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CMS Experiment at LHC: Detector Status and Physics Capabilities in Heavy Ion Collisions

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The Large Hadron Collider at CERN will collide lead ions at $\sqrt{S_{NN}} = 5.5$ TeV allowing 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, as well as Z^0 bosons. The Compact Muon Solenoid (CMS) detectors will allow a wide range of unique measurements in nuclear collisions. 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 excellent calorimeters combined with tracking will allow detailed studies of jets, particularly medium effects on the jet fragmentation function and the energy and p_T redistribution of particles within the jet. The large CMS acceptance will allow detailed studies of jet structure in rare $\gamma - jet$ and Z-jet events. The high resolution tracker will tag b quark jets. The muon chambers combined with tracking will study production of the Z^0 , J/ψ and the Υ family in the central rapidity region of the collision. In addition to the detailed studies of hard probes, CMS will measure charged multiplicity, energy flow and azimuthal asymmetry event-by-event.

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1. Introduction

The motivation of ongoing relativistic heavy-ion collision experiments is to understand the bulk properties of high energy density matter and the theory of the strong interaction, Quantum Chromo Dynamics (QCD).
The experiments at the Relativistic Heavy Ion Collider (RHIC) facility have found several important signatures for the Quark-Gluon Plasma (QGP) formation [1]. The LHC plans to collide Pb nuclei at $\sqrt{s_{NN}} = 5.5$ TeV which is 28 times higher than the highest energy available at RHIC. The collisions should produce copious hard probes such as jets, high-p_T hadrons, heavy-quarks, quarkonia and large yields of the weakly interacting perturbative probes (direct photons, dileptons, Z^0 and $W^{\pm}$ bosons). In this paper the Compact Muons Solenoid (CMS) detector capabilities for heavy-ion physics at LHC are summarized with an emphasis on the early measurements.

2. The CMS Detector and Heavy Ion Program

The Compact Muon Solenoid (CMS) [2] is a general purpose detector designed primarily to search for Higgs boson in proton-proton collisions at LHC. However this large acceptance detector is an excellent device for the study of hard and soft probes in both pp and AA collisions.
The basic element of CMS is a 13m-long, high field (4T) solenoid with internal radius of ~ 3 m. The tracking system covers the pseudorapidity region $|\eta| < 2.4$. It consists of thirteen layers of silicon detectors. The first three layers are pixel detectors (66 M $100 \times 150 \mu m^2$ pixels) followed by ten microstrip layers (strips pitch $80 \div 180 \mu m$). The tracking system allows track reconstruction and momentum estimation with resolution better than 2% in the p_T region from 0.5 to $50 GeV/c$. It provides the vertex position with $\sim 15 \mu m$ accuracy and it gives the possibility to clear resolving of the $\Upsilon-$family.
The muon chambers cover the pseudorapidity window $|\eta| < 2.4$, with detection planes made of three technologies: Drift Tubes (DTs), Cathode Strip Chambers (CSCs), and Resistive Plate Chambers (RPCs). Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution between 1 and 5 %, for p_T values up to 1 TeV/c.
The electromagnetic (ECal) and hadron (HCal) calorimeters cover the range $|\eta| < 3$ and the very forward (HF) calorimeters span the region $3 < |\eta| < 5.2$. The ECal has an energy resolution of better than 0.5% above 100 GeV. The calorimeter cells are grouped in projective towers, of granularity $\delta\eta \times \delta\phi = 0.087 \times 0.087$ at central rapidities and 0.175×0.175 at forward rapidities. A quartz-fibre calorimeter named CASTOR covers the region $5.2 < |\eta| < 6.6$, and yet another zero degree calorimeter (ZDC) located as far as 140 m from the interaction point the region $|\eta| \geq 8.3$.
The unique CMS trigger architecture only employs two trigger levels: the Level-1 trigger and the High Level Trigger (HLT). The Level-1 is implemented using custom electronics and it uses local data from the calorimeter and muon systems to make electron/photon, jets and muon triggers. In order to fully exploit the detector capabilities for rare hard probes at the LHC, the HLT uses a large cluster of workstations running offline analysis trigger algorithms on every single Pb+Pb event without filtering at the first level. This results in significant enhancements of various rare hard probes by a factor of $20 \sim 300$, compared to the minimum bias (MB) condition. Fig. 1 (left) shows the gain in statistics with respect to minbias writing to tape as achieved for high-E_T jets and

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dimuons. Fig. 1 (right) shows the invariant p_T spectra for charged hadrons expected with the CMS HLT at various Pb+Pb centralities.

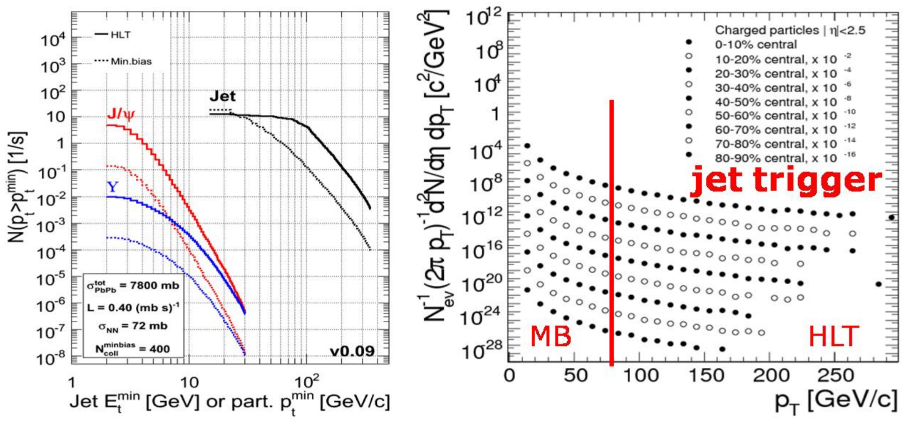

Figure 1: (Left) The gain in statistics with respect to minbias writing to tape as achieved with HLT for high-E_T jets and dimuons. (Right) Invariant p_T spectra for charged hadrons expected with the CMS HLT at various Pb+Pb centralities.

3. Charged Hadron Multiplicity

The charged particle multiplicity per unit of rapidity at mid-rapidity is related to the entropy density in the collisions and fixes the global properties of the produced medium. For example, the idea of Color Glass Condensate (CGC) [1] predicts a significant reduction of the number of produced hadrons at the LHC due to the reduced initial number of scattering centers in the parton distribution functions (PDFs). CMS is planning to make a first day measurement of the charged particle multiplicities by tree methods: 1) tracklets with a vertex constraint 2) hit counting in the pixels using a dE/dx cut and 3) reconstructed tracks.

4. Low-p_T Hadron Spectra and Elliptic Flow

Measurements of hadron momentum spectra and ratios at low p_T are an important tool to determine the amount of collective radial flow and the thermal and chemical conditions of the system at freeze-out. The CMS tracking algorithms allow to identify particles by comparing energy loss, dE/dx, and the momentum of track. Inclusive hadron spectra can be measured from $p \simeq 300 MeV/c$ up to $p \simeq 1 GeV/c$ for pions and kaons and up to $p \simeq 2 GeV/c$ for protons.

The elliptic flow parameter, v_2, is the strength of the second harmonic of the azimuthal distribution of hadrons with respect to the reaction plane. The measurement of v_2 in differential form will be primarily important to learn the collective properties, such as the viscosity, of the fluid-like matter and the equation-of-state. CMS will measure v_2 both by reconstructing the reaction plane and by using multiparticle correlators or cummulants. The differential v_2 parameter obtained by the event-plane method is displayed in Fig. 2 (left).

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5. Nuclear Modification Factor

A major discovery at the RHIC is the hadron suppression at relatively high-p_T, the so-called jet quenching effect. We presently understand that the high-p_T hadron suppression is due to the final state effect caused by the produced dense matter: the energy loss of partons traversing the strongly interacting medium.
Thanks to the enhanced hard cross sections at LHC energy, the excellent performance of the tracker, and the high-p_T triggering capability, the CMS can significantly extend the p_T reach of the charged hadron spectra to $\sim 300 GeV/c$. The CMS can also investigate the jet quenching effect with the fully reconstructed jets, measured by its calorimeters with almost 4π coverage. It has been demonstrated [2] that the CMS can reconstruct jets in a messy environment, generated by Pb+Pb collisions, after the subtraction of the underlying soft background on an event-by-event basis. The distinction of jets above the background begins at $E_T \sim 30 GeV$ and the full reconstruction is possible for $E_T > 75 GeV$ with good efficiency and purity ($\sim$ 100 % for both) and a good energy resolution (< 15 %).

6. Fragmentation Function

The energy loss mechanism of fast partons in the strongly interacting medium can be studied further by analyzing the $\gamma - jet$ events and extracting the parton fragmentation function (FF). The advantage of utilizing the $\gamma - jet$ channel is that we can infer the initial parton energy from the transverse energy of γ ($E_T^{jet} \approx E_T^{\gamma}$), since the prompt γ is not influenced by the final-state interactions. The full $\gamma - jet$ simulation study has shown that the FF can be measured within 10 % by constraining the away-side jet axis by $\Delta\phi_{\gamma - jet} < 3$ rad in addition to the low-E_T cuts on γ and jet as well as the special isolation cuts on γ [3]. The right side of Fig. 2 shows the ratio of the reconstructed quenched FF to the unquenched one, which allows us to investigate any modification of the fragmentation function by the medium.

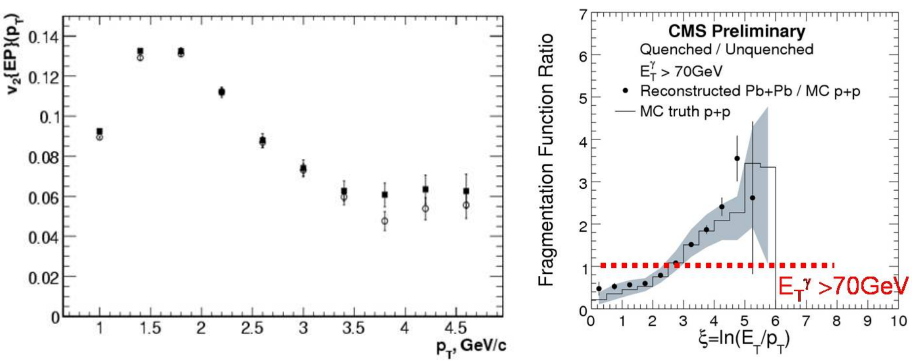

Figure 2: (Left) The differential v_2 parameter obtained by the event-plane method. The open circles represent the simulated data with the HYDJET event generator, and the closed squares represent the reconstructed ones (Pb+Pb collisions at A$\sqrt{s_{NN}} = 5.5 TeV$). (Right) Ratio of the reconstructed quenched FF to the unquenched one as function of $\xi = \ln(E_T^{\gamma} / p_T)$.

7. Quarkonia and Heavy Quarks

Quarkonia (J/ψ , ψ', Υs) and Z^0 should be observed with high statistics under the conditions of LHC. Large cross-section for heavy quark (b, c) production allows evaluation of medium-induced energy loss of partons basing on the spectra of large mass $\mu\mu$ pairs and secondary J/ψ [4].
Fig. 3 shows the reconstructed invariant mass distributions of opposite sign muon pairs near the J/ψ and Υ mass regions in $|\eta| < 0.8$. The mass resolution of Υs is about $54MeV/c^2$, and it worsens to about $90MeV/c^2$ if we include the endcap detectors for $|\eta| < 2.4$. In addition, the simulation study has shown that the efficiency for the muon pair detection is $\sim 80\%$ and the purity is $\sim 90\%$ even for the most central Pb+Pb collisions in the barrel region. The Υ state can be measured down to $p_T \sim 0GeV/c$ with the reconstruction efficiency between 15 and 40 %, depending on the momentum. The J/ψ mass resolution is about $35MeV/c^2$ for $|\eta| < 2.4$.

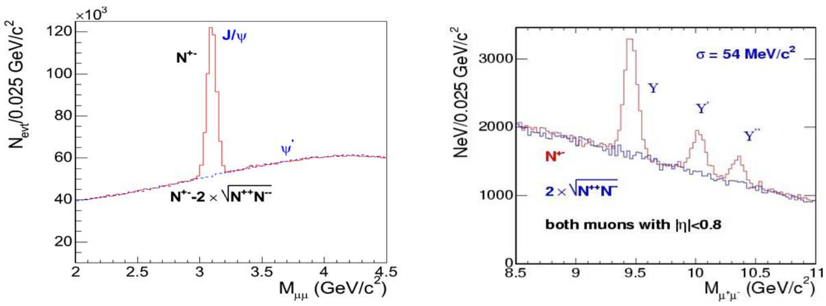

Figure 3: Invariant mass spectra of opposite sign muon pairs with $dNch/d\eta|_{\eta=0} = 2500$ in $|\eta| < 0.8$ (Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5TeV$) near the J/ψ (left) and the Υ (right) regions.

8. Summary

In summary, the CMS detector is equipped with high-granularity high-resolution Si pixels and trackers, calorimeters, and muon detection systems, covering almost 4π. As a consequence, the CMS detector is an excellent system not only for p + p, but also for heavy-ion collisions. In particular, the CMS has a strong advantage measuring various hard probes due to the large acceptance and the dedicated HLT.We have shown that the CMS can perform the detailed studies of almost all physics topics in both soft and hard sectors in heavy-ion collisions.

References

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