The Compact Muon Solenoid Experiment
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Exploring high-density QCD matter with CMS detector at LHC

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Abstract

This paper presents the capabilities of the CMS to explore the high-density QCD by using various soft and hard probes. The soft sector includes the charged hadron multiplicity, the low- p_T inclusive hadron spectra, and the elliptic flow, which provide information on the collective properties of the matter. The hard sector includes the high- p_T charged hadron spectra, jets, γ -jet, and quarkonium production, which provide “tomographic” information of the matter at the highest density.

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1 Introduction

The motivation of ongoing relativistic heavy-ion collision experiments is to understand the bulk properties of high-energy density matter and the theory of the strong interaction, Quantum Chromo Dynamics (QCD). Although QCD is well formulated in the perturbative regime in vacuum, its properties at finite density and temperature are largely unknown at the moment. In addition, the quark confinement of hadrons, which is the most fundamental property of QCD, and the phase transition between the hadronic gas state and the deconfined quark-gluon plasma (QGP) state in high-density and temperature condition should be understood.

The experiments at the Relativistic Heavy Ion Collider (RHIC) facility at BNL have found several new phenomena, such as high- p_t hadron suppression (the so-called jet quenching effect) and the constituent quark number scaling of the elliptic flow and momentum spectra [1]. These results have attracted much attention as they could be important signatures for the QGP formation. But, if the existence of a deconfinement phase transition is to be solidified, a quantitatively consistent picture has to emerge from various physics observables in the hadronic and the leptonic sectors, which is a real difficulty we confront for the detailed understanding of new state of matter. However, we expect that such a problem can be solved soon largely by the experiments at the Large Hadron Collider (LHC) at CERN as its commissioning is planned within less than a year from now.

The LHC plans to accelerate Pb nuclei at $\sqrt{s_{NN}} = 5.5$ TeV, which is about 28 times larger than the highest RHIC energy. Because the beam energy is much higher, cross sections for various hard processes are expected to be significantly larger than those at the RHIC by several orders of magnitude (Fig. 1 left) [2]. Measuring various hard probes with high accuracy will enable us to determine the characteristics of high-density QCD matter, precisely. On the other hand, the unprecedented beam energy at the LHC also enable us to reach the parton momentum fraction, x , as low as 10^{-5} and the characteristic saturation momentum square, Q_s^2 , between 5 and 10 GeV², which is about 2 $\sim$ 3 times larger than at the RHIC (Fig. 1 right). In this paper, we summarize the capabilities of the Compact Muon Solenoid (CMS) detector to explore the characteristics of the high-density QCD matter for heavy-ion collisions at the LHC [3].

Figure 1: (Left) Expected cross sections for various hard processes in Pb+Pb minimum bias collisions as a function of beam energy [2]. The next-to-leading order (NLO) $p + p$ cross sections were scaled by the square of the mass number, A^2 . (Right) Kinematic range of partons in the square of the particle mass, M^2 , vs. the parton momentum fraction, x , in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. For the comparison, the kinematic ranges for the highest RHIC and SPS energies are also displayed.

2 The CMS detector

The CMS, which is one of three major detector systems at LHC, is optimized for tracking charged particles ($|\eta| < 2.4$), measuring energy flow ($|\eta| < 3$ for electromagnetic and $|\eta| < 5$ for hadronic calorimeters), and muon detection ($|\eta| < 2.4$), covering full azimuth (Fig. 2). Moreover, the CMS has a unique feature to cover very forward region with the CASTOR ($5.1 < |\eta| < 6.6$) and the ZDC ($|\eta| > 8.3$ only for neutrals) calorimeters. The resolution and granularity of all CMS subsystems were designed to cope with extremely high luminosity in $p + p$ collisions ($\sim 10^{34}/\text{cm}^2/\text{s}$) at 14 TeV with a bunch crossing frequency of 40 MHz. Since it implies that the CMS can handle 25 $p + p$ collisions simultaneously per bunch crossing, it can also perfectly deal with the large particle multiplicity for central Pb+Pb collisions at 5.5 TeV at much lower luminosity ($\sim 4 \times 10^{26}/\text{cm}^2/\text{s}$).

Figure 2: Acceptance of the CMS detector for tracking (Pixels+Tracker), calorimetry (ECAL, HCAL, CASTOR, and ZDC), and muon detection (Muons) in the plane of azimuth (ϕ) and pseudo-rapidity (η). The size of a jet, corresponding to the cone radius $R = 0.5$, is also depicted for comparison.

In order to fully exploit the detector capabilities for rare hard probes at the LHC, the CMS has developed the specific high-level-trigger (HLT) system for heavy-ion collisions. Especially, the computing power with few tens of Tflops is large enough to run offline algorithms on every single Pb+Pb event without filtering at the first level. In this way, we can select interesting rare events while reducing the data stream from an average 3 kHz input rate to 10 (for central) $\sim$ 100 (for peripheral events) Hz output rate. This results in significant enhancements of various rare hard probes by a factor of 20 $\sim$ 300, compared to the minimum bias (MB) condition, as we will see in Sec. 4.

3 Soft probes

3.1 Charged hadron multiplicity

The charged hadron multiplicity as a function of pseudo-rapidity, $dN_{ch}/d\eta$, is an important measurement because it reflects the initial entropy density of the matter. For example, the idea of Color Glass Condensate (CGC), which is one of the shadowing models at the low- x region, predicts a significant reduction of the number of produced hadrons already at the RHIC due to the reduced initial number of scattering centers in the parton distribution functions (PDFs). Such a low- x QCD effect should be further enhanced at LHC energy.

The Si-pixel detector of the CMS with high granularity (total 66 M channels) is ideal for the measurement of the $dN_{ch}/d\eta$ distribution, as the occupancy of the innermost layer is merely 2 %. The left side of Fig. 3 shows the comparison of the generated and reconstructed primary hadrons in central Pb+Pb collisions. By using the hit counting method, previously employed by the PHOBOS collaboration at the RHIC [4], we expect to measure the $dN_{ch}/d\eta$ distribution with less than 10 % systematic uncertainty.

3.2 Low- p_T hadron spectra

Measurement of the copiously produced hadrons, such as pions, kaons, and protons, at low p_T provides the “bulk” properties of the matter, which include the equation-of-state (EoS), the freeze-out condition, and the expansion dynamics. The CMS has developed a special low- p_T tracking algorithm by using highly segmented Si-pixel layers, and demonstrated that the detector is suitable for reconstructing the hadron spectra at very low p_T down to 100 MeV/c. Furthermore, the particle identification is also possible by correlating the energy loss, dE/dx , and the momentum, p , in Si-pixels and strips. The inclusive hadron spectra can be measured up to $p \sim 1$ GeV/c for pions and kaons, and up to ~ 2 GeV/c for protons (Fig. 3 right).

3.3 Elliptic flow

The elliptic flow parameter, v_2 , is defined as the second harmonic coefficient of the fitted Fourier series function for the azimuthal distribution of the hadrons with respect to the reaction plane. One of the surprising results in Au+Au collisions at the RHIC is the strong azimuthal anisotropy observed in mid-central collisions. The comparison of the experimental data on v_2 with the hydrodynamic model calculations has revealed that the produced matter

Figure 3: (Left) Pseudo-rapidity distributions of the primary tracks (filled dots), simulated with the HIJING event generator, and the reconstructed hits (crosses) with the Si-pixel detectors. (Right) Low- p_T spectra of the generated hadrons (dotted lines), simulated with the HYDJET event generator, and the reconstructed hadrons (solid lines). All simulations were obtained for central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV.

Figure 4: (Left) Reaction-plane resolution as a function of impact parameter, simulated by the HYDJET event generator. The solid (dotted) histogram corresponds to a total multiplicity of 58000 (84000) for $b = 0$ fm. (Right) Extracted elliptic flow parameter, v_2 , as a function of p_T , estimated by the event-plane method for $b = 9$ fm. The open circles represent the simulated data with the HYDJET event generator, and the closed squares represent the reconstructed ones. Non-flow systematic uncertainties are not included. All simulations were obtained for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV.

behaves like a “perfect” fluid with the viscosity close to the conjectured low limit by AdS/CFT [5]. As a result, the measurement of v_2 in differential form will be primarily important to learn the collective properties, such as the viscosity, of the fluid-like matter and the equation-of-state.

The CMS detector is ideal to study the elliptic flow as the high granularity Si trackers and the large acceptance calorimeters can provide the orientation of the reaction plane precisely. As an example, the left side of Fig. 4 shows the expected resolution, $\sigma(\Psi_0)$, of the reaction plane’s azimuthal angle distribution as a function of impact parameter, b , for two different assumptions on the total particle multiplicity. The differential v_2 parameter obtained by the event-plane method, $v_2\{EP\}$, for $b = 9$ fm is displayed in the right side of Fig. 4.

4 Hard probes

4.1 High- p_T hadron spectra and the jet production

Another major discovery at the RHIC is the hadron suppression at relatively high p_T , the so-called jet quenching effect. The p_T dependence of the nuclear modification factor, R_{AA} , which is defined by the ratio of the particle yield in heavy-ion collisions to the binary-collision-scaled yield in $p + p$ collisions, shows that the amount of suppression is as high as a factor of 5 for the most central Au+Au collisions. Since this suppression is absent in $d+Au$ collisions, we presently understand that the high- p_T hadron suppression is due to the final state effect caused

Figure 5: (Left) Invariant p_T spectra for charged hadrons expected with the CMS HLT at various Pb+Pb centralities. (Right) Nuclear modification factor for high- p_T hadrons. For the simulation data at the LHC, the filled circles represent the results for the minimum bias condition, and the open circles represent those for HLT. For comparison, the R_{AA} data from the SPS and RHIC are also displayed. In addition, the theoretical calculations at the LHC are also given: the GLV [6] with $dN_g/dy = 2000 \sim 4000$ and the PQM [7] with $\langle \hat{q} \rangle = 30 \sim 80 \text{ GeV}^2/\text{fm}$. All simulations were obtained for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5 \text{ TeV}$.

by the produced dense matter: the energy loss of partons traversing the strongly interacting medium.

Thanks to the enhanced hard cross sections at LHC energy, the excellent performance of the tracker, and the high- p_T triggering capability, the CMS can significantly extend the p_T reach of the charged hadron spectra from 20 GeV/c at the RHIC to $\sim 300 \text{ GeV/c}$ (Fig. 5 left). The expected p_T dependence of the R_{AA} parameter from the CMS is shown in the right side of Fig. 5, where the filled circles are for the minimum bias condition and the open circles are for HLT. Comparing the measured R_{AA} values with various model calculations, e.g. GLV [6] and PQM [7], up to several hundred GeV/c, we can obtain the initial gluon density, dN_g/dy , and the transport coefficient, $\langle \hat{q} \rangle$, characterizing the dissipative properties of the medium.

The CMS can also investigate the jet quenching effect with the fully reconstructed jets, measured by its calorimeters with almost 4π coverage. It has been demonstrated that the CMS can reconstruct jets in a messy environment, generated by Pb+Pb collisions, after the subtraction of the underlying soft background on an event-by-event basis. The distinction of jets above the background begins at $E_T \sim 30 \text{ GeV}$ and the full reconstruction is possible for $E_T > 75 \text{ GeV}$ with good efficiency and purity ($\sim 100 \%$ for both) and a good energy resolution ($< 15 \%$).

4.2 Photon-tagged jet

The energy loss mechanism of fast partons in the strongly interacting medium can be studied further by analyzing the γ -jet (and the Z -jet that will not be discussed in this paper) events and extracting the parton fragmentation function (FF), which, in turn, is related to the theoretical coefficient $\langle \hat{q} \rangle$. The advantage of utilizing the γ -jet channel is that we can infer the initial parton energy (before any quenching effect has been introduced by the medium) from the transverse energy of γ ($E_T^{\text{jet}} \approx E_T^\gamma$), since the prompt γ is not influenced by the final-state interactions.

The full γ -jet simulation study has shown that the FF can be measured within 10 % by constraining the away-side jet axis by $\Delta\phi_{\gamma\text{-jet}} < 3 \text{ rad}$ in addition to the low- E_T cuts on γ and jet as well as the special isolation cuts on γ [8]. The left side of Fig. 6 shows the simulated FF for γ -jet events as a function of $\xi = \ln(E_T^\gamma/p_T)$ for all hadrons with p_T associated with the jet. The right side of Fig. 6 shows the ratio of the reconstructed quenched FF to the unquenched one, which allows us to investigate any modification of the fragmentation function by the medium. The major systematic uncertainty for the FF measurement, especially, for the quenched scenario, would come from the low jet reconstruction efficiency for low E_T^{jet} as the jets fragmenting into single high- p_T particles are more likely to be reconstructed.

4.3 Quarkonium production

The quarkonium production is crucial to understand the nature of the phase transition between the hadron gas and the partonic QGP. The lattice QCD calculations predict the step-wise suppression of the J/ψ and Υ families

Figure 6: (Left) Jet fragmentation function (filled circles) extracted by the γ -jet correlation, after the underlying event has been properly subtracted, in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV [8]. The reconstructed FF is compared with the Monte-Carlo truth signal (solid histogram). The quenched jets and underlying events were generated by PYQUEN and HYDJET, respectively. (Right) Ratio of the quenched FF for Pb+Pb collisions to the unquenched one for $p + p$ collisions [8]. The reconstructed ratio (filled circles) is compared with the Monte-Carlo truth (solid histogram). The bands represent the predicted statistical errors for the integrated luminosity of 0.5 nb^{-1} .

Figure 7: Invariant mass spectra of opposite sign muon pairs with $dN_{ch}/d\eta|_{\eta=0} = 2500$ in $|\eta| < 0.8$ near the J/ψ (left) and the Υ (right) regions. The like-sign muon pair distributions are also shown for the background estimation. All simulations were obtained for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV.

because of the different melting temperature for each $Q\bar{Q}$ state [9]. At the LHC, for the first time, Υ s, which are expected to survive up to 4 times the critical QCD temperature, will be accessible with large statistics.

The CMS detector has been primarily optimized for muon detection, as represented by its name. Therefore, we can reconstruct various $c\bar{c}$ and $b\bar{b}$ states via their $\mu^+\mu^-$ -decay channel with the best mass resolution at the LHC. For example, Fig. 7 shows the reconstructed invariant mass distributions of opposite sign muon pairs near the J/ψ (left) and Υ (right) mass regions in the barrel detector acceptance ($|\eta| < 0.8$). The mass resolution of Υ 's is about 54 MeV/c², and it worsens to about 90 MeV/c² if we include the endcap detectors for $|\eta| < 2.4$. In addition, the simulation study has shown that the efficiency for the muon pair detection is $\sim 80\%$ and the purity is $\sim 90\%$ even for the most central Pb+Pb collisions in the barrel region. The Υ state can be measured down to $p_T \approx 0$ GeV/c with the reconstruction efficiency between 15 and 40 %, depending on the momentum.

5 Summary

In summary, the CMS detector is equipped with high-granularity high-resolution Si pixels and trackers, calorimeters, and muon detection systems, covering almost 4π . As a consequence, the CMS detector is an excellent system not only for $p + p$, but also for heavy-ion collisions. In particular, the CMS has a strong advantage measuring various hard probes due to the large acceptance and the dedicated HLT. We have shown that the CMS can perform the detailed studies of almost all physics topics in both soft and hard sectors in heavy-ion collisions.

References

- [1] For example, see Adcox D *et al.* [PHENIX Collaboration] 2005 *Nucl. Phys. A* **757** 184
- [2] d’Enterria D for the CMS Collaboration 2008 *J. Phys. G* **35** 104039; arXiv:0805.4769
- [3] d’Enterria D (ed.) *et al.* [CMS Collaboration] 2007 *J. Phys. G* **34** 2307
- [4] Back B B *et al.* [PHOBOS Collaboration] 2000 *Phys. Rev. Lett.* **85** 3100
- [5] Kovtun P, Son D T, and Starinets A O 2005 *Phys. Rev. Lett.* **94** 111601
- [6] Vitev I and Gyulassy M 2002 *Phys. Rev. Lett.* **89** 252301
- [7] Loizides C 2007 *Eur. Phys. J. C* **49** 339
- [8] Chen Y *et al.* 2008 CMS CR-2008/055
- [9] Karsch F, Kharzeev D, and H. Satz 2006 *Phys. Lett. B* **637** 75