Recent results on J/ψ from experiment NA50

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The J/ψ production in Pb-Pb interactions induced by 158 GeV/c incident Pb ions is studied as a function of centrality, as estimated from the neutral transverse energy or, alternatively, from the very forward hadronic energy of the collision. The J/ψ yield exhibits a similar pattern with a first drop for mid-peripheral collisions and a steady decrease for the most central reactions. Conventional hadronic models are unable to fairly reproduce this trend which finds a natural explanation in a deconfined quark-gluon phase scenario. The J/ψ transverse momentum distributions and their dependence with centrality are also reviewed in this presentation.

1. Introduction

A phase transition from ordinary hadronic matter to a new state of deconfined quarks and gluons is predicted by non-perturbative Quantum ChromoDynamics [1] under extreme conditions which could be reached in reactions induced by ultrarelativistic heavy ion beams as available at the CERN-SPS. In this context, the NA50 experiment is mainly devoted to the study of a specific signature of the quark-gluon phase transition, the predicted suppression of charmonium states [2]. Indeed, the NA50 recent observations of an anomalous J/ψ suppression [3], a threshold effect [4] and a double stepwise suppression pattern [5] are a strong indication for the deconfinement transition. In this presentation, previous published conclusions find further support both with new (preliminary) results based on proton-induced interactions which lead to a more precise measurement of J/ψ normal absorption, and with different analyses of the same Pb-Pb data which either use directly minimum bias events for normalization or estimate the centrality of the collision from the forward hadronic energy measured in the "zero degree" calorimeter.

2. Experimental conditions and analysis

The NA50 apparatus mainly consists of a muon spectrometer, a segmented active target, and three independent centrality detectors: an electromagnetic calorimeter which measures the neutral transverse energy (E_T) produced in the interaction, a zero degree calorimeter measuring the very forward hadronic energy (E_{ZDC}) of the spectator nucleons and a silicon strip multiplicity detector. A detailed description of the spectrometer can be found in [6].

Pb-Pb data taking conditions were similar in all the periods reported here, except for the total thickness of the target and the number of individual sub-targets. The segmented lead target was made, in 1996, of 7 sub-targets with a total thickness of 12 mm corresponding to 30 % of an interaction length.

In order to eliminate events with possible unidentified re-interactions which could contaminate Pb-Pb central collisions, its total thickness was reduced to 3 mm (7 % λ_I) in 1998, leaving only one single Pb sub-target. As a consequence, for the 1998 sample of data, peripheral Pb-Pb collisions were not studied due to the the relative high contamination originating from Pb-air interactions. This problem will be solved in the recent 2000 run where the target is placed inside a vacuum pipe.

A contour-cut selection (based on the correlation $E_T - E_{ZDC}$) [3] which is satisfied by interactions originating from the target region was systematically applied to the data samples. Moreover, when studying the E_T dependence of J/ψ production, sub-target identification by the the target instrumentation was further required for the analysis which makes use of the muonless, and therefore more loosely constrained, minimum bias events.

Preliminary results on p-A reactions reported hereafter are based on new data collected with proton beams impinging on several targets (Be, Al, Cu, Ag, W and Pb). Two samples of events taken with different intensity beams, in short LI (low intensity) and HI (high intensity), are considered here. They were obtained with protons of 450 GeV/c (resp. 400 GeV/c) at an incident intensity of $\sim 5{\cdot}10^8$ (resp. $\sim 4{\cdot}10^9$) protons/burst.

Muon pairs are analyzed in the kinematical domain defined by $2.92 \leq y_{lab} \leq 3.92$

(i.e., $0 \leq y_{cms} \leq 1$, for Pb-Pb at 158 GeV/n) and $|cos\ \theta_{CS}| < 0.5$ which leads, in the mass region of interest, to acceptances of the order of 15%. They are selected according to the standard NA50 criteria [6].

Various physical processes account for the raw opposite sign muon pair invariant mass spectrum. Besides the J/ψ and ψ' resonances and the Drell-Yan mechanism, the mass continuum includes contributions from combinatorial background and from muon pairs originating from semi-leptonic decays of charmed mesons (mainly open charm ($D\bar{D}$) production). The combinatorial background is mainly due to uncorrelated π and K decays into muons. It is computed from the like-sign mass distributions using $\frac{dN}{dM}\Big|^{\rm bg} = 2\,{\rm R}\sqrt{\frac{dN^{++}}{dM}\frac{dN^{--}}{dM}}$, where R accounts for the effects of charge correlations. Its proper value has been determined as described in reference [7].

The opposite sign muon pair invariant mass distribution is fitted according to the following procedure in order to determine the amounts of its different components. The shapes of the muon pairs originating from J/ψ and ψ' decays and from the Drell-Yan process are obtained from a simulation of the NA50 detector using the same reconstruction and selection criteria as used for the real data. Each kind of events, J/ψ, ψ', Drell-Yan and $D\bar{D}$, is simulated and reconstructed with the NA50 program used for analysis of real data. The Drell-Yan contribution is calculated at leading order and uses the MRSA structure functions, which take into account the $\bar{u}/\bar{d}$ asymmetry as measured by the NA51 experiment [8]. The $D\bar{D}$ shape is taken from a Pythia simulation. A charm-like excess [7] is allowed in its normalization. Finally, the amplitudes of J/ψ, ψ' and Drell-Yan contributions are obtained from a fit to the experimental data for $M_{\mu\mu} > 2.9$ GeV/c^2 according to: $\frac{dN}{dM} = A_{J/\psi}\frac{dN_{J/\psi}}{dM} + A_{\psi'}\frac{dN_{\psi'}}{dM} + A_{DY}\frac{dN_{DY}}{dM} + \frac{dN_{D\bar{D}}}{dM} + \frac{dN_{BG}}{dM}$.

3. J/ψ Production

3.1. The ratio of J/ψ to Drell-Yan cross-sections as a function of E_T

A systematic study of Drell-Yan behaviour, ranging from p-p and some p-A systems to S-U and Pb-Pb is shown in Fig. 1 which displays the ratio between the measured and computed Drell-Yan cross-sections, the so-called K-factor, as a function of the product of the projectile and target atomic mass numbers A·B . Its constant value proves that the DY cross-section behaves normally and is proportional to the number of elementary nucleon-nucleon collisions. It can thus be used as a reference.

The J/ψ cross-section per nucleon-nucleon collision can thus be studied from the ratio of the J/ψ to Drell-Yan cross-sections. This ratio is almost free from systematic errors, which are identical in both samples and thus cancel out (only 1.5% left). Fig. 2 shows the ratio for a large number of interacting systems (from p-p and several p-A to S-U and Pb-Pb), as a function L, the path length that the pre-resonant $c\bar{c}g$ state has to go through in nuclear matter (which allows a common description of the different systems) [3].

A simple exponential parametrization applied to the lighter systems (NA38 [9–11] and NA51 [8] data ranging from p-p to S-U together with the new NA50 p-A data), namely assuming $B_{\mu\mu}\sigma^{\psi}/\sigma^{DY} \propto e^{-\rho L\sigma_{abs}}$, gives an absorption cross-section of the $c\bar{c}g$ state in nuclear matter of $\sigma_{abs} = 5.4 \pm 0.4$ mb, consistent with the previous result obtained only with the NA38 and NA51 data ($\sigma_{abs} = 5.8 \pm 0.6$ mb, a full calculation leading to 6.4 ± 0.5 mb). Whereas the more peripheral Pb-Pb points lie on the absorption curve, the

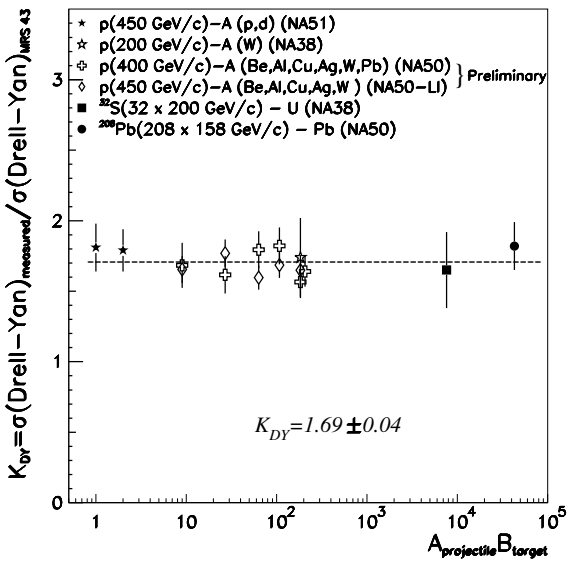


Figure 1. Drell-Yan K-factor as a function of $A_{proj} \cdot B_{tgt}$

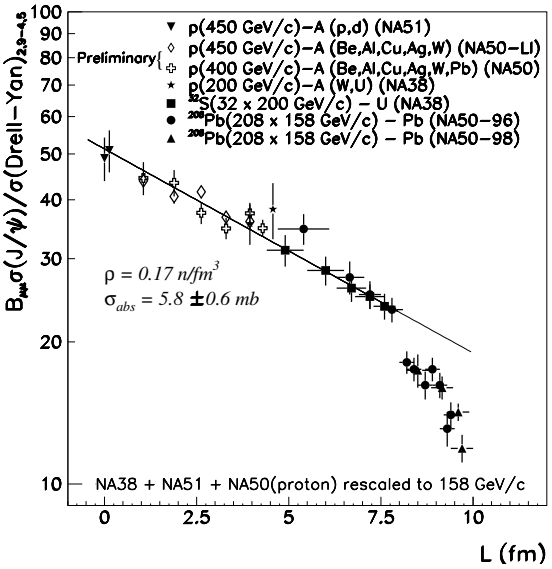


Figure 2. J/ψ/DY as a function of L; the absorption curve is a fit to p-A and S-U experimental data

more central ones show a sudden 20% drop at L $\simeq$ 8 fm, suggesting the onset of another J/ψ suppression mechanism.

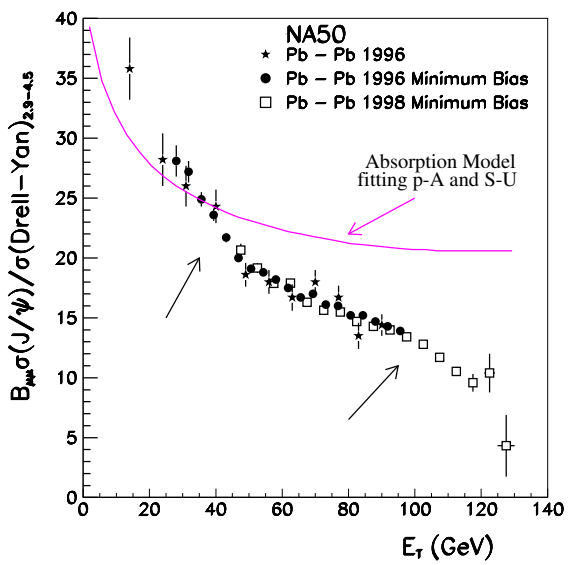


Figure 3. J/ψ/DY as a function of E_T

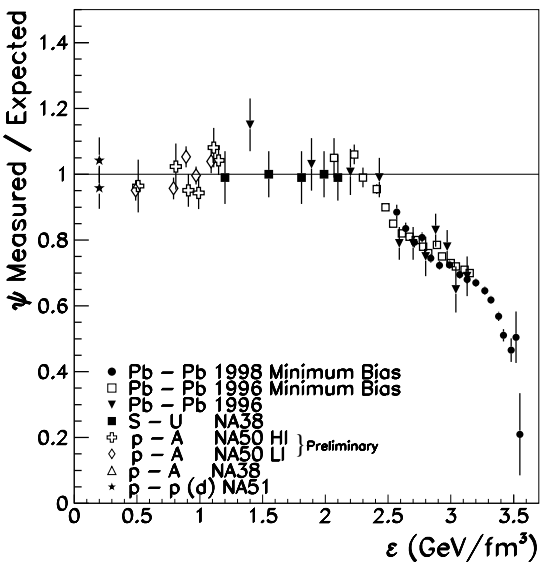


Figure 4. J/ψ Measured/Expected by our absorption model as a function of the energy density ϵ

The ratio of J/ψ to Drell-Yan cross-sections has also been studied as a function of E_T, for the various Pb-Pb data taking periods, using two different methods. In the first method, the Drell-Yan and J/ψ yields are obtained from the standard fit procedure described above. In the second method, which does not use any fit, the J/ψ yield is obtained from a simple counting procedure and the Drell-Yan is deduced from the large minimum bias sample of events (thus reducing significantly statistical errors) by a procedure described in [4].

As shown in Fig. 3, the two methods lead to very similar results. The same figure also displays the results based on the 1998 data analyzed with the minimum bias method, which agree with the 1996 analyses while exploring higher E_T values without reinteraction contamination. The solid line presented in the figure corresponds to the ordinary nuclear absorption obtained from the study of lighter systems data (from p-p to S-U) which lead to $\sigma_{abs} = 6.4$ mb. The overall displayed distribution exhibits, besides a 20% drop at 40 GeV (corresponding to L $\simeq$ 8 fm), an inflection point around 90 GeV followed by a steady steep decrease.

3.2. The ratio of J/ψ to Minimum Bias cross-sections and the E_{ZDC} dependence of J/ψ production

We also report the ratio of the J/ψ to minimum bias cross-sections as a function of E_T . As shown in Fig. 5, a clear departure from the absorption model, quoted above, is observed at $E_T \simeq 40$ GeV whereas at E_T around 90 GeV a change of behaviour is seen. Both observations are in agreement with the J/ψ/DY analysis, reinforcing thereby the J/ψ anomalous suppression picture.

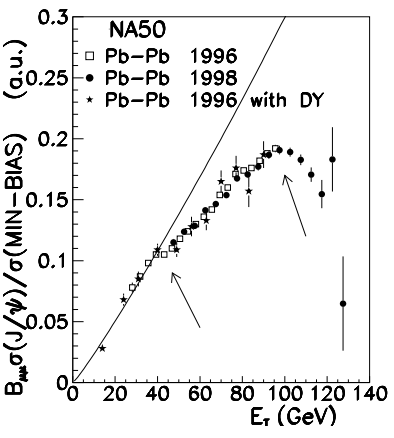


Figure 5. J/ψ/Minimum Bias as a function of E_T . The curve stands for our absorption model

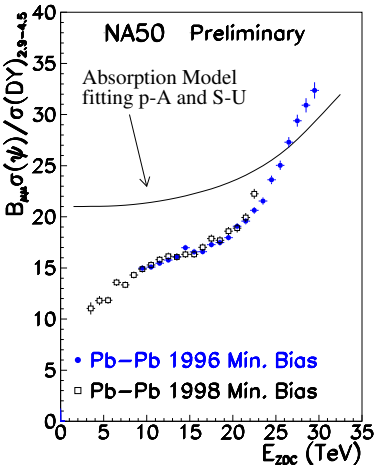


Figure 6. J/ψ/DY as a function of E_{ZDC}

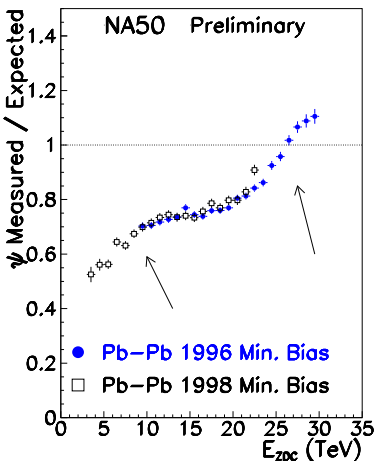


Figure 7. The measured over expected (from nuclear absorption) ratio of J/ψ/DY as a function of E_{ZDC}

Preliminary results of an independent analysis of J/ψ/DY using the forward energy E_{ZDC} measured in a zero degree calorimeter (ZDC) as an estimator of centrality are displayed in Figs. 6, 7. Once again the stepwise pattern of the J/ψ suppression is observed.

3.3. Comparison with theory

Different theoretical models based on absorption by comoving hadrons [12–16] or in a quark-gluon plasma phase transition [17,18] have been developed and compared to the NA50 observations. The comparision is seen in Fig. 8 . Conventional models (left and middle figs.) usually exhibit poor agreement with the whole set of experimental results, i.e., the complete set of results for light and heavier interacting systems. Moreover, they are unable to reproduce the peculiar stepwise suppression pattern. On the other hand, models including quark-gluon deconfinement (right fig.) with two thresholds, corresponding respectively to the χ_c and the J/ψ melting points [17] together with E_T fluctuations [18] are qualitatively in much better agreement with the experimental observations.

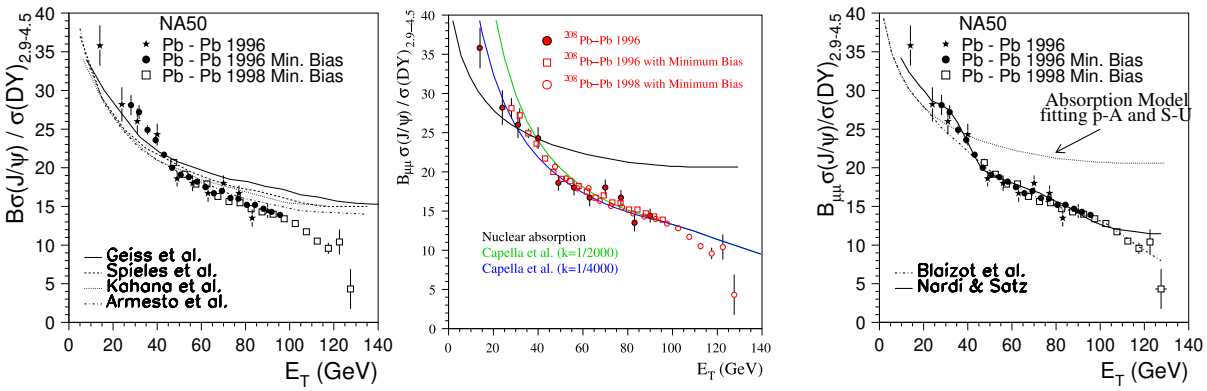


Figure 8. J/ψ/DY experimental results compared with different models as a function of E_T : the first two figures (left and middle) with co-movers and the last one (right) in a framework of QGP

4. Transverse momentum distributions

We summarize hereafter the results obtained on J/ψ transverse momentum distributions which are about to be published [19].

Fig. 9 shows the inverse slope parameter T for Pb-Pb and S-U interactions, respectively at 200 GeV/nucleon and 158 GeV/nucleon, as a function of energy density. The T parameter increases steadily with energy density, both for S-U and Pb-Pb with an obvious dependence on beam energy. The dependence pattern obtained for Pb-Pb does not exclude a first rate of increase as measured on S-U followed by a milder and then, finally, a stronger rate of increase for the most central Pb-Pb collisions.

The dependence of $\langle p_T^2 \rangle$ as a function of L, which can be related to initial state interactions through the gluon-nucleon (gN) scattering, is shown in Fig. 10 for several reactions at 200 GeV/nucleon and 158 GeV/nucleon. $\langle p_T^2 \rangle$ depends on the beam energy, but fits according to [20]:

$$\langle p_T^2 \rangle (E_T) = \langle p_T^2 \rangle_{pp} + a_{gN}\ L(E_T)$$

give compatible slopes for proton, sulphur and lead induced reactions. The numerical value $a_{gN} = 0.080 \pm 0.003\ GeV^2/c^2 fm^{-1}$ is obtained with a $\chi^2/ndf = 0.65$ when fitting all data with a common slope.

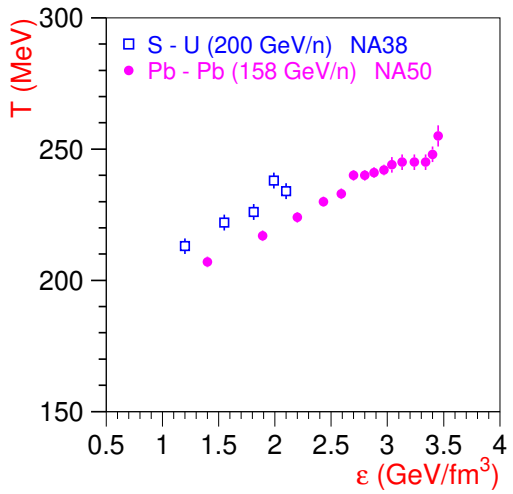
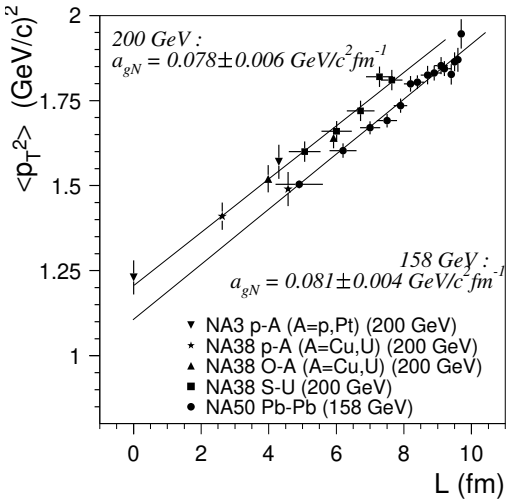


Figure 9. Inverse slope parameter T as a function of energy density



. Figure 10. $\langle p_{\mathrm{T}}^2 \rangle$ of J/ψ as a function of L

The ratio R(p_{T}) of the J/ψ p_{T} distributions for a given E_{T} region with respect to the lowest E_{T} region, normalized to the ratio of the corresponding Drell-Yan events, is shown in Fig. 11. The results clearly show a J/ψ suppression which is significantly stronger at low p_{T}. The ratio R(p_{T}) tends to saturate at high p_{T} for Pb-Pb reactions.

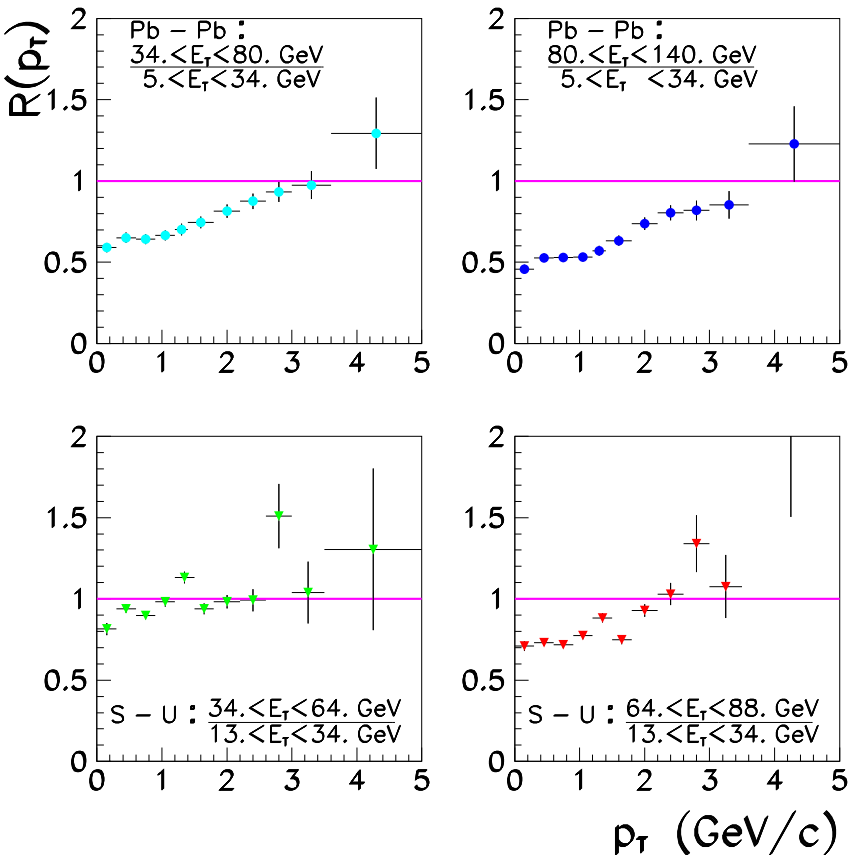


Figure 11. Ratios between p_{T} distributions of J/ψ corresponding to different centralities for Pb-Pb and S-U collisions

One should stress that, as the J/ψ acceptance is almost flat as a function of $p_{\rm T}$, the different $p_{\rm T}$ distributions of J/ψ for different $\rm E_T$ regions introduce no bias on the results of the $p_{\rm T}$ integrated J/ψ/DY suppression as a function of centrality.

5. Conclusions

New data and analyses give further support to published results on Pb-Pb reactions by experiment NA50 which show a stepwise J/ψ anomalous suppression pattern. While J/ψ production agrees with normal nuclear absorption for the most peripheral Pb-Pb reactions, a departure of about 20% from this normal behaviour occurs for semi-peripheral collisions and is followed, with increasing centrality, by an inflection point and a steady steep decrease for the most central reactions. This pattern can be interpreted as due to the successive melting of charmonium bound states (χ_c, J/ψ) as predicted by quark-gluon deconfinement.

From the J/ψ transverse momentum distributions we conclude that J/ψ is more suppressed at low $p_{\rm T}$. We also find that for Pb-Pb reactions, the $\langle p_{\rm T}^2 \rangle_\psi$ and the inverse slope parameter T of the formed J/ψ state exhibit a centrality dependence which suggests different rates of increase for different centrality ranges.

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