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DOI
10.1103/PhysRevLett.123.042001

Publication date
2019

Document Version
Final published version

Published in
Physical Review Letters

License
CC BY

Link to publication

Citation for published version (APA):
Aaboud, M., & ATLAS Collaboration (2019). Comparison of Fragmentation Functions for Jets Dominated by Light Quarks and Gluons from *pp* and Pb+Pb Collisions in ATLAS. *Physical Review Letters*, *123*(4), Article 042001. https://doi.org/10.1103/PhysRevLett.123.042001

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Comparison of Fragmentation Functions for Jets Dominated by Light Quarks and Gluons from pp and Pb + Pb Collisions in ATLAS

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(Received 28 February 2019; revised manuscript received 21 May 2019; published 22 July 2019)

Charged-particle fragmentation functions for jets azimuthally balanced by a high-transverse-momentum, prompt, isolated photon are measured in 25 pb^{-1} of pp and 0.49 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.

DOI: 10.1103/PhysRevLett.123.042001

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 (γ) [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, γ-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 γ-tagged jet measurements [16–18], inviting systematic comparisons of these with inclusive jet measurements and with theoretical predictions for inclusive and γ-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 pb^{-1} and 0.49 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 γ-tagged jet FF at the LHC compared the FF at detector level with theoretical calculations that parametrize 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, η, and ϕ [22] is expressed as $D(p_T) = (1/N_{\mathrm{jet}})[dN_{\mathrm{ch}}(p_T)/dp_T]$ or $D(z) = (1/N_{\mathrm{jet}})[dN_{\mathrm{ch}}(z)/dz]$ where N_{jet} is the total number of jets, N_{ch} is the number of charged particles associated with a jet, and the longitudinal

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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 end cap high-granularity lead and liquid-argon (LAr) sections divided into three layers in depth. Hadronic calorimetry is provided by a steel and scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper-LAr hadronic end cap 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^γ) 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, $\sum E_T$. Central events, which are those with a large nuclear overlap, are defined as those with $\sum E_T$ values in the highest 30% percentile (0%–30%) of all Pb + Pb events. Peripheral events have a $\sum E_T$ value in the 30%–80% percentile and a smaller nuclear overlap region. The mean number of nucleon-nucleon collisions in these events is 1080 ± 70 and 135 ± 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 γ+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^γ in the range 80 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^{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 ≈90%, 85%, and 65%–70%, and approximately 10000, 1800, and 6800 photons are selected, respectively. The selected sample contains backgrounds from hadrons and nonisolated 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 ≈80%–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_t 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 η-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 η- and p_T-dependent calibration derived from simulation and additional small corrections from *in situ* studies [43,44]. Jets are required to have 63 GeV $< p_T^{\text{jet}} < 144$ GeV and $|\eta^{\text{jet}}| < 2.1$, and be azimuthally balanced with the photon, with separation $|\Delta\phi| > 7\pi/8$. All γ-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^{jet} scale is within 1% of unity, while the resolution at $p_T^{\text{jet}} = 63$ GeV is 21% in central Pb + Pb events, 12% in pp events, and improves with increasing p_T^{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_{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_T^{jet} range of the measurement relative to the resolution.

The FFs $D(z)$ and $D(p_T)$ are measured using the differential yield of charged particles with $p_T > 1$ GeV, N_{ch}, within γ-balancing jets, divided by the total jet yield N_{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 $N_{\mathrm{ch}}(z)$ or $N_{\mathrm{ch}}(p_T)$ is initially determined by measuring the two-dimensional $(p_T^{\mathrm{jet}}, p_T)$ or (p_T^{jet}, z) distribution. Each entry is corrected for the tracking efficiency at the given p_T and η, 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 γ-jet measurements [11,50]. The simulated p_T^{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. Because of 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_T^{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 PYTHIA8 to perform the unfolding. For uncertainty sources with up or 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_{jet} and N_{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 $D(p_T)$ distributions and their ratios are typically 5% at moderate z or p_T values. At low p_T or z, the track-related uncertainties rise sharply due to the high occupancies in Pb + Pb 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 γ-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^{jet} in the range of 80–110 GeV, coinciding with the peak of the γ-tagged p_T^{jet} distribution [47]. This is consistent with the two samples having different quark jet fractions, and with expectations from, e.g., 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 Fig. 2 summarize ratios of the γ-tagged FFs in Pb + Pb events to those in pp events, and compares them to those for inclusively selected jets with $p_T^{\mathrm{jet}} = 100$–126 GeV measured in 2.76 TeV Pb + Pb and pp collisions [5]. Although the collision energy and p_T^{jet} range are slightly different than that for the γ-tagged jet data, inclusive jet FFs in this region have been observed to be compatible at the two energies and in nearby p_T^{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 γ-tagged measurement is chosen (i.e., 0%–10% for 0%–30% in the γ-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.

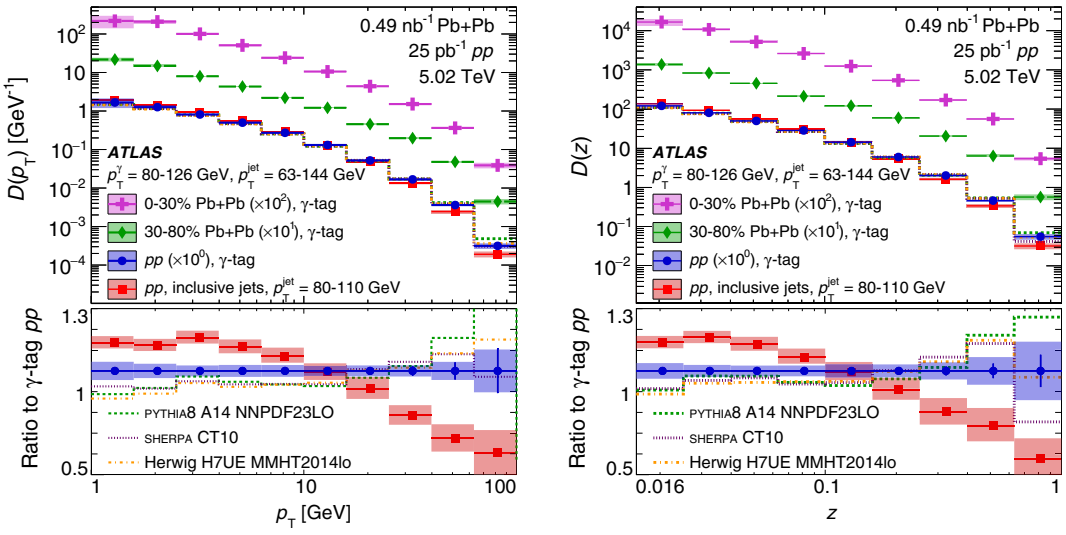

FIG. 1. Fragmentation function (FF) in γ-tagged jets in pp events, and in central and peripheral Pb + Pb events, as a function of charged-particle transverse momentum p_T (left) and longitudinal momentum fraction z (right). The pp results are compared with the analogous distribution in MC generators (dashed lines) and with the FF for inclusive jets in a similar p_T^{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 γ-tagged jet data, with these data plotted at unity.

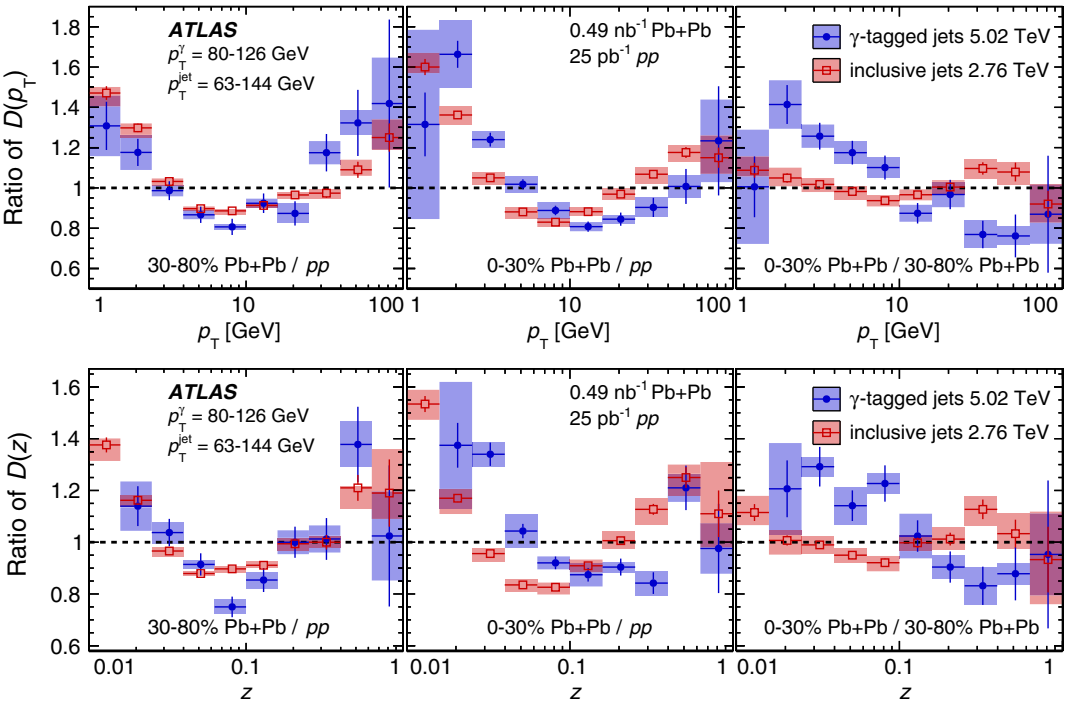

FIG. 2. Ratio of the fragmentation function in jets azimuthally balanced by a high-p_T photon: 30%–80% Pb + Pb collisions to pp collisions (left panels); 0%–30% Pb + Pb collisions to pp collisions (central panels); and 0%–30% to 30%–80% Pb + Pb collisions (right panels). Results are shown as a function of charged-particle transverse momentum p_T (top panels) or longitudinal momentum fraction z (bottom panels), for γ-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.

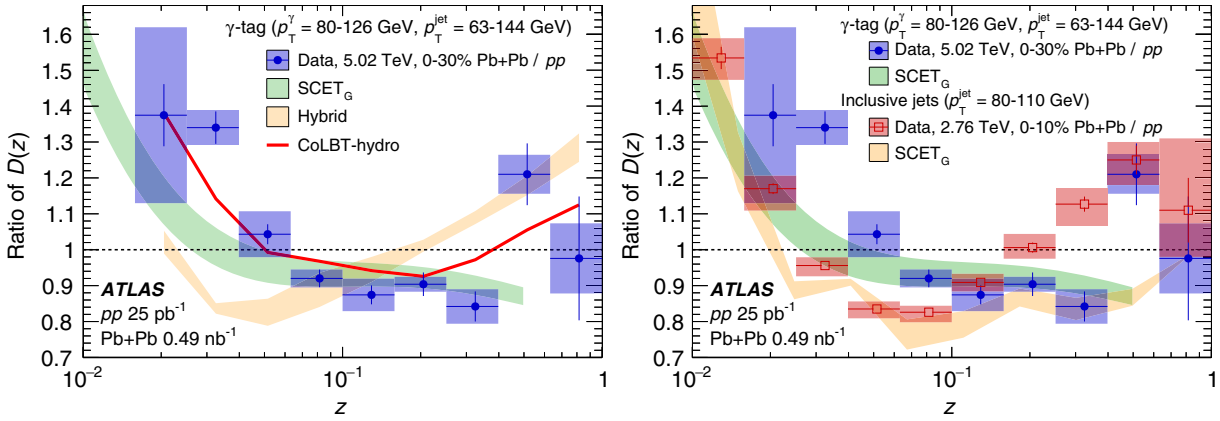

FIG. 3. Comparison of the ratio of γ-tagged fragmentation function $D(z)$ in central Pb + Pb events to pp events with theoretical calculations (left). The mutual comparison between γ-tagged and inclusive jet $D(z)$ ratios in data to each of these in the SCET$_G$ model is shown in the right panel. Shaded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

However, in central collisions, γ-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 γ-tagged jets is shifted to larger z or p_T 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 Fig. 2. For γ-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 γ-tagged events are modified in a different way than inclusively selected jets.

In Fig. 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$_G$) in the soft-gluon-emission (energy-loss) limit, with jet-medium coupling $g = 2.1 \pm 0.1$ [55,56], (2) the hybrid strong and weak coupling model [16], which combines initial production using PYTHIA with a parametrization 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$_G$ calculation and the CoLBT-hydro model successfully capture the key features of the γ-tagged jet FF data in the region $z < 0.5$. In the right panel, the inclusive and γ-tagged FF ratios in data are compared with those in SCET$_G$. The γ-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 pb^{-1} of pp and 0.49 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 γ-tagged jet fragmentation functions are systematically harder than those for inclusive jets at similar p_T^{jet}, consistent with the larger expected fraction of quark jets in γ-tagged events. In 30%–80% centrality Pb + Pb events, γ-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 γ-tagged events are modified in 0%–30% Pb + Pb events in a manner not observed for inclusive jets. The SCET$_G$ 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^{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 γ-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 path lengths.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR, and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG,

Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF, and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, USA. In addition, individual groups and members have received support from BCKDF, CANARIE, CRC, and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d' Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales, and Aristeia Programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya, Spain; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK), and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [58].

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