J/ψ SUPPRESSION IN PB–PB COLLISIONS AT CERN SPS

FRANCESCO PRINO FOR THE NA50 COLLABORATION

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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). In fact it was predicted 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 in central collisions and the observed pattern can be considered as a strong indication for QGP production.

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 named 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 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 can only be produced 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 and NA50 experiments 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 $2.8 \leq y_{lab} \leq 4.0$.

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 $1.5 \leq \eta_{lab} \leq 3.5$.

A quartz beam hodoscope (BH), placed about 33 m upstream the target is also 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. For a more detailed description of the detectors see Ref. 4.

3 Charmonium production in p–A and light ion interactions

NA38 and NA51 experiments collected an extensive set of measurements of J/ψ production using p, O and S beams on several targets. Since charmonium production is a hard process and therefore it scales as A×B (where A and B are the projectile and the target mass number respectively), it is possible to define a cross-section per nucleon-nucleon collision as $B_{\mu\mu}\sigma_{J/\psi}/(A \times B)$, where $B_{\mu\mu}$ is the branching ratio of J/ψ into two muons, in order to compare charmonium production in different colliding systems.

The standard analysis method has been described in detail in Ref. 4. 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 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. An example of invariant mass spectrum is presented 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 $\alpha = 0.918 \pm 0.015$[3]. Within the framework of the Glauber model, using a simple first order exponential fit, these data lead to a J/ψ absorption cross-section of 5.9 ± 0.6 mb (equivalent to 6.4 ± 0.8 mb for a full Glauber calculation)[3]. 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. This normal suppression sets the baseline with respect to which we can compare the pattern of J/ψ production in Pb-Pb interactions.

4 Anomalous J/ψ suppression in Pb–Pb collisions

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

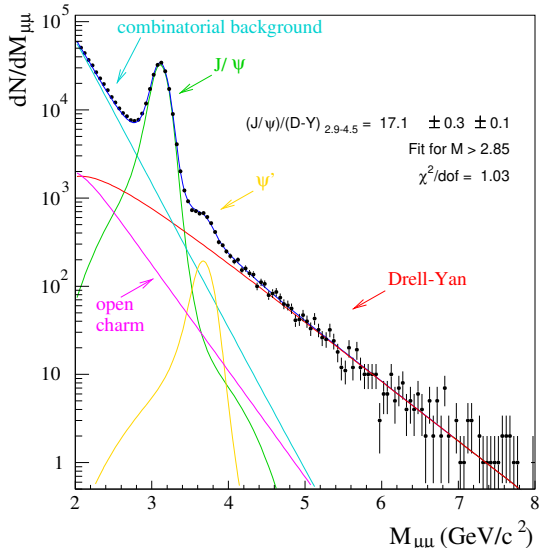

Figure 1. Opposite sign muon pair invariant mass spectrum for Pb–Pb collisions.

from p–p to S–U and this result indicates that there is a new suppression mechanism at work.

In order to perform a study of charmonium production as a function of the collision centrality, 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, the ratio $B_{\mu\mu}\sigma_{J/\psi}/\sigma_{DY}$ can be used to study the centrality dependence of the J/ψ suppression[5] with the advantage that in the ratio $\sigma_{J/\psi}/\sigma_{DY}$ systematic errors related to detector inefficiencies and flux uncertainties cancel. The transverse energy spectrum is then divided into bins: in each of these bins a fit to the invariant mass spectrum of the muon pairs is performed and the J/ψ over DY ratio is calculated[6].

The disadvantage of this analysis method is that there are statistical fluctuations in the $\sigma_{J/\psi}/\sigma_{DY}$ ratio, essentially due to the small statistics of the DY sample. In order to overcome this problem, a new independent analysis method has been developed[7] 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 every time that a non zero energy deposit is detected by the Zero

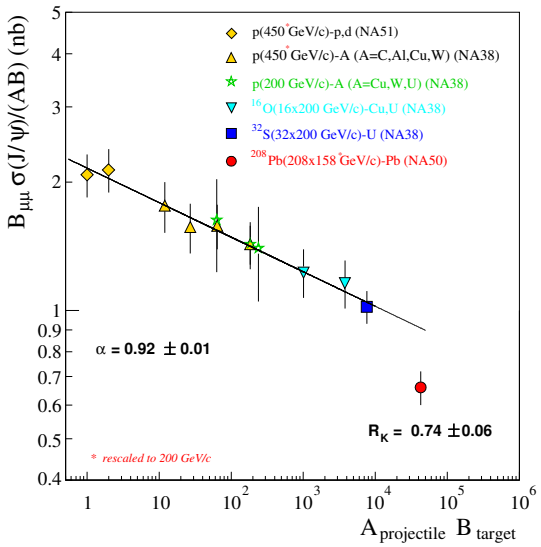

Figure 2. J/ψ cross section as a function of A×B from p–p to Pb-Pb interactions.

Degree Calorimeter (even for the most central collisions some energy, from produced particles, falls into the ZDC acceptance).

In this anaysis 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 multiplying the measured E_T spectrum of the MB events by the ratio of the theoretical shapes of the E_T spectra of DY and MB, evaluated in the frame 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 numbers.

The J/ψ over DY ratios obtained with the two independent analysis show a good agreement, as it can be seen in fig. 3 where the complete J/ψ suppression pattern obtained with the standard (closed circles) 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.

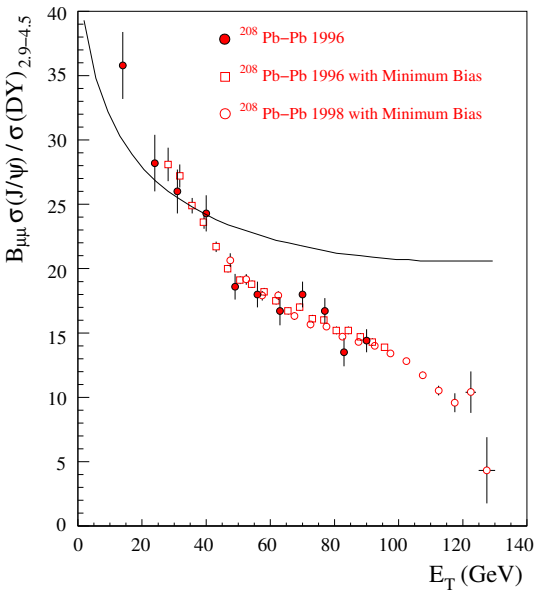

Figure 3. $B_{\mu\mu}\sigma_{J/\psi}/\sigma_{DY}$ ratio as a function of E_T, obtained with the standard and minimum bias analysis of the 1996 and 1998 data samples.

The solid line visible in the figure represents the "ordinary" nuclear absorption of the $c\bar{c}$ pair, which accounts for the J/ψ yield measured in lighter colliding systems (from p-p to S-U). 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, which approximately corresponds to an impact parameter of 8 fm. It is also evident that there is no saturation of J/ψ suppression for the most central Pb–Pb collisions: a second drop in the J/ψ suppression pattern can be observed at $E_T \approx 90$ GeV.

5 Conclusions

The combined results of the NA38 and NA50 experiments 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 pre-

dictions 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 in a deconfinement scenario. Since $\approx$ 30–40% of the J/ψ's come from radiative decay of χ_c mesons, the first anomalous step in charmonium suppression can be understood as due to the melting in deconfined matter of the χ_c, which is less tightly bound than the J/ψ. In this scenario, the second drop, observed for more central collisions, would be due to the dissolving of the more tightly bound J/ψ meson, which requires energy densities grater than the ones necessary to melt the χ_c.

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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