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J/ψ, ψ' and muon pair production in p–W and S–U collisions

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Abstract

In this paper we present a study on the production of the J/ψ and ψ' resonances, decaying into muon pairs, in S–U collisions, at 200 GeV per incident nucleon. We find that the ratio between ψ' and J/ψ yields decreases as E_T, the neutral transverse energy produced in the collision, increases. There is also a clear decrease of this ratio when going from p–W to S–U interactions. Assuming the high mass continuum to be Drell–Yan we discuss the possible understanding of the intermediate dimuon mass region as a superposition of Drell–Yan (extrapolated down in mass) and muon pairs from the semileptonic decays of charmed mesons. The p–W data is found to be explained by this procedure. However, the S–U data seems to be incompatible with a linear extrapolation from the proton–nucleus results.

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In this paper we present a study on the production of the J/ψ and ψ' resonances, decaying into muon pairs, in S–U collisions, at 200 GeV per incident nucleon. We find that the ratio between ψ' and J/ψ yields decreases as E_T, the neutral transverse energy produced in the collision, increases. There is also a clear decrease of this ratio when going from p–W to S–U interactions. Assuming the high mass continuum to be Drell–Yan we discuss the possible understanding of the intermediate dimuon mass region as a superposition of Drell–Yan (extrapolated down in mass) and muon pairs from the semileptonic decays of charmed mesons. The p–W data is found to be explained by this procedure. However, the S–U data seems to be incompatible with a linear extrapolation from the proton–nucleus results.

1. INTRODUCTION

The NA38 experiment has measured the muon pairs produced in proton–nucleus and nucleus–nucleus collisions. In this analysis we study the dimuon mass spectra above 1.5 GeV/c^2. Our main motivation is the study of J/ψ and ψ' production in ion collisions, both integrated and as a function of E_T. The ψ' behaviour is particularly interesting since the predictions of the Quark-Gluon Plasma model are different from those of the hadronic rescattering models [1].

The study of the ψ' behavior requires a good understanding of the "continuum" on top of which it sits, since the ψ' is only around 50 % of the events in its mass range, where the detector's mass resolution is ~ 9 % (FWHM). We assume that the "continuum" events,

*Also at ISEL, Instituto Politécnico de Lisboa, Portugal in the mass range between 1.5 and 5.5 GeV/c^2, are originated either by the Drell–Yan mechanism or by semi-leptonic decays of $D\bar{D}$ pairs.

We extract the number of events of each 'signal' process from a fit to the 'opposite-sign' dimuon mass spectra. Our estimation of the background from π and k meson's decay, is based on the measured 'like-sign' samples, using the standard formula (the subscript indicates the sign of the spectrometer's magnetic field):

$$N^{Bg} = 2 \times R_{Bg} \times (\sqrt{N_+^{++}\ N_+^{--}} + \sqrt{N_-^{++}\ N_-^{--}}) \tag{1}$$

The factor R_{Bg} was experimentaly measured with the p–W data, by using the two experimental setups, different in what concerns their hadron absorption properties. While the 'signal' cross sections must be the same in both data sets, the amount of background from π and k decays is higher in the setup with less hadron absorbers. A simultaneous fit to both data sets, leaving R_{Bg} as a free parameter, gives $R_{Bg} = 1.25 \pm 0.04$, in agreement with the value expected from a Monte Carlo simulation (based on the Fritiof event generator). In the case of S–U interactions we have assumed $R_{Bg} = 1$, as expected from the Monte Carlo, since the S–U data sets were taken with similar setups, not allowing a precise experimental measurement of R_{Bg}.

2. DATA SELECTION

Six sets of data have been used for this study, two for p–W collisions and four for S–U collisions. They will be refered to as pW 88 V, pW 88 D, SU 90 St, SU 90 Al, SU 91 Phi and SU 91 Psi. The experimental setups used for each data set were different in what concerns the materials and dimensions of the hadron absorbers. The beam energy was always 200 GeV per incident nucleon. For each data set, and each signal process, we have performed a complete Monte Carlo simulation of the detector response. Details on the NA38 detector can be found in ref. [2].

We have restricted our study to the mass region above 1.5 GeV/c^2, so that the contamination from the low mass vector mesons can be neglected. The kinematical window in dimuon (lab) rapidity is $3.0 \to 4.0$ and in dimuon (Collins-Soper) $\cos(\theta)$ is $-0.5 \to +0.5$.

As the p–W data was taken with a secondary proton beam, contaminated by pions, two gas Čerenkov detectors were used to eliminate them. The W target was divided in 5 sub-targets of 2 cm each. The S–U data was taken with an active target, divided in 10 thin sub-targets, of which only the first one is big enough to account for the beam transverse size. We calculate the effective length of the whole target from the length of the first sub-target, $l(1) = 0.1\ cm$, using the ratio between the number of events, with mass between 2.7 and 3.5 GeV/c^2, produced in all sub-targets, $N(all)$, and in the first sub-target, $N(1)$. The "Beam In" quartz detector, placed upstream from the target, absorbs a fraction, $a_{BI} = 3.15\%$, of the beam counted by the "Beam Hodoscope" detector, N_{inc}. In order to have a good measurement of E_T, we have rejected events with pile-up, η_{pileup}, or with reinteractions in the target, η_{reint}. Events with E_T below 15 GeV were rejected. The efficiency of the sub-target recognition (corrected event per event) is a growing function of E_T. For E_T values above 15 GeV its value is larger than 20 % and so the maximum weight applied to any event is below 5. We have calculated the fraction of events with E_T larger than 15 GeV, A_{E_T}, using the E_T distribution without sub-target recognition. We must correct for this 'acceptance' to obtain the total (all E_T) cross sections.

The luminosity was defined as:

$$\mathcal{L} = \frac{N_A \cdot \rho \cdot l(1)}{A} \cdot \frac{N(all)}{N(1)} \cdot N_{inc} \cdot (1 - a_{BI}) \cdot \eta_{reint} \cdot \eta_{pileup} \cdot \epsilon_{trig} \cdot \epsilon_{rec} \cdot A_{E_T} \tag{2}$$

The parameters that are needed for the S–U cross section calculations are summarized in Table 1. The values for the 1991 data sets are not yet available.

Table 1. Parameters of the S–U 1990 data sets.

	SU 90 St	SU 90 Al
$N(all)/N(1)$	9.028	8.799
N_{inc}	3.119×10^{11}	1.715×10^{11}
η_{reint}	0.871	0.913
$\eta_{pile\ up}$	0.916	0.834
ϵ_{trig}	0.94	0.94
ϵ_{rec}	0.992	0.978
A_{E_T}	0.87	0.88
$\mathcal{L}$ (nb^{-1})	8.46	4.30

3. SIMULATION OF THE SIGNAL PROCESSES

We have assumed that J/ψ, ψ', Drell–Yan and semi-leptonic decays of $D\bar{D}$ mesons, are the only processes that contribute to the signal mass distribution from 1.5 to 5.5 GeV/c^2. They were all simulated for each experimental setup.

The generation of Drell–Yan events was done with the PYTHIA event generator [3], version 5.6, using the GRV LO structure functions parametrization [4] ($\Lambda_{QCD} = 200\ MeV$; $Q^2_{min} = 0.25\ GeV^2$), taken from the PDFLIB package [5].

We have generated $p-p$, $p-n$, $n-p$ and $n-n$ collisions since the valence quark composition is relevant for Drell–Yan. The cross–sections given by PYTHIA, for the kinematical domain we are interested in, are: $\sigma^{DY}_{pp} = 270\ pb$; $\sigma^{DY}_{pn} = 261\ pb$; $\sigma^{DY}_{np} = 215\ pb$; $\sigma^{DY}_{nn} = 199\ pb$; $\sigma^{DY}_{pW} = 48.9\ nb$; $\sigma^{DY}_{SU} = 1.79\ \mu b$. We anticipate the need for a K^{DY} factor since PYTHIA only calculates Drell–Yan in leading order. We have verified [6] that PYTHIA, with GRV LO structure functions and $K^{DY} = 2.1$, reproduces the Drell–Yan cross sections measured by NA3 [7], in p–Pt at 400 GeV, from 4.5 to 8.5 GeV/c^2.

To get the predictions for p–W or S–U collisions, we must make some assumption on the "A dependence" of the studied processes. We have assumed that both Drell–Yan and charm production have a linear A dependence, which means that a p–A or S–U collision is just equivalent to a linear superposition of nucleon–nucleon collisions. In our x_1, x_2 kinematical window, nuclear effects on the quark distributions can be neglected [8].

The $D\bar{D}$ events were generated with the QCD fusion model, using the Lund fragmentation scheme, as implemented in PYTHIA, with GRV LO structure functions, and 0.80 GeV/c as the width of the gaussian primordial k_T distribution (as found by the LEBC-EHS experiment [9]). The mass of the c quark, m_c, was set to 1.5 GeV/c^2. Since charm production is dominated by gluon fusion (~ 80 % of the cross–section), only $p-n$ collisions were generated. The shape of the predicted charm contribution to the dimuon mass spectrum does not seem to be affected by changing the m_c value or the structure functions parametrization [6]. The corresponding predictions for the absolute charm cross section, however, are quite sensitive to the choice we make on these parameters.

There are some indications [10] that open charm production could scale less than linearly with A. So, if we see an excess in the data, relative to the expected contributions assuming $\alpha_{D\bar{D}} = 1$, we will surely be observing some unusual behaviour.

4. J/ψ AND ψ' PRODUCTION

4.1. p–W and S–U results, integrated in E_T

The charm contribution can be neglected for masses above 3 GeV/c^2 (figure 4). Thus, we can identify the dimuon mass distribution as a superposition of J/ψ, ψ' and Drell–Yan processes, in this high mass region. The shape of these contributions was determined (for each data set) by the Monte Carlo simulation explained in the previous section.

The fit to the measured opposite-sign dimuon mass distribution can be symbolically expressed by:

$$\frac{dN^{Exp}}{dM} = p_1\ A^{J/\psi}\ \frac{dN^{J/\psi}}{dM} + p_2\ A^{\psi'}\ \frac{dN^{\psi'}}{dM} + p_3\ A^{DY}\ \frac{dN^{DY}}{dM} + \frac{dN^{Bg}}{dM} \tag{3}$$

The signal contributions were normalized to unity, so that the fit, performed with the program MINUIT using the maximum likelihood method, sets the free parameters p_1, p_2 and p_3 to the absolute number of events of each process (corrected for acceptances). Actually, we do a simultaneous fit to all the data sets of each projectile–target combination, leaving also free the fraction of signal that comes from each specific data set.

Table 2 presents the number of events obtained from the p–W and S–U mass distributions (Figures 1 and 2). We see that the ratio $B\sigma^{\psi'}\ /\ B\sigma^{J/\psi}$ decreases from 1.77 ± 0.11 %, in p–W collisions, to 1.07 ± 0.08 %, in S–U (statistical errors only). These are ratios of cross sections, since the luminosity is the same for both resonances.

4.2. S–U results in 4 E_T bins

In the case of S–U collisions, the ratio between ψ' and J/ψ yields was also obtained as a function of E_T. The absolute calibrations of the electromagnetic calorimeters used in 1990 were rescaled (by ~ 5 %) to make sure that the four E_T distributions are in the same scale. We have defined four E_T bins, with lower limits: 15, 41, 67 and 87.5 GeV. For each bin, the corresponding energy density was calculated using the Bjorken formula

$$\epsilon\ =\ \frac{3 \cdot E_T^0}{\tau \cdot \Delta y \cdot S} \tag{4}$$

with S being computed by a geometrical model [11].

The mean E_T value of each bin and the corresponding energy density are presented in table 3, together with the values of the ratio $B\sigma^{\psi'}\ /\ B\sigma^{J/\psi}$ obtained by the fitting procedure described above. Again, we observe (Figure 3) a clear decrease of this ratio as the energy density increases (see also the talk of B. Ronceux at this conference).

4.3. Absolute cross–sections in S–U collisions

We start by extracting the K^{DY} factor from our S–U data. Taking the number of Drell–Yan events from table 2, knowing that the SU 90 St data set contributes with 23 %

Table 2. Number of events, corrected for acceptance.

	J/ψ	ψ'	DY
pW	74170 ± 710	1313 ± 82	32000 ± 3000
SU	331700 ± 1700	3550 ± 280	158600 ± 7100

Figure 1. Fit to the p–W 'opposite-sign' dimuon mass distribution (high mass region). The curves are the J/ψ, ψ', Drell–Yan and background contributions.

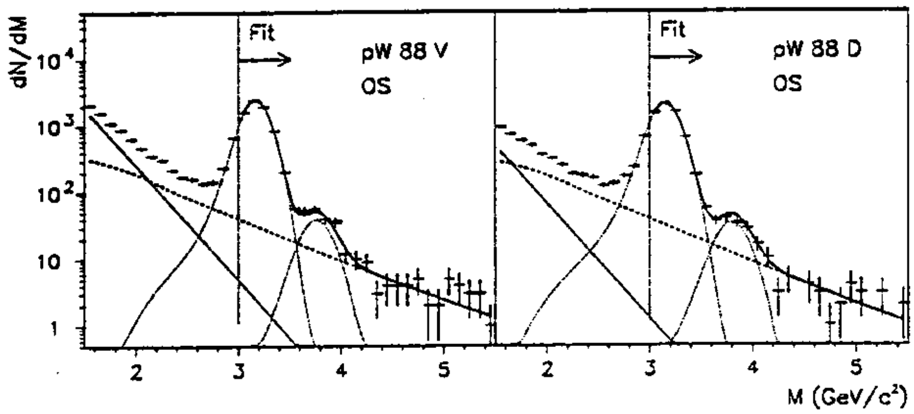


Figure 2. Same as the previous figure but for S–U collisions.

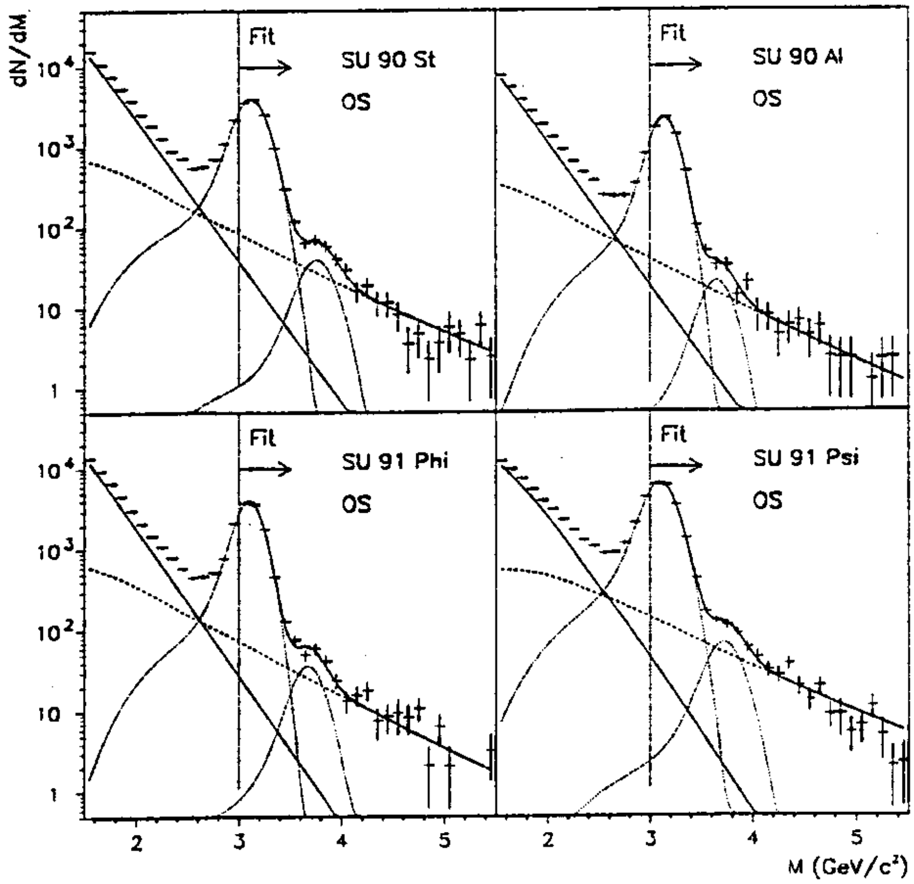
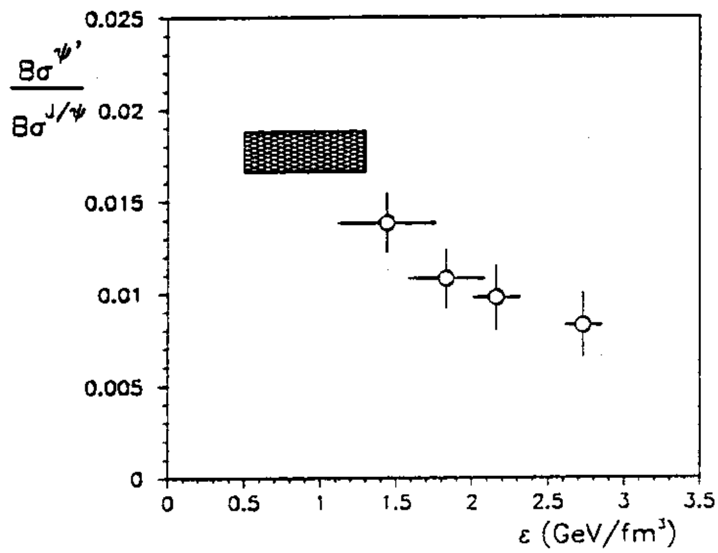


Table 3. Ratio of ψ' over J/ψ (statistical errors only).

$< E_T^0 >$ (GeV)	ϵ (GeV/fm^3)	$B\sigma^{\psi'}$ / $B\sigma^{J/\psi}$ (%)
27.1 ± 0.8	1.44 ± 0.32	1.38 ± 0.16
51.3 ± 2.2	1.83 ± 0.25	1.08 ± 0.16
74.9 ± 2.6	2.16 ± 0.15	0.98 ± 0.18
99.9 ± 4.3	2.73 ± 0.12	0.83 ± 0.18

Figure 3. ψ' suppression relative to J/ψ as ϵ increases (the box represents the p–W value).



of the events while the SU 90 Al one contributes with 11 % and using the luminosities presented in table 1, we calculate the Drell–Yan cross–section in our kinematical window. Comparing with the theoretical prediction, we obtain $K^{DY} = 2.3 \pm 0.1$. Notice that NA3 has measured values from 2.2 to 2.4, using several beam particles, at 150 and 200 GeV, on a platinum target [12].

The J/ψ and ψ' cross–sections (multiplied by the corresponding branching ratios into muons) are 8.54 ± 0.03 μb and 91 ± 5 nb, respectively (statistical errors only). These values should be multiplied by 2 to extrapolate for the whole $cos(\theta)$ domain. The J/ψ value is compatible with the one previously obtained from the 1987 data set [13].

5. INTERMEDIATE MASS REGION

We now turn to the study of the dimuon continuum below the J/ψ. We have fitted the p–W mass spectra above 1.5 GeV/c^2, including the charm contribution previously described (Figure 4). The free parameters in this fit were the R_{Bg} factor and the J/ψ and $D\bar{D}$ processes, while the ψ' and Drell-Yan contributions were kept as determined from the fit to the mass region above 3 GeV/c^2. The number of J/ψ events obtained in this fit is similar to the value in table 2.

As the p–W luminosities are still under study and since our main purpose is to compare S–U collisions with p–W ones, we have normalized the p–W data relative to the S–U data, assuming that the K^{DY} factor is the same in both cases. This means that we *set* the Drell-Yan cross–section in p–W collisions to 112 ± 5 nb. From the fit to p–W data we extract

Figure 4. 'Signal' dimuon mass distribution in p–W collisions.

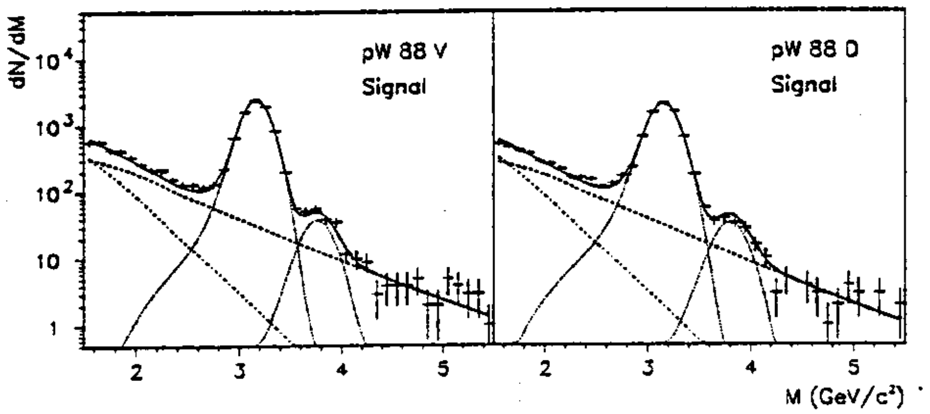
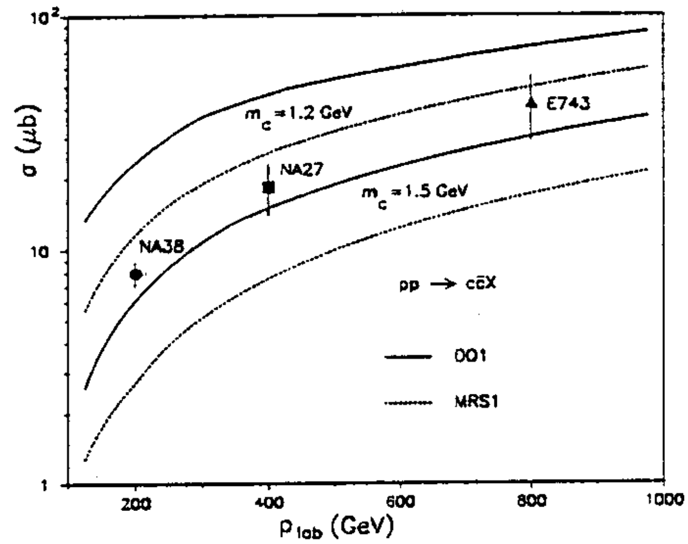


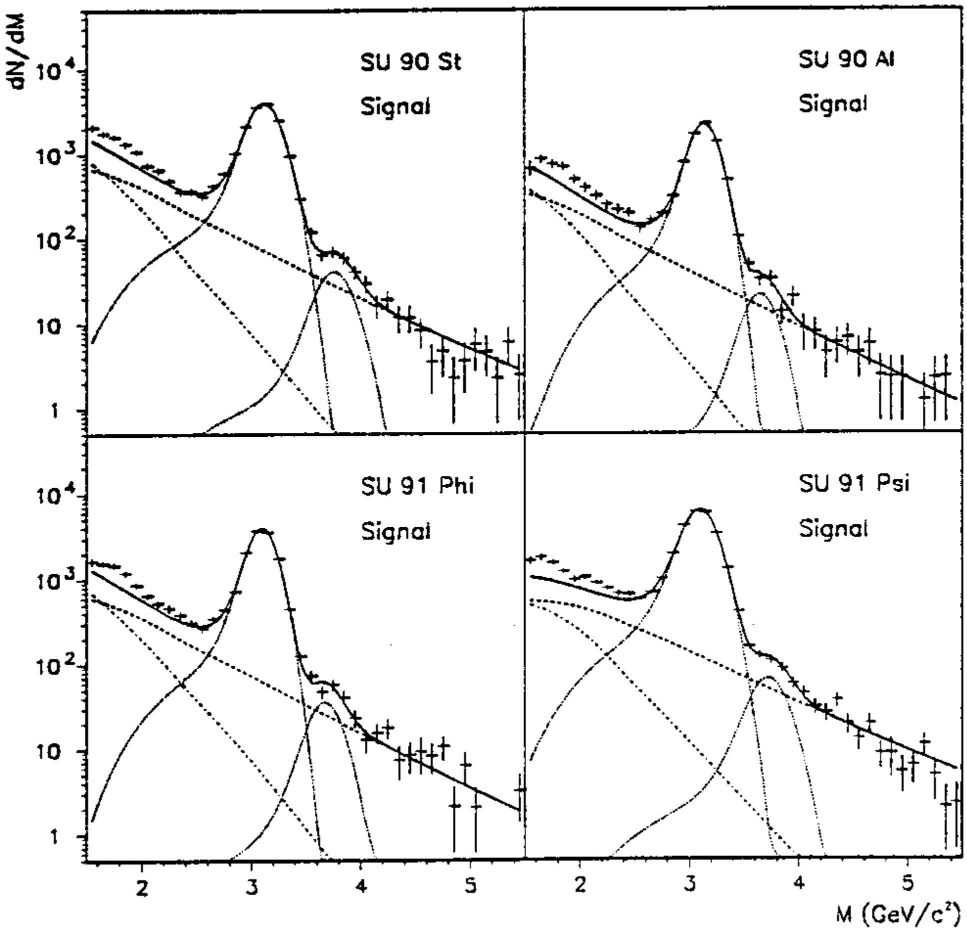
Figure 5. Charm production cross-sections. See the text for details.



the ratio between the $D\bar{D}$ and Drell–Yan processes, 66 ± 8 %, from which we deduce that charm production contributes with 74 ± 10 nb to the dimuon continuum, in our kinematical window. When we correct this value for phase space factors and branching ratios (taken from PYTHIA) and assuming a linear A dependence, we deduce a total charm production cross–section, in p–p collisions at 200 GeV, of 8 ± 1 μb. This value is consistent with the measurements of the LEBC-EHS (NA27) and LEBC-MPS (E743) experiments, at 400 GeV and 800 GeV, respectively, as can be seen in figure 5. This figure was taken from ref. [14], which should be consulted for further details. The curves it contains are $pp \to c\bar{c}X$ cross sections, versus p_{lab} of the incident proton, calculated in order α_s^3, using two values for the charm quark mass and two different sets for parton densities. They help to compare the value deduced from this analysis with the values measured, at higher energies, by NA27 and E743.

We conclude that the dimuon continuum measured in p–W collisions, both below the J/ψ and above the ψ', is well explained by Drell–Yan and charm production. A linear extrapolation of the p–W charm contribution, however, fails to explain S–U data, as shown in figure 6, where an excess is seen for masses around 1.8 GeV/c^2. In order to

Figure 6. 'Signal' dimuon mass distribution in S–U collisions.



quantify this excess [15], we have fitted the S–U data leaving free the J/ψ and $D\bar{D}$ normalizations. The charm contribution becomes 2 times bigger than expected from the p–W linear extrapolation. The fact that this hypothesis gives a good fit ($\chi^2/ndf = 1.5$) indicates that the cross section found in excess, with respect to what was expected, must have a shape similar to the charm contribution. So, an enhancement of charm production in S–U relative to p–W collisions is a possible explanation of this effect. The same analysis performed per E_T bin shows no dependence of this excess on E_T, but definite conclusions must wait for the improved statistics provided by the 1992 data set. We have verified [6] that this excess is not due to unsubstracted meson decay background.

6. CONCLUSIONS

We have observed that ψ' production is suppressed, relative to J/ψ production, from p–W to S–U and as the energy density of the S–U collisions increases. This behaviour was predicted as a signal of quark-gluon deconfinement in nucleus–nucleus collisions.

We have also shown that the dimuon continuum below the J/ψ, in p–W collisions, is compatible with a superposition of the Drell–Yan process, normalized from the high mass region, and charm semileptonic decays into muon pairs. A linear extrapolation of these p–W contributions fails to explain the S–U data, for masses below 2 GeV/c^2.

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15. Notice that a similar excess is observed, in S–W collisions, by the HELIOS/3 experiment. See the talk of M.A. Mazzoni at this conference.