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Observation of medium induced modifications of jet fragmentation in PbPb collisions using isolated-photon-tagged jets

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Abstract

Measurements of fragmentation functions for jets associated with an isolated photon are presented for the first time in pp and PbPb collisions. The analysis uses data collected with the CMS detector at the CERN LHC at a nucleon-nucleon center-of-mass energy of 5.02 TeV. Fragmentation functions are obtained for jets with $p_{\mathrm{T}}^{\text{jet}} > 30\,\text{GeV}/c$ in events containing an isolated photon with $p_{\mathrm{T}}^{\gamma} > 60\,\text{GeV}/c$, using charged tracks with transverse momentum $p_{\mathrm{T}}^{\text{trk}} > 1\,\text{GeV}/c$ in a cone around the jet axis. The association with an isolated photon constrains the initial p_{T} and azimuthal angle of the parton whose shower produced the jet. For central PbPb collisions, modifications of the jet fragmentation functions are observed when compared to those measured in pp collisions, while no significant differences are found in the 50% most peripheral collisions. Jets in central PbPb events show an excess (depletion) of low (high) p_{T} particles, with a transition around 3 GeV/c.

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*See Appendix A for the list of collaboration members

A deconfined state of quarks and gluons, called the quark-gluon plasma (QGP) [1], is believed to be produced on a short timescale, $\tau \approx 1\,\mathrm{fm}/c$, in high energy nucleus-nucleus collisions [2]. Occasionally, a pair of partons (quarks or gluons) in the colliding nuclei undergoes a high transverse momentum (p_{T}) scattering, a process that occurs over a shorter timescale, $\tau \sim 1/p_{\mathrm{T}}$. As they pass through and interact with the QGP, the scattered partons lose some of their energy, thereby acting as probes of the short-wavelength structure of the medium [3–8]. The relative importance of the various mechanisms by which these partons lose energy to the medium, whether by heating the medium, scattering off point-like constituents of the QGP, or by some other process, has been a continuous focus of the field of relativistic heavy ion collisions [9–13].

The outgoing hard-scattered partons eventually fragment, and each forms a jet of collimated particles that can be observed experimentally. The CERN LHC collaborations have studied various properties of jets and jet pairs, such as modifications of the jet yield in the medium (jet quenching) [14–16], jet fragmentation functions (the probability for a parton to fragment into particles carrying a given fraction of the jet momentum) [17, 18], missing p_{T} in dijet systems [19–21], jet-track correlations [22], and the radial p_{T} profile of tracks within jets [23]. However, understanding how the observed jets relate to their parent partons is challenging in these analyses. The energy lost by the partons diminishes the correlation between the final-state jet measurement (after energy loss) and the initial parton properties. One way to overcome this challenge is to study processes in which the initial hard scattering produces a parton and an electroweak boson. Since these bosons do not experience quantum chromodynamic interactions, they are largely unaffected by their passage through the QGP. As a result, in a sample selected by requiring the presence of a photon or a Z boson (whose p_{T} can be reliably measured), the jets associated with the boson should have parent partons whose p_{T} before any energy loss occurs is well defined. The analysis of such pairs allows for more constrained jet studies and comparisons with theoretical calculations. In addition, at LHC energies, the electroweak-boson+jet production is dominated by quark jets for $p_{\mathrm{T}}^{\mathrm{jet}} > 30\,\mathrm{GeV}/c$ [24], hence providing information specifically on quark energy loss and therefore constraining the dependence of energy loss on parton (quark or gluon) flavor.

The CMS Collaboration has previously measured the azimuthal correlation and momentum imbalance of isolated-photon+jet pairs in pp and PbPb collisions at nucleon-nucleon center-of-mass energies of $\sqrt{s_{_{\mathrm{NN}}}} = 2.76$ and $5.02\,\mathrm{TeV}$ [25, 26] and of Z+jet pairs at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ [27]. This Letter presents the first measurement of the fragmentation function of jets associated with an isolated photon, i.e. a photon for which no significant energy is deposited around its location in the detector. This definition suppresses dijet events in which a high-p_{T} photon originates from one of the jets, either via collinear fragmentation of a parton ("fragmentation photons") or via decays of neutral mesons ("decay photons"). The analysis uses PbPb and pp data at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ collected in 2015 and corresponding to integrated luminosities of $404\,\mu\mathrm{b}^{-1}$ and $27.4\,\mathrm{pb}^{-1}$, respectively. The results from PbPb and pp collisions are compared to search for QGP-induced modifications.

Photon-tagged fragmentation functions are presented as distributions of $\xi^{\mathrm{jet}} = \ln\left[|\vec{p}^{\,\mathrm{jet}}|^2/(\vec{p}^{\,\mathrm{trk}}\cdot\vec{p}^{\,\mathrm{jet}})\right]$, where $\vec{p}^{\,\mathrm{jet}}$ and $\vec{p}^{\,\mathrm{trk}}$ are the 3-momenta of the jet and charged particle, respectively, and $\xi_{\mathrm{T}}^{\gamma} = \ln\left[-|\vec{p}_{\mathrm{T}}^{\,\gamma}|^2/(\vec{p}_{\mathrm{T}}^{\,\mathrm{trk}}\cdot\vec{p}_{\mathrm{T}}^{\,\gamma})\right]$, where $\vec{p}_{\mathrm{T}}^{\,\gamma}$ and $\vec{p}_{\mathrm{T}}^{\,\mathrm{trk}}$ are the transverse momenta with respect to the beam direction of the photon and charged-particle, respectively. These ξ variables represent the longitudinal distribution of p_{T} along the jet axis and, hence, the fragmentation pattern of the jets [28, 29]. The ξ^{jet} variable gives the fragmentation pattern with respect to the transverse momentum of the reconstructed jet, and can be compared directly with results obtained using a dijet sample [17]. The $\xi_{\mathrm{T}}^{\gamma}$ variable is used to characterize the fragmentation pattern with respect to the transverse momentum of the initial parton before any energy loss occurred. Note that $\vec{p}_{\mathrm{T}}^{\gamma}$ is used instead of $\vec{p}^{\gamma}$ because the photon and parton from a hard scattering have the same $|p_{\mathrm{T}}|$ at leading order (because of transverse momentum conservation) but not necessarily the same magnitude of longitudinal momentum (because the colliding partons can have different x values).

The central feature of the CMS detector 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 (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Hadron forward (HF) calorimeters extend the pseudorapidity coverage up to $|\eta| = 5.2$ and are used for event selection. In addition, in the case of PbPb events, the HF signals are used to determine the degree of overlap ("centrality") of the two colliding Pb nuclei [20] and the event-by-event azimuthal angle of maximum particle density ("event plane") [30]. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. 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. [31].

The event samples are selected online with a dedicated photon trigger requiring one photon with $p_{\mathrm{T}}^{\gamma} > 40\,\mathrm{GeV}/c$ [26], and are subjected to offline requirements to remove non-collision events such as beam-gas interactions [26, 32]. For jets and photons, the reconstruction algorithms, analysis selections, and corrections for the energy scale and resolution are the same as in Ref. [26]. For the analysis of PbPb collisions, the event centrality is defined as the fraction of the total inelastic hadronic cross section, starting at 0% for the most central collisions, and is evaluated as percentiles of the distribution of the energy deposited in the HF calorimeters [20]. Results are presented in four centrality intervals: a central interval 0–10% (i.e., the 10% of the events having the largest overlap area of the two nuclei), two intermediate intervals 10–30% and 30–50%, and a peripheral interval 50–100% (the one closest to a pp-like environment).

The photon candidates are restricted to the barrel region of the ECAL, $|\eta^{\gamma}| < 1.44$, and are required to have $p_{\mathrm{T}}^{\gamma} > 60\,\mathrm{GeV}/c$. Electron contamination and anomalous signals caused by the interaction of heavily ionizing particles with the silicon avalanche photodiodes used for the ECAL readout are removed as described in Ref. [33]. Background from ECAL showers induced by hadrons are rejected using the ratio of HCAL over ECAL energy inside a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.15$ around the photon candidate [33, 34]. Background contributions from fragmentation and decay photons are rejected by imposing the same isolation requirements as in Refs. [26, 33]. The dominant remaining background is ECAL showers initiated by isolated neutral mesons decaying into pairs of photons that, because of their small opening angle, are reconstructed as a single photon. Because the pattern of energy deposited in the ECAL is wider in η for these decay photons, their contribution can be reduced by a factor of $\sim$2 using an upper limit on the "shower shape", which is a measure of the width of the η distribution [33].

The energy of the reconstructed photons is corrected to account for the effects of the material in front of the ECAL and for incomplete containment of the shower energy in the ECAL crystals [35]. An additional correction is applied in PbPb collisions to account for the contribution of the underlying event (UE). The corrections are obtained from photon events simulated using the CUETP8M1 tune [36] of the PYTHIA 8.212 [37] Monte Carlo (MC) event generator. The effect of the PbPb UE is modeled by embedding the PYTHIA output in events generated using HYDJET 1.9 [38]. The size of the resulting energy correction for isolated photons varies from 0 to 10%, depending on p_{T}^{γ} and the centrality of the collision.

The particle-flow (PF) algorithm [39] is used for the jet reconstruction with the anti-k_{T} algorithm provided in the FASTJET framework [40, 41] with a distance parameter $R = 0.3$ chosen to minimize the effects of UE fluctuations. In order to subtract the UE background in PbPb collisions, an iterative algorithm [42] is employed [20, 25, 43]. In pp collisions, where the UE level is negligible, jets are reconstructed without UE subtraction. The jet energy corrections are derived from simulation, separately for pp and PbPb, and are confirmed via energy-balance methods applied to dijet and photon+jet events in pp data [44]. Jets with $|\eta^{\mathrm{jet}}| < 1.6$ and corrected $p_{\mathrm{T}}^{\mathrm{jet}} > 30\,\mathrm{GeV}/c$ are selected. In order to compare the PbPb and pp results, the jet energy and ϕ^{jet} in pp events are smeared to match the jet energy and azimuthal angle resolution in each of the PbPb centrality intervals in which the comparison is made [26]. To match the 0–10% PbPb data, the energy resolutions of pp jets with $p_{\mathrm{T}}^{\mathrm{jet}} = 30(90)\,\mathrm{GeV}/c$ changes from 18% (12%) to 35% (17%), while the change in angular resolution is negligible (<2.2%).

In each event, photon+jet pairs are formed by associating the highest-p_{T}^{γ} isolated photon candidate with all jets that pass the jet selection criteria. An azimuthal separation of $\Delta\phi_{j\gamma} = |\phi^{\mathrm{jet}} - \phi^{\gamma}| > 7\pi/8$ is applied to the photon+jet pairs to suppress contributions from background jets (jets not originating from the same hard scattering as the photon) and photon+multijet events (jets originating from an early splitting of the original parton). The tracks used in the measurement of the fragmentation function have $p_{\mathrm{T}}^{\mathrm{trk}} > 1\,\mathrm{GeV}/c$ and must fall within a cone of radius $\Delta R = 0.3$ around the jet direction. These selection criteria, as well as the corrections for tracking efficiency, detector acceptance, and misreconstruction rate, are the same as in Ref. [32] for both pp and PbPb data.

The selected charged-particle tracks (N^{trk}) are used in conjunction with the selected photon+jet pairs to determine the fragmentation functions, $(1/N^{\mathrm{jet}})\,(\mathrm{d}N^{\mathrm{trk}}/\mathrm{d}\xi^{\mathrm{jet}})$ and $(1/N^{\mathrm{jet}})\,(\mathrm{d}N^{\mathrm{trk}}/\mathrm{d}\xi_{\mathrm{T}}^{\gamma})$, where N^{jet} represents the total number of photon+jet pairs. To isolate the contribution of photons, jets, and charged particles that are produced in the same hard scattering in PbPb collisions, several combinatorial backgrounds are subtracted: tracks from the UE that fall within the cone around the selected jet, misidentified jets resulting from UE fluctuations, and jets not produced in the same hard parton-parton scatterings as the photon. The shape and magnitude of these contributions to the ξ^{jet} and $\xi_{\mathrm{T}}^{\gamma}$ distributions are estimated from data with an event mixing procedure, in which either the isolated photon or the jet is combined with jets and tracks found in events chosen randomly from a minimum-bias (MB) PbPb dataset with similar event characteristics (centrality, interaction vertex position, and event plane angle). The background contribution from UE tracks is estimated by correlating each selected jet with tracks from MB events. The backgrounds from jets produced by UE fluctuations or a different parton-parton scattering are estimated as in Refs. [25, 26]. The normalizations of these combinatorial background fragmentation functions are given by the number of MB events used, and the normalized distributions are subtracted from those for tracks and photon+jet pairs in the same event.

The final correction accounts for the photon purity, defined to be the fraction of non-decay photons within the collection of isolated photon candidates that pass the shower shape requirement. This fraction is extracted from the data using a template fit to the shower shape distribution [25, 26]. The shape of the fragmentation functions from decay photons is estimated by repeating the analysis selecting photons with wider shower shapes. The purity values found from the shower shape fits are used to adjust the magnitude of this background contribution.

Several sources of systematic uncertainty are considered, including the photon purity, photon energy scale, photon isolation, electron contamination, jet energy scale, jet energy resolution, tracking efficiency, and UE background. The total uncertainty is the sum in quadrature of the individual uncertainties. The quoted systematic uncertainties are an average over all ξ^{jet} and ξ_{T}^{γ} bins and, in the case of the PbPb results, are quoted only for events with 0–10% centrality. To evaluate the systematic uncertainties related to the isolated photons, the same procedures as in Ref. [26] are applied. The uncertainty in the photon purity estimation is evaluated by varying the components of the shower shape template, as in Ref. [25]. The maximum variations with respect to the nominal case are propagated as systematic uncertainties, amounting to 3.2 (5.7)% for the 0–10% most central PbPb events, and 0.4 (0.4)% for the pp results, for ξ^{jet} (ξ_{T}^{γ}). In the following, the uncertainties will continue to be quoted for central PbPb first, then for pp. The total systematic uncertainties resulting from the experimental criteria for an isolated photon are 0.8 (1.3)% and 0.8 (0.7)% for ξ^{jet} (ξ_{T}^{γ}). The residual data-to-simulation photon energy scale difference after applying the photon energy corrections is also quoted as a systematic uncertainty of 1.4 (0.8)% and <0.1% for ξ^{jet} (ξ_{T}^{γ}). The level of electron contamination in the samples before applying the electron rejection criteria is 14% and reduces to roughly 5% after the rejection procedure. An uncertainty is evaluated by repeating the analysis without applying the electron rejection criteria, and scaling down the difference in the ξ observables to the remaining electron level of contamination after applying the electron rejection, giving 0.5 (0.4)% and 0.1 (0.1)% for ξ^{jet} (ξ_{T}^{γ}). The uncertainties related to the jet energy resolution and jet energy scale are evaluated as in Ref. [26]. When propagated, the uncertainty related to the jet energy scale amounts to 9.6 (7.4)% and 2.8 (0.6)% for ξ^{jet} (ξ_{T}^{γ}), while the energy resolution gives uncertainties of 2.9 (1.2)% and 1.0 (0.6)%. A systematic uncertainty is assigned to account for long-range η correlations [22] that contribute to the UE. It is estimated by constructing the observables using tracks lying within the same azimuthal angle as the jet, but separated by a large pseudorapidity interval, $1.5 < \Delta\eta < 2.4$. The uncertainty is found to be 4.2 (3.3)% and 1.7 (1.5)% for ξ^{jet} (ξ_{T}^{γ}). The uncertainty related to the tracking inefficiency is estimated as the difference in the track reconstruction efficiency between data and simulation, as in Ref. [32]. It is 5 (4)% for PbPb, pp) data, for both ξ^{jet} and ξ_{T}^{γ}, and is constant as a function of the track p_{T} and event centrality.

For the PbPb results only, two additional sources of systematic uncertainties are considered. One accounts for possible inaccuracies in the background subtraction method. This effect is estimated using an alternative background subtraction procedure (the so-called η-reflection method [17]), which has different sensitivities to various background sources. The observed difference of 3.4% for both ξ^{jet} and ξ_{T}^{γ} with respect to the nominal method is assigned as the uncertainty. The second uncertainty accounts for differences in the jet energy response due to ξ^{jet} and ξ_{T}^{γ} variances in the jet fragmentation pattern, as studied in simulation [26]. The observed differences of 11% for $\xi^{\text{jet}} < 1$ and 4.3 (7.0)% for ξ^{jet} (ξ_{T}^{γ}) > 2.5 are propagated as uncertainties in the corresponding ξ^{jet} and ξ_{T}^{γ} regions for the PbPb results, while there are no significant differences in other ξ^{jet} and ξ_{T}^{γ} bins.

Figure 1 shows the photon-tagged fragmentation functions as a function of ξ^{jet} for both PbPb and pp collisions, together with the ratio of the PbPb to pp results. The ξ^{jet} distributions in PbPb collisions represent the fragmentation pattern of jets that may have lost energy through interactions with the medium, while those for pp stand for unquenched jets. Because of this possibility of quenching, the collections of reconstructed jets in PbPb and pp collisions do not necessarily have the same $p_{\text{T}}^{\text{jet}}$ spectrum, even though the samples are selected based on photon energy. The ξ^{jet} distributions for 50–100% centrality PbPb collisions are consistent with those in pp collisions. In more central collisions, an enhancement of the fragmentation function in PbPb collisions with respect to the reference pp data is observed for $\xi^{\text{jet}} > 2.5$ (corresponding to $p_{\text{T}}^{\text{trk}} \lesssim 2.5\,\text{GeV}/c$ for $p_{\text{T}}^{\text{jet}} = 30\,\text{GeV}/c$ and $\Delta R = 0$ between the track and the jet), indicating that there is a small excess of soft particles near the jet. Additionally, a slight suppression of the fragmentation function in the region $0.5 < \xi^{\text{jet}} < 2.5$ (corresponding to $18 \gtrsim p_{\text{T}}^{\text{trk}} \gtrsim 2.5\,\text{GeV}/c$

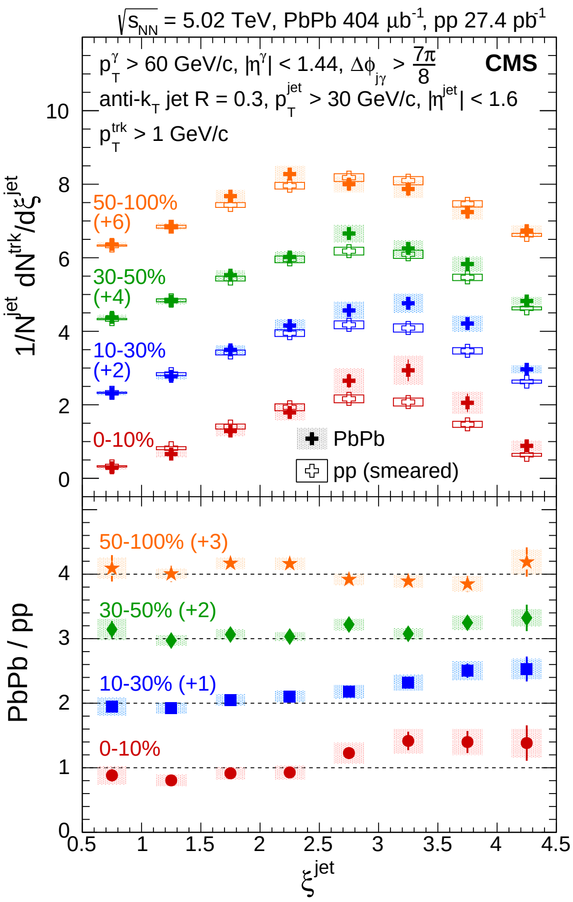

Figure 1: Top: The centrality dependence of the ξ^{jet} distribution for jets associated with an isolated photon for PbPb (full crosses) and pp (open crosses) collisions. The pp results are smeared appropriately for each PbPb centrality bin, and data for each centrality bin are shifted vertically as indicated, for clarity. Bottom: The ratios of the PbPb over smeared pp distributions. The vertical bars through the points represent statistical uncertainties, while the colored boxes indicate systematic uncertainties.

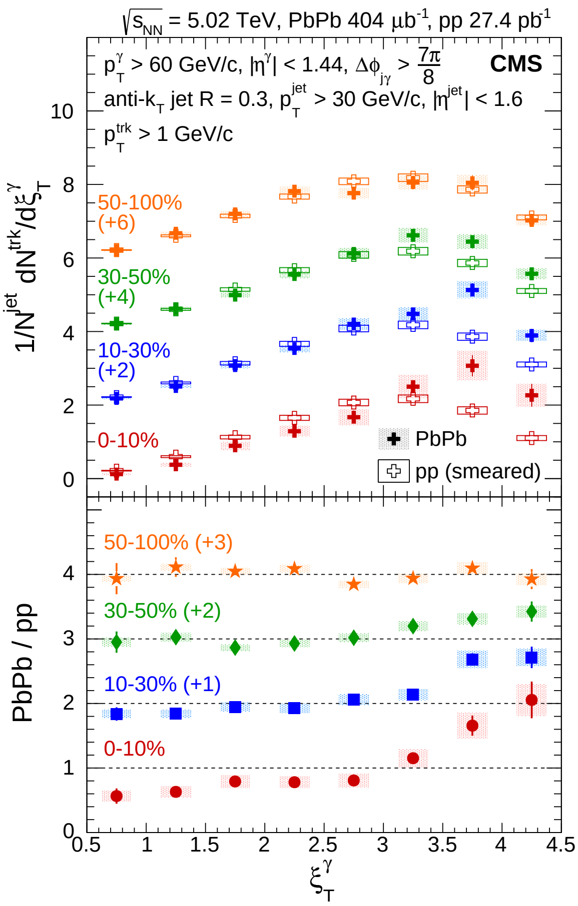

Figure 2: Top: The centrality dependence of the ξ_T^γ distribution for jets associated with an isolated photon for PbPb (full crosses) and pp (open crosses) collisions. The pp results are smeared appropriately for each PbPb centrality bin, and data for each centrality bin are shifted vertically as indicated, for clarity. Bottom: The ratios of the PbPb over smeared pp distributions. The vertical bars through the points represent statistical uncertainties, while the colored boxes indicate systematic uncertainties.

for $p_T^{jet} = 30\,\text{GeV}/c$ and $\Delta R = 0$) is also observed in the most central PbPb collisions.

Figure 2 shows the photon-tagged fragmentation functions as a function of ξ_T^γ for PbPb and pp collisions, as well as their ratio. As for ξ^{jet}, the ξ_T^γ distributions for peripheral PbPb events are consistent with those in pp data. An enhancement is observed in the PbPb data relative to pp data in the $\xi_T^\gamma > 3$ region (corresponding to $p_T^{trk} \lesssim 3\,\text{GeV}/c$ for $p_T^\gamma = 60\,\text{GeV}/c$ and $\Delta\phi = \pi$ between the track and the photon). The magnitude of this enhancement increases as the PbPb collisions become more central, and is more significant than the enhancement observed in the ξ^{jet} distributions. A suppression of the ξ_T^γ distribution for the most central PbPb collisions is also observed for $0.5 < \xi_T^\gamma < 3$ (corresponding to $36 \gtrsim p_T^{trk} \gtrsim 3\,\text{GeV}/c$ for $p_T^\gamma = 60\,\text{GeV}/c$ and $\Delta\phi = \pi$). This pattern of suppression and enhancement is direct evidence for energy loss by high-p_T partons as they traverse the high-density medium created in heavy ion collisions.

The enhancement at large ξ^{jet} and ξ_T^γ, together with the suppression at lower values, indicates that the showers of partons that emerged from the medium contain more particles with lower energy in PbPb collisions. The enhancements and suppressions of the fragmentation patterns measured using initial parton energy (ξ_T^γ) are observed to be more pronounced than the ones measured using detector level jet energy (ξ^{jet}). Qualitatively, this is not surprising. First, a shift of the distributions to lower values for ξ^{jet} compared to ξ_{T}^{γ} is also observed in the pp results, because of effects such as out-of-cone radiation not being captured in the anti-k_{T} $R = 0.3$ jet area. Additionally, in PbPb collisions a similar shift happens if the jet is quenched: the jet momentum is lower than that of the parton, resulting in a shift to lower ξ^{jet}. As a result, the modifications in the ratio PbPb/pp are weakened by quenching in the ξ^{jet} case. Apart from jet quenching, the measurements may also be sensitive to the response of the medium [29, 45, 46]. The enhancement of soft particles (large ξ values) can potentially arise from low-p_{T} particles produced in the interaction of the traversing parton with the medium. Events selected by a photon trigger, which ensures that the initial parton p_{T} spectra are the same for pp and PbPb, will allow testing the theoretical modelling of both the parton shower modification in the medium and the medium response to the passage of that parton.

In summary, the fragmentation functions of jets associated with isolated photons are measured for the first time in pp and PbPb data, using CMS samples collected at $\sqrt{s_{_{\text{NN}}}} = 5.02\,\text{TeV}$. Fragmentation patterns as functions of $\xi^{\text{jet}} = \ln\left[|\vec{p}^{\,\text{jet}}|^2/(\vec{p}^{\,\text{trk}}\cdot\vec{p}^{\,\text{jet}})\right]$ and $\xi_{\text{T}}^{\gamma} = \ln\left[-|\vec{p}_{\text{T}}^{\,\gamma}|^2/(\vec{p}_{\text{T}}^{\,\text{trk}}\cdot\vec{p}_{\text{T}}^{\,\gamma})\right]$ are constructed using charged particles with $p_{\text{T}}^{\text{trk}} > 1\,\text{GeV}/c$, for jets with $p_{\text{T}}^{\text{jet}} > 30\,\text{GeV}/c$ tagged by an isolated photon with $p_{\text{T}}^{\gamma} > 60\,\text{GeV}/c$. When compared to the results found using pp data, the ξ^{jet} and ξ_{T}^{γ} distributions in central PbPb collisions show an excess of low-p_{T} particles and a depletion of high-p_{T} particles inside the jet. This observation is more apparent in the ξ_{T}^{γ} distributions, where the photon-based selection allows for tagging the properties of the initial parton before quenching occurs. This measurement shows for the first time the in-medium parton shower modifications for events with well-defined initial parton kinematics, and constitutes a clear reference for testing theoretical models of the parton's passage through the QGP.

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