# J/psi Elliptic Flow in Pb-Pb Collisions at root s(NN)=2.76 TeV

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# $J/\psi$ Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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We report on the first measurement of inclusive $J/\psi$ elliptic flow $v_2$ in heavy-ion collisions at the LHC. The measurement is performed with the ALICE detector in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the rapidity range $2.5 < y < 4.0$. The dependence of the $J/\psi$ $v_2$ on the collision centrality and on the $J/\psi$ transverse momentum is studied in the range $0 \leq p_T < 10$ GeV/$c$. For semicentral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, an indication of nonzero $v_2$ is observed with a largest measured value of $v_2 = 0.116 \pm 0.046(\text{stat}) \pm 0.029(\text{syst})$ for $J/\psi$ in the transverse momentum range $2 \leq p_T < 4$ GeV/$c$. The elliptic flow measurement complements the previously reported ALICE results on the inclusive $J/\psi$ nuclear modification factor and favors the scenario of a significant fraction of $J/\psi$ production from charm quarks in a deconfined partonic phase.

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Ultrarelativistic heavy-ion collisions enable the study of matter at high temperature and pressure where quantum chromodynamics predicts the existence of a deconfined state of partonic matter, the quark-gluon plasma (QGP). Heavy quarks are expected to be produced in the primary partonic scatterings and to interact with this partonic medium making them ideal probes of the QGP. Quarkonia (a heavy quark and antiquark bound state) are therefore expected to be sensitive to the properties of the strongly interacting system formed in the early stages of heavy-ion collisions [1]. According to the color-screening model [2], quarkonium states are suppressed in the medium with different dissociation probabilities for the various states. Recently, the CMS Collaboration at the Large Hadron Collider (LHC) reported about the observation of the sequential suppression in the $\Upsilon$ sector [3]. The ALICE Collaboration published the inclusive [4] $J/\psi$ nuclear modification factor $R_{AA}$ down to zero transverse momentum ($p_T$) at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [5]. The $R_{AA}$ compares the yields in Pb-Pb to those in $pp$ collisions scaled by the number of binary nucleon-nucleon collisions. The inclusive $J/\psi$ $R_{AA}$ reported is larger than that measured at the SPS [6] and at RHIC [7,8] for central collisions and does not exhibit a significant centrality dependence. Complementarily, the CMS Collaboration measured the high $p_T$ ($6.5 \leq p_T < 30$ GeV/$c$) prompt $J/\psi$ $R_{AA}$ in the rapidity range $|y| < 2.4$ [9]. The CMS data show that high $p_T$ $J/\psi$ are more suppressed than low $p_T$ $J/\psi$ and that this suppression does exhibit a strong centrality dependence.

The low $p_T$ $J/\psi$ $R_{AA}$ can be qualitatively understood with models including full [10,11] or partial [12,13] regeneration of $J/\psi$ from deconfined charm quarks in the medium. This mechanism was first proposed by the statistical hadronization model, which assumes deconfinement and thermal equilibrium of the bulk of $c\bar{c}$ pairs to produce $J/\psi$ at the phase boundary by statistical hadronization only [10]. Later, the transport models proposed a dynamical competition between the $J/\psi$ suppression by the QGP and the regeneration mechanism, which enables them to also describe the $J/\psi$ $R_{AA}$ versus $p_T$ [12,13]. More differential studies, like the $J/\psi$ elliptic flow, could help to assess the assumption of charm quark thermalization in the medium.

The azimuthal distribution of particles in the transverse plane is also sensitive to the dynamics of the early stages of heavy-ion collisions. In noncentral collisions, the geometrical overlap region and, therefore, the initial matter distribution are anisotropic (almond shaped). If the matter is strongly interacting, this spatial asymmetry is converted via multiple collisions into an anisotropic momentum distribution [14]. The second coefficient of the Fourier expansion describing the final state particle azimuthal distribution with respect to the reaction plane $v_2$ is called elliptic flow. The reaction plane is defined by the beam axis and the impact parameter vector of the colliding nuclei.

Within the transport model scenario [12,13] observed $J/\psi$ have two origins. First, primordial $J/\psi$ produced in the initial hard scatterings traverse and interact with the created medium. During this process they may be dissociated. Second, $J/\psi$ could be regenerated from deconfined charm quarks in the QGP. Primordial $J/\psi$ emitted in plane traverse a shorter path through the medium than those emitted out of plane, resulting in a small azimuthal anisotropy for the surviving $J/\psi$. Regenerated $J/\psi$ inherit the elliptic flow of the charm quarks in the QGP. If charm quarks do thermalize in the QGP, then $J/\psi$ formed there

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can exhibit a large elliptic flow. In the calculation by Zhao *et al.* [15], the $v_2$ of $J/\psi$ at $p_T \approx 2.5$ GeV/$c$ is 0.02 and 0.2 for primordial and regenerated $J/\psi$, respectively.

At RHIC, the (preliminary) measurements by the (PHENIX) STAR Collaboration of the $J/\psi$ $v_2$ in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [16,17] are consistent with zero albeit with large uncertainties in the $p_T$ and centrality ranges (0–5 GeV/$c$) 2–10 GeV/$c$ and (20%–60%) 10%–40%. In Pb-Pb collisions at the LHC, the higher energy density of the medium should favor the charm quark thermalization, and thus increase its flow. In addition, the large number of $c\bar{c}$ pairs produced should favor the formation of $J/\psi$ by regeneration mechanisms. Both effects should lead to an increase of the $v_2$ of the observed $J/\psi$.

In this Letter, we report ALICE results on inclusive $J/\psi$ elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at forward rapidity, measured via the $\mu^+\mu^-$ decay channel. The results are presented as a function of transverse momentum and collision centrality.

The ALICE detector is described in [18]. At forward rapidity ($2.5 < y < 4$) the production of quarkonia is measured in the muon spectrometer [19] down to $p_T = 0$. The spectrometer consists of an absorber stopping the hadrons in front of five tracking stations comprising two planes of cathode pad chambers each, with the third station inside a dipole magnet. The tracking apparatus is completed by a triggering system made of four planes of resistive plate chambers downstream of an iron wall, which absorbs secondary hadrons escaping from the front absorber and low momentum muons. Also used in this analysis are two cylindrical layers of silicon pixel detectors, to determine the location of the interaction point, and two scintillator arrays (VZERO). The VZERO counters consist of two arrays of 32 scintillator sectors each distributed in four rings covering $2.8 \leq \eta \leq 5.1$ (VZERO-A) and $-3.7 \leq \eta \leq -1.7$ (VZERO-C). All of these detectors have full azimuthal coverage. The data sample used for this analysis, collected in 2011, amounts to $17 \times 10^6$ dimuon unlike sign (MU) triggered Pb-Pb collisions and corresponds to an integrated luminosity $\mathcal{L}_{\rm int} \approx 70$ $\mu$b$^{-1}$. The MU trigger requires a minimum bias (MB) trigger and at least a pair of opposite-sign (OS) track segments, each with a $p_T$ above the threshold of the on-line trigger algorithm. This $p_T$ threshold was set to provide 50% efficiency for muon tracks with $p_T = 1$ GeV/$c$. The MB trigger requires a signal in both VZERO-A and VZERO-C. The beam-induced background was further reduced off-line using the VZERO and the zero degree calorimeter timing information. The contribution from electromagnetic processes was removed by requiring a minimum energy deposited in the neutron zero degree calorimeters [20]. The centrality determination is based on a fit of the VZERO amplitude distribution [21,22]. The average number of participating nucleons $\langle N_{\rm part}\rangle$ for the centrality classes used in this analysis (see Table I) are derived from a Glauber model calculation [21,22].

TABLE I. $\langle N_{\rm part}\rangle$ and VZERO-A EP resolution for the centrality classes expressed in percentages of the nuclear cross section [21].

| Centrality | $\langle N_{\rm part}\rangle$ | EP resolution $\pm$(stat) $\pm$ (syst) |
|---|---|---|
| 5%–20% | $283 \pm 4$ | $0.548 \pm 0.003 \pm 0.009$ |
| 20%–40% | $157 \pm 3$ | $0.610 \pm 0.002 \pm 0.008$ |
| 40%–60% | $69 \pm 2$ | $0.451 \pm 0.003 \pm 0.008$ |
| 60%–90% | $15 \pm 1$ | $0.185 \pm 0.005 \pm 0.013$ |
| 20%–60% | $113 \pm 3$ | $0.576 \pm 0.002 \pm 0.008$ |

$J/\psi$ candidates are formed by combining pairs of OS tracks reconstructed in the geometrical acceptance of the muon spectrometer. To improve the muon identification, the reconstructed tracks in the tracking chambers are required to match a track segment in the trigger system above the $p_T$ threshold aforementioned.

The $J/\psi$ $v_2$ is calculated using event plane (EP) based methods. The azimuthal angle $\Psi$ of the second harmonic EP is used to estimate the reaction plane angle [23]. $\Psi$ is determined from the azimuthal distribution of the VZERO amplitude. A two step flattening procedure of the EP azimuthal distribution was applied as described in [24] and [25], respectively. It results in an EP azimuthal distribution uniform to better than 2% for all centrality classes under study. The VZERO-C has a common acceptance region with the muon spectrometer. Therefore, only the VZERO-A was used for the EP determination to avoid autocorrelations. The $J/\psi$ $v_2$ results were obtained determining $v_2 = \langle \cos 2(\phi - \Psi)\rangle$ versus the invariant mass ($m_{\mu\mu}$) [26], where $\phi$ is the OS dimuon azimuthal angle. The resulting $v_2(m_{\mu\mu})$ distribution is fitted using

$$v_2(m_{\mu\mu}) = v_2^{\rm sig}\alpha(m_{\mu\mu}) + v_2^{\rm bkg}(m_{\mu\mu})[1 - \alpha(m_{\mu\mu})], \quad (1)$$

where $v_2^{\rm sig}$ and $v_2^{\rm bkg}$ correspond to the $v_2$ of the $J/\psi$ signal and of the background, respectively [see Fig. 1(b)]. $v_2^{\rm bkg}$ was parametrized using a second order polynomial. Here, $\alpha(m_{\mu\mu}) = S/(S + B)$ is the ratio of the signal over the sum of the signal plus background of the $m_{\mu\mu}$ distributions. It is extracted from fits to the OS invariant mass distribution [see Fig. 1(a)] in each $p_T$ and centrality class. The $J/\psi$ line shape was described with a Crystal Ball (CB) function and the underlying continuum with either a third order polynomial or a Gaussian with a width linearly varying with mass. The CB function connects a Gaussian core with a power-law tail [27] at low mass to account for energy loss fluctuations and radiative decays. An extended CB function with an additional power-law tail at high mass, to account for alignment and calibration biases, was also used. The combination of several CB and underlying continuum parametrizations described before were tested to assess the signal and the related systematic

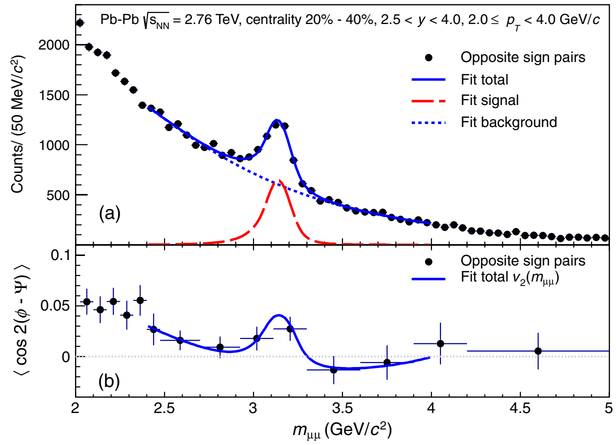


FIG. 1 (color online). Invariant mass distribution (a) and $\langle \cos 2(\phi - \Psi) \rangle$ as a function of $m_{\mu\mu}$ (b) of OS dimuons with $2 \leq p_T < 4$ GeV/$c$ and $2.5 < y < 4$ in semicentral (20%–40%) Pb-Pb collisions.

uncertainties. The $J/\psi$ $v_2$ and its statistical uncertainty in each $p_T$ and centrality class were determined as the average of the $v_2^{\text{sig}}$ obtained by fitting $v_2(m_{\mu\mu})$ using Eq. (1) with the various $\alpha(m_{\mu\mu})$, while the corresponding systematic uncertainties were defined as the rms of these results. Figure 1 shows typical fits of the OS invariant mass distribution [1(a)] and of the $\langle \cos 2(\phi - \Psi) \rangle$ as a function of $m_{\mu\mu}$ [1(b)] in the 20%–40% centrality class. The procedure above was repeated using either a first order polynomial or its inverse as $v_2^{\text{bkg}}$ parametrization. The largest deviation of the results obtained with the three different $v_2^{\text{bkg}}$ parametrizations was conservatively adopted as the systematic uncertainty related to the unknown shape of the $v_2^{\text{bkg}}(m_{\mu\mu})$. This turns out to often be the dominant source of systematic uncertainties with the uncertainty from the signal extraction being the second one. It was checked that different choices of invariant mass binnings yield $v_2$ values that are consistent within uncertainties. A similar method was used to extract the uncorrected (for detector acceptance and efficiency) average transverse momentum ($\langle p_T \rangle^{\text{uncor}}$) of the reconstructed $J/\psi$ in each centrality and $p_T$ class. The $\langle p_T \rangle^{\text{uncor}}$ is used to locate the data points when plotted as a function of $p_T$. Consistent $v_2$ values were obtained using an alternative method [23] in which the $J/\psi$ raw yield is extracted, as described before, in bins of $(\phi - \Psi)$ and $v_2$ is evaluated by fitting the data with the function $(dN/d(\phi - \Psi)) = A[1 + 2v_2 \cos 2(\phi - \Psi)]$, where $A$ is a normalization constant. As an additional check the first analysis procedure [26] was also applied to the same-sign (SS) dimuons. As expected, no $J/\psi$ signal is seen in either the invariant mass distribution or the $\langle \cos 2(\phi - \Psi) \rangle$ as a function of $m_{\mu\mu}$ of SS dimuons. In both cases the SS dimuons exhibit the same trend as the continuum of the OS dimuons.

The finite resolution in the EP determination smears out the azimuthal distributions and lowers the value of the measured anisotropy [23]. The VZERO-A EP resolution as a function of the centrality was determined using MB events and the 3 subevent method [23]. To estimate the systematic uncertainty from the EP determination two sets of 3 subevents were used: first, VZERO-A, VZERO-C, and the time projection chamber (TPC), with pseudorapidity gaps $\Delta\eta_{\text{V0A-TPC}} = 1.9$, $\Delta\eta_{\text{V0A-V0C}} = 4.5$, and $\Delta\eta_{\text{TPC-V0C}} = 0.8$; second, VZERO-A, ring 0 of VZERO-C, and VZERO-C 3rd ring, with pseudorapidity gaps $\Delta\eta_{\text{V0A-V0C0}} = 6.0$, $\Delta\eta_{\text{V0C0-V0C3}} = 1.0$, and $\Delta\eta_{\text{V0A-V0C3}} = 4.5$. The differences between the EP resolution for VZERO-A obtained from these two sets of subevents are taken as systematic uncertainties. Since $v_2$ is measured here in a wide centrality class, the resolution must reflect the distribution of events with a $J/\psi$ within the class. Therefore, the EP resolution for each wide class was calculated as the average of the values obtained in finer centrality classes weighted by the number of reconstructed $J/\psi$. Table I shows the corresponding resolution for each centrality class which is applied to the results reported in this Letter.

The $J/\psi$ reconstruction efficiency depends on the detector occupancy, which could bias the $v_2$ measurement. This effect was evaluated by embedding azimuthally isotropic simulated $J/\psi \to \mu^+\mu^-$ decays into real events. The measured $v_2$ of those embedded $J/\psi$ does not deviate from zero by more than 0.015 in the centrality and $p_T$ classes considered. This value is used as a conservative systematic uncertainty on all measured $v_2$ values.

Figure 2 shows the $p_T$ dependence of the inclusive $J/\psi$ $v_2$ for semicentral (20%–40%) Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The vertical bars show the statistical uncertainties while the boxes indicate the point-to-point uncorrelated systematic uncertainties, which include those from

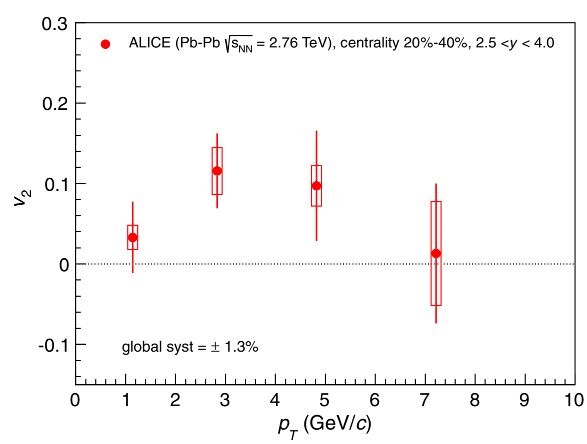


FIG. 2 (color online). Inclusive $J/\psi$ $v_2(p_T)$ for semicentral (20%–40%) Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (see text for details on uncertainties). The used $p_T$ ranges are 0–2, 2–4, 4–6, and 6–10 GeV/$c$.

the signal extraction, the $v_2^{\rm bkg}$ shape, and the reconstruction efficiency. The global correlated relative systematic uncertainty on the EP resolution is 1.3%. A nonzero $v_2$ is observed in the intermediate $p_T$ range $2 \leq p_T < 6$ GeV/$c$. Including statistical and systematic uncertainties the combined significance of a nonzero $v_2$ in this $p_T$ range is 2.7$\sigma$. At lower and higher $p_T$ the inclusive $J/\psi$ $v_2$ is compatible with zero within uncertainties.

To study the centrality dependence of the $v_2$ we select $J/\psi$ with $1.5 \leq p_T < 10$ GeV/$c$. Indeed, below 1.5 GeV/$c$ the $v_2$ of the $J/\psi$ is expected to be small [15] and the signal to background ratio is also low. Since the initial spatial anisotropy for head-on collisions is small, the expected $v_2$ is also small. In addition, for the 0%–5% centrality range the VZERO-A EP resolution is quite low and has higher systematic uncertainties. Therefore, the 0%–5% centrality range was excluded. Figure 3(a) shows $v_2$ for inclusive $J/\psi$ with $1.5 \leq p_T < 10$ GeV/$c$ as a function of $\langle N_{\rm part}\rangle$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Here, the point-to-point uncorrelated systematic uncertainties (boxes) also include, in addition to those discussed above, the uncertainty from the EP resolution determination. The measured $v_2$ depends on the $p_T$ distribution of the reconstructed $J/\psi$, which could vary with the collision centrality. Therefore, $\langle p_T\rangle^{\rm uncor}$ of the reconstructed $J/\psi$ is also shown in Fig. 3(b). The error bar indicates the statistical uncertainties while the boxes show the systematic uncertainties due to the $J/\psi$ signal extraction. For the most central collisions, 5%–20% and 20%–40%, the inclusive $J/\psi$ $v_2$ for $1.5 \leq p_T < 10$ GeV/$c$ are $0.101 \pm 0.044({\rm stat}) \pm 0.032({\rm syst})$ and $0.116 \pm 0.045({\rm stat}) \pm 0.041({\rm syst})$, respectively. The combined significance of a nonzero $v_2$ is 2.9$\sigma$. For more peripheral Pb-Pb collisions, the $v_2$ is consistent with zero within uncertainties. Although there is a small variation with centrality, the $\langle p_T\rangle^{\rm uncor}$ stays in the range 3.0–3.3 GeV/$c$, indicating that the bulk of the reconstructed $J/\psi$ are in the same $p_T$ range for all centralities. Thus, the observed centrality dependence of the $v_2$ for inclusive $J/\psi$ with $1.5 \leq p_T < 10$ GeV/$c$ does not result from any bias in the sampled $p_T$ distributions. For $J/\psi$ with $p_T < 1.5$ GeV/$c$ (not shown), the $v_2$ is compatible with zero within 1 standard deviation for the four centrality classes. The $\langle p_T\rangle^{\rm uncor}$ ranges from about 0.75 to 0.9 GeV/$c$.

To allow a direct comparison with current model calculations, the inclusive $J/\psi$ $v_2(p_T)$ was also calculated in a broader centrality range, namely, 20%–60%, and it is shown in Fig. 4. In this broader centrality range, the measured $v_2$ signal in the $p_T$ range 2–4 GeV/$c$ deviates from zero by 2$\sigma$. The same trend of $v_2(p_T)$ is observed in the 20%–60% and in the 20%–40% centrality classes. This trend seems qualitatively different from that of the STAR measurement [17] at lower collision energy, which is compatible with zero for $p_T \geq 2$ GeV/$c$ albeit in somewhat different (10%–40% and 0%–80%) centrality ranges. Also shown in Fig. 4 are two transport model calculations that include a $J/\psi$ regeneration component from deconfined charm quarks in the medium [15,28]. In both models about 30% of the measured $J/\psi$ in the 20%–60% centrality range are regenerated. First, thermalized charm quarks in the medium transfer a significant elliptic flow to regenerated $J/\psi$. Second, primordial $J/\psi$ emitted out of plane traverse a longer path through the medium than those emitted in plane, resulting in a small apparent $v_2$. The predicted maximum $v_2$ at $p_T \sim 2.5$ GeV/$c$ results from an interplay between the regeneration component, dominant at lower $p_T$, and the primordial $J/\psi$ component which takes over at higher $p_T$. The first model [28] is shown for the hypothesis of thermalization (full line) and

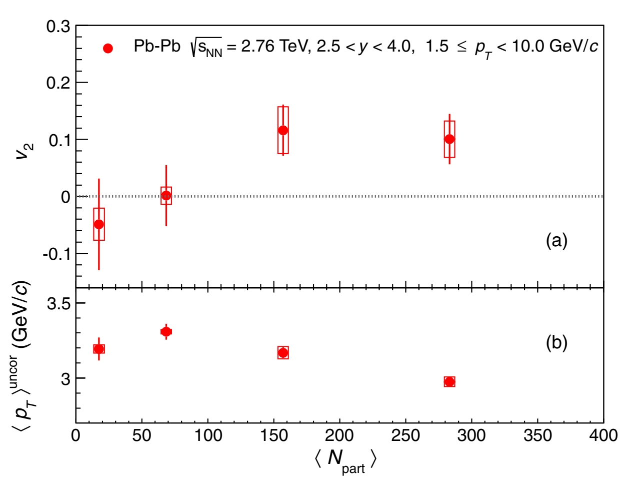


FIG. 3 (color online). $v_2$ (a) and $\langle p_T\rangle^{\rm uncor}$ (b) of inclusive $J/\psi$ with $1.5 \leq p_T < 10$ GeV/$c$ as a function of $\langle N_{\rm part}\rangle$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (see text for details on uncertainties).

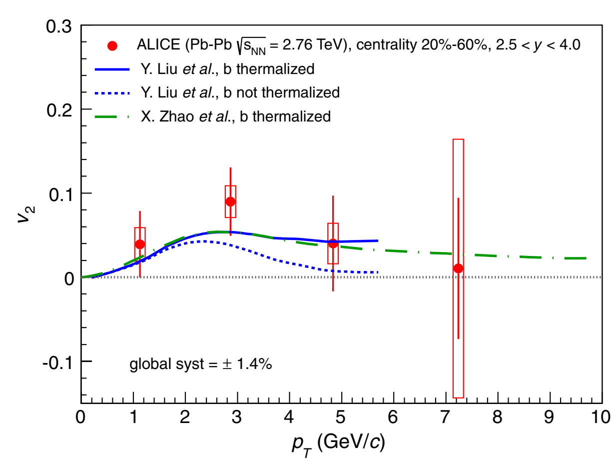


FIG. 4 (color online). Inclusive $J/\psi$ $v_2(p_T)$ for noncentral (20%–60%) Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (see text for details on uncertainties). The used $p_T$ ranges are 0–2, 2–4, 4–6, and 6–10 GeV/$c$. Calculations from two transport models [15,28] are also shown (see text for details).

nonthermalization (dashed line) of $b$ quarks. The LHCb Collaboration measured the fraction of $J/\psi$ from $B$ hadron decays in $pp$ collisions at $\sqrt{s} = 2.76$ and 7 TeV [29,30] in the rapidity acceptance used for this measurement. At 7 TeV this fraction increases from 7% at $p_T \sim 0$ to 15% at $p_T \sim 7$ GeV/$c$, while at 2.76 TeV it is about 7% for $p_T < 12$ GeV/$c$. In Pb-Pb collisions this fraction could increase up to 11% if the $B$ hadron $R_{AA} = 1$. If $b$ quarks do thermalize, then their elliptic flow will be transferred to $B$ mesons at hadronization and to the $J/\psi$ at the $B$ meson decay. In the second model [15] (dash-dotted line) only the case assuming $b$ quark thermalization is shown. Both models qualitatively describe the $p_T$ dependence of the $v_2$ and the $R_{AA}$ of inclusive $J/\psi$ [5].

In summary, we reported the ALICE measurement of inclusive $J/\psi$ elliptic flow in the range $0 \leq p_T < 10$ GeV/$c$ at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. For semicentral collisions indications of a nonzero $J/\psi$ $v_2$ are observed in the intermediate $p_T$ range. This measurement complements the results on the $J/\psi$ $R_{AA}$, where a smaller suppression was seen at low $p_T$ at the LHC compared to RHIC. Both results seem in agreement with the global picture in which a significant fraction of the observed $J/\psi$ is produced from deconfined charm quarks in the QGP phase.

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