Hard Probes in CMS

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This paper reviews recent experimental results on hard probes in heavy-ion collisions from the CMS Collaboration. These studies include various energy loss phenomena (jet nuclear modification factors, tagged b-quark jets, di-jet and photon-jet energy imbalance); observables characterizing jet properties like jet fragmentation function and jet shapes; and measurements of high-p_T charged hadrons from jet fragmentation (nuclear modification factors up to 100 GeV/c. All of the presented results utilize the high statistics PbPb data, about 150 μb^{-1}, collected in late 2011 at the LHC.

1 Introduction

Hard probes - processes involving scatterings with large momentum transfer - and their modification in Pb-Pb collisions with respect to pp collisions, can be used to study the transport properties of the hot quark-gluon plasma (QGP) medium created in heavy ion collisions at ultra-relativistic energies [1]. The objective is to understand how a color charge (carried by quarks and gluons) is transported in the colored medium. Among the observables, often chosen to be high p_T particles or jets, there are two categories: those that interact strongly and are thus expected to be modified, such as (charged) hadrons, inclusive jets and heavy-quark jets; and those that remain largely unmodified such as high-energy photons, Z^0 and $W^{\pm}$ bosons. The production of electroweak bosons can be used to calibrate the associated jet energy from $2 \rightarrow 2$ hard processes. The energy lost by energetic partons which traverse the hot and dense matter (in a phenomenon known as "jet quenching") measures the "stopping power" of the QGP, as well as its characteristic dependence on parton type (quark vs gluon), parton mass m (light vs. heavy quark), path length inside the medium, and parton energy. It is well established that the parton energy loss is a consequence of the modification of the hard-scattering processes in the final state of the heavy ion collisions at RHIC and LHC [2,3,4,5]. It is evident in the suppression of high p_T charged hadrons and jets, as well as in the associated yield in two-particle correlations measurements [6], which is accompanied by an enhancement of low p_T hadrons, suggesting a softening of jet fragmentations. The CMS experiment at the LHC is ideally suited to measure these hard probes, due to its large acceptance, good efficiency and low fake rate for track reconstructions, and high level trigger capable of full event reconstruction even in a high multiplicity environment [7]. Taking advantage of the high statistics data collected in 2011, the present analysis enables us to study the parton energy loss in more detail than previously possible.

In the following, we discuss the inclusive and b-tagged jet nuclear modification factor R_{AA}, the di-jets and $\gamma-$jets imbalance distribution, and the measurements of the jet fragmentation and the jet shapes.

2 Energy loss studies by inclusive jet properties

Jets are reconstructed using the anti-k_{T} jet algorithm, with a radius parameter R = 0.3, combining tracking and calorimetric information from CMS particle-flow (PF) objects [8,9]. The contribution of the underlying heavy-ion event is removed using an iterative pileup subtraction

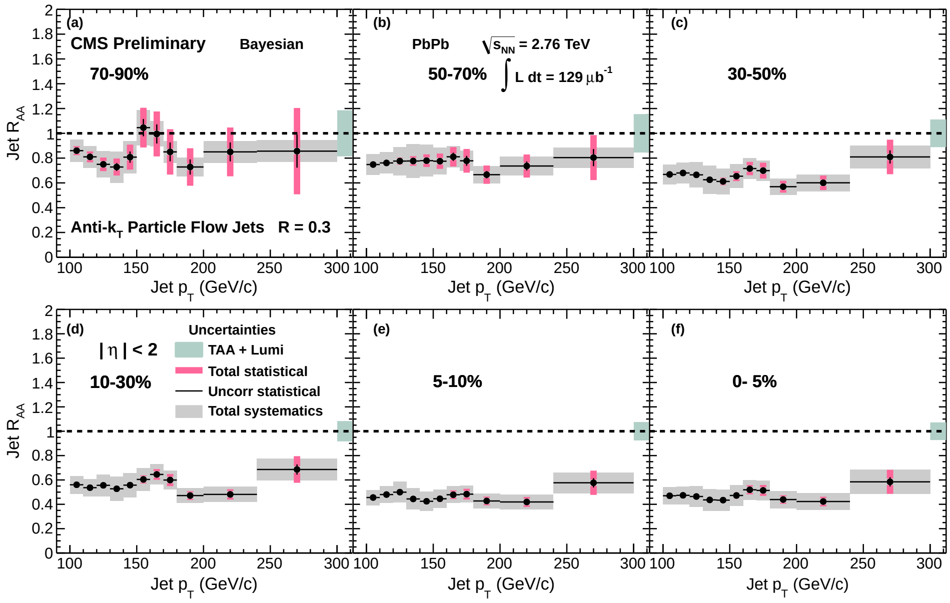

Figure 1: Nuclear modification factors, R_{AA}, for jets reconstructed with the anti-k_T algorithm using R = 0.3, after bayesion unfolding for jet p_T between 100 and 300 GeV/c in different centrality bins.

method [10]. In order to measure the inclusive jet p_T spectra in PbPb and compare them to the production in pp collisions, and form their ratios (nuclear modification factors, R_{AA}), scaled by the appropriate number of equivalent pp collisions, for each centrality bin, careful treatment of the jet energy resolutions, as well as the application of smearing or unfolding methods are necessary. The preliminiary results of the jet nuclear modification factors between 100 and 300 GeV/c of jet p_T are presented in Fig. 1, in six centrality bins, 0-5% representing the 5% most central PbPb collisions. A suppression of the jet yield reconstructed from PbPb data is observed, which is independent of the jet p_T, and increases reaching a value of about 0.5 in the most central events [11]. The jet nuclear modification factors can be compared to those of charged particles [3], and the similarity of R_{AA} obtained for charged particles in the 50 – 100 GeV/c, and for jets in the 100 – 200 GeV/c range, which implies that the hard part of the jet fragmentation in pp and PbPb collisions are very similar, taking into account that high p_T leading charged particles typically originate from the fragmentation of jets with about two times larger transverse momentum.

The inclusive jets are dominated by gluon- and light quark-jets. The parton energy loss is expected to be different for light and heavy flavor quarks due to their mass difference, arousing interest in the seperation of b-quark jets. The b-quark jets can be experimentally recognized by the presence of a B-hadron, creating a high-mass secondary vertex at its decay point. The purity of b-jet tagging is determined from template fits to the secondary vertex invariant mass distribution, and the efficiency of the secondary vertex tagging can be estimated in a data-driven way. Thus, the fraction of b-jet among inclusive jets can be measured as a function of transverse momentum after purity and efficiency corrections. The fraction of b-jets in pp and PbPb collisions are comparable, with no p_T dependence observed, indicating that b-quark jets are quenched similarly as light quark jets, i.e. the R_{AA} value is ~ 0.5 [12].

High energy photons are not modified by the strongly interacting medium, therefore serve as an energy tag for the jet parter in γ−jet events. These collisions produce a jet and a photon approximately back-to-back in azimuth, with similar transverse momenta. The ratio between momenta is denoted as $x_{J\gamma} = p_T^{jet}/p_T^{\gamma}$. The measured distribution of $x_{J\gamma}$ in central PbPb collisions is shifted to lower values with respect to the distribution in pp collisions [13]. The mean value of this ratio, $< x_{J\gamma} >$, is presented on the left panel of Fig. 2 as a function of

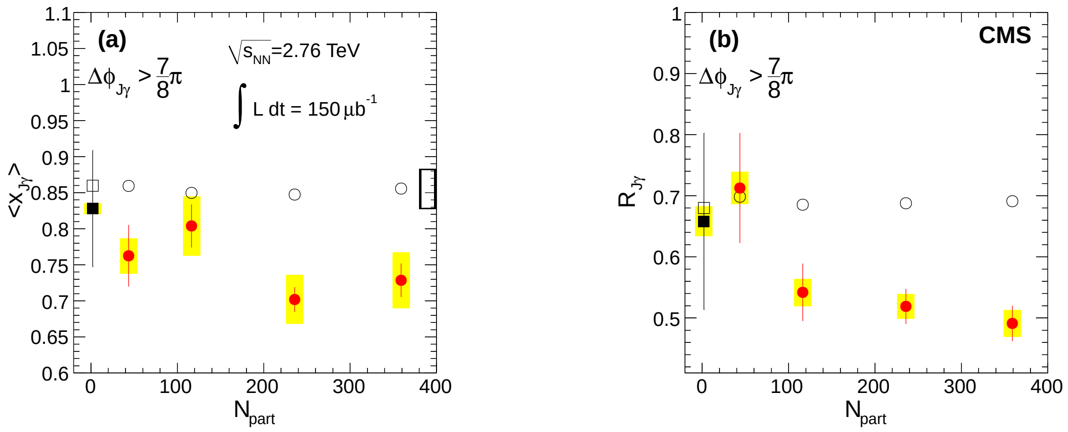

Figure 2: The average ratio of jet transverse momentum to photon transverse momentum, $< x_{J\gamma} >$ (left), and the average fraction of isolated photons are associated to a partner jet above 30 GeV/c, $R_{J\gamma}$ (right), as a function of N_{part} from PbPb (red) and pp (black rectangle) collisions and MC simulation (open circle).

the number of nucleons participating in the PbPb collision, N_{part}, used for characterizing the collision centrality. The filled rectangle indicates the results obtained from pp data taken at 2.76 TeV, limited by statistic uncertainties, but in agreement with pp events simulated by PYTHIA Monte Carlo generator, embedded in PbPb events simulated by HYDJET where no medium effect is included. While the pp reference shows almost no dependence of $< x_{J\gamma} >$ on centrality, the $\gamma-$jet PbPb events exhibit a significantly lower ratio in most central events. The right panel on Fig. 2 shows the average fraction of isolated photons that are associated to a partner jet with p_T above 30 GeV/c, $R_{J\gamma}$, as a function of N_{part}. In central PbPb events, a significant fraction of isolated photons lost their jet partner compared to pp reference. Therefore, a sizeable jet (parton) energy loss is observed in the $\gamma-$jet channel, similarly to the di-jet studies [14].

3 Anatomy of the jets

A significant amount of jet quenching was observed in inclusive jet, di-jet and $\gamma-$jet events. Those observations raise questions related to the parton energy loss mechanism: how do partons lose their energy in the nuclear medium? Does the energy loss changes the fragmentation pattern of the jets and modify the jet shape? Measurements of jet fragmentation properties provide an experimental constraint which is complementary to the measurement of the global jet properties, and can also be used to connect the jet observables to the measurements of high p_T particle production.

For the present analysis, the events with jets above $p_T > 100$ GeV/c within $0.3 < |\eta| < 2$ region are selected, where the jet trigger is fully efficient. The central pseudorapidity region $|\eta| < 0.3$ is excluded to avoid jet cones overlapping with the η-reflected cone used for the background estimation. The minimum transverse momentum for tracks entering the analysis is set to 1 GeV/c.

The jet shapes, $\rho(r)$, describing how the transverse momentum of the particles comprising the jet is distributed radially with respect to the jet axis $r = \sqrt{(\eta_{jet} - \eta_{trk})^2 + (\phi_{jet} - \phi_{trk})^2}$, are studied. The measured jet shapes in PbPb collisions are compared with the shapes obtained in pp collisions (Fig. 3 of top panels), with their ratios shown in the bottom panels. The ratios are close to unity for non-central collisions (50-100%), and show a rising trend towards large radii r for the mid-central and most central collisions (10–30% and 0–10%). This observed enhancement is consistent with the excess in the low p_T part of jet fragmentation functions, defined as the distribution of $\xi = ln(p^{jet}/p_{||}^{track})$, where $p_{||}^{track}$ is the projection of the track momentum onto the jet axis [15]. The jet shape and fragmentation function results indicate that suppression of

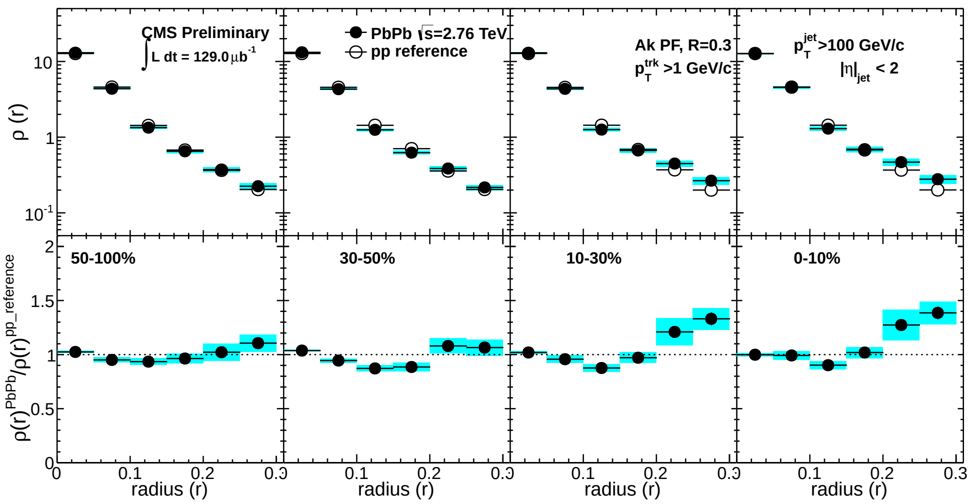

Figure 3: Differential jet shapes in PbPb and pp collisions for $p_T^{jet} > 100$ GeV/c with track $p_T > 1$ GeV/c (top panels) and the ratio of the PbPb and pp jet shapes (bottom panels).

intermediate p_T particles is transported to larger radii with low p_T particles enhancements by energy redistribution.

4 Summary

The CMS experiment has shown that the heavy quark jets quench the similar way as light quark jets, with no strong dependence on jet p_T. The photon-jet correlations support the di-jet quenching picture. Jet shapes and fragmentation functions indicate an energy transport to large distance from the jet axis (low p_T enhancement) from smaller jet radii (intermediate p_T suppression), consistent with results from two-particle correlation measurements[6]. In summary, the jet quenching picture painted by CMS hard probe results has become more precise, detailed and quantitative, providing a new insight into the behavior of the high energy density medium formed in heavy-ion collisions.

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