J/Ψ SUPPRESSION

Nora De Marco[11] for the NA50 Collaboration

M.C. Abreu[6,a], B. Alessandro[11], C. Alexa[3], R. Arnaldi[11], J. Astruc[8], M. Atayan[13], C. Baglin[1], A. Baldit[2], M. Bedjidian[12], F. Bellaiche[12], S. Beolè[11], V. Boldea[3], P. Bordalo[6,b], A. Bussière[1], V. Capony[1], L. Casagrande[6], J. Castor[2], T. Chambon[2], B. Chaurand[9], I. Chevrot[2], B. Cheynis[12], E. Chiavassa[11], C. Cicalò[4], M. P. Comets[8], S. Constantinescu[3], J. Cruz[6], A. De Falco[4], N. De Marco[11], G. Dellacasa[11,c], A. Devaux[2], S. Dita[3], O. Drapier[12], B. Espagnon[2], J. Fargeix[2], S. N. Filippov[7], F. Fleuret[9], P. Force[2], M. Gallio[11], Y. K. Gavrilov[7], C. Gerschel[8], P. Giubellino[11], M.B. Golubeva[7], M. Gonin[9], A.A. Grigorian[13], J.Y. Grossiord[12], F.F. Guber[7], A. Guichard[12], H. Gulkanyan[13], R. Hakobyan[13], R. Haroutunian[12], M. Idzik[11,d], D. Jouan[8], T. L. Karavitcheva[7], L. Kluberg[9], A. B. Kurepin[7], Y. Le Bornec[8] , C. Lourenço[5], M. Mac Cormick[8], P. Macciotta[4], A. Marzari-Chiesa[11], M. Masera[11], A. Masoni[4] , S. Mehrabyan[13], S. Mourgues[2], A. Musso[11], F. Ohlsson-Malek[12,e], P. Petiau[9], A. Piccotti[11], J. R. Pizzi[12], W. L. Prado da Silva[11,f], G. Puddu[4], C. Quintans[6], C. Racca[10], L. Ramello[11,c], S. Ramos[6,b], P. Rato-Mendes[11], L. Riccati[11], A. Romana[9], S. Sartori[11], P. Saturnini[2], E. Scomparin[5,g], S. Serci[4], R. Shahoyan[6,h], S. Silva[6], C. Soave[11], P. Sonderegger[5,b], X. Tarrago[8], P. Temnikov[4], N. S. Topilskaya[7], G. L. Usai[4], C. Vale[6], E. Vercellin[11], N. Willis[8].

[1] LAPP, CNRS-IN2P3, Annecy-le-Vieux, France; [2] LPC, Univ. Blaise Pascal and CNRS-IN2P3, Aubière, France; [3] IFA, Bucharest, Romania; [4] Università di Cagliari and INFN, Cagliari, Italy; [5] CERN, Geneva, Switzerland; [6] LIP, Lisbon, Portugal; [7] INR, Moscow, Russia; [8] IPN, Univ. de Paris-Sud and CNRS-IN2P3, Orsay, France; [9] LPNHE, Ecole Polytechnique and CNRS-IN2P3, Palaiseau, France; [10] IReS, Univ. Louis Pasteur and CNRS-IN2P3, Strasbourg, France; [11] Università di Torino and INFN, Torino, Italy; [12] IPN, Univ. Claude Bernard and CNRS-IN2P3, Villeurbanne, France; [13] YerPhI, Yerevan, Armenia.

a) also at FCUL, Universidade de Lisboa, Lisbon, Portugal; b) also at IST, Universidade Técnica de Lisboa, Lisbon, Portugal; c) Dipartimento di Scienze e Tecnologie Avanzate, II Facoltà di Scienze, Alessandria, Italy; d) now at Faculty of Physics and Nuclear Techniques, University of Mining and Metallurgy, Cracow, Poland; e) now at ISN, Univ. Joseph Fourier and CNRS-IN2P3, Grenoble, France; f) now at UERJ, Rio de Janeiro, Brazil; g) on leave of absence from Università di Torino and INFN, Torino, Italy; h) on leave of absence of YerPhI, Yerevan, Armenia.

The NA50 collaboration has studied the J/Ψ, Ψ' and Drell–Yan production via their dimuon decay in Pb–Pb interactions at 158 GeV per nucleon at the CERN SPS. Final results from the 1995 run and preliminary ones from the high-statistics 1996 run are presented. An anomalous J/Ψ suppression (relative to Drell-Yan) is observed in Pb–Pb collisions as compared to the extrapolations of the previous results obtained with proton and lighter ion beams. The 1996 data allow the study of the onset of the anomalous J/Ψ suppression within the Pb-Pb sample itself,

© Institute of Experimental Physics, SAS, Košice, Slovakia

showing a discontinuity around an E_T value of 45 GeV, whereas no difference has been observed in the Ψ' suppression pattern in S-U and Pb-Pb collisions.

1 Introduction

The NA50 experiment studies the production of vector meson resonances via their $\mu^+\mu^-$ decay in high energy heavy–ion interactions as a function of the collision centrality at the CERN SPS. The aim is the study of nuclear matter under extreme conditions of energy density in order to get evidence for the formation of a new state of matter, the Quark–Gluon Plasma (QGP), that statistical QCD calculations predict at sufficient high energy density. Signals originating from hard-scattering processes at the very early state of the interaction, as charmonium and Drell-Yan production, are an ideal tool to probe the state of the surrounding QCD matter. In particular the dissociation of the J/Ψ and Ψ' resonances, which might result from Debye screening in a medium of deconfined quarks and gluons[1], is one of the most promising signatures of the Quark–Gluon Plasma. The NA50 experiment follows the exploratory program started in 1986 by the NA38 collaboration[2, 3, 4] which studied J/Ψ, Ψ' and Drell–Yan production in collisions between protons, oxygen and sulphur on various heavy targets. This paper summarizes briefly the 1995 charmonium results, recently published[5, 6], and reports the preliminary results obtained from the data collected in 1996 on J/Ψ, Ψ' and Drell–Yan production in Pb–Pb interactions at 158 GeV per nucleon.

2 Apparatus and data taking conditions

The NA50 detector, which is an upgraded version of the previous NA38 apparatus, is composed of a dimuon spectrometer complemented by 3 independent detectors giving the centrality of the collision, namely an electromagnetic calorimeter, a zero-degree hadronic calorimeter and a silicon microstrip multiplicity detector. The $\mu^+\mu^-$ pair is detected by the magnetic spectrometer, which consists of a hadron absorber, an air core toroidal magnet, 8 MWPCs and 6 hodoscopes for trigger purposes. A segmented active target, made of 7 Pb subtargets, with vertex identification has been used in order to improve the dimuon invariant mass resolution and to reject reinteractions of spectator fragments; the incident Pb-ions are counted by a quartz beam hodoscope, which is also used to reject beam pile–up. To reduce the combinatorial background from the decays of π and K mesons while keeping a good resolution on the invariant mass of the dimuon the last target is located very close (15 cm) to the absorber, which is made of a 60 cm section of BeO, followed by 400 cm of carbon and finally 80 cm of iron. An iron wall located at the end of the spectrometer, before the last trigger hodoscope, ensures that the triggering particles are muons. Muons are detected with good acceptance in the pseudo–rapidity interval $2.8 \leq \eta \leq 4.0$.

The event centrality is estimated on an event by event basis by means of three independent detectors, covering different pseudo–rapidity intervals: the Pb-scintillating

fibers electromagnetic calorimeter ($1.1 \leq \eta \leq 2.3$), measuring the neutral transverse energy produced in the interaction; the tantalum-quartz fibers zero–degree calorimeter ($\eta \geq 6.3$), measuring the energy of beam spectator fragments, and the silicon strip detector ($1.6 \leq \eta \leq 4$), measuring the charged particle multiplicity.

Due to the small production cross sections (3 nb/nucleon^2 for J/Ψ) and the small branching ratios in the $\mu^+\mu^-$ channel ($6\ 10^{-2}$ for J/Ψ, $7.7\ 10^{-3}$ for Ψ')) high intensity beam and a thick target are needed in order to achieve enough statistic in several bins of centrality. In 1995 the average beam intensity was $3{\times}10^7$ Pb ions per burst, while in 1996 the intensity has been increased to $5{\times}10^7$ Pb ions per burst. In 1995 the 7 subtargets were 1 mm thick, leading to a total of 17.5% of an interaction length for Pb, while in 1996 5 of them were replaced by 2 mm thick ones, bringing the total thickness to 30% of an interaction length. In 1995 a total amount of $60{\times}10^6$ dimuon triggers were collected, giving a final sample of about 50000 J/Ψ at the end of the analysis; in 1996 $170{\times}10^6$ triggers were written on tape, leading to 200000 J/Ψ events after selection criteria thanks also to a better beam quality, which reduced significantly the out–of–target background.

3 Analysis method

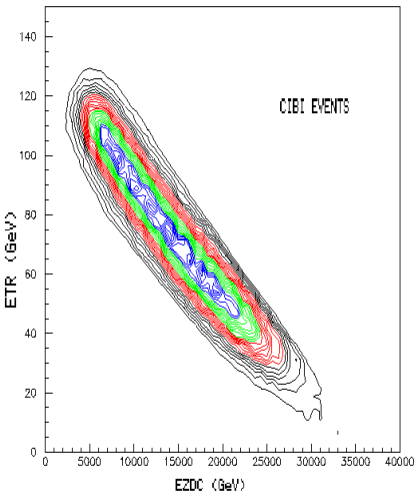

Fig. 1: E_T - E_{ZDC} correlation for J/Ψ events using the standard target identification.

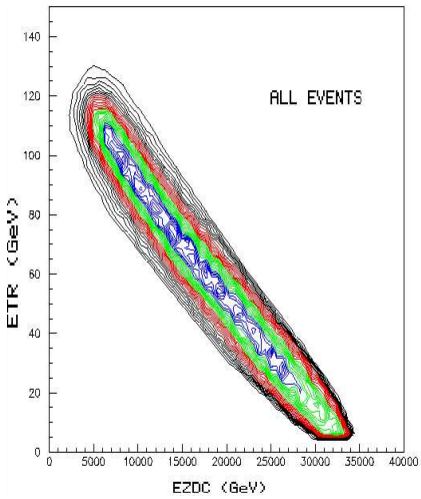

Fig. 2: E_T - E_{ZDC} correlation for J/Ψ events using the countour–cut identification.

The off–line reconstruction program requires that only one incident ion is detected by the beam hodoscope, with no interaction in the beam hodoscope itself; no signal has to be present in the halo counters surrounding the target. In addition it is required that two and only two muon tracks are in the acceptance of the spectrometer and that

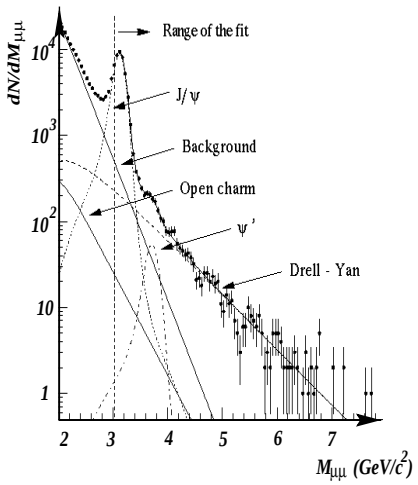

Fig. 3: $\mu^+\mu^-$ invariant mass spectrum.

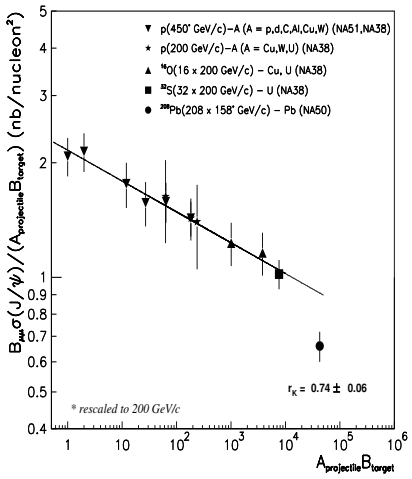

Fig. 4: J/Ψ cross–section per nucleon–nucleon collision versus $A \cdot B$.

they would both be accepted in a reversed magnetic field, in order to have the same acceptance for any charge state of the muon pair. In 1995 the standard target algorithm has been used, which provides a precise vertex identification[5, 6](fig. 1); in 1996, thanks to better beam conditions, a new method has been devoloped based on a countour–cut on the E_T-E_{ZDC} correlation at a 2σ level (fig. 2). This method allows to recover most of the lost peripheral collisions: for these events no precise target assignment can be done, therefore both the transverse energy and the mass distribution suffer from a slightly worse resolution. In order to reject events produced out of the target, a severe cut on the distance between each muon track and the beam axis is applied on the 1996 data.

The dimuon kinematical domain used in the analysis is restricted to $0 \leq y_{cm} \leq 1$ (y_{cm} = center of mass dimuon rapidity) and to $-0.5 \leq cos(\theta_{CS}) \leq 0.5$ (θ_{CS} = muon polar angle in the Collins–Soper frame), where the acceptance of the spectrometer is at least 10% of its maximum. The acceptances of the spectrometer for the 1995 and 1996 sets of kinematical cuts are respectively 13.5% and 7.5% for J/Ψ, 16.1% and 8.9% for Ψ' and 15.1% and 8.4% for Drell–Yan events (with $2.9 \leq M_{\mu\mu} \leq 4.5\ GeV/c^2$). The J/Ψ mass resolution is 96 MeV (3.1%) and increases to 104 MeV (3.3%) for the most peripheral events recovered by the countour–cut on the E_T-E_{ZDC} correlation.

Figure 3 shows the invariant mass spectrum of the opposite sign muon pairs, not corrected for acceptance, for the 1995 data sample. The main contribution to this sample is due to the combinatorial background originating from uncorrelated π and K decays, determined with a standard procedure using the two like–sign samples of muon pairs:

$$\frac{dN^{+-}_{Bg}}{dM} = 2R \cdot \sqrt{\left(\frac{dN^{++}}{dM} \cdot \frac{dN^{--}}{dM}\right)_{field+} + \left(\frac{dN^{++}}{dM} \cdot \frac{dN^{--}}{dM}\right)_{field-}} \quad (1)$$

where R=1 for ion induced reactions. The signal to background ratio is larger than 10 at the J/Ψ peak. The open charm contribution, originating from semi-leptonic decay of charmed mesons pairs ($D\bar{D}$), is previously fitted in the intermediate mass region ($1.9 \leq M_{\mu\mu} \leq 2.9\ GeV/c^2$) using a shape distribution generated by PYTHIA [7] and including a charm-like excess[8, 9]. The mass spectrum is finally fitted as the superposition of five contributions: J/Ψ, Ψ', Drell–Yan,open charm semileptonic decays and background (the last two contributions are constrained by previous fits):

$$\frac{dN^{+-}}{dM} = A_{J/\psi}\frac{dN^{J/\psi}}{dM} + A_{\Psi'}\frac{dN^{\Psi'}}{dM} + A_{DY}\frac{dN^{DY}}{dM} + \frac{dN^{D\bar{D}}}{dM} + \frac{dN^{Bg}}{dM} \quad (2)$$

The line shapes are determined via a MonteCarlo program followed by the standard reconstruction program. The final fit is performed above 3.05 GeV/c^2 with five free parameters: $A_{J/\psi}$, $A_{\Psi'}$, A_{DY}, and the mass and width of the gaussian line shape of the J/ψ; mass and width of the Ψ' are linked to those of the J/ψ.

4 Experimental results

4.1 J/ψ cross-section

The final 1995 results on J/ψ, recently published[5, 6], are only briefly summarized here.

The Pb–Pb cross–section measured at 158 GeV/c is $B_{\mu\mu} \cdot \sigma_{J/\Psi} = 21.9 \pm 0.3 \pm 1.6\ \mu b$. In figure 4 the J/$\psi$ cross–section per nucleon–nucleon collision is plotted versus $A_{projectile} \times B_{target}$ for several systems. In order to be compared, all results are rescaled to 200 GeV/c using the Schuler parametrisation[10] and recomputed if necessary in the same kinematical domain.

The nuclear dependence of the production cross–section for hard processes in $A_{projectile}$ on B_{target} collisions can be parametrized as

$$\sigma^{AB} = \sigma^{NN}\dot{(}AB)^{\alpha} \quad (3)$$

where A and B are the projectile and the target atomic mass numbers. This expression describes very well all J/ψ production data from proton–nucleus and nucleus–nucleus collisions up to sulfur–uranium collisions, with $\alpha = 0.92 \pm 0.01$, as shown in figure 4. This nuclear effect, actually understood in terms of absorption in the nuclear medium, is usually called "J/ψ suppression". The measured Pb–Pb cross–section is a factor 0.74 ± 0.04 smaller than the value one would extrapolate from the previous results suggesting the onset of an additional suppression, which is normally referred to as "anomalous J/ψ suppression".

4.2 Drell-Yan cross-section

To investigate further charmonium production we will use the Drell-Yan cross–section as a measurement of the number of nucleon–nucleon collisions. In fact Drell-Yan is understood as a hard process and is not affected by the surrounding nuclear matter in a nucleus–nucleus collision.

In Pb-Pb interactions the measured Drell-Yan cross section ($2.9 \leq M_{\mu\mu} \leq 8.0\, GeV/c^2$) at 158 GeV/c^2 is $\sigma_{Drell-Yan} = 1.49 \pm 0.03 \pm 0.11\ \mu b$. In order to compare this value with previous results obtained in p–A and S–U collisions (NA38 and NA51 experiments) the so–called "K factor" is used, which is the ratio between the measured value of the cross section and the lowest order Drell–Yan cross section computed at the appropriate center of mass energy and in the same kinematical domain, using the MRS–43[11, 12] set of parton distribution functions. The results, plotted in figure 5 as a function of the product of the target and projectile atomic mass numbers, show that the Pb–Pb data is in good agreement with the other measurements and lead to the average value $K = 1.78 \pm 0.09$.

In order to fit the p-A, S-U and Pb-Pb data with the power law of eq. 3 the measured Drell–Yan cross sections have been corrected for isospin effects, referring all data to p-p collisions:

$$\sigma_{DY}^{AB}(corrected) = \sigma_{DY}^{AB}(measured) \times \frac{AB\sigma_{DY}^{pp}(theory)}{\sigma_{DY}^{AB}(theory)} \tag{4}$$

where $\sigma(theory)$ is a theoretical cross–section for the Drell-Yan process computed at the leading order using the MRS–43 set of parton distributions[11, 12]. A fit to the corrected data gives an α value consistent with unity ($\alpha = 1.002 \pm 0.011$), indicating that no nuclear absorption is taking place.

4.3 J/ψ over Drell-Yan ratio

Since the Drell-Yan cross–section scales exactly with $A \times B$ from pp up to PbPb collisions, this process can be used as a reference. In this way the J/Ψ over Drell-Yan ratios are free from all systematic errors and the behaviour of the J/Ψ production cross section can be further investigated as a function of the centrality of the collision. Figure 6 shows for Pb-Pb interactions the measured J/Ψ to Drell–Yan ratio as a function of E_T for both the 1995 and 1996 data sample in 5 bins and 15 bins respectively, the last one extending to more peripheral collisions. Quoted errors are statistical only. All values are given at the actual beam momentum of 158 GeV/c and there is no isospin correction to the Drell-Yan cross–section. The two data sets are fully in agreement and exhibit a clear discontinuity at $E_T \simeq 45 GeV$ (where the E_T resolution is about 5 GeV) corresponding to an impact parameter $b \simeq 8\ fm$. It must be noted that this effect can now be observed within the PbPb data sample itself, without the need of beam energy and isospin corrections necessary for the comparison of different data sets.

In order to compare different systems, characterized by different kinematical domains and in some cases also different experimental E_T range, the variable L has been introduced in the past[13]. L is defined as the geometrical mean path length of the

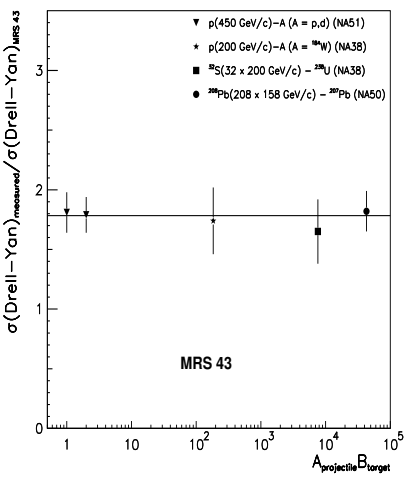

Fig. 5: The Drell–Yan cross–section versus $A \cdot B$.

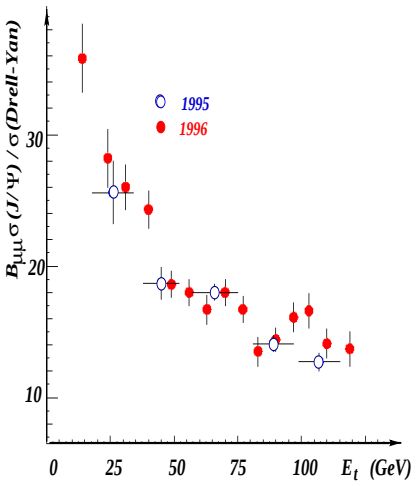

Fig. 6: The $B_{\mu\mu}\sigma_{J/\Psi}/\sigma_{Drell-Yan}$ ratio versus E_T.

produced $c\bar{c}$ state through nuclear matter and is computed via a Monte-Carlo program which, for a given impact parameter b, performs a weighted average over the possible production points using a standard Woods-Saxon nuclear density function ρ:

$$\bar{L}(b) = \frac{1}{\rho_0} < \rho L > \tag{5}$$

The average L for each E_T bin is computed using the relation between E_T and b, in a way that is essentially independent on the precise knowledge of the absolute E_T scale[5, 6]. The ratio of J/Ψ to Drell–Yan cross sections in Pb–Pb interactions is plotted in figure 7 as a function of $\bar{L}$ in each of the 15 E_T bins (1996 data) and compared with previous results from NA38 and NA51 experiments. All 450 and 200 GeV/c data presented in this figure are rescaled to 158 GeV/c using the Schuler parametrisation[10] and the measured Drell–Yan cross sections have been corrected for isospin effects according to eq. 4. A good fit to the p-A and S-U data is obtained with the absorption model

$$\frac{B_{\mu\mu}\sigma_{J/\Psi}}{\sigma_{DY}} = e^{-\rho_o \bar{L} \sigma_{abs}} \tag{6}$$

with $\sigma_{abs} = 5.8 \pm 0.6 mb$ (ρ_0=.17 fm^{-3}). It must be noted that the peripheral Pb-Pb points are essentially compatible with the S-U ones, while the exponential behaviour breaks down for the central Pb–Pb data (at $L \simeq 8\ fm$), showing a strong dependence of this effect with the centrality of the collision. The more central points lie almost 10 σ below the absorption line.

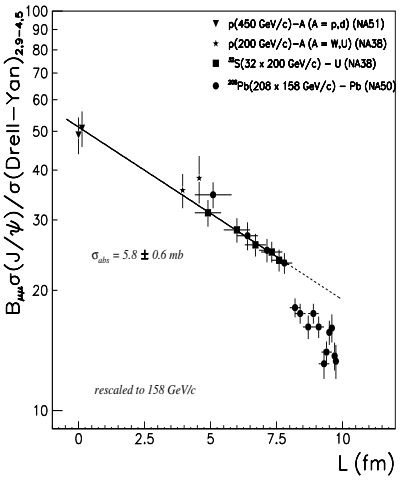

Fig. 7: The $B_{\mu\mu}\sigma_{J/\Psi}/\sigma_{Drell-Yan}$ ratio versus L.

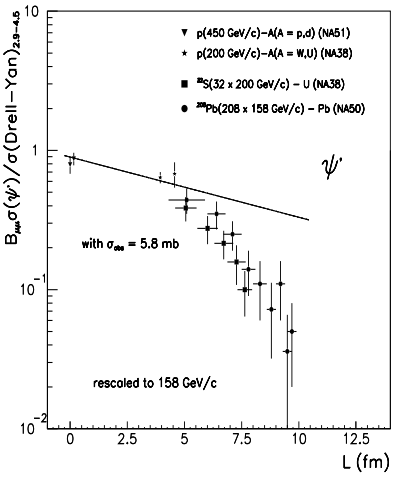

Fig. 8: The $B_{\mu\mu}\sigma_{\Psi'}/\sigma_{Drell-Yan}$ ratio versus L.

4.4 Ψ' over Drell-Yan ratio

Finally Ψ' production has been studied as it can provide complementary informations on the mechanisms at work for charmonium suppression, since Ψ' has a lower binding energy (60 MeV) with respect to the J/Ψ (600 MeV). In fig. 8 the measured Ψ' over Drell-Yan ratios are plotted as a function of L for p–A, S–U and Pb–Pb collisions. While the p–A data are compatible with the absorption cross-section $\sigma_{abs} = 5.8mb$ obtained in the J/Ψ case, both S–U and Pb–Pb ratios depart from the J/Ψ absorption law. In particular they show a very similar suppression pattern with respect to Drell-Yan, which starts at lower L values with respect to J/Ψ. This suggests that for Ψ' suppression a common mechanism could be at work in S–U and Pb–Pb collisions.

5 Conclusions

J/Ψ suppression data have originated a lot of theoretical works, that have been recently summarized in ref.[14]. It seems now established that all J/Ψ and Ψ' production data up to peripheral Pb–Pb interactions can be described in a conventional hadronic scenario. In fact J/Ψ and Ψ' suppression in p–nucleus is actually understood as the absorption of a pre–resonant $c\bar{c}g$ state[15], which would become later the J/Ψ or the Ψ' resonance. The similar absorption cross–section observed in p–A interactions for J/Ψ and Ψ' seems to confirm that the absorption occurs before the formation of the physical J/Ψ and Ψ' resonances. Furthermore the additional Ψ' suppression observed in S–U and Pb–Pb (fig. 8) can be described in the frame of a co–mover absorption model[16]; in fact because of its low binding energy the Ψ' can be readily dissociated by hadron

co–movers. Much more intriguing is the "anomalous" J/Ψ suppression observed in central Pb–Pb interactions, where an energy density of about 3.5 GeV/fm^3 can be achieved. Different interpretations have been proposed in the literature in the frame of a conventional[17, 18, 19, 20] or deconfined scenario[16, 21, 22, 23]. It is evident that the observed discontinuity in the J/ψ over Drell-Yan ratio at $L \simeq 8\ fm$ suggests the onset of an additional suppression mechanism and can be more easily reproduced by a model predicting a threshold effect, as in case of quark-gluon plasma formation.

References

[1] T.Matsui and H Satz, *Phys. Lett.* B **178**, 1986 (416).

[2] C. Baglin et al., *Phys. Lett.* B **220**, 1989 (471).

[3] C. Baglin et al., *Phys. Lett.* B **255**, 1991 (459).

[4] C. Baglin et al., *Phys. Lett.* B **270**, 1991 (105).

[5] M.C.Abreu et al., *Phys. Lett.* B **410**, 1997 (327).

[6] M.C.Abreu et al., *Phys. Lett.* B **410**, 1997 (337).

[7] T.Sjostrand, *Comp. Phys. Comm.* **82**, 1994 (74).

[8] E. Scomparin et al., *Nucl. Phys.* A **610**, 1996 (331c).

[9] E. Scomparin et al., presented at the *Strangeness in Quark Matter 98* Conference, Padova, July 20-24, 1998, submitted to *Jour. of Phys.* G.

[10] G.A. Schuler, CERN–TH 7170/94 (hep–ph/9403387), 1994.

[11] A.D. Martin et al., *Phys. Lett.* B **306**, 1993 (145).

[12] A.D. Martin et al., *Phys. Lett.* B **410**, 1997 (337).

[13] C. Gerschel and J. Hufner, *Z. Phys.* C **56**, 1992 (71).

[14] D.Kharzeev et al., *Nucl. Phys.* A **638**, 1998 (1-2).

[15] For example, D.Kharzeev and H. Satz, *Phys. Lett.* B **366**, 1996 (316).

[16] D.Kharzeev et al., *Z. Phys.* C **74**, 1997 (307).

[17] S. Gavin et al., *Phys. Rev. Lett.* **78**, 1997 (1006).

[18] N. Armesto and A. Capella, *Phys. Lett.* B **430**, 1998 (23).

[19] N. Armesto and A. Capella, hep–ph/9807258, preprint.

[20] W. Cassing et al., *Nucl. Phys.* A **623**, 1997 (570).

[21] J.-P. Blaizot and J.-Y. Ollitrault, *Phys. Rev. Lett.* **77**, 1996 (1703).

[22] C.Y. Wong, *Nucl. Phys.* A **610**, 1996 (434c).

[23] N. Armesto et al., *Phys. Rev. Lett.* **77**, 1996 (3736).