CHARMONIUM PRODUCTION IN p-A AND NUCLEUS-NUCLEUS INTERACTIONS AT THE CERN SPS

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Preliminary new results on J/ψ production in Pb-Pb collisions at 158 GeV/nucleon are presented. They are obtained from the most recent sample of data collected in year 2000 under improved experimental conditions. The results are compared with an updated normal absorption curve deduced from new high statistics proton-nucleus data. The new measurement shows a J/ψ suppression pattern departing from the normal absorption curve for mid-central lead-lead collisions and steadily decreasing for the most central interactions. It thus confirms the results obtained from previously collected data samples. The experiment

has also measured the transverse momentum and transverse mass distributions of J/ψ mesons produced in p-A and in Pb-Pb collisions. The behaviour of these distributions as a function of the centrality and energy of the collisions is also discussed.

Introduction

The NA50 experiment is mainly devoted to the study of a specific signature of quark-gluon plasma formation, the predicted suppression of charmonium states [1]. Indeed, the NA50 observation of an anomalous J/ψ suppression [2–4] indicates that the deconfinement transition could take place in Pb-Pb collisions, at SPS energies, for impact parameters smaller than ~ 8 fm. The study of the J/ψ transverse momentum and transverse mass distributions could provide additional information on the features of the reaction mechanism.

1. Experimental Conditions and Data Selection

The NA50 experimental setup is designed for a measurement of dimuon production in proton-nucleus and nucleus-nucleus interactions as a function of the centrality of the collision. The apparatus consists of a set of beam and anti-halo counters, three independent centrality detectors, and a hadron absorber followed by a muon spectrometer, as illustrated in Fig.1.

The incoming ion beam is counted by a 16-slab quartz Beam Hodoscope (BH), while interactions occurring out of the target and pile-up events are detected and rejected using a set of specific counters. The centrality of the collision can be estimated with three different detectors: an Electromagnetic Calorimeter (EMC) which measures the neutral transverse energy ($E_{\rm T}$) produced in the pseudo-rapidity interval $1.1 \leq \eta_{\rm lab} \leq 2.3$, a Zero Degree hadronic Calorimeter (ZDC) which measures the energy of the beam spectator nucleons ($E_{\rm ZDC}$) at $\eta_{\rm lab} > 6.3$ and a silicon Multiplicity Detector (MD) which measures the charged particle multiplicity in the range $1.65 \leq \eta_{\rm lab} \leq 3.5$. Residual non-target interactions are rejected from the data sample via a diagonal contour cut applied to the $E_{\rm T} - E_{\rm ZDC}$ correlation [3].

For the analysis presented here, the centrality of the collision has been estimated both from $E_{\rm T}$ and from $E_{\rm ZDC}$ [5]. The dimuon trigger of the experiment is provided by four scintillator hodoscopes, while a minimum bias (MB) trigger is defined by a minimal energy deposit in the ZDC. Dimuons are detected in the kinematical domain defined by $2.92 < y_{\rm lab} < 3.92$ and $-0.5 < \cos\theta_{\rm CS} < 0.5$.

The data taking conditions for Pb-Pb interactions were similar in all the periods reported here, except for the total thickness of the target. A segmented lead target made of 7 subtargets was used for the 1996 (1995) data taking periods with a total target thickness of 12 mm (7 mm), corresponding to 30 % (17 %) of an interaction length. In 1998, the experiment used a single target of 3 mm, corresponding to 7 % of an interaction length, in order to minimize reinteractions within the target itself. In the 2000 run, a single lead target of 4 mm (9.33 % of $\lambda_{\rm int}$) was placed in vacuum, to reduce potential contamination from Pb-air interactions in the most peripheral Pb-Pb collisions event sample. A new target identification method was developed, based on the two planes of the multiplicity detector, which led to a higher target identification efficiency for very peripheral events. The total number of collected J/ψ events for the 1995, 1996, 1998 and 2000 Pb-Pb runs is 50 000, 190 000, 90 000 and 110 000, respectively. The results on p-A transverse momentum distributions, also reported hereafter, are based on data collected in year 2000, using a 400 GeV incident proton beam of high intensity ($\sim 4{\cdot}10^9$ p/burst) and five different targets (Be, Al, Cu, W and Pb). The number of collected J/ψ events with each of the targets amounts to 40 000, 50 000, 47 000, 51 000 and 71 000, respectively.

2. Analysis

For masses higher than 1.5 GeV/c^2, the contributions to the invariant mass distribution of opposite-sign muon pairs originate from four known sources: the Drell—Yan process (DY), the J/ψ and ψ' decays and the semi-leptonic decay of pairs of charmed mesons ($D\bar{D}$). The spectrum includes also the contribution of a combinatorial background originating mainly from uncorrelated π and K decays. This background is estimated from the samples of like-sign muon pairs. The opposite-sign muon pair mass spectrum of the selected data sample is shown in Fig. 2. The dimuon invariant mass spectrum provides the amount for each of the physical components through a fit in the mass range 2.9 to 8.0 GeV/c^2. The shapes of each of the contributions are obtained via Monte Carlo simulation followed by the event reconstruction in the spectrometer, using the same software and selection criteria as for real data. The fit provides the ratio of J/ψ to DY events. After acceptance

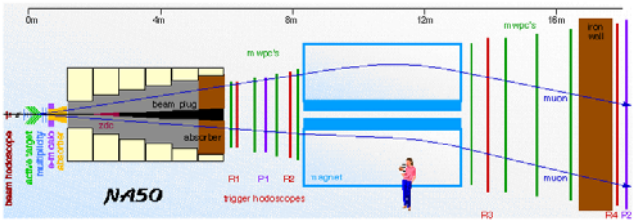

Fig. 1. The NA50 spectrometer

and smearing corrections, it allows one to obtain the ratio of cross-sections $(B_{\mu\mu}\sigma_{J/\psi})/\sigma_{DY}$. The DY cross-section is used as a reference, since it exhibits linear scaling with $A \times B$, the product of the target and projectile atomic mass numbers which is proportional to the number of nucleon-nucleon collisions in the interaction (see Fig.3). Besides, most of the systematic errors cancel out in the ratio of cross-sections which is insensitive, in particular, to the absolute incident flux uncertainty.

In the J/ψ mass region, the continuum contribution amounts to less than 8 % of the total in the range $2.7 < M_{\mu\mu} < 3.5$ GeV/c^2, and to 3 % in the narrower interval $2.9 < M_{\mu\mu} < 3.3$ GeV/c^2 used in the transverse momentum analysis of the 1995, 1996 and 2000 data sets. These continuum events are mainly DY dimuons.

To obtain the J/ψ transverse momentum distributions, the $p_{\rm T}$ distribution of the muon pairs in the resonance mass region is corrected with the $p_{\rm T}$ distribution measured for the continuum dimuons with mass just below or above the J/ψ peak. The details of the analysis method can be found in [6].

3. Published Results on J/ψ Production

NA50 has already published results on the J/ψ/DY cross-sections ratio in Pb-Pb collisions, obtained from the 1995 [2], 1996 [3] and 1998 [4] data samples, using mainly the transverse energy as the centrality measurement. In all cases, the so-called standard analysis method, which only needs dimuon triggered events, has been used. For the 1996 and 1998 data, an analysis method which makes use of the sample of minimum bias triggered events has also been applied. More recently, NA50 has published an analysis of the 1996 and 1998 data using the forward $E_{\rm ZDC}$ energy as the centrality estimator [5].

From these Pb-Pb data collected during the 1995-1998 years, the anomalous J/ψ suppression was established. The J/ψ/DY cross-sections ratio showed a departure from its normal expected behaviour for $E_{\rm T}$

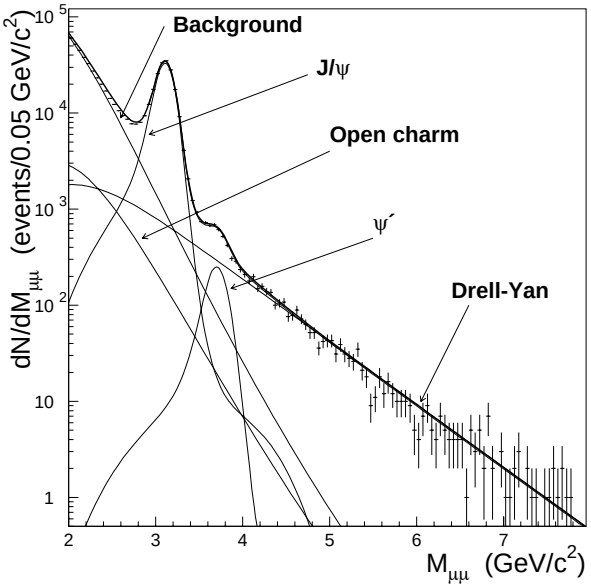

Fig. 2. Opposite-sign muon pair invariant mass spectrum for Pb-Pb collisions at 158 GeV/c incident momentum. Data collected in 1996

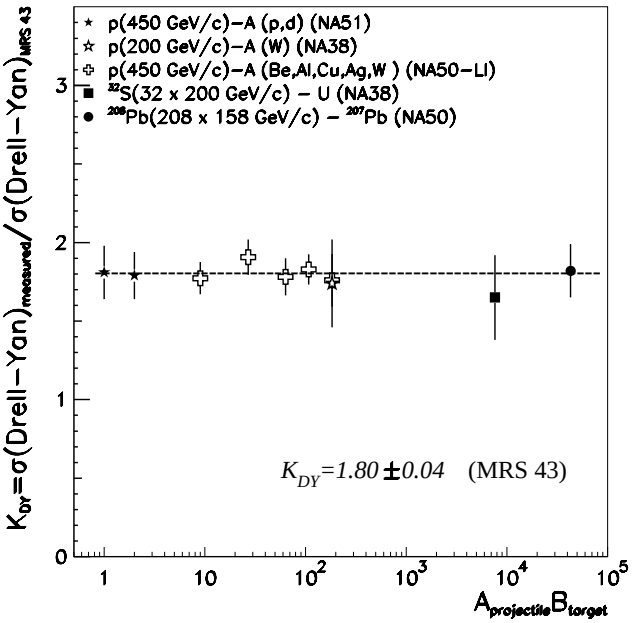

Fig. 3. The ratio of measured to computed Drell—Yan cross-sections from NA51, NA38 and NA50 experiments

near 40 GeV followed by a steady decrease with increasing $E_{\rm T}$ (see Fig.4). It must be noted that the

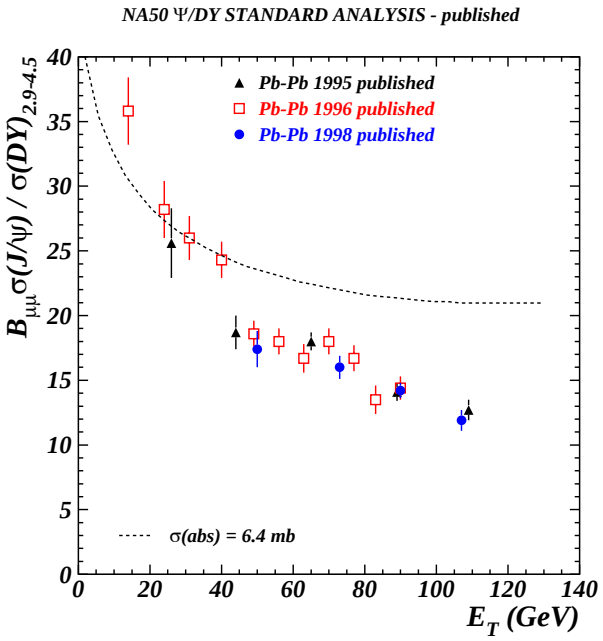

Fig.4. Published results for the J/ψ/DY cross-section ratio vs. $E_{\rm T}$

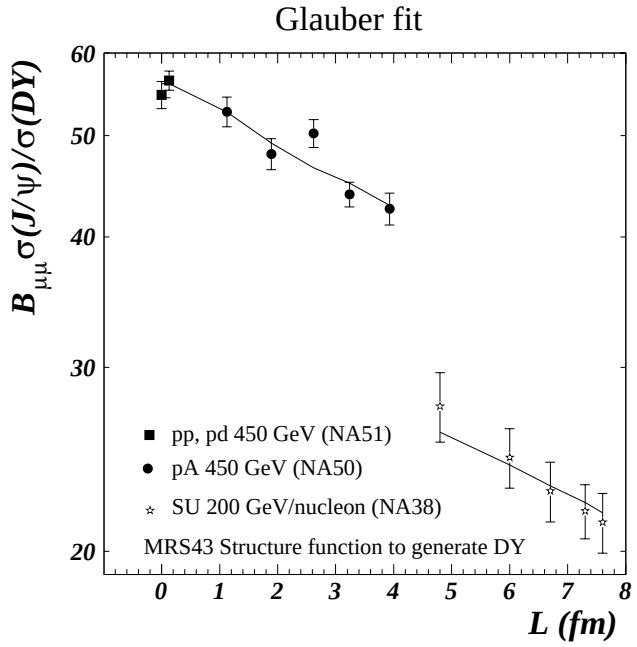

Fig. 5. The $J/\psi/{\rm DY}_{2.9-4.5}$ cross-section ratio vs. L. The kinematical domains at 450 and 200 GeV are different. The curve represents a Glauber fit giving $\sigma_{abs} = 4.3 \pm 0.5$ mb

normal absorption curve (dotted line in Fig.4) has been established using data obtained by the NA51 experiment in p-p and p-d interactions [7] and by the NA38 experiment in p-A and S-U collisions [8], although the NA38 p-A data suffered from somewhat low statistical accuracy.

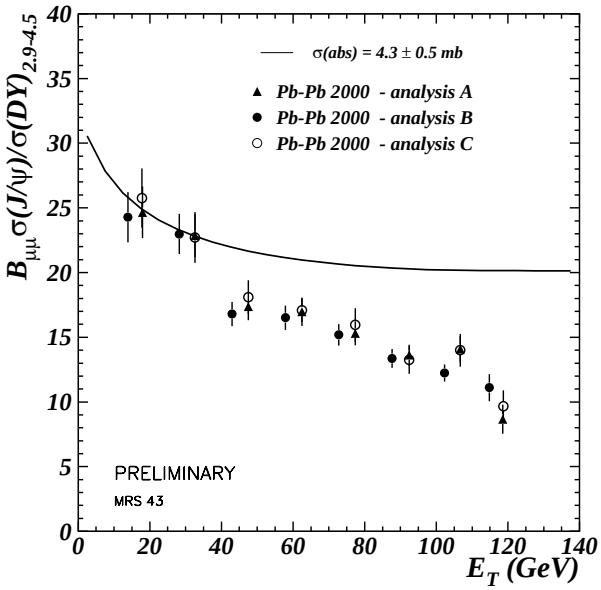

Fig. 6. The $J/\psi/{\rm DY}_{2.9-4.5}$ ratio as a function of the transverse energy

4. Normal Nuclear Absorption Curve for J/ψ

In order to check whether Pb-Pb peripheral collisions follow the J/ψ absorption behaviour seen in lighter systems, a new high statistics study of p-nucleus interactions was performed with improved accuracy. The J/ψ/DY ratios obtained from these new measurements have been fitted with a Glauber parametrization together with previous p-p and p-d results from NA51 at 450 GeV [7] and S-U results from NA38 at 200 GeV [8]. All these data have been collected with the same dimuon spectrometer as used by NA50. The results are plotted in Fig.5 as a function of the average length of nuclear matter, L, crossed by the $c\bar{c}$ pair after its production. The lines represent a Glauber fit to all the data which leads to an absorption cross-section $\sigma_{abs} = (4.3 \pm 0.5)$ mb [9].

5. J/ψ/DY Ratio from the Year 2000 Pb-Pb Run

Preliminary results from the Pb-Pb 2000 data are shown in Fig.6 as a function of $E_{\rm T}$. The ratio $J/\psi/{\rm DY}_{2.9-4.5}$ is given, as usually, with the DY cross-section in the mass

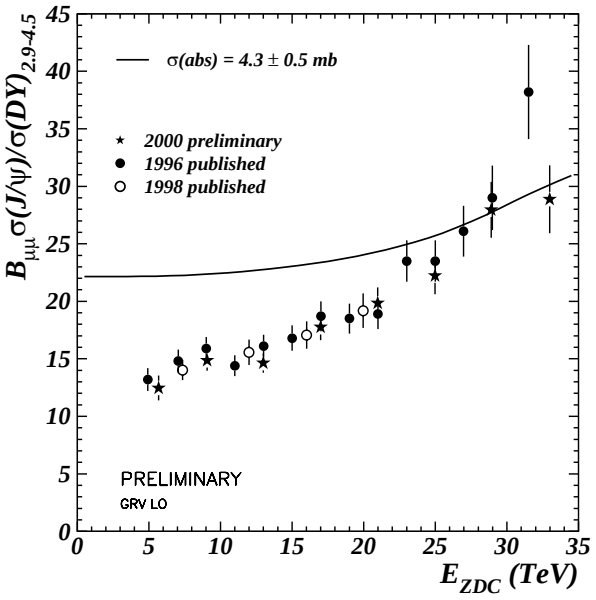

Fig. 7. The $J/\psi/\mathrm{DY}_{2.9-4.5}$ ratio as a function of the E_{ZDC} in comparison with published data

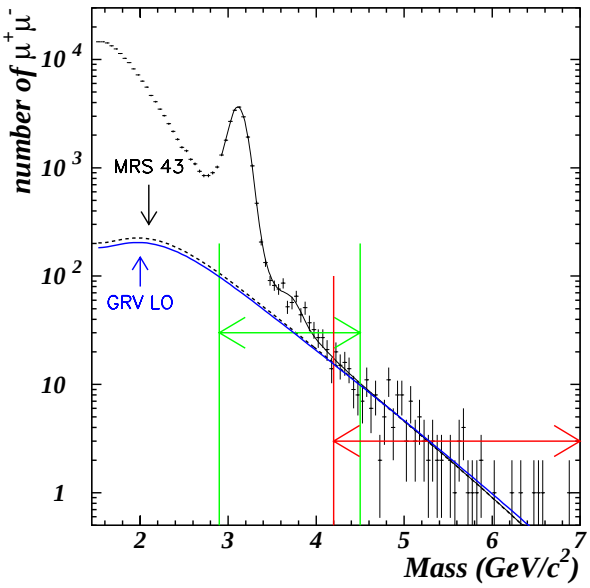

Fig. 8. Comparison of fits to the DY component, using GRV LO and MRS 43 parton distribution finctions

range 2.9—4.5 GeV/c^2. It is extracted from the data by fitting the DY cross-section with its shape derived from the MRS 43 parton distribution functions. Results from three different analyses, using different selection criteria and fit methods, show a quite fair agreement. Peripheral Pb-Pb data follow the normal absorption as deduced from p-A and S-U measurements. The pattern shows a departure from the normal absorption curve at mid-centrality followed by a steady decrease with increasing centrality, as already observed from previously collected data samples. A similar conclusion can be drawn from the analysis using E_{ZDC} as a centrality estimator and the GRVLO set of parton distributions to derive the shape of the DY cross-section (Fig.7). There is, in general, a quite good agreement between the 2000 year data and previous results, except for the most peripheral 1996 points which could be contaminated by Pb-air interactions.

6. A New Drell-Yan Reference

As shown in Fig.8, when normalizing at high mass, the DY yield in the mass range $2.9 < M_{\mu\mu} < 4.5$ GeV/c^2 differs by about 10 %, depending on the set of parton distributions (MRS43 or GRVLO). This situation can be overcome by using, as a reference for J/ψ, the DY cross-section in a higher mass region like, for example, $4.2 < M_{\mu\mu} < 7.0$ GeV/c^2, where the Drell—Yan one is

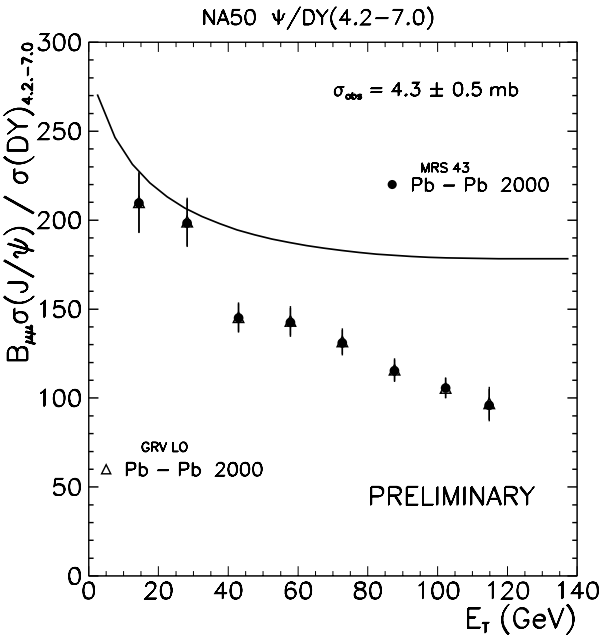

Fig. 9. The $J/\psi/\mathrm{DY}_{2.9-4.5}$ ratio as a function of E_{T}

the only contribution to the data invariant mass spectrum. In Fig.9, we present the cross-sections ratio $(B_{\mu\mu}\sigma_{J/\psi})/\sigma_{DY(4.2-7.0)}$ as a function of E_{T}. The two analyses of year 2000 data, performed with GRV LO

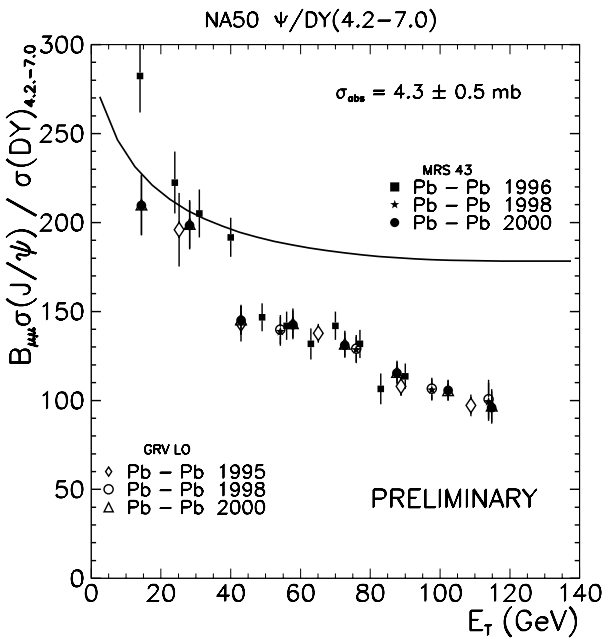

Fig. 10. The $J/\psi/\mathrm{DY}_{2.9-4.5}$ ratio as a function of E_{T} for all NA50 Pb-Pb data

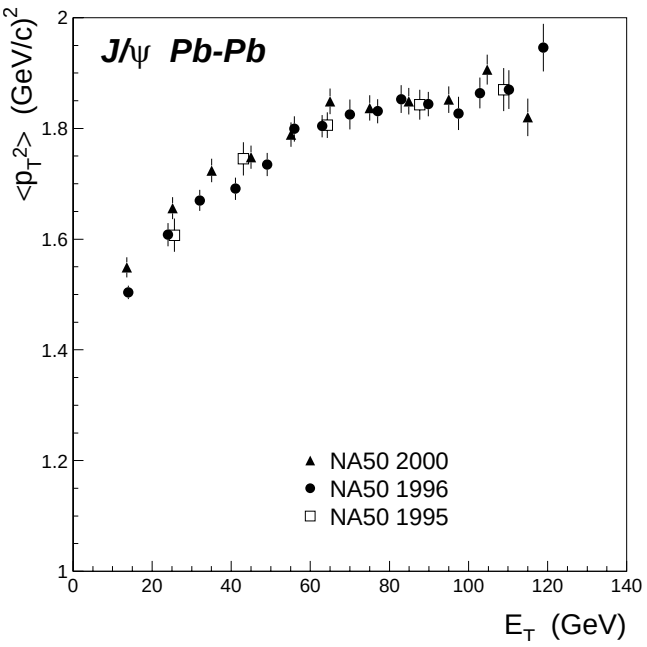

Fig. 11. $\langle p_{\mathrm{T}}^2 \rangle$ of the J/ψ as a function of the transverse energy, as measured in the several Pb-Pb data taking periods

and MRS 43 practically coincide in this case. The cross-check performed by simply counting the number of J/ψ and of high mass DY events is consistent, within good accuracy, with the usual result obtained by fitting the invariant mass spectra and suggest that there is no bias introduced by the fit procedure. The J/ψ suppression pattern remains the same with this new DY reference, but the overall normalization obviously changes. Finally, a comparison of year 2000 results with previous data analises, made either with GRV LO or MRS 43, is presented in Fig.10, using the new DY mass region as a reference. Except for the most peripheral 1996 data, all data agree reasonably well. The anomalous J/ψ suppression is present in all the Pb-Pb data, with the departure of the ratio J/ψ/DY from normal nuclear absorption at mid-centrality followed by its steady decrease with increasing centrality.

7. Transverse Momentum Distributions

In order to investigate the features of the reaction mechanism in more detail, we also study the transverse momentum and transverse mass distributions of J/ψ and their dependence on centrality. The $\langle p_{\mathrm{T}}^2 \rangle$ values for J/ψ obtained from the 1995, 1996 and 2000 Pb-Pb data samples are plotted in Fig. 11 as a function of E_{T}. The overall behaviour is the same in the three data sets, with a fast increase followed by a flatter dependence for the more central collisions. The $\langle p_{\mathrm{T}}^2 \rangle$ values obtained from the 1995 and 1996 data are in good agreement over the measured transverse energy range, but the 2000 year data points are slightly ($< 4\,\%$) but systematically higher in the most peripheral events. This could be due to Pb-air interactions contamination in the 1996 year data. The $\langle p_{\mathrm{T}}^2 \rangle$ values of J/ψ mesons produced in collisions induced by light projectiles (p, O, S) [10,11] have been successfully interpreted in terms of initial-state parton multiple scattering [12,13]. The $\langle p_{\mathrm{T}}^2 \rangle$ values obtained in Pb-Pb interactions at 158 GeV per nucleon together with p-A data at 200 and 400 GeV, and with O-Cu, O-U, and S-U data obtained in collisions at 200 GeV per nucleon, are plotted in Fig. 12, as a function of L, the length of nuclear matter traversed in the initial state, in order to study more precisely the effects of initial state interactions.

The values were fitted according to $\langle p_{\mathrm{T}}^2 \rangle = \langle p_{\mathrm{T}}^2 \rangle_{pp} + a_{gN} \times L$ [13], separately for the three energy sets of points. The $\langle p_{\mathrm{T}}^2 \rangle_{pp}$ term is the contribution from the $c\bar{c}$ production to an isolated pp collision, while the second term arises from gluon multiple scattering before J/ψ production.

The three fitted values for a_{gN} are compatible, and the $\langle p_{\mathrm{T}}^2 \rangle_{pp}$ values increase with beam energy. The result of a simultaneous fit to the three energy data sets, with

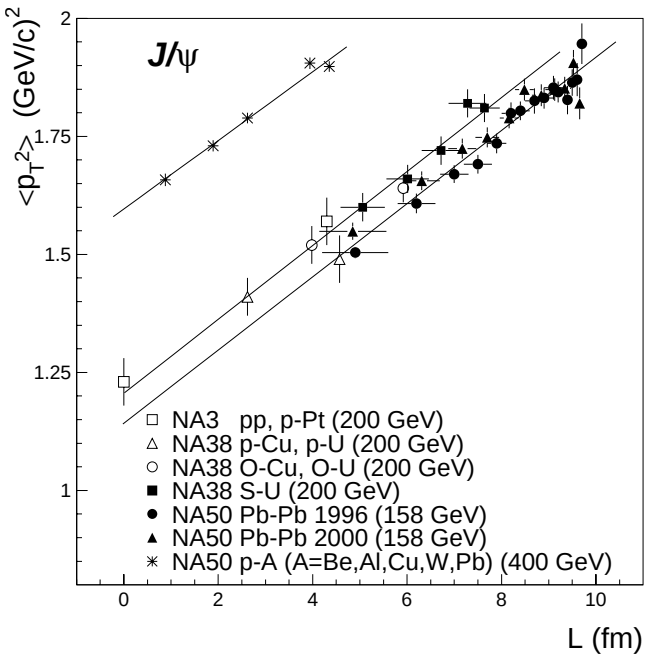

Fig. 12. $\langle p_{\mathrm{T}}^2 \rangle$ values of the J/ψ as a function of the length of matter traversed in the initial state, for three different energies

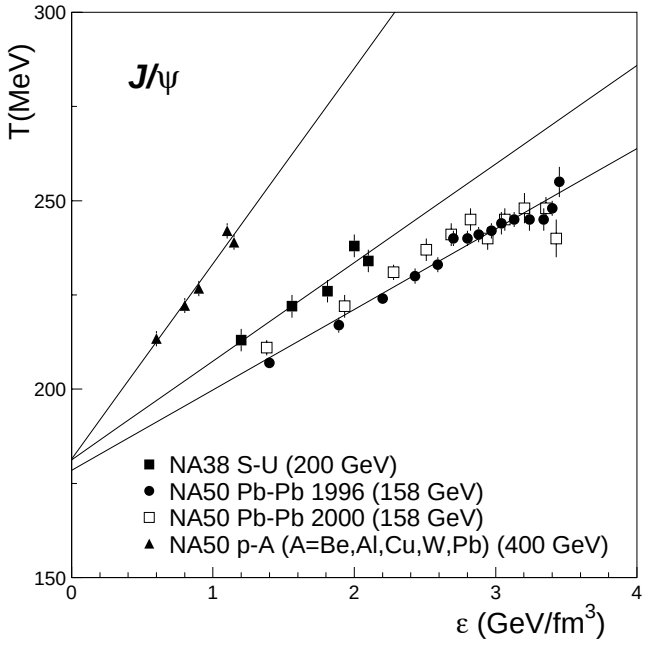

Fig. 13. Inverse slope parameter, T, of the J/ψ as a function of the energy density. The lines are linear fits to the data points, for each beam energy

a common slope, leads to $a_{gN} = 0.077 \pm 0.002$ $(\mathrm{GeV}/c)^2/\mathrm{fm}$.

Results show that $\langle p_{\mathrm{T}}^2 \rangle_{pp}$ increases linearly with $\sqrt{s}$, the total energy in the nucleon-nucleon center of mass system, as seen by the NA3 experiment with pion beams [10]. The observed dependence of the J/ψ $\langle p_{\mathrm{T}}^2 \rangle$ values as a function of the centrality of the collision could be due to initial state multiple scattering of the partons.

8. Transverse Mass Distributions

The J/ψ transverse mass distributions have also been studied. They were fitted with the analytical function $1/T \cdot M_{\mathrm{T}}^2 \cdot K_1(M_{\mathrm{T}}/T)$, where K_1 is the modified Bessel function and the inverse slope, T, can be related to the effective temperature of the system, in thermal models of particle production [14].

The obtained inverse slopes are plotted in Fig. 13 as a function of the energy density reached in the collision, ϵ, calculated in the framework of the Bjorken model [15]. For all systems, the effective temperature seems to increase linearly as a function of the energy density, with compatible T values at $\epsilon = 0$. A simultaneous fit with a common initial T for the three energy data sets gives $T(\epsilon = 0) = (179 \pm 2)$ MeV, while the slope increases linearly with $\sqrt{s}$.

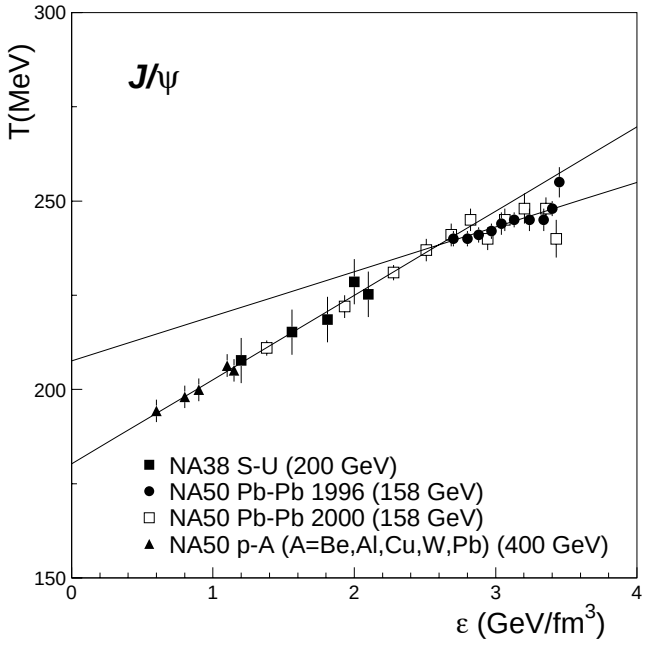

Fig. 14. Same as the previous figure, after rescaling all data sets to 158 GeV

Fig. 14 shows the dependence of T on ϵ, after having rescaled all the data sets to the same energy,

158 GeV. For peripheral Pb-Pb collisions, we only use the points from the data collected in year 2000, free from possible Pb-air contaminating collisions. Results show that the linear increase of T with ϵ becomes flatter when approaching the most central Pb-Pb collisions, with the slopes decreasing from a value of $(22 \pm 1) \cdot 10^{-3}$ to $(12 \pm 3) \cdot 10^{-3}$ fm^3.

Conclusions

In conclusion, the Pb-Pb data collected in different years, including the most recent 2000 year data obtained under improved experimental conditions for the study of very peripheral interactions, are in good agreement except for the most peripheral 1996 data, which could be due to Pb-air contamination in the peripheral Pb-Pb 1996 data set. Two different centrality estimators, $E_{\rm T}$ and $E_{\rm ZDC}$ have been used. New high statistics proton-nucleus data lead to a more accurate determination of the "normal" absorption curve for J/ψ suppression as deduced from lighter interaction systems. Peripheral Pb-Pb interactions are compatible with the normal absorption curve. All Pb-Pb data exhibit a suppression pattern with a departure from the normal nuclear absorption at mid-centrality, followed by a steady decrease for the most central collisions.

All data show a common trend in the evolution, with collision centrality, of the $\langle p_{\rm T}^2 \rangle$ and of T, the inverse slope of the transverse mass distributions, namely a strong initial increase followed by a flatter behaviour. At least in the lighter collision systems, including peripheral Pb-Pb interactions, the observed pattern of $\langle p_{\rm T}^2 \rangle$ with L may be explained in terms of initial state parton multiple scattering.

After taking into account the different energies of the collected data sets, all the collision systems show a very similar linear dependence between T and the energy density reached in the collision, with the same value of T at $\epsilon = 0$. However, the Pb-Pb pattern suggests a change in the slope of the linear increase of T with ϵ, for the most central Pb-Pb collisions.

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НАРОДЖЕННЯ ЧАРМОНІЯ В pA- І ЯДРА-ЯДЕРНИХ ВЗАЄМОДІЯХ НА ПРИСКОРЮВАЧІ SPS В ЦЕРНІ

Н.С. Топільська (від NA50-колаборації)

Р е з ю м е

Представлено нові попередні результати з народження J/ψ-частинок в Pb—Pb-зіткненнях при енергії 158 ГеВ/нуклон. Їх одержано з найостанніших наборів даних, накопичених в 2000 р. при покращених експериментальних умовах. Результати порівнюються з найновішою кривою нормального поглинання, що виведена з нових протон-ядерних даних з великою статистикою. Нові вимірювання дають форму J/ψ-поглинання, що відрізняється від кривої нормального поглинання для середньо-центральних Pb—Pb-зіткнень і продовжує зменшуватися для найбільш центральних взаємодій. Таким чином, підтверджуються результати, одержані з попередніх наборів даних. В експерименті також вимірюються розподіли за поперечними імпульсами та поперечними масами J/ψ-мезонів, що народжуються в pA- і Pb—Pb-зіткненнях. Обговорюється поведінка цих розподілів як функція центральності та енергії зіткнень.

РОЖДЕНИЕ ЧАРМОНИЯ В pA- И ЯДРА-ЯДЕРНЫХ ВЗАИМОДЕЙСТВИЯХ НА УСКОРИТЕЛЕ SPS В ЦЕРНЕ

Н.С. Топильская (от NA50-коллаборации)

Р е з ю м е

Представлены новые предварительные результаты по рождению J/ψ-частиц в Pb—Pb-соударениях при энергии

158 ГэВ/нуклон. Они получены из самых последних наборов данных, накопленных в 2000 г. при улучшенных экспериментальных условиях. Результаты сравниваются с новейшей кривой нормального поглощения, выведенной из новых протон-ядерных данных с большой статистикой. Новые измерения дают форму J/ψ-поглощения, отличающуюся от кривой нормального поглощения для среднецентральных Pb—Pb-соударений и продолжающую убывать для наиболее центральных взаимодействий. Таким образом подтверждаются результаты, полученные из предыдущих наборов данных. В эксперименте также измеряются распределения по поперечным импульсам и поперечным массам J/ψ мезонов, рождаемых в pA- и Pb—Pb-соударениях. Обсуждается поведение этих распределений как функция центральности и энергии соударений.