Dijet imbalance in 2.76 TeV PbPb collisions in CMS

Sevil Salur for the CMS Collaboration
Department of Physics and Astronomy Rutgers, the State University of New Jersey 136 Frelinghuysen Road Piscataway, NJ 08854-8019
E-mail: salur@physics.rutgers.edu

Abstract. We present the measurement of dijet production in PbPb collisions at a nucleon-nucleon center-of-mass energy of 2.76 TeV that is studied with the CMS detector at the LHC. We use data corresponding to an integrated luminosity of $150 \mu b^{-1}$. Jets are reconstructed using the anti-$k_T$ algorithm on particle flow objects. The dijet momentum balance and angular correlations are studied as a function of collision centrality and leading jet momentum. For the most peripheral PbPb collisions, good agreement of the dijet momentum balance distributions with pp data and reference calculations at the same collision energy is found. However, more central collisions show a strong imbalance of leading and subleading jet transverse momenta, confirming the previous observations made using a smaller dataset. The extended jet transverse momentum range significantly increases the discriminatory power of the measurement for different models of parton energy loss in hot QCD matter.

1. Introduction

Well identified decay products of partonic interactions at large momentum transfers, also called hard probes, are used to study the structure and dynamics of the Quark Gluon Plasma [1, 2, 3]. These probes are well calibrated, as their expected yields are calculable using the perturbative QCD theoretical framework and as their propagation through the medium are affected via strong interactions. At RHIC, indirect measurements of energy loss in the medium (“jet quenching”) have been made via observables of leading fragments of jets and their correlations [4, 5, 6]. Recent results from LHC confirmed these observations and expanded our knowledge of the jet-quenching effects by utilizing fully reconstructed jets, correlations between jets and single particles, and charged particle measurements [7, 8, 9, 10, 11].

By utilizing back to back jets, the LHC analyses revealed significant jet quenching, consistent with theoretical expectations that involve differential energy loss of back-to-back hard-scattered partons [12, 13, 14]. However, angular correlations between the jets are found to be almost unchanged, ruling out single-hard-gluon radiation as the leading energy loss mechanism. The jet fragmentation pattern also showed no change due to the existence of the hot QCD medium [16]. Similar quenching was also observed in isolated photon+jet pairs [15]. While these results constrain the mechanism of parton energy loss [17, 18], further understanding requires the measurement of the $p_T$ dependence of the observed effects. The goal of this analysis is to characterize possible modifications of dijet event properties as a function of centrality and leading jet transverse momentum in PbPb collisions. Further details of this analysis can be found in [19].
2. Analysis
For the di-jet analyses, a total integrated luminosity of 150 $\mu$b$^{-1}$ PbPb collisions and a total integrated luminosity of 231 nb$^{-1}$ of pp collisions at a nucleon-nucleon center-of-mass energy of 2.76 TeV, collected with the Compact Muon Solenoid (CMS) detector are used. The CMS experiment at the LHC is a general multi-purpose detector designed to explore physics at the large TeV energy scales [20]. The two most important detector requirements for a successful reconstruction of jets in heavy ion collisions are a good energy measurement of large species of particles and an efficient jet trigger. With its high quality electromagnetic and hadronic calorimeters covering a wide pseudorapidity and a full azimuthal range, by design CMS is extremely well suited to measure hard scattering processes [21]. Sub-detectors such as the high precision silicon tracker, which has very good momentum resolution, complement the calorimeters for jet studies.

Jet reconstruction in heavy-ion collisions in CMS is performed with anti-$k_T$ jet algorithm that is encoded in the FastJet framework [22]. A small value of 0.3 for resolution parameter R is selected to reduce the deterioration of the jet energy resolution in PbPb collisions due to fluctuations of the background from soft interactions. An algorithm that is a variant of an iterative “noise/pedestal subtraction” technique is used to estimate the heavy ion background event-by-event [23]. The input particles of the jet reconstruction are Particle Flow (PF) objects that are reconstructed by combining information from various sub-detectors, most importantly by combining tracks with clusters in electromagnetic and hadronic calorimeters [24]. The reconstructed jet energies are corrected by using a factorized multi-step approach used for all jet analyses in CMS [25]. Jet energy corrections are derived from PYTHIA [26] simulations without PbPb underlying events.

3. Di-Jet Asymmetry Results
The distribution of the angle $\Delta\phi$ between the leading and subleading jets as a function of leading jet $p_T$ is shown in Figure 1. The results from the most central (0-20% central) PbPb events are shown as black points. The red histogram shows the results for PYTHIA dijets embedded into HYDJET PbPb simulated events [27]. The error bars represent only the statistical uncertainties. The distribution around the $\Delta\phi = \pi$ peak reflects the back-to-back dijet production and although this distribution changes across the various leading-jet $p_T$ bins, there is no significant difference between PbPb data and the simulation. Compared with the simulated events, the two most central bins have an apparent excess of jets at low $\Delta\phi$ which is likely due to the matching of the leading jet with a random underlying event fluctuation instead of the true subleading jet partner. The difference in the rate of such events between the PbPb data and the simulated sample is compatible with the effect of quenching.

To characterize the jet energy balance or imbalance quantitatively, we define the asymmetry ratio $A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$ where the subscript 1 always refers to the leading jet so that $A_J$ is positive by construction. This asymmetry value was calculated for pairs of jets where the leading jet has $p_T > 120$ GeV/c and the subleading jet has $p_T > 30$ GeV/c. Jets are also required to be separated by $\Delta\phi > 2\pi/3$ to ensure that di-jets are approximately back-to-back. It is important to note that the use of $A_J$ to a large extent removes uncertainties due to possible constant shifts of the jet energy scale.

The fraction of the events as a function of $A_J$ for six centrality bins is shown in Figure 2. The data is compared to the reconstructed PYTHIA dijets embedded in HYDJET data events as shown as the red histograms. Only statistical errors are shown. For the most peripheral bins, the data point values are somewhat similar to those of the simulations. However, as the events become more central, a shift in data points becomes quite significant. Dijets found in the most central events show a very significant deficit of events in which the two jets are balanced and a significant excess of unbalanced pairs.
Figure 1. Distribution of the angle $\Delta \phi$ between the leading and subleading jets in bins of leading jet transverse momentum described in the figures for subleading jets of $p_{T}^{\text{sub}} > 30$ GeV/c. Results for 0-20% central PbPb events are shown as points while the histogram shows the results for PYTHIA dijets embedded into HYDJet PbPb simulated events.

The $A_{J_{1}}$ distributions in various leading jet $p_{T}$ selections are constructed for the most central 20% of the events and is presented in Figure 3. The shape of the distributions evolves in a different fashion in data and PYTHIA embedded simulations. This evolution is influenced by both the change in the relative jet resolution and splitting probability as present in pp collisions, and the medium induced energy loss which is present only in PbPb collisions. In order to extract the properties of medium induced energy loss from this phenomenon, one has to model the energy loss with these effects in mind.

The distributions of the $p_{T}^{\text{sub}}/p_{T}^{\text{lead}}$ is shown in Figure 4 to provide a more intuitive way of quantifying the energy loss. The arrows show the mean values of the distributions with equivalent shifts of data and simulations for all leading jet $p_{T}$. Both $A_{J}$ and $p_{T}^{\text{sub}}/p_{T}^{\text{lead}}$ distributions shows a strong evolution in the shapes across the various jet $p_{T}$ bins, while a significant difference between PbPb data and simulations persists.

Average dijet momentum ratio $p_{T}^{\text{sub}}/p_{T}^{\text{lead}}$ as a function of leading jet $p_{T}$ for three bins of collision centrality is shown in Figure 5. Results for PbPb data are shown as points with vertical bars and brackets indicating the statistical and systematic uncertainties. Results for the PYTHIA dijets embedded into HYDJet PbPb simulated events are shown as squares. In the 50-100% centrality bin, results are also compared with pp data, which is shown as the open circles. The difference between the PbPb measurement and the simulation expectations is shown in the bottom panels. Both the data and the simulations reveal an increasing trend for the mean value of the jet transverse momentum ratio, as a function of the leading jet $p_{T}$. This is mostly due to the improvement of the energy resolution and the reduction of the jet splitting in higher
4. Results from Missing $p_T$

Studies of jet-hadron correlations involving vector summation of charged hadron momenta, find that the energy balance in events with large di-jet asymmetry is recovered on average by an excess of low-momentum particles in the hemisphere of the away-side jet, at large angles relative to the jet axes [7]. Complementary information about the overall momentum balance in the di-jet events can be obtained using the projection of missing $p_T$ of reconstructed charged tracks onto the leading jet axis. For each event, this projection was calculated as

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

where the sum is over all tracks with $p_T > 0.5$ GeV/$c$ and $|\eta| < 2.4$. The results were then averaged over events to obtain $\langle p_T^\parallel \rangle$. No background subtraction was applied, which allows this study to include the $|\eta_{\text{jet}}| < 0.8$ and $0.5 < p_T^{\text{Track}} < 1.0$ GeV/$c$ regions.
Figure 3. Dijet asymmetry ratio, $A_J$, in bins of leading jet $p_T$ with subleading jets of $p_T > 30 \text{ GeV/c}$ with a selection of $\Delta \phi > 2\pi/3$ between the two jets, for 0-20% central events. The effect of energy loss is visible at high leading jet $p_T$ bins as well as lower ones, however the shape of the distribution evolves as one goes to higher $p_T$, both in MC and data. This is mostly because of a different amount of jet energy resolution being involved, and it should be taken into account when inferring about the change in the energy loss.

The $\langle p_T^d \rangle$ values are shown as a function of dijet asymmetry $A_J$ for 0-30% centrality in the right panel of Figure 6. Colored bands show the contribution to $\langle p_T^d \rangle$ for various ranges of track $p_T$. For the solid circles, vertical bars and brackets represent the statistical and systematic uncertainties, respectively and for the individual $p_T$ ranges, the statistical uncertainties are shown as vertical bars. Using tracks with $|\eta| < 2.4$ and $p_T > 0.5 \text{ GeV/c}$, one sees the momentum balance of the events, shown as solid circles, is recovered within uncertainties for all events including with large observed di-jet asymmetry events. This shows that the dijet momentum imbalance is not related to undetected activity in the event due to instrumental (e.g. gaps or inefficiencies in the calorimeter) or physics (e.g. neutrino production) effects. The radial dependence of the momentum balance can be studied with $\langle p_T^d \rangle$ for tracks inside cones of size $\Delta R = 0.8$ around the leading and subleading jet axes, and for tracks outside of these cones. The results of this study are shown in the middle and the right panel of the Figure 6 for the in-cone balance and out-of-cone balance for central events respectively. One observes that for an in-cone imbalance of $\langle p_T^d \rangle \approx -20 \text{ GeV/c}$ is found for the $A_J > 0.33$ selection. This is balanced by a corresponding out-of-cone imbalance of $\langle p_T^d \rangle \approx 20 \text{ GeV/c}$. The out-of-cone contribution is carried almost entirely by tracks with $0.5 < p_T < 4 \text{ GeV/c}$.
5. Conclusions

Quenching of jets in PbPb collisions is studied by utilizing the di-jets measured with the CMS detector. The anti-$k_T$ algorithm is used to reconstruct jets based on combined tracker and calorimeter information. The data is compared to the reconstructed PYTHIA dijets embedded in HYDJET data events tuned to reproduce the observed underlying event fluctuations. A good agreement between data and simulations is observed for the most peripheral collisions. This agreement starts to fail with increased centrality and for the most central collisions, the dijet momentum imbalance in the data appears to be significantly larger than as seen in the simulation. Across the entire range of jet momenta studied, no significant broadening of the dijet angular correlations is observed with respect to the reference distributions.

The dijet momentum imbalance is studied as a function of the leading jet $p_T$ for different centrality ranges in comparison to simulations. For mid-central (30-50%) and more central PbPb event selections, a significantly lower average dijet momentum ratio ($p_{T,sub}^{lead}/p_{T,lead}$) is observed than in the pp data and in the simulations. The mean values of the distributions of the $p_{T,sub}^{lead}/p_{T,lead}$ show a downward shift with respect to the simulation reference independent of the leading jet $p_T$. The missing energy was also recovered in the form of soft particles that are far away in phase space from the back to back jets.
Figure 5. Data and MC simulation comparison of the centrality dependent $<p_{T,2}/p_{T,1}>$ as a function of leading jet $p_T$. The difference between PbPb and MC results are also shown in the bottom panels.

Figure 6. Left: Average missing transverse momentum, $\langle |p_T^\parallel|\rangle$, for tracks with $p_T > 0.5\text{GeV/c}$, projected onto the leading jet axis (solid circles) for the 0-30% central collisions. Colored bands show the contribution to $\langle |p_T^\parallel|\rangle$ for various ranges of track $p_T$. The $\langle |p_T^\parallel|\rangle$ values are shown 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) [7].

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