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Measurement of jet fragmentation into charged particles in pp and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

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The CMS collaboration

Abstract: Jet fragmentation in pp and PbPb collisions at a centre-of-mass energy of 2.76 TeV per nucleon pair was studied using data collected with the CMS detector at the LHC. Fragmentation functions are constructed using charged-particle tracks with transverse momenta $p_{\mathrm{T}} > 4\,\mathrm{GeV}/c$ for dijet events with a leading jet of $p_{\mathrm{T}} > 100\,\mathrm{GeV}/c$. The fragmentation functions in PbPb events are compared to those in pp data as a function of collision centrality, as well as dijet-p_{T} imbalance. Special emphasis is placed on the most central PbPb events including dijets with unbalanced momentum, indicative of energy loss of the hard scattered parent partons. The fragmentation patterns for both the leading and subleading jets in PbPb collisions agree with those seen in pp data at 2.76 TeV. The results provide evidence that, despite the large parton energy loss observed in PbPb collisions, the partition of the remaining momentum within the jet cone into high-p_{T} particles is not strongly modified in comparison to that observed for jets in vacuum.

Keywords: Hadron-Hadron Scattering

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Contents

1 Introduction

When colliding lead nuclei (PbPb) at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$, one expects to form a system of hot and dense matter at energy densities that have not been explored before. One of the early proposed experimental signatures of the formation of a dense system in such collisions was "jet quenching", i.e. the suppression or disappearance of the spray of hadrons resulting from the fragmentation of a hard scattered parton having suffered energy loss in the medium [1]. The energy lost by a parton in the produced medium provides fundamental information on its thermodynamical and transport properties [2, 3]. Results on the suppression of inclusive hadron production at high transverse momenta (p_{T}), as well as on the modified high-p_{T} dihadron angular correlations obtained from nucleus-nucleus collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ at the Relativistic Heavy Ion Collider (RHIC) [4–7] have shown the existence of partonic energy loss in dense strongly interacting matter. Similar observations have been made at the Large Hadron Collider (LHC) [8–14].

At LHC energies, high-p_{T} jets have been fully reconstructed in heavy-ion collisions. A significant dijet transverse momentum imbalance is observed, when comparing to a reference distribution corresponding to pp collisions at the same nucleon-nucleon centre-of-mass energy [15–17]. Such an observation is consistent with energy loss of the hard scattered partons in the dense medium produced in central PbPb collisions. In the same set of results, the redistribution of the lost jet energy is studied using jet-track correlations [16]. It is found that the missing p_{T} opposite to the leading jet can be recovered only by summing up the contributions of particles down to a low p_{T} of $500\,\mathrm{MeV}/c$ with respect to the beam axis and out to large radii in pseudorapidity and azimuthal angle, $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.8$, with respect to the jet axis [16]. Since these results show that the quenched energy is transferred out of the jet cone, the jet clustering algorithm reconstructs jets with a reduced energy from the fragments of the partons after they have lost energy in the medium. The study presented here investigates to what extent the fragmentation pattern of partons that have traversed the medium resembles vacuum fragmentation, by constructing fragmentation functions in PbPb collisions and comparing them to those from unquenched jets, as measured in pp collisions. Fragmentation functions encode the probability for a parton to fragment into particles carrying a given fraction of the parton energy. Colour-charged partons undergo showering processes into partons of successively lower energy which hadronise into colour-neutral final-state particles. The evolution of such a parton radiation and splitting process leads to a characteristic shape of the fragmentation function [18]. Theoretical models of jet quenching predict an effective change of the shape of the fragmentation function due to the change of the parton radiation pattern in the medium [19–22]. Experimentally, fragmentation functions are constructed by correlating the reconstructed jet momentum with the momenta of charged particles projected onto the jet axis. The jets are defined using the final-state particles produced in the collision, clustered with the anti-k_{T} jet algorithm [23]. In this Letter, we present a measurement of fragmentation functions in pp and PbPb collisions and a detailed comparison of their shapes measured in the two systems. The measurement is restricted to the high-p_{T} component of the fragmentation function, using charged particles of $p_{\mathrm{T}} > 4\,\mathrm{GeV}/c$ that lie within $\Delta R < 0.3$ around the reconstructed jets.

2 Experimental setup

The Compact Muon Solenoid (CMS) detector is described in ref. [24]. Only the detector systems used in this analysis are discussed hereafter. The central part of the CMS detector contains a superconducting solenoid that provides a homogeneous magnetic field of 3.8 T parallel to the beam axis. Charged-particle trajectories are measured using silicon pixel and strip trackers that cover the pseudorapidity region $|\eta| < 2.5$, where η is defined as $\eta = -\log\left[\tan\left(\theta/2\right)\right]$ and θ is the polar angle with respect to the anticlockwise beam direction. An electromagnetic crystal calorimeter (ECAL) and a brass/scintillator hadron calorimeter (HCAL) surround the tracking volume and cover $|\eta| < 3.0$. The ECAL calorimeter is segmented in quasi-projective cells of a granularity in pseudorapidity and azimuthal angle of $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$ in the barrel ($|\eta| < 1.5$), increasing across the endcap ($1.5 < |\eta| < 3.0$) to 0.09×0.09 at $|\eta| = 3.0$. The HCAL has a cell granularity of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ in the barrel region and a variable cell granularity, changing as a function of η, in the endcap region [24]. A forward steel/quartz-fibre Cherenkov hadron calorimeter (HF) extends the coverage to $|\eta| = 5.2$. The CMS trigger system is composed of a first level made of custom hardware processors, which use information from the calorimeters and muon detectors to select events, and the High-Level Trigger (HLT) processor farm, that further decreases the event rate, before data storage.

3 Data selection

The PbPb and pp data analysed in this Letter were collected with the CMS detector in 2010 and 2011, respectively, at a centre-of-mass energy of 2.76 TeV per nucleon pair. The integrated luminosities for the PbPb and pp data samples used for this analysis are

$L_{\rm int} \approx 6.8\,\mu b^{-1}$ and $L_{\rm int} \approx 231\,{\rm nb}^{-1}$, respectively. The HLT system is used to select events containing high-$p_{\rm T}$ jets reconstructed from calorimeter towers. In PbPb collisions, the trigger threshold is $p_{\rm T} = 35\,{\rm GeV}/c$, applied on the raw calorimetric jet energy. For pp collisions, events are selected if they pass a jet trigger threshold of $p_{\rm T} = 40\,{\rm GeV}/c$ on the calorimetric jet energy. As found in ref. [16], for the jet selection used in this analysis, requiring a 100 GeV/c jet in $|\eta| < 2$, the triggers are more than 99% efficient. In addition to the trigger decision, standard event selection criteria are applied [16], including a rejection of beam related backgrounds, a selection of inelastic hadronic collisions by requiring a two-sided coincidence of signals in the HF and a well-reconstructed event vertex.

For the analysis of PbPb data, it is important to determine the degree of overlap between the two colliding nuclei in each event, termed collision centrality. Centrality is determined using the sum of transverse energy reconstructed in the HF. The distribution of the HF energy is used to divide the event sample into percentiles of the total nucleus-nucleus interaction cross section. For the purpose of this analysis, the data set is split into two centrality bins, the 0–30% most central events (i.e. those which have the largest overlap between the two colliding Pb nuclei) and the remaining peripheral events in the 30–100% centrality range. A detailed description of the centrality determination can be found in [16].

4 Jet and track reconstruction

For both pp and PbPb collisions, the analysis is based on jets reconstructed using the anti-$k_{\rm T}$ jet algorithm, with a radius parameter (R) of 0.3, utilizing particle-flow (PF) objects that combine tracking and calorimetric information [25, 26]. In the PbPb data, the contribution of the underlying heavy-ion event is removed using an iterative pileup subtraction method [27]. Since this procedure determines the underlying-event background using data outside the jet, the result is insensitive to the fragmentation properties of the jet. The jet-finding efficiency is above 95% for jets of $p_{\rm T} > 40$ GeV/c, and above 99% for jets of $p_{\rm T} > 50\,{\rm GeV}/c$ [25]. The relative jet momentum resolution in pp collisions is found to be 19 (13)% at $p_{\rm T} = 40$ (100) GeV/c, improving with jet momentum. In central PbPb collisions, the momentum resolution deteriorates to 24 (16)% at $p_{\rm T} = 40$ (100) GeV/c [25] due to fluctuations in the underlying event. For both pp and PbPb events, the jet momentum response has little or no deviations from a Gaussian shape.

In all cases the reconstructed jet momenta are corrected to final-state stable particle (lifetime τ with $c\tau > 10\,{\rm mm}$) level using factors derived from PYTHIA 6.422 [28] (tune D6T [29, 30], CTEQ6L1 PDFs [31]) pp simulations at $\sqrt{s} = 2.76\,{\rm TeV}$ [32]. The uncertainty in the corrected jet energy scale is about 3% for pp events, resulting in a per-bin jet-yield uncertainty of ±15%. In the case of PbPb events, due to the influence of the underlying event, the uncertainty in the jet energy scale increases to about 4% for peripheral events (30–100% centrality) and 5% for central events (0–30% centrality) which results in per-bin jet-yield uncertainties of ±20% and ±25%, respectively.

The dijets selected for this analysis consist of a leading jet (denoted by subscript 1) with $p_{\rm T,1} > 100\,{\rm GeV}/c$ and a subleading jet (subscript 2) of $p_{\rm T,2} > 40\,{\rm GeV}/c$, with axes that

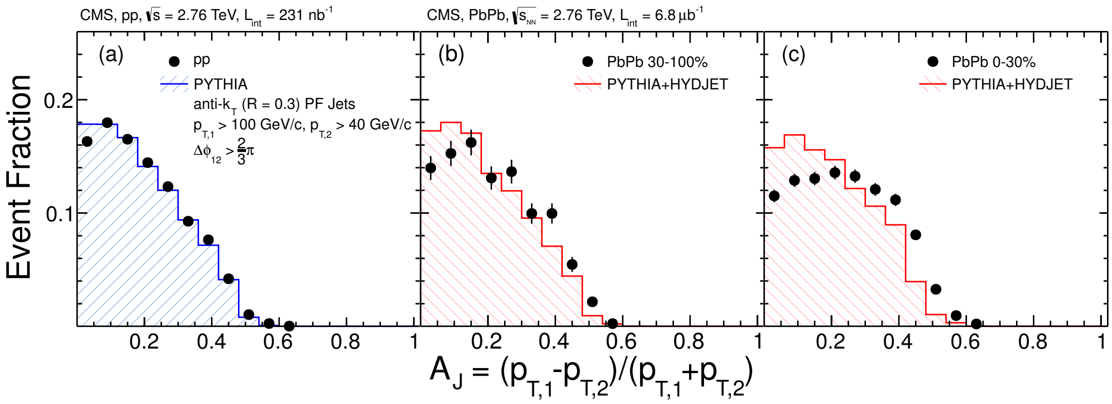

Figure 1. Dijet asymmetry, A_J, distributions in (a) pp collisions, (b) peripheral (30–100%) PbPb, and (c) central (0–30%) PbPb collisions. Data are shown as black points while the histograms show PYTHIA dijets, which when compared to PbPb data have been embedded into HYDJET events. Error bars represent the statistical uncertainty.

lie within $|\eta| < 2$. The p_{T} thresholds are chosen to ensure high reconstruction efficiency for the leading and, especially, the subleading jet. In addition, the azimuthal opening angle $\Delta\phi_{1,2}$ between the leading and subleading jet is required to be larger than $2\pi/3$. No explicit requirement is made on the presence or absence of a third jet in the event.

A detailed description of the charged-particle reconstruction algorithm and its performance can be found in ref. [9]. The track-finding efficiency in the kinematic range of this study is (60–70)% and the corresponding correction is applied as a function of track p_{T}, jet p_{T}, and event centrality by reweighting the found tracks with the inverse of the reconstruction efficiency. The track reconstruction efficiency correction is derived from a GEANT4 [33] simulation of the CMS detector applied to PYTHIA events, which are embedded into PbPb collisions simulated using HYDJET [34] in order to include the effect of the underlying PbPb event. The momentum resolution of the track reconstruction is $\sigma(p_{\mathrm{T}})/p_{\mathrm{T}} \approx 1$–3%.

The dijet momentum balance is studied in terms of the dijet asymmetry ratio [15–17],

$$A_J = \frac{p_{\mathrm{T},1} - p_{\mathrm{T},2}}{p_{\mathrm{T},1} + p_{\mathrm{T},2}}, \tag{4.1}$$

which is positive by construction. Figure 1 shows the A_J distributions in (a) pp and in (b,c) PbPb for two bins in event centrality. Central PbPb events (0–30%) show a significant excess of unbalanced pairs when compared to both peripheral PbPb collisions (30–100%) and pp data. This can be interpreted as a direct observation of parton energy loss in central PbPb collisions.

5 Fragmentation functions

The fragmentation functions are measured by correlating reconstructed charged-particle tracks falling within the jet cones, with the axis of the respective jet [35]. As done in previous measurements at hadron colliders [36], the fragmentation function is presented as

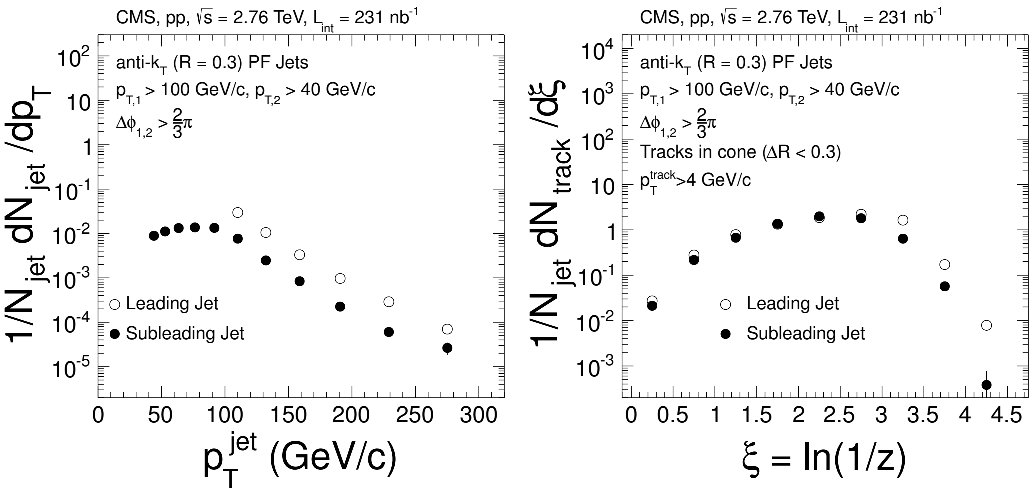

Figure 2. Data from pp collisions. Left: Leading and subleading jet p_{T} distributions (not corrected for jet-finding efficiency and not unfolded for the jet energy resolution). Right: Fragmentation functions reconstructed for the leading (open circles) and subleading (solid points) jets. The statistical uncertainties, shown as error bars, are smaller than the symbols in most cases.

a function of the variable

$$\xi = \ln \frac{1}{z} \quad ; \quad z = \frac{p_{\parallel}^{\mathrm{track}}}{p^{\mathrm{jet}}}, \tag{5.1}$$

where $p_{\parallel}^{\mathrm{track}}$ is the momentum component of the track along the jet axis, and p_{jet} is the magnitude of the jet momentum within the jet cone. The momentum components and the angle between the charged-particle and the jet axis are calculated in the dijet centre-of-mass frame, obtained by an approximate Lorentz transformation along the beam axis in the form of a pseudorapidity shift, defined as $\eta_{\mathrm{dijet}} = (\eta_1 + \eta_2)/2$. The tracks are selected to lie within a cone of $\Delta R < 0.3$ around the jet axis. The fragmentation functions, defined as $1/N_{\mathrm{jet}}\ dN_{\mathrm{track}}/d\xi$, are normalised to the total number of selected leading or subleading jets, N_{jet}, respectively. To minimise the contribution of tracks from the underlying event, only tracks with $p_{\mathrm{T}}^{\mathrm{track}} > 4\,\mathrm{GeV}/c$ are selected. This restricts the measurement of the fragmentation function to the region of $\xi \lesssim 4.5$. The remaining underlying event contribution, not associated with the jet, is estimated by selecting tracks that lie in a background cone, obtained by reflecting the original jet cone about $\eta = 0$, while keeping the same ϕ coordinate. The background contribution is accumulated jet-by-jet over the full event sample and subtracted to obtain the final $dN_{\mathrm{track}}/d\xi$ distribution. Due to this procedure, jets in the region $|\eta| < 0.3$ are excluded from the analysis, to avoid overlap between the signal jet region and the region used for background estimation.

Figure 2 shows the reconstructed leading and subleading jet fragmentation functions in pp collisions (right panel) and the corresponding jet p_{T} distributions (left panel), to illustrate the kinematic range in which the fragmentation functions are measured. Note that the higher jet momentum of the leading jet compared to the subleading jet, leads to an increased number of particles passing the $p_{\mathrm{T}}^{\mathrm{track}} > 4\,\mathrm{GeV}/c$ selection for the fragmentation function measurement. This results in the observed excess of $dN_{\mathrm{track}}/d\xi$ at high values

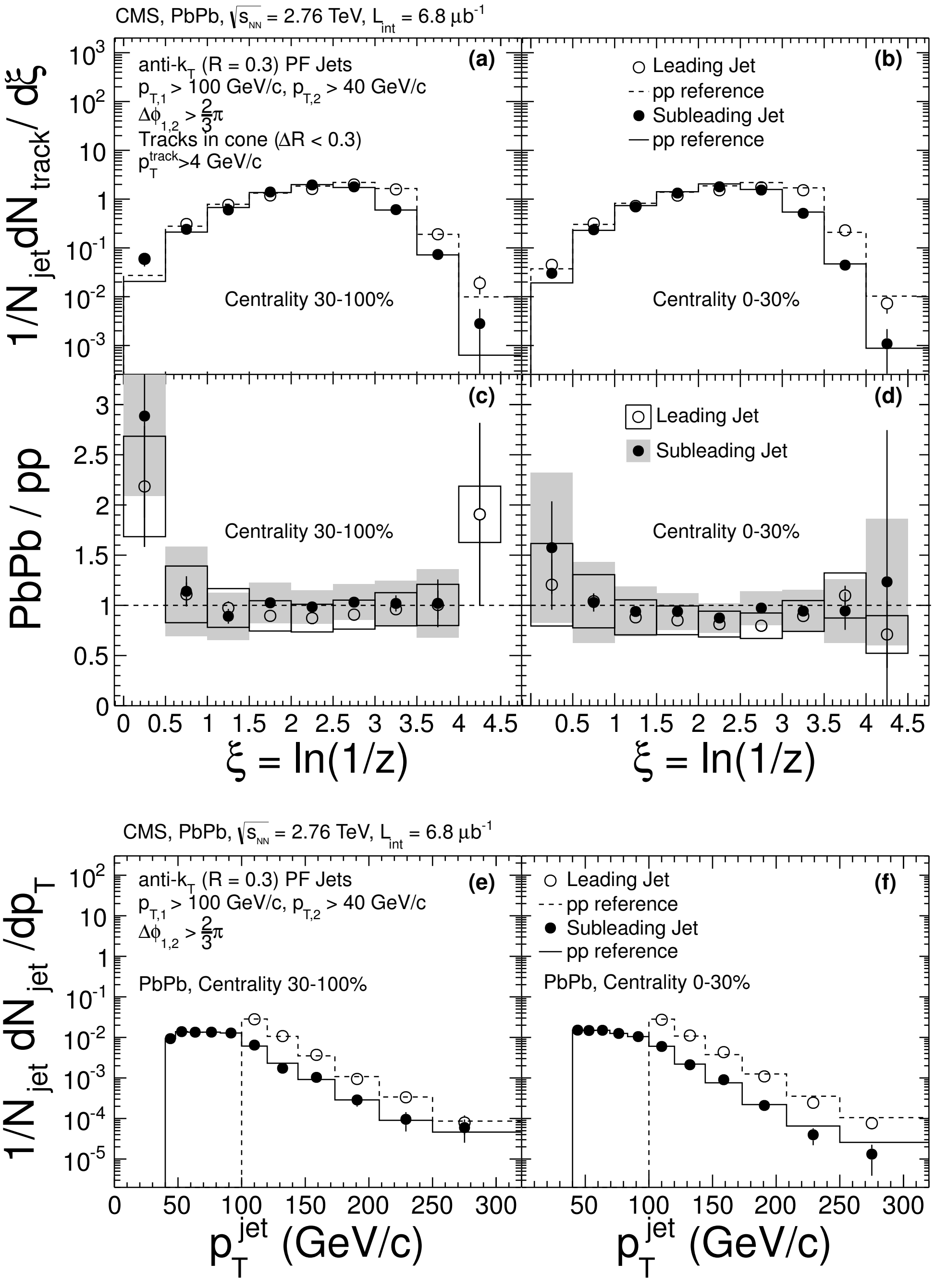

Figure 3. (a,b) Fragmentation functions reconstructed in peripheral and central PbPb data for the leading (open circles) and subleading (solid points) jets. (c,d) Ratio of each PbPb fragmentation function to its pp-based reference. Error bars are statistical, the hollow boxes represent the systematic uncertainty for the leading jet, and gray boxes show the systematic uncertainty for the subleading jet. (e,f) Jet p_T distributions in PbPb data (not corrected for efficiency and not unfolded for p_T resolution) compared to the pp-based reference (see text). Only statistical uncertainties are shown in panels a, b, e and f.

of ξ for the leading jet over the corresponding distribution for the subleading jet. The $p_{\mathrm{T}}^{\mathrm{track}}$ threshold on the tracks introduces a jet-p_{T}-dependent kinematic limit in the high ξ part of the spectrum. For a direct comparison between pp and PbPb collisions, the jet momentum resolution deterioration in PbPb events has to be taken into account. For this purpose, the ereconstructed p_{T} of every jet in the pp data is smeared by the quadratic difference of the underlying event fluctuations in PbPb and pp. Furthermore, in order to keep the kinematic constraints consistent, a jet-p_{T}-dependent reweighting is applied to the pp data, after fluctuation smearing, so that the resulting jet p_{T} distribution matches that in PbPb. The reweighting factor is applied to each jet when generating the fragmentation function for pp. The *pp-based reference* distributions obtained this way ensure that the jet fragmentation functions in PbPb and pp are compared for matching jet p_{T} spectra.

Figure 3 shows the fragmentation functions for (a) peripheral and (b) central PbPb collisions, for both the leading and subleading jets, compared to the pp-based reference. The ratios between the PbPb fragmentation functions and the pp-based reference distributions are shown in panels (c) and (d). The corresponding jet p_{T} distributions illustrating the kinematic range of the measurement are shown in panels (e) and (f). The overlaid histograms in the same set of figures show the pp-based reference distributions. The systematic uncertainty, represented by the boxes at each point in panels (c) and (d), is obtained from the propagated jet and track reconstruction uncertainties. These comparison plots show that the shape of the fragmentation functions in pp and PbPb collisions agrees within uncertainties at all centralities for the leading, as well as for the subleading, jets.

The uncertainties in the jet response may affect the results in different ways: smearing of jet energy due to fluctuations distorts the observed fragmentation functions, a miscalibration of the overall energy scale shifts the fragmentation function along the ξ axis, and a residual offset in the jet energy introduces a tilt of the shape of the distribution. These effects are studied using a Monte Carlo (MC) simulation, by varying the corresponding generator-level jet properties within the limits of the jet response uncertainty. The systematic uncertainties are determined by comparing the resulting fragmentation functions in the modified sample to the original MC reference.

The systematic uncertainty due to the charged-particle reconstruction efficiency is obtained by comparing fragmentation functions based on efficiency-corrected tracks, with the fragmentation functions using the MC generator information. Since the particle-flow event reconstruction algorithm uses reconstructed charged-particles for the jet p_{T} determination, a failure to reconstruct a high-p_{T} charged-particle can lead to an underestimation of the jet momentum, resulting in an artificially high A_J measurement. The modification of the fragmentation function measurement due to this effect is studied in PYTHIA + HYDJET events. Since the A_J distributions in data and simulation are different, the magnitude of the corresponding effect in the PbPb data is estimated based on the reconstructed A_J distributions, and is accounted for in the combined systematic uncertainty. The effect of momentum resolution on reconstructed charged-particle tracks is estimated by smearing PYTHIA + HYDJET generator-level information. This is found to have little effect on the fragmentation function, in comparison to the unsmeared generator level information. The above uncertainties are combined in quadrature to give the total systematic uncertainty.

Another potential source of systematic uncertainty comes from the response of the PF technique to jets with very different fragmentation functions. Since one component of the jet energy correction accounts for the loss of low-p_T particles, a large change in the contribution of such tracks will result in an incorrect reconstructed jet energy. To study this effect, we have compared the response to separate quark and gluon jets from PYTHIA, whose fragmentation functions differ by 20-40% in the region $2 < \xi < 4$ and by larger factors for $\xi < 1$. These dramatic differences in fragmentation pattern do result in systematic differences in the jet momentum but the effect is only at the few percent level [25]. The change in the reconstructed fragmentation function resulting from the tiny shifts in the ξ parameter caused by these jet momentum offsets are negligible.

To study in more detail the potential effect of medium-induced energy loss on the fragmentation properties of partons, the data sample of central events (0–30% centrality), where a large average dijet imbalance is observed, is divided into classes of dijet imbalance. Four A_J selections are chosen, which split the central PbPb data sample into approximately equal number of dijets: $0 < A_J < 0.13$, $0.13 < A_J < 0.24$, $0.24 < A_J < 0.35$, and $A_J > 0.35$. For each of these event classes, the fragmentation functions are constructed separately for the leading and subleading jets. In figure 4(a–d) the fragmentation functions are shown in bins of increasing dijet imbalance, from left to right. The corresponding jet p_T distributions used in the fragmentation functions are shown in Fig 4(i–l), illustrating the kinematic range of the measurement and the energy imbalance between leading and subleading jets, as selected by the A_J interval. The overlaid histogram in the same set of figures shows the pp-based reference distributions. Ratios of PbPb data to the pp-based reference are shown in figure 4(e–h). In the ξ range of 0.5–4.0 the PbPb and the pp distributions typically agree to within (10–20)% which is smaller than the systematic uncertainty in the PbPb measurement, as indicated by the size of the shaded area and open boxes for the leading and subleading jet, respectively. Within uncertainties, the PbPb data and pp-based reference show the same fragmentation properties, for different jet imbalance in leading, as well as subleading, jets.

6 Conclusions

The CMS detector has been used to study jet fragmentation properties in pp and PbPb collisions at $\sqrt{s_\mathrm{NN}} = 2.76\,\mathrm{TeV}$ in data samples corresponding to integrated luminosities of about $231\,\mathrm{nb}^{-1}$ and $6.8\,\mu\mathrm{b}^{-1}$, respectively. Jets were reconstructed based on particle-flow objects using the anti-k_T sequential clustering algorithm, with a radius parameter of 0.3. The reconstructed jet momenta were corrected to final-state particle level. Dijets were selected consisting of a leading jet with $p_{\mathrm{T},1} > 100\,\mathrm{GeV}/c$ and a subleading jet of $p_{\mathrm{T},2} > 40$ GeV/c, with axes that lie within $|\eta| < 2$. The azimuthal opening angle $\Delta\phi_{1,2}$ between the leading and subleading jet was required to be larger than $2\pi/3$. The selected jets were used to construct the high-p_T component of the fragmentation functions by correlating their momentum with the momenta of tracks of $p_\mathrm{T} > 4\,\mathrm{GeV}/c$ within a cone of $\Delta R < 0.3$ around the jet axis. The PbPb results were compared to those in a pp-based reference taking into account the different jet momentum distribution and the effect of

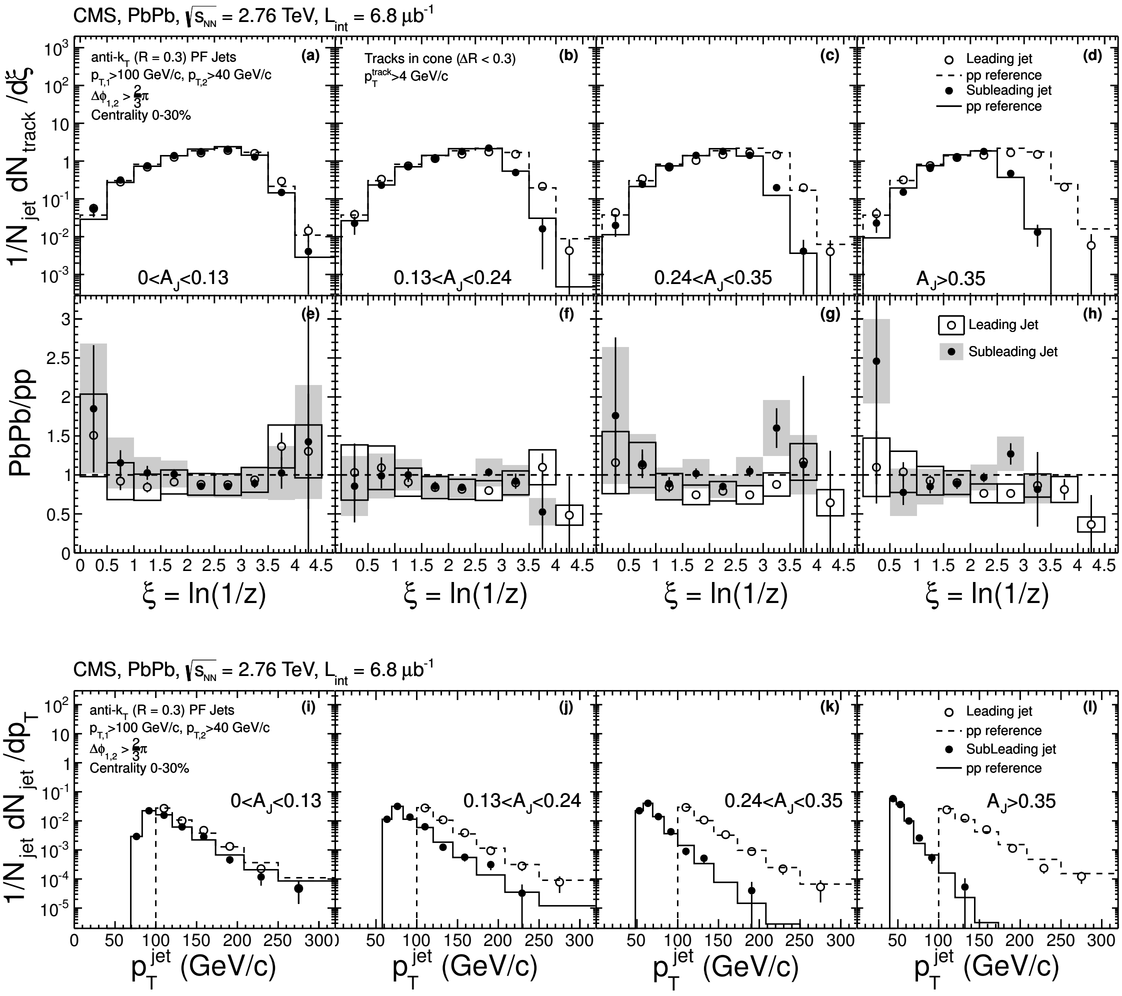

Figure 4. (a–d) Fragmentation functions for the leading (open circles) and subleading (solid points) jets in four regions of A_J in central PbPb collisions compared to the pp reference. (e–h) Ratio of each fragmentation function to its pp-based reference. Error bars shown are statistical. The systematic uncertainty is represented by hollow boxes (leading jet) or gray boxes (subleading jet). (i–l) Jet p_T distributions in PbPb collisions in four regions of A_J (not corrected for efficiency and not unfolded for p_T resolution) compared to the pp-based reference (see text). Only statistical uncertainties are shown.

fluctuations in the underlying PbPb event on the jet momentum reconstruction. The jet properties were studied as a function of the collision centrality and the dijet transverse momentum imbalance. Central PbPb events show a significant excess of unbalanced jet pairs. Nevertheless, the fragmentation functions reconstructed in PbPb collisions for different event centrality and dijet-p_T imbalance agree within the measurement uncertainty with the pp-based reference for jets of the same reconstructed momentum. This shows that, after traversing the dense strongly interacting medium, partons produced in PbPb collisions are reconstructed as jets with a significantly reduced momentum. However, the partition of the smaller momentum that remains within the jet cone into high-p_T particles corresponds to that observed for jets fragmenting in vacuum, as seen in pp collisions.

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