J/ψ PRODUCTION IN PROTON-NUCLEUS AND NUCLEUS-NUCLEUS INTERACTIONS AT THE CERN SPS

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Abstract

The NA38 and NA50 experiments at the CERN SPS have measured charmonium production in different colliding systems with the aim of observing a phase transition from ordinary hadronic matter towards a state in which quarks and gluons are deconfined (Quark Gluon Plasma, QGP). This experimental research is based on the prediction that the J/ψ yield should be suppressed in deconfined matter. The analysis of the data collected by the NA50 experiment with Pb–Pb collisions at 158 GeV/c per nucleon shows that the J/ψ is anomalously suppressed with respect to the pattern observed in proton-nucleus and light ion reactions.

1 Introduction

In ordinary nuclear matter, quarks and gluons are confined inside nucleons. Non-perturbative calculations of Quantum Chromo Dynamics predict that, when temperature exceeds a critical value $T_c \sim$ 150-180 MeV, nuclear matter should undergo a phase transition into a state of matter in which quarks and gluons are no more confined into hadrons and behave as free particles. Such a state of matter is called Quark-Gluon Plasma (QGP). Heavy-ion collisions are a powerful experimental tool to investigate nuclear matter under extreme conditions: the formation of the QGP is expected to occur in these collisions if the critical temperature and energy density required for the phase transition are reached.

Several probes have been proposed as signatures of the formation of a deconfined state of matter. In particular Matsui and Satz [1] predicted that the J/ψ yield would be strongly suppressed in a deconfined medium due to the Debye screening of the attractive colour force which binds the c and $\bar{c}$ quarks together. J/ψ suppression is a particularly interesting signature of QGP formation because it probes the state of matter in the earliest stages of the collision, since $c\bar{c}$ pairs are produced in hard partonic interactions occurring at that time. Moreover the J/ψ is a tightly bound state that can not be easily broken by interactions with the hadronic medium and therefore it carries its original message through the different stages of the reacting medium.

At the CERN SPS, the NA38, NA51 and NA50 experiments [2, 3, 4] have studied J/ψ production using the $\mu^+\mu^-$ decay channel with incident proton, oxygen, sulphur and lead ions on several targets.

2 Experimental setup and data taking conditions

The J/ψ is detected via its $\mu^+\mu^-$ decay by a dimuon spectrometer which consists of an air-gap toroidal magnet equipped with two sets of multiwire proportional chambers (4 MWPC upstream the magnet and 4 downstream) for muon tracking purposes and with 6 scintillator hodoscopes to provide the dimuon trigger. The covered rapidity window is $2.7 \leq y_{lab} \leq 3.9$.

A quartz beam hodoscope (BH), placed about 33 m upstream from the target, is used to count the incident lead ions and to reject beam pile-up. The NA50 target is a segmented active Pb target: there can be up to 7 subtargets separated by few centimeters of air. Two quartz blades located off the beam axis on the left and right side of each subtarget identify where the interaction has occurred.

The centrality of the collision is estimated event by event using three different detectors. The electromagnetic calorimeter measures the neutral transverse energy (E_T) produced in the interaction in the pseudorapidity window $1.1 \leq \eta_{lab} \leq 2.3$. The zero degree calorimeter measures the energy E_{ZDC}, essentially carried by the projectile spectator (non-interacting) nucleons. It covers the pseudorapidity interval $\eta_{lab} \geq 6.3$. Finally the silicon microstrip detector measures the multiplicity and the angular distribution of charged particles in the acceptance window $1.1 \leq \eta_{lab} \leq 4.2$. For a more detailed description of the detectors see [4].

3 Absolute J/ψ cross-section

NA38 and NA51 experiments collected an extensive set of measurements of J/ψ production using p, O and S beams on several targets.

In order to compare charmonium production in different colliding systems it is useful to define a cross-section per nucleon-nucleon collision as $\mathrm{B}_{\mu\mu}\sigma_{J/\psi}/(A \times B)$ where $\mathrm{B}_{\mu\mu}$ is the branching ratio of J/ψ into two muons and A and B are the projectile and the target mass number respectively. This assumption is based on the fact that charmonium production is a hard process and therefore it should scale as $A \times B$.

The number of J/ψ events is determined by fitting the invariant mass spectrum of opposite sign muon pairs above 2.9 GeV/c^2. The fit is performed

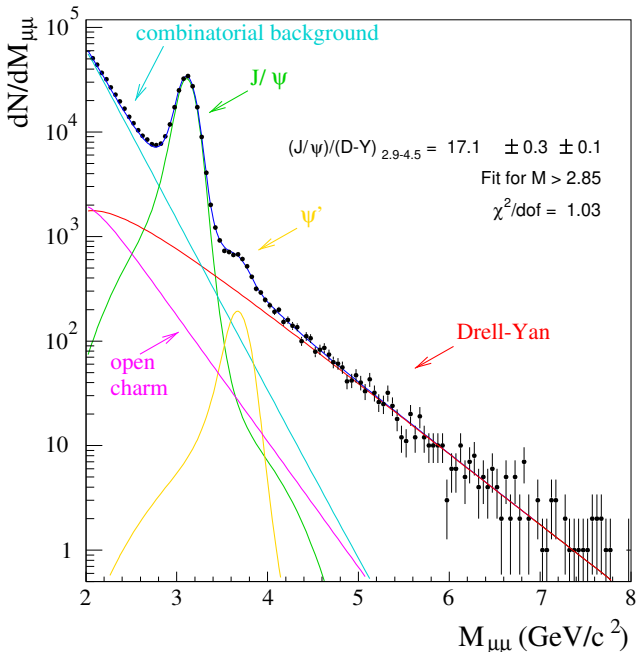

Figure 1: Opposite sign muon pair invariant mass spectrum for Pb–Pb collisions.

including 5 contributions: J/ψ, ψ', Drell-Yan, open charm (i.e. semileptonic decays of D and $\bar{D}$ mesons) and combinatorial background from π and K decays. The shapes of charmonium resonances, open charm and Drell-Yan are extracted from Monte Carlo simulations including the resolution of the NA50 spectrometer, while the combinatorial background is evaluated from the sample of "Like-Sign" muon pairs (i.e. $\mu^-\mu^-$ and $\mu^+\mu^+$) according to the relation:

$$N_{bck} = 2 \cdot \sqrt{N^{++} \times N^{--}}$$

The analysis method is described in detail in [4], an example of such a fit is shown in fig. 1.

In figure 2 the J/ψ cross-section per nucleon-nucleon collision as a function of A×B is represented: it can be seen that all the data from p-p up to central S-U collisions show a continuous and monotonic J/ψ suppression pattern from the lighter to the heavier interacting nuclei [2, 3]. The systematics of J/ψ production from p-p to S-U can be parametrized by the simple law $\sigma_{AB} = \sigma_0(AB)^\alpha$ with $\alpha = 0.918 \pm 0.015$ [2].

In order to appropriately parametrize the observed J/ψ yield, it is useful

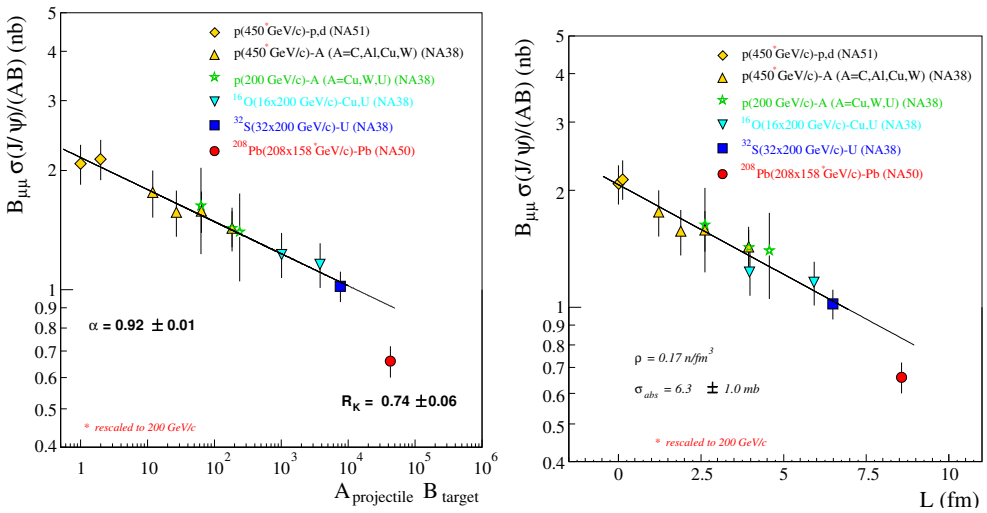

Figure 2: J/ψ cross section as a function of A×B (left panel) and L (right panel) from p–p to Pb-Pb interactions.

to introduce the L variable [1], defined as the average length of nuclear matter traversed by the $c\bar{c}$ bound state while escaping from the interaction region. In particular, L is proportional to the number of nucleons that the $c\bar{c}$ pair can potentially interact with, which is given by $\rho \cdot L$, where ρ is the nuclear density. As a first approximation, the J/ψ cross section can be simply parametrized as $\sigma^{\psi}_{AB} = \sigma_0 e^{-(\sigma^{\psi}_{abs}\rho L)}$ which leads to a J/ψ absorption cross-section of 6.3±1.0 mb. With a full Glauber calculation, a cross section $\sigma^{\psi}_{abs} = 7.2 \pm 1.2$ mb is found [2]. This result can be understood in terms of ordinary nuclear absorption of a preresonant $c\bar{c}$ state meant to become later on, if not destroyed, the fully formed J/ψ.

Successively, the experimental apparatus has been upgraded and the experimental program has been carried on with the Pb beam as well as with proton beams by the NA50 experiment. The ordinary nuclear absorption measured by the NA38 experiment sets the baseline with respect to which we can compare the pattern of J/ψ production in Pb-Pb interactions. In fig. 2 it can be seen that the J/ψ cross-section measured in Pb–Pb collisions lies ~ 5 standard deviations below the value expected from the fit to the data from p–p to S–U [5] and this result indicates that there is a new suppression mechanism at work.

[1] The L variable allow also to perform the J/ψ suppression study as a function of centrality for the same colliding system.

4 The J/ψ over DY ratio

In order to perform a study of charmonium production as a function of the centrality (impact parameter) of the collision, it is necessary to find a replacement for A×B in the definition of the cross section per nucleon-nucleon collision. Since the Drell-Yan (DY) process provides muons in the same mass range as the J/ψ and its cross section is expected to be proportional to the number of elementary nucleon-nucleon collisions without any sizeable nuclear effect [2], the ratio $B_{\mu\mu}\sigma_{J/\psi}/\sigma_{DY}$ can be used to study the centrality dependence of the J/ψ suppression [4] with the advantage that in the ratio $\sigma_{J/\psi}/\sigma_{DY}$ systematic errors related to detector inefficiencies and flux uncertainties cancel.

4.1 The "standard" analysis

The "standard" analysis method is based on the evaluation of J/ψ and DY cross-sections by means of a fit to the invariant mass spectrum of the $\mu^+\mu^-$ pairs, as described above. The whole sample of muon pairs is divided into subsamples according to the transverse energy E_T (or the forward energy E_{ZDC}) of the event; then in each of these subsamples the mass spectra are fitted and the J/ψ over DY ratio is calculated [6].

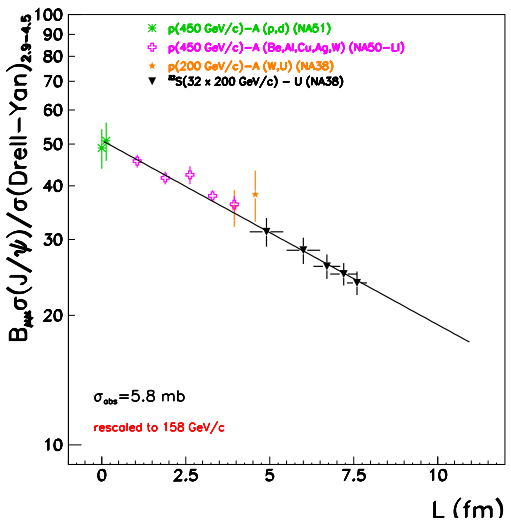

Figure 3: J/ψ/DY ratio in P-A and S-U collisions as a function of L.

[2] This theoretical expectation has been experimentally verified [4].

The results obtained from the p-A and S-U reactions and plotted as a function of L are shown in fig. 3. The fit to the $\sigma_{J/\psi}/\sigma_{DY}$ NA38 data points from p-p to S-U with a simple exponential function ($e^{-\sigma^{\psi}_{abs}\rho L}$), which describes the effect of nuclear absorption, leads to $\sigma^{\psi}_{abs} = 5.8 \pm 0.6$ mb , while the Glauber calculation leads to $\sigma^{\psi}_{abs} = 6.4 \pm 0.8$ mb [2, 6], in good agreement with the values found for the absolute J/ψ cross-section. The new NA50 measurements of $\sigma_{J/\psi}/\sigma_{DY}$ in p-A collisions (included in fig. 3 but not in the fit) appear to be in good agreement with the absorption pattern defined by NA38 data.

In fig. 4, the results obtained for the Pb-Pb data sample as a function of E_T and E_{ZDC} are shown. The solid line visible in figure 5 represents the "ordinary" nuclear absorption of the $c\bar{c}$ pair from the full Glauber calculation, which accounts for the J/ψ yield measured in lighter colliding systems (from p-p to S-U). It is evident that the "peripheral" Pb-Pb data ($L < 8$ fm) agree with the nuclear absorption curve obtained from lighter systems while there is a significative and abrupt departure from this behaviour at $E_T \approx 35$ GeV ($E_{ZDC} \approx 26$ TeV))

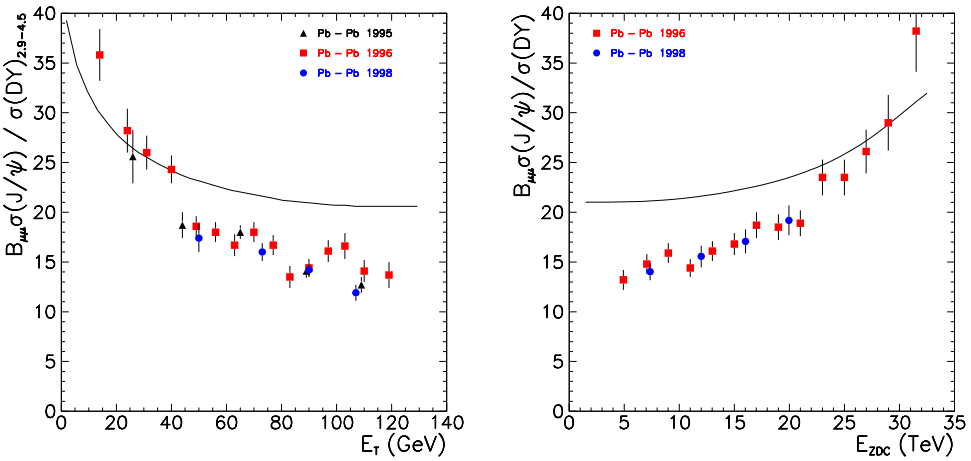

Figure 4: J/ψ/DY ratio in Pb-Pb collisions as a function of E_T (left panel) and E_{ZDC} (right panel) obtained with the standard analysis.

4.2 The "Minimum Bias" analysis

The disadvantage of the standard analysis method is that there are statistical fluctuations in the $\sigma_{J/\psi}/\sigma_{DY}$ ratio, essentially due to the small statistics of the

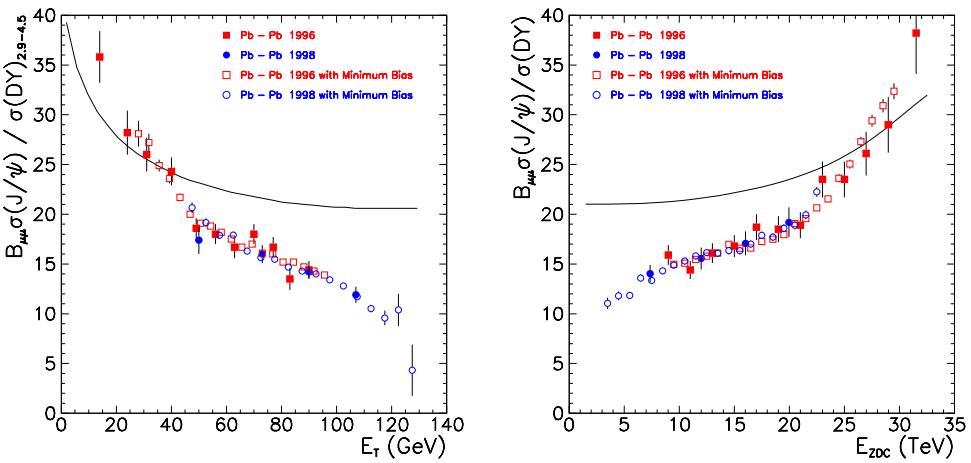

Figure 5: J/ψ/DY ratio in Pb-Pb collisions as a function of E_T (left panel) and E_{ZDC} (right panel) obtained with the standard and minimum bias analysis of the 1996 and 1998 data samples.

DY sample. In order to overcome this problem, a new independent analysis method has been developed [6] in which the sample of DY events is replaced by the huge sample of Minimum Bias (MB) events, collected with a beam trigger which fires each time a non zero energy deposit is detected by the Zero Degree Calorimeter (even for the most central collisions some energy, from produced particles, falls into the ZDC acceptance).

In this analysis method the number of J/ψ events is obtained without any fitting procedure, simply by counting the number of opposite sign muon pairs in the mass range from 2.9 to 3.3 GeV/c^2, after combinatorial background subtraction. In order to compare the results of this analysis with the ones obtained with the standard method, the minimum bias reference has to be converted into the Drell-Yan reference. This is done by multiplying the measured E_T (E_{ZDC}) spectrum of the MB events by the ratio of the theoretical shapes of the E_T (E_{ZDC}) spectra of DY and MB, which can be evaluated in the framework of the Glauber model. Because of the bigger size of the minimum bias sample, the new analysis is no more affected by statistical fluctuations and a finer E_T binning is possible. It is also free from most inefficiencies as it is still computed from a ratio of experimental quantities (namely the spectra of J/ψ and MB events).

The J/ψ over DY ratios obtained with the two independent analyses show a

good agreement, as it can be seen in fig. 5 where the complete J/ψ suppression pattern obtained with the standard (closed points) and the minimum bias (open points) analysis for the 1996 and 1998 data samples is plotted as a function of the transverse energy E_T [7] and of the forward energy E_{ZDC} [8].

The 1996 data points are plotted only for $E_T < 90$ GeV ($E_{ZDC} > 9$ TeV) because, due to the large thickness of the target (12 mm), the most central events could be affected by a not-negligible contamination from "re-interaction" events [6, 7, 8], i.e. events where a projectile spectator fragment from a first (peripheral) collision interacts again downstream (in a different subtarget) with a nucleus, leading to a measured E_T (E_{ZDC}) value typical of a central collision. If not properly identified and rejected, these events are incorrectly classified as central events inducing a systematic bias in the centrality measurement. In order to limit the effect of re-interactions and clarify the suppression pattern for the most central collisions, during 1998 data taking a thinner target (3 mm) has been used, with the drawback of a higher contamination from Pb-air events in the peripheral region. For this reason, 1998 data have been analyzed only for $E_T > 50$ GeV ($E_{ZDC} < 22$ TeV). In the intermediate centrality range the two data sets show a good agreement.

It can be observed that for the most peripheral Pb–Pb collisions the J/ψ suppression can be accounted for by ordinary nuclear absorption while a clear departure from this trend can be seen at $E_T \approx 40$ GeV, ($E_{ZDC} \approx 26$ TeV) which approximately corresponds to an impact parameter $b \approx 8$ fm. It is also evident that there is no saturation of J/ψ suppression for the most central Pb–Pb collisions: a second change of slope in the J/ψ suppression pattern can be observed at $E_T \approx 90$ GeV ($E_{ZDC} \approx 10$ TeV).

5 Conclusions

The combined results of the NA38, NA51 and NA50 experiments (fig. 6) clearly indicate a step-wise J/ψ suppression pattern with no saturation for the most central collisions.

The experimentally observed suppression is much steeper (when the experimental E_T resolution is taken into account) than the results of the predictions of all presently available models of J/ψ suppression based on the absorption of the meson by interactions with the surrounding hadronic matter.

On the contrary the observed suppression pattern can be naturally understood as due to successive melting of charmonium bound states [3] (χ_c and J/ψ)

[3]It is known that $\approx 30\%$ of the J/ψ's produced in hadronic interactions come from radiative decay of χ_c mesons

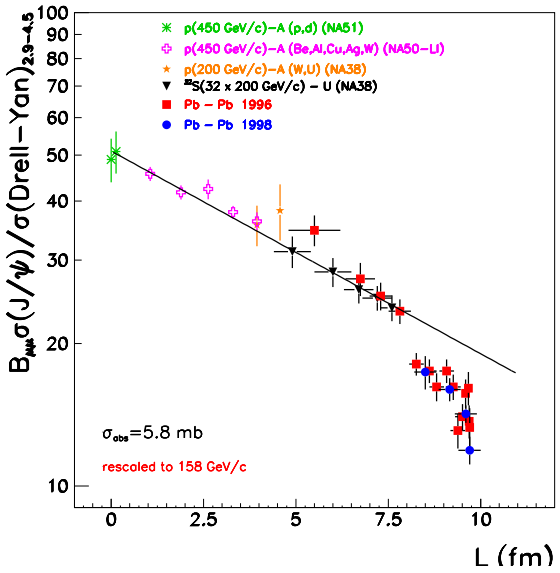

Figure 6: J/ψ/DY ratio from p-p to Pb-Pb collisions as a function of L.

in a deconfined medium, or to the dissociation of χ_c in hot hadronic matter (which may occur slightly below the critical temperature) and the melting of J/ψ in deconfined matter [9]. Hence it can be concluded that the J/ψ suppression pattern observed in the NA50 data provides significant evidence for deconfinement of quarks and gluons in Pb–Pb collisions.

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