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

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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". 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.

It was originally thought that small collision systems such as electron-positron, electron-proton, 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. 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. This raised the question of whether a tiny QGP droplet is created in such conditions. It is natural to ask what minimum system size is needed for QCD collective effects to develop. Although the dynamics of parton showering inside a jet is theoretically well described by perturbative QCD calculations, a possible build-up of correlations within the parton constituents of a jet had not been considered. It is postulated that collective effects can emerge from an initial system as small as an energetic parto n 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.

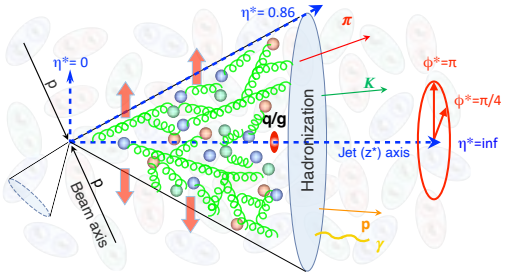

FIG. 1: An illustration showing the idea of an initially scattered parton evolving to a shower that eventually exhibits collective expansion transverse to the jet axis

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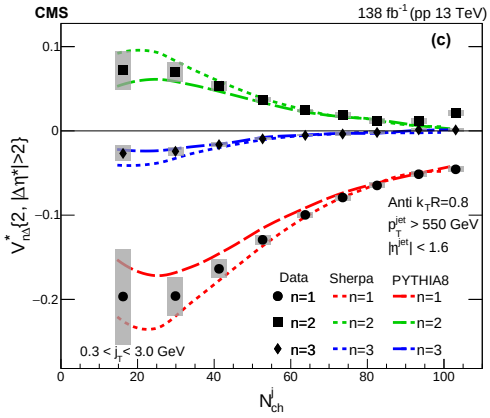

FIG. 2: Data and both MC models are compared with a continuous evolution of extracted two-particle Fourier coefficients $V^*_{n\Delta}$ as a function of $N^{\rm j}_{\rm ch}$. Vertical bars on data points indicate statistical uncertainty while shaded boxes represent systematic uncertainties. Projections are symmetrized about $\Delta\phi^* = 0$ and π.

The extracted two-particle Fourier coefficients for the first three harmonics $V^*_{n\Delta}$, as a function of $N^{\rm j}_{\rm ch}$, are shown in Fig. 2. Data points are placed at the average $N^{\rm j}_{\rm ch}$ value of each jet class for the horizontal axis. Over the full $N^{\rm j}_{\rm ch}$ 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 $N^{\rm j}_{\rm ch}$ increases. The contribution of few-body correlations to the two-particle Fourier coefficient is expected to diminish as $N^{\rm j}_{\rm ch}$ increases. 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 $N^{\rm j}_{\rm ch}$ range. There appears to be a slight deviation in $V^*_{2\Delta}$ between data and simulation.

Measurements are done for the the elliptic anisotropies $v^*_2 = \sqrt{V^*_{2\Delta}}$, in the jet basis, as a function of $N^{\rm j}_{\rm ch}$ inside the jet. To investigate possible $j_{\rm T}$ dependence of observed signals, particles from 0.3–3.0 GeV as well as 0.5–3.0 GeV are examined. Again, the MC simulation is generally successful at describing the data over a wide $N^{\rm j}_{\rm ch}$ range in both $j_{\rm T}$ ranges. For jets at $N^{\rm j}_{\rm ch} > 80$, however, the value v^*_2 no longer diminishes monotonically with increasing $N^{\rm j}_{\rm ch}$. Instead, the data start to show a steady increase with $N^{\rm j}_{\rm ch}$.

The non-monotonic dependence of v^*_2 versus $N^{\rm j}_{\rm ch}$ is not expected if few-body processes are the dominant sources of the observed correlations, as in either PYTHIA 8 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. Further experimental and theoretical inputs, including more $j_{\rm T}$-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 $\sqrt{s} = 13$ 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, $N^{\rm j}_{\rm ch}$. The first three Fourier harmonics of long-range azimuthal correlations are extracted and compared with those calculated using the 8 and Monte Carlo (MC) event generators which model the jet fragmentation process. While the data and MC predictions are in good agreement for particle correlations inside jets with $N^{\rm j}_{\rm ch} < 80$, the extracted long-range elliptic azimuthal anisotropy v^*_2 shows a distinct increase in data for $N^{\rm j}_{\rm ch} \gtrsim 80$, hinting at a possible onset of collective behavior, which is not reproduced by the MC simulations.

• **Reference**:- arXiv:2312.17103