Measurement of the distribution of event-by-event harmonic flow in Pb-Pb collisions at $\sqrt{s_{NN}}$ =2.76 TeV with the ATLAS detector

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Abstract. In recent years, the measurement of harmonic flow coefficients v_n has provided important insight into the hot and dense matter created in heavy ion collisions at RHIC and LHC. These coefficients are now understood to reflect the hydrodynamic response of the produced medium to the collision geometry. Due to finite number of nucleons in the system, the collision geometry can fluctuate from one event to another, and hence measuring the full distribution of the event-by-event v_n coefficients can provide better insights on the nature of these fluctuations and possible non-linear effects in the hydrodynamic response. This proceeding presents the first measurements of the event-by-event v_n distributions for n=2-4 in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector.

Relativistic heavy-ion collisions produce an extremely hot and dense medium commonly termed as the Quark Gluon Plasma. The produced medium expands anisotropically due to asymmetric pressure gradients with larger particle yields in the direction of the largest gradients. The azimuthal anisotropy can be expressed as a Fourier series:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n(p_{\mathrm{T}}, \eta) \cos n(\phi - \Phi_n) \tag{1}$$

where, v_n and Φ_n are the magnitude and phase of the n^{th} order harmonic flow [1]. Measurements of the p_{T} , η and centrality dependence of the harmonics v_n have been done via the event-plane (EP) method [1] as well as by multi-particle correlation methods [1, 2]. In these methods, the v_n are obtained by averaging over a large number of events. Due to event by event fluctuations in the initial geometry, the v_n values vary event by event. Averaging over events, the EP and multi-paricle correlation methods measure a mean response of the medium. For example, the EP method gives a value in between the mean and the RMS of the v_n distribution, i.e. $\langle v_n \rangle < v_n^{EP} < \sqrt{\langle v_n^2 \rangle}$ [3]. A deeper understanding of the initial geometry and the expansion mechanism of the produced medium can be obtained by measuring the event-by-event (EbE) v_n distributions.

The large multiplicity in Pb-Pb collisions at the LHC as well as the large acceptance of the ATLAS inner detector [5] covering $|\eta| < 2.5$ allow for the first measurements of the EbE v_n distributions in heavy-ion collisions. Figure 1 shows the azimuthal distribution (black points) of charged tracks with p_{T} >0.5 GeV for three individual events in the (0-5)% centrality class. The red points show the anisotropy in the detector acceptance (arbitrary normalization) obtained by averaging over many events. It is clear that the EbE fluctuations in particle distributions are much larger than the detector acceptance effects.

The v_n measurements presented here were made using 8 μb^{-1} of Minimum Bias Pb-Pb data at $\sqrt{s_{NN}}$ of 2.76 TeV. Details of the results presented here are published in [6].

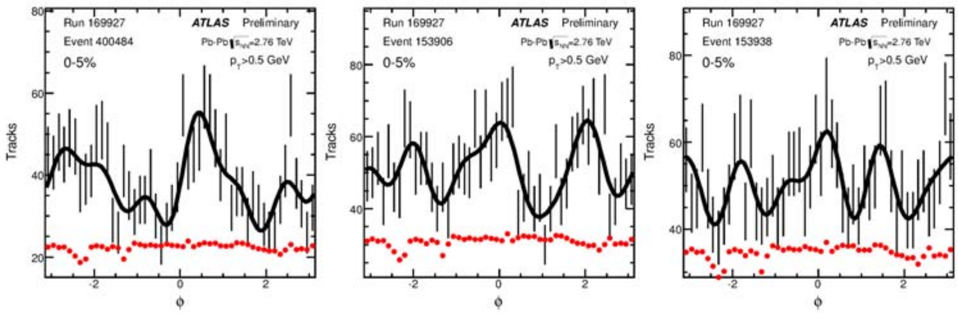

Figure 1. Single track ϕ distributions for three events (from left to right) in the (0-5)% centrality interval. The bars indicate the foreground distributions, the solid curves indicate a Fourier parameterization including first six harmonics and the red points indicate the detector acceptance functions. Charged tracks with $p_{\mathrm{T}} > 0.5\,\mathrm{GeV}$ are used. Figure taken from [6].

The azimuthal distribution of charged tracks in an event can be expanded in a Fourier series to obtain the *observed* flow-vector $(v_{n,x}^{obs}, v_{n,y}^{obs})$ as:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n^{obs} \cos n(\phi - \Phi_n^{obs}) = 1 + 2\sum_{n=1}^{\infty} (v_{n,x}^{obs} \cos n(\phi) + v_{n,y}^{obs} \sin n(\phi)) \tag{2}$$

To account for the detector efficiency effects, each track is weighted by the the inverse of the tracking efficiency. The v_n^{obs} in an event is obtained as $\sqrt{(v_{n,x}^{obs})^2 + (v_{n,y}^{obs})^2}$. Due to the finite number of tracks in the event, the $v_{n,x}^{obs}$ and $v_{n,y}^{obs}$ and hence the v_n^{obs} fluctuate about the true values. The v_n^{obs} distribution needs to be corrected for this smearing using the response function, which gives the probality distribution of v_n^{obs} for a given true v_n. To obtain the response function, each event is divided into two sub-events containing tracks with $\eta > 0$ and $\eta < 0$ respectively. Taking the difference of the flow-vector between the two sub-events, the physical signal cancels out and the resulting distribution $(v_{n,x}^{obs,1} - v_{n,x}^{obs,2}, v_{n,y}^{obs,1} - v_{n,y}^{obs,2})$ is consistent with a 2D Gaussian with identical widths $\delta_{2\mathrm{SE}}$ in the x and y directions. The response function can be obtained by shifting this 2D distribution to $(v_{n,x}, v_{n,y})$ and then projecting it along the radial direction [6]:

$$p(v_n^{obs}|v_n) \propto v_n^{obs} e^{-\frac{(v_n^{obs})^2 + v_n^2}{2\delta^2}} I_0(\frac{(v_n^{obs})^2 + v_n^2}{\delta^2}), \delta = \delta_{2\mathrm{SE}}/2 \tag{3}$$

where, I_0 is the modified Bessel function of the second kind. This response function is used along with the Bayesian unfolding procedure [4] to calculate the unfolded v_n distributions. Note that this procedure implicitly assumes that the physical flow signal is rapidity independent, which is true when averaged over many events [1], but might not hold event by event.

Figure 2 shows the final probability distributions for $v_2 - v_4$ for several different centrality classes. The shape of the v_2 distribution changes considerably from central to peripheral events while for v_3 and v_4 the change is relatively small. This is expected as the higher order harmonics v_3 and v_4 are produced due to fluctuations in the collision geometry, however v_2 is also driven by the average second order eccentricity, which increases from central to peripheral events. The v_3 and v_4 distributions are well described by radial projections of 2D Gaussian distributions in

$\vec{v_n}$ with $P(|\vec{v_n}|) = (|\vec{v_n}|/\sigma)e^{-|\vec{v_n}|^2/\sigma^2}$, $\sigma = \sqrt{2/\pi}\langle v_n\rangle$ (solid lines) across all centralities. For the v_2 distribution this only works for the (0-1)% central events.

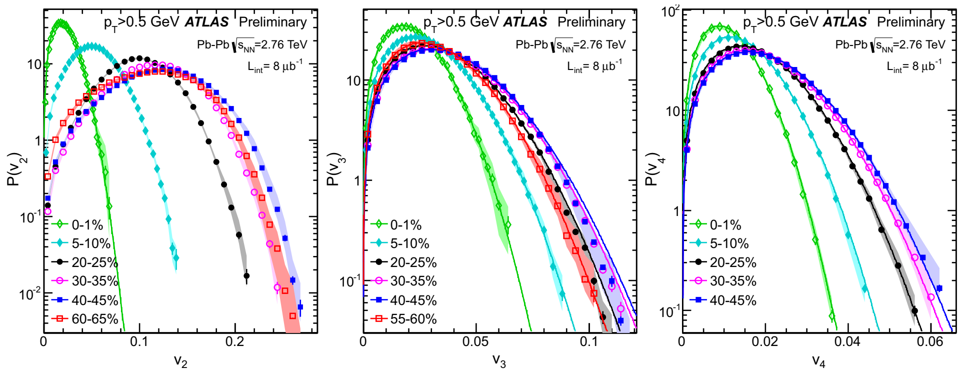

Figure 2. The probability distribution of the EbE v_n in several centrality intervals for n=2, 3 and n=4. The error bars are statistical uncertainties, and the shaded bands are uncertainties on the v_n shape. The solid curves are distributions calculated assuming the v_n are radial projections of 2D Gaussian distributions; they are shown for 0-1% centrality interval for v_2 and all centrality intervals for v_3 and v_4. Figure taken from [6].

Figure 3 compares the EbE distributions for the v_n for three different p_{T} ranges: 0.5< p_{T} <1.0 GeV, p_{T} > 1.0 GeV and p_{T} >0.5 GeV for the (20-25)% centrality class. The v_n distributions for tracks with p_{T} >1.0 GeV are much broader than the ones for p_{T} <1.0 GeV reflecting the fact that the v_n increase with p_{T}. However, once the three distributions are scaled to the same mean value, their reduced shapes are almost identical as shown in the lower panels. This indicates that the hydrodynamic response to the initial geometry scales linearly with p_{T}.

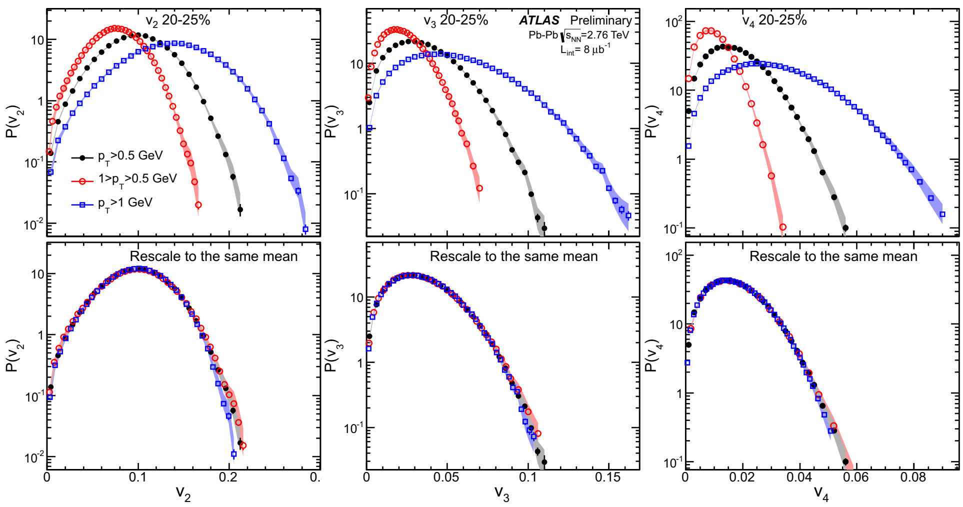

Figure 3. Top panels: The unfolded distributions for v_n in the (20-25)% centrality interval for charged particles in p_{T} >0.5 GeV, 0.5< p_{T} <1.0 GeV and p_{T} >1 GeV. Bottom panels: same distributions but rescaled horizontally so the v_n values match that for p_{T} >0.5 GeV. The shaded bands represent the systematic uncertainties on the v_n shape. Figure taken from [6].

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Figure 4 shows the mean values ($\langle v_n \rangle$) and RMS widths (σ_{v_n}) of the v_n distributions as well as the ratio of $\sigma_{v_n}/\langle v_n \rangle$ as a function of the number of participating nucleons $\langle N_{\rm part} \rangle$. While the $\langle v_n \rangle$ and σ_{v_n} change with $p_{\rm T}$ the ratio is independent for all three harmonics. The ratio $\sigma_{v3}/\langle v_3 \rangle$ is independent of $\langle N_{\rm part} \rangle$ and consistent with the value of $\sqrt{4/\pi - 1} = 0.52$ expected from 2D-Gaussian distributions, v_4 shows a similar behavior as well (not shown). For v_2 the Gaussian limit is reached only in most central events and shows a considerable deviation for mid-central and peripheral events, where the average collision geometry has a large second-order eccentricity. For all cases, the v_n measured via the EP method are found to lie in between $\langle v_n \rangle$ and $\sqrt{\langle v_n^2 \rangle}$ within statistical and systematic errors [6].

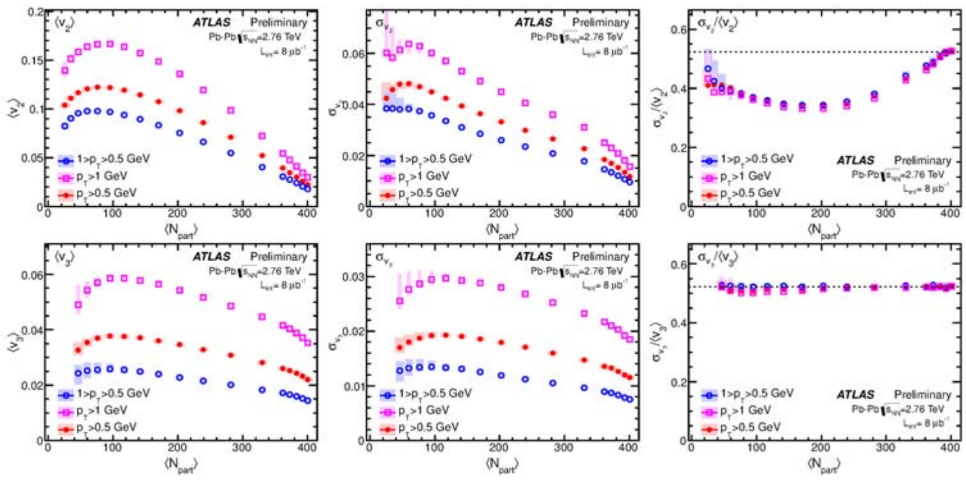

Figure 4. The $\langle N_{\rm part} \rangle$ dependence of $\langle v_n \rangle$ (left column), σ_{v_n} (middle column) and σ_{v_n}/v_n (right column) for n=2 (top row) and n=3 (bottom row). Each panel shows the results for three $p_{\rm T}$ ranges together with the total systematic uncertainties. The dotted lines in the right column indicate the value 0.52 expected for the radial projection of a 2-D Gaussian distribution. Figure taken from [6].

ATLAS has measured the event-by-event distribution of harmonic flow coefficients $v_2 - v_4$ in various centrality bins. The v_2 distribution is consistent with radial projection of 2D Gaussian distributions in most central events, but shows significant deviation for >5% centrality. For v_3 and v_4 the distributions are consistent with 2D Gaussian for all centralities. The reduced shape of the v_n distributions has no $p_{\rm T}$ dependence showing that the hydrodynamic response to the initial geometry is independent of $p_{\rm T}$ up to an overall normalization. These measurements are the first of their kind and provide constraints on the hydrodynamic response as well as initial geometry fluctuations of the produced medium [6].

References

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