Hard Probes in Heavy Ion Collisions with CMS

Yetkin Yilmaz, on behalf of the CMS Collaboration
Massachusetts Institute of Technology
77 Massachusetts Avenue, Cambridge, MA02139, USA

Heavy Ion collisions at LHC energies allow studies of high density medium in kinematic ranges where vacuum reference is well understood and reproduced with perturbative calculations. High transverse momentum particles from the medium provide information on the amount of energy loss they suffered in the medium, which is known as "jet quenching". Using the capabilities of the CMS detector, the analyses of jets and various types of correlations between reconstructed jets and hadrons provide a detailed picture of this mechanism.

Studies of heavy ion collisions have provided evidence for a new state of matter that is formed in . Previous studies at RHIC have examined certain properties of this matter, of which an interesting one is the opacity, which is the resistance displayed by the material to a fast moving color-charged particle which traverses it through. This phenomenon was referred to as jet quenching, and it was quantified through the modification in the production rates of high transverse momentum probes. Since the cross sections of the production channels of these probes significantly increase in $\sqrt{s_{NN}} = 2.76$ TeV [1] compared to earlier accelerators, the study of PbPb collisions at LHC provide a great opportunity to both test the conclusions of the studies from RHIC, and extend the measurements into a lot larger kinematic ranges.

With its tracking, calorimetry and lepton identification capabilities, CMS is an excellent detector for measurements for a variety of probes at high transverse momenta, such as charged hadrons, jets, photons, vector bosons and quarkonia, in both pp and PbPb collisions. With the availability of pp data at the same $\sqrt{s}$, one can observe the modifications to any process when produced in PbPb environment. One such measurement is the nuclear modification factor, R_{AA} is defined as:

$$R_{\mathrm{AA}} = \frac{dN_{\mathrm{PbPb}}/dm_{\mathrm{T}}}{\langle T_{\mathrm{AA}} \rangle \times d\sigma_{\mathrm{pp}}/dm_{\mathrm{T}}}$$

where $m_{\mathrm{T}} = \sqrt{m^2 + p_{\mathrm{T}}^2}$ is the transverse mass of the particle.

The CMS measurements of the R_{AA} [2,3,4,5] are summarized in Fig. 1. While confirming the charged hadron results of earlier experiments, extends the p_{T} range significantly, and provide results of new color-neutral probes such as vector bosons. Although the production of color-neutral probes are consistent with the N_{coll} scaled expectation, the products of color-charged particles exhibit a suppression which is attributed to effects due to interaction of partons with the medium.

The studies with CMS detector can further investigate this effect with fully reconstructed jets, which provide a more direct comparison to the initial state of the hard scattering in pp

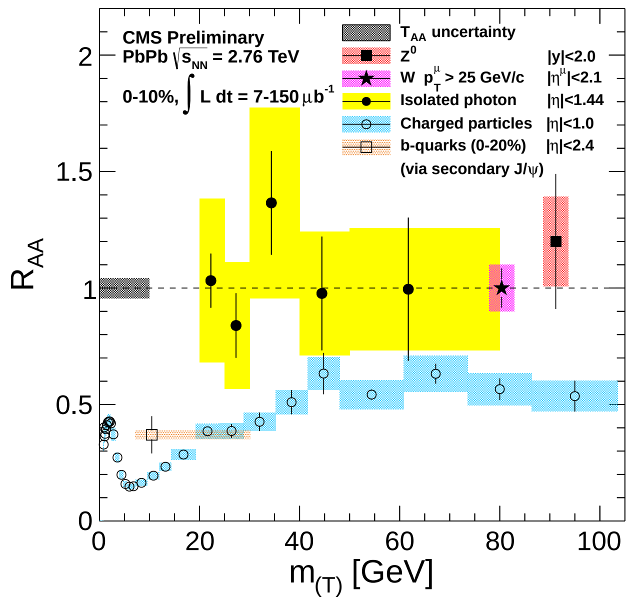

Figure 1: $R_{\rm AA}$ results in various CMS measurements, as a function of transverse mass ($m_{\rm T}$) for charged particles, photons and b-quarks, and mass (m) for W and Z bosons.

collisions and perturbative calculations. Earlier results from CMS[6], with the dataset of the 2010 LHC run with PbPb ions, have revealed various aspects of the energy loss mechanism. While the jets lost a significant fraction of their energy in the medium, their azimuthal correlations are not modified significantly. The energy that is deposited in the medium is redistributed over a large angular region[6] and the hadron composition of the reconstructed jets[7] resemble the same pattern as those in pp collisions.

With the availability of a large dataset from the 2011 LHC run with PbPb ions, earlier studies of dijets were repeated and more details are investigated through a more differential approach[8]. When correlating jets with highest reconstructed $p_{\rm T}$ values in each event, one observes that the distributions of the azimuthal angle between the two jets ($\Delta\phi_{1,2}$) are similar to those in PYTHIA simulations at each range of jet $p_{\rm T}$. However, an offset in these distributions due to background fluctuations which are reconstructed as low $p_{\rm T}$ jets, appears in different magnitudes in data and MC. This is consistent with the quenching effect, since when the $p_{\rm T}$ of the true subleading jet of the event is lower it is more likely for a background fluctuation to have higher $p_{\rm T}$. The analysis of the dijet imbalance selects dijets with $\Delta\phi_{1,2} > 2\pi/3$ and the residual contamination is subtracted by estimating the effects from dijets with $\Delta\phi_{1,2} < \pi/3$.

It is observed that when the leading jet of the event has high enough $p_{\rm T}$, it is always accompanied by a recoiled partner in the opposite direction in azimuth. The fraction of such correlated events after background subtraction and the fraction of the estimated background are shown in Fig. 3 as a function of leading jet $p_{\rm T}$ and event centrality.

In Fig. 4, the average ratio of subleading jet $p_{\rm T}$ to the leading jet $p_{\rm T}$, $\langle p_{\rm T,2}/p_{\rm T,1}\rangle$, is shown as a function of leading jet $p_{\rm T}$ in different bins of centrality. In the central events, a significant shift of the $\langle p_{\rm T,2}/p_{\rm T,1}\rangle$ with respect to the MC and pp results is observed. This shift, while changing monotonically with centrality, does not show a significant dependence on the leading jet $p_{\rm T}$. Since both data and MC include effects from detector resolution, the implications on the absolute amount of energy loss should be extracted via realistic models of quenching.

In summary, LHC has opened up a new territory for studies of the hard probes of the hot and dense medium. Although this paper discusses mainly the jet quenching related measurements,

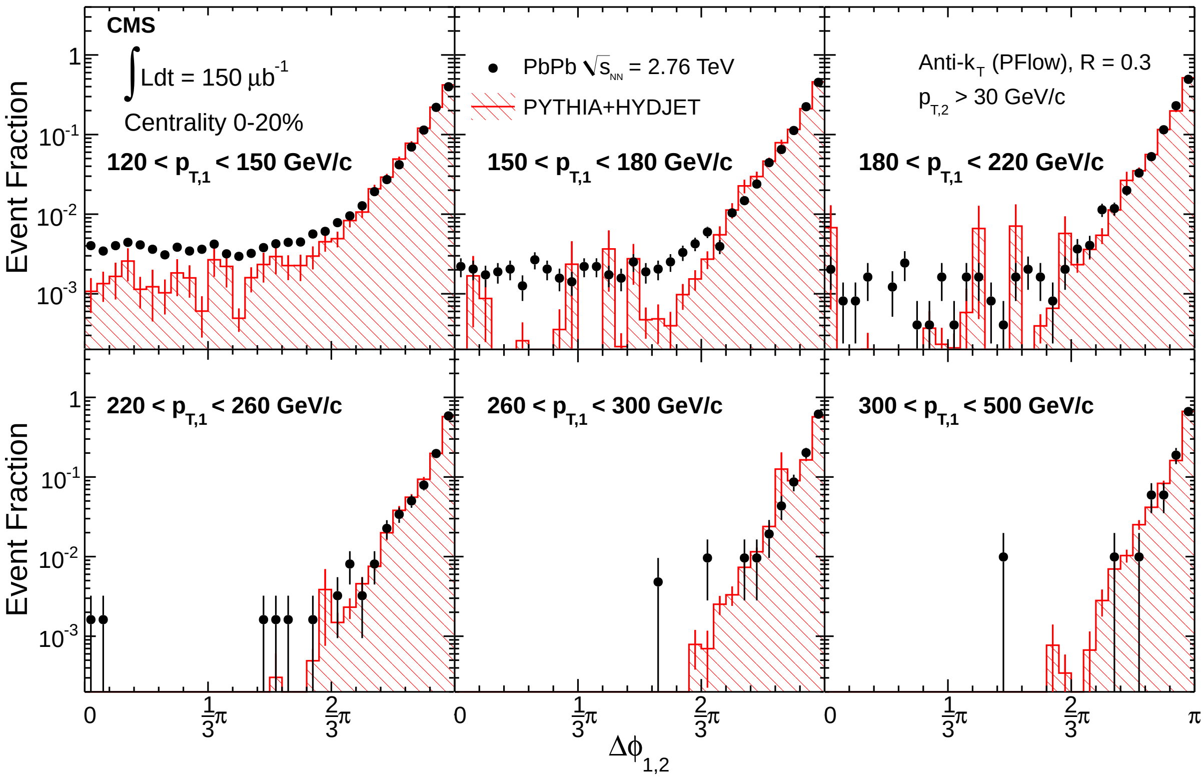

Figure 2: Distribution of the angle $\Delta\phi_{1,2}$ between the leading and subleading jets in bins of leading jet transverse momentum from $120 < p_{\mathrm{T},1} < 150$ GeV/c to $p_{\mathrm{T},1} > 300$ GeV/c for subleading jets of $p_{\mathrm{T},2} > 30$ GeV/c. Results for 0–20% central PbPb events are shown as points while the histogram shows the results for PYTHIA dijets embedded into HYDJET PbPb simulated events. The error bars represent the statistical uncertainties.

CMS also has measurements of quarkonia [5] which probe the color-screening phenomena. The variety of early results from LHC illustrate the potential for the future studies in the field of heavy ion collisions.

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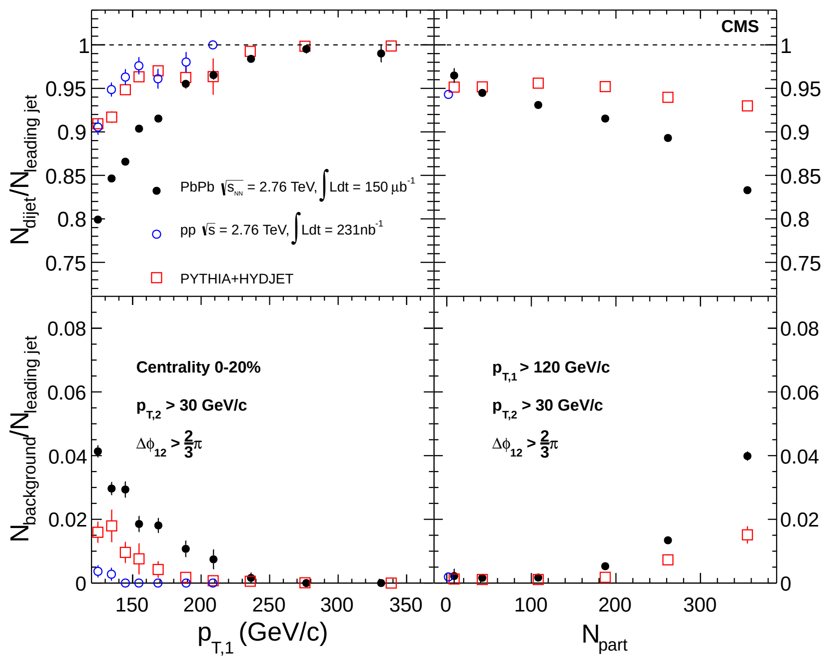

Figure 3: Fraction of events with a genuine subleading jet with $\Delta\phi_{1,2} > 2\pi/3$, as a function of leading jet $p_{\mathrm{T},1}$ (left) and N_{part} (right). The background due to underlying event fluctuations is estimated from $\Delta\phi_{1,2} < \pi/3$ events and subtracted from the number of dijets. The fraction of the estimated background is shown in the bottom panels. The error bars represent the statistical uncertainties.

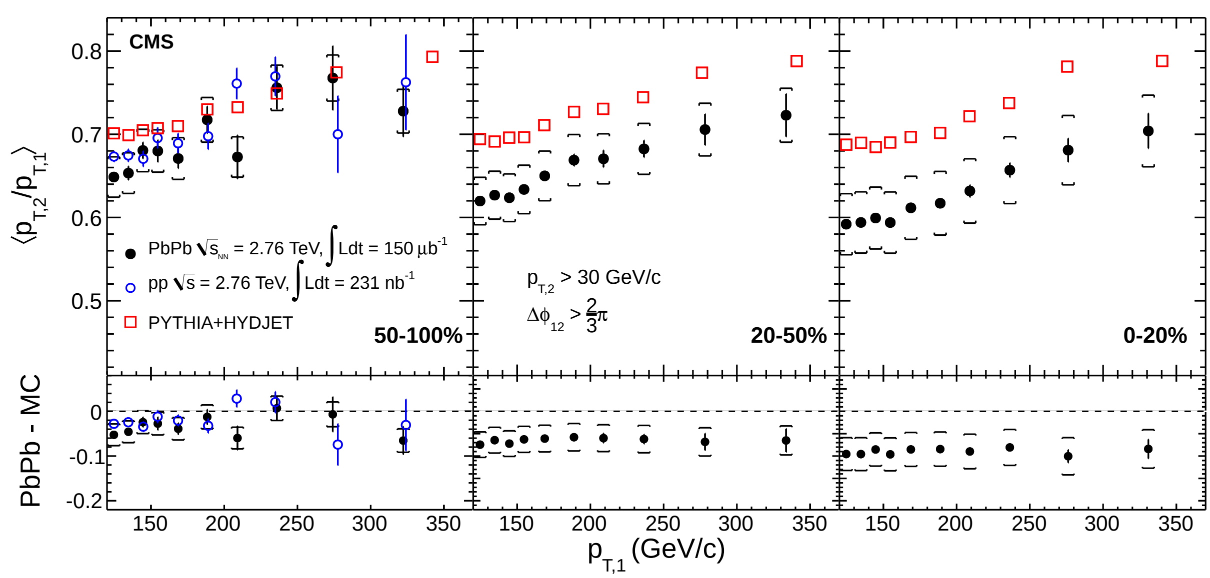

Figure 4: Average dijet momentum ratio $p_{\mathrm{T},2}/p_{\mathrm{T},1}$ as a function of leading jet $p_{\mathrm{T}}$for three bins of collision centrality, from peripheral to central collisions, corresponding to selections of 50–100%, 30–50% and 0–20% of the total inelastic cross section. Results for PbPb data are shown as points with vertical bars and brackets indicating the statistical and systematic uncertainties, respectively. Results for PYTHIA+HYDJET 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 PYTHIA+HYDJET expectations is shown in the bottom panels.