Overview of experimental results in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by the CMS Collaboration

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Abstract.
We present first results of the CMS experiment from PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, probing quark and gluon matter at unprecedented values of energy density. The capabilities of the CMS detector allow us to investigate various hard probes, as well as bulk particle production and collective phenomena, using the calorimetry, 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 November 2010 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. Global event properties, detailed study of jet production and jet properties, isolated photons, quarkonia and weak bosons were measured and compared to pp data and Monte Carlo simulations.

1. Introduction
The Large Hadron Collider (LHC) first produced collisions of heavy ions in November of 2010 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]. High precision tracking and calorimetry with fine granularity are augmented with a sophisticated multi-level triggering system. The initial analysis of CMS heavy ion data revealed information including global particle production which is related to the initial state formed in the collision, various observables sensitive to the hydrodynamical expansion of the system, and detailed probes of the produced medium by studying the propagation of a broad range of particles. More details on the analysis of specific results can be found in the measurements on global properties of charged particle production [2], transverse energy [3], high multiplicity [4] and HBT [5] in pp collisions, elliptic flow [6], dihadron correlations [7, 8], charged particle $R_{AA}$ [9], jet quenching and fragmentation [10, 11], photons [12], quarkonia suppression [13, 14] and weak bosons [15].

The CMS detector incorporates a broad suite of high precision subsystems which were originally optimized for very high energy pp collisions but which also provide unprecedented capabilities for studying nuclear collisions. The CMS uses a right-handed coordinate system with z-axis parallel and x, y-axis perpendicular to the LHC beam direction, azimuthal angle $\phi$.

1 On behalf of the CMS Collaboration
and polar angle $\theta$. Particles with energies $E$ and momenta $\vec{p}$ are characterized by transverse momentum $p_T = |\vec{p}| \sin \theta$, rapidity $y = \frac{1}{2} \ln \frac{E + p_T}{E - p_T}$, and pseudorapidity $\eta = -\ln \tan \frac{\theta}{2}$. A central feature of the CMS apparatus is the superconducting solenoid of 6 m internal diameter, providing a uniform magnetic field of 3.8 T. The inner tracking system is composed of a pixel detector with three barrel layers at radii between 4.4 and 10.2 cm and a silicon strip tracker with 10 barrel detection layers extending outwards to a radius of 1.1 m. Each system is completed by two endcaps, extending the acceptance up to a pseudorapidity $|\eta| = 2.5$. The nominal momentum resolution is typically 0.7 (5.0)% at 1 (1000) GeV/c in the central region [16].

The calorimeters inside the magnetic coil consist of a lead-tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadronic calorimeter (HCAL). These calorimeters provide a hermetic coverage over a large range of pseudorapidity ($|\eta| < 3$ for ECAL and $|\eta| < 5$ for HCAL). The return field is large enough to saturate 1.5 m of iron, allowing 4 layers of muon stations located outside the solenoid. Each muon station consists of several layers of aluminum drift tubes (DT) in the barrel region surrounding the solenoid and cathode strip chambers (CSC) in the endcap region, complemented by resistive plate chambers (RPC). All of these detectors have sufficient granularity and resolution to function well even in the highest multiplicities encountered in PbPb collisions. The CMS trigger and data acquisition systems were specially configured for the 2010 PbPb run to prepare for possible surprises related to the large multiplicities expected in these collisions. In particular, the silicon micro strip tracker and the ECAL and HCAL calorimeters were read out in non-zero suppressed mode, recording information from all channels. The zero suppression was done during the offline processing using algorithms optimized for PbPb environment. The maximum inelastic PbPb collision rate achieved during the run was about 220 Hz while the maximum rate that could be written to tape was about 140 Hz. 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.

The multiplicity of charged particles produced in the central rapidity region is a key observable to characterize the properties of the matter created in heavy-ion collisions. The pseudorapidity dependence of a measurement of charged particle multiplicity density $dN_{ch}/d\eta$ is shown in Figure 1(left) in various centrality bins. The $\eta$ dependence of the results is weak, varying by less than 10% over the $\eta$ average. The slight dip at $\eta=0$ is a trivial kinematic effect owing to the use of pseudorapidity rather than rapidity. The data for this measurement was taken without a magnetic field in order to include particles with transverse momenta down to about 30 MeV/c. The number of charged hadrons was obtained by two methods based on the inner silicon pixel system. One technique involved counting the number of reconstructed single particle hits in the pixel detector, while the other formed hit pairs (“tracklets”) from the different detector layers. Another key observable to study the medium properties which is sensitive to the energy density achieved in heavy-ion collisions is the transverse energy $E_T$. Measurement of the transverse energy provides very basic information on heavy-ion collisions about the dynamics of the collisions and the total entropy created. Figure 1(right) shows the $\eta$ dependence of $E_T$ production. For the most central collisions, $\sim 2.1$ TeV of transverse energy is created at $\eta = 0$. This is about three times higher than at Relativistic Heavy Ion Collider (RHIC).

The hydrodynamic expansion of matter produced in non-central heavy-ion collisions as well as the fluctuation of initial state lead to an azimuthal anisotropy in particle production, and the azimuthal anisotropy of charged particles is an important feature of the hot and dense medium produced in heavy-ion collisions. There are various methods to estimate the magnitude
Figure 1. (left) Charged particle multiplicity density $dN_{ch}/d\eta$ for different centralities as a function of $|\eta|$. (right) Transverse energy density $dE_T/d\eta$ as a function of $|\eta|$ for most central events (0-2.5%) of anisotropic flow, including event plane, 2- and 4-particle cumulants, Lee-Yang Zeros (LYZ) as well as dihadron correlations in the full CMS detector acceptance. These methods have different sensitivities to the initial conditions of the system and the interplay between soft-particle production and jet quenching effects. Figure 2 shows a comparison of $v_2(p_T)$ between CMS and PHENIX [17] using event plane method in mid-rapidity range. Despite a dramatic energy increase from RHIC to LHC, $v_2$ is only slightly larger than that at RHIC. The observed increase is within the systematic uncertainties. To better understand the pseudorapidity dependence of $v_2$ as a function of centrality, the results for the event plane method are shown for each centrality bins on Figure 3, in which negative and positive rapidities were averaged. The more peripheral collisions plotted in the right panel seem to indicate a stronger pseudorapidity dependence.

The charged particle $p_T$ spectrum is an important observable for studying the properties of the hot and dense medium produced in the collisions of heavy nuclei. The modification of charged particle $p_T$ spectrum, compared to nucleon-nucleon collisions at the same energy can shed light on the detailed mechanism by which hard partons lose energy traversing the medium. It has been already observed at RHIC that high $p_T$ particle production is suppressed relative to expectations from an independent superposition of nucleon-nucleon collisions. This observation is typically expressed in terms of the nuclear modification factors $R_{AA}$. The $R_{AA}$ was measured in CMS for all charged particles with $p_T$ up to 100 GeV/c. Figure 4 shows the charged particle invariant differential yields in six centrality bins and compared to the corresponding quantity taken from the interpolated pp reference spectrum [18]. By comparing the points to the dashed lines from the scaled pp reference spectrum, it is very clear that the charged particle spectrum is strongly suppressed in central PbPb events. Figure 5 shows the nuclear modification factor for charged particles as a function of transverse momentum for the same centrality bins. In the most peripheral events (70-90%), a moderate suppression of about two ($R_{AA}=0.5$) is observed at low $p_T$ while $R_{AA}$ rises gently with increasing transverse momentum.

High transverse energy prompt photons in nucleus-nucleus collisions are produced directly...
Figure 2. Comparison of $v_2$ using the event plane method as a function of $p_T$ from CMS (closed symbols) at $\sqrt{s_{NN}} = 2.76$ TeV and PHENIX (open symbols) at $\sqrt{s_{NN}} = 200$ GeV for mid-rapidity events ($|\eta| < 0.8$, and $|\eta| < 0.35$, respectively).

Figure 3. Dependence of $v_2$ on $|\eta|$ for the event plane method in 12 centrality classes. The error bars show the statistical uncertainties, and boxes give the systematic uncertainties.
Figure 4. (Upper) Invariant differential yield in bins of collision event centrality (symbols), compared to a pp reference spectrum, scaled by the corresponding number of binary nucleon-nucleon collisions (dashed lines). The spectra for different centrality bins have been scaled by the arbitrary factors shown in the figure for easier viewing. (Lower) The systematic uncertainties on the PbPb differential yields as a function of $p_T$ for the 0-5% and 5-90% centrality intervals.
Figure 5. Nuclear modification factor $R_{AA}$ (filled circles) as a function of $p_T$ for six centrality intervals. The error bars represent the statistical uncertainties, and the yellow boxes the $p_T$-dependent systematic uncertainties on the $R_{AA}$ measurements. An additional systematic uncertainty from the normalization of $T_{AA}$ [9], common to all points, is shown as the shaded band around unity in each plot.

from the hard scattering of two partons. The photons provide a direct test of perturbative Quantum Chromodynamics (pQCD) and the nuclear parton densities when they pass through the hot and dense medium without any interaction. However, the measurement of prompt photons is complicated by the much larger background coming from the electromagnetic decays of neutral mesons produced in the fragmentation of other hard scattered partons. One can suppress a large fraction of these decay photon backgrounds by imposing isolation cuts on the reconstructed photon candidates. The centrality and $p_T$ dependence of the direct photon production in PbPb collisions are compared to the NLO pQCD predictions [19]. Figure 6(left) shows the normalized yields ($dN/dE_T$) $/T_{AA}$. The normalized yields are compared to the pp spectrum predicted by JETPHOX calculation [19]. The normalized PbPb data and the predicted pp results are in agreement within the quoted statistical and systematic uncertainties.

With the increase of center-of-mass energy at the LHC, electroweak probes are accessible for the first time in heavy-ion collisions. Electroweak bosons ($Z, W$) are of interest because they go through the Quark Gluon Plasma (QGP) unaffected. Among the leptonic decays of the electroweak bosons, the study of the $Z$ in the $\mu^+\mu^-$ channel is the cleanest one experimentally. The dimuon decay channel is of special interest because the muons are unaffected by the strongly interacting QGP. Figure 6(right) shows the nuclear modification factor $R_{AA}$ as a function of transverse mass for $Z$ bosons, isolated photons and charged particles for the most central events. As expected, no modification is observed in $Z$ and isolated photon production while large suppression is observed in the charged particle spectra which is due to the final state
Figure 6. (left) Normalized isolated photon yields \((dN/dE_T)/T_{AA}\) as a function of photon \(E_T\) in 0-10%, 10-30%, 30-100% and MinBias PbPb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV. The results are compared with the pp prediction using JETPHOX, with its scale uncertainty. (right) The ratio \(R_{AA}\) for \(Z\), isolated photon and charged particles for the most central events (0-10%).

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 \(\Delta \phi > 2\pi/3\). The most striking observation is the large, centrality-dependent, imbalance in the energy of the two jets, as measured in the CMS calorimeters (See Figure 7). 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. To find the missing energy, the calorimetric measurement was complemented by a detailed study of low \(p_T\) charged particles in the tracker and by using missing \(p_T\) techniques. The apparent missing energy was found among the low \(p_T\) particles, predominantly with \(0.5 < p_T < 2\) GeV/c, emitted outside of the sub-leading jet cone. 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. The comparison of fragmentation functions for pp and PbPb events for different centralities is shown in Figure 8. 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 the equivalent jets energy produced in pp events.

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
Figure 7. Calorimetric jet imbalance in dijet events as a function of collision centrality for pp and PbPb events.

Figure 8. Fragmentation functions for jets produced in pp and in both peripheral (30-100%) and central (0-30%) PbPb collisions.
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 $J/\Psi$ mesons and of the $\Upsilon$ family. Non-prompt $J/\Psi$s (those produced from B-meson decays) are identified by their displaced decay vertex. The suppressions of prompt and non-prompt $J/\Psi$ particles were measured separately. The non-prompt $J/\Psi$ suppression is one measure of the quenching of $b$-quarks. The $R_{AA}$ as a function of the number of participants $N_{\text{part}}$ indicates that high transverse momentum $J/\Psi$s are strongly suppressed as shown in Figure 9(left). The excellent dimuon mass resolution allowed good separation of the three bound states of the $\Upsilon$ family. Figure 9(right) shows that the excited states, $\Upsilon(2S)$ and $\Upsilon(3S)$, are suppressed as compared to the $\Upsilon(1S)$. This is compatible with differential melting of quarkonium states in the high temperatures produced by PbPb collisions.

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 multiplicity, azimuthal asymmetry, dihadron correlations, 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.

2. References

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