Heavy ion physics from the CMS collaboration

P Sarin for the CMS collaboration
Indian Institute of Technology Bombay, Mumbai, India 400076

E-mail: pradeepsarin@iitb.ac.in

Abstract. We present an overview of results obtained by analyses of data from heavy ion (PbPb) collisions in the CMS experiment at LHC. The heavy ion physics program of the CMS collaboration spans a gamut of interesting measurements on high density multi-particle systems created in PbPb collisions at the TeV scale. We highlight key results from the inclusive production of charged particles at high $p_T$, the effect of QCD dynamics on jets and heavy quark bound states. Intriguing new results on long range angular two-particle correlations observed in PbPb and pPb collisions are also presented.

1. Overview of the CMS physics program and the context for heavy ion collision studies

The CMS experiment[1] has excellent capabilities for particle tracking and energy measurement. The CMS superconducting solenoid, 12.5 m long with an internal diameter of 6m, provides 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 out to a radius of 1.1 m. This is complemented by two endcaps, extending the acceptance up to $|\eta|=2.5$. The momentum resolution for reconstructed tracks in the central region is about 1% at $p_T = 100$ GeV/c.

The calorimeters inside the magnetic coil consist of a lead-tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadron calorimeter (HCAL) with coverage up to $|\eta|=3$. Quartz/steel forward hadron calorimeters extend the calorimetry coverage up to $|\eta|=5.2$. Muons are measured in gas-ionization detectors embedded in the steel return yoke of the magnet. The calorimeter cells are grouped in projective towers of granularity $\Delta\eta \times \Delta\phi=0.087 \times 0.087$ for central rapidity.

Fig 1 shows a schematic view of these numbers for tracking and calorimetric coverage. The azimuthal $\phi$ coverage is complete.

![Fig 1: $\eta$ coverage of the tracking and calorimeter detectors (left), and CMS (cutaway view right).](image)

Beam pseudorapidity for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is 8.

1 To whom any correspondence should be addressed.
For the high multiplicity of particles generated in PbPb collisions, this excellent ($\eta, \phi$) coverage and resolution are invaluable, though tracking does present a formidable challenge. Special high level triggers are used to record rare events with signals of interest like events with high $p_T$ jets and quarkonia. The details of the following analyses are described in the literature[2,7,8,13,14,15,16,17] where the results are published and not elaborated here.

A major advantage of the CMS detector setup is that it is used to perform a variety of physics measurements in pp collisions. By making our observations at the same centre of mass energy scaled by the number of binary nucleon-nucleon collisions in the same apparatus, many uncertainties are minimized that may creep in when comparing to baseline pp measurements in different setups.

The results presented in the following sections are derived from data acquired during the month long PbPb running periods in 2010 and 2011 at $(s_{NN})^{1/2}=2.76$ TeV. Each period corresponds to an integrated luminosity of 8 $\mu b^{-1}$ and 150 $\mu b^{-1}$ respectively. Comparisons to pp measurements are made using data from pp collisions at the same centre of mass energy in CMS. A short pPb test run lasting approximately 4 hours was performed at the end of 2012, in preparation of the pPb run planned for spring 2013. This run yielded about two million pPb collisions which show very interesting results – these results are also presented in this paper.

The rest of this paper is organized in four sections – each section deals with a key result from the CMS heavy ion program:

Section 2: Study of high $p_T$ charged particle suppression

Section 3: Measurements of jet quenching

Section 4: Observation of sequential heavy quark bound state suppression in PbPb collisions

Section 5: Measurements of long-range near-side angular correlations in PbPb and pPb collisions

A complete, up-to-date list of all the physics results published by the heavy ion physics group in CMS can be found at: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

2. Suppression of high $p_T$ charged particles

The charged particle spectrum at large transverse momentum $p_T$ is dominated by hadrons originating from parton fragmentation. A large density of energy is created in the centre of mass of two Pb ions colliding at TeV scale which is expected to produce a many body system with dynamics governed by many-body QCD interactions. The dynamics of such a system are vital to the understanding of many-body QCD in asymptotically large momentum exchange (and hence small distance) regime. The study of the modifications of the $p_T$ spectrum of charged particles in PbPb compared to pp collisions at the same collision energy can shed light on the mechanism by which hard partons lose energy traversing the medium.

The results of the invariant charged particle differential yield $E dN_{ch}/dp_T$ [2] as a function of $p_T$ for mid-rapidity $|\eta|<1$ are compared between pp and PbPb collisions in Fig 2. The left panel indicates that the yield in pp collisions is consistent with a global power law scaling prediction from NLO QCD[3]. The right panel shows the yield in PbPb collisions for six centrality bins. The collision centrality is determined from the total event-by-event energy deposited in both HF calorimeters[2].

Fig 2: Invariant charged particle yield as a function of $p_T$ in pp (left) and various centrality bins of PbPb collisions (right)
By comparing the PbPb measurements to the dashed lines representing the scaled pp reference spectrum, it is clear that the charged particle spectrum is strongly suppressed in central PbPb events compared to pp, with the most pronounced suppression at around 5–10 GeV/c.

$R_{AA}$ quantifies the amount of this suppression as a function of $p_T$:

$$R_{AA}(p_T) = \frac{1}{(T_{AA})} \frac{d^2N_{ch}^{AA}}{dp_T d\eta} / \frac{d^2\sigma_{ch}^{pp}}{dp_T d\eta}$$

where $N_{ch}^{AA}$ and $\sigma_{ch}^{pp}$ represent the charged particle yield per event in AA collisions and the charged particle cross section in pp collisions, respectively. In order to compare the yield of high-$p_T$ charged particles produced in PbPb and pp collisions, a scaling factor, the nuclear overlap function $T_{AA}$, calculated from the Glauber model[5,6] is used to provide a proper normalization as a function of centrality. The suppression $R_{AA}(p_T)$ is shown in Fig 3.

In the most peripheral events 70–90 % (top left in Fig 3), a moderate suppression $R_{AA} \approx 0.6$ is observed at low $p_T$. The suppression becomes more pronounced in central collisions (bottom right in Fig 3) as is expected from the increasingly dense final-state system and longer average path-length of hard-scattered partons before fragmenting into final hadrons.

In stark contrast to charged particles, isolated photon yield measured in CMS[7] shown in Fig 4 indicates an $R_{AA}$ consistent with 1 even for very high momentum photons in the most central (0-10%) collisions.
3. Measurements of jet quenching

The suppression of inclusive charged yield described in the previous section provides a hint of energy loss by fast partons traversing through a dense medium. Since these fast partons fragment into jets, further quantitative information on the transport properties of the medium can be gained by looking at the momentum imbalance between fully reconstructed jets[8].

To characterize the momentum imbalance between back-to-back jets produced in PbPb collisions, we define the asymmetry ratio:

\[ A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \]

where \( p_{T,1} \) is the total transverse momentum of the ‘leading’ jet and \( p_{T,2} \) is the total transverse momentum of the azimuthally opposed ‘sub-leading’ jet. In the absence of any effect caused by the dense many-body system that the jets have to traverse, \( p_{T,1} = p_{T,2} \) and \( A_J = 0 \) by construction. Fig 5 shows the measured values of \( A_J \) in various bins of centrality. A substantial degree of asymmetry is observed for the most central events.

The distributions of the mean ratio of sub-leading to leading jet momentum \( \frac{p_{T,2}}{p_{T,1}} \), shown in Fig 6, provide a more intuitive way of quantifying the energy loss[8]. The PbPb data and results of simulation of jet production and quenching performed using PYTHIA+HYDJET event generator reveal an increasing trend for the mean value of this ratio, as a function of the leading jet \( p_{T,1} \). This can be understood as the reduction in the effects of jet splitting and energy resolution as one goes to higher jet momenta. However, the central PbPb data points consistently fall below the predictions of PYTHIA+HYDJET.
4. Sequential suppression of heavy quark bound states in PbPb collisions

A dense and strongly interacting many particle QCD system, like the one formed in heavy-ion collisions, is expected to screen the confining potential of heavy quark-antiquark pairs[9], leading to the melting of charmonia (J/ψ, ψ, χc ...) and bottomonia (Y(1S), Y(2S), Y(3S)). The melting temperature depends on the binding energy of the quarkonium state. The ground states J/ψ, Y(1S) are expected to dissolve at significantly higher temperatures than the more loosely bound excited states. Quenched lattice QCD calculations [10,11] predict that the Y(nS) states melt at 1.2Tc (3S), 1.6Tc (2S), and above 4Tc(1S). This sequential melting pattern is generally considered a ‘smoking-gun’ signature of the QCD deconfinement transition. See the excellent review by H. Satz in these proceedings[12].

The muon momentum resolution of the CMS detector gives well-resolved Y peaks in the dimuon mass spectrum as shown in Fig 7. Y states are identified through their dimuon decay[13]. The yields of the Y(nS) states as a function of centrality[14]. Absolute suppression of the individual Y states and their dependence on the collision centrality are studied using the nuclear modification factor, \( R_{AA} \), defined as the yield per nucleon-nucleon collision in PbPb relative to that in pp. The \( R_{AA} \) observable:

\[
R_{AA} = \frac{L_{pp}}{T_{AA}N_{MB}} \frac{Y(nS)|_{PbPb}}{Y(nS)|_{pp}} \frac{\epsilon_{pp}}{\epsilon_{PbPb}}
\]

is evaluated from the ratio of total Y(nS) yields in PbPb and pp collisions corrected for the ratio of efficiencies \( \epsilon_{pp}/\epsilon_{PbPb} \), the average nuclear overlap function \( T_{AA} \), number of minimum bias (MB) events sampled by the event selection \( N_{MB} \), and integrated luminosity of the pp data set \( L_{pp} \) accounting for normalization. Fig 8 shows the obtained values of \( R_{AA} \) for Y(1S) and Y(2S) as a function of centrality.

Fig 7: Dimuon invariant-mass distributions from the pp(a) and PbPb(b) data at \( \sqrt{s_{NN}}=2.76 \) TeV. The same reconstruction algorithm and analysis criteria are applied to both data sets, including a transverse momentum requirement on single muons of \( p_T > 4 \) GeV/c.

Fig 8: The nuclear modification factor \( R_{AA} \) for the yield of Y(1S) and Y(2S) in PbPb/pp collisions at \( \sqrt{s_{NN}}=2.76 \) TeV. The ratio benefits from cancellation of the efficiencies \( \epsilon_{pp}/\epsilon_{PbPb} \) since the same muon reconstruction algorithms are used for both analyses.
The centrality integrated (0-100%) $R_{AA}$ values for the individual Y states are:

$R_{AA}(Y(1S)) = 0.56 \pm 0.08 \text{(stat)} \pm 0.07 \text{(sys)}$

$R_{AA}(Y(2S)) = 0.12 \pm 0.04 \text{(stat)} \pm 0.02 \text{(sys)}$

$R_{AA}(Y(3S)) = 0.03 \pm 0.04 \text{(stat)} \pm 0.01 \text{(sys)} < 0.1 \text{(95\% CL)}$

The measurement of the double ratio: ‘ratio of Y(nS)/Y(1S) ratios in PbPb to pp collisions’ is much more interesting from a physics perspective[12]. It is expected that it corresponds to the lowered melting temperature of the higher (loosely) bound quarkonium states. The double ratio benefits from an almost complete cancellation of possible acceptance or efficiency differences among the reconstructed resonances. A simultaneous fit to the PbPb and pp mass spectra gives the results:

$\frac{Y(2S)/Y(1S)}{Y(2S)/Y(1S)}_{PbPb} = 0.21 \pm 0.07 \text{(stat)} \pm 0.02 \text{(sys)} \quad \text{5\sigma result}$

$\frac{Y(3S)/Y(1S)}{Y(3S)/Y(1S)}_{PbPb} = 0.06 \pm 0.06 \text{(stat)} \pm 0.06 \text{(sys)} < 0.17 \text{ (95\% CL)}$

The double ratios are expected to be compatible with unity in the absence of suppression of the excited states relative to the Y(1S) state. The measured values are, instead, considerably smaller than unity. The significance of the observed suppression exceeds 5\sigma and does not show a significant dependence on the collision centrality[9].

5. Observation of long range, near-side angular correlations in PbPb and pPb collisions

Most of the results presented in sections 2 to 4 above shed light on the properties of the strongly interacting multi-particle system created in high energy PbPb collisions. Dihadron correlations provide information on how the medium affects the properties of the created particles. CMS has studied dihadron correlations over a range of relative azimuthal angles ($|\Delta\phi|$) and pseudorapidity ($|\Delta\eta|$) for all collision centralities and a broad range of $p_T$.

The correlations are performed with respect to a randomly chosen ‘trigger’ particle originating from the primary vertex and detected within the acceptance $|\eta|<2.4$ of the detector. A variety of bins of trigger transverse momentum, denoted by $p_T^{\text{trig}}$ are considered. There can be more than one such trigger particle in a single event and their total multiplicity in a particular data sample is denoted by $N_{\text{trig}}$. Within each event, every trigger particle is paired with all of the remaining particles (again within $|\eta|<2.4$). As for the trigger particles, these associated particles are binned in transverse momentum ($p_T^{\text{assoc}}$). The differential yield of associated particles per trigger particle is:

$$\frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{pair}}}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

The signal distribution is the per-trigger-particle yield of pairs found in the same event:

$$S(\Delta\eta,\Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{same}}}{d\Delta\eta d\Delta\phi}$$

The background distribution is obtained by mixing the trigger particle from one event with 10 randomly chosen other events:

$$B(\Delta\eta,\Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{mix}}}{d\Delta\eta d\Delta\phi}$$

The background distribution gives correlation if the only effects present were random combinatorics and pair acceptance. $B(\Delta\eta,\Delta\phi)$ at $\Delta\eta=0$ and $\Delta\phi=0$ (with a bin width of 0.3 in $\Delta\eta$ and $\pi/16$ in $\Delta\phi$) is used to find the normalisation factor $B(0,0)$.

Fig 9 shows the two-dimensional per-trigger-particle associated yield distribution of charged hadrons as a function of $|\Delta\eta|$ and $|\Delta\phi|$ interval for a sample $3<p_T^{\text{trig}}<3.5$ GeV/c and $1<p_T^{\text{assoc}}<1.5$ GeV/c in different centrality classes of PbPb collisions. The 2D correlations are rich in structure, and evolve with centrality. For the most central PbPb collisions, a clear and significant ridge structure mostly flat in $\Delta\eta$, and extending to the limit of $|\Delta\eta|=4$, is observed at $\Delta\phi \approx 0$. At mid-peripheral events, a pronounced $\cos(2\Delta\phi)$ component emerges, originating predominantly from elliptic flow[18]. In the
Fig 9: Two-dimensional (2D) per-trigger-particle associated yield of charged hadrons as a function of $|\Delta \eta|$ and $|\Delta \phi|$ for $3 < p_{T}^{trig} < 3.5$ GeV/c and $1 < p_{T}^{assoc} < 1.5$ GeV/c, for twelve centrality ranges of PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The near-side peak height is truncated in the two most peripheral distributions to better display the surrounding structure.

In September 2012, LHC performed a short 8 hour pilot run colliding protons on Pb, in preparation for the dedicated pPb run planned for spring 2013. A total of 2 million events passed all selection criteria, corresponding to an integrated luminosity of $\sim 1 \mu b^{-1}$ at $\sqrt{s_{NN}}=5.02$ TeV assuming a pPb interaction cross section of 2.1 barns. In the absence of a concept of ‘centrality’ in pPb collisions, the two particle correlations are obtained in classes of the number of reconstructed tracks $N_{\text{trk offline}}$.

Fig 10 compares 2-D two-particle correlation functions for events with low(a) and high(b) multiplicity, for pairs of charged particles with $1 < p_{T} < 3$ GeV/c. For the low-multiplicity selection ($N_{\text{trk offline}} < 35$), the dominant features are the correlation peak near $(\Delta \eta, \Delta \phi) = (0,0)$ for pairs of particles originating from the same jet and the elongated structure at $\Delta \phi \approx \pi$ for pairs of particles from back-to-back jets. High-multiplicity events ($N_{\text{trk offline}} \geq 110$) also show the same-side jet peak and back-to-back correlation structures. However, in addition, a pronounced “ridge”-like structure emerges at $\Delta \phi \approx 0$ extending to $|\Delta \eta|$ of at least 4 units.

When interpreting the similarities and differences in the correlation structure between the PbPb and pPb collisions as shown in Fig 9 and 10, it is important to consider the relative contributions of...
different particle production mechanisms to the observed particle yields. High-multiplicity pPb events should mostly result from particle production in multiple soft proton–nucleon scatterings. The ridge structure in PbPb collisions is expected from collective flow, but its origin in the smaller pPb system is unclear. A simultaneous description of the measurements in pPb and PbPb should provide significant constraints on models of the underlying physics processes.

Summary
An overview of results from the first two years of LHC running has been presented here. CMS has collected data on PbPb collisions with an integrated luminosity of 8 \( \mu \)b\(^{-1}\) (2010) and 150 \( \mu \)b\(^{-1}\) (2011) at \( \sqrt{s_{NN}} = 2.76\)TeV. The results provide a fascinating insight into the dynamics of a many body system of partons created in the collisions. We have also highlighted how the system affects the properties of particles emerging from the collisions. All data presented in this review is published in 19 peer-reviewed journals.

The key results presented here are:

1. Charged particles detected at high \( p_T \) in PbPb collisions scaled by the number of binary nucleon-nucleon collisions are significantly lesser than in pp collisions at the same centre of mass energy. The effect becomes more pronounced in central collisions relative to peripheral collisions and has a pronounced \( p_T \) dependence (Fig 3).

2. A substantial imbalance characterized by the asymmetry parameter \( A_J \) is observed between the momentum of back-to-back jets. The imbalance is most pronounced for central events (Fig 5). The \( p_T \) dependence of the mean sub-leading to leading jet \( p_T \) ratio shows an increasing trend with the collision centrality, indicating an increased parton energy loss. The magnitude of the trend is however over-predicted a PYTHIA+HYDJET simulation (Fig 6).

3. The yield of Y(nS) heavy quark bound states in PbPb collisions is suppressed compared to that in pp collisions. Specifically, we find that the relative yield of Y(2S) to Y(1S) is suppressed by a factor of 0.21 at the 5\( \sigma \) confidence level, and we place a 95% CL upper limit of 0.17 on the relative yield of Y(3S) to Y(1S).

4. We observe long-range near-side angular correlations of the produced charged particle tracks in both PbPb collisions (increasing with centrality) and high multiplicity pPb collisions.

A lot more data from the 2012 run period is being analysed and a rich new set of results are expected from the dedicated pPb LHC run in the spring of 2013.

Acknowledgements
We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for effectively delivering the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MEYS(Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS(Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC(Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEP, IPST and NECTEC (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).
References

[1] CMS collaboration, S Chatrchyan et al, *The CMS experiment at the CERN LHC*, 2008
JINST 3 S08004

[2] CMS collaboration, *Study of high-p_T charged particle suppression in PbPb compared to pp collisions at \sqrt{s_{NN}}=2.76 TeV*, 2012 Eur. Phys. J. C72 1945

[3] F. Arleo, D. d’Enterria, A.S. Yoon, *Single-inclusive production of large-p_T charged particles in hadronic collisions at TeV energies and perturbative QCD predictions*, 2010, J. High Energy Phys., 06, 035

[4] CMS Collaboration, *Charged particle transverse momentum spectra in pp collisions at \sqrt{s_{NN}}=0.9 and 7 TeV*, 2011 J. High Energy Phys. 08, 086

[5] B. Alver et al., *Importance of correlations and fluctuations on the initial source eccentricity in high energy nucleus-nucleus collisions*, 2008, Phys. Rev. C 77 014906

[6] Particle Data Group Collaboration, *Review of particle physics*, 2010, J. Phys. G 37 075021

[7] CMS collaboration, *Measurement of isolated photon production in pp and PbPb collisions at \sqrt{s_{NN}}=2.76 TeV*, 2012, Phys. Lett B710 256-277

[8] CMS collaboration, *Jet momentum dependence of jet quenching in PbPb collisions at \sqrt{s_{NN}}=2.76 TeV*, 2012, Phys. Lett B712 176-197

[9] T. Matsui and H. Satz, *J/ψ suppression by quark-gluon plasma formation*, 1986, Phys. Lett. B178 416

[10] H. Satz, *Color deconfinement and quarkonium binding*, 2006, J. Phys. G32 R25

[11] C. Y. Wong, *Heavy quarkonia in quark gluon plasma*, 2005, Phys. Rev. C72 034906

[12] H. Satz, 2012 Proceedings of Kruger2012 workshop

[13] CMS collaboration, *Indications of Suppression of Excited Y States in PbPb Collisions at \sqrt{s_{NN}}=2.76 TeV*, 2011, Phys. Rev. Lett. 107 052302

[14] CMS collaboration, *Observation of sequential suppression of Y states in PbPb collisions*, 2012 Phys. Rev. Lett. 109 222301

[15] CMS collaboration, *Long-range and short-range dihedron angular correlations in central PbPb collisions at \sqrt{s_{NN}}=2.76 TeV*, 2011 J. High Energy Phys. 07 076

[16] CMS collaboration, *Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb collisions at \sqrt{s_{NN}}=2.76 TeV*, 2012 Eur. Phys. J. C72 2012

[17] CMS collaboration, *Observation of long-range near side angular correlations in pPb collisions at the LHC*, 2013, Phys. Lett. B 718 795-814

[18] PHOBOS Collaboration, *System size dependence of cluster properties from two-particle angular correlations in Cu + Cu and Au + Au collisions at \sqrt{s_{NN}} = 200 GeV*, 2010, Phys. Rev. C 81 024904