The Compact Muon Solenoid Experiment
Conference Report

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25 July 2014 (v2, 31 July 2014)

Momentum flow relative to the dijet system in PbPb collisions

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Presented at *QM2014 Quark Matter 2014*

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The difference in charged particle multiplicity and momentum flow carried by charged particles near the leading and the subleading jet in dijet events is measured in PbPb and pp collisions. In PbPb collisions, there is an increase in the fraction of dijet events with large momentum asymmetry between the leading and subleading jets compared to what is seen in pp collisions. In this analysis, the radiation balancing the dijet asymmetry is characterized in terms of the multiplicity, angular (up to $\Delta R = 1.8$) and momentum spectra of charged particles with $p_T > 0.5$ GeV/c. The measurement is done as a function of PbPb collision centrality and dijet asymmetry.

1. Introduction

An increase in the dijet transverse momentum imbalance [1, 2] is observed in PbPb collisions which is due the energy loss induced by interactions of partons created in a hard scattering processes with the hot and dense medium produced in multiple soft interactions. The momentum that is lost by the parton into the medium inevitably modifies the momentum flow in the event. The angular and p_T spectrum of this modification can provide insight on the dominant mechanisms of medium parton interactions that control the energy loss.

In dijet events both leading and subleading jets lose energy, but the increase in dijet imbalance implies that the subleading jets on average lose more energy than the leading jets. It is possible to make use of this information and tag quenched jets as the subleading jets belonging to central PbPb events with large dijet imbalance. In such collisions, the amount of additional transverse momentum loss of subleading jet compared to leading jet on average is ≈ 10 GeV/c, which is 10^3 times smaller than the total transverse momentum generated in the event.

The transverse momentum flow which is uncorrelated to jets is distributed symmetrically in azimuthal angle with respect to the dijet direction. In Ref. [1], CMS used a “missing p_T ” method to make use of this symmetry. In this method azimuthally symmetric part of the transverse momentum flow cancels and leaves behind the part of the flow with nontrivial angular dependence with respect to the dijet direction. Note that momentum flow induced by jet quenching can also have an azimuthally symmetric component, which will also cancel in this measurement. In this analysis same idea is used to do provide detailed information on the angular distribution.

2. Jet reconstruction

Jet reconstruction in heavy-ion collisions in CMS is performed with the anti- k_T algorithm, with a distance parameter $R = 0.3$, that is encoded in the FastJet framework [3, 4]. Jets were reconstructed based on energy deposits in the CMS calorimeters. For pp collisions no underlying event (UE) subtraction is employed. Whereas, for PbPb collisions, in order to subtract the heavy ion background, a new algorithm (“HF/Voronoi”) is used [5, 6], which removes the UE by mapping information in the forward region of the detector to mid-rapidity.

3. Track reconstruction

For studies of pp data and Pythia MC [7], charged particles are reconstructed using the same iterative method [8] as in previous CMS analyses of pp collisions. While, for PbPb data and PYTHIA+HYDJET [9], an iterative charged particle reconstruction similar to what is used in earlier heavy ion analyses [10, 11] is employed with the difference that global tracking, which uses the information of hits from both pixel and silicon strip sub-detectors, extends down to $p_T = 0.4$ GeV/c. However, for this analysis only tracks with p_T above 0.5 GeV/c are used.

4. Event selection

The analysis uses data sets for PbPb and pp collisions with integrated luminosities of $150\mu\text{b}^{-1}$ and 5.3pb^{-1} , respectively, collected in 2011 and 2013 at collision energies of $\sqrt{s_{\text{NN}}} = 2.76$ TeV. Events are selected using an inclusive single-jet trigger with a threshold of $p_T > 80$ GeV/c and they are required to have a leading (highest transverse momentum) calorimeter jet in the pseudorapidity range of $|\eta| < 2$ with a corrected jet $p_T > 120$ GeV/c and subleading (next highest transverse momentum) 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 $5\pi/6$. For events this event selection the trigger is fully efficient.

Only events in which both leading and subleading jets fall within $|\eta| < 1.6$ are included in the part of the analysis that does not depend on angular distribution of tracks with respect to jets. While, for the angular dependence analysis, in order to ensure tracker acceptance, an even tighter restriction on the pseudorapidity of leading and subleading jet ($|\eta| < 0.5$) is used, after the leading and subleading jets are found within $|\eta| < 2$.

5. Results

A selection of results from Ref. [6] are shown in this section.

The direction of dijet system in the transverse plane, ϕ_{Dijet} , is determined as the average azimuthal direction of leading jet and that of subleading jet flipped around the origin. Each event is bisected into two hemispheres with the plane perpendicular to this axis. The difference of the multiplicity of charged particles in subleading and leading jet hemispheres, ΔMult , is shown in Fig. 1. It increases as a function of dijet asymmetry, $A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$ in both pp and PbPb collisions as the number of jets in the subleading jet hemisphere increases. The difference between ΔMult in pp and PbPb collisions due the extra particles created in the energy loss process in PbPb collisions is enhanced in central collisions and in dijet events with large A_J , and amounts to as large as ≈ 15 particles in the most central and most asymmetric events.

Detailed information about the difference between the p_T spectrum of charged particles correlated to leading and subleading jets is obtained by the missing p_T measurement. Missing p_T , $p_T^{\parallel}$, is defined as:

$$p_T^{\parallel} = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Dijet}}), \quad (1)$$

This projection is calculated in bins of charged particle p_T to measure the spectrum. In Fig. 2 missing p_T is shown as a function of A_J . The $\langle p_T^{\parallel} \rangle$ contribution of charged particles with $p_T > 8$ GeV/c in leading jet direction increases as a function of A_J both in pp and PbPb. In pp collisions, this is balanced by the contribution of charged particles with $2 < p_T < 4$ GeV/c. In PbPb collisions, spectrum is softened and a significant amount of momentum balance is gained by $\langle p_T^{\parallel} \rangle$ of particles with $p_T < 2$ GeV/c.

To measure the angular spectrum of transverse momentum flow with respect to the dijet system, $\langle p_T^{\parallel} \rangle$ is calculated in slices of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ between the charged particle and jet axis for leading and subleading jet, and the two values are summed. The slices are defined around the jet axes, while the projections are done on the ϕ_{Dijet} axis.

The results are shown in Fig. 3 for events without an A_J requirement on the left and in events with $A_J > 0.22$ on the right. The characteristic properties of the angular distribution of $\langle p_T^{\parallel} \rangle$ is an in-cone imbalance at $\Delta R < 0.2$ in the leading jet direction which is balanced by particles in the subleading jet direction outside this radius. The balancing distribution extend up to large ΔR in all cases and the shape of the balancing distribution is very similar in pp and PbPb collisions even if the p_T spectrum is significantly different. The similarity in the shape of the momentum flow

Figure 1. (Upper panels) $\langle \Delta_{\text{mult}} \rangle$ between the away-side hemisphere and leading jet hemisphere as a function of dijet asymmetry A_J . Measurements in pp (blue markers), PbPb (red markers), PYTHIA (dashed histogram) and PYTHIA+HYDJET MC (black histogram) are compared. (Lower panels) Difference of $\langle \Delta_{\text{mult}} \rangle$ between PbPb and pp collisions.[6]

with respect to the dijet system in pp and PbPb collisions can also be seen by comparing the the curves which show the integrated $\langle p_T^{\parallel} \rangle$ for all charged particles, for a cone of ΔR instead of an annulus.

In the bottom panels of the Fig. 3 the difference of $\langle p_T^{\parallel} \rangle$ as a function of ΔR in PbPb and pp collisions is shown. There is an excess of imbalance of charged particles at $\Delta R < 0.2$ in PbPb, which is expected as in PbPb collisions the dijet imbalance is also greater. This excess of high p_T imbalance is accompanied by an enhancement of low p_T particles which extends over the whole range of the measurement up to $\Delta R = 1.8$.

6. Conclusions

The momentum flow in PbPb and pp collisions containing high momentum jets has been studied. The dijet in-cone momentum imbalance in PbPb is found to be compensated by particles at lower transverse momentum ($p_T = 0.5 - 2$ GeV/c) than in pp collisions, where most of the momentum balance is found in the $p_T = 2 - 8$ GeV/c range. Correspondingly, a larger multiplicity of associated particles is seen in PbPb compared to pp. Both measurements show an increasing difference between PbPb and pp for more central PbPb collisions, reflecting a softening of the radiation carrying the momentum balance of the asymmetric dijet system. The current data allow the first detailed study of the angular dependence of the charged particle momentum balance up to large distances to the jet axis ($\Delta R = 1.8$). The angular pattern of the energy flow in PbPb as a function of ΔR matches that seen in pp collisions, despite the large shift in the momentum spectrum of radiated particles. These results constrain the angular and momentum spectra of charged particles involved in the QCD energy loss processes of partons traversing the hot and dense medium created in heavy ion collisions.

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Figure 2. (Upper row) $\langle p_T^{\parallel} \rangle$ for pp collisions (left) and four selections of PbPb collision centrality ranging from 50–100% to 0–10%. The solid markers show $\langle p_T^{\parallel} \rangle$ averaged over all tracks, while the colored boxes show the contribution to $\langle p_T^{\parallel} \rangle$ for various momentum ranges from $0.5 < p_T < 1$ GeV/c (light blue) to $p_T > 8$ GeV/c (red). For each panel $\langle p_T^{\parallel} \rangle$ values are shown as a function of dijet asymmetry from almost balanced ($A_J < 0.11$) to unbalanced ($A_J > 0.33$) dijets. For the solid circles, vertical bars and brackets represent the statistical and systematic uncertainties, respectively. For the individual p_T ranges, the statistical uncertainties are shown as vertical bars. (Lower row) Difference PbPb–pp of the $\langle p_T^{\parallel} \rangle$ [6]

Figure 3. Upper row: 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 ΔR . Also shown is the total $\langle p_T^{\parallel} \rangle$ (i.e., integrated over all p_T for a given ΔR bin) as a function of ΔR for pp (open squares) and PbPb data ($\times$ symbols). Dashed lines (pp) and solid lines (PbPb) show the cumulative $\langle p_T^{\parallel} \rangle$ (i.e., integrating the total $\langle p_T^{\parallel} \rangle$ over ΔR starting at $\Delta R = 0$). Lower row: Difference between the PbPb and pp differential $\langle p_T^{\parallel} \rangle$. Differences of cumulative $\langle p_T^{\parallel} \rangle$ are not shown. Left: Inclusive A_J selection. Right: $A_J > 0.22$. [6]