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Hard probes in 2.76 TeV PbPb collisions at CMS

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This paper presents a brief overview of recent results from CMS at $\sqrt{s}$=2.76 TeV using hard probes to study quark and gluon matter in high-energy PbPb collisions. The capabilities of the CMS apparatus allow us to investigate these various hard probes using the calorimeter, muon and tracking systems covering a large range in pseudorapidity, complemented by a flexible two-level trigger system for both proton-proton and ion-ion collisions. The data collected during the 2010 and 2011 PbPb run at $\sqrt{s_{NN}}$ = 2.76 TeV, was analyzed and multiple measurements of the properties of the hot and dense matter were obtained. Detailed studies of jet production and jet properties, isolated photons, quarkonia and weak bosons were performed and compared to pp data and Monte Carlo simulations.

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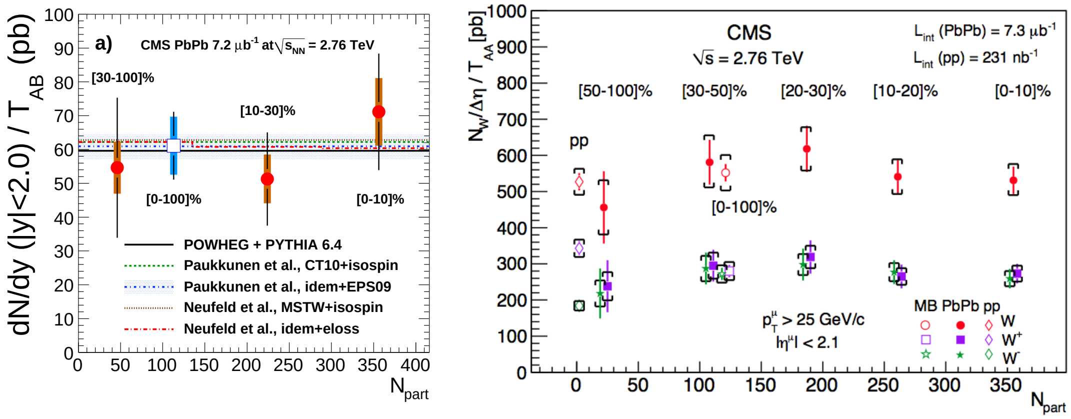
1. Introduction

The Large Hadron Collider (LHC) first produced collisions of heavy ions in November of 2010 and later in November 2011 at a nucleon-nucleon center of mass energy of $\sqrt{s_{NN}}$ = 2.76 TeV. Nuclear interactions at these energies are expected to produce matter at energy densities exceeding any previously explored in experiments conducted at particle accelerators. The CMS detector was used to study the properties of the matter created in this new regime. CMS is a general purpose particle detector very well suited to study high energy nuclear collisions [1], with its strong, 3.8 T magnetic field, electromagnetic and hadronic calorimeters covering a large pseudorapidity range $|\eta| < 5.2$, high-precision silicon tracking system ($|\eta| < 2.4$) and muon detectors outside the superconducting solenoid and the calorimeter layers. At very small angles with respect to the beam line, the CASTOR calorimeter and the Zero Degree Calorimeters (ZDCs) complement the central apparatus. CMS employed its flexible triggering system to select and write to tape all events containing high p_T jets, photons and muons while recording a scaled-down random sample of minimum bias events. For analysis of PbPb events, it is important to determine the overlap or impact parameter of the two colliding nuclei, usually called "centrality". Centrality in CMS was determined using the total sum of transverse energy in reconstructed towers from both positive and negative Hadronic Forward (HF) calorimeters. Centrality for specific event classes is expressed as a percentage of the inelastic nucleus-nucleus interaction cross section.

2. Hard Probes

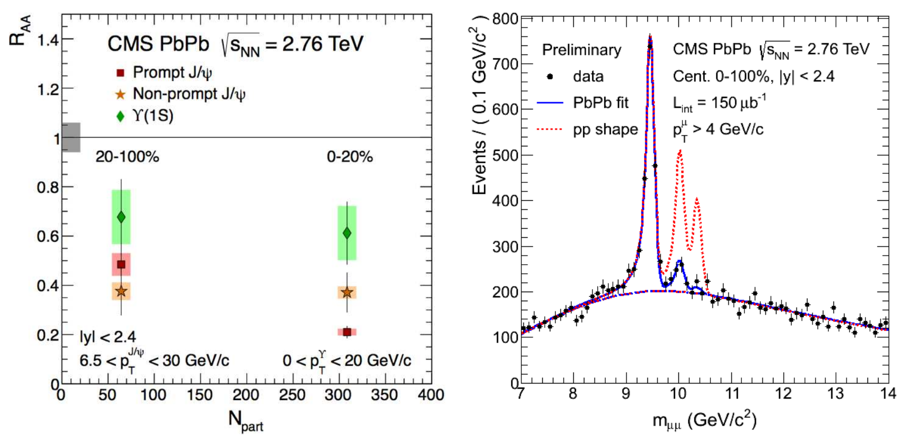
Hard scattering processes creating electroweak bosons play an important reference role in the heavy-ion research at LHC. These electroweak bosons (γ, Z, W) are of interest because these particles or their leptonic decays can be observed without modification when they go through the Quark Gluon Plasma (QGP). Measurements of the cross sections of isolated photons at high p_T [2], as well as $Z \to \mu^+\mu^-$ [3] and $W^\pm \to \mu^\pm\nu$ [4] processes in PbPb collisions were completed using the CMS electromagnetic calorimeters, tracker and muon systems and the capabilities of measuring the missing transverse momentum, respectively. The production yields of these three particles, normalized by the nuclear overlap function, is consistent with that measured or calculated for pp collisions at the same center-of-mass energy. For instance, the full circles in Figure 1(a) show the centrality dependence of the Z yield divided by T_{AB}, while the open square is for MB collision events. The variable used on the abscissa is the average number of participating nucleons N_{part} corresponding to the selected centrality intervals. No centrality dependence of the binary-scaled Z yields is observed in data. Different yields of W^+ and W^- particles were observed in PbPb with respect to that in pp collisions, reflecting the different u and d quark content in the proton and neutron and the Z/A ratio of the Pb ion, as can be seen in Figure 1(b).

Quarkonia are important for studying the QGP since they are produced early in the collision and their survival is affected by the surrounding medium. The bound states of charm and bottom quarks are expected to be suppressed in heavy ions, as compared to pp. The magnitude of the suppression for different quarkonium states is expected to depend on their binding energy. By selecting events with opposite-sign dimuons, CMS obtained production rates of J/Ψ mesons and of the Υ family. Non-prompt J/Ψs (those produced from B-meson decays) are identified by good



(a) (b)

Figure 1: (a) The yields of $Z \rightarrow \mu^+\mu^-$ per event are shown and compared to various theoretical calculations. dN/dy divided by the expected nuclear overlap function T_{AB} and as a function of event centrality parametrised as the number of participating nucleons N_{part} (b) Centrality dependence of the $W^{\pm} \rightarrow \mu^{\pm}\nu$ yields in PbPb and pp collisions.



(a) (b)

Figure 2: (a) The R_{AA} for prompt and non-promt J/Ψ in two different centrality binning, overlaid with the Υ(1S). (b) $\mu^+\mu^-$ invariant mass spectrum in the Υ region measured in PbPb overlaid with two fits. The red continuous line is a free fit to the PbPb data. The dashed blue line is a fit with a free background shape.

momentum resolution and precise vertex pointing capabilities of the CMS tracker system. The suppressions of prompt and non-prompt J/Ψ particles were measured separately [5]. The non-prompt J/Ψ suppression is one measure of the quenching of b-quarks. The R_{AA} as a function of the number of participants N_{part} indicates that high transverse momentum J/Ψs are strongly suppressed compared to non-prompt J/Ψs and Υ(1S) for most central events, as can be seen in Figure 2(a). The excellent dimuon mass resolution allowed good separation of the three bound states of the Υ family [6]. The excited states, Υ(2S) and Υ(3S), are found to be suppressed as compared to the Υ(1S), Figure 2(b). This is compatible with differential melting of quarkonium states in the high temperatures produced by PbPb collisions.

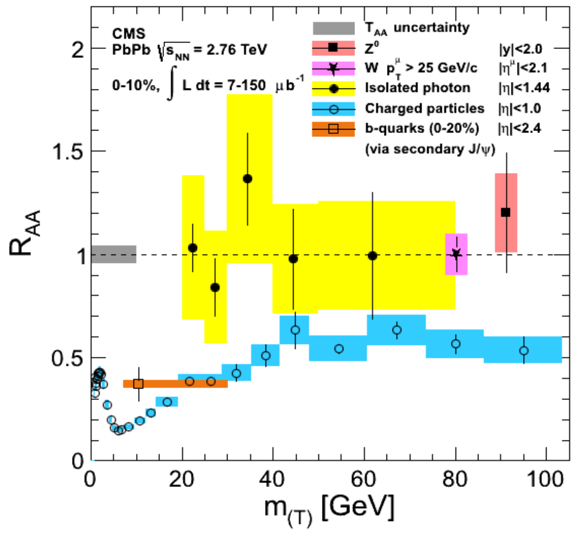


Figure 3: The ratio R_{AA} for Z, isolated photon and charged particles for the most central events (0-10%).

We can conclude that the production of charged hadrons [7] and J/Ψ particles created from b-quark decays are strongly suppressed in central PbPb collisions compared to the pp reference, as shown in Figure 3. As expected, no modification is observed in W, Z and isolated photon production.

Studying the modification of jets as they are formed from high p_T partons passing through the hot and dense medium has been proposed as a particularly useful tool for probing QGP properties. The energy lost by a parton in this medium is often referred to as "jet quenching" and provides fundamental information on the thermodynamical and transport properties of the traversed medium. Of particular interest are the dominant "dijets", consisting of the most energetic ("leading") and second most energetic ("sub-leading") jets. To study medium effects, dijets are selected with a leading (sub-leading) jet with p_T of at least 120 (50) GeV/c, both within $|\eta| < 2$ and with an opening angle $\Delta\phi > 2\pi/3$ [8, 9]. The most striking observation is the large, centrality-dependent, imbalance in the energy of the two jets, as measured in the CMS calorimeters. While their energies are very different, the two jets are observed to be very close to back-to-back in the azimuthal plane, implying little or no angular scattering of the partons during their traversal of the medium. Figure 4 shows the mean transverse-momentum ratio, $\langle p_{T,2}/p_{T,1}\rangle$, of subleading and leading jets as a function of the transverse momentum of the leading jet, $p_{T,1}$, in three centrality classes. With increasing centrality, the imbalance grows, while the difference between the measured ratio in PbPb collisions and the reference pp is independent of transverse momentum. To further study jet properties in the PbPb environment, the hard component of the fragmentation function was compared to the fragmentation of jets produced in pp collisions at the same energy [10]. The distribution of charged particle momenta within the jet, normalized to the measured jet energy, is strikingly the same, within uncertainties, to that seen in jets produced with equivalent energy in pp collisions.

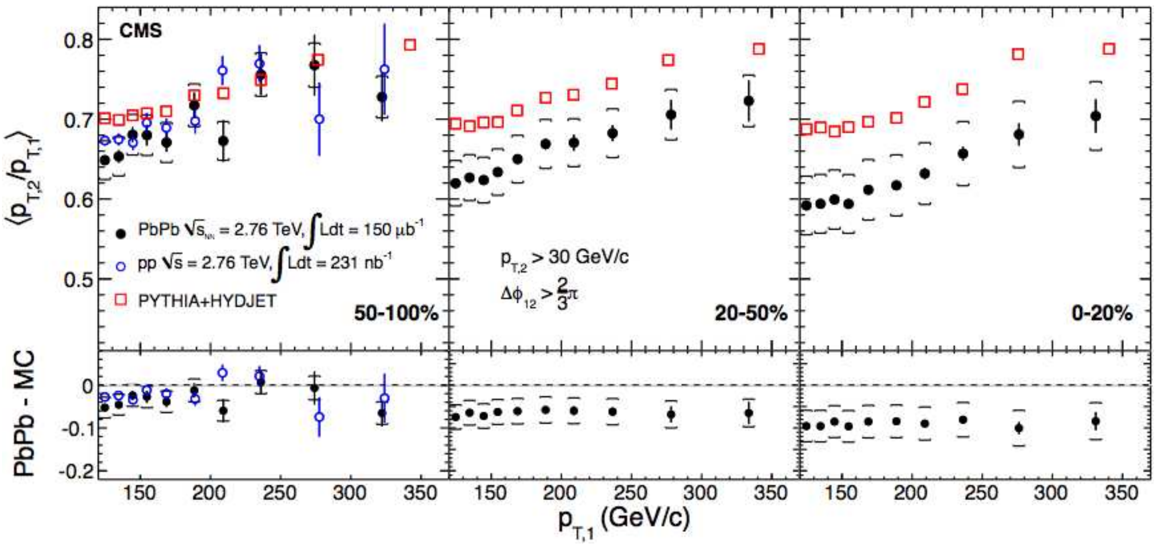


Figure 4: Average dijet momentum ratio, $\langle p_{T,2}/p_{T,1}\rangle$, as a function of leading jet p_T for three bins of collision centrality. PbPb data are shown as filled circles, while predictions from the PYTHIA+HYDJET model are shown as squares. In the most peripheral bin, results are compared with pp data (open circles). The difference between the PbPb measurement and the expectations from PYTHIA+HYDJET is shown in the bottom panels.

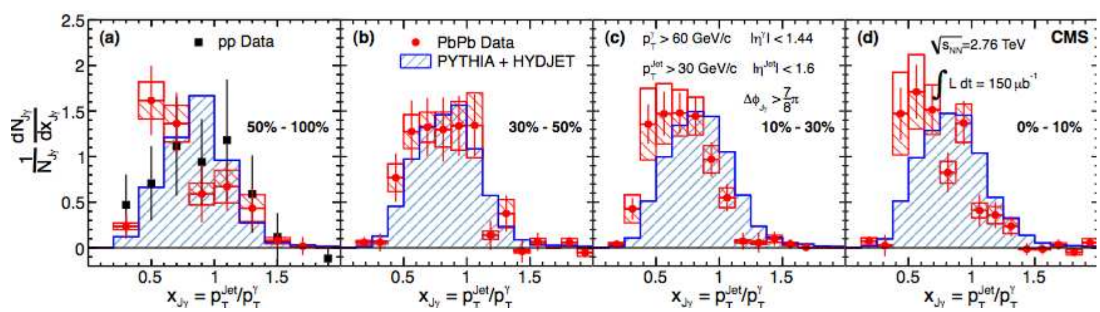


Figure 5: Ratio of p_T between the photon ($p_T^{\gamma} > 60\ GeV/c$) and jet ($p_T^{Jet} > 30\ GeV/c\ \Delta\phi_{J\gamma} > \frac{7}{8}\pi$) after subtracting background and comparison to the PYTHIA+HYDJET MC simulation in bins of increasing centrality left to right.

A recent measurement of the transverse momentum balance in isolated photon-jet pairs in PbPb collisions was implemented [11]. This “golden channel" is particularly interesting since the direct photon is not affected by the presence of the medium, and can thus have its transverse momentum compared to that of the jet to identify quenching. The asymmetry ratio $x_{J\gamma} = p_{Jet}/p_{\gamma}$ is used to quantify the photon+jet momentum imbalance. Figure 5 shows the centrality dependence of $x_{J\gamma}$ for PbPb collisions as well as that for PYTHIA+HYDJET simulation. While the photon+jet momentum ratio in the PYTHIA+HYDJET simulation shows almost no change in the peak location and only a modest broadening, even in the most central PbPb events, the PbPb collision data exhibit a change in shape, shifting the distribution towards lower $x_{J\gamma}$ as a function of centrality.

3. Summary

The CMS collaboration has measured the properties of heavy-ion collisions at the highest energies available with the CMS detector performing very well in all major sectors. Measurements of charge particle spectra, photons, jets, quarkonia and weak bosons were conducted over a wide azimuthal and rapidity range and with high resolution. It has been shown that a strongly interacting medium can be well described by hydrodynamics. The detailed pattern of suppression was measured using reconstructed quarkonium states with varying binding energies. Large suppression of strongly interacting probes has been observed while the photons and weak bosons appear not to be suppressed. These results provide quantitative input to models of the transport properties of the medium created in the heavy-ion collisions.

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