RESULTS FROM THE NA50 EXPERIMENT

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The NA50 Collaboration studies the $\mu^+\mu^-$ production in Pb–Pb collisions at 158 GeV per nucleon. The experimental apparatus is optimized to detect dimuons in the invariant mass range of the charmonia states J/ψ and ψ' in order to allow the measurement of these mesons through their $\mu^+\mu^-$decay channel. In this paper, results from the 1996 high statistics run will be presented. The J/ψ meson production is suppressed with respect to the Drell–Yan process and this suppression differs from what is expected when extrapolating from data obtained with lighter colliding systems. The suppression pattern as a function of the neutral electromagnetic transverse energy (E_T) shows a clear discontinuity at $E_T \simeq 40\,GeV$: the J/ψ meson is *anomalously* suppressed when going from peripheral to more central interactions. The observed ψ' suppression relative to Drell-Yan in Pb–Pb collisions is similar to what has been measured in S–U interactions.

1 Introduction

The NA50 collaboration is carrying out measurements at the CERN SPS in order to address the question of confinement: since 1986 several experiments both at the Brookhaven AGS and at the Cern SPS are studying ultrarelativistic nucleus–nucleus collisions in order to reach some evidence of the formation of a new state of hadronic matter called Quark Gluon Plasma (QGP). A phase transition from the ordinary nuclear matter, in which quarks and gluons are confined into hadrons, to a plasma state in which partons are free over a larger volume, is predicted by Quantum Chromo Dynamics (QCD) calculations [1] in its non perturbative regime, when energy density exceeds a value of $2 \div 3\,GeV/fm^3$. Such extremely high energy density can be achieved in laboratory only with ultra–relativistic heavy ion collisions.

Since deconfinement changes the nature of the medium, heavy resonances like J/ψ and ψ', produced in the first nucleon nucleon collisions, melt down in the plasma phase when the screening length becomes smaller than the distance among the constituent $\bar{c}c$ pair. The J/ψ suppression has been considered for a long time as the golden signature for the QGP formation [2].

The production of J/ψ and ψ' vector mesons is studied via their two–body decay in $\mu^+\mu^-$ pairs by the NA50 experiment that is an upgrade of the NA38 experiment which took data with Proton, Oxygen and Sulphur beams [3]. A suppression of J/ψ and ψ' was actually measured by the NA38 experiment and the considerable amount of theoretical work triggered by its results [4] led to a clearer understanding of the observed phenomena in terms of charmonium absorption in nuclear matter. The results from the analysis of data collected by NA50 in 1995, recently published[5], show that charmonium suppression in Pb–Pb collisions is greater than what expected when extrapolating from lighter colliding systems (*anomalous suppression*). In this paper, we report on the analysis of the 1996 high statistics run on Drell–Yan, J/ψ and ψ'

production in 158 $A\,GeV$ Pb–Pb interactions.

2 The experiment and the analysis method

A detailed description of the NA50 apparatus can be found in Ref. [5], so only a very schematic description will be given here. The detector basically consists of a muon spectrometer and a set of three independent detectors that measure the global features of the events: a zero degree calorimeter determines the energy carried by projectile spectators, an electromagnetic calorimeter covers the region $1.1 \leq \eta \leq 2.3$ and two silicon strip detectors placed close to the target measure the charged particle multiplicity in the region of the spectrometer ($1.6 \leq \eta \leq 4$). The target used for 1996 run was made up of seven Pb subtargets of different thickness ($1\,mm$ the first and the last and $2\,mm$ the others) for a total length $\sim 0.32\,\lambda_{int}$ [a]. Each subtarged is viewed by a pair of quartz Čerenkov detectors used to determine the subtarget in which the interaction occurs. The first part of the muon spectrometer is a hadron absorber placed $15\,cm$ after the target in order to minimize the number of muons originating from decays of charged pions and kaons. The absorber is mostly made by light materials ($60\,cm$ of BeO, $400\,cm$ of graphite and finally $80\ cm$ of iron) to reduce the effects of multiple scattering on the dimuon mass resolution. The momentum of the muons emerging from the absorber is measured with the aid of eight multiwire proportional chambers and an air core toroidal magnet. Six scintillator hodoscopes are used to trigger on muon pairs. Finally, punch–through hadrons in the spectrometer are vetoed at trigger level by a $1\ m$ thick iron wall sandwiched between the last two scintillator hodoscopes.

In order to collect $\sim$ 200000 J/ψ events, the beam intensity during the 1996 run was as high as $5\,10^7$ Pb ions in a $5\ s$ spill [b]. The standard offline analysis for Drell Yan and charmonium study starts from events collected triggering on at least two *muon like* tracks in the spectrometer. The online selection is then refined by applying cuts, based on dedicated detectors, in order to eliminate beam pile up, interactions in the beam hodoscope and ions not well collimated (halo). A given event is considered for the analysis only if exactly two muon tracks are reconstructed by the multiwire proportional chambers within a fiducial region. Furthermore, a muon pair is rejected if it were not detected in the fiducial region with a reversed magnetic field in the spectrometer (*image cut*): in this way, the particular charge state of the

[a] $\sim 0.175\,\lambda_{int}$ for 1995 run

[b] $3\,10^7$ ions per burst in 1995 leading to 50000 J/ψ

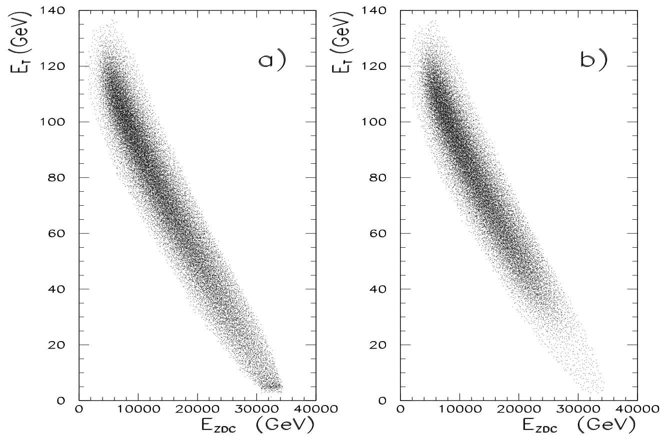

Figure 1. Neutral transverse energy versus very forward energy. (a) 1996 analysis. (b) Events with vertex identified by the standard target algorithm.

muon pair has no influence on the acceptance of the spectrometer. Muon pairs originating out of the target region are rejected applying a strict cut on the distance between each muon track and the beam axis. The vertex of the primary Pb–Pb interaction is identified by means of the quartz blades system, which is also designed to identify the possible interactions of projectile fragments in subsequent subtargets (*re–interactions*). The main background to this detection system is given by knock–on electrons (δ rays) produced with high cross section by non interacting Pb ions in the thick target used in 1996: as a consequence, peripheral interactions cannot be identified properly, since the signal due to secondary charged particles is comparable with the signal originating from δ rays. Moreover, the efficiency in detecting reinteractions is low, since one of the two collisions is likely to be peripheral. The loss of peripheral events is minimized by means of a different selection method, developed for the 1996 data set: it is based on the observed anticorrelation (see Fig. 1) between the very forward energy (E_{ZDC}) measured by the Zero Degree Calorimeter and the electromagnetic transverse energy (E_T). A contour cut is applied to the $E_T - E_{ZDC}$ plane, limited to a 2σ distance from the average correlation. In this way events without an interaction in the target region are rejected. Most of the events excluded with this technique are related to interactions downstream of the target and are characterized by a very low E_T and actually the multiplicity measured for these events by the silicon strip detectors is compatible with the signal generated by δ rays coming from non interacting Pb ions. The primary vertex of the events accepted by the contour cut is arbitrarily assigned to the fourth (middle) subtarget. This leads to a slight decrease of the dimuon mass resolution when going from central collisions, where the vertex is detected with high efficiency by the quartz blade system to peripheral ones, namely σ_M goes from 96 MeV to 104 MeV at the J/ψ mass.

The kinematical domain used for the analysis is defined by:

$$
\begin{aligned}
0 \leq y_{cms} \leq 1 \qquad (3 \leq y_{lab} \leq 4) \\
-0.5 \leq \cos\theta_{CS} \leq 0.5
\end{aligned}
\tag{1}
$$

where y_{cms} (y_{lab}) is the rapidity in centre of mass (laboratory) reference system and θ_{CS} is the polar angle of the μ^+ in the Collins–Soper reference frame[c]. The acceptance of the spectrometer is of the order of 15% at the J/ψ mass and, within the kinematical domain, its value is greater than 10% of the maximum. The information on J/ψ and ψ' production are deduced by fitting the

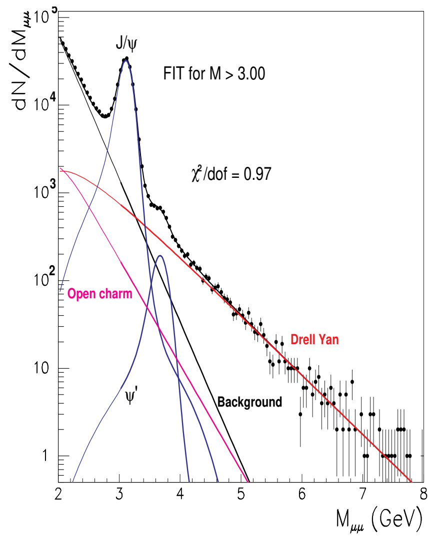

Figure 2. $\mu^+\mu^-$ invariant mass spectrum. 1996 Data set.

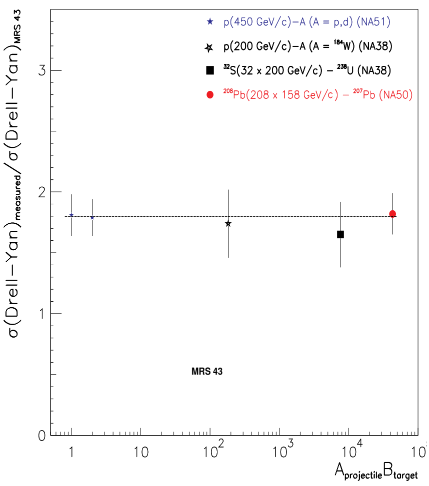

Figure 3. Drell–Yan cross section vs. $A_{proj} \cdot B_{targ}$

[c]The Collins–Soper reference system is a frame in which the dimuon is at rest and the $\hat{z}$ axis is the bisector of the projectile momentum ($\mathbf{p}_p$) and target momentum ($-\mathbf{p}_t$) and the $\hat{y}$ axis is parallel to $\mathbf{p}_p \times \mathbf{p}_t$

invariant mass spectra of muon pairs as it is shown in Fig. 2, where the different sources of dimuons, as resulting from the fit, are displayed separately. The dominant source of pairs at masses smaller than $\sim 2.8\,GeV/c^2$ is given by opposite sign muons originating from uncorrelated charged π and K meson decays. This combinatorial background is evaluated starting from the number of like–sign muon pairs (N^{++} and N^{--}) as:

$$\frac{dN^{+-}_{bgr}}{dM} = 2R\sqrt{\left(\frac{dN^{++}}{dM}\cdot\frac{dN^{--}}{dM}\right)_{B>0} + \left(\frac{dN^{++}}{dM}\cdot\frac{dN^{--}}{dM}\right)_{B<0}} \qquad (2)$$

where $R = 1$ for Pb–Pb collisions and $B < 0$ ($B > 0$) is the sign of the magnetic field in the spectrometer, that was changed from positive to negative several times during the run in order to minimize systematic effects. Another non resonant source is given by semi–leptonic decays of charmed mesons (D and $\bar{D}$). This source is especially relevant to explain the dimuon yield in the intermediate region between the φ and J/ψ masses[6] and, even if its importance at masses above J/ψ mass is negligible, it must be taken into account properly in order to obtain stable results as a function of the mass value arbitrarily chosen as a starting point for the fitting procedure. To this purpose, the open charm contribution is evaluated by fitting the spectrum in the mass range $1.9 \leq M_{\mu\mu} \leq 2.9\,GeV/c^2$ using a shape given by the PYTHIA event generator[7]. The shapes of the mass spectra related to J/ψ and ψ' decays and to Drell–Yan process are given by a detailed Monte Carlo simulation of the experimental apparatus followed by the standard reconstruction programme used for real data. Drell–Yan process is calculated at the leading order with the MRS43 structure functions[8] that account for the $\bar{u}/\bar{d}$ asymmetry measured by the NA51 experiment[9]. The mass spectrum is thus fitted as the superpostion of these sources as follows:

$$\frac{dN^{\mu^+\mu^-}}{dM} = A_{\mathrm{J}/\psi}\frac{dN^{\mathrm{J}/\psi}}{dM} + A_{\psi'}\frac{dN^{\psi'}}{dM} + A_{DY}\frac{dN^{DY}}{dM} + \frac{dN^{D\bar{D}}}{dM} + \frac{dN^{bgr}}{dM} \qquad (3)$$

with $M \geq M_0 = 3.05\,GeV/c^2$ and $A_{\mathrm{J}/\psi}$, $A_{\psi'}$, A_{DY}, J/ψ mass and J/ψ width as free parameters for the fit. The mass and width of the ψ' meson are linked to those of the J/ψ and the last two terms in Eq. 3 are determined separately.

3 Experimental results

In the following, E_T will be used as a centrality estimator and the Drell–Yan mechanism will be used as a comparison term to evaluate the production of J/ψ and ψ' mesons. As far as E_T is concerned, it should be noted that new calibrations imply a rescaling of the E_T absolute values already published[5] or shown as preliminary data[10]. The average correction factor is 0.81 for 1996 data and 0.74 for the 1995 published results. The Drell–Yan mechanism is used as a reference for two reasons: the first is that it simply reflects the number of primary nucleon–nucleon interactions and its behaviour in nucleus–nucleus collisions does not show any evidence for nuclear effects; the second is that systematic effects concerning the spectrometer cancel out when making ratios like $B_{\mu\mu}(\sigma_{\mathrm{J}/\psi})/\sigma_{DY}$. There is a price to pay for these advantages: it is the low number of Drell–Yan events. They are $\sim$ 2300 for 1996 data set; so the statistical fluctuations in the $B_{\mu\mu}(\sigma_{\mathrm{J}/\psi})/\sigma_{DY}$ ratio are mainly due to the denominator. A completely independent approach has been developed in order to check these results: an estimate of this ratio is done starting from the very high statistics set of *minimum bias* events, collected triggering on a minimum deposit of energy in the Zero Degree Calorimeter. The procedure and the results of this new analysis are fully described elsewhere[11] and they show an excellent agreement with the standard analysis based on Drell–Yan presented here.

3.1 Drell–Yan and J/ψ cross sections

The measured cross section for Drell–Yan $\mu^+\mu^-$ pair production in Pb–Pb collisions at $158\,GeV$ per nucleon is $\sigma_{DY} = 1.49 \pm 0.03 \pm 0.11\,\mu b$ in the mass interval $2.9 \leq M_{\mu\mu} \leq 8.0\,GeV/c^2$. This result can be compared to cross sections measured for other colliding systems by NA38 and NA51 experiments. To this purpose, in Fig. 3 the *K factor* is shown as a function of the product of $A_{proj} \cdot B_{targ}$. The *K factor* is the ratio between the measured cross section and the theoretical one, computed at the leading order in the appropriate conditions (centre of mass energy and kinematical domain). The Fig. 3 clearly shows that the *K factor* is the same for all the systems considered within the statistical uncertainties. The compatibility among the different systems is more relevant than the numerical value $K = 1.78 \pm 0.09$ experimentally found, that depends on the particular set of parton distribution functions chosen to evaluate the theoretical cross section (MRS43[8]).

The nuclear dependance on the cross section can be parametrized as:

$$\sigma_{DY}^{AB} = \sigma_{DY}^{pp}(AB)^{\alpha} \tag{4}$$

where σ_{DY}^{pp} is the cross section for proton–proton interactions. The exponent α in eq. 4 can be fitted starting from data, provided that the necessary centre of mass energy[12] and isospin corrections are applied. The latter correction accounts for the fact that different systems have different proportions of protons and neutrons:

$$\left(\sigma_{DY}^{AB}\right)_{corr} = \sigma_{DY}^{AB} \left(\frac{AB\sigma_{DY}^{pp}}{\sigma_{DY}^{AB}}\right)_{theor.} \tag{5}$$

The result of the fit is $\alpha = 1.002 \pm 0.011$ meaning that Drell–Yan scales as the number of primary nucleon–nucleon collisions without sizeable nuclear effects. The cross section for J/ψ production in Pb–Pb collisions at 158 GeV

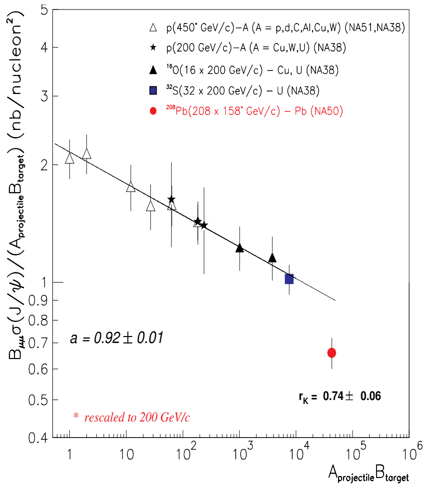

Figure 4. J/ψ cross section per nucleon nucleon collision as a function of A×B

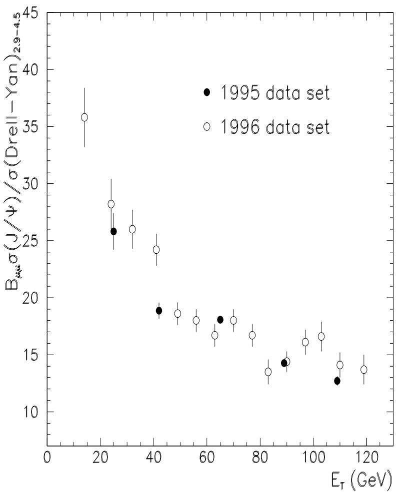

Figure 5. J/ψ over Drell–Yan versus E_T: a comparison among 1995 and 1996 data sets.

per nucleon is $B_{\mu\mu}(\sigma_{\mathrm{J}/\psi}) = 21.9 \pm 0.3 \pm 1.6\,\mu b$. In Fig. 4 the ratio $\sigma_{\mathrm{J}/\psi}/AB$ is plotted against the product AB for several systems where data have been rescaled to 200 GeV per nucleon and to the same kinematical region. A nuclear effect is clearly present in J/ψ production. A fit to a power law like eq. 4 can be done up to S–U collisions and it leads to a value $\alpha = 0.92 \pm 0.01$ for the exponent. This J/ψ suppression is now understood in terms of the absorption in the nuclear medium of a pre–resonant charmonium state and the transition to the QGP is not needed to account for the data. The Pb–Pb point in Fig. 4 is not compatible with the power law that fits the results of light colliding nuclei: it is a factor 0.74 ± 0.06 smaller than the extrapolated value from the fit. The J/ψ appears to be anomalously suppressed in Pb–Pb collisions.

3.2 J/ψ and ψ' suppression as a function of centrality

The J/ψ production can be further investigated as a function of centrality. In Fig. 5, the J/ψ/DY ratio is plotted as a function of the electromagnetic transverse energy for the data samples of 1995 and 1996. The different number of E_T bins in the two samples (5 for 1995 data and 15 for 1996 data) reflects the different amount of data available in the two cases. The agreement is rather good except for the high E_T region where a small rise of the J/ψ/DY ratio is observed in 1996 data sample. This rise is compatible with an experimental bias due to the known inefficiency in detecting multiple interactions in the target, which mimic the E_T yield of central events. The 1998 run, with a target $\sim 0.08\,\lambda_{int}$ thick, will provide new experimental insight to study the high E_T region. A clear discontinuity is present in the data at $E_T \sim 40GeV$: a drop of yield in a $10GeV$ wide E_T range corresponding to an impact parameter $b \simeq 8\,fm$ is observed.

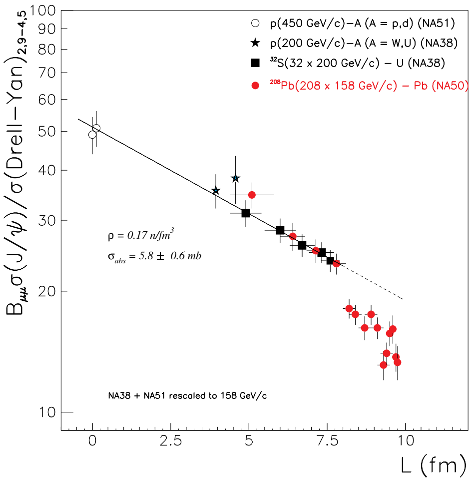

Figure 6. J/ψover Drell–Yan ratio versus $\bar{L}$.

A system–independent parameter has to be adopted instead of E_T in order to estimate the centrality when comparing p–A and A–B data. For J/ψ study in nuclear collisions, it is customary to use the geometrical mean path length of the produced charmonium state in nuclear matter $\bar{L}$[5]:

$$\bar{L}(b) = \frac{1}{\rho_0} < \rho L > \tag{6}$$

where $\rho_0 = 0.17\ fm^{-3}$ is the nuclear average density and ρ is the Woods–Saxon nuclear density function. The value of $\bar{L}$ is computed for each E_T bin starting from its relation with the impact parameter[d]. The ratio of J/ψ to Drell–Yan cross sections is shown in Fig. 6 as a function of $\bar{L}$ for different systems. All data have been rescaled to 158 GeV per nucleon and the isospin correction according to eq. 5 has been applied. Data up to S–U collisions can be fitted according to the absorption model, leading to the following value for the absorption cross section:

$$B_{\mu\mu}\left[\sigma_{J/\Psi}(\bar{L})\right]/\sigma_{DY} = e^{-\rho_0 \bar{L} \sigma_{abs}} \Longrightarrow \sigma_{abs} = 5.6 \pm 0.6\, mb \qquad (7)$$

It turns out that peripheral Pb–Pb collisions are in agreement with the absorption model and with the S–U points, while the anomaly shows up at $\bar{L} \simeq 8\ fm$.

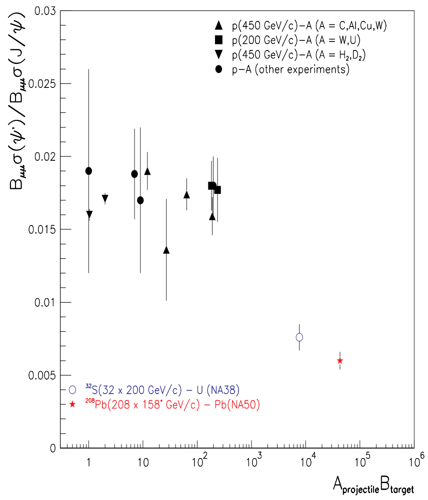

Figure 7. ψ' to J/ψ ratio versus $A \times B$.

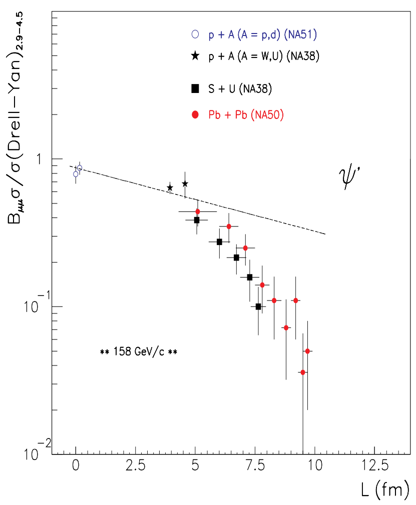

Figure 8. ψ' over Drell–Yan ratio versus $\bar{L}$.

The NA50 spectrometer allows also the study of ψ' vector meson, albeit with lower statistics ($\sim$ 1400 ψ' in 1996). Since ψ' is a loosely bound state (its binding energy being 1/10 of the binding energy of J/ψ) it should be suppressed more than J/ψ. The ratio of ψ' to J/ψ cross sections is shown in Fig. 7 as a function of $A_{proj}B_{targ}$. In a framework in which a preresonant

[d] It must be noted that the determination of $\bar{L}$ does not rely on the knowledge of the absolute E_T scale

charmonium state ($c\bar{c}g$) is absorbed in nuclear matter, a constant value of this ratio for all colliding systems is expected. Despite large statistical errors, data indeed suggest a common value of $\psi'/\mathrm{J}/\psi$ ratio for proton induced interactions, in agreement with this scenario. The study of the $B_{\mu\mu}\sigma_{\psi'}/\sigma_{DY}$ as a function of $\bar{L}$ (Fig. 8) shows that ψ' follows the same nuclear absorption law as J/ψ in proton–nucleus interactions. From both Fig. 7 and 8, it is clear that an additional suppression mechanism occurs for nucleus–nuclues interactions. The suppression pattern as a function of $\bar{L}$ is similar in S–U and Pb–Pb collisions and it starts from $\bar{L} \simeq 6\ fm$, well before the onset of the anomalous suppression of the J/ψ meson. This behaviour suggests that the physical process responsible of the ψ' absorption is the same for Sulphur and Lead induced collisions and that the mechanism responsible for J/ψ anomalous suppression at $\bar{L} > 8\ fm$ is not the same that causes the dissociation of ψ'. Several authors[4] claim that ψ' can be easily broken by interactions with co–moving hadrons (*the comovers*).

4 Conclusions

Muon pairs originating from Drell–Yan process, J/ψ and ψ' decays have been studied in several systems ranging from p–p to Pb–Pb collisions. In particular, results from the high statistics 1996 Pb–Pb data set are compared with previous results. The production of Drell–Yan pairs is confirmed to be insensitive to the nuclear medium and it is proportional to the number of nucleon–nucleon collisions. The ratio between J/ψ and Drell–Yan cross sections studied as a function of the $\bar{L}$ follows a nuclear absorption pattern up to peripheral Pb–Pb interactions, then at $\bar{L} \simeq 8\ fm$ a sudden 25% drop in the J/ψ cross section occurs. The robustness of this result has been succesfully tested both with trivial tests (like changing the centrality binning criteria) and completely independent analyses (using minimum bias events)[11]. The ψ' suppression in p–A interactions supports the colour octet model in which it is a pre–resonant $c\bar{c}g$ state that is absorbed in the nuclear medium. The observed additional absorption of ψ' in nucleus induced reactions shows different features when compared to J/ψ suppression and seems to be ascribed to other processes like interactions with comovers.

The observed anomalous suppression of J/ψ meson is triggering a lot of phenomenological work: many possible explanations of the observed phenomena have been proposed so far, both in terms of conventional hadronic physics and in terms of quark gluon plasma formation. The latter scenario naturally predicts the observed threshold effect, that can be hardly interpreted otherwise.

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