EPJ Web of Conferences **364**, 05005 (2026) https://doi.org/10.1051/epjconf/202636405005
Quark Matter 2025

Evidence for the collective nature of radial flow in Pb+Pb collisions with the ATLAS detector

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Abstract. In heavy-ion collisions, the isotropic radial expansion of the formed Quark-Gluon Plasma (QGP) has been studied using its influence on other experimental observables. This proceeding summarizes the first direct evidence for the collective nature of radial flow fluctuations, using a transverse momentum (p_{T}) differential observable, $v_0(p_{\mathrm{T}})$, measured in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV by the ATLAS Collaboration [1]. The measurement reveals three key signatures of the collective behavior of radial flow: factorization, long-range pseudorapidity correlations, and a centrality-independent shape. Comparisons with hydrodynamic model calculations show that $v_0(p_{\mathrm{T}})$ is highly sensitive to the bulk viscosity of the QGP.

1 Introduction: Ultra-relativistic heavy-ion collisions generate the Quark-Gluon Plasma (QGP), a medium whose dynamical evolution is described by relativistic hydrodynamics. Driven by initial pressure gradients, the system undergoes a collective expansion that maps initial-state fluctuations onto final-state particle distributions. This collective motion is broadly categorized as *anisotropic flow*, arising from initial-state azimuthal asymmetries, and *radial flow*, corresponding to the isotropic expansion driven by fluctuations in the initial energy density. While anisotropic flow primarily constrains the shear viscosity to entropy density ratio (η/s), radial flow is predicted to be particularly sensitive to the bulk viscosity to entropy density ratio (ζ/s).

However, until now, no direct measure existed to experimentally test whether fluctuations in the magnitude of radial flow are collective in nature. To investigate whether radial flow exhibits collectivity analogous to anisotropic flow, we employ the p_{T}-differential observable $v_0(p_{\mathrm{T}})$, proposed in Refs. [2, 3]. This observable quantifies the correlated fluctuations between the shape of the p_{T} spectrum, $n(p_{\mathrm{T}})$, and event-wise mean transverse momentum, $[p_{\mathrm{T}}]$. As illustrated in Fig. 1, events with stronger radial flow (higher $[p_{\mathrm{T}}]$) are characterized by a harder (flatter) spectrum. This leads to a depletion of $n(p_{\mathrm{T}})$ for $p_{\mathrm{T}} < \bar{p}_{\mathrm{T}}$ and an enhancement for $p_{\mathrm{T}} > \bar{p}_{\mathrm{T}}$, relative to the average, where $\bar{p}_{\mathrm{T}}$ represents the ensemble average, $\langle [p_{\mathrm{T}}] \rangle$ in the 0.5–10 GeV range. Thus, the effect of radial push on the spectra can be quantified using:

$$\frac{\langle \delta n(p_{\mathrm{T}})\, \delta[p_{\mathrm{T}}] \rangle}{\langle n(p_{\mathrm{T}}) \rangle \langle [p_{\mathrm{T}}] \rangle} = v_0(p_{\mathrm{T}})\, v_0 \,. \tag{1}$$

where, $\delta[p_{\mathrm{T}}]\rangle = [p_{\mathrm{T}}] - \langle [p_{\mathrm{T}}] \rangle$, and $v_0 \equiv \sqrt{\langle (\delta[p_{\mathrm{T}}])^2 \rangle} / \langle [p_{\mathrm{T}}] \rangle$.

2 Methodology: This analysis used 470 μb^{-1} of Pb+Pb collision data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV recorded by ATLAS. Charged-particle tracks are reconstructed within $|\eta| < 2.5$ and $0.5 < p_{\mathrm{T}} < 10$ GeV. Centrality is determined via the Forward Calorimeters (FCal).

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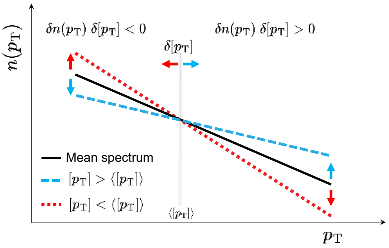

Figure 1. Schematic illustrating how radial flow fluctuations correlate the event-by-event p_{T} spectrum $n(p_{\mathrm{T}})$ with the event-wise mean $[p_{\mathrm{T}}]$.

$v_0(p_{\mathrm{T}})$ is measured using two-subevent method to suppress non-flow. Tracks are divided into subevents separated by pseudorapidity gaps, η_{gap}, of 0, 1, 2, and 3. Tracks are corrected for efficiency and fakes using Hijing and Geant4 simulations.

3 Results: This section presents experimental evidence for three key hallmarks of collectivity in $v_0(p_{\mathrm{T}})$: (i) factorization into a single-particle response, (ii) persistence over large pseudorapidity separations, and (iii) a centrality-independent differential shape expected from a common hydrodynamic response.

If radial flow fluctuations arise from collective dynamics, then $v_0(p_{\mathrm{T}})$ should behave as a single-particle property and therefore be independent of the p_{T} of the reference particle, $p_{\mathrm{T}}^{\mathrm{ref}}$, used to evaluate $\langle[p_{\mathrm{T}}]\rangle$ and v_0 in Eq. 1. We check this in Figure 2. The left panel shows the centrality dependence of v_0 normalized to its 0–5% value for three $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges. Before normalization, the magnitude of v_0 increases with increasing $p_{\mathrm{T}}^{\mathrm{ref}}$ [1]. However, after normalization by $v_0^{0\text{–}5\%}$, the ratio $v_0/v_0^{0\text{–}5\%}$ exhibits a common centrality evolution across all $p_{\mathrm{T}}^{\mathrm{ref}}$, already indicating a common global origin of radial flow fluctuations for all $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges.

The right panel in Fig. 2 shows $v_0(p_{\mathrm{T}})$ compared for different $p_{\mathrm{T}}^{\mathrm{ref}}$ selections in central (0–5%) and peripheral (50–60%) events. The shape of $v_0(p_{\mathrm{T}})$ is unchanged for $p_{\mathrm{T}} \lesssim 3\,\mathrm{GeV}$, independent of $p_{\mathrm{T}}^{\mathrm{ref}}$, demonstrating that the correlator factorizes into a single-particle response. At higher p_{T}, where hard processes and residual non-flow can contribute, small deviations from perfect factorization appear, consistent with expectations. Comparison with Hijing simulations [1] shows a strong under-prediction of the data for $p_{\mathrm{T}} < 6\,\mathrm{GeV}$, reinforcing that the observed signal is driven by collective dynamics rather than non-collective correlations.

A defining property of collectivity in heavy-ion collisions is that correlations persist over large separations in pseudorapidity, indicating a common global behavior. Figure 3 (left) tests this by comparing $v_0(p_{\mathrm{T}})$ measured with four pseudorapidity gaps, $\eta_{\mathrm{gap}} = 0, 1, 2, 3$, in the 0–5% centrality interval. The measured $v_0(p_{\mathrm{T}})$ shows negligible dependence on η_{gap}, demonstrating that the correlation underlying $v_0(p_{\mathrm{T}})$ is genuinely long-range.

Figure 3 (right) shows that the normalized ratio $v_0(p_{\mathrm{T}})/v_0$ is remarkably stable across centrality intervals for $p_{\mathrm{T}} \lesssim 2.5\,\mathrm{GeV}$. This scaling indicates that centrality primarily controls the overall *magnitude* of radial flow fluctuations, and that the differential response function $k_0(p_{\mathrm{T}}) \approx v_0(p_{\mathrm{T}})/v_0$, remains centrality independent. Such behavior closely parallels the scaling patterns observed for anisotropic flow measurements, strengthening the interpretation of $v_0(p_{\mathrm{T}})$ as collective.

The established collective nature of radial flow fluctuations makes $v_0(p_{\mathrm{T}})$ a valuable tool for constraining QGP transport properties. In particular, the normalized shape $v_0(p_{\mathrm{T}})/v_0$ provides sensitivity to the medium response while minimizing trivial centrality-dependent initial-state effects. Figure 4 compares the measured shape in 0–5% centrality to Trento+MUSIC

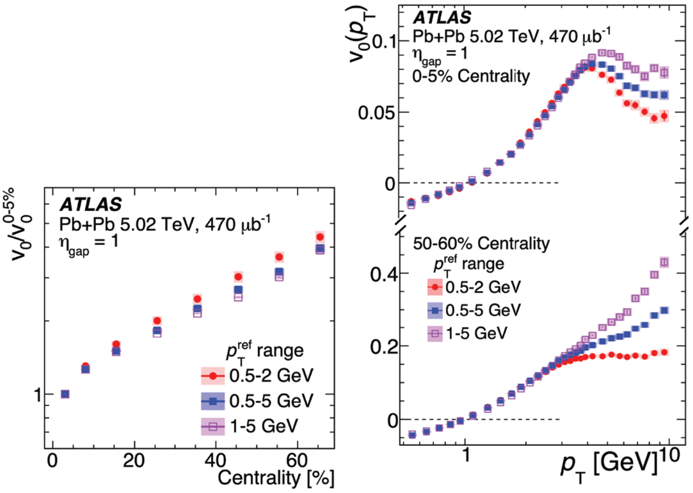

Figure 2. (Left) Centrality dependence of $v_0/v_0^{0\text{–}5\%}$ for different reference p_T ranges. (Right) Centrality dependence of $v_0(p_\mathrm{T})$ in 0–5% and 50–60% centrality.

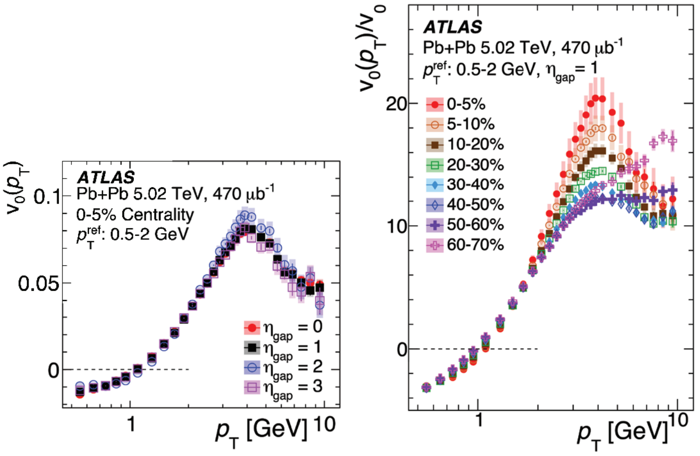

Figure 3. (Left) $v_0(p_\mathrm{T})$ for $\eta_\mathrm{gap} = 0, 1, 2, 3$ in 0–5% centrality. (Right) The normalized ratio $v_0(p_\mathrm{T})/v_0$ showing a centrality-independent shape.

hydrodynamic calculations [2]. Simulations with ideal (zero viscosity) dynamics or with shear viscosity fail to reproduce the measured trend. In contrast, a model including a temperature-dependent bulk viscosity, $\zeta/s(T)$, shows significantly better agreement with the data. This comparison underscores the unique sensitivity of $v_0(p_\mathrm{T})$ to bulk viscosity and highlights its potential to complement anisotropic flow observables in constraining QGP transport coefficients.

As a consistency test, the measured $v_0(p_\mathrm{T})$ was validated against two sum rules expected for collective radial flow fluctuations [2, 3]. The first requires $\int v_0(p_\mathrm{T})\langle n(p_\mathrm{T})\rangle\, dp_\mathrm{T} = 0$, implying that $v_0(p_\mathrm{T})$ changes sign near $\overline{p}_T$. The second relates the p_T-differential and p_T-integrated fluctuations: $\int (p_\mathrm{T} - \langle p_\mathrm{T}\rangle)\, v_0(p_\mathrm{T})\langle n(p_\mathrm{T})\rangle\, dp_\mathrm{T} = v_0\ \langle[p_\mathrm{T}]\rangle$.

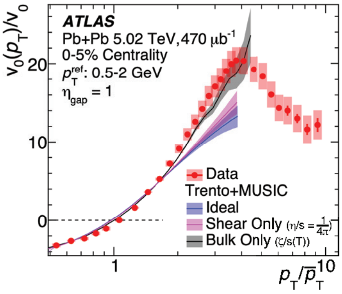

Figure 4. $v_0(p_T)/v_0$ in 0–5% centrality compared with hydrodynamic model calculations [2] without viscosity (red), with constant η/s and with $\zeta/s(T)$.

The fractional closure for the first and second sum rules is shown in the left and right panels of Fig. 5, respectively. The first closes within 0.5%, indicating excellent agreement. The second shows a deviation of about 5%, consistent with expectations within systematic uncertainties, and confirms that the v_0 extracted from the second sum rule is consistent with the direct two-subevent measurement.

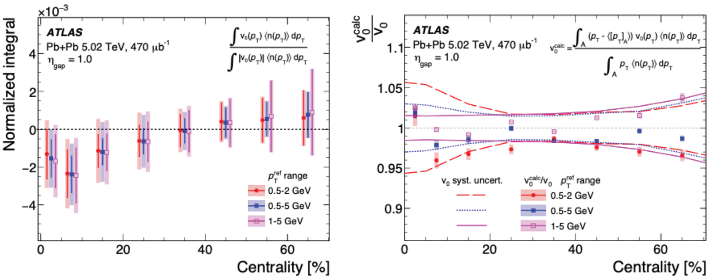

Figure 5. Fractional closure for the first sum rule (Left) and second sum rule (Right) across different reference p_T ranges. Bars and shaded areas indicate statistical and total uncertainties, respectively.

4 **Summary**: We presented the first measurement of $v_0(p_T)$ in Pb+Pb at 5.02 TeV [1]. Factorization, long-range correlations, and centrality-independent scaling establish its collective origin. Comparison to hydrodynamics demonstrates strong sensitivity to bulk viscosity, providing new constraint on QGP transport properties.

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