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Heavy Ion Physics with the CMS experiment at the LHC

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Abstract

The LHC will collide protons at $\sqrt{s} = 14$ TeV and lead beams at $\sqrt{s_{NN}} = 5.5$ TeV as well as other AA and pA combinations. The physics program of the Compact Muon Solenoid (CMS) includes the study of heavy ion collisions. The collision energy, much higher than at RHIC, will allow the study of the dense partonic system with very hard probes: heavy quarks and quarkonia with an emphasis on b and Υ , $W^\pm$ and Z bosons, high p_T jets and photons. The production of these particles is likely to be modified, relative to pp collisions, by the presence of the hot medium.

1 Introduction

Nuclear collisions at the LHC will start a new chapter in heavy ion physics. At 5.5 TeV per nucleon [1], the Pb+Pb centre-of-mass energy is a factor of almost 30 higher than that of Au+Au collisions at RHIC. Measurements at these new energies will contribute significantly to the understanding of quantum chromodynamics (QCD). It is expected that the lifetime of the quark-gluon plasma relative to the thermalization time effectively increases by an order of magnitude. Therefore, much of the lifetime of the system is spent in a purely partonic state, allowing a more detailed study of the system using hard processes. High-energy partons are predicted to undergo radiative or collisional energy losses in the plasma [2], leading to a change in the rapidity distribution of particles and the suppression of high- p_T jets emitted in AA with respect to pp interactions. The cross sections for many hard probes such as high- p_T jets, photons, quarkonia (J/ψ , Υ) and electroweak gauge bosons ($W^\pm$ and Z) are small at RHIC, making their study extremely difficult. The higher collision energy at the LHC leads to cross sections up to several orders of magnitude larger. The variety and abundance of hard probes available at the LHC allow detailed studies of the parton energy loss mechanism in nuclear matter.

The physics program of the Compact Muon Solenoid (CMS) encompasses many aspects of heavy ion physics. The evaluation of simulated data indicates that CMS will be an excellent detector for event-by-event charged multiplicity and energy flow measurements as well as azimuthal asymmetry [3]; quarkonia and heavy quarks [4]; high- p_T particles and jets, including detailed studies of jet fragmentation, jet shapes and jet+jet, jet+ γ and jet+ Z correlations [5]; energy flow measurements in the very forward region, including neutral and charged energy fluctuations [6]; studies of ultraperipheral collisions [3]; and pp , pA and AA comparison studies.

2 The CMS Detector

The CMS [7] experiment features a general-purpose detector for the study of hadronic collisions at the LHC. It consists of a tracking system, electromagnetic and hadron calorimeters and muon detectors. A solenoidal magnet provides a 4T magnetic field surrounding the tracking and calorimetric systems. The tracker, covering the pseudorapidity region $|\eta| < 2.5$, is based on silicon technology. 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 $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$ 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 $\Delta\eta \times \Delta\phi$ segmentation is 0.087×0.087 rad. The combination of electromagnetic and hadron calorimeters thus provides coverage of the central rapidity region with energy resolution of about 16% for 100 GeV jets after subtracting background due to low- p_T particles present in heavy ion events. In addition, coverage at large rapidity, $3 < |\eta| < 5$, is achieved by two very forward calorimeters. The muon system covers the region $|\eta| < 2.5$. In the barrel, $|\eta| < 1.5$, muons with $p_T \geq 3.5$ GeV/c are required for efficient detection.

A set of forward calorimeters, including two Zero Degree Calorimeters (ZDCs) [8] and CASTOR [6], have been proposed to complement the existing detector for heavy ion studies. The ZDCs improve the collision centrality determination while CASTOR, covering $5 < |\eta| < 7$, allows studies of charged and neutral particle energy fluctuations.

The CMS Data Acquisition (DAQ) and Triggering systems are designed to handle high luminosity pp collisions, resulting in a 40 MHz event rate at the lowest trigger level. The large event multiplicities in heavy ion collisions can be handled by the existing DAQ due to the much lower 7.6 kHz collision rate for PbPb collisions. In fact, the computer processing power available at the High-Level Trigger (HLT) online farm can execute sophisticated trigger algorithms that will efficiently reject backgrounds. Studies of how to take full advantage of the DAQ and HLT capabilities are in progress.

3 CMS performance in the heavy ion environment

The CMS detector was designed and optimized for physics with high-energy, high-luminosity pp collisions. Nevertheless, it is a superb detector for the study of heavy ion collisions which, in contrast to pp , are characterized by a much lower rate (10^{-4} fewer events with high multiplicity of primarily low- p_T particles). Although the data volumes in pp and heavy ion collisions are comparable, the latter may place strain on the single event detector occupancy and, for example, make tracking more difficult.

The effects of the increased particle density are most noticeable in the silicon tracker. The dimensions of the pixels in the innermost three layers are, however, sufficiently small for the occupancy to still be only in the 1-3%

range. This small occupancy allows the reconstruction of the event vertex with a resolution of $20\ \mu\text{m}$, which is in turn used to generate track seeds from this vertex plus hits in the three pixel layers. Full tracks are then reconstructed with algorithms adapted from the pp reconstruction software. A requirement that charged particle tracks be reconstructed with three hits in the pixel layers plus nine hits in the strip layers results in geometrical efficiency of $\sim 80\%$ and a low- p_T cutoff of $\sim 1\ \text{GeV}/c$. The efficiency for finding such reconstructable tracks together with the rate of fake tracks is shown as a function of p_T and primary charged particle multiplicity in Fig. 1. The momentum resolution is shown as a function of p_T in Fig. 2. This performance is more than adequate for heavy ion physics studies. The 4T magnetic field in CMS effectively shields the calorimeters from the large

Figure 1: Efficiency for finding reconstructable tracks (upper curves) and fake rate (lower curves) vs. p_T , for $dN/dy = 1000$ (solid curves), 5000 (dashed curves).

Figure 2: Estimated momentum resolution of the track finder. Shown is the p_t dependence of momentum resolution for events with $dN/dy = 3000$ and an embedded 100 GeV jet.

number of low- p_T charged particles. Jets are therefore easily observed on top of the background of soft particles, as illustrated in Fig. 3(a). A standard “sliding window” algorithm is used to subtract the background, as shown in Fig. 3(b). The efficiency and purity with which jets can be reconstructed are shown as a function of jet E_T in Fig. 4. The efficiency at low E_T is expected to improve by the inclusion of tracking information on the particles comprising the jet. In heavy ion physics, the primary interest in muon detection arises from the desire to study quarkonium and gauge boson production, measurable through their decays to muon pairs. Open charm and beauty production can also be studied through the measurement of high p_T decay muons with displaced vertices. The CMS

Figure 3: A 100 GeV jet superimposed on low p_T background without(a) and with(b) background subtraction.

Figure 4: Reconstruction efficiency and purity vs. jet E_T for the standard sliding-window jet-finding algorithm.

muon detector is the largest such detector for heavy ions at the LHC. The muon reconstruction algorithm utilizes the event vertex and outside-in tracking from the muon detectors to determine the muon momentum. A detailed study of the feasibility of quarkonia detection in CMS has been carried out [9]. The quarkonium cross sections per nucleon in AA interactions are calculated in the colour evaporation model [4] including nuclear shadowing but no additional absorption effects. The per nucleon AA cross sections were scaled up by A^2 to obtain the AA rates. The study indicates that about $24 \times 10^3 J/\psi$, $18 \times 10^3 \Upsilon$ and $5.4 \times 10^3 \Upsilon'$ can be reconstructed after a one-month PbPb run, with 50% accelerator and detector efficiency. Quarkonia reconstruction was studied with detailed simulations and full reconstruction programs. The muon backgrounds from π , K and heavy quark semileptonic decays were included. Information from the silicon tracking detectors is used to reduce backgrounds from π and K decays in flight (“kinks”). The analysis currently includes hits in only the outer silicon strip layers. Nevertheless, the reconstruction efficiency for muon pairs from Υ decays is 85-90% for $dN/dy = 2500$ -5000 and the Υ mass resolution is 50 MeV/ c^2 , as shown in Fig. 5.

4 Hadron yields and jet structure

Recent results from RHIC [10, 11] on the suppression of the hadron yields above $p_T \geq 3$ GeV/ c and the reduction of back-to-back hadron correlations based on the underlying nucleus-nucleus collisions [12], indicate a pronounced energy loss of fast partons. The absence of these effects in central d+Au collisions suggests that the suppression is an effect of the dense medium created during the collision. Due to the large increase in the yield of high p_T hadrons at the LHC, suppression studies can be extended to higher p_T and to fully formed jets. In addition to the yield suppression, jet fragmentation and jet shape are expected to be modified by the presence of the hot medium. At the LHC, 10^7 dijets with $E_T^{\text{jet}} > 100$ GeV are produced in $|\eta| < 2.6$ during a one-month Pb+Pb run [5]. This number is reduced by about a factor two if only the barrel is considered, $|\eta| < 1.5$. High-energy jets appear as localized energy deposits in the high-granularity calorimeters. The jet energy and direction are reconstructed using an iterative-cone-type jet-finding algorithm modified to include background subtraction [3]. The jet-finding efficiency and purity are shown in Fig. 4. Even jets with energies as low as 50 GeV can be reconstructed with good efficiency and low background using the calorimeters.

The CMS high resolution silicon tracker provides additional information about the jet structure. The p_T distribution of particles reconstructed with respect to jet axis within an embedded 100 GeV jet is shown in Fig. 6(a). The presence of a plasma is expected to modify this distribution compared to jets produced in pp collisions [5].

This good performance of the CMS apparatus allows the study of jet quenching in dijet production [13]. Jet energy loss in hadronic matter can also be measured by tagging jets opposite electroweak probes such as Z or photons, produced in the reactions $qg \rightarrow qV$ and $q\bar{q} \rightarrow gV$ where $V = Z$ or γ .

The charged particle multiplicity N_{ch} and the charged particle multiplicity density $dN_{\text{ch}}/d\eta$ are of fundamental importance in heavy ion physics. They give information about the system after cooling and hadronization and they offer insight into the initial production and evolution of the hot and dense matter produced in heavy ion collisions. The particle density is reconstructed for individual events by counting the pixel clusters in a single pixel layer closest to the beam pipe using a method similar to that developed by PHOBOS [14]. The charged particle multiplicity density distribution for a single event is shown in Fig. 6(b).

5 Summary

The CMS detector is a unique tool to study heavy ion collisions at the LHC. It probes hot matter through studies of J/ψ 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.

Figure 5: Opposite sign dimuon invariant mass in the J/ψ and Υ mass regions.

Figure 6: Transverse momentum of charged particles in a 100 GeV jet(a). Charged particle multiplicity density in single event(b).

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