Eur. Phys. J. C (2005)
Digital Object Identifier (DOI) 10.1140/epjc/s2005-02208-y

THE EUROPEAN
PHYSICAL JOURNAL C

J/ψ production in Indium-Indium collisions

The NA60 Collaboration

R. Arnaldi[9,a], R. Averbeck[11], K. Banicz[2,4], J. Castor[3], B. Chaurand[7], C. Cicalo[1], A. Colla[9], P. Cortese[9], S. Damjanovic[4], A. David[2,5], A. de Falco[1], A. Devaux[3], A. Drees[11], L. Ducroux[6], H. En'yo[8], A. Ferretti[9], M. Floris[1], P. Force[3], N. Guettet[2,3], A. Guichard[6], H. Gulkanian[10], J. Heuser[8], M. Keil[2,4], L. Kluberg[2,7], J. Lozano[5], C. Lourenço[2], F. Manso[3], A. Masoni[1], P. Martins[2,5], A. Neves[5], H. Ohnishi[8], C. Oppedisano[9], P. Parracho[2], P. Pillot[6], G. Puddu[1], E. Radermacher[2], P. Ramalhete[2,5], P. Rosinsky[2], E. Scomparin[9], J. Seixas[2,5], S. Serci[1], R. Shahoyan[2,5], P. Sonderegger[5], H.J. Specht[4], R. Tieulent[6], G. Usai[1], R. Veenhof[2,5], H.K. Wöhri[2,5]

[1] Università di Cagliari and INFN, Cagliari, Italy
[2] CERN, Geneva, Switzerland
[3] LPC, Université Blaise Pascal and CNRS-IN2P3, Clermont-Ferrand, France
[4] Universität Heidelberg, Heidelberg, Germany
[5] IST-CFTP, Lisbon, Portugal
[6] IPN-Lyon, Université Claude Bernard Lyon-I and CNRS-IN2P3, Lyon, France
[7] LLR, Ecole Polytechnique and CNRS-IN2P3, Palaiseau, France
[8] RIKEN, Wako, Saitama, Japan
[9] Università di Torino and INFN, Italy
[10] YerPhI, Yerevan, Armenia

Received: 16 February 2005 / Revised version: 26 February 2005 /

Abstract. The study of dilepton production in heavy-ion collisions at the CERN SPS provided some of the most interesting observations done so far in the search for the quark gluon plasma. However, several aspects of the understanding of these measurements need to be clarified. For example, the study of the J/ψ production in different colliding systems should help to disentangle which is the variable driving the J/ψ suppression. The NA60 experiment, with a new radiation tolerant Silicon pixel detector, studied Indium-Indium interactions in the year 2003. In this paper, we present the J/ψ / DY ratio, integrated over all the centralities of the collisions, together with a first study of the J/ψ transverse momentum and polarization.

PACS. 25.75.Dw, 25.75.Nq, 13.20.Gd

1 Introduction

According to the predictions of lattice QCD, a phase transition between hadronic matter and a new state named Quark Gluon Plasma (QGP) is expected, if a certain critical temperature or energy density is reached. This new state of matter, where quarks and gluons are no longer confined into hadrons, has been searched, since 1986, at the CERN SPS, exploiting heavy-ion collisions. This research program provided compelling evidence for the production of a new state of matter, by studying several "signatures". However, further work remains to be done in order to clarify some aspects of the "anomalous" behaviours which have been observed.

Among the different signatures of the formation of a deconfined state, we will concentrate, in the following, on the J/ψ suppression, as suggested, for the first time, by Matsui and Satz in 1986 [1].

The NA38 and NA50 experiments studied the J/ψ production in different colliding systems, like p-A, S-U and Pb-Pb, and as a function of the centrality of the interaction. In particular, the pattern observed in Pb-Pb collisions shows that, above a certain centrality threshold, the J/ψ yield is considerably lower than expected from the "nuclear absorption" curve derived from proton-nucleus and light-ions data. The current interpretation of this behaviour is that the hot and dense matter formed in the central Pb-Pb collisions dissolves the χ_c resonance, leading to the disappearance of the fraction ($\sim 30\,\%$) of J/ψ mesons that would otherwise originate from χ_c decays. The NA38 and NA50 results, however, are not enough to answer all the questions related to the J/ψ behaviour.

The NA60 experiment, with an innovative experimental apparatus, should clarify some of the questions left open. For example, it is important to understand which is

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[a] e-mail: arnaldi@to.infn.it

the variable driving the J/ψ suppression, in order to disentangle the different models leading to the disappearance of the charmonium state. Is it the number of participant nucleons? Or the local energy density? Or the average length of nuclear matter, L, traversed by the charmonium state? The answer to this question can be obtained by measuring the J/ψ suppression pattern in a different collision system, with respect to those studied by NA38 and NA50. This is why NA60 collected, in 2003, Indium-Indium collisions at 158 A GeV. Moreover, since a large fraction of the J/ψ yield comes from χ_c decays, it is very important to know with good precision the nuclear dependence of χ_c production, in order to understand the importance of this feed-down source. To clarify this point NA60 collected proton-nucleus data at 400 GeV, in 2004, measuring the χ_c through its radiative decay $\chi_c \rightarrow \mathrm{J}/\psi + \gamma$, with the γ being detected via its conversion to an e^+e^- pair.

2 The experimental apparatus

The NA60 detector complements the muon spectrometer inherited from the NA50 experiment with a completely new target region, constituted by a beam tracker and a vertex telescope placed in a 2.5 T dipole magnet.

The muon spectrometer consists of a hadron absorber, 8 multi-wire proportional chambers for tracking, 4 scintillator hodoscopes providing the dimuon trigger and a toroidal magnet. NA60 collected data with two different spectrometer settings, corresponding to two values of the magnet current: 4000 A and 6500 A. The events collected with the lower current have a better acceptance for the low mass dimuons. In this paper we address the 6500 A data set, which has a better mass resolution at the J/ψ mass. The analysis of the 4000 A sample is in progress.

The reconstruction of the muon tracks in the muon spectrometer is affected by the multiple scattering and energy loss fluctuations induced when the muons traverse the hadron absorber. To overcome this limitation, NA60 measures the tracks before the hadron absorber, by means of the vertex telescope. Therefore, muon trajectories measured from the muon spectrometer can be matched, in coordinate and momentum space, to tracks reconstructed in the vertex telescope, resulting in an improvement of the dimuon mass resolution. Moreover, the back-tracking of the charged particles permits the determination of the interaction vertex with very good accuracy. As a consequence, the origin of the muons can be determined, allowing us to separate prompt dimuons (Drell-Yan, thermal, J/ψ, etc) from muon pairs due to the decay of secondary particles, like D mesons. Details on the tracking, vertexing and muon track matching can be found in [2].

The new detectors introduced in the NA60 setup need to have high granularity and to be radiation-hard, because of the high luminosity (collisions rate) and of the high multiplicity of charged particles produced in Indium-Indium collisions. The NA60 vertex telescope used in the Indium run of October-November 2003 was made of 16 Silicon pixel modules, covering the muon spectrometer's angular acceptance ($3 < \eta_{\mathrm{lab}} < 4$). The trajectories of the charged particles can be reconstructed thanks to 12 tracking points. The basic unit of these planes is a single chip assembly, made of one sensor chip bump-bonded to the radiation-tolerant ALICE1LHCb readout pixel chip. The chip is composed of 32×256 cells of 425×50 μm^2 area. Some of the tracking planes have the chips oriented such that the small size measures the x coordinate, others the y coordinate. A more detailed description of the vertex telescope can be found in [3].

The beam tracker is used to measure the transverse coordinates of the incoming beam particles. It is composed of two Silicon microstrip tracking stations placed 10 and 30 cm upstream of the target centre; the sensors, developed and produced at BNL, have 24 strips of 50 μm pitch. This detector works at 130 K, to withstand the very high radiation doses reached in the NA60 beam line.

The target system is made of 7 Indium targets, 1.5 mm thick each, placed in vacuum, corresponding to a total interaction probability of $\sim 20\,\%$. Finally, the NA60 setup is complemented by a Zero Degree Calorimeter, ZDC, also inherited from the NA50 experiment. By measuring the energy released by the projectile nucleons which have not taken part in the interactions, it provides an estimate of the centrality of the collisions.

3 J/ψ results from the 2003 In-In run

In the 5 weeks long run of year 2003, we collected ~ 230 million dimuon triggers, running with beam intensities around 5×10^7 ions per 5-seconds burst. In order to extract the J/ψ yield, we need to define an event selection procedure, to select only dimuons produced in Indium-Indium interactions. This event selection is mainly based on the information extracted from the vertex telescope.

The resolution on the determination of the z coordinate of the interaction vertex is ~ 200 μm, so that we can easily distinguish the 7 Indium targets in-between the target box windows, as can be seen in Fig. 1. Therefore, it is possible to select only events having the primary vertex in one of the seven Indium targets.

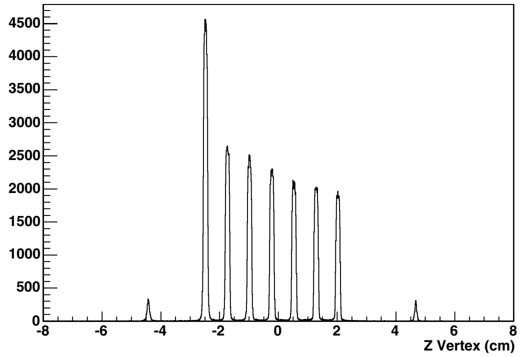

Fig. 1. z coordinate of the reconstructed vertices, showing the 7 Indium targets and the two vacuum windows of the target box. The first target has a bigger transverse dimension (12 mm diameter) than the others, to fully cover the beam profile

As already discussed, an important innovation of NA60 is the possibility of matching the muons reconstructed in the muon spectrometer with the tracks measured by the vertex telescope. Knowing with good precision the origin of the dimuon, we can select events having the vertex of the muon pair coincident with or upstream of the vertex of the primary interaction. In this way we are sure to select only dimuons produced by Indium-Indium collisions. For high mass dimuons, the z coordinate of the muon pair vertex is determined with a resolution around 800 µm. Requiring muon track matching we obtain a cleaner dimuon event sample, with an improved mass resolution and a reduced contribution from the combinatorial background due to π and K decays. Quantitatively, the width of the J/ψ peak decreases from ~ 105 to ~ 70 MeV for the matched sample and the percentage of combinatorial background in $\pm 1\sigma$ around the J/ψ peak drops from $\sim 3\,\%$ to less than $1\,\%$. The only drawback of requiring the track matching is the reduction of the available statistics, since the dimuon matching efficiency in the J/ψ mass region is $\sim 65\,\%$, regardless of centrality.

The muon track matching is not mandatory for the J/ψ study, since the J/ψ peak is clearly visible on top of the underlying continuum. The advantage of not applying the muon track matching is that we work with a sample of events with higher statistics. In this case, since we cannot profit from the determination of the dimuon vertices to reject dimuons originating downstream from the target (e.g. due to collisions in the ZDC), we use a cut on the muon $p \cdot D_{\mathrm{Targ}}$ variable, where p is the muon momentum and D_{Targ} is the transverse distance between the extrapolated muon track and the beam axis, at the target centre. In Fig. 2 we compare the invariant mass spectra with and without muon track matching.

The dimuons are studied in the phase space window $2.92 < y_{\mathrm{lab}} < 3.92$ and $-0.5 < \cos\theta_{\mathrm{CS}} < 0.5$, where y_{lab} is the rapidity in the lab frame and θ_{CS} is the polar decay angle of the muons in the Collins-Soper reference system.

From our final event sample, we can extract the J/ψ yield with respect to the Drell-Yan (DY) events. The ratio of two dimuon processes has the advantage of being insensitive to most experimental inefficiencies and to the integrated luminosity. Furthermore, the Drell-Yan process is known to scale linearly with the product of the projectile and target mass numbers, and is insensitive to the nature of the medium formed in the collisions.

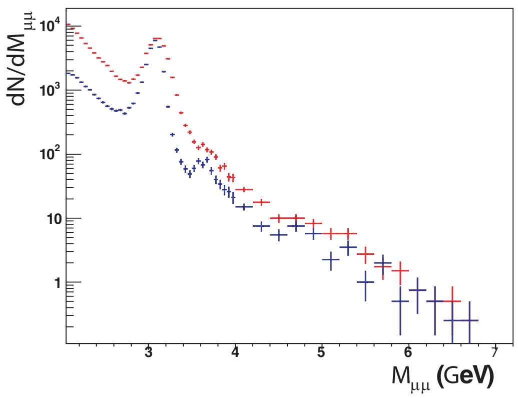

Fig. 2. Dimuon mass spectra, after event selection, before (above) and after (below) the muon track matching. The ψ' peak becomes clearly visible if the matching is required

The results given in the following refer to the J/ψ / DY ratio integrated over all collision centralities for the sample of events without muon track matching, but the same procedure can be applied to the matched sample.

The ratio between the J/ψ and Drell-Yan cross sections is extracted by fitting the opposite-sign dimuon mass distribution to a superposition of different contributions. The dimuon mass region above 2 GeV contains the J/ψ and the ψ' resonances sitting on a continuum composed of Drell-Yan dimuons and muon pairs from the simultaneous semi-muonic decay of D and $\overline{D}$ mesons, besides the combinatorial background from π and K decays, which is estimated from the measured like-sign pairs. The "signal" contributions are evaluated through a detailed Monte Carlo simulation, using Pythia as event generator, with "MRS A (Low Q^2)" [4] parton distribution functions, and GEANT for the reproduction of the detector effects. The events are then reconstructed as the real data. Besides giving invariant mass spectra, these simulations also provide the J/ψ and Drell-Yan acceptances, $A_{\mathrm{J}/\psi} \sim 12.4\,\%$ and $A_{DY(2.9\text{–}4.5)} \sim 13.4\%$.

The fit proceeds in three consecutive steps: first we determine the Drell-Yan yield from the mass region above 4.2 GeV, where it is the dominant contribution; then, keeping the Drell-Yan normalization fixed to the value obtained in the previous step, we determine the charm normalization from the mass window $2.2 < M < 2.5$ GeV. Finally, having fixed the charm and Drell-Yan contributions, we extract the J/ψ and ψ' yields with a fit to the mass region $2.9 < M < 4.2$ GeV. In this step of the fit, also the exact position and width of the J/ψ peak are left as free parameters. From the sample of events collected with 6500 A we obtain ~ 250 Drell-Yan events with $M > 4.2$ GeV (which correspond to ~ 2000 events estimated in the mass region 2.9–4.5 GeV) and $\sim 35\,000$ J/ψ counts. Finally, after applying the acceptance corrections, we obtain the cross-section ratio $B_{\mu\mu}\sigma(\mathrm{J}/\psi)/\sigma(DY)$. The Drell-Yan cross-section is integrated in the region $2.9 < M < 4.5$ GeV, so that our value can be directly compared with the results previously obtained by the NA38 and NA50 experiments. The $B_{\mu\mu}\sigma(\mathrm{J}/\psi)/\sigma(DY)$ ratio extracted from the fit to the invariant mass spectrum without muon track matching, shown in Fig. 3, is 19.2 ± 1.2.

The stability of the result has been checked changing several steps of the data analysis procedure. The result is almost insensitive to reasonable changes in the background normalization or to different event selection criteria or fitting procedures. The study of the systematic uncertainties is in progress. Furthermore, the analysis of the dimuon mass spectrum obtained from the matched data sample (Fig. 4) gives a J/ψ / DY value perfectly compatible with the one without matching.

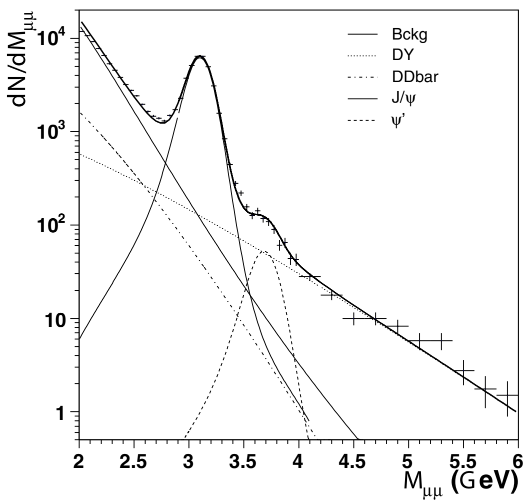

Fig. 3. Fit to the dimuon mass spectrum obtained before muon track matching, for the 6500 A event sample

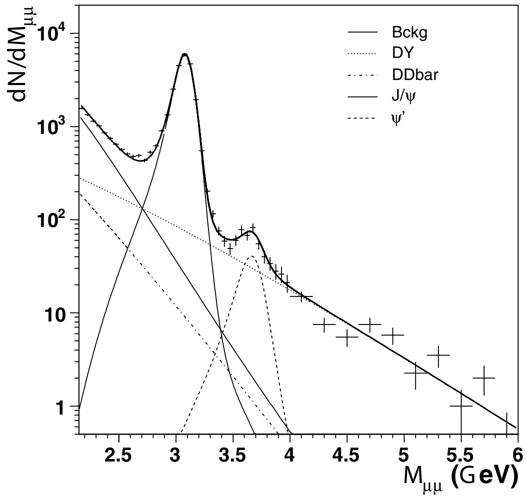

Fig. 4. Fit to the dimuon mass spectrum obtained after muon track matching, for the 6500 A event sample

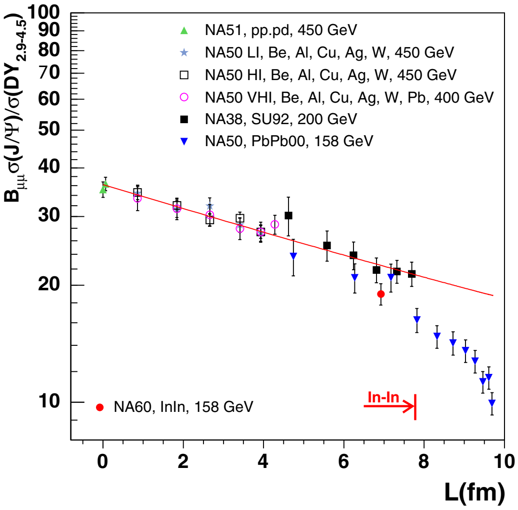

Fig. 5. J/ψ suppression pattern as a function of L, including the Indium-Indium value. The arrow indicates the maximum L reachable in Indium-Indium collisions

The result we get in Indium-Indium collisions can be compared with the previous J/ψ / DY ratios obtained in p-nucleus, S-U and Pb-Pb collisions [5]. The comparison can be done as a function of L, the average length of nuclear matter traversed by the charmonium state, and N_{part}, the number of participant nucleons.

The average centrality values we have calculated in order to present our Indium-Indium result have been obtained from a geometrical (Glauber) model, by integrating over all the collision centralities, and convoluting the geometrical probability for the occurrence of that centrality with the corresponding number of binary nucleon–nucleon collisions. This procedure gives the weighted average value of L and N_{part} pertinent to the study of a hard process like Drell-Yan production in integrated Indium-Indium collisions. However, we should keep in mind that, unlike what happens to Drell-Yan dimuons, the production of J/ψ mesons is suppressed as a function of centrality in heavy-ion collisions. Therefore, a correct evaluation of the L and N_{part} average values appropriate to the measured J/ψ / DY ratio would require knowing the specific J/ψ suppression pattern as a function of centrality in Indium collisions. This problem affects only marginally a measurement performed in a narrow centrality bin, since the variation of the L or N_{part} distributions inside such a bin is very small. Therefore, our integrated result cannot be quantitatively compared with the S–U and Pb–Pb patterns, since it corresponds to a wide range of centrality while the previously published points are obtained in much narrower centrality bins.

In Fig. 5 the Indium-Indium measurement is plotted, together with the previously established suppression pattern, as a function of L. The continuous line represents the normal nuclear absorption curve, derived from the p-A data. Figure 6 shows the Indium-Indium value with respect to the expected value of the normal nuclear absorption, as a function of the number of participant nucleons involved in the collision. The result is 0.84 ± 0.05.

Work is in progress to determine the J/ψ / DY pattern as a function of the centrality of the collision. The comparison of the J/ψ behaviour as a function of the centrality and in different colliding systems should allow us to understand which is the variable and, therefore, the physics mechanism, driving the disappearance of the J/ψ. For example, the normal nuclear absorption is governed by the L variable, while if the J/ψ is suppressed because of a geometrical phase transition, as the one foreseen by the percolation model [6], the scaling variable should be related to the density of N_{part}, i.e. the ratio between N_{part} and the transverse area of the overlap collision region. Alternatively, a thermal (QGP) phase transition should lead to a J/ψ suppression driven by the local energy density [7]. As can be seen in Fig. 7 the correlations between centrality variables depend on the colliding system: for instance,

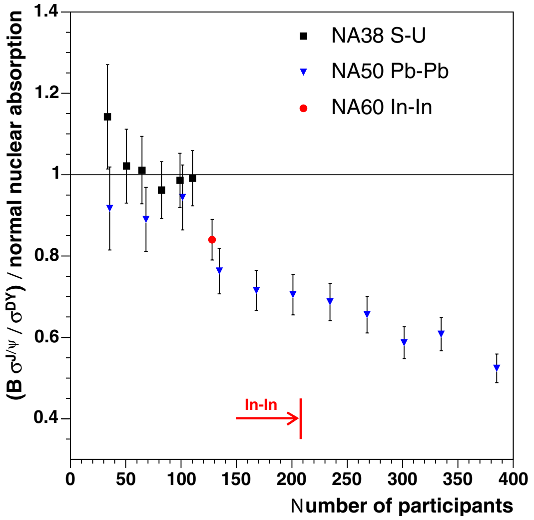

Fig. 6. J/ψ suppression pattern as a function of N_{part}. The arrow has the same meaning as in Fig. 5

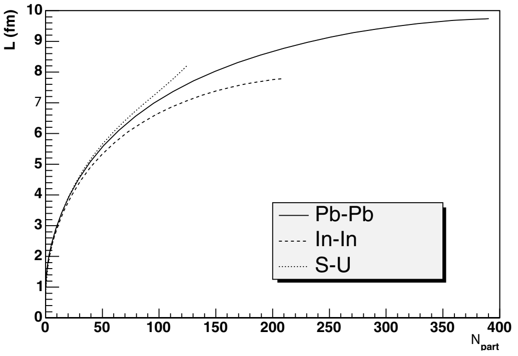

Fig. 7. Correlations between L and N_{part} in different colliding systems: Pb-Pb, In-In and S-U

central S-U and central In-In events correspond to the same L value, while they cover a different range in N_{part}. Hence, if the physics mechanism causing the J/ψ disappearance is the normal nuclear absorption, the two data sets should show a similar behaviour if plotted as a function of the L variable, and a different trend if plotted as a function of the density of participant nucleons.

Apart from the J/ψ / DY behaviour integrated over all the collision centralities, also other preliminary information on the J/ψ kinematical variables, such as the transverse momentum and the polarization angle, can be extracted from the Indium data. Such a study needs a precise knowledge of the acceptance of the experimental apparatus as a function of the kinematical values of the produced dimuon. Since the kinematical parameters are correlated, the acceptance in one variable may depend on the other variables. Therefore, a three-dimensional method for the acceptance calculation has been developed. Monte Carlo events are generated according to flat distributions in p_{T}, $\cos\theta$ and y_{lab}, and then tracked through the experimental apparatus and reconstructed with the same procedure as used for the real data. Fine grained acceptance matrices are obtained from the ratio between the reconstructed and generated events. This method has been checked by injecting realistic distributions of the kinematical variables as inputs for the Monte Carlo. The comparison between the generated and the reconstructed Monte Carlo samples, after the acceptance correction, allows us to determine the phase space window where the method can be applied: $p_{\text{T}} < 5$ GeV/c, $3.2 < y_{\text{lab}} < 3.8$, $|\cos\theta_{\text{CS}}| < 0.4$, and $|\cos\theta_{\text{H}}| < 0.7$, where θ_{H} is the polarization angle, to be discussed further down.

From the Indium data, with the 6500 A magnet current and without muon track matching, a preliminary behaviour of the J/ψ transverse momentum has been extracted as a function of the centrality of the collisions, always estimated from the energy released in the ZDC. In Fig. 8 the $\langle p_{\text{T}} \rangle$ and $\langle p_{\text{T}}^2 \rangle$ behaviours are shown as a function of L. The plotted errors are only statistical. The observed increase of $\langle p_{\text{T}}^2 \rangle$ as a function of L follows the previous resultss, interpreted by NA50 in terms of initial-state parton multiple scattering [8].

Finally, also preliminary results concerning the J/ψ polarization have been obtained. The polarization of the J/ψ is strongly related to the quarkonium production mechanism. Different models predict different polarizations. For example, NRQCD predicts a strong transverse polarization at large transverse momentum [9], which is not confirmed by the results obtained up to now [10]. An accurate study of this kinematical variable should help improving our knowledge of charmonium production. Moreover, a visible increase in the J/ψ polarization would signal QGP formation [11]: since the QGP screens away non-perturbative effects, the J/ψ escaping from the plasma

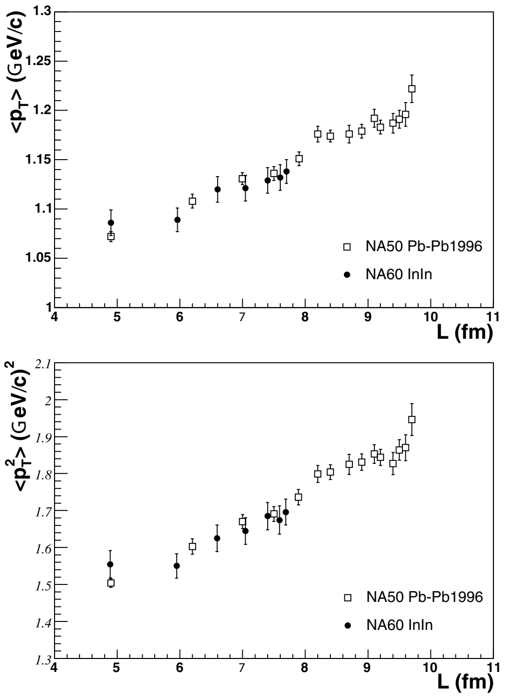

Fig. 8. The J/ψ $\langle p_{\text{T}} \rangle$ (top) and $\langle p_{\text{T}}^2 \rangle$ (bottom) measured in the Indium data, as a function of L, compared with the 1996 Pb-Pb data published by NA50 [8]

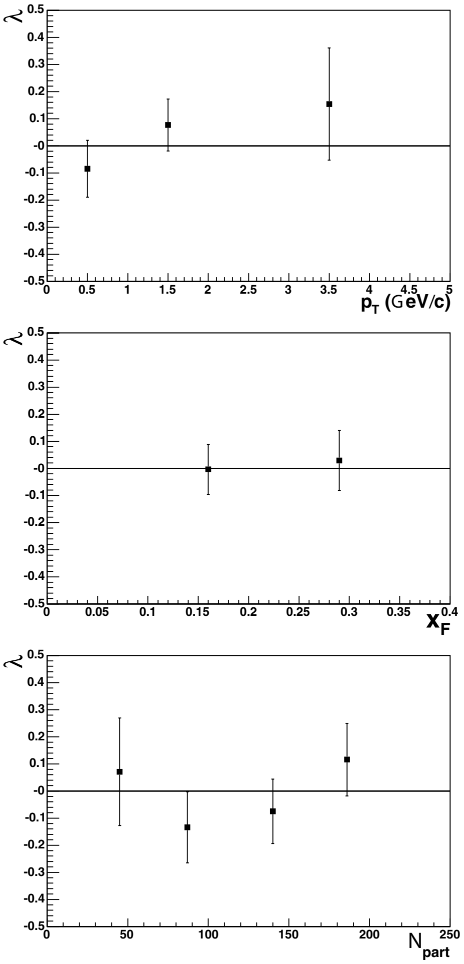

Fig. 9. The polarization parameter λ as a function of the J/ψ's transverse momentum (top), of x_{F} (middle), and of the number of participants (bottom)

should be polarised, as predicted by perturbative QCD. Experimentally, the polarization of the J/ψ is measured from the distribution of the emission angle θ_H of the μ^+ from the J/ψ decay in the J/ψ rest frame, with respect to the direction of the J/ψ in the centre of mass frame. This angular distribution can be fitted according to the formula

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_{\mathrm{H}}} \sim 1 + \lambda \cos^2\theta_{\mathrm{H}} \quad . \tag{1}$$

If $\lambda < 0$ the J/ψ is longitudinally polarized, if $\lambda = 0$ it is unpolarized, and if $\lambda > 0$ it is transversely polarized. The values of the λ parameter extracted from the Indium data are shown in Fig. 9 as a function of the transverse momentum, of x_{F} and of the number of participants.

According to [11], in case of QGP formation the expected λ value should be $\sim$0.6, decreasing to 0.35–0.4 if the initial transverse momentum of gluons is taken into account. The value is estimated taking into account both J/ψ direct production and χ_c feed down. Although with rather large error bars, our preliminary results seem to exclude a strong transverse polarization in Indium-Indium collisions.

4 Conclusions

We have shown first results on the J/ψ analysis from the Indium-Indium data collected in the year 2003. The ratio between the J/ψ and Drell-Yan production cross-sections, J/ψ / DY, integrated over all the collision centralities, has been presented and compared with previous results obtained in p-A, S-U and Pb-Pb collisions. Further analysis, including the centrality dependence of the J/ψ suppression, is under way. First results on the J/ψ transverse momentum and polarization have also been shown.

The analysis of the proton-nucleus data collected in 2004 will complement the Indium results, providing an accurate reference baseline to understand the heavy-ion observations.

Acknowledgements. Our Beam Tracker would not exist without the help of Zheng Li, who developed and produced the silicon sensors at BNL, and of Kurt Borer, who built the readout electronics chain at LHEP, Bern. The ALICE pixel team helped in the development of our silicon pixel telescope. Many other people contributed to the feasibility of our experiment, including L. Casagrande, B. Cheynis, E. David, J. Fargeix, W. Flegel, L. Gatignon, V. Granata, J.Y. Grossiord, F. Hahn, S. Haider, L. Kottelat, D. Marras, I. McGill, T. Niinikoski, R. Oliveira, A. Onnela, V. Palmieri, J.M. Rieubland, J. Rochez, M. Sanchez, and H. Vardanyan. We would also like to acknowledge the good quality of the Indium beam provided to the experiment by the teams running the PS and SPS accelerators, including the ion source.

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