The Compact Muon Solenoid Experiment
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Heavy ion physics for high density QCD with the CMS detector at the LHC

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Abstract

The main goal of the heavy ion physics programs at high energy colliders is to produce hot and dense partonic matter for studying quantum chromodynamics (QCD) under extreme conditions. The Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) can measure various soft and hard probes with high accuracy. We present various unique features of the CMS detector as they relate to the exploration of high density QCD in heavy ion collisions.

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1 Introduction

In the Standard Model, quantum chromodynamics (QCD) is well formulated in the perturbative regime in a vacuum, but its characteristics at finite density and temperature are largely unknown. In addition, quark confinement, which is the most fundamental property of QCD, and the phase transition between hadronic matter and the deconfined quark-gluon plasma (QGP) at high-density and/or temperature should be understood. The ongoing relativistic heavy ion collision experiments at hadron colliders are expected to provide the key to these questions.

Experiments at the relativistic heavy ion collider (RHIC) revealed several interesting phenomena such as jet quenching, constituent quark number scaling of the elliptic flow parameter (v_2), and the modified shape of a jet in a medium. All results indicate the formation of a new form of high-density QCD matter. However, a detailed characterization in a large kinematic domain has yet to be performed at the Large Hadron Collider (LHC).

In addition to the elementary $p+p$, the LHC also plans to run Pb+Pb at $\sqrt{s_{NN}} = 5.5$ TeV, which is about 28 times larger than the highest RHIC energy. Therefore, heavy ion collisions at the LHC are expected to produce unprecedented hot and dense QCD matter with a much longer lifetime. At LHC energy, the cross sections for hard processes will be larger than those at the RHIC by several orders of magnitude, which will enable us to precisely characterize high density QCD matter. Furthermore, the LHC can reach a parton momentum fraction, x , as low as 10^{-5} .

In this paper, we summarize the expected performance of the Compact Muon Solenoid (CMS) detector for Pb+Pb collisions at the LHC [1]. For the soft sector, we discuss the charged hadron multiplicity, the low- p_T inclusive hadron spectra, and the elliptic flow, which describe the collective properties of the matter. For the hard sector, we discuss the high p_T charged hadron spectra and jets, γ -jet correlation, and quarkonium production, which describe the tomography of the matter at the highest density.

2 COMPACT MUON SOLENOID DETECTOR

CMS is one of the major detectors at the LHC. The CMS detector was designed and built to cover large acceptance with high resolution [2]. The charged particles can be measured by Si-pixel and strip detectors for $|\eta| < 2.4$, and the energy flow can be measured by PbWO₄ ($|\eta| < 3$) and Cu-scintillator sampling calorimeters ($|\eta| < 5$). The muons are detected by the resistive plate chambers, the drift tubes, and the cathode strip chambers for $|\eta| < 2.4$. In particular, all CMS detector components cover the full azimuth. Moreover, for heavy ion collisions, CMS will use not only the previously mentioned standard detectors, but also a unique forward detector system composed of CASTOR ($5.1 < |\eta| < 6.6$) and ZDC ($|\eta| > 8.3$ only for neutrals) calorimeters.

The granularity and resolution of all CMS subsystems were designed to deal with $p+p$ collisions at extremely high luminosity ($\sim 10^{34}/\text{cm}^2/\text{s}$) at $\sqrt{s} = 14$ TeV with a bunch crossing frequency of 40 MHz. This implies that the CMS detector can handle 25 $p+p$ collisions simultaneously per bunch crossing, and that the detector can perfectly handle large particle multiplicity for central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV at a much lower luminosity ($\sim 4 \times 10^{26}/\text{cm}^2/\text{s}$).

3 Soft probes

The charged hadron multiplicity density, $dN_{ch}/d\eta$, is an important observable because it reflects the initial entropy density of the matter. For example, the color glass condensate model predicts a significantly reduced number of produced hadrons because of the reduced number of partons at low x . The Si pixel detector of CMS with high granularity (a total of 66 M channels) is ideal for this study, as the occupancy of the innermost layer is a mere 2%. Figure 1 shows a comparison of the generated and reconstructed primary hadrons in central Pb+Pb collisions. We expect about 10% systematic uncertainty for the $dN_{ch}/d\eta$ distribution.

On the other hand, hadron spectra at low p_T are useful in studying the bulk properties of the matter, which include the equation-of-state and expansion dynamics. CMS has devised a special low p_T tracking algorithm by using highly segmented Si pixel layers. CMS can reconstruct the pion, kaon, and proton spectra for $p_T \geq 200$ MeV/ c as in Fig. 2.

The CMS detector is also ideal for elliptic flow analysis because high granularity Si trackers and large acceptance calorimeters can precisely provide the orientation of the reaction plane. The reaction plane resolution is expected to be $\sim 20\%$ for semi-central collisions. We demonstrated that the differential v_2 parameter can be faithfully reproduced using the event plane method [1].

Figure 1: Pseudo-rapidity distributions of the primary tracks (filled dots) simulated with the HIJING event generator, and reconstructed hits (crosses) with Si pixel detectors.

Figure 2: Low p_T spectra of the generated hadrons (dotted lines) and reconstructed hadrons (solid lines).

Figure 3: (Left) Jet fragmentation function (filled circles) extracted by the γ -jet correlation. The solid histogram represents the Monte Carlo truth signal. (Right) Ratio of the quenched FF for Pb+Pb collisions to the unquenched FF for $p+p$ collisions. The bands represent predicted statistical errors for an integrated luminosity of 0.5 nb^{-1} .

4 Hard probes

Due to the large cross sections of hard processes and to high p_T triggering capability, CMS can significantly extend the p_T reach of the charged hadron spectra to $\sim 300 \text{ GeV}/c$. CMS can also reconstruct jets in the hostile environment generated by the central Pb+Pb collisions. Full reconstruction is possible for $E_T > 75 \text{ GeV}$ with high efficiency and purity ($\sim 100\%$ for both) and good energy resolution ($< 15\%$). The analysis of the nuclear modification factor, R_{AA} , using the high- p_T charged hadron spectra and jets will enable us to determine the initial gluon density and the transport coefficient, thereby characterizing the dissipative properties of the medium.

The energy loss mechanism of fast partons in the strongly interacting medium can be studied further using γ -jet events and extracting the parton fragmentation function (FF). The advantage of this approach is that we can infer the initial parton energy from the transverse energy of γ . A full γ -jet simulation study showed that the FF can be measured within 10% by constraining the away-side jet axis by $\Delta\phi_{\gamma-jet} < 3 \text{ rad}$ in addition to proper E_T cuts on the γ and jet, as well as special isolation cuts on γ [3]. Figure 3 shows the simulated FF for γ -jet events as a function of $\xi = \ln(E_T^\gamma/p_T^{\text{hadron}})$ and the ratio of the reconstructed quenched FF to the unquenched FF from $p+p$.

Quarkonium production is the crucial observable for understanding the nature of the phase transition to QGP. Lattice QCD predicts the sequential suppression of the J/ψ and Υ families due to the different melting temperature for each quarkonium state. At the LHC, Υ , which are expected to survive up to approximately four times the critical temperature, will be available with large statistics. The CMS detector is primarily optimized for the muon detection. We can reconstruct various $c\bar{c}$ and $b\bar{b}$ states via the $\mu^+\mu^-$ channel with the best mass resolution. Figure 4 shows the invariant mass spectrum of opposite sign muon pairs near J/ψ and Υ mass regions in the barrel

Figure 4: Invariant mass spectra of $\mu^+\mu^-$ pairs with $dN_{ch}/d\eta|_{\eta=0} = 2500$ in $|\eta| < 0.8$ near the (left) J/ψ and (right) Υ regions.

acceptance ($|\eta| < 0.8$). The mass resolution of Υ is about $54 \text{ MeV}/c^2$, and it increases to about $90 \text{ MeV}/c^2$ when we include the endcap acceptance for $|\eta| < 2.4$. In addition, the simulation has shown that the efficiency of muon pair detection is $\sim 80\%$ and the purity is $\sim 90\%$, even for the most central Pb+Pb collisions in the barrel region.

Finally, Υ can also be produced by ultraperipheral collisions at the LHC. About 500 Υ s in γ -Pb and γ - γ interactions are expected for an integrated luminosity of 0.5 nb^{-1} . We can explore the structure function for $x = 10^{-4} \sim 10^{-3}$ and $Q^2 \sim 100 \text{ GeV}^2/c^2$.

References

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