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Measurement of the Splitting Function in pp and Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Data from heavy ion collisions suggest that the evolution of a parton shower is modified by interactions with the color charges in the dense partonic medium created in these collisions, but it is not known where in the shower evolution the modifications occur. The momentum ratio of the two leading partons, resolved as subjets, provides information about the parton shower evolution. This substructure observable, known as the splitting function, reflects the process of a parton splitting into two other partons and has been measured for jets with transverse momentum between 140 and 500 GeV, in pp and PbPb collisions at a center-of-mass energy of 5.02 TeV per nucleon pair. In central PbPb collisions, the splitting function indicates a more unbalanced momentum ratio, compared to peripheral PbPb and pp collisions.. The measurements are compared to various predictions from event generators and analytical calculations.

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Scattering processes with large momentum transfer Q between the partonic constituents of colliding nucleons occur early in heavy ion collisions. Further interactions of the outgoing partons with the produced (colored) hot and dense quantum chromodynamics (QCD) medium (the quark-gluon plasma, QGP) may modify the angular and momentum distributions of final-state hadronic jet fragments relative to those in proton-proton collisions. This process, known as jet quenching, can be used to probe the properties of the QGP [1,2]. Jet quenching was first observed at the Relativistic Heavy Ion Collider [3–9] and then at the Large Hadron Collider (LHC) [10–25]. This Letter reports an attempt to isolate parton splittings to two well separated partons with high transverse momentum (p_T), probing medium induced effects during the parton shower evolution in the QGP. Information about these leading partons of a hard splitting can be obtained by removing the softer wide-angle radiation contributions, done through the use of jet grooming algorithms that attempt to split ("decluster") a single jet into two subjets [26–30]. For a parton shower in vacuum, these subjets provide access to the properties of the first splitting in the parton evolution [31,32]. Interactions of the two outgoing partons with the QGP potentially modify the properties of subsequent splittings resulting in different subjet properties. This Letter reports a study of hard parton splittings in pp and PbPb collisions.

An observable characterizing the parton splitting, denoted by z_g, is defined as the ratio between the p_T of the less energetic subjet, $p_{T,2}$, and the p_T sum of the two subjets [32], $z_g = p_{T,2}/(p_{T,1} + p_{T,2})$. A measurement of the z_g distribution in pp collisions, using CMS open data, was recently reported [33,34]. In PbPb collisions, this measurement reflects how the two color-charged partons produced in the first splitting propagate through the QGP, probing the role of color coherence of the jet in the medium [35]. If the partons act as a single coherent emitter, the two subjets will be equally modified, leaving z_g unaffected [36]. If, instead, the partons in the medium act as decoherent emitters, the two subjets should be modified differently, thereby altering z_g. In addition, z_g is sensitive to semihard medium-induced gluon radiation [37], modifications of the initial parton splitting [38], and the medium response [39].

The analysis uses data collected by the CMS experiment in 2015. The PbPb and pp data samples, both at a nucleon-nucleon center-of-mass energy of 5.02 TeV, correspond to integrated luminosities of 404 μb^{-1} and 27.4 pb^{-1}, respectively. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity, η, coverage provided by the barrel and endcap detectors. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [40].

The particle-flow (PF) algorithm reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector [41]. The PF candidates identified as a photon or a

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neutral hadron are treated as massless, while for charged hadrons the pion mass is assumed. The electron and muon PF candidates are assigned the corresponding lepton masses. Jets are reconstructed from the PF candidates using the anti-k_T jet algorithm [42–44] with a distance parameter $R = 0.4$. The kinematics of the jet are determined using the vectorial sum of all particle momenta in the jet. For this analysis, jets are required to have $p_{T,\mathrm{jet}} >$ 140 GeV and $|\eta| < 1.3$.

The online event selection trigger also uses the anti-k_T algorithm with $R = 0.4$ but applies a lower threshold on $p_{T,\mathrm{jet}}$; all events with a PF jet with $p_{T,\mathrm{jet}} > 80$ GeV were recorded in the pp case, while in PbPb collisions the triggers (based on jets reconstructed from calorimeter deposits including a subtraction for the uncorrelated underlying event) use a 100 GeV threshold. Noncollision events, such as beam-gas interactions or cosmic-ray muons, are rejected offline [19]. The events are required to have a primary vertex reconstructed within 15 cm (0.15 cm) of the nominal interaction point along the beam direction (in the transverse plane). The average number of additional collisions per bunch crossing is less than 0.9 in both data sets, having a negligible effect on the measurement. The PbPb event sample is divided into centrality intervals, reflecting the impact parameter of the colliding nuclei, using the percentage of the total inelastic hadronic cross section, which is evaluated using the sum of the total energy deposited in both forward hadron calorimeters, covering the $3 < |\eta| < 5$ range [45].

The PYTHIA 6.423 [46] event generator (tune Z2* [47,48]) is used to calculate Monte Carlo (MC) corrections. For PbPb simulations, the PYTHIA 6 events are embedded into an underlying event produced with HYDJET 1.9 [49]. All generated events undergo a full GEANT4 [50] simulation of the CMS detector response. Additional cross check samples are produced with PYTHIA 8.212 [51] (tune CUETP8M1 [48]) and HERWIG++ [52] (tune EE5C [53]).

In PbPb collisions, the constituents of the jet are corrected for the underlying event contribution using the “constituent subtraction” method [54], a particle-by-particle approach that removes or corrects jet constituents based on the average underlying event density. The subtraction corrects both the four-momentum of the jet and its substructure. Underlying event densities are determined by calculating the median p_T per unit area, ρ, and a density term related to the jet mass, ρ_m, using a procedure in which all of the particles in the event are clustered into jets using the k_T algorithm with $R = 0.4$ [42,43,55]. To match the jets used in this analysis, only k_T jets with $|\eta| < 1.3$ are included in the density determination. The influence of true hard jet fragments on the background estimation is reduced by excluding the two leading k_T jets. The constituent-subtracted jets are corrected for the detector response with jet energy corrections derived from independent pp and PbPb simulations. Additional corrections for the mismodeling of the detector response are also applied [56].

Jet grooming algorithms aim to isolate the hard prongs of a jet and remove soft wide-angle radiation. The “soft drop” declustering procedure, used in this analysis, is an extension of the modified mass drop tagger [29]. The procedure starts by selecting an anti-k_T jet that has already been constituent-subtracted and reclustered with the Cambridge-Aachen algorithm [57] to form a pairwise clustering tree with an angular-ordered structure. A pairwise declustering is performed on this tree. In each step of the declustering, a branching into two subjets is accepted if they pass the soft drop condition [30],

$$\frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}, \tag{1}$$

where the subscripts “i” and “j” indicate the subjets at that step of the declustering, ΔR_{ij} is the distance between the two subjets in the η-ϕ plane, R_0 is the cone size of the anti-k_T jet, and z_{cut} is an adjustable parameter. If the soft drop condition is not satisfied, the softer subjet is dropped. For this study, z_{cut} is set to 0.1 [30]. The parameter β is set to 0, which satisfies an extended version of infrared and collinear safety by absorbing the collinear divergences into a generalized fragmentation function recovering the QCD splitting function [32]. Once the soft drop condition is satisfied, the two subjets at that position in the tree are used in the analysis. If the soft drop condition is never satisfied, the jet is not used. This is the case for 1.5% of the jets measured at $p_{T,\mathrm{jet}} = 140$ GeV, increasing to 3.0% at $p_{T,\mathrm{jet}} = 300$ GeV, independent of collision centrality.

Groomed jets with a small distance between the two subjets frequently result from the ambiguous case where the two subjets cannot be distinctly resolved, leading to a significant misassignment of particle constituents to subjets. An additional selection of $\Delta R_{12} > 0.1$ is applied, removing 40% (60%) of the jets measured at low (high) $p_{T,\mathrm{jet}}$, to avoid an unphysical modification of z_g. This selection rejects an additional 15% (5%) of the jets at low (high) $p_{T,\mathrm{jet}}$ in the 10% most central PbPb collisions, in comparison to the noncentral collisions, an effect well reproduced by the simulation. The systematic uncertainty on the z_g variable is evaluated by varying the ΔR_{12} minimum distance requirement by its one standard deviation MC resolution of 10%; this variation results in a 2% uncertainty, independent of centrality.

The transverse momentum of the jet after grooming, $p_{T,g}$, is identical to or smaller than the original $p_{T,\mathrm{jet}}$. The groomed p_T fraction, $p_{T,g}/p_{T,\mathrm{jet}}$, is compared to simulations in Fig. 1 for jets with $160 < p_{T,\mathrm{jet}} < 180$ GeV, in pp and central PbPb collisions. The measured and simulated distributions are in agreement.

The potential bias due to the online jet trigger is evaluated by using events collected with a lower threshold

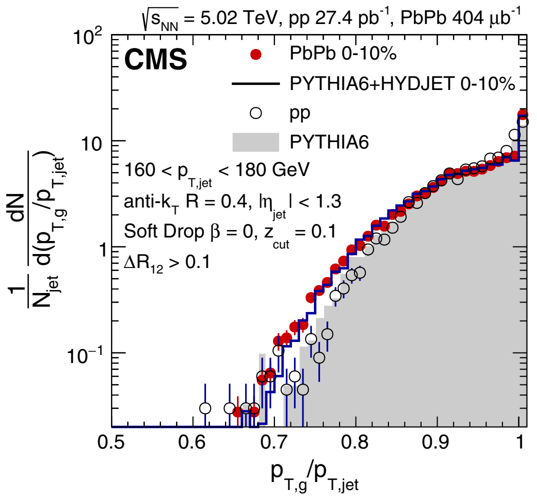

FIG. 1. Groomed jet energy fraction in pp and in the 10% most central PbPb collisions, for jets with $160 < p_{T,\text{jet}} < 180$ GeV and $|\eta_{\text{jet}}| < 1.3$. The pp (PbPb) data are compared to PYTHIA 6 (embedded in HYDJET) distributions.

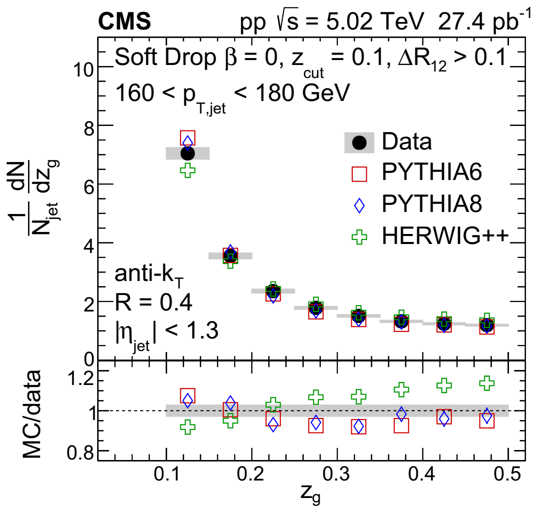

FIG. 2. The z_g distribution in pp collisions for $160 < p_{T,\text{jet}} < 180$ GeV, compared to predictions from event generators. The error bars (shaded area) represent the statistical (systematic) uncertainty.

and also minimum bias events. For the 10% most central PbPb collisions, a bias is found in the lowest $p_{T,\text{jet}}$ range, $140 < p_{T,\text{jet}} < 160$ GeV, changing the yield by values linearly decreasing from +6% at $z_g = 0.1$ to −15% at $z_g = 0.5$. In the 10%–30% centrality class, the bias is half as large, and it vanishes for more peripheral events. The full bias is corrected for and the magnitude of the correction is treated as a z_g systematic uncertainty. The trigger has no effect on the measurements at higher $p_{T,\text{jet}}$.

The systematic uncertainty in the jet energy scale, on the measured and simulated distributions, is obtained by propagating the uncertainties in the jet response correction [56,58]. A maximum deviation in yield of 4% is found in central PbPb collisions, decreasing to 2% in pp and peripheral PbPb collisions. This effect tends to increase (decrease) the p_T of the leading (subleading) subjet. The systematic uncertainty in the normalization of the z_g distributions is estimated to be 5% (3%) in central (peripheral) collisions. The relative uncertainty in the jet energy resolution is 10%, leading to an uncertainty smaller than 0.5% on the z_g distribution.

Figure 2 shows the z_g distribution measured in pp collisions, together with results obtained with PYTHIA 6, PYTHIA 8, and HERWIG++, including a full simulation of detector effects. Both PYTHIA simulations have a slightly steeper z_g distribution than the data, while HERWIG++ shows an opposite trend.

To compare the z_g distribution in pp and PbPb collisions, in given $p_{T,\text{jet}}$ and centrality ranges, the measurements in pp collisions are adjusted to match the subjet resolution in PbPb data. The resolution correction is derived, for each $p_{T,\text{jet}}$ and collision centrality range, from full detector simulation studies of the ratio of the z_g distributions between PYTHIA and PYTHIA embedded into HYDJET. The ratio between simulated PbPb and pp z_g distributions shows a relative decrease in the number of PbPb events at high z_g, reaching ∼40% in central collisions and negligible in peripheral collisions. The uncertainty in the correlation between the response of the two subjets is estimated by varying the individual subjet resolution by 10%, the relative correlation by 15%, and the subjet energy scale by 5%, corresponding to one standard deviation in resolution. This results in an uncertainty of 8%–10% in z_g. The mismodeling of the z_g distribution in PYTHIA, evaluated by reweighting to the z_g measurement in pp collisions, adds an uncertainty of 4%–5%. These uncertainties are assigned to the "smeared" pp data points. The resolution correction is validated with a parametric resolution model that uses the jet resolution and a sampled z_g in each $p_{T,\text{jet}}$ range, and recreates the correction function for each centrality selection by sampling the individual subjet resolutions.

Figure 3 shows the z_g distributions measured in PbPb collisions, for several centrality intervals, in comparison to the smeared pp reference data. The systematic uncertainties on the z_g distributions are fully correlated from point to point, resulting in an anticorrelated uncertainty on the self-normalized distributions, and are uncorrelated between the pp and PbPb data sets. The z_g distribution in peripheral PbPb collisions agrees with the pp reference, while the more central collisions exhibit a steeper z_g distribution. Differences between the z_g of quark- and gluon-initiated jets are found to be a few percent [32], so that the observed modification cannot be attributed to the flavor composition within a fixed $p_{T,\text{jet}}$ interval. The observation indicates that the splitting into two branches becomes increasingly more unbalanced as the PbPb collisions become more central.

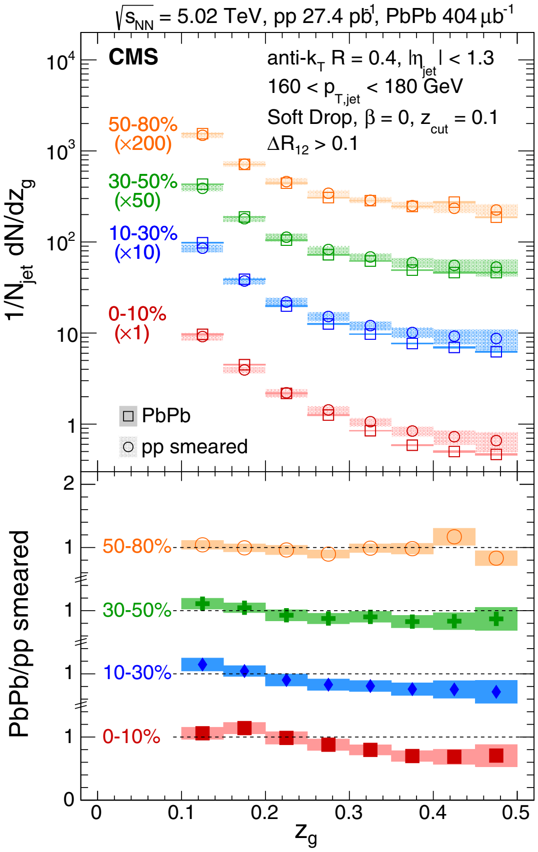

FIG. 3. The z_g distributions in PbPb collisions for $160 < p_{T,\mathrm{jet}} < 180$ GeV, in several centrality ranges, compared to pp data smeared to account for the differences in resolution. The error bars (shaded area) represent the statistical (systematic) uncertainty.

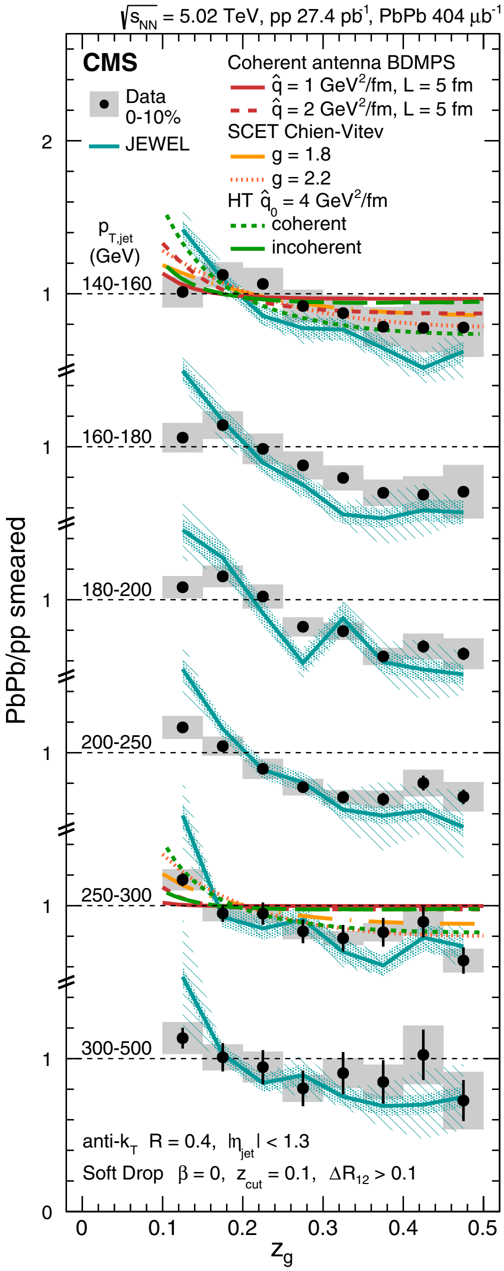

FIG. 4. Ratios of z_g distributions in PbPb and smeared pp collisions in the 10% most central events, for several $p_{T,\mathrm{jet}}$ ranges, compared to various jet quenching theoretical calculations [37–39,63]. The error bars (shaded area) represent the statistical (systematic) uncertainty. The diagonally hatched band denotes the uncertainty from the treatment of the medium response using the JEWEL event generator.

The modification of the z_g distribution in central PbPb collisions is shown in Fig. 4 over a wide kinematic range in $p_{T,\mathrm{jet}}$. The measurement is compared to a prediction of the JEWEL event generator (shown with statistical and theoretical uncertainties originating from the treatment of the medium response), which incorporates medium-induced interactions while the partons propagate through the QGP [39,59,60]. The measurement is also compared with a soft-collinear effective theory (SCET) with Glauber gluon interactions [38] for two different quenching strengths, with a calculation incorporating multiple medium-induced gluon bremsstrahlung (BDMPS) [2,61,62] assuming that the two hard partons radiate gluons as a coherent emitter [37], and with a higher twist (HT) approach employing both coherent and incoherent energy loss [63]. Each of the three models is presented for two settings of the parameters reflecting their medium properties, as indicated in the legends, where L is the medium length, $\hat{q}$ and $\hat{q}_0$ denote medium transport coefficients, and g is the coupling strength between the jet and the medium. The BDMPS medium effect is too weak to describe the observed $p_{T,\mathrm{jet}}$ dependence, while the other models reproduce the data at low and high $p_{T,\mathrm{jet}}$, using medium properties previously tuned to match measurements of the nuclear modification factors of charged hadrons and jets. For the HT calculation, the presence or absence of color coherence makes a significant difference. Since the detector resolution effects have a negligible impact on the theoretical calculations, given that they largely cancel in the PbPb to (smeared) pp ratio, the theoretical curves are shown without detector smearing.

In summary, the first measurement of the splitting function in pp and PbPb collisions at a center-of-mass energy of 5.02 TeV per nucleon pair has been presented. This represents the first application of a grooming technique to PbPb data, removing soft wide-angle radiation from the jet and thereby isolating the two leading subjets. The momentum sharing between these subjets is used to obtain information about hard parton splitting processes during the shower evolution. The PYTHIA and HERWIG++ event generators reproduce the measured splitting function in pp and peripheral PbPb collisions, at the level of 15%. In central PbPb collisions, a steeper z_g distribution is observed, indicating that the parton splitting process is modified by the hot medium created in heavy ion collisions. These results provide new insight into the role of color coherence and other attributes of the interactions of partons in the quark-gluon plasma.

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[1] M. Gyulassy and M. Plumer, Jet quenching in dense matter, Phys. Lett. B **243**, 432 (1990).

[2] R. Baier, Yu. L. Dokshitzer, S. Peigné, and D. Schiff, Induced gluon radiation in a QCD medium, Phys. Lett. B **345**, 277 (1995).

[3] K. Adcox *et al.* (PHENIX Collaboration), Suppression of Hadrons with Large Transverse Momentum in Central Au + Au Collisions at $\sqrt{s_{\mathrm{NN}}} = 130$ GeV, Phys. Rev. Lett. **88**, 022301 (2001).

[4] S. S. Adler *et al.* (PHENIX Collaboration), Suppressed π^0 Production at Large Transverse Momentum in Central Au + Au Collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, Phys. Rev. Lett. **91**, 072301 (2003).

[5] J. Adams *et al.* (STAR Collaboration), Transverse Momentum and Collision Energy Dependence of High p_{T} Hadron Suppression in Au + Au Collisions at Ultrarelativistic Energies, Phys. Rev. Lett. **91**, 172302 (2003).

[6] I. Arsene *et al.* (BRAHMS Collaboration), Transverse Momentum Spectra in Au + Au and d + Au Collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV and the Pseudorapidity Dependence of High p_{T} Suppression, Phys. Rev. Lett. **91**, 072305 (2003).

[7] B. B. Back *et al.* (PHOBOS Collaboration), Charged hadron transverse momentum distributions in Au + Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, Phys. Lett. B **578**, 297 (2004).

[8] L. Adamczyk *et al.* (STAR Collaboration), Dijet Imbalance Measurements in Au + Au and pp Ccollisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV at STAR, Phys. Rev. Lett. **119**, 062301 (2017).

[9] L. Adamczyk *et al.* (STAR Collaboration), Measurements of jet quenching with semi-inclusive hadron + jet distributions in Au + Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, Phys. Rev. C **96**, 024905 (2017).

[10] ALICE Collaboration, Suppression of charged particle production at large transverse momentum in central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Lett. B **696**, 30 (2011).

[11] ALICE Collaboration, Particle-Yield Modification in Jetlike Azimuthal Dihadron Correlations in Pb-Pb Collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Rev. Lett. **108**, 092301 (2012).

[12] ATLAS Collaboration, Measurement of charged-particle spectra in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC, J. High Energy Phys. 09 (2015) 050.

[13] CMS Collaboration, Study of high-p_{T} charged particle suppression in PbPb compared to pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Eur. Phys. J. C **72**, 1945 (2012).

[14] ATLAS Collaboration, Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with the ATLAS Detector at the LHC, Phys. Rev. Lett. **105**, 252303 (2010).

[15] CMS Collaboration, Jet momentum dependence of jet quenching in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Lett. B **712**, 176 (2012).

[16] ATLAS Collaboration, Measurement of the jet radius and transverse momentum dependence of inclusive jet suppression in lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with the ATLAS detector, Phys. Lett. B **719**, 220 (2013).

[17] ALICE Collaboration, Measurement of charged jet suppression in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, J. High Energy Phys. 03 (2014) 013.

[18] ALICE Collaboration, Measurement of jet suppression in central Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Lett. B **746**, 1 (2015).

[19] CMS Collaboration, Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, J. High Energy Phys. 04 (2017) 039.

[20] ALICE Collaboration, Measurement of jet quenching with semi-inclusive hadron-jet distributions in central Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, J. High Energy Phys. 09 (2015) 170.

[21] CMS Collaboration, Modification of jet shapes in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Lett. B **730**, 243 (2014).

[22] CMS Collaboration, Measurement of jet fragmentation in PbPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Rev. C **90**, 024908 (2014).

[23] ATLAS Collaboration, Measurement of jet fragmentation in Pb + Pb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with the ATLAS detector at the LHC, Eur. Phys. J. C **77**, 379 (2017).

[24] ALICE Collaboration, First measurement of jet mass in Pb-Pb and p-Pb collisions at the LHC, Phys. Lett. B **776**, 249 (2018).

[25] CMS Collaboration, Measurement of transverse momentum relative to dijet systems in PbPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, J. High Energy Phys. 01 (2016) 006.

[26] S. D. Ellis, C. K. Vermilion, and J. R. Walsh, Recombination algorithms and jet substructure: Pruning as a tool for heavy particle searches, Phys. Rev. D **81**, 094023 (2010).

[27] J. M. Butterworth, A. R. Davison, M. Rubin, and G. P. Salam, Jet Substructure as a New Higgs Search Channel at the LHC, Phys. Rev. Lett. **100**, 242001 (2008).

[28] D. Krohn, J. Thaler, and L.-T. Wang, Jet trimming, J. High Energy Phys. 02 (2010) 084.

[29] M. Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, Towards an understanding of jet substructure, J. High Energy Phys. 09 (2013) 029.

[30] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, Soft drop, J. High Energy Phys. 05 (2014) 146.

[31] G. Altarelli and G. Parisi, Asymptotic freedom in parton language, Nucl. Phys. **B126**, 298 (1977).

[32] A. J. Larkoski, S. Marzani, and J. Thaler, Sudakov safety in perturbative QCD, Phys. Rev. D **91**, 111501 (2015).

[33] A. Larkoski, S. Marzani, J. Thaler, A. Tripathee, and W. Xue, Exposing the QCD Splitting Function with CMS Open Data, Phys. Rev. Lett. **119**, 132003 (2017).

[34] A. Tripathee, W. Xue, A. Larkoski, S. Marzani, and J. Thaler, Jet substructure studies with CMS open data, Phys. Rev. D **96**, 074003 (2017).

[35] Y. Mehtar-Tani and K. Tywoniuk, Jet (de)coherence in Pb–Pb collisions at the LHC, Phys. Lett. B **744**, 284 (2015).

[36] J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, and K. Tywoniuk, New picture of jet quenching dictated by color coherence, Phys. Lett. B **725**, 357 (2013).

[37] Y. Mehtar-Tani and K. Tywoniuk, Groomed jets in heavy-ion collisions: sensitivity to medium-induced bremsstrahlung, J. High Energy Phys. 04 (2017) 125.

[38] Y.-T. Chien and I. Vitev, Probing the Hardest Branching within Jets in Heavy-Ion Collisions, Phys. Rev. Lett. **119**, 112301 (2017).

[39] G. Milhano, U. A. Wiedemann, and K. C. Zapp, Sensitivity of jet substructure to jet-induced medium response, Phys. Lett. B **779**, 409 (2018).

[40] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. **3**, S08004 (2008).

[41] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. **12**, P10003 (2017).

[42] M. Cacciari, G. P. Salam, and G. Soyez, Fastjet user manual, Eur. Phys. J. C **72**, 1896 (2012).

[43] M. Cacciari and G. P. Salam, Dispelling the N^3 myth for the k_t jet-finder, Phys. Lett. B **641**, 57 (2006).

[44] M. Cacciari, G. P. Salam, and G. Soyez, The anti-k_t jet clustering algorithm, J. High Energy Phys. 04 (2008) 063.

[45] CMS Collaboration, Observation and studies of jet quenching in PbPb collisions at nucleon-nucleon center-of-mass energy = 2.76 TeV, Phys. Rev. C **84**, 024906 (2011).

[46] T. Sjöstrand, S. Mrenna, and P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026.

[47] CMS Collaboration, Study of the underlying event at forward rapidity in pp collisions at $\sqrt{s} = 0.9$, 2.76, and 7 TeV, J. High Energy Phys. 04 (2013) 072.

[48] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, Eur. Phys. J. C **76**, 155 (2016).

[49] I. P. Lokhtin and A. M. Snigirev, A model of jet quenching in ultrarelativistic heavy ion collisions and high-p_{T} hadron spectra at RHIC, Eur. Phys. J. C **45**, 211 (2006).

[50] S. Agostinelli *et al.* (GEANT4), GEANT4: A simulation toolkit, Nucl. Instrum. Methods, Phys. Res., Sect. A **506**, 250 (2003).

[51] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. **178**, 852 (2008).

[52] M. Bähr, S. Gieseke, M. A. Gigg, D. Grellscheid, K. Hamilton, O. Latunde-Dada, S. Plätzer, P. Richardson, M. H. Seymour, A. Sherstnev, and B. R. Webber, Herwig++ physics and manual, Eur. Phys. J. C **58**, 639 (2008).

[53] M. H. Seymour and A. Siodmok, Constraining MPI models using σ_{eff} and recent Tevatron and LHC underlying event data, J. High Energy Phys. 10 (2013) 113.

[54] P. Berta, M. Spousta, D. W. Miller, and R. Leitner, Particle-level pileup subtraction for jets and jet shapes, J. High Energy Phys. 06 (2014) 092.

[55] G. Soyez, G. P. Salam, J.-H. Kim, S. Dutta, and M. Cacciari, Pileup Subtraction for Jet Shapes, Phys. Rev. Lett. **110**, 162001 (2013).

[56] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, J. Instrum. **6**, P11002 (2011).

[57] Y. L. Dokshitzer, G. D. Leder, S. Moretti, and B. R. Webber, Better jet clustering algorithms, J. High Energy Phys. 08 (1997) 001.

[58] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. **12**, P02014 (2017).

[59] K. C. Zapp, F. Krauss, and U. A. Wiedemann, A perturbative framework for jet quenching, J. High Energy Phys. 03 (2013) 080.

[60] R. K. Elayavalli and K. C. Zapp, Medium response in JEWEL and its impact on jet shape observables in heavy ion collisions, J. High Energy Phys. 07 (2017) 141.

[61] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigné, and D. Schiff, Radiative energy loss of high-energy quarks and gluons in a finite volume quark-gluon plasma, Nucl. Phys. **B483**, 291 (1997).

[62] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigné, and D. Schiff, Radiative energy loss and p_{T} broadening of high-energy partons in nuclei, Nucl. Phys. **B484**, 265 (1997).

[63] N.-B. Chang, S. Cao, and G.-Y. Qin, Probing medium-induced jet splitting and energy loss in heavy-ion collisions, arXiv:1707.03767.

A. M. Sirunyan,[1] A. Tumasyan,[1] W. Adam,[2] F. Ambrogi,[2] E. Asilar,[2] T. Bergauer,[2] J. Brandstetter,[2] E. Brondolin,[2] M. Dragicevic,[2] J. Erö,[2] M. Flechl,[2] M. Friedl,[2] R. Frühwirth,[2,b] V. M. Ghete,[2] J. Grossmann,[2] J. Hrubec,[2] M. Jeitler,[2,b] A. König,[2] N. Krammer,[2] I. Krätschmer,[2] D. Liko,[2] T. Madlener,[2] I. Mikulec,[2] E. Pree,[2] N. Rad,[2] H. Rohringer,[2] J. Schieck,[2,b] R. Schöfbeck,[2] M. Spanring,[2] D. Spitzbart,[2] W. Waltenberger,[2] J. Wittmann,[2] C.-E. Wulz,[2,b] M. Zarucki,[2] V. Chekhovsky,[3] V. Mossolov,[3] J. Suarez Gonzalez,[3] E. A. De Wolf,[4] D. Di Croce,[4] X. Janssen,[4] J. Lauwers,[4] H. Van Haevermaet,[4] P. Van Mechelen,[4] N. Van Remortel,[4] S. Abu Zeid,[5] F. Blekman,[5] J. D'Hondt,[5] I. De Bruyn,[5] J. De Clercq,[5] K. Deroover,[5] G. Flouris,[5] D. Lontkovskyi,[5] S. Lowette,[5] S. Moortgat,[5] L. Moreels,[5] Q. Python,[5] K. Skovpen,[5] S. Tavernier,[5] W. Van Doninck,[5] P. Van Mulders,[5] I. Van Parijs,[5] D. 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