Jets In Heavy Ion Collisions with CMS

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Abstract.
Jet physics in heavy ion collisions is a rich field which has been rapidly evolving since the first observations of medium interactions at RHIC through back-to-back hadron correlations and at LHC via reconstructed jets. In order to completely characterize the final state via jet-medium interactions and distinguish between competing energy loss mechanisms, complementary and robust jet observables are investigated. Latest developments of jet finding techniques and their applications to heavy ion environments are discussed with an emphasis given on experimental results from CMS experiment.

1. Introduction
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 that is produced in heavy ion collisions [1, 2, 3]. Indirect measurements of energy loss in the medium (“jet quenching”) have been made via observables of nuclear modification factors of single particles and the correlations of leading particles [4, 5, 6, 7].

Jets, the most common hard probe of QCD, are collimated sprays of hadronic decay products of hard-scattered partons. They are experimental signatures of quarks and gluons and are expected to reflect kinematics and topology of the initial hard scattered partons. However due to its scale dependence, the definition of the parton is ambiguous, resulting in different jet definitions corresponding to various jet reconstruction algorithms. Therefore, for an acceptable jet algorithm, the main requirement is to merge measured particles to form a jet in a procedure that matches the theoretical calculations without a strong dependence on modeling [8]. For example, the algorithm must be insensitive to soft and collinear radiation i.e., infrared and collinear safety with a seedless implementation for data analysis.

Jets in hadronic colliders are not new phenomena. Successful observation and reconstruction of jets in high transverse energy events at the CERN proton antiproton collider dates back to 1980’s [9]. As can be seen in the left panel of Fig. 1 as a publication summary, more than 60% of ATLAS and CMS analyses use jet definitions since the commissioning of LHC due to the fact that if an analysis require the existence of a quark, a gluon or their absence in an event, jet reconstruction tools have to be used. The search for new physics in high luminosity pp collisions at the LHC requires the precise measurement of jet energies over large backgrounds caused by pile up. This has motivated the development of many powerful set of discriminative jet tools including pile up subtraction strategies to correct the jet energy [10, 11]. These algorithms are also applicable in heavy ion environments. Since the beginning of the LHC heavy ion program,
jets were used as a way to probe the non-perturbative QCD physics of jet quenching by utilizing pairs of jet-jet and photon-jet measurements. These first measurements showed that the angular correlations of jet pairs were conserved with large transverse momenta imbalance [12, 13, 14, 15]. In this article, we summarize the more recent jet measurements in heavy ion collisions that are collected during the Run 1 period of LHC data taking with the CMS experiment.

2. Experimental Methods

CMS is a multipurpose detector system that was built with many different layers each serving a purpose in particle identification and measurement [16]. By design it is extremely well suited to measure hard scattering processes. Jet reconstruction is performed with anti-$k_T$ sequential reconstruction algorithm that is encoded in the FastJet framework [17]. A small resolution parameter $R$ is used in heavy ion collisions to reduce the deterioration of the jet energy resolution due to fluctuations of the PbPb background from soft interactions. 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 [18] and only calorimetric measurements from HCAL and ECAL are used as inputs to the jet reconstruction algorithms. The reconstructed jet energies are corrected by using a factorized multi-step approach used for all jet analyses in CMS [19]. An algorithm that is a variant of an iterative “noise/pedestal subtraction” technique is used to estimate the heavy ion background event-by-event [20]. And jet energy corrections are derived from PYTHIA [21] simulations without PbPb underlying events.

3. Measurements

3.1. Jet Morphology

Most of the momentum of a jet on average is expected be found close to the jet axis and are carried by high transverse momentum particles. The large angle component of an average jet contains only a small fraction of the overall jet energy, which are carried by softer particles. This can be seen on the right panel of Fig 1 for Pythia jets. Angular and momentum structures of
jets are expected to change in heavy ion collisions due to jet quenching. The internal structure of reconstructed jets are observed to be modified towards an excess of particles far from the jet axis [22]. The momentum structure of reconstructed jets are also observed to be modified towards an excess of particles at low transverse momentum [23]. Further change in the jet morphology was observed in the jet-jet events through the projection of missing transverse momentum of reconstructed charged tracks onto the leading jet axis [13]. These measurements reveal that the missing energy is also recovered in the form of soft particles at large angles with respect to the jet axes. Recently the missing transverse momentum analysis is extended to large annular regions for various jet definitions [24]. This new study suggests possible modifications of leading jets towards getting narrower, and/or the subleading jets towards getting broader due to jet quenching effects. More recently, jets are correlated with charged tracks to study the broadening of jet energy in further detail. The projection of jet-track correlations measured for charged tracks with transverse momentum between 1 and 2 GeV on the $\Delta \phi$ is shown in Fig. 2 [25].

While the distributions look similar in peripheral PbPb and pp events [25] the differences of the correlations strengths are most pronounced in the 0-10% central events for both leading and subleading jets as can be seen in Fig. 2. The integrals of the excess yields (PbPb minus pp) as a function of the transverse momentum of tracks for two PbPb event centralities are shown in Fig. 3. For both centralities the excess yield was found to be largest at the lowest charged track transverse momentum (1-2 GeV) in the most central (0-10%) PbPb data. For peripheral (50-100%) PbPb collisions, correlated charged particle yields are only slightly larger than those for the pp reference. The excess diminishes for higher momentum tracks and becomes similar to the pp reference for charged tracks transverse momentum larger than 4 GeV.

3.2. Parton Dependence

The jet quenching 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 quarks, are expected to radiate less than light ones due to the so-called dead cone effect [26]. To tag jets and extract information regarding their initiating partons’ flavor has been performed by CMS experiment. The following subsections summarizes the current status of these investigations.

3.2.1. Heavy Flavor Tagged Jets Jets formed from heavy flavor quark fragmentation can be tagged by the presence of displaced secondary vertices, either by direct reconstruction of these
Figure 3. The charge track transverse momentum dependence of the difference between the correlations strengths of PbPb and pp events for both leading and subleading jets [25].

Figure 4. Left: Efficiency of light vs c tagged jet quarks for 2 track vs 3 track vertex tagger [30]. Right: Nuclear modification factors from CMS for heavy flavour associated jets [30, 31, 32].

vertices or by the impact parameter of tracks originating from these vertices [28, 29]. Information from these tracks and vertices are typically combined into a quantity which optimizes their discrimination between heavy and light flavor jets. A variation of this method by including additional discriminative variables such as requiring at least three tracks at the secondary vertex can be used to tag charm quark jets [30]. The left panel of Fig. 4 shows how the purity of charm quark tagging can be improved with the requirement of three tracks at the secondary vertex. The right panel of Fig. 4 shows the current compilation of all heavy flavor associated jet measurements at LHC with CMS experiment. A strong suppression in the nuclear modification of bottom quark associated jets is observed in central PbPb collisions while the nuclear modification calculation is consistent with unity in pPb collisions at a larger centre of mass energy. Similarly the yield of charm quark jets in pPb collisions is observed to be consistent with that predicted by PYTHIA within the systematic uncertainties of the measurement as can be seen with open squares in
the right panel of Fig. 4. The inclusive bottom quark jet production at these high transverse momentum appears to have a negligible mass effect, and that the attenuation of bottom quark tagged jets appears to be comparable to the one observed for light quark jets [33]. The situation appears to be different for isolated-photon and B meson tagged bottom quark jets as they are expected to be produced at the early stages of the collision [34]. Additional tagging of bottom quark jets with B mesons or photons are predicted to have a more direct connection to the physics of bottom quark jet energy loss. With high statistics Run 2 data, it is possible to explore multi tags such as c/b jets with additional D/B mesons and photons.

3.2.2. Quark vs Gluon Tagged Jets A large collection of experimental measurements show that hadronic jets initiated by gluons exhibit differences with respect to jets from light-flavor quarks [35, 36, 37, 38, 39]. These observations are primarily grouped into three categories. The first one is the charged particle multiplicity being higher in gluon jets than in light-quark jets. The second one is the considerably softer fragmentation functions of gluon jets than that of quark jets. And finally the gluon jets appeared to be less collimated than quark jets. These differences have been already exploited to differentiate gluon and quark jets in pp collisions [40]. The simplest and most studied variable that is used experimentally is the multiplicity, i.e. the total number of constituent candidates of reconstructed jet. Since gluon hadronization is expected to produce jets which are ‘wider’ than jets induced by quark hadronization, jet shapes are studied with jet width variables. Since quark jets have harder fragmentation functions compared to gluon jets they are therefore more likely to produce jets with hard constituents that carry a significant fraction of the jet energy. This can be studied with the \( p_T^D \) variable, defined as

\[
p_T^D = \sqrt{\sum_i p_{T,i}^2 / \sum_i p_{T,i}}.
\]

Based on studies of single-variable discrimination power, a likelihood-product discriminator can be defined, built on the product of the studied variables. The left panel of Fig. 5 shows the shape comparisons of the \( p_T^D \) variable used in the discriminator. The data (black markers) are compared to the MADGRAPH/PYTHIA simulation, on which the different components are shown: quarks (blue), gluon (red) and unmatched/pileup (grey). The expected discriminator performance is shown in the right panel of Fig. 5, in terms of light-quark efficiency and gluon rejection. While this study shows a good background rejection and signal efficiency, its stability against pile-up events is under investigation. It might be possible to utilize these tools that are developed for pp to PbPb events especially when combined with other taggers and/or variables.

3.2.3. Z Boson Tagged Jets During the 2015 running of the LHC, the PbPb data at 5.02 TeV per nucleon-pair, corresponding to an integrated luminosity of 404 \( \mu b^{-1} \) and 25.8 \( pb^{-1} \) of pp data at the same energy were collected by the CMS experiment. With this data, the so-called “Golden Probe” for jet tomography of the QGP, i.e., coincidences of \( Z^0 \) and jet pairs became experimentally accessible [41, 42, 43]. While this channel have served as an essential calibrator of jet energy in TeV pp collisions, in heavy ion collisions they can be used to calibrate in-medium parton energy loss as they carry no color charge and are expected to escape the medium unattenuated. An event display with a back-to-back Z Boson and a jet candidate from Run 2 data taking is shown in the left panel of Fig. 6. The right panel of Fig. 6 shows the invariant mass spectra of \( Z^0 \) bosons through their muonic decay channel in pp and PbPb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV.

\(^1\) The preliminary measurement of the Z Boson tagged jets in PbPb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV recently became available [44]. These measurements show that while angular correlations between Z bosons and jets are mostly preserved in central PbPb collisions, the transverse momentum ratio of jets to their Z boson pairs appears to be shifted to lower values with respect to the observations in pp collisions as expected from jet quenching.
Figure 5. Left: Data-MC comparisons of the pull variable [40]. Right: Shape comparison, in simulated QCD dijet events, of the likelihood discriminator for jets [40].

Figure 6. Left: An event with a Z+jet candidate at $\sqrt{s_{NN}} = 5$ TeV PbPb collisions. Right: Invariant mass distribution of Z bosons in pp and PbPb collisions at $\sqrt{s_{NN}} = 5$ TeV.

4. Summary
The jet quenching is studied by complimentary and robust measurements with the data that are collected by the CMS experiment during Run 1 of LHC. A strong increase in the fraction of back-to-back jet pairs with unbalanced transverse momentum with no angular de-correlations are observed. The missing energy is recovered in the form of soft particles at large angles with respect to the jet axis. Jet shapes and fragmentation functions appears to be modified in the PbPb collisions. Through studies of bottom and charm quark tagged jets, it appears that jet quenching does not have a strong dependence on parton mass and flavor of the jet for the studied momentum. 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 first data taking
period of Run 2 is also recently completed with success. This provides high statistics PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Many powerful set of discriminative jet tools that are developed for high-precision studies in pp events could now be explored with this data and future data taking periods of upcoming LHC runs to explore the jet quenching and dependence on its underlying parton flavour. These measurements are essential to distinguish between competing energy loss mechanisms to determine key features of QCD and to extract quantitative properties of QGP.

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