Centrality dependence of J/ψ suppression in Pb-Pb collisions at 158 GeV/c

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The NA50 experiment at the CERN SPS studies charmonia and Drell-Yan production in Pb–Pb collisions at 158 GeV/c per nucleon. The J/ψ was predicted to be one of the best signatures for the phase transition from ordinary hadronic matter towards quark-gluon plasma (QGP). The analysis of the data collected by the NA50 experiment 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

Non-perturbative Quantum Chromo Dynamics predicts that under extreme conditions of temperature and energy density a phase transition between ordinary nuclear matter and a new state named Quark-Gluon Plasma (QGP) can occur. In a QGP, quarks and gluons are no more confined into hadrons and behave as free particles.

Experimentally, heavy ion collisions seem to be the best tool to reach the extreme conditions required for the phase transition and several probes are investigated as signatures of the formation of the deconfined state of matter. In particular Matsui and Satz [1] predicted that the formation of QGP would screen the colour binding potential, preventing c and $\bar{c}$ quarks to form charmonia states, and therefore leading to a suppression of the J/ψ yield. This signature is particularly interesting since $c\bar{c}$ pairs can only be produced in the early stages of the collision, therefore probing the matter in which they are created. Besides, tightly bound states as J/ψ are not easy to break in soft interactions with the hadronic medium. Finally dimuons resulting from the decay of the J/ψ mesons are not affected by strong interactions, therefore bringing to the detectors an undistorted image of the earlier phases of the collision.

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. All the data from p-p up to central S-U collisions show a continuous and monotonic J/ψ suppression trend from the lighter to the heavier interacting nuclei [2, 3, 4]. The result can be understood in terms of normal nuclear absorption of the $c\bar{c}$ pair before it forms the J/ψ state. This normal suppression sets the baseline with respect to which we can compare the pattern of J/ψ production in Pb-Pb interactions.

The results presented in the following concern the 1995, 1996 and 1998 run periods.

2 Experimental setup and data taking conditions

A schematic overview of the NA50 apparatus is shown in Fig. 1. The main detector component is a dimuon spectrometer which includes a hadron absorber, an air gap toroidal magnet, 8 multiwire proportional chambers for muon tracking and a system of 6 scintillator hodoscopes for triggering purposes. The covered rapidity window is $2.8 \leq y_{lab} \leq 4.0$. The centrality of the collision is estimated on an event by event basis by means of three different detectors. The electromagnetic calorimeter measures the

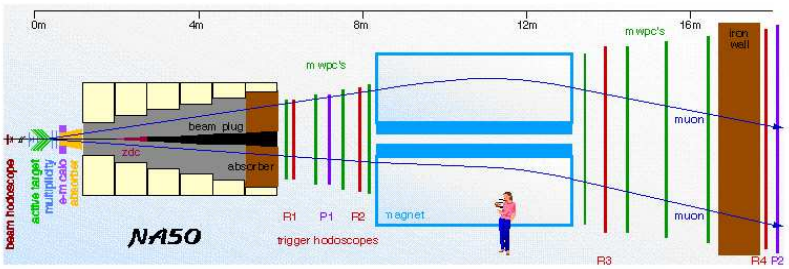

Fig. 1: The NA50 experimental setup

neutral transverse energy released in the interaction (E_T) and it covers the acceptance window $1.1 \leq \eta_{lab} \leq 2.3$. The zero degree calorimeter [5] measures the energy E_{ZDC}, mainly carried from the projectile nucleons which have not participated in the collision. It covers the pseudorapidity interval $\eta_{lab} \geq 6.3$. Finally a silicon microstrip detector measures the multiplicity of charged particles in the acceptance window $1.5 \leq \eta_{lab} \leq 3.5$. The incident lead ions are counted by a quartz beam hodoscope (BH), placed about 33 m upstream the target. The detector is also used to detect pile-up events. The NA50 active target [6] can be made up to 7 subtargets and two quartz blades located off the beam axis on the left and right side of each subtarget identify the subtarget where the primary interaction has occurred. For a more detailed description of the detectors see [7]. The setup is very similar for the 1995, 1996 and 1998 ion runs, except for the number of subtargets and their thickness. A brief summary of the data taking conditions is given in Table 2.

Year	1995	1996	1998
Beam Intensity (Pb/burst)	$3 \star 10^7$	$5. \star 10^7$	$5.5 \star 10^7$
Target thickness	$17\%\lambda_I$	$30\%\lambda_I$	$7\%\lambda_I$
Number of subtargets	7	7	1
Number of triggers	$60 \star 10^6$	$170 \star 10^6$	$80 \star 10^6$
J/ψ events	50000	190000	40000
Drell-Yan events ($M_{\mu\mu} > 4.2 \;\; GeV/c^2$)	630	2100	500

Table 1 Comparison of some characteristics of the three Pb–Pb data taking periods.

3 The standard $J/\psi/DY$ analysis

The standard analysis method has been described in details in [7]. J/ψ and ψ' resonances are identified through their decay into two muons. Since the Drell-Yan (DY) process provides muons in the same mass range as the J/ψ and its cross section scales with the number of primary collisions from p-p to Pb-Pb collisions without showing sizeable nuclear effects, it is used as a reference to study the charmonium suppression pattern as a function of the collision centrality [10]. Therefore in the ratio $\sigma_{J/\psi}/\sigma_{DY}$ systematic errors related to inefficiencies and flux uncertainties cancel.

The number of J/ψ and DY events is determined by fitting the invariant mass spectrum of opposite sign muon pairs above 2.9 GeV/c^2. An example of the invariant mass spectrum collected in 1996 is shown in Fig. 2. In this mass range the contribu-

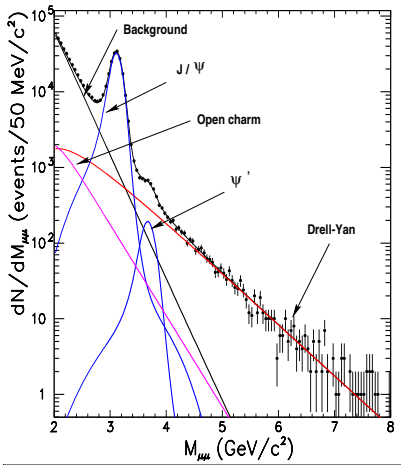

Fig. 2: Opposite sign muon pair invariant mass spectrum for Pb–Pb collisions at 158 GeV/c per nucleon.

tions of J/ψ, ψ', DY, open charm (i.e. semileptonic decays of D and $\bar{D}$ mesons) and combinatorial background from π and K decays are considered.

Fig. 3 shows the J/ψ to DY ratio, multiplied by the branching ratio of J/ψ into two muons, as a function of the transverse energy E_T, for the 1996 data sample. The transverse energy spectrum has been divided into 15 bins, in order to study the centrality dependence of the $\sigma_{J/\psi}/\sigma_{DY}$ ratio [9].

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 collisions). The estimated absorption cross section is $\sigma_{abs}^{J/\psi} = 5.8 \pm 0.7\, mb$ (equivalent to $6.4 \pm 0.8\, mb$ for a full Glauber calculation) [4]. A clear departure from this "normal" trend can be seen in the E_T range around 40 GeV, which approximately

corresponds to an impact parameter of 8 fm.

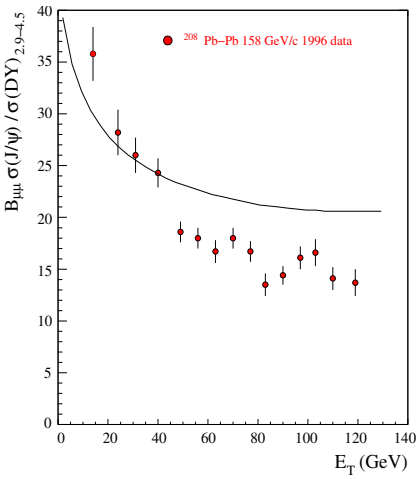

Fig. 3: Ratio of J/ψ to Drell–Yan cross sections as a function of centrality in Pb–Pb collisions at 158 GeV/c. The line account for normal nuclear absorption, as deduced from a fit to lighter interacting nuclei.

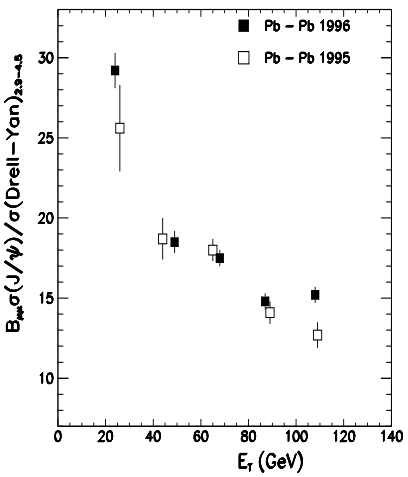

Fig. 4: Comparison between the 1995 (open squares) and 1996 (closed squares) $\sigma_{J/\psi}/\sigma_{DY}$ standard analysis. The difference at the upper end of the E_T range is due to re-interactions in the target.

The 1996 and 1995 results are compared in Fig. 4. Due to the lower statistics collected in 1995, the data have been divided into 5 centrality bins instead of 15. The two sets of data turn out to be in good agreement, except for the highest E_T bin, where the 1996 point is significantly above the 1995 one. This is interpreted as a consequence of the thicker target used in 1996: with a target thickness of $30\%\lambda_I$, it is conceivable that a spectator fragment from a first peripheral collision reinteracts downstream, resulting in measured values of E_T typical of a much more central collision. If not properly identified and rejected, these events are incorrectly considered as central interactions, while the measured dimuons were actually produced in peripheral collisions.

4 The minimum bias analysis

The statistical fluctuations in the $\sigma_{J/\psi}/\sigma_{DY}$ ratio, visible in Fig. 3, are essentially due to the small statistics sample of DY events. In order to overcome this problem, a new independent analysis method has been developed [8]. The sample of DY events is now replaced by the huge sample of minimum bias events. Minimum bias (MB) events are those collected with a beam trigger which fires when a minimum amount of energy is detected by the zero degree calorimeter.

The J/ψ sample is the same as used in the standard analysis. The number of J/ψ events are obtained without any fitting procedure, by simply counting those events in the dimuon mass range from 2.9 to 3.3 GeV/c^2, after combinatorial background subtraction.

In order to compare the results of this new method with the results previously obtained with the standard method, the minimum bias reference has to be converted into the Drell-Yan reference. The analysis is based on the very similar structure of the transverse energy distribution for minimum bias and Drell-Yan events in AB collisions. The theoretical shapes of both spectra (N^{th}_{MB} and N^{th}_{DY}) can be evaluated in the frame of the Glauber method. Given the fact that the ratio between N^{th}_{MB} and N^{th}_{DY} is proportional to the number of nucleon-nucleon collisions N_{AB}:

$$\frac{N^{th}_{MB}}{N^{th}_{DY}} \sim N_{AB} \tag{1}$$

the new Drell-Yan estimator N_{DY^*} can be obtained according to:

$$N_{DY^*} = N_{MB} * N_{AB} \tag{2}$$

where N_{MB} is the sample of minimum bias events. To compare the minimum bias analysis and the standard one, a normalization has been made in the E_T range 55-75 GeV. The comparison between the standard (closed circles) and the minimum bias

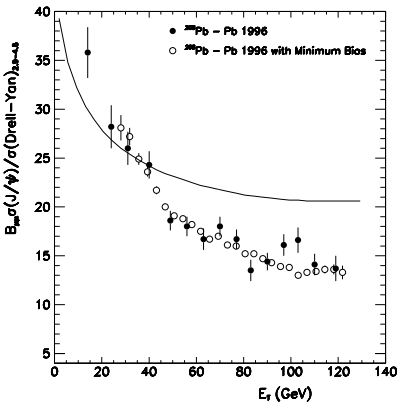

Fig. 5: Comparison of the ratios $\sigma_{J/\psi}/\sigma_{DY}$ and $\sigma_{J/\psi}/\sigma_{DY^*}$ based on the standard (closed circle) and minimum bias (open circle) analysis.

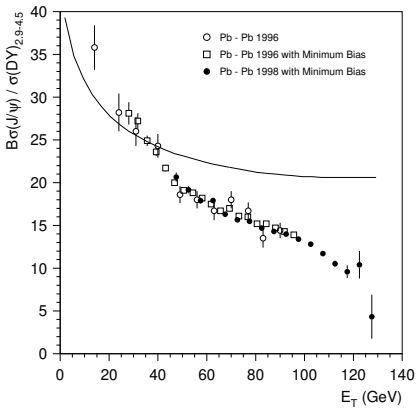

Fig. 6: $\sigma_{J/\psi}/\sigma_{DY}$ ratio as a function of E_T, obtained with the standard and minimum bias analysis of the 1996 and 1998 data samples.

(open circle) analysis is shown in Fig. 5 for the 1996 data sample. Because of the bigger 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 at least up to $E_T = 90\,GeV$. This confirms that the drop around 40 GeV can only be due to a J/ψ suppression, since it is the only sample in common between the two analysis.

The 1998 data taking period has been devoted to understand the behaviour in the high E_T region, since the 1996 data sample seems to be affected by the reinteractions problem.

The complete J/ψ suppression pattern obtained within the 1996 and 1998 data sample is shown in Fig. 6. In this figure the 1996 data points were limited to the range of E_T where the reinteraction events have a negligible influence. In this limited E_T range the two data sets show good agreement. The figure reveals that the J/ψ suppression pattern continues increasing for the most central Pb–Pb collisions, rather than saturating. In fact the data show a second drop in the J/ψ suppression pattern at E_T around 90 GeV.

In order to check the behaviour in the most central region, the J/ψ suppression pattern has also been studied as a function of the forward energy distribution E_{ZDC}. Compared to E_T, the E_{ZDC} variable has a more direct correlation with the geometry of the nucleus-nucleus collisions. In fact the energy collected in the ZDC is mainly carried by the beam spectator nucleons. The result is shown in Fig. 7 for $E_{ZDC} < 22.5$ TeV. It can be observed that even in this case the suppression does not saturate for the most central collisions.

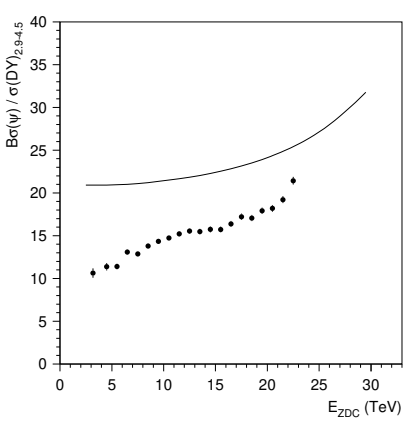

Fig. 7: $\sigma_{J/\psi}/\sigma_{DY}$ ratio obtained within the minimum bias analysis of the 1998 data sample. The centrality of the collision has been estimated from the zero degree energy E_{ZDC}.

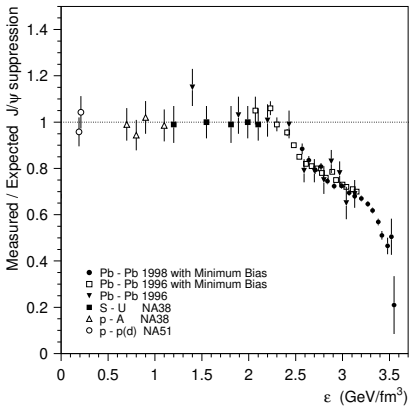

Fig. 8: J/ψ production yields, normalised to the yields expected assuming ordinary absorption as the only source of suppression. Data are shown as a function of the energy density reached in the collisions.

5 Conclusions

The J/ψ over DY patterns obtained with the two different analysis techniques are very similar and both indicate a step-wise trend with no visible saturation for very central collisions.

Moreover the experimentally observed suppression is much steeper 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 pattern can be understood in the framework of a deconfinement scenario.

In order to describe in a more quantitative way the observed trend, the energy density reached in the reactions is estimated. Following Bjorken's model an energy density of the order of $3.5\,GeV/fm^3$ is evaluated for central Pb–Pb collisions [8]. In Fig. 8 the ratio between the observed J/ψ suppression pattern and the normal absorption curve is represented. From the figure it can be deduced that the first drop in the J/ψ production yield happens at energy density above $2.3\,GeV/fm^3$ while the stronger suppression takes place around $3.1\,GeV/fm^3$.

The first anomalous step can be understood as due to the disappearance of the χ_c mesons, responsible for a fraction of the observed J/ψ yield through its (experimentally unidentified) radiative decay. In proton induced collisions this fraction is around 30–40%. The second drop, corresponding to more central collisions, signals the presence of energy densities high enough to also dissolve the more tightly bound J/ψ charmonium state. The binding of the χ_c states starts becoming screened for energy densities above $\sim$ 2.3 GeV/fm^3, while the tightly bound J/ψ requires an energy density above $\sim$ $3\,GeV/fm^3$.

Hence it can be concluded that the J/ψ suppression pattern observed in the data provides significant evidence for deconfinement of quarks and gluons in Pb–Pb collisions.

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