Strong Constraints on Jet Quenching in Centrality-Dependent $p + \mathrm{Pb}$ Collisions at 5.02 TeV from ATLAS

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Jet quenching is the process of color-charged partons losing energy via interactions with quark-gluon plasma droplets created in heavy-ion collisions. The collective expansion of such droplets is well described by viscous hydrodynamics. Similar evidence of collectivity is consistently observed in smaller collision systems, including pp and $p + \mathrm{Pb}$ collisions. In contrast, while jet quenching is observed in $\mathrm{Pb} + \mathrm{Pb}$ collisions, no evidence has been found in these small systems to date, raising fundamental questions about the nature of the system created in these collisions. The ATLAS experiment at the Large Hadron Collider has measured the yield of charged hadrons correlated with reconstructed jets in 0.36 nb^{-1} of $p + \mathrm{Pb}$ and 3.6 pb^{-1} of pp collisions at 5.02 TeV. The yields of charged hadrons with $p_T^{\mathrm{ch}} > 0.5$ GeV near and opposite in azimuth to jets with $p_T^{\mathrm{jet}} > 30$ or 60 GeV, and the ratios of these yields between $p + \mathrm{Pb}$ and pp collisions, $I_{p\mathrm{Pb}}$, are reported. The collision centrality of $p + \mathrm{Pb}$ events is categorized by the energy deposited by forward neutrons from the struck nucleus. The $I_{p\mathrm{Pb}}$ values are consistent with unity within a few percent for hadrons with $p_T^{\mathrm{ch}} > 4$ GeV at all centralities. These data provide new, strong constraints that preclude almost any parton energy loss in central $p + \mathrm{Pb}$ collisions.

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Over two decades of measurements of relativistic nucleus-nucleus collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have established that a quark-gluon plasma is formed in these collisions and undergoes a collective expansion described by viscous hydrodynamics [1]. High-momentum colored probes, such as quarks and gluons, lose some of their energy as they traverse the plasma and produce a highly modified hadron fragmentation pattern, a process referred to as "jet quenching" [2–4]. On the other hand, colorless photons and Z bosons pass through unscathed [5–10]. Over the past decade, measurements in smaller collision systems, such as pp and $p + \mathrm{Pb}$ at the LHC and $p + \mathrm{Au}$, $d + \mathrm{Au}$, and $^3\mathrm{He} + \mathrm{Au}$ at RHIC display similar experimental evidence of collectivity [11,12]. These observations have prompted theoretical discussion as to whether jet quenching should be present in these small systems as well [13–19]. However, measurements of jet [20,21] and hadron [22–24] production rates at high transverse momentum (p_T) [25] and measurements of jet-to-hadron fragmentation functions [26] in minimum-bias $p + \mathrm{Pb}$ collisions show no indication of jet quenching, relative to pp, in these small systems [27].

Experiments have also examined the subset of $p + \mathrm{Pb}$ collisions where the proton undergoes many interactions in the Pb nucleus (i.e., a large number of proton-nucleon collisions $\langle N_{\mathrm{coll}} \rangle$) and which typically have larger-than-average particle multiplicities. These so-called "central" events may produce a larger and longer-lived quark-gluon plasma that would induce a bigger jet quenching effect. Measurements that characterize the centrality of events according to the charged-particle multiplicity or energy at midrapidity have found significant deviations of high-p_T charged-hadron production rates from the pp expectation [28]. However, Monte Carlo (MC) simulations using the HIJING [29] generator, and other models of small collision systems [30], indicate that most of this behavior is the result of physics correlations between the charged-particle multiplicity and the probability to produce a high-p_T jet or hadron in individual proton-nucleon collisions [28,31]. In addition, in extreme kinematic regions, such as those with large Bjorken x, the production of high-p_T jets or hadrons becomes anticorrelated with the centrality signal [20,32], which may arise from the decreasing interaction strength of protons in these configurations [33,34] or from other effects [35,36]. Model-dependent corrections for the effect of these correlations can be derived [30,37], but they have strongly limited the precision of searches for jet quenching phenomena in central $p + \mathrm{Pb}$ events. A measurement of the yield of charged hadrons ($8 < p_T < 15$ GeV) correlated

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with the highest p_T charged hadron indicate no nuclear modification within uncertainties [38].

An alternative method, which does not exhibit the physics biases described above, is to select $p+\mathrm{Pb}$ events by counting the number of spectator neutrons produced by the disintegrating Pb nucleus that strike a zero-degree calorimeter (ZDC), where central events yield more neutrons on average. However, estimating $\langle N_{\mathrm{coll}} \rangle$ in the resulting event categories is challenging due to limited understanding of how spectator nucleons are distributed in terms of single neutrons, protons, and larger charged fragments (only the first of which strike the ZDC). Nevertheless, the ALICE Collaboration has used this method and found that rates of charged [28] and heavy-flavor [39] hadrons in central $p+\mathrm{Pb}$ collisions are unmodified in comparison with those derived from pp interactions, albeit within significant modeling uncertainties. To avoid the reliance on $\langle N_{\mathrm{coll}} \rangle$, jet quenching in these events may instead be searched for by examining jet-hadron kinematic correlations or the internal structure of jets. A measurement of hadron-triggered jet yields in ZDC-selected central $p+\mathrm{Pb}$ events has placed limits on the total amount of energy transported across the boundary of an $R=0.4$ jet cone [40], which is one possible signature. The measurement presented here can additionally constrain the parton energy loss, even in the case where the jet shape remains unmodified.

This Letter presents a measurement of the charged-hadron yield in events with jets in the ATLAS calorimeters satisfying two different selections ($p_T^{\mathrm{jet}} > 30$ GeV or $p_T^{\mathrm{jet}} > 60$ GeV) in $p+\mathrm{Pb}$ and pp collisions at a 5.02 TeV nucleon-nucleon center-of-mass energy. The $p+\mathrm{Pb}$ and pp data were recorded in 2016 and 2017, respectively, with triggers sampling integrated luminosities of $0.36\ \mathrm{nb}^{-1}$ and $3.6\ \mathrm{pb}^{-1}$. In $p+\mathrm{Pb}$ running, the proton and lead beams had per-nucleon energies of 4 TeV and $(Z/A) \times 4\ \mathrm{TeV} \approx 1.58$ TeV, respectively, leading to a rapidity shift of the center-of-mass frame, $\Delta y^{\mathrm{com}} = 0.465$, from the laboratory frame (while $y^{\mathrm{com}} = 0$ in pp running). Charged hadrons are required to have $p_T^{\mathrm{ch}} > 0.5$ GeV and lie within $|\eta - y^{\mathrm{com}}| < 2.035$, and their yields are measured in two azimuthal regions with respect to the jet: the "away-side" region $\Delta\phi_{\mathrm{ch,jet}} = |\phi_{\mathrm{ch}} - \phi_{\mathrm{jet}}| > 7\pi/8$ and the "near-side" region $\Delta\phi_{\mathrm{ch,jet}} < \pi/8$. The total yield in each region, $Y(p_T^{\mathrm{ch}})$, is normalized by the number of jets and reported in pp events and in $p+\mathrm{Pb}$ events for different ZDC energy selections. To quantify any modification that would result from the partons' propagation through a created quark-gluon plasma, the ratio of the per-jet charged-particle yields between $p+\mathrm{Pb}$ and pp collisions, $I_{p\mathrm{Pb}} = Y_{p\mathrm{Pb}}/Y_{pp}$, is reported and compared with predictions from theoretical calculations. Importantly, this observable does not depend on a quantitative estimate of $\langle N_{\mathrm{coll}} \rangle$.

The ATLAS experiment [41] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle. It consists of an inner tracking detector surrounded by a superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead plus liquid-argon sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel or scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). Liquid-argon calorimeters with separate EM and hadronic compartments instrument the end cap (up to $|\eta| = 3.2$) and forward (FCal, up to $|\eta| = 4.9$) regions. Two ZDCs are each composed of four longitudinal layers of tungsten absorbers and quartz rods. They are situated in the far forward region $|\eta| > 8.3$ and, in $p+\mathrm{Pb}$ events, the downstream ZDC, relative to the Pb beam direction, primarily measures spectator neutrons from the struck Pb nucleus. An extensive software suite [42] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

Events are selected for analysis using a combination of minimum-bias and calorimeter jet triggers [43], which are used for the measurements with $p_T^{\mathrm{jet}} > 30$ GeV and > 60 GeV, respectively. Both the pp and $p+\mathrm{Pb}$ events are required to have a primary reconstructed vertex with z coordinate $|z| < 150$ mm [44]. The pp and $p+\mathrm{Pb}$ data were recorded at low collision rates, and an additional requirement that events have only one reconstructed interaction vertex further reduces pileup. In the pp ($p+\mathrm{Pb}$) data, this requirement accepts approximately 40% (99%) of triggered events.

The centrality of $p+\mathrm{Pb}$ events is characterized using the total energy in the Pb-going side of the ZDC, E_{ZN}. The ZDC energy is calibrated by matching the single- and double-neutron peaks to their known beam energies (1.58 TeV and 3.15 TeV) [45]. The resulting energy distribution is shown in Fig. 1, with more central (lower centrality) events at high E_{ZN}. Using a ZDC with similar acceptance, the ALICE Collaboration has used multiple bootstrapping methods to estimate that the $\langle N_{\mathrm{coll}} \rangle$ values in these events range from approximately 13.6 (±11%) in 0%–20% centrality $p+\mathrm{Pb}$ events to 1.2 (±24%) in 80%–100% events [28], which are likely to be similar in ATLAS. These values and uncertainties are not explicitly used in the measurement in this Letter but may be useful for modeling comparisons.

Jets are reconstructed from calorimeter energy deposits as described in Ref. [46], using the anti-k_t algorithm [47,48] with radius parameter $R=0.4$. The jet kinematics are corrected event by event for the contribution from

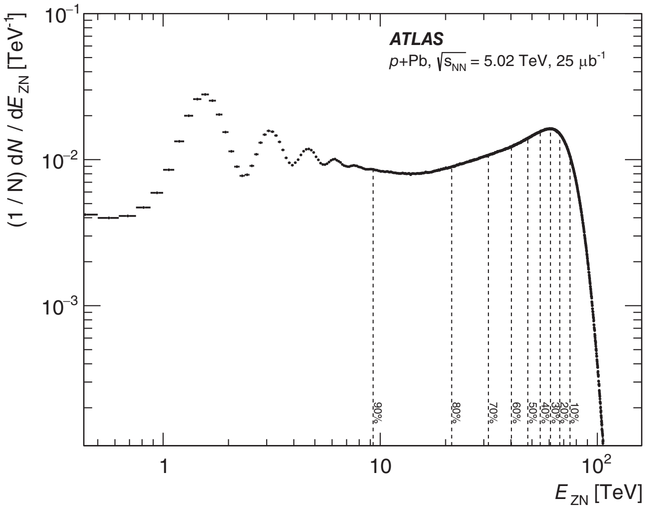

FIG. 1. Distribution of energy measured in the Pb-going side of the zero-degree calorimeter (E_{ZN}) in $p+\mathrm{Pb}$ collisions at 5.02 TeV selected with a minimum-bias trigger. Dashed vertical lines indicate the percentile boundaries between the 0%–10%, 10%–20%, etc., centrality intervals.

underlying event (UE) particles, and are calibrated using simulations [42,49,50] of the calorimeter response and *in situ* measurements of the absolute energy scale in data. The accepted jets lie within $|\eta| < 2.8$.

Reconstructed charged-particle tracks must satisfy quality criteria outlined in Ref. [51]. The charged-particle yield is corrected for imperfect reconstruction and selection efficiency with a per-track weight, and for the small contribution of secondary-particle and fake tracks, with both corrections derived from PYTHIA 8 [52] pp and HIJING $p+\mathrm{Pb}$ MC event samples. The contribution of UE particles to the total yields is estimated by measuring these yields in minimum-bias $p+\mathrm{Pb}$ or pp events with the same selection requirements and with matched intervals in FCal energy (which is well-correlated with UE activity [53]). The UE contribution is subtracted from the yield measured in jet-containing events. The ratio of signal to UE background is approximately 0.25 (1) for $p_T^{\mathrm{ch}} = 0.5$ GeV rising quickly to 3 (30) for $p_T^{\mathrm{ch}} = 4$ GeV, in central $p+\mathrm{Pb}$ (pp) events. Finally, the finite resolution of the p_T^{jet} and p_T^{ch} measurements affects the measured yields. This effect is typically smaller than 10% and is similar in $p+\mathrm{Pb}$ and pp events. It is corrected for via an iterative Bayesian unfolding procedure [54] applied to the two-dimensional $(p_T^{\mathrm{jet}}, p_T^{\mathrm{ch}})$ distributions derived from PYTHIA 8 pp MC events and minimum-bias $p+\mathrm{Pb}$ data events overlaid with PYTHIA 8 pp events.

The dominant sources of systematic uncertainty in the measurement are those affecting the measurement of the jet kinematics, the charged-particle selection, and the unfolding correction. The jet-related uncertainties are derived from *in situ* studies of the calorimeter response [49] and their application to the jets used in heavy-ion data [50] (where they accommodate large jet quenching effects), and from comparisons of the simulated response in samples from different generators. They typically dominate at high p_T^{ch}. Several sources of tracking-related uncertainty are considered, such as the uncertainty in the absolute efficiency and the sensitivity to selection cuts. They are described in previous measurements of charged-particle fragmentation functions [26,55] and typically dominate at low p_T^{ch}. The uncertainty in the unfolding correction is evaluated by considering different priors and by performing the analysis procedure, including the UE subtraction, in simulation to evaluate how accurately the generator-level distributions are recovered. This uncertainty is significant at all p_T^{ch}. Many of these uncertainties, such as the jet-related ones, have a quantitatively similar impact on the yields in the $p+\mathrm{Pb}$ and pp data and largely cancel out in the $I_{p\mathrm{Pb}}$ ratio.

Figure 2 (top row) shows $I_{p\mathrm{Pb}}$ for charged particles on the away side of jets with $p_T^{\mathrm{jet}} > 60$ GeV. In the region $p_T^{\mathrm{ch}} > 1$ GeV, the $I_{p\mathrm{Pb}}$ values in all centrality selections are consistent with unity within the uncertainties. At the lowest measured p_T^{ch} values, the $I_{p\mathrm{Pb}}$ value decreases by about 10%, albeit with growing uncertainties. In a leading-order parton-parton scattering picture, the away-side hadrons arise from the fragmentation of $p_T \approx 60$ GeV partons azimuthally opposite to the parton producing the jet. A jet quenching effect in $p+\mathrm{Pb}$ should lead to $I_{p\mathrm{Pb}}$ values below unity. As such, these results strongly constrain any possible modification of parton fragmentation in the region $z = p_T^{\mathrm{ch}}/p_T^{\mathrm{jet}} \approx 0.05$–1.0, within uncertainties that decrease to 2%–4% at high z, with respect to that in pp collisions.

Figure 2 (bottom row) shows the $I_{p\mathrm{Pb}}$ ratios for charged particles on the near side of jets with $p_T^{\mathrm{jet}} > 60$ GeV. In the region $p_T^{\mathrm{ch}} > 4$ GeV, there is a centrality-independent enhancement of approximately 5%. Similar to that observed on the away side, there is a characteristic suppression in the region $p_T^{\mathrm{ch}} < 1$ GeV. Additionally, the $I_{p\mathrm{Pb}}$ value shows a modest systematic enhancement in the region $1 < p_T^{\mathrm{ch}} < 4$ GeV. It is notable that the pattern from 0.5 to 4 GeV is consistent between the away and near sides, and also with the nuclear modification factor (ratio of total yields between $p+\mathrm{Pb}$ and $\langle N_{\mathrm{coll}}\rangle$-scaled pp) for inclusive charged hadrons [56]. The latter is often interpreted in terms of initial-state parton scattering in the nuclear target, also known as the "Cronin effect" [57]. In heavy-ion collisions, the "soft" particle production regime can be described via hydrodynamics and it is known that the radial flow of the quark-gluon plasma may play a role in this p_T^{ch} region. The measurement in this Letter suggests that low-p_T particles that arise from jet fragmentation also exhibit a similar pattern.

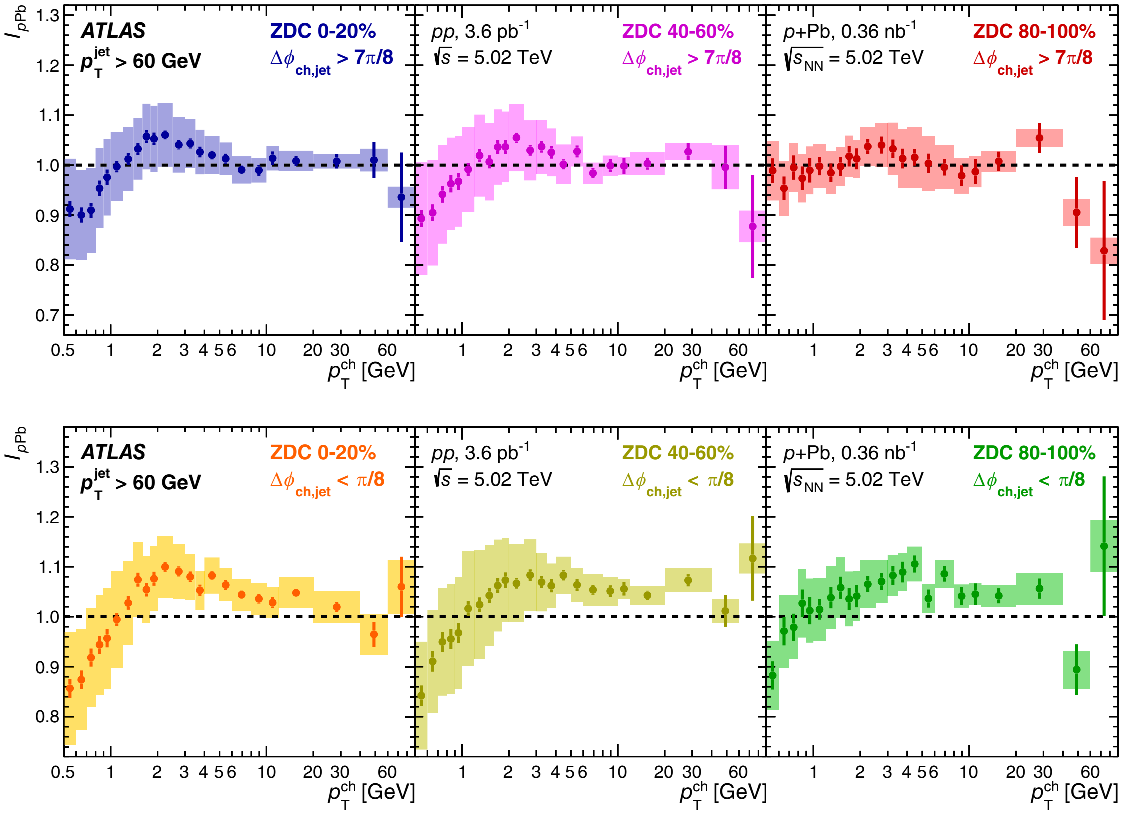

FIG. 2. The ratio of per-jet charged-particle yields between $p+\mathrm{Pb}$ and pp collisions, $I_{p\mathrm{Pb}}$, for hadrons opposite ($\Delta\phi_{\mathrm{ch,jet}} > 7\pi/8$, top row) and near ($\Delta\phi_{\mathrm{ch,jet}} < \pi/8$, bottom row) a jet with $p_T^{\mathrm{jet}} > 60$ GeV. Results are shown for different ZDC-selected $p+\mathrm{Pb}$ centralities in each column. Statistical uncertainties are shown as vertical lines and systematic uncertainties as filled boxes.

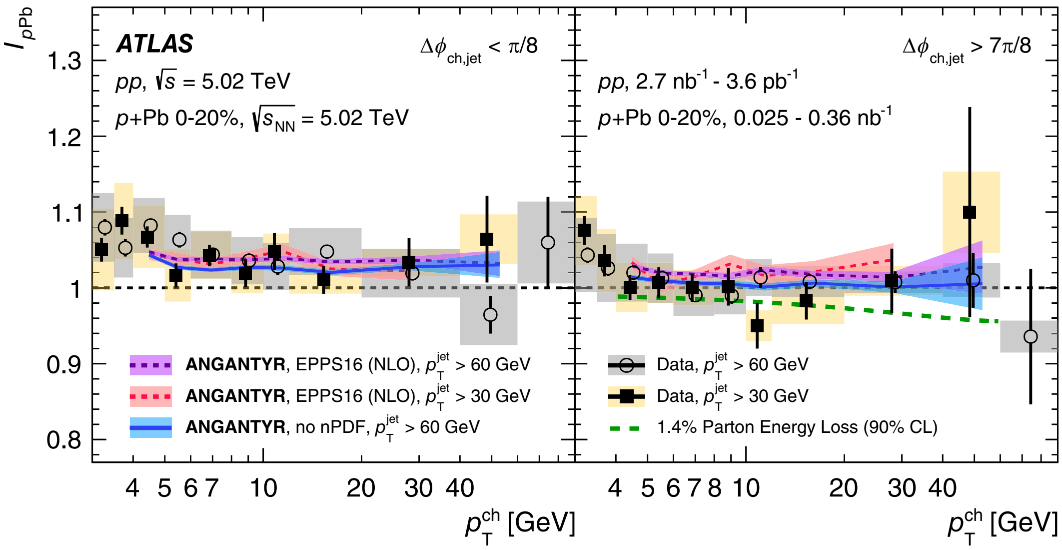

FIG. 3. The ratio of per-jet charged-particle yields, $I_{p\mathrm{Pb}}$, on the near side (left) and away side (right) between $p+\mathrm{Pb}$ and pp are plotted for the 0%–20% $p+\mathrm{Pb}$ ZDC-selected centralities. Particles correlated with a jet above 30 GeV and 60 GeV are shown. Statistical uncertainties are shown as vertical lines and systematic uncertainties as filled boxes. Also shown are calculations from the ANGANTYR generator [58] with two treatments of nuclear-modified parton distribution functions (nPDFs): EPPS16 [59] at next-to-leading order and no nPDF modification, and with a PYTHIA 8-based model for parton energy loss with vacuum fragmentation (see text). ANGANTYR results are only shown for $p_T^{\mathrm{ch}} > 4.5$ GeV where no UE subtraction is necessary. The colored bands represent statistical uncertainties only.

The same measurements were also performed for jets with $p_T^{\mathrm{jet}} > 30$ GeV, which are sensitive to quenching effects on lower-p_T partons. These are shown in Fig. 3, focusing on $p_T^{\mathrm{ch}} > 4$ GeV and 0%–20% centrality ZDC-selected events to emphasize the region of potential jet quenching. Within the larger uncertainties, which arise from the larger relative UE background, poorer jet energy resolution, and smaller sampled luminosity, they are compatible with the $p_T^{\mathrm{jet}} > 60$ GeV results. Since the near-side $I_{p\mathrm{Pb}}$ is similar to a modified jet fragmentation function, it can be compared with the previous measurement in $p+\mathrm{Pb}$ collisions by ATLAS [26]. For jets in a similar p_T^{jet} range, the $p+\mathrm{Pb}$-to-pp ratios of fragmentation functions in Ref. [26] are compatible with the results in this Letter, although with larger uncertainties due to the different datasets used.

In Fig. 3, the $I_{p\mathrm{Pb}}$ measurements are also compared with calculations from the heavy-ion MC generator ANGANTYR [58] run in $p+\mathrm{Pb}$ mode. ANGANTYR is based on PYTHIA 8 and has no final-state effects producing collectivity or jet quenching—noting that this is run with so-called “string shoving” turned off [60]. ANGANTYR shows a near-side enhancement similar to that in data, and studies with varied generator settings indicate that this does not arise from either the nuclear modification of parton densities or the isospin composition difference between Pb nuclei and protons. On the away side, the generator features a small enhancement, but is also compatible with the data within its uncertainties.

The data are compared to a parton energy loss scenario, modeled using PYTHIA 8, where the parton opposite a $p_T >$ 60 GeV jet loses a percentage of its energy before undergoing vacuumlike fragmentation into $p_T > 4$ GeV charged hadrons. Considering both statistical and systematic data uncertainties, the parton energy loss is constrained to be $0.2\% \pm 0.5\%$ and less than 1.4% at the 90% confidence level (shown in the right panel of Fig. 3).

Despite experimental observations consistent with collectivity in $p+\mathrm{Pb}$ collisions [11], these data severely constrain the amount of jet quenching in central $p+\mathrm{Pb}$ collisions. It has been proposed that soft (low-momentum) quarks and gluons are only formed on a timescale of 1 fm/c, and thus the high-p_T partons may undergo their virtuality evolution and showering unscathed and fragment in vacuum if the quark-gluon plasma is small, i.e., with radius < 1–2 fm [61]. A quantitative calculation incorporating this virtuality evolution is necessary to confront the $I_{p\mathrm{Pb}}$ measurements presented here.

In conclusion, this Letter reports a measurement of charged-hadron yields in the azimuthal directions away from and near to jets in $p+\mathrm{Pb}$ collisions, compared with those in pp collisions, using data collected with the ATLAS detector at the LHC. Central $p+\mathrm{Pb}$ collisions, where the effects of a quark-gluon plasma are expected to be largest, are selected in an unbiased way by detecting forward spectator neutrons. The per-jet yields on the near side indicate a modest, of order 5%, enhancement for $p_T^{\mathrm{ch}} > 4$ GeV that is well described by the MC generator ANGANTYR. The per-jet yields on the away side are consistent with unity for all $p_T^{\mathrm{ch}} > 1$ GeV, with uncertainties that are particularly small for $p_T^{\mathrm{ch}} > 4$ GeV. These data serve as a sensitive probe of jet quenching effects and place strong limits on the degree to which the propagation and fragmentation of hard-scattered partons is modified in small hadronic collisions. The results in this Letter heighten the challenge to the theoretical understanding of the quark-gluon system produced in $p+\mathrm{Pb}$ collisions.

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