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Heavy Ion Physics at LHC (Hard probes)

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We will present the capabilities of the ATLAS and CMS experiments to explore the heavy-ion physics programme in hard probes sector offered by the CERN Large Hadron Collider (LHC). The collisions of lead nuclei at energies $\sqrt{s_{NN}}$ = 5.5 TeV, will probe quark and gluon matter at unprecedented values of energy density. The prime goal of this research is to study the fundamental theory of the strong interaction (QCD) in extreme conditions of temperature, density and low parton momentum fraction. The current paper will give an overview of the potential of ATLAS and CMS to carry out a set of representative hard probes measurements with Pb–Pb beams.

These include perturbative processes, such as quarkonia, heavy-quarks, jets, γ-jet, and high p_{T} hadrons — which yield "tomographic" information of the hottest and densest phases of the reaction.

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1. Introduction

The study of the fundamental theory of strong interaction (QCD) in extreme conditions of temperature, density and the parton momentum fraction (low-x) is the motivation for the previous, on-going and future heavy–ion experiments. The heavy–ion program in ATLAS and CMS is strongly motivated by the J/ψ anomalous suppression discovered at Super Proton Synchrotron (SPS) and several new phenomena observed at the Relativistic Heavy Ion Collider (RHIC). The top list of observations at RHIC [1, 2] includes lower hadron multiplicity than expected (possible saturation of the gluon density), the constituent quark number scaling of the elliptic flow and momentum spectra, strong interaction of high p_T hadrons with the dense matter and a significant suppression of the J/ψ, similar to that seen at the SPS, accompanied with more suppression of J/ψ's in forward than in the central region. The LHC plans to collide Pb nuclei at $\sqrt{s_{NN}} = 5.5$ TeV which is 28 times higher than the highest energy available at RHIC. According to our current understanding the regime accessible at the LHC will be characterized by the following properties - an initial state dominated by high-density (saturated) parton distribution with relevant range of parton momentum fraction x as low as 10^{-5} with a characteristic saturation momentum, $Q_s^2 \simeq 5-10$ GeV^2 [3]; copious production of hard probes (jets, high-p_T hadrons, heavy-quarks, quarkonia); large yields of the weakly interacting perturbative probes (direct photons, dileptons, Z^0 and $W^{\pm}$ bosons) [4].

2. The LHC detectors for Heavy Ions

Both ATLAS and CMS are general purpose detectors designed to explore the physics at the TeV energy scale. In spite of the design differences the detectors can provide successful measurements both for proton-proton and nuclei-nuclei collisions at LHC energies.

ATLAS and CMS detectors have a tracker, a muon system, and calorimeters with full azimuth angle and wide pseudorapidity coverage. The tracker covers $|\eta| < 2.5$ in full azimuthal angle for both detectors. Muon chambers are extended up to $\eta = \pm 2.4$ in CMS and ± 2.7 in ATLAS. Electromagnetic (ECAL) and hadronic (HCAL) calorimeters cover $|\eta| < 3.2$ in ATLAS and $|\eta| < 3$ in CMS. Both detectors are equipped with forward calorimeters (FCAL in ATLAS and HF in CMS) up to $\eta = \pm 5$. From $\eta = \pm 5.5$ and up to $\eta = \pm 6$ ATLAS has the additional Lucid detector and CMS has CASTOR calorimeter in pseudorapidity range $5 < |\eta| < 6.7$. Zero degree calorimeters are located with $|\eta| > 8$ both in ATLAS and CMS systems. A detailed description of ATLAS and CMS detectors can be found in Ref. [5]. We have the unique possibility to cross-check measurements done in the same phase space but using different types of detectors.

3. Hard ("tomographic") probes of dense QCD matter

Hard probes (particles with large transverse momentum and/or high mass) are of crucial importance for several reasons: (i) they originate from parton scattering with large momentum transfer Q^2 and are directly coupled to the fundamental QCD degrees of freedom; (ii) their production timescale is short, allowing them to propagate and potentially be affected by the medium; (iii) their cross-sections can be theoretically predicted with pQCD.

3.1 Jets and high-p_T hadrons production

One of the major discoveries at the RHIC is the hadron suppression at relatively high p_T, i.e. jet quenching effect. This effect is visible with the p_T dependence of the nuclear modification factor, R_{AA} which is defined by the ratio of particle yield in heavy-ion collisions to the binary collisions scaled yield in p+p collisions. The expected spectrum of high-p_T hadrons obtained for minbias events (without High Level Trigger) is shown in Fig. 1 for ATLAS detector. The reach for the p_T dependence of R_{AA} function using sample of events selected with High Level Trigger is shown in Fig. 2 for CMS [4].

New hard probes are available at the LHC, such as jet production, and boson-tagged (γ,Z^0) jet production. To investigate jet quenching in a full set of available signatures ATLAS and CMS developed jet, high-p_T tracks and photon reconstruction in the high occupancy conditions in detector [4],[7]. The ratio of the reconstructed quenched fragmentation function to the unquenched one is presented in Fig. 3 in comparison with Monte-Carlo (MC) truth [8] for CMS detector and the comparison of the quenched and unquenched fragmentation functions is shown in Fig. 4 for ATLAS detector for the integrated luminosity of 0.5 nb^{-1}.

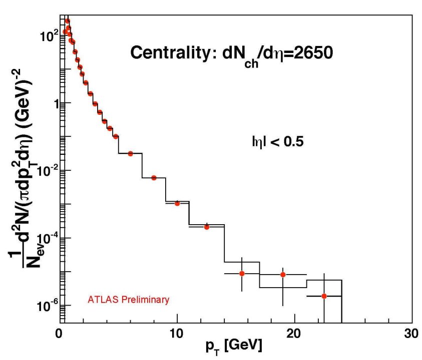

Figure 1: Charged particle p_T spectrum expected for Pb-Pb collisions at 5.5 TeV for a nominal integrated luminosity of 0.5 nb^{-1} using the minbias sample (ATLAS).

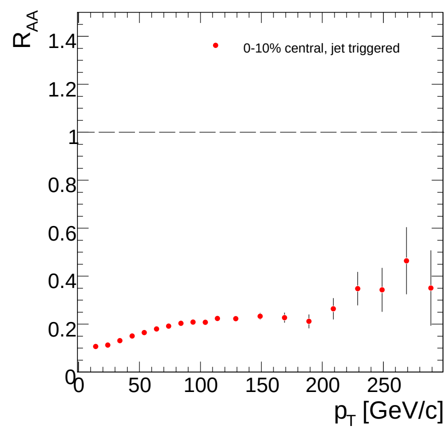

Figure 2: Expected statistical reach for the nuclear modification function, $R_{AA}(p_T)$ for inclusive charged hadrons in central Pb-Pb collisions generated with HYDJET [6] for a nominal integrated luminosity of 0.5 nb^{-1} for data triggered on high-p_T jets (CMS).

3.2 Quarkonium production

The study of heavy-quark bound states in high energy A-A collisions was proposed as a sensitive probe of the thermodynamical properties of the produced medium in [9]. The recent lattice calculations predict the step-wise suppression of the J/ψ and Υ families because of the different melting temperature for each $Q\bar{Q}$ state [10]. At the LHC Υ family will be available with large statistics for the first time. Unlike the J/ψ family the Υ family will be less affected by the recombination process due to less amount of $b\bar{b}$ compared to $c\bar{c}$ pairs in A-A collisions.

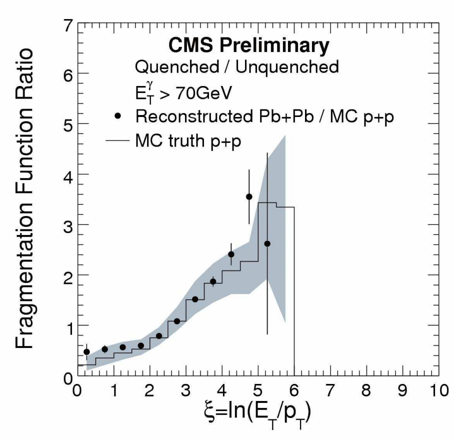

Figure 3: The ratio of the reconstructed quenched fragmentation function to the unquenched one (filled circles) is compared with the Monte-Carlo truth (solid histograms) for the integrated luminosity of 0.5 nb^{-1} (CMS).

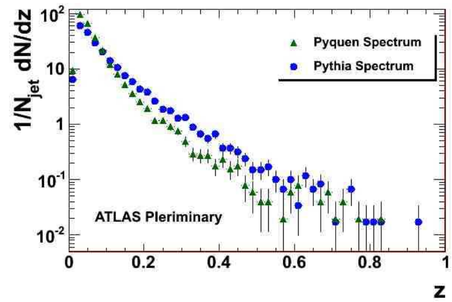

Figure 4: The comparison of the reconstructed quenched fragmentation function (triangles) with unquenched one (circles) (ATLAS).

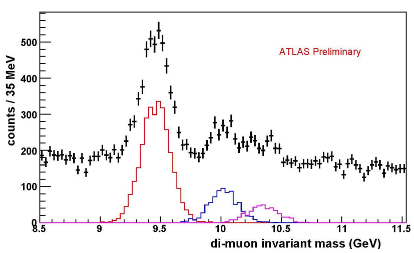

Figure 5: The Υ mass distribution and invariant mass spectra of opposite sign muon pairs in Υ mass range (ATLAS).

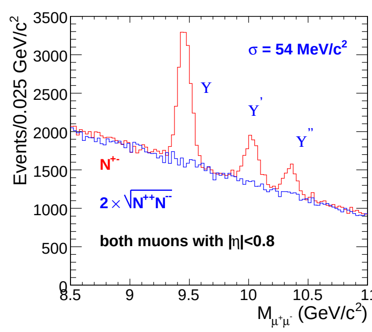

Figure 6: Invariant mass spectra of opposite–sign and same–sign muon pairs in Υ mass range with $dN_{ch}/d\eta|_{\eta=0} = 2500$ with both muons in $|\eta| < 0.8$ (CMS detector)

The dimuon mass distribution for Υ together with the invariant mass spectra of opposite–sign muon pairs in Υ mass range is presented in Fig. 5 for ATLAS detector [11], in Fig. 6 for CMS detector [4] in barrel region. The falling in the similar way same-sign dimuon spectrum used for background subtraction is presented in Fig. 6.

The dimuon spectra and p_T distribution for J/ψ family into muons obtained with CMS detector [4] are shown in the Figs. 7, 8, correspondingly. The mass resolution in Υ mass range is 120 MeV/c^2 for ATLAS detector. The mass resolution for Υ is about 54 MeV/c^2 for CMS barrel and it worsens to 90 MeV/c^2 if endcap detectors are included. For J/ψ, mass resolution is 70 MeV/c^2 for ATLAS and 35 MeV/c^2 for CMS in full η range. Around 20k events of Υs and a few hundreds ($\simeq$200k) events of J/ψs are expected in 0.5 nb^{-1}.

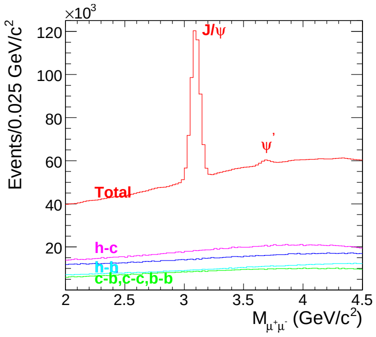

Figure 7: Invariant mass spectra of opposite–sign muon pairs in J/ψ mass range with $dN_{ch}/d\eta|_{\eta=0} = 2500$ with both muons in $|\eta| < 2.4$ (CMS)

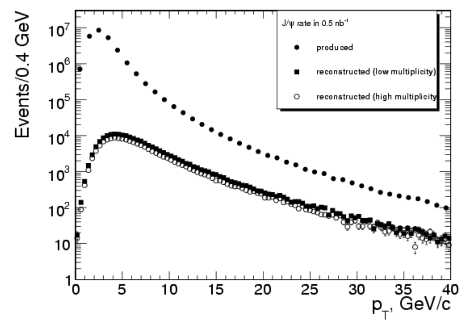

Figure 8: p_{T} distribution of the muon pairs in the J/ψ mass peak for Pb–Pb at 5.5 TeV assuming no quarkonia suppression. The three distributions are the J/ψ's produced in 0.5 nb^{-1} (solid circles), and the reconstructed ones with either $\frac{dN}{d\eta} = 2500$ (squares) or $\frac{dN}{d\eta} = 5000$ (open circles).

4. Summary

The excellent capabilities of ATLAS and CMS give the unique possibility of measuring hard probes of the dense medium state, such as hard spectra of charged particles, photons, jets, quarkonia. The similar $p_T - \eta$ acceptance of ATLAS and CMS detectors allows to cross-check measurements done with different technologies.

5. Acknowledgment

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