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Evidence for deconfinement of quarks and gluons from the J/ψ suppression pattern measured in Pb-Pb collisions at the CERN-SPS

NA50 Collaboration

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Abstract

The analysis of the data collected by the NA50 experiment in 1998, reported in this paper, extends and clarifies the pattern of the previously observed J/ψ anomalous suppression. This new measurement, besides providing a deeper understanding of the previous observations, reveals a steady significative decrease in the J/ψ production rate up to the most central Pb-Pb collisions. It clearly rules out the presently available conventional (hadronic) models of J/ψ suppression, which unanimously predict a saturation of the J/ψ rate for central Pb-Pb collisions. On the contrary and together with the sharp onset of the anomalous suppression previously reported, the new observation leads to a global production rate pattern which finds its natural explanation in the framework of the formation of a deconfined state of quarks and gluons.

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1 Introduction

Non-perturbative calculations of Quantum-ChromoDynamics predict that at a critical temperature $T_c \simeq 150$–180 MeV, the ordinary nuclear matter, where quarks and gluons are confined in colourless hadrons, should undergo a phase transition into a state of matter with partonic degrees of freedom, where quarks and gluons behave as free particles. If the partons remain deconfined for long enough, their kinematical distributions reach thermal characteristics, and such a state of matter is named Quark-Gluon Plasma (QGP). Several signals have been proposed as signatures of the formation of a deconfined state of matter in heavy ion collisions. In particular, Matsui and Satz [1] predicted that the formation of a QGP would screen the colour binding potential, preventing the c and $\bar{c}$ quarks to form charmonia states and, therefore, leading to a measurable suppression of the J/ψ yield.

This signature is particularly interesting because the $c\bar{c}$ states, composed of heavy quarks, can only be produced at the earliest times in the collision evolution, in hard processes (gluon fusion) that happen early enough to probe the formation of the QGP. Besides, tightly bound states as the J/ψ meson are not easy to break in the relatively soft interactions they may suffer while crossing the surrounding (hadronic) matter. Finally, the dimuons resulting from the decay of the J/ψ mesons are not affected by the strong interactions that reign during hadronization, flying through and bringing to the detectors an undistorted image of the earlier phases.

At the CERN SPS, the NA38 and NA50 experiments have extensively studied J/ψ production in nucleus-nucleus collisions, to establish a detailed production pattern that can be used to probe the existence of the deconfined phase predicted by QCD. Over many years, the NA38 experiment has collected several data samples with proton, oxygen and sulphur beams, on several targets [2]. The analysis of these data sets resulted in the conclusion that the measured J/ψ yield is suppressed with respect to the yield of Drell-Yan dimuons, an observation understood in terms of nuclear absorption of the $c\bar{c}$ pair before it forms the J/ψ state [3]. This normal suppression, which increases continuously and monotonically from p-p up to the most central S-U collisions [4], sets the baseline with respect to which we can compare the pattern of J/ψ production in Pb-Pb interactions.

A first clear departure from this smooth trend was seen in the Pb-Pb data collected in 1995 [5]. Indeed, the J/ψ production cross-section in Pb-Pb collisions was found to be a factor 0.77 ± 0.04 below the value expected on the basis of the normal nuclear absorption established from the p-A and S-U data [6]. A detailed study of the centrality dependence of this anomalous suppression could not be done with only the 5 centrality classes imposed by the limited statistics of the 1995 data sample.

The increased luminosity of the 1996 data taking period, which resulted from higher beam intensity and a much thicker target, allowed to triple the number of data points in the ratio between the J/ψ and Drell-Yan yields [6]. Even more data points, 26, were obtained by using the minimum bias events as the reference to study the J/ψ suppression. The achieved granularity has allowed us to confirm that the J/ψ

yield in peripheral Pb-Pb collisions follows the normal behaviour established with the lighter projectiles. However, the yield of observed J/ψ mesons is considerably reduced in Pb-Pb collisions with an impact parameter smaller than 8 fm, which release more than 40 GeV of neutral transverse energy, E_T, in the acceptance of the NA50 electromagnetic calorimeter. The rather sudden nature of the observed decrease, the first observation of a threshold effect in the field of heavy ion physics, strongly suggests that the source of the observed J/ψ suppression is the formation of a system of deconfined quarks and gluons [6].

The comparison of the results obtained with the 1996 and 1995 data samples has revealed a disagreement in the highest E_T bin, which we have attributed to a bias related to the thickness of the targets used [6]. With a target thickness of 30 % of an interaction length, it is conceivable that a spectator fragment from a first peripheral collision reinteracts downstream, resulting in measured values of E_T and E_{ZDC} typical of a much more central (single) 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. The study of the most central Pb-Pb interactions is quite crucial since the conventional hadronic models and the models assuming QGP formation predict different patterns for the J/ψ production rate. Therefore, we have devoted the 1998 data taking period to fully clarify this situation. This paper presents the final results of an analysis restricted to the central collisions of the new data. Preliminary results were already reported at QM99 [7].

2 Experimental setup

The experimental setup used by the NA50 experiment in the 1998 data taking period was quite similar to the ones used in 1995 and 1996. A detailed description can be found in Refs. [8, 9, 10]. The main detector components are a dimuon spectrometer, an electromagnetic calorimeter which measures the neutral transverse energy released in the interaction (E_T), a zero degree calorimeter that essentially measures the energy of the projectile nucleons which have not participated in the collision (E_{ZDC}), and a silicon microstrip detector that measures the multiplicity of charged particles. A set of quartz counters located upstream of the target identifies the incident lead ion and flags pile-up events, i.e. events with two incoming Pb ions separated in time by less than 20 ns. Such events are rejected from the final analysis data sample.

The only change in the 1998 setup concerns the target. While in 1995 and 1996 the target was made of 7 sub-targets, with a total thickness of 7 and 12 mm respectively, i.e. 17 % and 30 % of an interaction length, in 1998 we have used a single target of 3 mm, i.e. 7 % λ_I. The much smaller thickness significantly reduces the probability to have re-interactions of projectile fragments. As in the previous data taking periods, the target used in 1998 was instrumented with quartz blades located to the left and to the right of the beam axis. The resulting information can be used to identify the interaction sub-target, using the "target algorithm", except if the collected signal is too weak, as is often the case in the most peripheral collisions.

During the 1998 data taking period, the average beam intensity was 5.5×10^7 Pb ions per burst, with a spill of 4.5 s nominal duration. As in the previous years, the energy of the Pb beam was 158 GeV per nucleon. A total of about 80 million events were recorded, among which $\sim 90\,\%$ required two muons and $\sim 10\,\%$ a non-zero energy deposit in the ZDC (minimum bias triggers). After applying the standard offline event selection criteria, the number of J/ψ events used in the data analysis is roughly 40 000. Table 1 collects some characteristics of the three data taking periods: 1995, 1996 and 1998.

Data period	1995	1996	1998
Target thickness	$17\,\%\ \lambda_{\mathrm{I}}$	$30\,\%\ \lambda_{\mathrm{I}}$	$7\,\%\ \lambda_{\mathrm{I}}$
Number of sub-targets	7	7	1
Beam intensity (ions/burst)	3×10^7	5×10^7	5.5×10^7
Number of J/ψ	50 000	190 000	40 000

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

3 Data selection and analysis

The event selection procedure used in the analysis of the 1998 data followed basically the same criteria as applied to the previous data samples, and a detailed description can be found in Refs. [8, 6]. Muon pairs are selected in the usual phase space window, namely $2.92 < y_{\mathrm{lab}} < 3.92$ and $|\cos\theta_{\mathrm{CS}}| < 0.5$, where θ_{CS} is the polar decay angle of one muon in the Collins-Soper reference frame. For the minimum bias events an offline cut on the neutral transverse energy is applied in order to reject events where the incident Pb ion crosses the target without interacting.

To properly compare the centrality dependence of the 1998 data with the results obtained in the previous years, the absolute transverse energy scale for the 1998 data has been renormalized to the 1996 transverse energy scale, using as reference the "knee" of the two minimum bias E_{T} distributions. Further details on this procedure can be found in Ref. [6]. Figure 1 compares these distributions after the renormalization. As expected, the reduction of the target extension along the beam axis improved the resolution of the E_{T} measurement in 1998. The spectra shown in this figure are not corrected for the efficiency of the target identification algorithm, which is lower than unity for E_{T} lower than ~ 60 GeV.

The main difference between the raw event samples collected in 1996 and 1998 is the ratio between "on-target" and "off-target" events. Although the pre-interaction and halo detectors, located upstream of the target, helped very significantly in rejecting off-target interactions, as they did in 1996, the much smaller thickness of the target naturally resulted in a higher contamination of Pb-air interactions in the collected events. The fraction of such spurious events that survived our quality selection cuts can be estimated with the special "empty target runs", also recorded during the data taking period, and has been found to be negligible for the events with E_{T} above 40 GeV. Since the main goal of the 1998 run is the study of the J/ψ suppression pattern in central Pb-Pb collisions, we have limited the analysis presented in this paper to the events with $E_{\mathrm{T}} > 40$ GeV. To further minimize this potential contamination, we only select events for which the interaction vertex has been determined with the target identification algorithm.

The two different types of analyses reported here are the same as used in the 1996 data set, and explained in detail in our previously published paper [6]. The first one, referred to as the "standard analysis", uses the Drell-Yan events directly as the reference with respect to which we study the behaviour of the J/ψ production in Pb-Pb collisions. It has the advantage that both event samples result from hard processes but it suffers from the very small production cross section of high mass Drell-Yan dimuons. Indeed, in this type of analysis the detail with which we can study the J/ψ signal is limited by the small statistics of the reference process. The second analysis scheme uses the much larger sample of minimum bias events as the reference in the studies of the centrality dependence of the J/ψ yield, thereby reducing very significantly the statistical uncertainties.

In the standard analysis, the yields of J/ψ and Drell-Yan events are obtained, for each centrality interval, by fitting the dimuon invariant mass spectrum. The fit is performed for dimuon masses above 2.9 GeV/c^2 and includes five contributions: the combinatorial background from π and K decays, the muon pairs from simultaneous semileptonic decays of D and $\bar{D}$ mesons, the Drell-Yan dimuons, and the J/ψ and ψ' resonances.

In the "minimum bias analysis", on the other hand, the numbers of J/ψ and minimum bias events, for each centrality interval, are obtained from simple counting procedures. The number of J/ψ events, in particular, is determined as the number of signal events in the dimuon mass range from 2.9 to 3.3 GeV/c^2, after subtracting the small contribution from the underlying dimuon continuum. In order to compare the results of the two analyses with each other, and also with the results previously obtained with proton and sulphur projectiles, based only on the direct method, we need to convert the minimum bias reference into the Drell-Yan reference. We do this using the Glauber model to calculate the *ratio* between the Drell-Yan and the minimum bias yields, $\Theta(E_{\mathrm{T}})$. This method is explained in detail in Ref. [6].

The J/ψ suppression pattern has also been studied as a function of the forward energy, E_{ZDC}, measured in the zero degree calorimeter. Figure 2 shows the E_{ZDC} distribution, as collected with the minimum bias trigger. The measured correlation between E_{T} and E_{ZDC} can be seen in Fig. 1 of Ref. [6]. Compared to E_{T}, the E_{ZDC} variable has a more direct correlation with the geometry of the nucleus-nucleus collision. Indeed, the energy collected in the ZDC is mainly due to the energy carried by the beam spectator nucleons, $E_s = N_s(b) \times 158$ GeV, where N_s is a function of the impact parameter of the collision. In addition, secondary particles emitted in the angular acceptance of the ZDC ($\eta > 6.2$), contribute to the measured E_{ZDC}. This contribution can be assumed to be proportional to the number of participant nucleons, $\alpha \cdot N_p(b)$.

The E_{ZDC} dependence of the J/ψ yield has been determined using the minimum bias event sample, which provides the best statistical accuracy. Similarly to what has been done for the E_{T} analysis, this method requires the evaluation of the ratio $\Theta(E_{\mathrm{ZDC}})$. It needs therefore a description of the centrality dependence of the signal measured by the ZDC, through the quantities $N_s(b)$, $N_p(b)$ and α, introduced above. For this analysis, $N_s(b)$ and $N_p(b)$ have been evaluated with a geometrical model based on the Glauber formalism, using Woods-Saxon nuclear density profiles, with the parameters tabulated in Ref. [11]. The parameter α has been fixed by means of a fit to the measured minimum bias E_{ZDC} distribution. The fraction of E_{ZDC} due to the secondary particles is less than 10 % for $E_{\mathrm{ZDC}} \geq 10$ TeV and reaches 40 % for $E_{\mathrm{ZDC}} \sim 3$ TeV.

For a given impact parameter, b, the values of E_{ZDC} are Gaussian distributed, with a width $\sigma(E_{\mathrm{ZDC}})$ which reflects the finite resolution of the detector and was studied with measurements done with low intensity proton and ion beams [9]. The results indicate that $\sigma(E_{\mathrm{ZDC}})/E_{\mathrm{ZDC}}$ varies from $\sim$10 % for peripheral collisions to $\sim$20% for the most central ones.

4 Results

Although the high mass Drell-Yan data sample collected in 1998 has rather reduced statistics, we have been able to calculate the standard ratio, $\sigma_\psi/\sigma_{\mathrm{DY}}$, in four centrality intervals. Figure 3 compares the results of the present analysis with the previously published data points [8, 6], from the 1995 and 1996 data sets, showing good overall agreement, except for the highest E_{T} bin. This result confirms our suspicion (explicitly stated in Ref. [6]) that the 1996 high E_{T} data were biased by re-interaction effects, due to the target thickness. The close overlap of the high E_{T} points from the 1995 and 1998 data sets, collected with targets of rather different thicknesses (17 % λ_{I} and 7 % λ_{I}, respectively) indicates that any remaining contamination of re-interaction events must be negligible.

The "minimum bias analysis" of the 1998 data set gives the results presented in Fig. 4, where they are compared to the corresponding results from the 1996 data. The absolute normalization of the ratio $\sigma_\psi/\sigma_{DY^*}$, derived from the minimum bias analysis, was calculated using the E_{T} range between 40 and 100 GeV, which corresponds to the first three data points of the standard analysis. It is worthwhile noting that, in this figure, the published 1996 data points were limited to the range of E_{T} where the re-interaction events have a negligible influence. In this limited E_{T} range the two data sets show a good agreement.

The curve included in Fig. 4 corresponds to the baseline established by the data collected with lighter projectiles [4]. It accounts for the normal nuclear absorption of the $c\bar{c}$ pair, with an absorption cross section of $\sigma_{\rm abs} = 6.4$ mb. This figure reveals that the anomalous J/ψ suppression continues increasing for the most central Pb-Pb collisions, rather than saturating with increasing $E_{\rm T}$. In fact, the data show a second drop in the J/ψ suppression pattern, at $E_{\rm T}$ around 90 GeV.

The ratio $\sigma_\psi/\sigma_{\rm DY^*}$ is presented in Fig. 5 for $E_{\rm ZDC} < 22.5$ TeV. The overall normalisation of the data points has been taken from the values obtained with the $E_{\rm T}$ dependent analysis, in the range $60 < E_{\rm T} < 100$ GeV, corresponding to the $E_{\rm ZDC}$ range $17 > E_{\rm ZDC} > 8$ TeV. The anomalous J/ψ suppression $E_{\rm ZDC}$ pattern is very similar to the one observed as a function of $E_{\rm T}$. In particular, the suppression does not saturate for the most central collisions. Note, however, that the very loose $E_{\rm T}$–$E_{\rm ZDC}$ correlation in this region only allows qualitative comparisons.

5 Discussion

The steady decrease of the J/ψ suppression pattern, seen in the most central Pb-Pb collisions collected in 1998, is in clear disagreement with the presently existing conventional hadronic models [12, 13, 14, 15]. Indeed, the main characteristic of these models is that they predict a smooth decrease of the J/ψ production yield, from p-p to Pb-Pb collisions, tending to a saturation of the J/ψ suppression in the most central collisions. The measurements displayed in Fig. 4 rule out such models. This is clearly illustrated in Fig. 6, where our data are compared to the curves calculated by models which assume that the charmonia states are absorbed by interactions with comoving hadrons [12, 13, 14, 15].

A first incompatibility with the predictions of conventional models was the sharp onset of the anomalous J/ψ suppression, seen for collisions releasing around 40 GeV of neutral transverse energy in our electromagnetic calorimeter. The steady decrease reported in the present paper constitutes another strong piece of evidence that the J/ψ mesons are not being absorbed by the hot and dense hadronic matter assumed in the conventional models. On the contrary, our results agree with the pattern expected in the framework of the production of a deconfined state of quarks and gluons [16].

In order to describe more quantitatively the observed suppression pattern, we will now evaluate the energy density reached in the reactions we are studying. Besides, the energy density variable is also suited to compare in a single figure the results obtained with the several collision systems probed by the NA38 and NA50 experiments.

We have followed Bjorken's model to compute the energy density reached in the nucleus-nucleus collisions,

$$\epsilon = \frac{{\rm d}E_{\rm T}^{\rm tot}/{\rm d}y\,|_{y^*=0}}{c\,\tau \times A_{\rm T}} \quad ,$$

where τ is the lifetime of the system ($\simeq 1$ fm/c) and $A_{\rm T}$ is the overlap transverse area of the two colliding nuclei. The value of ${\rm d}E_{\rm T}^{\rm tot}/{\rm d}y$ has been computed multiplying by three the measured neutral $E_{\rm T}$ values and taking into account the rapidity coverage

($1.1 < y_{\rm lab} < 2.3$) of our measurements, which is significantly displaced with respect to mid-rapidity. This calculation leads to an energy density of 3.5 GeV/fm^3 for our most central Pb-Pb data point, consistent with the value of 3.2 GeV/fm^3 reported by the NA49 collaboration [17] for "head-on" Pb-Pb collisions, for which the RQMD cascade model [18] gives 3.3 GeV/fm^3.

The results are presented in Fig. 7, for the Pb-Pb data and for the smaller collision systems studied by the NA38 and NA51 collaborations [2]. We have estimated the energy density reached in the p-A collisions with the RQMD Monte-Carlo event generator. The figure shows the ratio between the observed J/ψ suppression pattern and the normal nuclear absorption curve, that properly reproduces the p-A and S-U results. The data points are obtained from the measured J/ψ to Drell-Yan cross section ratios, except for the NA38 p-A data points, which are based on the J/ψ absolute cross-sections. Although the proton, sulphur and lead induced collisions were taken at different energies, they are immediately comparable in this "measured over expected" ratio.

From this figure we deduce that the first drop in the J/ψ production yield happens for Pb-Pb collisions reaching energy densities above 2.3 GeV/fm^3, while an even stronger suppression is seen when a higher value, around 3.1 GeV/fm^3, is exceeded. 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 signals the presence of energy densities high enough to also dissolve the more tightly bound J/ψ charmonium state.

6 Conclusions

We reported in this paper the results of the analysis of the data collected in 1998, aimed at extending and clarifying the study of the J/ψ suppression pattern up to the most central Pb-Pb collisions. Together with the results previously established by the NA38 and NA50 collaborations, a rather clear picture emerges, indicating a step-wise pattern, with no visible saturation in the collisions generating the highest energy densities and temperatures.

The pattern visible in our data can be naturally anticipated and understood in a deconfinement scenario as resulting from the melting of the χ_c states above a certain energy density, followed by the suppression of the directly produced J/ψ mesons, when the collisions are central enough to generate (local) energy densities above a higher threshold.

We have estimated in this paper that the binding of the χ_c states starts becoming screened for energy densities above $\sim$2.3 GeV/fm^3, while the breaking of the more tightly bound J/ψ states require collisions capable of generating energy densities above $\sim$3 GeV/fm^3.

Our observations exclude the presently available models of J/ψ suppression based on the absorption of the J/ψ mesons by interactions with the surrounding hadronic (confined) matter. On the contrary, the behaviour seen in our data follows the step-wise pattern expected in case the matter produced in the Pb-Pb collisions undergoes a phase transition into a deconfined state of quarks and gluons. Therefore, we must conclude that the J/ψ suppression pattern observed in our data provides significant evidence for deconfinement of quarks and gluons in the Pb-Pb collisions probed by NA50.

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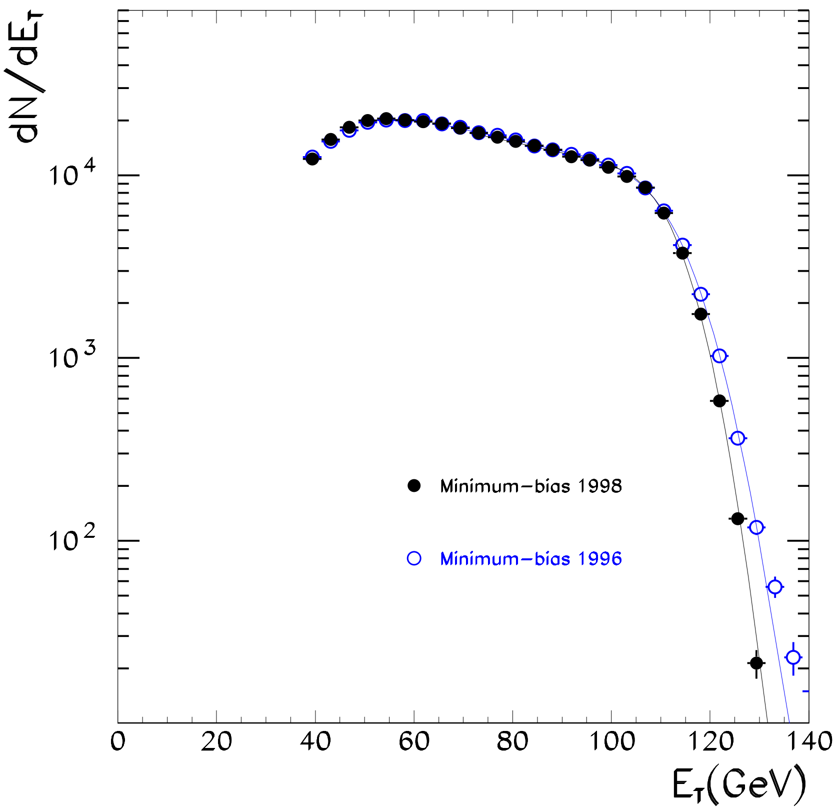

Figure 1: Comparison of the Pb-Pb neutral transverse energy distributions collected in 1996 and 1998 with the minimum bias trigger.

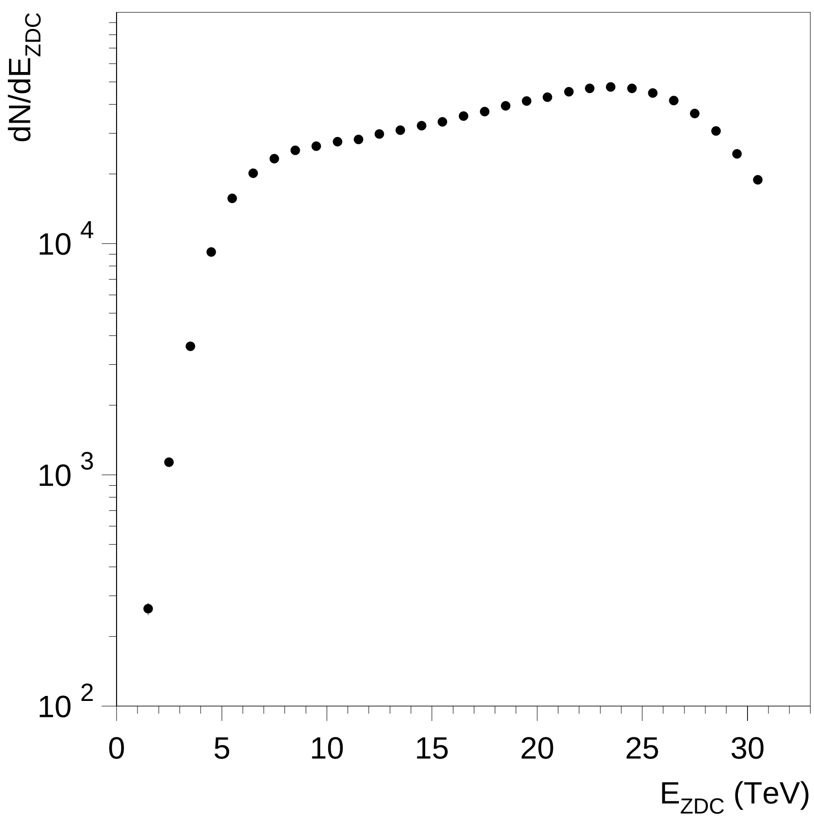

Figure 2: E_{ZDC} spectrum measured in 1998 with the minimum bias trigger. The data are not corrected for the efficiency of the target algorithm and the contribution from secondary particles has not been subtracted.

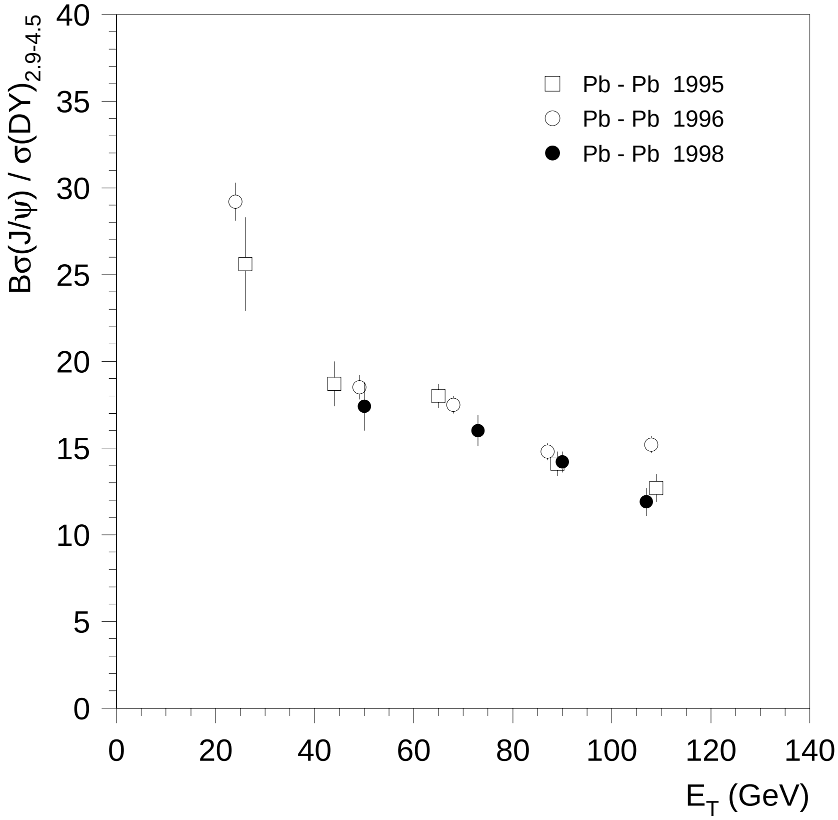

Figure 3: $\sigma_\psi/\sigma_{\rm DY}$ ratio as a function of $E_{\rm T}$, obtained with the standard analysis of the 1995, 1996 and 1998 data samples.

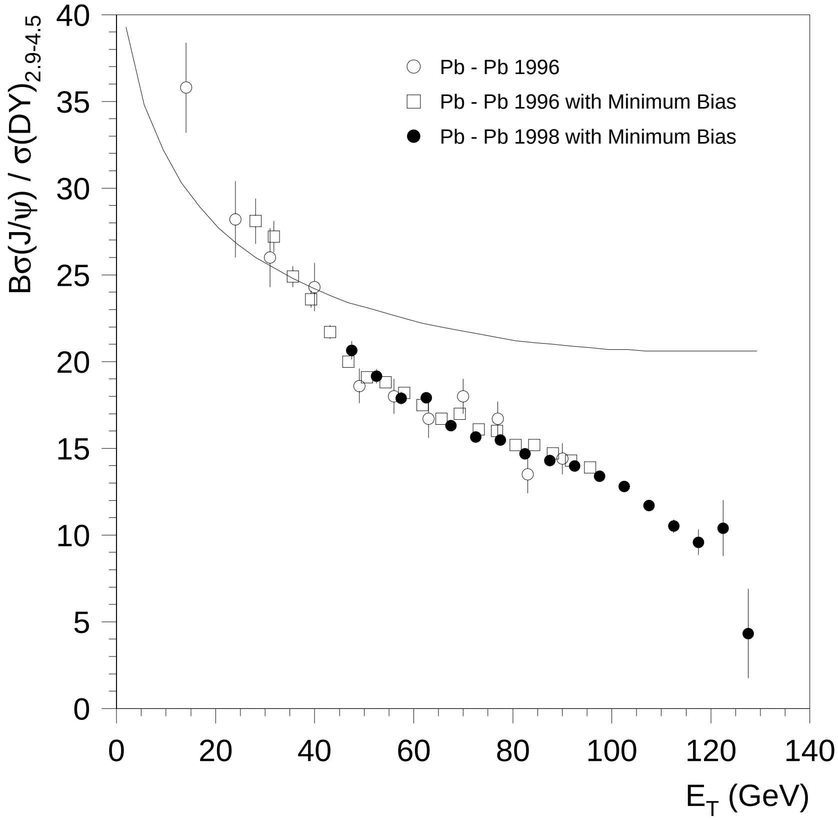

Figure 4: $\sigma_{\psi}/\sigma_{\mathrm{DY}}$ ratio as a function of E_{T}, obtained with the standard and minimum bias analyses of the 1996 and 1998 data samples. The curve represents the J/ψ suppression due to ordinary nuclear absorption.

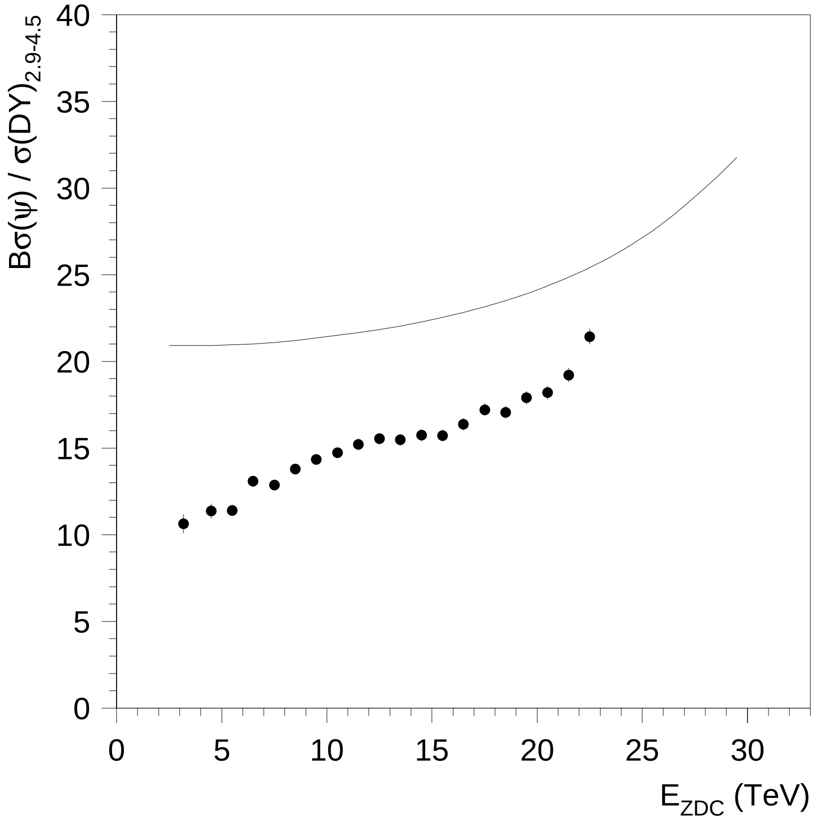

Figure 5: $\sigma_\psi/\sigma_{\rm DY}$ ratio as a function of $E_{\rm ZDC}$, obtained with the minimum bias analysis of the 1998 data sample. The curve represents the J/ψ suppression due to ordinary nuclear absorption.

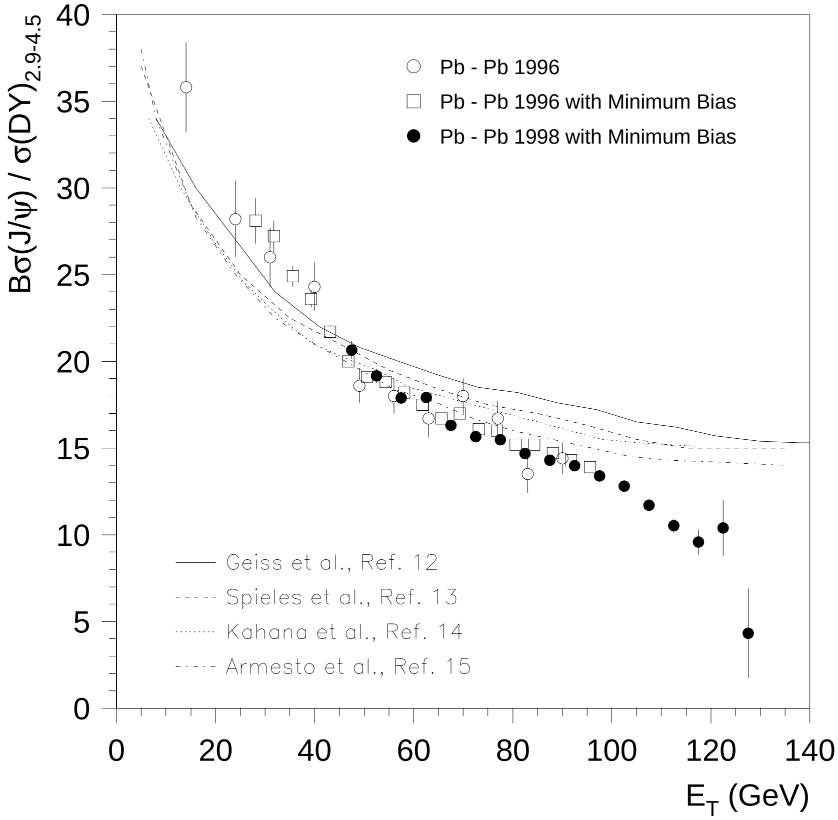

Figure 6: Comparison between our data and several conventional calculations of J/ψ suppression.

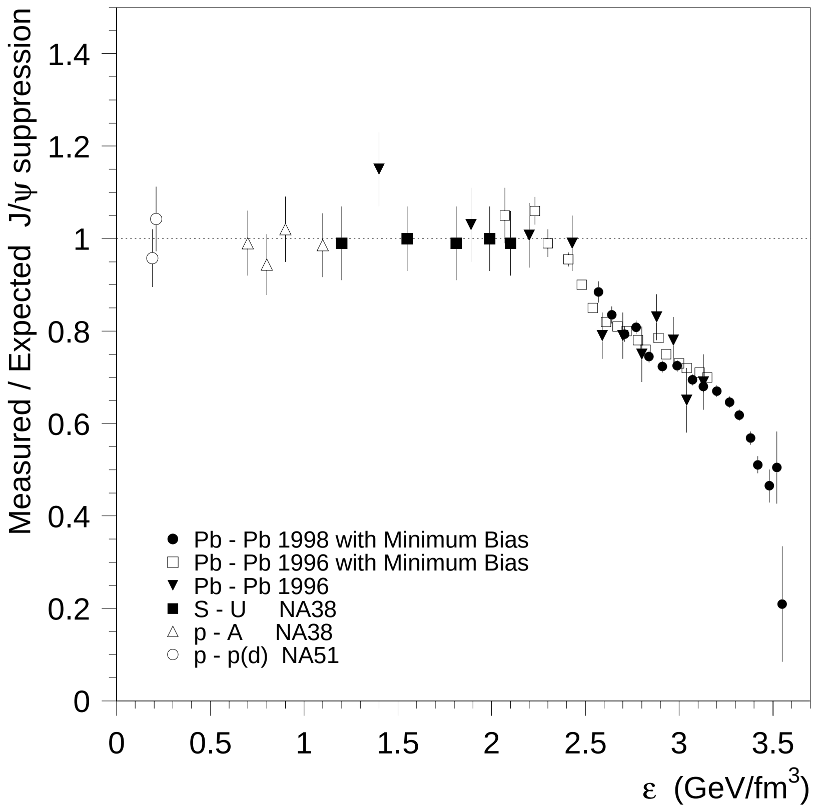

Figure 7: Measured J/ψ production yields, normalised to the yields expected assuming that the only source of suppression is the ordinary absorption by the nuclear medium. The data is shown as a function of the energy density reached in the several collision systems.