Eur. Phys. J. C (2005)
Digital Object Identifier (DOI) 10.1140/epjc/s2005-02245-6

THE EUROPEAN PHYSICAL JOURNAL C

20 years of J/ψ suppression at the CERN SPS

Results from experiments NA38, NA51 and NA50

L. Kluberg[1,2,a]

[1] CERN, Geneva, Switzerland
[2] LLR, Ecole Polytechnique and CNRS-IN2P3, Palaiseau, France

Received: 9 March 2005 / Revised version: 23 March 2005 /
Published online: 15 July 2005 –

Abstract. J/ψ suppression was predicted to be a signature of deconfinement and has been extensively studied at the CERN-SPS in proton, light and heavy ion induced reactions. Indeed, proton, O, S and Pb ion beams, at various incident energies, have been used at CERN on different targets, in order to precisely quantify J/ψ production as a function of both the colliding nuclei and the centrality of the collision itself. This paper reviews the results obtained so far with a critical discussion of the experimental conditions and successive improvements implemented for the various data samples. It makes a tentative summary of what has been learned on the subject, from the experimental point of view, in the SPS energy range.

PACS. 25.75.-q, 25.75.Nq, 13.20.Gd

1 Introduction

After almost 20 years of continuous efforts to try and understand J/ψ production, we summarize, hereafter, what has been learned on the subject and how the way has been paved for second generation experiments.

Since 1986, experiments NA38, NA51 and NA50 have been studying J/ψ production at the CERN SPS. The first of these experiments, NA38, submitted a Letter of Intent in 1984 and was on the floor in 1986, taking data with a beam of Oxygen ions. Since then, a large harvest of results has been obtained under different experimental conditions. After successive refinements and deeper understanding of various features, it is time to ask again the question whether an *anomalous* J/ψ suppression has been or not discovered, as claimed in past publications. The question is of first importance because J/ψ suppression is considered as one of the golden signatures for Quark Gluon Plasma formation. But the question is, at the same time, difficult to answer because, as worded above, it requires to precisely define what is *normal* J/ψ suppression. In the following, we will try to clearly state what can be considered as normal and what is labeled abnormal, look back whether an anomaly was ever present in the data, whether it survived successive experimental refinements and what are its presently updated features.

[a] e-mail: louis.kluberg@cern.ch

2 The starting point: Experiment NA38

The starting point was experiment NA38 proposed in March 1985 after a Letter of Intent in 1984.

2.1 The NA38 proposal

The proposal aimed at the study of thermal dimuon production in O-induced reactions. Several authors [1] had predicted that, although difficult to identify, the emission of thermal dimuons would be a challenging experimental signature of a deconfined Quark Gluon Plasma. An excerpt of the abstract of the proposal is worth to be recalled here: *"... Thermal dimuons are expected to be emitted from a quark-gluon plasma at a reasonable rate in the 1–3 GeV/c^2 transverse mass range, and to differ from ordinary dimuons by their p_T and rapidity distributions..."*. As a matter of fact, the proposal did not even mention the study of charmonium production which, at that time, was of no interest whatsoever in the field of QGP research. On the other hand, the proposal intended to use, as basic detector of the apparatus, what at that time was (and probably is still today) one of the best muon spectrometers for fixed target experiments. The apparatus had been built and used for five years by the NA10 Collaboration as a second generation detector to study structure functions and Drell-Yan muon pairs. It was located in a purpose-built high intensity experimental area called NAHIF (North Area High Intensity Facility). The J/ψ was considered as a highly unwanted background by

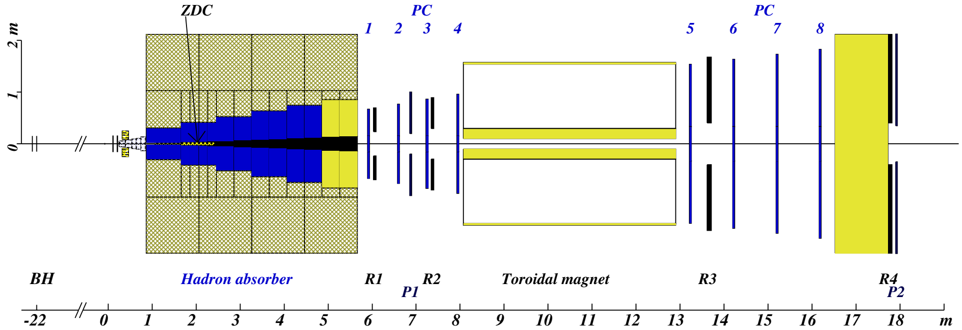

Fig. 1. Schematics of the muon spectrometer used by experiments NA38, NA51 and NA50

the NA10 experiment and, therefore, efficiently suppressed by appropriate cuts at the trigger level.

2.2 The turning point

The turning point came after the publication, in October 1986, of a nowadays famous paper [2]. Its abstract should be quoted *in extenso*: *"If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents c binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation."*

This prediction definitely changed the main goal of experiment NA38 from the search of thermal dimuons to the study of J/ψ production in proton and (light) ion-induced reactions. It also had, some time later, a decisive influence on the whole field of Quark Gluon Plasma search. It led, in the theoretical sector, to the publication of many hundreds of papers on the subject, and, in the experimental sector, to the integration of specific detection capabilities in the design of future experiments, both for RHIC and for the LHC.

2.3 The NA38 experiment

The detector used by experiment NA38 is based on a muon spectrometer and an electromagnetic calorimeter. The muon spectrometer, already used in the NA10 experiment [3], is shown in Fig. 1.

It is separated from the target region by a 4.8 m long hadron absorber made of carbon, with a tungsten-uranium central plug to absorb the beam particles which do not interact in the target. The air-core magnet, with hexagonal symmetry, produces a toroidal field which leads to a bending angle inversely proportional to the transverse momentum of the muon. Four plastic scintillator hodoscopes, R1–R4, provide the trigger. Two sets of four multiwire proportional chambers, PC1–PC4 and PC5–PC8, located respectively upstream and downstream of the magnet, measure the muon tracks. The spectrometer detects dimuons in the rapidity range $2.8 < y < 4.0$ in the laboratory frame. Mass resolution and acceptances depend on the precise absorber material components (where some carbon can be replaced by iron) and on the value of the magnetic field; for a muon pair of invariant mass 3 GeV/c^2 they amount respectively to ~ 110 MeV/c^2 and to ~ 15 % for the phase space window covered by the detector. The electromagnetic calorimeter is the only detector allowing to label each individual interaction according to the centrality of the collision. It is located downstream of the target and covers the pseudo-rapidity range $1.7 < \eta < 4.1$. It estimates, on an event by event basis, the neutral transverse energy (mainly from the detected neutral pions) produced in the reaction. Its resolution amounts to 5 % for Oxygen-Uranium central collisions. A more complete description of the whole setup can be found in [4].

2.4 The very first results from O-U reactions

The first experimental studies of J/ψ production in ultra-relativistic heavy ion collisions became feasible when high intensity Oxygen ion beams of 200 GeV/nucleon were successfully delivered, for the first time in the fall of 1986, by the CERN accelerators. The study of J/ψ production as a function of the centrality of the collision highly benefits, from the experimental point of view, from the simultaneous study, under identical conditions, of a well understood process which can be used as a reference for comparison purposes. The most natural choice for an experiment detecting the J/ψ through its decay into two muons is, obviously, the simultaneous detection and study of Drell-Yan muon pairs. The first data sample of O-U events collected in 1986, although encouraging from the point of view of the methodology, had its own limits as shown in Fig. 2. The J/ψ could be easily identified and counted. The number of muon pairs with mass above 4 GeV/c^2, corresponding to pure Drell-Yan events, was small. It turned the study of the ratio of J/ψ to Drell-Yan events as a function of the centrality of the collision into an unrealistic challenge, as shown in Fig. 3. These first results were therefore formulated as the ratio of J/ψ over N_c, the number of muon pairs in the mass continuum with invariant mass in the range 2.7–3.5 GeV/c^2. N_c is a somewhat crude estimate of the Drell-Yan contribution in this mass range. The fit of the mass spectrum was purely phenomenologi-

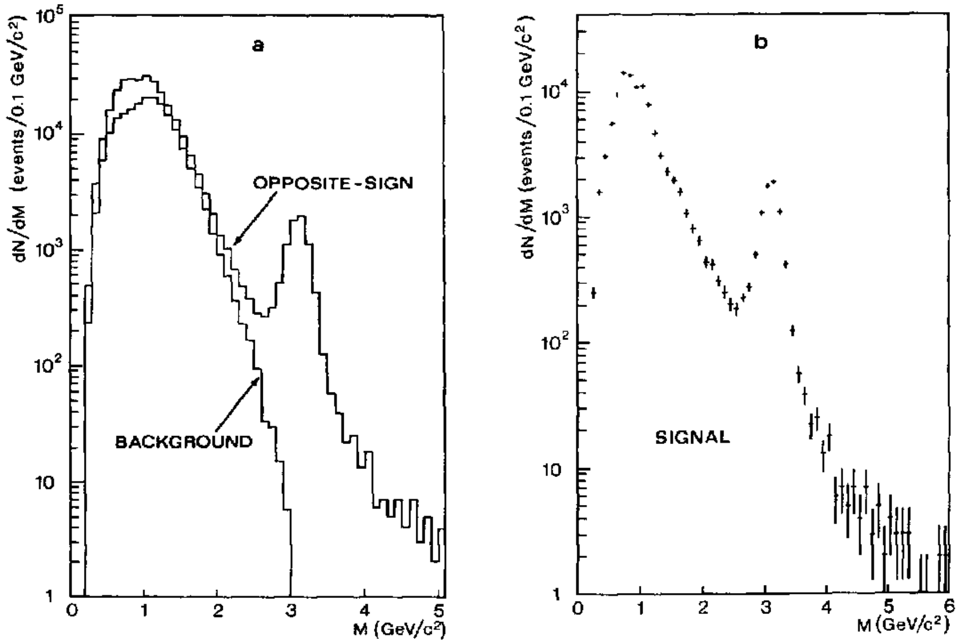

Fig. 2. Invariant mass distribution of muon pairs for O-U events. *Left*: Opposite-sign and like-sign (background) pairs separately. *Right*: "Signal" obtained after combinatorial background subtraction

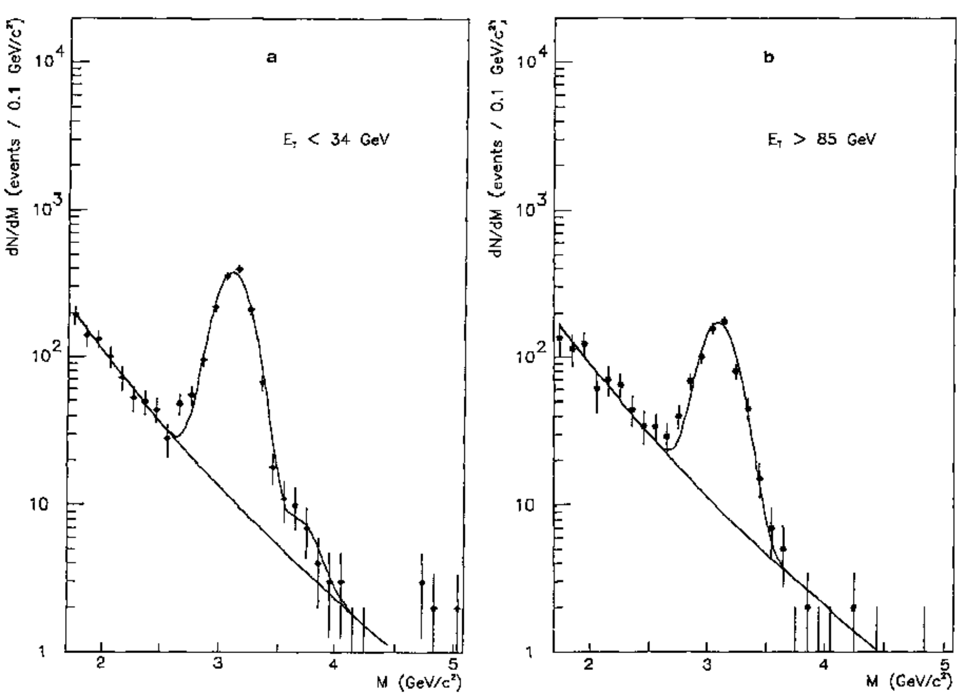

Fig. 3. Background subtracted invariant mass distribution of muon pairs for O-U events. *Left*: Peripheral collisions. *Right*: Central collisions

cal and included all muon pairs with mass above 1.7 (or 2.1) GeV/c^2, a mass range which was later discovered to contain a centrality dependent continuum source. Figure 4 shows the J/ψ suppression pattern obtained from this first analysis, albeit without the appropriate "normal" reference for comparison purposes.

2.5 More light ions: S-U, pp and pd reactions

Soon after the first Oxygen ion beam was available in 1986, pressure became strong to increase the mass of the incident ions and therefore reach more favourable conditions for the study of QGP formation. The first Sulphur beam was delivered already in 1987 although with a modest intensity, given the NA38 goals and needs. After these exploratory runs, a new Sulphur beam became available in 1989 and production runs took place from 1990 to 1992. Moreover, in 1992, the muon spectrometer was also used with liquid hydrogen and deuterium targets in the frame of experiment NA51 [5], devoted to the study of the sea of the nucleon. The data collected for this specific experiment were later used to measure charmonium production in pp and pd collisions [6]. Results obtained in S-U, pp and pd collisions became of first importance for the systematic

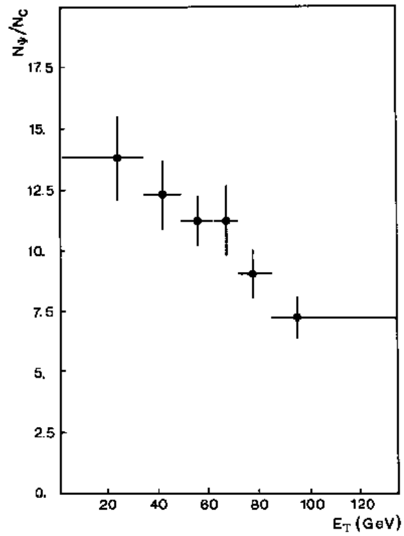

Fig. 4. The ratio J/ψ / N_c, for O-U collisions, as a function of the centrality of the collision

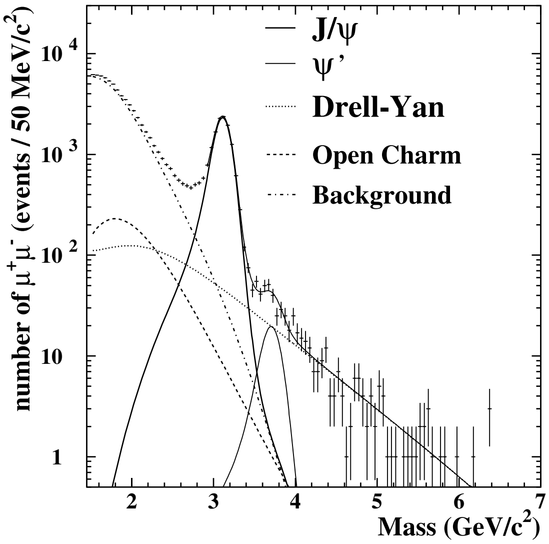

Fig. 5. The opposite-sign muon pair invariant mass distribution for the centrality class $35 < E_T < 45$ GeV, from the sample of Pb-Pb events collected by NA50 in year 2000

study which was later developed by experiment NA50. Although not described here in detail, they are included in most of the plots presented in the following sections.

3 The study of J/ψ production in Pb-Pb collisions

3.1 The NA50 experimental setup

The study of Pb-Pb reactions starts at CERN in 1994. Experiment NA38 becomes NA50. The muon spectrometer remains practically unchanged. The target region of the setup is upgraded with significant changes aimed at coping with the expected increase in multiplicity and radiation levels resulting from Pb-Pb interactions, as compared to the previously studied O- and S-induced collisions. Moreover, two new detectors are added to the apparatus: a silicon strip multiplicity detector, located immediately downstream of the target, which measures the multiplicity of the produced charged particles [7], and a hadronic calorimeter embedded in the carbon absorber, the so-called "Zero Degree Calorimeter", which measures, for each Pb-Pb interaction, the energy of the spectator nucleons of the incident Pb ion [8]. Altogether, the centrality of a Pb-Pb collision can be labeled by three independent quantities: neutral transverse energy, multiplicity of secondary charged particles and very forward energy.

3.2 The muon pair mass spectrum

It is worthwhile comparing here the muon pair invariant mass spectrum shown in Fig. 2 with one obtained from the last data sample of Pb-Pb events collected by experiment NA50 in year 2000 and shown in Fig. 5. The ratio of cross-sections J/ψ / Drell-Yan is obtained from a fit to this mass spectrum, according to the formula:

$$\frac{\mathrm{d}N^{+-}}{\mathrm{d}M} = A_{\mathrm{J}/\psi}\frac{\mathrm{d}N_{\mathrm{J}/\psi}}{\mathrm{d}M} + A_{\psi'}\frac{\mathrm{d}N_{\psi'}}{\mathrm{d}M} + A_{DY}\frac{\mathrm{d}N_{DY}}{\mathrm{d}M} + A_{D\bar{D}}\frac{\mathrm{d}N_{D\bar{D}}}{\mathrm{d}M} + \frac{\mathrm{d}N_{BG}}{\mathrm{d}M}$$

which accounts for the various sources feeding the spectrum, namely J/ψ and ψ', Drell-Yan, associated charm meson production decaying semi-leptonically and combinatorial background. The shapes of the J/ψ , ψ', Drell-Yan and $\mathrm{D\overline{D}}$ contributions are deduced from a Monte-Carlo simulation of events, reconstructed exactly as real data. Mass resolutions of J/ψ and ψ' amount to $\simeq 100$ MeV/c^2. The combinatorial background originates from random association of meson decays and is estimated from the like-sign muon pairs present in our data. The final fit is performed for masses above 2.9 GeV/c^2, which has been checked to minimize the sensitivity of the J/ψ and ψ' yields to the other components of the spectrum.

3.3 The Drell-Yan normalization

When studying J/ψ production in nucleus-nucleus collisions as a function of the centrality of the collision, the normalization problem is unavoidable. In principle, the choice of such a normalization is arbitrary. In reality, it deeply affects the required experimental treatment of the data and the systematic uncertainties of the results. The easiest and most robust choice in a dilepton experiment, when possible, is to take another well known dilepton process detected under identical experimental conditions. This is the reason why, when dealing with muon pairs, Drell-Yan is the natural choice. It is a computable process, the cross-section is proportional to the number of elementary nucleon-nucleon collisions (after correcting for

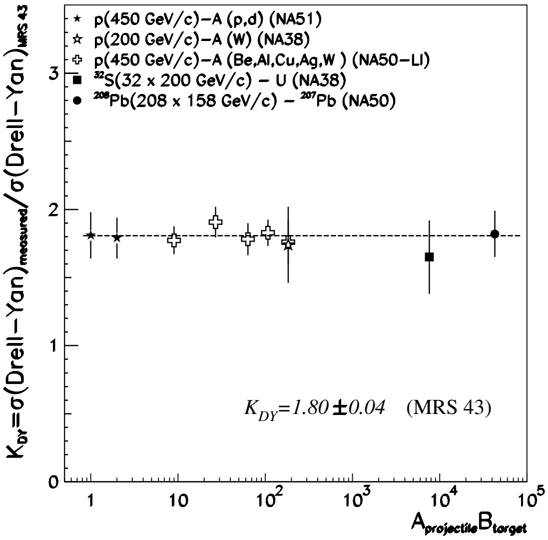

Fig. 6. The Drell-Yan K factor as determined for a large variety of colliding systems

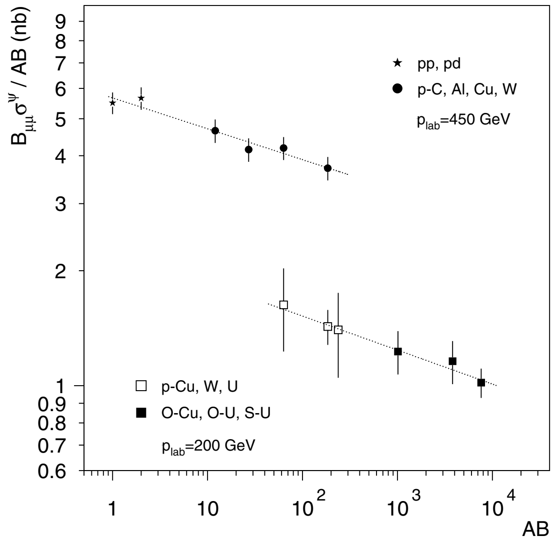

Fig. 7. The J/ψ cross-section divided by the product of the mass numbers of target and projectile. The results for 450 and 200 GeV are obtained in a different rapidity interval

the proton and neutron content of the interacting nuclei) and its experimental detection through a muon pair, when compared to the detection of a J/ψ, benefits from the following priceless advantages:
– identical experimental biases
– identical detection inefficiencies
– identical selection criteria.

The corrections cancel out in the ratio J/ψ / Drell-Yan which is, moreover, insensitive to luminosity factors and uncertainties. The counterpart of these advantages is, of course, the small number of Drell-Yan events as compared to the number of J/ψ events, which leads to significantly larger statistical uncertainties in the ratio than in the J/ψ yield.

Figure 6 displays the measured Drell-Yan cross-section divided by its value computed with the MRS43 parton distribution functions, for different colliding systems at various energies: the ratio is constant from pp up to Pb-Pb interactions, as expected.

3.4 The reference and the original J/ψ anomaly

In order to address the issue of whether the J/ψ is abnormally suppressed in nucleus-nucleus collisions, the definition of "normal" production (or better, survival) is a must. It is known since long that J/ψ production in p-nucleus interactions does not scale with the mass number A of the target nucleus but rather with A^α, where $\alpha < 1$, as if the J/ψ survival in p-nucleus reactions was already affected by nuclear absorption. The natural reference for nucleus-nucleus reactions is, therefore, J/ψ production in p-nucleus reactions under the same conditions. The first reference curve has been based on results obtained from p-A, O-Cu, O-U and S-U reactions on data collected more than 10 years ago at 450 and 200 GeV. These results, as displayed in Fig. 7, show that the nuclear absorption, as characterized by the value of α, is $\sqrt{s}$ independent.

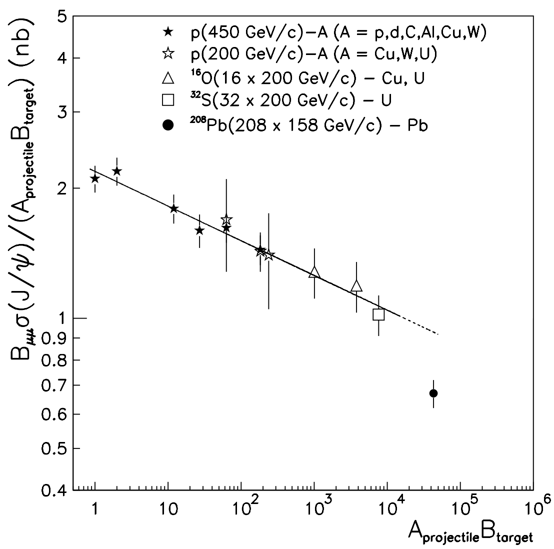

Fig. 8. Same as Fig. 7 with the 450 GeV data rescaled to 200 GeV using a simultaneous fit. The Pb-Pb result, obtained at 158 GeV, is also rescaled to 200 GeV

This allows for a simultaneous fit of the results at the two energies and leads to $\alpha = 0.918 \pm 0.015$ and to the J/ψ production cross-section in the phase space of the experiment at 200 GeV. As shown in Fig. 8, the J/ψ survival follows the same so called "normal" pattern from pp up to S-U collisions, whereas results on Pb-Pb behave anomalously, with a significantly lower value than expected from the extrapolation of lighter nuclei [9].

As a function of $\bar{L}$, the J/ψ nuclear absorption can be parametrized according to $\sigma_\psi(AB) \propto AB\exp(-\rho_0\sigma_{\rm abs}\bar{L})$ and leads to a fitted value of $\sigma_{\rm abs} = 6.2 \pm 1.1$ mb. If the fit is performed using the more elaborated Glauber model, then $\sigma_{\rm abs} = 6.9 \pm 1.2$ mb. The use of $\bar{L}$, the average path in nuclear matter of the produced $c\bar{c}$ pair, allows

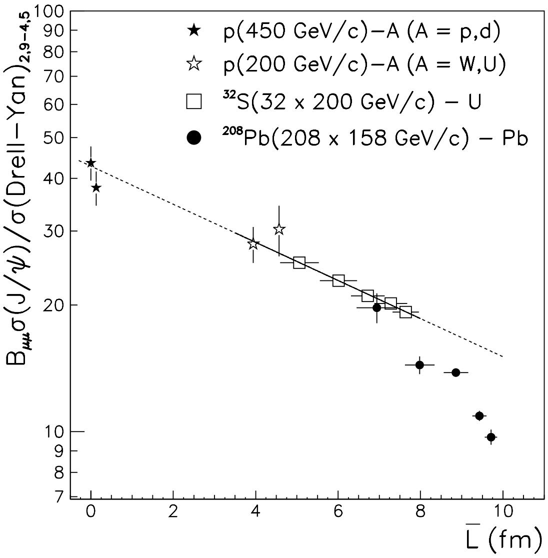

Fig. 9. The ratio of cross-sections J/ψ / Drell-Yan as a function of $\bar{L}$. Results are all rescaled to 200 GeV and the Drell-Yan cross-section is "isospin" corrected as required for comparing different colliding nuclei

us to extend the study as a function of the centrality of the collision, as shown in Fig. 9. In this first published result on J/ψ suppression as a function of centrality [9], the reference curve could only be established from data samples with a significant number of Drell-Yan events and the nuclear absorption cross-section $\sigma_{\rm abs} = 7.1 \pm 3.0$ mb was based on preliminary unpublished S-U results with, at that time, underestimated uncertainties.

4 Further studies of the J/ψ survival anomaly

4.1 1996: A high statistics data sample

The experimental evidence of an unexpected J/ψ suppression, as supported by the results of the first data sample collected in 1995 and summarized in Figs 8 and 9, led experiment NA50 to aim for a much larger sample of events. The incident beam intensity could not be significantly increased because of pile-up problems in certain detectors, so that the only open possibility was to increase the total target length. The final 1996 data sample amounted to 190 000 J/ψ events collected on 7 targets (2×1 mm + 5×2 mm thick) but suffered from the following unforeseen drawbacks:
– The incident Pb ions induced Pb-air reactions on air surrounding the targets. This parasitic background, difficult to identify, affected the most peripheral Pb-Pb reaction sample with centrality and mass smearings.
– Peripheral Pb-Pb reactions were also affected by sub-target identification inefficiencies leading to further centrality and mass smearings.
– Finally, the 12 mm total length of the target induced downstream in-target reinteractions of produced secondary particles and projectile fragments identified by the detectors surrounding the targets. Inefficiencies of this identification and of the corresponding offline rejection algorithm resulted in a centrality smearing which mainly affected the most central Pb-Pb interactions.

4.2 The standard and "minimum bias" methods

The analysis of the muon pair invariant mass spectrum leads, through separate fits for each centrality bin, to the number of J/ψ and Drell-Yan events.
– In the "standard" method of analysis, acceptance corrections are applied to these numbers and allow us to determine the ratio:

$$\frac{B_{\mu\mu}\sigma_{{\rm J}/\psi}}{\sigma_{DY}}$$

– In the "minimum bias" method, the fitted number of J/ψ events has to be corrected for acceptance and inefficiencies like target identification, trigger and reconstruction efficiencies, and others, although the relevant ones are those which could depend on the centrality of the collision (the others do not affect the *shape* of the survival pattern). Independently, the number of "minimum bias" events (requiring only an incoming ion, an interaction in the target and some signal in the electromagnetic calorimeter, for example) is determined in each centrality bin. It allows us to *compute* the corresponding number of Drell-Yan events, through the ratio Θ of the centrality distributions of Drell-Yan and "minimum bias" events, parametrized with theoretical and phenomenological inputs, according to the relation:

$$({\rm d}N/{\rm d}E_{\rm T})_{DY^*} = ({\rm d}N/{\rm d}E_{\rm T})_{MB}^{exp} \times \frac{({\rm d}N/{\rm d}E_{\rm T})_{DY}^{th}}{({\rm d}N/{\rm d}E_{\rm T})_{MB}^{th}}$$

It is then possible to compute, within an arbitrary normalization constant (due to undefined relative luminosity between the two samples of events), the ratio of the J/ψ cross-section to the calculated Drell-Yan cross-section according to:

$$\frac{B_{\mu\mu}\sigma_{{\rm J}/\psi}}{(\sigma_{DY})^*}$$

The results obtained with the above two methods are summarized in Figs. 10 and 11. It is true that the "minimum bias" method takes full advantage of the size of the J/ψ sample of events and therefore minimizes statistical uncertainties. Nevertheless, the differences between the collection and treatment of muon pairs like J/ψ or Drell-Yan and minimum bias events requires special care in identifying and keeping under control the systematic effects and uncertainties inherent to the method itself. This point is addressed in [10], where a comparison between the theoretically computed ratio Θ and the same ratio obtained from real events allows us to assess the validity of the method.

4.3 The pattern for central collisions

Learning from the problems discovered on the data collected in 1996, a new sample of data was recorded in 1998 with the aim of clarifying some of these points. The use of one single 3 mm thick target indeed solved the problem of

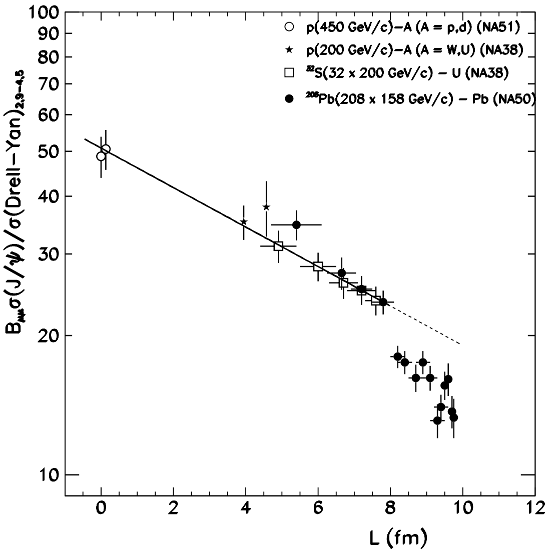

Fig. 10. The cross-section ratio J/ψ / Drell-Yan versus $\bar{L}$. All results are rescaled to 158 GeV and the Drell-Yan cross-section is "isospin" corrected as required for comparison purposes

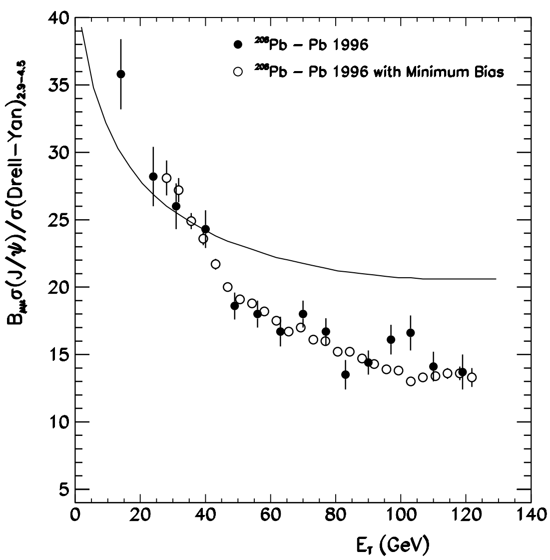

Fig. 11. The ratio of cross-sections J/ψ / Drell-Yan as a function of E_{T}, the transverse energy of the collision, with the two different analysis methods (see text)

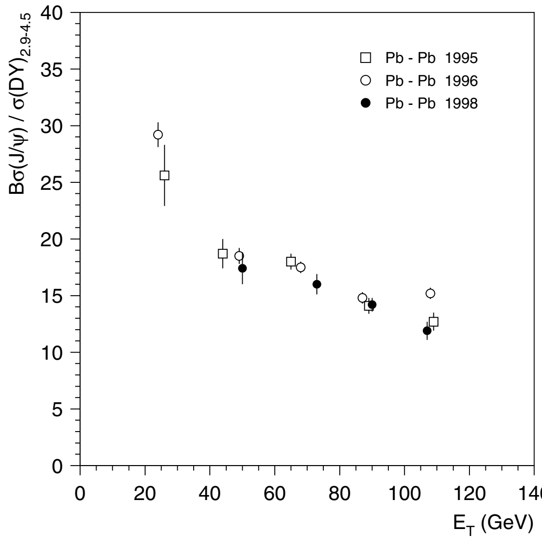

Fig. 12. Same as Fig. 11, for five centrality bins and three independent data samples

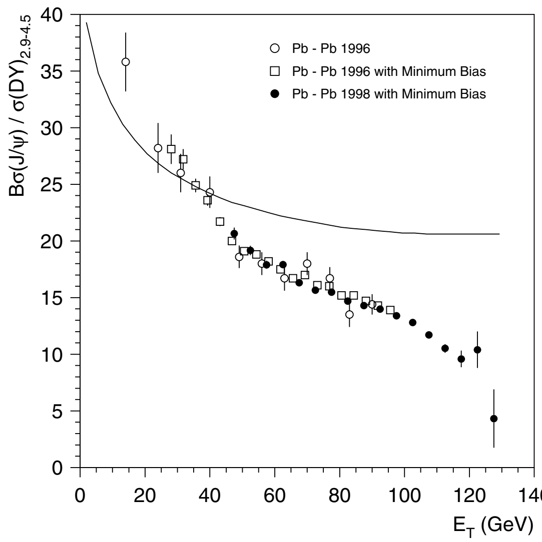

Fig. 13. The ratio of cross-sections J/ψ / Drell-Yan as a function of E_{T}, from the 1996 and 1998 data samples

reinteractions affecting the most central collisions. On the other hand, the relative amount of air with respect to Pb material in the target region increased significantly. As a result, the contamination of Pb-air reactions in peripheral Pb-Pb reactions was such that the latter could just not be studied in the new sample, at least using the usual tools available at that time for target identification purposes. Figures 12 and 13, as published in [11], show the results obtained from this new data sample and compare them with previously published results.

They suggest, indeed, that the J/ψ survival pattern does not flatten out even for the most central collisions.

5 The J/ψ survival pattern in Pb-Pb collisions

5.1 An event sample collected under significantly improved conditions

For its last collection of events, experiment NA50 made two main changes in the setup in order to definitely try and clarify the still unanswered details of the J/ψ survival pattern. A single 4 mm thick Pb target was used and, moreover, it was installed in a vacuum vessel. This target configuration was aimed at solving the problems mentioned in Sect. 4.1. Furthermore, it allowed the use of the two-plane silicon strip multiplicity detector, located immediately downstream from the target, to make a rough tracking of the produced secondary particles and thereby

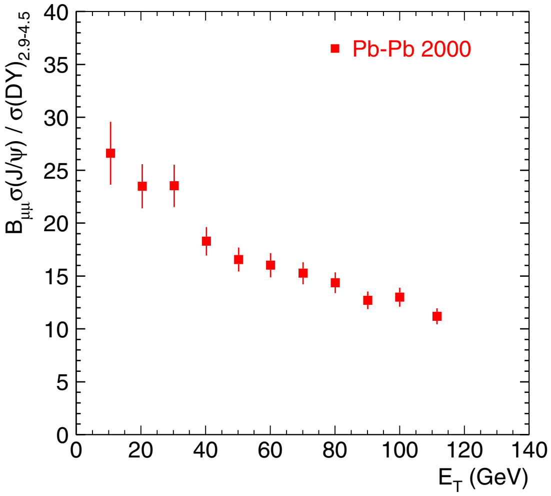

Fig. 14. The ratio of cross-sections J/ψ / Drell-Yan as a function of E_{T} for the data collected in year 2000

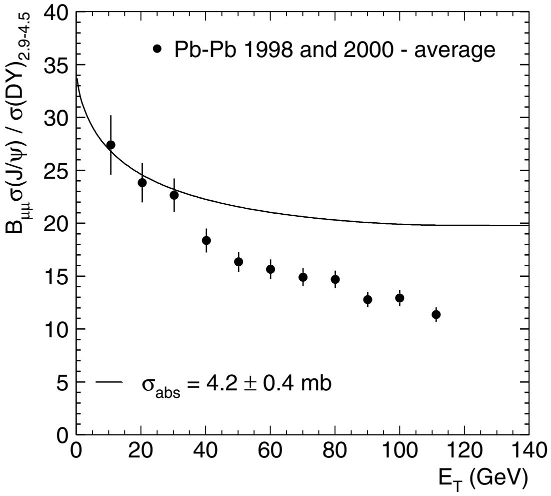

Fig. 15. The cross-section ratio J/ψ / Drell-Yan versus E_{T}, averaged over the samples collected in years 1998 and 2000

locate the origin of the interaction and discriminate between on and off-target events. This technique was later extended to the data collected in 1998 which were reanalyzed in order to recover the sample of peripheral events which had to be discarded in the first analysis.

5.2 Data analysis and results

All the details and results obtained from this last sample of events can be found in [14]. They are just summarized hereafter.

The data were analyzed with only minimal cuts as allowed by an extremely clean measurement. The dimuon invariant mass distributions were fitted with an improved J/ψ line shape and also making use of the GRVLO94 [15] parton distribution functions, which account for the light sea quark asymetry in the nucleon [5]. The use of LO PDFs leads to an increased coherence in the analysis procedure. These analysis features affect the absolute normalization of the ratio J/ψ / Drell-Yan, although its dependence as a function of the collision centrality remains unaffected. As displayed in Fig. 14, as a function of the transverse energy E_{T} used again as a centrality estimator, the ratio of cross-sections $B_{\mu\mu}\sigma_{\mathrm{J}/\psi}/\sigma_{DY}$ persistently decreases, from peripheral to central collisions by a factor $\sim$2.5, showing no saturation in the decrease even for the most central collisions. Figure 15 shows the results averaged over the samples collected in years 1998 and 2000, with events selected and analyzed under identical criteria, in particular for the vertex identification algorithm based on the multiplicity detector. They are compared to the normal nuclear absorption curve as determined from the most recent and accurate p-A results, obtained in the same experiment at 450 and 400 GeV, together with results obtained from S-U data collected at 200 GeV. The technique of the "simultaneous" fit described in Sect. 3.4 leads to a normal absorption cross-section $\sigma_{\mathrm{abs}} = 4.2 \pm 0.4$ mb and provides the rescaling factor from 450/400 GeV to 200 GeV in the lab system. (It should be noted here that this value of σ_{abs} results from new and accurate studies of the ratio J/ψ / Drell-Yan from 3 large samples of p-A events. Previous values quoted in Sect. 3.4 where obtained either from significantly smaller p-A data samples with no Drell-Yan events, therefore providing only absolute J/ψ cross-sections with irreducible systematic uncertainties as reflected in the errors, or from the old S-U collection of events, which contained a modest sample of Drell-Yan events and led to a significant statistical uncertainty). The curve is further analytically rescaled to 158 GeV under the assumption that σ_{abs} is energy independent. The comparison with the normal absorption curve shows that the data behave normally for peripheral collisions while increasingly departing from this normal behaviour with increasing centrality.

5.3 The reference curve

Up to this point, the reference curve was obtained as detailed in Sect. 3.4. The method led to a curve with its corresponding errors, as plotted in Fig. 16.

It has been pointed out that this reference could be biased by the use of S-U data in its determination since comoving produced hadrons, for example, could already affect J/ψ production in S-U reactions. A new determination of the reference curve has therefore been implemented as detailed hereafter. Use has been made of the most precise results on absolute J/ψ production cross-sections obtained by NA50 in p-A collisions at 450 and 400 GeV, together with the results obtained at 200 GeV, again in p-A collisions exclusively, by experiments NA38 [12] and NA3 [13]. The Glauber "simultaneous fit" method detailed in Sect. 3.4 leads then to an absorption cross-section $\sigma_{\mathrm{abs}} = 4.1 \pm 0.4$ mb which, it is worth noting, is in excellent agreement with the value of 4.2 ± 0.4 mb obtained from the ratio of cross-sections J/ψ / Drell-Yan. Figure 17 (top and centre) illustrates the method and further shows that results from O-Cu, O-U and even S-U data exhibit, within errors, a so-called normal p-A like behaviour. Figure 17

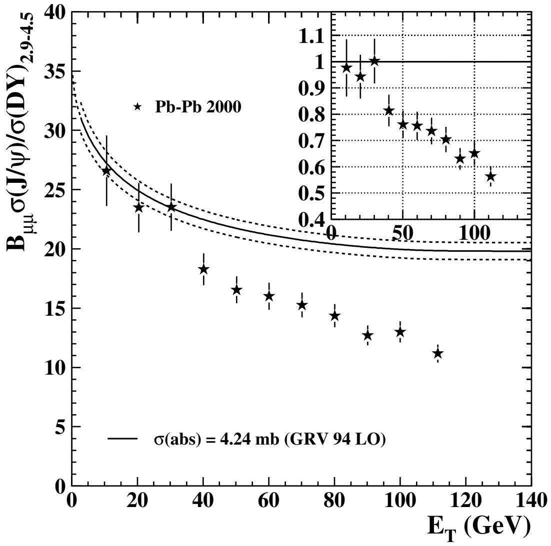

Fig. 16. The ratio J/ψ / Drell-Yan compared to the normal nuclear absorption, as deduced from p-A and S-U data. The inset shows the ratio *data / (normal suppression)*

(bottom) confirms that, with respect to a pure p-A reference curve, the J/ψ is "anomalously" suppressed in Pb-Pb collisions at 158 GeV. It is worthwhile underlining here that the new reference curve for the ratio J/ψ / Drell-Yan at 158 GeV is deduced by analytical rescaling: the J/ψ cross-section is rescaled from 200 to 158 GeV with a Schuler-type formula and, on the other side, the appropriate factor is applied to the Drell-Yan cross-section to rescale it from 450 to 158 GeV. This pure p-A "normal" reference curve has identical shape as the one which made use of S-U data. It is globally lower by 0.6 % whereas its experimental uncertainty is increased by a factor 2.

The most recent results obtained from Pb-Pb can now be compared with this new p-A based reference curve. As a function of three independently measured quantities tagging the centrality of the collision (see Sect. 3.1), the J/ψ survival pattern exhibits very similar trends, as shown in Fig. 18.

5.4 J/ψ suppression: some p_T features

In an attempt to investigate the p_T dependence of the J/ψ abnormal suppression, J/ψ and Drell-Yan events have been considered within nine centrality bins. Within each centrality bin, the p_T distribution of the J/ψ has been studied, normalized to the total number of Drell-Yan events with the same centrality. The ratios F_i and R_i are thus defined as

$$F_i = \frac{\mathrm{d}N^i_{J/\psi}/\mathrm{d}p_T}{N^i_{DY\,(M>4.2\ \mathrm{GeV}/c^2)}} \qquad \text{and} \qquad R_i = \frac{F_i}{F_1} \quad ,$$

where
- i is the i^{th} centrality bin;
- $\mathrm{d}N^i_{J/\psi}/\mathrm{d}p_T$ is the number of J/ψ events of a given p_T, in centrality bin i;

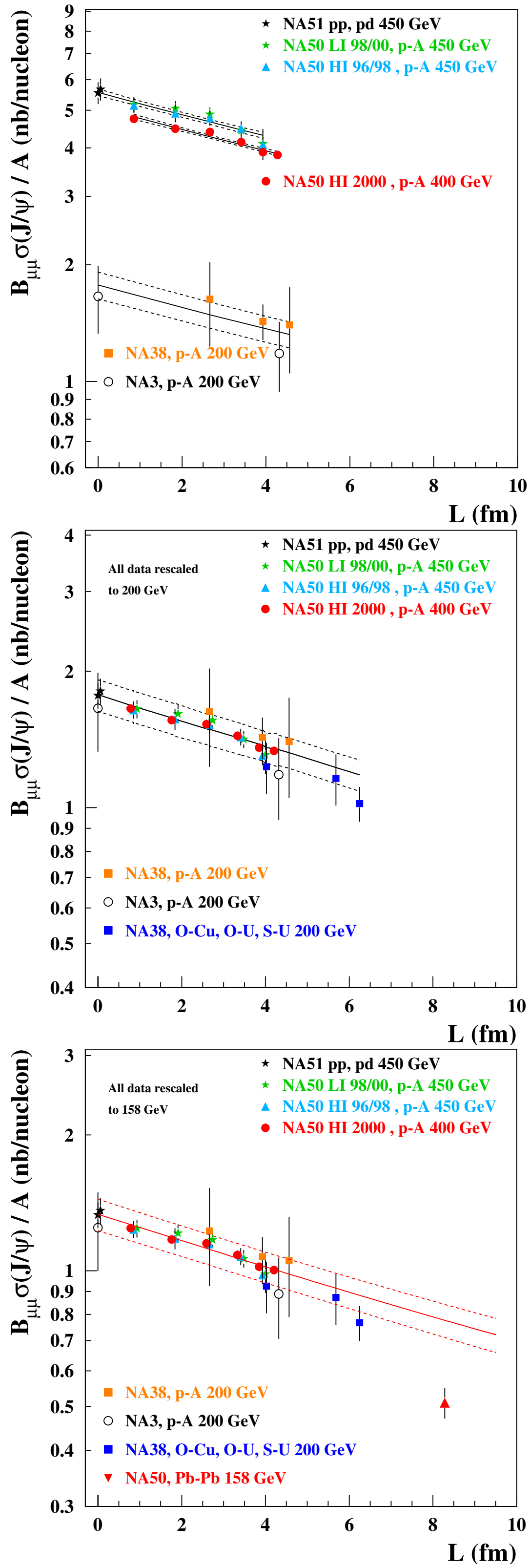

Fig. 17. Absolute J/ψ cross-sections per nucleon in p-A collisions as a function of L. *Top:* Results obtained at 450, 400 and 200 GeV separately. *Centre:* Same results rescaled to 200 GeV and compared with results from light nuclei collisions. *Bottom*: Same results rescaled to 158 GeV and further compared with J/ψ production in Pb-Pb collisions

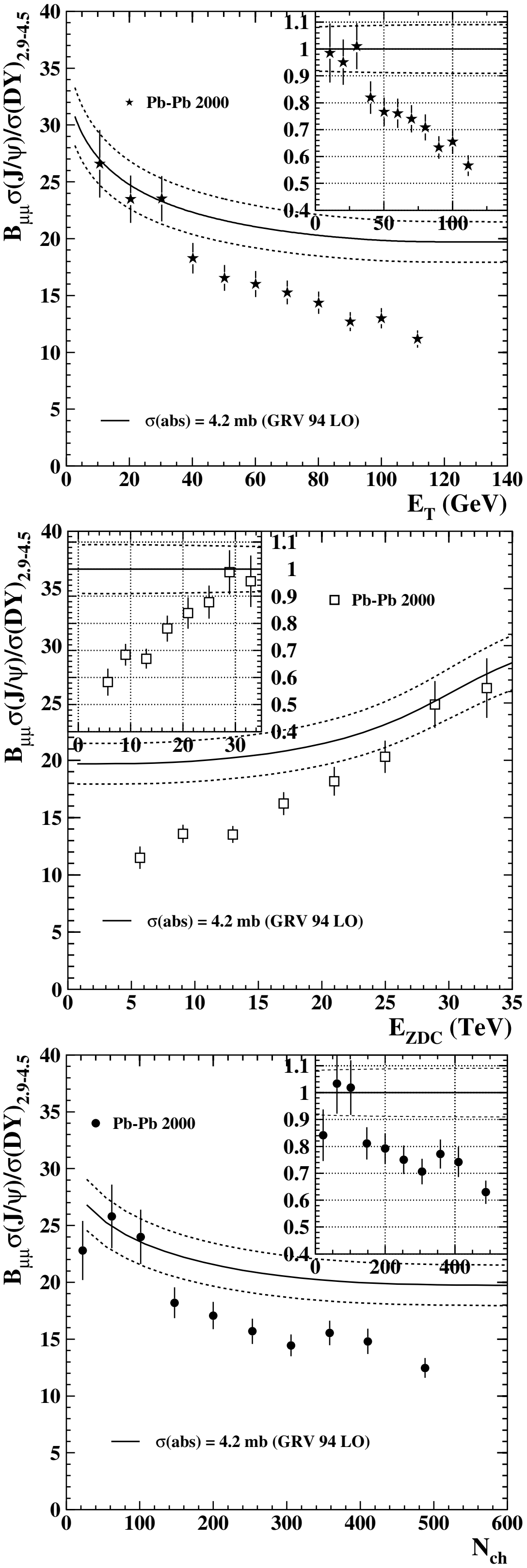

Fig. 18. The ratio of cross-sections J/ψ / Drell-Yan in Pb-Pb collisions as a function of, from top to bottom, the neutral transverse energy, the "very forward" hadronic energy and the charged multiplicity. The curve displays the normal suppression pattern as deduced from p-A interactions only. The insets show the ratio *data / (normal suppression)*

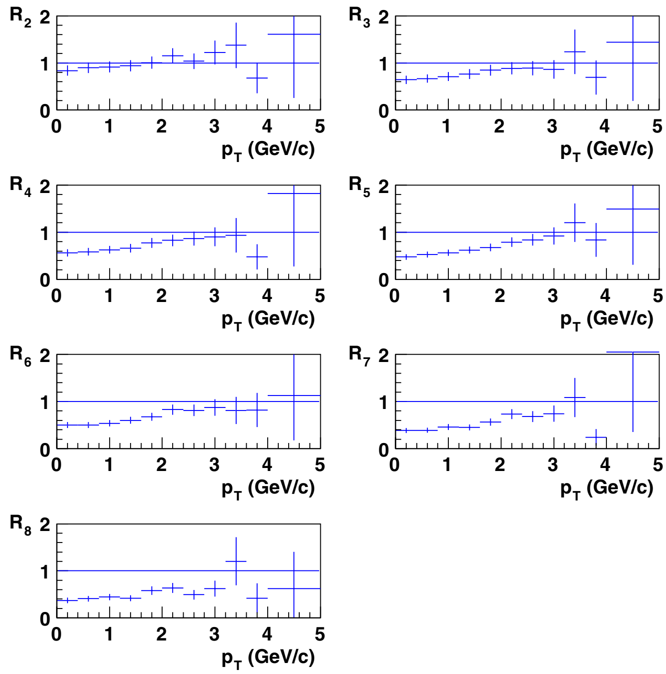

Fig. 19. The ratio of the J/ψ p_{T} distribution in a given bin of centrality to the same distribution for the most peripheral bin. With respect to the latter, the low p_{T} part of the distibutions deplete with increasing centrality

- $N^i_{DY\,(M>4.2\ \mathrm{GeV}/c^2)}$ is the *total* number of Drell-Yan events with $M > 4.2$ GeV/c^2, in centrality bin i.

Figure 19 displays the p_{T} dependence of the eight ratios R_i. It shows that, whereas low p_{T} J/ψ 's are more and more suppressed when the centrality of the collision increases, for transverse momenta larger than 3 GeV/c the relative rate of the J/ψ survival is centrality independent.

6 The J/ψ survival pattern: from pp to Pb-Pb

Figure 20 shows the ratio of cross-sections J/ψ / Drell-Yan for the collision systems studied up to now, from the lightest (pp) up to heaviest (Pb-Pb). When necessary, they have been reanalyzed in order to ensure a fully coherent selection and treatment. They have also been rescaled to an incident momentum of 158 GeV/c when required. This rescaling has used the "simultaneous fit" method to bring data at higher momenta down to 200 GeV/c and an analytical calculation to further bring the 200 GeV results down to 158 GeV. Figure 21 shows the same ratio of cross-sections, J/ψ / Drell-Yan, obtained in S-U and in Pb-Pb collisions as a function of ϵ, the energy density averaged over the whole transverse area of the collision. The latter is obtained with the Bjorken formula with the total transverse energy deduced from the mesurement of its neutral component in the electromagnetic calorimeter. It shows that the departure from the normal nuclear absorption curve sets in for energy densities around 2.5 GeV/fm^3.

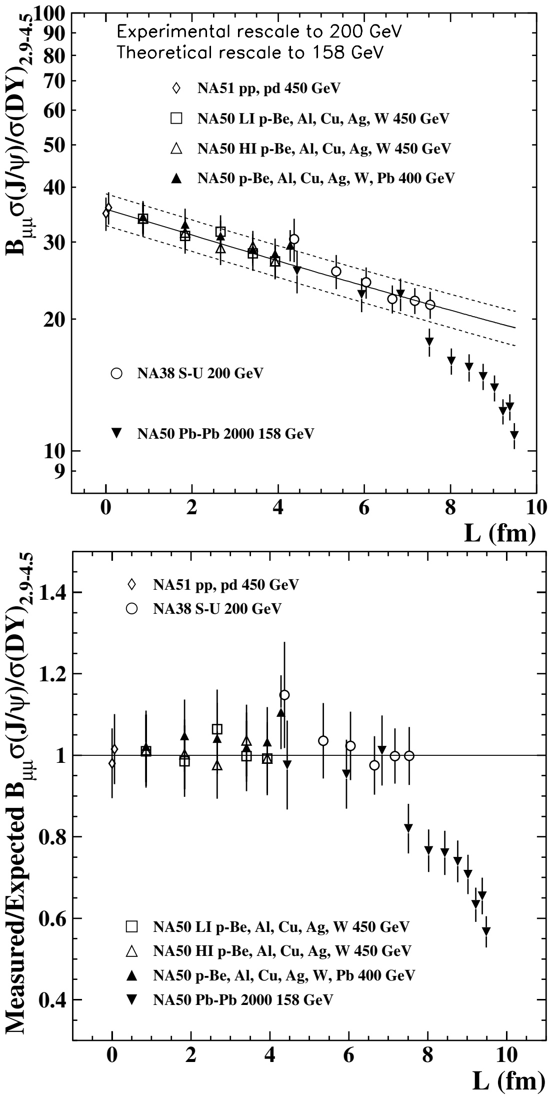

Fig. 20. The J/ψ / Drell-Yan ratio of cross-sections vs. L, for several collision systems, compared to (top) and divided by (bottom) the normal nuclear absorption pattern. All data are rescaled to 158 GeV/nucleon

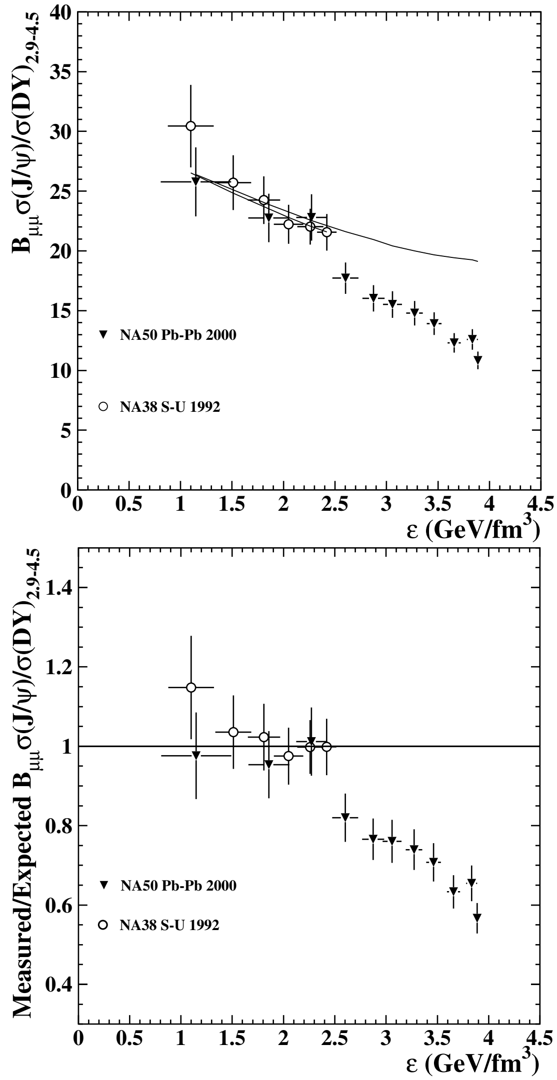

Fig. 21. Same as Fig. 20 for S-U and Pb-Pb collisions only, as a function of energy density. The absorption curves for S-U and Pb-Pb in the top panel are slightly different because the relation between energy density and L (obtained from a Glauber calculation) depends on the colliding nuclei

7 Conclusions

The 20 year long study devoted to J/ψ production in ultra-relativistic heavy ion collisions has been an excellent school to learn how to properly carry out such a search. As a matter of fact, several points have shown their relevance for a systematic investigation. The study as a function of the centrality of the collision, in particular if the results for different interacting nuclei are to be compared, requires some kind of normalization which, in order to minimize assumptions, calculations and systematic biases ought to be an experimental observable. If J/ψ is detected via its dileptonic decays, a process with a similar signature like Drell-Yan, for example, is certainly a good choice, despite its drawbacks. In particular, it has been shown experimentally that Drell-Yan production is indeed proportional to the number of nucleon-nucleon collisions from pp up to Pb-Pb interactions. In order to detect potential anomalies of J/ψ production in heavy ion collisions, it is a must to be able to make a fair comparison, not only with p-induced reactions but also with collisions of lighter nuclei and thus set the normal behaviour of J/ψ survival. The ideal case is to have all these studies done under identical conditions, in particular at the same energy and within the same phase space. This, unfortunately, has not been the case up to now so that references, based either exclusively in p-A reactions or in p-A and light ion collisions, are the result of mixed experimental and analytical procedures. This point would benefit from a more coherent program. Nevertheless, present results, based on an impressive systematic study, strongly suggest that J/ψ production follows the same behaviour in p-A and light ion-induced reactions up to S-U. On the contrary, results obtained on

J/ψ production in Pb-Pb collisions show a behaviour that clearly departs from what is observed up to S-U collisions. Whereas for peripheral Pb-Pb collisions J/ψ production behaves as observed for lighter ions, for more central collisions it departs from this normal behaviour and exhibits an abnormal suppression which increases with increasing centrality.

After a recent and deep scrutiny for experimental biases and for full coherence in the treatment of the various samples of data, collected during a period extending over almost 15 years, the results obtained so far will surely pave the way, in this specific sector, for second generation challenges.

Acknowledgements. I would like to give all the credit of this impressive set of results, as briefly overviewed in this presentation, to my colleagues in the NA38, NA51 and NA50 Collaborations. Their enthusiasm, their constant self-critical attitude and, finally, their systematic efforts to thoroughly understand the collection and the analysis of the various data sets have been the basic tools for the success of this twenty year long pioneering campaign. Let them find here the expression of my gratitude. I would also like to thank Carlos Lourenço who helped me for these proceedings with an extremely careful reading of my draft followed by many remarks and suggestions.

References

1. E.V. Shuryak, Phys. Rep. **61** (1980) 71; K. Kajantie, H.I. Miettinen, Z. Phys. **C14** (1982) 356; R.C. Hwa, K. Kajantie, Phys. Rev. **D32** (1985) 1109; L.D. McLerran, T. Toimela, Phys. Rev. D **31**, 545 (1985)
2. T. Matsui, H. Satz, Phys. Lett. B **178**, 416 (1986)
3. L. Anderson et al. Nucl. Instrum. Meth. **223**, 26 (1984)
4. C. Baglin et al. (NA38 Coll.), Phys. Lett. B **220**, 471 (1989)
5. A. Baldit et al. (NA51 Coll.), Phys. Lett. B **332**, 244 (1994)
6. M.C. Abreu et al. (NA51 Coll.), Phys. Lett. B **438**, 35 (1998)
7. B. Alessandro et al., Nucl. Instrum. Meth. A **493**, 30 (2002)
8. R. Arnaldi et al., Nucl. Instrum. Meth. A **411**, 1 (1998)
9. M.C. Abreu et al. (NA50 Coll.), Phys. Lett. B **410**, 337 (1997)
10. M.C. Abreu et al. (NA50 Coll.) Phys. Lett. B **450**, 456 (1999)
11. M.C. Abreu et al. (NA50 Coll.), Phys. Lett. B **477**, 28 (2000)
12. M.C. Abreu et al. (NA38 Coll.), Phys. Lett. B **466**, 408 (1999)
13. J. Badier et al. (NA3 Coll.), Z. Phys. C **20**, 101 (1983)
14. B. Alessandro et al. (NA50 Coll.), Eur. Phys. J. C **39**, 335 (2005)
15. M. Glück et al., Z. Phys. C **67**, 433 (1995)