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Heavy Ion Physics at the LHC with CMS

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Abstract

The CMS detector is an excellent tool for measuring high mass and low-x phenomena in heavy-ion collisions. Its exceptional acceptance and resolution combined with a fast and sophisticated trigger offer the potential for unexpected discoveries.

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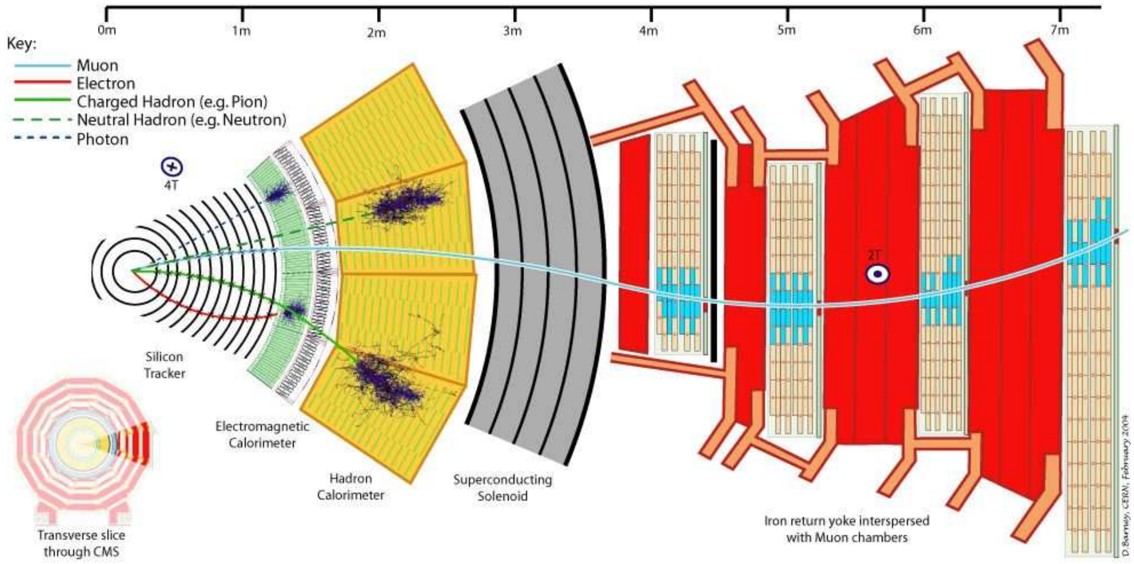

Figure 1: Schematic transverse slice of the detector with n, γ, e, μ^+ and π^+ tracks.

1 Introduction

At LHC it will be possible to explore strongly interacting matter at higher densities, higher temperatures and longer lifetimes than ever before. The cross sections of many hard probes, such as flavorless mesons with hidden charm and bottom (J/Ψ and Υ) as well as those with open flavor (D and B mesons), energetic photons, electroweak gauge bosons (W$^{\pm}$ and Z^{0}), and high-p_T jets are too small to be easily accessible experimentally at the $\sqrt{s_{\mathrm{NN}}} = 0.2$ TeV collision energy at RHIC. However, at the LHC Pb+Pb energy of 5.5 TeV [1] these cross sections will be orders of magnitude larger. Partons with high transverse momentum are predicted to suffer radiative and collisional energy loss in the plasma [2], suppressing the yield of jets found with high transverse energy in a heavy-ion collision compared to a p+p collision. The measured quarkonia yields depend on the properties of the high energy density partonic matter created in the collision. The abundance and variety of these hard probes at the LHC makes the study of partonic energy loss possible. The increase of collision energy also extends the kinematical region studied to low Bjorken-x at small scattering angles, even at $y = 0$. At $y = 6$ CMS can sample 400 times smaller x values than RHIC. The initial gluon density (and also the measured hadron abundances) will be governed by saturation effects in this low-x region, described in the framework of the Color Glass Condensate [3], a new region to be explored in the QCD phase diagram.

Analysis of the simulated data show that the CMS detector is a powerful tool for studying the following aspects of heavy-ion physics: charged particle multiplicity (event-by-event); azimuthal asymmetry of particle production [4]; quarkonia and heavy quark production [5]; jets and individual particles at high p_T; jet fragmentation and jet shapes; correlations between jets and other jets, photons, and Z^{0} bosons [6]; neutral and charged energy fluctuations to search for Centauro, DCC and strangelet states [7]; ultraperipheral collisions [4] and comparisons between p+p, p+A and A+A collisions.

2 The CMS detector

The CMS detector system was designed primarily to study new physics in p+p interactions at collision rates of about 1 GHz (corresponding to 10^{34} cm^{-2}s^{-1} luminosity). The main components of CMS [8] are the tracking system, made of silicon pixel and strip layers; finely segmented electromagnetic and hadronic calorimeters; a large solenoid magnet with a 4T field; and, outside the magnet coil, muon detectors and absorbers serving also as a magnet yoke, as shown in Figure 1. The readout of all the systems is fast enough to allow not only lower level decisions to be made, but detailed analysis of each Pb+Pb event by the high level trigger computer farm at the maximum expected Pb+Pb collision rate of about 8 kHz. The CMS detector features a unique, large geometrical acceptance of tracking and calorimetry in pseudorapidity, η, and full 2π coverage in azimuthal angle.

The CMS tracker is a cylinder of 5.5 m length and 1.1 m radius with endcaps, featuring three silicon pixel detector layers in the center ($R \leq 10$ cm) with less than 15 μm spatial resolution and (in the barrel region) 10 silicon strip layers surrounding the pixels with 10-60 μm resolution in $R\phi$. The electromagnetic calorimeter is assembled from lead-tungstate crystals. The barrel covers $|\eta| < 1.48$ and the endcaps extend to $|\eta| < 3$. The granularity of the barrel is uniform in the $\eta - \phi$ plane, corresponding to a segmentation of 1×1 degrees at $\eta \approx 0$. The hadronic calorimeter is made of brass-scintillator sandwiches, arranged in a barrel and two endcap segments. The $\theta \times \phi$ granularity (at $\eta \approx 0$) is 5×5 degrees. The forward calorimeters, made of iron and quartz fibers, cover $3 < |\eta| < 5$. Muons are identified by the muon system covering the $|\eta| < 2.4$ region, while their momentum is measured by the Si tracker.

3 Heavy-ion collisions with the CMS detector

Although designed for p+p collisions, various capabilities of CMS makes it a very powerful *heavy-ion* detector system. The high readout rate allows inspection of all minimum bias Pb+Pb events by the high level trigger farm. The 4T magnetic field in a large volume and the high granularity of the silicon tracker results in excellent momentum resolution, $\Delta p_T/p_T < 1.5\%$ (for $p_T < 100$ GeV/c). The resolution of the track impact parameter at the event vertex is less than 50 μm, and improves to 20 μm at high p_T (above 10 GeV/c). The CMS heavy-ion group is building two Zero Degree Calorimeters for event characterization and ultra-peripheral measurements [9]. In addition, the group has proposed building the CASTOR calorimeter to cover the $5 < |\eta| < 7$ region. The performance of the CMS detector was extensively studied in simulations of Pb+Pb events with reasonable assumptions of the charged multiplicity, azimuthal anisotropy, jet, muon and hadron spectra [10].

Besides the momentum and impact parameter resolution, the algorithmic *tracking* efficiency in the high-multiplicity heavy-ion environment is about 80% with less than a few percent fake track rate for $p_T > 1$ GeV/c, assuming a charged particle density of about $dN/dy = 3000$. Even at these high multiplicities, the pixel layers operate at less than a few percent occupancy. That also makes it possible to evaluate the charged particle pseudorapidity distribution $dN_{\mathrm{ch}}/d\eta$ in the $|\eta| < 2.5$ range using the single innermost silicon pixel layer, even in one central Pb+Pb event.

The *quarkonium states* are reconstructed from decays to muon pairs. The muons are efficiently detected and identified in the muon system above $p_T > 3.5$ GeV/c. Muon background sources from K, π and heavy quark decays are included. After one month Pb+Pb run, the estimated number of reconstructed J/Ψ, Υ and Υ' states is in the 10^4 range, allowing measurements as a function of rapidity and p_T. With the excellent momentum resolution of the CMS tracker, an overall Υ mass resolution of 90 MeV/c^2 can be achieved in Pb+Pb collisions in the full muon detector acceptance, separating the members of the Υ family, as shown on the left panel of Figure 2.

The high granularity and good resolution of the CMS calorimeters help to isolate individual *jets* over the background of the heavy-ion collision. Charged particles with $p_T < 0.8$ GeV/c will not reach the calorimeters in the 4T axial magnetic field. Early results from RHIC showed the importance of jet measurements for hadron yield suppression at $p_T > 3$ GeV/c and the disappearance of back-to-back correlations of high-p_T particles. These results suggest significant in-medium energy loss of fast partons, absent in d+Au collisions. Due to the much larger jet production cross section, this energy loss will be accessible experimentally by observing fully formed jets. At the LHC collision energy, about five million dijets with $E_T > 100$ GeV are expected to hit the calorimeter barrel over a one month Pb+Pb run [6]. Jets are reconstructed using an iterative cone algorithm modified to subtract the underlying soft background. The jet-finding efficiency and purity is shown in the right panel of Figure 2. The lower limit of transverse energy needed for efficient and clean reconstruction is about 50 GeV. The energy resolution for jets with 100 GeV transverse energy at $\eta \approx 0$ is about 16%. With the CMS tracker, the longitudinal and transverse momentum distributions of the charged component of the jets identified in the calorimeter can be studied with high precision. These distributions are expected to be influenced by the produced medium. Thus, comparisons to p+p collisions and the centrality dependence of jet structure measurements are highly important for the CMS heavy-ion program. The ability to study the balance between jets and γ or Z^0 bosons emitted back-to-back is especially exciting, since the bosons are not affected by the strongly interacting environment.

4 Summary

The CMS detector studies the hot and dense medium created in heavy-ion collisions by measuring quarkonium production, jet energy loss and structure, charged particle spectra, charged particle multiplicity event-by-event and particle flow. These studies are possible due to the high resolution and highly segmented tracker and large acceptance calorimetry, making the CMS detector a unique and powerful tool to study heavy-ion collisions at the LHC.

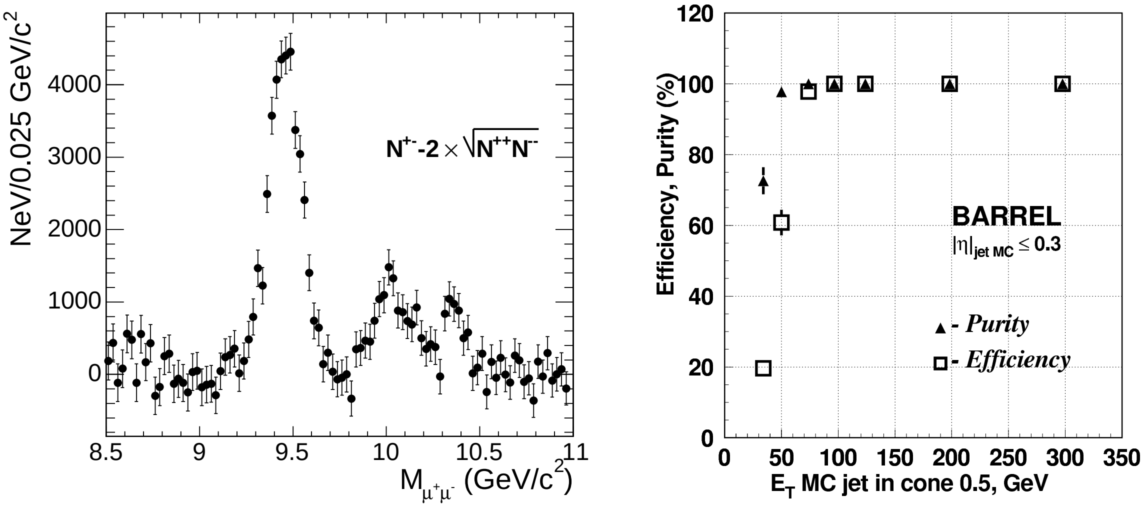

Figure 2: Unlike sign muon invariant mass spectra for the Υ family (left panel), and jet reconstruction efficiency and purity in the calorimeters as a function of transverse energy in Pb+Pb collisions (right panel).

5 Acknowledgments

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