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What Have Hard Probes Taught Us about the Quark-Gluon Plasma as Measured in CMS

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This paper reviews recent CMS measurements from hard probes and their implications in assessing the properties of the QGP. Results from pPb collisions are compared and contrasted to measurements in PbPb collisions. The role of pPb collisions as a “control experiment” separating initial from final state effects is discussed.

Keywords: heavy ion collisions, quark-gluon plasma, hard probes, jets, charged hadrons, electroweak bosons, quarkonia

1. Introduction

The study of the high energy density phase of nuclear matter (the quark-gluon plasma) usually relies on one of two approaches: studies of the bulk medium produced in the collisions via measurements of low momentum particles and correlations between them, or using “probes” that propagate through the medium and sense its properties. It is imperative that the particles that would be used as probes are not part of the thermalized medium itself. It has long been recognized that jets and high-momentum particles that are produced in scatterings with large momentum transfer can serve as tomographic probes of the medium. The majority of the produced jets originate in the hard scatterings of gluons or light quarks. In more rare instances, the outgoing parton is a heavy (c or b) quark, or the jet partner may be an electroweak boson. Particles that interact via the strong interaction are expected to lose a significant fraction of their energy, while propagating through the quark-gluon plasma (QGP) and this energy loss may depend on the parton flavor, while particles that only participate in electroweak interactions are not expected to experience energy loss. Hard scattering processes may also produce bound states of heavy quark-antiquark pairs. The production rate of these quarkonium states in different collisions systems is of particular interest, since in the presence of deconfined quarks and gluons the force that binds the pair together is reduced; the modification of the yield of the different quarkonium states is sensitive to the temperature of the QGP. In addition to the measurements in nucleus-nucleus (AA) collisions, the study of the QGP requires reference measurements from systems in which the QGP is not expected to be formed, such as pp and pA collisions. The long-standing paradigm in the heavy ion community has been that in pA collisions due to the absence of a produced medium one can isolate the nuclear effects from the initial state of the hard-scattering process; the effects from the final state in AA collisions can then be assessed more reliably. Some of these assumption are now tested more carefully both in LHC and in RHIC data.

Equipped with high-resolution tracking and muon systems, along with highly segmented calorimetry and a sophisticated two-level trigger system the CMS detector is ideally suited for studies involving hard probes. A full description of the CMS detector can be found in Ref. [1]. This paper gives a brief overview of the measurements performed by CMS in PbPb and pp collisions at a nucleon-nucleon center-of-mass energy of 2.76 TeV, and in pPb collisions at 5.02 TeV. The results are based on integrated luminosity of $150 \mu\text{b}^{-1}$ for PbPb collisions, 5.3 pb^{-1} of pp collisions collected

in 2013, and 35 nb^{-1} of pPb collisions. More information on all of the CMS heavy ion physics results can be found on the Public Physics Results web page [2].

2. Evidence for QGP in PbPb collisions

The studies of jets in heavy ion collisions using CMS began in 2010 with the observation that the momentum imbalance between pairs of back-to-back jets was much larger in central PbPb collisions than in either pp or peripheral PbPb collisions [3]. Despite this evidence for significant parton energy loss, there was no sign of any deflection, the two jets still emerged essentially back to back. By studying charged particles in events with unbalanced jets, the missing energy was found to emerge predominantly in low momentum particles at large angles with respect to the jet axis. A more detailed study of the jet energy loss was performed using the high-statistic data from 2011. In Ref. [4], the ratio of the transverse momenta of the two jets is studied as a function of centrality and the transverse momentum of the leading jet. The jet energy loss is found to increase as the collisions become more central, but for any given centrality the dijet imbalance is found to be independent of jet p_T up to the highest momentum studied.

CMS has conducted a comprehensive set of measurements aiming to understand how the medium interacts with particles of different nature. The jet-quenching phenomenon is investigated using a variety of rare probes and fully reconstructed jets. The quenching of the heavy b-quarks is studied via their decays into J/ψ mesons [5] and with fully reconstructed b jets [6]. Figure 1 presents a collection of results [5–11] for the nuclear modification factors (R_{AA}) of various single particles (left panel) and fully reconstructed jets (right panel). Electroweak bosons (γ , W, Z) remain unmodified by the medium and their production serves as a reference process. A similar suppression is observed for all other probes, including the heavy b jets, indicating that the medium is extremely opaque. Some indication of parton flavor dependence is seen at low p_T where the non-prompt J/ψ appear to be less suppressed than the charged hadrons, but the non-prompt J/ψ spectra are known to be influenced by the difference in the parent parton p_T spectra, the harder fragmentation function of B mesons compared to that of light hadrons, and the decay kinematics of $B^- \rightarrow J/\psi + X$.

Figure 1. CMS measurements [5–9, 11] of the nuclear-modification factor, R_{AA} , for a variety of hard probes produced in PbPb collisions. Single particle measurements are shown in the left panel, while measurements of fully reconstructed jets are shown in the right panel.

To quantify the amount of jet energy loss in the medium precisely, photon-jet events have been studied in collisions of varying centrality [12]. Events containing an isolated photon with $p_T > 60 \text{ GeV}/c$ and an associated jet with $p_T > 30 \text{ GeV}/c$ are examined and the transverse momenta of the jet and the photon are compared, as well as the fraction of isolated photons with an associated jet partner. In Ref. [12] the measurements in PbPb collisions are compared to those in simulated pp collisions. With the high-luminosity pp data collected in 2013, the γ -jet correlations

Figure 2. Ratio of the fragmentation function (left) and the differential jet shape (right) in the 0-10% most central PbPb collisions and in pp reference measurements.

were studied in pp data as well [13] and presented for the first time at the Hard Probes 2013 conference. A significant decrease in the jet to photon p_T ratio compared to the same quantity in the pp reference is observed as PbPb collisions become more and more central, indicating a larger parton energy loss in the collisions where the volume of the medium is larger. Similarly, the fraction of photons with an associated jet partner decreases in the central PbPb collisions.

To evaluate in detail the effects of the energy loss, the jet longitudinal and transverse structure is studied in PbPb collisions of different centrality and compared to measurements in pp collisions at the same center-of-mass energy. The jet fragmentation functions [14] and jet shapes [15] are measured including charged hadrons down to low transverse momentum ($p_T = 1$ GeV/c). At this conference, the final results from these measurements that include the high-luminosity pp data from 2013 were presented. A centrality dependent modification is observed in the transverse profile of the jets at large distance from the jet axis, and in the fragmentation into particles with low momenta (appearing at large values of $\xi = \ln 1/z$, where z is the ratio of the momentum component of the track along the jet axis and the jet momentum within a cone of $R=0.3$). The results for the most central 0-10% of the collisions are shown in Fig. 2. The jets get broader and contain more low momentum particles, when the volume of the medium is larger.

In addition to the studies of jet quenching, CMS performed a series of measurements [5, 16, 17] that are sensitive to deconfinement and the temperature of the medium produced in PbPb collisions. The production rates of several quarkonium states ($\Upsilon(1S,2S,3S)$, $J/\psi, \psi(2S)$) have been measured in PbPb and pp collisions. Although suppression in production of quarkonium states has been previously observed in heavy-ion collisions, the CMS results show for the first time a suppression pattern of five different particles, ordered according to their binding energy. These measurements taken together give a strong support of the hypothesis that the quarkonium suppression is caused by the QGP as predicted by theory, but a detailed understanding of cold nuclear matter effects is still in progress.

3. Proton-lead collisions

Proton-lead collisions brought new insights and new challenges. The first surprise came from the short "pilot" run of the LHC in September 2012 when strong 2-particle correlations extending to a large range in pseudorapidity were discovered [18] in high-multiplicity events. In AA collisions, such correlations are typically explained to be a consequence of the collective flow in the QGP. It is essential to unravel the origin of these correlations in pPb collisions. With the high luminosity PbPb run in 2013 measurements of multiparticle correlations became possible. Strong azimuthal anisotropy parameter v_2 was measured with 4-particle correlations as well [19], and at the time of this writing CMS has also obtained preliminary results [20] from 6, 8 and all-particle correlations. The same value of

Figure 3. Left: Single ratios $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ for $|y_{CM}| < 1.93$ versus charged-particle multiplicity measured in $|\eta| < 2.4$, for pp at $\sqrt{s} = 2.76$ TeV (open symbols), pPb at $\sqrt{s_{NN}} = 5.02$ TeV (closed symbols). The global uncertainties on the pp results are 7% and 8% for $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ respectively, while on the pPb results they amount to 8% and 9% respectively. Right: Comparison of the $\Upsilon(2S)/\Upsilon(1S)$ ratio in pp, pPb and in PbPb collisions. For PbPb collisions (open stars), the global uncertainty is 8%. In all bins, the abscissae are given by the bin-average value as measured in the dimuon data sample used in the analysis.

the v_2 harmonic coefficient is found from all multiparticle correlation measurements, which suggests that collective phenomena are also present in high multiplicity pPb events. This calls into question the assumption that pA collisions can serve as a control experiment to separate the effects of the initial state from those of the medium present in the final state of the hard scattering. Prompted by the findings in the soft particle correlations, the hard probe measurements were also carried out by classifying the events based on the event activity.

The ratios of the yields of excited-to-ground state bottomonia, $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$, as a function of event multiplicity are shown in Fig. 3 (left) for pp collisions at $\sqrt{s} = 2.76$ TeV and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [21]; in the right panel the $\Upsilon(2S)/\Upsilon(1S)$ ratio is also shown for PbPb collisions. Surprisingly, these ratios depend on the event multiplicity even in the pp collisions. This result poses a question of what the correct reference is from pp collisions against which the suppression of the quarkonium states in nuclear collisions should be evaluated. As the event multiplicity increases, the ratios decrease in all collision systems, but they are much smaller in PbPb collisions than in pPb collisions.

The dijet momentum balance, azimuthal angle correlations, and pseudorapidity distributions are studied as a function of the transverse energy in the forward calorimeters [22]. The dijet transverse momentum ratio between the leading and subleading jet is found to be insensitive to the event activity and is comparable to the results from PYTHIA simulations. This suggests that in pPb collisions the jets are not modified significantly by final state effects. Further, based on PYTHIA simulations, a close correlation is found between the momentum fraction of the hard-scattered partons from the Pb nucleus and the dijet pseudorapidity making it possible to study the initial state effects with the dijet pseudorapidity measurement. In Fig. 4 the normalized η_{dijet} distributions in inclusive pPb collisions are compared to Next-to-Leading-Order (NLO) calculations using CT10 (free nucleon) and CT10+EPS09 (nuclear) parton distribution functions (PDFs) and are found to agree better with the latter. The dijet pseudorapidity distribution shifts in the Pb going direction with increasing forward activity. The observed magnitude of the modification of dijet pseudorapidity is larger than the predictions from the NLO calculations based on impact-parameter dependent nPDFs [23].

In another approach, we study the inclusive charged particle transverse momentum spectra over a broad kinematic range, $0.4 < p_T < 120$ GeV/c, and in several different pseudorapidity intervals [24]. In comparison to the dijet study, this measurement provides access to lower parton momentum fractions x and the possibility to compare the results to the theoretical predictions [23] on an absolute scale. To construct the nuclear modification factor R_{pPb} a reference pp spectrum is needed, but there are no data available at $\sqrt{s} = 5.02$ TeV. Therefore, a pp reference spectrum is obtained

Figure 4. a) The normalized η_{dijet} distribution is shown for 0 – 100% pPb collisions with red solid circles. The error bars represent the statistical uncertainties and the total systematic uncertainties are shown as yellow boxes. The results are compared to NLO calculations using CT10 (Blue solid line) and CT10+EPS09 (Black dashed curve) PDFs. (b) The difference of data and CT10 calculation. (c) The difference of data and EPS09 calculation. The curves in panels (b) and (c) denote the theoretical uncertainties.

using a direct interpolation method utilizing measured p_T spectra from $|\eta_{\text{CM}}| < 1.0$ at 0.63, 1.8, and 1.96 TeV collision energies from CDF [25, 26], and 0.9, 2.76, and 7 TeV collision energies from CMS [27, 28]. The R_{pPb} obtained with this pp reference is shown in the left panel of Fig. 5 in comparison to the theoretical prediction [23] for π^0 mesons obtained using the CT10+EPS09 nPDFs. At high p_T , which corresponds to the anti-shadowing region in the nPDFs ($0.02 < x < 0.2$), an enhancement is seen in the charged hadron R_{pPb} which is stronger than expected from the theoretical prediction. This may be due to additional final state effects related to the hadronization process. In the right panel of Fig. 5 we examine the yield asymmetry about mid-rapidity in the center-of-mass frame. The yield in the Pb-going direction is divided by the yield in the p-going direction. At low p_T this ratio is sensitive to saturation effects in the nucleus at low x , and the data show an enhancement in Y_{asym} for $p_T < 10$ GeV/c, which is qualitatively consistent with this expectation. At high p_T , the x -values that contribute to hadron production in the measured forward and backward pseudorapidity ranges are both in the anti-shadowing region and the yield asymmetry is consistent with unity. This indicates that similar initial and final state effects are at play for $p_T \geq 10$ GeV/c in the pseudorapidity range of $|\eta_{\text{CM}}| < 1.8$.

4. Summary

Based on data from Run 1 of the LHC, CMS has obtained a comprehensive set of measurements from hard probes in PbPb, pPb and pp collisions. In PbPb collisions all measurements give a consistent picture of a hot and dense medium being formed, although the detailed theoretical understanding and establishing precisely the key properties of this medium are still to be achieved. Proton-lead collisions present new challenges and new opportunities. The separation of initial and final state effects may not be possible in all observables as previously assumed, in particular in events with high activity. The CMS data indicate that nuclear effects are present in pPb collisions and further

Figure 5. Left panel: Measured nuclear modification factor for charged particles in $|\eta_{CM}| < 1$ shown along with the theoretical nuclear modification factor for neutral pions at $y=0$ as determined using EPS09 fDSS NLO calculation [23]. The light gray uncertainty band represents the uncertainty of the Glauber calculation of N_{coll} . The light brown uncertainty band around the measured values shows the uncertainty coming from the following sources that are strongly correlated in specific p_T regions: combination of spectra, track selection, and trigger efficiency. All other uncertainties are shown by the yellow band. Right panel: Charged particle asymmetry as a function of p_T for $1.3 < |\eta_{CM}| < 1.8$. The asymmetry is computed as the charged particle yields on the Pb-going side divided by the those on the p-going side.

experimental and theoretical studies are needed to assess their implications for the properties of the QGP produced in PbPb collisions.

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