

# A Brief Review of CMS Jet Measurements

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**Abstract.** We present an overview of the current status of the recent jet measurements in PbPb and pp collisions at a nucleon-nucleon center-of-mass energy of 2.76 TeV that are studied with the CMS detector at the LHC. Jets are reconstructed using the anti- $k_T$  sequential reconstruction algorithm on particle flow objects. To distinguish between different possible energy loss mechanisms and to provide an important experimental check on the validity of the assumed jet fragmentation, inclusive jets, flavor tagged jets and jet shapes are studied.

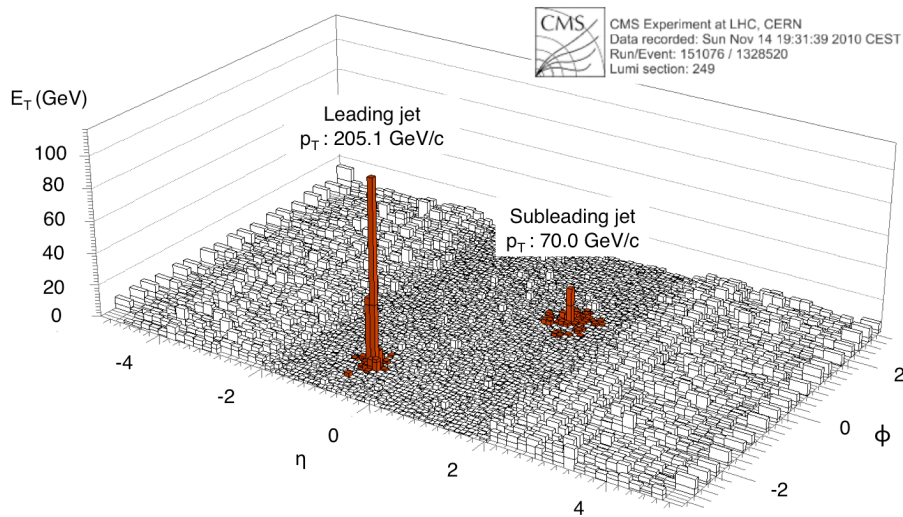
## 1. Introduction

During the last three decades, relativistic heavy ion collisions have been studied to map out the phase diagram of quantum chromodynamics (QCD) matter at increasing center-of-mass energies of  $< 5$  GeV at the Alternating Gradient Synchrotron in Brookhaven,  $< 20$  GeV at the the Super Proton Synchrotron at CERN and  $\leq 200$  GeV at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven. The Large Hadron Collider (LHC) at CERN was commissioned at the end of 2009 and started delivering pp collisions at a center-of-mass energy of 7 TeV. In 2010 and 2011, LHC also delivered the heavy ion collisions (PbPb) at a center-of-mass energy of 2.76 TeV per nucleon pair along with reference data of pp collisions at the same center of mass energy. This was followed by a pPb run at 5.02 TeV together with a higher statistics pp run at 2.76 TeV in early 2013. A center-of-mass energy of 5 TeV per nucleon pair for heavy ion collisions at LHC is expected to be delivered starting in 2015.

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 QGP [1, 2, 3]. These probes are well calibrated, as their expected yields are calculable using the perturbative QCD (pQCD) theoretical framework and as their propagation through the medium is affected by strong interactions. Also, due to their short production time ( $\tau \sim 1/p_T \leq 0.1$  fm/c), they can be used to identify the properties of the medium starting from the early stages of the collision. Their interactions within the hot QCD medium can be measured experimentally via the modification of the internal structure of jets by medium induced soft gluon radiation [4]. 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 [5, 6, 7]. These techniques were developed in order to suppress the large underlying event backgrounds in heavy ion collisions. While this approach has provided significant insights, including the color opaqueness of the QGP, these findings are only qualitative and are limited by the intrinsic biases of these measurements. For example, the leading hadron measurements are preferentially from the population of jets that has the least interaction with the medium. These measurements are also not sufficient to discriminate

quantitatively between partonic energy loss formalisms and to extract key parameters such as the transport coefficient of the hot QCD medium to measure the stopping-power of the QGP precisely [8]. Measurements of jet structure and its modification in terms of energy flow therefore provides a much closer connection to the underlying theory.

Jets, the most common hard probe of QCD, are collimated sprays of hadronic decay products of hard-scattered partons. Measuring jets above the complex heavy ion background is a challenging task. With the order of magnitude increase in the centre-of-mass energy compared to RHIC, jets with energies well above the background from the underlying events are observed at the LHC. Numerous numbers of jet pairs appeared to be not balanced indicating strong jet quenching in PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. An example of a typical unbalanced di-jet event reconstructed in central PbPb collisions collected by the CMS experiment is shown in Figure 1 [9].



**Figure 1.** An example of a jet pair in a central PbPb collision event at  $\sqrt{s_{NN}} = 2.76$  TeV. Plotted is the summed transverse energy in towers of electromagnetic and hadron calorimeters vs.  $\eta$  and  $\phi$ , with the identified jets highlighted in red and labeled with the corrected jet transverse momentum [9].

## 2. Jet Measurements

For jet analyses presented here, a total integrated luminosity of  $150 \mu\text{b}^{-1}$  PbPb collisions and a total integrated luminosity of  $5.3 \text{ pb}^{-1}$  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 [10]. The two most important detector requirements for a successful reconstruction of jets in heavy ion collisions are a good energy measurement 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 [11]. 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- $k_T$  sequential reconstruction algorithm that is encoded in the FastJet framework [12]. 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 [13]. 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 [14]. The reconstructed jet energies are corrected by using a factorized multi-step approach used for all jet analyses in CMS [15]. Jet energy corrections are derived from PYTHIA [16] simulations without PbPb underlying events.

### 2.1. Jet-Jet Pairs

By utilizing back to back jet pairs, it is possible to study modification of the jet properties such as back-to-back alignment of hard scattered partons, their energy balance, and even their fragmentation. An example of such study can be seen in Figure 8 of Ref. [9] that shows distributions of  $\Delta\phi$  between leading and sub-leading jets and Figure 10 of Ref. [9] that shows the evolution of the dijet momentum balance. In these measurements, angular correlation of jet pairs appear to be unmodified by the medium although a significant jet quenching at LHC independent of jet transverse momentum is observed [9, 17]. With the recent data collected earlier this year, jet pair production is also studied in pPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. In these collisions the pseudorapidity of the dijet system appears to change monotonically with increasing forward calorimeter activity consistent with expectations based on nuclear parton distribution effects [18, 19].

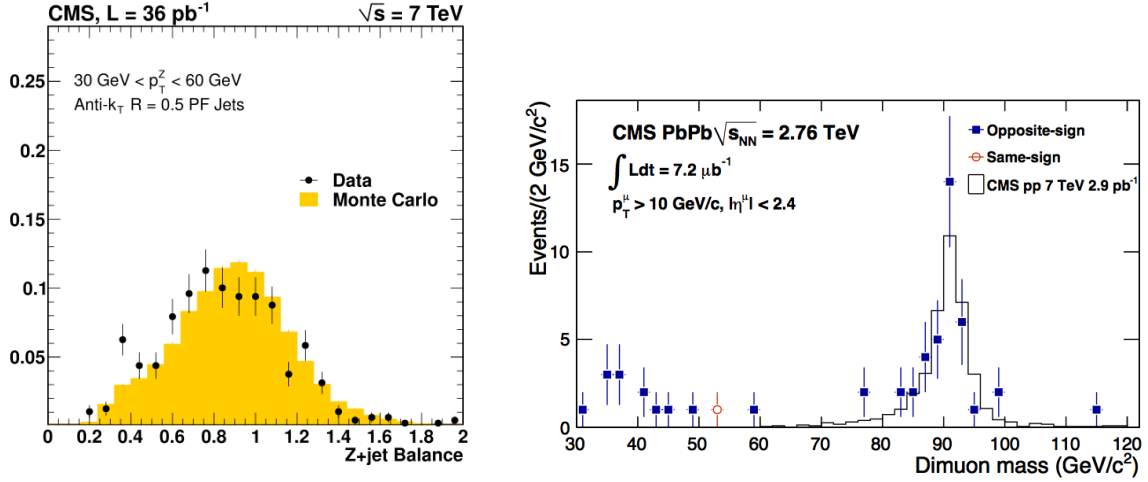
Studies of jet-hadron correlations involving vector summation of charged hadron momenta, find that the energy balance in events with large dijet asymmetry is recovered on average by an excess of low-momentum particles in the hemisphere of the away-side jet, at large angles relative to the jet axes [9]. Complementary information about the overall momentum balance in the dijet events can be obtained using the projection of missing  $p_T$  of reconstructed charged tracks onto the leading jet axis. These measurements reveal that the missing energy is also recovered in the form of soft particles at large angle with respect to the jet axes.

### 2.2. Boson Tagged Jet Pairs

While back-to back jet pair measurements confirm the jet quenching at LHC, these measurements introduce a selection bias towards scatterings occurring at, and oriented tangential to, the surface of the medium. A more complete measurement could be the so-called “Golden Probe” for jet tomography of the QGP, such as the  $Z^0$  + jet and the photon+jet channel [20, 21, 22]. These channels have served as an essential calibrator of jet energy in TeV p+p collisions. In heavy ion collisions, they can again be used to calibrate in-medium parton energy loss, as they carry no color charge and escape the medium unattenuated.

As an example to show CMS detector capabilities, the absolute jet energy response measurement from the  $Z^0$ +jet events from the integrated luminosity of  $36 \text{ pb}^{-1}$   $\sqrt{s} = 7$  TeV p+p collisions is presented in the left panel of Figure 2. A good agreement between data and simulation is observed showing a good overall understanding of the detector. The invariant mass spectra of  $Z^0$  bosons from  $\sqrt{s_{NN}} = 2.76$  TeV PbPb collisions collected during the first heavy ion run is shown in the right panel of Figure 2. The shape of the spectrum is compared with the results from pp collisions, and the distribution is found to be consistent. Within uncertainties, no modification is observed with respect to theoretical next-to-leading order pQCD proton-proton cross sections scaled by the number of elementary nucleon-nucleon collisions. This measurement confirms the validity of the Glauber scaling for perturbative cross sections in nucleus-nucleus collisions at the LHC and establishes the feasibility of carrying out detailed  $Z^0$ +jet physics studies in heavy-ion collisions with the CMS detector.

However due to the limited available statistics of the collected data, the coincidence of  $Z^0$ +jet measurement is only feasible after 2015 with expected  $\sim 2000$   $Z^0$ +jet coincidence counts that



**Figure 2.** Left: jet energy response from  $Z(\mu^+\mu^-)+\text{jets}$   $p_T$ -balancing for p+p collisions at  $\sqrt{s} = 7$  TeV [23]. Right: Dimuon invariant mass spectra from  $\sqrt{s_{NN}} = 2.76$  TeV PbPb collisions collected during the first heavy ion run [24]. Full squares are opposite-sign dimuons, while the empty circle shows a like-sign dimuon candidate. The histogram shows the corresponding distribution measured in pp collisions at 7 TeV scaled to the PbPb candidates.

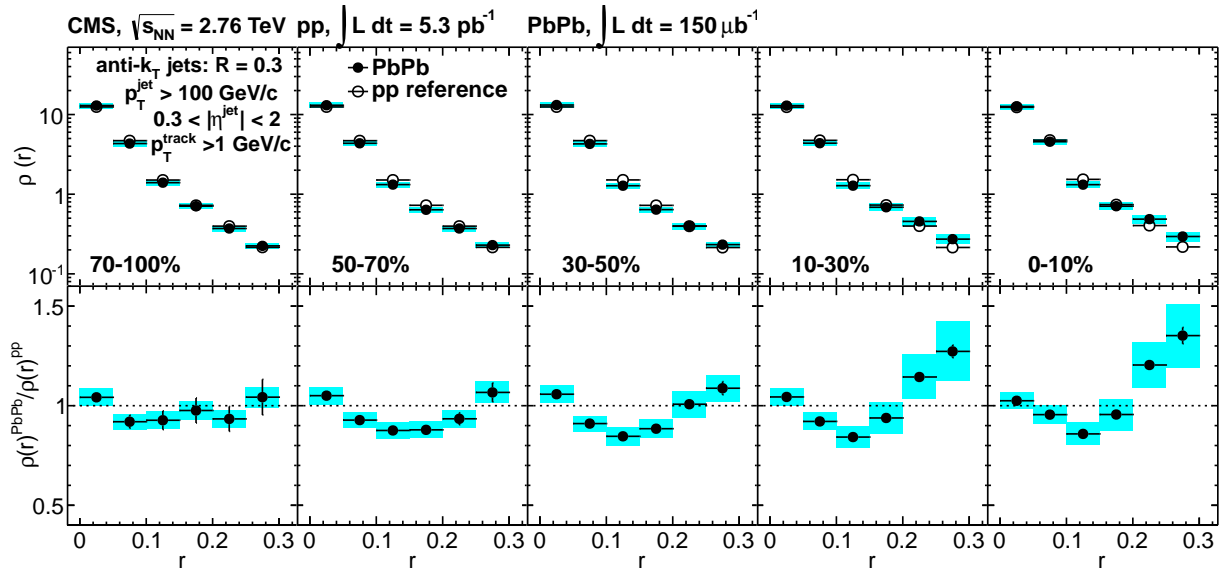
decay into dimuons within the CMS acceptance from the expected one month of  $\sqrt{s_{NN}} = 5$  TeV Pb+Pb run [11]. It is possible to perform photon+jet coincidence measurements with the available statistics [25]. In these measurements, the jet appears to be quenched but still back-to-back to its  $\gamma$  partner. This implies that jet energy is not lost in single hard gluon-radiation. Similar to jet pair coincidence measurements, energy loss observed also depends on centrality of the PbPb collisions.

### 2.3. Inclusive Jet Measurements

To gain sensitivity to the properties of the QGP and to quantify the underlying mechanism of the quenching effects, the ratios of inclusive jet cross-sections in PbPb collisions over the ones in pp are studied via the nuclear modification factors. If the full jet energy is recovered independent of the fragmentation details, even in the presence of strong jet quenching, this ratio should be equivalent to one. If the ratio is less than one, it would suggest broadening of the jet structure due to jet-medium interactions. The preliminary nuclear modification results show a suppression factor of 0.5 for high  $p_T$  jets in central PbPb collisions in comparison to pp collisions [26]. Also, no strong dependence on the jet radius is observed, unlike the predictions from theoretical NLO calculations that demonstrate the sensitivity of nuclear modification factors of different jet definitions to the properties of the medium-induced gluon radiation [27]. Other jet-medium interactions, initial state or cold nuclear matter effects might be affecting the interpretation of these measurements [28, 29, 30, 31]. The measurement of nuclear modification factors of jets in pPb collisions at  $\sqrt{s_{NN}} = 5$  TeV will be performed to disentangle some of these effects on jet production.

Jet shape measurements describe how the jet transverse momentum is distributed as a function of the radial distance from the jet axis and are complementary to nuclear modification factor measurements. They are also robust against the elimination of low momentum particles, which can also be used to suppress and study heavy ion event fluctuations. The jet shape measurements are expected to be affected by the QGP induced gluon emission through substantial broadening of jets in medium relative to vacuum. They contain discriminative

information on the energy loss mechanism to help characterize the parton-medium interactions such as transport coefficients [27, 33]. An example of differential jet shape measurements in PbPb and pp collisions as a function of the distance from the jet axis for inclusive jets with jet  $p_T > 100$  GeV/c in various PbPb centrality intervals is presented in the top panel of Figure 3. To see the effect of the medium on jet shapes more clearly, the ratios of differential jet shapes in PbPb and pp collisions are also presented in the Figure 3. Deviations from unity indicate modification of jet structure in the nuclear medium. For example in the most central PbPb collisions an excess of transverse momentum fraction emitted at large radius  $r > 0.2$  emerges, indicating a moderate broadening of the jets in the medium. This is also consistent with the jet fragmentation measurements [35] that indicate a transport of energy from intermediate to low  $p_T$  jet constituents.

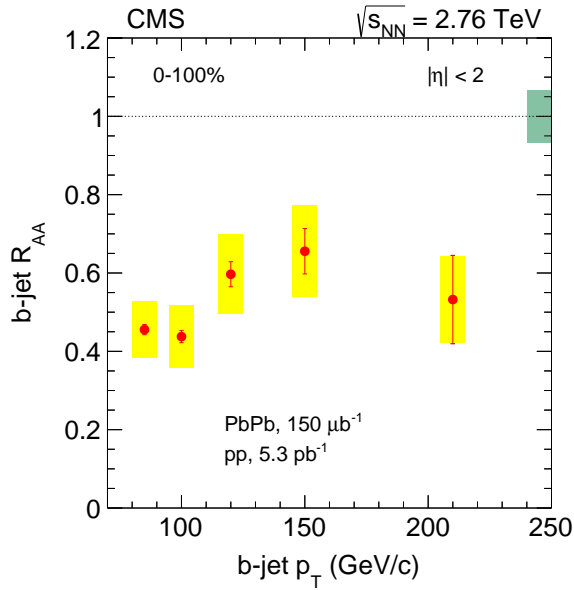


**Figure 3.** Top panel: Differential jet shapes in PbPb and pp collisions as a function of distance from the jet axis for various PbPb centrality intervals. Bottom panel: The ratio of jet differential jet shapes in PbPb and pp collisions [34].

#### 2.4. Flavor Tagged Jets

The quenching of jets in heavy-ion collisions is expected to depend on the flavor of the initiating parton. For example, under the assumption that radiative energy loss is the dominant mechanism, gluon jets should be quenched more strongly than light quark jets, due to their larger color factor for gluon emission. On the other hand, jets initiated by heavy quarks, particularly bottom, are expected to radiate less than light ones. This is due to the so-called dead cone effect whereby radiation is suppressed in the direction of propagation as a result of coherence effects [36]. Recent CMS data demonstrates that non-prompt  $J/\psi$ , i.e., those coming from decay of B mesons, are indeed suppressed in PbPb collisions with respect to the pp expectation [37]. This indirect measurement, which samples typical  $J/\psi$   $p_T$  values on the order of 10 GeV/c, provides a strong motivation to perform a more direct measurement using fully reconstructed jets. Such a measurement would enable a direct comparison of b quark energy loss to that of inclusive jets at much larger values of jet  $p_T$ , where the flavor dependence of parton energy loss can be probed in detail.

Jets formed from heavy flavor quark fragmentation can be tagged by the presence of displaced vertices, either by direct reconstruction of these vertices or by the impact parameter (i.e., the distance of closest approach to the primary vertex) of tracks originating from these vertices [38]. Information from these tracks and vertices are typically combined into a quantity which optimizes their discrimination between heavy and light flavor jets. A discriminator based on the flight distance significance of reconstructed secondary vertices as the primary b-jet tagger is implemented in heavy ion collisions [39]. The b-jet coincidence measurement from the jet triggered  $\sqrt{s_{NN}} = 2.76$  TeV Pb+Pb collisions were performed for the first time in heavy ion collisions [40, 41, 42].



**Figure 4.** The centrality integrated b-jet nuclear modification factor as a function of jet  $p_T$  [40].

See Figure 4 for the centrality integrated b-jet nuclear modification factor, which is the ratio of PbPb yield scaled with the number of nucleon-nucleon collisions equivalent of pp and the measured pp cross section. The suppression of b-jets appears to be qualitatively consistent with that of inclusive jets [26]. The absence of a strong dependence of the jet suppression on the mass of the fragmenting parton is surprising. However a more detailed understanding of the parton mass and flavor dependence of energy loss would require precision studies such as back-to-back jet pairs to eliminate the contribution of b jets from gluon spitting and fragmentation functions to constrain the dynamics of heavy quark energy loss.

### 3. Conclusions

The quenching of jets in PbPb collisions is studied by complimentary jet measurements reconstructed in data collected by the CMS experiment. The anti- $k_T$  sequential reconstruction algorithm is used to reconstruct jets based on combined tracker and calorimeter information. A strong increase in the fraction of jet pairs with very unbalanced transverse momentum is observed in central PbPb collisions compared to peripheral collisions while angular correlations observed to be conserved. The missing energy is also recovered in the form of soft particles at large angles with respect to the jet axis. A suppression factor of 0.5 for high  $p_T$  jets is observed in central PbPb collisions in comparison to pp collisions. A centrality dependent modification of the jet shapes and fragmentation functions appears in the central PbPb collisions. Through

studies of bottom quark tagged jets, it appears that jet quenching does not have a strong dependence on parton mass and flavor in the jet. These results are all consistent and important for characterizing the jet quenching and shower evolution in the presence of a hot and dense nuclear medium.

The age of quantitative jet tomography has just begun, but we have yet to characterize the medium parton interactions in detail. High-precision studies of jets are expected to be possible in upcoming LHC running periods. We will measure complementary and robust jet observables in order to distinguish between competing energy loss mechanisms to determine key features of QCD and to extract quantitative properties such as QGP density and the corresponding stopping-power.

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