Acta Physica Polonica B Proceedings Supplement **16**, 1-A136 (2023)

INVESTIGATION OF IN-MEDIUM EFFECTS OF CHARMONIA USING AZIMUTHAL ANISOTROPY AND JET FRAGMENTATION FUNCTION IN PbPb AT 5.02 TeV WITH CMS*

Geonhee Oh

on behalf of the CMS Collaboration

University of Illinois at Chicago, USA

Received 16 August 2022, accepted 1 September 2022, published online 14 December 2022

The second-order (v_2) and the third-order (v_3) Fourier coefficients which describe the azimuthal anisotropy of prompt and nonprompt J/ψ and prompt $\psi(2S)$ mesons are measured in PbPb collisions at 5.02 TeV. The v_2 and v_3 values are extracted using the scalar product method. The measured v_2 values for the prompt J/ψ mesons are larger than those for nonprompt J/ψ mesons. No significant nonzero v_3 values for both prompt and nonprompt J/ψ mesons, reported for the first time in heavy-ion collisions, are found. The prompt $\psi(2S)$ meson v_n values are reported also for the first time.

DOI:10.5506/APhysPolBSupp.16.1-A136

1. Introduction

Quarkonia (bound states of a heavy quark and its antiquark such as J/ψ, $\psi(2S)$, $\varUpsilon(1S, 2S, 3S)$) are useful probes to study the properties of the quark–gluon plasma (QGP) in heavy-ion collisions. Since heavy quarks are dominantly produced from hard parton scattering at the early stage of the collision, quarkonia experience the whole space-time evolution of the medium. The study of the azimuthal distribution of quarkonia is a prominent way to probe the dynamics of the QGP [1, 2]. Azimuthal correlation of the particles can be characterized by the Fourier coefficients (v_n) of the azimuthal distribution. In particular, the second (v_2) and the third (v_3) order components are sensitive to the initial-collision geometry and event-by-event fluctuations, respectively [3]. Due to the anisotropic shape of the QGP in the transverse plane, quarkonia produced by initial hard-scattering

* Presented at the 29th International Conference on Ultrarelativistic Nucleus–Nucleus Collisions: Quark Matter 2022, Kraków, Poland, 4–10 April, 2022.

processes experience different path lengths while traveling through the medium. As a result, the amount of suppression is larger for quarkonia which move in directions corresponding to larger average path lengths [4].

This contribution reports on a measurement of the v_2 and v_3 values for J/ψ for both prompt and nonprompt components, and prompt $\psi(2S)$ mesons based on the scalar product method. The data set used in this analysis was collected with the CMS detector in PbPb collisions at $\sqrt{s_{NN}} =$ 5.02 TeV, corresponding to an integrated luminosity of 1.6 nb^{-1} [5]. The v_n values of charmonia, reconstructed via their decays to $\mu^+\mu^-$, are presented as functions of p_{T} and collision centrality.

2. Analysis and results

The separation of the prompt and nonprompt charmonium components relies on the measurement of a secondary $\mu^+\mu^-$ vertex displaced from the primary collision vertex. To measure the fraction of J/ψ mesons coming from b-hadron decays (the so-called *b-fraction*), the invariant mass spectrum of $\mu^+\mu^-$ pairs and their $\ell_{J/\psi}$ distributions are fitted using a two-dimensional (2D) extended unbinned maximum likelihood fit. For $\psi(2S)$ mesons, the nonprompt component is reduced by placing tight constraints on the pseudo-proper decay length. The cut of the pseudo-proper decay length to reject contributions from b-hadron decays is studied using Monte Carlo simulations. The detailed description of the fitting procedure can be found in Ref. [6].

The v_n ($n = 2$ and 3) values of J/ψ and $\psi(2S)$ candidates are determined using the scalar product (SP) method [7]. The event plane angles for the second- and third-order harmonics are defined using Q-vectors in the complex plane; $Q_n = \sum_{k=1}^{M} \omega_k \mathrm{e}^{in\phi_k}$. Here, k iterates over the particles sampled by the subdetector; M is the multiplicity of particles in the tracker or the number of towers for HF; ϕ is the azimuthal angle of the particle or the tower; ω is the weighting factor, here considered to be the transverse momentum of a particle for the tracker or the transverse energy deposited in an HF tower. In this analysis, three event plane Q-vectors are calculated using the tracker at the midrapidity ($|\eta| < 0.75$) and, similarly, the two HF calorimeters covering the forward ($3 < \eta < 5$, HF+) and backward ($-5 < \eta < -3$, HF$-$) rapidity regions. The Q-vector of the J/ψ or $\psi(2S)$ candidate is defined as $Q_n^{J/\psi} = \mathrm{e}^{in\phi}$, where ϕ is the azimuthal angle of the candidate. The v_n coefficient for J/ψ or $\psi(2S)$ mesons is obtained as follows:

$$v_n\,\{\mathrm{SP}\} \equiv \frac{\left\langle Q_n^{J/\psi,\psi(2S)} Q_{nA}^{*} \right\rangle}{\sqrt{\frac{\left\langle Q_{nA} Q_{nB}^{*} \right\rangle \left\langle Q_{nA} Q_{nC}^{*} \right\rangle}{\left\langle Q_{nB} Q_{nC}^{*} \right\rangle}}}\,. \tag{1}$$

The subscripts A (B) refer to either HF+ or HF−, depending on the rapidity of the J/ψ or $\psi(2S)$ candidate. To avoid autocorrelations, the η gap between the J/ψ or $\psi(2S)$ candidate and the detector used for event plane determination is required to be at least three units of rapidity [7–9]. For this purpose, HF+ is selected for A (B) when J/ψ and $\psi(2S)$ candidates are produced at negative (positive) rapidity. The $\langle\,\rangle$ indicates the real component of the average Q-vector product of all the candidates in a given invariant mass bin. The subscript C denotes the event plane taken from the tracker. The denominator in Eq. (1) is the correction factor to remove the finite resolution effects of the detectors.

To extract the prompt and nonprompt J/ψ meson v_n values, the J/ψ candidates are classified into fine v_n intervals. The prompt J/ψ meson v_n values can be obtained by

$$v_n^{\text{prompt}} = \frac{\sum(1-f_i)v_n^i Y^i}{\sum(1-f_i)Y^i}\,, \tag{2}$$

while the nonprompt J/ψ meson v_n values can be obtained by

$$v_n^{\text{nonprompt}} = \frac{\sum f_i v_n^i Y^i}{\sum f_i Y^i}\,. \tag{3}$$

Here, v_n^i is the center of the i^{th} scalar product bin, f_i and Y^i are the nonprompt J/ψ meson fraction and inclusive J/ψ meson yield in the same bin, respectively.

A different method is used to extract the prompt $\psi(2S)$ meson v_n values. All prompt $\psi(2S)$ candidates are divided in bins of invariant mass. The $\psi(2S)$ candidate invariant mass spectrum and v_n distribution as a function of invariant mass are fit simultaneously using binned χ^2 fits. The v_n distribution is fitted to the following formula:

$$v_n^{\text{Sig+Bkg}}(m_{\text{inv}}) = \alpha(m_{\text{inv}})v_n^{\psi(2S)} + [1-\alpha(m_{\text{inv}})]v_n^{\text{Bkg}}(m_{\text{inv}})\,, \tag{4}$$

where $v_n^{\psi(2S)}$ are the prompt $\psi(2S)$ v_n values, which is independent of m_{inv} by definition; $v_n^{\text{Bkg}}(m_{\text{inv}})$ is the background v_n modeled as a first-order Chebyshev polynomial function of invariant mass; and $\alpha(m_{\text{inv}})$ is the $\psi(2S)$ signal fraction as a function of invariant mass:

$$\alpha(m_{\text{inv}}) = \frac{\text{Sig}_{\psi(2S)}(m_{\text{inv}})}{\text{Sig}_{\psi(2S)}(m_{\text{inv}}) + \text{Bkg}(m_{\text{inv}})}\,. \tag{5}$$

The p_{T} and collision-centrality-dependent v_n values for prompt and nonprompt J/ψ are shown in Fig. 1. Results for the prompt J/ψ mesons show a flat v_2 for $p_{\mathrm{T}} > 9$ GeV$/c$, while no clear dependence on p_{T} is found for nonprompt J/ψ mesons. The results in Fig. 1 also show nonzero v_2 values for prompt J/ψ mesons at high p_{T}, up to 50 GeV$/c$. A large fraction of prompt J/ψ mesons is produced from jet fragmentation [10]. This implies that jet quenching should be considered to model the prompt meson J/ψ v_2 values. The measured v_2 values for nonprompt J/ψ mesons are found to be smaller than those for prompt J/ψ mesons in the studied region. This finding shows that the behavior of charm and bottom quarks induced by the interaction with the QGP medium is different in PbPb collisions. No significant nonzero v_3 values for both prompt and nonprompt J/ψ are found in the studied kinematic intervals.

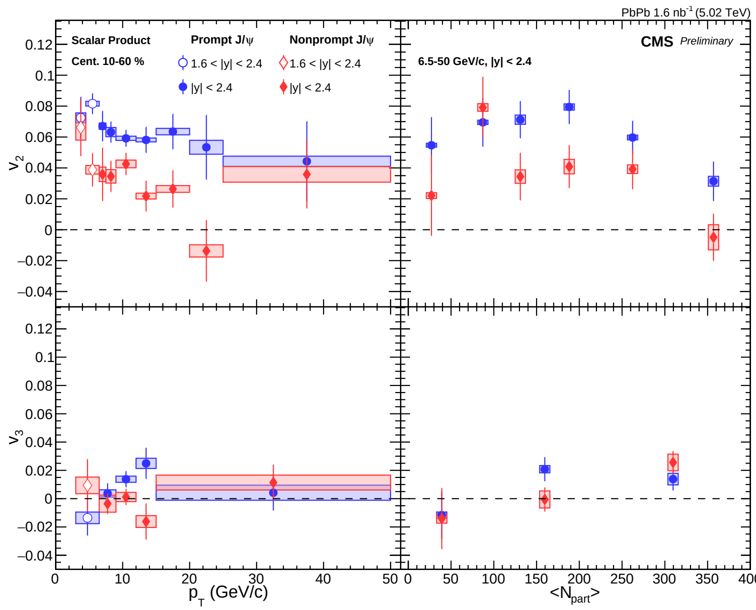

Fig. 1. The p_{T} (left) and collision centrality (right) dependent v_2 (upper) and v_3 (lower) values for prompt and nonprompt J/ψ mesons are shown [6]. The results for $p_{\mathrm{T}} = 3$–6.5 and 6.5–50 GeV$/c$ are studied in the rapidity range of $1.6 < |y| < 2.4$ and $|y| < 2.4$, respectively (left). The p_{T} bins on the right panel are 6.5–50 GeV$/c$ and rapidity of $|y| < 2.4$. The vertical bars denote the statistical uncertainties, and the rectangular bands show the systematic uncertainties.

Figure 2 shows the first v_n measurements of the prompt $\psi(2S)$ mesons in heavy-ion collisions together with the results for prompt J/ψ mesons. The v_2 values are found to be slightly larger for the prompt $\psi(2S)$ than for the prompt J/ψ mesons, especially at higher p_{T} and in peripheral PbPb collisions, but the statistical significance of this difference is too low to draw any conclusion. The v_3 values are found to be consistent with zero in the studied kinematic intervals.

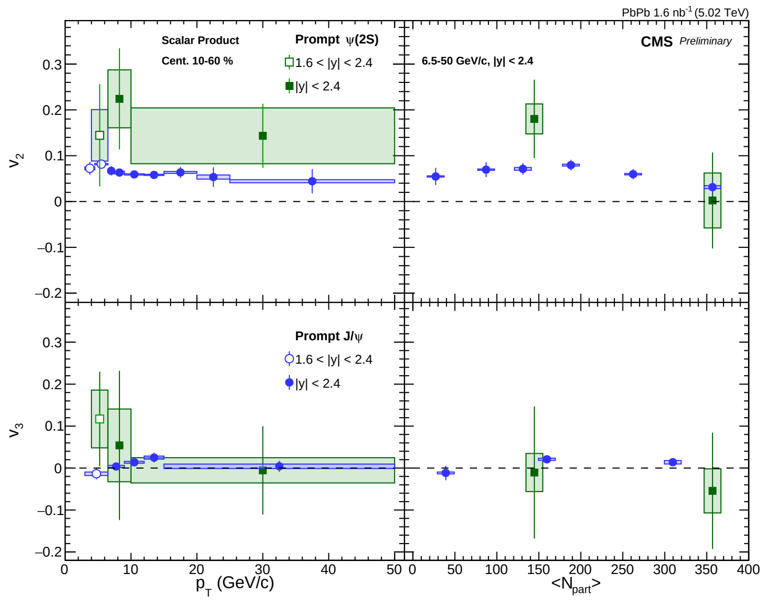

Fig. 2. The p_{T} (left) and collision centrality (right) dependent v_2 (upper) and v_3 (lower) values for prompt $\psi(2S)$ mesons are compared to prompt J/ψ, which as shown in figure 1 [6]. The results for $p_{\mathrm{T}} = 4$–6.5 and 6.5–50 GeV$/c$ are studied in the rapidity range of $1.6 < |y| < 2.4$ and $|y| < 2.4$, respectively (left). The p_{T} bins on the right panel are 6.5–50 GeV$/c$ and rapidity of $|y| < 2.4$. The vertical bars denote the statistical uncertainties, and the rectangular bands show the systematic uncertainties.

3. Summary

The second-order (v_2) and the third-order (v_3) Fourier coefficients of the azimuthal distributions for prompt and nonprompt J/ψ mesons and prompt $\psi(2S)$ mesons are reported as functions of p_{T} and collision centrality. The v_2 values for prompt and nonprompt J/ψ mesons both indicate a decreasing trend from mid-central towards central collision events. On the other hand, the v_2 is found to be flat for $p_{\mathrm{T}} > 9$ GeV$/c$ for prompt J/ψ mesons, while the dependence on p_{T} is found to be weak for nonprompt J/ψ mesons. The prompt J/ψ meson v_2 values are found to be larger than those of nonprompt J/ψ mesons throughout the studied kinematic region, suggesting different in-medium effects for charm and beauty quarks. The observation of sizable and flattened v_2 values at high p_{T} for prompt J/ψ mesons provides a hint of the contribution of jet quenching to prompt J/ψ meson suppression. The v_3 values of prompt and nonprompt J/ψ mesons are reported for the first time, where the results indicate consistency with zero in the measured p_{T} and centrality intervals. The v_2 and v_3 values are also measured for prompt $\psi(2S)$ mesons for the first time in heavy-ion collisions. Both the v_2 and the v_3 values are found to be compatible with those of prompt J/ψ mesons within the uncertainties. These J/ψ and $\psi(2S)$ meson measurements provide new insights into studying the dynamics and in-medium effects of charmonia in heavy-ion collisions.

REFERENCES

[1] T. Matsui, H. Satz, *Phys. Lett. B* **178**, 416 (1986).

[2] S. Digal, P. Petreczky, H. Satz, *Phys. Rev. D* **64**, 094015 (2001).

[3] CMS Collaboration (V. Khachatryan *et al.*), *Eur. Phys. J. C* **77**, 252 (2017).

[4] Yunpeng Liu, Nu Xu, Pengfei Zhuang, *Nucl. Phys. A* **834**, 317C (2010).

[5] CMS Collaboration, «CMS luminosity measurement using nucleus–nucleus collisions at $\sqrt{s_{NN}} = 5.02$ TeV in 2018», CMS Physics Analysis Summary, CMS-PAS-LUM-18-001, http://cds.cern.ch/record/2809613

[6] CMS Collaboration, «Measurements of the azimuthal anisotropy of charmonia in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV», CMS Physics Analysis Summary, CMS-PAS-HIN-21-008, https://cds.cern.ch/record/2805923

[7] CMS Collaboration, *Phys. Lett. B* **819**, 136385 (2021).

[8] CMS Collaboration (A.M. Sirunyan *et al.*), *Phys. Rev. Lett* **120**, 202301 (2018).

[9] M. Luzum, J. Ollitrault, *Phys. Rev. C* **87**, 044907 (2013).

[10] CMS Collaboration, *Phys. Lett. B* **825**, 136842 (2022).