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CMS results on collectivity in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV

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Abstract. Nonlinear response coefficients of higher-order v_n anisotropy harmonics for charged particles, as a function of transverse momentum (p_T) and collision centrality, are measured in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. The nonlinear response coefficients are obtained using v_n harmonics measured with respect to their own plane and the mixed harmonics. Using a fine splitting between $v_2\{4\}$ and $v_2\{6\}$ cumulants, the centrality dependence of the elliptic flow skewness is measured at 5.02 TeV PbPb collisions. The CMS also measured the v_2 and v_3 anisotropy harmonics of charged particles and prompt D^0 mesons at $|y| \leq 1$ as a function of p_T and centrality in PbPb data at $\sqrt{s_{NN}} = 5.02$ TeV collected with the CMS detector. Prompt D^0 mesons, formed from the c quarks produced via initial hard scatterings, are separated up to a high extent from nonprompt D^0 mesons emerged from decays of b hadrons. The results indicate that the charm quarks interact strongly with the QGP medium. Comparisons between theoretical models and data provide new constraints on the initial-state conditions and the interaction between charm quarks and the QGP medium.

1 Introduction

Investigation of the hydrodynamical behavior of Quark Gluon Plasma (QGP) through measurements of v_n harmonics indicates that the higher order v_n harmonics (n >3) have a non-linear contribution [1] which may be composed of lower order harmonics (n <4) [2]. A deeper insight into the influence of the initial-state fluctuations onto the hydrodynamic flow can be obtained by studying the correlations between $v_n\{\Psi_n\}$ harmonics measured with respect to their own plane, and mixed harmonics $v_n\{\Psi_{mkl}\}$ $(m, k, l < n)$ measured with respect to the direction of multiple lower order harmonics. The following relations [2, 3] decompose higher order harmonics into their linear (V_{nL}) and non-linear contributions

$$
\begin{aligned}
V_4 &= V_{4L} + \chi_{422}(V_2)^2 \\
V_5 &= V_{5L} + \chi_{523}V_2V_3 \\
V_6 &= V_{6L} + \chi_{6222}(V_2)^3 + \chi_{633}(V_3)^2 \\
V_7 &= V_{7L} + \chi_{723}(V_2)^2V_3.
\end{aligned} \quad (1)
$$

References [2, 3] provide the definitions of the mixed higher order harmonics $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$ and $v_7\{\Psi_{223}\}$, and the corresponding non-linear response coefficients, χ_{mkl}. The sen-

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sitivity of the $v_n\{\Psi_{mkl}\}$ and the χ_{mkl} coefficients to the initial-state conditions and transport properties of the formed medium could be used to test theoretical models.

Another observable which could constrain the initial-state conditions is the skewness [10]. As a consequence of the non-gaussian fluctuations of the participant eccentricity a fine splitting between $v_2\{4\}$ and $v_2\{6\}$ magnitudes obtained from 4- and 6-particle cumulants appears. Then the skewness, which is experimentally defined as

$$\gamma_1^{exp} = -6\sqrt{2}v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}}, \tag{2}$$

can be measured and compared with theoretical models.

Does c quarks show collectivity similar to the one which u and d quarks exhibit? If yes, then measurements of the azimuthal anisotropy of the final-state charm hadrons can give additional information for understanding the properties of the QGP and the interactions between charm quarks and the QGP [4]. Additionally, such measurements can complement the measurements of the nuclear modification factor R_{AA} [5, 6]. The v_2 and v_3 harmonics of the D^0 meson are extracted using the scalar product (SP) method which employs a huge pseudorapidity gap, $|\Delta\eta| > 3$, in order to avoid influence of the short-range correlations. Details of the applied methodology can be found in [7].

2 Experiment and data used

A super-conducting solenoid producing 3.8 T magnetic field surrounds the CMS tracker detector. This enables precise transverse momentum (p_T) measurements above 0.3 GeV/c with a typical resolution of 1.5% in p_T. The data sets of 30 million minimum-bias PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and 100 million at 5.02 TeV are used. The results of these analyses are based on the silicon tracker and hadron forward (HF) calorimeters. A pseudorapidity coverage of $|\eta| < 2.5$ for the tracker and $2.9 < |\eta| < 5.2$ for the HF calorimeters together with a full azimuthal coverage excellently suites for studying the collective effects. A more detailed description of the CMS detector can be found in Ref. [8].

3 Results

Figure 1 presents the mixed higher harmonics $v_n\{\Psi_{mkl}\}$ coefficients as a function of p_T measured using the SP method in PbPb collisions at a center-of-mass energy of 2.76 and 5.02 TeV [9]. The measurement is performed in two centrality classes: 0–20% and 20–60%. The mixed harmonics $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{33}\}$ and $v_7\{\Psi_{223}\}$ are measured for the first time. Mixed harmonics of all measured orders have a very weak energy dependence. The magnitudes of $v_n\{\Psi_{mkl}\}$, as expected, increase going from central to peripheral collisions.

Figure 2 shows the non-linear response coefficients χ as a function of p_T in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV for the same centrality classes as those from Fig. 1. The non-linear response coefficients χ_{422}, χ_{523}, χ_{6222}, χ_{633} and χ_{723} are measured for the first time. The odd, χ_{523} and χ_{723}, have a stronger non-linear response with respect to the even harmonics. The non-linear response coefficients for two analyzed collision energies show nearly no energy and a weak centrality dependence.

Centrality dependence of mixed order harmonics, averaged over $0.3 < p_T < 3.0$ GeV/c, for the two energies in PbPb collisions is presented in Fig. 3. A weak energy dependence is found. Except for $v_6\{\Psi_{33}\}$, mixed harmonics exhibit a strong centrality dependence. In the same figure is drawn a hydrodynamic calculations with a deformed symmetric Gaussian density profile [2] for $v_5\{\Psi_{23}\}$ and

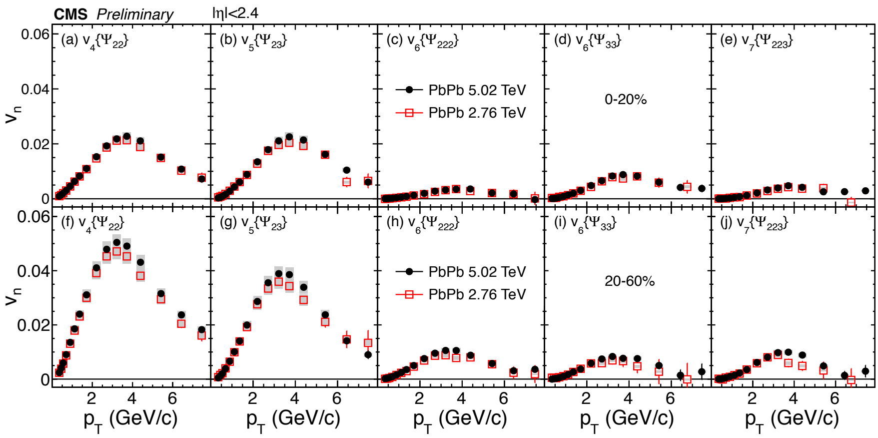

Figure 1. The mixed higher order harmonics $v_n\{\Psi_{mkl}\}$ as a function of p_{T} measured using the SP method in PbPb collisions at 2.76 and 5.02 TeV [9]. Top row corresponds to 0–20% and bottom row to 20–60% centrality range. Statistical (systematic) uncertainties are shown as error bars (shadow boxes).

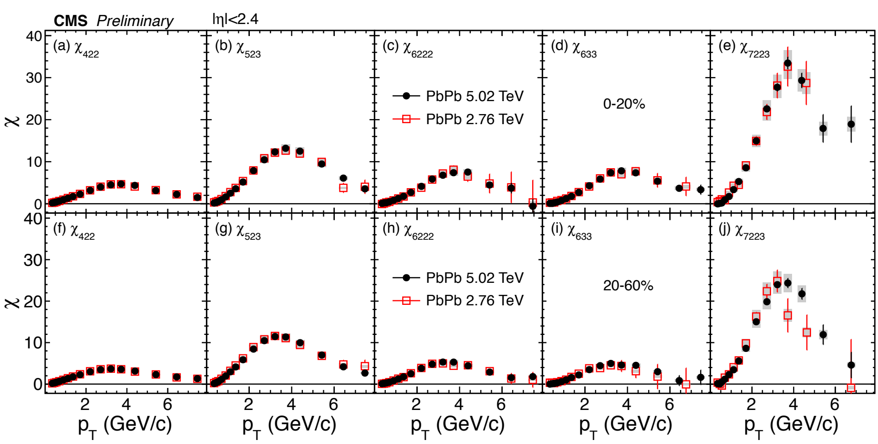

Figure 2. The non-linear response coefficients χ as a function of p_{T} measured using the SP method in PbPb collisions at 2.76 and 5.02 TeV [9]. Top row corresponds to 0–20% and bottom row to 20–60% centrality range. Statistical (systematic) uncertainties are shown as error bars (shadow boxes).

for $v_7\{\Psi_{223}\}$ calculated with $\eta/s = 0.08$ for PbPb collisions at 2.76 TeV. The calculations describes rather well $v_5\{\Psi_{23}\}$ data, but not $v_7\{\Psi_{223}\}$.

In Fig. 4 the centrality dependence of the non-linear response coefficients χ averaged over $0.3 < p_{\mathrm{T}} < 3.0$ GeV/c is shown. The χ coefficients do not show a strong energy and centrality dependence. The AMPT model describes the experimental results for all harmonics well. Comparisons to hydrodynamic model with a deformed symmetric Gaussian density profile [2] and with iEBE-VISHNU hydrodynamic [3], where both calculations have been performed with $\eta/s = 0.08$,

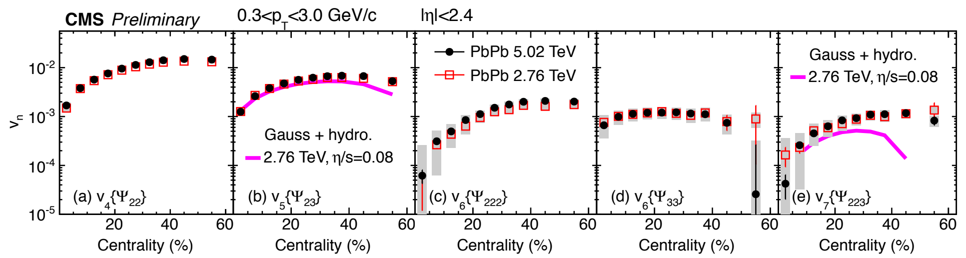

Figure 3. The mixed higher order harmonics *vs* centrality in PbPb collisions at 2.76 and 5.02 TeV [9]. Statistical (systematic) uncertainties are shown as error bars (shadow boxes). The line represents a hydrodynamic calculation performed with a deformed symmetric Gaussian density profile [2] with $\eta/s = 0.08$ in 2.76 TeV PbPb collisions.

show a strong sensitivity of the non-linear response coefficients to the initial-state conditions. It also shows that the sensitivity increases with an increase of the harmonic order n.

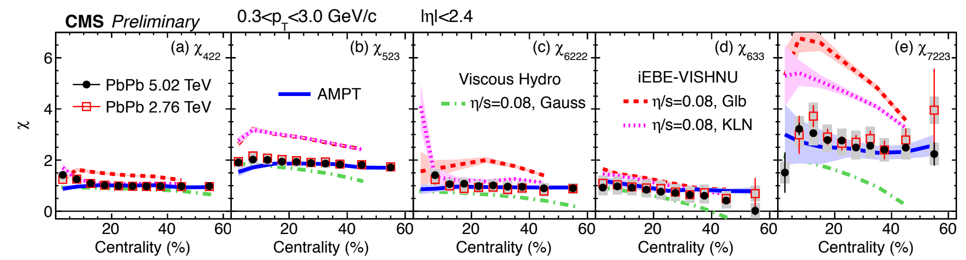

Figure 4. The non-linear response coefficients as a function of centrality in PbPb collisions at 2.76 and 5.02 TeV [9]. Statistical (systematic) uncertainties are shown as error bars (shadow boxes). With the lines are presented results of different hydrodynamic calculations [2, 3] with $\eta/s = 0.08$ at different initial-state conditions. With a full blue line is presented result from the AMPT model.

In Fig. 5 are shown the same experimental data as in Fig. 4, compared with iEBE-VISHNU model [3], computed with the same KLN initial-state condition but with different η/s values. The non-linear response coefficients are sensitive to the η/s values, especially for the odd harmonics.

In Fig. 6 are depicted results for the centrality dependence of the elliptic flow extracted using cumulants of different orders $v_2\{2k\}$ [11]. Roughly, the $v_2\{2k\}$ results show an expected ordering $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$. A weak splitting of the higher-order cumulants, especially in peripheral collisions, is visible. The splitting can be seen better by looking at the ratios between the higher-order cumulants. These ratios are shown in Fig. 7 in which one can clearly see that the earlier observation $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ is not fully valid. Namely, a fine splitting between higher-order cumulants exists, and they are ordered as $v_2\{4\} > v_2\{6\} > v_2\{8\}$. The effect is small, on the percent level. The magnitude of the effect increases going from central to peripheral collisions. The event-by-event hydrodynamic result with η/s =0.08 for PbPb collisions at 2.76 TeV, taken from Ref. [12], is consistent with the experimental measurement at 5.02 TeV. As any changes in the initial state eccentricities between 2.76 and 5.02 TeV energies are expected to be small, the similarity between the experimental results for these two energies is expected.

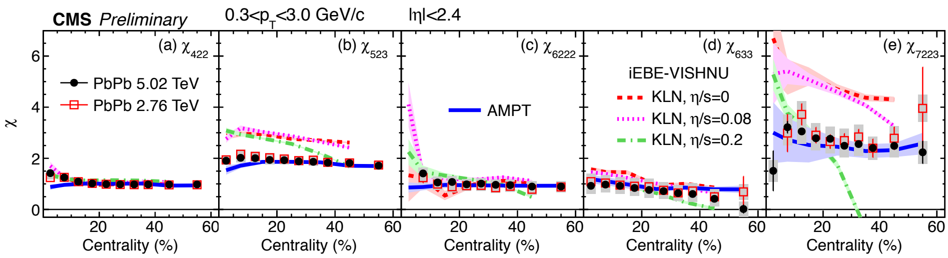

Figure 5. The non-linear response coefficients *vs* centrality in PbPb collisions at 2.76 and 5.02 TeV [9]. Statistical (systematic) uncertainties are shown as error bars (shadow boxes). The lines represent hydrodynamic results [3] obtained at a given KLN initial-state condition under different η/s values. The full blue line is the calculation from AMPT model .

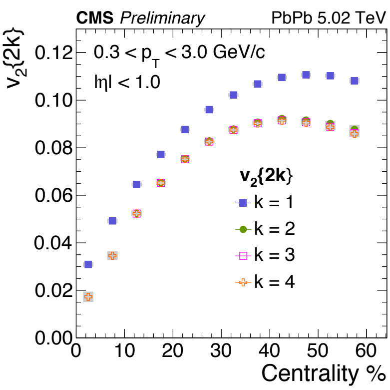

Figure 6. Elliptic flow cumulant results as a function of centrality [11]. Statistical uncertainties are covered by the symbol size. Systematic uncertainties are shown as gray bands.

Figure 8 shows the skewness, γ_1^{exp}, for PbPb collisions at 5.02 TeV calculated according to the Eq.(2) and plotted *vs* centrality [11]. It has non-zero values and the size of the effect increases going from central to peripheral collisions. These experimental results are in a very good agreement with the hydrodynamic result for the skewness in PbPb collisions at 2.76 TeV, taken from Ref. [12].

The v_2 and v_3 of the prompt D^0 mesons (including both the D^0 and $\bar{D}^0$ states) measurements are performed by a simultaneous fit on the invariant D^0 mass and the magnitude of the azimuthal anisotropy v_n [7]. An example of simultaneous fit to the invariant mass spectrum and the magnitude of the anisotropy harmonic as a function of the invariant mass ($v_2^{S+B}(m_{inv})$) is shown in Fig. 9. The analysis is performed in each p_{T} interval. Details of the applied procedure are presented in [7].

The D^0 candidates are considered by assuming one of the tracks has the pion mass while the other track has the kaon mass. Within the applied SP method, a large distance in η (at least 3 units) between the D^0 candidates and the correlated event plane is required. The analysis is performed differentially in p_{T} in three centrality classes: 0–10%, 10–30% and 30–50%. The obtained results are shown in Fig. 10. Both, the v_2 and v_3 harmonics have a shape of the p_{T} dependence similar to the one seen for charged particles with a fast increase at low-p_{T}, reaching a maximum at ≈3 GeV/c after which v_2 decreases again. The v_2 is positive up to 40 GeV/c, while at high-p_{T} the v_3 is close to zero. The D^0 v_2 also shows a typical centrality dependence with an increase going from central to peripheral collisions, while, as expected, the v_3 centrality dependence is much weaker than in the v_2 case. In the

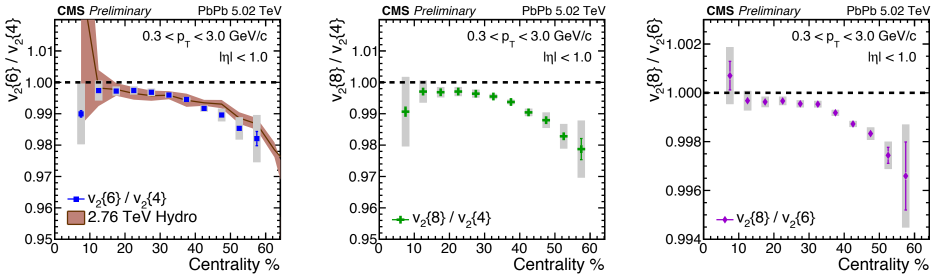

Figure 7. Ratios of higher-order cumulant elliptic flow harmonics [11]. Both statistical (error bars) and systematic (gray bands) uncertainties are shown. Hydrodynamic result for 2.76 TeV PbPb collisions from Ref. [12] is presented as a colored band and are compared to the measured $v_2\{6\}/v_2\{4\}$ ratio.

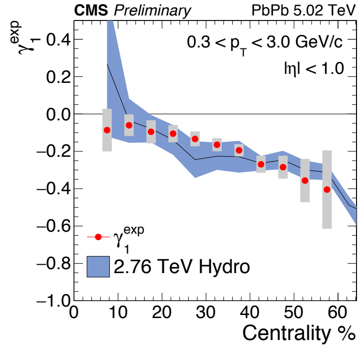

Figure 8. The skewness calculated according to the Eq.(2) in PbPb collisions at 5.02 TeV [11]. Statistical and systematic uncertainties are shown. Hydrodynamic result for 2.76 TeV PbPb collisions from Ref. [12] is shown as a colored band.

low-p_T region, both D^0 v_2 and v_3 magnitudes are smaller than the ones of the charged particles, while in the high-p_T region they are roughly equal. In Fig. 10 a comparison between the CMS experimental results of D^0 flow and several model calculations is shown (see Ref. [7] and the references in it). The fact that the v_n values from models calculations are close to or even lower than the measured v_n results suggests that the charm quarks take part in the collective motion of the system. But, whether and how well the D^0 anisotropy can be described by hydrodynamics and thermalization requires further investigation.

4 Summary

For the first time, the mixed higher order v_n harmonics and nonlinear response coefficients of charged particles as a function of p_T and centrality in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV are measured by the CMS Collaboration. Especially in the centrality range 20–60%, the nonlinear part of the odd harmonics is larger than for the even ones. The results are compared with AMPT and hydrodynamic models with different η/s values and initial conditions. The AMPT model is favored by the measurement. The results can provide constraints on the theoretical description of the medium close to the freeze-out temperature, which is not well understood so far.

A non-Gaussian behavior is observed for the event-by-event fluctuations of the v_2 coefficients in PbPb collisions at 5.02 TeV. It manifests as splitting of higher order cumulants which are ordered as

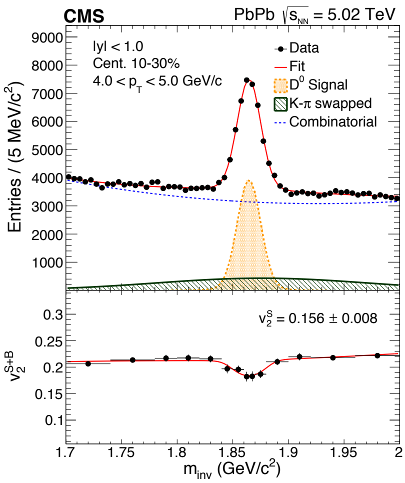

Figure 9. Example of simultaneous fit to the invariant mass spectrum and $v_2^{S+B}(m_{inv})$ in the p_T interval 4–5 GeV/c for the centrality class 10–30% [7].

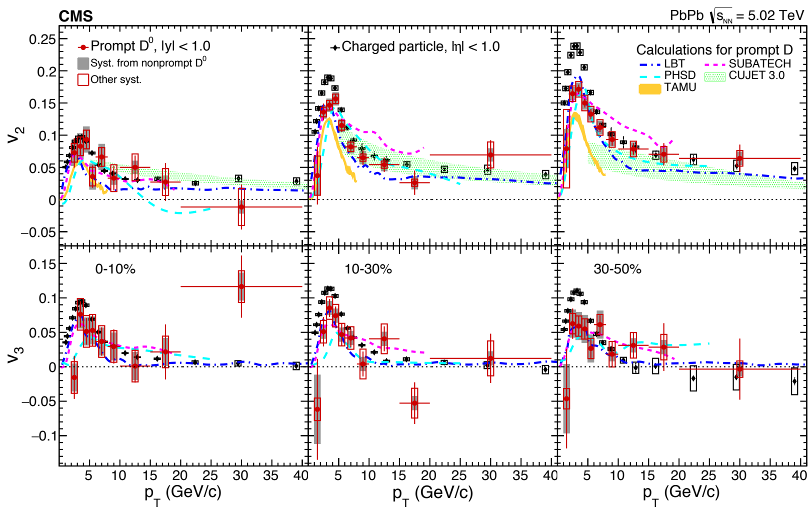

Figure 10. Prompt D^0 meson v_2 (upper) and v_3 (lower) harmonics for centralities 0–10% (left), 10–30% (middle), and 30–50% (right) [7]. The error bars represent statistical, grey bands systematic uncertainties from nonprompt D^0 mesons and open boxes other systematic uncertainties. The v_n harmonics of charged particles, and model calculations for prompt D^0 meson are also plotted for comparison (see references in [7]).

$v_2\{4\} > v_2\{6\} > v_2\{8\}$ for non-central events with centralities greater than ≈ 15%. The skewness, γ_1^{exp}, quantify the effect, and is found to be negative with an increasing magnitude as collisions become less central. Presented results will provide constraints on the theoretical description of the medium formed in heavy-ion collisions.

Prompt D^0 meson v_2 and v_3 harmonics are measured using the SP method in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The v_2 values remain positive up to 40 GeV/c in p_T. The v_3 harmonic is measured for the first time. Both harmonics have the p_T and centrality dependence similar to the one seen for charged particles. Comparison with theoretical calculations at low-p_T suggest that the charm quarks take part in the collective motion of the system. The measured v_2 at high-p_T suggests that the path length dependence of charm quark energy loss is similar to that of light quarks.

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