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Heavy Ion Physics with the CMS Detector at the LHC

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The Large Hadron Collider at CERN will collide protons at $\sqrt{S} = 14$ TeV and lead ions at $\sqrt{S_{NN}} = 5.5$ TeV. The physics program of the Compact Muon Solenoid (CMS) includes the study of heavy ion collisions. The CMS detector consists of a 13 m long, 6 m wide superconducting solenoid providing a uniform 4 T magnetic field. Charged particles will be measured with a large acceptance, high resolution silicon tracker consisting of pixel and strip detector layers. The tracker is surrounded by electromagnetic and hadronic calorimeters located inside the magnet while the muon detector is positioned on the outside. The central detector will be complemented by CASTOR, a proposed forward calorimeter, and a Zero Degree Calorimeter (ZDC). The CMS data acquisition system, with its reliance on a multipurpose, high-level trigger system, is uniquely qualified for efficient triggering in high-multiplicity heavy ion events. The high energies available at the LHC will allow high statistics studies of the dense partonic system with hard probes: heavy quarks and quarkonia with an emphasis on the b and Υ; high p_T jets; photons and Z^0 bosons.

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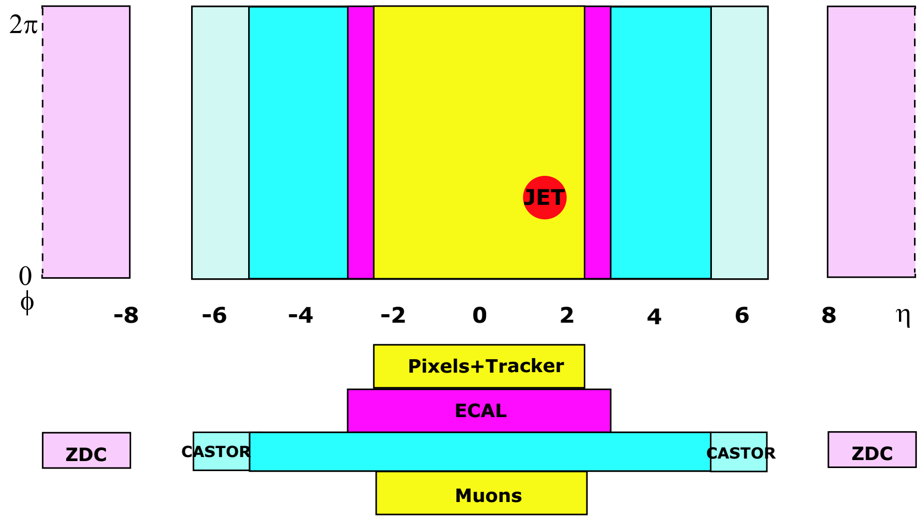

Figure 1: Acceptance of tracking, calorimeters and muon identification in pseudorapidity and azimuth. The size of a jet with cone radius $R = 0.5$ is also depicted for illustration purposes.

1. Introduction

Heavy ion collisions at the LHC will provide a fascinating opportunity to study QCD under extreme conditions. Apart from probing bulk properties of nuclear matter that gave rise to the strongly interacting QGP interpretation of data obtained in Au+Au collisions at the Relativistic Heavy Ion Collider (RHIC), the 27 times higher center of mass energy available at the LHC will dramatically increase the kinematic reach of physics observables to previously unaccessible regions. The large cross sections for high mass probes such as very high p_T jets, Z^0 bosons, the Υ, D and B mesons and high-mass dileptons will provide a new set of tools to study the strongly interacting matter produced in the collision. The increase in energy also allows to extend angular range of studies into the very low Bjorken x region, where saturation effects, such as the “Color Glass Condensate" [1, 2], are expected to dominate the initial state gluon density. The initial state of these probes will be calculable in pertubative QCD.

The shift of emphasis to these newly available observables at high energy and high luminosity accelerators like the LHC calls for large acceptance, high rate and high resolution detectors. The following section lists the assets which make the CMS apparatus an ideal state-of-the-art heavy ion detector.

2. The CMS Detector and Heavy-Ion Collisions

The CMS detector system is designed to measure proton proton collisions at luminosities of up to 10^{34} cm^{-2}s^{-1}, corresponding to collision rates of 40 MHz. Accordingly, the fast detector technologies chosen for tracking (Si-pixels and -strips), electromagnetic and hadronic calorimetry and muon identification will allow CMS to be read out with a minimum bias trigger at the full expected Pb+Pb luminosity. This fast readout will allow detailed inspection of every event in the high level trigger farm.

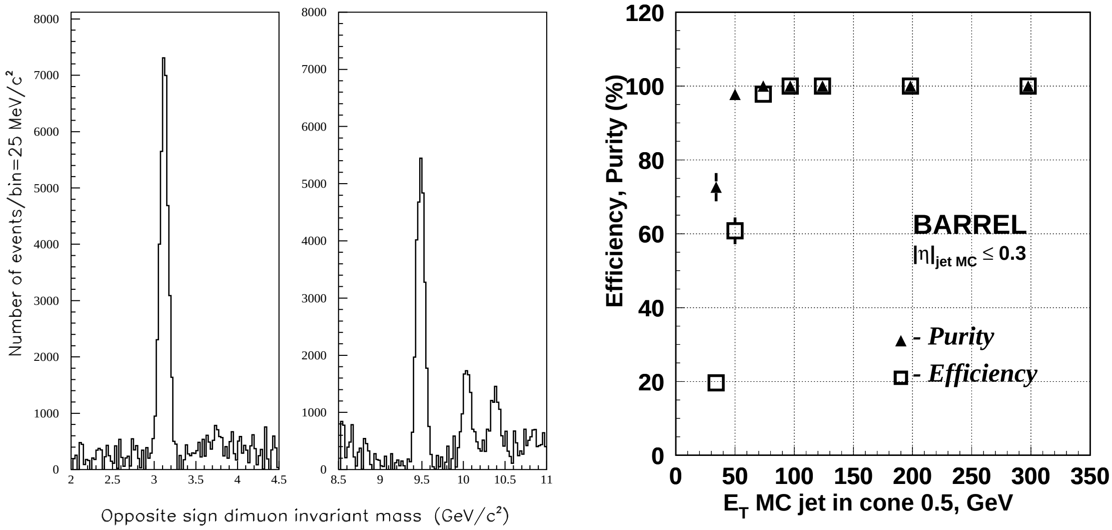

Figure 2: Left panel: Quarkonia yields as a function of the muon invariant mass in the J/ψ (left) and Υ (right) mass regions. The like-sign background has been subtracted. Right panel: Jet reconstruction efficiency and purity using calorimeters for PYTHIA generated jets embedded in $dN/dy = 5000$ background events.

CMS offers high resolution tracking and calorimetry over a uniquely large range in pseudorapidity (η) and 2π in azimuth (ϕ). The acceptance of the tracking detectors, calorimeters and muon chambers can be seen in Fig. 1.

The CMS Tracker is a 5.5 m long, 1.1 m radius cylindrical detector. It is equipped with silicon pixel detectors in the innermost part ($R < 14$ cm, $|z| < 50$ cm) and silicon strip detectors for the outer layers ($R < 110$ cm, $|z| < 275$ cm). The pixel detectors provide 2-3 3D hits with a precision of about 10 μm in $R\phi$ and 15 μm in z. The strip detectors measure 8-14 hits with a precision ranging from 10 μm to 60 μm in $R\phi$. Out of those hits 5 are recorded on double sided detectors which add a small-angle stereo measurement to provide 3D information [3].

In heavy ion collisions, the high granularity of the silicon pixel layers, in combination with the 4T magnetic field, gives an excellent momentum resolution, $\Delta p_T/p_T < 1.5\%$ up to $p_T \approx 100$ GeV/c. At the same time, a track impact parameter resolution at the event vertex of less than 50 μm (< 20 μm at $p_T > 10$ GeV/c) is achieved. At a charged particle density of about 3000 per unit rapidity tracks can be reconstructed with an algorithmic efficiency of about 80%, which is more than adequate for heavy ion physics studies.

The muon system covers the region $|\eta| < 2.5$. Muon tracks are tagged by the muon chambers inserted into return yoke of the CMS magnet. The momentum assignment is performed by matching the muon tracks to the track measured in the CMS tracker. In the barrel, $|\eta| < 1.5$, muons with $p_T > 3.5$ GeV/c are required for efficient detection. The excellent momentum resolution of the Tracker translates into a Υ mass resolution of 50 MeV/c^2 as shown in the right panel of the left-hand side of Fig. 2.

The electromagnetic calorimeter consists of 75848 lead-tungstate crystals arranged in a central barrel covering $|\eta| < 1.5$ along with endcaps which extend the range to $|\eta| < 3$. In the central barrel, the granularity is as high as $\Delta\phi \times \Delta\phi$ = 0.0175 $\times$ 0.0175 rad. The hadron calorimeter consists of barrel and endcap sections, each composed of copper plate and plastic scintillator sandwiches. In the central region, $|\eta| < 2$, the $\Delta\phi \times \Delta\phi$ segmentation is 0.087 $\times$ 0.087 rad. In addition, coverage at large rapidity, $3 < |\eta| < 5$, is achieved by two very forward calorimeters.

The jet energy and direction are reconstructed using an iterative cone type jet-finding algorithm modified to include subtraction strategy for low p_T background [4]. The jet-finding efficiency and purity are shown in the right hand panel of Fig. 2. Even jets with energies as low as 50 GeV can be reconstructed with good efficiency and low background using the calorimeters. In the central rapidity region 100 GeV jets can be reconstructed with an energy resolution of about 16%.

CMS further proposed the CASTOR calorimeter [5] and two zero degree calorimeters (ZDCs) [6]. The CASTOR detector will extend the acceptance out to very large rapidity (up to $|\eta| = 7$). The ZDCs are needed to improve the collision centrality determination.

The evaluation of simulated data indicates that the CMS detector will be well suited for a wide variety of measurements encompassing many aspects of heavy ion physics, including: *(i)* event-by-event charged particle multiplicity and energy flow measurements as well as azimuthal asymmetry [4]; *(ii)* production of quarkonia and heavy quarks [7]; *(iii)* p_T spectra of charged particles out to very high p_T and jets, including detailed studies of jet fragmentation, jet shapes and jet+jet, jet+γ and jet+Z^0 correlations [8]; *(iv)* energy flow measurements in the very forward region, including neutral and charged energy fluctuations [5]; *(v)* studies of ultra-peripheral collisions [4]; *(vi)* comparison studies of pp, pA and AA collisions.

3. Summary

The CMS detector is a unique tool to study heavy ion collisions at the LHC. It probes hot matter through studies of J$/\psi$ and Υ production rates. Its excellent calorimetry and high resolution tracker provides large coverage and good energy resolution for jet quenching studies. These capabilities have been extensively simulated and evaluated. In addition, studies of its capabilities for event-by-event charged particle multiplicity, particle flow, and jet fragmentation indicate superb detector performance.

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