# CMS Conference Report

# Heavy Ion Physics with the Compact Muon Spectrometer at the Large Hadron Collider

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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 $\mathrm{b}$ and $\Upsilon$, $\mathrm{W}^{\pm}$ and $\mathrm{Z}$ 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.

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The RHIC discoveries have not only transformed our picture of nuclear matter at extreme densities, but also greatly 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 the elliptic flow coefficient, very high $p_T$ jets, and heavy quarkonia. This change of paradigm for the probes of the medium suggests 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. The proposal to use CMS [2, 3, 4, 5, 6] for heavy ion collisions takes this development to its logical conclusion. The utility of the convergence of heavy ion and particle physics techniques is illustrated by the extent to which CMS fulfills the criteria for an ideal heavy ion detector.

1. **High rate**: CMS is designed to deal with p+p collisions at luminosities of up to $10^{34}$ cm$^{-2}$s$^{-1}$, corresponding to p+p collision rates of $10^9$ Hz. As a result, 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. The bandwidth of the farm is sufficient to run complex analysis algorithms on each of the events, allowing a complete selection and archiving of events containing rare probes such as extremely high $p_T$ jets or events having unusual global properties.

2. **High resolution and granularity**: At the full p+p luminosity, there will be, on average, 25 collisions per bunch crossing. To be able 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 ideally 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 resolution, $\Delta p_T/p_T < 1.5\%$ up to $p_T \approx 100$ GeV/c. At the same time, a track-pointing resolution of less than 50 $\mu$m (less than 20 $\mu$m for $p_T > 10$ GeV/c) is achieved. At $dN_{\rm ch}/dy \approx$ 3000, tracks can be reconstructed with an efficiency of $\sim 80\%$, which is more than adequate. The electromagnetic calorimeter can be used to find jet locations with resolutions in $\eta$ and $\phi$ of 0.028 and 0.032, respectively.

3. **Large acceptance tracking and calorimetry**: CMS includes high resolution tracking and calorimetry over $2\pi$ in azimuth and a uniquely large range in rapidity. The acceptance of the tracking detectors, calorimeters, and muon chambers can be seen in Fig. 1. 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 experiment will constitute the largest acceptance system ever built at a hadron collider.

4. **Particle identification**: At the LHC, charm and bottom quarks will be copiously produced. The large acceptance, high resolution muon system, in combination with the tagging of secondary decays by the silicon tracker, will allow studies of the interaction of identified quarks with the medium. In addition, the physics of meson vs. baryon production at large $p_T$ can be studied using the results for reconstructed $\pi^0$s, 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 assess the information that can be obtained from measurements of specific ionization in the silicon detectors as well as the reconstruction of hadronic resonances using invariant mass analysis.

The CMS performance in most categories far exceeds the capabilities of existing or planned heavy ion detectors. However, many of the physics topics that can be addressed depend on the ability to reconstruct individual charged particles. Track reconstruction in the CMS silicon tracker is thus a key element to the success of the CMS heavy ion program.

The maximum charged particle density of central Pb+Pb collisions cannot easily be extrapolated from RHIC energies to the LHC. Assuming a logarithmic increase of the charged particle density with the nucleon-nucleon center-of-mass energy [7], between 1500 and 4000 charged particles per unit rapidity will be produced in central Pb+Pb collisions at the LHC. For this study the parameters of the simulation were set to produce a midrapidity charged particle density of about 3000 per unit rapidity. The combinatorial challenge resulting from the high hit density requires robust reconstruction algorithms to achieve efficient pattern recognition while maintaining a low fake rate.

The performance of the tracker in the environment of central Pb+Pb collisions was evaluated[9] using a data sample generated with the HYDJET event generator [8]. Events simulated with this generator consist of contributions from soft particle production modeled by a hydrodynamic module and multiple hard collisions simulated with

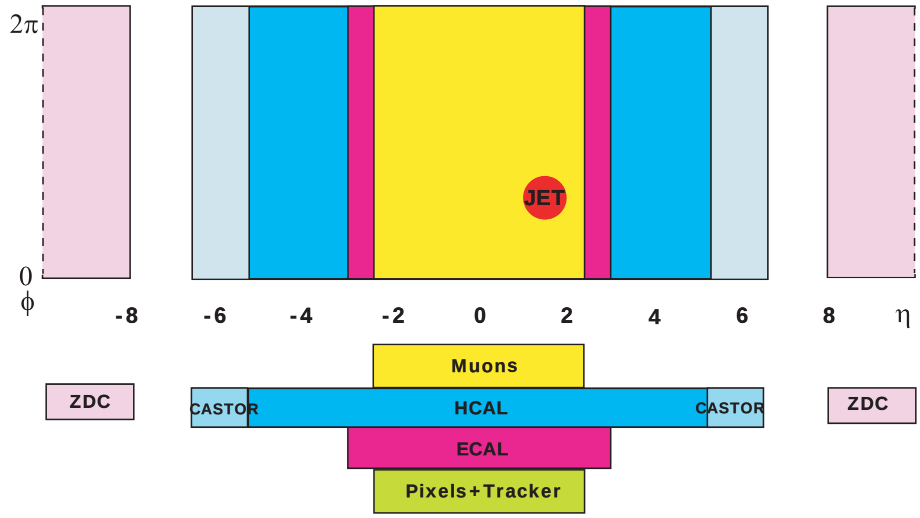


Figure 1: Acceptance of tracking, calorimetry, and muon identification in pseudorapidity and azimuth. The size of a jet with cone $R = 0.5$ is also depicted as an illustration.

PYTHIA. The standard track reconstruction algorithm, initially tuned for p+p, was optimized for the high density environment. In order to reject fake tracks, cuts on the minimum number of required hits, a maximum $\chi^2$, and a minimum distance of closest approach to the primary vertex were applied. Figure 2 shows the track reconstruction

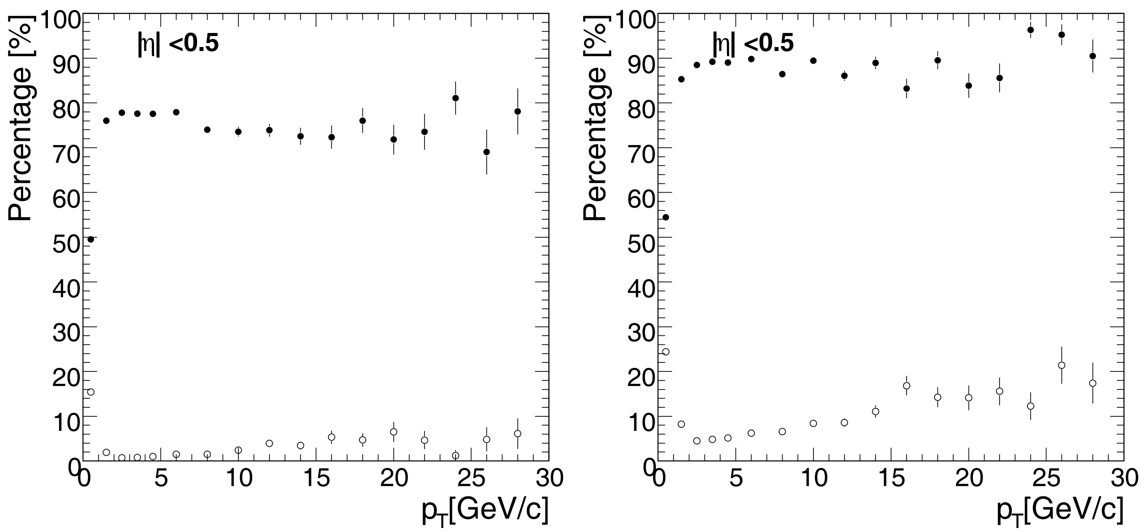


Figure 2: Track reconstruction efficiency (full symbols) and fake track rate (open symbols) as a function of transverse momentum near midrapidity for central Pb+Pb collisions with $dN_{\rm ch}/dy \approx 3000$. (Left) Track quality cuts optimized for low fake track rate (cut on number of hits $> 12$, fit probability $> 0.01$, and dca $< 3$). (Right) Track quality cuts optimized for high efficiency (only cut on number of hits $> 12$).

efficiency and fake track rate as a function of transverse momentum in the barrel region of the tracker for two sets of quality cuts imposed in the reconstruction. The momentum and track-pointing resolution achieved in heavy ion collisions (see Fig. 3) are comparable to those in low occupancy p+p events.

Given the excellent pointing accuracy of single tracks and the high event multiplicity, the primary event vertex can be reconstructed with a resolution of better than 10 $\mu$m in all 3 dimensions. The precision of the primary event vertex reconstruction will clearly be limited only by the alignment precision of the tracker components.

With the nominal magnetic field setting, the current tracking algorithms have been found to have good efficiency and purity down to a transverse momentum of $p_T \approx 1$ GeV/c. For broader global measurements, preliminary feasibility studies of measuring bulk charged particle multiplicities using individual layers in the CMS silicon tracker have been performed. These early analyses will be expanded to enable a more detailed study of charged particle yields versus centrality, pseudorapidity and angle with respect to the reaction plane. In order to extend the

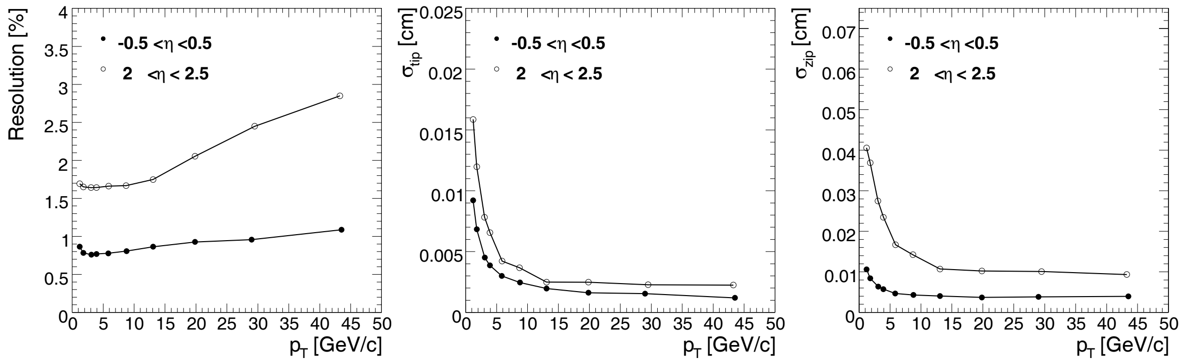


Figure 3: The $p_T$ dependence of the track parameter resolution achieved in heavy ion events in the barrel region (full symbols) and in the forward region (open symbols). (Left) Transverse momentum resolution. (Center) Transverse track-pointing resolution. (Right) Longitudinal track-pointing resolution.

analysis even further, there is also interest in investigating the (low) momentum tracking and particle identification possibilities using the multiple layers of silicon detectors. The preliminary results indicate that there is a good possibility of extending the tracking limit to well below $p_T \approx 1$ GeV/c.

CMS is an ideal detector for muon reconstruction with an acceptance spanning 4.8 units in pseudorapidity, the largest of any heavy ion detector. The proximity of the electromagnetic calorimeter to the beam axis (1.29 m) minimizes the background from pion and kaon decays. An additional background rejection of a factor of 6 (2) in the barrel (endcaps) is obtained using the excellent muon momentum resolution given by the tracking detector.

The good muon momentum resolution translates to an $\Upsilon$ mass resolution in p+p of 53 MeV/c $^2$ in the barrel pseudorapidity region, the best of all LHC detectors. When the signal is superimposed on a background event and measured in the full pseudorapidity region, the mass resolution is 90 MeV/c $^2$. This provides a clean separation between the members of the $\Upsilon$ family and also a significant improvement in the signal to background ratio.

To further illustrate the resolution and yield, Fig. 4 shows the dimuon mass distributions, after background subtraction, for two different scenarios: $dN_{\rm ch}/d\eta|_{\eta=0}$ = 5000, $|\eta| < 2.4$; and $dN_{\rm ch}/d\eta|_{\eta=0}$ = 2500, $|\eta| < 0.8$. Except for the $\psi'$, all quarkonia states are clearly visible. These yields correspond to one month of Pb+Pb running [10].

To date, most quarkonium studies in CMS have focused on detection through their decays to $\mu^+\mu^-$. This decay channel provides the cleanest signals at the cost of a lower rate and a reduced acceptance for low $p_T$ $J/\psi$s, which can be reconstructed only above $p_T$ ~3 GeV/c in the forward regions and $p_T$ ~7 GeV/c near midrapidity. The higher mass $\Upsilon$ is unaffected by the muon $p_T$ cut and can thus be measured to zero $p_T$. In the future, these studies may be extended to the $e^+e^-$ decay channel using the CMS electromagnetic calorimeter.

Jet reconstruction in heavy ion collisions faces the challenge of identifying localized $E_T$ clusters in the calorimeters on top of a substantial background from the underlying event. In the CMS heavy ion analysis, a modified iterative cone type jet finder is employed that includes an event-by-event subtraction of background energy. In each event, the average tower transverse energy and the dispersion are calculated for each $\eta$ ring in the barrel and endcap calorimeters and then this average transverse energy plus dispersion are subtracted from all tower energies. Using the corrected tower energies, jets are found with an iterative cone algorithm. Then, the average tower energies and dispersions are recalculated using only towers outside the jets and the process is repeated with these recorrected tower energies.

This fast method using only 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 $\eta$ and $\phi$ are 0.028 and 0.032, respectively. The resulting quality of reconstructing the fragmentation function for the momentum of individual particles both transverse and longitudinal to the jet axis is shown in Fig. 6.

The four components of the hadronic calorimeter system, namely the Barrel (HB), Forward (HF), and Endcap (HE) units provide good segmentation and hermeticity, moderate energy resolution, and full azimuthal angle coverage up to $|\eta| = 5$. The HB and HE calorimeters are made of brass plates interleaved with scintillator. The granularity is $\Delta\eta$ x $\Delta\phi$=0.087 x 0.087 except at the highest $\eta$. The forward calorimeter (HF) is an iron quartz-fiber calorimeter with electromagnetic and hadronic sections.

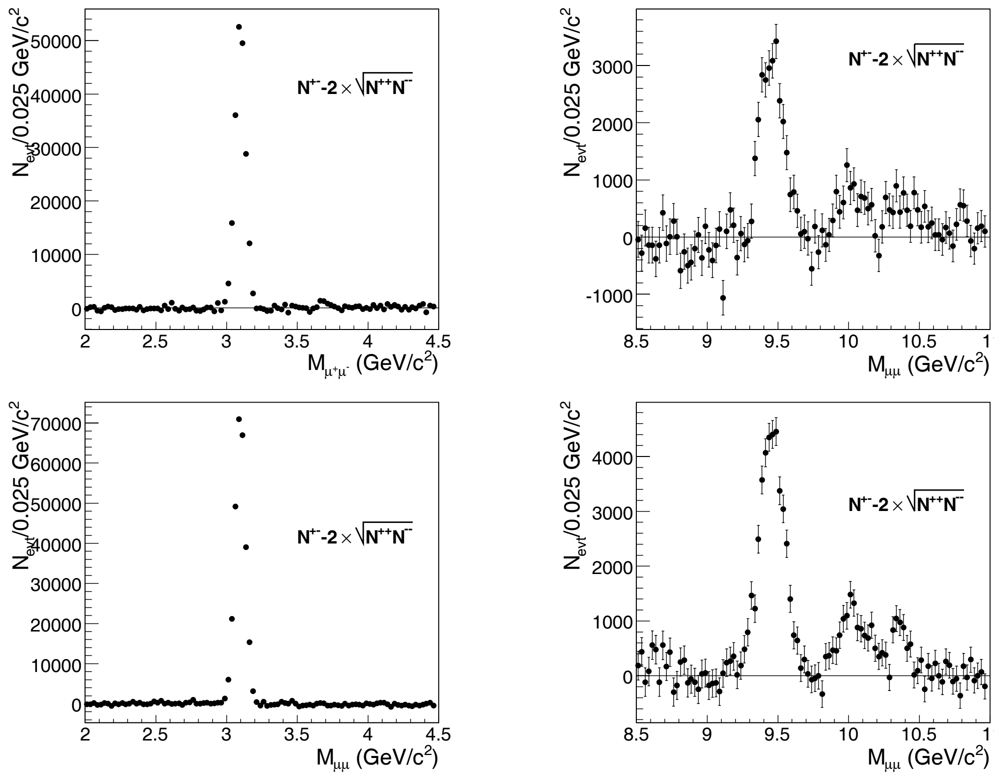


Figure 4: Signal dimuon mass distributions after background subtraction in the $J/\psi$ (left) and $\Upsilon$ (right) mass regions expected after one month of Pb+Pb running. Top panels are for $dN_{\rm ch}/d\eta|_{\eta=0} = 5000$ and $|\eta| < 2.4$; bottom panels are for $dN_{\rm ch}/d\eta|_{\eta=0} = 2500$ and $|\eta| < 0.8$.

The ECAL is built of high density lead tungstate ($PbWO_4$) crystals, producing a detector which is fast, high resolution, finely segmented, and radiation resistant, all important properties for the LHC environment. The granularity is $\Delta\eta$ x $\Delta\phi$=0.0174 x 0.0174 in the barrel and it varies from $\Delta\eta$ x $\Delta\phi$=0.0174 x 0.0174 to 0.05 x 0.05 in the endcap. Studies have shown the ability of CMS to identify $\pi^0$s in the transverse momentum range 4-20 GeV/c$^2$, even for the highest multiplicities expected in Pb+Pb collisions. It is also possible to get statistical separation of neutral particle yields even when the shower-by-shower invariant mass cannot be reconstructed by selecting showers with electromagnetic features. Unless there is very significant jet-quenching, electromagnetic showers will be largely dominated by $\pi^0$s for $p_T < 100$ GeV/c.

In summary, initial investigations of the CMS detector's properties have found outstanding capabilities for performing important physics analyses in the heavy ion environment. These preliminary studies will be refined and expanded and many additional physics topics will be considered in order to define the full physics potential of the experiment.

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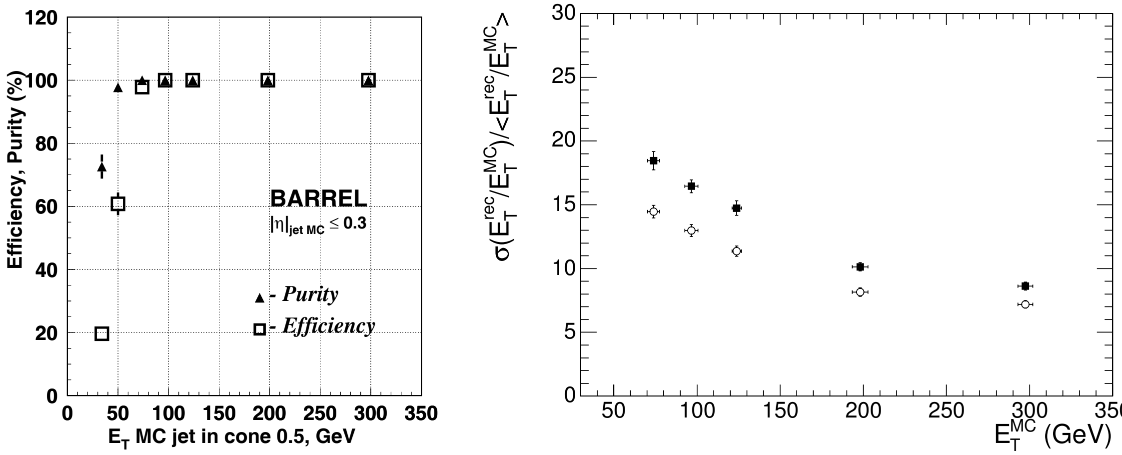


Figure 5: (Left) Jet reconstruction efficiency and purity using barrel calorimeters for PYTHIA generated jets embedded in Pb+Pb events with $dN_{\rm ch}/dy = 5000$. (Right) The resolution of the jet $\mathrm{E}_T$ determination in p+p (open symbols) and Pb+Pb (closed symbols), also with $dN_{\rm ch}/dy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

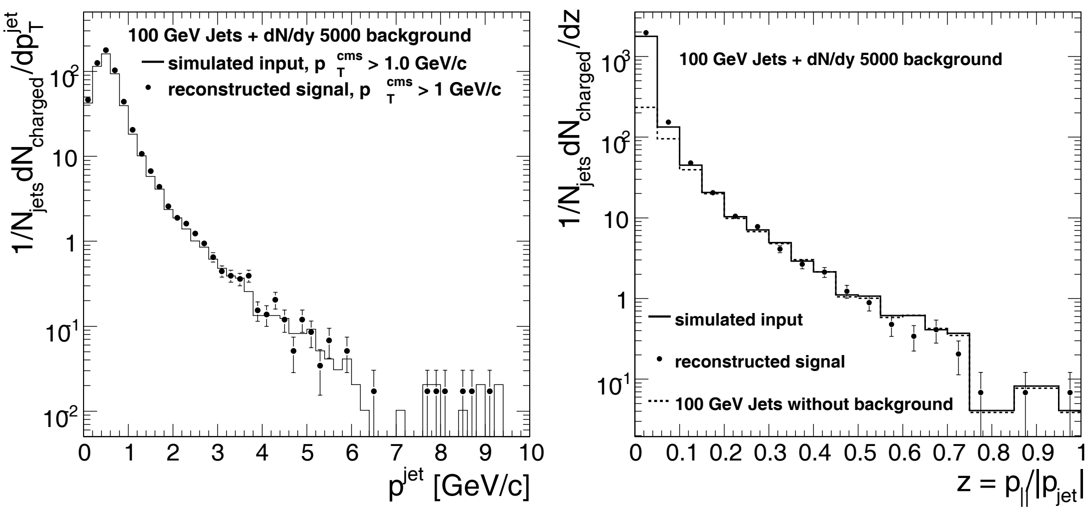


Figure 6: (Left) Input and reconstructed fragmentation function for individual particle momentum transverse to the jet axis for 100 GeV jets embedded in Pb+Pb events with $dN_{\rm ch}/dy = 5000$. (Right) Fragmentation function for longitudinal momentum fraction under the same conditions. The dashed line shows the distribution for those particles which were actually part of the input jet, rather than the underlying Pb+Pb background.


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