J/ψ production and suppression at SPS energies

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Abstract

We present the set of measurements carried out by the NA50 experiment to study J/ψ production in proton- and in ion-induced reactions. We also make use of results obtained previously under similar conditions by experiments NA51, NA38 and NA3. All these measurements were performed in fixed target experiments at the CERN SPS. Due to accelerator constraints, momentum was 450, 400 and 200 GeV/c for incident proton beams (corresponding to $\sqrt{s} = 29.0, 27.4, 19.4$ GeV respectively) whereas, for ion beams, incident momentum was 200 GeV/nucleon for oxygen and sulfur and 158 GeV/nucleon for Pb beams ($\sqrt{s} = 19.4$ and $\sqrt{s} = 17.2$ GeV respectively). The p-A data allow

us to determine with high accuracy the absorption cross section of the (pre-)resonant $c\bar{c}$ state with nuclear matter. The J/ψ production cross-section normally expected for ion-induced reactions can then be determined and compared to the results obtained from the data collected for oxygen- and sulfur-induced collisions. Finally, we also present the most recent results on J/ψ production in Pb-Pb interactions. They are based on the last data sample collected with an improved experimental setup and are compared with the expectations inferred from similar measurements on lighter nuclei collisions.

1 Introduction

In 1986, Matsui and Satz predicted that, due to color screening, the production of J/ψ and other quarkonium states would be suppressed in a QGP [1]. Following this prediction, an extensive search has been carried out by the NA38, NA50 and NA51 experiments to investigate J/ψ production in different nuclear colliding systems. The SPS heavy ion program has led to the acceleration of increasingly heavier nuclei: oxygen, sulfur and lead (from 1994 on) in order to reach more and more favorable conditions for the formation of a deconfined state.

In parallel and in order to provide a reference for the evaluation of the suppression effects, J/ψ production has been measured in p-A collisions. Early results by experiment NA38 have shown, although with limited statistics, that J/ψ production in p-A interactions is already suppressed with respect to binary collision scaling [2].

These results have been used to perform a comparison with the J/ψ suppression observed in S-U and Pb-Pb collisions. It has been shown that, in sulfur-induced reactions, the measured suppression could be explained in terms of the ("normal") nuclear absorption effects already observed in p-A interactions [3], while in Pb-Pb reactions a further "anomalous" suppression appears [4, 5, 6]. This result has been interpreted as the indication that the deconfinement conditions have been reached in Pb-Pb collisions at SPS energies [7].

Nevertheless, when the high statistics Pb-Pb results were first published, the need for a much more accurate measurement of the p-A reference became evident. To provide such a baseline, several data samples were collected between 1996 and 2000 to study J/ψ production in proton-induced collisions on a variety of nuclear targets [8, 9, 10, 11].

Finally, a new high statistics sample of Pb-Pb data has been collected in year 2000 with an upgraded setup and the aim of studying and clarifying potential problems which could affect previously studied data samples. In this paper, results obtained from the most recent NA50 data will be presented, discussed and critically compared with previous measurements.

2 The experimental apparatus

A detailed description of the NA50 muon spectrometer can be found in [4]. We recall here some characteristics that are relevant for the discussion.

The coverage of the spectrometer allows to study muon pairs with $2.92 < y_{lab} < 3.92$ and with $|\cos\theta_{CS}| < 0.5$, where θ_{CS} is the decay angle of the μ^+ in the Collins-Soper reference frame. When considering the rapidity of the dimuons in the collision center of mass (y^*), the coverage of the spectrometer depends on the beam momentum. It changes from $-0.5 < y^* < 0.5$ at 450 GeV to $0 < y^* < 1$ at 158 GeV. Typical acceptances are $A_{\mathrm{J}/\psi}$ ~14% and $A_{\psi'} \sim$ 15% for Pb-Pb collisions at $158\,\mathrm{A}\cdot\mathrm{GeV}$ using a moderate track-quality cut.

The main difference between the proton and ion setups lies in the target region. During proton runs, no centrality estimation is performed while, for the Pb-Pb runs, the NA50 spectrometer is equipped with three centrality detectors: the Electromagnetic Calorimeter that measures neutral transverse energy E_T in the angular range $1.1 < \eta < 2.3$, the Multiplicity Detector that measures charged particle multiplicity N_{ch} in the angular domain $1.9 < \eta < 4.2$ and the Zero-Degree-Calorimeter which measures the energy E_{ZDC} carried by the beam spectator nucleons. The NA38 experiment was equipped with an Electromagnetic Calorimeter covering $1.7 < \eta < 4.1$.

Year	Thickness λ_i	Type	Target environment	Target id.
1995	17 %	segmented	air	interaction id.
1996	30 %	segmented	air	interaction id.
1998	7 %	single	air	interaction id. / vertex id.
2000	9.5 %	single	vacuum	vertex id.

Tab. 1: Features of the target systems for the different Pb-Pb data taking periods. In the first years the identification of the interaction vertex has been performed using interaction detectors placed downstream of each target. For the 1998 data analysis, the first publication adopted this strategy. The reanalysis presented in this work uses a more precise vertex identification that allows us to reject Pb-Air interactions.

2.1 Issues relative to the p-A data taking

In order to obtain the best possible accuracy on the evaluation of the J/ψ absorption cross-section in p-A, several data samples, collected with a high intensity incident beam ($\sim 10^9$ p/s), were taken in 1996-1997. For these data, the error on the measured J/ψ yield is mainly systematical, due to the uncertainties connected with the estimate of the luminosity and detection efficiency that may vary from period to period. For the last data taking period (year 2000), a different approach has been adopted. In practice, six different targets were mounted on a revolving frame that allowed very frequent target changes. In this way the relative luminosity uncertainties and the oscillations of the detection efficiency have been minimized, allowing a significant decrease of the systematical errors on the evaluation of the J/ψ cross-sections.

2.2 Issues relative to the Pb-Pb data taking

The experiment underwent several changes along the years, especially in the arrangement of the target region. A summary of the target characteristics can be found in Table 1.

The 1996 data sample was collected using a segmented multiple target with the twofold aim of a) maximizing its total interaction length and thus the event yield of the experiment and b) tag possible fragment reinteractions within the target. The limited efficiency of this reinteraction identification resulted, for a certain number of events, in an improper estimate of the transverse energy (and of the zero degree energy) of the reaction which affected, in particular, the sample of the most central collisions. It consequently led to the use of one single thin target for the data collections of years 1998 and 2000.

Another feature which could affect the sample of peripheral interactions, is a potential contamination from Pb-air collisions. Such events, in fact, might not be completely rejected by the interaction identification system. This led us to put the target in a vacuum vessel for the year 2000 data taking.

From the experimental point of view the environment for this (last) data taking must be considered as the cleanest one achieved by NA50. Thanks to the optimal conditions, a new algorithm for the identification of the interaction vertex, based on the correlation of the hits on the two planes of the Multiplicity Detector, has been applied to the data. It has therefore become possible to extend the centrality range of the analyzed data down to very peripheral collisions ($E_T = 3$ GeV). The same method has been applied also to the 1998 data sample.

3 Data analysis

The analysis procedure makes use of a set of cuts that ensures the quality of the data and covers three main issues: the quality of track reconstruction, the rejection of dimuons from out-of-target collisions and the quality of the centrality measurement. A fourth cut ensures that the acceptance does not depend on the charge of the muons. It allows to extract the combinatorial background from the "like sign" dimuon invariant mass spectra. More details on these procedures can be found in the recent NA50 paper [13].

The extraction of the signals is performed by means of a fit to the $\mu^+\mu^-$ invariant mass spectrum. The line shapes of the different sources are determined by means of a Monte-Carlo simulation. The GRV94 LO

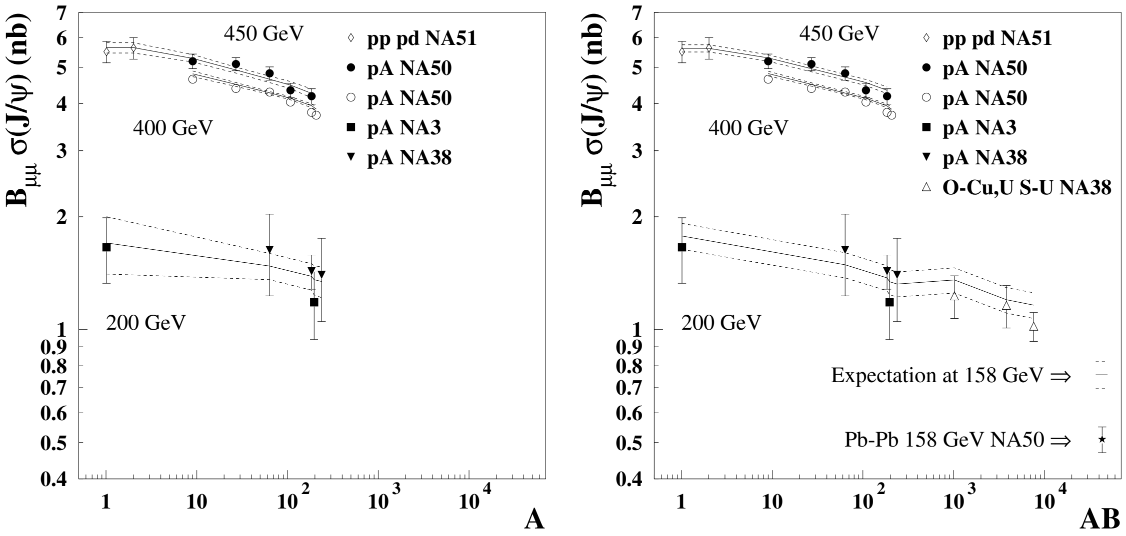

Fig. 1: The J/ψ production cross-sections for different colliding systems divided by the product of the atomic numbers of the projectile and the target. In the left figure, we show a fit with the Glauber model to the 450, 400 and 200 GeV p-A data sets. In the right figure, we show the fit to the same data using a common absorption cross section. The dashed bands represent the uncertainty on the fit. The behavior is extrapolated to heavier nuclear collisions at 200 and 158 GeV.

set of parton distribution functions has been used in the analysis of p-A, S-U and Pb-Pb data sets in order to allow a coherent comparison of (J/ψ)/Drell-Yan) cross-section ratios for the various colliding systems.

4 J/ψ production

In Figure 1 we plot a compilation of results on J/ψ absolute cross-section from the NA38, NA50 and NA51 experiments [3, 8, 11, 14] together with the results from the NA3 experiment [15]. In the left part, we show a fit to the p-A data at the three energies using the Glauber model that allows to extract σ_{abs}, the J/ψ absorption cross-section in nuclear matter. We obtain $\sigma^{pA}_{abs}(450) = 4.5 \pm 0.8$ with $\chi^2/d.o.f. = 0.5$ and $\sigma^{pA}_{abs}(400) = 4.1 \pm 0.5$ with $\chi^2/d.o.f. = 0.6$ respectively. The points at 200 GeV, due to the large uncertainties, do not allow a precise determination of $\sigma^{pA}_{abs}(200)$. Nevertheless they lead to a value which is fully compatible with those obtained at 450 and 400 GeV. A simultaneous fit to the three data sets (see the right part of Figure 1) leads to $\sigma^{pA}_{abs} = 4.1 \pm 0.4$ with $\chi^2/d.o.f. = 0.43$. The corresponding normalizations for J/ψ production in pp collisions at the 3 energies are $B_{\mu\mu}\sigma(450) = 5.6 \pm 0.1$ nb, $B_{\mu\mu}\sigma(400) = 5.1 \pm 0.1$ nb and $B_{\mu\mu}\sigma(200) = 1.8 \pm 0.1$ nb.

The results of the fit to p-A data is extrapolated to heavier nuclear systems at 200 GeV and to Pb-Pb system at 158 GeV taking into account the energy dependence of J/ψ production using a NLO calculation [16]. While J/ψ production in O-Cu, O-U and S-U collisions is compatible, within errors, with this extrapolation, the results of Pb-Pb show a huge suppression ($B_{\mu\mu}\sigma(\mathrm{J}/\psi, 158)/A^2_{Pb} = 0.51 \pm 0.04$ nb [4] to be compared with an expected value of 0.76 ± 0.06 nb) and completely miss the extrapolation.

We have henceforth based the estimation J/ψ production in Pb-Pb collisions only on the behavior extracted from p-A data because some additional suppression mechanism could be present in O-Cu, O-U and S-U reactions in addition to nuclear absorption. Nevertheless, this concern is not completely supported by the available data which exhibit very good compatibility of the J/ψ cross-section in oxygen- and sulfur-induced reactions with the values extrapolated from p-A data. We could as well make the hypothesis that J/ψ suppression in oxygen- and sulfur-induced reactions is caused only by nuclear absorption and therefore we can try to include these results in the simultaneous fit. With this assumption we obtain $\sigma_{abs} = 4.2 \pm 0.4$ mb with $\chi^2/d.o.f. = 0.43$ that is in agreement with the result extracted from p-A only. The estimation

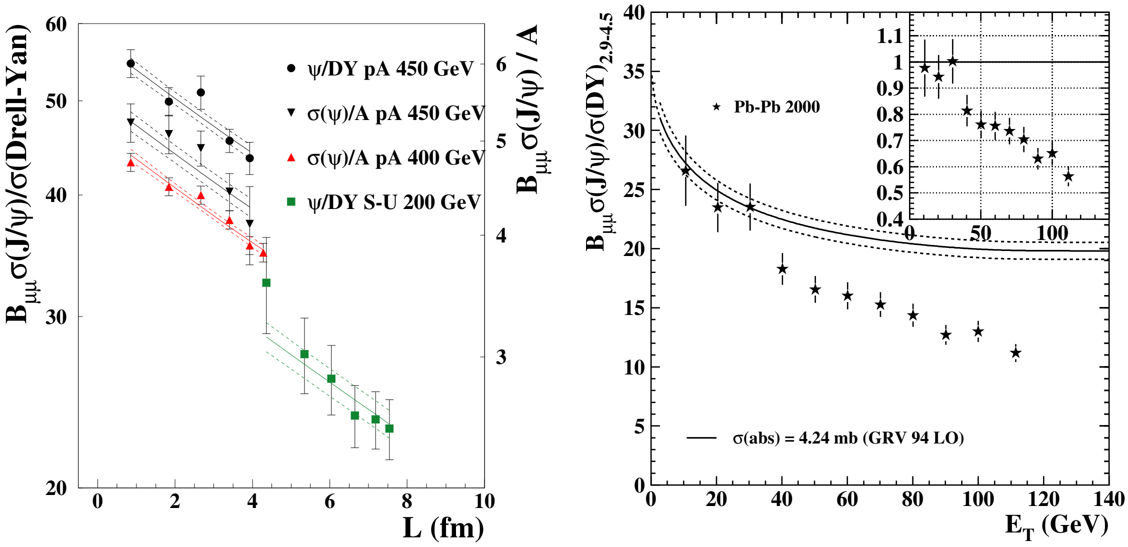

Fig. 2: (left) The J/ψ production yield for different colliding systems. The left scale is for the ratio $B_{\mu\mu}\sigma(\mathrm{J}/\psi)/\sigma(Drell - Yan)$, the right scale for absolute cross-sections.
(Right) The ratio $B_{\mu\mu}\sigma(\mathrm{J}/\psi)/\sigma(Drell - Yan)$ in Pb-Pb collisions from the data sample collected in year 2000, as a function of E_T. The curve is the extrapolated expected behavior based on the measured nuclear absorption. The inset shows the ratio "Measured/Expected", i.e. the results obtained from the data divided by the values expected from normal nuclear absorption only.

of the J/ψ cross section in pp at 200 GeV decreases to $B_{\mu\mu}\sigma(200) = 1.68 \pm 0.09$ nb. Consequently the expectation for Pb-Pb collisions at 158 GeV becomes 0.71±0.04 nb, far higher than the experimental result.

5 Centrality dependence of J/ψ production

To study the centrality dependence of J/ψ production we make use of the informations from the different centrality detectors. When convenient to minimize errors, namely when the Drell-Yan data sample is large enough, we study the ratio of the J/ψ and Drell-Yan cross-sections which provides the appropriate normalization, as the Drell-Yan process is proportional to the number of binary nucleon-nucleon collisions. Moreover, in the cross-sections ratio, most of the detection efficiencies cancel out, therefore reducing the systematic uncertainties.

Results are plotted as a function of L, the length of nuclear matter seen by the $c\bar{c}$ state on its way out from the interaction region. The use of this variable helps to unveil the effects of normal absorption as nuclear absorption scales approximately with $\exp(-L/L_0)$. It allows us, at the same time, to study the centrality dependence of J/ψ production for different colliding systems.

Figure 2 (left) shows the results obtained for J/ψ production in different colliding systems in terms of absolute J/ψ cross-sections or of cross-sections normalized by Drell-Yan. A Glauber fit that assumes a common J/ψ absorption cross section, gives a satisfactory description of the observed data with $\sigma_{abs}^{pA-SU} = 4.2 \pm 0.4$ mb and $\chi^2/d.o.f. = 0.55$.

Figure 2 (right) shows the results of J/ψ production in Pb-Pb collisions from the year 2000 data sample, as a function of E_T. The curve corresponds the behavior expected from nuclear absorption only. It is based on the fit to the data shown in the left part of the figure and takes into account (dashed curves) the experimental uncertainties affecting its determination. The peripheral Pb-Pb points agree with the expectation. As centrality increases, the data show a departure from the “normal” suppression followed by a persistent decrease with no saturation for central collisions. The same pattern is observed using the other two centrality estimators, N_{ch} and E_{ZDC}, as can be seen from Figure 3.

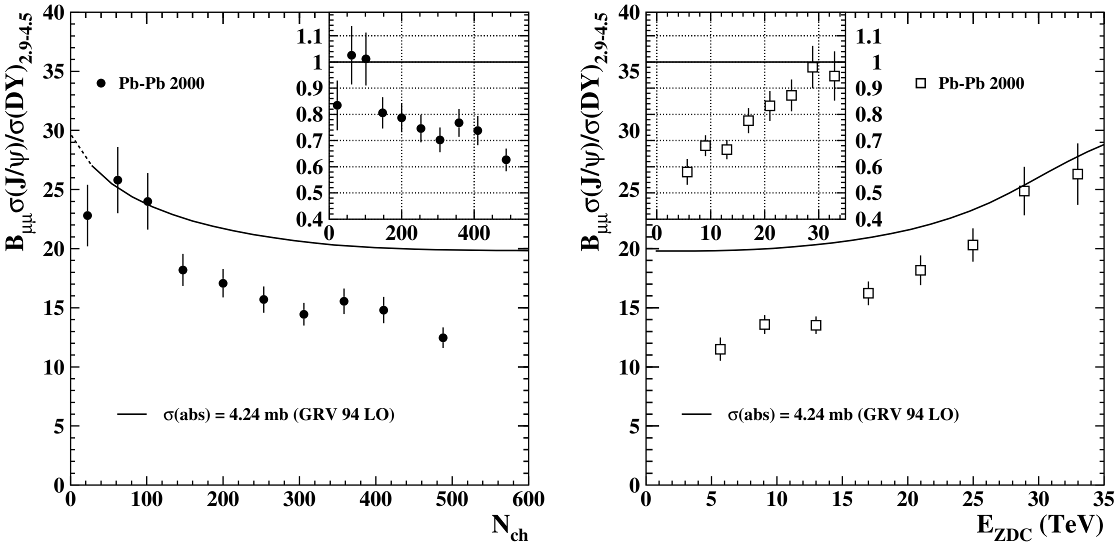

Fig. 3: The (J/ψ) / Drell-Yan cross-section ratio as a function of the charged multiplicity N_{ch} (left) and of the forward energy E_{ZDC} (right) for the Pb-Pb 2000 data sample. The curve represents the normal nuclear absorption in the Pb-Pb system. The insets show the ratio "Measured/Expected".

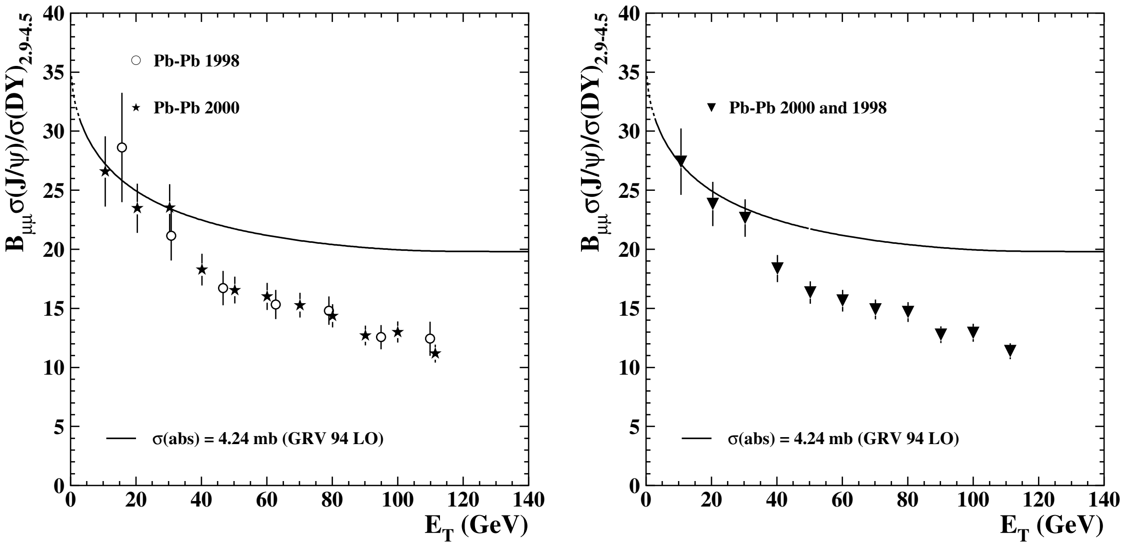

Fig. 4: Comparison between the results obtained from the data collected in years 2000 and 1998 for the ratio $B_{\mu\mu}\sigma(J/\psi)/\sigma(Drell - Yan)$. The right plot shows the weighted average of the two results as a function of the transverse energy.

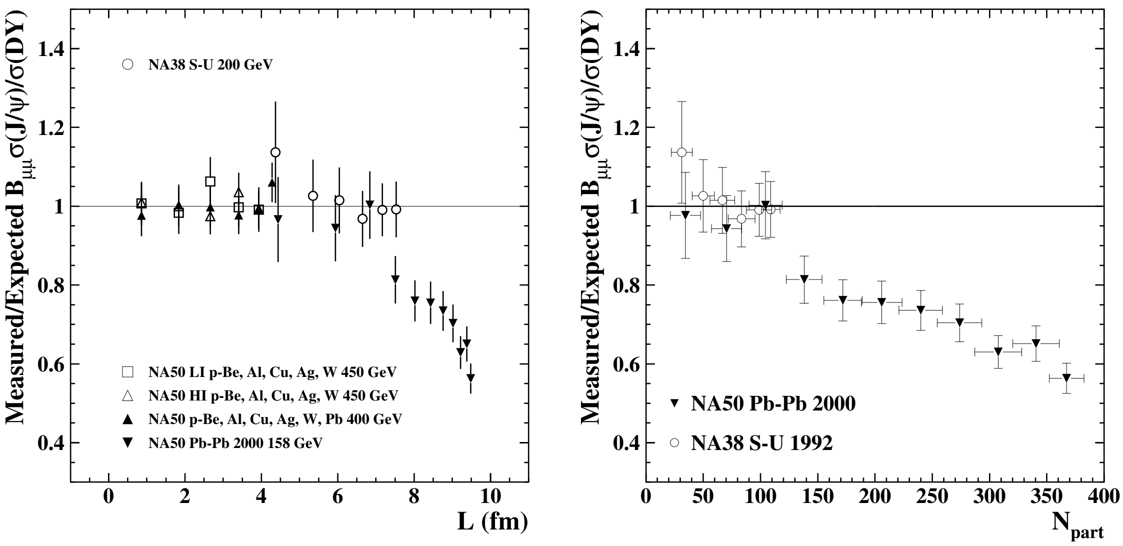

Fig. 5: The ratio "Measured/Expected" for the ratio $B_{\mu\mu}\sigma(\mathrm{J}/\psi)/\sigma(Drell-Yan)$ in p-A, S-U and Pb-Pb collisions, as a function of L (left) and N_{part} (right).

Figure 4 shows the comparison between the results of year 2000 data sample with the reanalysis of year 1998 data. The new analysis techniques allow to access a wider centrality range even for this 1998 data sample. The two sets of results are in very good agreement.

In Figure 5, for the ratio of cross-sections $B_{\mu\mu}\sigma(\mathrm{J}/\psi)/\sigma(\text{Drell-Yan})$, we plot its effectively measured value divided by the value expected in the case where only normal nuclear absorption would determine the J/ψ yield. The left plot shows this ratio "Measured/Expected" as a function of L and the right plot shows it as a function of the number of participants.

6 Conclusions

A systematic study of p-A collisions in the NA50 experiment at 450/400 GeV/c proton incident momentum has led us to a very precise determination of the J/ψ normal absorption cross-section in nuclear matter. These p-A data are combined with results obtained in reactions induced at 200 GeV/c incident momentum, both with proton and sulfur beams, to obtain the normal J/ψ yield at lower incident momenta and reliably extrapolate to 158 GeV. The extrapolation is then used as an experimental reference for the study of J/ψ production in Pb-Pb interactions at 158 GeV/nucleon. The results obtained from the last sample of Pb-Pb data collected in year 2000 allow us to study the J/ψ production rate over the whole centrality range. They show that, for peripheral Pb-Pb collisions, J/ψ production agrees with expectations from normal nuclear absorption. For mid and more central collisions, the production rate departs from expectations and exhibits an increasingly abnormal suppression.

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