Studies of Jet Quenching in HI Collisions at CMS

Frank Ma for the CMS Collaboration

Abstract

Jet production in PbPb collisions at a nucleon-nucleon center-of-mass energy of 2.76 TeV was studied using the CMS detector at the LHC, using a data sample corresponding to an integrated luminosity of 6.7 inverse microbarn. Dijets were reconstructed using the CMS calorimeters, and a significant energy imbalance was observed between the leading jet and the away-side jet with increasing centrality. Correlation studies of jets and tracks reveal that the fragmentation of the away-side jet is redistributed to lower pt and wider angle outside of the jet cone.

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Studies of Jet Quenching in HI Collisions at CMS

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Jet production in PbPb collisions at a nucleon-nucleon center-of-mass energy of 2.76 TeV was studied using the CMS detector at the LHC, using a data sample corresponding to an integrated luminosity of 6.7 inverse microbarn. Dijets were reconstructed using the CMS calorimeters, and a significant energy imbalance was observed between the leading jet and the away-side jet with increasing centrality. Correlation studies of jets and tracks reveal that the energy of the away-side jet is redistributed to lower pt and wider angle outside of the jet cone.

1 Introduction

Heavy ion collisions at the Large Hadron Collider (LHC) allow one to study the thermodynamic properties of the fundamental theory of the strong interaction — Quantum Chromodynamics (QCD). Studying the modification of jets that are created from within the medium has long been proposed as a particularly useful tool for probing the QCD medium properties. In the presence of a QCD medium, the partons may lose energy to the medium via elastic processes (collisional parton energy loss) or inelastic processes (radiative parton energy loss). The study of medium-induced modifications of dijet properties can therefore shed light on the transport properties of collective QCD matter created by heavy ion collisions.

2 Experimental Methods

This analysis was performed using the data collected in 2010 from PbPb collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV at the Compact Muon Solenoid (CMS) detector. Jets were reconstructed with background subtraction based on their energy deposits in the CMS calorimeters, and the events were selected from a jet-triggered dataset.

Because heavy ions are extended objects, the impact parameter is an important characterization of the events. The amount of overlap between the two colliding nuclei is what we mean by “centrality” of the collision. In this analysis, centrality was determined from minimum events based on the total energy from both forward hadronic calorimeters. Simulations can be used to correlate centrality, as quantified using the fraction of the total interaction cross section, with physically meaningful quantities such as the total number of nucleons in the two lead ($^{208}$Pb) nuclei which experienced at least one inelastic collision ($N_{\text{part}}$).
3 Results

3.1 Dijet Properties in pp and PbPb data

To obtain a clean dijet selection, we select events with a leading jet having corrected $p_{T,1} > 120$ GeV/c, a subleading jet with $p_{T,2} > 50$ GeV/c, and a minimum azimuthal angle between them ($\Delta \phi_{12} > 2\pi/3$). Only jets within $|\eta| < 2$ were considered. Given this selection, we observe a sharp $\Delta \phi_{12}$ correlation between leading and subleading jets, indicating true dijet pairs.

In-medium induced parton energy loss can significantly alter the detector level jet energy (and hence dijet energy balance) by either transporting energy outside of the jet cone or shifting the energy towards low momentum particles that will not be detected in the calorimeter. To characterize the dijet momentum balance quantitatively, we use the asymmetry ratio, 

$$ A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} , $$

where $p_T$ is the corrected $p_T$ of the reconstructed calorimeter jet. The subscript 1 always refers to the leading jet, so that $A_J$ is positive by construction.

In Fig. 1(a), the $A_J$ dijet asymmetry observable calculated by PYTHIA is compared to pp data at $\sqrt{s} = 7$ TeV. We see that data and event generator are found to be in excellent agreement, demonstrating that PYTHIA (at $\sqrt{s} = 2.76$ TeV) can serve as a good reference for the dijet imbalance analysis in PbPb collisions. Figs. 1(b)-(f) show the centrality dependence of $A_J$ for PbPb collisions. To separate effects due to the medium itself from effects simply due to reconstructing jets in the complicated environment of the underlying PbPb event, the reference PYTHIA dijet events were embedded into a minimum bias selection of PbPb events at the raw data level. In contrast to PYTHIA+DATA, we see that data shows a dramatic decrease of balanced dijets with increasing centrality.

![Figure 1](image_url)

Figure 1: Left 6 panels show dijet asymmetry distribution, $A_J$, of selected dijets for 7 TeV pp collisions (a) and 2.76 TeV PbPb collisions in several centrality bins: (b) 50–100%, (c) 30–50%, (d) 20–30%, (e) 10–20% and (f) 0–10%. Data are shown as black points, while the histograms show (a) PYTHIA events and (b)-(f) PYTHIA events embedded into PbPb data. Right panel shows fraction of selected dijets with $A_J < 0.15$ out of all events with a leading jet with $p_{T,1} > 120$ GeV/c as a function of $N_{part}$. The result for reconstructed PYTHIA dijet events (blue filled star) is plotted at $N_{part} = 2$. The other points (from left to right) correspond to centrality bins shown in (b)-(f) in the left 6 panels. The red squares are for reconstruction of PYTHIA+DATA events and the filled circles are for the PbPb data. For the data points, vertical bars and brackets represent the statistical and systematic uncertainties, respectively.

The centrality evolution of the dijet momentum balance can be explored more quantitatively by studying the fraction of balanced jets in the PbPb events. The balanced fraction, $R_B(A_J <
0.15), is plotted as a function of collision centrality (in terms of \( N_{\text{part}} \)) in the right panel of Fig. 1. It is defined as the fraction of all events with a leading jet having \( p_T > 120 \text{ GeV}/c \) for which a subleading partner with \( A_J < 0.15 \) and \( \Delta \phi_{12} > 2\pi/3 \) is found. The \( A_J \) threshold of 0.15 was chosen because it is the median of the \( A_J \) distribution for selected dijets in pure PYTHIA events. In contrast to PYTHIA+DATA dijets, the PbPb data show a rapid decrease in the fraction of balanced jets with collision centrality. The effect is much larger than the combined systematic uncertainties. These results imply a degradation of the parton energy, or jet quenching, in the medium produced in central PbPb collisions. The final systematic uncertainties, stemming mainly from uncertainties in the jet energy scale, are described in [5].

### 3.2 Overall Momentum balance of Dijet Events

We next turn to the question of where and how the medium energy loss occurs by exploiting additional information from the entire CMS tracker. We measure overall transverse momentum balance in the dijet events using the projection of missing \( p_T \) of reconstructed charged tracks onto the leading jet axis, defined as,

\[
p_T^\parallel = -\sum_i p_T^i \cos(\phi_i - \phi_{\text{Leading Jet}}),
\]

where the sum is over all tracks with \( p_T > 0.5 \text{ GeV}/c \) and \( |\eta| < 2.4 \). For this study, the leading and subleading jets are required to have a slightly smaller \( \eta \) range (\( |\eta| < 1.6 \)) to allow the jets to remain fully inside the CMS tracker acceptance. No background subtraction in the track distribution is needed since the underlying PbPb tracks cancel in the \( p_T^\parallel \) sum.

In Fig. 2, \( \langle p_T^\parallel \rangle \) is shown as a function of \( A_J \) in the 0–30% centrality bin, where we expect the medium effects to be the strongest. Here \( A_J \) is the same calorimeter jet \( A_J \) as described in Sec. 3.1. The left column shows \( \langle p_T^\parallel \rangle \) using all selected tracks. One sees that in both data and simulation, the overall momentum balance of the events (shown as solid circles) is recovered within uncertainties even for dijets with large energy asymmetry. This cross-checks the soundness of the detector, since regardless of medium effects, net transverse momentum is conserved. The figure also shows the contributions to \( \langle p_T^\parallel \rangle \) for five transverse momentum ranges from 0.5–1 GeV/c to \( p_T > 8 \text{ GeV}/c \), shown as stacked histograms.

Important insights into the dijet asymmetry emerge when we look at the \( \langle p_T^\parallel \rangle \) differential in radial distance from the jets. The middle and right columns of Fig. 2 show \( \langle p_T^\parallel \rangle \) separately for tracks inside cones of size \( \Delta R = 0.8 \) around the leading and subleading jet axes, and for tracks outside of these cones. We see that for both data and MC an in-cone imbalance of \( \langle p_T^\parallel \rangle \approx -20 \text{ GeV}/c \) is found for the \( A_J > 0.33 \) selection. This shows that track momentum sums within the leading and subleading jet cones confirm the calorimeter dijet asymmetry results showed earlier in Sec. 3.1. In addition, both data and simulation show similar large negative contribution to \( \langle p_T^\parallel \rangle \) (i.e., in the direction of the leading jet) in the \( p_T > 8 \text{ GeV}/c \) range. This cross-checks that the dijet energy asymmetry in data is not caused by fake jets from background fluctuation, because only genuine high \( p_T \) jets give rise to high \( p_T \) tracks. Looking now at the right column, we see that in both data and MC the in-cone energy difference is balanced by a corresponding out-of-cone imbalance of \( \langle p_T^\parallel \rangle \approx 20 \text{ GeV}/c \). However, in the PbPb data the out-of-cone contribution is carried almost entirely by tracks with \( 0.5 < p_T < 4 \text{ GeV}/c \) whereas in MC more than 50% of the balance is carried by tracks with \( p_T > 4 \text{ GeV}/c \), with a negligible contribution from \( p_T < 1 \text{ GeV}/c \). The PYTHIA+HYDJET results are indicative of semi-hard initial or final-state radiation as the underlying cause for large \( A_J \) events in the MC study. This is in contrast to the results for large-\( A_J \) PbPb data, which show that a large part of the momentum balance is carried by soft particles (\( p_T < 2 \text{ GeV}/c \)) and radiated at large angles to the jet axes (\( \Delta R > 0.8 \)).
Figure 2: Average missing transverse momentum, $\langle \not{p}_T \rangle$, for tracks with $p_T > 0.5$ GeV/c, projected onto the leading jet axis (solid circles). The $\langle \not{p}_T \rangle$ values are shown as a function of dijet asymmetry $A_J$ in 0–30% central events, for the full event (left), inside ($\Delta R < 0.8$) one of the leading or subleading jet cones (middle) and outside ($\Delta R > 0.8$) the leading and subleading jet cones (right). For the solid circles, vertical bars and brackets represent the statistical and systematic uncertainties, respectively. Colored bands show the contribution to $\langle \not{p}_T \rangle$ for five ranges of track $p_T$. The top and bottom rows show results for PYTHIA+HYDJET and PbPb data, respectively. For the individual $p_T$ ranges, the statistical uncertainties are shown as vertical bars. Note that as the underlying PbPb event in both data and MC is not $\phi$-symmetric on an event-by-event basis, the back-to-back requirement was tightened to $\Delta \phi_{12} > 5\pi/6$.

4 Summary and Conclusion

A strong increase in the fraction of highly unbalanced jets has been seen in central PbPb collisions compared with peripheral collisions and model calculations, consistent with a high degree of parton energy loss in the produced QCD medium. A large fraction of the momentum balance of these unbalanced jets is carried by low-$p_T$ particles at large radial distance, in contrast to PYTHIA simulations embedded into heavy ion events. The results provide qualitative constraints on the nature of the jet modification in PbPb collisions and quantitative input to models of the transport properties of the medium created in these collisions.

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