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Measurement of Suppression of Large-Radius Jets and Its Dependence on Substructure in Pb + Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS Detector

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This letter presents a measurement of the nuclear modification factor of large-radius jets in $\sqrt{s_{NN}} = 5.02$ TeV Pb + Pb collisions by the ATLAS experiment. The measurement is performed using 1.72 nb^{-1} and 257 pb^{-1} of Pb + Pb and pp data, respectively. The large-radius jets are reconstructed with the anti-k_t algorithm using a radius parameter of $R = 1.0$, by reclustering anti-k_t $R = 0.2$ jets, and are measured over the transverse momentum (p_T) kinematic range of $158 < p_T < 1000$ GeV and absolute pseudorapidity $|y| < 2.0$. The large-radius jet constituents are further reclustered using the k_t algorithm in order to obtain the splitting parameters, $\sqrt{d_{12}}$ and ΔR_{12}, which characterize the transverse momentum scale and angular separation for the hardest splitting in the jet, respectively. The nuclear modification factor, R_{AA}, obtained by comparing the Pb + Pb jet yields to those in pp collisions, is measured as a function of jet transverse momentum (p_T) and $\sqrt{d_{12}}$ or ΔR_{12}. A significant difference in the quenching of large-radius jets having single subjet and those with more complex substructure is observed. Systematic comparison of jet suppression in terms of R_{AA} for different jet definitions is also provided. Presented results support the hypothesis that jets with hard internal splittings lose more energy through quenching and provide a new perspective for understanding the role of jet structure in jet suppression.

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Heavy-ion collisions at high energies lead to the creation of matter composed of unconfined quarks and gluons known as quark-gluon plasma (QGP). Studies of the collective expansion of the QGP [1] have demonstrated that the plasma is strongly coupled. A major goal of the experimental high-energy nuclear physics programs at the Relativistic Heavy Ion Collider and Large Hadron Collider (LHC) is to understand how the strong coupling of the QGP arises from a theory that is asymptotically free [2,3]. Jets, collimated sprays of hadrons originating in hard scattering processes, represent a key tool for studying the microscopic interactions between color charges within the QGP that ultimately determine its properties. Those interactions can alter the energy and angular distributions of constituents within the jets—a phenomenon referred to as “jet quenching” [4,5]. As a result, the jet yields are suppressed and jet properties are significantly modified in heavy-ion collisions relative to those measured in elementary proton-proton (pp) collisions.

At the LHC, jet quenching was studied using many observables [6]. Jet substructure observables [7], constructed from measured jet constituents, are versatile tools to measure the changes in jet properties due to jet quenching. These observables, calculated separately for each jet using a variety of algorithms, were originally motivated by studies of highly Lorentz-boosted massive resonances in elementary collisions [8]. Jet grooming algorithms that remove soft and wide-angle radiation can help mitigate the impact of backgrounds from multiple collisions within one bunch crossing (pileup) or the underlying event (UE) on these observables. They also can be used to separate hard components of a parton shower, for example, subjets, in a jet with multiprong structure [9,10]. In the context of jet quenching, these methods enable distinguishing subjets resulting from hard splittings in the parton shower from soft medium-induced radiation [11], soft particles resulting from jet-induced medium excitations [12], and the UE. Furthermore, the dependence of the jet quenching on such splittings, and more generally, the complexity of the parton shower [13] can be studied using substructure techniques.

One specific phenomenon connected with the parton shower complexity is color (de)coherence [14–16]. In the vacuum, the quantum interference in the parton cascade suppresses wide-angle gluon emissions [17–19]. This phenomenon in the medium-induced parton cascade is believed to largely dictate the magnitude of the energy loss [20,21]. In-medium jet evolution is then characterized by a vacuumlike parton cascade whose constituents are either resolved by the medium due to color decoherence

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leading to a radiation of individual color charges [22–24] or remain unresolved and radiate coherently as a single color charge. This induces a dependence of the observed jet suppression on the structure of splittings, which may be experimentally accessed and tested by substructure techniques [13].

Jet substructure was measured in lead-lead (Pb + Pb) collisions at the LHC using several observables: the momentum ratio of two leading subjets, z_g [25–27]; the groomed jet radius, θ_g [27]; the groomed jet mass [28]; the number of branches obtained in the iterative declustering of the jet [26]; the N subjetiness [29] and momentum fraction of subjets [30]. Typically the per-jet normalized distributions of substructure observables are measured in Pb + Pb collisions and compared with the same quantity measured in pp collisions or to that obtained from Monte Carlo (MC) simulations. A recent measurement of z_g, fully corrected for detector effects and with a robust grooming method to reduce the impact of fluctuating backgrounds on the subjet selection, reported no significant change of the z_g distribution in Pb + Pb collisions [27]. A narrowing of the θ_g distribution was observed in Pb + Pb collisions [27], which may be due to the color coherence effects or due to the difference in the relative suppression of quark- and gluon-initiated jets [31]. No change of the groomed mass distribution for the core of the jet was observed, and only a hint of an increase for jets with large jet mass was seen [28]. Furthermore, no significant change in the per-jet yields of the two-pronged structure was observed in Pb + Pb collisions relative to the MC-based reference in the measurement of N subjetiness [29].

One important conceptual issue associated with jet substructure measurements is that the QGP may not directly modify the hard splittings of a jet since their formation time may be much shorter than the formation time of the QGP [21]. Thus, modifications of substructure distributions due to quenching may depend on the structure of the part of the parton shower that is dictated by the vacuum. Rather than measuring the per-jet normalized distributions of a substructure variable, which result from an admixture of vacuum-driven and medium-driven substructure, it may be advantageous to, instead, quantify the suppression of jets having different substructure using the jet nuclear modification factor R_{AA} [32–35].

This Letter provides the first observation and quantification of the dependence of the large-radius jet suppression on the jet substructure. The large-radius ($R = 1.0$) jets are reconstructed using a new method of reclustering from small-radius ($R = 0.2$) jets. The measurement is done with the ATLAS detector differentially in jet transverse momentum (p_T) and also in two specific substructure observables. The jet suppression is quantified in terms of jet R_{AA}. The two substructure observables are the splitting parameter, $\sqrt{d_{12}}$, and the angular separation, ΔR_{12}, which characterize the transverse momentum scale and the angular separation, respectively, for the hardest splitting in the jet. The differential jet suppression measurement allows direct quantification of the difference between the energy loss of jets with single subjet and the energy loss of jets with more complex structure involving early hard splittings. This quantification was not directly accessible in previous measurements. The use of large-radius jets then delimits the measured kinematics of the internal splitting. The results also provide a direct quantification of cone-size dependence of energy loss. Detailed quantification of jet suppression as a function of angular separation at small opening angles using tracks associated with calorimeter small-radius jets follows in a separate study by ATLAS [36].

The principal components of the ATLAS detector [37] used in this measurement are the inner tracking detector, the electromagnetic and hadronic calorimeters, and the online trigger system. The inner tracking detector is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field and it covers the pseudorapidity range $|\eta| < 2.5$ [38]. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead and liquid-argon sampling calorimeters provide electromagnetic energy measurements with high granularity. A steel and scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). Liquid-argon calorimeters with separate electromagnetic and hadronic compartments instrument the end cap (up to $|\eta| = 3.2$) and forward calorimeter (FCal) (up to $|\eta| = 4.9$) regions. Both the inner detector and calorimeter systems have a 2π coverage in azimuth. Two zero-degree calorimeters are composed of four longitudinal layers of tungsten absorbers and quartz rods. They are situated in the far forward region $|\eta| > 8.3$ and primarily measure the spectator neutrons from the struck Pb nuclei. An extensive software suite [39] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

The analysis uses 1.72 nb^{-1} of Pb + Pb data at $\sqrt{s_{NN}} = 5.02$ TeV recorded in 2018 and 257 pb^{-1} of pp data collected in 2017 at the same center-of-mass energy. Events were selected using a combination of calorimeter-based jet triggers [40,41]. Both the pp and Pb + Pb events are required to contain at least one primary vertex. All jets in the analysis are in a kinematic range where the jet trigger was fully efficient. The Pb + Pb data contain only a small fraction of events ($< 0.5\%$) with multiple collisions per bunch crossing, which are further suppressed using the anticorrelation of signal from the zero degree calorimeter and FCal. The pp data were collected with typically 1.4–4.4 inelastic interactions per bunch crossing. No pileup rejection is applied in the analysis of pp data.

The centrality of Pb + Pb events is defined using the total transverse energy measured in the FCal, $\Sigma E_T^{\mathrm{FCal}}$ [42,43]. Events in Pb + Pb data are classified into four centrality intervals, ordered from the most central to the most peripheral: 0%–10%, 10%–30%, 30%–50%, and 50%–80%. The values of the mean nuclear thickness function with their uncertainties, $\langle T_{AA}\rangle$ (used as an input to R_{AA}), are evaluated in each centrality interval by a Glauber model analysis of the $\Sigma E_T^{\mathrm{FCal}}$ distribution [44,45].

Several MC simulation samples are used to evaluate the performance of the analysis procedure and to correct the measured distributions for detector effects. The pp MC sample uses 4×10^7 PYTHIA8 [46] jet events at $\sqrt{s}=5.02$ TeV with the A14 ATLAS tune [47] and the NNPDF23LO parton distribution functions (PDF) [48]. Pileup from additional pp collisions is generated by PYTHIA8, with parameter values set to the A2 tune [49] and using the MSTW2008 [50] PDF set, with a distribution of the number of extra collisions matching that of data.

The Pb + Pb MC sample uses 4×10^7 pp PYTHIA8 events with the same tune and PDFs as in pp MC samples that are overlaid on top of events from a dedicated sample of Pb + Pb data events. This sample was recorded with a combination of minimum-bias and total energy triggers requiring 1.5 TeV or 6.5 TeV to enhance the number of central collisions. This "MC overlay" sample was reweighted on an event-by-event basis such that it has the same centrality distribution as the jet-triggered data sample. The detector response in all MC samples was simulated using GEANT4 [51,52].

First, jets with radius parameter $R=0.2$ are reconstructed using the anti-k_t algorithm [53,54] from calorimeter energy deposits as described in Ref. [55]. The jet kinematics are corrected event-by-event for the contribution from the UE particles, and are calibrated using simulations of the calorimeter response and *in situ* measurement of the absolute energy scale [56].

The large-radius jets are defined by clustering the small-radius, $R=0.2$, jets with $p_T>35$ GeV and $|\eta|<3.0$ using anti-k_t algorithm with radius parameter $R=1.0$ [57]. These requirements and procedure limits the impact of UE on the measurement but prohibits recovering the quenched jet energy [11] transferred outside of the $R=0.2$ subjets. This procedure allows to perform the measurement in a wide kinematic range and reduces systematics uncertainties. The k_t jet-finding algorithm [54,58] is used to recluster constituents of $R=1.0$ jet (i.e., $R=0.2$ jets) to obtain two observables of interest, ΔR_{12} and $\sqrt{d_{12}}$. These are defined as the angular separation and the splitting parameter of the k_t algorithm calculated for two jets before the final clustering step of $R=1.0$ jet

$$\Delta R_{12}=\sqrt{\Delta y_{12}^2+\Delta\phi_{12}^2},$$
$$\sqrt{d_{12}}=\min(p_{T1},p_{T,2})\times\Delta R_{12}.$$

The large-radius jet yields in Pb + Pb collisions and jet cross section in pp collisions measured in the kinematic range of $158<p_T<1000$ GeV and $|y|<2.0$ are evaluated inclusively and differentially in each of the two substructure observables. The k_t clustering of large-radius jet constituents with only a single subjet defaults to $\sqrt{d_{12}}=0$ and $\Delta R_{12}=0$. These jets, which consist of a single $R=0.2$ jet, centered on the $R=1.0$ jet axis with no other clustered activity in the large-radius cone, populate only the first interval in $\sqrt{d_{12}}$ and ΔR_{12}. The fraction of reconstructed large-radius jets with a single subjet in pp collisions is 75% in the p_T interval of 158–200 GeV and 62% in the p_T interval of 316–500 GeV. More details of the subjet multiplicity can be found in the Appendix. The jet performance of large-radius reclustered jets was analyzed using MC samples. The jet energy scale (JES) was found to be within a 3% range from 1.

The measured inclusive and differential distributions are corrected for detector effects by the iterative Bayesian unfolding method [59,60] in one dimension and two dimensions, respectively, to return the distributions to the particle level. The unfolding accounts for the effects of bin migrations due to the jet energy resolution (JER) and JES. It also corrects the combinatoric subjet contribution originating from fluctuations of the UE and from jets from different hard partonic interactions in the same Pb + Pb collision resulting in migration in the substructure observable. To better represent the data, the simulated distributions are reweighted along the generator-level jet p_T, $\sqrt{d_{12}}$, and ΔR_{12} axes by the reconstruction-level data-to-simulation ratio before the unfolding. The number of iterations in the unfolding was chosen such that the result is stable when changing the number of iterations while minimizing the amplification of statistical uncertainties. Four iterations were used for inclusive $R=0.2$ and $R=1.0$ jet yields and cross sections, while six and eight iterations were used in the unfolding of $\sqrt{d_{12}}$ and ΔR_{12} distributions, respectively. Generator-level jets that do not match to a reconstructed jet passing the selection criteria are incorporated as an inefficiency correction after the unfolding.

A dominant source of systematic uncertainty is the uncertainty in the JES. For more central collisions, the uncertainty in JER is equally important. The systematic uncertainty on the JES contains components from calorimeter response uncertainties derived from *in situ* studies [56], a component connected with the JES in the Pb + Pb environment [61], components accounting for inaccuracies in the description of the relative abundances of jets initiated by quarks and gluons and their calorimetric response, and a component connected with the jet radius. The magnitude of the uncertainty in the R_{AA} from the JES uncertainty varies from 5% to 20% as a function of p_{T}, $\sqrt{d_{12}}$, ΔR_{12}, and centrality. The primary component of the JER uncertainty is derived using an *in situ* technique involving studies of dijet energy balance [62,63]. The resulting uncertainty in R_{AA} reaches ~20% in 0–10% central collisions at low $\sqrt{d_{12}}$ and ΔR_{12}, but it is typically below 5%. The systematic uncertainty of the unfolding procedure is estimated by repeating the analysis with response matrices without the re-weighting to match the shapes of measured distributions in data and it is typically bellow 5%. Other systematic uncertainties consist of the deviation between the unfolded result and the underlying generator-level distribution in simulation, the uncertainty in the determination of $\langle T_{\mathrm{AA}} \rangle$ values [55], and the uncertainty in the determination of the pp luminosity [64].

The nuclear modification factor for large-radius jets evaluated in the p_T interval of 200–251 GeV as a function of the $\sqrt{d_{12}}$ is shown in the left panel of Fig. 1. The R_{AA} values for large-radius jets with a single subjet are significantly larger compared with the R_{AA} for large-radius jets with a more complex substructure having a nonzero $\sqrt{d_{12}}$. This observation is qualitatively consistent with the scenario in which the medium cannot resolve partonic fragments below a certain transverse scale [65]. This result is also consistent with the previous measurement of correlated production of pairs of nearby jets in Pb + Pb collisions [66] where a larger suppression of neighboring jets compared with inclusive jets was observed. For $\sqrt{d_{12}} > 0$, the R_{AA} values are constant as a function of $\sqrt{d_{12}}$ within uncertainties for all the centrality intervals.

The right panel of Fig. 1 shows R_{AA} of large-radius jets evaluated as a function of ΔR_{12} for $p_T = 200$–251 GeV. The trends seen for $R_{AA}(\Delta R_{12})$ are the same as those seen for $R_{AA}(\sqrt{d_{12}})$: suppression is significantly smaller for the single subjet case, and then constant within uncertainties for nonzero ΔR_{12} values. The other p_T intervals spanning the range of $158 < p_T < 500$ GeV show the same trends. These observations are in contrast with nonmonotonic p_T and radial dependence of production of charged particles associated with jets measured using fragmentation functions or jet shapes [67–69]. The measurement of the k_t splitting scale by $\sqrt{d_{12}}$ and radial dependence of subjet suppression by ΔR_{12} thus provide new information relative to previously measured transverse and radial structure of $R = 0.4$ jets using charged particles. The measurement also provides new information relative to the recent substructure measurement of θ_g distributions of $R = 0.4$ jets [27]. In that measurement, a difference in the slope of per-jet normalized θ_g distribution was seen in Pb + Pb with respect to pp collisions, while here we report a difference in the suppression connected with particular subjet topology.

A systematic comparison of jet suppression in terms of jet $R_{AA}(p_T)$ for different jet definitions is provided in Fig. 2. The jet R_{AA} is measured for: $R = 1.0$ reclustered jets with single subjet, $R = 1.0$ reclustered jets with multiple subjets, $R = 1.0$ reclustered inclusive jets, $R = 0.2$ jets, and $R = 0.4$ jets [55].

Production of $R = 1.0$ reclustered inclusive jets is suppressed more than the production of $R = 0.2$ or $R = 0.4$ jets. Various theoretical calculations of the jet quenching where the jet energy is distributed to soft particles predict less suppression when expanding the jet radius by recovering more lost energy, see, e.g., Ref. [24]. This energy recovery may however not happen in the case of reclustered large-radius jets where energy radiated outside of $R = 0.2$ subjets is removed. A singular situation when the reclustered large-radius jet is completely removed due to all subjets being suppressed below the 35 GeV cut is very unlikely given the minimum p_T threshold of 158 GeV on the $R = 1.0$ jet and relatively small multiplicity of subjets. Thus, in general, variations in the jet definition used in this study allow including different fractions of the lost energy and energy from the medium response to the showering

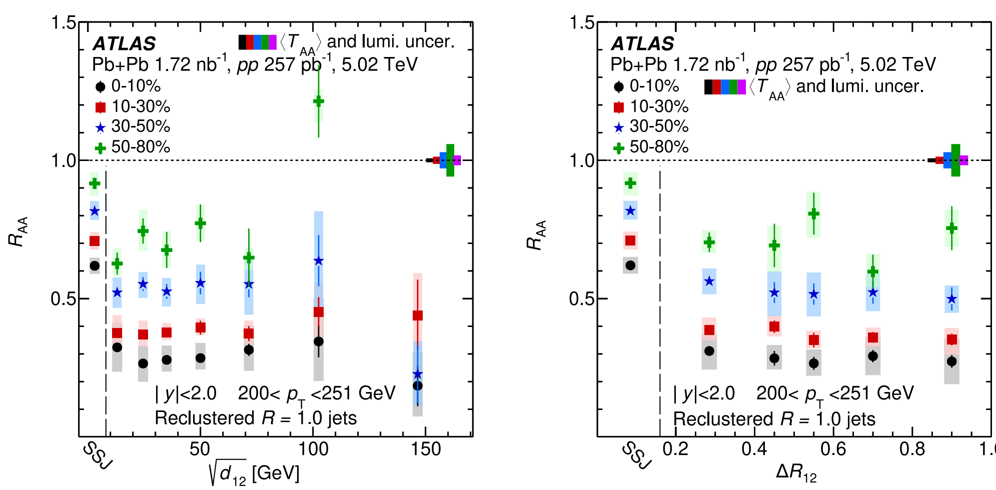

FIG. 1. The values of R_{AA} for $R = 1.0$ reclustered jets as function of $\sqrt{d_{12}}$ (left) and ΔR_{12} (right) in four centrality intervals. The label "SSJ" on the x-axis identifies the single sub-jet configuration. The vertical bars on the data points indicate statistical uncertainties, the shaded boxes indicate systematic uncertainties. The fully correlated fractional uncertainties due to the luminosity and $\langle T_{\mathrm{AA}} \rangle$ are represented by boxes at $R_{\mathrm{AA}} = 1$. One data point with a relative statistical uncertainty above 50% is not displayed.

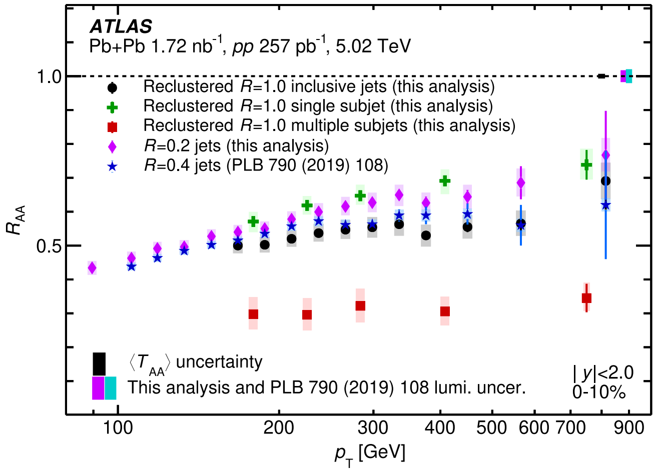

FIG. 2. Comparison of R_{AA} distributions evaluated in 0%–10% central collisions as a function of p_T for several jet definitions: $R = 1.0$ reclustered inclusive jets (circles), $R = 1.0$ reclustered jets with a single subjet (crosses), $R = 1.0$ reclustered jets with multiple subjets (squares), $R = 0.2$ jets (diamonds), $R = 0.4$ jets (stars) [55]. The vertical bars on the data points indicate statistical uncertainties, the shaded boxes indicate systematic uncertainties. The colored boxes at $R_{AA} = 1$ represent fractional uncertainty in $\langle T_{AA} \rangle$ and pp luminosity in this measurement and pp luminosity in previous analysis [55], which both affect the overall normalization.

process. Comparing new results with theoretical calculations may therefore help to understand possible biases in the quantification of energy loss using traditional, small-radius jets. The presented quantification of cone-size dependence of R_{AA} may also be used to constrain theoretical uncertainties in the recently analytically calculated cone-size dependent energy loss [70].

The $R = 1.0$ reclustered jets with multiple subjets show the largest suppression while the $R = 1.0$ reclustered jets with a single subjet show the smallest suppression out of all jet definitions. The sizable difference between the R_{AA} for multiple subjet and single subjet configurations provides an important input for understanding the role of color decoherence in the jet quenching. This sizable difference is not due to missing a contribution from the energy radiated out of the $R = 0.2$ cone since this radiated energy is not measured in all configurations of $R = 1.0$ jets with subjets. The lack of jet p_T dependence in the R_{AA} of $R = 1.0$ reclustered jets with multiple subjets might be understood to be the consequence of increasing subjet multiplicity with increasing jet p_T (see subjet multiplicity distributions in Appendix). More subjets may imply more sources of radiation which may lead to flattening of R_{AA} at high p_T. Presented results can be also used to obtain ratios of per-jet normalized substructure distributions for $R = 1.0$ jets by dividing distributions in Fig. 1 by the inclusive $R = 1.0$ jet R_{AA} in Fig. 2. Finally, it should be noted that any direct comparisons of R_{AA} between different jet definitions should be treated with care as the same particles reconstructed with a different procedure might appear in different jet p_T intervals.

In conclusion, this Letter provides a measurement of the jet nuclear modification factor for large-radius jets that is differential in p_T and in transverse and radial substructure observables. Presented observations are qualitatively consistent with the hypothesis that jets with hard internal splittings lose more energy, and provide a new perspective for understanding the role of jet structure in jet suppression in the QGP.

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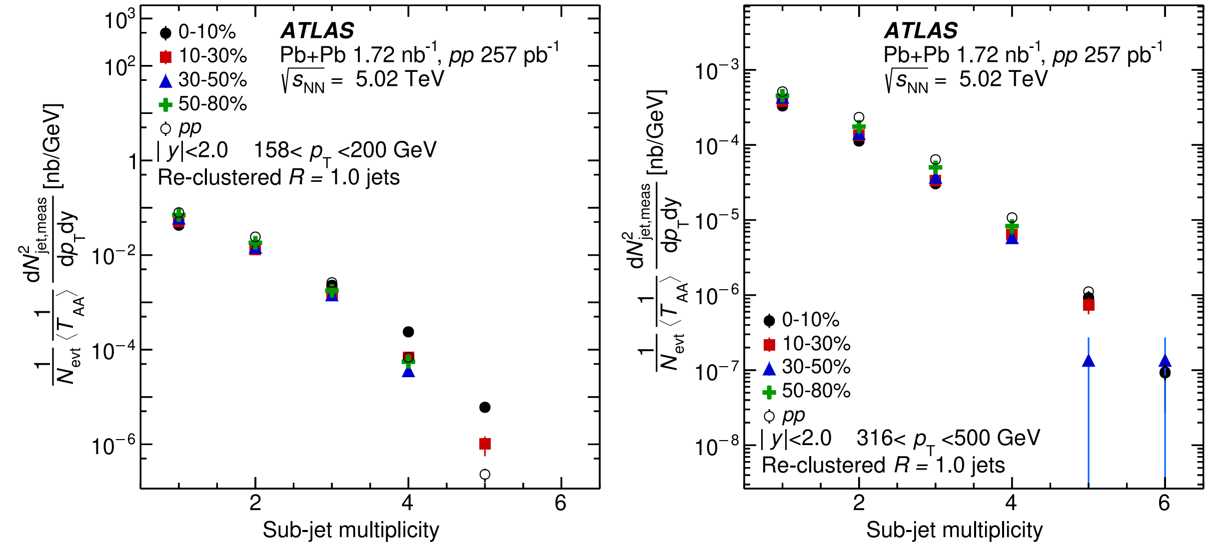

FIG. 3. Measured uncorrected distributions of the number of subjets of the large-radius jets in pp collisions and four centrality intervals of Pb + Pb collisions for jet p_T in the range 158–200 GeV (left) and 316–500 GeV (right).

Appendix.—The measured uncorrected distribution of the yield of jets evaluated as a function of a number of subjets with p_T above 35 GeV is shown in Fig. 3. The yield is shown for large-radius jets measured in pp collisions and in four centrality intervals of Pb + Pb collisions. The fraction of reconstructed large-radius jets with a single subjet in pp collisions is 75% in the p_T interval of 158–200 GeV and 62% in the p_T interval of 316–500 GeV. In 0%–10% central Pb + Pb collisions, the fractions are 73% and 68% in the p_T interval of 158–200 GeV and 316–500 GeV, respectively. In 50%–80% peripheral collisions, the fractions are 77% and 65%, in the p_T interval of 158–200 GeV and 316–500 GeV, respectively. The measured distributions in Pb + Pb collisions include a contribution from jets that originate from different hard partonic interactions in the same Pb + Pb collision and from the spurious fluctuations of UE. These two contributions increase with the increasing centrality of the collision. In general, the observed increase of yield of large-radius jets with multiple subjets with increasing jet p_T is expected both in pp and Pb + Pb collisions, since it was previously measured that the yield of neighboring jets that accompany a given higher-p_T jet increases with increasing jet p_T [66,71].

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