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LHC Heavy Ions: a CMS Perspective

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Abstract

The LHC will collide protons at $\sqrt{s}$ = 14 TeV and lead ions at $\sqrt{s_{NN}}$ = 5.5 TeV. These energies are much higher than with the Fermilab Tevatron or RHIC. Huge experiments are being assembled at four interaction points along the 27 km LHC ring. Although it is a large step into the unknown, there have been extensive calculations predicting data rates for a wide variety of processes to be observed by these experiments. Here we consider primarily the results of lead collisions as will be observed by the CMS experiment.

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1 Introduction

Four huge detector arrays (CMS, ATLAS, ALICE, and LHCb) are located at four beam-beam interaction points of the LHC (Linear Hadron Collider) at CERN. Considerable information about the LHC and the experiments can be found at [1]. The LHC will feature protons at $\sqrt{s}$ = 14 TeV and lead ions at $\sqrt{s_{NN}}$ = 5.5 TeV and a variety of pA and AA at intermediate energies. All four experiments have extensive silicon trackers surrounding the interaction point, magnetic fields to provide momentum resolution, and electronic and hadronic calorimeters. CMS (Compact Muon Solenoid) features a 4 T solenoid (13 m long and 6 m in diameter), electromagnetic and hadronic calorimeters for $\mid \eta \mid$ out to 6.7 (0.14°) and excellent resolution for high-energy muons for $\mid \eta \mid< 2.4$. ATLAS (A Toroidal LHCApparatuS) has a different coverage in η and particle energy and uses calorimeters with liquid argon detectors. ALICE (A Large Ion Collider Experiment) features a TPC (Time Projection Chamber) and a large volume (12.1 m long, 11.2 m diam.) solenoidal magnet with a weak, 0.2 T field (good for measuring charge particles with small transverse momentum). The LHCb specializes in heavy flavor physics with pp and will not take part in the heavy-ion studies. The experiments are not in competition with each other. Each has its own special features that allows it to make measurements that are beyond the reach of the other experiments.

2 Heavy-ion vs pp

Although the same types of reaction products are produced with pp and AA there are differences in the rates and distributions. At the designed luminosity of 10^{34} cm^{-2}s^{-1} there are two dozen pp interactions at every beam crossing with beam crossings occurring every 25 ns. With Pb + Pb running at the maximum luminosity of 10^{27} cm^{-2}s^{-1}, the beam crossings occur every 100 ns but with minimum bias events occurring at an average interval of 130 μs. Because of this long time both ATLAS and CMS can accommodate central Pb + Pb interactions even though they produce more than an order of magnitude more particles than a full luminosity pp beam crossing. The parts most affected by the higher multiplicity are the outer parts of the inner central tracker. In ATLAS the long straws of the TRT layer may not be able to contribute to the tracking, however, simulations show that there still remains adequate tracking capability [2]. Tracking with PbPb has the advantage over pp tracking in that there is only one interaction vertex. With CMS, some of the silicon strip detectors will experience high occupancy, but will still contribute useful information. ALICE, which is designed for PbPb studies, will be used also for pp but only at low luminosity because of the time required for tracks to be swept out of the TPC.

The four RHIC experiments have made extensive use of Zero Degree Calorimeters (ZDC) to measure spectator neutrons [3]. A ZDC pair has been a part of the ALICE experiment from the beginning. It is expected that ZDCs will be added to CMS and ATLAS. CASTOR will extend the seamless electronic and hadronic calorimeter coverage of CMS from $\mid \eta \mid$ = 5 out to $\mid \eta \mid$ = 6.7, a feature of great value for heavy-ion studies. These forward angle detectors are also useful for pp and will be used at least for pp at low luminosity. The present challenge is to find a design that can withstand the radiation levels of pp at high luminosity.

The largest part of the adaptation of a pp experiment to heavy ions is the development of software, not hardware. This includes both the development of new triggers and extensive simulations of the multitude of different processes that are expected to occur.

The CMS Data Acquisition (DAQ) and triggering systems are designed to handle high luminosity pp collisions with 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.

There are many rewards for studying heavy ions at the LHC. The PbPb center of mass energy is almost 30 times larger than that of AuAu collisions at RHIC. Measurements at these higher energies will contribute significantly to the understanding of quantum chromodynamics. The lifetime of the quark-gluon plasma relative to the thermalization time increases significantly so that a large fraction of the system lifetime is spent in a purely partonic state. This allows more detailed studies of the system using hard processes. High energy partons are predicted to undergo radiative or collisional energy losses in the plasma [4], leading to a change in the rapidity distribution of particles, or to the suppression of high p_T emitted in AA with respect to pp interactions. The cross sections for many hard probes, such as high-p_T jets, photons, quarkonia ($J/\psi, \Upsilon$) and electroweak gauge bosons ($W^{\pm}$ and Z^0) are small at RHIC so that their study is difficult. At the LHC the cross sections are larger by orders of magnitude. The variety and abundance of hard probes available at the LHC allows for detailed studies of the mechanism driving partonic energy loss in nuclear matter.

High-energy cosmic ray interactions show a wide spectrum of exotic events that can not be explained by any "normal" reaction mechanisms [5]. They are thought to be the result of high-energy nuclei, such as Fe, interacting with nitrogen and oxygen the atmosphere. At the LHC the energy will be high enough to allow such reactions to be studied in quantity under laboratory conditions. Even more spectacular events may occur with the heavier PbPb system.

3 Heavy-ion physics studies for CMS

The physics program of 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 [6]; production of quarkonia and heavy quarks [7]; high-p_T particles and jets, including detailed studies of jet fragmentation, jet shapes and jet + jet, jet + γ, and jet + Z^0 correlations [8]; energy flow measurements in the very forward region, including neutral and charged energy fluctuations searching for Centauro, DCC, and other "exotic" states [9]; studies of ultraperipheral collisions [6]; and comparison studies of pp, pA, and AA collisions.

A detailed study of the feasibility of quarkonia detection in CMS shows high reconstruction efficiency over $\mid \eta \mid \leq$ 2.4. The quarkonium cross sections per nucleon for AA interactions are calculated in the color evaporation model [7] including nuclear shadowing but no additional absorption effects. The AA per nucleon cross sections were scaled up by A^2 to obtain AA rates. The study indicates that $\approx$ 2.4 $\times$ 10^4 J/ψ, 1.8 $\times$ 10^4 Υ and 5.4 $\times$ 10^3 Υ' can be reconstructed after a one month PbPb run, assuming 50% accelerator and detector efficiencies. Quarkonia reconstruction was studied with detailed simulations and full reconstruction programs. The muon backgrounds from π, K, and heavy quark semi-leptonic decays were included. The charged particle multiplicity in central PbPb collisions was assumed to be dN_{ch}/dy = 5000. The expected di-muon invariant mass spectra in the J/ψ and Υ mass regions, after background subtraction are shown in Fig. 1. The excellent muon momentum and direction resolution allows clear separation of the $\Upsilon(S)$ states.

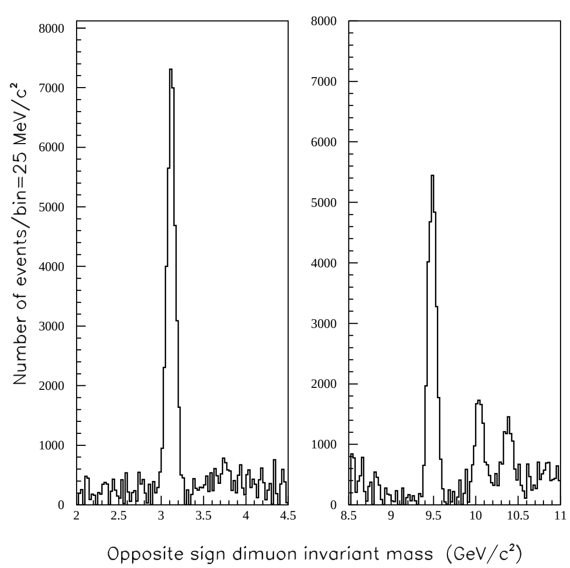

Fig. 1. The opposite sign di-muon invariant mass.

Recent results from RHIC [10, 11] concerning 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 by fast partons. The absence of these effects in central dAu 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 di-jets with $E_T^{\rm jet} > 100$ GeV are produced at $\mid \eta \mid \leq 2.6$ over a month PbPb run

[8]. This number is reduced by about a factor of two if only the barrel is considered, $|\eta| \leq 1.5$. High-energy jets appear as localized depositions 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 [6]. The jet-finding efficiency and purity are shown in Fig. 2.

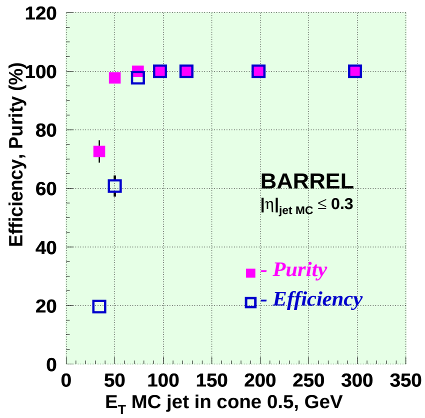

Fig. 2. Jet reconstruction efficiency and purity using calorimeters.

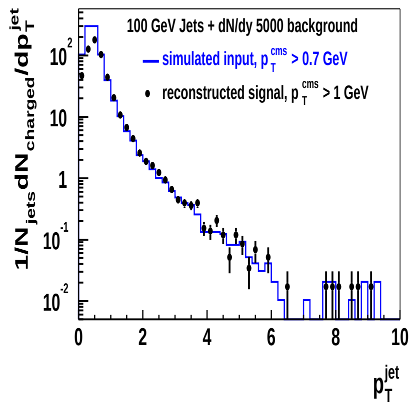

Fig. 3. Transverse momentum of charged particles in a 100 GeV/c^2 jet.

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 and the pixel detector allow the reconstruction of charged hadrons of $p_T > 1$ GeV/c with good efficiency, a low level of contamination, and excellent momentum resolution at the highest particle densities expected at the LHC. Fig. 3 shows the p_T distribution of particles reconstructed within a 100 GeV jet with respect to the jet axis. The presence of a plasma is expected to modify this distribution compared to jets produced in pp collisions [8]. This good detector performance allows detailed studies of jet quenching in di-jet production [13]. Jet energy loss in hadronic matter can also be measured by tagging jets opposite electroweak probes, such as Z^0 or photons, produced in the reactions $qg \to qV$ and $q\bar{q} \to gV$ where $V = Z^0$ or γ. The charged particle multiplicity N_{ch}, and the charged particle multiplicity density, $dN_{ch}/d\eta$, 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 charge particle multiplicity density distribution for a single event is shown in Fig. 4.

4 Conclusions

Exciting new physics is anticipated at the LHC with its large increase in energy compared to all current accelerators. For heavy ions the increase is almost a factor of 30. The excellent calorimetry and high-resolution tracking of CMS provide large coverage and good energy resolution. The exceptional capability of CMS for high-energy muons allows detailed studies of J/ψ and Υ as probes for the interior of hot nuclear matter. These capabilities have been extensively simulated and evaluated. Studies of event-by-event charged particle multiplicity, particle flow, and jet fragmentation indicate superb performance of CMS with heavy-ion reactions.

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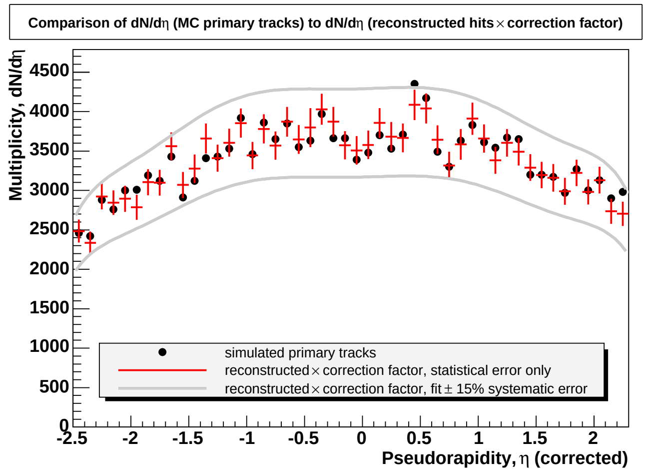

Fig. 4. Charged particle multiplicity density.

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