Jet quenching studies in CMS

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Abstract. CMS has a wide set of results exploring the radiation patterns of jets in the quark gluon plasma and the medium response to jets, through studies of correlations between charged hadrons and jets. This talk reviews the various CMS results that examine the phenomena from different perspectives, and reports on the recent additions to these results. In particular, a study of dijet momentum imbalance, studied differentially in distance from dijet axis, sets limits on the propagation of the radiated momentum, and a study of the jet-track correlation functions examines the extent to which the radiated energy remains correlated with the jet axes.

1. Introduction

The modification of highly energetic probes traversing the quark gluon plasma, known as “jet quenching,” has been firmly established at RHIC and LHC [1, 2]. High-precision measurements at the LHC have furthermore shown that the detailed structures within the jet cone (radius parameter $R = 0.3$) are modified by the medium in terms of both $p_T$ and angular distributions [3, 4, 5, 6]. However, these observed in-cone changes only explain a small fraction of the centrality-dependent dijet momentum imbalance, indicating that a large amount of energy is radiated outside of the jet cone or to very low momentum particles. Extending such measurements to large angles is crucial to properly constrain the energy loss mechanisms and to quantify the interaction strength within the QGP. Taking advantage of the kinematic reach of hard probes and the availability of detailed characterization of the event bulk properties, the CMS detector is able to separate the perturbative quantum chromodynamics (QCD) components of jet-track correlations from the hydrodynamic background to explore the two-dimensional energy flow about the jet axis beyond the limit of the small cone radius. Here, we present two complementary analyses that extend previous measurements to large angles in relative pseudorapidity ($\Delta \eta$) and relative azimuth ($\Delta \phi$), while providing a more detailed look at energy redistribution about high transverse momentum jets.

First, presenting results from CMS analysis [7], we analyze overall momentum imbalance between the leading and subleading sides of high-$p_T$ dijets. This technique measures subleading-to-leading excesses in track multiplicity and transverse momentum when comparing the total energy in the hemispheres associated with the subleading versus leading jet. Next, presenting new results from CMS analysis [8], we study charged particle per-trigger yields correlated to high-$p_T$ jets, looking for energy redistribution both inside and outside of the jet cone. This allows for analysis of modifications and energy flow on each side of the dijet individually, as well as for an inclusive sample of high-$p_T$ jets.
2. Data Samples and Jet and Track Reconstruction

The analyses presented here use data collected with the CMS detector (described in detail in [9]) at a center-of-mass energy of 2.76 TeV, with PbPb collisions taken in 2011 with an integrated luminosity of 166\(\mu\)b\(^{-1}\), and pp reference taken in 2013 with an integrated luminosity of 5.3 pb\(^{-1}\). The events for these analyses were selected using the CMS High Level Trigger (HLT), an inclusive single-jet trigger that selects \(p_T > 80\) GeV/c. The HLT is fully efficient for events containing reconstructed jets with \(p_T > 120\) GeV/c satisfying offline selection as documented in [2, 10]. The dijet samples in both analyses are selected by the following criteria: events are first required to contain a leading (highest \(p_T\)) jet in the pseudorapidity range of \(|\eta| < 2\) with a corrected jet \(p_T > 120\) GeV/c and a subleading (next-highest \(p_T\)) jet of \(p_T > 50\) GeV/c, also in \(|\eta| < 2\). The azimuthal angle between the leading and subleading jets is required to be at least \(5\pi/6\). No explicit requirement is made either on the presence or absence of a third jet in the event. To ensure stable jet reconstruction performance and good tracker acceptance for tracks on all sides of each jet, only events in which both leading and subleading jets fall within \(|\eta| < 1.6\) are included in the final selected data sample. For the dijet imbalance study, jets are further restricted to \(|\eta| < 0.5\) so that tracks within \(|\Delta\eta| < 1.9\) of a jet fall within the tracker coverage of \(|\eta| < 2.4\): the correlation study instead corrects for geometrical pair-acceptance effects.

For both pp and PbPb collisions, jet reconstruction is performed with the anti-\(k_T\) algorithm with distance parameter \(R = 0.3\), that is encoded in the FastJet framework [11, 12]. Jets are reconstructed based on energy deposits in the CMS calorimeters. For PbPb collisions the CMS algorithm "HF/Voronoi" is used to predict and subtract the heavy ion underlying event based on information from HF energy measurements as well as Voronoi decomposition of particle flow [13, 7]. For pp collisions no underlying event subtraction is employed. For track reconstruction in PbPb data, we employ an iterative charged particle reconstruction capable of reconstructing tracks with transverse momentum as low as 0.4 GeV/c. For studies of pp data, charged particles are reconstructed using the same iterative method [14] as in the previous CMS analyses of pp collisions. Detailed descriptions of track reconstruction and studies of tracking efficiency corrections can be found in Ref. [7].

Monte Carlo (MC) event generators have been used for evaluation of the jet and track reconstruction performance, to establish the jet energy scale (JES), and to correct for tracking efficiency. Jet events are generated by the PYTHIA MC generator [15] (version 6.423, tune Z2 [16]). These generated PYTHIA events are propagated through the CMS detector using the GEANT 4 package [17] to simulate the detector response. In order to account for the influence of the underlying PbPb events, the PYTHIA events are embedded into fully simulated PbPb events, generated by HYDJET [18] (version 1.8) that is tuned to reproduce the total particle multiplicities, charged hadron spectra, and elliptic flow at all centralities. Detailed information about sources of systematic uncertainty in the dijet imbalance and jet-track correlation analyses is provided in [7] and [8] respectively.

3. Results: Dijet Momentum Imbalance

Detailed information about the overall momentum balance in dijet events can be obtained using the projection of the \(p_T\) of reconstructed charged particles onto an axis in the azimuthal plane (\(\phi_{\text{Dijet}}\)) midway between the direction of the leading jet and the opposite direction of the subleading jet. As the leading and subleading jets are required to be approximately back-to-back, this axis is very close to that for the leading jet (\(\phi_{\text{Dijet}} \approx \phi_1\)). For each event, this projection was calculated as

\[
\vec{p}_\parallel^i = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Dijet}}),
\]

where the sum is over all tracks with \(p_T > 0.5\) GeV/c and \(|\eta| < 2.4\). The results were then
averaged over events in a given $A_J$ bin to obtain $\langle p_T^J \rangle$.

Figure 1 shows $\langle p_T^J \rangle$ for pp collisions and four selections of PbPb collision centrality. For each panel, $\langle p_T^J \rangle$ is plotted in four bins of dijet asymmetry $A_J$ ranging from almost balanced to very unbalanced pairs. On each panel in the upper row, $\langle p_T^J \rangle$ averaged over all tracks with $p_T > 0.5 \text{GeV}/c$, and the contributions to $A_J$ from individual ranges of track $p_T$ are shown. Following the definition of $\langle p_T^J \rangle$, negative values indicate an excess in the direction of the leading jet, while positive values indicate an excess in the direction of the subleading jet. When selecting events containing dijets with $A_J > 0.11$, an excess of high $p_T$ particles in the direction of the leading jet (indicated by the red boxes) is seen for all selections in pp and PbPb collisions, as expected. For pp and peripheral PbPb collisions, this excess is mostly balanced by intermediate $p_T$ particles from 2–8 GeV/c. Going to more central collisions, the balancing contribution shifts from the intermediate $p_T$ range towards low $p_T$ particles in the 0.5–2 GeV/c range. This effect is most pronounced for large $A_J$ dijets seen in central PbPb collisions, where pathlength effects are expected to be largest. In the lower row of Fig. 1, the difference between the contributions of different track $p_T$ ranges to $\langle p_T^J \rangle$ in PbPb and pp collisions is shown after requirements on the PbPb collision centrality and the dijet imbalance. While the contributions from the various $p_T$ ranges are similar for to pp reference peripheral collisions, a difference can be seen for central collisions, with a significant excess of low $p_T$ charged particles for asymmetric jets in PbPb collisions.

![Figure 1](image_url)

**Figure 1.** Upper row shows average missing transverse momentum, $\langle p_T^J \rangle$, for pp collisions (left) and four selections of PbPb collision centrality. The solid markers show $\langle p_T^J \rangle$ averaged over all tracks with $p_T > 0.5 \text{GeV}/c$, while the colored boxes show the contribution to $\langle p_T^J \rangle$ for various momentum ranges from 0.5 < $p_T$ < 1 GeV/c (light blue) to $p_T$ > 8 GeV/c (red). For each panel $\langle p_T^J \rangle$ values are shown as a function of dijet asymmetry from almost balanced ($A_J < 0.11$) to unbalanced ($A_J > 0.33$) dijets. Vertical bars and brackets represent the statistical and systematic uncertainties, respectively. The lower row shows the difference PbPb–pp of the $\langle p_T^J \rangle$ contribution for the individual momentum ranges shown in the upper panel. Error bars and brackets represent statistical and systematic uncertainties respectively.
A key question for understanding the physics of QCD radiation in the parton energy loss process concerns the angular distribution of the energy loss relative to the axis defined by the parton direction. To study this question, the contribution to the overall $\langle p_T^J \rangle$ from annular regions around the leading and subleading jet axes is extracted. Annular regions in $\Delta R = \sqrt{\Delta \phi^2_{\text{jet}} + \Delta \eta^2_{\text{jet}}}$ of width 0.2 from 0 < $\Delta R$ < 0.2 to 1.6 < $\Delta R$ < 1.8 are defined, with an additional region for 1.8 < $\Delta R$ < 2.9. For each region, $\langle p_T^J \rangle$ for tracks falling into the region is calculated in the momentum ranges defined previously. For large $\Delta R$, the annuli around the leading and subleading jet may overlap. In this case, each track in the overlap region is only counted once in the $\langle p_T^J \rangle$ sum, with the track belonging to the annulus of smaller radius.

The analysis is performed for pp collisions and for two PbPb centrality selections, 30 – 100% and 0 – 30%. The resulting differential $\langle p_T^J \rangle$ spectra as a function of $\Delta R$ are shown in the upper row of Fig. 2, for pp and PbPb collisions. The plots show a large $\langle p_T^J \rangle$ contribution from high-$p_T$ particles towards the leading jet for small radii $\Delta R < 0.2$, with balancing contributions from low-$p_T$ particles towards the subleading jet for larger $\Delta R$. The cumulative $\langle p_T^J \rangle$ values (i.e., integrating the total $\langle p_T^J \rangle$ over $\Delta R$ starting at $\Delta R = 0$) are shown as dashed lines for pp and solid lines for PbPb, demonstrating the evolution of the overall momentum balance from small to large distances to the dijet axis. A comparison of pp and PbPb collisions is provided in the lower row of Fig. 2, showing the difference in the contributions of various momentum ranges to $\langle p_T^J \rangle$ and the difference of the total $\langle p_T^J \rangle$ vs. $\Delta R$. For peripheral events, the momentum spectrum of the $\langle p_T^J \rangle$ contributions is nearly identical between pp and PbPb. For central PbPb events, however, the PbPb-pp difference shows an excess of low momentum tracks (0.5 – 2 GeV/c) towards the subleading jet side for all regions with $\Delta R > 0.2$ – 0.4. While the momentum distribution in each $\Delta R$ bin is different between pp and central PbPb, the overall angular dependence of the balancing contribution is similar, as is seen in the nearly $\Delta R$ independent PbPb-pp difference of the total $\langle p_T^J \rangle$ plotted as the open circles.

4. Results: Jet-Track Correlations

To further study modifications to the particle yields associated with with individual jets (leading and subleading sides of the dijet as well as an inclusive sample of high-$p_T$ jets), we turn to a complementary analysis of correlations between charged hadrons and reconstructed jets. In this study, all charged tracks in the event with $p_T$ above 1 GeV/c are used to construct a two-dimensional relative pseudorapidity ($\Delta \eta = \eta_{\text{jet}} - \eta_{\text{track}}$), relative-azimuth ($\Delta \phi = \phi_{\text{jet}} - \phi_{\text{track}}$) correlation with respect to the measured jet axis for inclusive jets and for leading and subleading jets in unbalanced dijets. The jet-track correlations are constructed following the procedure established in [19], for the following bins in charge particle transverse momentum: $1 < p_T^{\text{assoc}} < 2$ GeV/c, $2 < p_T^{\text{assoc}} < 3$ GeV/c, $3 < p_T^{\text{assoc}} < 4$ GeV/c, and $4 < p_T^{\text{assoc}} < 8$ GeV/c. To correct for detector acceptance effects, raw correlation plots are divided by correlations between jets and minimum bias events (following the method of previous works [20, 21, 22]). The long-range contributions of the full 2D correlation is estimated by the $\Delta \phi$ projection of this correlation over the range $1.5 < |\Delta \eta| < 3.0$. The fit to this $\Delta \phi$ distribution is propagated uniformly in $\Delta \eta$, and subtracted from the acceptance-corrected yield. This background-subtracted yield is projected into $\Delta \eta$ and $\Delta \phi$ respectively. Mixed event correction and background subtraction are described in detail in [8].

The projections of the 2D correlations for leading and subleading jets onto $\Delta \eta$ (projected over $|\Delta \phi| < 1.0$) are shown in Fig. 3, for the lowest charged particle momentum selection. The upper panel of each figure shows the centrality evolution of the correlations for inclusive jets with $p_T > 120$ GeV/c. In every panel a reference measurement from pp data at the same collision energy is shown with open symbols. To better visualize the PbPb to pp comparisons,
Figure 2. Upper row shows differential missing $p_T$ distributions for pp, 30-100% and 0-30% PbPb data for various $p_T$ ranges (colored boxes), as a function of $\Delta R$. Also shown is the total $\langle p_{T}^{\parallel} \rangle$ (i.e., integrated over all $p_T$ for a given $\Delta R$ bin) as a function of $\Delta R$ for pp (open squares) and PbPb data (× symbols). Dashed lines (pp) and solid lines (PbPb) show the cumulative $\langle p_{T}^{\parallel} \rangle$. The lower row shows the difference between the PbPb and pp differential $\langle p_{T}^{\parallel} \rangle$ distributions per $p_T$ range as a function of $\Delta R$ (colored boxes) and difference of the total $\langle p_{T}^{\parallel} \rangle$ as a function of $\Delta R$ (open circles). Differences of cumulative $\langle p_{T}^{\parallel} \rangle$ are not shown. Error bars and brackets represent statistical and systematic uncertainties respectively.

the difference of the PbPb and pp correlation distributions is presented in the bottom panel for all centralities. Correlations are symmetrized in $\Delta \eta$ and display. Projections of leading and subleading jets onto $\Delta \phi$ (projected over $|\Delta \eta| < 1.0$) may be found in reference [8], and are very similar in width and shape to the $\Delta \eta$ correlations shown.

For the most peripheral events studied (centrality 50-100%), the PbPb correlations at low transverse momentum $1 < p_{T}^{assoc} < 2$ GeV$/c$ remain similar to those of pp reference events for our jet selections, with perhaps a hint of a small additional yield in PbPb collisions. This hint turns into a stronger signal as a function of collision centrality, with the most significant excess present in the most central collisions. The observed excess in the low-$p_T$ per-trigger particle yields extends to large angles far beyond the jet cone parameter $\Delta R = 0.3$, and exhibits a Gaussian-like shape relative to the jet direction in both $\Delta \eta$ and $\Delta \phi$. We note that these observations are consistent with the CMS results of jet-shape modifications (Ref. [5]) and fragmentation function measurements (Ref. [6]), and furthermore extend both of these measurements outside of the
jet-cone radius parameter of 0.3 enabling a more detailed assessment of the medium-induced modifications.

For this lowest track $p_T$ bin we observe that the excess of correlated yield extends significantly beyond the typical jet reconstruction radius. The excess of the soft correlated yields is more pronounced on the more “quenched” subleading side. Detailed cross-checks have been performed that confirm the consistency of these results with missing transverse momentum measurements discussed above. To summarize our findings and quantify the total yield excess observed in the PbPb data with respect to the pp reference at the same energy, we plot the integrals of the PbPb-pp yield differences as a function of track $p_T$ and collision centrality in Fig. 4. As this figure shows, in both leading and subleading jets the excess yield diminishes for higher momentum tracks until the yield becomes similar to or even less than that of the pp reference for the highest track $p_T$ bin of 4–8 GeV/c.

![Figure 3](image_url)

**Figure 3.** The top panel shows the $\Delta\eta$ distributions of charged particle background-subtracted yields correlated to PbPb and pp leading jets with $p_T > 120$ GeV/c. The middle panel shows the same distributions for subleading jets, and the bottom panel shows the difference PbPb minus pp for both leading and subleading jets. The total systematic uncertainties are shown as shaded boxes.
Figure 4. Total yield excess observed in the PbPb data with respect to the reference measured in pp collisions is shown as a function of track $p_T$ in four different centrality intervals (0–10%, 10–30%, 30–50%, 50–100%) for both leading and subleading jets. The total systematic uncertainties are shown as shaded boxes.

To characterize the widths in $\Delta \eta$ and $\Delta \phi$ of the charged particle distributions, we fit the measured correlations with a double Gaussian function (found to best describe the overall correlation shapes). The width is defined as the $\Delta \eta$ or $\Delta \phi$ value that contains 67% of the total correlated yield. Width uncertainties are calculated by determining widths of $\Delta \eta$ and $\Delta \phi$ distributions varied by their respective systematic uncertainties, which are treated as fully correlated for the purposes of this determination. Widths are obtained for $\Delta \eta$ and $\Delta \phi$ projections of correlations to leading and subleading jets in CMS analysis [8]. Here for demonstration widths are shown as a function of track $p_T$ for $\Delta \eta$ correlations to leading jets only, in Fig. 5.

Figure 5. Width of the $\Delta \eta$ distributions after background subtraction as a function of track $p_T$ comparing PbPb to pp data for leading jets with $p_T > 120$ GeV/$c$. The shaded band corresponds to the systematic uncertainty.
5. Summary

Energy redistribution about high transverse momentum jets in heavy ion collisions has been studied using two complementary techniques. First, in a study of dijet momentum imbalance between leading and subleading hemispheres of an event, the missing-\(p_T\) balancing momentum distribution was studied as a function of dijet asymmetry and radial distance from dijet axis. In these results the subleading-to-leading energy balance showed a centrality-dependent redistribution of transverse momentum from high-\(p_T\) particles within the jet cone into low-\(p_T\) particles extending to large angles in radius parameter \(\Delta R\). Next, in an analysis of two-dimensional \(\Delta \eta - \Delta \phi\) correlations, a centrality-dependent excess of correlated yield in PbPb collisions with respect to pp reference was observed for both leading and subleading jets, as well as for an inclusive jet sample. This excess yield (PbPb - pp) grows with centrality and decrease with transverse momentum, and remains correlated with jet axis while extending to large angles for all jet samples studied. Together, these two sets of results provide a comprehensive evaluation of medium modifications to jet properties, extending measurements to large angles in relative pseudorapidity (\(\Delta \eta\)) and relative azimuth (\(\Delta \phi\)) far beyond the typical jet cone radii.

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