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

The ALICE Collaboration[*]

Abstract

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

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[*] See Appendix A for the list of collaboration members

The aim of ultra-relativistic heavy nuclei collisions is the study of nuclear 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. The measurement of quarkonium states and hadrons with open heavy flavor is therefore expected to provide essential information on 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 will be suppressed in the medium with different dissociation probabilities for the various states. Recently, the CMS Collaboration at the Large Hadron Collider (LHC) claimed the observation of the sequential suppression in the Υ sector [3]. The ALICE Collaboration published the inclusive J/ψ nuclear modification factor $R_{\rm AA}$ down to zero transverse momentum ($p_{\rm T}$) at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV [4]. The $R_{\rm AA}$ compares the yields in Pb-Pb to those in pp collisions scaled by the number of binary nucleon-nucleon collisions. The inclusive J/ψ nuclear modification factor reported is larger than that measured at the SPS [5] and at RHIC [6, 7] for central collisions and does not exhibit a significant centrality dependence. Complementarily, the CMS Collaboration measures the high $p_{\rm T}$ ($6.5 \leq p_{\rm T} < 30$ GeV/c) prompt J/ψ $R_{\rm AA}$ in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV in the rapidity range $|y| < 2.4$ [8]. The data of CMS shows that high $p_{\rm T}$ J/ψ are found to be more suppressed than low $p_{\rm T}$ J/ψ and that this suppression does exhibit a strong centrality dependence.

The centrality dependence of the J/ψ $R_{\rm AA}$ at low transverse momentum can be qualitatively understood with models including full [9, 10] or partial [11, 12] regeneration of J/ψ from deconfined charm quarks in the medium. The J/ψ regeneration mechanism was first proposed by the Statistical Hadronization Model (SHM), which assumes deconfinement and thermal equilibrium of the bulk of $c\bar{c}$ pairs to produce J/ψ at the phase boundary by statistical hadronization only [9]. Later, the transport models proposed a dynamical competition between the J/ψ suppression by the QGP and the regeneration mechanism, which enables them to describe also the $p_{\rm T}$ dependence of the J/ψ $R_{\rm AA}$ [11, 12]. These models have in common the assumption of deconfinement and some degree of charm quark thermalization. More differential studies, like the J/ψ elliptic flow, could help to assess the charm quark thermalization in the medium.

The azimuthal distribution of particles in the plane perpendicular to the beam direction is an experimental observable also sensitive to the dynamics of the early stages of heavy-ion collisions. When nuclei collide at finite impact parameter (non-central collisions), the geometrical overlap region and, therefore, the initial matter distribution is anisotropic (almond-shaped). If the matter is strongly interacting, this spatial asymmetry is converted via multiple collisions into an anisotropic momentum distribution [13]. 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 [11, 12] the observed J/ψ have two origins. First, primordial J/ψ , which are produced in the initial hard scatterings, traverse and interact with the created medium. During this process they may be dissociated. Second, J/ψ could be regenerated from deconfined charm quarks and anti-quarks in the QGP. Primordial J/ψ 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/ψ. Regenerated J/ψ inherit the elliptic flow of the charm quarks in the QGP. If charm quarks do thermalize in the QGP then J/ψ formed there can exhibit a significant elliptic flow.

At RHIC energies, the (preliminary) measurements by the (PHENIX) STAR Collaboration of the J/ψ elliptic flow in Au-Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV [14, 15] are consistent with zero albeit with large uncertainties in the $p_{\rm T}$ and centrality ranges (0–5 GeV/c) 2–10 GeV/c and (20%–60%) 10%–50%. The measurement of quarkonium elliptic flow is especially promising at the LHC where the high energy density of the medium and the large number of c$\bar{\rm c}$ pairs produced in Pb-Pb collisions should favor the development of flow and the regeneration mechanisms.

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

The ALICE detector is described in [16]. At forward rapidity ($2.5 < y < 4$) the production of quarkonium states is measured via the decay channel $\mu^+\mu^-$ in the muon spectrometer [1] down to $p_{\mathrm{T}} = 0$. The spectrometer consists of a ten interaction length thick 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 delivering a 3 Tm field integral. The tracking apparatus is completed by a triggering system made of four planes of resistive plate chambers downstream of a 1.2 m thick iron wall, which absorbs secondary hadrons escaping from the front absorber and low momentum muons coming mainly from π and K decays. In addition, the silicon pixel detector (SPD) and scintillator arrays (VZERO) were used in this analysis. 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). The SPD, used to determine the location of the interaction point, consists of two cylindrical layers covering $|\eta| \leq 2.0$ and $|\eta| \leq 1.4$ for the inner and outer layers, respectively. All of these detectors have full azimuthal coverage. The data sample used for this analysis, collected in 2011, amounts to 17×10^6 dimuon unlike sign (MU) triggered Pb-Pb collisions and corresponds to an integrated luminosity $\mathscr{L}_{\mathrm{int}} \approx 70\ \mu\mathrm{b}^{-1}$. In addition to a minimum bias (MB) trigger, the MU trigger requires at least a pair of opposite sign track segments, each with a p_{T} above the threshold of the on-line trigger algorithm. The p_{T} threshold of the trigger algorithm was set to provide 50% efficiency for muon tracks with p_{T} = 1 GeV/c. The MB trigger requires a signal in VZERO-A and a signal in VZERO-C. The beam induced background was further reduced offline using the VZERO and the zero degree calorimeter (ZDC) timing information. The contribution from electromagnetic processes was removed by requiring a minimum energy deposited in the neutron ZDCs [17]. The centrality determination is based on a fit of the VZERO amplitude distribution as described in [18]. A cut corresponding to the most central 90% of the nuclear cross section was applied; for these events the MB trigger is fully efficient and the contribution from electromagnetic processes is negligible.

J/ψ candidates are formed by combining pairs of opposite-sign (OS) tracks reconstructed in the geometrical acceptance of the muon spectrometer. To improve the muon identification, the reconstructed tracks in the muon tracking chambers are required to match a track segment in the muon trigger system above the p_{T} threshold of the on-line trigger algorithm.

The J/ψ v_2 is calculated using event plane (EP) based methods. The azimuthal angle Ψ of the second harmonic event plane is used as an estimate of the reaction plane angle [19]. Ψ is determined from the azimuthal distribution of the VZERO amplitude. The VZERO-C has a common acceptance region with the muon spectrometer. Therefore, only the VZERO-A was used for the event plane determination to avoid autocorrelations. The J/ψ v_2 results were obtained determining $v_2 = \langle \cos 2(\phi - \Psi) \rangle$ versus invariant mass ($m_{\mu\mu}$) [20], where ϕ is the dimuon azimuthal angle. In this method, v_2 of the OS dimuons is calculated as a function of $m_{\mu\mu}$ and then the resulting $v_2(m_{\mu\mu})$ distribution is fitted using:

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

where v_2^{sig} and v_2^{bkg} correspond to the v_2 of the J/ψ signal and of the background, respectively. v_2^{bkg} was parametrized using a second order polynomial (see Fig. 1 (b)). 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 OS dimuon invariant mass distribution was fitted with a Crystal Ball (CB) function to reproduce the J/ψ line shape,

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[1] In the ALICE reference frame, the muon spectrometer covers a negative η range and consequently a negative y range. We have chosen to present our results with a positive y notation.

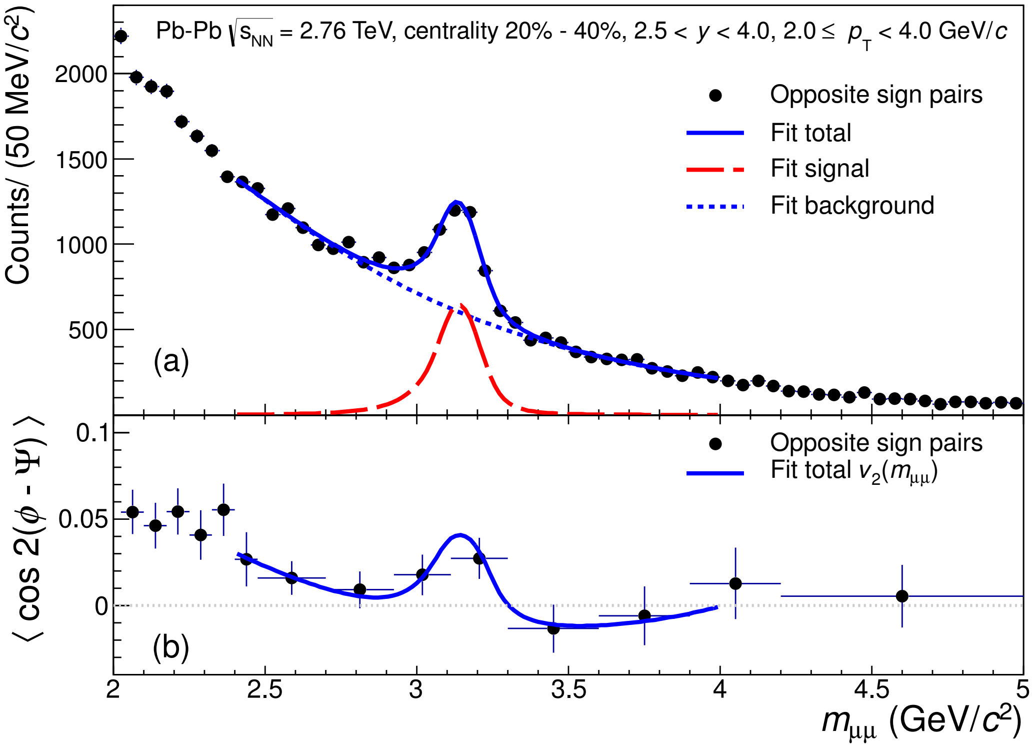

Fig. 1: (Color online) Invariant mass spectrum (a) and $\langle\cos 2(\phi - \Psi)\rangle$ (b) as a function of the invariant mass of $\mu^+\mu^-$ pairs (fitted with Eq. 1) with $2 \leq p_{\rm T} < 4$ GeV/c and $2.5 < y < 4$ in the 20%–40% semi-central Pb-Pb collisions.

and either a third order polynomial or a gaussian with a width linearly varying with mass to describe the underlying continuum. The CB function connects a Gaussian core with a power-law tail [21] 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 uncertainties. The J/ψ v_2 and its statistical uncertainty in each $p_{\rm T}$ and centrality class were determined as the average of the $v_2^{\rm sig}$ 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 (a) and of the $\langle\cos 2(\phi - \Psi)\rangle$ as a function of $m_{\mu\mu}$ (b) in the 20%–40% centrality class. The systematic uncertainty related to the unknown shape of the $v_2^{\rm bkg}(m_{\mu\mu})$ was evaluated by repeating the procedure above using either a first order polynomial or its inverse as $v_2^{\rm bkg}$ parametrization. The largest deviation of the results obtained with the three different $v_2^{\rm bkg}$ parametrizations was conservatively adopted as the systematic uncertainty. A similar method is used to extract the uncorrected (for detector acceptance and efficiency) average transverse momentum ($\langle p_{\rm T}\rangle^{\rm uncor}$) of the reconstructed J/ψ in each centrality and $p_{\rm T}$ class. The $\langle p_{\rm T}\rangle^{\rm uncor}$ is used to locate the data points when plotted as a function of transverse momentum. Consistent v_2 values were obtained using an alternative method [19] in which the J/ψ raw yield is extracted, as described before, in bins of $(\phi - \Psi)$ and the v_2 values are evaluated using a fit to the data with the function $\frac{dN}{d(\phi-\Psi)} = A[1+2v_2\cos 2(\phi-\Psi)]$, where A is a normalization constant.

The finite resolution in the event plane determination smears out the azimuthal distributions and leads to a lower value for the measured anisotropy [19]. The VZERO-A event plane resolution as a function of the centrality was determined using MB events and the 3 sub-event method [19]. To estimate the systematic uncertainty from the event plane determination two sets of 3 sub-events were used: first, VZERO-A,

Table 1: VZERO-A event plane resolution for the centrality classes expressed in percentages of the nuclear cross section [18].

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

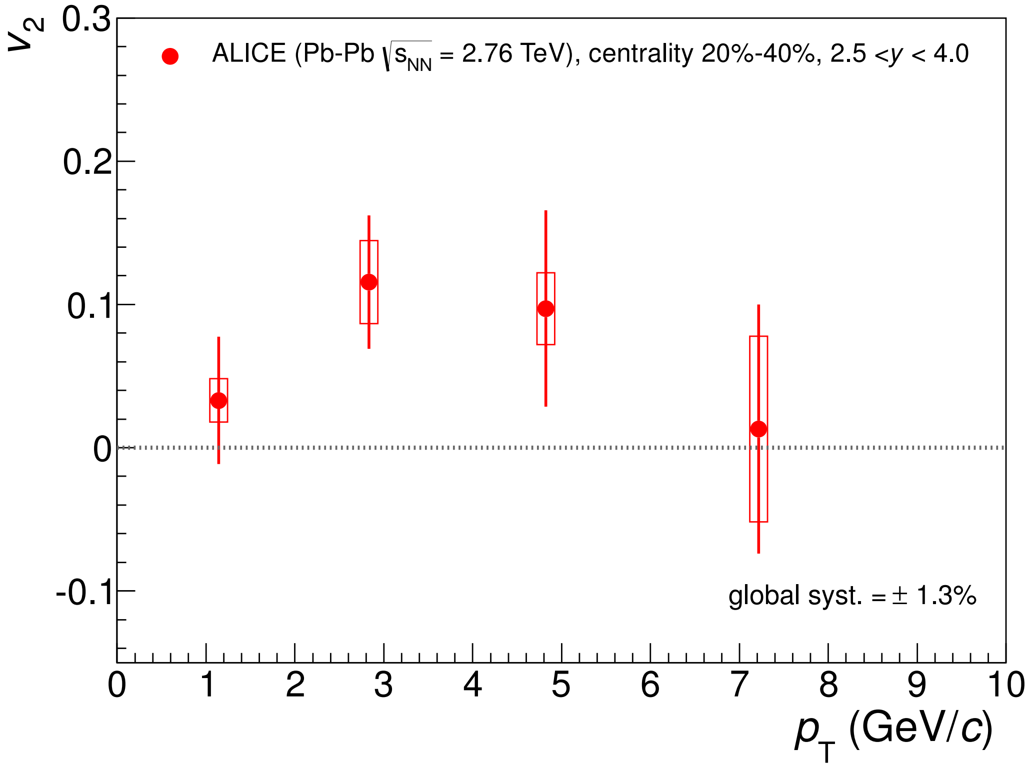

Fig. 2: (Color online) Inclusive J/ψ $v_2(p_{\rm T})$ for semi-central (20%–40%) Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV. The v_2 was measured in the $p_{\rm T}$ ranges: 0–2, 2–4, 4–6 and 6–10 GeV/c and the points are located at the measured $\langle p_{\rm T}\rangle^{\rm uncor}$.

VZERO-C and the Time Projection Chamber (TPC), with pseudo-rapidity gaps $\Delta\eta_{\rm V0A-TPC}$=1.9 and $\Delta\eta_{\rm TPC-V0C}$=0.8; second, VZERO-A, VZERO-C-1st ring and VZERO-C-4th ring, with pseudo-rapidity gaps $\Delta\eta_{\rm V0A-V0C1}$=4.5 and $\Delta\eta_{\rm V0C1-V0C4}$=1.1. The differences between the event plane resolution for VZERO-A obtained from these two sets of sub-events 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/ψ within the class. Therefore, the event plane 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/ψ. Table 1 shows the corresponding resolution for each centrality class which is applied to the results reported in this Letter.

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

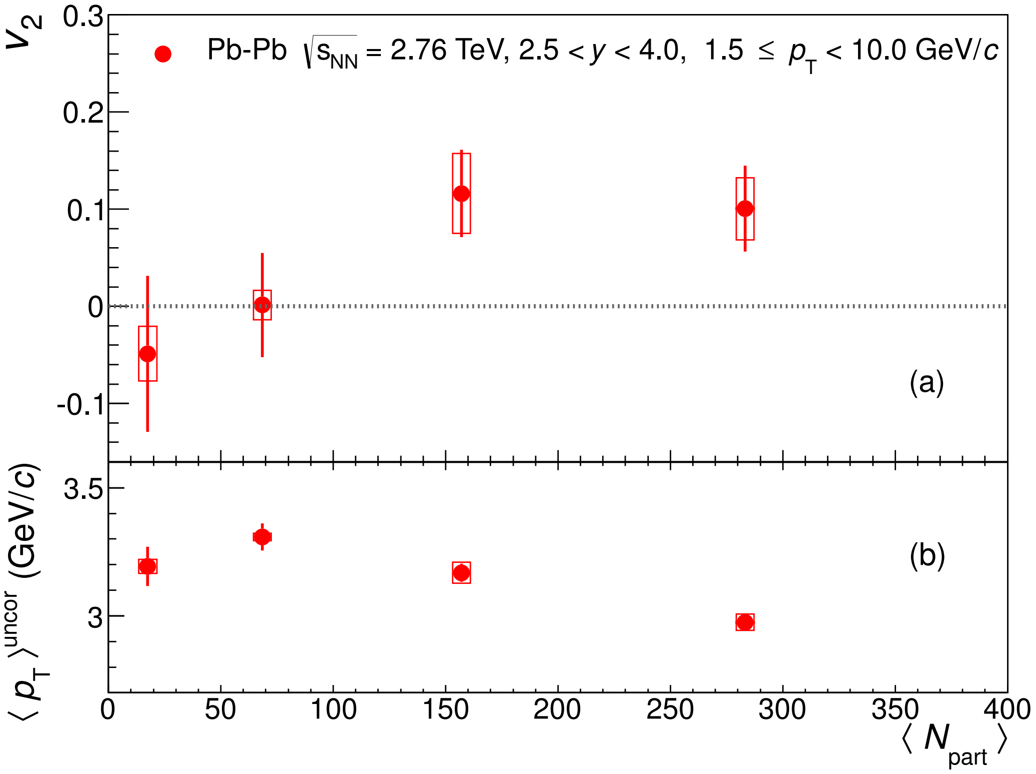

Fig. 3: (Color online) v_2 (a) and $\langle p_{\mathrm{T}} \rangle^{\mathrm{uncor}}$ (b) of inclusive J/ψ with $1.5 \leq p_{\mathrm{T}} < 10$ GeV/c as a function of the number of participating nucleons in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV.

Figure 2 shows the transverse momentum dependence of the inclusive J/ψ v_2 for semi-central (20%–40%) Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV. The vertical bars show the statistical uncertainties while the boxes indicate the point-to-point uncorrelated systematic uncertainties, which include the uncertainties from the signal extraction, the v_2^{bkg} shape and from the reconstruction efficiency. The global correlated relative systematic uncertainty on the event plane resolution is 1.3%. A non-zero v_2 is observed in the intermediate transverse momentum range $2 \leq p_{\mathrm{T}} < 6$ GeV/c. Taking into account statistical and systematic uncertainties the combined significance of a non-zero v_2 in this p_{T} range is 2.7σ. At lower and higher transverse momentum the inclusive J/ψ v_2 is compatible with zero within uncertainties.

To study the centrality dependence of the v_2 we select J/ψ with $1.5 \leq p_{\mathrm{T}} < 10$ GeV/c for which the signal to background ratio as well as the observed v_2 are maximized. Since the initial spatial anisotropy for head-on collisions is small, the expected elliptic flow is also small. Therefore, we do not consider the 0%–5% centrality range. Figure 3 (a) shows v_2 for inclusive J/ψ with $1.5 \leq p_{\mathrm{T}} < 10$ GeV/c as a function of the number of participating nucleons in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV. The average number of participant nucleons $\langle N_{\mathrm{part}} \rangle$ for the centrality classes used in this analysis are derived from a Glauber model calculation [18]. The vertical bars show the statistical uncertainties while the boxes indicate the point-to-point uncorrelated systematic uncertainties, which in addition to those discussed above also include the uncertainty from event plane resolution determination. The measured v_2 depends on the p_{T} distribution of the reconstructed J/ψ, which could vary with the centrality of the collision. Therefore, $\langle p_{\mathrm{T}} \rangle^{\mathrm{uncor}}$ of the reconstructed J/ψ is also shown in Fig. 3 (b) as a function of $\langle N_{\mathrm{part}} \rangle$. For the most central collisions, 5%–20% and 20%–40% the inclusive J/ψ v_2 for $1.5 \leq p_{\mathrm{T}} < 10$ GeV/c are $0.101 \pm 0.044(\mathrm{stat.}) \pm 0.032(\mathrm{syst.})$ and $0.116 \pm 0.045(\mathrm{stat.}) \pm 0.041(\mathrm{syst.})$, respectively. The combined significance of a non-zero v_2 measurement is 2.9σ. For most peripheral Pb-Pb collisions, i.e. the two classes with low $\langle N_{\mathrm{part}} \rangle$ values, the v_2 is consistent with zero within uncertainties. Although there is a small variation with centrality, the $\langle p_{\mathrm{T}} \rangle^{\mathrm{uncor}}$ stays in the range 3.0–3.3 GeV/c indicating that the bulk of the reconstructed J/ψ are in the same p_{T} range for all centralities. Thus, the observed centrality

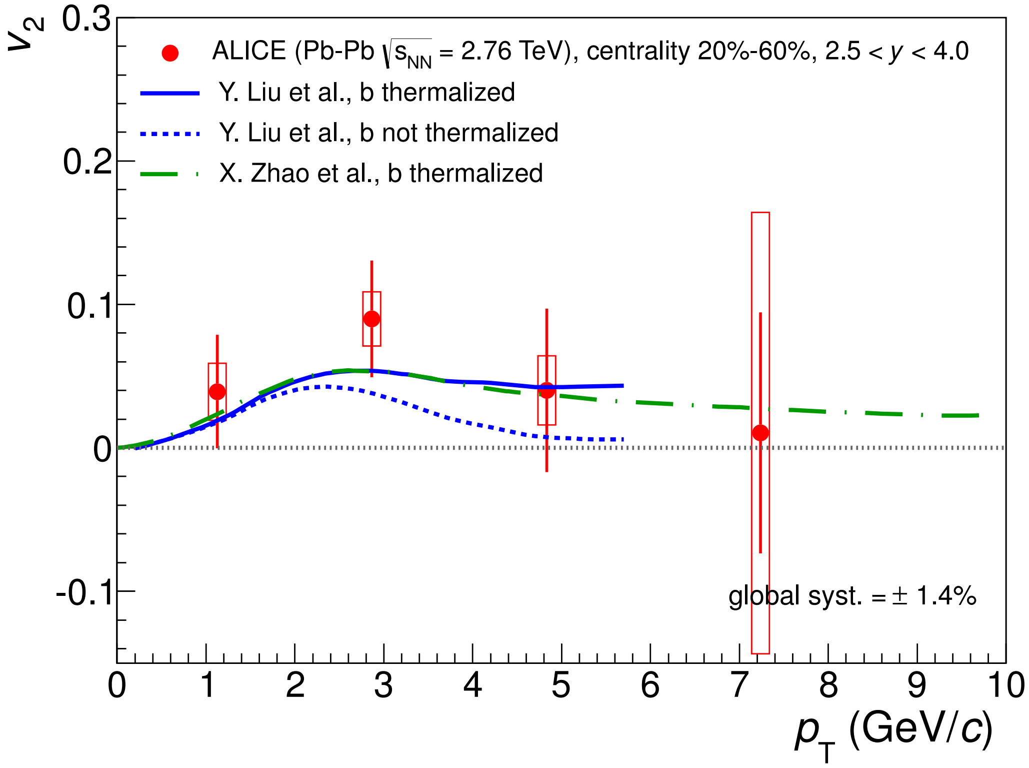

Fig. 4: (Color online) Inclusive J/ψ $v_2(p_{\rm T})$ for semi-central (20%–60%) Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV. The v_2 was measured in the $p_{\rm T}$ ranges: 0–2, 2–4, 4–6 and 6–10 GeV/c and the points are located at the measured $\langle p_{\rm T}\rangle^{\rm uncor}$. Calculations from two transport models [22] and [23] in the same kinematic range are also shown (see text for details).

dependence of the v_2 for inclusive J/ψ with $1.5 \leq p_{\rm T} < 10$ GeV/c does not result from any bias in the sampled $p_{\rm T}$ distributions. For J/ψ with $p_{\rm T} < 1.5$ GeV/c (not shown) the v_2 was found to be compatible with zero within one standard deviation for the four centrality classes. The $\langle p_{\rm T}\rangle^{\rm uncor}$ ranges from about 0.75 to 0.9 GeV/c.

To allow a direct comparison with current model calculations, the inclusive J/ψ $v_2(p_{\rm T})$ was also calculated in a broader centrality range, namely 20%–60%. Figure 4 shows the inclusive J/ψ $v_2(p_{\rm T})$ for non-central (20%–60%) Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV. In this broader centrality range, the measured v_2 signal in the $p_{\rm T}$ range 2–4 GeV/c deviates from zero by 2σ. The same trend of $v_2(p_{\rm T})$ is observed in the 20%–60% and in the 20%–40% centrality classes. This trend is different from the STAR measurement [15] at lower collision energy, which is compatible with zero for $p_{\rm T} \geq 2$ GeV/c albeit in somewhat different (10%–50% and 0%–80%) centrality ranges. Also shown in Fig. 4 are two transport model calculations that include a J/ψ regeneration component from deconfined charm quarks in the medium [22, 23]. In both models about 30% of the measured J/ψ in the 20%–60% centrality range are regenerated. On the one hand, thermalized charm quarks in the medium transfer a significant elliptic flow to regenerated J/ψ. On the other hand, initial J/ψ 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 $p_{\rm T} \sim 2.5$ GeV/c results from an interplay between the regeneration component, dominant at lower $p_{\rm T}$, and the initial J/ψ component which takes over at higher $p_{\rm T}$. The first model [22] is shown for the hypothesis of thermalization (full line) and non-thermalization (dashed line) of b quarks. The LHCb Collaboration measured the fraction of J/ψ from B hadron decays in pp collisions at $\sqrt{s}$ = 2.76 and 7 TeV [24, 25] in the rapidity acceptance used for this measurement. At 7 TeV this fraction increases from about 7% at $p_{\rm T} \sim 0$ to 15% at $p_{\rm T} \sim 7$ GeV/c, while at 2.76 TeV it is about 7% for $p_{\rm T} < 12$ GeV/c. In Pb-Pb collisions this fraction could increase to a maximum of 11% if the B hadron $R_{\rm AA}$= 1. If b quarks do thermalize then their elliptic flow will be transferred to B mesons at hadronization and to the J/ψ at the B meson decay. In the second model [23] (dash-dotted line) only the case assuming thermalization of the b quark is shown. Both models are able to qualitatively describe the $p_{\rm T}$ dependence of the v_2 and the nuclear modification factor of inclusive J/ψ [4].

In summary, we reported the ALICE measurement of inclusive J/ψ elliptic flow in the range $0 \leq p_{\rm T} < 10$ GeV/c at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$=2.76 TeV. For semi-central collisions indications of a non-zero J/ψ v_2 are observed in the intermediate $p_{\rm T}$ range. This measurement complements the results on the J/ψ nuclear modification factor, where a smaller suppression was seen at low transverse momentum at the LHC compared to RHIC. These results suggest that a significant fraction of the observed J/ψ is produced from deconfined charm quarks in the QGP phase.

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A The ALICE Collaboration

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