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J/ψ Measurements with the ALICE Experiment at the LHC

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Abstract. We review recent results on J/ψ production measured by the ALICE collaboration at the LHC. For pp collisions at $\sqrt{s}$ = 7 TeV yields and spectra of inclusive and prompt J/ψ, as well as results on their polarization and the charged particle multiplicity dependence of yields are presented. Measurements of the nuclear modification factor R_{AA} of inclusive J/ψ at mid- ($|y| < 0.9$) and forward-rapidities ($2.5 < y < 4$), covering the range to $p_{\mathrm{t}} = 0$, for centrality selected Pb-Pb collisions are discussed. Also, first results on the J/ψ v_2 at forward-rapidities are shown.

1 Introduction

The understanding of J/ψ production processes in elementary collisions still poses a challenge to theoretical models. The main question is to what extend q$\bar{\mathrm{q}}$ octet states have to be included in the calculation [1, 2]. A consistent description of the measured cross sections and polarization has to be achieved within a given model approach, such as the Color Singlet Model (CSM), Color Evaporation Model (CEM), or the Non-Relativistic QCD model (NRQCD). It is important to distinguish between the different sources contributing to inclusive J/ψ measurements. Roughly 10% of these originate from the weak decay of b-hadrons, while the 90% prompt J/ψ are either directly produced (50%) or are due to feed down from heavier states (40%), such as ψ' or χ_{c}. The J/ψ from b-decays can be measured by exploiting the the fact that the secondary decay vertex will have a displacement relative the main interaction vertex and allow thus a direct determination of the beauty cross section. Another interesting aspect is the question whether Multi-Parton Interactions (MPI) affect the J/ψ production in pp collisions. This can be addressed by measuring the dependence of the yield as a function of the underlying charged particle multiplicity. Finally, pp collisions serve as an important reference measurement to heavy ion collisions in order to identify any medium effects.

Quarkonia in general are a unique probe for the properties of the hot and dense medium produced in high energy heavy ion collisions. It has been suggested very early on that J/ψ production should be suppressed in AA collisions relative to pp due to screening of the q$\bar{\mathrm{q}}$ potential by free color charges [3]. Indeed, such a suppression beyond what is expected due to Cold Nuclear Matter (CNM) effects has been observed experimentally for J/ψ at the SPS and at RHIC [4–6]. The CNM include nuclear absorption and shadowing of parton distributions and can be determined from pA collisions. A surprising aspect of these measurements is the observation that the amount of suppression is very similar

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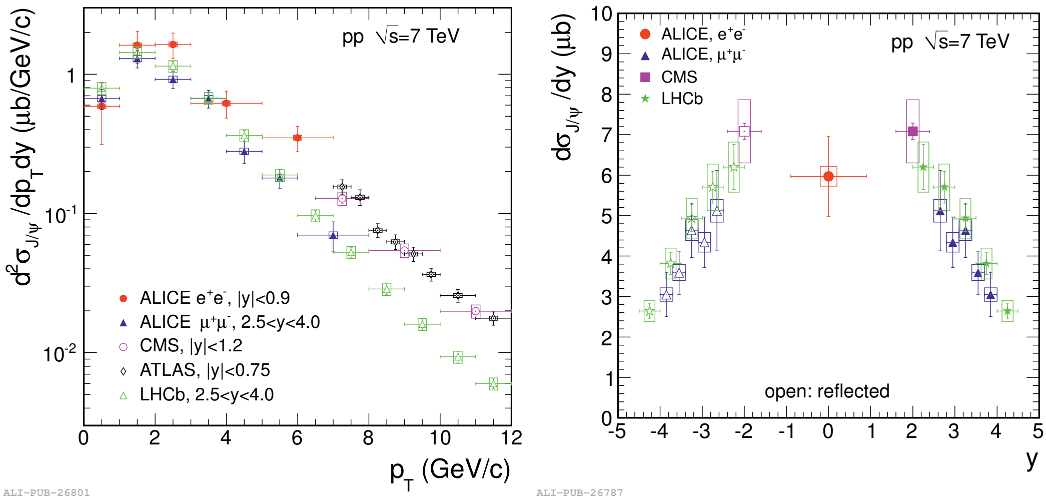

Figure 1. The differential J/ψ cross section for pp collisions at $\sqrt{s} = 7$ TeV as a function of transverse momentum $\mathrm{d}^2\sigma_{\mathrm{J}/\psi}/\mathrm{d}p_{\mathrm{t}}\mathrm{d}y$ measured at midrapidity ($|y| < 0.9$) and at forward rapidity ($2.5 < y < 4$) (left panel) and as a function of rapidity $\mathrm{d}\sigma_{\mathrm{J}/\psi}/\mathrm{d}y$ [11]. The ALICE results are compared to data from the other LHC experiments [12–14], obtained in similar rapidity ranges.

at SPS and RHIC, despite the clearly different energy densities. In addition, a larger suppression at forward rapidities than at mid-rapidity has been seen at RHIC. These findings have led to the idea that in addition to suppression also regeneration mechanisms might play a role at higher energies where the number of produced $c\bar{c}$ pairs is large [7, 8]. This regeneration might happen throughout the evolution of the Quark-Gluon Plasma (QGP) [9] or statistically at hadronization [10] and counteracts the suppression within a QGP.

ALICE is capable of measuring J/ψ at mid-rapidity ($|y| < 0.9$) with the detectors of the central barrel (ITS, TPC, TRD) via the di-electron decay channel. Electrons are identified using the particle identification capabilities of TPC, TRD, and TOF. In addition, secondary vertices of B$\rightarrow$ J/ψ decays can be localized with the help of the ITS. At forward rapidities ($2.5 < y < 4$) J/ψ are detected with muon arm via their di-muon decay channel. Hadrons are suppressed by an absorber of ten interaction lengths thickness and the muons passing through it are tracked by several layers of pad chambers. A trigger on single and di-muons allows the collection of a high statistics J/ψ sample. The acceptance covers in both cases, central barrel and muon arm, the region of low J/ψ transverse momenta down to $p_{\mathrm{t}} = 0$.

2 pp Collisions

Figure 1 shows the J/ψ spectra measured for pp collisions at $\sqrt{s} = 7$ TeV [11]. The presented data correspond to an integrated luminosity of 5.6 nb^{-1} (15.6 nb^{-1}) for the di-electron (di-muon) measurement. A good agreement of the p_{t} spectrum at forward rapidity with the corresponding measurement by the LHCb collaboration [13] is found. Due to the coverage of the low p_{t} region, the data at mid-rapidity complement the results by the ATLAS and CMS experiments for higher p_{t} [12, 14]. Therefore

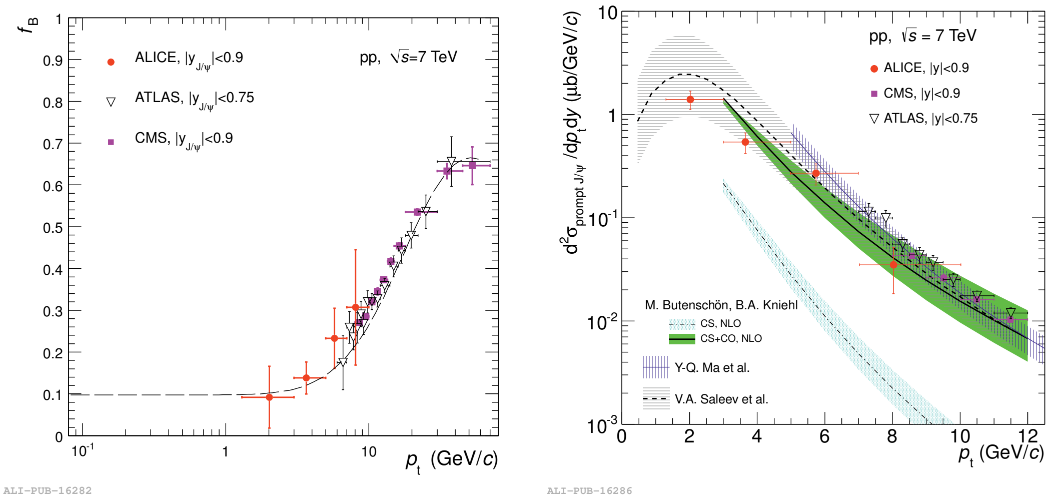

Figure 2. Left: The fraction of J/ψ from the decay of b-hadrons as a function of $p_{\rm t}$ [16] together with results from ATLAS [14] and CMS [17] in pp collisions at $\sqrt{s}$ = 7 TeV. Right: The differential cross section of prompt J/ψ as a function of $p_{\rm t}$ compared to results from ATLAS [14] and CMS [17] at mid-rapidity and to theoretical calculations [18–20].

they allow to fill the gap in der J/ψ rapidity distribution (right panel of Fig. 1) and a determination of the integrated cross section is possible.

The same measurement has been performed for pp collisions at $\sqrt{s}$ = 2.76 TeV, although in the di-electron case based only on a limited integrated luminosity due to the brevity of the run (1.1 nb^{-1} for J/$\psi \to e^+e^-$, 19.9 nb^{-1} for J/$\psi \to \mu^+\mu^-$) [15]. Since these data serve as a reference for the determination of the nuclear modification factor $R_{\rm AA}$ in heavy ion collisions, they currently limit the achievable statistical and systematic errors on $R_{\rm AA}$.

The fraction of J/ψ originating from decays of beauty hadrons $f_{\rm B}$ is extracted from fits with simulated templates to distributions of the pseudo-proper decay length

$$x = \frac{c\, L_{\rm xy}\, m_{J/\psi}}{p_{\rm t}^{J/\psi}} \quad \text{with} \quad L_{\rm xy} = \vec{L}\, \vec{p}_{\rm t}^{\,J/\psi} / p_{\rm t}^{J/\psi}, \tag{1}$$

where $\vec{L}$ is the vector pointing from the primary to the decay vertex. The left panel of Fig. 2 shows the resulting $p_{\rm t}$ dependence of $f_{\rm B}$ at mid-rapidity in pp collisions at $\sqrt{s}$ = 7 TeV. Due to its unique acceptance at very low $p_{\rm t}$, ALICE allows to determine $f_{\rm B}$ down to $p_{\rm t} > 1.3$ GeV/c. At higher $p_{\rm t}$ a good agreement with data by the ATLAS [14] and CMS [17] collaborations is found. Combining the measurement of $f_{\rm B}(p_{\rm t})$ with the $p_{\rm t}$ spectrum of inclusive J/ψ (left panel Fig. 1) yields the corresponding spectrum of prompt J/ψ (right panel of Fig. 2). The data match the NLO NRQCD calculations which include color singlet as well as octet contributions [18–20]. However, the theory is below the measurements by roughly an order of magnitude, if only the color singlet part is considered.

Another observable that can help to discriminate between the different theory approaches is the J/ψ polarization. ALICE measures it via the distributions of the polar angle θ and the azimuthal angle

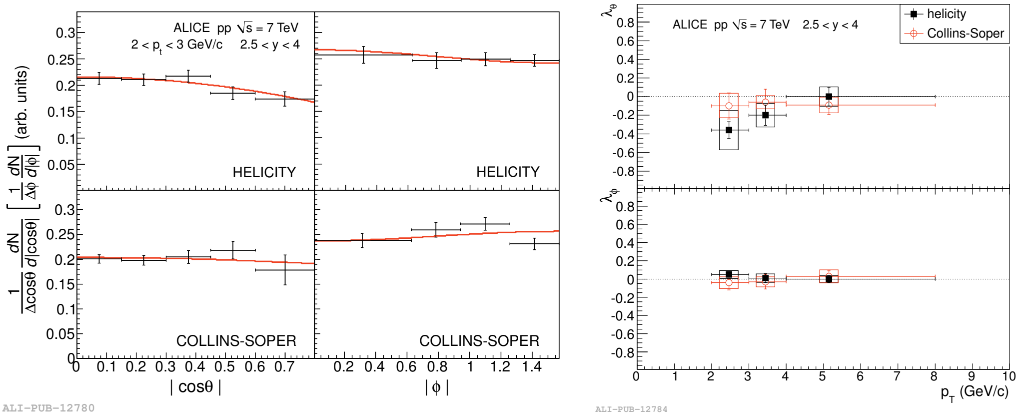

Figure 3. Left: The acceptance corrected angular distributions for the J/ψ decay muons in the range $2 < p_\mathrm{t} < 3$ GeV/c. The simultaneous fit to the results in the Collins-Soper and helicity frames is also shown. Right: λ_θ and λ_ϕ as a function of p_t for inclusive J/ψ, measured in the helicity (closed squares) and Collins-Soper (open circles) frames [21].

ϕ of the decay muons at forward rapidities ($2.5 < y < 4$) in the p_t range 2 - 8 GeV/c [21]

$$W(\cos\theta) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta) \quad \text{and} \quad W(\phi) \propto 1 + \frac{2\lambda_\phi}{3+\lambda_\theta}\cos 2\phi. \tag{2}$$

An example for the fits, which are performed in the Collins-Soper and the helicity frame, is shown in the left panel of Fig. 3. The p_t -dependence of the resulting values for λ_θ and λ_ϕ is shown in the right panel of Fig. 3. All values are found to be close to zero. It should be pointed out that these fits are for inclusive J/ψ, i.e. they contain the contributions from ψ'-, χ_c-, and b-decays.

The interplay between processes on soft and hard scales can be investigated by studying the dependence of the J/ψ yield on the charge particle multiplicity of the underlying event. The latter is dominated by soft processes, which usually require a modeling of MPI in order to achieve a proper theoretical description, and thus probes the impact parameter of the pp collision. ALICE has measured the relative J/ψ yield as a function of $\mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta$ up to four times the mean multiplicity of $\langle \mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta\rangle = 6.01 \pm 0.01(\mathrm{stat.})^{+0.20}_{-0.12}(\mathrm{syst.})$ [22]. As shown in Fig. 4 an almost linear increase of the J/ψ yield is observed, both at mid-rapidity and at forward rapidities, while $\mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta$ is determined in both cases around mid-rapidity ($|\eta| < 1$). Such a behavior is not seen in Monte Carlo models as Pythia6.4, if only J/ψ from hard productions processes are considered. In this case the J/ψ yield is essentially independent from the charged particle multiplicity of the underlying event. The experimental finding suggests that MPI affect also processes on a harder scale, such as J/ψ production [23], and thus introduce an impact parameter dependence even in elementary pp collisions [24].

3 Pb-Pb Collisions

The nuclear modification factor, defined as

$$R_\mathrm{AA} = \frac{\mathrm{d}^2 N^\mathrm{AA}_{\mathrm{J}/\psi}/(\mathrm{d}p_\mathrm{t}\mathrm{d}y)}{\langle T_\mathrm{AA}\rangle\, \mathrm{d}^2\sigma^\mathrm{pp}_{\mathrm{J}/\psi}/(\mathrm{d}p_\mathrm{t}\mathrm{d}y)}, \tag{3}$$

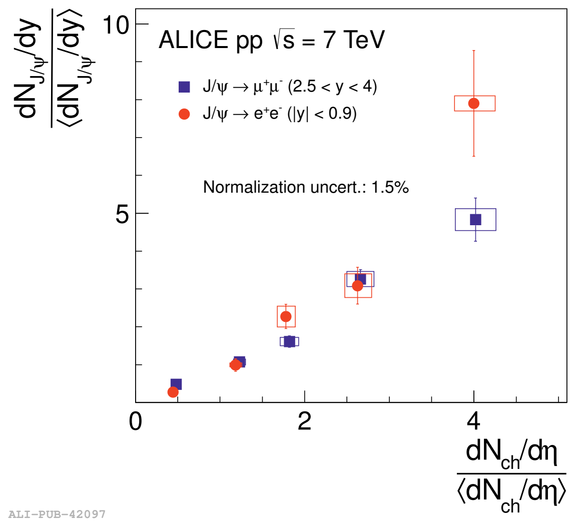

Figure 4. J/ψ yield $dN_{J/\psi}/dy$ as a function of the charged particle multiplicity densities at mid-rapidity $dN_{ch}/d\eta$. Both values are normalized by the corresponding value for minimum bias pp collisions ($\langle dN_{J/\psi}/dy\rangle$, $\langle dN_{ch}/d\eta\rangle$). Shown are measurements at forward rapidities ($2.5 < y < 4$) and at mid-rapidity ($|y| < 0.9$) [22].

where $\langle T_{AA}\rangle$ is the nuclear overlap function as determined by Glauber calculations, has been measured by ALICE for inclusive J/ψ at mid-rapidity ($|y| < 0.9$) and forward rapidities ($2.5 < y < 4$) for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [25, 26]. A clear suppression relative to pp collisions is observed in both cases. While at forward rapidities R_{AA} quickly drops to a value of 0.5 and then is independent of centrality for $N_{part} > 100$, there might be an indication for a slight increase towards very central collisions at mid-rapidity (see left panel of Fig. 5). However, the current systematic errors, especially on the pp reference, are still large and do not allow for a firm conclusion yet. Since the ALICE acceptance allows to measure J/ψ down to $p_t = 0$, the p_t dependence of R_{AA} can be studies in this low transverse momentum region. This is shown in the left panel of Fig. 5 for forward rapidities. A significant decrease of R_{AA} with increasing p_t is observed. While R_{AA} is about 0.6 for $p_t < 1$ GeV/c, it drops to values below 0.4 at higher p_t and thus agrees with the measurement by the CMS collaboration in this p_t region [27]. Also shown in this figure is a comparison with PHENIX results for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [6], which indicates a sizable rise of R_{AA} at lower p_t with increasing center-of-mass energy.

A possible explanation for the increase of R_{AA} with $\sqrt{s_{NN}}$ might be that at higher energies an additional contribution from J/ψ recreation is playing a stronger role, due to the higher number od $c\bar{c}$ pairs present in the fireball. In fact, models that include this effect in addition to suppression mechanisms provide a reasonable description of the data (see Fig. 6). The transport models include CNM effects (shadowing and absorption), suppression in the hot medium due to color screening, feed down from b-hadrons, and continuous $c\bar{c}$ recombination throughout the evolution of the plasma phase [29, 30]. The statistical hadronization model assumes that all J/ψ are dissolved inside the plasma and that they are only formed at the hadronization stage by distributing the $c\bar{c}$ quarks formed in initial hard scatterings according to statistical weights [28]. Another approach models the suppression via

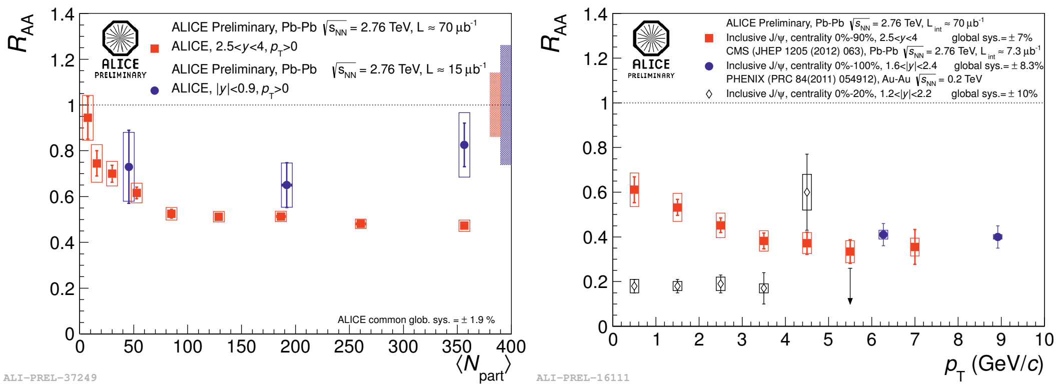

Figure 5. Left: The nuclear modification factor R_{AA} as a function of the number of participating nucleons $\langle N_{part}\rangle$, measured in centrality selected Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV at mid-rapidity ($|y| < 0.9$) and forward rapidity ($2.5 < y < 4$) [25, 26]. Right: R_{AA} at forward rapidities ($2.5 < y < 4$) as a function of p_t in comparison to date by PHENIX [6] and CMS [27].

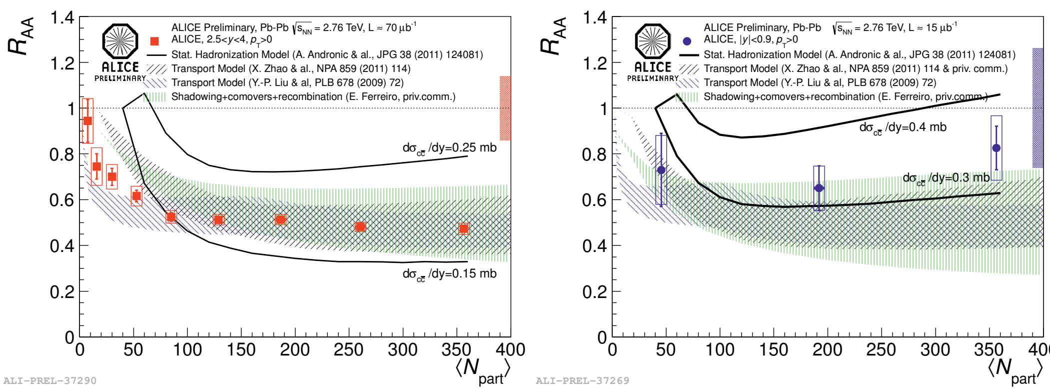

Figure 6. The nuclear modification factor R_{AA} as a function of the number of participating nucleons $\langle N_{part}\rangle$, measured in centrality selected Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV at forward rapidity ($2.5 < y < 4$, left panel) and at mid-rapidity ($|y| < 0.9$, right panel) [25, 26]. Shown are comparisons to several model predictions [28–31].

nuclear shadowing and comover absorption, but also has to include recombination in order to match the data [31]. However, for a final interpretation a precise understanding of CNM effects is mandatory and will be addressed by the upcoming pA run.

Figure 7 shows the preliminary result of a J/ψ v_2 measurement by ALICE for the 20% - 60% most central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [32]. It is determined in the region $2.5 < y < 4$ by applying a fit with

$$\frac{dN_{J/\psi}}{d\Delta\phi} \propto 1 + 2v_2^{obs}\cos(2\,\Delta\phi) \quad \text{with} \quad \Delta\phi = \phi_{\mu\mu} - \Psi_{EP,2}, \tag{4}$$

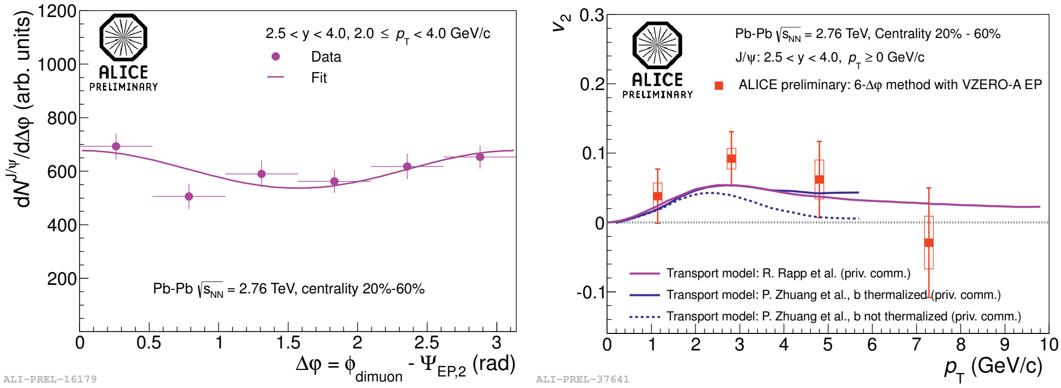

Figure 7. Left: Example of the J/ψ v_2 signal extraction in $\Delta\phi$ bins. Right: The inclusive J/ψ v_2 measured in the 20% - 60% most central Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV [32], compared to the STAR measurement [33] and to predictions from parton transport models [34, 35].

where $\phi_{\mu\mu}$ is the azimuthal angle of the di-muon pair and $\Psi_{\rm EP,2}$ the event plans angle. $\Psi_{\rm EP,2}$ is measured with a 2% resolution using the VZERO detectors. In the range $2 < p_{\rm t} < 4$ GeV/c an indication for a non-zero v_2 is observed, as shown in the right panel of Fig. 7, although with a significance of only 2.2 σ. However, the magnitude of the effect is in agreement with transport model calculations that include regeneration effects [34, 35].

4 Conclusions

Transverse momentum and rapidity spectra of inclusive J/ψ have been measured down to $p_{\rm t} = 0$ for pp collisions at $\sqrt{s}$ = 2.76 TeV and 7 TeV. A good agreement with NRQCD calculations is observed. The same applies to the spectra of prompt J/ψ. No significant J/ψ polarization in the forward region is seen in pp collisions at $\sqrt{s}$ = 7 TeV. An almost linear increase of the J/ψ yield with the charged particle multiplicity of the underlying event is observed, indicating an impact parameter dependence of J/ψ production even in elementary pp collisions.

The nuclear modification factor $R_{\rm AA}$ has been measured for Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV at forward and mid-rapidity for $p_{\rm t} > 0$. A clear indication for less suppression at low $p_{\rm t}$ than at high $p_{\rm t}$ is found and the $R_{\rm AA}$ at low $p_{\rm t}$ is clearly higher at LHC than at RHIC. Also, a first hint of a non-zero v_2 has been observed. These observations might indicate that at LHC energies regeneration effects are effective in addition to the suppression mechanisms seen at lower energies.

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