

Exposing the parton-hadron transition within jets with energy-energy correlators in pp collisions at $\sqrt{s} = 5.02$ TeV

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 (Received 31 October 2024; accepted 12 June 2026; published 4 August 2026)

This paper presents a fully corrected measurement of the energy-energy correlator (EEC) within jets in pp collisions. The EEC traces the energy flow as a highly energetic parton undergoes a QCD shower followed by the confinement of partons into hadrons, probing the correlation function of the energy flow inside jets. The EEC observable is measured as a function of the charged particle pair angular distance, R_L , for $20 < p_T^{\text{chjet}} < 80$ GeV/c. In the perturbative region (large R_L), a good agreement between the data and a next-to-leading-log perturbative QCD calculation is observed. In the nonperturbative region (small R_L), the data exhibit a linear R_L dependence. There is a transition region in between, characterized by a turnover in the EEC distribution, indicating where hadronization effects begin to dominate. The peak of this transition region is located at 2.43 ± 0.14 GeV/c/ $\langle p_T^{\text{chjet}} \rangle$ for jets of various energies, indicating a common energy scale for the hadronization process. State-of-the-art Monte Carlo event generators are compared with the measurements, and can be used to constrain the parton shower and hadronization mechanisms.

DOI: [10.1103/tgtl-7xb9](https://doi.org/10.1103/tgtl-7xb9)

I. INTRODUCTION

Jets serve as powerful probes for studying QCD. At the LHC, they are produced abundantly via hard scattering processes (large momentum transfer) between quarks and gluons (partons) from each colliding proton. The high-energy partons from the initial scattering undergo QCD radiation and split into lower energy partons. This process can be described using perturbative QCD (pQCD) calculations and modeled by Monte Carlo (MC) parton shower routines. Below a certain energy scale, color-neutral particles emerge when partons are confined into hadrons; eventually the final stable particles stream into detectors. The internal structure of the particles inside jets, referred to as jet substructure, encodes both the radiation pattern of the parton shower and information about the hadronization process [1]. To unravel the QCD dynamics within the fragmentation and hadronization processes, a variety of jet substructure observables have been studied [2–36]. Measurements of the jet substructure offer new opportunities for studying the properties of nuclei and the quark-gluon plasma via the interplay between the jet and the cold or the hot QCD medium in proton-nucleus and nucleus-nucleus collisions, respectively [37–39].

A novel jet substructure observable, referred to as energy-energy correlator (EEC) [40–42], focuses on the correlation function of energy flow inside jets. Originally introduced as an event shape observable in e^+e^- collisions [43–46] or as the observable needed to construct jet discriminators [47–49], the EEC is IR-collinear safe [50] and can be calculated from first principles in QCD in the perturbative limit [46]. It has been used to constrain the strong coupling constant α_s [44–46]. EEC observables can be defined in different ways, offering precision probes of both perturbative and nonperturbative QCD dynamics in collisions ranging from e^+e^- annihilation and hadronic collisions, to deep inelastic scattering, as summarized in Refs. [51,52].

Experimentally, the EEC is an energy-weighted two-particle correlation as a function of the angular distance between pairs of particles. In this paper, we study the EEC inside high-energy jets produced in pp collisions at $\sqrt{s} = 5.02$ TeV. This approach focuses on the energy correlation function in the collinear limit instead of over the whole event, providing a new perspective on jet evolution, from perturbative splittings to parton confinement into hadrons [40]. The energy-energy correlation function, $\Sigma_{\text{EEC}}(R_L)$, is defined as

$$\Sigma_{\text{EEC}}(R_L) = \frac{1}{N_{\text{jet}} \cdot \Delta} \int_{R_L - \frac{1}{2}\Delta}^{R_L + \frac{1}{2}\Delta} \times \sum_{\text{jets}} \sum_{i,j} \frac{p_{T,i} p_{T,j}}{(p_T^{\text{jet}})^2} \delta(R'_L - R_{L,ij}) dR'_L. \quad (1)$$

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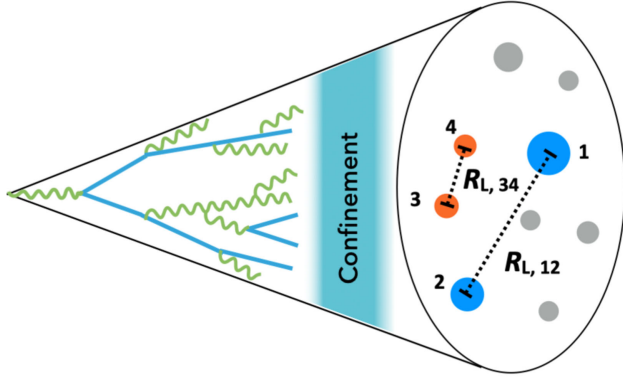


FIG. 1. Schematic of the jet evolution through parton shower (lines), confinement process (shaded area), to final state particles (circles).

The sum runs over all final state particle pairs (i, j) inside each jet.¹ The angular distance between each pair in the $\eta - \phi$ plane is $R_{L,ij} = \sqrt{(\phi_j - \phi_i)^2 + (\eta_j - \eta_i)^2}$. Δ is the angular bin width and N_{jet} is the total number of jets. Figure 1 illustrates how particles inside a jet are paired when constructing the EEC observable.

Recent theoretical developments have enabled the analytical calculation of energy correlators inside jets to high accuracy [40], and the calculation has been extended to charged particles using track functions [42,53–56]. As the soft radiation is suppressed by the energy weight, this observable has reduced sensitivity to higher-order corrections, the underlying event, and soft jet fragments in the perturbative regime.

Another advantage of the EEC observable arises from the angular scale, R_L . Based on the angular ordering of the QCD radiation (splitting), the time scale τ of splitting can be approximated by $\tau \sim 1/(p_T^{\text{jet}} \cdot R_L^2)$, where τ is the splitting time and p_T^{jet} represents the scale of the initial hard process [40,41]. The large- R_L regime corresponds to the perturbative regime during the early parton splitting stage of the jet dynamics, hence is referred to as the perturbative or parton scaling region. Nonperturbative effects become more significant as the QCD radiation evolves towards lower energy scales and smaller angles. Below a certain angular scale, confinement effects are expected to dominate. This separation of the perturbative and nonperturbative regimes into distinct angular regions was already observed by the Compact Muon Solenoid (CMS) experiment [41,57], and they have extracted α_s to high precision using the energy correlators in the perturbative regime.

In this paper, we take advantage of the excellent track reconstruction capabilities of A Large Ion Collider Experiment (ALICE) [38] to construct the EEC using

¹Both pair (i, j) and (j, i) are considered. For example, a pair of particle 1 and particle 2 is counted twice, $(1, 2)$ and $(2, 1)$.

charged particle tracks within reconstructed charged-particle jets. The measurement of jet EEC in pp collisions with detector effects fully corrected at the LHC is presented. The measurements are reported in charged particle jet p_T ($p_T^{\text{ch,jet}}$) intervals of 20–40, 40–60, 60–80 GeV/c, which marks the first EEC measurement in jets in such a low- p_T kinematic regime at the LHC. In this regime, the measured R_L range extends from the perturbative to the nonperturbative regime, allowing a closer examination of the transition region between them. The results are compared with state-of-the-art MC models with different hadronization mechanisms and pQCD calculations. The transition region is analyzed to study hadronization as a function of jet p_T .

II. EXPERIMENTAL SETUP AND DATASETS

This analysis utilizes pp collisions at $\sqrt{s} = 5.02$ TeV collected by the ALICE experiment in 2017. Minimum bias events are triggered by coincidence hits on the V0 scintillator detectors [58] at forward and backward rapidity. Events are required to have a primary vertex within ± 10 cm of the nominal interaction point to provide uniform acceptance and high tracking efficiency. Events with more than one reconstructed collision vertex are removed to avoid pileup of multiple collisions. A total of 870×10^6 minimum bias events passed the event selection criteria, corresponding to an integrated luminosity of $18.0 \pm 0.4 \text{ nb}^{-1}$ [59].

The central barrel tracking system is the main detector used in this analysis. The central tracker consists of the inner tracking system (ITS) [60] and time projection chamber (TPC) [61]. They are inside a 0.5 T magnetic field and have a high efficiency for detection of charged particles with p_T ($p_{T,\text{track}}$) from 0.15 to 100 GeV/c, $|\eta| < 0.9$, and $0 < \phi < 2\pi$. The single track efficiency is p_T dependent, increasing from $\sim 60\%$ at 0.15 GeV to $\sim 80\%$ at 1 GeV and remaining above 75% at higher p_T . The momentum resolution, σ_p/p , is $\approx 1\%$ at $p_{T,\text{track}} = 1$ GeV/c increasing to $\approx 4\%$ at $p_{T,\text{track}} = 40$ GeV/c. The angular resolution is ≈ 1 mrad at $p_{T,\text{track}} = 1$ GeV/c decreasing to < 0.6 mrad for $p_{T,\text{track}} > 5$ GeV/c. ALICE uses a standard cylindrical coordinate system where η is the pseudorapidity and ϕ is the azimuthal angle. More detailed descriptions of the ALICE detector and performance can be found in Refs. [62,63].

III. ANALYSIS METHOD

Charged particles measured by the central barrel tracking system are selected using the same criteria as in Refs. [62,64]. The selected charged particles are clustered into jets via the anti- k_T algorithm with $R = 0.4$ using the FastJet 3.3.3 package [65]. The E-scheme recombination is used, assigning all charged particles the pion mass. Reconstructed jets with $|\eta_{\text{jet}}| < 0.9 - R$ are used to avoid detector edge effects in the jet reconstruction. The EEC observable is measured in charged jet p_T ranges of

$20 < p_T^{\text{chjet}} < 40 \text{ GeV}/c$, $40 < p_T^{\text{chjet}} < 60 \text{ GeV}/c$, and $60 < p_T^{\text{chjet}} < 80 \text{ GeV}/c$. Only constituents inside the reconstructed jets with $p_{T,\text{track}} > 1 \text{ GeV}/c$ enter the EEC, in order to reduce the impact of nonjet particles from the underlying event (UE).² No additional corrections are applied for the presence of the UE.

Detector effects are assessed by simulating pp collisions with PYTHIA 8 (version 8.210) [66] Monash tune [67] and then propagating the final-state particles through a Geant 3 model [68] of the ALICE detector. The key detector effects for EEC are the track momentum resolution, angular resolution, and efficiency for both single tracks and track pairs. The track momentum resolution and efficiency affect the calculated energy weights, the number of reconstructed pairs, and the reconstructed p_T^{chjet} . Track pairs at very small angular separation with the same charge have very similar trajectories in the tracking volume, which may cause the track reconstruction algorithm to miss one of the tracks or misreconstruct them. This effect is referred to as the track-merging effect, and was quantified for the femtoscopy measurements in ALICE [69]. Track merging decreases the pair efficiency for tracks at small distance, causing a reduced Σ_{EEC} at low R_L . A $\sim 90\%$ pair efficiency is observed in the Geant simulation for pairs with $R_L > 0.01$, which drops steeply to $< 20\%$ for pairs with smaller R_L . To achieve precise measurements with small systematic uncertainties, results are reported for $R_L > 0.01$.

The values of the corrections are $< 10\%$, except for the R_L bins near 0.01, for which the corrections are about 20%. As each track pair has a unique energy weight, full unfolding to correct for detector effects is complicated and requires higher statistics. However, the excellent momentum and position resolution in ALICE results in little bin migration in R_L . Hence, in this analysis, instead of unfolding, a two-dimensional bin-by-bin correction is utilized where the correction factors are obtained from the simulation by comparing the generator-level and corresponding detector-level information for each p_T^{chjet} and R_L bin. The bin-by-bin correction can be more sensitive to differences between the generator used for deriving the correction factor and the physics events collected; this is included in the systematic uncertainty. A cross-check was performed using a Bayesian unfolding technique [70,71]. The difference between the unfolded and bin-by-bin corrected EEC distributions is small and is included in the systematic uncertainties. More information about the unfolding procedure can be found in Appendix A.

²In PYTHIA 8, the $p_{T,\text{track}} > 1 \text{ GeV}/c$ cut reduces the multiparton interactions effect from up to 6% to up to 3% in the large R_L region.

IV. SYSTEMATIC UNCERTAINTIES

The main systematic uncertainty sources in this measurement are the single-track efficiency, the track pair efficiency, the generator dependence of the correction factors and the unfolding cross-check. The single-track efficiency uncertainty is estimated to be $\approx 3\%$ based on previous studies where the track selection and ITS-TPC matching criteria are varied [72]. The impact of this uncertainty is determined by randomly rejecting 3% of the detector-level tracks in simulated events and recalculating the correction factors. It leads to an R_L dependent change of $< 3\%$, which is quoted as the systematic uncertainty for single-track efficiency and also includes the track efficiency uncertainty effect upon the jet p_T . The systematic uncertainty due to the pair efficiency is evaluated by studying the variation of the corrected data points with different pair selection parameters, yielding $< 2\%$ variation in the R_L range reported. The uncertainty from the generator dependence of the correction factors is determined by comparing the correction factors extracted from events simulated with PYTHIA 8 [72] and Herwig 7 [73], with parametrized detector responses included, yielding $< 3\%$ variation. The unfolded EEC shows $< 3\%$ difference from the bin-by-bin corrected results, and the difference is assigned as a systematic uncertainty on the bin-by-bin correction method. The systematic uncertainties are assumed to be independent and are added in quadrature, resulting in a total uncertainty of $< 4\%$ for most of the reported R_L range.

V. RESULTS AND DISCUSSION

The EEC distributions for p_T^{chjet} ranges of 20–40, 40–60, and 60–80 GeV/c are shown in Fig. 2. In each p_T^{chjet} range, distinct R_L dependences are observed at the large-angle and

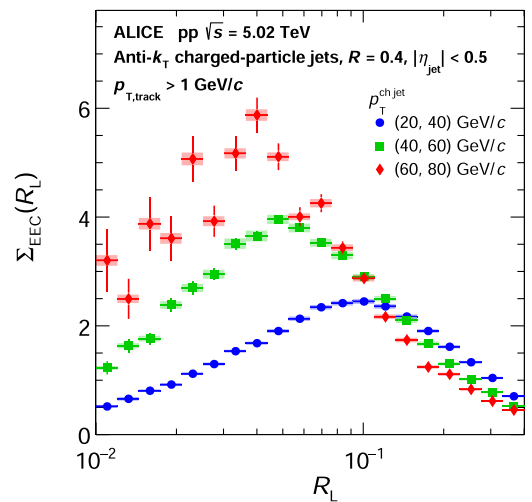


FIG. 2. Fully corrected Σ_{EEC} as a function of R_L in the p_T^{chjet} intervals 20–40, 40–60, and 60–80 GeV/c .

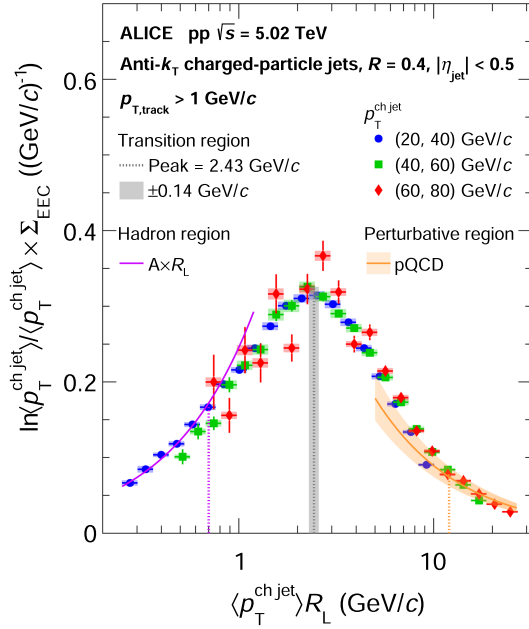


FIG. 3. Normalized Σ_{EEC} as a function of $\langle p_T^{\text{chjet}} \rangle R_L$. $\ln \langle p_T^{\text{chjet}} \rangle$ in the y-axis represents $\ln(\langle p_T^{\text{chjet}} \rangle / (\text{GeV}/c))$, a unit-less number, used throughout this paper for simplicity in notation. The gray line corresponds to the maximum location of the distribution and the gray band corresponds to a ± 0.14 GeV/c uncertainty along the x-axis. The orange curves show pQCD calculations [42], which are normalized to data such that the integral inside R_L range of $12 \text{ GeV}/c / \langle p_T^{\text{chjet}} \rangle$, marked by the vertical dashed orange line, to 0.4 are the same. The purple curve represents a linear functional form that is fit to data ($\chi^2 = 1.65$) in the R_L range of 0.01 to $0.7 \text{ GeV}/c / \langle p_T^{\text{chjet}} \rangle$, marked by the vertical dashed purple line. As the fitting range for the linear curve is mostly accessible by the data in 20–40 GeV/c, the comparison of linear fit to data is only shown for 20–40 GeV/c. As the normalization range for the orange pQCD curve is mostly accessible by the data in 60–80 GeV/c, the comparison of pQCD to data is only shown for 60–80 GeV/c.

small-angle limits, with a transition region in between. Similar distinct regions have been observed in EEC measurements from pp collisions at different beam energies [57,74] and in e^+e^- collisions [75]. The three regions can be intuitively understood with the following explanations:

- (i) The region at large R_L (partonic degrees of freedom) is dominated by the early time jet evolution where partons split and shower perturbatively. Harder splittings with larger R_L occur less frequently than soft emissions with smaller R_L , resulting in Σ_{EEC} scaling approximately as $1/R_L$.
- (ii) The region at small R_L (hadronic degrees of freedom) reflects the jet structure at later times dominated by the features of QCD inaccessible with perturbative methods, namely hadronization. Hadron pairs with larger R_L occur more frequently as the available phase space increases, resulting in Σ_{EEC} scaling approximately linearly with R_L .

- (iii) The intermediate R_L transition region exhibits a peak structure where the hadronization contribution diminishes toward larger R_L and the perturbative splitting contribution diminishes toward smaller R_L .

The EEC distributions exhibit a significant jet p_T dependence, even within the limited range of jet momenta in this work. For jets in the higher p_T^{chjet} range, the perturbative region extends to smaller R_L values, consequently shifting the peak of the transition region to a lower R_L . This behavior is expected since the energy scale or virtuality, μ , of the parton splitting is proportional to the product of the jet p_T and R_L . When μ approaches the confinement scale Λ from above, parton splitting ceases and the Σ_{EEC} stops increasing. Instead, hadronization takes over and shapes the EEC distributions down to $R_L = 0$. As a result, the transition peak should be located at $R_L \sim \Lambda / p_T^{\text{chjet}}$ [76,77], implying that the EEC in more energetic jets peaks at smaller angular scales, consistent with our observations.

To further examine the dependence of the transition region on the energy of jets, the peak position (R_L^{peak}) and peak height ($\Sigma_{\text{EEC}}^{\text{peak}}$) are extracted for the measured p_T^{chjet} ranges (see Appendix B). We find that R_L^{peak} is proportional to $1 / \langle p_T^{\text{chjet}} \rangle$ and $\Sigma_{\text{EEC}}^{\text{peak}}$ is proportional to $\langle p_T^{\text{chjet}} \rangle / \ln \langle p_T^{\text{chjet}} \rangle$.³ $\langle p_T^{\text{chjet}} \rangle$ is the average p_T for charged-particle jets in each p_T bin, extracted from PYTHIA 8 (Monash tune) reweighted to reproduce the ALICE data in Ref. [72]. To directly visualize the jet p_T dependence of the transition peak position and height, Σ_{EEC} as a function of $\langle p_T^{\text{chjet}} \rangle R_L$ is shown in Fig. 3. The vertical scale of the EEC distribution is scaled by $\ln \langle p_T^{\text{chjet}} \rangle / \langle p_T^{\text{chjet}} \rangle$. Strikingly, the scaled EEC distributions, $\ln \langle p_T^{\text{chjet}} \rangle / \langle p_T^{\text{chjet}} \rangle \Sigma_{\text{EEC}}$, for different p_T^{chjet} bins collapse into a common curve. The transition peak location has been investigated in several recent theoretical studies [78,79], where it is found to be described by nonperturbative transverse momentum dependent fragmentation functions. This framework provides predictive power for the transition position in other collision systems such as e^+e^- annihilation. Importantly, both theoretical calculations and PYTHIA studies [80,81] indicate that the EEC distribution and transition position depend on the color charge and mass of the jet-initiating parton. In the p_T^{chjet} range reported here at LHC beam energy, the inclusive jet sample is predominantly gluon initiated, and thus the observed scaling behavior reflects the characteristic behavior of gluon jets. At higher jet energies, the quark-initiated jet fraction increases, which may lead to modifications in the scaling relation $R_L^{\text{peak}} \propto \langle p_T^{\text{chjet}} \rangle$. Testing this evolution and potential

³The $\langle p_T^{\text{chjet}} \rangle$ inside $\ln \langle p_T^{\text{chjet}} \rangle$ actually represents $\langle p_T^{\text{chjet}} \rangle / (\text{GeV}/c)$, which is a unit-less number. For simplicity in notation, we use $\ln \langle p_T^{\text{chjet}} \rangle$ for $\ln(\langle p_T^{\text{chjet}} \rangle / (\text{GeV}/c))$ throughout this paper.

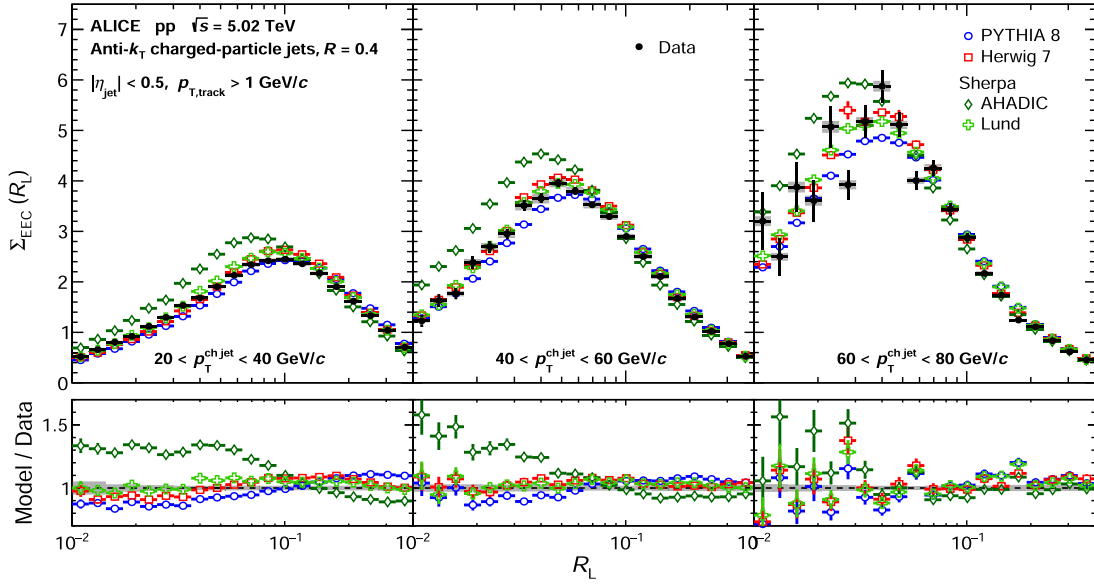


FIG. 4. Top: fully corrected Σ_{EEC} as a function of R_L . Bottom: ratio of Σ_{EEC} from MC event generators to data. The gray band centered at 1 represents systematic uncertainty from data.

deviations from the observed scaling will be possible with the high-statistics data from ALICE Run 3.

At large R_L , a next-to-leading-logarithmic pQCD calculation [42] is shown in the orange curve. The overall magnitude of the pQCD curve is normalized to data in the large-angle region where $\langle p_T^{\text{ch,jet}} \rangle R_L \gg \Lambda_{\text{QCD}}$ [42]. The normalization range is R_L between $12 \text{ GeV}/c / \langle p_T^{\text{ch,jet}} \rangle$ (indicated by the dashed orange line in Fig. 3) and 0.4 (jet radius), which is accessible in the measured EEC distribution of the 60–80 GeV/c range. Inside this R_L range, qualitative agreement is observed between the pQCD prediction and the measurement, except for the last point where R_L approaches the jet radius. With higher p_T jets, the R_L range accessible for comparison with perturbative predictions extends to smaller values, as demonstrated in the CMS measurement at higher jet energies [57]. At smaller R_L , the data deviate from perturbative scaling, which is expected as nonperturbative effects such as soft radiation and hadronization become important. Recent theoretical studies show that power corrections for non-perturbative effects [82,83] can be added to pQCD calculations, which extend the description of EEC measurements to smaller angles.

After the transition region where a broad peak structure is observed, the data follow a different R_L dependence at very small R_L . This can be described by a linear function in R_L , shown by the purple curve in Fig. 3. The linear function is fit to the EEC distribution of 20–40 GeV/c in R_L range of 0.01, the lower limit of measured R_L range, to $0.7 \text{ GeV}/c / \langle p_T^{\text{ch,jet}} \rangle$, which is represented by the dashed purple line in Fig. 3. Linear scaling is expected if the energy is uniformly distributed, where the correlation strength

depends only on the area of the infinitesimal ring at distance R_L and is thus proportional to $R_L dR_L$, which is often referred to as the nonperturbative or free hadron scaling region [41,57,74]. This linear dependence, resulting from hadronization, breaks down towards larger angles because hadrons are produced from localized color fields, leading to a suppression of correlations between hadrons at large angular separations (R_L). In this region, parton splittings become the dominant contribution to the distribution.

The maxima of the transition peaks coincide at $\langle p_T^{\text{ch,jet}} \rangle R_L = 2.43 \pm 0.14 \text{ GeV}/c$. This observation implies a common energy scale where QCD radiations stop and hadronization effects take over, independent of the jet energy. Interestingly, the transition peak position is not affected by lowering the $p_{T,\text{track}}$ selection to 0.15 GeV/c for the measured $p_T^{\text{ch,jet}}$ range (see Appendix C). The shape of the transition region in Fig. 3 is also independent of jet energy, up to 80 GeV/c—the highest p_T accessible with our data sample.

Figure 4 compares the measured EEC distributions and the MC models PYTHIA 8.235 (Monash tune) [67], Herwig 7.2.1 (default tune) [73], and Sherpa 2.2.15 [84]. The default parton shower models are used for PYTHIA 8 (p_T -ordered), Herwig 7 (angular-ordered), and Sherpa (p_T -ordered). The MC models used here implement different hadronization mechanisms. PYTHIA 8 uses the Lund string hadronization model, which produces hadrons by breaking a color string into color-neutral hadrons. Herwig 7 uses a cluster hadronization model, where locally color-connected partons are collected into clusters which then decay into hadrons. In Sherpa, the AHADIC tune uses a cluster hadronization model, while the Lund tune uses the Lund string hadronization. Both PYTHIA 8 and Herwig 7 describe the data within 20% across

the measured R_L range. The transition region peaks at a slightly larger angle in PYTHIA 8 compared to Herwig 7. Herwig 7 better describes the transition peak position, but overestimates the maximum value of the transition peak. For Sherpa, the Lund tune agrees with the data quite well, while the AHADIC tune shows up to a 50% deviation in the small-angle region. The agreement with data improves for MC models as the jet p_T increases. When comparing the EEC distributions from Sherpa with different hadronization models to data, it is worth noting that the transition region from AHADIC (cluster hadronization) is at a smaller angle compared to the Lund tune (string hadronization). Such a shift of the transition region is also observed when comparing Herwig 7 and PYTHIA 8, where Herwig 7 shows a transition region at smaller angles compared to PYTHIA 8. The impact of the different hadronization parameters in PYTHIA 8 on the transition region of EEC distributions can be found in Appendix D. More detailed comparisons with MC models could constrain the parton shower, hadronization, and hadronic interactions in the models.

VI. CONCLUSIONS

We report the EEC distributions for charged-particle jets produced in pp collisions measured with the ALICE detector. This marks the first energy correlator measurements that are fully corrected for detector effects at the LHC for low- p_T jets. The data are in good agreement with a pQCD calculation in the large angle region. EEC at small R_L can be described by a linear function of R_L , consistent with a spatially uniform population of particles produced from hadronization. The transition region is established at the crossover of the two mechanisms, with perturbative contributions diminishing toward smaller R_L and hadronization contributions diminishing toward larger R_L . The transition region shows a clear jet energy dependence, peaking at a smaller angular scale for jets with higher p_T . The renormalized EEC distributions as a function of $\langle p_T^{\text{ch,jet}} \rangle R_L$ reveal that this quantity governs the shape of the EEC distribution, directly relating to the energy scale (virtuality) of jets. A common transition position occurs at $R_L \sim (2.4 \text{ GeV}/c)/\langle p_T^{\text{ch,jet}} \rangle$.

MC models describe the data within 20% across the measured R_L range, except for Sherpa with AHADIC tune. The discrepancy between models and data decreases for jets with higher energy. As the hadronization process is a nonperturbative phenomenon, theory predictions based on first principles are challenging, and developments in lattice QCD and quantum computation may offer needed improvements [85]. In the future, measurements of higher-order energy correlators and comparison of EEC measurements from different collision systems can provide further insight on the confinement process [40,41,86]. The study presented in this paper provides a baseline for using EEC to study cold

and hot nuclear medium effects on jet formation and propagation.

ACKNOWLEDGMENTS

The ALICE Collaboration gratefully acknowledges Kyle Lee for providing theoretical predictions. The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all grid centers and the Worldwide LHC Computing Grid (WLCG) Collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF) [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Bulgarian Ministry of Education and Science, within the National Roadmap for Research Infrastructures 2020-2027 (object CERN), Bulgaria; Ministry of Education of China (MOEC), Ministry of Science & Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the VILLUM FONDEN and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l’Energie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Forschung, Technologie und Raumfahrt (BMFTR) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial

Research (CSIR), India; National Research and Innovation Agency–BRIN, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Academico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Pontificia Universidad Católica del Perú, Peru; Ministry of Science and Higher Education, National Science Centre and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics, Ministry of Research and Innovation and Institute of Atomic Physics and Universitatea Nationala de Stiinta si Tehnologie Politehnica Bucuresti, Romania; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSTDA) and National Science, Research and Innovation Fund (NSRF via PMU-B B05F650021), Thailand; Turkish Energy, Nuclear and Mineral Research Agency (TENMAK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and U.S. Department of Energy, Office of Nuclear Physics (DOE NP), USA. In addition, individual groups or members have received support from: Czech Science Foundation (Grant No. 23-07499S), Czech Republic; FORTE project, Reg. No. CZ.02.01.01/00/22_008/0004632, Czech Republic, cofunded by the European Union, Czech

Republic; European Research Council (Grant No. 950692), European Union; ICSC–Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, European Union–NextGenerationEU; Academy of Finland (Center of Excellence in Quark Matter) (Grants No. 346327 and No. 346328), Finland, CONVECS project, CUP C97H23001700002 FESR 2021-2027 program, Italy.

APPENDIX A: ADDITIONAL ANALYSIS INFORMATION

Figure 5 shows a detailed breakdown of the systematic uncertainties from individual sources.

The unfolding is performed in three dimensions for EEC pairs inside jets similar to the CMS measurement [57], R_L , $p_T^{\text{ch jet}}$, and energy weight. The same simulation setup used to derive the bin-by-bin correction factors is used to construct the response matrices. The energy weights are divided into 20 equal intervals on a logarithmic scale, ranging from 10^{-5} to 1. The unfolded energy weight is then summed to calculate the Σ_{EEC} using the following equation:

$$\Sigma_{\text{EEC}}(R_L, p_T^{\text{ch jet}}) = \sum_{w_{\text{pair}} \text{ bins}} w_{\text{pair}} \times N_{\text{pair}}(w_{\text{pair}}, R_L, p_T^{\text{ch jet}}), \quad (\text{A1})$$

where w_{pair} represents a certain energy weight bin, and $N_{\text{pair}}(w_{\text{pair}}, R_L, p_T^{\text{ch jet}})$ is the number of pairs in the corresponding energy weight bin.

The finite number of bins used for energy weight in the unfolding method results in a slightly higher Σ_{EEC} than the truth value obtained from directly summing over weights of all EEC pairs, which is $\approx 1.2\%$ for our binning choice. To account for such effect with our binning choice, a multiplicative correction factors are applied on the Σ_{EEC} calculated from Eq. (A1).

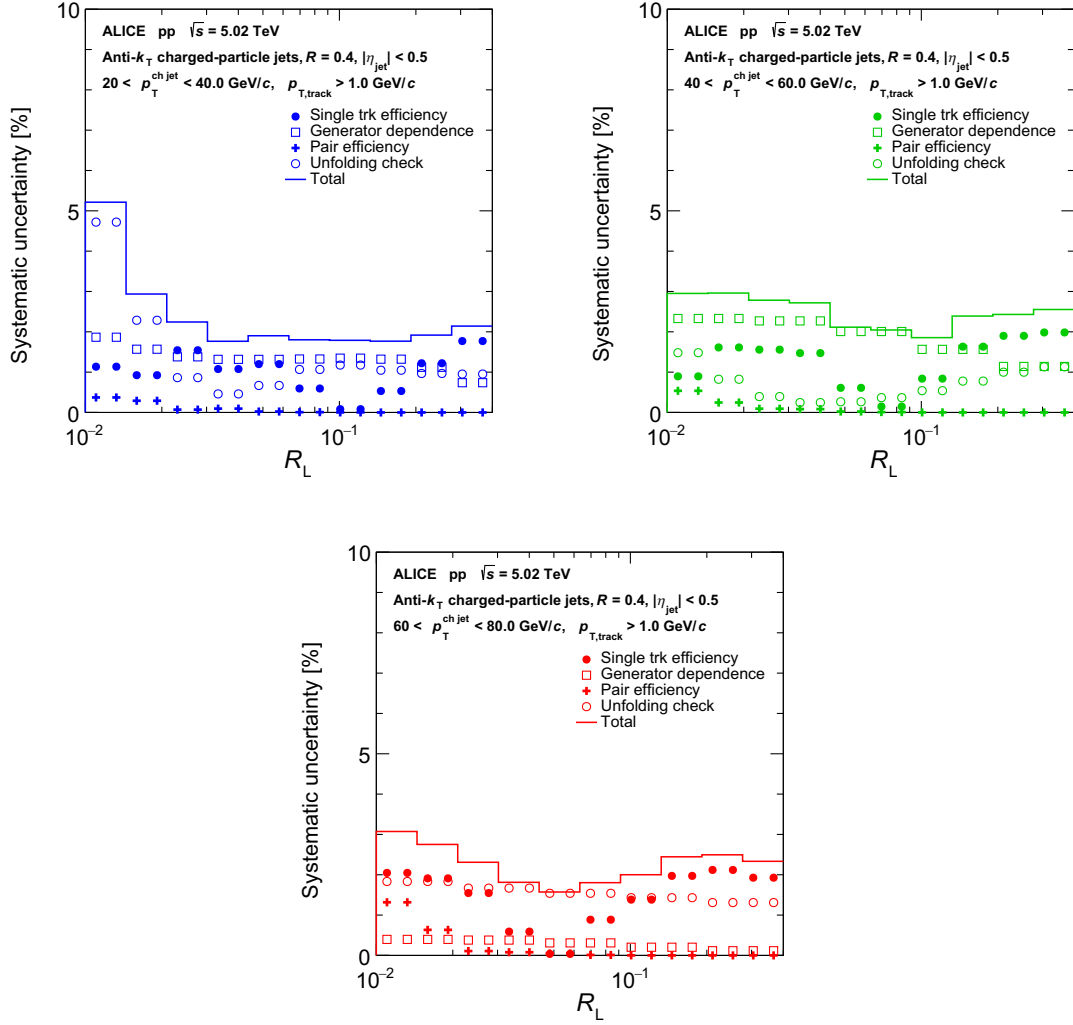


FIG. 5. Systematic uncertainties for fully corrected Σ_{EEC} as a function of R_L in the p_T^{chjet} intervals 20–40, 40–60, and 60–80 GeV/c.

APPENDIX B: CHARACTERIZATION OF THE TRANSITION REGION

To quantitatively characterize the transition region, we employ two complementary fitting approaches to extract the transition peak position and peak height, as detailed below.

1. Method 1: Local log-normal fits on the EEC distributions

We perform local fits to the EEC distributions in each jet p_T range separately using a log-normal function:

$$\text{Gaus}(\ln(R_L)) = C \cdot \exp\left(-\frac{(\ln R_L - \mu)^2}{2\sigma^2}\right), \quad (\text{B1})$$

where C is a normalization constant. The fit range is restricted to $\mu \pm 0.7\sigma$, the region where the function provides a reasonable description of the transition peak.

The fit results are shown in Fig. 6. The peak position R_L^{peak} and its uncertainty are extracted via $R_L^{\text{peak}} = \exp(\mu)$.

Using the extracted values from Fig. 6, we examine the jet p_T dependence of the peak position and peak height in Fig. 7. The mean values $\langle p_T^{\text{chjet}} \rangle$ for the three jet p_T^{chjet} intervals (20–40, 40–60, 60–80 GeV/c) are 25.1, 46.7, and 67.5 GeV/c, respectively. The notation $\ln\langle p_T^{\text{chjet}} \rangle$ represents $\ln(\langle p_T^{\text{chjet}} \rangle / (\text{GeV}/c))$ as explained in footnote 3. Using this method, we obtain $R_L^{\text{peak}} \times \langle p_T^{\text{chjet}} \rangle \approx 2.36 \pm 0.04 \text{ GeV}/c$ and $\Sigma_{\text{EEC}}^{\text{peak}} \times \ln\langle p_T^{\text{chjet}} \rangle / \langle p_T^{\text{chjet}} \rangle \approx 0.316 \pm 0.003 (\text{GeV}/c)^{-1}$.

2. Method 2: Global fit to scaled EEC distributions

As an alternative approach, we employ the following functional form:

$$f(x) = C \frac{x}{(x^2 + T^{3/2})}, \quad (\text{B2})$$

where C and T are fit parameters and the maximum occurs at $x = \sqrt{T/2}$. This function exhibits linear dependence at

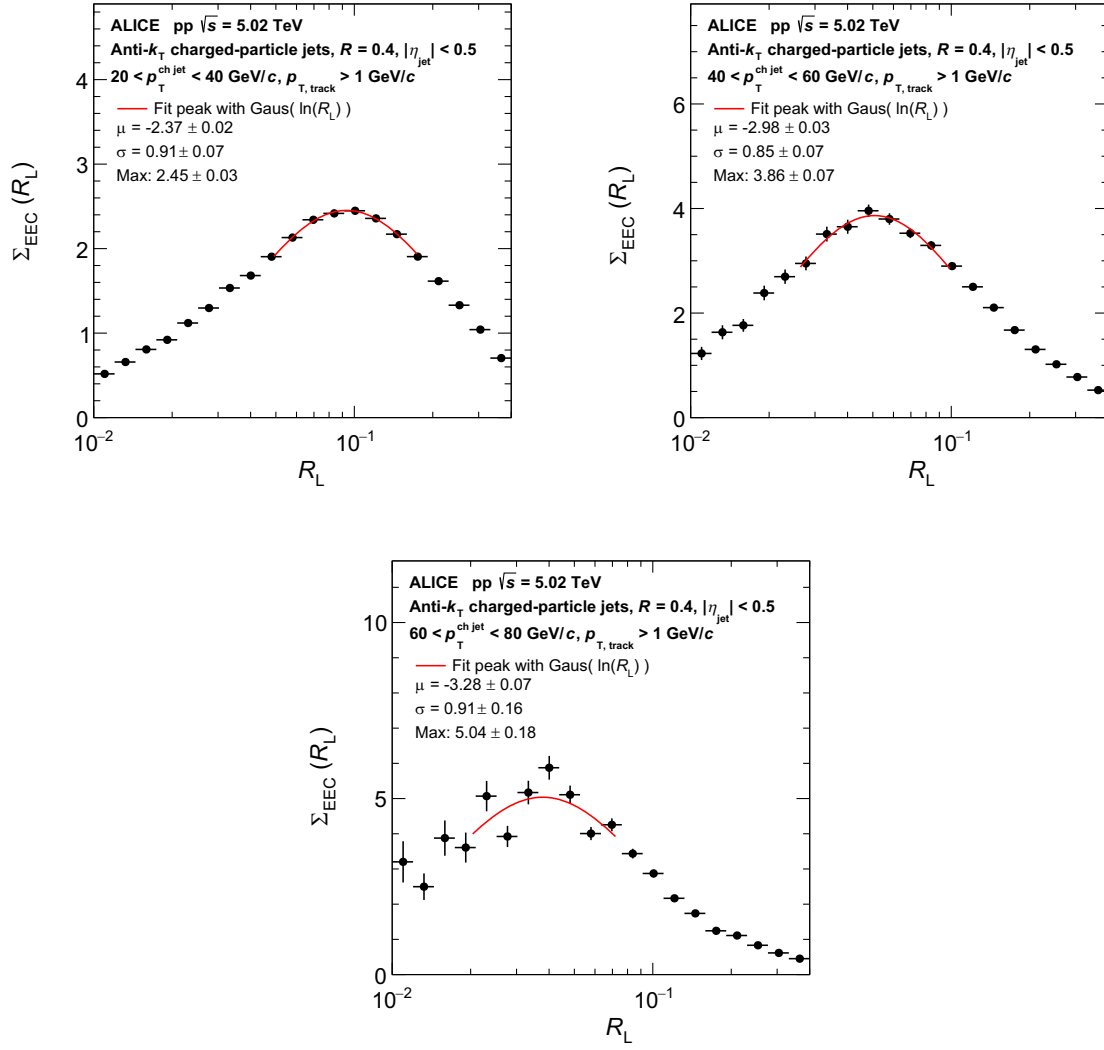


FIG. 6. Extraction of the peak position and height of the EEC distributions in different jet p_T ranges using local log-normal fits. The fit function and fitting range are shown by the red curves.

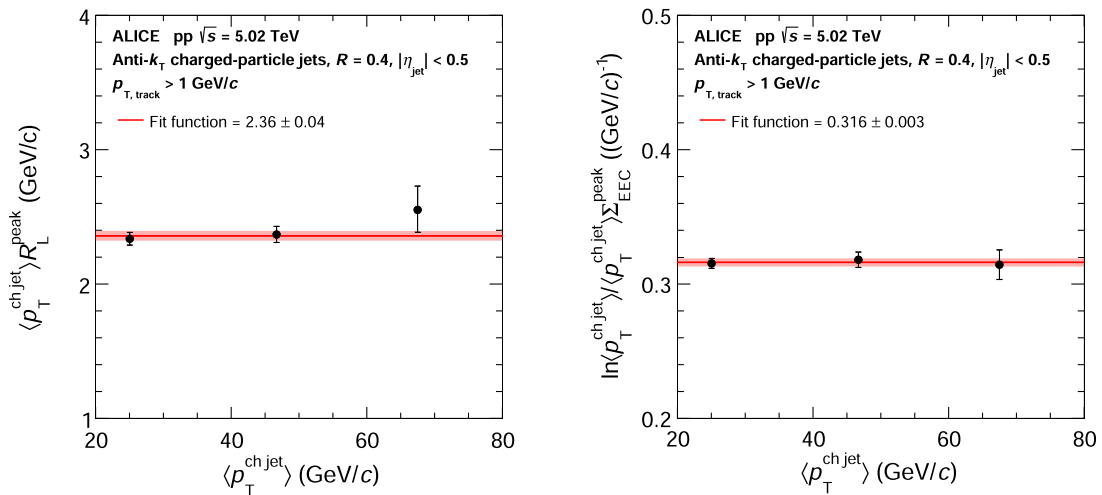


FIG. 7. Left: jet p_T dependence of the transition peak position R_L^{peak} . Right: jet p_T dependence of the transition peak height $\Sigma_{\text{EEC}}^{\text{peak}}$. The notation $\ln(\langle p_T^{\text{ch jet}} \rangle)$ in the y-axis represents $\ln(\langle p_T^{\text{ch jet}} \rangle / (\text{GeV}/c))$, a unit-less number, used throughout this paper for simplicity in notation.

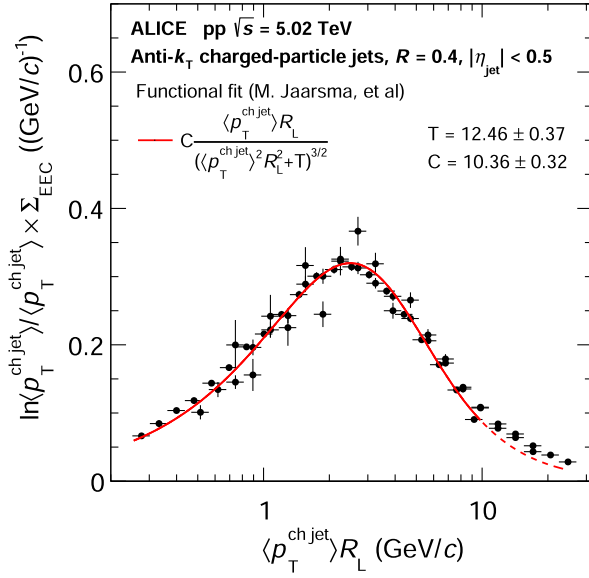


FIG. 8. Normalized Σ_{EEC} as a function of $\langle p_T^{\text{ch,jet}} \rangle R_L$ for $p_T^{\text{ch,jet}}$ in 20–40, 40–60, and 60–80 GeV/c. Statistical and systematic uncertainties are combined in quadrature. The fit function is shown by the red curve, with the solid portion indicating the fitting range.

small x , x^{-2} behavior at large x , and a smooth transition between these limits, making it well suited to describe the full shape of the transition region [74].

We fit this function to the combined p_T scaled EEC distribution from all three jet p_T ranges, which is shown in Fig. 8. The fitting range is restricted to exclude the perturbative region at large $\langle p_T^{\text{ch,jet}} \rangle R_L$, where this functional form is not expected to apply. From this global fit, we extract $R_L^{\text{peak}} \times \langle p_T^{\text{ch,jet}} \rangle = \sqrt{T/2} \approx 2.50 \pm 0.04$ GeV/c and $\Sigma_{\text{EEC}}^{\text{peak}} \times \ln \langle p_T^{\text{ch,jet}} \rangle / \langle p_T^{\text{ch,jet}} \rangle \approx 0.320 \pm 0.003$ (GeV/c) $^{-1}$.

3. Final results

To obtain robust estimates of the peak position and height, we average the results from both methods and assign the maximum difference between them as the uncertainty, as follows:

$$R_L^{\text{peak}} \times \langle p_T^{\text{ch,jet}} \rangle \approx 2.43 \pm 0.14 \text{ GeV/c} \quad (\text{B3})$$

$$\Sigma_{\text{EEC}}^{\text{peak}} \times \ln \langle p_T^{\text{ch,jet}} \rangle / \langle p_T^{\text{ch,jet}} \rangle \approx 0.314 \pm 0.004 \text{ (GeV/c)}^{-1}. \quad (\text{B4})$$

The jet p_T dependence of the transition region described in Eqs. (B3) and (B4) can also be viewed in Fig. 2.

APPENDIX C: RESULTS WITH DIFFERENT TRACK THRESHOLD SELECTIONS

The reported results in the main text use charged-particle tracks with $p_{T,\text{track}} > 1$ GeV/c threshold cut when constructing the EECs. We also carried out the measurement with lower threshold cuts, $p_{T,\text{track}} > 0.15$ GeV/c and $p_{T,\text{track}} > 0.5$ GeV/c. The comparison of the EEC distributions with different track threshold selections is shown in Fig. 9. Different track threshold selections lead to a small difference in the EEC distributions at large R_L and the difference becomes negligible for jets with higher p_T . The transition peak positions are not affected by the different $p_{T,\text{track}}$ selections used.

APPENDIX D: PYTHIA 8 STUDIES

To obtain more intuition about the transition region in the EEC distributions and the hadronization process, we studied with PYTHIA 8.235 (Monash tune) how different parameters impact the EECs. The parameters checked are the following:

- (i) Parameter related to the hadron fragmentation: StringPT:sigma, which corresponds to the average transverse momentum from string breaking.
- (ii) Parameter related to the parton shower: TimeShower:pTmin, which corresponds to the parton shower cutoff p_T for QCD emissions.

We then vary the above parameters up and down by 30% from the default values and compare how it impacts the EEC cross section as a function of R_L . We looked both at the charged hadron level and parton level to gain further insight into the impact at different stages of the jet evolution modeled by PYTHIA 8. The results are shown in Figs. 10 and 11. The blue markers always correspond to the default PYTHIA 8 tuning in Monash tune.

From Fig. 10, it can be seen that the TimeShower:pTmin parameter has a significant impact on the EECs at the parton level but shows almost no visible impact on the EEC at the charged hadron level. Such an observation indicates that the transition peak of the hadron level EEC (what can be measured) is not very sensitive to the QCD shower cutoff parameter. Despite not being able to measure the parton level EEC, it is interesting to see that there is a turnover transition region and the location of that moves to a smaller angle when changing the QCD shower cutoff to a smaller value, while the transition location moves towards a larger angle with increasing QCD shower cutoff. This is consistent with the intuition that the R_L is related to the energy scale of the parton splitting, hence when we lower the shower cutoff, the EEC continues on the parton shower trend for a wider R_L region. Once the hadronization effects are included, the transition region with different TimeShower:pTmin appear at a very similar location.

Contrary to the observation in Fig. 10, in Fig. 11 we observe that when we alter StringPT:sigma, which is

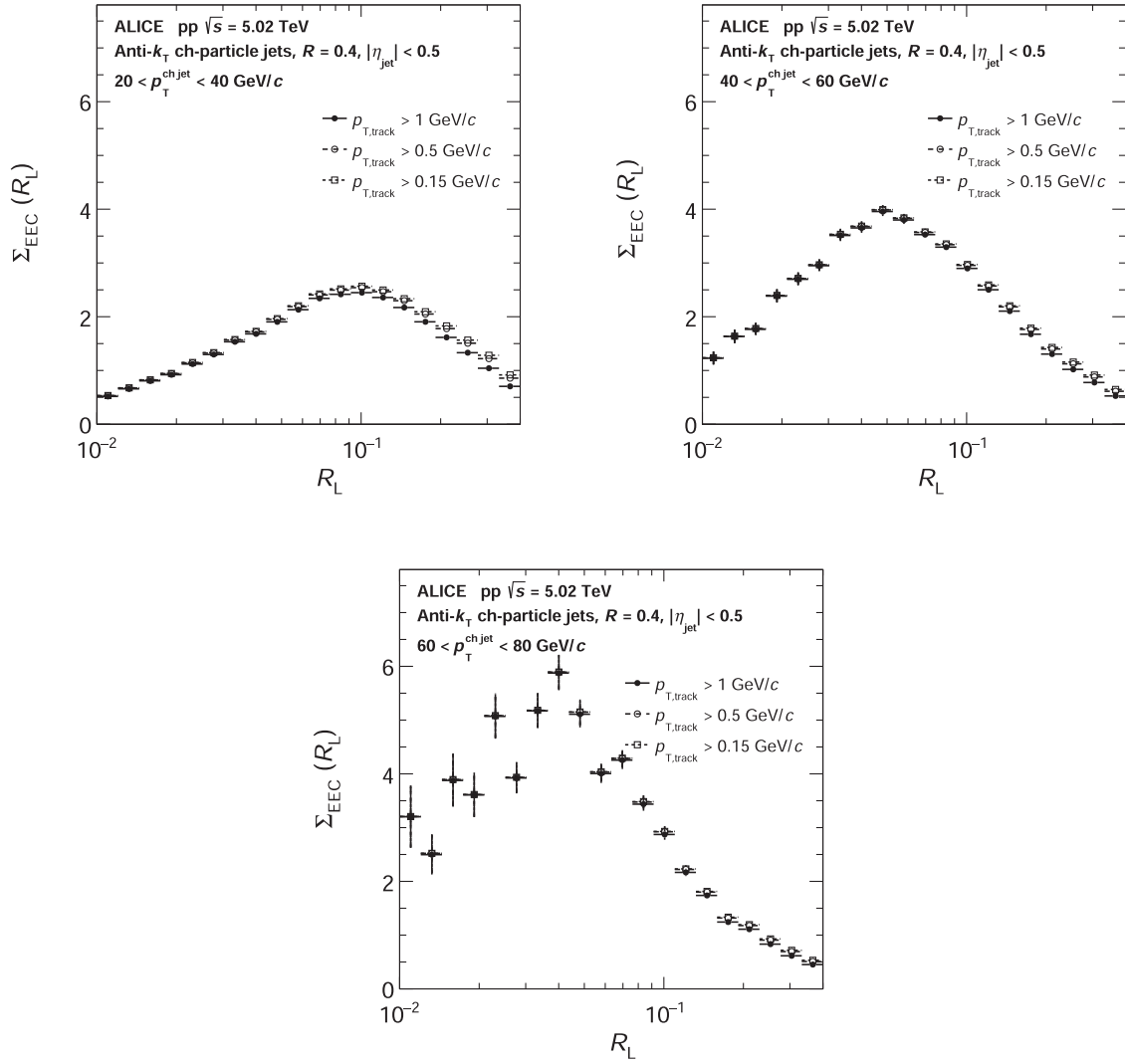


FIG. 9. Comparison Σ_{EEC} as a function of R_L with 0.15 GeV/ c , 0.5 GeV/ c , and 1 GeV/ c track p_T threshold cut in the p_T^{chjet} intervals 20–40, 40–60, and 60–80 GeV/ c . Systematic uncertainties are not shown here.

directly related to the hadronization process, a significant change is observed in the EECs at hadron level but no visible difference at the parton level. Since StringPT:sigma is only related to the hadron fragmentation, it makes sense that the variation of this parameter does not affect the EECs at parton level. On the other hand, at the hadron level, the transition peak seems to be sensitive to the variations of StringPT:sigma. The transition location shifts to smaller angles when we decrease this parameter. The smaller

StringPT:sigma corresponds to smaller string tension where the Lund strings break up later and a lower energy scale. This picture is consistent with the observed shift when StringPT:sigma is decreased.

These PYTHIA 8 studies support that the transition peak is sensitive to hadronization process. We hope these studies and the reported measurement can motivate first principle calculations which can help draw conclusive statements.

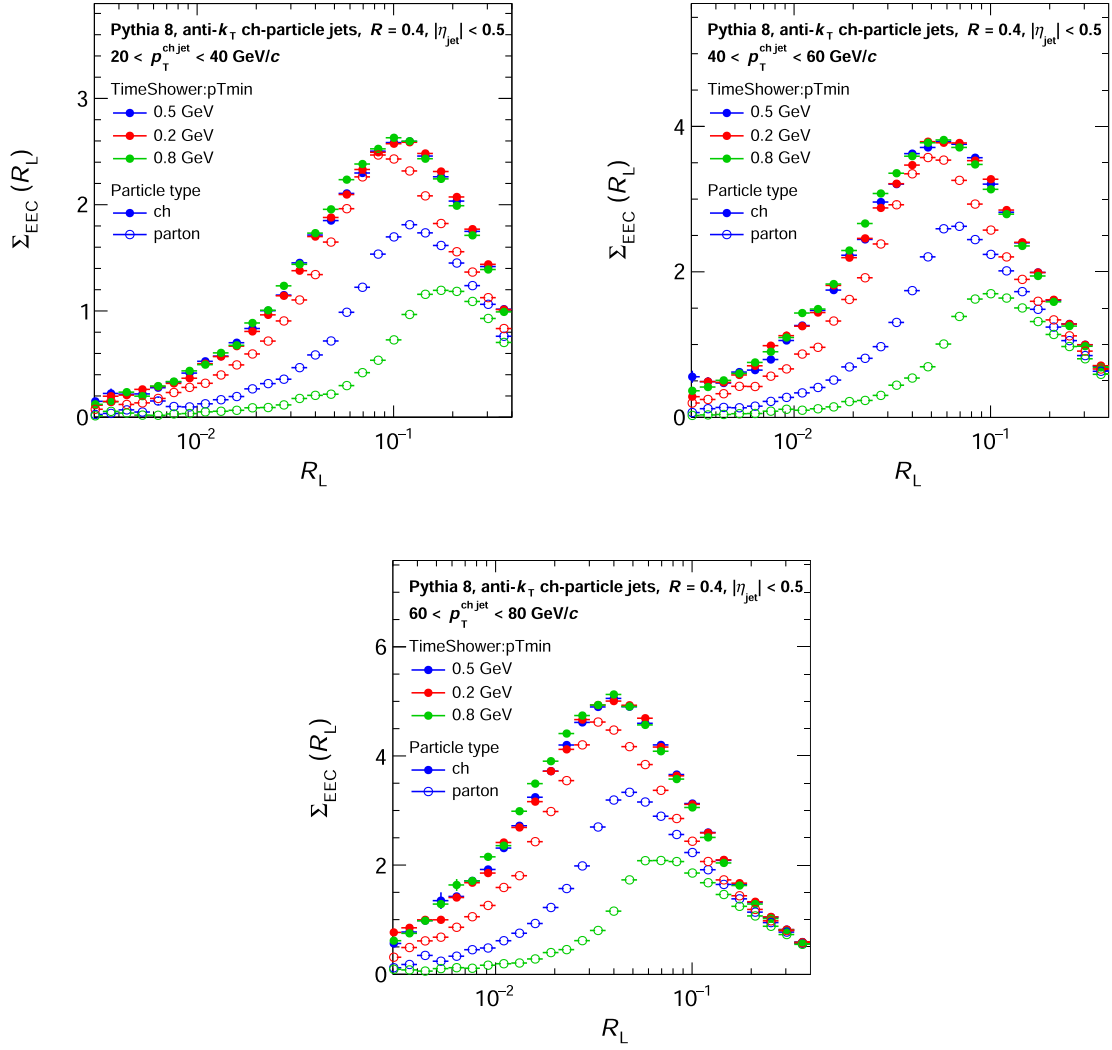


FIG. 10. Comparison of Σ_{EEC} as a function of R_L with different values for TimeShower:pTmin using generated PYTHIA events. The default setting is 0.5 (blue markers). The parton level distributions are made from parton jets that are matched to the charged jets with p_T range indicated in each figure.

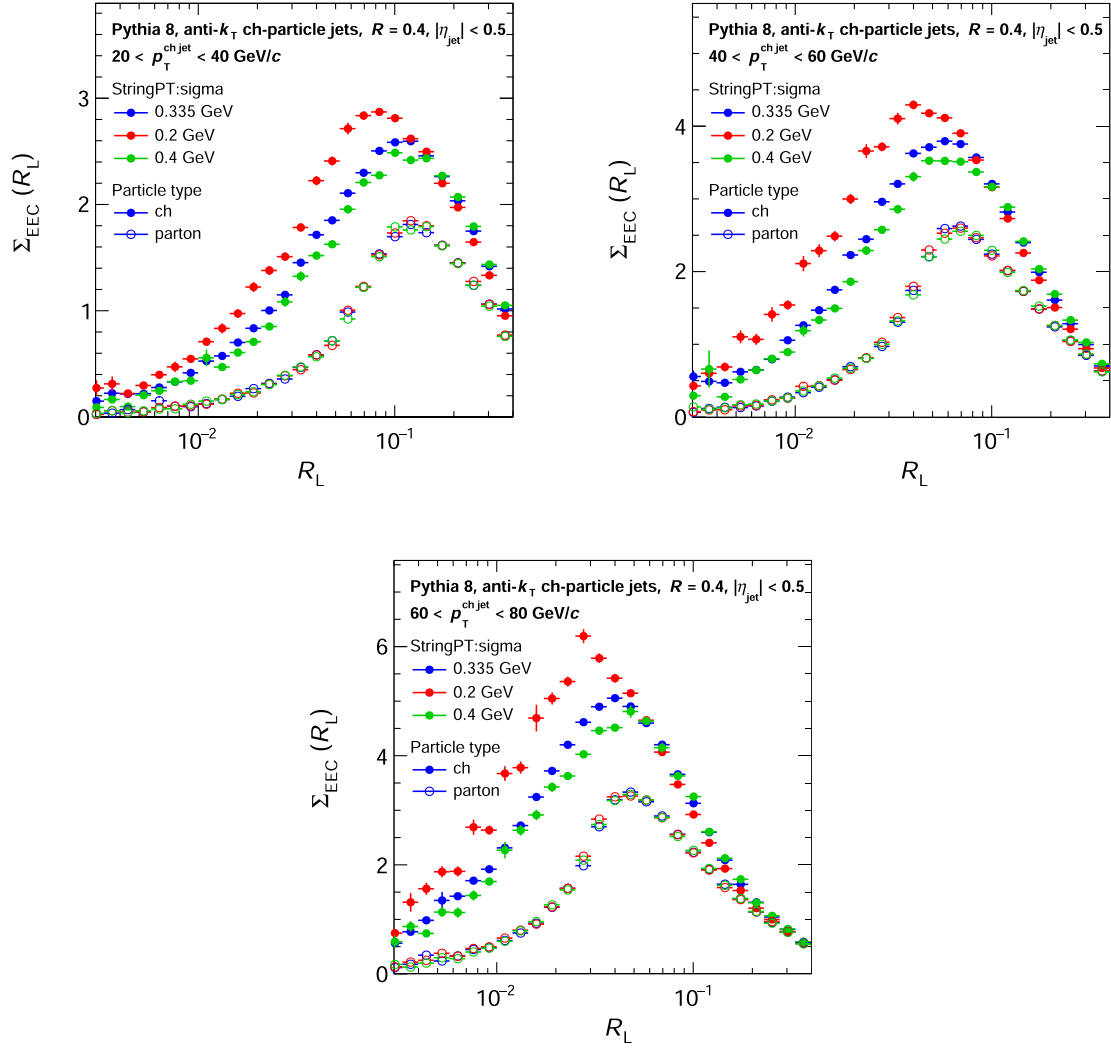


FIG. 11. Comparison of Σ_{EEC} section as a function of R_L with different values for StringPT:sigma using generated PYTHIA 8 events. The default setting is 0.335 (blue markers). The parton level distributions are made from parton jets that are matched to the charged jets with p_T range indicated in each figure.

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