The Compact Muon Solenoid Experiment

Conference Report

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First CMS results from PbPb collisions

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Abstract

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Abstract

We present the first results on PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the CMS experiment at the LHC. This is a huge energy jump of a factor of 14 over RHIC creating the hottest matter ever produced in a laboratory. 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 an overview of the measurements by CMS in PbPb collisions both in “soft” and “hard” regimes. The first results on the reconstruction of jets, Z and quarkonia are described. These signals are the probes of the hottest and densest phases of the reaction. Also, an overview of the bulk observables such as charged hadron multiplicity, low p_T inclusive hadron identified spectra and elliptic flow which provide information on the collective properties of the system is given.

Key words: CMS, PbPb collisions, dijet, Z boson, quarkonia

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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 $\sqrt{s_{NN}} = 200$ GeV a strongly interacting quark gluon liquid is produced [1]. The scaling of elliptic flow with quark number, and the suppression of the 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 temperature system was created [2,3]. 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 [4,5]. At the LHC, we expect the initial state to be dominated by saturated parton momentum distributions with the parton momentum fraction x as low as 10^{-5} and a characteristic saturation momentum, $Q^2 \simeq 5\text{-}10$ GeV²/c².

The proton-proton physics run at the LHC started in November 2009 at center of mass energies $\sqrt{s} = 0.9, 2.36$ and 7 TeV. The PbPb run started on 8th November 2010 at $\sqrt{s_{NN}}$

= 2.76 TeV. The run finished with an integrated luminosity $8.6 \mu\text{b}^{-1}$ delivered and $7.2 \mu\text{b}^{-1}$ certified by CMS. All the results presented here are not for the full luminosity. The CMS detector is well suited for hard probes such as jets, high- p_T hadrons, heavy-quarks, quarkonia and large yields of the non interacting perturbative probes (direct photons, dileptons, Z and $W^\pm$ bosons) [6]. An overview of the first measurement is given in this article. Also an overview of ongoing measurements on soft probes is given.

The second heavy-ion run is expected in November-December 2011 at the same or slightly higher energy but with an increase in luminosity. In 2013-14, the plan is to collide Pb nuclei at $\sqrt{s}_{NN} = 5.5$ TeV which is 28 times higher than the highest energy available at RHIC.

2. The CMS detector

A detailed description of the CMS detector can be found in Ref. [7] and is shown in Fig. 1. Its central feature is a superconducting solenoid of 6 meter internal diameter, providing a magnetic field of 3.8 Tesla. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas chambers embedded in the iron return yoke. In addition, CMS has extensive forward calorimetry.

The inner silicon tracker measures charged particle trajectories in the pseudorapidity range $|\eta| \leq 2.5$. It consists of 66 million pixels, followed by ten microstrip layers with strips of pitch between 80 and $180 \mu\text{m}$. This provides an impact parameter resolution of $15 \mu\text{m}$ and a transverse momentum (p_T) resolution of about 1.5 % for 100 GeV/c particles. The ECAL has an energy resolution of better than 0.5 %. The HCAL combined with the ECAL measures jets with very good jet energy resolution. 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 detected in the $|\eta| \leq 2.4$ range, with detection layers based on three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. A high- p_T muon originating from the interaction point produces track segments in typically three or four muon stations. Matching these segments to tracks measured in the inner tracker results in a p_T resolution between 1 to 2 %, for p_T values up to 100 GeV/c. The centrality of heavy-ion collisions is determined from the two steel/quartz-fiber Cerenkov calorimeters, Hadron Forward (HF), which cover the $2.9 \leq |\eta| \leq 5.2$ range. Centrality is defined as percentile of the HF energy distribution. The centrality classes used in Z and dijet analyses presented here after are 0–10 % most central, 10–30 % and 30–100 %, ordered from the highest to the lowest HF energy deposit.

3. Bulk measurement in PbPb 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 lend support to the color glass picture and it will be interesting to see if this model works at LHC energies. CMS can measure 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

Fig. 1. 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 their dE/dx with the momenta of their tracks. 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 second harmonic of 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 to a fully thermalized perfect fluid. There are a number of predictions for elliptic flow in heavy-ion collisions at the LHC energy [8]. Compared with the RHIC energies a decrease, an increase or a saturation will be possible. CMS measures particles using both tracker and calorimeters [9]. The differential p_T , η and centrality dependencies of the elliptic flow are being analyzed and will reveal the properties of hot matter.

Recently CMS observed long range near side correlation of hadrons pairs up to $\Delta\eta = 4$ at $\Delta\phi = 0$ in high-multiplicity pp events at 7 TeV [10]. This effect is known as the 'ridge effect' and it has been observed for the first time in pp collisions. It will be interesting to see the magnitude of this effect in PbPb collisions.

Fig. 2. Examples of unbalanced dijet events in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

4. Hard Probes of QCD matter

Hard probes, the objects with large transverse momentum and/or high mass are important 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 RHIC is the suppression of high p_T hadrons [1] compared to what would be expected in the corresponding number of binary pp collisions. This effect is known as jet quenching. Another method to measure the jet quenching at RHIC is through two particle correlations. An advantage of CMS is that full jet reconstruction is possible enabling the tomography of QCD matter. Also a new and cleaner probe becomes available; the leptonic decays of the Z boson [12] which will give interesting possibilities such as the measurement of Z-tagged jet production. At the LHC, the J/ψ and Υ family will be available with large statistics enabling a systematic study of suppression and recombination phenomena.

4.1. Dijet asymmetry in PbPb collisions

Using the CMS detector, jets were reconstructed using primarily the calorimeter information in a data sample corresponding to an integrated luminosity of $3.4 \mu b^{-1}$. For the jet analysis, events with a leading jet with $E_T \geq 120$ GeV and $|\eta| \leq 2$ were selected. Dijet events with a subleading jet of $E_T \geq 50$ GeV in the same pseudorapidity range were selected. Examples of unbalanced dijet events in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are shown in Fig. 2.

To characterize the dijet momentum balance (or imbalance) quantitatively, we use the asymmetry ratio:

$$A_J = \frac{E_{T,1} - E_{T,2}}{E_{T,1} + E_{T,2}}. \quad (1)$$

Fig. 3. Dijet asymmetry ratio, A_J , for leading jets of $E_{T,1} > 120$ GeV, subleading jets of $E_{T,2} > 50$ GeV and $\Delta\phi_{12} > 2\pi/3$ radians for 2.76 TeV PbPb collisions in several centrality classes: 30–100%, 10–30% and 0–10%. Data are shown as black circles while the histograms show PYTHIA events embedded into PbPb data. Error bars shown are statistical.

where the subscript 1 always refers to the leading jet, so that A_J is positive by construction. The use of A_J removes uncertainties due to possible constant shifts of the jet energy scale.

In Fig. 3, we show the dijet asymmetry ratio, A_J , for leading jets of $E_{T,1} > 120$ GeV, subleading jets of $E_{T,2} > 50$ GeV and $\Delta\phi_{12} > 2\pi/3$ radians for 2.76 TeV PbPb collisions in several centrality classes: 30–100%, 10–30% and 0–10%. Data are shown as black circles while the histograms show PYTHIA events embedded into PbPb data. Error bars shown are statistical. The figure shows that the dijet energy imbalance is well beyond that expected from unquenched pythia events embedded in real data.

In Fig. 4, we show the fraction of all events with a leading jet of $E_{T,1} > 120$ GeV for which a subleading jet with $A_J > 0.24$ and $\Delta\phi_{12} > 2\pi/3$ was found, as a function of N_{part} . The black solid circles are for the PbPb data, with vertical bars for statistical and brackets for the systematic uncertainties. The result for reconstructed PYTHIA dijet events (blue circle) is plotted at $N_{part}=2$. The other points (from left to right) correspond to centrality bins of 30–100%, 10–30% and 0–10%. The figure shows that the dijet energy imbalance increases with collision centrality.

As a function of centrality, dijet events with a subleading jet of $E_{T,2} \geq 50$ GeV and $|\eta| \leq 2$ were found to have an increasing momentum imbalance. Data were compared to PYTHIA dijet simulations for pp collisions at the same energy which were embedded into heavy ion events. The momentum imbalances observed in the data were significantly larger than those predicted by the simulations. While the relative imbalance between the leading and subleading jets increased with increasing collision centrality, it was found to be largely independent of the leading jet $E_{T,1}$, up to the largest values observed (200 GeV).

Fig. 4. Fraction of all events with a leading jet with $E_{T,1} > 120$ GeV for which a subleading jet with $A_J > 0.24$ and $\Delta\phi_{12} > 2\pi/3$ was found, as a function of N_{part} . The black solid circles are for the PbPb data, with vertical bars for statistical and brackets for the systematic uncertainties. The result for reconstructed PYTHIA dijet events (blue circle) is plotted at $N_{part}=2$. The other points (from left to right) correspond to centrality bins of 30–100%, 10–30% and 0–10%.

4.2. *Z* boson

The *Z* bosons decay within the medium with a life time of 0.1 fm/*c*. Their dilepton decays are of particular interest since leptons pass freely through the produced medium regardless of its nature (partonic or hadronic) and properties. Being insensitive to the strong interaction, high-mass dileptons can thus serve as a reference to other processes, such as quarkonia production, or the production of an opposite-side jet in *Z*+jet processes [13], which are expected to be heavily modified by the presence of the QGP. *Z* bosons are therefore uniquely able to serve as a standard candle of the initial state in PbPb collisions at the LHC energies.

The present analysis is conducted on a sample selected with a higher-level trigger which requires two reconstructed tracks in the muon detectors, each with a p_T of at least 3 GeV/*c*. Background muons from cosmic rays and heavy-quark semi-leptonic decays are rejected by requiring vertex constraints. Loose criteria on the reconstructed muons are applied such as the reduced $\chi^2 < 10$ for the global track fit.

The dimuon mass spectrum is shown in Fig. 5 which does not correspond to full luminosity analyzed at the time of the conference. A simple fit to the relativistic Breit-Wigner shape, with the width fixed to the world average value [14], and convolved with a Gaussian, yields the expected dimuon mass resolution, better than 2%, within the statistical precision.

Fig. 5. Dimuon invariant mass spectrum. Full squares are opposite-sign dimuons, while the circles show like-sign dimuon candidates. The curve is Breit-Wigner function convolved with a Gaussian fitted to the data.

Fig. 6. Dimuon mass spectra for J/ψ (left) and Υ (right). Full squares are opposite-sign dimuons, while the circles show like-sign dimuons. The curves are a Gaussian plus a 2nd order polynomial fitted to the data.

4.3. Quarkonia

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]. At the LHC the Υ family will be available with large statistics for the first time. Unlike the J/ψ family, the bottomonia will be less affected by the recombination process. Our first dimuon spectra for the J/ψ and Υ are shown in Fig. 6. These spectra are not for full luminosity. The data sample and the cuts used to get these spectra are the same as those used for Z analysis. The quarkonia mass resolutions for full CMS are similar to the expected ones.

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 reported some of the most important first measurements in PbPb collisions by the CMS experiment. Also 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, jets and quarkonia to study QCD at very high temperatures, high energy densities and also very low x are highlighted.

A strong increase in the fraction of highly unbalanced jets has been seen in central PbPb collisions compared with peripheral collisions and model calculations. The momentum imbalances observed in the data were significantly larger than those predicted by the simulations. The results provide qualitative constraints on the nature of the jet modification in PbPb collisions and on quantitative input to models of the transport properties of the medium created in these collisions.

The Z-boson yield has been measured for the first time in heavy-ion collisions. This measurement establishes the feasibility of carrying out detailed Z-physics studies in heavy-ion collisions with the CMS detector. With upcoming PbPb collisions at higher luminosity and energy, the Z boson promises to be a powerful reference tool for initial-state (nuclear PDFs) and final-state (Z+jet) processes in nucleus-nucleus collisions at the LHC.

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