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Heavy Ion Physics with CMS

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Abstract. The study of ultra-relativistic nuclear collisions with CMS is reviewed. The ability of the detector to function in the resulting high multiplicity environment is demonstrated. Simulated results for some physics signals are presented.

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1 Introduction

Collisions of heavy nuclei at Large Hadron Collider (LHC) energies (5.5 TeV/u) open new opportunities in the study of hot and dense hadronic matter. At these extreme energies, the initial nuclear state is expected to be dominated by gluons that carry only a small fraction, x, of the momentum of each nucleon. Such "low-x" gluons in the nuclear environment may saturate into what has been termed a "Color Glass Condensate". Regardless of the saturation issue, it is expected that heavy ion collisions result in the formation of a baryon-free system in the central rapidity region ($y \sim 0$) that is well above the critical temperature for quark-gluon deconfinement and chiral symmetry restoration. This system should be larger and longer lived than what has been formed in lower energy collisions at the CERN SPS and BNL RHIC, and thus more amenable to detailed study.

The enormously increased cross sections for high momentum transfer processes at LHC energies allow the use of probes barely accessible at RHIC. High-p_T jets, photons, quarkonia (J/ψ, Υ), and weak gauge bosons (W, Z) are all produced with sufficient rates for detailed and systematic study of their production and interaction with the matter in which they are produced and through which they propagate. It is thus expected that phenomena such as quarkonium suppression and jet quenching can be quantitatively studied in detail over a wide range of the relevant parameter space — collision centrality, rapidity, etc. — even though the LHC is only expected to collide heavy ions for one month of every year.

In this presentation, the use of the Compact Muon Solenoid (CMS) in experimental studies of nuclear collisions at the LHC [1, 2] is described. The performance of CMS in the high multiplicity environment (dN/dy = 2000–8000) of heavy ion collisions is discussed. The features and capabilities of detectors specific to the study of heavy ion collisions are also presented.

The work reported in this talk is largely the result of work by scientists at Lyon and Strasbourg, France; Tbilisi, Georgia; Athens, Demokritos and Ioannina, Greece; Moscow State and Dubna, Russia; and UC Davis, UC Riverside, UIC, U Iowa, U Kansas, MIT and Rice U, USA.

2 The CMS detector

The CMS detector [3] and its performance has been discussed in great detail in other presentations at this conference and in these proceedings, and therefore is only outlined in this paper – with particular reference to heavy ion measurements. An overview of the CMS detector is shown in Fig. 1. The central element is a 13 m long, superconducting solenoid, which provides a 4 T field.

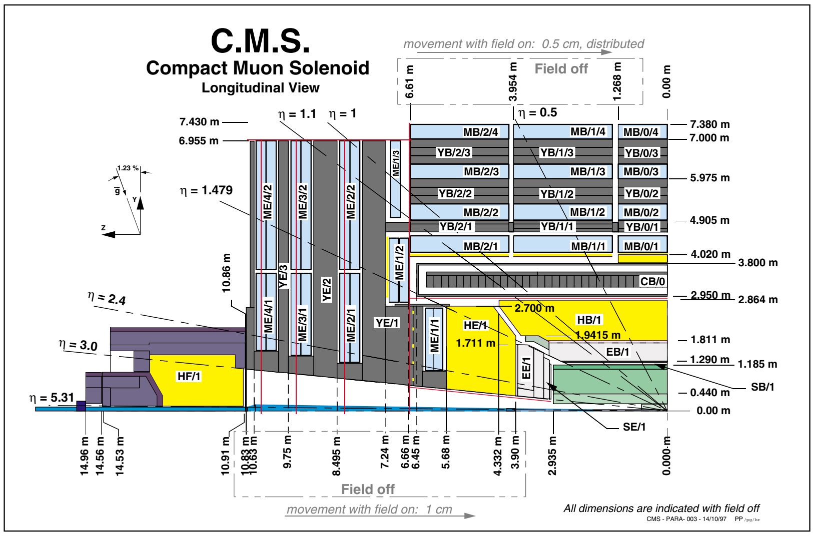

Fig. 1. Longitudinal view of the CMS detector.

Moving out from the beam axis, the interaction region is covered by a silicon tracker composed of three cylindrical pixel layers plus ten cylindrical silicon strip layers and endcap pixel and strip disks. These detectors cover all pseudorapidity values η between -2.5 and $+2.5$. Additional tracking coverage out to $|\eta| = 6.7$ is provided by the silicon telescope T2, which is part of the total pp cross section measurement detector TOTEM [4].

The central silicon tracker is immediately followed by an electromagnetic calorimeter made of 75,848 $PbWO_4$ crystals covering $|\eta| < 3$. In the region $1.5 < |\eta| < 2.5$, the resolution is improved by a preshower detector comprised of two orthogonal planes of silicon strips interspersed with Pb radiator.

Outside the electromagnetic calorimeter, a copper/scintillator hadron calorimeter covers $|\eta| < 3$, augmented by a forward steel/quartz fibre Cerenkov calorimeter (HF), which covers the region $3 < |\eta| < 5$. This coverage is further extended on one side with the addition of the CASTOR (Centauro And STrange Object Research) detector [5] ($5.3 < \eta < 6.9$) and with Zero Degree Calorimeters (ZDC) located at $z = 140$ m on both sides of the interaction point.

Muons are detected and tracked in drift tubes ($|\eta| < 1.3$) and cathode strip chambers ($0.9 < |\eta| < 2.4$), interspersed with the solenoid return yoke. Resistive plate chambers provide triggering for muons.

An important feature of the CMS detector is the Trigger/DAQ system, which foregoes the usual multi-level system for a Level-1 and High-Level Trigger which, for Heavy Ion Physics, allows partial reconstruction in real time of all interesting events at the full collision rate.

3 Performance of CMS 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 with pp, are characterized by a much lower rate (1/10,000) of events with high multiplicity (up to perhaps 30,000) of largely low-p_T particles. Although the data volume in pp and heavy ion collisions is 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. However, the dimensions of the pixels in the innermost three layers are sufficiently small for the occupancy to still be only in the % range. This small occupancy allows the reconstruction of the event vertex with a resolution of 20 μm, which in turn is 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 ~ 1 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. 2. The momentum and vertex impact-parameter resolutions are shown as a function of p_T in Fig. 3. This performance is more than adequate for heavy ion physics studies.

The 4 T magnetic field in CMS effectively shields the calorimeters from the large number of low-p_T charged particles. Jets are therefore easily observed on top of the background of soft particles as illustrated in Fig. 4. Energy fluctuations of this soft background contaminate the jet sample, as any particles within a cone of radius 0.5, for example, in $\eta\phi$ space about the local energy maximum are included as part of the jet. The efficiency with which jets can be reconstructed with this standard "sliding window" jet cone algorithm and the resulting purity of the sample are shown as a function of jet E_T in Fig. 5. The efficiency at low E_T is expected to improve with the inclusion of tracking information on the particles comprising the jet.

In heavy ion physics, muon reconstruction is primarily important for the study of quarkonium and gauge boson production, which can be measured through their muon pair decay. Open charm and beauty production can also be studied via their decay to high-p_T muons with displaced vertices. The CMS 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. 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

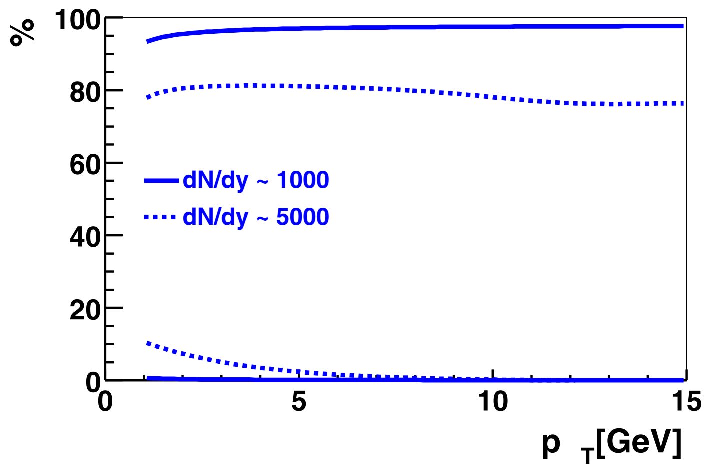

Fig. 2. Efficiency for finding reconstructable tracks (upper curves) and fake rate (lower curves) vs. p_T for $dN/dy = 1000$ and 5000.

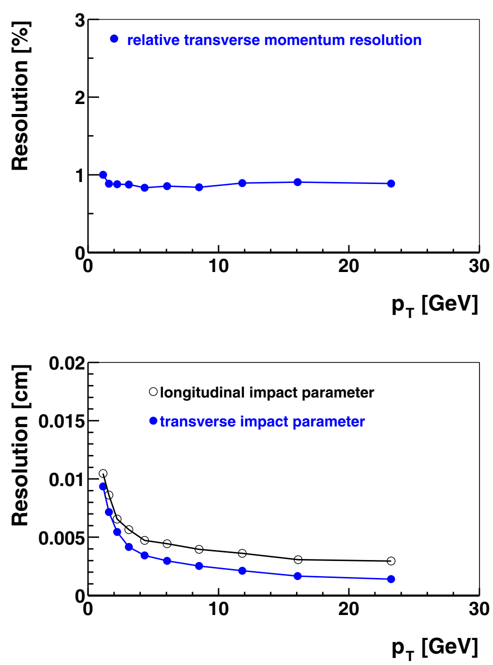

Fig. 3. The p_T dependence of the momentum resolution (top) and vertex impact parameter resolution (bottom) for events with $dN/dy = 3000$ and an embedded 100 GeV jet.

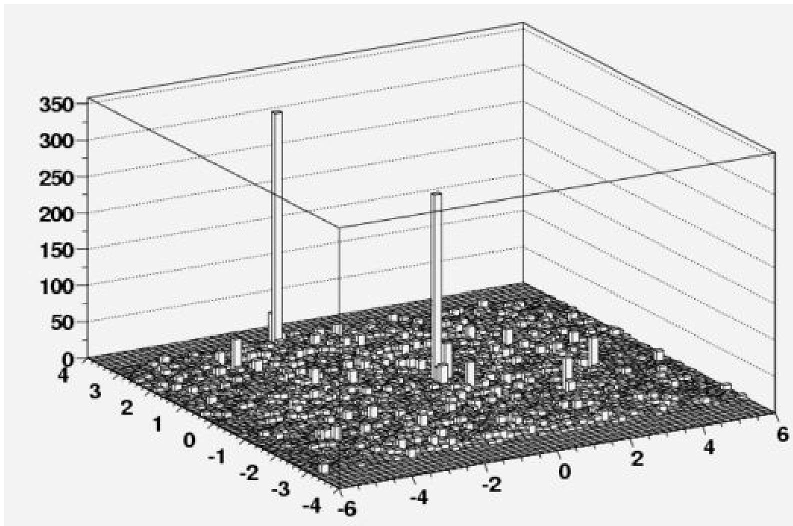

Fig. 4. Simulated energy deposits in the calorimeters for a Pb+Pb event with two embedded jets.

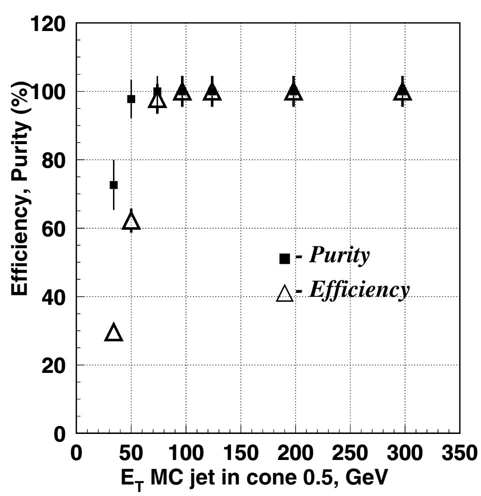

Fig. 5. Reconstruction efficiency and purity vs. jet E_T for the standard sliding-window jet-finding algorithm.

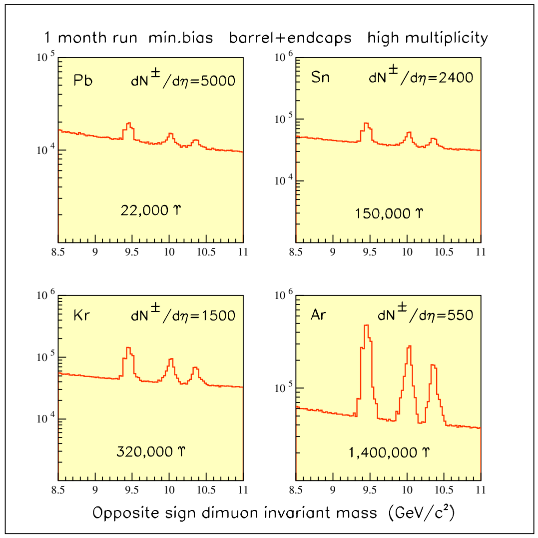

Fig. 6. Invariant mass distribution of $\mu^+\mu^-$ pairs in simulations involving various beam species and conservatively high multiplicity estimates. In the Υ region, the three S states are visible and well separated.

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 is shown in Fig. 6 for different ion species and charged particle multiplicities.

4 Heavy ion physics studies

The range of topics in heavy ion physics that can be addressed with CMS appears to be continuously growing as the full capabilities of the detector become evident. To date, therefore only the most basic features have been addressed in any detail. Some of these are briefly discussed here.

The impact parameter of the colliding nuclei, which determines the collision centrality, has shown itself to be one of the most interesting parameters with which to study the behaviour of various probes of the hot and dense matter formed in heavy ion collisions. The overlap of the nuclei defines the number of nucleons participating in the collision and the number of primary nucleon-nucleon collisions, both of which are interesting scaling variables. This overlap may be determined, as demonstrated at RHIC, by measurement of quantities showing a monotonic variation with the impact parameter. In CMS, this measurement may be achieved in a number of ways using for example, measurement of spectator neutrons in the ZDCs, global measurements of the transverse energy E_T, or charged particle multiplicity. The results of CMS studies indicate an impact parameter resolution from the E_T measurement of better than 10% .

Crucial to any analysis is the determination of the collision vertex. The high multiplicity and low event rate make this much easier than for pp collisions where multiple interactions occur with each beam crossing. Using straight line (in rz) "tracklets" reconstructed from the inner pixel layer hits, a vertex resolution better than 20 μm can be achieved. Given the collision vertex, the pixel hits can also be used to measure the charged particle multiplicity over the range $|\eta| < 2.4$. Here, the several techniques developed in PHOBOS at RHIC [6] provide event-by-event information on the mid-rapidity ($y \approx 0$) charged particle multiplicity, which can be used for a variety of physics studies. These results also complement similar studies using the global calorimeter information. The addition of the forward tracking detectors from TOTEM extends the range of multiplicity studies to $\eta < 6.7$ – a unique capability at the LHC, which opens the door to additional physics such as limiting fragmentation [7].

The study of jets and jet-jet correlations has emerged from RHIC as a major area of interest. This interest has been prompted by the observation of a suppression of high-p_T particles in central Au+Au collisions and the disappearance of the correlated back-to-back particles expected for pure parton-parton scattering [8]. These observations, and the lack thereof in d+Au collisions [9], are thought to originate from the predicted enhanced energy loss of struck partons as they propagate through the hot dense matter formed in the Au+Au collision [10]. As mentioned in the introduction, the enormous increase in high-p_T cross sections at the LHC allows a very detailed and systematic study of the modification of jet behaviour as a function of jet energy, rapidity and flavour, etc. Some 10^7 jet pairs with $E_T > 100$ GeV are expected in a one month run. In this theme, several studies have been carried out with CMS.

Events in which a jet is opposite a photon or a Z are of particular interest as the weakly or electromagnetically interacting particle can be used to "calibrate" the energy of its partner and thus provide a direct measure of the partner energy loss during its propagation in the surrounding "matter". The Z is readily reconstructed from muon pairs as shown in Fig. 7. The expected yield [2] is some 10,000 detected Zs during one month of LHC running at full Pb+Pb luminosity. An example of the sensitivity to the energy loss of the accompanying hadronic jet is shown in Fig. 8, where the measured difference in energy between a photon with $E_T > 120$ GeV and its partner is shown for energy losses of 0, 4 and 8 GeV. It is also worth noting that the dominant background under the Z peak in Fig. 7 arises from combinatorial muons from b decays. It is expected that jets originating from heavy quarks lose energy at a lower rate than light quark jets. Thus, the yield of high-p_T muons, which dominantly come from b quark decays, should provide further information on the energy-loss question. Of course, b decays are further enhanced by selection on displaced vertices, using the vertexing capability of CMS.

A consequence of the enhanced energy loss of jets as they propagate through matter is a modification of the jet fragmentation function relative to that in, for example, pp collisions. To study the fragmentation function, it is crucial to be able to study the momentum spectrum of charged particles both inside and outside the jet cone. Figure 9 is a reconstructed p_T spectrum for a single event with $dN/dy = 5000$ generated with the HIJING [11] Monte Carlo program, showing the excellent performance of the tracker and reconstruction software for particles with $p_T > 1$ GeV/c. Further work may allow this threshold to be pushed

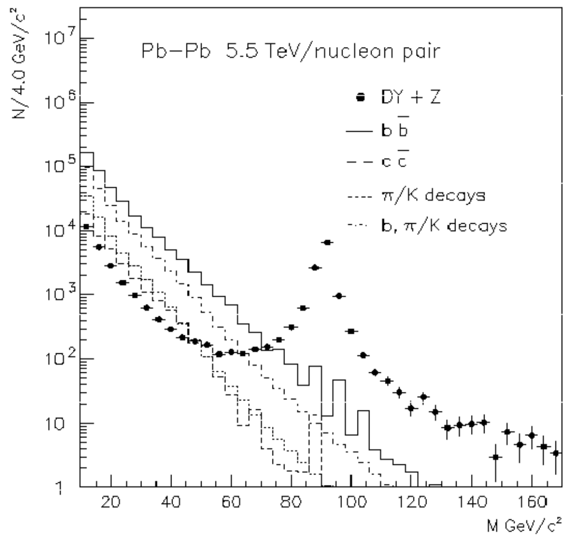

Fig. 7. Dimuon invariant mass peak in Drell-Yan and direct Z production, plus contributions to $\mu\mu$ from heavy quark and π/K decays.

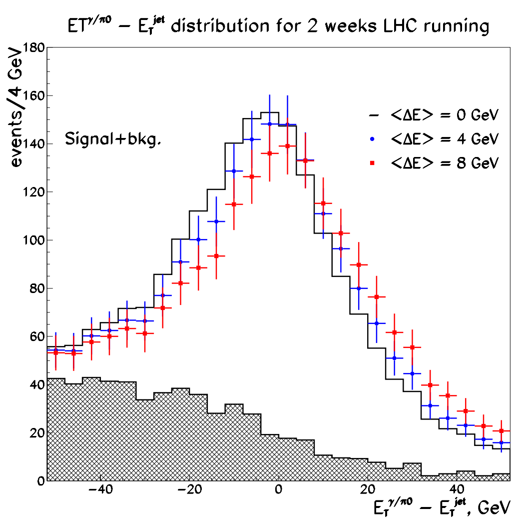

Fig. 8. Difference in transverse energy of the photon and jet in γ-jet events, with $E_T^\gamma, E_T^{\mathrm{jet}} > 120$ GeV and $|y_\gamma, y_{\mathrm{jet}}| < 1.5$ and two weeks of LHC running at $\mathcal{L} = 10^{27}$ cm^{-2}s^{-1}.

to lower p_T. The results for 100 GeV jets embedded in the same $dN/dy = 5000$ event are shown in Fig. 10, which demonstrates the quality of the fragmentation function measurement afforded by the momentum resolution of the CMS tracker and the ability to separate jets from the soft background.

As mentioned above, the CMS detector has the ability to detect muon pairs from quarkonium states in the heavy ion environment with adequate mass resolution. Preliminary studies show that a measurement of electron pairs should also be possible. Due to momentum cuts on the muons, the acceptance for charmonium decays is primarily at forward rapidity. For the heavier upsilon family, the acceptance covers a much wider range of rapidity and, for a typical p_T distribution, the reconstruction efficiency is between 80 and 90%. With the ability to study the families of quarkonium states, CMS is able to distinguish between different scenarios of suppression, which affect the various states differently [2]. Figure 11 shows an invariant mass spectrum of muon pairs, with the combinatorial background subtracted, after one month of Pb+Pb collisions at $\mathcal{L} = 10^{27}$ cm^{-2}s^{-1}.

5 New detectors and hardware for heavy ions

The desire to study heavy ion collisions with CMS has led to the proposal of new detectors and hardware specific to this physics. These are the ZDCs, the CASTOR forward rapidity calorimeter, and heavy-ion-specific contributions to the CMS High Level Trigger.

The ZDCs are designed along the lines of those already developed and in use at RHIC and measure neutral spectators from the non-interacting pieces of the colliding nuclei. They are part of a current proposal to DoE from the US groups (UC Davis, UC Riverside, UIC, U Iowa, U Kansas, MIT and Rice U) to carry out nuclear physics research with CMS. The neutrons are detected in calorimeters placed at ± 140 m from the interaction point where the collider rings first separate. The ZDCs should be compact, fast and highly radiation resistant with good energy and time resolution. It is planned to use tungsten as the absorber and to collect the signal from Cerenkov light emitted by relativistic charged particles in quartz fibres, similar to the HF and CASTOR. The ZDCs are located inside the TAN, an absorber designed to protect the first superconducting magnet from radiation, and they provide an unbiased determination of collision centrality as well as a fast trigger and vertex information from timing (~ 3 cm resolution). With CASTOR, they also complete the CMS calorimetric coverage.

The CASTOR detector, proposed by groups from Greece and Poland, is designed to study the very forward, baryon-rich region in heavy ion collisions and is motivated in part by the search of exotic events such as those reported in cosmic ray studies. It also has more general uses since, as mentioned above, it completes the coverage of CMS in the forward region. For heavy ions, it allows measurements in a region of finite baryon chemical potential and, for pp, improves the missing energy resolution over all phase space.

As the architecture of the CMS trigger and DAQ is divided into Level-1 and High-Level Trigger (HLT), where the latter runs the same software as the offline reconstruction programs, work is needed to develop and evaluate algorithms for

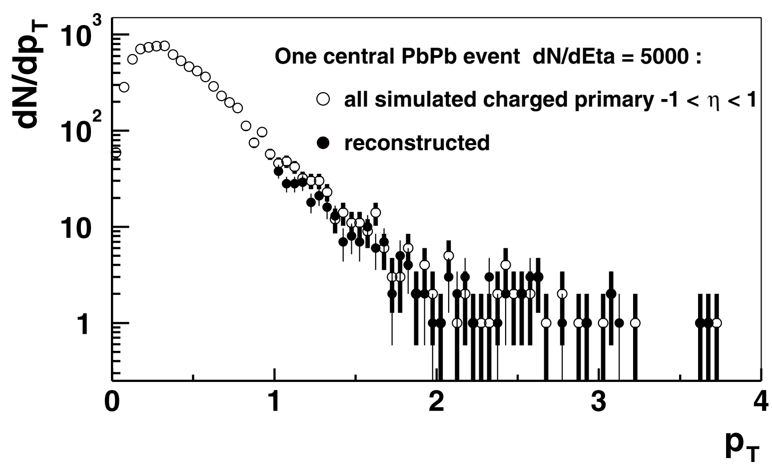

Fig. 9. Generated and reconstructed p_T distributions for charged particles in a single HIJING event with $dN/dy = 5000$.

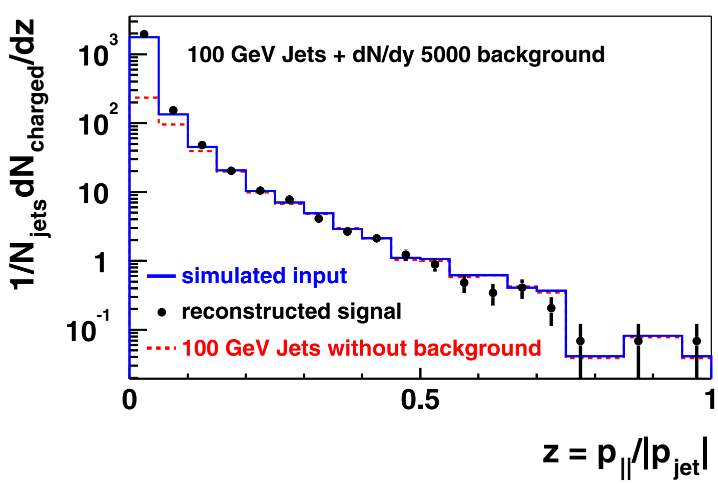

Fig. 10. Jet fragmentation function for a 100 GeV jet, with generated and reconstructed charged particle tracks, both with and without a $dN/dy = 5000$ background event.

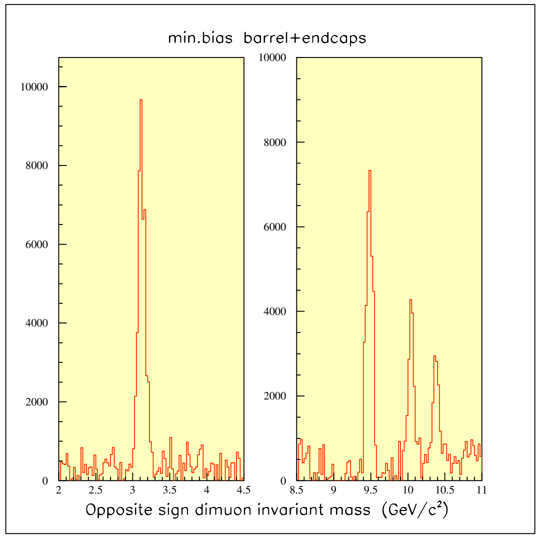

Fig. 11. J/ψ and Υ resonances in the dimuon invariant mass spectrum of a Pb+Pb event, after background subtraction of uncorrelated muons.

heavy ion physics. These algorithms are, in general, quite different from those for pp. Accordingly, it has been proposed by the US groups to contribute "slices" of the HLT computer farm, to allow independent development and testing of heavy-ion-specific software so that a short timescale switchover from pp to heavy ion running can be achieved. The planned capabilities of the HLT allow essentially all events to be analysed online at the full heavy ion collision rate.

6 Summary

In summary, heavy ion physics promises to be a rich and exciting area for investigation at the LHC. The major topics of interest play well to the strengths of the CMS detector which has outstanding capabilities for the study of high-p_T probes. The performance of the CMS detector continues to be evaluated and the range of physics topics that can be addressed continues to expand. The group of physicists interested in and participating in this program is growing and will continue to be very active.

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