The Compact Muon Solenoid Experiment
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The heavy ion program of the CMS experiment

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Abstract

We present the capabilities of the CMS experiment to explore the heavy-ion physics program offered by the CERN Large Hadron Collider (LHC). Collisions of lead nuclei at energies up to $\sqrt{s_{NN}} = 5.5$ 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 parton momentum fraction. We give the overview of the potential of 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. In addition, reference measurements that have been performed on early p+p collision data will be reviewed.

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1 Introduction

The study of the strong interaction in extreme temperature and density conditions has been the driving force for experiments from the Bevalac to the the Large Hadron Collider. The RHIC experiments have produced the evidence that at the energy in c.m.s. $\sqrt{s} = 63\text{--}200$ GeV per nucleon pair 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 clear signals of this. At both SPS and RHIC energies the suppression of the J/ψ resonance suggests that a very high temperatures system was created [2, 3, 4]. In addition there is evidence that at small parton momentum fraction the initial state of the nuclei may be a sheet of gluons, the color glass condensate [5, 6].

The start of the heavy-ion program at the LHC with lead-lead collisions at the energy in c.m.s. $\sqrt{s} = 2.76$ TeV per nucleon pair is planned for the end of 2010. It seems that this is the last publication about the CMS heavy-ions program without the real data. In 2013–14 LHC plans to collide Pb nuclei at $\sqrt{s} = 5.5$ TeV which is 28 times higher than the highest energy available at the 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, $Q_s^2 \simeq 5\text{--}10$ GeV²/c² [7]. The collisions should produce the 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].

2 The CMS detector

The central feature of the CMS apparatus [9] is a 3.8 T 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 gas chambers embedded in the iron return yoke. CMS has extensive forward calorimetry, HF ($3 < |\eta| < 5.2$), CASTOR ($5.3 < \eta < 6.6$) and Zero Degree ($|\eta| > 8.3$) calorimeters.

Near mid-rapidity ($|\eta| < 2.4$) charged particles are tracked by three layers of silicon pixel detectors, made of 66 million 100×150 μm^2 pixels, followed by ten microstrip layers, with strips of pitch between 80 and 180 μm . The silicon tracker provides the vertex position with ~ 15 μm accuracy. The good momentum resolution of the tracker allows us to clearly resolve the Υ -family. The ECAL has an energy resolution of better than 0.5 %. The HCAL combined with the ECAL measures jets with jet energy 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 tracker results in a transverse momentum p_T resolution 1–5 % for up to 1 TeV/c.

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 energy loss dE/dx cut and 2) tracklets with a vertex constraint. Using the CMS detector we can accurately reconstruct particle pseudorapidity distribution $dN/d\eta$ using the hit counting technique.

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 on the pixels. This allows us to identify particles by comparing dE/dx and the momentum of track. Inclusive hadron spectra can be measured from $p \simeq 100$ MeV/c up to $p \simeq 1$ GeV/c for pions and kaons and up to $p \simeq 2$ GeV/c for protons.

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 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. There is a number of predictions for elliptic flow in heavy-ion collisions at the LHC energy [10, 11, 12]; compared with

the RHIC energies the decrease, increase or saturation will be possible. CMS will measure v_2 using both tracker and calorimeters [13]. The differential p_T and η dependencies of the elliptic flow calculated using method with event plane angle determination in Pb-Pb collisions for impact parameter $b = 9$ fm are shown in Fig. 1 and Fig. 2, respectively. HYDJET event generator [14] was used with full GEANT simulation of the CMS detector responses.

Figure 1: The p_T dependence of v_2 in Pb-Pb collisions for impact parameter $b = 9$ fm, calculated with the simulated (open circles) and reconstructed events (closed squares).

Figure 2: The η dependence of v_2 in Pb-Pb collisions for impact parameter $b = 9$ fm, calculated with the simulated (open circles) and reconstructed events (closed squares).

4 Hard (“tomographic”) probes of dense QCD matter

Hard probes, i.e. objects 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 pp 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/c, see Fig. 3. Using the HLT we can double our p_T reach, see Fig. 4.

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. Photon-jet events are a convenient way to study jet fragmentation since the photon does not loose energy as it propagates through the partonic medium. 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.

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 the LHC the Υ family will be available with large statistics for the first time. Unlike the J/ψ family the botomonium one will be less affected by the recombination process. Our simulated dimuon spectra for the J/ψ and Υ families are shown in Figs. 5 and 6. The mass resolution for Υ is about 54 MeV/ c^2 in the tracker barrel ($|\eta| < 0.8$) and it worsens to 90 MeV/ c^2 if the endcap ($0.8 < |\eta| < 2.4$) tracker detectors are included. For the J/ψ , our mass resolution is 35 MeV/ c^2 for CMS in full η range. Around 20, 000 Υ 's and 200,000 J/ψ 's 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, elliptic flow, 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, ultra-peripheral collisions etc.

Figure 3: Charged particle $R_{AA}(p_T)$ for an integrated luminosity of 0.5 nb^{-1} using the minbias sample.

Figure 4: Same as Fig. 3 but for data triggered on high- p_T jets.

Figure 5: 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 6: Invariant mass spectra of $\mu^+\mu^-$ pairs in Υ mass range, $dN_{ch}/d\eta|_{\eta=0} = 2500$ and both muons have $|\eta| < 0.8$.

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.

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