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Heavy Ion Physics with CMS

Olga Kodolova and Michael Murray for the CMS Collaboration

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We present the capabilities of the CMS experiment to explore the heavy-ion physics program offered by the CERN Large Hadron Collider (LHC). The prime goal of this research is to test the fundamental theory of the strong interaction (QCD) in extreme conditions of temperature, density and parton momentum fraction by colliding nuclei at energies of $\sqrt{s_{NN}}$ = 5.5 TeV. This presentation will give the overview of the potential of the CMS to carry out a full set of representative Pb-Pb measurements both in ”soft” and ”hard” regimes. Measurements include “bulk” observables – charged hadron multiplicity, low p_{T} inclusive hadron identified spectra and elliptic flow – which provide information on the collective properties of the system; as well as 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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Heavy Ion Physics with CMS

Olga Kodolova[a] and Michael Murray[b] for the CMS collaboration

[a]*Moscow State University, 119991,Leninskie Gory, 1/2, Moscow, Russia, kodolova@mail.cern.ch*
[b]*University of Kansas, Lawrence KS 66045-7582, USA, mjmurray@ku.edu*

Abstract

We present the capabilities of the CMS experiment to explore the heavy-ion physics program offered by the CERN Large Hadron Collider (LHC). The prime goal of this research is to test the fundamental theory of the strong interaction (QCD) in extreme conditions of temperature, density and parton momentum fraction by colliding nuclei at energies of $\sqrt{s_{NN}} = 5.5$ TeV. This presentation will give the overview of the potential of the CMS to carry out a full set of representative Pb-Pb measurements both in ”soft” and ”hard” regimes. Measurements include “bulk” observables – charged hadron multiplicity, low p_{T} inclusive hadron identified spectra and elliptic flow – which provide information on the collective properties of the system; as well as 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. Understanding the strong force under extreme conditions

The study of the strong interaction (QCD) in extreme conditions of temperature and density has been the driving force for experiments from the Bevalac to the the Large Hadron Collider. In the last decade the four RHIC experiments have produced beautiful evidence that in the energy range $\sqrt{s_{NN}} = 63 - 200$ GeV a strongly interacting quark gluon liquid is produced [1]. The scaling of the elliptic flow with quark number, the suppression of fast quarks in the medium are clears signals of this but a great wealth of other evidence is shown in the proceedings of this conference. At both SPS and RHIC energies the suppression of the J/ψ resonance suggests that we have created a very high temperatures system [2, 3, 4]. In addition there is evidence, from work at forward rapidities that the at small parton momentum fraction (low-x) the initial state of the nuclei may be a sheet of gluons, the color glass condensate [5, 6]. 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. We expect the initial state to be dominated by saturated parton distribution with relevant range of parton momentum fraction x as low as 10^{-5} and a characteristic saturation momentum, $Q_s^2 \simeq 5 - 10$ GeV^2 [7]. The collisions should produce copious hard probes such as jets, high-p_T hadrons, heavy-quarks, quarkonia and large yields of the weakly interacting perturbative probes (direct photons, dileptons, Z^0 and W$^\pm$ bosons) [8]. This paper will concentrate on our best guess of the physics at the LHC with an emphasis on early measurements. However the great strength of CMS is that it is a generic detector for heavy ions well suited to discovering the completely unexpected.

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2. The CMS detector

The central feature of the CMS apparatus is a 3.8T superconducting solenoid, of 6 m internal diameter. Within the field volume there are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass-scintillator hadronic calorimeter (HCAL). Besides the barrel and endcap calorimeters ($|\eta| < 3$), CMS has extensive forward calorimetry, HF ($3 < |\eta| < 5.2$), CASTOR ($5.3 < |\eta| < 6.6$) and Zero Degree ($|\eta| > 8.3$) calorimeters. Muons are measured in gaseous chambers embedded in the iron return yoke. A full description of the experiment can be found elsewhere [9]. A slice through CMS is shown in Fig. 1.

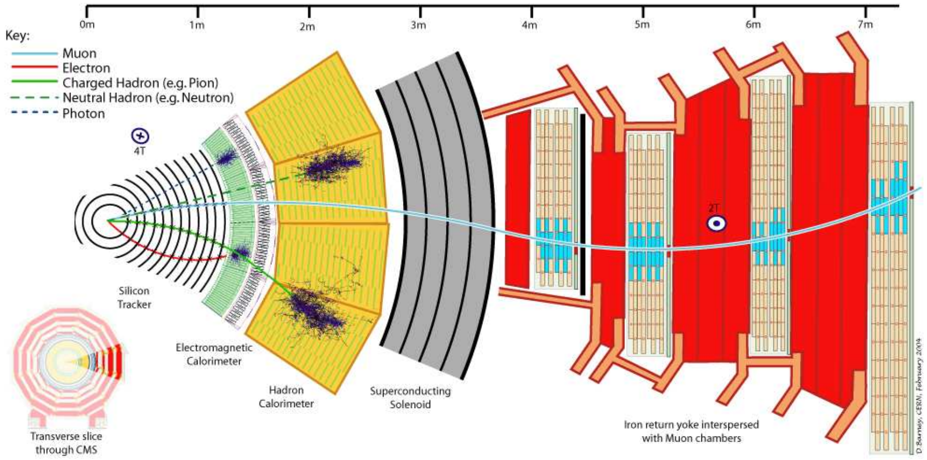

Figure 1: CMS detector (slice view).

Near mid-rapidity ($|\eta| < 2.5$) charged particles are tracked by three layers of silicon pixel detectors, made of 66 million $100 \times 150\,\mu\text{m}^2$ pixels, followed by ten microstrip layers, with strips of pitch between 80 and 180 μm. The silicon tracker provides the vertex position with $\sim 15\,\mu$m accuracy. The ECAL has an energy resolution of better than 0.5 % above 100 GeV. The HCAL, when combined with the ECAL, measures jets with a resolution $\Delta E/E \approx 100\,\%/\sqrt{E} \oplus 5\,\%$. The calorimeter cells are grouped in projective towers, of granularity $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ at central rapidities and 0.175×0.175 at forward rapidities. Muons are measured in the pseudorapidity window $|\eta| < 2.4$, with detection planes made of three technologies: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers. Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution between 1 and 5 %, for p_{T} values up to 1 TeV/c. The good momentum resolution of the tracker allows us to clearly resolve the Υ–family.

The first level (L1) of the CMS trigger system, uses information from the calorimeters and muon detectors to select the most interesting events (only one bunch crossing in 1000 in pp collisions). It is composed of custom hardware processors and takes less than 1 μs to reach a decision. The High Level Trigger (HLT) processor farm further decreases the event rate from 100 kHz to 100 Hz, before data storage. For Pb-Pb runs the low collision rate (8 kHz) together with fast L1 trigger will allow to send almost all the events triggered by L1 MinBias trigger to HLT-farm and provide full reconstruction of events in real time.

3. Bulk ("hydro") measurements in A-A collisions

The charged particle multiplicity per unit of rapidity at mid-rapidity is related to the entropy density in the collisions and fixes the global properties of the produced medium. The unexpectedly low multiplicities seen at RHIC have lent support to the color glass picture and it will be interesting to see if this model works at LHC energies. CMS is planning to make a first day measurement of the charged particle multiplicities by two methods: 1) hit counting in the pixels using a *dE/dx* cut and 2) tracklets with a vertex constraint. Figure 2 shows that for one event we can accurately reconstruct $dN/d\eta$ using the hit counting technique.

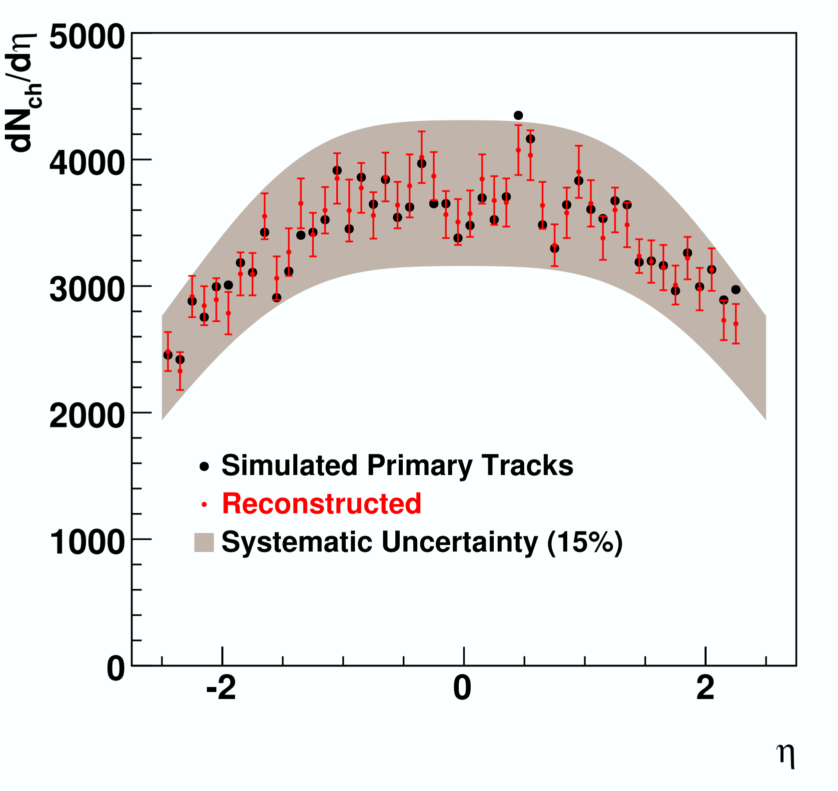

Figure 2: Comparison of the original distribution of primary simulated tracks (black) to the estimate obtained from reconstructed hits in layer 1 of the pixels (smaller) for one central Pb-Pb event [8]. The grey band indicates a somewhat conservative systematic uncertainty.

Measurements of hadron momentum spectra and ratios at low p_T are an important tool to determine the amount of collective radial flow and the thermal and chemical conditions of the system at freeze-out. CMS has developed a special low p_T tracking algorithm based only on the pixels. This allows us to identify particles by comparing energy loss, *dE/dx*, and the momentum of track. Inclusive hadron spectra can be measured from $p \simeq$400 MeV/c up to $p \simeq$1 GeV/c for pions and kaons and up to $p \simeq$2 GeV/c for protons (Fig. 3).

Unless the two lead nuclei collide head on the overlap region will have an elliptical shape. For a liquid, this initial space anisotropy is translated into a final elliptical asymmetry in momentum

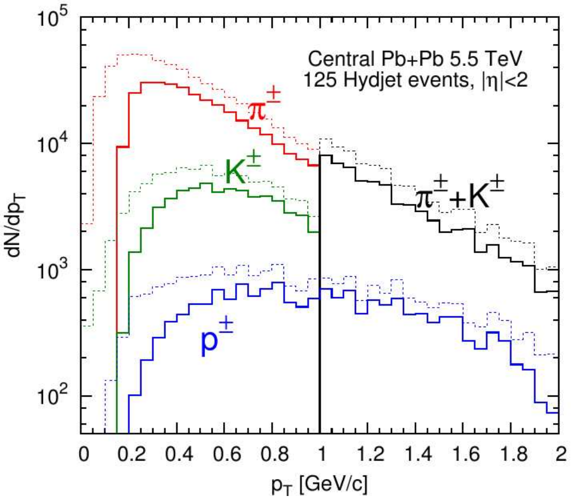

Figure 3: Low-p_T spectra of generated hadrons (dotted line) and the reconstructed hadrons (solid lines).

space. However for a gas any anisotropy should be much weaker. The elliptic flow parameter, v_2 is the strength of the second harmonic of the the azimuthal distribution of hadrons with respect to the reaction plane. Comparing the experimental v_2 with hydrodynamical calculations will show us how close the matter is fully thermalized perfect fluid close [8]. CMS will measure v_2 both by reconstructing the plane plane and by using multiparticle correlators or cummulants. The resolution of the event plane determination for CMS is shown in Fig. 4 while Fig. 5 shows our ability to measure v_2 as a function of p_T.

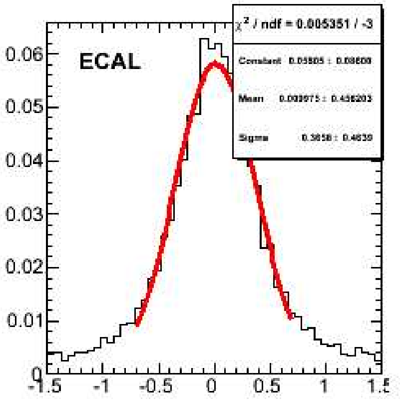

Figure 4: The reaction plane resolution estimated with the electromagnetic calorimeter

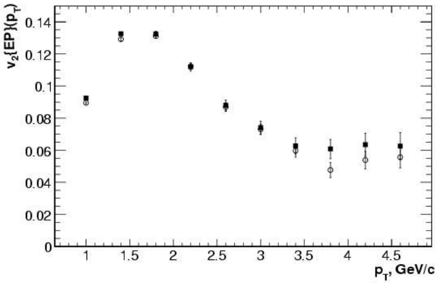

Figure 5: Reconstructed v_2 parameter on the p_T of track for CMS. Elliptic flow was included in HYDJET [12]

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

Hard probe, i.e. 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.

One of the major discoveries at the RHIC is the suppression of high p_T hadrons compared to what would be expected the corresponding number of binary pp collisions. This effect is known as jet quenching. The nuclear modification factor, $R_{AA}(p_T)$ is defined by the ratio of particle yield in heavy-ion collisions to the binary collisions scaled yield in p+p collisions. It provides a convenient first measure of the strength of jet quenching. In a typical run without the high level trigger we expect to be able to measure R_{AA} out to 150 GeV see Fig. 6. Using the HLT we can double our p_T reach, see Fig. 7 [8].

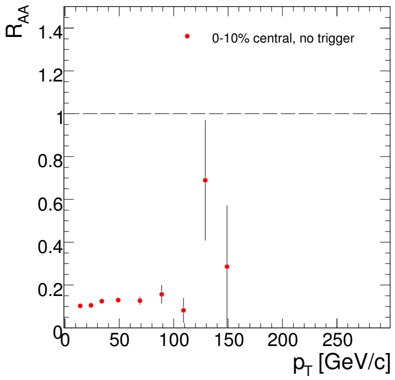

Figure 6: Charged particle $R_{AA}(p_T)$ for an integrated luminosity of 0.5 nb^{-1} using the minbias sample.

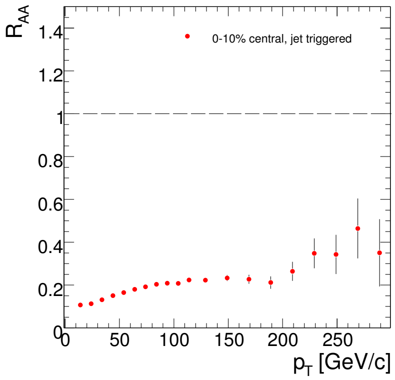

Figure 7: Same as Fig. 5 but for data triggered on high-p_T jets.

New hard probes are available at the LHC, such as boson-tagged (γ,Z^0) jet production. We have developed algorithms to reconstruct jets, high-p_T tracks and photons in the heavy ion environment [8]. Photon-jet events are a convenient way to study jet fragmentation since the photon does not lose energy as it propagates through the partonic medium. Figure 8 shows that the ratio of the reconstructed quenched fragmentation function to the unquenched one can be measured accurately for tracks with p_T values between 1 and 7 * 10^{-3} times the momentum of the photon [13].

The suppression of heavy-quark bound states in high energy A-A collisions was one of the first proposed signatures for a deconfined medium of quarks and gluons to be actually observed in experiment [2, 4]. At RHIC PHENIX has found that the suppression is stronger at forward rapidity, [3]. Recent lattice calculations predict a step-wise suppression of the J/ψ and Υ families because of the different melting temperatures for each $Q\bar{Q}$ state [14]. At the LHC the Υ family will be available with large statistics for the first time. Unlike the J/ψ family the botomonium family will be less affected by the recombination process since there are only a few b and bbar quarks per events. Our simulated dimuon spectra for the J/ψ and Υ families [8] are shown in Figs. 9 and 10. The mass resolution for Υ is about 54 MeV/c^2 in the barrel and it worsens to

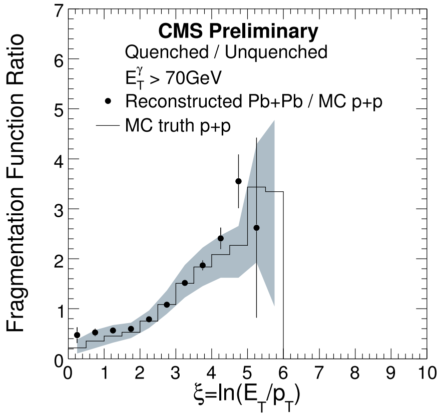

Figure 8: The ratio of the reconstructed quenched fragmentation function to the unquenched one (filled circles) is compared with the Monte-Carlo truth (solid histograms) for the integrated luminosity of 0.5 nb^{-1}.

90 MeV/c^2 if the endcap detectors are included. For the J/ψ, our mass resolution is 35 MeV/c^2 for CMS in full η range. Around 20 000 Υs and ≃200, 000 J/ψs are expected for an integrated luminosity of 0.5 nb^{-1}.

5. Summary

CMS is a superb detector for measuring muons, photons, jets and charged tracks from lead-lead collisions at high rate over a very large rapidity range. In this paper we have been able to highlight some of our capabilities to use both soft and hard probes such as multiplicity, low and high p_T spectra of charged particles, photons, jets and quarkonia to study QCD at very high temperatures, high energy densities and also very low x. Lack of space prevents us from discussing other probes such as dijet correlations and ultra-peripheral collisions. One can think of CMS as a generic detector for heavy ions that is able to measure almost the full phase space of the collisions. The collaboration is ready and eager to make the measurements described above but also is on the lookout for the completely unexpected.

Acknowledgments

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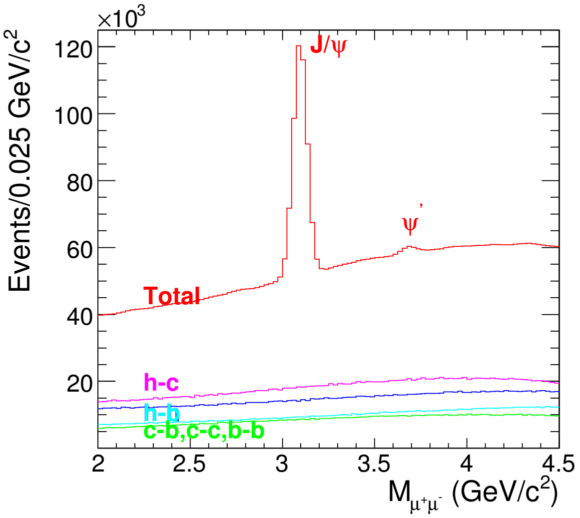

Figure 9: Invariant mass spectra of opposite–sign muon pairs in J/ψ mass range with $dN_{ch}/d\eta|_{\eta=0}$ = 2500 with both muons in $|\eta| < 2.5$

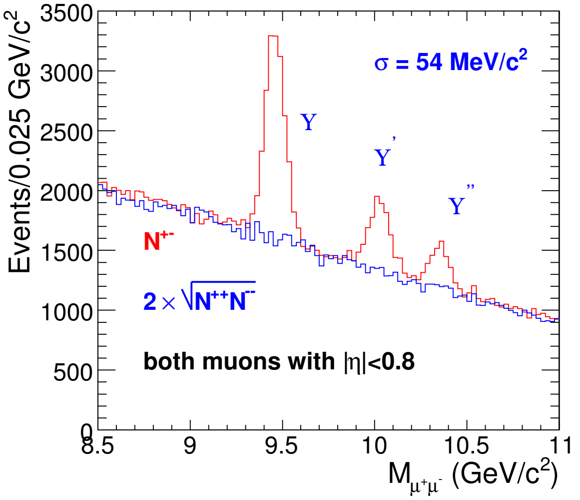

Figure 10: Invariant mass spectra of $\mu^+\mu^-$ pairs in Υ mass range, $dN_{ch}/d\eta|_{\eta=0}$ = 2500 and both muons have $|\eta| < 0.8$

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