Abstract

An overview of the most recent results on jet quenching physics obtained using PbPb and pPb collision data collected with the CMS experiment at \( \sqrt{s_{NN}} = 2.76 \) TeV and \( \sqrt{s_{NN}} = 5.02 \) TeV, respectively, will be presented. These measurements make use of many different observables, including momentum imbalance, nuclear modification factor \( R_{AA} \) and \( R_{pA} \), as well as flavor dependence of jet quenching, jet shapes and jet fragmentation functions. All these measurements in PbPb and pPb collisions will be presented and compared measurements from reference results. Since many of these observables have low correlation to one-another they serve as useful independent constraints to the nature of the parton energy loss mechanism.

1. Introduction

Heavy ion collisions at the Large Hadron Collider (LHC) present a great opportunity to study the phases of nuclear matter predicted by Quantum Chromodynamics (QCD), the theory of the strong interaction. Jets originating from hard scatterings of partons are a powerful probe of the hot, dense matter created in heavy-ion collisions. This medium is commonly referred to as a Quark-Gluon Plasma (QGP). High transverse momentum partons produced by the initial hard scatterings in heavy ion collisions are expected to suffer energy loss due to strong interactions [1], in a phenomenon known as “jet quenching” that has been discovered at the Relativistic Heavy-Ion Collider (RHIC). More recently, the Compact Muon Solenoid (CMS) [2] detector has been used to study parton energy loss in the QGP with leading particle and jet coincidence measurements. We present some selected measurements related to parton energy loss in PbPb and pPb collisions at a nucleon-nucleon center-of-mass energy of \( \sqrt{s_{NN}} = 2.76 \) TeV and 5.02 TeV, respectively using the CMS detector.

2. Experimental Techniques

In order to study medium-induced modifications, we first perform a measurement where the medium is present, and then compare them to the same measurement in vacuum-like collisions. The reference measurement is performed at the same centre-of-mass energy using data, or (in cases where data is not available) a simulated sample. The capabilities of the CMS detector allows us to investigate various hard probes, using excellent tracking, calorimeter, and muon systems which cover a large range in pseudorapidity. It is important to note that heavy ions are extended objects, so the impact parameter is an important characterization of the events. The centrality of the collisions is defined as a fraction of the total nucleus-nucleus inelastic cross section, with 0% denoting the most central collisions with impact parameter 0, and 100% - the most peripheral collisions. In these analyses, centrality was determined from minimum bias events based on the total summed transverse energy from both forward hadronic calorimeters [3].
3. Selected Results

Early in 2011, in comparison to pp collisions, a large fraction of dijets with imbalanced transverse momentum was observed in PbPb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \). It was also observed that the lost energy of a quenched jet was transferred to large angles and lower momentum particles [3]. The redistribution of the quenched jet energy is now studied more diagrammatically and compared to pp collisions at the same energy [5] with dijet events using missing-\( p_T \) observable, defined as \( p_T^\parallel = \sum_i -p_i^T \cos (\phi_i - \phi_{\text{DiJet}}) \), where the sum is evaluated over all tracks with \( p_T > 0.5 \text{ GeV/c} \) and \( \eta < 2.4 \). The results were then averaged over the event ensemble to obtain \( \langle p_T^\parallel \rangle \). No explicit background subtraction is applied in this method, as the heavy-ion underlying event is not expected to give a net \( p_T \) contribution along the dijet axis. Fig. 1 highlights one of these results for unbalanced pairs of jets, with \( A_j = \frac{p_{T1}^\parallel - p_{T2}^\parallel}{p_{T1}^\parallel + p_{T2}^\parallel} > 0.22 \). In a central (0–30%, top-right panel) PbPb collisions, the large deficit of energy in a small cone (\( < 0.2 \)), arises from a lack of energetic particles, of \( p_T > 4 \text{ GeV} \) (green and red histograms). It is slowly compensated by lower \( p_T \) particles up to very large values of \( \Delta R \). Noticeably, the \( \Delta R \) distribution is similar between pp and PbPb dijet events, when integrated over \( p_T \) (hashed and plain black curves). However, to distinguish various energy loss model scenarios experimentally, it is important to complement the differential studies of momentum imbalance between the leading and subleading jets with detailed measurements of the energy flow for each side of the dijet.

While studies using dijets benefit from the large dijet production cross section, correlations between isolated photons and jets have been proposed in the literature as the “golden channel” to study jet energy loss. This is because the photon retains the kinematic information of the hard scattering since it is not expected to interact with the medium. The correlation of isolated photons and jets shows a \( p_T \) imbalance and a fraction of photons unassociated to jets (i.e., jets falling below the reconstruction threshold) which are comparable between pp and pPb collisions, though heavily modified in PbPb collisions [7]. Further details about the measurement of isolated-photon+jet correlations in \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) pp and PbPb collisions and \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) pPb collisions with CMS can be found elsewhere [6, 7].

Quenching of jets in heavy-ion collisions is expected to depend heavily on the flavor of the fragmenting parton. Gluon jets are expected to be quenched more strongly than light quark jets due to the larger color factor for gluon emission from gluons than from quarks. On the other hand, jets initiated by heavy quarks, particularly bottom quarks, are expected to radiate less than light ones. To measure this flavour dependence, the CMS collaboration has applied a b-jet identification algorithm for the first time in heavy ion collisions to perform such a measurement [8]. The purity of b-jet tagging is determined from template fits to the secondary vertex invariant mass distribution, and the efficiency of the secondary vertex tagging is estimated in a data-driven technique. The fraction of b-jets among the inclusive jets is measured as a function of transverse momentum after purity and efficiency corrections in the range of \( 80 < p_T^\text{jet} < 250 \text{ GeV/c} \). Fig. 2 shows the fraction of b-jets in PbPb is found to decrease with increasing collision centrality. The b jets observed in pPb show virtually no suppression effects and may show possible hints of a Cronin enhancement due to cold nuclear matter effects, with no \( p_T \) dependence [9]. Fig. 3 shows measurements of both \( R_{AA} \) and \( R_{pA} \) as a function of \( p_T \) for inclusive jets [10, 11]. We observe a very consistent result between the flavored jets and the inclusive-jet measurements, indicating that the suppression effects in PbPb collisions and enhancement effects in pPb are roughly parton-mass independent at very high \( p_T \).
The momentum that is lost by the parton into the medium modifies the energy flow in the jet. The angular and $p_T$ spectrum of this modification can provide insight on the dominant mechanisms of medium parton interactions that control the energy loss. In this regard we also performed differential jet shapes and jet-fragmentation functions measurements to address this phenomena.

The jet shapes are a sensitive tool for the characterization of the parton-medium interactions by utilizing the energy flow inside the jet. Predictions have been made that the jet shapes will become wider due to quenching. The jet shapes can be studied by using both the $R_{AA}$ and $R_{AA}$ curves between the b-jet and inclusive-jet data.

A small cone size ($R_{AA}$) jet is used as the annulus size, which is 0.05. The momentum that is lost by the parton into the medium is redistributed at large radius $r = r - \delta r / 2$ and an outer radius $r_b = r + \delta r / 2$ as specified in the following equation

$$\rho(r) = \frac{1}{\delta r} \sum_{r_b < r < r_a} \frac{p_{T,i}}{\sum_{r_b < r < R} p_{T,j}},$$

where $\delta r$ is used as the annulus size, which is 0.05. The sums run over the reconstructed particles, with the distance $r_i = \sqrt{(\eta_i - \eta_{jet})^2 + (\phi_i - \phi_{jet})^2}$ relative to the jet axis described by $\eta_{jet}, \phi_{jet}$. A small cone size ($R=0.3$) was used for the jet reconstruction in order to suppress the underlying-event contribution in the high multiplicity PbPb environment. All charged particles that pass a $p_T > 1$ GeV/c threshold are used to reconstruct jet shapes. The hot-and-dense medium is expected to modify a measured jet shape in two ways. First, the partons that fragment into jets interact with the medium directly. Secondly, the soft particle production from the underlying event adds many extra particles to the jet, predominantly at low momentum. This latter effect produces a background that must be subtracted. In order to subtract the heavy-ion background, an $\eta$-reflection technique [13] was used. In order to understand the medium-parton interactions we compare the PbPb jet shapes results with those obtained from a pp reference. The measured differential jet shapes ratio for PbPb and pp reference data are presented in Fig. 4 for the most central collisions. Deviations from unity indicate modification of jet structure in the nuclear medium. We note that the jet shape spectra are normalized to unity. As a result, an excess at one distance $r$ from the jet axis has to be compensated by a depletion in another region. The ratio has a concave shape, which is more pronounced in the more central collisions. An excess at large radius $r > 0.2$ emerges, indicating a moderate broadening of the jets in the medium. Further details about the analysis can be found here [13]. These results are consistent with other studies in CMS which find that the energy that the jets lose in the medium is redistributed at large distances from the jet axis outside the jet cone [3, 5].

One can further investigate in which track $p_T$ ranges the fragmentation function exhibits an excess by examining the $p_T$ spectra for tracks inside the jet cone [14].

Figure 2: Nuclear modification factor comparison for b-jet $R_{PYTHIA}$ and $R_{AA}$. The $R_{AA}$ values pA shown are for 0–10% centrality, while the $R_{PYTHIA}$ values pPb are for inclusive-centrality. Note the similarity between both the $R_{AA}$ and $R_{AA}$ curves between the b-jet and inclusive-jet data.

Figure 3: Nuclear modification factor comparison for inclusive-jet $R_{PYTHIA}$ and $R_{AA}$.
Differential jet shape nuclear modification factors, $\rho(r)_{PbPb}/\rho(r)_{pp}$ in the most central (0–10%) collisions. The error bars show the statistical uncertainties, and the shaded boxes indicate the systematic uncertainties.

These distributions are obtained with the same background subtraction described above. Fig. 5 shows the difference in the spectra of tracks in the jet cone between PbPb and pp reference data that quantifies the excess of tracks at a given $p_T$. A modest excess (rises to 0.45) is observed for low $p_T$ tracks ($p_T < 3$ GeV/c) with some depletion around 6 GeV/c. The jet shape and fragmentation function results indicate that suppression of intermediate $p_T$ particles is transported to larger radii with low $p_T$ particles enhancements by energy redistribution.

4. Conclusions

The CMS collaboration has performed many interesting measurements in PbPb, pp and pPb collisions. PbPb measurements are compared with observations in 2.76 TeV pp collisions to probe for distortions from energy loss in the hot and dense medium. Similarly the results extracted from the pPb collisions are compared with 5.02 TeV PYTHIA reference. However, all available pPb results show that the suppression effects observed in PbPb collisions do not arise from initial cold nuclear matter effects. The results presented here serve as useful independent confirmations of the quenching properties, and indicate a consistent view of the hot and dense medium.

References

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