ANOMALOUS J/ψ PRODUCTION IN Pb-Pb COLLISIONS AT 158 GeV PER NUCLEON

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Cross-sections for J/ψ, ψ' and Drell-Yan production in Pb-Pb collisions at 158 GeV/c per nucleon are presented and compared with previous results obtained with lighter projectiles and targets by the NA38 and NA51 collaborations using the same apparatus. An anomalous decrease of J/ψ and ψ' production is observed.

Introduction

The aim of the NA50 experiment is to study the dimuon decay of vector mesons in high energy heavy ion collisions, in order to get evidence for the eventual formation of the quark-gluon plasma: the so-called "J/ψ suppression", resulting from colour screening induced by quark and gluon deconfinement, is supposed to be one of the clearest signature of the existence of the plasma [1].

The first attempts to look for J/ψ suppression in heavy ion collisions at CERN started in 1986 with an extensive program developed by the collaboration NA38, which studied the collisions between protons and nuclei such as oxygen and sulphur on various heavy targets. The data collected by the collaboration NA38 between 1986 and 1992 are used as a systematic experimental reference.

This paper reports preliminary results on

J/ψ and ψ' production obtained at the CERN SPS using a beam of Pb ions at 158 GeV/c incident momentum per nucleon hitting a fixed Pb target.

1 Experimental conditions

The NA50 detector is an upgraded version of the previous NA38 apparatus [2], which was mainly composed of a dimuon spectrometer, an electromagnetic calorimeter, an active segmented target and beam counters.

The dimuon spectrometer has been in use at CERN since 1980. In this experiment, it intercepts the pseudo-rapidity interval $2.8 < \eta < 4.0$ and the mass resolution obtained for J/ψ is 3.2%. The acceptance for muon pairs produced in the selected kinematical domain (see section 2 below) is 13.4% in the J/ψ mass region.

The spectrometer has been complemented by additional detectors in order to get several independent estimates of the centrality of the collisions.

The electromagnetic calorimeter is an essential tool for this purpose. A new version of this device has been built for NA50. Its resolution is 5% for central Pb-Pb collisions. It measures the neutral transverse energy produced in the interaction, in a pseudo-rapidity interval $1.1 < \eta < 2.3$, just outside the acceptance of the spectrometer, in order to preserve the muon mass resolution. This transverse energy is directly correlated to the impact parameter of the collision.

A very forward hadronic calorimeter (called ZDC for Zero Degree Calorimeter) detects the spectator fragments of the interacting Pb projectile, and thus provides another information on the centrality of the reaction, which is of course correlated with the previous one.

Data were taken at CERN during 5 weeks in November and December 1995. An incident flux of 3.5 $10^7 Pb^{82+}$ ions/burst on 7 Pb subtargets 1 mm thick (17 % interaction length) provided an average of 1000 dimuon triggers/burst. Approximately 6.0 10^7 dimuon triggers were registered during the run, and 85% of the available data are used in this analysis.

2 Data selection and analysis

The spectrometer off-line reconstruction program requires that two tracks in the toroidal magnet are reconstructed from the hits of the proportional chambers, and that the corresponding trigger counters are fired. The target algorithm identifies which one of the seven subtargets was the origin of the two reconstructed muons. Finally, for background subtraction purpose, a fiducial cut is required which guarantees that the acceptance of the spectrometer is independent from the sign of the electric charge of the muons. This is obtained by rejecting all muon pairs where at least one of the muons would be lost if it happened to carry the opposite charge.

The analysis is restricted to muon pairs within the kinematical domain where the acceptance of the spectrometer is larger than 10 %. This domain is defined as follows:

$$0.0 < y_{cm} < 1.0 \iff 2.92 < y_{lab} < 3.92$$
$$-0.5 < \cos\theta_{CS} < 0.5$$

where y is the dimuon rapidity and θ_{CS} the polar angle of one of the muons in the Collins-Soper reference frame.

The invariant mass spectrum of the opposite sign muon pairs beyond 2 GeV/c^2 , not corrected for acceptance, is presented in figure 1. The background of π and K meson decays leading to uncorrelated muons is included in this spectrum: a well-known procedure allows to estimate it accurately using the spectra of the like-sign muon pairs. Its contribution is negligible beyond 4.5 GeV/c^2.

In order to determine the absolute numbers of J/ψ, ψ' and Drell-Yan events, the mass spectrum is then fitted beyond 2.9 GeV/c^2 as the superposition of the four contributions mentioned above, neglecting at this level the small contribution of charmed meson decay. The shapes of the J/ψ, ψ' and Drell-Yan spectra are deduced from Monte-Carlo generated events having satisfied all detection, reconstruction and selection criteria. The final data sample contains roughly 50000 J/ψ, 350 ψ' and 650 Drell-Yan pairs with $M_{\mu\mu} > 4.0\mathrm{GeV}/c^2$).

3 Absolute cross-sections

In order to calculate the absolute cross-sections, the raw numbers of events have to be corrected to

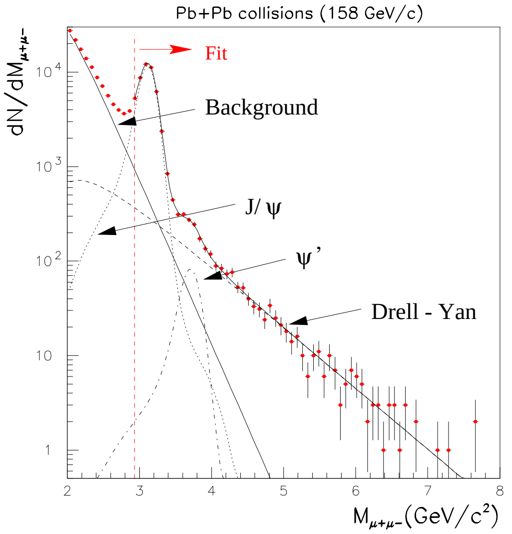

Figure 1: Mass spectrum of the final sample of dimuons.

take account of detector efficiencies, selection cut losses and acceptances. The uncertainties on various efficiencies and cut corrections lead to a total systematic error of 7 % on absolute cross-sections. In the kinematical domain defined in section 2 and where the cross-sections are measured, the acceptance of the spectrometer is 13.4 % for J/ψ, 15.8 % for ψ', and 18.0 % for Drell-Yan events (with $M_{\mu\mu} > 4.5$ GeV/c^2). The following values are obtained for the cross-sections:

$$B_{\mu\mu}\sigma_{J/\psi} = 19.0 \pm 0.2 \pm 1.4\,\mu\text{b}$$

$$\sigma_{Drell-Yan} = 1.42 \pm 0.04 \pm 0.10\,\mu\text{b}$$

$$(2.9\ \text{GeV}/c^2 < M_{\mu\mu} < 8.0\ \text{GeV}/c^2)$$

3.1 Comparison of the Drell-Yan cross-section with NA38 results

The comparison of the Drell-Yan cross-section in Pb-Pb collisions with the results obtained with other projectiles and targets provides a good check of the absence of systematic hidden effects in our cross-section measurements. To account for differences in the kinematical domains and beam energies, the comparison is made after computing, for each system, the value of the so-called "K factor", which is the ratio between the measured value of the cross-section and the lowest order Drell-Yan cross-section calculated from the Glück, Reya and Vogt [3] set of parton distributions, with the appropriate values of $\sqrt{s}$ and in the experimental kinematical domain.

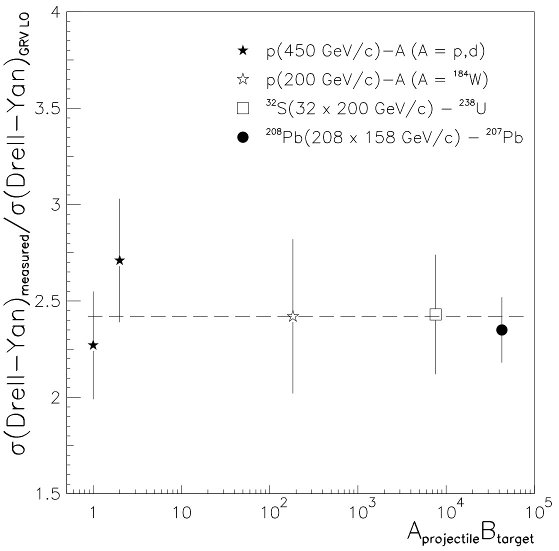

Figure 2: The Drell-Yan K factor as a function of the product of the projectile and target atomic mass numbers.

The results presented in figure 2 show that the Pb-Pb data are in good agreement with the other measurements and with the well-known Drell-Yan theoretical calculations. Consequently, they show the absence of any significant bias in our absolute cross-section determinations.

3.2 Comparison of the J/ψ production cross-section with NA38 results

The J/ψ production cross-section in Pb-Pb interactions is compared in figure 3 with previous values obtained with different beam and target conditions, but with the same spectrometer [4]. For comparison purpose, we show the cross-sections "per nucleon-nucleon collision", obtained by dividing the nucleus-nucleus cross-sections by the product $A \times B$ of the projectile and target atomic mass numbers. All results are rescaled when necessary to the same 200 GeV/c incident beam momentum value and to the same kinematical domain. Our Pb-Pb data have been scaled up from 158 GeV/c to 200 GeV/c using the Schuler [5] scaling function $(1 - M_{J/\psi} / \sqrt{s})^{12}$. The correction factor is 1.32, which leads to increase the value of $B_{\mu\mu}\sigma_{J/\psi} / A_{proj} \times B_{tgt}$ from 0.44 $\pm$ 0.03 nb to 0.58 $\pm$ 0.04 nb.

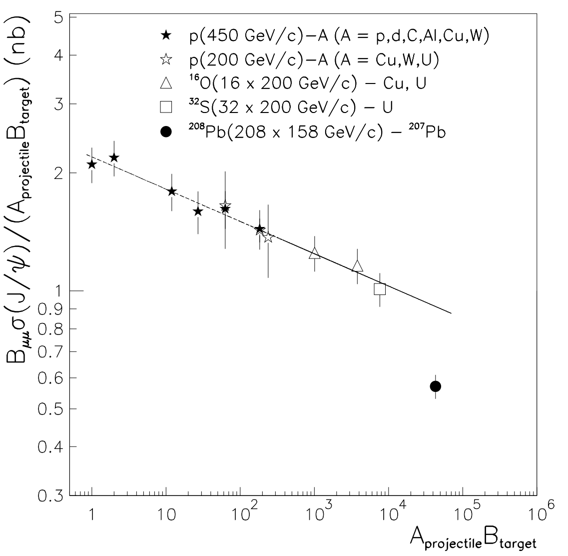

Figure 3: The J/ψ cross-section divided by the product $A_{proj} \times B_{tgt}$ of the projectile and target atomic mass numbers (J/ψ cross-section "per nucleon-nucleon collision") as a function of the product $A_{proj} \times B_{tgt}$.

All the measured cross-sections, except for Pb-Pb interactions, fit correctly a power law $(A \times B)^{\alpha}$, with $\alpha = 0.91 \pm 0.02$, and this value is in perfect agreement with other p-A data [6]. Contrasting with this result, the Pb-Pb cross-section is more than 5 standard deviations off the fitted straight line describing the NA38 results.

This behaviour of the J/ψ production observed in NA38, corresponding to an exponent α slightly smaller than 1, can be interpreted [7] as the result of the break-up, inside the nuclear matter, of a pre-resonant $c\bar{c}g$ state which would have become later the resonant J/ψ state. The J/ψ observed cross-section reflects then the survival probability of the $c\bar{c}g$ state.

This observation has led in the past [8] to introduce a new parameter called L, which is the average path length of the pre-resonant $c\bar{c}g$ or J/ψ state through the two colliding nuclei, calculated in their rest frame. For a given value of b and for any couple of projectile and target, $L(b)$ can be derived from purely geometrical considerations.[a] Thus, $\sigma_{J/\psi}$ can be written as $\sigma_0\, e^{-n_0\, \bar{L}\, \sigma_{abs}}$ where $n_0 = 0.14\ \mathrm{fm}^{-3}$ is the standard nucleon density in nuclear matter, $\bar{L}$ is averaged over all the possible values of the impact parameter b and σ_{abs} is the absorption cross-section. A fit of this expression to the experimental data leads to $\sigma_{abs} = 6.3 \pm 1.2$mb, when excluding the Pb-Pb data from the fit.

[a] A model of hard spheres has been used.

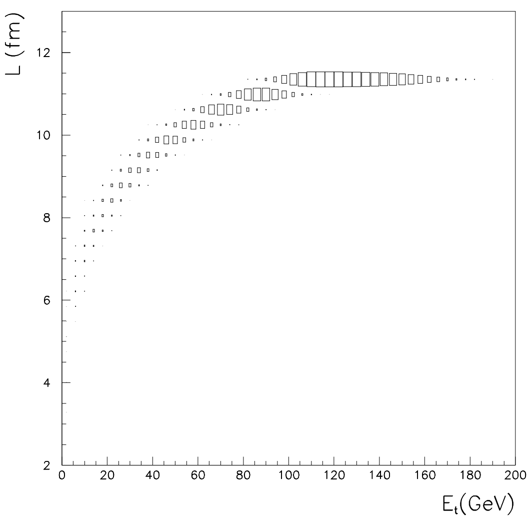

Figure 4: The average path length L of the $c\bar{c}g$ state inside nuclear matter as a function of the transverse energy E_T in Pb-Pb collisions.

4 Cross-sections as a function of centrality

As already mentioned in section 1, the transverse energy E_T measured with the electromagnetic calorimeter is correlated with the impact parameter b. A selection of the events in transverse energy bins is therefore equivalent to a selection in b bins, or in L bins. The relation between L and E_T is presented in figure 4, where the saturation of L for large values of E_T reflects the shape of $L(b)$. Thus, in order to study the cross-sections as a function of centrality, the data have been divided into 5 transverse energy bins, as shown in figure 5, where the distribution of the measured E_T value is presented.

The accuracy of our results can be substantially improved if we consider the ratio of the J/ψ to Drell-Yan cross-sections, rather than the previous "cross-section per nucleon-nucleon collision", as the Drell-Yan cross-section is proportional to the product $A \times B$. There is indeed a significant advantage, from an experimental point of view, to adopt this new presentation, since the ratio $\sigma_{J/\psi}/\sigma_{DY}$ is unsensitive to all systematic errors, including inefficiencies and beam flux uncer-

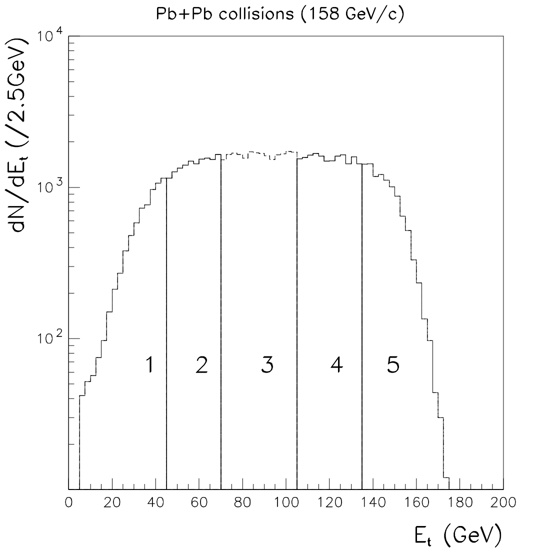

Figure 5: The neutral transverse energy E_T spectrum of opposite-sign muon pairs for masses larger than 2.9 GeV/c^2. The data are not corrected for subtarget identification inefficiency at low E_T.

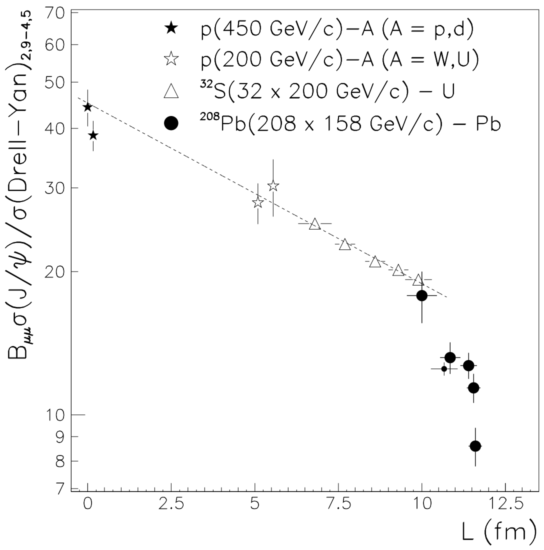

Figure 6: The ratio of J/ψ to Drell-Yan cross-sections as a function of L. The Pb-Pb data are rescaled at 200 GeV/c, as well as the p-p and p-d results.

tainties, which are identical for the two samples of events. A correction has to be applied to the measured Drell-Yan cross-sections to take account of the differences between the elementary p-p, p-n and n-n Drell-Yan cross-sections.

Figure 6 shows the ratio of J/ψ to Drell-Yan cross-sections measured in NA50 in the five E_T bins defined in figure 5, rescaled at 200 GeV/c, and compared with other available results from NA38 and NA51 obtained for different values of $\bar{L}$. The NA50 result integrated over all values of E_T and corrected for subtarget identification inefficiency is also presented in figure 6. When the Pb-Pb points are excluded, an absorption cross section of 6.2 ± 0.7 mb is obtained from the fit to the data of the exponential relation given in section 3.2. The Pb-Pb integrated result ($B_{\mu\mu}\sigma_{J/\psi}/\sigma_{DY} = 12.5 \pm 0.4$) corresponding to an average $\bar{L}$ of 10.7 fm, lies more than 9 standard deviations below the value expected from pure nuclear absorption models :

$$R_K = (\sigma_{meas.}/\sigma_{expec.})_{Pb-Pb} = 0.71 \pm 0.03$$

The measurements in the 5 bins in E_T show a strong dependence of this effect with the centrality of the collision. The point corresponding to the most central Pb-Pb collisions ($b < 2.5$ fm) is lower than the expected value by a factor 0.52 ± 0.05, while for the most peripheral one ($b > 8$ fm) the result is close to the value observed in the most central S-U interactions.

5 $\psi'/(J/\psi)$ cross-section ratio

In order to perform the analysis of ψ' production, ψ' events are extracted from the NA50 dimuon mass spectra by the same method as already explained. However, care has to be taken of the high mass tail of the $D\bar{D}$ contribution, which is also introduced in the mass spectrum fit, as this contribution is no longer negligible compared to the total number of ψ' events. Averaged over all E_T values, the measured ratio of ψ' to J/ψ cross-sections is :

$$(B'_{\mu\mu}\ \sigma_{\psi'}/B_{\mu\mu}\ \sigma_{J/\psi})_{Pb-Pb} = (0.59 \pm 0.09)\%$$

This ratio is compared to the results of other previous experiments in figure 7. No rescaling correction has been applied to take account of the various beam energies, as Fermilab E789 experiment has shown [9] that the ratio $\psi'/(J/\psi)$ is independent of the energy. For proton-nucleus collisions, the ratio appears also independent of the mass of the target, the average value beeing $(1.8 \pm 0.1)\%$. This is well understood in the frame of the absorption model, where the preresonant $c\bar{c}g$ state is expected to have the same behaviour inside nuclear matter, whatever the final charmonium state. As shown in figure 7, a deviation from this behaviour was already observed in NA38 S-U collisions, where the result was $B'_{\mu\mu}\,\sigma_{\psi'}/B_{\mu\mu}\,\sigma_{J/\psi} = (0.76 \pm 0.06)\%$. Taking account of the large statistical error of the NA50 result, we can only conclude that the suppression of the ψ' relative to the J/ψ does not change significantly between S-U and Pb-Pb collisions. It can be deduced from the data shown in figures 6 and 7 that the absolute ψ' production normalised to the Drell-Yan cross-section seems to decrease even more than the J/ψ production when S-U and Pb-Pb interactions are compared :

$$\left(\frac{B'_{\mu\mu}\,\sigma_{\psi'}}{\sigma_{D-Y}}\right)_{Pb-Pb} = (0.46 \pm 0.08).\left(\frac{B'_{\mu\mu}\,\sigma_{\psi'}}{\sigma_{D-Y}}\right)_{S-U}$$

while the corresponding number for J/ψ production is 0.56 ± 0.02 The analysis of the $\psi'/(J/\psi)$ cross-section ratio as a function of E_T, i.e. of centrality, does not show any significant variation in the Pb-Pb data, in contrast with the NA38 S-U results [10]. So, while a first indication of unexpected charmonium suppression had been already observed with ψ' in central S-U collisions [10], the NA50 results show that, in Pb-Pb interactions, both J/ψ and ψ' are increasingly suppressed with centrality in the same proportion.

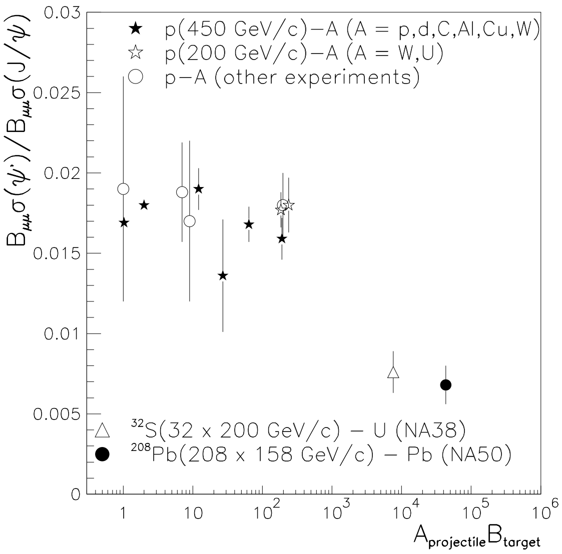

Figure 7: The ratio of ψ' to J/ψ cross-sections in p-A, S-U and Pb-Pb collisions.

Conclusion

We have observed in Pb-Pb collisions at 158 GeV per nucleon a strong reduction in the J/ψ and ψ' production cross-sections compared to the extrapolations based on the "absorption" model from previous experiments. Several authors [11] consider that this effect could indeed be explained by the occurrence of the quark and gluon plasma phase, the J/ψ production being totally suppressed in regions where the energy density exceeds a critical value slightly greater than the density obtained in central S-U collisions. Other attempts [12] considering the interaction of the charmonia with "comoving" particles do not seem presently to describe quantitatively all the available results on J/ψ and ψ' production in nuclear collisions.

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