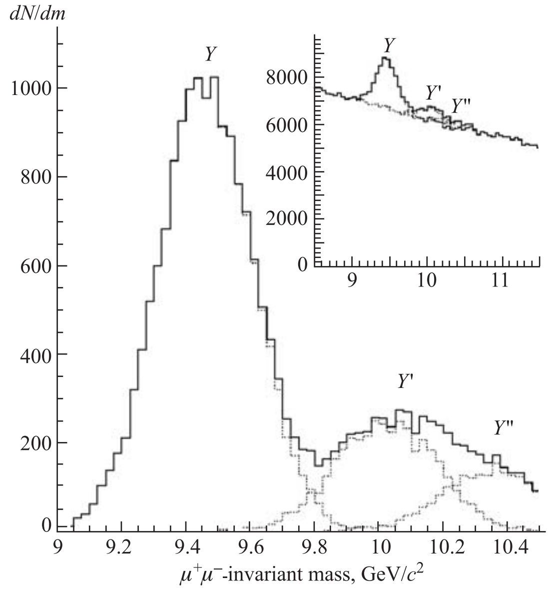

Fig. 5. Reconstructed $\mu^+\mu^-$-invariant mass in the simulation of Υ production

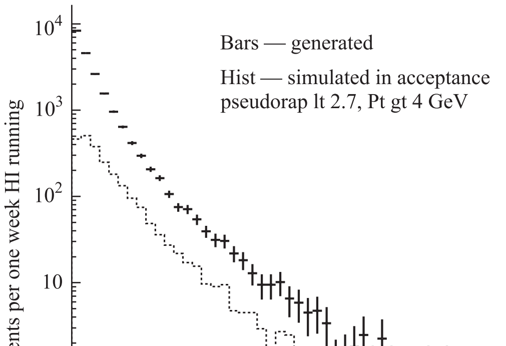

Fig. 6. $\mu^+\mu^-$-invariant mass in the simulation of ultraperipheral collisions for generated events (bars) and for events accepted in the barrel domain of the setup (histogram)

tions of photon induced processes in the collisions of heavy ions are quite large. These *ultraperipheral collisions* (UPC) occur as either purely electromagnetic gamma–gamma interactions or photonuclear reactions. Here the first estimations for some of two-photon interactions are presented. Lepton pair production is considered at first.

Few thousands lepton pairs are expected to be reconstructed within one-month heavy-ion LHC runs. Since the topology of such kind of events are rather simple and clean, the sample is background free. The study of these events can also help with methodical tasks: in-situ calibration of electromagnetic calorimeters; the efficiency of the muon system; luminosity monitoring as well. Expected distribution of muon invariant mass is shown in Fig. 6 for generated events and for events within detector acceptance. Other reactions under study are multiple e^+e^- pairs; a single meson (including bottomonium states) and a meson pair ($\rho^0\rho^0$) production. At LHC energies a maximum of energy of emitted photons is around 100 GeV. The search for new physics in two-photon collisions will be possible including a possibility to detect Higgs boson production via the $\gamma\gamma$ fusion [21].

CONCLUSION

The ATLAS detector enters now to final stage of commissioning and the data taking is scheduled for 2008 year. The detailed simulation of physics processes with heavy-ion beams shown that the detector performance is well suited for such tasks. The heavy-ion physics program includes measurement of global event variables; study of collective flows and azimuthal asymmetries; search for J/ψ and Υ suppression via their leptonic decays; study of jet properties including jet profile and jet quenching effects; investigation of ultraperipheral collisions including lepton pair production, meson spectroscopy and search for new states. Most of the mentioned topics are important probes to quark$-$gluon plasma studies. All these measurements allow one to use the physics potential of the ATLAS experiment in physics of heavy-ion collisions and to contribute to the LHC research program as well.

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