ELSEVIER

29 November 2001

PHYSICS LETTERS B

Physics Letters B 521 (2001) 195–203

www.elsevier.com/locate/npe

The dependence of the anomalous J/ψ suppression on the number of participant nucleons

NA50 Collaboration

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Received 6 July 2001; received in revised form 8 October 2001; accepted 9 October 2001
Editor: L. Montanet

PII: S0370-2693(01)01225-4

Abstract

The observation of an anomalous J/ψ suppression in Pb–Pb collisions by the NA50 Collaboration can be considered as the most striking indication for the deconfinement of quarks and gluons at SPS energies. In this Letter, we determine the J/ψ suppression pattern as a function of the forward hadronic energy E_{ZDC} measured in a Zero Degree Calorimeter (ZDC). The direct connection between E_{ZDC} and the geometry of the collision allows us to calculate, within a Glauber approach, the precise relation between the number of participant nucleons N_{part} and E_{ZDC}. Then, we check if the experimental data can be better explained by a sudden or a smooth onset of the anomalous J/ψ suppression as a function of the number of participants.

1. Introduction

J/ψ suppression has been proposed a long time ago as a clear and unambiguous signature for the deconfinement of quarks and gluons in ultrarelativistic nucleus–nucleus collisions [1]. It became however clear very soon that also absorption mechanisms at the hadronic level could lead to a sizeable J/ψ suppression [2,3]. Consequently, in the following years, the efforts on the experimental side were aimed at the establishment of a solid systematics on charmonia production with various projectile and target combinations. High statistics data have been collected by the NA38 Collaboration both for p–A collisions [4], where no QGP-induced suppression is expected, and for interactions induced by light ions (oxygen, sulphur) [5,6].

The study of Pb–Pb collisions at 158 GeV/c incident momentum has marked a turning point in the evolution of this field. In fact, experimental data from NA50 on J/ψ suppression as a function of the centrality estimator E_T, the neutral transverse energy released in the pseudorapidity window $1.1 < \eta < 2.3$, have shown that:

- there is an additional J/ψ suppression mechanism in Pb–Pb collisions, not present in S–U interactions (the so-called anomalous suppression) [7];
- the onset of the anomalous J/ψ suppression occurs in a narrow E_T range, indicating the presence of a threshold effect [8];
- the J/ψ suppression pattern shows, from peripheral to central collisions, a two-step behaviour, possibly linked with the successive melting in a deconfined medium of two charmonium resonances: the χ_c, which, through its radiative decay, is an important J/ψ source, and the more strongly bound J/ψ itself [9].

Even if there is still debate on the interpretation of the E_T structure of J/ψ suppression [10,11], these results cannot be satisfactorily reproduced by theoretical approaches based on charmonia dissociation by comoving hadrons [12].

In this Letter we go a step further in the analysis of the NA50 Pb–Pb results, with a two-fold purpose. On one side we investigate if the same two-step structure, seen as a function of E_T, is still present when the J/ψ suppression pattern is studied versus another centrality estimator, namely E_{ZDC}, the energy released in the NA50 Zero Degree Calorimeter. On the other side, we determine the correlation of E_{ZDC} with the number of projectile spectator nucleons, and consequently with the number of participants N_{part}, taking into account the smearing on the N_{part} measurement due to the experimental resolution on E_{ZDC}. We finally investigate the nature of the onset of the suppression as a function of the number of participant nucleons.

2. Experimental set-up and data reduction

A detailed description of the NA50 experimental apparatus can be found in [13–15] and we only recall its basic features hereafter. The main component of

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the set-up is a dimuon spectrometer covering the pseudorapidity range $2.8 < \eta < 4.0$. The centrality of the interaction is estimated with three detectors: an electromagnetic calorimeter, which measures the neutral transverse energy E_T released in the region $1.1 < \eta < 2.3$, a silicon microstrip detector (MD), which allows to estimate the charged multiplicity in the range $1.5 < \eta < 3.9$, and a zero degree calorimeter (ZDC), measuring the forward energy E_{ZDC}, mainly carried by projectile nucleons which have not taken part in the collision. This calorimeter is placed on the beam line, inside the hadron absorber, and covers the pseudorapidity region $\eta \geqslant 6.3$.

The data analyzed in this paper have been collected with the NA50 set-ups of 1996 and 1998. The difference between the two set-ups concerns only the target region. In 1996, the target assembly was made of 7 sub-targets with a total thickness corresponding to 30% of λ_I, while in 1998 a single thinner target (7% of λ_I) has been employed. The average incident beam intensity was 5×10^7 Pb ions/burst, with a 5 s spill. Data have been collected with two different kinds of trigger. The main one, called "dimuon trigger", selects events where the spectrometer detects two muons produced in the target region. The second one, called "minimum bias trigger", fires whenever a small amount of energy is released in the ZDC. More details on data taking conditions can be found in [8,9].

The event selection procedure is very similar to the one described in [8,9]. The only notable difference is that the present analysis does not require the identification of the individual sub-target where the interaction has taken place, a selection criterion used in previous analyses and based on specific detectors located near each one of the sub-targets. In fact, it has been realized [16] that the use of this cut, in a ZDC-based analysis, may induce large systematic errors on the measurement of J/ψ suppression for peripheral events. The possible contribution from Pb-air events has been removed by means of special "empty target" runs, recorded periodically during the standard data taking by moving the target away from the beam line. The size of this contamination, negligible for central collisions, is of the order of 9% for minimum bias events with $E_{ZDC} > 20$ TeV. Since the dimuon trigger requires the two muons to point to the target, and this requirement is reinforced by offline cuts at the single muon level, the target-out contribution to the dimuon event sample is obviously smaller and amounts to only 2.5% in the same E_{ZDC} range.

Apart from Pb-air interactions, the minimum bias sample also contains events corresponding to non-interacting Pb ions. To eliminate such events, a very low E_T cut has been imposed on the data. The cut has been tuned in order to retain in the event sample used for the analysis a number of events corresponding to the total hadronic Pb–Pb cross section, calculated in the frame of the Glauber model.

Finally, for dimuon triggers we have imposed the cuts $2.92 \leqslant y_{lab} \leqslant 3.92$ (corresponding to $0 \leqslant y_{cm} \leqslant 1$) and $|\cos\theta_{CS}| < 0.5$, where θ_{CS} is the polar decay angle of one muon in the Collins–Soper reference frame, in order to remove events produced at the edges of the acceptance of the spectrometer.

3. E_{ZDC} and the centrality of the collision

The geometry of a nucleus–nucleus collision is usually characterized by the value of the impact parameter b, which of course is not directly accessible to the experiment. Nevertheless, this quantity can be deduced from the measured E_{ZDC} value. In fact, being placed on the beam line, the ZDC intercepts all the projectile spectator nucleons. These particles are not affected by the collision and reach the detector with their initial energy. Any loss of spectators is prevented by choosing for the ZDC an angular acceptance larger than the transverse spread induced by Fermi motion. Hence a small amount of zero degree energy corresponds to a small number of projectile spectator nucleons, and therefore to a central collision; on the contrary, in a peripheral collision only few nucleons undergo an interaction, the number of spectators is large and a large amount of energy is released in the ZDC. In a more detailed approach, one should take into account that also some participant nucleons plus some secondary particles can be emitted within the angular acceptance of the calorimeter, contributing to E_{ZDC}. However, it will be shown that this contribution is negligible for most events and becomes sizeable only for very central collisions.

From the previous considerations, we can express, for a generic Pb–Pb collision with an impact parameter b, the average E_{ZDC} as a sum of two terms, a dominant one, $E_{ZDC}^{spec}(b)$, proportional to the number of projectile

spectators $N_{\rm spec}$, plus a small contribution $E_{\rm ZDC}^{\rm part}(b)$ proportional to the number of participants $N_{\rm part}$:

$$\begin{aligned}\langle E_{\rm ZDC}(b)\rangle &= E_{\rm ZDC}^{\rm spec}(b) + E_{\rm ZDC}^{\rm part}(b)\\ &= 158 \times N_{\rm spec}(b) + \alpha \times N_{\rm part}(b)\\ &= 158 \times \left(208 - \frac{N_{\rm part}(b)}{2}\right)\\ &\quad + \alpha \times N_{\rm part}(b), \end{aligned} \tag{1}$$

where 158 GeV is the energy per spectator nucleon and $\alpha \times N_{\rm part}$ is the energy released in the ZDC by participants and secondary particles. The link between $N_{\rm part}$ (or $N_{\rm spec}$) and the impact parameter b has been obtained with a calculation based on a Glauber model of nucleus–nucleus collisions, using Woods–Saxon nuclear density profiles, with the parameters tabulated in [17]. The same $N_{\rm part}$ versus b dependence has been reproduced using the VENUS 4.12 [18] and RQMD 2.3 [19] event generators.

Eq. (1) gives the average value of $E_{\rm ZDC}$ for a given b. In order to describe the measured $E_{\rm ZDC}$ spectra we must take into account that for a given impact parameter b, because of the experimental resolution of the detector and of fluctuations on $N_{\rm part}$ at fixed b, the values of $E_{\rm ZDC}$ are Gaussian distributed. The width $\sigma_{E_{\rm ZDC}}(b)$ is expressed as the quadratic sum:

$$\begin{aligned}\sigma_{E_{\rm ZDC}}(b) &= \left(\beta \cdot \sqrt{E_{\rm ZDC}(b)} + \gamma \cdot E_{\rm ZDC}(b)\right)\\ &\quad \oplus \delta \oplus \sigma_{N_{\rm part}}(b). \end{aligned} \tag{2}$$

The β and γ parameters are related to the resolution of the detector and their values have been fixed with measurements done with low intensity proton and ion beams [14]; the δ term takes into account the smearing of the signal due to the pedestal width and to calibration uncertainties. The quantity $\sigma_{N_{\rm part}}(b)$ represents the size of the physics fluctuations on $E_{\rm ZDC}$, at fixed b, due to the width of the correlation between b and $N_{\rm part}$. It has been estimated through a simulation, using either VENUS or RQMD as inputs, with fully compatible results. The values of the remaining parameters have been fixed by means of a fit to the measured minimum bias $E_{\rm ZDC}$ distribution. We get, for the 1996 data sample, the values $\alpha = 5.67$ GeV, $\beta = 3.39$ GeV$^{1/2}$, $\gamma = 0.062$, $\delta = 1227$ GeV. In Fig. 1 we plot the $E_{\rm ZDC}$ spectrum, for the 1996 data sample, together with our result based on the Glauber model, shown as a continuous line. The fair agreement between the data and our calculation allows us to conclude that this approach reproduces reasonably well the connection between $E_{\rm ZDC}$ and the geometry of the collision.

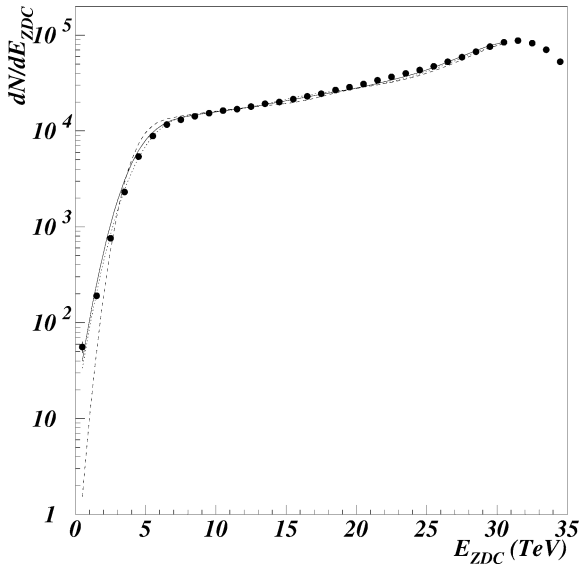

Fig. 1. Comparison of the minimum bias $E_{\rm ZDC}$ spectrum with the result of the Glauber calculation (full line), and of the Monte Carlo simulations based on VENUS (dashed line) and on RQMD (dotted line).

As discussed before, the α parameter, which parametrizes the size of the participant contribution to $E_{\rm ZDC}$, is directly fitted on the measured data. However, event generators give quantitative predictions for this contribution. Therefore we have also run a Monte Carlo simulation to directly determine an $E_{\rm ZDC}$ spectrum where the energy carried by participants is included at the generation level, through VENUS and RQMD. After introducing the smearing due to the detector's resolution we have compared the simulated spectrum with our experimental data and with the result of the Glauber calculation (see Fig. 1). The qualitative agreement between the various approaches confirms that the participant contribution is properly taken into account in our model. Quantitatively, it is almost negligible for most centralities, since it accounts for less than 10% of $E_{\rm ZDC}$ for $E_{\rm ZDC}$ values larger than 12 TeV. On the contrary, it is sizeable for very central collisions, reaching 50% of the measured $E_{\rm ZDC}$ when $E_{\rm ZDC} \sim 3$ TeV.

Having successfully described the measured $E_{\rm ZDC}$ spectrum, we can determine the distribution of the var-

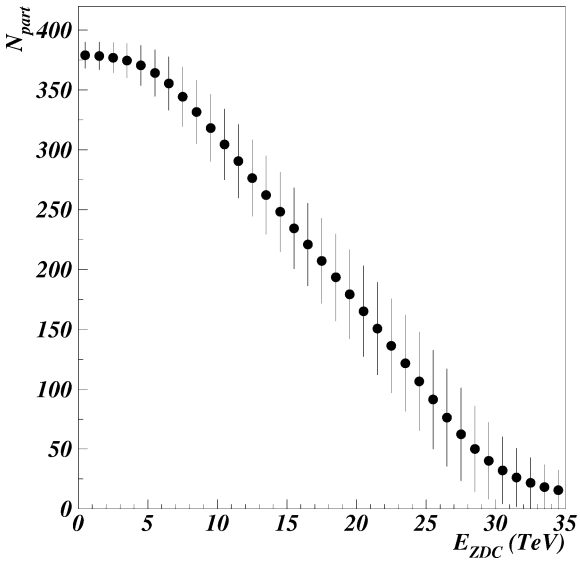

Fig. 2. The number of participants N_{part} as a function of E_{ZDC}, calculated in our Glauber approach. The error bars represent the r.m.s. of the N_{part} distribution at fixed E_{ZDC}.

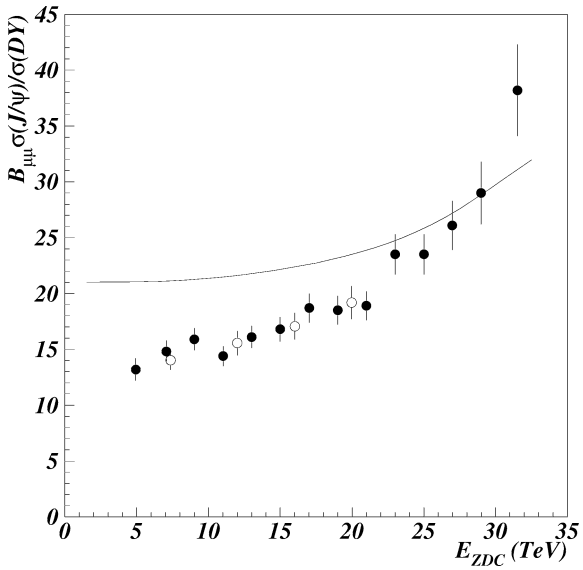

Fig. 3. The results of the standard analysis for the 1996 (closed circles) and 1998 (open circles) data samples. The curve represents the results of a Glauber calculation which takes into account the J/ψ suppression due to ordinary nuclear absorption, with $\sigma^{\text{abs}}_{\text{J}/\psi} = 6.4$ mb.

ious centrality variables as a function of the measured E_{ZDC}. We plot in Fig. 2 the distribution of N_{part} versus E_{ZDC}, which is particularly relevant for the J/ψ suppression analysis described hereafter.

4. Study of the J/ψ suppression

As in the case of the analysis as a function of the neutral transverse energy, two complementary techniques, the so-called "standard analysis" and "minimum-bias analysis" have been used to study the J/ψ suppression pattern versus E_{ZDC}. They have been explained in detail in previously published papers [8,9].

Very shortly, in the standard analysis the high-mass Drell–Yan (DY) events are directly used as a reference for the J/ψ suppression study. The ratio $\sigma_{\text{J}/\psi}/\sigma_{DY}$ is obtained by means of a fit to the measured invariant mass spectrum. The shapes of the invariant mass distributions for the various physical processes are obtained by means of a Monte Carlo simulation. In the minimum bias analysis we use instead as a reference the much larger sample of minimum bias (MB) triggers. To be able to compare the results of the two analyses, a "calculated DY" (DY*) is obtained starting from the measured minimum bias reference. In particular, we calculate, using the Glauber model described in the previous section, the ratio between Drell–Yan and MB yields as a function of E_{ZDC}. Multiplying this quantity, for each E_{ZDC} bin, by the measured number of MB events, we get the DY* distribution. In this second approach the number of J/ψ events for each E_{ZDC} bin is obtained by simply counting the events in the mass range $2.9 \leqslant M \leqslant 3.3$ GeV/c^2, after subtraction of the small dimuon continuum contribution.

The result of the standard analysis for the 1996 and 1998 data sets is shown in Fig. 3. For the 1998 sample, because of the very thin single target, the contamination due to Pb-air events is important for peripheral events [9]. For this reason, we have limited the analysis of the 1998 data to the region $E_{\text{ZDC}} < 22$ TeV. The continuous line in Fig. 3 represents the value of $\sigma_{\text{J}/\psi}/\sigma_{\text{DY}}$ expected in case of pure nuclear absorption. It has been obtained assuming for the interaction cross section of the pre-resonant $c\bar{c}$ pair that will form the J/ψ [20] the value $\sigma_{\text{abs}} = 6.4$ mb [6]. This value results from a Glauber analysis

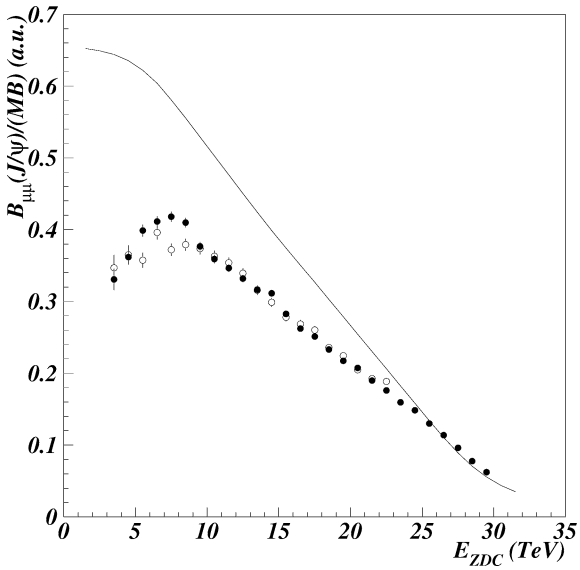

Fig. 4. The ratio (J/ψ)/MB versus E_{ZDC}. Closed symbols correspond to 1996 data and open symbols to 1998 data. The curve represents the results of a Glauber calculation which takes into account the J/ψ suppression due to ordinary nuclear absorption, with $\sigma^{abs}_{J/\psi} = 6.4$ mb.

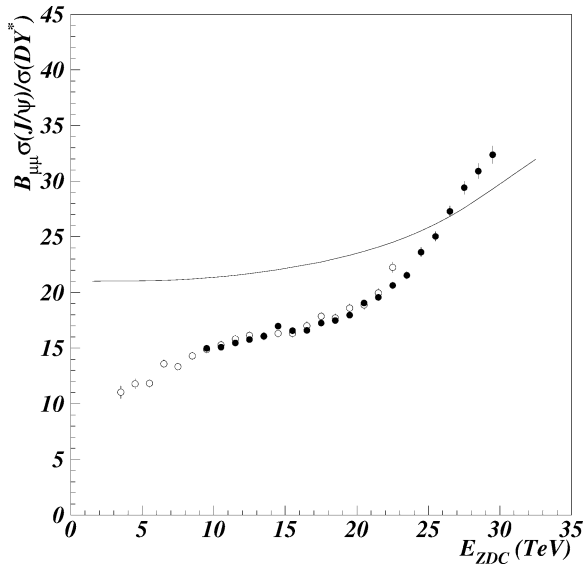

Fig. 5. The results of the minimum bias analysis. The full symbols refer to 1996 data and the open symbols to 1998 data. The curve represents the results of a Glauber calculation which takes into account the J/ψ suppression due to ordinary nuclear absorption, with $\sigma^{abs}_{J/\psi} = 6.4$ mb.

of J/ψ production in p–A and S–U collisions, where no anomalous suppression is present [6].

The results of the standard analysis, even if almost free from systematic errors, are affected by large error bars, due to the low Drell–Yan statistics. This problem is solved introducing the minimum bias analysis. First, as an intermediate step in the presentation of the results, we plot in Fig. 4 the J/ψ distribution versus E_{ZDC} directly divided by the measured minimum bias sample, for the 1996 and 1998 data sets. The comparison of the data with the continuous line representing ordinary nuclear absorption reveals two clear features: a departure from the absorption curve at $E_{ZDC} \sim 26$ TeV, and a change of slope in the region around $E_{ZDC} = 10$ TeV. Furthermore, the two sets of data show a discrepancy for very central events. This problem, already discussed in [9] for the E_T analysis, is connected with the use, in the 1996 set-up, of a relatively thick target. In this situation, it is known that possible reinteractions of projectile fragments in the target could bias the centrality measurement, leading to a systematic error for central events. On the contrary these effects are negligible for the thin target used in the 1998 set-up.

In Fig. 5 we show the result of the minimum bias analysis versus E_{ZDC}. For clarity, in this plot the 1996 data set is used only down to $E_{ZDC} = 9$ TeV, i.e., in the region where the bias induced by reinteractions is negligible. The absolute normalization for the ratio $\sigma_{J/\psi}/\sigma_{DY^*}$ has been calculated using the results of the standard analysis, in the range $9 \leqslant E_{ZDC} \leqslant 16$ TeV. In Fig. 6 we plot the same ratio, divided by the normal absorption curve. The results presented in Figs. 5 and 6 exhibit the same features already visible in the (J/ψ)/MB ratio (Fig. 4), namely two clear changes of slope. The first one corresponds to the E_{ZDC} region around 26 TeV, where we observe a departure from the trend of the normal absorption curve, while the second one is visible in the zone corresponding to the most central collisions.

A suppression pattern with the same characteristics has already been obtained from the analysis of the J/ψ yield as a function of E_T [9]. The result presented here as a function of E_{ZDC} thereby confirms the two-step structure of the anomalous J/ψ suppression in Pb–Pb collisions. A quantitative comparison of the results of the E_T and E_{ZDC}-based suppression patterns is however far from being trivial, due to the loose E_T

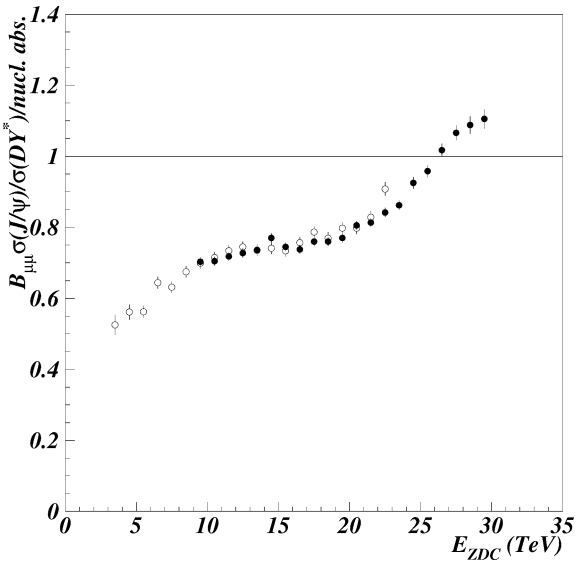

Fig. 6. The $\sigma_{J/\psi}/\sigma_{DY^*}$ ratio divided by the absorption curve, as a function of E_{ZDC}. The full symbols refer to the 1996 data and the open symbols to the 1998 data.

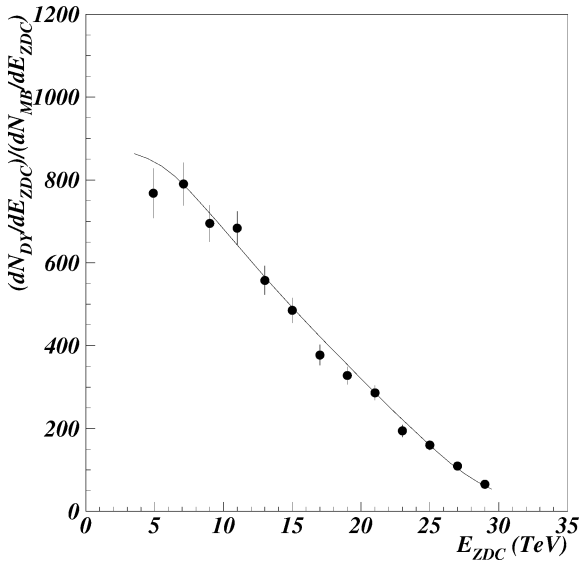

Fig. 7. Comparison between the experimentally measured DY/MB ratio (closed circles) and the corresponding quantity in our calculation (continuous line). The Drell–Yan yield has been integrated in the interval $2.9 \leqslant M_{\mu\mu} \leqslant 4.5$ GeV/c^2.

versus E_{ZDC} correlation and to the possible different behaviour of the centrality resolution for the two quantities. Further work along these lines is being carried out and will be the subject of a forthcoming paper. Qualitatively, one can consider as the onset point of the anomalous J/ψ suppression in the two analyses the value of E_T or E_{ZDC} where the second derivative of $\sigma_{J/\psi}/\sigma_{DY^*}$ goes to zero. The impact parameter values corresponding to such points ($E_T = 41$ GeV, $E_{ZDC} = 25$ TeV) are roughly in agreement, and are of the order of 8.5 fm.

It should be mentioned that the results of the minimum bias analysis are based on the ratio of two event samples corresponding to different triggers and could be affected by a systematic error induced by the different background contamination for the two kinds of events. It turns out that the dominant source of systematic error could be due to possible very small timing differences between the dimuon and the minimum bias trigger. This effect induces a systematic error on the absolute E_{ZDC} scale, which we estimate to be not larger than 3%. The consequent systematic uncertainty on $\sigma_{J/\psi}/\sigma_{DY^*}$ is smaller than 3% for $E_{ZDC} < 22$ TeV, and of the order of 8% at $E_{ZDC} = 28$ TeV.

Finally, we have checked that the results of the MB analysis are not biased by possible problems in our calculation of the minimum bias reference and of the Drell–Yan processes. For this purpose, we show in Fig. 7 the ratio between the experimentally measured Drell–Yan and minimum bias spectra compared with the corresponding quantities, as calculated in the Glauber approach. We see that the agreement is good ($\chi^2/\text{ndf} = 0.99$), excluding the presence of significative systematical errors in our approach. Furthermore we show in Fig. 8 the comparison between the results of the standard and the minimum bias analysis, separately for the 1996 and 1998 data sets. The results of the two analyses are consistent within error bars.

5. J/ψ suppression versus N_{part}

As reported in [21], one basic feature of the suppression pattern in a deconfinement scenario is a well defined onset. In fact, all the approaches based on conventional suppression mechanisms predict a smoother trend as a function of centrality. However, the variable governing the onset of the anomalous J/ψ suppression is a priori not known. In the following, from the strict

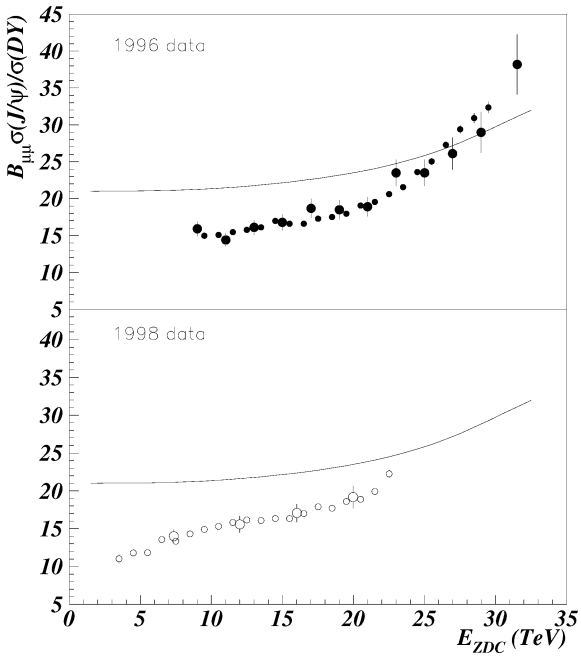

Fig. 8. Comparison between the standard (large circles) and the minimum bias analysis (small circles) for the 1996 and 1998 data.

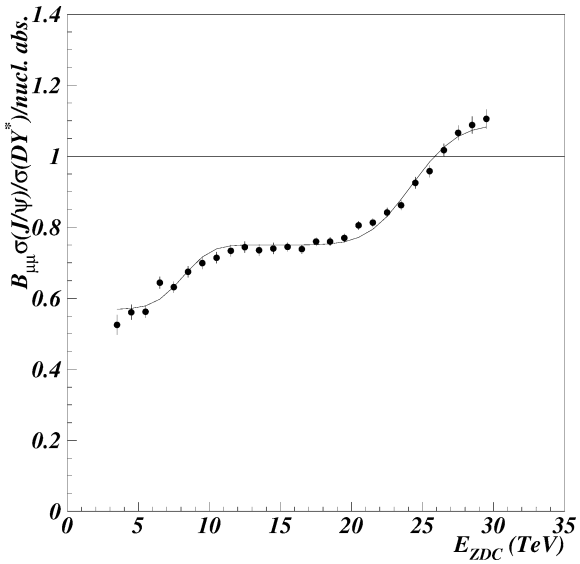

Fig. 9. The fit of $\sigma_{J/\psi}/\sigma_{DY^*}$ versus E_{ZDC}, assuming two sharp absorption mechanisms of free amplitude occurring at $N_{part} = 122$ and $N_{part} = 334$.

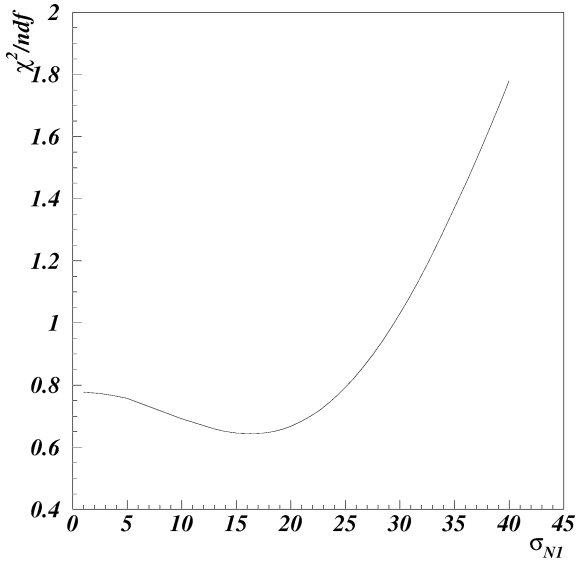

Fig. 10. The quality of the fit of $\sigma_{J/\psi}/\sigma_{DY^*}$ as a function of σ_{N_1} (see text for details).

correlation between E_{ZDC} and N_{part}, derived in Section 3 and plotted in Fig. 2, we check if the two-step pattern of Fig. 6 is compatible with two sharp drops in the J/ψ yield occurring at well defined N_{part} values.

Basically, we assume that for two critical values of N_{part}, i.e., N_1 and N_2, certain fractions X_1, X_2 of the produced J/ψ's are suddenly suppressed. In the interpretation of [9] the two steps correspond to the melting, in a deconfined state, of the χ_c, suppressing the J/ψ's from the decays $\chi_c \to J/\psi\,\gamma$ at $N_{part} = N_1$, followed by the suppression of directly produced J/ψ's at $N_{part} = N_2$. Then, taking into account the N_{part} versus E_{ZDC} correlation, and the finite resolution on N_{part} due to the detector response, we calculate $\sigma_{J/\psi}/\sigma_{DY^*}$ vs. E_{ZDC}. The values N_1, N_2, X_1, X_2 have been directly fitted on the measured data. For simplicity, in the E_{ZDC} region where the 1996 and 1998 points overlap, we have used in the fit only the 1996 data. The result is shown in Fig. 9. We can describe the experimental points with $N_1 = 122$, $N_2 = 334$.

However, it is clear that the data could accommodate equally well an onset of the suppression smeared over a certain N_{part} range. To investigate this possibility we have performed a study of the region around $N_{part} = N_1$, introducing a Gaussian-smeared onset of the J/ψ suppression. More in detail, we vary the width σ_{N_1} of the Gaussian and we fit the data in the region

$17 < E_{\mathrm{ZDC}} < 29$ TeV. In Fig. 10 we show the χ^2/ndf of the fit as a function of σ_{N_1}. It is roughly constant up to $\sigma_{N_1} \sim 25$, and then steadily increases. This result shows that our data on $\sigma_{\mathrm{J}/\psi}/\sigma_{\mathrm{DY}^*}$ versus E_{ZDC} clearly suggest an onset of the anomalous suppression occurring in a very limited centrality range.

6. Conclusions

In this Letter we have presented the results of an analysis of the J/ψ yield in Pb–Pb collisions as a function of the forward energy E_{ZDC}. The two-step pattern of the J/ψ suppression, already established as a function of the neutral transverse energy E_{T} and interpreted as an evidence for deconfinement at SPS energies [9], is also observed here. This fact rules out the possibility that the structure observed in the E_{T} variable could be due to an experimental accident, or to a bias in the analysis procedure.

The connection between E_{ZDC} and the number of participants has been investigated in detail, using a Glauber model of the Pb–Pb collisions. The results have been found to be consistent with the predictions of the VENUS and RQMD event generators. We have shown, taking into account the finite resolution on N_{part} induced by the experimental resolution on E_{ZDC}, that our data imply a very steep onset of the anomalous J/ψ suppression.

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