AZIMUTHAL CORRELATIONS AND MIXED HIGHER ORDER FLOW HARMONICS FROM CMS AT THE LHC*

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Two-particle correlations measurements of v_n ($n = 2$–4) in 8.16 TeV pPb collisions, and event-by-event correlations of different v_n are measured using symmetric cumulants in 13 TeV pp, 5.02 and 8.16 TeV pPb and 5.02 TeV PbPb collisions at the LHC. These new results give important insights to the origin of collectivity observed in small collision systems. Additionally, using the scalar product method and the method of two-particle correlations, the mixed higher order flow harmonics and extracted nonlinear response coefficients of charged particles are measured for the first time as a function of p_{T} and centrality in 2.76 and 5.02 TeV PbPb collisions. The obtained results are compared with different theoretical predictions.

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1. Introduction

Initial geometry of colliding nuclei overlapping region and its fluctuations lead to space anisotropy. As a consequence, there is a different pressure gradient in different directions in created medium — strongly-coupled quark–gluon plasma (QGP). Therefore, there are preferential directions of emission of particles created in the collision. Particle distribution over azimuthal angle can be described by the Fourier decomposition [1]

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

where coefficients v_n present the magnitude of azimuthal anisotropy, while the event plane angle (Ψ_n) stands for the direction of the maximum final-

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state particle density. Since Fourier harmonics v_n are driven by initial conditions and medium transport properties, they can be used for studying the properties of created matter in heavy-ion collision. Furthermore, a correlation observed between the event plane angles of different order [2] points out that higher order harmonics can be measured with respect to the direction of multiple lower order event planes, which can provide additional constraints on understanding the properties of QGP [3].

Also event-by-event anti-correlation of flow amplitudes between v_2 and v_3 is shown that is much more sensitive to the initial conditions, while the correlation between v_2 and v_4 is sensitive to both initial conditions and medium properties, in PbPb collisions [4]. Since the collectivity is also observed in *pp* and *p*Pb collisions [5–9], this new observable can offer a possibility for better understanding the origin of collectivity in small systems.

2. Analysis techniques

For studying correlations between flow harmonics, two different methods have been used: *mixed order harmonics*, applied on PbPb data at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, and *symmetric cumulant* applied on *pp* at $\sqrt{s} = 13$ TeV, *p*Pb at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV, and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. All the data are taken with the CMS detector [10].

2.1. Mixed order harmonics

Mixed harmonics measurement is based on scalar product method (SP) [11] and follow the procedure introduced here [3]. For second and third harmonic, flow coefficients are linearly proportional to the initial eccentricity, *i.e.* $v_n \propto \epsilon_n$ [12]. For $n \geq 4$, on the other hand, there are nonlinear terms coming from lower order harmonics [3]. In standard (SP) approach, v_n with respect of its own event plane, Ψ_n, would be

$$v_n\{\Psi_n\} = \frac{\mathrm{Re}\langle V_n V_n^* \rangle}{\sqrt{\langle |V_n|^2 \rangle}}\,, \tag{2}$$

where $V_n = v_n \exp(in\Psi_n)$ is the n^{th} flow harmonic complex coefficient. But if one measures v_5, for example, with respect to the direction of 2^{nd}, Ψ_2, and 3^{rd}, Ψ_3, harmonic v_5 in (2) becomes

$$v_5\{\Psi_{23}\} = \frac{\mathrm{Re}\langle V_5 V_2^* V_3^* \rangle}{\sqrt{\langle |V_2|^2 |V_3|^2 \rangle}}\,. \tag{3}$$

A contribution from v_2 and v_3 in v_5 can be evaluated via nonlinear response coefficient

$$\chi_{523} = \frac{v_5\{\Psi_{23}\}}{\sqrt{\langle v_2^2 v_3^2 \rangle}} \,. \tag{4}$$

Measurements of mixed order flow harmonics, v_4 with respect to the Ψ_2 ($v_4\{\Psi_{22}\}$), v_5 with respect to the Ψ_2 and Ψ_3 ($v_5\{\Psi_{23}\}$), v_6 with respect to the Ψ_2 ($v_6\{\Psi_{222}\}$) and with respect to the Ψ_3 ($v_6\{\Psi_{33}\}$), v_7 with respect to the Ψ_2 and Ψ_3 ($v_7\{\Psi_{223}\}$), and corresponding nonlinear response coefficients $\chi_{422}, \chi_{523}, \chi_{6222}, \chi_{633}$ and χ_{7223} are presented in this contribution.

2.2. Symmetric cumulant

The symmetric cumulant method is based on four-particle correlation calculation with cumulants, first time introduced by the ALICE Collaboration in [4]. As a first step, one should build 2- and 4-particle correlator

$$\langle\langle 2 \rangle\rangle_n = \left\langle\left\langle e^{in(\phi_1-\phi_2)} \right\rangle\right\rangle \,, \qquad \langle\langle 4 \rangle\rangle_{n,m} = \left\langle\left\langle e^{i(n\phi_1+m\phi_2-n\phi_3-m\phi_4)} \right\rangle\right\rangle \,, \tag{5}$$

where $\langle\langle \ldots \rangle\rangle$ denotes averaging over all particles and events of interest. More details about standard cumulant technique and generic code, which this analysis framework is based on, can be found in [13].

Symmetric cumulant for n^{th} and m^{th} flow coefficient is then defined as

$$\mathrm{SC}(n,m) = \langle\langle 4 \rangle\rangle_{n,m} - \langle\langle 2 \rangle\rangle_n = \left\langle v_n^2 v_m^2 \right\rangle - \left\langle v_n^2 \right\rangle \left\langle v_m^2 \right\rangle \,, \tag{6}$$

and it is a measure of correlations between flow amplitudes of the harmonics. In order to obtain results that are independent of magnitude of v_n and v_m, one can normalise $\mathrm{SC}(n,m)$ with $\langle v_n^2 \rangle \langle v_m^2 \rangle$. In this work, $\langle v_n^2 \rangle$ and $\langle v_m^2 \rangle$ are extracts from two-particle correlations technique, which is described in [6]. SC measurement has been done as a function of multiplicity ($N_{\mathrm{trk}}^{\mathrm{offline}}$) in $0.3 < p_{\mathrm{T}} < 3.0$ GeV/c transverse momentum region.

3. Results

Mixed higher order harmonics, $v_4\{\Psi_{22}\}, v_5\{\Psi_{23}\}, v_6\{\Psi_{222}\}, v_6\{\Psi_{33}\}$ and $v_7\{\Psi_{223}\}$ as a function of centrality are measured at two energies, 2.76 and 5.02 TeV [14]. The results are integrated over pseudorapidity and transverse momentum intervals $\eta < 2.4$ and $0.3 < p_{\mathrm{T}} < 3.0$ GeV/c, respectively. They are presented in Fig. 1 and compared with hydrodynamic calculations from [3]. All mixed harmonics show a weak energy dependence and all except $v_6\{\Psi_{33}\}$ show a strong centrality dependence.

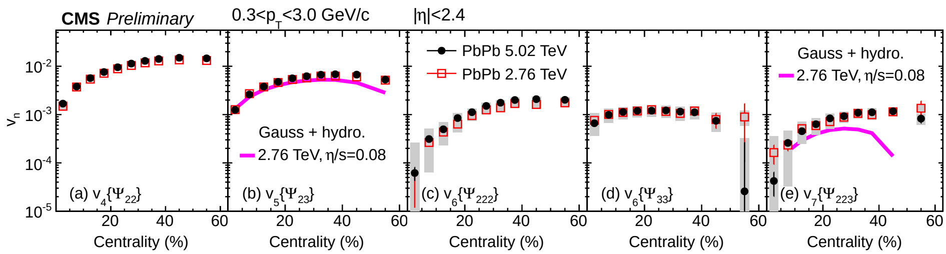

Fig. 1. (Colour on-line) The mixed higher order flow harmonics, $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$ and $v_7\{\Psi_{223}\}$ from SP method at 2.76 (red squares) and 5.02 TeV (black circles) as a function of centrality with $|\eta| < 2.4$ in the $0.3 < p_{\mathrm{T}} < 3.0$ GeV$/c$ range [14]. The hydrodynamic calculation from [3] are presented with grey/magenta line.

Corresponding nonlinear response coefficients, $\chi_{422}, \chi_{523}, \chi_{6222}, \chi_{633}$ and χ_{7223}, as a function of centrality, with $|\eta| < 2.4$ in the $0.3 < p_{\mathrm{T}} < 3.0$ GeV$/c$ range [14], are presented in Figs. 2 and 3. In the former, the results are compared with predictions from AMPT and hydrodynamics with a deformed symmetric Gaussian density profile with the initial condition using $\eta/s = 0.08$ in Ref. [3], and from iEBE-VISHNU hydrodynamics with Glauber and KLN initial conditions using the same η/s [16]. Predictions

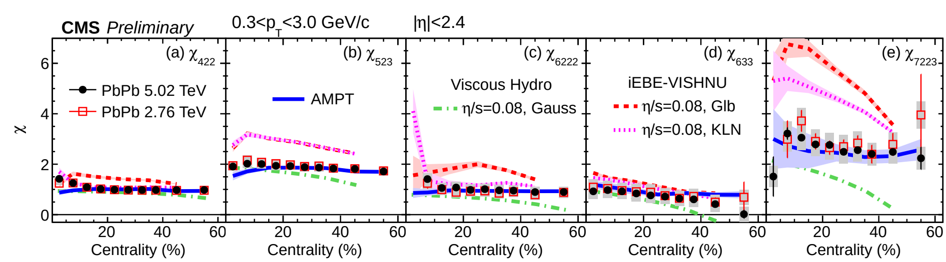

Fig. 2. The nonlinear response coefficients, $\chi_{422}, \chi_{523}, \chi_{6222}, \chi_{633}$ and χ_{7223} from the SP method at 2.76 and 5.02 TeV as a function of centrality with $|\eta| < 2.4$ in the $0.3 < p_{\mathrm{T}} < 3.0$ GeV$/c$ range [14]. The results are compared with theoretical predictions that use different initial conditions [3, 16].

from AMPT are favoured by the data. While in Fig. 3 the same results are compared with predictions from AMPT in Ref. [3] and from iEBE-VISHNU hydrodynamics with KLN initial condition using $\eta/s = 0$, 0.08 and 0.2 [16]. The large difference between hydrodynamic predictions with different viscosities indicates that our results can provide constraints on the value of viscosity at freeze-out [3, 16]. However, based only on these comparisons, it is not unambiguously clear which viscosity and initial conditions are the best choices.

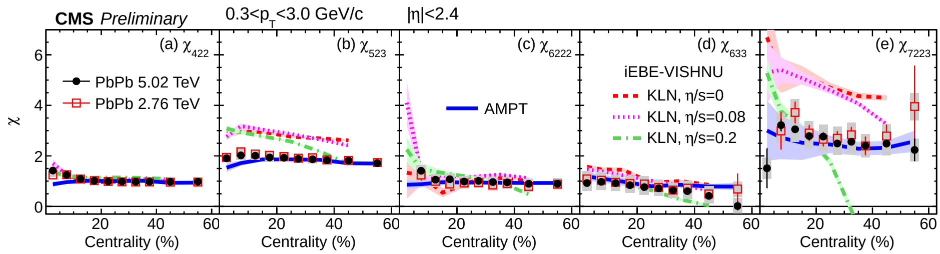

Fig. 3. The nonlinear response coefficients, $\chi_{422}, \chi_{523}, \chi_{6222}, \chi_{633}$ and χ_{7223} from the SP method at 2.76 and 5.02 TeV as a function of centrality with $|\eta| < 2.4$ in the $0.3 < p_{\mathrm{T}} < 3.0$ GeV/c range [14]. The results are compared with theoretical predictions with different η/s values [3, 16].

Figure 4 shows symmetric cumulants, normalised by flow magnitudes, of second and third flow harmonics and second and forth flow harmonics for $0.3 < p_{\mathrm{T}} < 3.0$ GeV/c region, as a function of multiplicity, in *pp* at 13 TeV, *p*Pb at 5.02 and 8.16 TeV and PbPb collisions at 5.02 TeV [15]. Results for PbPb are in agreement with results published by ALICE [4]. Similar results for high multiplicity *p*Pb and PbPb suggest that initial-state fluctuations are the same in those two systems. This conclusion may also be applicable to *pp* collisions, but statistical uncertainties are too large to make stronger claim. At the same time, clear ordering in normalised SC(2, 4) results of different systems may suggest different medium properties if one assumes hydrodinamical origin of collectivity in small systems.

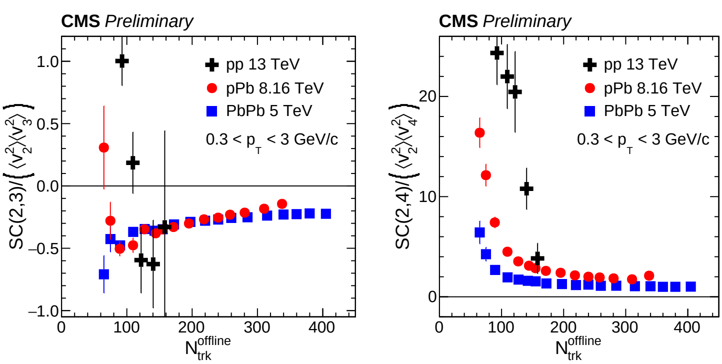

Fig. 4. The SC for the second and third harmonic (left) and the second and forth harmonic (right) normalised by $\langle v_2^2\rangle\langle v_3^2\rangle$ and $\langle v_2^2\rangle\langle v_4^2\rangle$ from dihardon correlations respectively. The p_{T} range for considered tracks is $0.3 < p_{\mathrm{T}} < 3.0$ GeV/c and the results are shown as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ in *pp* at $\sqrt{s} =$ 13 TeV, *p*Pb at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV, and PbPb at $\sqrt{s_{NN}} = 5.02$ TeV [15].

4. Summary

Results of mixed higher-order harmonics and nonlinear response coefficients show sensitivity to the initial conditions and medium properties close to the freeze-out stage. Comparison with different theoretical predictions is shown and AMPT model is favoured by data. A quantitative agreement between *p*Pb and PbPb collisions of normalised symmetric cumulant for the second and third harmonics suggest similar initial conditions in those two systems. High multiplicity *pp* collisions may follow the similar trend but statistical uncertainties are too large to make stronger claim. At the same time, different results for normalised correlations of the second and fourth harmonic may suggest different medium properties if one assumes hydrodynamical origin of flow.

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