# DIFFERENT MODES OF ELLIPTIC AND TRIANGULAR FLOW IN ULTRARELATIVISTIC PbPb COLLISIONS FROM HYDJET MODEL*

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Observed dependence of flow symmetry plane in ultra-relativistic heavy-ion collisions on transverse momentum ($p_{\rm T}$) and pseudorapidity $\eta$ is attributed to lumpy hot-spots raised by the fluctuations of the initial states. Studying different orthogonal modes of the same flow harmonic has been suggested as a promising way to explore this phenomena. Prediction of leading and sub-leading modes for elliptic and triangular flow for charged pions for PbPb collisions at the center-of-mass energy per nucleon pair of 2.76 TeV from HYDJET++ model are presented. Calculations are done by applying principal component analysis technique (PCA) on a long-range two-particle azimuthal correlations, requesting $|\Delta\eta| > 2$ gap in order to avoid non-flow effects. The results are shown as a function of transverse momentum in a range of $0.3 < p_{\rm T} < 3.0$ GeV/$c$, pseudorapidity range of $|\eta| < 2.4$, and in a various centrality classes, from ultra-central events (0–0.2%) up to rather peripheral ones (50–60%). Obtained values are compared with data measurement from the CMS experiment. Rather good agreement between the model and the experimental data is a step in a better understanding of the initial-state fluctuations and dynamics of QGP expansion.

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## 1. Introduction

Collective anisotropic flow is an important way to study properties of strongly coupled quark–gluon plasma (QGP). Azimuthal anisotropy can be described by Fourier transform [1–3]

$$\frac{2\pi}{N}\frac{{\rm d}N}{{\rm d}\phi} = 1 + \sum_n 2v_n \cos[n(\phi - \Psi_n)]\,, \tag{1}$$

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where $v_n$ are collective flow coefficients, sensitive to the initial states and medium properties, while $\Psi_n$ represents event plane angle, defined with the direction of the maximum final-state particle density for the given harmonic.

The second order Fourier coefficient, $v_2$, called "elliptic flow", appears due to an lenticular overlapping region in the collision of two nuclei. On the other hand, the third Fourier coefficient, $v_3$, called "triangular flow", comes entirely from the initial-state fluctuations [4].

If particles are correlated with the event plane, then they are also mutually correlated. Thus, the investigation of the azimuthal anisotropies can be performed using the two-particle correlations [5]. These correlations can be Fourier decomposed too as

$$\frac{1}{N_{\mathrm{trig}}}\frac{2\pi}{N_{\mathrm{assoc}}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi} = 1 + \sum_n 2V_{n\Delta}\cos[n(\Delta\phi)]\,, \tag{2}$$

where $\Delta\phi$ is a relative azimuthal angle of a particle pair, while $V_{n\Delta}$ are corresponding two-particle Fourier coefficients. The $p_{\mathrm{T}}$ differential single-particle Fourier coefficients $v_n(p_{\mathrm{T}})$ can be then obtained from the two-particle coefficients $V_{n\Delta}$ as

$$v_n(p_{\mathrm{T}}) = \frac{V_{n\Delta}\left(p_{\mathrm{T}}, p_{\mathrm{T}}^{\mathrm{ref}}\right)}{\sqrt{V_{n\Delta}\left(p_{\mathrm{T}}^{\mathrm{ref}}, p_{\mathrm{T}}^{\mathrm{ref}}\right)}}\,, \tag{3}$$

where $p_{\mathrm{T}}^{\mathrm{ref}}$ denotes a wide $p_{\mathrm{T}}$ range, between 1 and 3 GeV/$c$, used for the "reference particles".

At first, $\Psi_n$ was considered as a global quantity, however measurements showed that it is $p_{\mathrm{T}}$- and $\eta$-dependent and, therefore, measured $v_n\{2\}$ is dependent on the choice of the reference bin [6]. This event-plane decorrelation effect is the most expressive for $v_2$ in central collisions and increase with $p_{\mathrm{T}}$. Effect is negligible for $v_3$ in all kinematic range.

Recently, a new method is proposed [7,8] to study flow fluctuations inside one event. It applies a principal component analysis (PCA) on two-particle correlations. In this paper, PCA is used on the charged pions from the PbPb events at $\sqrt{s_{NN}} = 2.76$ TeV created with HYDJET++ generator [9].

## 2. Analysis techniques

Charged pions with $|\eta| < 2.4$ and $0.3 < p_{\mathrm{T}} < 3.0$ GeV/$c$ are grouped in 7 $p_{\mathrm{T}}$ bins. Paired correlations are made in $\Delta\eta$ and $\Delta\phi$ combining particles from the different $p_{\mathrm{T}}$ bins. Pseudorapidity gap $|\Delta\eta| > 2$ is imposed for pairs to remove short-range correlations. Thus, Fourier coefficients $V_{n\Delta}(p_{\mathrm{T}}^a, p_{\mathrm{T}}^b)$ can create covariant, $7\times 7$, matrix. PCA technique is applied by solving the eigenvalue problem of the $\hat{V}_{n\Delta}$. The obtained eigenvalues, $\lambda^{(\alpha)}$, and eigenvectors, $e^{(\alpha)}$, give the *flow modes*

$$v_n^{(\alpha)}(p_{\mathrm{T}}) = \frac{\sqrt{\lambda^{(\alpha)}}e^{(\alpha)}(p_{\mathrm{T}})}{\langle M(p_{\mathrm{T}})\rangle}\,, \tag{4}$$

where $\langle M(p_{\mathrm{T}})\rangle$ denotes average multiplicity of the $p_{\mathrm{T}}$ bin, used as a normalization factor.

The modes are ordered by the size of the data variance. The first mode is equivalent to the flow measured with standard two-particle correlations approach, $v_n\{2\}$. The higher modes present the effect of the event-plane decorrelation. In this analysis, only first two modes are calculated.

## 3. Results

Leading and sub-leading flow mode for elliptic flow as a function of transverse momentum in six centrality ranges, from ultra-central 0–0.2% up to peripheral ones, 50–60% of centrality are shown in Fig. 1. $v_2^{(1)}$ has a typical elliptic flow $p_{\mathrm{T}}$ and centrality dependence. $v_2^{(2)}$ shows much smaller signal than $v_2^{(1)}$, becoming larger than zero only for $p_{\mathrm{T}} > 1.5$ GeV/$c$. In the central collisions, this kind of behavior is expected from the event-plane

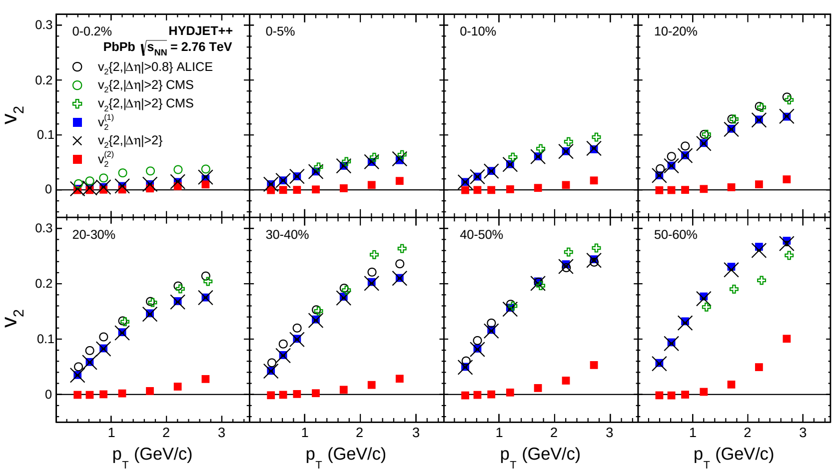


Fig. 1. Predictions for the leading and the sub-leading flow mode of the elliptic flow as a function of $p_{\mathrm{T}}$ in various centrality ranges from HYDJET++ model for PbPb collisions at 2.76 TeV. Leading flow mode is compared with the corresponding two-particle correlations results from the same generator, HYDJET++, as well as with the results from the CMS [5, 10] and ALICE [11] experiments.

deccorelation effect. On the other hand, sudden increase of $v_2^{(2)}$ in peripheral events can suggests that non-flow effects are not entirely removed by pseudorapidity gap. As a check of method consistency, leading flow mode is compared with the elliptic flow measured with the two-particle correlations method, $v_2\{2, |\Delta\eta| > 2\}$ applied on the exactly same set of events as PCA. Excellent agreement between the two supports the claim that $v_2^{(1)}$ is essentially the same as $v_2\{2\}$. Elliptic flow from HYDJET++ model is in a rather good agreement with data, published by CMS [5, 10] and ALICE [11] collaborations.

Figure 2 shows results for leading and sub-leading triangular flow mode as a function of $p_{\mathrm{T}}$. $v_3^{(2)}$ is consistent with zero in all centralities and $p_{\mathrm{T}}$ ranges which is expected since no decorrelation in transverse momentum is observed for $v_3$. Again, as in the case of the elliptic flow, a very good agreement between $v_3\{2\}$ and $v_3^{(1)}$ is noticeable. Also, there is a qualitative agreement with $v_3\{2\}$ measured by the CMS [5, 10] and ALICE [11] experiments.

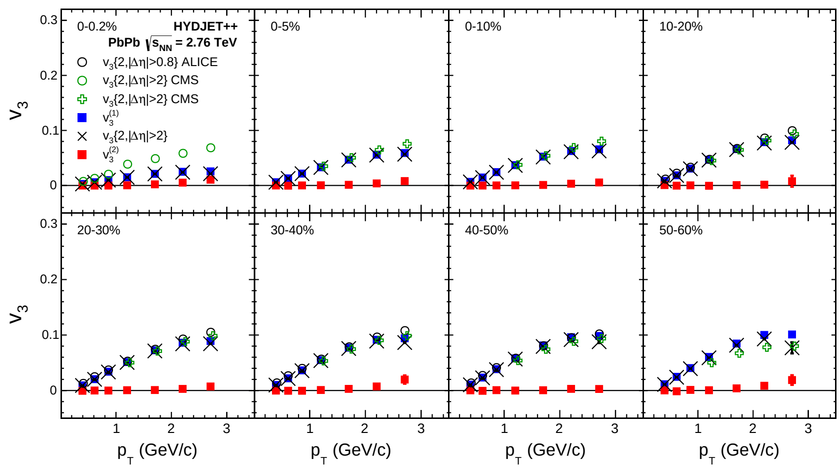


Fig. 2. Predictions for the leading and the sub-leading flow mode of the triangular flow as a function of $p_{\mathrm{T}}$ in various centrality ranges from HYDJET++ model for PbPb collisions at 2.76 TeV. Leading flow mode is compared with the corresponding two-particle correlations results from the same generator, HYDJET++, as well as with the results from the CMS [5, 10] and ALICE [11] experiments.

Both sub-leading flow modes, $v_2^{(2)}$ and $v_3^{(2)}$, are in a qualitative agreement with recently published data from the CMS Collaboration [12].

In order to analyze influence of non-flow correlations on the sub-leading flow modes, comparison between results using only soft "thermal" state in system evolution with results obtained with model that combines soft state and hard parton scattering in the fluid is made. Figure 3 shows comparison of the results for leading and sub-leading mode for elliptic flow using only soft and both soft and hard processes of the HYDJET++ generator. $v_2^{(1)}$ from events with pure hydrodynamic evolution is higher than from events which include both hydrodynamics and jets, while $v_2^{(2)}$ shows no difference for two cases except in the most peripheral case for the data point with largest transverse momentum, where pure hydro events show much higher sub-leading elliptic flow.

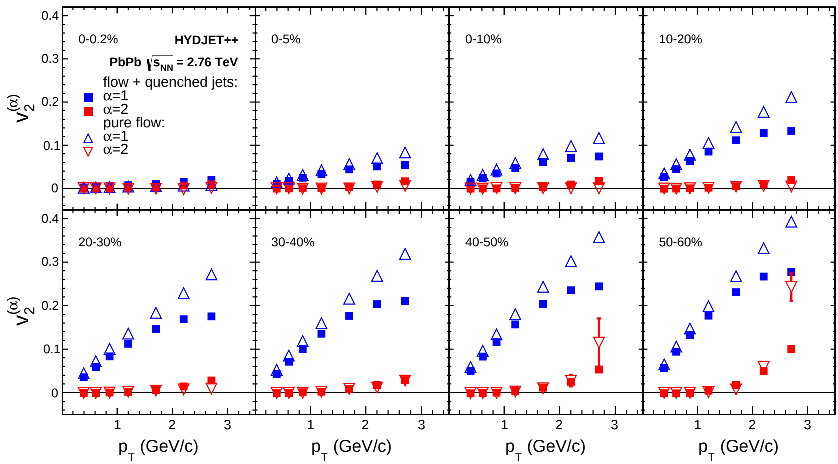


Fig. 3. Predictions for the leading and the sub-leading flow mode of the elliptic flow as a function of $p_T$ in various centrality ranges for PbPb collisions at 2.76 TeV from HYDJET++ model by generating only soft "thermal" state (open triangles) and using both, soft "thermal" and hard multi-jet state (closed squares).

## 4. Summary

Leading and sub-leading flow modes are calculated for charged pions from PbPb collisions at 2.76 TeV generated with HYDJET++ model. Predictions qualitatively agree with data recently published by the CMS Collaboration. It is also shown that leading mode is the same as the flow measured with two-particle correlations, while sub-leading modes in central collisions are consistent with the expectations from the event-decorrelations effect. However, increasing $v_2^{(2)}$ in peripheral events can suggest that sub-leading modes are much more sensitive to non-flow effects than the leading ones.

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