



# Comparison of fragmentation functions for light-quark- and gluon-dominated jets from $pp$ and Pb+Pb collisions in ATLAS

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Charged-particle fragmentation functions for jets azimuthally balanced by a high-transverse-momentum, prompt, isolated photon are measured in  $25 \text{ pb}^{-1}$  of  $pp$  and  $0.49 \text{ nb}^{-1}$  of Pb+Pb collision data at 5.02 TeV per nucleon pair recorded with the ATLAS detector at the Large Hadron Collider. The measurements are compared to predictions of Monte Carlo generators and to measurements of inclusively selected jets. In  $pp$  collisions, a different jet fragmentation function in photon-tagged events from that in inclusive jet events arises from the difference in fragmentation between light quarks and gluons. The ratios of the fragmentation functions in Pb+Pb events to that in  $pp$  events are used to explore the parton color-charge dependence of jet quenching in the hot medium. In relatively peripheral collisions, fragmentation functions exhibit a similar modification pattern for photon-tagged and inclusive jets. However, photon-tagged jets are observed to have larger modifications than inclusive jets in central Pb+Pb events.

Ultrarelativistic nucleus–nucleus collisions create a quark–gluon plasma, a hot, dense, and long-lived system of deconfined quarks and gluons. The high density of unscreened color charges causes hard-scattered partons with large transverse momentum ( $p_T$ ) to lose energy as they traverse the medium, a phenomenon referred to as jet quenching. In lead–lead (Pb+Pb) collisions at the Large Hadron Collider (LHC), jet production rates at fixed  $p_T$  are suppressed relative to proton–proton ( $pp$ ) collisions [1–4]. Since the parton shower develops inside the quark–gluon plasma, the momentum distributions of hadrons in the quenched jet are also modified. Measurements of the jet fragmentation function (FF) for inclusively produced jets in Pb+Pb collisions [5–7] exhibit differences from  $pp$  collisions. In these measurements, jets are selected by their final-state  $p_T$ , i.e. after the effects of quenching, which may result in a bias towards jets that have suffered only modest modifications and complicates interpretation of the data [8, 9]. Alternatively, the initial parton  $p_T$  can be tagged with a particle unaffected by the medium, such as a photon ( $\gamma$ ) [10–12]. The photon approximately balances the parton  $p_T$  before quenching and thus selects populations of jets in  $pp$  and Pb+Pb collisions with identical initial conditions. A jet recoiling against a prompt photon is more likely to be initiated by the showering of a light quark, whereas inclusive jets are mostly initiated by gluons. Thus  $\gamma$ -tagged jets can provide information about how energy loss depends on the color charge of the initiating parton. Finally, the photon selection equally samples all geometric production points, whereas the inclusive selection may be biased towards jets which have lost less energy or were produced near the surface of the medium [13–15].

Many theoretical models of jet quenching have highlighted the value of  $\gamma$ -tagged jet measurements [16–18], inviting systematic comparisons of these with inclusive jet measurements and with theoretical predictions for inclusive and  $\gamma$ -tagged jets. The comparisons are best performed if the measurements are fully corrected for detector effects and presented at particle level. This Letter presents such a measurement of the FF in high- $p_T$  jets azimuthally balanced by a prompt, isolated photon in  $pp$  and Pb+Pb collisions at a center-of-mass energy of 5.02 TeV per nucleon pair, using data samples with integrated luminosities of  $25 \text{ pb}^{-1}$  and  $0.49 \text{ nb}^{-1}$ , respectively. Photon–hadron  $p_T$  correlations in gold–gold collisions were measured at the Relativistic Heavy Ion Collider [19, 20]. A measurement of the  $\gamma$ -tagged jet FF at the LHC compared the FF at detector level with theoretical calculations that parameterize the detector smearing effects [21].

Following previous measurements in ATLAS [5, 6], the FF for a jet to contain a charged particle with a given  $p_T$ ,  $\eta$  and  $\phi$  [22] is expressed as  $D(p_T) = (1/N_{\text{jet}})(dN_{\text{ch}}(p_T)/dp_T)$  or  $D(z) = (1/N_{\text{jet}})(dN_{\text{ch}}(z)/dz)$  where  $N_{\text{jet}}$  is the total number of jets,  $N_{\text{ch}}$  is the number of charged particles associated with a jet, and the longitudinal momentum fraction,  $z$ , is defined as  $p_T \cos(\Delta R) / p_T^{\text{jet}}$ ,  $\Delta R = ((\eta^{\text{jet}} - \eta^{\text{part}})^2 + (\phi^{\text{jet}} - \phi^{\text{part}})^2)^{1/2}$ . Only particles with  $\Delta R < 0.4$  are considered.

The principal components of the ATLAS detector [23, 24] used in this measurement are the inner tracking detector, electromagnetic and hadronic calorimeters, and an online trigger system. The inner detector is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range  $|\eta| < 2.5$ . It consists of a high-granularity silicon pixel detector, a silicon microstrip tracker, and a transition radiation tracker. In the region  $|\eta| < 3.2$ , electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) sections divided into three layers in depth. Hadronic calorimetry is provided by a steel/scintillator-tile calorimeter, segmented into three barrel structures within  $|\eta| < 1.7$ , and two copper/LAr hadronic endcap calorimeters, covering the region  $1.5 < |\eta| < 3.2$ . The forward calorimeter is composed of copper/LAr and tungsten/LAr modules and extends the coverage to  $|\eta| = 4.9$ . During data-taking, events with a high transverse energy ( $E_T^\gamma$ ) photon are selected using a two-level trigger system based on energy deposition in the electromagnetic calorimeter [25].

Events in Pb+Pb and  $pp$  data with photon candidates are selected by the trigger and are required to contain

a vertex reconstructed from inner-detector tracks. Two centrality classes of Pb+Pb events are defined using the total transverse energy measured in the forward calorimeter,  $\Sigma E_T$ . Central events, which are those with a large nuclear overlap, are defined as those with  $\Sigma E_T$  values in the highest 30% percentile (0–30%) of all Pb+Pb events. Peripheral events have a  $\Sigma E_T$  value in the 30–80% percentile and a smaller nuclear overlap region. The mean number of nucleon–nucleon collisions in these events is  $1080 \pm 70$  and  $135 \pm 9$ , respectively, evaluated using the Glauber model [26].

Monte Carlo (MC) simulations are used to study the performance of the detector and provide comparisons with data. The main simulation sample was generated with the PYTHIA 8.186 [27] generator, with the NNPDF23LO parton distribution function (PDF) set [28], and parameters tuned to reproduce  $pp$  data (“A14” tune) [29]. Events were passed through a full GEANT4 simulation of the detector [30, 31], and reconstructed in the same way as the data. Two million  $pp$  events were generated, and an additional sample of eight million events were overlaid with Pb+Pb collision data to describe the effects of the underlying event (UE). Additional samples of SHERPA 2.1.1 [32] events using the CT10 PDF [33] and HERWIG 7 [34] events with the MMHT H7UE tune and leading-order PDF set [35], which have a different description of  $\gamma$ +multijet topologies, quark/gluon jet composition and hadronization, are used to study systematic uncertainties. At particle level, jets and photon isolation energies are defined using stable particles [36].

Photons are measured following a procedure used previously in Pb+Pb collisions [10, 11], which includes an event-by-event estimation and subtraction of the UE contribution to the energy deposited in each calorimeter cell [37]. Photon candidates are reconstructed from clusters of energy in the calorimeter and identified using requirements on the properties of their showers [38]. Events with a prompt, isolated photon with  $E_T^\gamma$  in the range 80 GeV to 126 GeV (chosen to match the range used in Ref. [11]) and absolute pseudorapidity smaller than 2.37, excluding the region 1.37–1.56 which has more inactive material, are selected for analysis. The isolation energy,  $E_T^{\text{iso}}$ , is determined from the sum of the transverse energy in cells inside a cone size of  $\Delta R = 0.3$  centered on the photon, after subtracting the photon’s contribution to this quantity, and is required to be  $E_T^{\text{iso}} < 3$  GeV ( $< 10$  GeV) in  $pp$  (Pb+Pb) collisions.

The combined photon reconstruction and selection efficiencies in  $pp$ , peripheral and central Pb+Pb events are  $\approx 90\%$ ,  $85\%$  and  $65\text{--}70\%$ , and approximately 10 000, 1800 and 6800 photons are selected, respectively. The selected sample contains backgrounds from hadrons and non-isolated photons, called fake photons, that must be removed statistically. The background contribution is determined using a double-sideband approach [10, 39, 40] in which the identification and isolation requirements are inverted to select background-enriched samples. These are used to estimate the purity of the selection, which is  $\approx 80\text{--}94\%$  depending on the collision system.

Jets are measured following the procedure used previously in  $pp$  and Pb+Pb collisions [1, 37, 41]. The anti- $k_r$  algorithm [42] with  $R = 0.4$  is applied to  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$  calorimeter towers. An iterative procedure is used to obtain an event-by-event estimate of the average  $\eta$ -dependent UE energy density, while excluding jets from that estimate. The jet kinematics are corrected for this background and for the detector response using an  $\eta$ - and  $p_T$ -dependent calibration derived from simulation and additional small corrections from *in situ* studies [43, 44]. Jets are required to have  $63 \text{ GeV} < p_T^{\text{jet}} < 144 \text{ GeV}$  and  $|\eta^{\text{jet}}| < 2.1$ , and be azimuthally balanced with the photon, with separation  $|\Delta\phi| > 7\pi/8$ . All  $\gamma$ -jet pairs meeting the criteria are included in the analysis, but the requirements mainly select topologies with a single high- $p_T$  balancing jet [11, 45]. In simulation, the  $p_T^{\text{jet}}$  scale is within 1% of unity, while the resolution at  $p_T^{\text{jet}} = 63 \text{ GeV}$  is 21% in central Pb+Pb events, 12% in  $pp$  events, and improves with increasing  $p_T^{\text{jet}}$ . Among these jets, 73–83% are quark jets depending on the generator. The jet flavor is defined by the highest- $p_T$  parton within  $\Delta R < 0.4$  of the jet [46].

The jet yield  $N_{\text{jet}}$  is corrected for the combinatorial pairings of the photon with a jet not associated with the photon-producing hard scattering, and for the contribution of jets paired with fake photons. The first is evaluated in the data-overlay simulation and subtracted on a per-photon basis. The second is subtracted by measuring this yield in the background-dominated sidebands described above and scaling it to match the determined impurity. After these background corrections, the yields are corrected for the effects of bin migration, which are small due to the large  $p_{\text{T}}^{\text{jet}}$  range of the measurement relative to the resolution.

The FFs  $D(z)$  and  $D(p_{\text{T}})$  are measured using the differential yield of charged particles with  $p_{\text{T}} > 1$  GeV,  $N_{\text{ch}}$ , within  $\gamma$ -balancing jets, divided by the total jet yield  $N_{\text{jet}}$ . This approach was used in previous measurements [5, 47] and is needed, together with the unfolding procedure described below, to account for the simultaneous bin migration in the jet and particle kinematic variables, which is correlated through the fragmentation of each jet. Charged-particle tracks are reconstructed from hits in the inner detector using an algorithm that is optimized for the high-occupancy conditions in Pb+Pb collisions [2, 6]. They are required to meet several criteria including a minimum number of hits, the presence of hits predicted by the algorithm, and a small distance-of-closest approach to the vertex.

The raw charged-particle yield  $N_{\text{ch}}(z)$  or  $N_{\text{ch}}(p_{\text{T}})$  is initially determined by measuring the two-dimensional  $(p_{\text{T}}^{\text{jet}}, p_{\text{T}})$  or  $(p_{\text{T}}^{\text{jet}}, z)$  distribution. Each entry is corrected for the tracking efficiency at the given  $p_{\text{T}}$  and  $\eta$ , which varies from 60% to 80% depending on occupancy and pseudorapidity. Three background contributions are estimated and are subtracted statistically: (1) UE particles and misreconstructed or secondary tracks, estimated using the rate of tracks not matched to a generated particle in the data-overlay simulation, (2) charged particles in jets not produced in the same hard process as the photon, also estimated in simulation, and (3) the charged-particle yield in jets correlated with fake photons, determined using the sideband approach described above.

The two-dimensional yield is corrected for bin migration along both axes using a Bayesian unfolding procedure [48, 49] as in previous dijet and  $\gamma$ -jet measurements [11, 50]. The simulated  $p_{\text{T}}^{\text{jet}}$  distributions are reweighted to match those in data, and the number of unfolding iterations is chosen to minimize the combination of the total statistical uncertainty and residual sensitivity to the assumed prior distribution. Due to the large size of the kinematic bins relative to the experimental resolution, the unfolding changes the yields by typically 5% (10%) in  $pp$  (Pb+Pb) collisions. This procedure is further validated with a test performed by dividing the simulated events into statistically independent halves.

The measurement and correction of the  $p_{\text{T}}^{\text{jet}}$  is affected by uncertainties in the jet energy scale and resolution, which are evaluated following the procedure [44] used in previous ATLAS measurements of heavy-ion collisions. The fake photon background subtraction is sensitive to the determination of the photon purity, which is evaluated as in Ref. [11]. Uncertainties related to the charged-particle yield measurement are described in detail in Ref. [6]. The sensitivity to the unfolding and physics modeling is determined through a pseudoexperiment resampling of the response matrices, varying the prior distributions used in the unfolding, and using the SHERPA simulation instead of PYTHIA 8 to perform the unfolding. For uncertainty sources with up/down variations, the changes in the results are averaged to make a symmetric uncertainty. For those with a single variation, an identical uncertainty in the opposite direction is assigned.

Many of these variations change  $N_{\text{jet}}$  and  $N_{\text{ch}}$  in a significant but highly correlated way, with the result that the FFs are less sensitive to them. Furthermore, most uncertainties are correlated between the  $pp$  and Pb+Pb systems, and these partially cancel out when they are evaluated for the ratios of FFs. The total uncertainties in the  $D(z)$  and  $D(p_{\text{T}})$  distributions and their ratios are typically 5% at moderate  $z$  or  $p_{\text{T}}$  values. At low  $p_{\text{T}}$  or  $z$ , the track-related uncertainties rise sharply due to the high occupancies in Pb+Pb

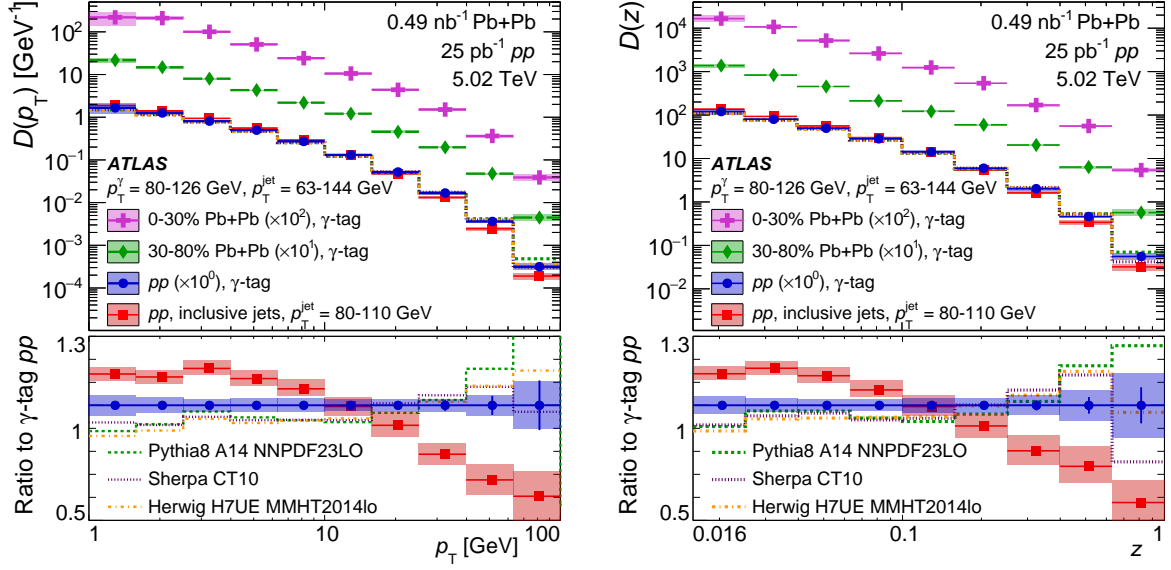


Figure 1: Fragmentation function (FF) in  $\gamma$ -tagged jets in  $pp$  events, and in central and peripheral Pb+Pb events, as a function of charged-particle transverse momentum  $p_T$  (left) and longitudinal momentum fraction  $z$  (right). The  $pp$  results are compared with the analogous distribution in MC generators (dashed lines) and with the FF for inclusive jets in a similar  $p_T^{\text{jet}}$  range (red squares). The shaded bands correspond to the total systematic uncertainties in the data. The bottom panels show the ratios of MC distributions and inclusive jet data, in  $pp$  collisions, to the  $\gamma$ -tagged jet data, with these data plotted at unity.

events. At large  $p_T$  or  $z$ , where the FF is very steeply falling, the uncertainties related to the choice of prior and physics models dominate.

Figure 1 shows the corrected  $D(p_T)$  and  $D(z)$  distributions for jets azimuthally balanced by a high- $p_T$  photon in  $pp$  events, and in central and peripheral Pb+Pb events. The  $\gamma$ -tagged jet FF in  $pp$  collisions is observed to be harder than the FF for inclusive jets at the same collision energy with  $p_T^{\text{jet}}$  in the range 80–110 GeV, coinciding with the peak of the  $\gamma$ -tagged  $p_T^{\text{jet}}$  distribution [47]. This is consistent with the two samples having different quark jet fractions, and with expectations from, for example, data from the Large Electron–Positron collider [51–53], where harder FFs for quark jets were observed compared with those for gluon jets. The  $pp$  data are also compared with generator distributions, which are typically compatible with the data at low to moderate values of  $z$  or  $p_T$  within uncertainties.

The left and central panels of Figure 2 summarize ratios of the  $\gamma$ -tagged FFs in Pb+Pb events to those in  $pp$  events, and compares them to those for inclusively selected jets with  $p_T^{\text{jet}} = 100$ –126 GeV measured in 2.76 TeV Pb+Pb and  $pp$  collisions [5]. Although the collision energy and  $p_T^{\text{jet}}$  range are slightly different than that for the  $\gamma$ -tagged jet data, inclusive jet FFs in this region have been observed to be compatible at the two energies and in nearby  $p_T^{\text{jet}}$  ranges within uncertainties [6]. Since the inclusive-jet measurement uses different centrality ranges, the centrality range corresponding to the top of that in the  $\gamma$ -tagged measurement is chosen (i.e. 0–10% for 0–30% in the  $\gamma$ -tagged case, and 30–40% for 30–80%). In peripheral collisions, the modification pattern is quantitatively similar for both sets of jets, featuring a depletion at moderate  $z$  or  $p_T$ , and an enhancement at very low and very high  $z$  or  $p_T$ . However, in central collisions,  $\gamma$ -tagged jets show an additional relative suppression at high  $z$  or  $p_T$  and a counterbalancing enhancement at low  $z$  or  $p_T$ . In addition, the minimum value of the Pb+Pb-to- $pp$  ratio for  $\gamma$ -tagged jets is shifted to larger  $z$  or  $p_T$

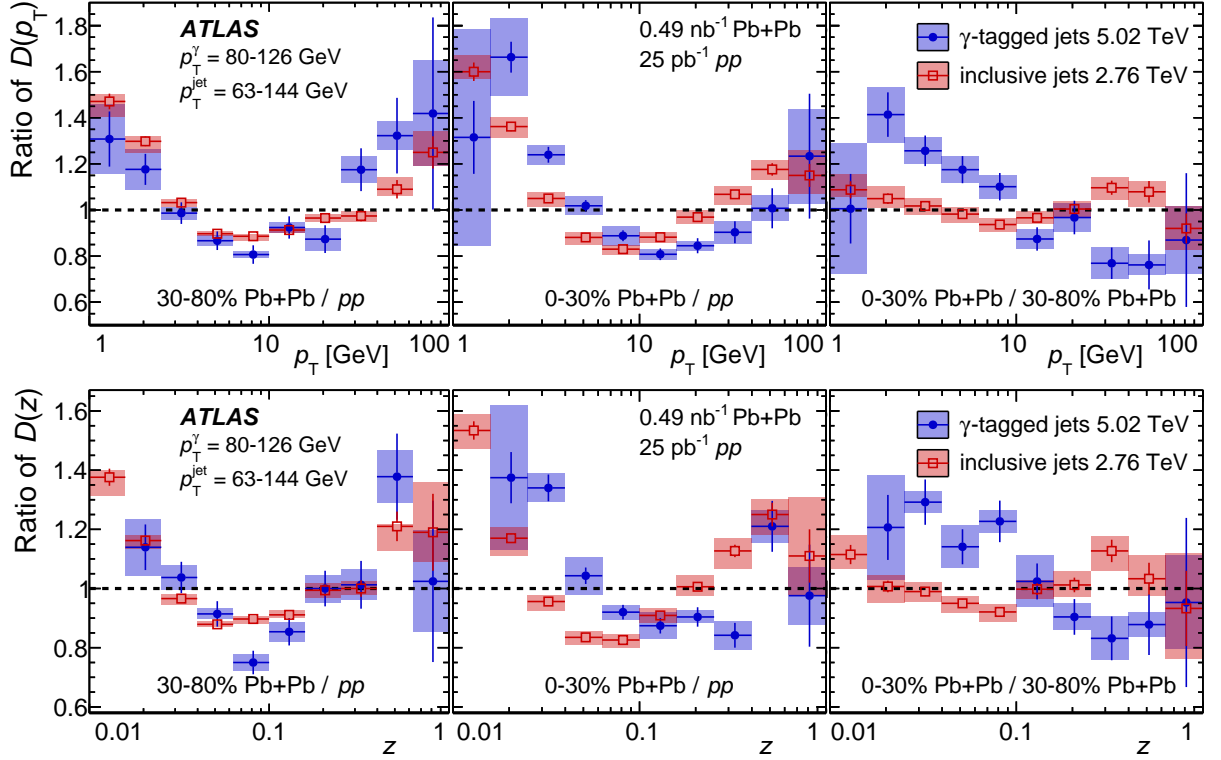


Figure 2: Ratio of the fragmentation function in jets azimuthally balanced by a high- $p_T$  photon: 30–80% Pb+Pb collisions to  $pp$  collisions (left panels); 0–30% Pb+Pb collisions to  $pp$  collisions (central panels); and 0–30% to 30–80% Pb+Pb collisions (right panels). Results are shown as a function of charged-particle transverse momentum  $p_T$  (top panels) or longitudinal momentum fraction  $z$  (bottom panels), for  $\gamma$ -tagged jets (this measurement, full markers) and for inclusive jets in 2.76 TeV Pb+Pb collisions [5, 54] (see text, open markers). The centrality selections for the inclusive jet data are 0–10% (left), 30–40% (central), and (0–10%)/(30–40%) (right). Hatched bands and vertical bars show for each measurement the total systematic and statistical uncertainties, respectively.

values.

To further explore the relative change in the FF between Pb+Pb event classes, the ratio between central and peripheral collisions is shown in the right panels of Figure 2. For  $\gamma$ -tagged jets, the ratio is consistent with a decreasing linear function of  $\log(z)$  or  $\log(p_T)$ , crossing unity at  $z \approx 0.1$  or  $p_T \approx 10$  GeV. It is inconsistent with the analogous ratio for inclusive jets, which is closer to unity. Thus, the data indicate that, in central collisions, jets in  $\gamma$ -tagged events are modified in a different way than inclusively selected jets.

In Figure 3, the data in central events are compared with the results of theoretical calculations at particle level. In the left panel, these include: (1) a perturbative calculation within the framework of soft-collinear effective field theory with Glauber gluons (SCET<sub>G</sub>) in the soft-gluon-emission (energy-loss) limit, with jet-medium coupling  $g = 2.1 \pm 0.1$  [55, 56], (2) the Hybrid Strong/Weak Coupling model [16], which combines initial production using PYTHIA with a parameterization of energy loss derived from holographic methods, including back reaction effects, and (3) the linearized Boltzmann transport (CoLBT-hydro) model [57] of parton propagation through quark–gluon plasma with jet-induced medium-excitation effects. The SCET<sub>G</sub> calculation and the CoLBT-hydro model successfully capture the key features of the  $\gamma$ -tagged jet FF data in the region  $z < 0.5$ . In the right panel, the inclusive and  $\gamma$ -tagged FF ratios in data are



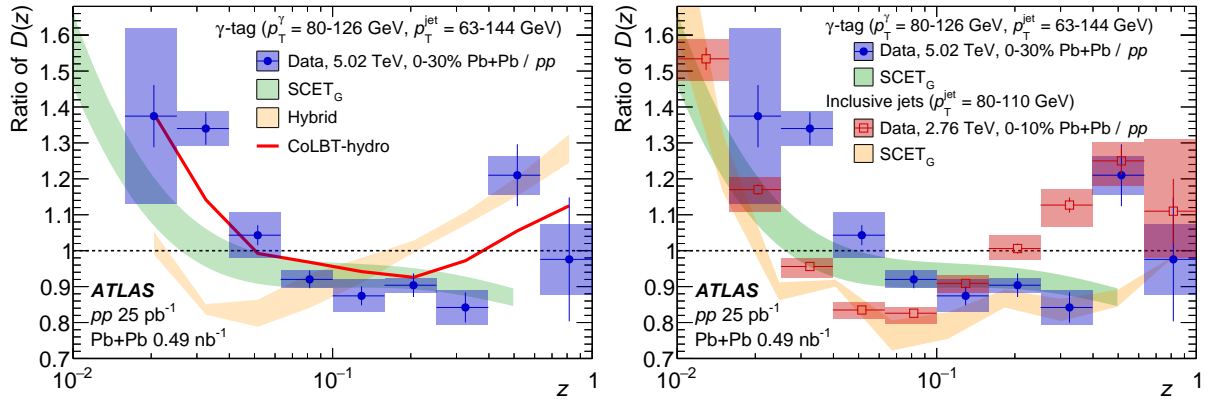


Figure 3: Comparison of the ratio of  $\gamma$ -tagged fragmentation function  $D(z)$  in central Pb+Pb events to  $pp$  events with theoretical calculations (left). The mutual comparison between  $\gamma$ -tagged and inclusive jet  $D(z)$  ratios in data to each of these in the SCET<sub>G</sub> model is shown in the right panel. Shaded rectangles and vertical bars show the total systematic and statistical uncertainties, respectively, in the data.

compared with those in SCET<sub>G</sub>. The  $\gamma$ -tagged FF ratio is larger than the inclusive-jet one in the region  $z < 0.1$  in both data and theory.

In summary, this Letter presents a measurement of the charged-particle fragmentation functions for jets azimuthally balanced by a high- $p_T$  prompt and isolated photon. The measurement is performed using 25  $\text{pb}^{-1}$  of  $pp$  and 0.49  $\text{nb}^{-1}$  of Pb+Pb collision data at 5.02 TeV, with the ATLAS detector at the LHC. The kinematic selections result in events with a single leading jet, a large fraction of which are quark jets. In  $pp$  collisions, the  $\gamma$ -tagged jet fragmentation functions are systematically harder than those for inclusive jets at similar  $p_T^{\text{jet}}$ , consistent with the larger expected fraction of quark jets in  $\gamma$ -tagged events. In 30–80% centrality Pb+Pb events,  $\gamma$ -tagged jets are observed to be modified through interaction with the medium, with an overall pattern consistent with that for inclusive jets. However, jets in  $\gamma$ -tagged events are modified in 0–30% Pb+Pb events in a manner not observed for inclusive jets. The SCET<sub>G</sub> calculation describes this key feature of the data. However, interpreting this observed difference is complicated by the different jet populations in the two cases. In Pb+Pb collisions, the inclusive jet population at fixed  $p_T^{\text{jet}}$  is biased towards jets which have lost the least amount of energy. In a geometric picture, such a survivor bias selects jets produced only near the surface of the medium. This bias is largely avoided for  $\gamma$ -tagged jets, which can be selected based on the photon kinematics. Thus they may include jets that are more quenched on average than inclusively selected jets, including ones which sample particularly large of path lengths.

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