The Compact Muon Solenoid Experiment
Conference Report

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29 December 2015 (v3, 02 January 2016)

Angular distributions of the quenched energy flow from dijets with different radius parameters in CMS

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Presented at *QM2015 Quark Matter 2015, XXV INTERNATIONAL CONFERENCE ON ULTRA-RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS*

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The flow of the quenched energy in imbalanced dijet events has been previously studied by transverse vector sum of charged particles with the CMS detector, namely the missing p_T measurement. The results have led to new theoretical insights in order to explain the wide angle radiation. The missing p_T technique has been improved so that it allows the study of angular distribution of the energy flow with respect to the dijet axis. The measurements are performed using different distance parameters R with the anti- k_T clustering algorithm, which provide information about how the angular distribution of the quenched energy depends on the jet width.

Keywords: Jet quenching, Jet-track correlations, Heavy ions, Parton energy loss

1. Introduction

Partons produced via hard-scattering processes with a large initial transverse momentum (p_T) are expected to lose some fraction of their energy as they traverse the simultaneously produced hot and dense medium in heavy ion collisions. This has been observed at the LHC via dijet momentum asymmetry ($A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$) modification in PbPb relative to pp collisions [1]. The observed lost momentum can be recovered by summing softer particles through large angular space η - ϕ . Study of the precise angular distribution of this lost momentum can help constrain energy loss models as partons traverse the medium [2, 3, 4, 5]. In PbPb dijet events, the subleading jet is typically the more quenched jet of the dijet pair, and can be used as the quenched jet in central-most collisions. Studying such quenched jets proves difficult, as parton energy loss is typically on the order of 10 GeV, while the total produced transverse momentum in a central PbPb event is several orders of magnitude larger.

An initial study of the interaction of the partons produced in hard scattering with the softer medium was first performed with the CMS detector [6] in Ref. [7]. By studying the missing p_T ($p_T^{\parallel}$) after transverse momentum sum, the large background contribution cancels, and what is left is associated with the parton. In this analysis, the missing p_T technique is used to characterize the angular distribution of the energy lost by the parton. By choosing a new azimuthal axis that is symmetric with respect to the dijet system, the contribution from underlying event cancels completely even when mapping in η - ϕ space, and the momentum flow of the dijet system can be studied in detail [8].

2. Jet Reconstruction

Jets are reconstructed from CMS calorimeter energy depositions in this analysis, with the anti- k_T algorithm as implemented in the FastJet framework [9, 10]. Clustering is done with a varied distance parameter of $R = 0.2, 0.3, 0.4$, and 0.5 . A background subtraction to remove contributions from the underlying event is employed in PbPb jet reconstruction. The HF/Voronoi subtraction algorithm [11] correlates the energy density in the hadronic forward calorimeter (HF) to mid-rapidities and then subtracts the predicted background region-by-region. The background subtracted energy depositions are then clustered to give the final jet collections. In reference pp analysis, no such subtraction is applied.

3. Track Reconstruction

Tracks are reconstructed with the CMS detector out to the full tracker acceptance of $|\eta| < 2.4$. Tracks in pp and in PYTHIA MC [12] are reconstructed using an iterative method common to previous CMS pp analyses [13]. Tracks in PbPb and PYTHIA+HYDJET MC are reconstructed using an iterative method common to previous CMS PbPb analysis. Reconstructed tracks are corrected in PbPb and pp for fake rate and efficiency. Additionally in pp, a correction for multiple reconstruction and secondary rate is applied. Corrections are binned in p_T , ϕ , η , centrality, and local track density as determined by proximity to a jet. Corrections for PbPb and pp are derived iteratively with remaining non-closure quoted as a systematic.

4. Event Selection

Events are selected in PbPb and pp using a single jet trigger of p_T threshold 80 GeV. At analysis level, leading and subleading jets are found within $|\eta| < 2.0$. Once found, the leading and subleading jets are then both required to be within $|\eta| < 0.6$, for plotting the $p_T^\parallel$ as a function of $\Delta = \sqrt{(\eta_{\text{trk}} - \eta_{\text{jet}})^2 + (\phi_{\text{trk}} - \phi_{\text{jet}})^2}$, without leaving the tracker acceptance. Leading jet p_T is selected to be greater than 120 GeV, and subleading jet p_T is selected to be greater than 50 GeV. Requiring $\Delta\phi > 5\pi/6$ ensures jets are back-to-back in azimuth.

5. Results

Full results of this analysis can be found in Ref. [8], along with more detailed discussion of analysis procedure and systematics.

Initial study of $p_T^\parallel$ in dijet events relied on cancellation of underlying events in a momentum sum when projected along the leading jet axis. To study the $p_T^\parallel$ angular distribution as parametrized by Δ , cancellation of the underlying event requires a new projection axis, ϕ_{dijet} , which is symmetric with respect to the azimuthal position of the leading and subleading jet. The axis itself is defined as the bisecting axis of the leading jet ϕ and subleading jet ϕ after the subleading jet is rotated by π . The choice of this axis, ϕ_{dijet} , ensures that contributions to the track momentum sum within the leading and subleading jet cone receive an equivalent contribution from the cosine term in the definition of $p_T^\parallel$, the sum of $p_T^\parallel$ which is

$$p_T^\parallel = -c^{\text{trk}} p_T^{\text{trk}} \cos(\phi_{\text{trk}} - \phi_{\text{dijet}}), \quad (1)$$

where the p_T of the track is corrected for fake rate and efficiency (as well as multiple reconstruction and secondary rate in pp) as denoted by term

$$c^{\text{trk}} = \frac{(1 - \text{misreconstruction})(1 - \text{secondary-particle})}{(\text{efficiency})(1 + \text{multiple-reconstruction})}, \quad (2)$$

previously discussed in Section 3. Note the sign convention means leading jet hemisphere corresponds to negative contributions to the sum.

Fig. 1. Upper row: $\langle p_T^{\parallel} \rangle$ distributions for pp, 30–100% PbPb, and 0–30% PbPb for five track- p_T ranges (colored boxes), from $0.5 < p_T < 1$ GeV (light blue) to $8 < p_T < 300$ GeV (red), as a function of Δ . Also shown is total $\langle p_T^{\parallel} \rangle$ as a function of Δ for pp (open squares) and PbPb data (open plus symbols). Dashed lines (pp) and solid lines (PbPb) show $\langle p_T^{\parallel} \rangle_{[0,\Delta]}$ (i.e. integrating the total $\langle p_T^{\parallel} \rangle$ over Δ from $\Delta = 0$ up to the point of interest). Lower row: Difference between the PbPb and pp $\langle p_T^{\parallel} \rangle$ distributions according to the range in p_T , as a function of Δ (colored boxes), and difference of total $\langle p_T^{\parallel} \rangle$ as a function of Δ (open circles), error bars and brackets represent statistical and systematic uncertainties, respectively.

Fig. 1 shows the $p_T^{\parallel}$ for $R = 0.3$ jets as a function of Δ , for reference pp and PbPb in 30-100% and 0-30% centrality binning across the top panels. The bottom set of panels is the difference of the corresponding top panel centrality binned PbPb $p_T^{\parallel}$ with the reference pp. The $p_T^{\parallel}$ is binned in track p_T , as denoted by the colored bins, and the total $p_T^{\parallel}$ sum of all binned track p_T contributions is denoted as the points. Cumulative curves of $p_T^{\parallel}$ over Δ , or

$$\langle p_T^{\parallel} \rangle_{[0,\Delta]} = \sum_{\Delta'=0}^{\Delta=\Delta} \langle p_T^{\parallel} \rangle_{\Delta'}, \quad (3)$$

are shown as dashed line in pp and solid line in PbPb for each centrality binning. Fig. 1 is for an inclusive A_J selection, with balanced and imbalanced A_J available in Ref. [8]. In the first bin Δ , there is a large imbalance towards leading jet side made up of high- p_T tracks, most pronounced in the central PbPb binning. As Δ increases, contributions from softer particles towards the subleading side make up this initial imbalance. In pp, these particles are characteristically in the 2-8 GeV p_T range. In PbPb, the constituents are characteristically in the 0.5-2 GeV p_T range. The $p_T^{\parallel}$ approaches closure at the last bin Δ , a catch-all including all particles more than $\Delta = 1.8$ away from either leading or subleading jet. The shape of the cumulative curves, $\langle p_T^{\parallel} \rangle_{[0,\Delta]}$ are similar in both pp and PbPb, making the primary difference between the systems the typical momentum of the sum constituents.

Fig. 2 shows the $p_T^{\parallel}$ for (left to right) $R = 0.2, 0.3, 0.4$, and 0.5 jets as a function of Δ , for reference pp (top) and PbPb in 0-30% centrality bin (middle). The bottom set of panels is the difference of the PbPb $p_T^{\parallel}$ with the corresponding pp. Cumulative curves for all radii are shown as dashed lines for pp and solid lines

Fig. 2. Upper row: $\langle p_T^{\parallel} \rangle$ in pp collisions as a function of Δ , for a distance parameter $R = 0.2, 0.3, 0.4$, and 0.5 , from left to right for different ranges of track p_T , and total $\langle p_T^{\parallel} \rangle$ (i.e. $\langle p_T^{\parallel} \rangle$ summed over all p_T ranges for a given Δ bin). Dashed lines indicate cumulative results for $\langle p_T^{\parallel} \rangle_{[0,\Delta]}$ in pp, for each distance parameter (i.e. integrating total $\langle p_T^{\parallel} \rangle$ over the Δ range from $\Delta = 0$ to the point of interest). Middle row: $\langle p_T^{\parallel} \rangle$ in PbPb collisions of centrality range 0–30% as a function of Δ , for distance parameters $R = 0.2, 0.3, 0.4$, and 0.5 from left to right. Solid line indicates $\langle p_T^{\parallel} \rangle_{[0,\Delta]}$ in PbPb for each distance parameter. Lower row: Difference between PbPb and pp. Error bars and brackets represent statistical and systematic uncertainties, respectively. The results are inclusive in the dijet asymmetry parameter A_J .

for PbPb. Cumulative curve shape is similar between pp and PbPb within each distance parameter selection, as is constituent content differences within each system. Both reference pp and PbPb show a shift in the position of the subleading jet side $p_T^{\parallel}$ peak towards larger Δ as R increases from 0.2 to 0.5. The shift can be understood as an exclusion of the space in Δ where a third jet can potentially exist, as a third jet within Δ of 0.5 at $R = 0.5$ would be clustered as part of the subleading jet.

6. Conclusions

Momentum flow in PbPb and pp dijet events has been studied through large angles relative to the dijet system for multiple distance parameters R . Initial momentum imbalances within the jet cone are made up by summing softer particles through large angles away from the jet. In pp, these particles are characteristically of p_T 2–8 GeV. In PbPb, the particles making up initial imbalance are typically of a lower p_T , 0.5–2 GeV. The cumulative curves are consistent between PbPb and pp within each R parameter. The balancing momentum peak on the subleading side shifts towards larger Δ with increasing R for both PbPb and pp. The shift is more pronounced in pp than PbPb, where the softer particles are closer to the jet axes with the largest distance parameter, $R = 0.5$. These results characterize momentum distributions in dijet events through

large angles, and constrain the redistribution of dijet missing momentum through the rest of the event in the modeling of parton energy loss in the hot and dense medium produced in collision of heavy ions.

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