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CMS CR -2009/200

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

24 July 2009 (v2, 27 July 2009)

Heavy Ion Physics with CMS detector

Olga Kodolova for the CMS Collaboration

Abstract

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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.

Presented at *IPM09: 1st IPM Meeting On LHC Physics,20-24 Apr 2009,Isfahan,Iran,01/08/2009*

1 April 2005

Heavy Ion Physics with CMS detector

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Abstract

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1 QGP searches from SPS and RHIC to LHC

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, ongoing and future heavy–ion experiments. The high temperature and density that can be achieved in the nuclei-nuclei interactions with reliativistic nuclei may lead to the phase transition of the hadronic matter into the Quark-Gluon Plasma (QGP state with assymptotically free quarks and gluons in the quasi-macroscopic volume). Quark-gluon plasma produced at the early stage of relativistic heavy-ion collisions is initially in a non-equilibrium state but afterwards it evolves towards equilibrium creating the expanding blob. As temperature and density lowering QGP falls into freeze out and hadronization state. The registration of the QGP state and the investigation of its properties can be done with different probes. These probes are divided into "soft" and "hard" ones depending on the objects that are used for studying QGP. As hard probes we consider processes that happened before equilibrium and look how the products (f.e. hard photons, partons) penetrated through the dense matter. As soft probes we consider the soft particles spectra, energy flows and ratios which are the result of the partons mixture during the equilibrium state. The difference of the processes characteristics in nuclei-nuclei collisions and in pp collisions or in peripheral niclei-nuclei collisions is used to conclude the QGP observation and its properties.

The heavy–ion program in 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 evidences at RHIC [1] 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 the one 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 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 CMS detector as for Heavy Ion collisions

A detailed description of the Compact Muon Solenoid (CMS) experiment can be found elsewhere [5]. The central feature of the CMS apparatus is a 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). Muons are measured in gaseous chambers embedded in the iron return yoke. Besides the barrel and endcap detectors, CMS has extensive forward calorimetry.

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. The very forward angles are covered by the CASTOR ($5.3 < |\eta| < 6.6$) and Zero Degree ($|\eta| > 8.3$) calorimeters.

The 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. Good momentum resolution in tracker gives possibility to clear resolving of the Υ–family.

Mid-rapidity charged particles are tracked by three layers of silicon pixel detectors, made of 66 million $100 \times 150\ \mu$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 first level (L1) of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select (in less than 1 μs) the most interesting events (only one bunch crossing in 1000). The High Level Trigger (HLT) processor farm further decreases the event rate from 100 kHz to 100 Hz, before data storage.

Low collision rate (8 kHz) for A-A events together with fast L1 trigger allow to send almost 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

Experience at SPS and RHIC has demonstrated that global variables, such as the charged-particle pseudorapidity density ($dN_{\rm ch}/d\eta$), transverse energy (both $E_{\rm T}$ and $dE_{\rm T}/d\eta$), and energy of neutral spectators are essential for event categorisation (i.e. to estimate the attained initial parton and energy densities in a nucleus-nucleus collision at a given centrality) in various analyses, as well as for placing important constraints on fundamental properties of particle production. The large coverage of the CMS tracking and muon detectors ($|\eta| < 2.5$) and the nearly full coverage of the CMS calorimeters ($|\eta| < 6.3$) provides access to all these measurements with high precision.

3.1 Charged particle multiplicity

The charged particle multiplicity per unit of rapidity at mid-rapidity is related to the produced entropy density in the Pb-Pb collisions and fixes the global properties of the produced medium. Extrapolations from SPS to RHIC energies gave essential overestimation relative to the measured multiplicity at RHIC. This evidence gives rise to the Color Glass Condensate (CGC) approaches which effectively take into account a reduced initial number of scattering centers in PDFs and reproduces results from RHIC. The expected hadron multiplicities at midrapidity in the frame of CGC model is much lower ($dN/d\eta|_{\eta=0}$ =2000) than the $dN/d\eta|_{\eta=0}$ =8000 predictions before RHIC results.

CMS assumes the first day measurement of the charged particle multiplicities by two methods: hit counting in pixel detectors accomplished with *dE/dx* cut and tracklets with vertex constraint. The comparison of the reconstructed multiplicity with hits counting and generated one in Fig. 1 for CMS detector. Hits from all charged particles in the first layer of the pixel barrel detector are first connected into clusters of hits to incorporate the possibility that a single charged particle could deposit energy in more than one pixel. This clustering algorithm is still effective for multiplicities as high as $dN_{\rm ch}/d\eta \approx 5000$ at midrapidity, i.e. much larger than expected in central Pb–Pb collisions at the LHC, as the occupancy in that scenario remains less than 2%. The background particles can be removed from the analysis via a cut in $\cosh\eta$ that selects only energy loss in the silicon consistent with particles emanating from the true collision vertex.

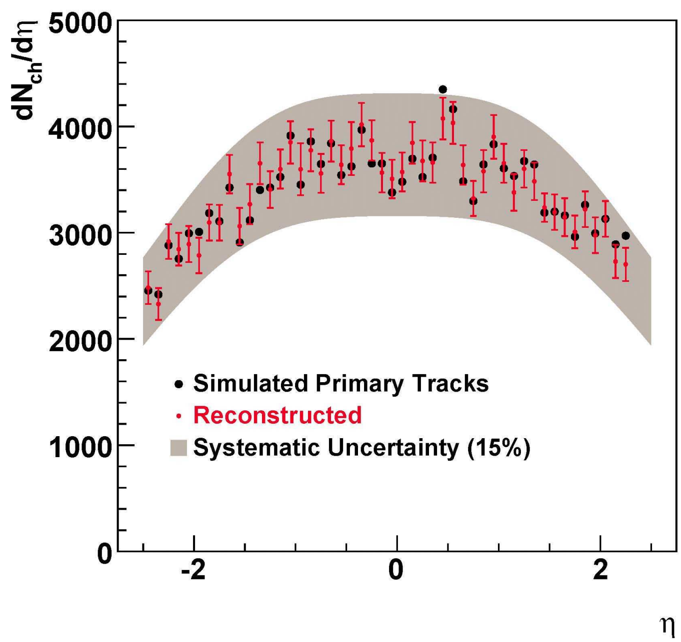

Figure 1: Comparison of the original distribution of primary simulated tracks (black large points) to the estimate obtained from the reconstructed hits in layer 1 of the Si pixel tracker (red smaller points) with statistical error bars, the grey band indicates a somewhat conservative systematic uncertainty of Ref. [4] for CMS detector.

3.2 Low-p_T hadron spectra

Measurements of hadron momentum spectra and ratios at low p_T are the important tool to determine the amount of collective radial flow and the thermal and chemical conditions of the final (freeze-out) state of reaction. The CMS has developed a special low p_T tracking algorithm with the possibility of particle identification by correlating energy loss, *dE/dx*, and the momentum of track, *p*, in Si-pixels and strips. The 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. 2).

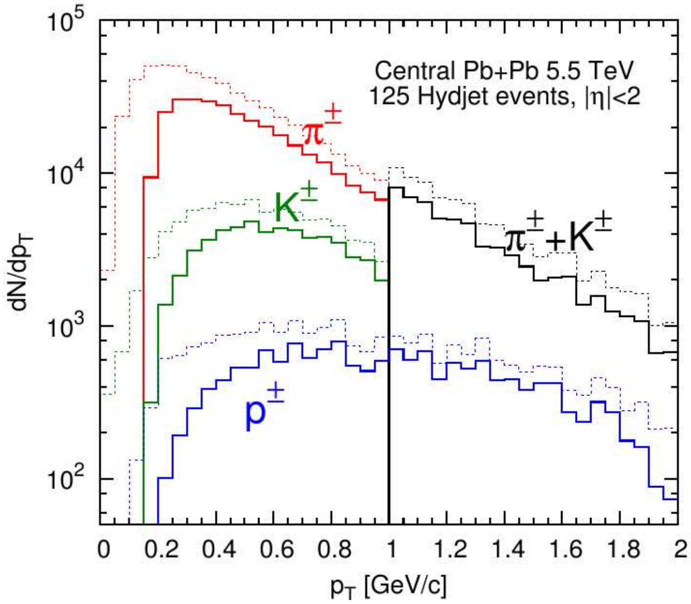

Figure 2: Low-p_T spectra of generated hadrons (dotted line) and the reconstructed hadrons (solid lines). Simulation was done for central Pb-Pb events at $\sqrt{S_{NN}}$ =5.5 TeV.

3.3 Elliptic flow

The initial state in A-A collisions with non-zero impact parameter is characterized by an anisotropic distribution in coordinate space. In collective system, the initial space anisotropy translates into a final elliptical asymmetry in momentum space with respect to reaction plane because the pressure gradient is larger for directions parallel to the smallest dimension of the ellipse. The elliptic flow parameter, v_2 is defined as the second harmonic coefficient of the fitted Fourier series function for the azimuthal distribution of hadrons with respect to the reaction plane. The comparison of the experimental data on v_2 with hydrodynamical calculations reveals that the produced matter behaves like perfect fluid close to the hydrodynamical limit expectations for a fully thermalized system [4]. CMS will provide measurements of v_2 parameter with and without (via multiparticle correlators or cummulants) event plane determination. The resolution of the event plane determination for CMS is shown in Fig. 3. The dependence of v_2 parameter on the momentum of track is presented in Fig. 4 for CMS for the parameterization of elliptic flow included in the input generator.

4 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.

4.1 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

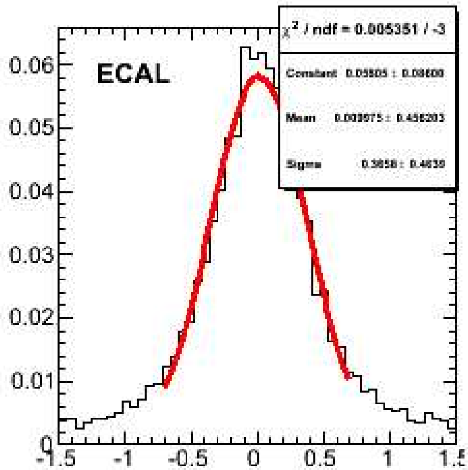

Figure 3: The reaction plane resolution estimated with the CMS electromagnetic calorimeter

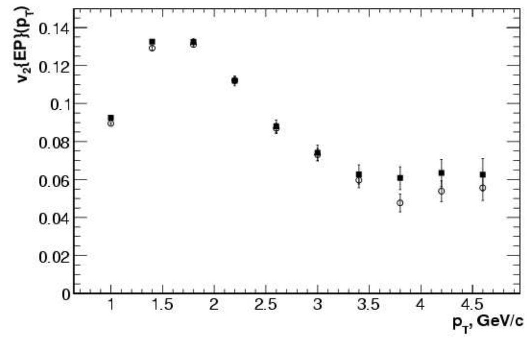

Figure 4: The dependence of the reconstructed v_2 parameter on the p_T of track for CMS. Elliptic flow was included in HYDJET [8]

spectrum of high-p_T hadrons obtained for minbias events (without High Level Trigger) is shown in Fig. 5. The reach for the p_T dependence of R_{AA} function using sample of events selected with High Level Trigger is shown in Fig. 6 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 CMS developed jet, high-p_T tracks and photon reconstruction in the high occupancy conditions in detector [4]. The fragmentation function can be extracted from (γ,Z^0) jet events relative to the γ,Z^0 energy using (γ,Z^0) parton balance. The advantage of this approach is that we do not rely on the jet energy reconstruction and calibration which is a difficult task for nuclei-nuclei event reconstruction. While for photons reconstruction in ECAL, on average, for $E_T > 70$ GeV, the transverse energy resolution for isolated photons is about 4.5%. The spatial resolution in η and ϕ is better than 0.005. We present the fragmentation function extracted from the γ-jet events. The contamination of the background from dijet events with leading π_0 was eliminated using mutivariate analysis of the cluster shape in ECAL. Obtained signal to background ratio is as good as 4.5.

The underlying event contribution from the copious soft particles production is estimated by using the momentum distributions of tracks found in an area outside of the jet cone, which is assumed to only contain background particles. For this purpose, for each reconstructed isolated ECAL cluster-jet pair, the charged tracks within a 0.5 radius cone perpendicular in ϕ angle to the reconstructed jet axis are selected.

The ratio of the reconstructed quenched fragmentation function to the unquenched one is presented in Fig. 7 in comparison with Monte-Carlo (MC) truth [9] for the integrated luminosity of 0.5 nb^{-1}.

This measurement will allow a quantitative test of proposed mechanisms for parton energy loss in the medium, testing fundamental properties of the high-density QCD medium produced in high-energy nuclear collisions.

4.2 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 [10]. 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 [11]. At the LHC 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 due to less amount of $b\bar{b}$ compared to $c\bar{c}$ pairs in A-A collisions.

The dimuon spectra for J/ψ and Υ family obtained with CMS detector [4] are shown in Figs. 8, 9. 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 35 MeV/c^2 for CMS in full η range. Around 20 Kevents of Υs and a few hundreds ($\simeq$200) kevents of J/ψs is expected in 0.5 nb^{-1}.

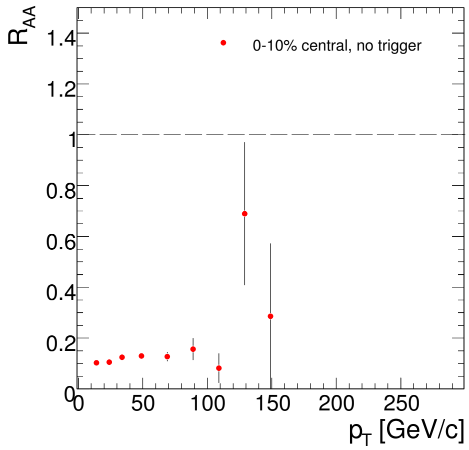

Figure 5: Charged particle p_T spectrum expected for Pb-Pb collisions at 5.5 TeV for a nominal integrated luminosity of 0.5 nb^{-1} using the minbias sample.

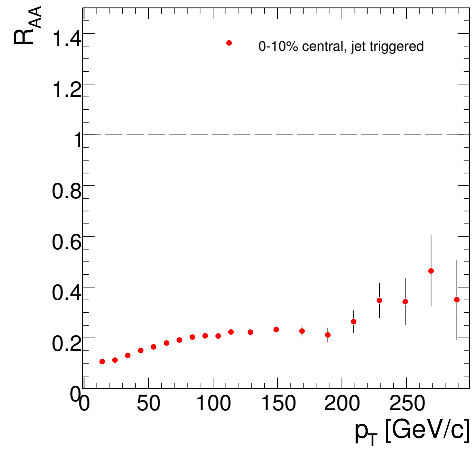

Figure 6: Expected statistical reach for the nuclear modification function, $R_{AA}(p_T)$ for inclusive charged hadrons in central Pb-Pb collisions generated with HYDJET [8] for a nominal integrated luminosity of 0.5 nb^{-1} for data triggered on high-p_T jets.

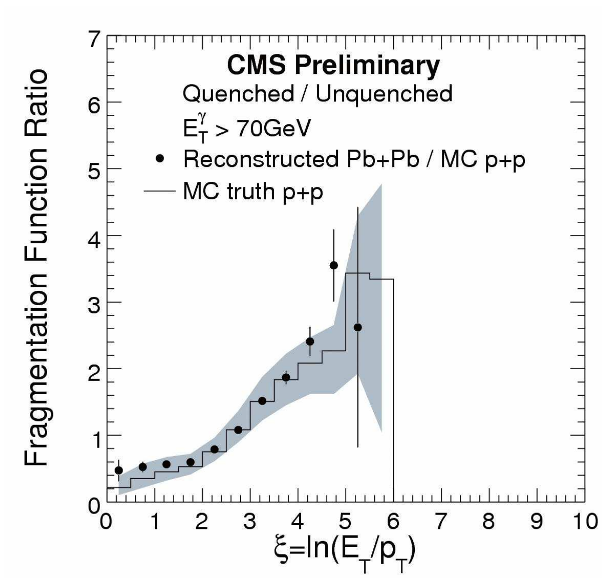

Figure 7: The ratio of the reconstructed quenched fragmentation function to the unquenched one (filled circles) is compared with the Monte-Carlo truth (solid histograms) for the integrated luminosity of 0.5 nb^{-1} (CMS).

5 Summary

The excellent capabilities of CMS detector give the unique possibility of measuring both soft and hard probes of the dense medium state, such as multiplicity, soft and hard spectra of charged particles, photons, jets, quarkonia and some other probes (ultra-peripheral collisions,dihadron and dijet correlations,HBT) that are not covered in the current paper.

Acknowledgments

The authors wish to express her gratitude to CMS colleagues for help in preparation of presentation of the CMS Heavy Ion program. The authors also gratefully acknowledges support from Russian Foundation for Basic Research (grant No 08-02-91001).

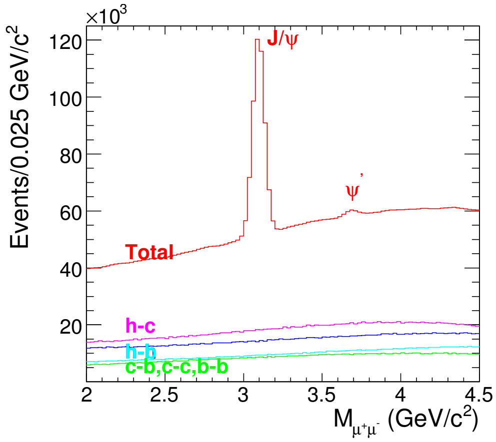

Figure 8: Invariant mass spectra of opposite–sign muon pairs in J/ψ mass range with $dN_{ch}/d\eta|_{\eta=0} = 2500$ with both muons in $|\eta| < 2.5$

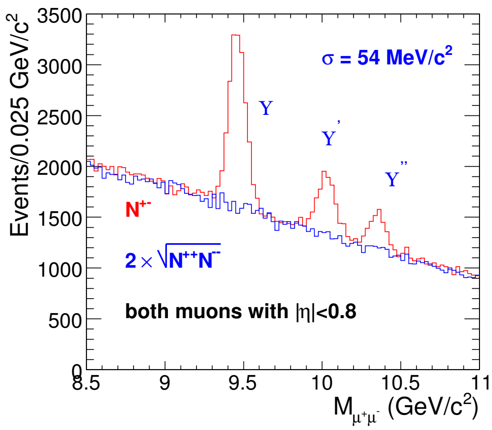

Figure 9: Invariant mass spectra of opposite–sign muon pairs in Υ mass range with $dN_{ch}/d\eta|_{\eta=0} = 2500$ with both muons in $|\eta| < 0.8$

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