

Observation of Enhanced Long-Range Elliptic Anisotropies Inside High-Multiplicity Jets in pp Collisions at $\sqrt{s} = 13$ TeV

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A search for collective effects inside jets produced in proton-proton collisions is performed via correlation measurements of charged particles using the CMS detector at the CERN LHC. The analysis uses data collected at a center-of-mass energy of $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 138 fb^{-1} . Jets are reconstructed with the anti- k_T algorithm with a distance parameter of 0.8 and are required to have transverse momentum greater than 550 GeV and pseudorapidity $|\eta^{\text{jet}}| < 1.6$. Two-particle correlations among the charged particles within the jets are studied as functions of the particles' azimuthal angle and pseudorapidity separations ($\Delta\phi^*$ and $\Delta\eta^*$) in a jet coordinate basis, where particles' η^* , ϕ^* are defined relative to the direction of the jet. The correlation functions are studied in classes of in-jet charged-particle multiplicity up to $N_{\text{ch}}^j \approx 100$. Fourier harmonics are extracted from long-range azimuthal correlation functions to characterize azimuthal anisotropy for $|\Delta\eta^*| > 2$. For low- N_{ch}^j jets, the long-range elliptic anisotropic harmonic, v_2^* , is observed to decrease with N_{ch}^j . This trend is well described by Monte Carlo event generators. However, a rising trend for v_2^* emerges at $N_{\text{ch}}^j \gtrsim 80$, hinting at a possible onset of collective behavior, which is not reproduced by the models tested. This observation yields new insights into the dynamics of jet evolution in the vacuum.

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The theory of quantum chromodynamics (QCD) describes the strong interaction among partons (quarks and gluons) carrying color charges. At low energies, the color force is very strong and partons are confined in color-neutral objects (hadrons)—a property that results from the nonperturbative nature of QCD in this regime. In high-energy proton collisions, large momentum transfers between partons inside the colliding protons can result in a collimated spray of hadrons originating from the fragmentation and hadronization of an outgoing parton. This collimated spray is called a “jet.” [1,2]. Energetic jets are produced abundantly at LHC collision energies and can generate large final-state hadron multiplicities (e.g., > 100 charged particles) resulting from a single parton.

Final states containing thousands of hadrons are routinely produced in high-energy nucleus-nucleus (AA) collisions, where a hot medium of deconfined partons known as a quark-gluon plasma is formed [3–9]. The extreme parton densities realized in these collisions result in strong partonic rescatterings that quickly drive the

system toward a nearly ideal hydrodynamic limit. As a result, long-range collective flow effects have been observed at the BNL RHIC [3–6] and the CERN LHC [10–14].

It was originally thought that small collision systems such as electron-positron (e^+e^-), electron-proton (ep), and proton-proton (pp) collisions would produce final states that were too small and dilute for secondary partonic rescatterings to drive the system toward thermal equilibrium. Collective hydrodynamic behavior was not expected to play an important role in these final states, notwithstanding some early studies [15,16]. Surprisingly, strong long-range collective correlations, similar to those observed in AA collisions, were discovered in the azimuthal distributions of charged particles in the laboratory reference frame of pp collisions having a large final-state multiplicity in the entire event [17–20]. This raised the question of whether a tiny quark-gluon plasma droplet is created in such conditions [21]. Subsequently, similar collective phenomena were observed in proton-nucleus (pA) collisions [22–32], and lighter AA systems [32–35]. Correlation studies in e^+e^- [36–38], ep [39,40], photon-proton (γp) [41], and photonuclear (γA) [42] systems have been limited to relatively low-multiplicity events (less than a total of 30–40 charged particles per event) and have not unambiguously demonstrated such behavior.

It is natural to ask what minimum system size is needed for QCD collective effects to develop. Although the

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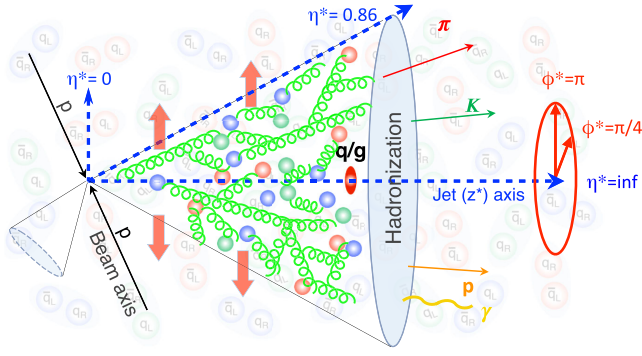


FIG. 1. An illustration showing the idea of an initially scattered parton evolving to a shower that eventually exhibits collective expansion transverse to the jet axis (represented by red arrow boxes). A jet cone (not to scale) and emerging final state particles are drawn in a coordinate system, denoted as the “jet basis,” where the z axis coincides with the jet direction. The redefined pseudorapidity η^* is shown with key values in dotted blue lines, and the azimuthal angle ϕ^* is shown with key values in solid red.

dynamics of parton showering inside a jet is theoretically well described by perturbative QCD calculations [43,44], a possible buildup of collective correlations within the parton constituents of a jet had not been considered. In Ref. [45], it is postulated that collective effects can emerge from an initial system as small as an energetic parton that fragments and hadronizes in the vacuum, as illustrated in Fig. 1. Motivated by that idea, this Letter presents a search for such collective effects inside individual jets (as opposed to full events) produced in pp collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV using the CMS detector at the LHC. Using a coordinate system defined with respect to the jet axis—a proxy for the direction of the parton initiating the jet—the two-particle correlation of charged particles of a jet is measured as a function of the in-jet charged particle multiplicity, N_{ch}^j . Tabulated results are provided in the HEPData record for this analysis [46].

The CMS apparatus [47] is a multipurpose, nearly hermetic detector designed to trigger on [48,49] and identify electrons, muons, photons, and hadrons [50–52]. The initial triggering is done with the level-1 system, which uses customized hardware to make the rapid online decision whether or not to accept an event and deliver it to the second system, the high level trigger. This trigger uses a large CPU farm to perform optimized online event reconstruction and characterize an event. A global “particle-flow” algorithm [53] reconstructs all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build more complex objects such as jets [54–57].

The $\sqrt{s} = 13$ TeV pp collisions used in this analysis were delivered from 2016–2018 and correspond to an integrated luminosity of 138 fb^{-1} . The data were collected using an online trigger searching for events containing anti- k_T jets [58,59] with distance parameter $R = 0.8$ having a transverse momentum (p_T^{jet}) above 500 GeV. In the offline analysis, jets were required to have $p_T^{\text{jet}} > 550$ GeV and pseudorapidity $|\eta^{\text{jet}}| < 1.6$ in the laboratory reference frame.

The generator-level events from two Monte Carlo (MC) models, PYTHIA8.306 [60] with the CP5 tune [61] and SHERPA2.2 [62], are compared with the data. The leading order PYTHIA8 uses the Lund string fragmentation model [63], while the SHERPA generator uses a cluster fragmentation model [64]. Additionally, the PYTHIA8 events are input into GEANT4 [65] to emulate the CMS detector response for calculating correction factors for the tracking efficiency and jet energy scale. The effects of secondary pp interactions within the same or nearby bunch crossings (“pileup”) are incorporated in the simulation.

This analysis is particularly interested in the charged particles of jets. These charged particles are required to have $|\eta| < 2.4$ and $p_T > 0.3$ GeV in the laboratory reference frame. Additional, they must have a p_T uncertainty of $< 10\%$, and a distance of closest approach significance with respect to the primary vertex of at most 3 standard deviations (σ) [52]. The PUPPI algorithm [66,67] is used to mitigate the effect of pileup at the reconstructed particle level, using local shape information, event pileup properties, and tracking information. Jets are classified into different classes based on the number of charged particles of the jet passing these selections and PUPPI subtraction before correcting for detector effects.

Jet energy corrections are derived from MC simulation studies so that the average measured energy of jets equals that of generator-level jets. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures. The jet energy resolution is typically 10% at 100 GeV, and 5% at 1 TeV [55].

The two-particle correlation analysis is similar to that employed in Ref. [22], except that the momentum vectors of all charged particles of a jet are defined in the “jet basis,” as illustrated in Fig. 1. A unique jet reference coordinate basis is defined for every jet such that the z axis is aligned with the direction of the jet momentum [45]. Momentum vectors of charged particles are redefined in this new basis, $\vec{p}^* = (j_T, \eta^*, \phi^*)$. Here, j_T is the particle p_T with respect to the jet axis. The symbols η^* and ϕ^* are the pseudorapidity and azimuthal angle coordinates with respect to the jet axis. Therefore, $\eta^* = 0$ and ∞ correspond to vectors that are perpendicular and parallel to the jet axis, as illustrated in Fig. 1. In this system, $\eta^* = 0.86$ is the approximate boundary of the anti- k_T jet. The origin of the ϕ^* coordinate

is defined as $\hat{p}_{\text{jet}} \times (\hat{p}_{\text{jet}} \times \hat{z})$, where $\hat{p}_{\text{jet}}$ is a unit vector along the jet momentum and $\hat{z}$ is the direction of the $+z$ axis. The choice of $\phi^* = 0$ is irrelevant to the relative ϕ^* between two particles. The azimuthal coordinates of tracks that are approximately parallel to the direction of the jet axis ($\eta^* > 5$) are sensitive to small changes in the jet axis direction caused by resolution effects. These tracks are excluded in the subsequent analysis. Reconstructed particles in the event that are not clustered into the jet of interest are not considered in the analysis. For each jet with $p_T^{\text{jet}} > 550$ GeV, the two-dimensional (2D) angular correlation function is calculated using charged particles from the jet as follows:

$$\frac{1}{N_{\text{ch}}^{\text{trg}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta^* d\Delta\phi^*} = B(0,0) \frac{S(\Delta\eta^*, \Delta\phi^*)}{B(\Delta\eta^*, \Delta\phi^*)}, \quad (1)$$

where $\Delta\eta^*$ and $\Delta\phi^*$ are the relative separation in pseudorapidity and azimuthal angle in the jet basis between a pair of charged particles selected from a given j_T range. The functions $S(\Delta\eta^*, \Delta\phi^*)$ and $B(\Delta\eta^*, \Delta\phi^*)$ represent the signal and combinatorial distributions, respectively,

$$S(\Delta\eta^*, \Delta\phi^*) = \frac{1}{N_{\text{ch}}^{\text{trg}}} \frac{d^2 N_{\text{ch}}^{\text{sig}}}{d\Delta\eta^* d\Delta\phi^*}, \quad (2)$$

and

$$B(\Delta\eta^*, \Delta\phi^*) = \frac{1}{N_{\text{ch}}^{\text{trg}}} \frac{d^2 N_{\text{ch}}^{\text{combin}}}{d\Delta\eta^* d\Delta\phi^*}, \quad (3)$$

where $N_{\text{ch}}^{\text{sig}}$ and $N_{\text{ch}}^{\text{combin}}$ are the numbers of signal and combinatorial pairs, respectively, and $N_{\text{ch}}^{\text{trg}}$ is the number of particles within a specific j_T range used to calculate the correlation functions. The measurement is performed for each class of N_{ch}^j , which is corrected for detector effects (a tracking efficiency of about 90%). The $S(\Delta\eta^*, \Delta\phi^*)$ distribution is calculated with pairs of charged particles from each unique jet individually, and then averaged over all jets. The combinatorial distribution serves as both a reference and a correction to the pair acceptance due to the limited η^* range. To construct the $B(\Delta\eta^*, \Delta\phi^*)$ distribution, a two-dimensional (2D) single-particle η^* - ϕ^* distribution for charged particles of all jets within the N_{ch}^j range chosen for the signal distribution is first obtained. Pairs of (η^*, ϕ^*) points are then randomly selected from this distribution to construct $B(\Delta\eta^*, \Delta\phi^*)$ such that no intrinsic correlations other than the pair acceptance effect are present in $B(\Delta\eta^*, \Delta\phi^*)$. Correlations present in the signal distribution that are related to single-particle distributions or detector effects are canceled by the $B(0,0)/B(\Delta\eta^*, \Delta\phi^*)$ term in Eq. (1). The quantities $\Delta\eta^*$ and $\Delta\phi^*$ are always taken to be positive and used to fill one quadrant of the $(\Delta\eta^*, \Delta\phi^*)$

histograms with the other three quadrants filled by reflection.

The resulting 2D distribution can be further studied by integrating over $|\Delta\eta^*| > 2$ and decomposing into a one-dimensional (1D) Fourier series, as done in previous analyses [17,19,20,22,27–29],

$$\frac{1}{N_{\text{ch}}^{\text{trg}}} \frac{dN^{\text{pair}}}{d\Delta\phi^*} \propto 1 + 2 \sum_{n=1}^{\infty} V_{n\Delta}^* \cos(n\Delta\phi^*). \quad (4)$$

By applying $|\Delta\eta^*| > 2$, short-range few-body correlations, such as resonance and cluster decays [17], are excluded. Of particular interest is the second Fourier component, which is associated with elliptic anisotropies. The elliptic anisotropy coefficient, v_2^* , is the main observable of interest and is related to the two-particle Fourier coefficient by assumed factorization as $v_2^* = \sqrt{V_{2\Delta}^*}$ [20,27].

The primary sources of systematic uncertainty come from the jet axis pointing resolution, the p_T^{jet} resolution, residual pileup effects, and the tracking efficiency. These four sources are added together in quadrature to calculate the total systematic uncertainty for each N_{ch}^j class. To minimize statistical fluctuations, the four highest jet multiplicity classes examined are combined together when evaluating systematic effects. The effect of the jet pointing resolution is studied by smearing each jet axis in the 2D η - ϕ plane according to the resolution calculated in MC samples. The coordinate transformation of particles' j_T , η^* , and ϕ^* into the jet basis is recalculated with the new smeared jet axis, and the analysis procedure is repeated. The difference of $V_{n\Delta}^*$ values before and after smearing is taken as the systematic uncertainty. The impact of this effect on $V_{n\Delta}^*$ is between 0.01 and 0.04 (depending on the j_T range examined) at lower N_{ch}^j , where particles inside a jet tend to have a narrower angular distribution and therefore larger changes to their jet basis kinematic values for a given jet axis variation. On the other hand, this uncertainty is < 0.001 at higher N_{ch}^j because the particles of these jets tend to have a wider angular separation from the jet axis on average. A similar smearing procedure found the uncertainty in $V_{n\Delta}^*$ coming from the p_T^{jet} resolution to range from negligible to 0.002. The systematic uncertainty from residual pileup effects is estimated by first splitting the data into two roughly equal subsets based on the number of reconstructed vertices in each event. The resulting high and low vertex number subsets were then treated independently and the full analysis procedure was carried out on both. The root mean square of the deviations in measured observables of these two subsets from the nominal result is taken as the uncertainty. For $V_{2\Delta}^*$, this uncertainty ranges from 0.001–0.003. Additional pileup studies varying PUPPI selection requirements were found to have a negligible impact. Potential contamination of collective effects from the underlying event was investigated by injecting a sizable

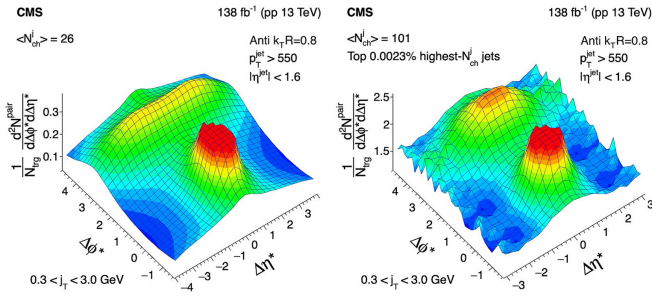


FIG. 2. Results for 2D two-particle angular correlation functions for particle $0.3 < j_T < 3.0$ GeV from inclusive (left) and the highest (right) N_{ch}^j jets, for anti- k_T $R=0.8$ algorithm with $p_T^{\text{jet}} > 550$ GeV and $|\eta^{\text{jet}}| < 1.6$.

lab frame v_2 signal, and is found to have no impact on the jet frame v_2^* . The systematic uncertainty resulting from the tracking efficiency correction is evaluated by applying tighter and looser restrictions on the relative p_T uncertainty and track vertex association criteria, repeating the analysis procedure, and calculating the root mean square of the deviations of these variations from the nominal case. The uncertainty in $V_{2\Delta}^*$ from this source is less than 0.003.

Figure 2 shows an example of 2D two-particle angular correlation functions in the jet basis for inclusive and high- N_{ch}^j jets for charged particles in the range $0.3 < j_T < 3.0$ GeV. The average N_{ch}^j value for the two classes of jets shown, $\langle N_{\text{ch}}^j \rangle$, is 26 and 101. The high- N_{ch}^j jet class corresponds to a fraction of only 2×10^{-5} of all jets with $p_T^{\text{jet}} > 550$ GeV. The central peak at $(\Delta\eta^*, \Delta\phi^*) = (0, 0)$, truncated for better visualization, is the result of short-range correlations from the parton shower and hadronization. The far-side ridge at $\Delta\phi^* \approx \pi$ is mostly related to back-to-back particle production and conservation of momentum. These prominent features have also been found in laboratory-frame analyses of pp collisions [17], where they can also be reproduced using MC simulations for both low- and high- N_{ch}^j jets. This indicates that the dynamics of bulk hadron production in the jet fragmentation process may share similarities to those of a hadron-hadron collision process. Moreover, a feature commonly observed in AA collisions is the near-side enhancement at $\Delta\phi^* \approx 0$ over a long range in $\Delta\eta^*$, commonly known as the near-side “ridge.” The N_{ch}^j reached in the single jet system of this work is comparable to the event multiplicity of pp collisions where a near-side ridge was first observed using a laboratory-frame analysis [17]. There appears to be some indication of a near-side ridge in the high- N_{ch}^j plot in Fig. 2, however, this feature is less prominent than the ridges observed in pp and pA collisions. There is no corresponding near-side enhancement visible in the high- N_{ch}^j 2D distributions from either PYTHIA8 or SHERPA.

The 1D $\Delta\phi^*$ correlation functions extracted using Eq. (4) and averaged over $|\Delta\eta^*| > 2$ are shown for data and MC in Figs. 3(a) and 3(b), respectively, for particles with $0.3 < j_T < 3.0$ GeV from jets in two N_{ch}^j classes. For high- and inclusive N_{ch}^j classes in data, PYTHIA8 and SHERPA, strong away-side correlations observed are consistent with dominant contributions of back-to-back momentum conservation effects. For inclusive N_{ch}^j jets, the near-side at $\Delta\phi^* \approx 0$ clearly shows a minimum. However, for the class of highest- N_{ch}^j jets studied in data, with $\langle N_{\text{ch}}^j \rangle \approx 100$,

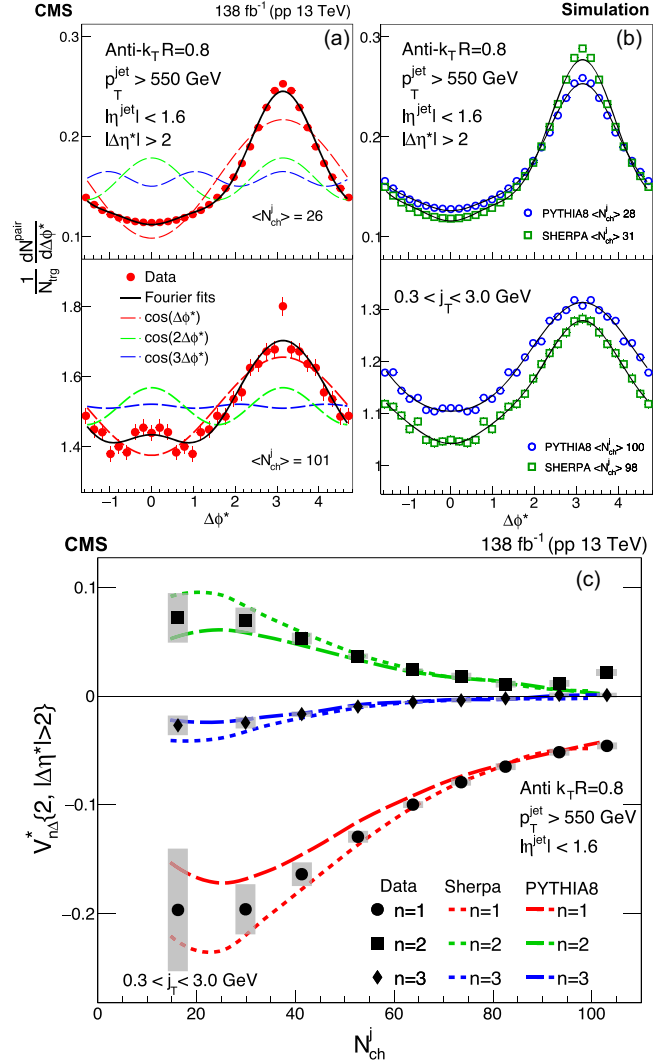


FIG. 3. Examples of two-particle angular correlations projected onto 1D $\Delta\phi^*$ for $|\Delta\eta^*| > 2$. The panels show (a) data and (b) PYTHIA8 and SHERPA for inclusive N_{ch}^j (upper) and high- N_{ch}^j (lower) jet selections. Data and both MC models are compared in (c) with a continuous evolution of extracted two-particle Fourier coefficients $V_{n\Delta}^*$ as a function of N_{ch}^j . Vertical bars on data points indicate statistical uncertainty while shaded boxes represent systematic uncertainties. Projections are symmetrized about $\Delta\phi^* = 0$ and π .

[Fig. 3(a) lower] an indication of a near-side enhancement is seen, which is less obvious or possibly absent from PYTHIA8 or SHERPA events having comparable N_{ch}^j [Fig. 3(b) lower]. The Fourier fits used to extract $V_{n\Delta}^*$ are also shown and are dominated by a negative $V_{1\Delta}^*$ component. The addition of more Fourier terms has little impact on the first three Fourier coefficients. The significant deviation from the fit at $\Delta\phi^* \approx 0$ in Fig. 3(a) lower is attributed to a local statistical fluctuation, as similar deviations are not observed in any other N_{ch}^j class.

The extracted two-particle Fourier coefficients for the first three harmonics $V_{n\Delta}^*$, as a function of N_{ch}^j , are shown in Fig. 3(c). Data points are placed at the average N_{ch}^j value of each jet class for the horizontal axis. Over the full N_{ch}^j range, the odd-order harmonics, $V_{1\Delta}^*$ and $V_{3\Delta}^*$, are negative, while $V_{2\Delta}^*$ is positive. The magnitudes of all harmonics tend to decrease as N_{ch}^j increases. The contribution of few-body correlations to the two-particle Fourier coefficient is

expected to diminish as N_{ch}^j increases [68]. These features are consistent with back-to-back correlations, as observed in laboratory-frame analyses, that are not related to collective effects. Both MC generators are generally successful in describing the experimental data for all three Fourier harmonics over a wide N_{ch}^j range. There appears to be a slight deviation in $V_{2\Delta}^*$ between data and simulation. Figure 4 shows the elliptic anisotropies $v_2^* = \sqrt{V_{2\Delta}^*}$, in the jet basis, as a function of N_{ch}^j inside the jet. To investigate possible j_T dependence of observed signals, particles from 0.3–3.0 GeV (Fig. 4 upper) as well as 0.5–3.0 GeV (Fig. 4 lower) are examined. Again, the MC simulation is generally successful at describing the data over a wide N_{ch}^j range in both j_T ranges. For jets at $N_{\text{ch}}^j > 80$, however, the value v_2^* no longer diminishes monotonically with increasing N_{ch}^j . Instead, the data start to show a steady increase with N_{ch}^j . The nonmonotonic dependence of v_2^* versus N_{ch}^j is not expected if few-body processes are the dominant sources of the observed correlations, as in either PYTHIA8 or SHERPA, and may indicate an onset of novel QCD phenomena related to nonperturbative dynamics of a parton fragmenting in the vacuum. These phenomena could include the emergence of collective effects possibly driven by final-state rescatterings, as suggested in Ref. [45]. Further experimental and theoretical inputs, including more j_T -differential studies with larger data samples, are needed to investigate the physical origin of the observed enhancement.

In summary, the first search for long-range near-side correlations and quantum chromodynamics (QCD) collective effects in jets produced in $\sqrt{s} = 13$ TeV proton-proton collisions is presented. The measurement is performed using charged particles from individual jets, after their kinematic variables have been calculated in a coordinate basis having the z axis coinciding with the jet direction. Two-particle correlations are studied as a function of the number of charged particles in the jet, N_{ch}^j . The first three Fourier harmonics of long-range azimuthal correlations are extracted and compared with those calculated using the PYTHIA8 and SHERPA Monte Carlo (MC) event generators that model the jet fragmentation process. While the data and MC predictions are in good agreement for particle correlations inside jets with $N_{\text{ch}}^j < 80$, the extracted long-range elliptic azimuthal anisotropy v_2^* shows a distinct increase in data for $N_{\text{ch}}^j \gtrsim 80$, hinting at a possible onset of collective behavior, which is not reproduced by the MC simulations.

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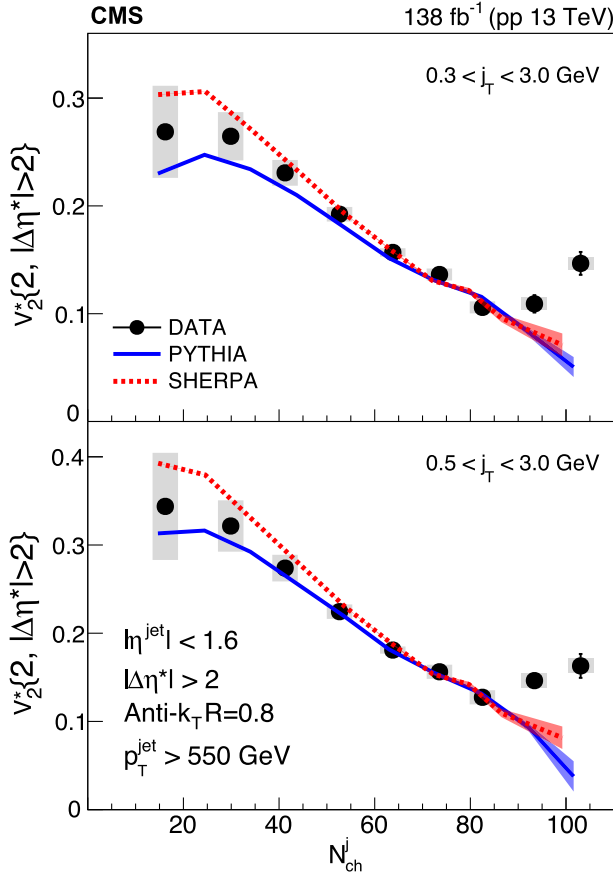


FIG. 4. The elliptic anisotropies v_2^* , obtained from two-particle correlations as a function of N_{ch}^j , for anti- k_T $R = 0.8$ jets with $p_T^{\text{jet}} > 550$ GeV and $|\eta^{\text{jet}}| < 1.6$ in pp collisions at 13 TeV from data, PYTHIA8, and SHERPA. Vertical bars on data points indicate statistical uncertainty, while shaded boxes represent systematic uncertainties. The shaded envelope around the MC curves shows statistical uncertainty.

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