Probing Hydrodynamics in PbPb Collisions at 5.02 TeV with Higher-order Cumulants

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Abstract. The elliptic flow of charged hadrons is studied through multiparticle correlations in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, corresponding to an integrated luminosity of 0.607 nb^{-1}. $v_2\{2k\}$ are measured up to the tenth order (k = 5) as functions of the collision centrality. They are shown to follow the ordering : $v_2\{2\} > v_2\{4\} \gtrsim v_2\{6\} \gtrsim v_2\{8\} \gtrsim v_2\{10\}$. The centrality-dependent moments - skewness, kurtosis and, for the first time, superskewness, are measured for the fluctuation-driven event-by-event v_2 distribution. These moments can be good probes of the initial-state geometry in high-energy nucleus-nucleus collisions, assuming a hydrodynamic expansion.

1 Introduction

The quark-gluon plasma (QGP) is a strongly interacting state of highly energetic and dense matter which has been achieved in experiments [1–3] by colliding heavy nuclei at ultra-relativistic speeds. The QGP is known to undergo collective hydrodynamic expansion. The initial spatial anisotropy in the overlap region of the colliding nuclei leads to anistropic pressure gradients, which in turn leads to the azimuthally anisotropic flow of outgoing particles. The distribution of the anisotropic flow of particles can be expressed in terms of the Fourier series [4, 5] :

$$P(\phi) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \psi_n)\right] \tag{1}$$

where ϕ is the particle azimuthal angle, ψ_n is the n^{th} order flow symmetry plane, and v_n are the n^{th} order Fourier coefficients called the flow harmonics. v_2 refers to elliptic flow, and is the leading term in this Fourier expansion.

Event-by-event fluctuations of the v_2 distribution lead to non-zero values of its higher-order moments, like skewness, kurtosis and superskewness. Skewness refers to the overall asymmetry of the distribution, kurtosis measures the peakedness or flatness, while superskewness quantifies the asymmetry of the tails. Assuming hydrodynamic expansion, initial-state eccentricity (ϵ_2) fluctuations directly lead to non-Gaussianities in the v_2 distribution, giving us insight into the initial-state geometry and structure. These have been measured using multi-particle cumulants [6].

In this paper [7], v_2 from 10 particle correlations, $v_2\{10\}$, has been measured for the first time in PbPb collisions. Two hydrodynamic probes - one introduced in Ref.[8] and another one using $v_2\{10\}$ and all lower-order $v_2\{2k\}$, have been derived using these higher-order moments. The higher-order moments have been defined in terms of $v_2\{2k\}$. Introduction of these higher-order moments have been shown to describe the centrality dependence of the hydrodynamic probes very accurately.

2 Analysis Technique

In order to calculate $v_2\{2k\}$ and the two hydrodynamic probes, the Q-cumulant method [9] has been used. With this method, any arbitrary $2k^{th}$ order cumulant can be constructed from the recursion relation [10] :

$$c_n\{2k\} = \langle\langle 2k \rangle\rangle - \sum_{m=1}^{k-1} \binom{k}{m} \binom{k-1}{m} \langle\langle 2m \rangle\rangle c_n\{2k-2m\} \tag{2}$$

From Eq. (2), we can get the $v_n\{2k\}$ values as :

$$v_n\{2k\} = \sqrt[2k]{a_{2k}^{-1} c_n\{2k\}} \tag{3}$$

where

$$a_{2k} = 1 - \sum_{m=1}^{k-1} \binom{k}{m} \binom{k-1}{m} a_{2k-2m} \tag{4}$$

Writing the higher-order moments in terms of $v_2\{2k\}$, the two hydrodynamic probes have been defined as :

$$h_1 = \frac{v_2\{6\} - v_2\{8\}}{v_2\{4\} - v_2\{6\}} \approx h_1^{Taylor} = \frac{1}{11} - \frac{1}{11} \frac{v_2\{4\}^2 - 12 v_2\{6\}^2 + 11 v_2\{8\}^2}{v_2\{4\}^2 - v_2\{6\}^2} \tag{5}$$

$$h_2 = \frac{v_2\{8\} - v_2\{10\}}{v_2\{6\} - v_2\{8\}} \approx h_2^{Taylor} = \frac{3}{19} - \frac{1}{19} \frac{3 v_2\{6\}^2 - 22 v_2\{8\}^2 + 19 v_2\{10\}^2}{v_2\{6\}^2 - v_2\{8\}^2} \tag{6}$$

Finally, the "corrected" skewness, kurtosis and superskewness have been constructed [7], making them independent of the other moments. This has been done by assuming an elliptic power distribution [11], setting the initial eccentricity parameter $\epsilon_0 \leq 0.15$. This shows the utility of these observables to constrain the initial state.

3 Results

The measured $v_2\{2k\}$ ($k = 1, .., 5$) are shown in Figure 1 as functions of collision centrality in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Charged particles having pseudorapidity values $|\eta| < 2.4$ and transverse momentum $0.5 < p_T < 3.0$ GeV/c have been used.

It is observed that there is a clear splitting between $v_2\{2\}$ and the higher-order cumulant based $v_2\{2k\}$ values. The difference is due to flow fluctuations, with $v_2\{2\}^2 \approx v_2\{2k\}^2 + 2\sigma_v^2$ for $k > 1$ [8], where σ_v^2 is the v_2 variance. It is also seen that the flow fluctuations become larger going to more peripheral collisions (higher centrality percentages).

The cumulants of different orders have been used to calculate the hydrodynamic probes given by the left-hand sides of Eqs. (5) and (6). Figure 1 displays these distributions with closed symbols. Open symbols in the same figure show the right-hand sides of Eqs. (5) and (6). Without taking the higher-order moments into consideration, the distributions are represented by the constant values of $\frac{1}{11}$ and $\frac{3}{19}$, represented by the blue and red lines for the

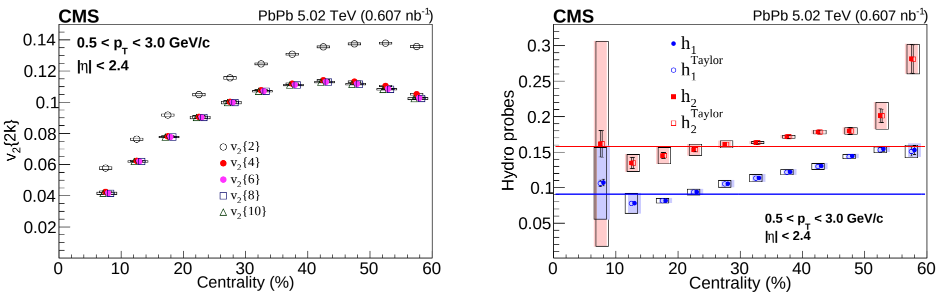

Figure 1. Left : $v_2\{2k\}$ ($k = 1, .., 5$) as functions of centrality in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Right : The two hydrodynamic probes as functions of centrality. The vertical sizes of the open boxes denote the systematic uncertainties. Statistical uncertainties are negligible compared to the marker size. Points are plotted at the center of the respective centrality ranges. The markers are displaced horizontally for better visibility.

two probes respectively in the right-hand side plot of Figure 1. However, it is clear that the values of these probes are centrality-dependent and are very well described by the right-hand side expansions of Eqs. (5) and (6).

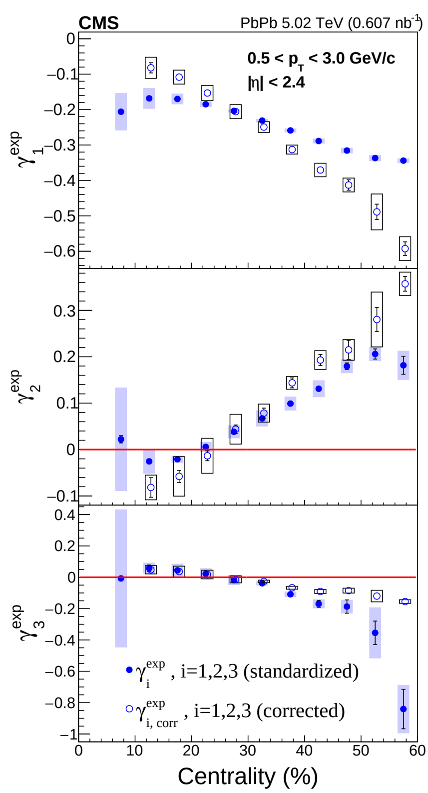

Figure 2. The skewness, kurtosis and superskewness and their corrected values as functions of centrality in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Finally, the standardized higher-order moments - skewness, kurtosis and superskewness (full circles) and their corrected versions (open circles) are plotted as functions of centrality in Figure 2. Both the standardized and corrected skewness are negative for the whole centrality range. This indicates that the $v_{2,x}$ distribution has a long tail on the low $v_{2,x}$ side (as shown in Figure 1 of [8]). This measurement confirms the prediction that the skewness becomes more negative as the centrality percentage increases. The corrected kurtosis values are positive for the whole centrality range except 10-20%, which qualitatively agrees with the prediction in [12], as it is driven by the mean eccentricity. Except for centrality 5-25%, superskewness is negative, with its absolute magnitude increasing towards more peripheral collisions. This is the first measurement of this moment.

4 Summary

The different orders of multiparticle cumulants, $v_2\{2k\}$ ($k = 1, .., 5$), are determined as functions of centrality in PbPb collisions at 5.02 TeV, with an integrated luminosity of 0.607 nb^{-1}. A splitting is observed between $v_2\{2\}$ and higher-order $v_2\{2k\}$ due to flow fluctuations. Two hydrodynamic probes have been defined in terms of $v_2\{2k\}$, which are well-explained with the inclusion of higher-order moments of the v_2 distribution. The centrality-dependent values of standardized and corrected skewness, kurtosis and superskewness are measured. These results can provide basic input for a precision test of models that assume a hydrodynamic expansion of the QGP.

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