

Observation of enhanced long-range elliptic anisotropies inside high-multiplicity jets in pp collisions at $\sqrt{s} = 13$ TeV

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Abstract

A search for partonic collective effects inside jets produced in proton-proton collisions is performed via correlation measurements of charged constituents 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 $|\eta| < 1.6$. Two-particle correlations among the charged constituents 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 constituents' 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-multiplicity 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 parton fragmentation processes 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 reflects the non-perturbative nature of QCD in this regime. In high energy hadron collisions, “hard scattering” of constituent partons with large momentum transfers 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.” Highly energetic jets are produced abundantly at LHC collision energies and can generate large final-state hadron multiplicities (e.g., more than 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, dense medium of nearly free partons known as a quark-gluon plasma (QGP) is formed. The extreme parton densities realized in these collisions result in strong partonic rescatterings which quickly drive the system toward a nearly ideal hydrodynamic limit. As a result, long-range collective flow effects have been observed and extensively studied at the BNL RHIC [1–4] and the CERN LHC [5–9].

It was originally thought that small collision systems such as electron-positron (e^+e^-), electron-proton (ep), and proton-proton (pp) collisions would produce partonic final states that were too small and dilute for secondary partonic rescatterings to drive the system toward thermal equilibrium. Collective hydrodynamic behavior was in general not expected to play an important role in these final states, notwithstanding some early studies [10, 11]. Surprisingly, strong long-range collective correlations, similar to those observed in AA collisions, were discovered in the azimuthal distributions of pp collision events with large final-state particle multiplicity [12–15]. This raised the question of whether a tiny QGP droplet is created in such conditions [16]. Subsequently, similar collective phenomena were observed in proton-nucleus (pA) collisions [17–26], and lighter AA systems [26–29]. Correlation studies in e^+e^- [30–32], ep [33, 34], photon-proton (γp) [35] and photonuclear (γA) [36] systems have been limited to relatively low-multiplicity events (less than 30–40 charged particles) and have not unambiguously demonstrated such behavior.

It is natural to ask what minimum system size is needed for collectivity to emerge. Although the dynamics of parton showering inside a jet is theoretically well described by perturbative QCD calculations [37, 38], a possible build-up of collective correlations within the parton constituents of a jet had not been considered. In Ref. [39], 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. This study examines the possibility that a sufficiently large number of rescatterings during the fragmentation that produces a very high multiplicity jet could lead to a flow-like behavior similar to that seen in QGP. 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 constituents of a jet is measured as a function of the in-jet charged particle multiplicity. Tabulated results are provided in the HEPData record for this analysis [40].

The CMS apparatus [41] is a multipurpose, nearly hermetic detector, designed to trigger on [42, 43] and identify electrons, muons, photons, and hadrons [44–46]. 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 (HLT). The HLT uses a large CPU farm to perform optimized online event reconstruction

and characterize an event. A global “particle-flow” algorithm [47] 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 [48–50].

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 [51, 52] with distance parameter $R = 0.8$ having a transverse momentum (p_T) above 500 GeV. In the offline analysis, jets were required to have a $p_T > 550$ GeV. Additionally, each jet contribution is weighted by the inverse of the trigger efficiency at that jet’s p_T . Jets are also required to have pseudorapidity $|\eta| < 1.6$ in the laboratory reference frame.

The two Monte Carlo (MC) generators used in this analysis are PYTHIA 8.306 [53] with the CP5 tune [54] and SHERPA 2.2 [55]. The leading order PYTHIA 8 uses the Lund String fragmentation model based on nonperturbative QCD from lattice computations and treats color fields as QCD flux tubes, the breaking of which leads to new $q\bar{q}$ pairs. The SHERPA generator uses a cluster model that groups quarks and gluons into color neutral clusters from which hadronization occurs. Additionally, the PYTHIA 8 events are input into GEANT4 [56] to emulate the response of the CMS detector for the purposes of calculating correction factors.

This analysis is particularly interested in the charged constituents of jets. These charged particles are required to have $|\eta| < 2.4$ and $p_T > 0.3$ GeV in the laboratory reference frame. Additionally, they are selected for p_T uncertainty of less than 10%, and a distance of closest approach significance with respect to the primary vertex of at most three standard deviations (σ) [46]. Secondary pp interactions within the same or nearby bunch crossings (“pileup”) can contribute tracks and calorimetric energy depositions to the jet reconstruction. The pileup per particle identification algorithm (PUPPI) [57, 58] 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 then classified into different classes based on the number of charged constituents 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 becomes identical to that of particle-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 [49]. The two-particle correlation analysis is similar to that employed in Ref. [17], except that the momentum vectors of all charged constituents of a jet are defined in the “jet basis”, as illustrated in Fig. 1 [39]. 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. Momentum vectors of charged constituents 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 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

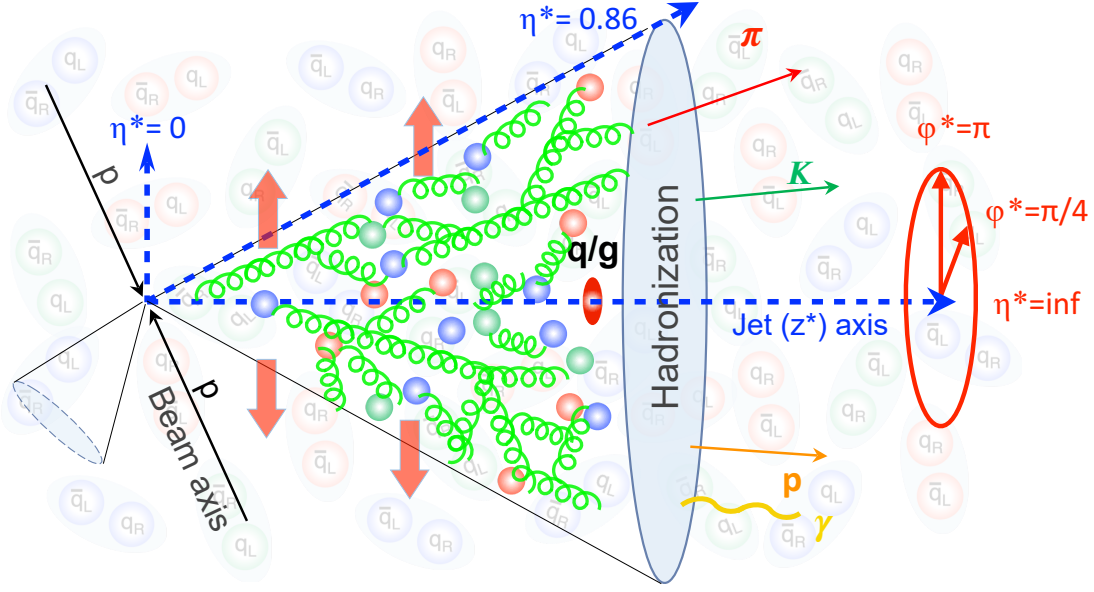


Figure 1: An illustration showing the idea of an initially scattered parton evolving to a shower that eventually exhibits collective expansion transverse to the jet axis. A jet cone (not to scale) and emerging final state particles are drawn in a coordinate system, denoted as the “jet basis,” where the 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.

in the analysis. For each jet with $p_T > 550$ GeV, the two-dimensional (2D) angular correlation function is calculated using charged constituents 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 for a particle pair. The functions $S(\Delta\eta^*, \Delta\phi^*)$ and $B(\Delta\eta^*, \Delta\phi^*)$ represent the signal and combinatorial distributions, respectively:

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

and

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

where N^{sig} and N^{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 as a function of N_{ch}^j , the j_T -inclusive in-jet charged multiplicity after correcting for detector effects. Equation (1) is constructed for jets in various classes of N_{ch}^j , such that the jets used to populate the $S(\Delta\eta^*, \Delta\phi^*)$ and $B(\Delta\eta^*, \Delta\phi^*)$ distributions are the same and fall within a specific range of N_{ch}^j . The $S(\Delta\eta^*, \Delta\phi^*)$ distribution is calculated with charged particles paired from the constituents of 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 $\eta^*-\phi^*$ distribution for charged constituents of all

jets within the N_{ch}^j range chosen for the signal distribution is first derived. Pairs of (η^*, ϕ^*) points from this distribution are then randomly selected to construct $B(\Delta\eta^*, \Delta\phi^*)$. Correlations present in the signal distribution that are related to single-particle distributions or detector effects can be canceled by the $B(0,0)/B(\Delta\eta^*, \Delta\phi^*)$ term in Eq. (1).

The resulting 2D distribution can be further studied by integrating over $|\eta^*| > 2$ and decomposing into a 1D Fourier series:

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

By applying $|\Delta\eta^*| > 2$, we exclude short-range correlations. The strength of the Fourier components in this decomposition could give indications of the existence of collective effects. Of particular interest is the second Fourier component, which is associated with elliptic anisotropies. The single-particle elliptic anisotropy coefficient, v_2^* , is the main observable of interest and is related to the two-particle Fourier coefficient by assumed factorization as $v_2^* = \sqrt{V_{2\Delta}^*}$. Results are presented as a function of $\langle N_{\text{ch}}^j \rangle$, the average N_{ch}^j .

The primary sources of systematic uncertainty come from the jet axis pointing resolution, the jet p_{T} resolution, residual pileup effects (after applying the PUPPI algorithm), and the tracking efficiency. These four sources are added together in quadrature to calculate the total systematic uncertainty. To reduce the effects of statistical fluctuations, the four highest jet multiplicity classes examined (corresponding to the last four data points in Figs. 3(c) and 4, and the rarest jets with $\langle N_{\text{ch}}^j \rangle > 70$), are treated 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 constituents' p_{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 charged multiplicities, where jet constituents 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 charged multiplicities because the constituents 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 jet p_{T} 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 negligible impact.

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 $0.3 < j_{\text{T}} < 3.0$ GeV. The $\langle N_{\text{ch}}^j \rangle$ is

26 and 101 for the two classes of jets shown. The high- N_{ch}^j jet class corresponds to a fraction of only 2×10^{-5} of all jets with $p_T > 550$ 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 lab-frame analyses of pp collisions [12], where they can also be reproduced using MC simulations. This indicates that the dynamics of bulk hadron production in the parton 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 [12]. 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 PYTHIA 8 or SHERPA. The 1D $\Delta\phi^*$ correlation

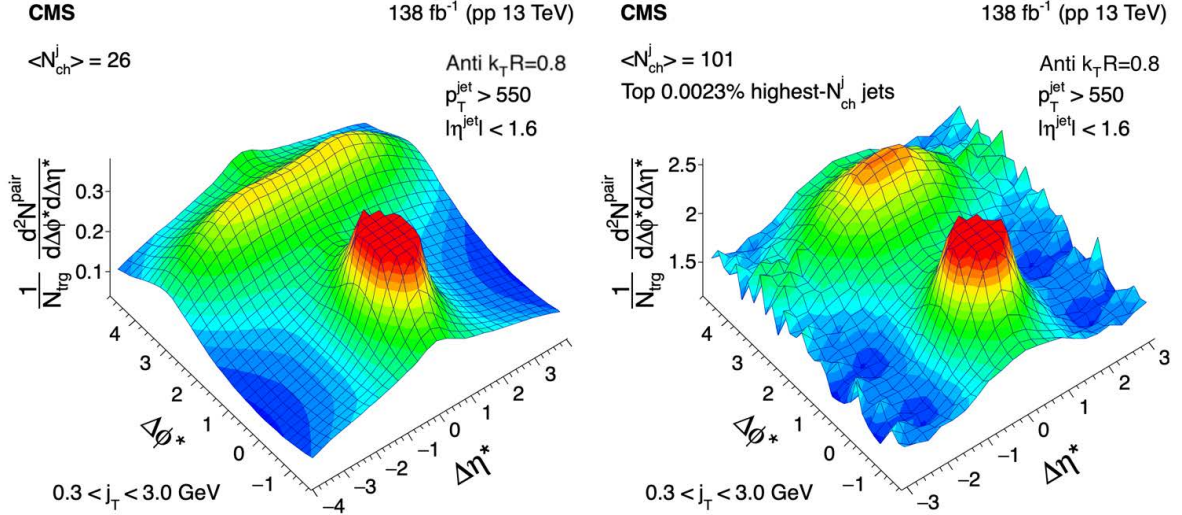


Figure 2: Results for 2D two-particle angular correlation functions for particle $0.3 < j_T < 3.0$ GeV from all jet multiplicities (left) and the highest (right) in-jet N_{ch}^j , for anti- k_T $R = 0.8$ jets with jet $p_T > 550$ GeV and $|\eta| < 1.6$.

functions extracted using Eq. (4) and averaged over $|\Delta\eta^*| > 2$ are shown for data and MC in Fig. 3(a) and (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, PYTHIA 8 and SHERPA, we find strong away-side correlations consistent with dominant contributions of back-to-back momentum conservation effects. For inclusive N_{ch}^j jets, the near-side at $\Delta\phi^* \sim 0$ clearly shows a minimum. However, for the highest- N_{ch}^j jets studied in data, with $\langle N_{\text{ch}}^j \rangle \approx 100$, (Fig. 3(a) lower) an indication of a near-side enhancement is seen, which is less obvious or possibly absent from PYTHIA 8 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 extracted two-particle Fourier coefficients for the first three harmonics $V_{n\Delta}^*$, as a function of $\langle N_{\text{ch}}^j \rangle$, are shown in Fig. 3(c). 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

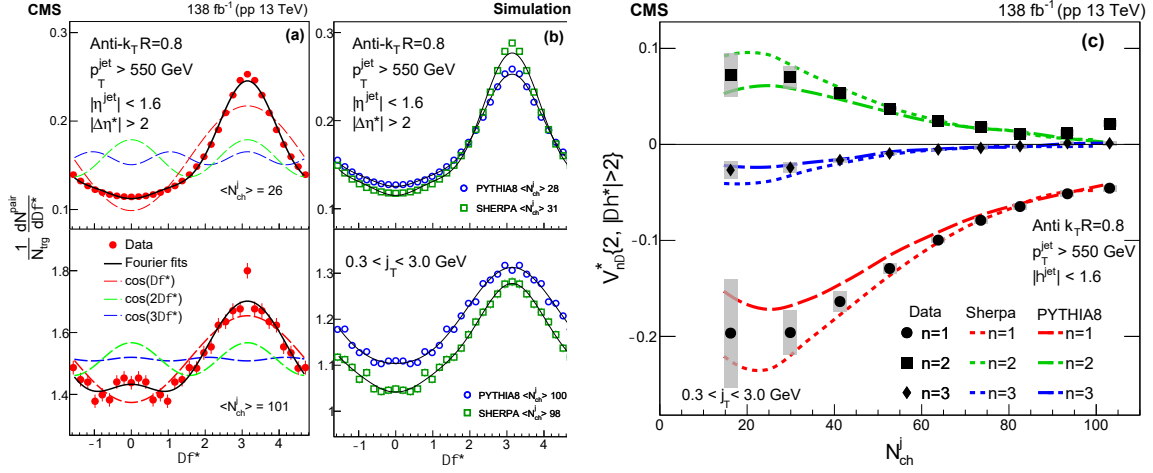


Figure 3: Examples of two-particle angular correlations projected onto 1D $\Delta\phi^*$ for $|\Delta\eta^*| > 2$. The panels show (a) data and (b) PYTHIA 8 and SHERPA for inclusive N_{ch}^j (upper) and high- N_{ch}^j (lower) jet selections. Data and both MC models are compared in (c) with a continuous 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 .

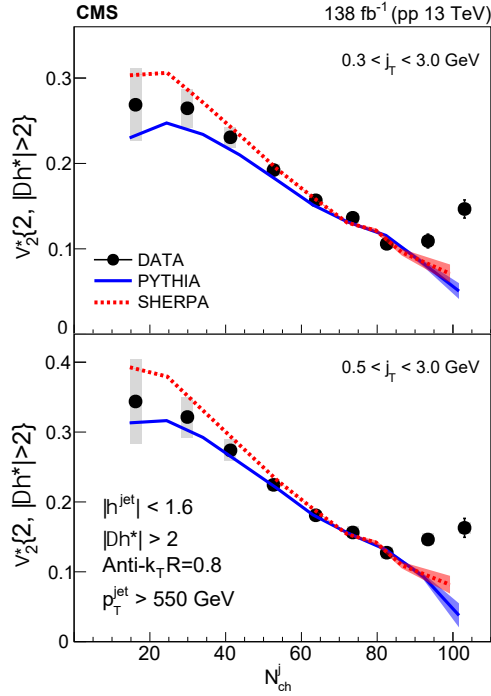


Figure 4: The single-particle elliptic anisotropies v_2^* , as a function of N_{ch}^j , for anti- $k_T R = 0.8$ jets with jet $p_T > 550$ GeV and $|\eta| < 1.6$ jets in pp collisions at 13 TeV from data, PYTHIA 8, and SHERPA. Vertical bars on data points indicate statistical uncertainty, while shaded boxes represent systematic uncertainties. The shaded envelope around the MC curves show statistical uncertainty.

increases. The contribution of short-range few-body correlations to the two-particle Fourier coefficient is expected to diminish at a rate inversely proportional to N_{ch}^j . These features are consistent with short-range back-to-back correlations, as observed in lab-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 single-particle elliptic anisotropies v_2^* , in the jet basis, as a function of N_{ch}^j inside the jet. To investigate possible j_T dependence of observed signals, we examine particles from 0.3–3.0 GeV (Fig. 4 upper) as well as 0.5–3.0 GeV (Fig. 4 lower). 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 as $1/N_{\text{ch}}^j$, as would be expected if only short-range few-body correlation are present. Instead, the data start to show a steady increases with N_{ch}^j . Such an increase of v_2^* for very high- N_{ch}^j jets is not observed in either PYTHIA 8 or SHERPA and may be an indication of the onset of new QCD effects, e.g., collectivity, in the parton fragmentation processes.

The increasing trend of v_2^* with N_{ch}^j in the data is observed for both j_T ranges investigated. To quantify the deviating trends in MC and data, a linear fit to the three highest multiplicity points in Fig. 4 (where the deviation occurs) was performed using both data and simulated samples. The fitted slope values in data versus both PYTHIA 8 and SHERPA differ with a significance greater than 5σ when examining the results for both j_T ranges of 0.3–3.0 GeV and 0.5–3.0 GeV over the last three data points. The non-monotonic dependence of v_2^* versus N_{ch}^j is not expected if few-body processes are the dominant sources of the observed correlations, 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 driven by secondary partonic rescatterings, as suggested in Ref. [39]. Further experimental and theoretical inputs 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 constituents 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 constituents 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 PYTHIA 8 and SHERPA Monte Carlo (MC) event generators which model the parton fragmentation process. While the data and MC predictions are in good agreement for particle correlations inside low- and mid- N_{ch}^j jets, 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. Therefore, results presented in this Letter may pave a new direction in uncovering novel effects related to nonperturbative QCD dynamics of parton fragmentation in vacuum.

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













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






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


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


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














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




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


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



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

















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








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











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



















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


































































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




































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




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






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

























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

























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












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


















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









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




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

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





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




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





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

























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









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















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

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M. Bachtis , R. Cousins , A. Datta , G. Flores Avila, J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 





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









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A. Barzdukas , L. Brennan , C. Campagnari , A. Dorsett , J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vámi , S. Wang 














California Institute of Technology, Pasadena, California, USA

A. Bornheim , O. Cerri, A. Latorre, J. Mao , H.B. Newman , M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 


















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J. Alison , S. An , M.B. Andrews , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson , A. Harilal , C. Liu , T. Mudholkar , S. Murthy , P. Palit , M. Paulini , A. Roberts , A. Sanchez , W. Terrill 










































































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J.P. Cumalat , W.T. Ford , A. Hart , A. Hassani , G. Karathanasis , E. MacDonald, N. Manganelli , A. Perloff , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper 





















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J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , D. Gadkari , S. Hogan , P. Kotamnives, J. Monroy , M. Oshiro , J.R. Patterson , J. Reichert , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 














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M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁶ , F. Ravera , A. Reinsvold Hall⁸⁷ , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 






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






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

















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






Johns Hopkins University, Baltimore, Maryland, USA

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 

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







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B. Allmond , A. Ivanov , K. Kaadze , A. Kalogeropoulos , D. Kim, Y. Maravin , K. Nam, J. Natoli , D. Roy , G. Sorrentino 












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F. Rebassoo , D. Wright 










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






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B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , S. Pandey , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud

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


















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


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
















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














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

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




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




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



















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