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Hard Probe Capabilities of CMS in Heavy Ion Collisions at the LHC

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Abstract

Heavy ion collisions at the Large Hadron Collider (LHC) will produce strongly interacting matter at unprecedented energy densities. At LHC collision energies, new hard probes of the dense initial collision system will become readily available. We present an overview of the capabilities of the Compact Muon Solenoid (CMS) detector to use these probes for a detailed study of QCD phenomenology at the highest energy densities.

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1 Overview

Data collected by the four experiments at the Relativistic Heavy Ion Collider (RHIC) suggest that in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV an equilibrated partonic system is formed. There is strong evidence that this dense medium is highly interactive, perhaps best described as a quark-gluon liquid, and is almost opaque to fast partons. In addition, many surprisingly simple empirical relationships describing the global characteristics of particle production have been found [1]. The LHC will collide Pb ions at $\sqrt{s_{NN}} = 5.5$ TeV, the biggest step in collision energy in the history of our field. Measurements at this energy will either confirm and extend the theoretical picture emerging from RHIC or challenge and redirect our understanding of strongly interacting matter at extreme densities. Progress at the LHC will not only come from the increased initial energy density, but also through a greatly expanded mass and p_T range of hard probes, such as high p_T jets and photons, Z^0 bosons, the Υ states, D and B mesons, and high-mass dileptons. Below we describe the characteristics of the Compact Muon Solenoid (CMS) detector that will allow us to exploit the new opportunities presented by the LHC.

2 CMS as a detector for heavy ion physics

The discoveries at RHIC have not only transformed our picture of nuclear matter at extreme densities, but have also shifted the emphasis in the observables best suited for extracting the properties of the initial high-density QCD system [1]. Examples of these observables include elliptic flow, very high p_T jets and heavy quarkonia. The importance of hard probes implies the need for detectors with large acceptance, high rate capability and high resolution, leading to a convergence of experimental techniques between heavy ion and particle physics. Using CMS for heavy ion collisions takes this development to its logical conclusion, leveraging the extensive resources that have already gone into the development and construction of the apparatus. Below we discuss the extent to which CMS fulfills the criteria for an ideal heavy ion detector.

CMS was designed to provide tracking and calorimetry with high resolution and granularity over the full azimuthal angle as well as over a very large rapidity range. It is capable of precise detection of muons, electrons, photons, jets, and heavy flavor tagging via secondary vertices. The detector is symmetric about both the beam axis and the center of the nominal interaction region. The overall layout of the apparatus is illustrated in Fig. 1. A detailed description is provided in the Technical Design Reports [2]. Four of the requirements for a heavy ion detector at LHC for which CMS excels are discussed below.

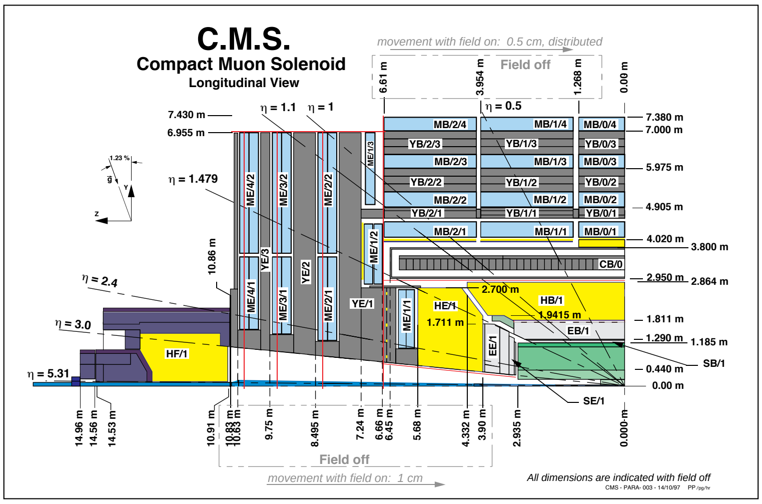

Figure 1: A vertical slice through one quadrant of the CMS detector. The other three quadrants are identical and symmetric about the center of the interaction region and about the beam axis.

High rate: The CMS DAQ and trigger system (see Fig. 2) is designed to deal with p+p collisions at luminosities of up to 10^{34} cm^{-2}s^{-1}, corresponding to p+p event rates of 40 MHz. As a result, the fast detector technologies chosen for tracking (Si-pixels and strips), electromagnetic and hadronic calorimetry, and muon identification means that, for Pb+Pb collisions, CMS can be read out with a minimum bias trigger at the full expected luminosity. This fast readout allows detailed inspection of every event in the High Level Trigger (HLT) farm. The HLT CPU resources are sufficient to run complex analysis algorithms on each event, making a complete selection and archiving of events containing rare probes, such as extremely high p_T jets or high mass dileptons, possible.

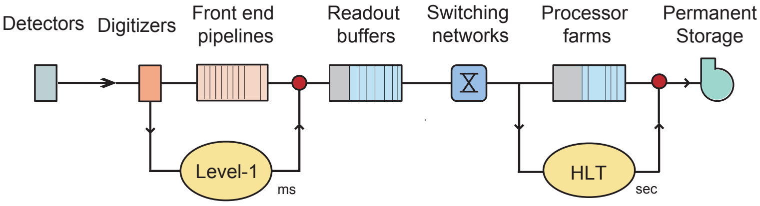

Figure 2: Schematic of the data flow through the CMS DAQ system.

High resolution and granularity: At the full p+p luminosity there will be, on average, 20 collisions per bunch crossing. To disentangle very high momentum observables with $p_T > 500$ GeV/c in this environment, the resolution and granularity of all detector components has been pushed to the extreme, consequently making the detector well suited to the high multiplicity conditions in central heavy ion collisions. The high granularity of the Si-pixel layers, in combination with the 4 T magnetic field, results in the world's best momentum resolutioni for charged particle tracks, $\Delta p_T/p_T < 1.5\%$ up to $p_T \approx 100$ GeV/c. At the same time, a track-pointing resolution of better than 50 μm (less than 20 μm for $p_T > 10$ GeV/c) is achieved. For $dN_{\rm ch}/dy \approx 3000$ in Pb+Pb collisions, tracks can be reconstructed with an efficiency of $\sim 80\%$ with a low rate of of fake tracks. The momentum and track-pointing resolution achieved in heavy ion collisions (see Fig. 3) are comparable to those in the low occupancy p+p events.

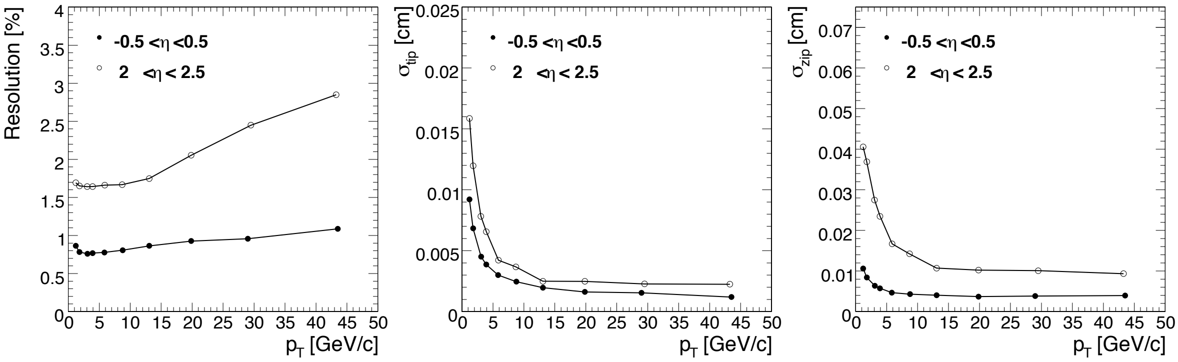

Figure 3: The p_T dependence of the track parameter resolution achieved in heavy ion events in the barrel region (full symbols) and in the forward region (open symbols). (Left) Transverse momentum resolution. (Center) Transverse track-pointing resolution. (Right) Longitudinal track-pointing resolution.

Large acceptance tracking and calorimetry: CMS includes high resolution tracking and calorimetry over 2π in azimuth and a uniquely large range in rapidity. The acceptance of the tracking detectors, calorimeters and muon chambers can be seen in Fig. 4. The Zero Degree Calorimeters ($|\eta_{\rm neutral}| > 8.0$) and the CASTOR detector ($5.2 < |\eta| < 6.6$) will allow measurements of low-x phenomena and particle and energy flow at very forward rapidities.

The CMS calorimeters allow jet reconstruction in heavy ion collisions over full azimuth and a large rapidity range. We employ a modified iterative cone-type jet finder that includes an event-by-event subtraction of background energy. This fast method, based on calorimeter information, is available at the trigger level and already provides excellent reconstruction efficiency and purity, as shown in the left panel of Fig. 5. The energy resolution for 100 GeV jets is $\approx 16\%$ (see right panel of Fig. 5) and the jet location resolutions in η and ϕ are 0.028 and 0.032, respectively.

Particle identification: At the LHC, identification of particles with open and hidden heavy flavors will be of primary importance. The large acceptance, high-resolution muon system, in combination with secondary decay tagging by the silicon tracker, probes the interaction of identified heavy quarks with the medium.

CMS allows dimuon reconstruction with an acceptance spanning 4.8 units in pseudorapidity, the largest of any heavy ion detector. In the central barrel, the dimuon reconstruction efficiency is above $\sim 80\%$ for all multiplicities, while the purity decreases slightly with $dN_{\rm ch}/d\eta$ but stays above 80% even at multiplicities as high as $dN_{\rm ch}/d\eta|_{\eta=0}$ = 6500.

Figure 6 shows the mass resolution of the reconstructed muon pairs from Υ decays obtained with full simulation

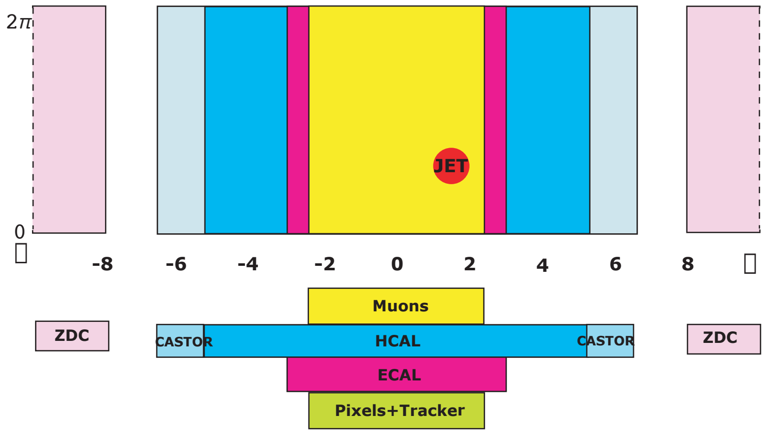

Figure 4: Acceptance of tracking, calorimetry, and muon identification in pseudorapidity and azimuth. The size of a jet with cone $R = 0.5$ is also depicted as an illustration.

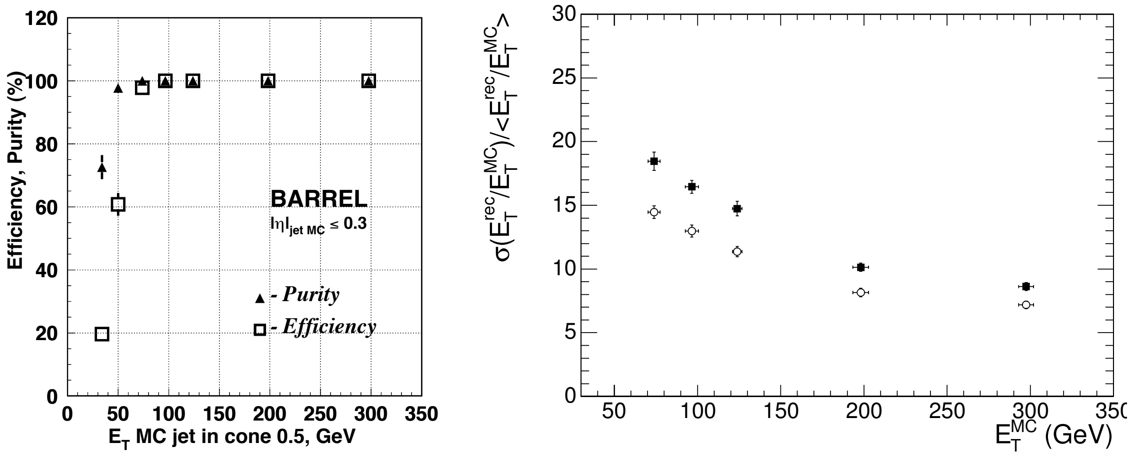

Figure 5: (Left) Jet reconstruction efficiency and purity using barrel calorimeters for PYTHIA-generated jets embedded in Pb+Pb events with $dN_{\rm ch}/dy = 5000$. (Right) The resolution of the jet E_T determination in p+p (open symbols) and Pb+Pb (closed symbols), also with $dN_{\rm ch}/dy = 5000$.

and reconstruction. The good muon momentum resolution translates to an Υ mass resolution in p+p of 53 MeV/c ^{2} in the barrel pseudorapidity region, the best of all LHC detectors, providing a clean separation between the members of the Υ family.

The physics of meson vs. baryon production at intermediate and large p_T can be studied using the results for reconstructed π^0s as well as the information provided by the silicon tracker, in combination with the electromagnetic and hadronic calorimeters. In the low transverse momentum regime, further studies will be performed to evaluate particle identification based on the specific ionization in the silicon detectors and the reconstruction of hadronic resonances using invariant mass analysis.

3 Learning about QCD from heavy ion collisions at LHC

Heavy ion collisions at the LHC will extend our knowledge about strongly interacting matter at the highest energy density in two ways. First, the energy densities of the thermalized matter are predicted to be 20 times higher than at RHIC, implying a doubling of the initial temperature [6]. The higher densities of the produced partons result in more rapid thermalization and a large increase in the time spent in the quark-gluon plasma phase [6]. In addition, the abundance of hard probes will allow more detailed quantitative measurements of the properties of the the initial hot and dense medium. Below we describe several of the physics measurements planned with CMS at the LHC.

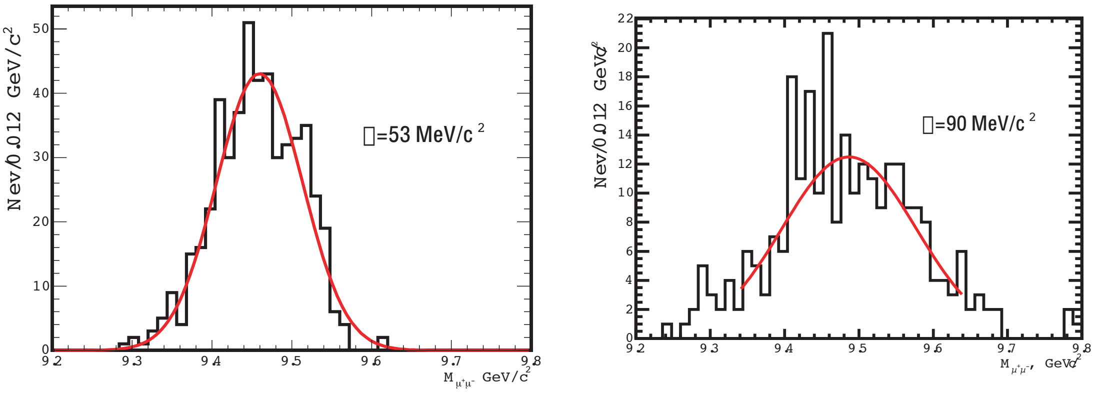

Figure 6: The reconstructed Υ mass. (Left) Without Pb+Pb background events and with both muons in $|\eta| < 0.8$ (barrel region only). (Right) In a Pb+Pb event with multiplicity $dN_{\rm ch}/d\eta|_{\eta=0}$=2500 and both muons in $|\eta| < 2.4$.

3.1 The Initial State and Global Observables

Measurements at RHIC suggest that the initial state described by the concept of parton saturation is directly reflected in the multiplicity of produced hadrons and their phase space distribution. These global features of multiparticle production, measured by PHOBOS and others, exhibit great simplicity such as factorization into separate dependencies on energy and geometry and limiting fragmentation over a large fraction of the rapidity range.

The large coverage of the CMS tracking detectors and the nearly full coverage of the CMS calorimeters allows the precise determination of $dN_{\rm ch}/d\eta$, transverse energy (both E_T and dE_T/dy), azimuthal anisotropy, and the energy of neutral spectators. This information will be used for event categorization in various analyses. These measurements will also be important for understanding the fundamental properties of particle production in high energy collisions, following the studies performed at RHIC.

3.2 Thermalization and Elliptic Flow

At RHIC, measurements of the elliptic flow of produced hadrons through their azimuthal distributions relative to the reaction plane have become the main experimental tool addressing the question of thermalization (or at least isotropization) in the early stage of the collision. Comparisons to hydrodynamic calculations suggest that, at the highest energies, approximate thermal equilibrium is achieved and the produced medium is characterized by a very small shear viscosity [8].

Measurements at the LHC will add crucial new information to the existing studies through the measurement of flow at significantly higher initial densities. The density dependence is particularly important since the elliptic flow data exhibit a steady rise in v_2 with particle density, continuing up to the highest RHIC energies.

CMS will be able to perform these measurements with high precision. The highly segmented, large acceptance calorimeters allow very accurate determination of the event plane in each event. Measurements sensitive to heavy quark flavors, e.g. based on single muons not originating from the main vertex, will be performed over a large rapidity range and out to higher p_T than accessible at RHIC. In addition, the full suite of observables such as charged hadrons, π^0s, and jets can be studied over a wide kinematic range as a function of both event plane and centrality.

3.3 Initial Temperature and Quarkonia Yields

Measurements of the charmonium (J/ψ, ψ') and $b\bar{b}$ (Υ, Υ', Υ'') resonances provide crucial information about the properties of high-temperature QCD matter. Sequential suppression of heavy quarkonia is thought to be one of the most direct probes of quark-gluon plasma formation. Lattice QCD calculations indicate that color screening dissolves the ground-state quarkonium states, J/ψ and Υ, at $T \approx 2T_{\rm c}$ and $4T_{\rm c}$, respectively. Studies of Υ and Υ' production as a function of p_T have been predicted to be sensitive to the temperature of the early dense medium, directly addressing one of the most important questions in our field [7]. The CMS detection capabilities for the Υ family in terms of acceptance, resolution, and statistical power make it uniquely poised to perform this measurement.

3.4 Transport Properties of the Medium

Studies of parton propagation through the matter formed in heavy ion collisions provide access to the transport properties of the dense medium, one of the key questions in heavy ion physics. Measurements of leading hadron production and correlations at RHIC have already pointed to strong collective effects governing high p_T phenomena. The new kinematic regime at LHC and the new probes available through precision vertexing and large coverage calorimetry will enable decisive studies of the medium properties.

Measurements of fully formed jets above the background of soft hadron production require transverse energies of $E_T > 50$ GeV/c, outside the range accessible at RHIC. Quark jets of known energy can be produced in reactions such as $gq \rightarrow q\gamma$ [9] or $gq \rightarrow qZ^0$ [10]. In these cases, the energy can be determined since the parton energy can be tagged by the electro-weak gauge bosons which is unaffected by the presence of the medium. The high granularity, large acceptance hadronic and electromagnetic calorimeters of the CMS detector are well suited for these measurements. The vertexing capabilities of the tracking system provide additional information on the energy loss of heavy quarks, which will help shed light on the underlying mechanism.

4 Summary

In summary, measurements of hard probes in heavy ion collisions at the LHC allow quantitative studies of the transport properties of the QCD medium. The much larger cross sections at the LHC will provide not only better statistics than at RHIC, but will also give access to qualitatively new observables, including fully formed jets of known energy and jets originating from identified partons. CMS is ideally suited for these studies using its large acceptance, high resolution calorimetry and high precision tracking. The dimuon detection capabilities of CMS allow precision studies of the initial medium via sequential quarkonium suppression. Qualitatively new measurements include spectra of charged hadrons to $p_T > 100$ GeV/c, jet E_T spectra to several 100 GeV, jet-jet correlations, tagged jets from heavy flavors and calibrated jets tagged via real or virtual photons or Z^0's.

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