Editors' Suggestion

Evidence for the Collective Nature of Radial Flow in Pb + Pb Collisions with the ATLAS Detector

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Anisotropic flow and radial flow are two key probes of the expansion dynamics and properties of the quark-gluon plasma (QGP). While anisotropic flow has been extensively studied, radial flow, which governs the system's radial expansion, has received less attention. Notably, direct experimental evidence for the global and collective nature of radial flow fluctuations has been lacking. This Letter presents the first measurement of transverse momentum (p_{T}) dependence of radial flow fluctuations ($v_0(p_{\mathrm{T}})$) over $0.5 < p_{\mathrm{T}} < 10$ GeV and demonstrates its collective nature using a two-particle correlation method in Pb + Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The data reveal three key features supporting the collective nature of radial flow: long-range correlation in pseudorapidity, factorization in p_{T}, and centrality-independent shape in p_{T}. The comparison with a hydrodynamic model demonstrates the sensitivity of $v_0(p_{\mathrm{T}})$ to bulk viscosity, a crucial transport property of the QGP. These findings establish a new, powerful tool for probing collective dynamics and properties of the QGP.

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Introduction—Heavy-ion collisions at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) provide unique conditions for creating and studying the quark-gluon plasma (QGP). The spacetime evolution of the QGP is well described by relativistic hydrodynamics [1,2], where the system, driven by pressure gradients, expands collectively and cools until hadronization. This gradient-driven expansion turns geometric anisotropies and size variations in the initial state into two distinct final-state collective phenomena: anisotropic flow (v_n, $n = 1, 2, \ldots$) and radial flow (v_0), respectively. Anisotropic flow quantifies azimuthal momentum anisotropy, while radial flow characterizes the radial boost of the system, which influences the average transverse momentum of particles $[p_{\mathrm{T}}]$ in each event [3].

Extensive measurements of anisotropic flow, particularly differential studies of $v_n(p_{\mathrm{T}})$ and their event-by-event (EbE) fluctuations [4–13], have provided crucial insights into the initial conditions and transport properties of the QGP. In contrast, experimental studies of radial flow have been more limited. Traditional approaches focus on particle spectra and moments of the $[p_{\mathrm{T}}]$ distribution over event ensembles, such as the mean $\langle[p_{\mathrm{T}}]\rangle$ [14] and the scaled variance $v_0 = \sqrt{\langle(\delta[p_{\mathrm{T}}])^2\rangle}/\langle[p_{\mathrm{T}}]\rangle$ [15–19], where $\delta[p_{\mathrm{T}}] = [p_{\mathrm{T}}] - \langle[p_{\mathrm{T}}]\rangle$. While the v_0 observable characterizes global EbE radial flow fluctuations [20,21] and scales with the square root of charged-particle multiplicity [18], it provides only the p_{T}-integral information about the radial flow.

Anisotropic and radial flow are thought to originate from single-particle distributions and hence are expected to exhibit long-range correlations in pseudorapidity (η) [3,22]. For anisotropic flow, these two features have been verified by the approximate factorization of the coefficients of two-particle azimuthal correlation into single-particle coefficients: $V_{n\Delta}(p_{\mathrm{T}1}, p_{\mathrm{T}2}) \approx v_n(p_{\mathrm{T}1})v_n(p_{\mathrm{T}2})$ [8,22] and $V_{n\Delta}(\eta_1, \eta_2) \approx v_n(\eta_1)v_n(\eta_2)$ [23–25]. Furthermore, $v_n(p_{\mathrm{T}})$ divided by the integrated flow v_n exhibits a near-universal behavior across centralities [26]. This universality arises because the magnitude of $v_n(p_{\mathrm{T}})$ scales with initial state eccentricity, while its shape, characterized by $k_n(p_{\mathrm{T}}) = v_n(p_{\mathrm{T}})/v_n$, reflects the hydrodynamic response, which is nearly independent of centrality [27]. While this factorization and centrality-independent scaling hold at $p_{\mathrm{T}} \lesssim 4$ GeV in central to midcentral Pb + Pb collisions, deviations are observed in peripheral collisions or at higher p_{T}, attributable to nonflow correlations such as resonance decays or jet fragmentation. These direct correlation measurements have established the multiparticle collective nature of anisotropic flow.

In contrast to anisotropic flow, the collective nature of radial flow has traditionally been inferred from model studies of identified particle p_{T} spectra and their $[p_{\mathrm{T}}]$ and v_0 [14,28]. These model-dependent approaches, incorporating radial expansion, have enabled acecss to average

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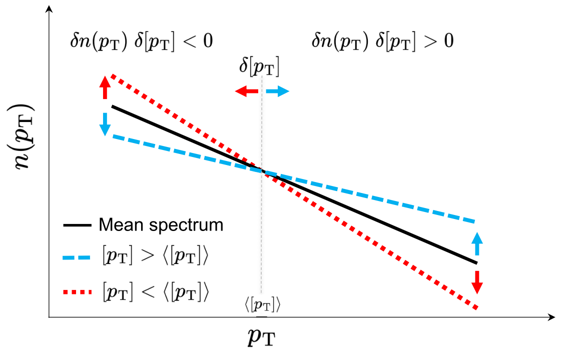

FIG. 1. Schematic illustration of how radial flow fluctuations lead to correlations between the EbE p_T-differential yield $n(p_T)$ and the EbE average transverse momentum $[p_T]$. The blue curve represents an event with larger-than-average radial flow, the red curve an event with smaller-than-average radial flow, and the black curve the ensemble-averaged spectrum. Events with larger radial flow have flatter spectra, resulting in a positive covariance ($\langle \delta n(p_T)\delta[p_T] \rangle > 0$) at $p_T \gtrsim \langle [p_T] \rangle$ and a negative covariance ($\langle \delta n(p_T)\delta[p_T] \rangle < 0$) at $p_T \lesssim \langle [p_T] \rangle$ [31]. The zero-crossing point of $v_0(p_T)$, $p_T \approx \langle [p_T] \rangle$, depends on the p_T range used for measurement, which is 0.5–10 GeV in this analysis, but does not depend on p_T^{ref} (see Ref. [35]).

radial flow velocities and temperatures [29]. Yet, they do not directly probe the many-body nature of the radial flow, as has been achieved for anisotropic flow. A new observable, $v_0(p_T)$, was proposed recently [30] to fill this gap. Unlike anisotropic flow, which is more sensitive to shear viscosity, $v_0(p_T)$ is predicted to be more sensitive to bulk viscosity [30,31], which remains less well constrained. Precision measurements of $v_0(p_T)$, including factorization and scaling checks as well as particle species dependence, thus offer valuable opportunities to constrain the properties of the QGP [32,33] and possibly disentangle contributions from flow velocity fluctuations and thermal fluctuations [34].

The $v_0(p_T)$ observable is defined based on the correlation between particle spectra in narrow p_T ranges, $N(p_T)$, and $[p_T]$ [30,31] (see Fig. 1). To avoid fluctuations in the total multiplicity and capture only shape variations [35], the fractional spectrum $n(p_T) = N(p_T)/\int N(p_T)dp_T$ in each event is used. Events with a larger (smaller) radial flow feature a flatter (steeper) distribution of $n(p_T)$ and a correspondingly higher (lower) $[p_T]$. The resulting fluctuations in the spectrum, $\delta n(p_T) = n(p_T) - \langle n(p_T) \rangle$, and in $\delta[p_T]$ are correlated in a characteristic pattern: negative correlation at $p_T \lesssim \langle [p_T] \rangle$ and positive at $p_T \gtrsim \langle [p_T] \rangle$. By assuming a factorization of the normalized covariance [30,31],

$$\frac{\langle \delta n(p_T)\delta[p_T] \rangle}{\langle n(p_T) \rangle \langle [p_T] \rangle} = v_0(p_T)v_0, \tag{1}$$

$v_0(p_T)$ can be calculated from the data. The normalization reduces sensitivity to the particle reconstruction efficiency. If radial flow is collective, v_0 is related to $v_0(p_T)$ by an approximate sum rule [30,35],

$$v_0 \equiv \frac{\sqrt{\langle (\delta[p_T])^2 \rangle_A}}{\langle [p_T] \rangle_A} \approx \frac{\int_{p_T \in A} (p_T - \langle [p_T] \rangle_A) \langle n(p_T) \rangle v_0(p_T) dp_T}{\int_{p_T \in A} p_T \langle n(p_T) \rangle dp_T}, \tag{2}$$

where "A" denotes the reference-p_T (p_T^{ref}) range for integration and calculating v_0. The measured $v_0(p_T)$ is expected to be independent of p_T^{ref} and exhibit centrality-independent scaling. However, this factorization and scaling can be broken in the presence of significant nonflow correlations.

This Letter presents measurements of $v_0(p_T)$ using 470 μb^{-1} of Pb + Pb collision data at $\sqrt{s_{NN}} = 5.02$ TeV from 2015. Results are obtained for several p_T^{ref} and various centrality ranges. Comparison with a hydrodynamic model further reveals the impact of QGP viscosities, particularly bulk viscosity, on radial flow fluctuations. This analysis closely follows a previous ATLAS analysis that measured v_0 and its centrality scaling properties [18].

ATLAS detector and data selection—The measurements are performed using the ATLAS inner detector (ID), forward calorimeter (FCal), and zero-degree calorimeters (ZDCs) along with the trigger and data acquisition systems [36–38]. The ID detects charged particles within $|\eta| < 2.5$ [39] using a combination of silicon pixel and microstrip detectors, along with a straw-tube transition-radiation tracker, all immersed in a 2 T axial magnetic field [37]. The FCal consists of three sampling layers, covering $3.2 < |\eta| < 4.9$. The ZDCs are positioned at ±140 m from the interaction point and detect neutrons with $|\eta| > 8.3$. The ATLAS trigger system [38] consists of a hardware-based level-one (L1) and software-based high-level triggers. A software suite [40] is used in data simulation, in the reconstruction and analysis of real and simulated data, in the detector operations, and in the trigger and data acquisition systems.

Pb + Pb events are selected by requiring the total transverse energy deposited in calorimeters over $|\eta| < 4.9$ at L1 to exceed 50 GeV. Additionally, dedicated central collision triggers enhance the number of events with large FCal transverse energy [13].

Charged-particle tracks are reconstructed from hits in the ID using a procedure optimized for heavy-ion collisions [41]. The distance of the closest approach of the track to the primary vertex must be within 1.25 mm in both the transverse and longitudinal directions. More details of the track selection are found in Ref. [26]. Tracks used in this analysis have $0.5 < p_T < 10$ GeV and $|\eta| < 2.5$. This p_T range spans the regime predominantly influenced by radial flow as well as the transition region where jet-quenching effects become significant. The total number of such tracks is denoted by $N_{\text{ch}}^{\text{rec}}$. Events containing multiple inelastic collisions (pileup) are suppressed by exploiting the correlation between $N_{\mathrm{ch}}^{\mathrm{rec}}$ and the transverse energy measured in the FCal, $E_{\mathrm{T}}^{\mathrm{FCal}}$, as well as between the energy deposited in the ZDCs and $E_{\mathrm{T}}^{\mathrm{FCal}}$. The residual pileup probability is 0.17% among all selected events, but is smaller than 0.01% in central collisions [18,42].

Events are categorized into centrality ranges using a parametrization of the $E_{\mathrm{T}}^{\mathrm{FCal}}$ distribution [13] based on a Glauber model [43], starting at 0% for the most central collisions with the highest $E_{\mathrm{T}}^{\mathrm{FCal}}$ value and ending at 70%. Events in this centrality range are fully efficient against the L1 event selection criteria.

Analysis—The track reconstruction efficiency, $\epsilon(p_{\mathrm{T}}, \eta, N_{\mathrm{ch}}^{\mathrm{rec}})$, is evaluated using Monte Carlo (MC) simulated events for Pb + Pb collisions generated with HIJING [44] and charged particles definition according to Ref. [41]. The detector response is simulated using Geant4 [45,46], and events are reconstructed with the same algorithms as used for the data. The HIJING spectra have been reweighted to match the data. In central Pb + Pb collisions, the efficiency ranges from 71% at $\eta \approx 0$ to about 40% for $|\eta| > 2$ at $p_{\mathrm{T}} > 0.8$ GeV, and it decreases by 12% from 0.8 to 0.5 GeV in p_{T}. In peripheral collisions, the efficiency is up to 4% higher. The rate of falsely reconstructed ("fake") tracks, $f(p_{\mathrm{T}}, \eta, N_{\mathrm{ch}}^{\mathrm{rec}})$, is significant for $p_{\mathrm{T}} < 1$ GeV in central collisions, ranging from 2% for $|\eta| < 1$ to 8% at larger $|\eta|$. The fake-track rate drops rapidly for higher p_{T} and more peripheral collisions.

The observables in this analysis are obtained using a two-subevent method [47,48], which takes particles from two η regions labeled a and b: $-2.5 < \eta_a < -(\eta_{\mathrm{gap}}/2)$ and $(\eta_{\mathrm{gap}}/2) < \eta_b < 2.5$. This subevent method was first used to measure the v_0 at RHIC in Ref. [19]. Four choices of gaps, $\eta_{\mathrm{gap}} = 0$, 1, 2, and 3, are used to evaluate the effects of short-range non-flow correlations as well as possible longitudinal radial flow decorrelations [49]. Each reconstructed charged track i is assigned a weight w_i to correct for reconstruction efficiency ϵ_i and fake rate f_i: $w_i \equiv (1 - f_i)/\epsilon_i$ [50]. The charged-particle multiplicity, corrected for detector effects, in $0.5 < p_{\mathrm{T}} < 5$ GeV and $|\eta| < 2.5$ is obtained as $N_{\mathrm{ch}} = \Sigma_i w_i$.

For each collision subevent, the following quantities are calculated: $[p_{\mathrm{T}}] = \Sigma_i w_i p_{\mathrm{T},i}/\Sigma_i w_i$, $\delta[p_{\mathrm{T}}] = \Sigma_i w_i \delta p_{\mathrm{T},i}/\Sigma_i w_i$ with $\delta p_{\mathrm{T},i} \equiv p_{\mathrm{T},i} - \langle [p_{\mathrm{T}}] \rangle$, and $n(p_{\mathrm{T}}) = \Sigma_i^{p_{\mathrm{T}}} w_i/\Sigma_i w_i$, where $\Sigma_i^{p_{\mathrm{T}}}$ represents the sum over all tracks in a narrow p_{T} range. The two-particle observables are calculated in narrow N_{ch} ranges as: $\langle (\delta[p_{\mathrm{T}}])^2 \rangle = \langle \delta[p_{\mathrm{T}}]_a \delta[p_{\mathrm{T}}]_b \rangle$, $\langle \delta n(p_{\mathrm{T}}) \delta[p_{\mathrm{T}}] \rangle = \frac{1}{2} \langle \delta n_a(p_{\mathrm{T}}) \delta[p_{\mathrm{T}}]_b + \delta n_b(p_{\mathrm{T}}) \delta[p_{\mathrm{T}}]_a \rangle$. The measurements are performed for three $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges, 0.5–2, 0.5–5, and 1–5 GeV; according to Eq. (1), v_0 can only be calculated in fairly wide $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges, motivating the partial overlap in their choices. Statistical uncertainties for all observables are computed using a standard Poisson bootstrap method.

Systematic uncertainties stem from track selection, reconstruction efficiency, residual pileup, centrality definition, and MC closure test of the analysis procedure. These uncertainties obtained in $0.5 < p_{\mathrm{T}}^{\mathrm{ref}} < 2$ GeV and $\eta_{\mathrm{gap}} = 1$ are summarized below for v_0 and for $v_0(p_{\mathrm{T}})$ at a low p_{T} (0.5–0.8 GeV) and a high p_{T} region (2–3 GeV).

Track selection uncertainties are assessed by comparing nominal results with those obtained under looser or stricter criteria. This results in a deviation of 0.5–5% for v_0, and 1–8% at low p_{T} and 0.5–1.5% at high p_{T} for $v_0(p_{\mathrm{T}})$. The $v_0(p_{\mathrm{T}})$ as defined in Eq. (1) is insensitive to the track reconstruction efficiency. Indeed, repeating the analysis without track weights leads to variations in $v_0(p_{\mathrm{T}})$ smaller than uncertainties due to track selection. Uncertainties in the efficiency, mainly due to the modeling of the detector material in Geant4, can be as large as 4%. Their impacts are within 0.5–1% for v_0 and 2–3% at low p_{T} and 0.5–1% at high p_{T} for $v_0(p_{\mathrm{T}})$. The impact of the azimuthal efficiency variation is assessed by including it in the track weight; no observable changes are found in the results. Residual pileup effects are estimated by adjusting the pileup rejection criteria, leading to uncertainties less than 0.5% for all observables. Centrality definition uncertainties, assessed by varying the Glauber model parameters, are relevant only when results are presented in centrality ranges and are below 3% for all observables.

The HIJING MC samples are used to evaluate the consistency of calculated observables, obtained using truth particles or the reconstructed tracks with the same correction procedures as for the real data applied [13]. This check also accounts for the smearing of measured $[p_{\mathrm{T}}]$ and $n(p_{\mathrm{T}})$ from their true values. The differences are about 1% for v_0 and 2% for $v_0(p_{\mathrm{T}})$.

The full systematic uncertainties for each observable are obtained by adding contributions from individual sources in quadrature. Track selection is the dominant source of systematic uncertainty, particularly in midcentral and central collisions. The total uncertainties are 1.5–5% for v_0, and 3–8.5% for $v_0(p_{\mathrm{T}})$ at low p_{T} and 2–3.5% at high p_{T}. The uncertainties are largest in central collisions and reduce to less than half their size in peripheral collisions. The uncertainties are generally smaller for the other two $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges, and are somewhat larger for bigger η_{gap}. The total uncertainties for each data point are obtained by combining statistical and systematic uncertainties, which are then shown alongside the statistical uncertainties when presenting the results.

Results—Figure 2(a) shows the centrality dependence of v_0 computed in three $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges. The magnitude of v_0 depends on the choice of $p_{\mathrm{T}}^{\mathrm{ref}}$, and shows a characteristic decrease toward central collisions as observed in Ref. [18]. It is the largest for the widest $p_{\mathrm{T}}^{\mathrm{ref}}$ range, as expected from Eq. (2). However, when dividing v_0 by its value in the 0–5% centrality range, $v_0/v_0^{0-5\%}$, the trend in centrality is similar across all $p_{\mathrm{T}}^{\mathrm{ref}}$ selections, as shown in Fig. 2(b).

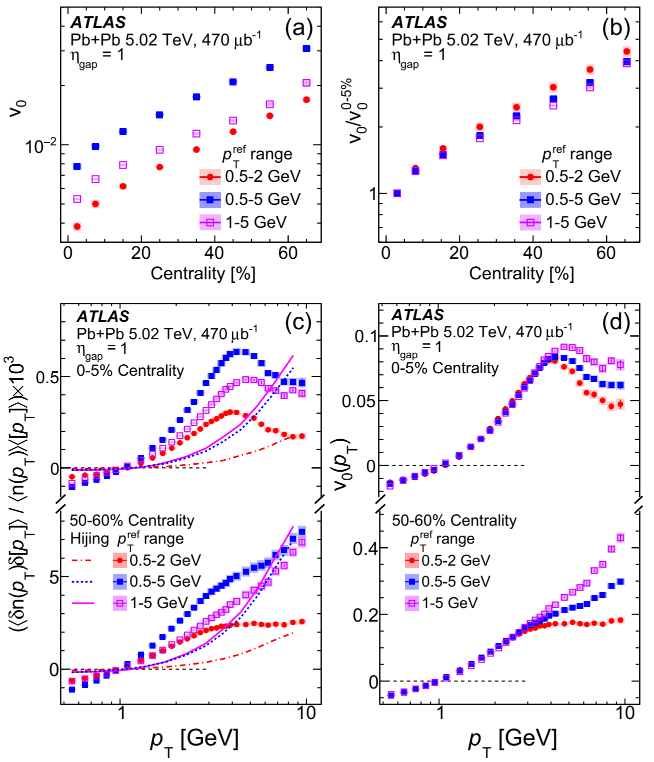

FIG. 2. Centrality dependence of v_0 (a) and $v_0/v_0^{0\text{–}5\%}$ (b) for three $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges, and normalized covariance from Eq. (1) (c) and $v_0(p_{\mathrm{T}})$ (d) obtained in 0–5% centrality (top) and 50–60% centrality (bottom) in three $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges. The color lines indicate the predictions from the HIJING model containing only nonflow correlations. Bars and shaded areas indicate statistical and total uncertainties, respectively.

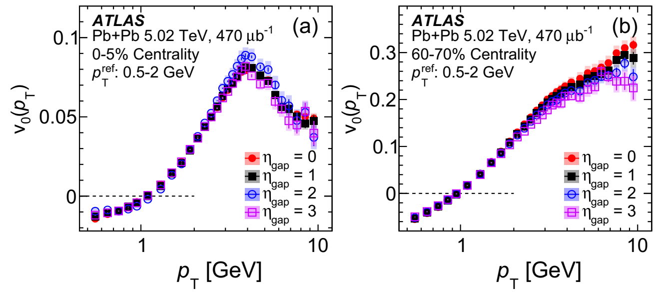

FIG. 3. $v_0(p_{\mathrm{T}})$ for $\eta_{\mathrm{gap}} = 0$, 1, 2, and 3 in 0–5% (a) and 60–70% (b) centrality. Bars and shaded areas indicate statistical and total uncertainties, respectively.

Hence, v_0 captures EbE fluctuations in the overall spectral shape, consistent with a collective nature of radial flow fluctuations.

To quantify this collective nature, the factorization of the covariance into a product of $v_0(p_{\mathrm{T}})$ and v_0 from Eq. (1) is examined in Figs. 2(c) and 2(d) for two representative centralities (0–5% and 50–60%). While the normalized covariance varies substantially with $p_{\mathrm{T}}^{\mathrm{ref}}$, the extracted $v_0(p_{\mathrm{T}})$ remains nearly $p_{\mathrm{T}}^{\mathrm{ref}}$-independent up to $p_{\mathrm{T}} \approx 3$ GeV. This factorization, akin to what is observed for anisotropic flow, further supports the collective nature of radial flow. The $v_0(p_{\mathrm{T}})$ data for the three $p_{\mathrm{T}}^{\mathrm{ref}}$ cross zero at $p_{\mathrm{T}} \approx 1$ GeV, approximately the $\langle [p_{\mathrm{T}}] \rangle$ for the 0.5–10 GeV range. The $v_0(p_{\mathrm{T}})$ data are also found to satisfy the sum rule in Eq. (2) within 4%. Above $p_{\mathrm{T}} \approx 3$ GeV and in more peripheral collisions, the data become dependent on $p_{\mathrm{T}}^{\mathrm{ref}}$ due to larger non-flow contributions. Among the three reference ranges, results for $p_{\mathrm{T}}^{\mathrm{ref}} \in 0.5$–2 GeV are least affected by non-flow correlations, as suggested by the trend of $v_0(p_{\mathrm{T}})$ at high p_{T}.

In central collisions, $v_0(p_{\mathrm{T}})$ shows a decrease above $p_{\mathrm{T}} \approx 4$ GeV, similar to anisotropic flow, which might be associated with a transition from a flow-dominated regime to a jet-quenching dominated regime [30], which changes the shape of the underlying spectrum and its EbE fluctuations [51]. No such decrease is observed in peripheral collisions.

In Fig. 2(c), the covariance is compared to calculations from the HIJING model containing only nonflow correlations. HIJING underpredicts the magnitude of the data at $p_{\mathrm{T}} < 6$ GeV, implying that the collective radial flow generates most of the signal in the data. Above $p_{\mathrm{T}} \approx 6$ GeV, HIJING predictions become comparable to the data, suggesting that the high p_{T} behavior of the covariance could be impacted by nonflow correlations, especially in peripheral collisions.

The impact of nonflow correlations on $v_0(p_{\mathrm{T}})$ is further investigated by varying η_{gap} between the subevents. A larger η_{gap} reduces the short-range nonflow contributions but also enhances the flow decorrelation effects [25,49]. Figure 3 shows the $v_0(p_{\mathrm{T}})$ data in 0–5% and 60–70% centrality ranges for different η_{gap} selections. Little change is observed in central collisions when η_{gap} is varied from 0 to 3. In contrast, $v_0(p_{\mathrm{T}})$ in peripheral collisions at $p_{\mathrm{T}} >$ 3 GeV decreases slightly, which is consistent with residual non-flow contributions from away-side jet fragmentation. The weak dependence on η_{gap} supports the interpretation that radial flow is a long-range, global correlation similar to anisotropic flow. Based on these observations, $\eta_{\mathrm{gap}} = 1$ is used as the default configuration.

Next, the shape of $v_0(p_{\mathrm{T}})$ across centralities is investigated using the normalized quantity $v_0(p_{\mathrm{T}})/v_0$, which has the advantage of being insensitive to the initial-state effects [30]. Figure 5 compares $v_0(p_{\mathrm{T}})$ and $v_0(p_{\mathrm{T}})/v_0$ for several centrality ranges. While $v_0(p_{\mathrm{T}})$ exhibits a pronounced centrality dependence, $v_0(p_{\mathrm{T}})/v_0$ is almost independent of centrality in the range $p_{\mathrm{T}} \lesssim 2.5$ GeV. This observation indicates that the magnitude of $v_0(p_{\mathrm{T}})$ is primarily driven by the fluctuations in nuclear overlap area and density, which is larger in peripheral collisions [18,20]. In contrast, the shape of $v_0(p_{\mathrm{T}})$ is governed by the hydrodynamic response $k_0(p_{\mathrm{T}}) \approx v_0(p_{\mathrm{T}})/v_0$ [31], which is nearly independent of centrality. This scaling behavior is analogous to that observed for $v_n(p_{\mathrm{T}})/v_n$. However, $v_n(p_{\mathrm{T}})/v_n$ is

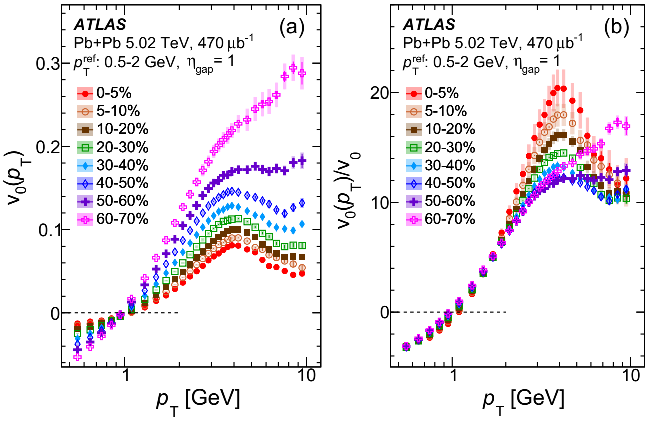

FIG. 4. The $v_0(p_\mathrm{T})$ (a) and $v_0(p_\mathrm{T})/v_0$ (b) for different centrality ranges. Bars and shaded areas represent statistical and total uncertainties, respectively.

sensitive to both shear and bulk viscosities, while $v_0(p_\mathrm{T})/v_0$ is mostly sensitive to bulk viscosity [3].

Above $p_\mathrm{T} \approx 3$ GeV, where the nonflow contribution is more significant, this scaling is imperfect. Up to 40–50% centrality, $v_0(p_\mathrm{T})/v_0$ is observed to first rise and then fall, which could be due to the change in the baryon-meson composition or onset of jet quenching that reduces the fractional momentum fluctuations [51]. For more peripheral collisions, the data exhibit either a flat behavior or an increasing trend with p_T, consistent with a larger nonflow contribution at high p_T and in peripheral collisions.

Figure 5 compares the data from the 0–5% centrality range to hydrodynamic model predictions from Ref. [31], based on the Trento + MUSIC framework with either constant shear viscosity or temperature-dependent bulk viscosity from Refs. [32,52]. Since these calculations are not fully tuned to reproduce overall p_T spectra and fluctuations, following conformal scaling arguments [27],

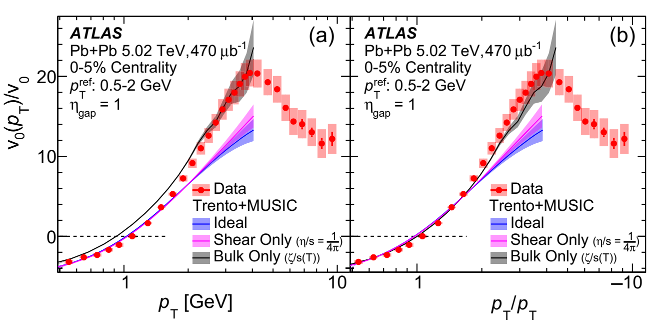

FIG. 5. The $v_0(p_\mathrm{T})/v_0$ as a function of p_T (*a*) and $p_\mathrm{T}/\bar{p}_\mathrm{T}$ (*b*) in 0–5% centrality range, where $\bar{p}_\mathrm{T}$ is the mean p_T in 0.5–10 GeV. Bars and shaded areas represent statistical and total uncertainties, respectively. They are compared with hydrodynamic model predictions without viscosity (blue), with a constant shear viscosity (in terms of shear viscosity to entropy density ratio of $\eta/s = (1/4\pi)$, magenta), and with a temperature-dependent bulk viscosity (grey) [32,52]. The shaded bands on the model curves represent the statistical uncertainties.

the authors recommend comparing $v_0(p_\mathrm{T})/v_0$ as a function of $p_\mathrm{T}/\bar{p}_\mathrm{T}$, where $\bar{p}_\mathrm{T}$ is the average transverse momentum in the range of 0.5–10 GeV in this analysis. The ratio $v_0(p_\mathrm{T})/v_0$ reduces the dependence on initial conditions, while the scaled quantity $p_\mathrm{T}/\bar{p}_\mathrm{T}$ reduces dependencies on model descriptions of $[p_\mathrm{T}]$.

As shown in Fig. 5, calculations with and without shear viscosity lead to similar predictions, whereas calculation with bulk viscosity alters both the zero-crossing in p_T and the high-p_T behavior. Without bulk viscosity, the model underestimates the data at high p_T, while using a standard temperature-dependent bulk viscosity [32,52] improves agreement with the data, albeit reducing the zero-crossing point. The zero-crossing point shift reflects a reduction of average transverse momentum in the presence of bulk viscosity. This reduction is expected to be systematic across centralities and should preserve the universal scaling observed in Fig. 4(b). Rescaling the horizontal axis by $\bar{p}_\mathrm{T}$ further improves the agreement, isolating the clear sensitivity of the $v_0(p_\mathrm{T})$ data at $p_\mathrm{T} > 2$ GeV to the bulk viscosity of the QGP. Further model tuning for a precise description of the initial conditions and other bulk observables, such as yields of baryons and mesons and N_ch distribution, is expected to improve the description of the data and provide more precise constraints on the bulk viscosity. Our measurement provides the foundation for such quantitative constraints.

Summary—This Letter reports the first measurement of the p_T-differential radial flow fluctuations $v_0(p_\mathrm{T})$ using charged particle tracks over the range $0.5 < p_\mathrm{T} < 10$ GeV in Pb + Pb collisions at $\sqrt{s_\mathrm{NN}} = 5.02$ TeV using the ATLAS detector at the LHC. This observable is extracted from the correlations between each event's p_T-differential spectrum and its average transverse momentum $[p_\mathrm{T}]$ in separate subevents. A characteristic rise of $v_0(p_\mathrm{T})$ up to 3–4 GeV, a decrease at higher p_T, and a sign change near 1 GeV are observed. This rise and fall behavior could be associated with an interplay between collective flow, changes in baryon-meson composition, and jet quenching, although a quantitative understanding of such interplay requires a realistic model calculation. The $v_0(p_\mathrm{T})$ is nearly independent of the pseudorapidity gap between subevents, supporting the long-range nature of the radial flow. These results are confirmed by a similar study from the ALICE Collaboration [53] that appeared after submission of this Letter for publication. A factorization test shows that $v_0(p_\mathrm{T})$ for $p_\mathrm{T} \lesssim 3$ GeV is nearly independent of the p_T range used to calculate $[p_\mathrm{T}]$, establishing the collective nature of the radial flow. Notably, the shape of $v_0(p_\mathrm{T})$ for $p_\mathrm{T} \lesssim 3$ GeV is nearly centrality independent, implying a universal hydrodynamic response to radial expansion. Taken together, these results confirm three hallmarks of collectivity—long-range correlation, factorization, and centrality-independent shape—now demonstrated for radial flow. Comparisons with a hydrodynamic model reveal that

$v_0(p_{\mathrm{T}})$ is sensitive to bulk viscosity, highlighting its potential for quantitative constraints on QGP transport properties.

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End Matter

Appendix—The default analysis was performed using normalized EbE spectra, i.e., $n(p_{\rm T})$, and then averaging in narrow $N_{\rm ch}$. The impact of residual multiplicity fluctuation in this observable can be checked by repeating the analysis either by using the spectra without normalization and/or performing an average in narrow $E_{\rm T}^{\rm FCal}$. This procedure results in four measurements of the $v_0(p_{\rm T})$, which are displayed in Fig. 6 for four centrality ranges. The results show that the global multiplicity fluctuations could shift the $v_0(p_{\rm T})$ vertically and change the zero-crossing point in $p_{\rm T}$, but not the shape of $v_0(p_{\rm T})$ [35].

Figure 7 shows the zero-crossing point of the $v_0(p_{\rm T})$ obtained for the three $p_{\rm T}^{\rm ref}$ ranges, and compared to the $\langle[p_{\rm T}]\rangle$ over 0.5–10 GeV. Figure 8 shows the performance of the two sum rules of the $v_0(p_{\rm T})$ expected due to its collective nature.

The results for v_0 were previously presented as a function of the efficiency-corrected charged-particle multiplicity, $N_{\rm ch}$ [18]. Figure 9 shows the v_0 and v_0 divided by its value at 5% as a function of $N_{\rm ch}$, complementing Fig. 2. The v_0 were observed to scale as $\sqrt{N_{\rm ch}}$ in a previous ATLAS paper [18]; such scaling is shown in Fig. 10 for the three $p_{\rm T}^{\rm ref}$ ranges. Figure 11 shows that the $v_0(p_{\rm T})$ scaled by $\sqrt{N_{\rm ch}}$ approximately falls on a common trend at low $p_{\rm T}$, expected from the independent source model scenario.

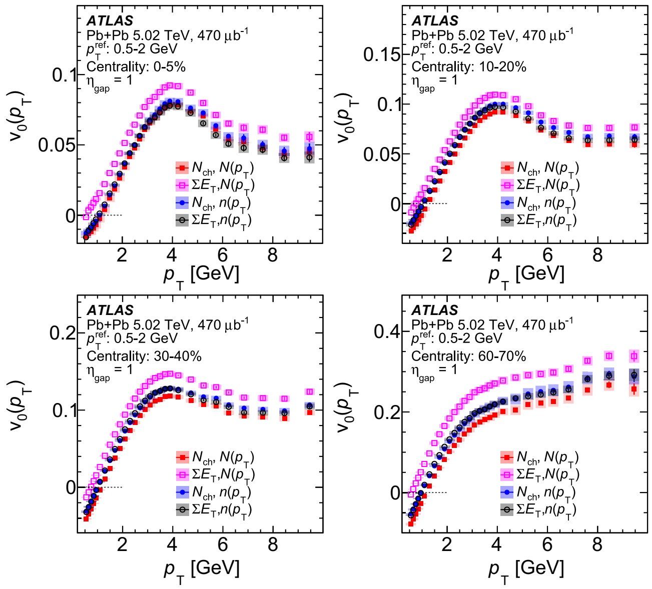

FIG. 6. Comparison of $v_0(p_\mathrm{T})$ measured using EbE spectra $N(p_\mathrm{T})$ and EbE normalized spectra $n(p_\mathrm{T})$ for several centralities. The event averages are done by combining observables calculated in narrow slices of N_ch or $E_\mathrm{T}^\mathrm{FCal}$. They are obtained for $p_\mathrm{T}^\mathrm{ref} \in 0.5$–2 GeV and $\eta_\mathrm{gap} = 1$. Bars and shaded areas indicate statistical and total uncertainties, respectively.

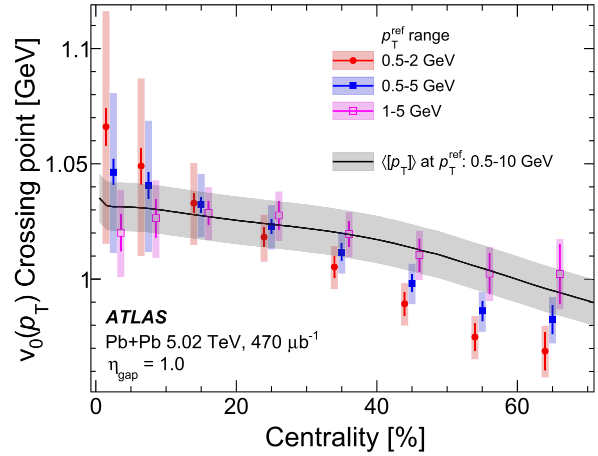

FIG. 7. The zero-crossing point of the $v_0(p_\mathrm{T})$ obtained for the three $p_\mathrm{T}^\mathrm{ref}$ ranges. They are compared to the $\langle[p_\mathrm{T}]\rangle$ calculated for charged particles over 0.5–10 GeV. The data are shifted slightly along the x axis for better visibility. Bars and shaded areas indicate statistical and total uncertainties, respectively.

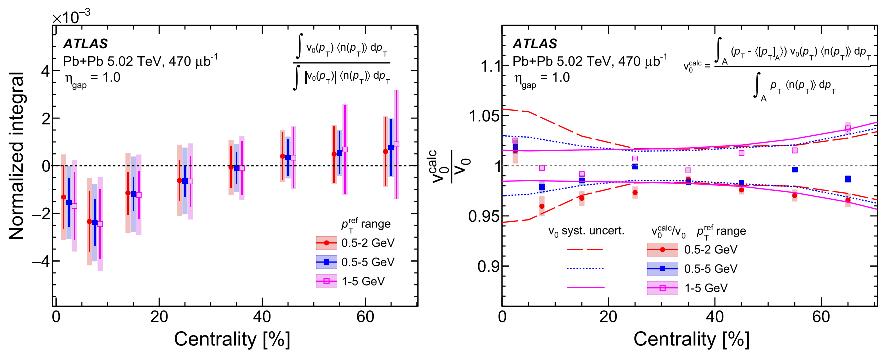

FIG. 8. The closure of the two sum rules: $\int v_0(p_\mathrm{T})\langle n(p_\mathrm{T})\rangle dp_\mathrm{T} = 0$ (left) and Eq. (2) (right) obtained for the three $p_\mathrm{T}^\mathrm{ref}$ ranges. Bars and shaded areas indicate statistical and total uncertainties, respectively.

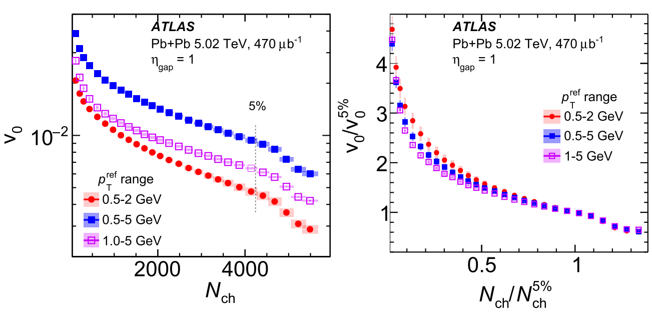

FIG. 9. Left: v_0 as a function of N_ch for three $p_\mathrm{T}^\mathrm{ref}$ ranges and $\eta_\mathrm{gap} = 1$. Right: v_0 divided by its value at 5% centrality. Bars and shaded areas indicate statistical and total uncertainties, respectively.

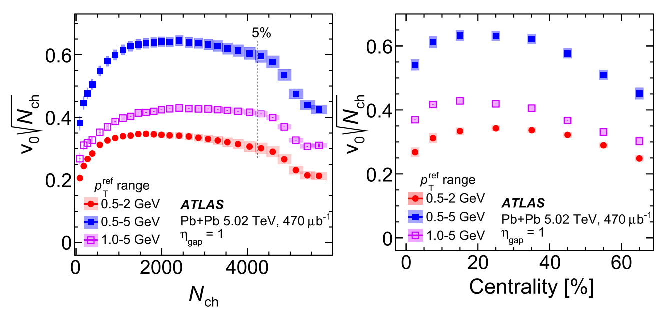

FIG. 10. $\sqrt{N_\mathrm{ch}}v_0(p_\mathrm{T})$ as a function of N_ch (left) and centrality (right) for three $p_\mathrm{T}^\mathrm{ref}$ ranges and $\eta_\mathrm{gap} = 1$. Bars and shaded areas indicate statistical and total uncertainties, respectively.

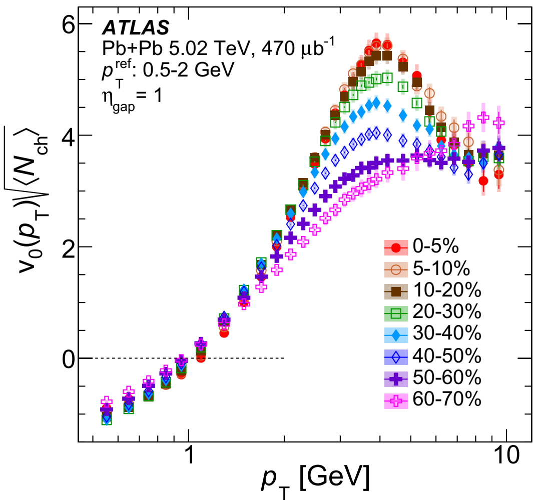

FIG. 11. The $\sqrt{N_{\mathrm{ch}}}v_0(p_{\mathrm{T}})$ for different centrality ranges. Bars and shaded areas represent statistical and total uncertainties, respectively.

G. Aad,[104] E. Aakvaag,[17] B. Abbott,[123] S. Abdelhameed,[119a] K. Abeling,[55] N. J. Abicht,[49] S. H. Abidi,[30] M. Aboelela,[45] A. Aboulhorma,[36e] H. Abramowicz,[157] Y. Abulaiti,[120] B. S. Acharya,[69a,69b,b] A. Ackermann,[63a] C. Adam Bourdarios,[4] L. Adamczyk,[87a] S. V. Addepalli,[149] M. J. Addison,[103] J. Adelman,[118] A. Adiguzel,[22c] T. Adye,[137] A. A. Affolder,[139] Y. Afik,[40] M. N. Agaras,[13] A. Aggarwal,[102] C. Agheorghiesei,[28c] F. Ahmadov,[39,c] S. Ahuja,[97] X. Ai,[143b] G. Aielli,[76a,76b] A. Aikot,[169] M. Ait Tamlihat,[36e] B. Aitbenchikh,[36a] M. Akbiyik,[102] T. P. A. Åkesson,[100] A. V. Akimov,[151] D. Akiyama,[174] N. N. Akolkar,[25] S. Aktas,[22a] G. L. Alberghi,[24b] J. Albert,[171] P. Albicocco,[53] G. L. Albouy,[60] S. Alderweireldt,[52] Z. L. Alegria,[124] M. Aleksa,[37] I. N. Aleksandrov,[39] C. Alexa,[28b] T. Alexopoulos,[10] F. Alfonsi,[24b] M. Algren,[56] M. Alhroob,[173] B. Ali,[135] H. M. J. Ali,[93,d] S. Ali,[32] S. W. Alibocus,[94] M. Aliev,[34c] G. Alimonti,[71a] W. Alkakhi,[55] C. Allaire,[66] B. M. M. Allbrooke,[152] J. S. Allen,[103] J. F. Allen,[52] P. P. Allport,[21] A. Aloisio,[72a,72b] F. Alonso,[92] C. Alpigiani,[142] Z. M. K. Alsolami,[93] A. Alvarez Fernandez,[102] M. Alves Cardoso,[56] M. G. Alviggi,[72a,72b] M. Aly,[103] Y. Amaral Coutinho,[83b] A. Ambler,[106] C. Amelung,[37] M. Amerl,[103] C. G. Ames,[111] T. Amezza,[130] D. Amidei,[108] B. Amini,[54] K. Amirie,[161] A. Amirkhanov,[39] S. P. Amor Dos Santos,[133a] K. R. Amos,[169] D. Amperiadou,[158] S. An,[84] C. Anastopoulos,[145] T. Andeen,[11] J. K. Anders,[94] A. C. Anderson,[59] A. Andreazza,[71a,71b] S. Angelidakis,[9] A. Angerami,[42] A. V. Anisenkov,[39] A. Annovi,[74a] C. Antel,[37] E. Antipov,[151] M. Antonelli,[53] F. Anulli,[75a] M. Aoki,[84] T. Aoki,[159] M. A. Aparo,[152] L. Aperio Bella,[48] M. Apicella,[31] C. Appelt,[157] A. Apyan,[27] S. J. Arbiol Val,[88] C. Arcangeletti,[53] A. T. H. Arce,[51] J-F. Arguin,[110] S. Argyropoulos,[158] J.-H. Arling,[48] O. Arnaez,[4] H. Arnold,[151] G. Artoni,[75a,75b] H. Asada,[113] K. Asai,[121] S. Asai,[159] S. Asatryan,[179] N. A. Asbah,[37] R. A. Ashby Pickering,[173] A. M. Aslam,[97] K. Assamagan,[30] R. Astalos,[29a] K. S. V. Astrand,[100] S. Atashi,[165] R. J. Atkin,[34a] H. Atmani,[36f] P. A. Atmasiddha,[131] K. Augsten,[135] A. D. Auriol,[41] V. A. Austrup,[103] G. Avolio,[37] K. Axiotis,[56] G. Azuelos,[110,e] A. Azzam,[13] D. Babal,[29b] H. Bachacou,[138] K. Bachas,[158,f] A. Bachiu,[35] E. Bachmann,[50] M. J. Backes,[63a] A. Badea,[40] T. M. Baer,[108] P. Bagnaia,[75a,75b] M. Bahmani,[19] D. Bahner,[54] K. Bai,[126] J. T. Baines,[137] L. Baines,[96] O. K. Baker,[178] E. Bakos,[16] D. Bakshi Gupta,[8] L. E. Balabram Filho,[83b] V. Balakrishnan,[123] R. Balasubramanian,[4] E. M. Baldin,[38] P. Balek,[87a] E. Ballabene,[24b,24a] F. Balli,[138] L. M. Baltes,[63a] W. K. Balunas,[33] J. Balz,[102] I. Bamwidhi,[119b] E. Banas,[88] M. Bandieramonte,[132] A. Bandyopadhyay,[25] S. Bansal,[25] L. Barak,[157] M. Barakat,[48] E. L. Barberio,[107] D. Barberis,[18b] M. Barbero,[104] M. Z. Barel,[117] T. Barillari,[112] M-S. Barisits,[37] T. Barklow,[149] P. Baron,[136] D. A. Baron Moreno,[103] A. Baroncelli,[62] A. J. Barr,[129] J. D. Barr,[98] F. Barreiro,[101] J. Barreiro Guimarães da Costa,[14] M. G. Barros Teixeira,[133a] S. Barsov,[38] F. Bartels,[63a] R. Bartoldus,[149] A. E. Barton,[93] P. Bartos,[29a] A. Basan,[102]

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