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Latest results on anisotropy flow of light and heavy flavors in PbPb collisions at CMS

Jovan Milosevic on behalf of the CMS Collaboration*
University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
E-mail: Jovan.Milosevic@cern.ch

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. The results are compared with hydrodynamic models with different shear viscosity to entropy density ratios and initial conditions. Additionally, the v_2 and v_3 anisotropy harmonics of charged particles and prompt D^0 mesons are measured 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 interaction between charm quarks and the QGP medium.

EPS-HEP 2017, European Physical Society conference on High Energy Physics
5-12 July 2017
Venice, Italy

*Speaker.

PoS(EPS-HEP2017)175

1. Introduction

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]. The influence of the initial-state fluctuations on the hydrodynamic flow can be studied by 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

$$\begin{aligned} V_4 &= V_{4L}+\chi_{422}(V_2)^2 \\ V_5 &= V_{5L}+\chi_{523}V_2V_3 \\ V_6 &= V_{6L}+\chi_{6222}(V_2)^3+\chi_{633}(V_3)^2 \\ V_7 &= V_{7L}+\chi_{723}(V_2)^2V_3 \end{aligned} \tag{1.1}$$

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

Does c quarks show collectivity similar to the one which u and d quarks exhibit? If the answer is yes, then measurements of the azimuthal anisotropy of the final-state charm hadrons can give additional information for understanding the properties of the quark-gluon plasma (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 $\sqrt{s_{\mathrm{NN}}}=2.76$ TeV and 100 million at 5.02 TeV are used. A pseudorapidity coverage of $|\eta|<2.5$ for the tracker and $2.9<|\eta|<5.2$ for the hadronic forward (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

Fig. 1 presents mixed higher harmonics $v_n\{\Psi_{mkl}\}$ as a function of p_{T} measured using the Scalar Product (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% centrality. 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.

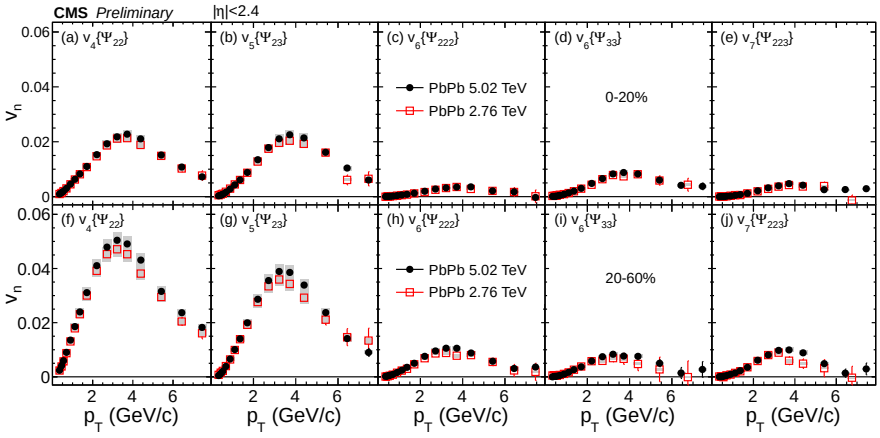

Figure 1: The mixed higher order harmonics $v_n\{\Psi_{mkl}\}$ as a function of p_{T} measured using the SP method in PbPb collisions at 2.76 and 5.02 TeV [9]. Top row corresponds to 0–20% and bottom row to 20–60% centrality range. Statistical (systematic) uncertainties are shown as error bars (shadow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

Fig. 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.

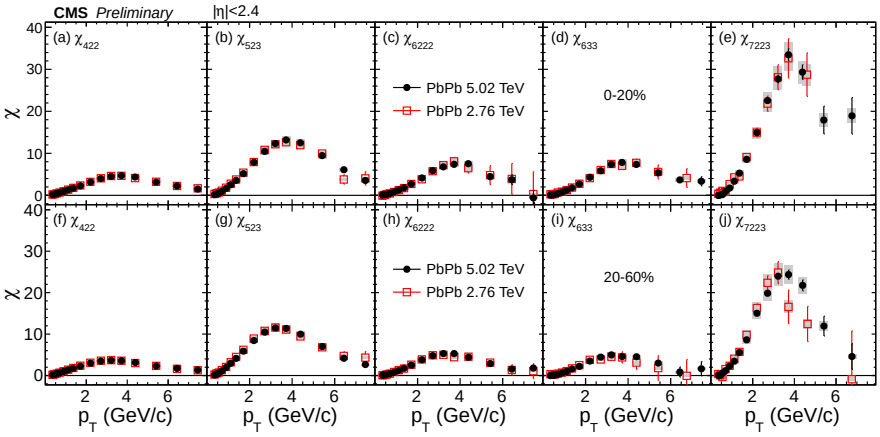

Figure 2: The non-linear response coefficients χ as a function of p_{T} measured using the SP method in PbPb collisions at 2.76 and 5.02 TeV [9]. Top row corresponds to 0–20% and bottom row to 20–60% centrality range. Statistical (systematic) uncertainties are shown as error bars (shadow boxes).

In Fig. 3 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 $\eta/s = 0.08$, 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. The comparison to the hydrodynamic model [3] calculated with the same KLN initial-state condition but with different η/s values which is performed in [9] shows that the non-linear response coefficients are sensitive to the η/s values too, especially for the odd harmonics.

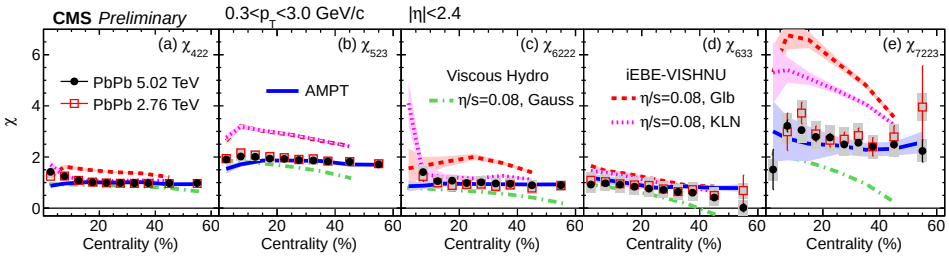

Figure 3: The non-linear response coefficients as a function of centrality in PbPb collisions at 2.76 and 5.02 TeV [9]. Statistical (systematic) uncertainties are shown as error bars (shadow boxes). With the lines are presented results of different hydrodynamic calculations [2, 3] with $\eta/s = 0.08$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

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]. 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. 4. 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 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. 4 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 com-

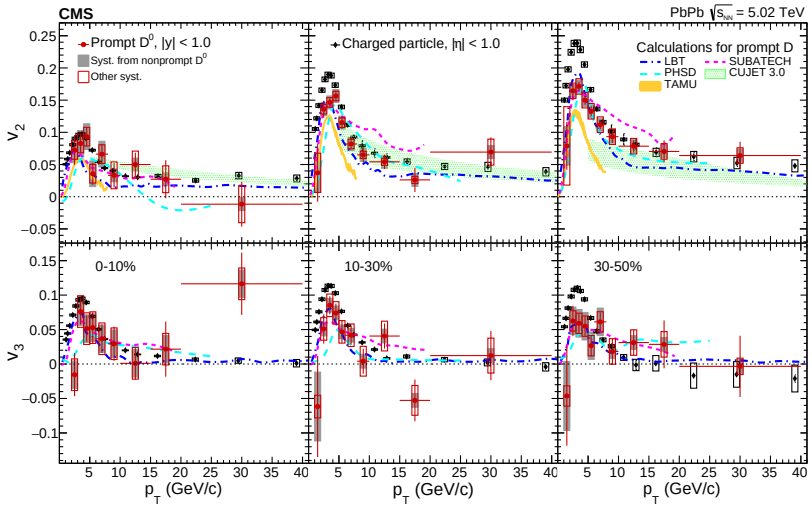

Figure 4: Prompt D^0 meson v_2 (upper) and v_3 (lower) harmonics for centralities 0–10% (left), 10–30% (middle), and 30–50% (right) [7]. The error bars represent statistical, grey bands systematic uncertainties from nonprompt D^0 mesons and open boxes other systematic uncertainties. The v_n harmonics of charged particles, and model calculations for prompt D^0 meson are also plotted for comparison (see references in [7]).

pared 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.

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} range suggest that the path length dependence of charm quark energy loss is similar to that of light quarks.

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