Measurement of groomed jet mass in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Abstract

A measurement of the groomed jet mass ($M_g$) normalized by the jet transverse momentum ($p_T^{\text{jet}}$) for anti-$k_T$ jets with the radius parameter 0.4 in PbPb and pp collisions at a center of mass energy of 5.02 TeV per nucleon pair is presented. The jet grooming algorithm is a recursive procedure which sequentially removes soft constituents of a jet until a pair of hard subjets is found. The results of this grooming can be used to study modifications to partons and their evolution while traversing the hot and dense medium created in heavy ion collisions, via small angle splitting of quarks and gluons inside the jet cores. The CMS detector at the LHC is used to perform this analysis for $p_T^{\text{jet}}$ between 140 and 300 GeV and pseudo-rapidity less than 1.3 in both PbPb and pp collisions, and for a range of PbPb collision centralities. The measurements in pp collisions are compared to predictions from the PYTHIA and HERWIG++ event generators and agreement at the 20% level is found. When compared to pp data, an increase of jets with large jet mass is observed for the PbPb results. However, the core of the jet is observed to be unmodified for all event centrality classes.
1 Introduction

In a PbPb collision, scattering processes with large momentum transfer $Q$ (of order of 100 GeV or more) between the partonic constituents of the colliding nuclei occur early ($\ll 1$ fm). As the collision evolves, further interactions of the probe, i.e., the outgoing parton (quark or gluon), with the colored, hot and dense quantum chromodynamics (QCD) medium created in heavy ion collisions (the quark-gluon plasma or QGP) may modify the angular and momentum distribution of jet fragments relative to pp collisions. Energy loss experienced by the probe, known as jet quenching, can be used to study the properties of the hot QCD medium [1, 2]. Jet quenching was first observed at the Relativistic Heavy Ion Collider (RHIC) [3–7] and then at the LHC at CERN [8–18]. From these measurements, one concludes that as the parton loses energy, a significant amount of the lost energy is carried by softer particles at larger angles relative to the jet axis [19, 20].

Interactions with the hot QCD medium can lead to an increase in the gluon radiation probability of the propagating partons [21–25] and can also lead to modifications of the distribution of momentum (splitting function) of radiated parton as well as opening angle between the original and the radiated partons. Hard splitting in the parton shower, where the radiated parton carries a significant amount of energy, happen before the medium is formed. After a hard splitting, the two energetic partons then evolve into two subjets inside the full jet that corresponds to all the fragments from the original parton. By isolating the hard radiation, the interactions of the color charges of the medium with the two outgoing highly energetic partons can be studied. Additionally, in the medium, a hard radiation at large angle comparable to the radius of the jet can happen late in the parton shower [26] giving rise to different phenomenology compared to jets in pp collisions, in which the hot medium is not formed.

The jet grooming algorithms [27–31] remove large angle soft radiation inside a jet, leaving the hard structure of the jet as two subjets. The subjets provide information on the outgoing partons in the hard splitting. The hard structure of the jet is also expected to be sensitive to semi-hard medium-induced gluon radiation [32], modifications of the initial parton splitting [33], and the medium response [34]. A modification in the splitting function distribution $z_g$, defined as the energy of the sub-leading subjet over the sum of the two subjets, was previously studied in central lead-lead (PbPb) collisions [35]. Measurements of the opening angles, in addition to the splitting function distributions, lead to further insight about the nature of the modifications in the medium [32, 33]. This motivates studies of the groomed jet mass ($M_g$), defined as the invariant mass of the two groomed subjets, which is sensitive to both the parton splitting function and the opening angle between the two outgoing partons. This measurement complements studies on the jet mass [36] which did not include grooming in order to be sensitive to underlying event activity and large-angle radiation.

In this article, we report the measurement of the jet transverse momentum-normalized groomed jet mass in both proton-proton (pp) collisions and lead-lead (PbPb) collisions using the Soft Drop jet grooming algorithm [31] (SD) with different grooming parameter settings. This analysis is based on an integrated luminosity of $27.4 \text{ pb}^{-1}$ of pp collisions and $404 \mu \text{b}^{-1}$ of PbPb collisions collected by the CMS detector at the LHC in November 2015 at a nucleon-nucleon center of mass collision energy of 5.02 TeV.

2 The CMS apparatus and event selection

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing an axial magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel
and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Extensive forward hadronic calorimeter (HF), in the pseudorapidity range of $3 < |\eta| < 5$, complements the coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. The first level of the CMS trigger system, composed of specialized hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 $\mu$s. A detailed description of the CMS detector can be found in Ref. [37].

Events with multiple collisions have a negligible effect on the measurement, since the average number of additional collisions per bunch crossing is less than 0.9 in both data sets. Events are selected with triggers requiring a jet with high transverse momentum ($p_T^{\text{jet}}$). In pp collisions, these triggers are based on jets reconstructed from the particle-flow (PF) candidates [38]. An unprescaled trigger with a $p_T^{\text{jet}}$ threshold of 80 GeV is used. In PbPb collisions, triggers are based on jets reconstructed from calorimeter deposits including a subtraction for the uncorrelated underlying event (UE) [39]. The thresholds for these triggers are $p_T^{\text{jet}} = 100$ GeV, 80 GeV and 60 GeV. For the jet triggers in pp and PbPb collisions, the anti-$k_T$ algorithm [40, 41] with a distance parameter $R = 0.4$ is used.

Several offline event selections are applied to reject events from beam-gas, beam-pipe, beam-halo, cosmic ray muon, and beam-scraping interactions. This includes the requirement of a coincidence in the HF detectors [37]: three towers with at least 3 GeV of total transverse energy are required on each side of the interaction point to select the event. In pp collisions, this coincidence requirement is not present, as the contamination from electromagnetic interactions in the pp data set is negligible. For both collision systems, a requirement is placed on the primary vertex to be reconstructed within 15 cm from the nominal interaction point along the beam direction and within 0.15 cm from the nominal interaction point in the transverse plane.

In order to cope with the high multiplicity PbPb environment, the event reconstruction algorithms are modified compared to the ones used for pp data. The performance in tracking efficiency is comparable but not identical [42]. In this analysis, the collision centrality for PbPb events is determined using the total sum of transverse energy from calorimeter towers in the HF region. The transverse energy distribution is used to divide the event sample into bins of total hadronic interaction cross section [43]. In this analysis, we present the results in four event centrality classes: 0-10%, 10-30%, 30-50% and 50-80%.

The PYTHIA 6.246 [44] (tune Z2* [45, 46]) event generator is used for the study. For PbPb simulation, events generated with PYTHIA are embedded into an UE produced with the HYDJET 1.9 event generator [47]. All generated events undergo a full GEANT4 [48] simulation of the CMS detector response. Additional samples for cross checks and for comparison to experimental data are produced with HERWIG++ 2.7.1 (tune EE5C [49, 50]).

3 Jet reconstruction

Offline particle candidates are reconstructed with the PF algorithm [38]. The PF algorithm reconstructs and identifies each individual particle (PF candidate) using an optimized combination of information from various elements of the CMS detector. PF candidates are treated as massless. Jets are clustered from the PF candidates using the anti-$k_T$ jet algorithm with a distance parameter of 0.4. A preselection of $p_T^{\text{jet}} > 140$ GeV and $|\eta|^{\text{jet}} < 1.3$ is applied to all jets
In PbPb collisions, the constituents of the jet are corrected for the UE contribution using the “Constituent Subtraction” algorithm [51]. This algorithm uses a particle-level approach that removes or corrects jet constituents for the uncorrelated background based on the average UE density in a given $\eta$ region. This particle-by-particle subtraction allows the correction of both the 4-momentum of the jet and its substructure. A more detailed description of this method can be found in Ref. [35].

The scale of reconstructed jets is corrected to the particle level response with jet energy corrections derived from simulation and applied to the reconstructed jets in pp and PbPb collisions. Additional corrections for the mis-modeling of the true detector response with that predicted by the simulation are also applied [52, 53].

4 Groomed jet mass

Jet grooming isolates the hard prongs of a jet and removes soft and wide-angle radiation, thereby enhancing reconstructed jet substructure features. Such procedure allows an isolation of the hard splitting in the parton shower evolution. The soft components of a jet can originate from many sources including uncorrelated UE, initial state radiation, other hard scattering in the collision, or soft gluons radiated by the hard parton which initiated the jet. This analysis is focused on the hard structure of the jet by using the “Soft Drop” [31] (SD) jet grooming algorithm to measure the impact of parton-medium interactions on the jet evolution. With this grooming technique the hard and soft parts of the jets can be separated in a completely theoretically-controlled way [30, 31, 54–57]. The procedure starts with a jet and reclusters the constituent-subtracted candidates with the Cambridge/Aachen algorithm [58] to form an angular-ordered structure from the jet constituents. A recursive pairwise declustering step is performed. In each step during the grooming procedure, the softer leg of the considered subject pair is dropped if the SD condition is not satisfied, resulting in a smaller groomed transverse momentum than that of the original jet. The SD condition is the following [31]:

$$z_g = \min\left(\frac{p_{T,i} + p_{T,j}}{p_{T,i} + p_{T,j}}\right) \frac{\Delta R_{ij}}{R_0} > z_{cut}^{\beta},$$

where the subscripts “$i$” and “$j$” indicate the subjects at that step of the declustering, $\Delta R_{ij}$ is the distance between the two subjects in the $\eta-\phi$ plane, $R_0$ is the cone size of the jet, and $z_{cut}$ and $\beta$ are adjustable parameters. The parameter $z_{cut}$ is the threshold for $z_g$ when the two subjects are separated by the jet resolution parameter $R_0$, and $\beta$ controls the grooming profile as a function of subject separation $\Delta R_{ij}$. When $\beta = 0$, the SD grooming threshold is flat as a function of $\Delta R_{ij}$, and the grooming procedure is equivalent to the modified mass drop tagger (mMDT) [30]. The jet is discarded if the SD condition is never satisfied before only one constituent remains. This constitutes less than 1% of the jets for the grooming parameter settings used in this analysis. All jet constituents are taken as massless.

In this analysis, two sets of parameters are considered: $z_{cut} = 0.1$ with $\beta = 0.0$, denoted as $(0.1, 0.0)$, and $z_{cut} = 0.5$ with $\beta = 1.5$, denoted as $(0.5, 1.5)$. The first set of parameters, $(0.1, 0.0)$, has the advantage of being largely insensitive to higher order QCD corrections such as multiple emissions; while the second set of parameters, $(0.5, 1.5)$, is preferred experimentally since it reduces the impact from UE fluctuations by applying a stronger (weaker) SD constraint for subjects with larger (smaller) opening angle, thereby focusing on the core of the jet. Once the SD condition is satisfied, the two subjects at that position in the angular-ordered tree are used to
compute the mass. The $p_T$-normalized groomed jet mass, $M_g/p_T^{\text{jet}}$, is defined as the invariant mass between the two resulting subjets divided by the ungroomed $p_T^{\text{jet}}$. For this observable, the characteristic “Sudakov peak” (caused by the evolution of shower) stays the same as $p_T^{\text{jet}}$ is varied [30].

Figure 1: Groomed jet energy fraction in pp (left) and the 10% most central PbPb collisions (right) for jets with $140 < p_T^{\text{jet}} < 160$ GeV and $|\eta^{\text{jet}}| < 1.3$. The pp data is compared to the PYTHIA event generator and the PbPb data to PYTHIA embedded into the HYDJET event generator. The parameters used for the SD algorithm are $z_{\text{cut}} = 0.5$, $\beta = 1.5$. The jets are selected based on the ungroomed jet transverse momentum.

If two subjets are very close to each other in the $\eta - \phi$ plane, the two subjets cannot be distinctly resolved leading to a significant worsening of the mass resolution. To avoid unphysical modification to the $M_g/p_T^{\text{jet}}$ measurement, an additional selection on the subjet opening angle of $\Delta R_{12} > 0.1$ is applied, leaving jets in the sample with an angular resolution on $\Delta R_{12}$ of 10% or better. Due to this $\Delta R_{12}$ cut, for the jets in 0–10% PbPb collisions, an additional 30% of the jets are discarded when compared to non-central collisions using the $(0.1, 0.0)$ grooming parameters and an additional 50% of jets are discarded for the $(0.5, 1.5)$ setting. This fraction is well reproduced by PbPb MC.

The groomed $p_T^{\text{jet}}$ divided by the original $p_T^{\text{jet}}$ in data is compared to simulation at the reconstructed level in Fig. 1 for the $(0.5, 1.5)$ setting. More energy is removed in the 10% most central PbPb collisions than in pp events in both data and simulation, indicating that the grooming procedure removes part of the residual background activity surviving the constituent subtraction procedure.

Resolution effects from charged particle detection inefficiency, the particle angular resolution from the granularity of the calorimeter and the UE fluctuations in the $M_g/p_T^{\text{jet}}$ spectra are not unfolded. In order to compare results from pp collisions with those of PbPb collisions in a given $p_T^{\text{jet}}$ range, a smearing procedure is applied to the pp data in order to account for the effects of the presence of UE and differences in the reconstruction procedure between PbPb and pp collisions data. This is achieved by mixing a pp event with a generated PbPb UE at the reconstructed PF candidate level, separately for data and simulation. The generated UE is tuned to reproduce the $p_T$ spectra of the PF candidates in minimum bias events in three
bins of $\eta$ and five bins in average UE density. The candidates in the resulting mixed event are clustered into jets using the anti-$k_T$ algorithm with a jet radius of 0.4, and follow the same subtraction and grooming procedure as done in PbPb events to obtain the smeared quantities. The “smeared” jets correspond to the expected modification in the presence of UE activity and detector effects but without any medium-induced modification to the jet structure. The procedure is validated using simulation by comparing the smeared PYTHIA sample with the embedded PYTHIA+HYDJET sample with full detector simulation.

The different tracking reconstruction in PbPb and pp collisions [59, 60] leads to a different $M_g$ scale. A correction on $M_g/p_T^{\text{jet}}$ is derived from simulation as a function of $\Delta R_{12}$ and applied to the smeared jets. The magnitude of the correction ranges from 1% to 3% depending on the sub-jet separation. The effect on $M_g/p_T^{\text{jet}}$ from the merging of candidates is found to be negligible compared to the $M_g$ scale difference from the different tracking reconstruction algorithms.

### 5 Systematic uncertainties

The systematic uncertainties on the $M_g/p_T^{\text{jet}}$ measurement are derived separately in pp and PbPb collisions. The uncertainties are determined for each centrality and $p_T^{\text{jet}}$ selection. The following sources of systematic uncertainties are taken into account: trigger, jet energy scale, jet energy resolution, subjet angular resolution, smearing procedure, quark-to-gluon fractions and the $M_g$ scale correction.

In pp collisions and PbPb collisions with 30-100% centrality, the trigger is fully efficient for the type of jets used in the kinematic range considered for this analysis. For the 30% most central PbPb collisions a trigger bias is present for the lowest considered $p_T^{\text{jet}}$ range, $140 < p_T^{\text{jet}} < 160$ GeV. The measurement in this range is compared to the measurement using a lower threshold trigger. The difference in the observed distributions is assigned as a systematic uncertainty. It is also observed that the trigger used in the pp data can induce a bias to the smeared $M_g/p_T^{\text{jet}}$ measurement for the 0-10% central events in the lowest $p_T^{\text{jet}}$ bin. The difference is caused by the worse $p_T^{\text{jet}}$ resolution after applying the smearing procedure resulting in a different true $p_T^{\text{jet}}$ spectrum. The bias is studied by comparing the smeared jets with different $p_T^{\text{jet}}$ triggers. An uncertainty of 7% over the whole $M_g/p_T^{\text{jet}}$ range is assigned.

The systematic uncertainty due to the jet energy scale (resolution) is estimated by changing the jet energy scale (resolution) by 5% to cover the expected uncertainty on these quantities [52] followed by a comparison of the modified spectra with the nominal spectrum. The systematic uncertainty as a function of $M_g/p_T^{\text{jet}}$ is derived from the difference between the spectra; it is generally of the order of 5%.

The subjet angular resolution is found to be around 0.01 (10% of the $\Delta R_{12}$ cut at 0.1) for a typical jet in this analysis with subjet separation of 0.1. The effect of the angular resolution on $M_g/p_T^{\text{jet}}$ is estimated by comparing spectra obtained by varying the selection of $\Delta R_{12}$ by 10% up and down. Only the low $M_g/p_T^{\text{jet}}$ region is affected by changing the cut due to the correlation between $\Delta R_{12}$ and $M_g/p_T^{\text{jet}}$, resulting in an uncertainty that can go up to 20% for the stronger grooming strength. Any change at high $M_g/p_T^{\text{jet}}$ is induced by the self normalization of the spectra.

Uncertainties associated with the pp smearing procedure are obtained by varying the inputs. The density of UE is varied by 10% which translates to a change on the $M_g/p_T^{\text{jet}}$ spectrum by
up to 10% towards the tail \((M_g/p_T^{\text{jet}} > 0.2)\). The fluctuation on the UE energy density is varied by 5%, resulting in a change on \(M_g/p_T^{\text{jet}}\) spectrum of 5% percent across the whole range.

Since the amount of quark- and gluon-initiated jets for a fixed \(p_T^{\text{jet}}\) selection in PbPb collisions is not known, a systematic uncertainty is applied to the smeared jets in order to account for the difference in detector response to quark and gluon jets. It is estimated with simulation by taking half of the difference of smeared \(M_g/p_T^{\text{jet}}\) spectra between jets originated from quarks and gluons. It is of order of 10–20% towards the tail \((M_g/p_T^{\text{jet}} > 0.2)\).

The systematic uncertainty related to the \(M_g\) scale correction is estimated by comparing the smeared spectra obtained with different tracking algorithms used in PbPb and pp collisions data. It is found that the change due to this is up to 6% towards the tail of the \(M_g/p_T^{\text{jet}}\) spectrum and of order of 2% in the bulk of the spectrum \((M_g/p_T^{\text{jet}} \simeq 0.05 − 0.10)\).

### 6 Results

The per jet normalized \(M_g/p_T^{\text{jet}}\) spectrum in pp collisions for various \(p_T^{\text{jet}}\) selections is presented in Fig. 2 for the \((0.1, 0.0)\) and \((0.5, 1.5)\) settings. The results are compared to jets generated with PYTHIA and HERWIG++. At large \(M_g/p_T^{\text{jet}}\), HERWIG++ over-predicts the \(M_g/p_T^{\text{jet}}\) spectra and PYTHIA under-predicts the spectra when compared to data in the \((0.1, 0.0)\) grooming setting. Similar differences between data and event generators were observed for jets with higher \(p_T^{\text{jet}}\) in pp collisions at \(\sqrt{s} = 13\) TeV [61]. For the \((0.5, 1.5)\) setting, the data and simulation are in agreement within statistical and systematic uncertainties. In this scenario the \(M_g/p_T^{\text{jet}}\) spectrum is steeper than for the softer \((0.1, 0.0)\) grooming setting due to the larger amount of energy removed during the grooming procedure.

The measurement of the \(M_g/p_T^{\text{jet}}\) in PbPb collisions for several centrality intervals for \(p_T^{\text{jet}}\) between 160-180 GeV is presented in Fig. 3 for the two SD grooming settings. For the \((0.1, 0.0)\) setting, no significant modification is observed for this \(p_T^{\text{jet}}\) range except for an indication of enhancement for the 10% most central collision. For the \((0.5, 1.5)\) setting where the grooming disfavors jets with highly imbalanced large angle subjets, no significant modification is observed.

The measured \(M_g/p_T^{\text{jet}}\) in 0-10% central collisions for several \(p_T^{\text{jet}}\) intervals is shown in Fig. 4 for both considered SD settings. Some difference between jets from PbPb collisions and those smeared from pp collisions is seen in the \((0.1, 0.0)\) SD setting in the lowest \(p_T^{\text{jet}}\) intervals where it can be observed that in central PbPb collisions it is more likely to produce a jet with large \(M_g/p_T^{\text{jet}}\) than in pp collisions.
Figure 2: The $p_T^{\text{jet}}$ dependence of $M_{g/p_T^{\text{jet}}}$ for pp events for two SD settings: (0.1, 0.0) (upper panels) and (0.5, 1.5) (lower panels). Results are compared to PYTHIA and HERWIG++ event generators. The ratio of data to MC is also shown. The height of the vertical lines (colored boxes) indicate statistical (systematic) uncertainties.
Figure 3: The centrality dependence of $M_g/p_T^{jet}$, for events with $160 < p_T^{jet} < 180$ GeV for two SD settings: $(0.1, 0.0)$ (upper panels) and $(0.5, 1.5)$ (lower panels). Results are compared to the smeared pp spectra. The ratio of PbPb data over smeared pp is also shown. The height of the vertical lines (colored boxes) indicate statistical (systematic) uncertainties.
Figure 4: The $p_T^{\text{jet}}$ dependence of $M_g/p_T^{\text{jet}}$, for events in the centrality class 0-10% for two SD settings: $(0.1, 0.0)$ (upper panels) and $(0.5, 1.5)$ (lower panels). Results are compared to the smeared pp spectra. The ratio of PbPb data over smeared pp is also shown. The height of the vertical lines (colored boxes) indicate statistical (systematic) uncertainties.
7 Summary

The first measurement of the groomed jet mass normalized by the transverse momentum of the jet, $M_g/p_{T\text{jet}}$, in pp and PbPb collisions at a center of mass energy of 5.02 TeV per nucleon pair has been presented. Both the PYTHIA and HERWIG++ event generators do not reproduce the measurement in pp collisions. When the grooming of jets is performed with a profile that removes more radiation at distances far away from the jet axis, the $M_g/p_{T\text{jet}}$ distribution in PbPb collisions is within uncertainties equivalent to that measured in pp collisions for all studied centrality and $p_{T\text{jet}}$ regions. Using a grooming setting which is independent of the angular separation of the subjets, no modification of the $M_g/p_{T\text{jet}}$ spectra in 10-80% peripheral collisions with respect to the measurement in pp collisions is observed. In 0-10% central collisions, however, an increased probability to produce a jet with large $M_g/p_{T\text{jet}}$ is observed when compared to pp collisions for jets with $140 < p_{T\text{jet}} < 180$ GeV. This measurement shows that the core of the jet is not altered in central PbPb collisions within the uncertainties of this measurement, but the periphery of the jet is sensitive to interactions of the partons with the dense colored medium during the parton shower evolution.

References


