Results from the NA50 experiment on J/Ψ suppression in Pb-Pb collisions at the CERN SPS

M. Monteno[10] on behalf of the NA50 Collaboration,

M.C. Abreu[6,a], B. Alessandro[10], C. Alexa[3], R. Arnaldi[10], M. Atayan[12], C. Baglin[1], A. Baldit[2], M. Bedjidian[11], S. Beolè[10], V. Boldea[3], P. Bordalo[6,b], A. Bussière[1], L. Capelli[11], L. Casagrande[6,c], J. Castor[2], T. Chambon[2], B. Chaurand[9], I. Chevrot[2], B. Cheynis[11], E. Chiavassa[10], C. Cicalò[4], T. Claudino[6], M.P. Comets[8], N. Constans[9], S. Constantinescu[3], N. De Marco[10], A. De Falco[4], G. Dellacasa[10,d], A. Devaux[2], S. Dita[3], O. Drapier[11], L. Ducroux[11], B. Espagnon[2], J. Fargeix[2], P. Force[2], M. Gallio[10], Y.K. Gavrilov[7], C. Gerschel[8], P. Giubellino[10], M.B. Golubeva[7], M. Gonin[9], A.A. Grigorian[12], J.Y. Grossiord[11], F.F. Guber[7], A. Guichard[11], H. Gulkanyan[12], R. Hakobyan[12], R. Haroutunian[11], M. Idzik[10,e], D. Jouan[8], T.L. Karavitcheva[7], L. Kluberg[9], A.B. Kurepin[7], Y. Le Bornec[8], C. Lourenço[5], P. Macciotta[4], M. Mac Cormick[8], A. Marzari-Chiesa[10], M. Masera[10], A. Masoni[4], S. Mehrabyan[12], M. Monteno[10], A. Musso[10], P. Petiau[9], A. Piccotti[10], J.R. Pizzi[11], F. Prino[10], G. Puddu[4], C. Quintans[6], S. Ramos[6,b], L. Ramello[10,d], P. Rato Mendes[6], L. Riccati[10], A. Romana[9], I. Ropotar[5], P. Saturnini[2], E. Scomparin[10] S. Serci[4], R. Shahoyan[6,f], S. Silva[6], M. Sitta[10,d], C. Soave[10], P. Sonderegger[5,b], X. Tarrago[8], N.S. Topilskaya[7], G.L. Usai[4], E. Vercellin[10], L. Villatte[8], 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/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] Università di Torino/INFN, Torino, Italy.
[11] IPN, Univ. Claude Bernard Lyon-I and CNRS-IN2P3, Villeurbanne, France.
[12] YerPhI, Yerevan, Armenia.

a) also at UCEH, Universidade de Algarve, Faro, Portugal
b) also at IST, Universidade Técnica de Lisboa, Lisbon, Portugal
c) now at CERN
d) Universitá del Piemonte Orientale, Alessandria and INFN-Torino, Italy
e) now at Faculty of Physics and Nuclear Techniques, University of Mining and Metallurgy, Cracow, Poland
f) on leave of absence of YerPhI, Yerevan, Armenia

The NA50 experiment has measured, at the CERN SPS, the dimuon production in Pb-Pb collisions at 158 GeV/c per nucleon, following the program of the previous NA38 and NA51 experiments, performed with proton and light ion beams. The J/ψ production has been studied by NA50 as a function of the centrality of the collisions. The results of the analyses performed on three data samples, collected from 1995 to 1998, show that for peripheral collisions the J/ψ cross section can be understood in terms of ordinary nuclear absorption, consistently with the extrapolation of previous measurements extending from p-p to S-U. On the contrary, the central events show an anomalous J/ψ suppression, and the pattern of J/ψ yield versus centrality features two discontinuities that cannot be described by conventional models based on hadronic scenarios. These results can be considered as a strong indication of the creation of a new state of matter in central Pb-Pb collisions at the SPS.

1. INTRODUCTION

Finite temperature QCD predicts that strongly interacting matter undergoes a phase transition at a critical temperature $T_c \sim 150 - 180\, MeV$; at this point the ordinary nuclear matter, where quarks and gluons are confined in colourless hadrons, turns into a deconfined state, where quarks and gluons behave as free particles. This state of matter is named Quark Gluon Plasma (QGP). It has been suggested that such a phase transition could occur in ultra-relativistic heavy ion collisions, where temperature and energy density could reach the needed critical values. The opportunity to test this prediction of QCD was therefore offered from the feasibility to accelerate ion beams at different machines, since the mid eighties.

Several signals have been proposed as signatures of the formation of a QGP in heavy ion collisions. In particular, in 1986 Matsui and Satz [1] predicted that the formation of a QGP would screen the colour forces between the c and $\bar{c}$ quarks forming charmonia states, leading to a measurable suppression of the J/ψ yield. Some experiments were designed to study the formation of charmonia states through the detection of their decay channel into prompt dileptons; these are an ideal tool to look for QGP formation, since they probe the early stages of the collision and are slightly perturbed by the surrounding strongly interacting matter.

In particular, the experiments NA38, NA51 and NA50 at the CERN SPS, that include a muon spectrometer within their set of detectors, were devoted to the study of dimuons produced in nuclear collisions. Over the last 15 years, these experiments have collected several data samples with proton, oxygen, sulphur and lead beams, on several targets, and have studied systematically the J/ψ production in proton-nucleus and nucleus-nucleus collisions.

The scenario emerged from the data collected with protons and light ions appeared to be consistent with the absorption properties of ordinary nuclear matter, with no indications of a QGP formed during the collisions. In this sense, the observed pattern of J/ψ suppression, increasing continuously and monotonically from p-p up to the most central S-U collisions, was defined as "normal", and it was taken as the baseline with respect to which deviations could be searched for, as a signature of the onset of deconfinement.

However, the data collected with Pb beams at $158\, GeV/c$, since the first sample collected in 1995, showed a totally different behaviour, with an "anomalous" J/ψ suppression appearing as a clear departure from the smooth trend revealed by previous data. Moreover, a "threshold effect" could be inferred from the suppression measurement versus centrality. The new data collected in 1996 and 1998, with larger statistics and refined apparatus, provided a better understanding of the previous observations, and confirmed the existence of an anomaly in the Pb-Pb data.

The purpose of this paper is to discuss systematically the full set of experimental data on J/ψ suppression collected by NA50. A description of the experiment is given in Sect. 2. The presentation of the NA50 results follows in Sect. 3, together with details about the data analysis methods. In Sect. 4 the NA50 results are compared with some theoretical models and the experimental evidence of the formation of a new state of matter in central Pb-Pb collisions is discussed. Finally, a summary is given in Sect. 5.

2. THE NA50 EXPERIMENT

The main detector element of the NA50 experiment (but also of its precursors NA38 and NA51) is the muon spectrometer, optimised for the measurement of high invariant-mass muon pairs. It is composed by a toroidal air-gap magnet placed between two sets of multi-wire proportional chambers (where the angle and the momentum of the muon tracks are measured) and four trigger hodoscope planes. The spectrometer is protected against the high multiplicity environment of the target region by a $5m$ long hadron absorber. The centrality of the collision is estimated by an electromagnetic calorimeter which measures E_T, the neutral transverse energy produced in the reaction. In addition, there are two other detectors measuring quantities related with the centrality of the collisions: 1) a very forward ("zero degree", or ZDC) hadronic calorimeter, covering high rapidities and measuring the energy E_{ZDC} carried by the non-interacting spectator nucleons from the incoming Pb-beam projectile; 2) a two-planes silicon strip detector, measuring the charged particle multiplicity.

A segmented active target, with up to seven sub-targets, is used to reject events contaminated by beam fragments reinteractions; the sub-target where the primary interaction takes place is identified by means of the signals of two quartz blades located off the beam axis, on both sides of each sub-target. Other complementary detectors define the incoming beam, or reject pile-up events. Further details on the detectors and on the different configurations of targets used at different times can be found in Refs. [2–5].

3. DATA ANALYSIS AND RESULTS

3.1. The standard analysis

The J/ψ and ψ' resonances are identified through their decays into muon pairs. The muon pairs selected for the final data analysis have to satisfy the normal quality selection criteria, as detailed in Refs. [2–5]; moreover, the events can be selected as originating in the target, with the help of the active target system. However this method is inefficient for peripheral collisions, when small signals in the quartz blades are indistinguishable from delta-rays produced by non-interacting Pb ions crossing the target. Therefore a second selection method, based on the analysis of the correlation between E_T and E_{ZDC} variables, was used for the 1996 data sample [4] to recover the most peripheral events.

The “standard” method of data analysis to determine the numbers of J/ψ, ψ' and Drell-Yan events, is based on the fit of the muon pair invariant-mass spectra, taking into account also the contributions from the $D\bar{D}$ semileptonic decays (also known as open charm associated production) and from the combinatorial background due to π and K uncorrelated decays. The amount of such background is estimated from the analysis of the like-sign muon pair sample. Then the invariant-mass spectrum is fitted, leaving the normalization of the other processes as free parameters. An example of such a fit is shown in Fig. 1.

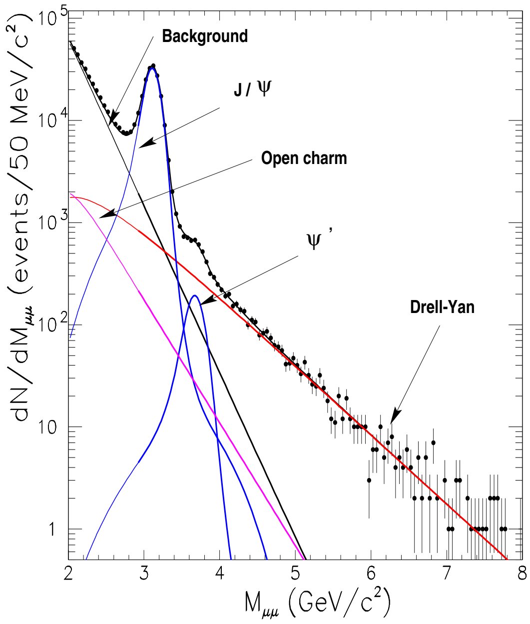

Figure 1. Example of a fit of dimuon invariant-mass spectrum in NA50.

3.2. The anomalous J/ψ suppression

The NA38 and NA51 collaborations have published in 1998 and 1999 their final results on charmonia production in interactions induced by proton [6,7] and light ion [8] beams at the CERN SPS. Here we don't give details about those data (a complete review on them can be be found in Ref. [9]), but rather we infer from them a reference scenario on charmonia production, relative to which the specific behaviour of NA50 Pb-Pb data must be studied.

The several data sets collected by NA38 and NA51 were obtained with different incident beams (protons at 200 and 450 GeV/c, oxygen and sulphur ions at 200 GeV/c), and different targets (p, d, C, Al, Cu, W, U), but always with the same basic apparatus. The NA50 data were collected with Pb beams at 158 GeV/c incident momentum, and with an updated set of detectors, as described in Sect. 2.

In order to compare the J/ψ production in different colliding systems (from p-p to nucleus-nucleus collisions) the appropriate observable was the "cross section per nucleon-nucleon collision", proportional to the measured J/ψ cross section divided by the product $A \times B$ of the mass numbers of the interacting nuclei.

The J/ψ production cross section was derived from the number of reconstructed J/ψ events, the incident flux, the acceptance of the detector for muon pairs from J/ψ decays, and the efficiencies of the trigger hardware, of the acquisition system and of the offline reconstruction procedures.

The J/ψ production cross section per nucleon-nucleon collision (multiplied by the branching ratio into the dimuon channel) is plotted in Fig. 2 versus $A \times B$, for the different data sets, with the 450 GeV/c proton data and the 158 GeV/c Pb data rescaled for comparison purposes to the kinematical conditions of the 200 GeV/c ion data.

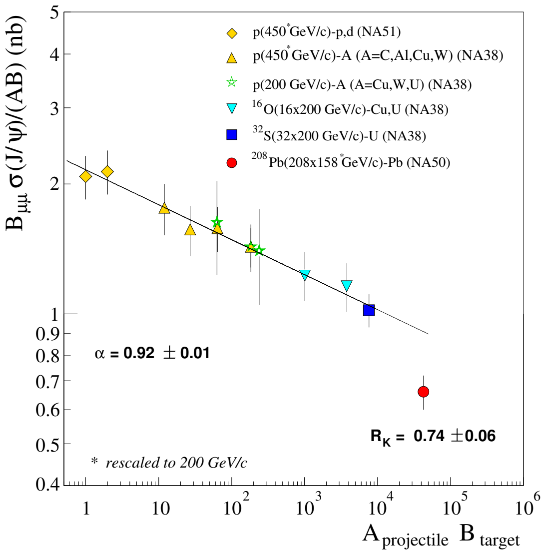

Figure 2. J/ψ cross sections as a function of $A \times B$, for NA38, NA50 and NA51 data.

The line superimposed on the data shows the global fit to the cross sections measured by NA38 and NA51 with the power-law $\sigma_{AB} = \sigma_0(A \times B)^{\alpha}$. The fit [9] leads to: $\alpha^{\psi} = 0.918 \pm 0.015$.

Therefore, the results show that the measured J/ψ yield, from p-p up to S-U collisions, scales less than linearly with $A \times B$. This is commonly interpreted as due to final state interactions between the charmonium state and the surrounding nuclear matter. This interpretation is supported by the linear dependence exhibited by Drell-Yan production for which there are no final state interactions. It can be clearly seen from Fig. 3, which shows the Drell-Yan K-factor (the ratio between the measured Drell-Yan cross section and the lowest order computed cross section) plotted versus $A \times B$, obtained from the NA38, NA51 and NA50 data.

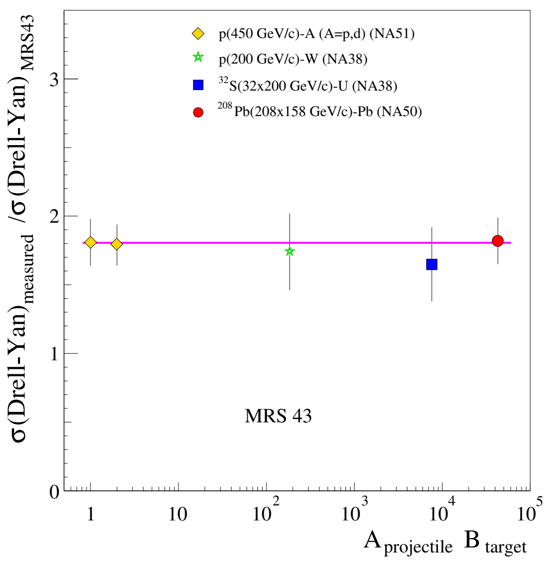

Figure 3. Drell-Yan dimuon K-factor versus $A \times B$.

On the other hand, the plot of J/ψ yield versus $A \times B$ shows that the Pb-Pb point is about five standard deviations off the fitted function;

this was the first hint that the J/ψ production is anomalously suppressed in Pb-Pb interactions.

Another variable appropriate to parametrize the measured J/ψ cross sections, is the number of nucleons that the charmonium state can potentially interact with before escaping from the interaction region, as it directly accounts for possible final state interactions. This number can be be estimated from the nuclear density ρ and the path length L of nuclear matter travelled by the created charmonium state.

The dynamics of a nucleus-nucleus collisions cannot be described from first principles, but only within a framework of a phenomenological model, as the Glauber model. It is based on the concept of multiple collisions between target nucleons and incident hadrons (including particles created inside the target nucleus), with the assumption of an elementary hadron-nucleon collision. During this process the involved particles deposit a big amount of energy, and they can eventually be absorbed within the interaction region.

As a first order approximation, if the nuclear dependence of J/ψ production can be accounted for by nuclear absorption, a parametrization as $\exp(-\sigma^{\psi}_{abs}\rho_0 L)$ (where $\rho_0 = 0.17\, fm^{-3}$ is the nuclear matter average density, and σ^{ψ}_{abs} is the J/ψ absorption cross section), should provide a good description of the J/ψ survival probability [10].

The path length L is calculated, for each impact parameter b, as an average over a realistic distribution of $c\bar{c}$ production points, following the Glauber formalism and using Woods-Saxon nuclear densities. Fig. 4 shows, as a function of the average value of L, the same J/ψ production cross section per nucleon-nucleon collision as Fig. 2.

The line superimposed on the experimental points corresponds to the best fit of NA38/NA51 data to this function, and leads to the value $\sigma^{\psi}_{abs} = 6.5 \pm 1.0\, mb$ for the J/ψ absorption cross section. A more refined analysis, based on the Glauber formalism and described in Ref. [11], leads to very similar values: $\sigma^{\psi}_{abs} = 7.2 \pm 1.2\, mb$. The significant departure of the Pb point from the fitted exponential function is a clear evidence that the J/ψ suppression observed in Pb-Pb collisions cannot be accounted for by an ordinary

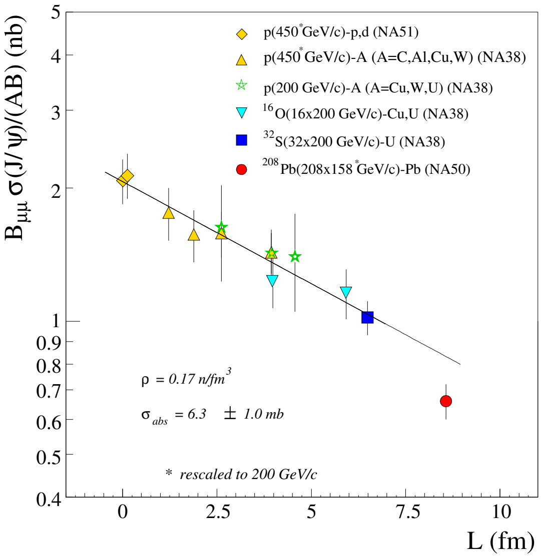

Figure 4. J/ψ cross sections as a function of L, for NA38, NA50 and NA51 data.

nuclear absorption mechanism.

The values of σ^{ψ}_{abs} derived from the fit of the NA38/NA51 data are however bigger by at least a factor two with respect to the estimates of $\sigma_{abs}(J/\psi - hadron)$ given by short-distance QCD [13] and J/ψ photoproduction experiments [14]: this fact is explained by assuming that the measured value σ_{abs} does not regard the absorption of a fully-formed charmonium state, but rather of a pre-resonance state of the quark $c\bar{c}$ pair. This hypothesis is supported by the knowledge of the most recent models on quarkonium production [15–17]; it is nowadays assumed that this process goes through two steps: 1) the creation of the heavy $c\bar{c}$ pair (at high energies the dominant process is gluon fusion), that takes place in a very short time, $\tau_c \sim 1/2m_c$; 2) the subsequent colour neutralization of the $c\bar{c}$ pair, via the exchange of an additional gluon, and the formation of the final bound state with the J/ψ quantum numbers, that takes place on a larger time-scale $\tau_f \sim 1/\Lambda_{QCD} \gg \tau_c$.

This two-step picture for charmonia production is also useful to understand the results on ψ' suppression. The analysis of the NA38 and NA51 data has shown that the two charmonia states suffer the same nuclear absorption in p-A collisions, following the same absorption law in the target nuclear matter. On the contrary, in S-U and in Pb-Pb collisions the ψ' appears more strongly suppressed than expected from extrapolations of p-A data (preliminary results on ψ' suppression in Pb-Pb data can be found in [18]). These results can be understood by assuming that in p-A collisions the formation time of the J/ψ and ψ' particles is larger than the size of the target nucleus. The nuclear absorption effects are the same for both particles since the nuclear medium is crossed by a $c\bar{c}$ pair (pre-resonance state) before full formation of the final charmonium state. On the other hand the S-U and Pb-Pb collisions provide a larger volume of the interaction region; in this volume the $c\bar{c}$ pair has time to become a fully formed resonance, either a J/ψ or a ψ'. We can expect the ψ' to be more absorbed than the J/ψ because of its bigger size and because it is a more loosely bound state.

3.3. Centrality dependence of J/ψ suppression and the "threshold effect"

The first Pb-Pb data sample, collected by NA50 in 1995, was also explored as a function of the collision centrality [2,3]. The events are subgrouped into five classes, according to the neutral transverse energy E_T measured in each collision, as already done by the NA38 Coll. on S-U data (see Ref. [9]).

For these studies the J/ψ cross section per nucleon-nucleon collision is obtained by replacing the product $A \times B$ with the measured Drell-Yan cross section, which is well known, both experimentally and theoretically, to be proportional to the number of elementary nucleon-nucleon collisions (see Fig. 3). Moreover, since the Drell-Yan process is insensitive to the eventual formation of QGP, it is a good reference process to which J/ψ production can be compared, in the search for anomalous signals due to colour deconfinement.

The ratio between the J/ψ and the Drell-Yan cross sections is derived directly from the fit to the dimuon mass spectra, for each E_T bin. The results, plotted directly versus E_T or otherwise versus the calculated variable L, show that the observed anomaly of J/ψ suppression increases with increasing centrality [3].

Indeed the statistics of the 1995 data sample do not allow an accurate reconstruction of the pattern of J/ψ suppression versus centrality. However, the comparison on a same plot of the NA50 data with the data from NA38 and NA51 show that the last ones follow a common pattern, that can be fitted with an exponential function, describing the effects of ordinary nuclear absorption, with values of σ^{ψ}_{abs} comparable with the ones found from the analysis of the absolute J/ψ cross sections. This pattern is followed also by the S-U data binned versus centrality, from peripheral to central events, and by the most peripheral Pb-Pb data point. On the contrary, NA50 events of higher centrality show a disagreement with that pattern, which increases with centrality.

These results, reported by the NA50 Coll. [2,3] after the analysis of the 1995 Pb-Pb data sample, triggered considerable excitement and a large number of tentative explanations. But it was evident that the accuracy of that first measurement was limited by large statistical errors, due to the small size of the data sample. Therefore further measurements were performed, with larger statistics, in 1996. They confirmed the existence of the anomaly; the ratio of cross sections $\sigma_{J/\psi}/\sigma_{DY}$ was measured, integrating the Drell-Yan differential cross section in the mass interval $2.9 \leq M \leq 4.5\, GeV/c^2$. The result was $B_{\mu\mu}\sigma_{J/\psi}/\sigma_{DY} = 17.0 \pm 0.2$; when divided by the value extrapolated from the final results of NA38/NA51 [9], it led to $R = 0.77 \pm 0.04$ for the anomalous suppression factor, as defined in [2] (ordinary nuclear absorption would correspond to $R = 1$), thus showing the high statistical significance of the observed anomaly.

Furthermore, the larger size of 1996 data sample allowed a more detailed analysis in 15 centrality bins; a very spectacular feature of these data [4] was the presence of a "break" in the plots representing the ratio of J/ψ over Drell-Yan cross sections versus a centrality variable.

In Fig. 5 one can see the plot of the ratio R of the J/ψ over Drell-Yan cross sections as a function of L, the average path length in nuclear mat-

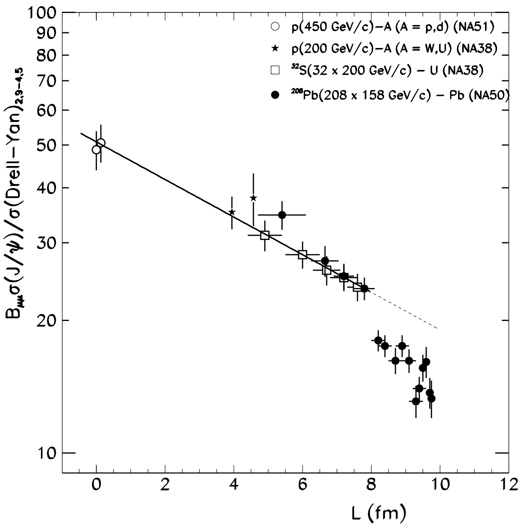

Figure 5. Ratios of the J/ψ to Drell-Yan cross sections as a function of $\bar{L}$, for NA38, NA50 and NA51 data.

ter; in this plot the NA38 and NA51 data are rescaled to $158\,GeV/c$, and the solid line corresponds to the simple exponential fit of these data, with $\sigma^{\psi}_{abs} = 5.8\,mb$. In this figure a discontinuity is clearly visible for $L \sim 7.5fm$ (which corresponds to an impact parameter $b \sim 8\,fm$): the points corresponding to the most peripheral Pb-Pb collisions agree with the NA38/NA51 data, collected with proton and light ion beams, while more central events show a clear departure from this trend. When E_T is used as centrality variable, the discontinuity occurs at $E_T \sim 40\,GeV$.

However, the evidence of this break as the first signature of a "threshold effect" in heavy ion collisions, was weakened by the possible effects of fluctuations on the ratio $R(E_T)$; therefore it seemed necessary to check whether the discontinuity of the ratio was really due to some abrupt change in J/ψ cross section, or rather due to fluctuations in the J/ψ and Drell-Yan ones. This point was investigated by the NA50 Collaboration by developing a new analysis, totally independent from the standard one, that we have already described in Sect. 3.1.

3.4. The minimum bias analysis

The new analysis (named "minimum bias" analysis) uses the much larger sample of minimum bias events (defined as the ones triggering the ZDC forward-calorimeter), as the reference in the studies of centrality dependence of the J/ψ rate, thereby reducing significantly the statistical uncertainties affecting the standard method.

The analysis is based on a simple counting technique; in each E_T bin the minimum bias events are counted, while the number of J/ψ events is determined as the number of dimuon events in the mass region $2.9 - 3.3\,GeV/c^2$, after subtracting the contributions from the combinatorial background and from the underlying dimuon continuum.

In order to compare the results of the two analyses with each other, and also with the results obtained by NA38 and NA51, the minimum bias reference is converted into the Drell-Yan reference, exploiting the very similar structures of the E_T distributions for minimum bias (MB) and Drell-Yan (DY) events. The Drell-Yan E_T distribution is estimated from the measured MB one, according to:

$$(dN/dE_T)^{est}_{DY} = (dN/dE_T)^{meas}_{MB} \times \Theta(E_T)$$

where $\Theta(E_T)$ is the ratio between the Drell-Yan and minimum bias yields, both calculated by the Glauber model. The ratio $\Theta(E_T)$ is plotted as a function of E_T in Fig. 6: for comparison purposes the same figure also shows the ratio of experimental distributions. More details on this method can be found in Ref. [4].

The results obtained with the minimum bias analysis show good overall agreement with the ones derived from the standard analysis on the same data sample; the agreement is good also with the results found on 1995 data, apart from the upper end of the E_T range, where 1996 data shows an excess. However, it has been found that this excess was a bias due to reinteraction effects in the thick target used in 1996 runs. That has been clarified with a special data collection performed in 1998 with a thinner target. On the other hand, this data sample presented a larger

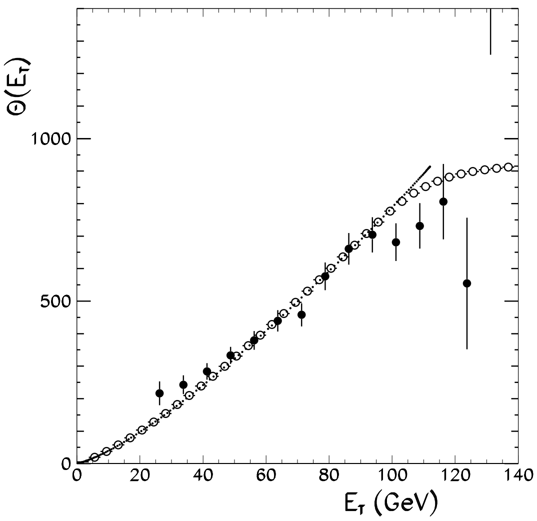

Figure 6. The ratio $\Theta(E_T)$ of Drell-Yan to minimum bias theoretical E_T distributions (open circles); the ratio $\Theta(E_T)$ as results from the data (closed circles with experimental error bars).

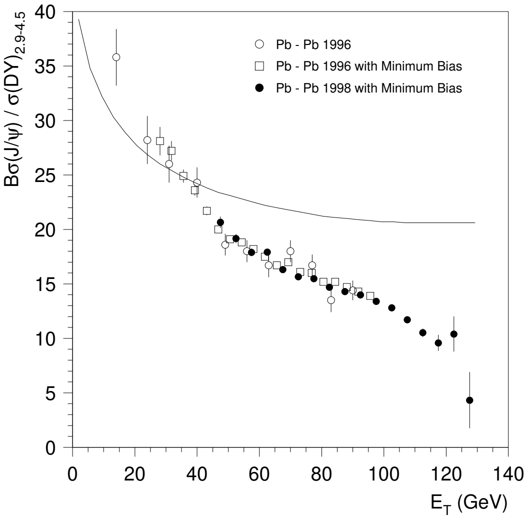

Figure 7. $\sigma_{J/\psi}/\sigma_{DY}$ ratio as a function of E_T, obtained with the standard and minimum bias analyses of the 1996 and 1998 data samples. The curve represents the J/ψ suppression due to ordinary nuclear absorption.

contamination from Pb-air collisions for the most peripheral events.

The results of the various analysis methods performed on the data collected by NA50 in 1996 and 1998 are put together in Fig. 7, where they are superimposed to the prediction of the nuclear absorption model (solid line). In this figure the results obtained from 1996 data are represented by open circles (standard analysis) and open squares (minimum bias analysis), while those obtained from the 1998 data with the minimum bias method are represented by closed circles. It must be remarked that some data points are excluded from the plot: events of $E_T > 90\,GeV$ from the 1996 data sample (because biased by reinteractions), and events of $E_T < 50\,GeV$ from the 1998 data sample (because biased by background interactions on air).

It is evident that the minimum bias analysis describes the E_T dependence of the J/ψ suppression with much better accuracy, especially in the region of the discontinuity, thus confirming the general pattern of the anomalous suppression already reported from the 1995 data.

The shapes of all the curves appear compatible, and in excellent agreement with each other in the interval where the drop of J/ψ yield is observed. In this region the E_T-resolution is $\sigma_{E_T}/E_T \sim 10\%$. Therefore the slope of the discontinuity appears as large as we would expect from the smearing effects due to experimental resolution, when a sharp transition would occur in that E_T range.

Fig. 7 reveals also that the anomalous J/ψ suppression continues increasing for the most central Pb-Pb collisions, rather than saturating with increasing E_T. As a matter of fact, the data show a second drop in the J/ψ suppression pattern, at $E_T \sim 90\,GeV$.

3.5. The ZDC analysis

Finally, it must be added that the NA50 detector allows the study of the centrality dependence of the J/ψ suppression also in an alternative way, based on the use of E_{ZDC} as centrality variable, instead of E_T. As can be seen in Fig. 8, which shows the ratio $\sigma_{J/\psi}/\sigma_{DY}$ for $E_{ZDC} < 22.5\,TeV$, the main features of the J/ψ suppression pattern observed as a function of E_T, the threshold and the non-flattening at high centralities, are confirmed also from the study with the variable E_{ZDC}. However, the very loose $E_T - E_{ZDC}$ correlation for the most central collisions allows only qualitative comparisons between the suppression patterns found with these independent techniques.

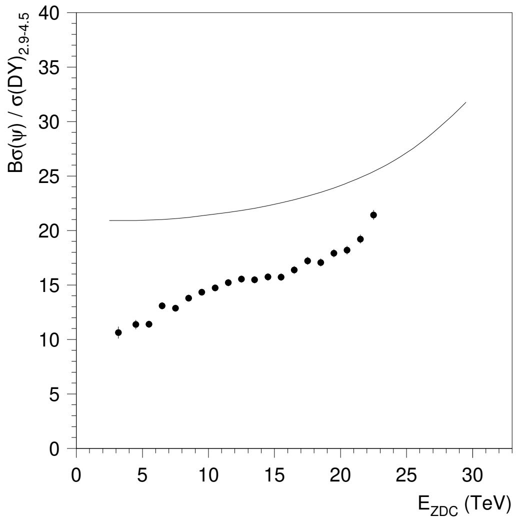

Figure 8. The ratio $\sigma_{J/\psi}/\sigma_{DY}$ as a function of E_{ZDC}, obtained with the minimum bias analysis of the 1998 data sample. The curve represents the J/ψ suppression due to ordinary nuclear absorption.

4. INTERPRETATION OF THE NA50 RESULTS

The experimental data from NA50 have generated an intense controversy about the necessity of a new suppression mechanism, e.g. due to the quark-gluon plasma formation, to explain the data, or whether the suppression could be due only to hadronic interactions.

Charmonium production and absorption have been studied first by means of semianalytical models of heavy ion collisions [10–12] as well as, more recently, in the framework of microscopic hadronic transport models [19–21].

In simple analytical models of J/ψ suppression, based on a semiclassical Glauber approach, nuclear absorption is calculated by convoluting nuclear density profiles with an assumed cross section for dissociation by nucleons. The model parameters can generally be tuned to fit all p-A data as well as all nucleus-nucleus data, except the ones from Pb-Pb. In order to explain the Pb-Pb data, some models [22,23] included an additional absorption of J/ψ by secondary hadrons (comovers) produced in the collision region, with different assumptions on the comover density proposed by different authors. On the other hand, microscopic transport models approximate the soft hadron dynamics of a heavy ion collision as a cascade of binary scatterings, and describe the complete space-time evolution of scattered nucleons as well as of secondary hadrons.

However all these models, involving conventional physics (i.e. no phase transition to QGP), are unable to account for the J/ψ suppression observed in Pb-Pb. This can be clearly seen in Fig. 9, where the ratio $\sigma_{J/\psi}/\sigma_{DY}$ is compared to the curves calculated by models assuming the absorption of charmonia states by the interactions with comoving hadrons.

A first incompatibility between the data and such models is the sharp onset of the J/ψ anomalous suppression, observed at $E_T \sim 40\,GeV$, while all the models predict a smooth decrease of the J/ψ production yield for increasing centrality.

Moreover, the data show a second drop of the J/ψ production yield at $E_T \sim 90\,GeV$, while the hadronic models predict a saturation of its steady decrease.

Therefore the NA50 measurements rule out such models, while they seem more in agreement with the patterns predicted by scenarios assuming a phase transition to a deconfined state of quarks and gluons [24–26]. However, the predicted pattern of J/ψ suppression as a function of E_T results indeed much smoother than the experimental data, when fluctuations in the $E_T - b$

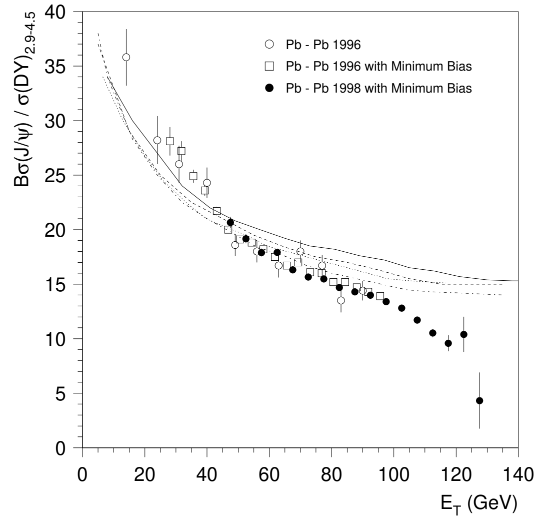

Figure 9. Comparison between the NA50 data and several hadronic models of J/ψ suppression: solid line [19], dashed [20], dotted [21], dot-dashed [22].

correlations are included. Moreover, a really complete and self-consistent theory is still lacking, and some improvements are still required.

In order to describe more quantitatively the observed suppression pattern, we have evaluated the energy density reached in the reactions under study. This variable is also suitable to compare in a single figure all the results obtained with different experiments. We used the Bjorken's formula to compute the energy density reached in a nucleus-nucleus collision:

$$\epsilon = \frac{dE_T^{tot}/dy\mid_{y^*=0}}{c\tau \times A_T} \quad (1)$$

where $\tau \sim 1\,fm/c$ is the lifetime of the created system, and A_T is the overlap transverse area of the two colliding nuclei. The value of dE_T^{tot}/dy has been computed multiplying by three the measured neutral E_T values, and taking into account the rapidity coverage ($1.1 < y_{lab} < 2.3$) of our measurements, which is significantly displaced with respect to mid-rapidities. This calculation leads to an energy density of $3.5\,GeV/fm^3$ for the NA50 most central data point.

The results presented in Fig. 10 show the ratio between the measured J/ψ suppression pattern and the expected one (from the normal nuclear absorption), for Pb-Pb data and for the smaller collision systems probed by NA38 and NA51 experiments.

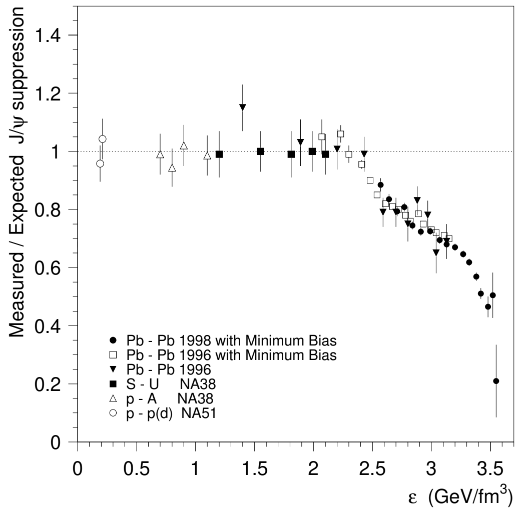

Figure 10. Measured J/ψ production yields, normalized to the expectations from normal nuclear absorption, plotted versus energy density.

The data points were obtained from the measured J/ψ over Drell-Yan cross section ratios, except for the NA38 p-A data points, which are based on the J/ψ absolute cross sections. Another advantage of the presentation of the data through this "measured over expected" ratio is that they are immediately comparable, even if they were collected at different energies.

From this figure we see that a first drop in the J/ψ production yield occurs for Pb-Pb collisions reaching an energy density above $2.3\,GeV/fm^3$, while a second drop, signature of an even stronger suppression, occurs above $3.1\,GeV/fm^3$.

This step-wise pattern can be naturally understood in a deconfinement scenario, as resulting from the melting of different charmonium resonances, the χ_c and the J/ψ, whenever different energy densities are reached. In fact we know that about 32% and 8% of the experimentally observed J/ψ, come respectively from χ_c and ψ' radiative decays. The χ_c states should be more easily dissociated than the directly produced J/ψ, because of their larger size ($r_{\chi_c} \sim 0.4\,fm > r_\psi \sim 0.2\,fm$) and of their smaller binding energy ($\Delta E_{\chi_c} \sim 0.3\,GeV < \Delta E_\psi \sim 0.6\,GeV$).

According to this picture, the NA50 data would suggest that the binding of χ_c states starts becoming screened for (local) energy densities above $2.3\,GeV/fm^3$, while the breaking of the more tightly bound J/ψ states requires collisions generating at least $3.1\,GeV/fm^3$ of energy density. The first anomalous step can be understood in this scenario as due to the disappearance of the "indirect" J/ψ, produced by the χ_c decays, while the second drop would signal an energy density high enough to dissolve also the directly produced J/ψ.

However, other authors have recently argued [27] that the second drop at high E_T could be accounted for by a simpler mechanism, involving fluctuations of E_T.

5. SUMMARY AND CONCLUSIONS

We report in this paper the results of the studies on J/ψ suppression in nuclear collisions, performed over many years by the NA38, NA51 and NA50 Collaborations, using the data collected with proton, oxygen, sulphur and lead ion beams on several targets, at the CERN SPS.

The results obtained by NA38 and NA51, with proton and light ions, are consistent with the absorption properties of ordinary nuclear matter, while the data collected by NA50 with Pb beams show a completely different behaviour, not consistent with the extrapolation of the previous data, the so-called "anomalous" J/ψ suppression.

Moreover the J/ψ suppression pattern, plotted as a function of a centrality variable, presents two apparent changes of slope, thus suggesting the existence of some threshold effect occurring in central and semi-central Pb-Pb collisions. All the theoretical studies based only on hadronic interactions of ordinary nuclear matter fail in reproducing this pattern.

On the contrary, the data seem more successfully described by models incorporating a deconfinement scenario. Even if some of the assumptions of these models are still under investigation, the detailed pattern of experimental data strongly suggests that in central and semi-central Pb-Pb collisions a new phase of nuclear matter is created.

These results open the way to the future generation of experiments, that will be performed at the forth-coming RHIC and LHC accelerators, where the nuclear matter will be probed at even higher energy densities than at the SPS.

REFERENCES

1. T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416.
2. NA50 Coll., M.C. Abreu et al., Phys. Lett. B 410 (1997) 327.
3. NA50 Coll., M.C. Abreu et al., Phys. Lett. B 410 (1997) 337.
4. NA50 Coll., M.C. Abreu et al., Phys. Lett. B 450 (1999) 456.
5. NA50 Coll., M.C. Abreu et al., Phys. Lett. B 477 (2000) 28.
6. NA51 Coll., M.C. Abreu et al., Phys. Lett. B 438 (1998) 35.
7. NA38 Coll., M.C. Abreu et al., Phys. Lett. B 444 (1998) 516.
8. NA38 Coll., M.C. Abreu et al., Phys. Lett. B 449 (1999) 128.
9. NA38 Coll., M.C. Abreu et al., Phys. Lett. B 466 (1999) 408.
10. C. Gerschel and J. Hufner, Phys. Lett. B 207 (1988) 253, and Z. Phys. C 56 (1992) 171.
11. D. Kharzeev, C. Lourenco, M. Nardi and H. Satz, Z. Phys. C 74 (1997) 307.
12. J.-P. Blaizot and J.-Y.Ollitrault, Phys. Rev. Lett. 77 (1996) 1703.
13. D. Kharzeev and H. Satz, Phys. Lett. B 334 (1994) 155.
14. S.D. Holmes, W. Lee and J.E. Wiss, Ann. Rev. Nucl. Part. Sci. 35 (1985) 397.
15. G.T. Bodwin, E. Braaten and G.P. Lepage, Phys. Rev. D 51 (1995) 1125.

16. E. Braaten and S. Fleming, Phys. Rev. Lett. 74 (1995) 3327.
17. M.L. Mangano, CERN-TH/95-190.
18. L. Ramello (for the NA50 Coll.), in "Proc. of Quark Matter '97", Nucl. Phys. A 638 (1998) 261c.
19. J. Geiss et al., Phys. Lett. B 447 (1999) 31.
20. C. Spieles et al., Phys. Rev. C 60 (1999) 054901.
21. D.E. Kahana and S.H. Kahana, Prog. Part. Nucl. Phys. 42 (1999) 269.
22. N. Armesto, A. Capella and E.G. Ferreiro, Phys. Rev. C 59 (1999) 395.
23. S. Gavin and R. Vogt, Phys. Rev. Lett. 78 (1997) 1006, and in "Proc. of Quark Matter '96", Nucl. Phys. A 610 (1996) 442c.
24. H. Satz in "Proc. of Quark Matter '99", Nucl. Phys. A 661 (1999) 104c.
25. J. Dias de Deus, R. Ugoccioni and A. Rodrigues, hep-ph/9907352.
26. M. Nardi and H. Satz, Phys. Lett. B 442 (1998) 14.
27. J.-P. Blaizot, P.M. Dinh and J.-Y.Ollitrault, nucl-th/0007020, 4 Sep. 2000.