# Jet results from PbPb and pPb collisions with CMS

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**Abstract.** The Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) has used a wide variety of observables to study the hot and dense medium created in heavy ion collisions. The extraction of fully reconstructed jets is one area in which the higher center of mass energy provided by the LHC is particularly helpful. This paper provides an overview of some of the jet and jet-related results that have been extracted from CMS data. The systems studied include PbPb and pp at $\sqrt{s_{NN}} = 2.76$ TeV and more recently pPb at $\sqrt{s_{NN}} = 5.02$ TeV.

The start of data taking at the Large Hadron Collider (LHC) at CERN expanded the accessible heavy ion center-of-mass energy range by more than an order of magnitude. These higher-energy collisions provide greatly enhanced production cross sections for a number of entities, most significantly heavy particles and high transverse momentum ($p_{\mathrm{T}}$) jets. More specifically, these higher-$p_{\mathrm{T}}$ jets have sufficient energy to stand out very clearly from the background of soft particles (the so-called "underlying event") created in the heavy ion collision. This allows the extraction of a number of observables using fully reconstructed jets alone or correlations between jets and charged particles. Compared to a high-$p_{\mathrm{T}}$ particle, the properties of an observed jet are more closely related to those of the initially hard-scattered parton. As a result jet studies allow the extraction of more direct information about the interactions of those partons with the hot and dense medium created in heavy ion collisions.

The Compact Muon Solenoid (CMS) detector at the LHC is particularly well suited for these types of studies. Its high-precisions calorimetry and tracking allow very accurate reconstruction of both jets and charged particle tracks. The combination of a fast Level-1 (L1) trigger with a sophisticated High Level Trigger (HLT) capable of running full particle and jet algorithms allows efficient extraction of the most interesting events. Thus far, the systems studied include PbPb and pp at $\sqrt{s_{NN}} = 2.76$ TeV and more recently pPb at $\sqrt{s_{NN}} = 5.02$ TeV. Jets are reconstructed using the anti-$k_T$ algorithm with a radius parameter of $R = 0.3$. A full description of the CMS detector can be found in Ref. [1]. More information on all of the CMS heavy ion physics results can be found on the "Public Physics Results" web page [2].

The studies of jets in heavy ion collisions using CMS began with the observation that the momentum imbalance between pairs of back-to-back jets was much larger in central PbPb collisions than in either pp or peripheral collisions [3]. Despite this evidence for significant parton energy loss, there was no sign of any deflection, the two jets still emerged essentially back to back. By studying charged particles in events with unbalanced jets, the missing energy was found to emerge predominantly in low momentum particles at large angles with respect to the jet axis [3]. In a different approach, the ratio of the transverse momenta of the two jets was studied as a function of centrality and the transverse momentum of the leading jet. This ratio rises smoothly with increasing leading-jet $p_{\rm T}$ in pp collisions. The same pattern was found in PbPb at all centralities, except that the ratio is systematically shifted down, i.e. the $p_{\rm T}$ of the sub-leading jet is smaller [4]. The size of this shift was found to increase monotonically with increasing centrality of the PbPb collision. Furthermore, at a fixed centrality, the shift was found to be independent of jet $p_{\rm T}$ up to the highest values studied. CMS has also measured the yield of both high-$p_{\rm T}$ jets [5] and charged particles [6] and found comparable levels of suppression.

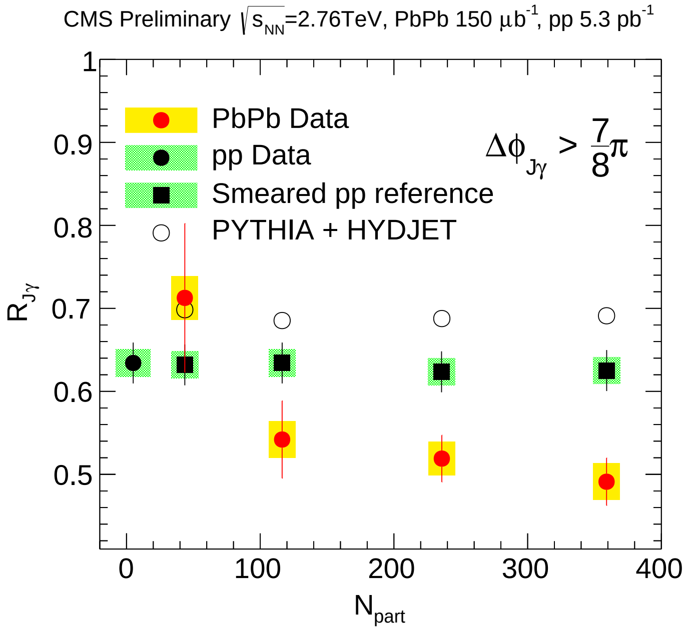


**Figure 1.** Associated jet fraction in $\gamma$-jet events as a function of centrality for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are compared to a reference generated using pp data at the same energy. The fraction $R_{\gamma j}$ represents the fraction of events with a high-$p_{\rm T}$ photon in which an associated jet is found. The momenta of jets in pp were smeared by the relative jet energy resolution to be used as the reference of each centrality bin.

One disadvantage of using dijet events to study parton energy loss is that both partons are traversing the medium. Thus, only the *difference* in energy loss can be measured, Furthermore, the lower cutoff on jet $p_{\rm T}$ in the analysis leads to a surface bias in the event sample. Dijets originating deep inside the medium are more likely to have both jets fall below the limit. An alternative that avoids both problems is the study of $\gamma$-jet events. Data from several experiments, including CMS [7], have already established that isolated photons are not quenched by the medium. The $p_{\rm T}$ spectrum of $\gamma$s, even in central PbPb events is identical within uncertainties to that found in pp at the same center of mass energy. Furthermore, the yield of high $p_{\rm T}$ photons matches the prediction based on pp data and the number of nucleon-nucleon collisions for a given PbPb centrality. The biggest disadvantage of $\gamma$-jet compared to dijets is the significantly smaller production rate. Nonetheless, the first measurement of parton energy loss using isolated photons to tag the initial parton momentum (both magnitude and direction) has been performed by CMS [8]. As for the dijets, the data showed evidence for increasing energy loss with increasing centrality but no evidence for any parton deflection. This conclusion has recently been strengthened by repeating the analysis using a reference spectrum extracted from CMS pp data as opposed to PYTHIA [9]. Figure 1 shows $R_{\gamma j}$, the fraction of events containing a high-$p_{\rm T}$

photon in which a jet was also found as a function of centrality. The PbPb data are compared to pp data and also to a reference in which the pp data was smeared to account for the different jet energy resolution in PbPb events of different centralities.

Having established the basic parameters of parton energy loss, CMS data have also been used to investigate the detailed properties of the quenched jets, primarily through the use of jet-particle correlations. Two different approaches have been used, analyzing the distribution of both the transverse momentum of the associated particles and their angular distribution with respect to the jet axis. The former analysis, in the form of fragmentation functions, initially found essentially no change with respect to similar $p_T$ jets in pp collisions, even for the most unbalanced events in very central PbPb collisions [10]. However, this first study was restricted to particles with $p_T$ above 4 GeV/c. Further analysis did reveal a difference, namely an excess of low momentum particles which increased with increasing PbPb centrality [11]. The angular distribution of the jet fragmentation pattern has also been studied. Rather than simply counting particles, the distribution of the total jet $p_T$ in rings of increasing radius around the jet axis was extracted [12]. This so-called "jet shape" revealed significant deviations from the pattern seen in pp, especially far from the jet axis in the most central PbPb collisions. Some evidence for a modest decrease slightly closer to the jet axis were also seen. Both analyses suggest that the core of the jet fragmentation pattern, consisting predominantly of high $p_T$ particles is not significantly modified by the presence of the hot and dense medium.

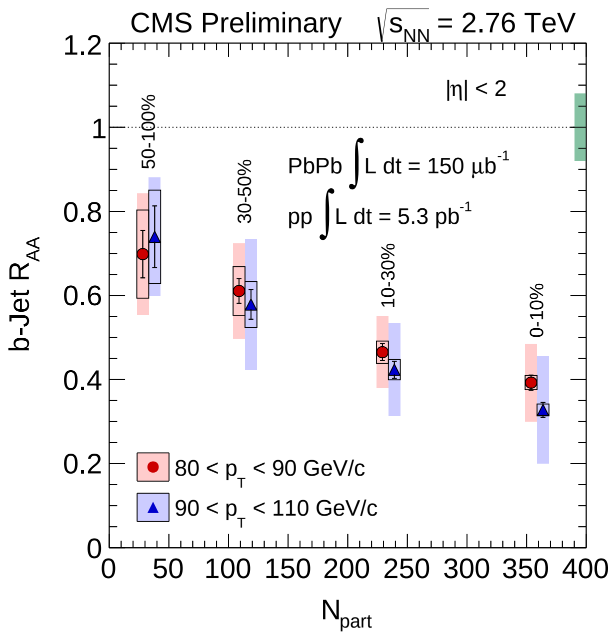


**Figure 2.** Nuclear modification factor ($R_{AA}$) as a function of centrality for b jets in two $p_T$ bins (80-90 GeV/c, and 90-110 GeV/c) in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. The centrality is quantified using $N_{part}$, the number of interacting nucleons in the collision.

The Strangeness in Quark Matter conference series has specifically focused on the physics of the strange (and more recently heavier) quarks. Thus far, CMS has not extracted any jet-related physics using strange or charm quarks. However, it is possible to use the high precision vertexing capability of the CMS tracker to tag jets from b quarks, using their displaced secondary vertex. Contrary to some expectations, the suppression of b jets was found to be comparable to that for inclusive jets [13]. Figure 2 shows the nuclear modification factor ($R_{AA}$) for b jets in PbPb collisions as a function of centrality. Results are shown for two different ranges in b-jet $p_{\mathrm{T}}$. It may also be possible to use more differential analysis of fragmentation functions as well as comparison of both dijets with $\gamma$-jet and 2-jet with 3-jet events to determine the relative energy loss of quark and gluon jets.

In the spring of 2013, pPb collisions were performed for the first time at the LHC. Because of the different rigidities of the proton and Pb ion, these collisions were at a nucleon-nucleon center of mass energy of $\sqrt{s_{NN}} = 5.02$ TeV. The data have revealed several unexpected finding, including possible evidence for hydrodynamical collective effects in events with very high multiplicity [14, 15]. The ratio of transverse momenta for dijets emitted in pPb collisions has been analyzed for a range of centralities [16]. Since there is no pp data currently available at this same $\sqrt{s_{NN}}$, these ratios were compared to PYTHIA predictions. No modification of the dijet $p_{\mathrm{T}}$ ratios were found over the entire range of $p_{\mathrm{T}}$ studied, even for the most central 2.5% of the events.

The future prospects for using a variety of jet data to probe the hot and dense system formed in ultra-relativistic heavy ion collisions is bright indeed. Observables of interest include individual jets, both inclusive and with tagged flavor, as well as correlations of jets with other jets, photons, and charged particles. The next PbPb run, expected in late 2015 following the current LHC shut-down, will provide significantly higher integrated luminosity. The CMS L1 trigger is being upgraded to provide better selection capability for triggering on jets. Currently, that selectivity is limited because the CMS front-end electronics are configured in such a way as to make efficient jet background subtraction impossible. As a result, a large fraction of the events that fire the various jet triggers are actually due to energy from the underlying event. The upgraded trigger will allow new combinations of information from different regions of the detector, making the fast jet trigger much more efficient. This significantly reduced data stream can then be processed by the HLT for the final decision on what events to keep. With larger data sets, more selective as well as more differential analyses will be possible. Precision tomography of the quark gluon plasma using jets and other high-$p_{\mathrm{T}}$ probes is just beginning.

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