Collectivity inside high-multiplicity jets in high-energy proton-proton collisions

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We present the first study of collectivity inside jets with high charged multiplicity $N_{\rm ch}^{j}$ in proton-proton collisions at the Large Hadron Collider. By incorporating final-state partonic and hadronic interactions through cascade models among jet shower partons and final hadrons, we investigate and compare to the CMS experimental data on multiplicity distribution, pseudorapidity distribution, and elliptic anisotropy coefficient v_2^j of two-particle correlations within the jet. We show that final-state partonic interactions are essential for producing the flow-like long-range correlation, which leads to the enhanced tail in the $N_{\rm ch}^{j}$ dependence of v_2^j above the non-flow correlation from jet parton showering at high multiplicities ($N_{\rm ch}^{j} \gtrsim 70$) as observed in the CMS experimental data. In addition, we provide predictions for the pseudorapidity-gap dependence of v_2^j that can be tested in future experimental measurements.

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1. Introduction. Ultra-relativistic collisions of heavy ions aim to create a novel state of matter known as the quark-gluon plasma (QGP) and to investigate its properties. Extensive measurements of various flow observables conducted at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), along with successful descriptions by viscous hydrodynamic calculations, have provided evidence that the created QGP fireball behaves like a nearly perfect liquid with very small specific shear viscosity (see reviews [1–6]).

Features of collective expansion have been observed not only in large but also in small collision systems, such as p+Au, d+Au, and ^{3}He+Au at RHIC [7–9] as well as p+p and p+Pb collisions at the LHC [10–12]. Intriguing experimental results on two-particle azimuthal correlations have even been reported in ultra-peripheral Pb+Pb collisions (UPCs) at the LHC [13], which involve appreciable rates of photo-nuclear interactions [14, 15]. Measurements of photo-nuclear interactions in Pb+Pb UPCs by the ATLAS experiment indicate the persistence of collective phenomena, with the observed strength of correlations being comparable to that seen in p+p and p+Pb collisions in similar multiplicity ranges [13]. These flow-like signals in small systems can be interpreted as a result of the hydrodynamic [16–25] or transport/kinetic response [26–32] of the QGP medium to the initial collision geometry. Theoretical frameworks that incorporate both initial-state correlations and final-state interactions (FSI) have been employed to better understand the origin of the observed collective behavior in these small systems [4, 33, 34]. Moreover, searches for QCD collective effects have been extended to other small collision systems, including $e^+ + e^-$ [16, 35–37], deeply inelastic $e + p$ [38, 39], and photon-proton (γ+p) collisions [40].

Recently, the CMS Collaboration has reported a new measurement of two-particle correlations among charged hadrons within a single jet with a given cone-size in p+p collisions at $\sqrt{s} = 13$ TeV [41]. For jets with low multiplicities, the elliptic anisotropy (or flow) coefficient v_2^j extracted from these correlations agrees well with the expectations from PYTHIA8 [42] or SHERPA [43] simulations, in which the azimuthal angle correlation is attributed to the transverse momentum conservation in parton-splitting. The elliptic flow coefficient v_2^j therefore decreases with the multiplicity $N_{\rm ch}^{j}$. Surprisingly, the CMS data on the multiplicity dependence of v_2^j show a remarkable rising tail at high multiplicities, which cannot be described by the PYTHIA8 and SHERPA model. Such enhanced correlations resemble the effect of collective flow in a small system with strong interaction. One compelling question then arises: to what extent can collectivity emerge in small partonic systems, and what are the specific conditions that lead to its manifestation? The observation of flow-like behaviors in single jets with extremely high multiplicities opens new avenues for understanding the "thermal" behavior seen in small and large systems, from high-multiplicity e^+e^- events to heavy-ion collisions.

In this Letter, we present the first study of collectivity as a result of multiple parton rescatterings inside single jets with high multiplicities in high-energy proton-proton collisions. We incorporate both the final-state partonic and hadronic rescatterings through parton and hadron transport models. The strength of the final-state interactions, at both the partonic and hadronic levels, is systematically varied to discern their impact on the onset of collective signatures in two-particle correlations exhibited by high multiplicity jets. We show that only partonic rescatterings with a moderate partonic cross section can describe the high multiplicity tail of the $N_{\rm ch}^{j}$ dependence of v_2^j. We also present predictions for the elliptic flow coefficients with different pseudorapidity gaps. These results help us to have a comprehensive understanding of the intricate interplay of final-state interactions and their roles in the collective behavior within high multiplicity jets in proton-proton collisions and other small systems.

2. Methodology. To study collective phenomena within jets, we incorporate final-state interactions at both the partonic and hadronic level. In our framework, we employ PYTHIA8 [42] with the CP5 tune [44] to generate initial jet shower partons. The parton formation time, denoted as t_f, is assigned by tracking the full sequence of splittings from the hard scattering to each final-state parton in PYTHIA8. It is calculated as $t_f = \sum_i 2E_i x_i(1-x_i)/k_{\perp i}^2$ [45, 46]. Here, E_i represents the energy of the mother parton in the i-th splitting, while x_i and $k_{\perp i}$ are the fractional energy and transverse momentum of a daughter with respect to the mother parton, respectively. Each parton free-streams until its respective formation time. Afterwards, it is allowed to undergo elastic rescatterings utilizing the Zhang's Parton Cascade (ZPC) component of a multi-phase transpot model [47–49]. ZPC solves the Boltzmann equations through Monte Carlo simulations of parton cascades, where two partons scatter whenever their closest-approach distance is smaller than $\sqrt{\sigma_p/\pi}$, with σ_p being the cross section for partonic two-body scattering. We will vary the value of σ_p to investigate the effects of final-state partonic interactions on collectivity within the jet. After partonic interactions, these partons are hadronized using the Lund string fragmentation model for hadronization [42, 50–52]. Following the approach in Refs. [53, 54], hadronization time is assumed to be 1 fm/c in hadron's local rest frame. Subsequent hadronic rescatterings are modeled using Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model [55, 56].

To compare with CMS data [41], our analysis focuses on charged hadrons in the jets. These charged particles must satisfy $|\eta| < 2.4$ and $p_T > 0.3$ GeV/c in the laboratory collision frame. Jet reconstruction is performed using the anti-k_T algorithm [57, 58] with jet-cone size of $R = 0.8$, requiring the jet transverse momentum $p_T^{\rm jet}$ to be above 550 GeV/c. Following the procedure outlined in Refs. [41, 59], we define a new coordinate frame known as the jet frame, in which the z-axis aligns with the direction of the reconstructed jet. The momentum vectors of constituent charged hadrons are then redefined in this new basis as $\vec{p^*} = (j_T, \eta^*, \phi^*)$, where j_T represents the particle's transverse momentum, η^* and ϕ^* denote the pseudorapidity and azimuthal angle, respectively, with respect to the jet axis. In this frame, $\eta^* = 0$ and ∞ correspond to vectors that are perpendicular and parallel to the jet axis, respectively. In this study, we compute the anisotropy coefficient (v_n^j) in the azimuthal angle ϕ^* using the Q-cumulant [60–62] method with a given $|\Delta\eta^*|$ gap.

3. Hadron distributions inside single inclusive jets. In our framework, the cross section of final-state partonic interactions is controlled by the parameter σ_p in the parton cascade, and we can include or exclude hadronic final state interactions (hFSI) in the UrQMD.

Our model results on the multiplicity distribution of charged particles within jets reconstructed with the anti-k_T algorithm with a cone size $R = 0.8$, $p_T^{\rm jet} > 550$ GeV/c and $|\eta_{\rm jet}| < 1.6$ are compared to CMS measurements in p+p collisions at 13 TeV in Fig. 1. They exhibit narrower multiplicity distributions compared to the experimental data and are not visibly influenced by the inclusion of final-state interactions. Since the focus of this work is on collectivity within the jet, we have verified that reweighting the multiplicity distribution according to CMS data has negligible effect on the v_2^j results presented below. The inclusion of inelastic parton scattering in the ZPC model can broaden the multiplicity distribution to better describe the experimental data, especially at high multiplicities. However, we do not expect this to qualitatively affect the study of collective behavior due to final-state interaction in the following.

The charged hadron pseudorapidity distributions in

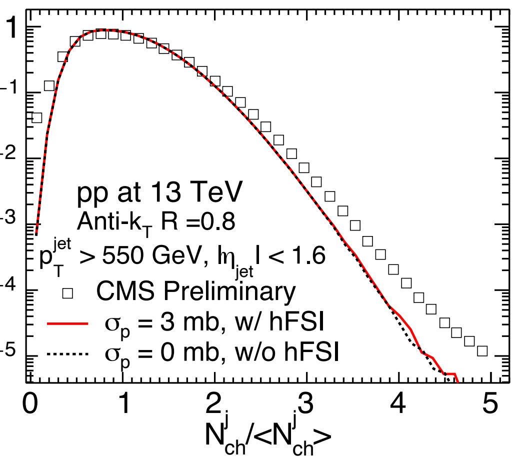

FIG. 1. (Color online) The charged hadron multiplicity distributions inside jets in p+p at 13 TeV from model calculations as compared with the CMS data [41, 63].

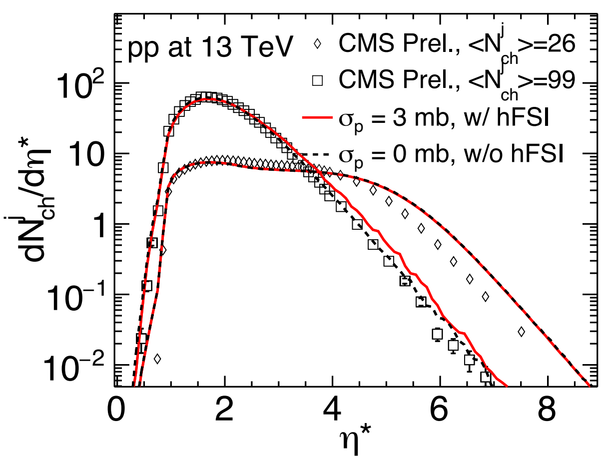

FIG. 2. (Color online) Charged hadron pseudo-rapidity distributions in the jet frame from model calculations as compared with the CMS data [41, 63].

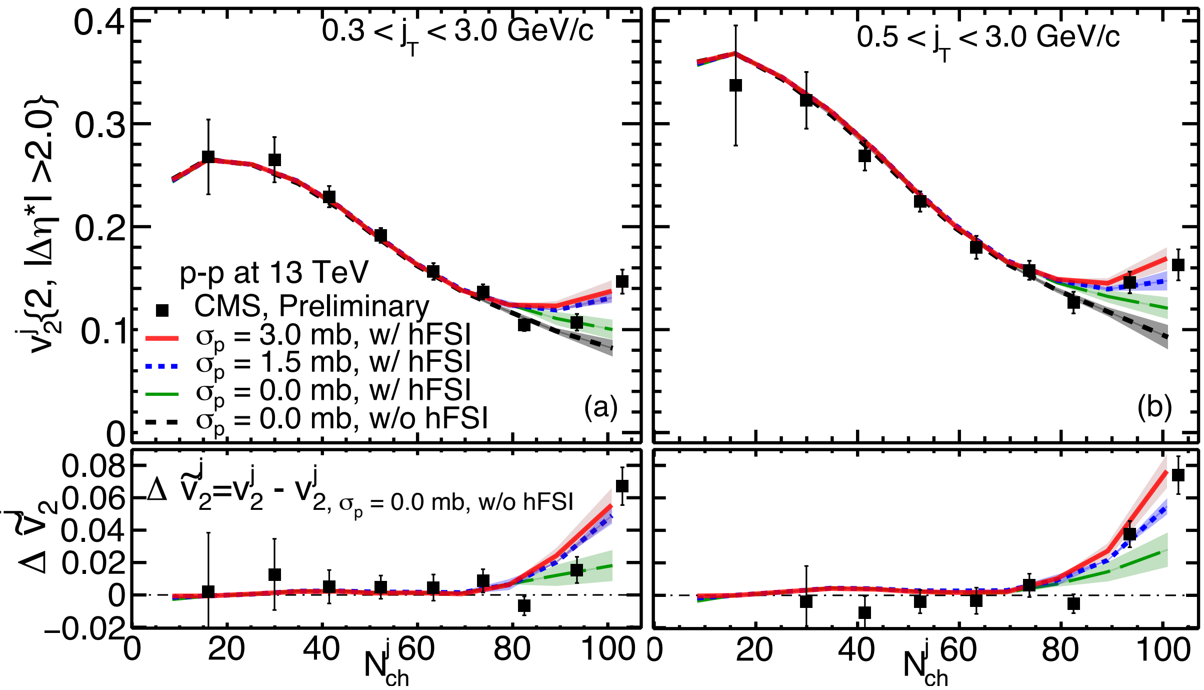

FIG. 3. (Color online) The elliptic flow coefficients $v_2^j\{2,|\Delta\eta^*|>2\}$ as functions of charged hadron multiplicity $N_{\rm ch}^j$ inside jets in p+p collisions at 13 TeV (top panels), and the v_2^j difference due to final-state interactions (bottom panels) from model calculations as compared to the CMS data [41].

single jets, $dN_{\rm ch}^j/d\eta^*$, in $p+p$ collisions at 13 TeV are presented in Fig. 2. In the jet coordinate frame, lower η^* values correspond to particles with large angles relative to the jet axis, while higher η^* values correspond to particles with small angles that are more collimated with the jet direction. The distribution for high multiplicity jets noticeably shifts towards lower values of η^* compared to that for low multiplicity jets. This shift can be attributed to larger initial emission angles, which lead to more subsequent parton showers and higher multiplicities of charged hadrons inside the jet. Both multiplicity selections exhibit a sharp rise around $\eta^*\approx 0.86$, corresponding to the angle of hadrons close to the cone-size $R=0.8$ relative to the jet axis. These features are well-described by the PYTHIA8 model, particularly at large multiplicities with an average $\left\langle N_{ch}^j\right\rangle = 99$. Our calculations also show that final-state interactions slightly broaden $dN_{ch}^j/d\eta^*$ for the high multiplicity jets.

4. Collectivity inside high-multiplicity jets. With a good description of charged hadron rapidity distributions, we can now explore quantitatively the flow observables with the same kinematic cuts as in the experimental analysis. In Fig. 3, elliptic anisotropies $v_2^j\{2,|\Delta\eta^*|>2\}$ are presented as functions of the charged multiplicity $N_{\rm ch}^j$ inside the jet with two transverse momentum cuts in the jet frame. In calculations without final-state interactions, the magnitudes of $v_2^j\{2,|\Delta\eta^*|>2\}$ decrease monotonically with $N_{\rm ch}^j$. This aligns with the expected short-range correlations from parton showering in the vacuum. The azimuthal anisotropy of such two-particle correlation in general decreases with $N_{\rm ch}^j$.

With the inclusion of final-state interactions, the behavior of $v_2^j\{2,|\Delta\eta^*|>2\}$ at large $N_{\rm ch}^j$ undergoes a significant change. Instead of a continued monotonic decrease, it exhibits an ascending "tail", i.e., a steady increase with $N_{\rm ch}^j$ at high multiplicities. The lower panels show the differences between the model calculations with and without final-state interactions. These differences can be interpreted as the "collectivity" caused by the final-state interactions. It is evident that a stronger partonic final-state interaction leads to a more pronounced ascending "tail" or stronger collective flow at high multiplicities. For instance, at $N_{\rm ch}^j\approx 100$, $v_2^j\{2,|\Delta\eta^*|>2\}$ for $0.5<j_T<3.0$ GeV$/c$ is around 0.17 for calculations with $\sigma_p=3.0$ mb and hadronic rescatterings, which is significantly larger than the $v_2^j\approx 0.10$ for calculations without final-state interaction. The results for $0.5<j_T<3.0$ GeV$/c$ show a slightly stronger ascending "tail" than those for $0.3<j_T<3.0$ GeV$/c$. These trends are also consistent with the experimental data. In addition, our model calculations show that final-state interaction from hadronic rescatterings alone cannot generate sufficiently large "collectivity" in high multiplicity jets. Therefore, partonic rescatterings are necessary for explaining the unexpected "tail" of the $N_{\rm ch}^j$ dependence of v_2^j, and consequently the observed $v_2^j\{2,|\Delta\eta^*|>2\}$ "tail" at high

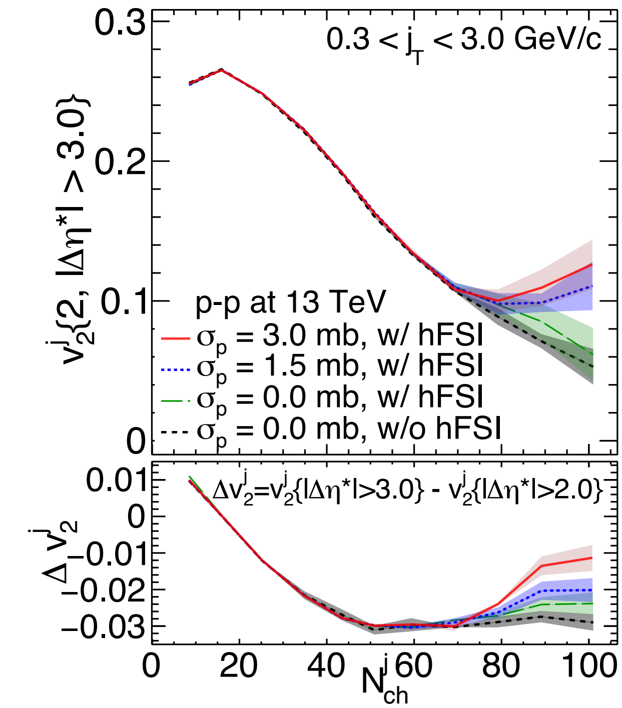

FIG. 4. (Color online) The elliptic flow coefficients $v_2^j\{2, |\Delta\eta^*| > 3\}$ as functions of charged hadron multiplicity $N_{\rm ch}^j$ inside jets in p+p collisions at 13 TeV (top panel), and the difference $\Delta v_2^j = v_2^j\{2, |\Delta\eta^*| > 3\} - v_2^j\{2, |\Delta\eta^*| > 2\}$ (bottom panel).

$N_{\rm ch}^j$ indicates the existence of partonic collectivity inside high multiplicity jets. It's interesting to note that the onset of the "collectivity" in high multiplicity jets in both our calculations and the experimental data occurs at $N_{ch}^j \sim 70$. This value is comparable to the multiplicity range where flow-like signals have been observed in high-multiplicity $p + p$ collisions [64–66].

Since the non-flow correlations are mostly short range in rapidity, one can in principle suppress their effect by increasing the η^*-gap and study the interplay between flow and non-flow contributions to the two-particle correlation. Figure 4 shows the $v_2^j\{2, |\Delta\eta^*| > 3\}$ from our model calculations as a function of charged hadron multiplicity inside jets with $0.3 < j_T < 3.0$ GeV/c. The calculated v_2^j without final state interaction decreases monotonically with $N_{\rm ch}^j$ due to transverse momentum conservation in jet showering as expected. When the final-state interactions are included, $v_2^j\{2, |\Delta\eta^*| > 3\}$ has the similar ascending "tail" at high $N_{\rm ch}^j$. To illustrate the η^*-gap dependence of the elliptic flow coefficient, we show in the lower panel the difference $\Delta v_2^j = v_2^j\{2, |\Delta\eta^*| > 3\} - v_2^j\{2, |\Delta\eta^*| > 2\}$ as a function of $N_{\rm ch}^j$. As expected, v_2^j with a larger η^*-gap is mostly smaller because of the greater suppression of non-flow effect from short-range correlations. In other words, a larger η^*-gap dilutes the transverse momentum conservation in parton showering that causes the non-flow effect. Such dilution increases with $N_{\rm ch}^j$, therefore Δv_2^j decreases monotonically with $N_{\rm ch}^j$ in the absence of final-state interactions. At asymptotically large multiplicity beyond the $N_{\rm ch}^j$ range in our calculation, two-particle correlation due to short-range correlations in the parton showering will approach zero, and so will the v_2^j difference Δv_2^j. This thus leads to flattening of Δv_2^j for $60 \lesssim N_{\rm ch}^j \lesssim 100$ in our calculation. When final-state interactions are included, long-range collective flow dominates over the short-range non-flow effect in the high $N_{\rm ch}^j$ region in our calculation. Since the long-range collective correlations from final-state interactions at high multiplicities weakly depend on the pseudorapidity gap, the v_2^j difference Δv_2^j with final-state interactions will start to approach to zero at moderately high $N_{\rm ch}^j$. Combined with the behavior of Δv_2^j from non-flow correlations at low $N_{\rm ch}^j$, our calculations predict a high $N_{\rm ch}^j$ ($N_{\rm ch}^j \gtrsim 70$) ascending "tail" for the multiplicity dependence of Δv_2^j. This can be tested in future experimental measurements of the anisotropic flows in jets.

5. Summary. In this Letter, we have carried out the first quantitative study of the impact of final-state interactions on collective behavior within high multiplicity jets in proton-proton collisions at 13 TeV. Our model provides reasonable descriptions of the $dN_{ch}^j/d\eta^*$ distributions for two different jet multiplicity selections. Notably, our model calculations with final-state partonic and hadronic interactions quantitatively capture the non-monotonic dependence of $v_2^j\{2, |\Delta\eta^*| > 2\}$ on $N_{\rm ch}^j$ inside high transverse momentum jets. Furthermore, we find that partonic rescatterings are crucial for reproducing the observed v_2^j inside high multiplicity jets while hadronic rescatterings alone are insufficient.

Our model supports the hypothesis that final-state interactions, particularly at the partonic level, lead to collectivity that is responsible for the enhanced "tail" of the $N_{\rm ch}^j$ dependence of v_2^j for hadrons inside jets with high multiplicities. In addition, we provide model predictions for $v_2^j\{2, |\Delta\eta^*| > 3\}$ as a function of $N_{\rm ch}^j$ as well as the difference in v_2^j between two different η^* gaps, which are testable in future experimental measurements.

Moreover, our study has the potential to be extended to $e^+ + e^-$ collisions. The study within the theoretical framework developed here is expected to provide insights into the collective phenomena in diverse high-energy interactions and contribute to our understanding of the space-time structure and interactions among the shower partons inside energetic and high multiplicity jets.

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