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Jet Quenching with CMS

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

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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). The partons are expected to lose energy while traversing the medium via elastic processes (collisional parton energy loss) or inelastic processes (radiative parton energy loss) [1]. At RHIC, indirect measurements of energy loss in the medium ("jet quenching") have been made by studying high momentum jet fragmentation products. More recently, the Compact Muon Solenoid (CMS) [2] detector has been used to study for 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 collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\mathrm{NN}}}$ =2.76 TeV collected in 2010 and 2011 using the CMS detector.

2. Experimental Techniques

In order to study medium-induced modifications, we first perform a measurement in PbPb collisions where the medium is present, and then compare them to the same measurement in pp collisions. The reference measurement in pp collisions is performed at the same centre-of-mass energy using the data sample from 2013, which yields a kinematic reach for the jets similar to that in the PbPb data. 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. All of these detectors have sufficient granularity and resolution to function well even in the highest multiplicities encountered in PbPb collisions. It is also 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 energy from both forward hadronic calorimeters [3].

3. Results

In comparison to pp collisions, a large fraction of dijets with imbalanced transverse momentum is observed in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. To characterize the dijet momentum balance (or imbalance) quantitatively, we use the asymmetry ratio $A_j = \frac{p_{T_1} - p_{T_2}}{p_{T_1} + p_{T_2}}$, where p_{T_1} is the transverse momentum of the leading jet and required to be $p_{T_1} > 120$ GeV, and p_{T_2} is the transverse momentum of the subleading jet in the opposite hemisphere with $p_{T_2} > 30$ GeV. The centrality dependence of A_j for PbPb collisions is shown in Fig. 1, in comparison to PYTHIA+HYDJET simulations. The most peripheral events are also compared to results from pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, where the same jet algorithm is used. The shape of the dijet momentum balance distribution gradually changes with collision centrality, towards a larger imbalance. In contrast, dijets from simulated

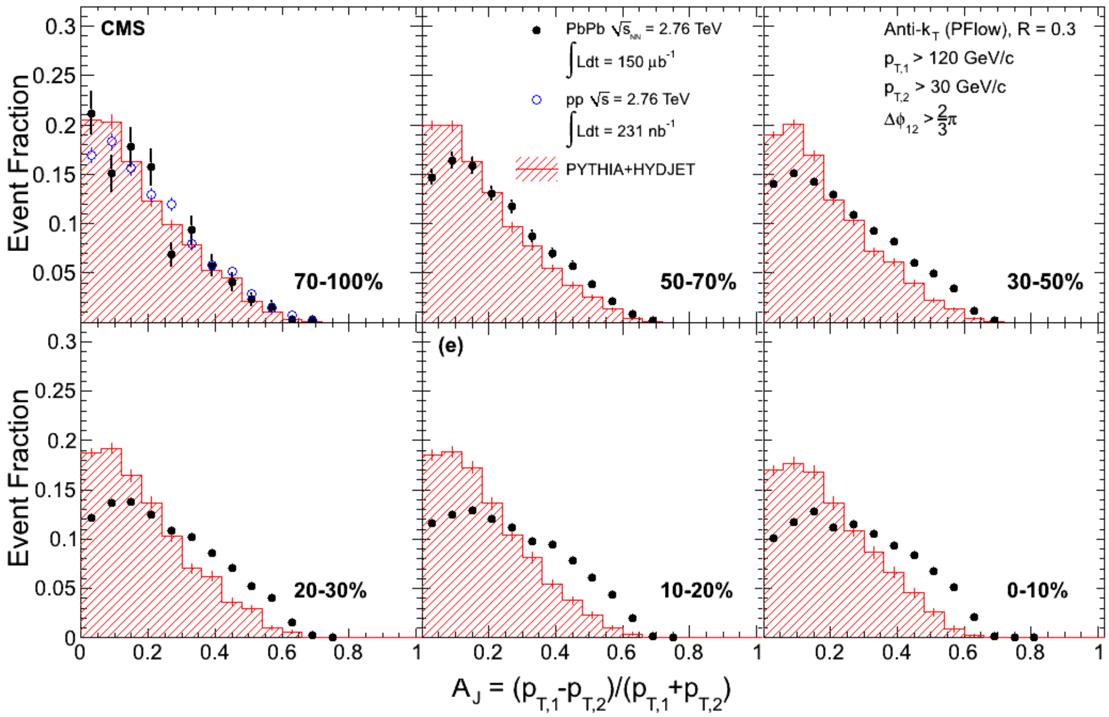

Figure 1: Dijet asymmetry ratio, A_J, for leading jets of $p_{T_1} > 120$ GeV/c and subleading jets of $p_{T_2} > 30$ GeV/c with a selection of $\Delta\phi > 2\pi/3$ between the two jets [4]. Results from data are shown as points, while the histogram shows the results for PYTHIA dijets embedded into HYDJET PbPb simulated events. Data from pp collisions at 2.76 TeV are shown as open points in comparison to PbPb results of 70–100% centrality. The error bars represent the statistical uncertainties.

PYTHIA events only exhibit a modest broadening, even when embedded in the highest multiplicity PbPb events.

In a more detailed study of the parton energy loss mechanism [3], CMS has investigated the redistribution of the quenched jet energy using the transverse momentum balance of charged tracks projected onto the direction of the leading jet axis, defined as $p_T^{\parallel} = \sum_{\mathrm{i}} -p_T^{\mathrm{i}} \cos(\phi_{\mathrm{i}} - \phi_{\mathrm{Leading\ Jet}})$, where the sum is evaluated over all tracks with $p_T > 0.5$ GeV/c and $|\eta| < 2.4$. The results were then averaged over the event ensemble to obtain $\langle p_T^{\parallel} \rangle$. Fig. 2 (left) shows $\langle p_T^{\parallel} \rangle$ as a function of A_J for the most central PbPb collisions (0–30%). Even for events with a very unbalanced dijet (large A_J values), the total summed projected momentum of all the included tracks (solid circles) is close to zero. The colored bands (with vertical bars for statistical uncertainties) show the summed momentum for tracks restricted to specific p_T ranges. The main conclusion here is that a large fraction of the momentum balance of the jets in unbalanced events is carried by low-p_T particles at large radial distance to the jet axis [3].

While studies using dijets benefit from the large dijet production cross section, the energy loss of both partons makes the determination of the amount of energy lost by each parton more difficult. 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

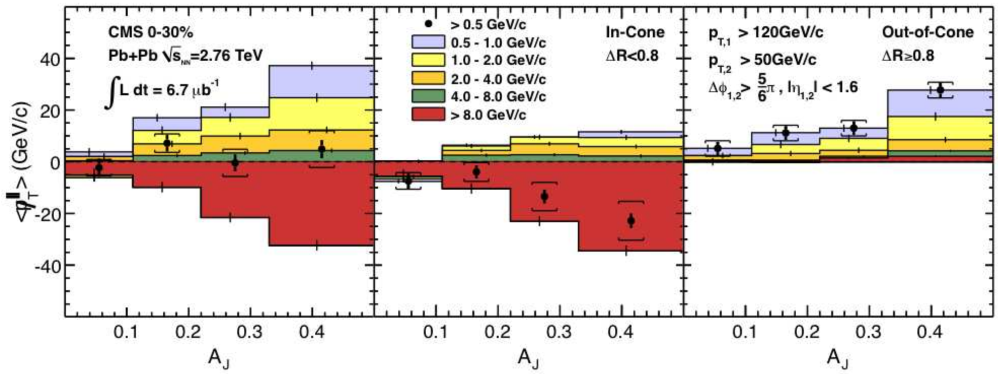

Figure 2: (Left) Average missing transverse momentum, $\langle p_T^{\parallel} \rangle$, for tracks with $p_T > 0.5$ GeV/c, projected onto the leading jet axis (solid circles). The $\langle p_T^{\parallel} \rangle$ values are shown as a function of dijet asymmetry for the 30% most central events. (Middle) The $\langle p_T^{\parallel} \rangle$ values as a function of A_J inside ($\Delta R < 0.8$) one of the leading or subleading jet cones. (Right) $\langle p_T^{\parallel} \rangle$ outside ($\Delta R > 0.8$) the leading and subleading jet cones. For the solid circles, vertical bars and brackets represent the statistical and systematic uncertainties, respectively. Colored bands, with vertical bars for statistical uncertainties, show the contribution to $\langle p_T^{\parallel} \rangle$ for five ranges of track p_T [3].

the hard scattering since it is not expected to interact with the medium. In addition, the energy resolution for photons is better, making the photon an ideal object against which to compare the jet. In order to quantify any angular broadening, the PbPb data were compared to both pp data and a PYTHIA+HYDJET reference which included the effect of the underlying PbPb event but no parton energy loss. Similar to dijet events, no angular broadening was observed beyond that seen in the pp data and MC reference at all centralities. Further details about the measurement of isolated-photon+jet correlations in $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV pp and PbPb collisions with CMS can be found elsewhere [5].

Another interesting analysis is a measurement of the jet flavor dependence of the jet quenching, which is expected to depend on the flavor of the initial 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 [6]. 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-jet among inclusive jets is measured as a function of transverse momentum after purity and efficiency corrections in the range of 80 $< p_T^{jet} <$ 200 GeV/c. The fraction of b-jets in pp and PbPb collisions are comparable, with no p_T dependence, indicating that b-quark jets are quenched similar to the light quark jets, i.e. the R_{AA} value is $\approx 0.5 \pm 0.21$ (syst) [7]. These measurements have significant statistical uncertainties at present. The use of a larger pp data sample, along with a more precise calibration of tagging efficiencies and fit template shapes, may lead to significant improvements in precision in the future.

A differential measurement to test the effects of the medium using a jet shape observable is performed using the CMS experiment. 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 effects [8]. We present the first experimental test of this prediction. The jet shapes can be studied by using an integrated or a differential distribution. The differential jet shapes are defined as the average fraction of the transverse momentum contained inside an annulus of an inner radius $r_{\mathrm{a}} = r - \delta r/2$ and an outer radius $r_{\mathrm{b}} = r + \delta r/2$ as specified in the following equation

$$\rho(r) = \frac{1}{\delta r} \frac{\sum\limits_{r_{\mathrm{a}}<r_i<r_{\mathrm{b}}} p_{\mathrm{T},i}}{\sum\limits_{r_i<R} p_{\mathrm{T},i}}, \tag{3.1}$$

where δr 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 η_{jet}, ϕ_{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. Corrections for the tracking inefficiency are applied. In order to subtract the heavy-ion background, an η-reflection technique [9] 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 for PbPb and pp reference data are presented in Fig. 3 for different centrality bins, ranging from most-peripheral (70-100%) to most central (0–10%). The bottom panel shows the ratio of the PbPb jet shapes to the jet shapes for a pp reference obtained for the respective selections. 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. In all centrality classes, the ratios have a concave shape, which is more pronounced in the more central collisions. In central collisions (10–30% and 0–10%), an excess at large radius $r > 0.2$ emerges, indicating a moderate broadening of the jets in the medium. This result is consistent with previous 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].

The observed enhancement in jet shapes results is consistent with the excess in the low p_T part of jet fragmentation functions, formulated with ξ and defined as $\xi = \ln\frac{1}{z}$; z= $\frac{p_{\parallel}^{track}}{p_T^{jet}}$ where $p_{\parallel}^{track}$ is the momentum component of the track along the jet axis, and p_T^{jet} is the transverse momentum of the reconstructed jet, respectively [10]. 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.

The CMS collaboration has performed many interesting measurements in PbPb collisions. All these measurements in PbPb collisions are presented and compared with observations in 2.76 TeV pp collisions to probe for distortions from energy loss in the hot and dense medium. Since many of these observables have low correlation to one-another they serve as useful independent confirmations of the quenching properties, and indicate a consistent view of the hot and dense medium.

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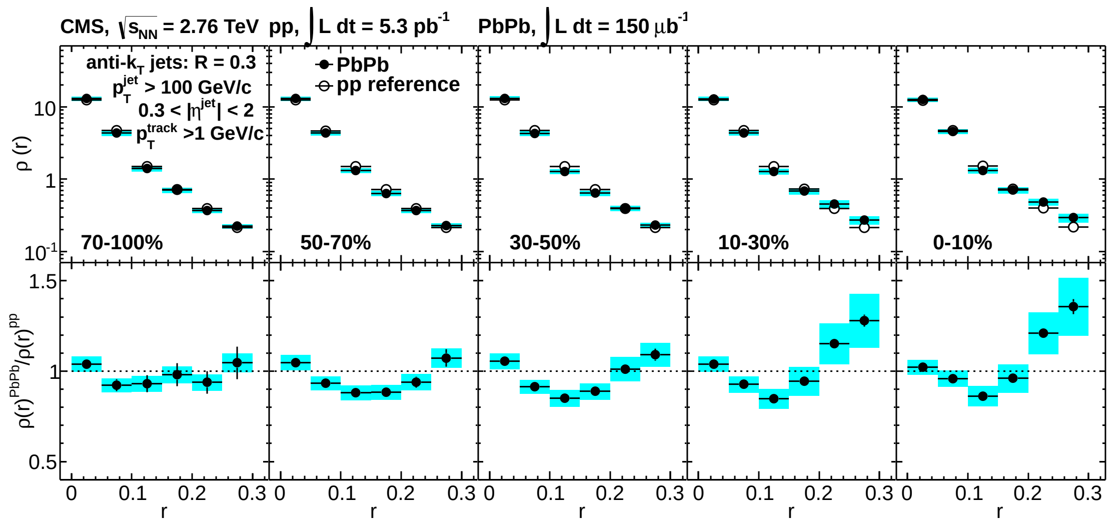

Figure 3: Differential jet shapes in PbPb and pp collisions are presented for different centrality bins for $p_T^{jet} > 100$ GeV/c with track $p_T > 1$ GeV are shown in the top panels. Results from data are shown as black points while the open circles show the reference pp. In the bottom row, the ratio of the PbPb and pp jet shapes is shown. The blue band shows the total systematic uncertainty while the error bars indicate the statistical errors [9].

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