Chapter 7

Results and discussion

In the previous chapter, the pA, SU and PbPb dimuon mass spectra in the IMR have been described as a superposition of DY dimuons and dimuons from the semi-leptonic decay of charmed hadrons (also indicated as $D\overline{D}$), after background subtraction. The DY and $D\overline{D}$ contributions have been extracted by means of a fit of the mass spectra, obtaining the 'measured' $D\overline{D}/DY$ ratio. As a result, an enhancement in the open charm yield has been found in nucleus-nucleus collisions. The found enhancement increases with the collision centrality and the system size.

In this chapter, the absolute value of the found enhancement with respect to QCD expectations is calculated and the excess measured in SU and PbPb collisions is compared, after normalisation to the pA result. This is accomplished computing the open charm yield expected in p-A, S-U and Pb-Pb collisions at the relevant energies, on the basis of the FNAL and CERN direct measurement of charm production in pion and proton induced collisions. For each system, the expected $D\overline{D}/DY$ is then calculated.

The ratio of the measured and expected $D\overline{D}/DY$'s, which measures the size of the open charm enhancement found in the fit of the mass spectra, is then derived and plotted against the number of participants in the collision.

The final results are then discussed in the light of the existing theoretical interpretations and qualitatively compared with the results of the HELIOS/3 experiment and with the previous NA38/NA50 results.

7.1 The expected open charm cross section

In fig.7.1, from ref.[1], the cross sections for forward ($x_F > 0$) D^0,$\overline{D^0}$ and D^+,D^- production, as measured in proton and pion induced reactions at CERN and FNAL, are plotted as a function of the centre of mass energy. The results obtained on nuclear targets have been divided by the target atomic mass number A. The error bars in fig.7.1 have been obtained in ref.[1] adding the statistical and systematic errors in quadrature, including the incertitude on the branching ratio.

It is well known that leading order (LO) QCD calculations, on which the event generator PYTHIA is based, do not reproduce the absolute value of the charm cross section; the same is true when the measured DY cross section is compared with leading order pQCD calculations. On the other hand, as shown in chapter 1 and in the same ref.[1], the differential distributions of charmed mesons are well reproduced by PYTHIA. Besides, this is the reason why the PYTHIA event generator has been used to generate the open charm differential distributions as explained in chapter 4. In fig.7.1, the dotted line represents PYTHIA predictions scaled up by an ad-hoc factor K_{PYTHIA}, which corrects for the above mentioned discrepancy between LO pQCD predictions and absolute cross section measurements. Since PYTHIA does not correctly reproduce the ratio D^+/D^0, two different K_{PYTHIA} factor have been used in fig.7.1 for neutral (K_{PYTHIA}=3.5) and charged (K_{PYTHIA}=7.) charmed mesons. As shown in fig.7.1, PYTHIA well reproduces the overall centre of mass energy dependence of the open charm cross section. Since the same K_{PYTHIA} has been used for all the considered cms energies, we can conclude that the K_{PYTHIA} factor does not depend on the cms energy of the collision.

Thereafter, PYTHIA has been used to compute the expected cross sections for open charm dimuon production in 450 GeV/c, 158 A GeV/c and 200 A GeV/c p-p collisions. In the analysis presented in the previous chapter, two different values of the width of the intrinsic transverse momentum of the colliding partons have been used, i.e., σ_{k_T}=0.8 GeV/c for SU and PbPb and σ_{k_T}=0.9 GeV/c for pA (see chapter 4 and 6). In the following, the same values have been adopted. For the sake of comparison, the open charm cross section for 450 GeV/c p-p collisions has also been computed with σ_{k_T}=0.8 GeV/c.

The cross section for open charm production can be directly extrapolated from the experimental results plotted in fig.7.1, without referring to an event generator like PYTHIA. On the other hand, in order to calculate the dimuon production from charmed mesons (and baryons) in the phase space covered by NA50, the kinematics of the charmed hadron semi-leptonic decay into muons has to be taken into account. Moreover, branching ratio weighting has to be introduced and kinematic cuts applied. We then proceed as follows :

- Compute the *dimuon mass differential spectra for charmed pair production* :

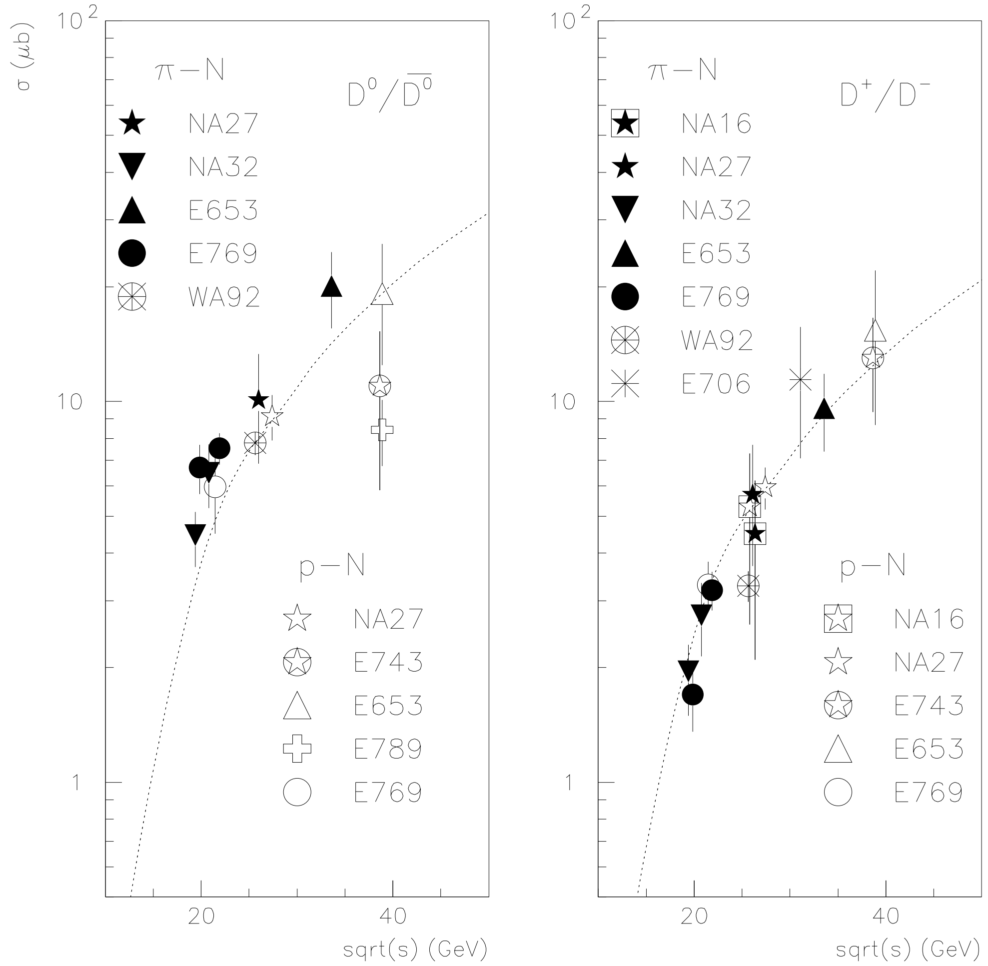

Figure 7.1: *Cross section for forward ($x_F > 0$) D^0, $\overline{D^0}$ (left) and D^+, D^- (right) production in p-p collisions measured in proton and pion induced reactions, as a function of the c.m.s. energy. The solid lines represent the pp PYTHIA calculation scaled up by a factor 3.5 (left panel) and 7.0 (right panel)[1].*

1. Use PYTHIA, with m_c=1.35 GeV/c^2, to compute the differential cross section d$\sigma^{pp}_{c\bar{c}}$/dM for the process

$$pp \rightarrow c\bar{c} \rightarrow D\overline{D} \rightarrow \mu\overline{\mu} \tag{7.1}$$

at 450 GeV/c, 158 GeV/c and 200 GeV/c. As in chapter 4, in order to improve the statistics of generated events and reduce the needed CPU time, a 100% branching ratios has been assigned to the semi-leptonic channel $H_c \rightarrow \mu\nu_\mu X$ (where H_c is a generic charmed hadron), and 0% to all the other decay channels. The appropriate B.R. weighting can be applied in a second time, as later explained.

2. Weight the differential spectra with the K_{PYTHIA} factors suggested in ref.[1], i.e., 3.5 for neutral D mesons and 7 for charged ones. The K_{PYTHIA} value adopted for baryons and strange mesons has a negligible influence on the final value of the cross section for open charm dimuon production, after branching ratio weighting. For baryons (mainly Λ_c) the value K_{PYTHIA}=7 has been used since the Λ_c and D^+ cross sections have been measured to be compatible[3, 4] and since D^+'s and Λ_c's are equally generated by PYTHIA when m_c=1.5 GeV/c^2. The same enhancement factor, K_{PYTHIA}=7, has also been used for strange D mesons and anti-baryons, which contribution is anyway negligible.

3. Within the above choice of the generation parameters, the *total cross section for charmed pair production* in p-p collisions at the related energy can be obtained integrating the mass differential cross section. These same cross section values are then imposed when repeating the calculations with m_c=1.5 GeV/c^2 and m_c=1.2 GeV/c^2.

- Calculate the *cross section for open charm dimuon production in the NA50 phase space* :

  1. Weight the computed mass differential spectra for charmed pair production with the branching ratios for the charmed meson and baryon decays into muons. The adopted B.R. values have already been listed in chapter 4.

  2. Impose the NA50 kinematic cuts on the y and $cos\theta_{CS}$ variables as listed in chapter 3 and consider only dimuon events with M>1.5 GeV/c^2. No explicit cut has been applied on x_F. Since the open charm pairs have been generated for -1< x_F <1, our absolute cross section has to be divided by a factor 2 when comparing with the CERN and FNAL results presented for x_F >0.

3. Integrate the weighted differential distribution in order to obtain the total cross section for open charm dimuon production in pp collisions in our experimental kinematic domain and for M> $1.5 GeV/c^2$.

4. Assume that the open charm cross section in nucleus-nucleus collisions can be linearly extrapolated from the cross section measured in p-p interactions at the same energy. Then, multiply the calculated p-p cross section by A×B, where A and B are the projectile and target atomic numbers, in order to obtain the cross section for open charm dimuon production in A-B collisions.

Fig.7.2 illustrates the above described different stages in the cross section calculation for 158 GeV/c Pb-Pb collisions and for m_c=1.35 GeV/c^2. In tab.7.1 the calculated cross sections are listed for the three studied systems at the related energies and for m_c=1.2, 1.35 and 1.5 GeV/c^2. The values obtained with the three different m_c differ after kinematic cuts are applied; this is due to the different shapes of the charm distributions generated with different m_c. The cross section for 450 GeV/c p-p interactions have been calculated for both σ_{k_T}=0.8 GeV/c and σ_{k_T}=0.9 GeV/c finding a discrepancy of $\simeq$ 0.3% *before* B.R. weighting and kinematic cuts and of $\simeq$ 8% between the final values. The latter is due to the modification of the p_T distribution of the generated and reconstructed open charm dimuons within our acceptance window, as shown in the previous chapter. The calculated cross section is affected by a statistical error due to the number of generated events ($\approx$ 0.2%) and by a systematic incertitude due to the square of the $\simeq$12% uncertainty on the B.R.'s.

7.1.1 The expected $D\overline{D}/DY$ ratio

From the calculated open charm dimuon cross section, the expected number N of open charm dimuons in the dimuon mass spectrum measured by NA38/NA50 can be calculated using the equation

$$N = \sigma^{AB}_{c\bar{c}\to\mu^+\mu^-} A_{D\overline{D}} \cdot L \tag{7.2}$$

where $\sigma^{AB}_{c\bar{c}\to\mu^+\mu^-}$ (μb) is the cross section for open charm dimuon production in AB collisions (A≥1 and B>1) for M>1.5 GeV/c^2, and after kinematic cuts have been applied. L is the luminosity in μb^{-1} and $A_{D\overline{D}}$ is the acceptance for open charm dimuons in the mass range M> 1.5 GeV/c^2. The luminosity L has been evaluated using eq.7.2 for the J/ψ. The J/ψ cross section has been taken from ref.[5] for the PbPb system and from ref.[6] for the SU one, whilst for the 450 GeV/c pW system the results of a recent analysis[7] have been used, which are in very good agreement with the results of ref.[8]. The acceptances listed in chapter 4 have been used and the number of J/ψ have been deduced from the fits of the all E_T mass spectra. The errors on the computed luminosity mainly reflect the incertitude on the J/ψ cross

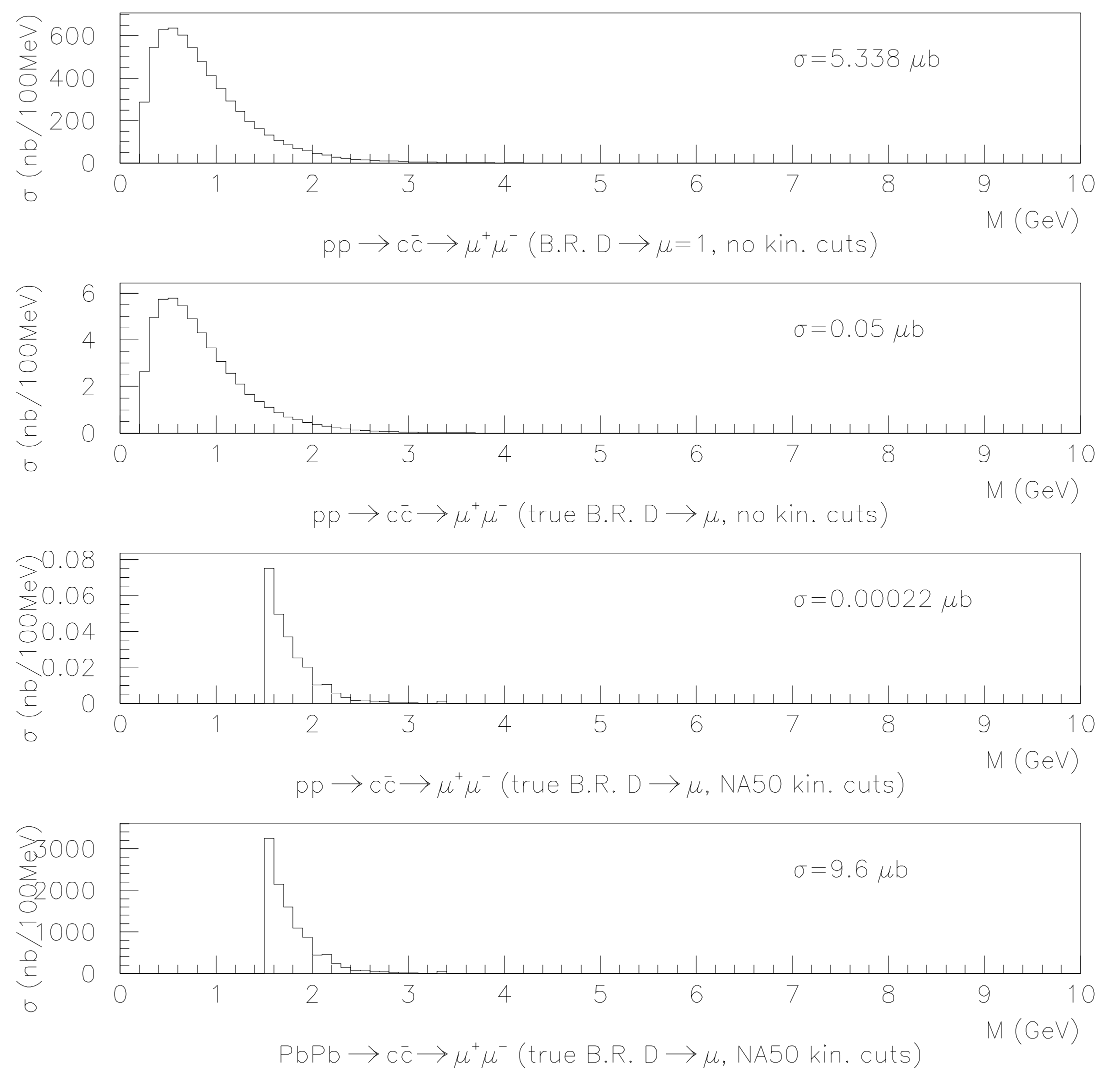

Figure 7.2: *Different stages in the calculation of the cross section for open charm dimuon production in Pb-Pb collisions at 158 A GeV/c and for m_c=1.35 GeV/c^2.*

Process	σ_{k_T} (GeV/c)	σ (μbarn) (m_c=1.2 GeV/c^2)	σ (μbarn) (m_c=1.35 GeV/c^2)	σ (μbarn) (m_c=1.5 GeV/c^2)
p-p 450 GeV/c	0.8	22.62 ± 0.04	22.62 ± 0.04	22.62 ± 0.04
p-p B.R.	0.8	0.19 ± 0.05	0.22 ± 0.05	0.20 ± 0.05
p-p B.R., k.c.	0.8	0.0009 ± 0.0002	0.0014 ± 0.0003	0.0015 ± 0.0004
p-W B.R., k.c.	0.8	0.17 ± 0.04	0.25 ± 0.06	0.28 ± 0.08
p-p 450 GeV/c	0.9	22.68 ± 0.03	22.68 ± 0.03	22.68 ± 0.03
p-p B.R.	0.9	0.23 ± 0.05	0.25 ± 0.06	0.23 ± 0.06
p-p B.R., k.c.	0.9	0.0012 ± 0.0003	0.0015 ± 0.0003	0.0019 ± 0.0004
p-W B.R., k.c.	0.9	0.21 ± 0.05	0.27 ± 0.06	0.35 ± 0.08
p-p 158 GeV/c	0.8	5.338 ± 0.008	5.338 ± 0.008	5.338 ± 0.008
p-p B.R.	0.8	0.04 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
p-p B.R., k.c.	0.8	0.00017 ± 0.00004	0.00022 ± 0.00005	0.00026 ± 0.00006
Pb-Pb B.R., k.c.	0.8	7.4 ± 1.8	9.6 ± 2.3	11.3 ± 2.7
p-p 200 GeV/c	0.8	7.62 ± 0.01	7.62 ± 0.01	7.62 ± 0.01
p-p B.R.	0.8	0.06 ± 0.01	0.07 ± 0.01	0.07 ± 0.01
p-p B.R., k.c.	0.8	0.00025 ± 0.00006	0.00030 ± 0.00008	0.00039 ± 0.00009
S-U B.R., k.c.	0.8	1.9 ± 0.5	2.7 ± 0.6	3.0 ± 0.7

Table 7.1: *Cross sections calculated for the three studied systems at the related energies. The four different cross section values listed for each of the three systems correspond to : B.R.($D \rightarrow \mu$) = 1 and no.kin.cuts (p-p), true B.R.($D \rightarrow \mu$) and no.kin.cuts (p-p B.R.) true B.R.($D \rightarrow \mu$) and NA50 k.c (p-p B.R., k.c.) true B.R.($D \rightarrow \mu$) and NA50 k.c and nuclear effects (A-B B.R., k.c.).*

	PbPb	SU	pW
$\sigma^{meas.}_{J/\psi}$ (μb)	21.9 ± 1.6	7.77 ± 0.84	0.68 ± 0.048
$N^{meas.}_{J/\psi}$	151593 ± 704	113115 ± 578	438000 ± 1314
$A_{J/\psi}$	0.0744	0.164	0.144
L (μb^{-1})	93550 ± 6800	88770 ± 9600	$(4400 \pm 315.7) \cdot 10^3$

Table 7.2: *Quantities needed to calculate the luminosity for the PbPb, SU and pW systems : measured J/ψ cross section $\sigma^{meas.}_{J/\psi}$, number of J/ψ measured in the fit to the indicated systems and J/ψ acceptance. The calculated luminosities are also listed.*

section measurement. Tab.7.2 lists all the quantities needed for the calculation of the luminosities and the calculated luminosity values.

The cross section for hard processes is expected to scale with A in p-A and with $A \times B$ in A-B collisions. More generally, at fixed impact parameter b the cross section for the considered hard process in a nucleus-nucleus collision is expected to be proportional to the number of effective nucleon-nucleon collisions[13]. This has been verified for the DY in both p-A and A-B collisions[9, 5]. The DY process can therefore be used as a reference in order to evaluate any deviation of the open charm cross section from the expected behaviour, as already done in chapter 6 on the measured quantities. The expected $D\overline{D}/DY$ ratios can therefore be calculated and compared with the ones listed in chapter 6 for all the studied systems. For the PbPb and SU systems the number of DY dimuon pairs is taken from the result of the fit of the all E_T mass spectrum. For the pA systems, where the same number of DY pairs is used when calculating the measured and the expected $D\overline{D}/DY$, the number of DY dimuon pairs measured for any of the four pA systems can be taken as a reference; the number of expected open charm dimuons has to be calculated for the same pA system. In the following the pW system is used, as already done in the previous section.
Tab.7.3 lists the acceptances, the number of open-charm dimuons and DY dimuons and the resulting expected $D\overline{D}/DY$ ratios for the PbPb, SU and pW systems; the values in tab.7.3 have been obtained when the charm mass value m_c=1.5 GeV/c^2 is used to generate the open charm mass differential distribution and the fit is started at M=1.5 GeV/c^2. The error on the expected number of open charm dimuon comes from the error on the luminosity L.

	PbPb	SU	pW
$A_{D\overline{D}}$ $(M > 1.5GeV/c^2)$	0.0111	0.0482	0.0218
A_{DY} $(M > 1.5GeV/c^2)$	0.0281	0.0901	0.0578
$N_{D\overline{D}} \mid_{expect.}$	11771 ± 856	12720 ± 1375	33093 ± 2256
$N_{DY} \mid_{meas.}$ (all E_T)	45924 ± 1033	29437 ± 843	33070 ± 593
$\frac{\frac{N_{D\overline{D}}}{A_{D\overline{D}}}}{\frac{N_{DY}}{A_{DY}}} \mid_{expect.}$	0.648 ± 0.049	0.808 ± 0.090	2.63 ± 0.19

Table 7.3: *Quantities needed to compute the expected number of dimuons from open charm decay for the PbPb, SU and pW systems and for m_c=1.5 GeV/c^2. The listed number of dimuons from DY is necessary in order to calculate the ratio $D\overline{D}/DY$ which is also given.*

7.2 The pA reference

If the $D\overline{D}/DY$ ratio obtained in chapter 6 for the pA systems is compared with the one calculated in the previous sections, we find

$$E \mid_{pA} = \frac{D\overline{D}/DY \mid_{meas.}}{D\overline{D}/DY \mid_{expec.}} = \frac{4.20 \pm 0.25}{2.63 \pm 0.19} = 1.60 \pm 0.15 \qquad (7.3)$$

It is necessary to check whether the above value of E corresponds to a cross section for charmed pair production compatible, at the related energy, with the cross sections extrapolated from the FNAL and CERN results plotted in fig.7.1. Therefore, from the cross sections for inclusive D production measured at CERN and FNAL, the $c\overline{c}$ cross section can be deduced as outlined in ref.[2], i.e.

- Divide the FNAL and CERN inclusive $\sigma(D/\overline{D}, x_f > 0)$ by a factor 2 to get the exclusive $D\overline{D}$ pair cross section.
- In order to account for the partial x_F coverage, multiply by a factor 2 in p induced collisions and 1.6 in π induced ones or, vice-versa, divide our experimental value by a factor 2.
- Account for the Λ_c and D_s contributions to the total cross section. From the experimentally measured Λ_c and D_s cross sections, the following seems to hold

$$\frac{\sigma(D_s)}{\sigma(D^+ + D^0)} \simeq 0.2 \qquad (7.4)$$

$$\frac{\sigma(\Lambda_c)}{\sigma(D^+ + D^0)} \simeq 0.3 \tag{7.5}$$

Thereafter, the $c\bar{c}$ cross section can be obtained multiplying the exclusive $D\overline{D}$ cross section by a factor 1.5.

The open charm cross section measured in 450 GeV/c pp collisions, can be calculated using the value listed in tab.7.1 multiplied by the $E\mid_{pA}$ factor 1.60±0.15 and divided by 2 in order to correct for the x_F coverage,

$$\sigma_{c\bar{c}}^{pp,450GeV/c} = (22.68 \pm 0.03) \cdot \frac{(1.60 \pm 0.15)}{2} = 18.14 \pm 1.70\ \mu b \tag{7.6}$$

If we also take into account the 24% uncertainty on the calculated cross section for open charm dimuon production due to the squared 12% uncertainty on the B.R., we find an overall 25% error on the value quoted in eq.7.6. In fig.7.3 the $c\bar{c}$ cross section extrapolated from our cross section for open charm dimuon production in pA collisions at 450 GeV/c, as quoted in eq.7.6, with the additional systematic error due to B.R., is compared with the previous FNAL and CERN experimental results. We find that our point does not significantly deviate from the $\sqrt{s}$ systematics, as shown by the dotted curve in fig.7.3. From the dotted curve in fig.7.1 we can see that the chosen PYTHIA enhancement factors, as suggested in ref.[1], give a curve which does not perfectly interpolate all experimental points. A larger enhancement factor for neutral mesons could perhaps give a better agreement, and a lower $E\mid_{pA}$.

Since the open charm cross section measured in 450 GeV/c pA collisions is in agreement with previous experimental results, the corresponding cross section for open charm dimuon production can be used as a reference when studying the PbPb and SU systems.

7.3 Results

In tab.7.4 the ratios of the measured and expected $D\overline{D}/DY$'s are listed after normalization to the 450 GeV/c pA result. The normalised ratio E is defined as

$$E = \frac{E\mid_{AB}}{E\mid_{pA}} = \frac{\frac{D\overline{D}}{DY}\mid_{meas.}^{AB}}{\frac{D\overline{D}}{DY}\mid_{expec.}^{AB}} \cdot \frac{\frac{D\overline{D}}{DY}\mid_{expec.}^{pA}}{\frac{D\overline{D}}{DY}\mid_{meas.}^{pA}} \tag{7.7}$$

The errors on E in tab.7.4 come from two sources :

- The statistical error on the $D\overline{D}/DY$ extracted from the fit of the mass differential distributions as performed in the previous chapter.
- The error on the calculation of the luminosity L (7÷10%), which originates from the incertitude on the measured J/ψ cross section.

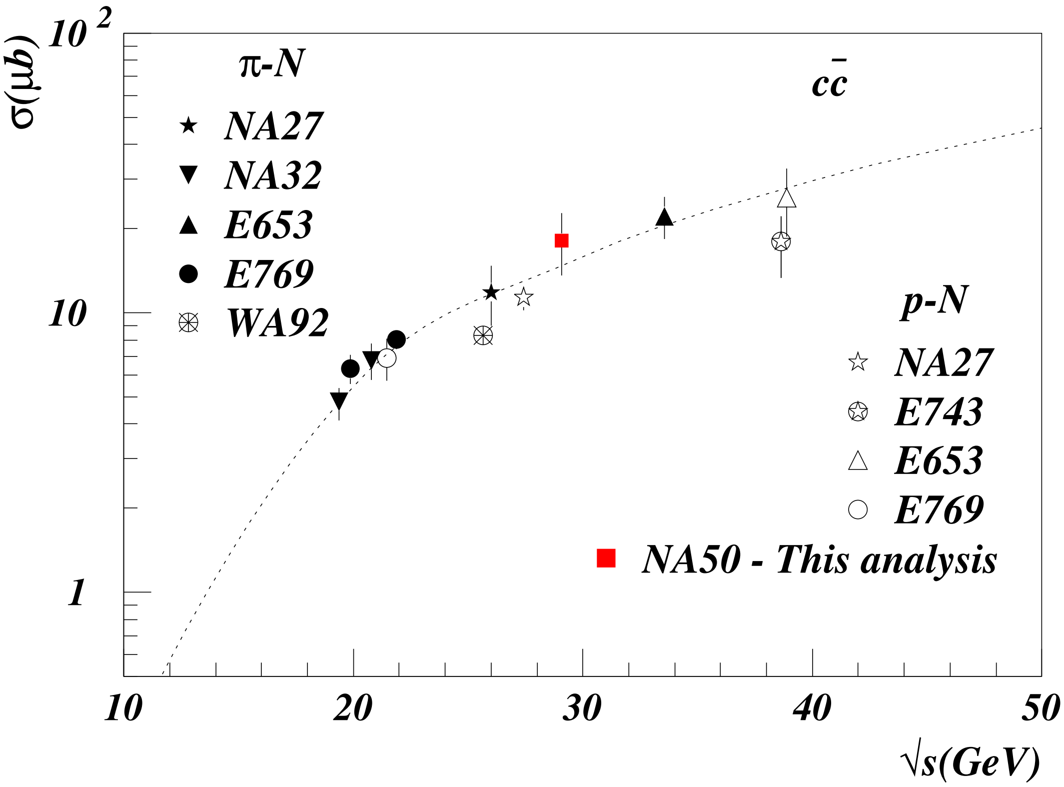

Figure 7.3: *Cross sections for forward (x_F>0) $c\bar{c}$ production compared with the value extrapolated from this analysis.*

	Energy (GeV/c)	E_T bin (GeV)	$\langle N_{part} \rangle$	$E_{open-charm}$
pW	450	all	$5. \pm 2.$	1.00
SU	200	1	$43. \pm 7.$	1.26 ± 0.18
SU	200	2	$65. \pm 6.$	1.29 ± 0.18
SU	200	3	$84. \pm 5.$	1.51 ± 0.20
SU	200	4	$101. \pm 5.$	1.88 ± 0.23
SU	200	5	$116. \pm 3.$	1.61 ± 0.22
PbPb	158	1	$63. \pm 18.$	2.38 ± 0.36
PbPb	158	2	$110. \pm 11.$	1.94 ± 0.27
PbPb	158	3	$149. \pm 11.$	1.94 ± 0.26
PbPb	158	4	$189. \pm 12.$	2.03 ± 0.26
PbPb	158	5	$231. \pm 13.$	3.05 ± 0.36
PbPb	158	6	$273. \pm 11.$	3.16 ± 0.38
PbPb	158	7	$310. \pm 10.$	2.57 ± 0.33
PbPb	158	8	$347. \pm 11.$	3.35 ± 0.43
PbPb	158	9	$381. \pm 7.$	3.56 ± 0.45

Table 7.4: *Enhancement of the open-charm dimuon yield with respect to pA results for the pW, PbPb and SU systems. The enhancement E has been calculated for each of the considered E_T bin; the number of participant nucleons in the collision is also listed. The errors on E come from the error on the measured $D\overline{D}/DY$ ($\simeq$10%) and from the error on the calculation of the luminosity (7÷10%). The systematic errors due to the normalisation to the $E\mid_{pA}$ value, 8%, and to the 12% incertitude in the B.R. measurement, have not been included because they would affect all the listed values in the same way (and direction).*

Two more systematic errors have not been included in the final error calculation because they affect all the listed E values in the same way (and direction) :

- The error carried by $E\mid_{pA}$ (9%), since all the measured E, $E\mid_{pA}$ included, have been normalised to $E\mid_{pA}$.
- The $\approx$ 24% error on the calculated cross sections for open charm dimuon production, which originates from the squared 12% incertitude on the used B.R.'s.

In fig.7.4 the same values have been plotted as a function of the number of participant nucleons N_{part} in the collision. The number of participants in the collision can be easily deduced using the known b vs. E_T correlation (see chapter 5); for each average value of the impact parameter b, the number of participants from the projectile and target nuclei can be computed using VENUS. The line superimposed on fig.7.4

corresponds to a fit to the plotted points with the function

$$E = m \cdot (N_{part} - 5.0) + 1.0 \tag{7.8}$$

with

$$m = 0.0068 \pm 0.0004 \tag{7.9}$$

and χ^2=1.2. Eq.7.8 implies that

$$\frac{\frac{(D\overline{D})}{DY}\mid^{AB}_{meas.}}{\frac{(D\overline{D})}{DY}\mid^{AB}_{expec.}} \propto N_{part} \tag{7.10}$$

which in turn means that the found open charm enhancement increases *quadratically* with the collision centrality, as explained in the following :

- The total number of participants, or number of wounded nucleons in a collision, at a impact parameter b, is proportional to the transverse energy E_T. If each wounded nucleon produces a fraction q of the total measured transverse energy, we can write[10] :

$$E_T = qN_{part} \tag{7.11}$$

- The number of DY pair produced in a collision at impact parameter b, is proportional to the number of effective nucleon-nucleon collisions $N_{coll}(b)$,

$$N_{DY}(b) \propto N_{coll}(b) \tag{7.12}$$

  which, when integrated over all impact parameter b, leads to

$$N_{DY}\mid_{all-E_T} \propto AB \tag{7.13}$$

- The number of effective nucleon-nucleon collisions N_{coll} also linearly increases with the number of wounded nucleons N_{part}[11]. We can therefore define[10] :

$$k(b) = \frac{N_{coll}(b)+1}{N_{part}(b)} \propto q\frac{N_{DY(E_T)}}{E_T} \tag{7.14}$$

  The coefficient k is by definition equal to 1 in p-p and p-A collisions, but larger than 1 in nucleus-nucleus interactions where each wounded nucleon can participate to more than one elementary collision. The value of k therefore increases with the atomic number of the colliding nucleus and with the cms energy, since the number of N-N collisions depends on the inelastic nucleon-nucleon cross section[10], and increases with centrality within the same nuclear system.

Since the number of participants N_{part} in the collision and the number of produced DY pairs both linearly increase with the transverse energy E_T, the measured excess in the open charm dimuon yield increases *quadratically* with the collision centrality. This can be made evident if eq.7.10 is written as

$$\frac{D\overline{D}(b)\mid_{meas.}}{D\overline{D}\mid_{expec.}} \propto N_{part}(b)\cdot\frac{DY(b)\mid_{meas.}}{DY\mid_{all-E_T}} \propto k\frac{N_{part}^2}{AB} \tag{7.15}$$

Since the open charm hadro production is a hard process, its contribution to the dimuon yield is expected to linearly increase with the collision centrality (see chapter 1). We could therefore imagine that the open charm enhancement originates from a new softer source, and define

$$D\overline{D}(b)\mid^{total}_{meas.} = D\overline{D}(b)\mid^{new-source}_{meas.} + D\overline{D}(b)\mid^{hadro-prod.}_{meas.} \tag{7.16}$$

With the above, eq.7.15 could also be written as

$$D\overline{D}(b)\mid^{new-source}_{meas.} \propto N_{part}^2 \tag{7.17}$$

Thereafter, the quadratical dependence of the total open charm dimuon yield on the collision centrality reveals the existence of a new source for open charm production in nucleus-nucleus collisions already at SPS energy.

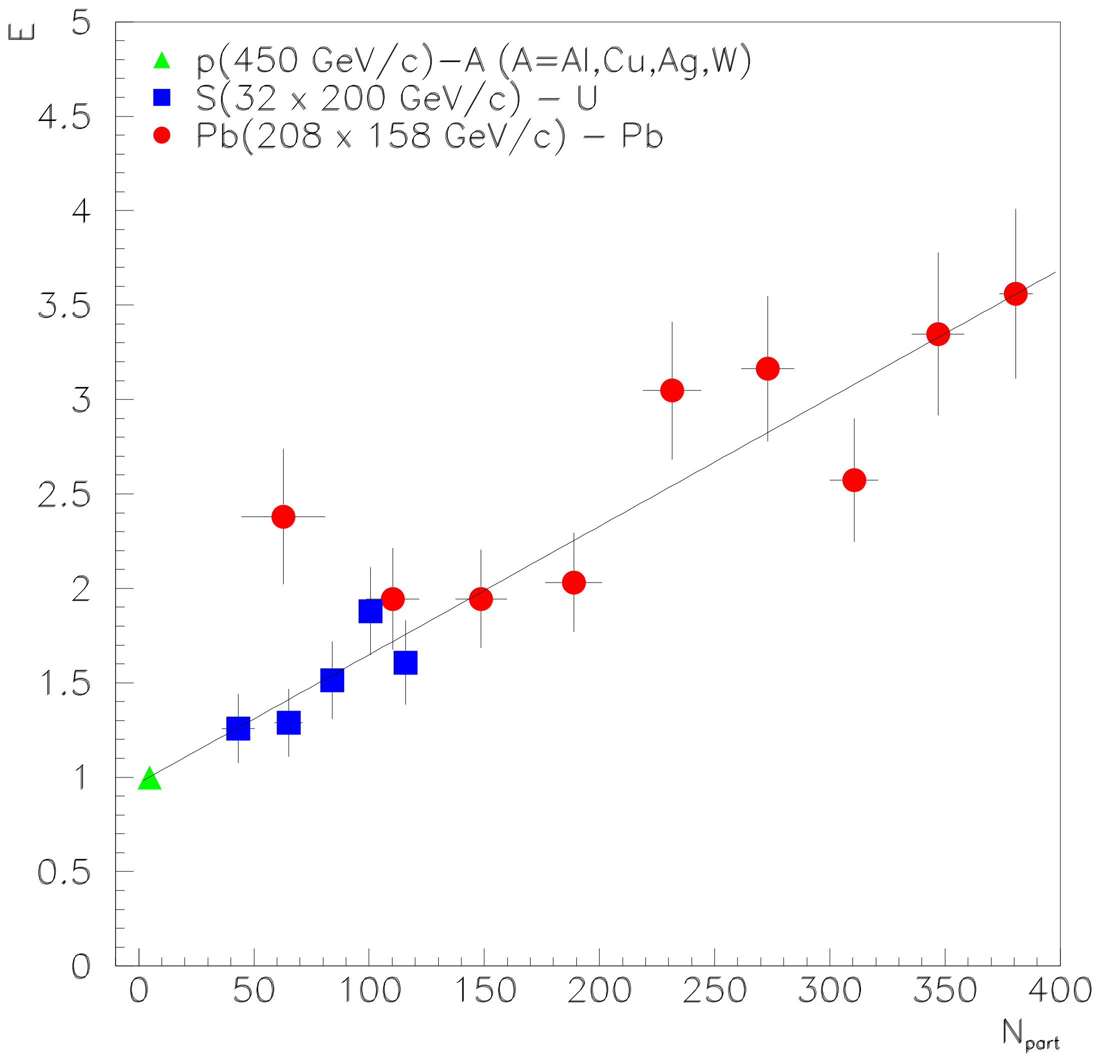

Figure 7.4: *Enhancement E of the open-charm dimuon yield, as defined in eq.7.7, versus the number of participant nucleons, as measured in 450 GeV/c p-A, 200 A GeV/c S-U and 158 A GeV/c Pb-Pb collisions. The corresponding values are listed in tab.7.4.*

7.4 Discussion

Since the results of the present work have been only very recently communicated to the scientific community[24, 25, 26], only few models exist which give a quantitative description of the measured IMR excess. In fact, different interpretations of the measured IMR excess also exist as, for instance, an enhanced dimuon yield from secondary Drell-Yan production. Furthermore, since the combinatorial background contribution to the IMR in very central PbPb collisions amounts to 95% of the opposite-sign dimuon events, it is necessary to prove that the measured excess is not unsubtracted background.

7.4.1 The measured excess *is not* unsubtracted BCK

In order to check whether the dimuon excess in the intermediate mass region can be accounted for with the background contribution only, the following test has been performed :

- The open charm contribution has been fixed at its expected value, as calculated in the present chapter.
- As in the previous analysis, the DY contribution is free but determined by the very high mass region, M>4.5 GeV/c^2.
- The background contribution is left free, i.e., the R_{BCK} factor is a free parameter in the fit of the opposite sign mass spectra.

In fig.7.5 the result of the fit to the most central PbPb bin is shown. It is evident that the shape of the measured excess can not be reproduced by the combinatorial background shape. Besides, the obtained R_{bck} values are unreasonably large; for instance, when fitting the most central PbPb bin we obtain R_{bck}=1.025, leading to a negative signal for M$\simeq$1.3 GeV/c^2.

7.4.2 D meson final state re-scattering

In a very recent paper[14], the open-charm enhancement measured in the present work is interpreted as due to a modification of the p_T differential distribution of charmed mesons. This modification, provoked by final state re-scattering of the D mesons inside the interaction volume created in the collision, would increase the percentage of D mesons decaying in the NA50 phase space. On the other hand, the actual open charm yield integrated over the whole phase space would remain unchanged. The model presented in ref.[14] is based on the following reasoning :

- The p_T differential distributions of the secondary hadrons produced in a nucleus-nucleus collision can be parametrised with an exponential

$$\frac{dN}{m_T dm_T} \propto e^{-(m_T - m)/T_{eff}} \tag{7.18}$$

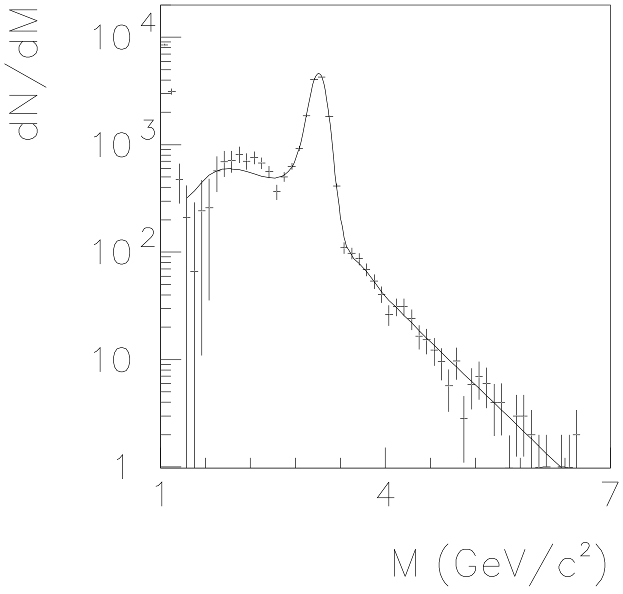

Figure 7.5: *Signal dimuon mass spectra for the* 9^{th} *PbPb bin. The curve has been obtained fitting the opposite-sign mass spectra; in the fit the open charm contribution has been fixed at the expected value whilst the* R_{BCK} *factor has been left free.*

The *slope* parameter T_{eff} has been measured[19, 20] to depend linearly on the particle mass and to increase with the size of the system created in the nucleus-nucleus collision. This is attributed to a collective transverse flow, which in turn is due to final state re-scattering among the secondary particles.

- D mesons are assumed to be affected by final state re-scattering in the same way as other hadrons do, thus T_{eff} for D mesons in central Pb-Pb collisions has the same value as the one measured for protons and ϕ mesons, T_{eff}=290 MeV.

- D mesons are assumed to thermalise within their *local* environment at the local temperature T. In the model, if T_{eff}=290 MeV, T $\approx$ 150 MeV.

- Open charm production is then computed using PYTHIA to simulate pp interactions at 158 GeV/c, with m_c=1.3 GeV/c^2 and σ_{k_T}=1 GeV/c. The charm pair differential distributions are thus obtained. The $\sigma_{c\bar{c}}^{PbPb}$ is derived using the $\sigma_{c\bar{c}}^{pp}$ for 200 A GeV/c pp collisions from ref.[21] and then correcting for the energy difference. The expected number of produced charm pairs is then calculated. The charm quarks then fragmentate (hadronize) in charmed hadrons.

- In the D mesons rest frame a local thermal momentum is randomly chosen from a thermal distribution and then boosted back to the laboratory frame.

In this way, both the transverse flow due to final state re-scattering and the longitudinal flow are taken into account. Thus, a strong correlation still exist between the scattered D mesons, due to the assumed longitudinal flow. If the D mesons where no more correlated, the generated cosθ distribution before kinematic cuts would be flat, which is not the case.

- An average branching ratio of 12% is assumed for the semileptonic decays of D mesons to muons.
- The NA50 acceptance cuts, as given in chapter 5 of the present work, are applied on the D meson differential distributions.

In fig.7.6 the predicted effect of final state re-scattering on the mass, rapidity and cosθ differential distribution *within* the NA50 acceptance is shown. The effect on the shape of the spectra is well visible on the mass distribution, whilst the shape of the cosθ and rapidity distributions are little affected. The strength of the effect depends on the chosen value for the local temperature T, as shown in fig.7.7 for the m_T distribution. To quantify the open charm enhancement in the NA50 phase space, the ratio R of accepted dimuon yield after and before final state re-scattering is defined. It is found that, when T=150 MeV, R=3.

If the measured open charm enhancement was actually due to the above mentioned mechanism, we would have probably not been able to reproduce the experimental p_T distributions as it was done in chapter 6. In chapter 6, the experimental p_T distributions were reproduced using the p_T differential shapes predicted by PYTHIA and normalised to the results of the fit of the mass spectra. Since we obtained a good data reproduction without invoking any additional mechanism, such as final state re-scattering, the hypothesis that such a mechanism plays an important role in the observed enhancement can be probably ruled out. Unfortunately, in ref.[14] the calculated dimuon p_T distribution has not been given, making it impossible to draw a direct comparison between the prediction of the final state re-scattering model and our p_T distributions.

It could be argued that, because of acceptance effects, the expected modification of the p_T distribution of the generated D mesons could be hardly resolved when the dimuon reconstructed spectra are studied. In fig.7.8 the generated and reconstructed p_T spectra of open charm dimuons are shown for two different values of σ_{k_T} and after kinematic cuts. For a dimuon invariant mass of 1.5 GeV/c^2, the difference in the generated spectra is $\approx$ a factor 2. The same factor is found when comparing the reconstructed spectra. We therefore conclude that even a small change in the generated spectra, within the phase space covered by NA50, would be easily resolved at the reconstruction level.

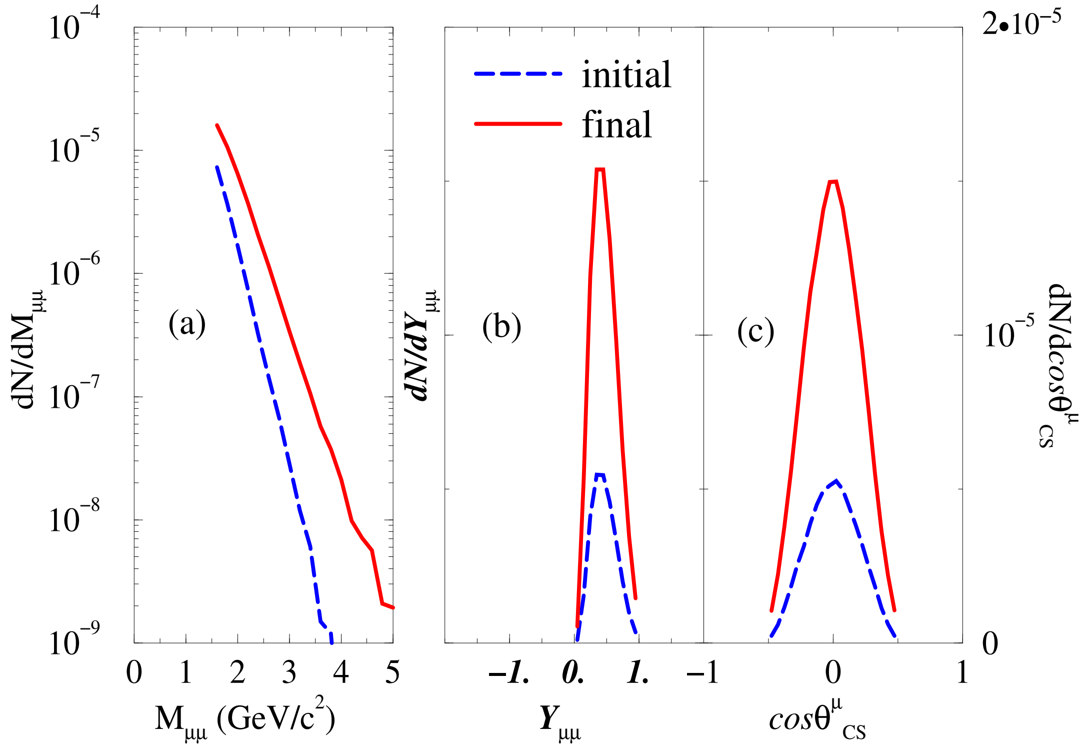

Figure 7.6: *(a) Invariant mass, (b) pair rapidity (c) $cos\theta_{CS}$ distributions of dimuons from D meson decays within NA50 acceptance as calculated in the model[14].*

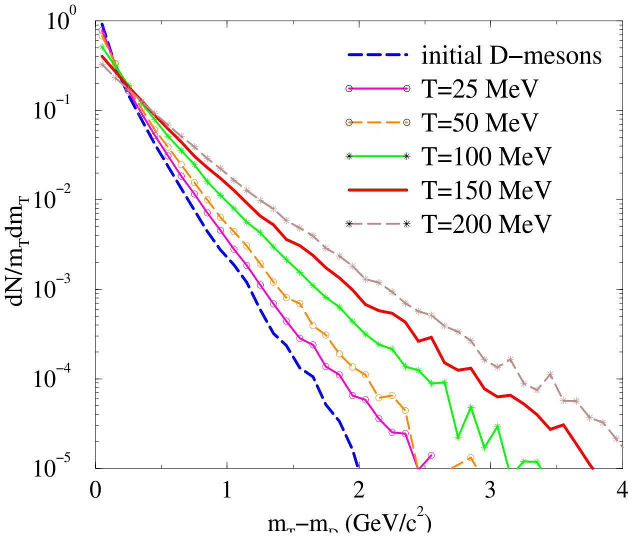

Figure 7.7: *m_T spectra of D mesons at mid-rapidity after final state re-scattering for different local temperature T[14].*

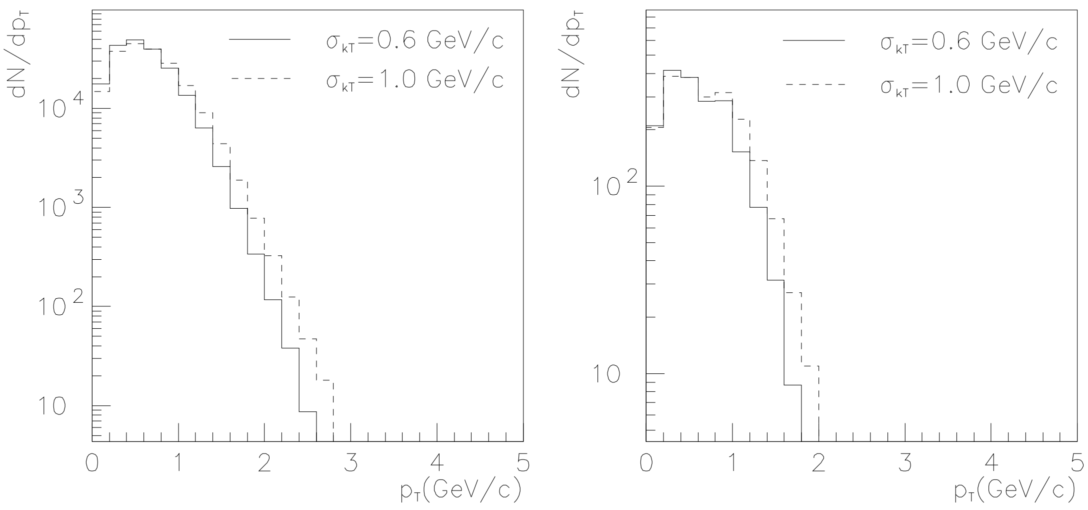

Figure 7.8: *Generated and reconstructed p_T differential distribution of dimuons from charmed hadron decays. Kinematic cuts have been applied on both distributions. Two different values of σ_{k_T} are compared. The two different σ_{k_T} values induce an equal difference on the generated and the reconstructed spectra.*

Initial state re-scattering

The authors in the same ref.[14] indicate that multiple scattering of partons in the initial state accounts for less than 10% of the observed excess.

Gluon anti-shadowing

Gluon anti-shadowing is the effect seen in the region of values of the parton longitudinal momentum fraction x where the ratio R, defined as the ratio of the PDF's for gluons in a heavy nucleus and in a proton, is larger than 1 (see chapter 1). For the values of x where R is larger than 1, the density of gluons in the nucleus is larger than the density of gluons in a free nucleon; the increased number of gluons could therefore lead to an enhanced heavy quark production. At SPS charm production takes places for $x \approx 0.2$, where gluon anti-shadowing is close to its maximum. In ref.[14] the contribution of gluon anti-shadowing to the open charm enhanced production has been evaluated to account for no more than $\approx 20\%$ of the observed excess.

7.4.3 Open charm production in soft baryon-baryon collisions

In ref.[15], a model for charm production in soft baryon-baryon collisions is developed. In the octet model for J/ψ and ψ' production and suppression in a hadron gas (see chapter 1), the fully formed ψ' can be easily broken by the interactions with co-moving hadrons. In ref.[15] it is argued that the aforementioned comovers could either be fully formed hadrons (interacting via the exchange of gluons) or bare gluons. If a high density of bare energetic gluons existed in the interaction volume created in nucleus-nucleus collisions, the heavy quark production could be enhanced with respect to the yield measured in p-A interactions. Two energetic gluons could in fact easily interact to create a heavy quark pair via the gluon fusion process; two hadrons with the same energy would instead interact through the exchange of gluons carrying only a small fraction x of the hadron momenta, thus having a much smaller probability of exceeding the heavy quark mass threshold. Gluons would be produced in soft baryon-baryon collisions because of the strong field created when, after the collision, one q and one $\overline{q}$ (or a diquark) pull apart. Since the produced gluons would finally hadronize, the characteristics of their momentum spectrum could be deduced from the measured hadron spectra. Therefore, they would mainly be found in the mid-rapidity region.

To quantify the expected heavy quark pair production, the authors assume that in pA collisions the created gluons hadronize before they had time to fuse in a heavy quark pair. In nucleus-nucleus collisions the opposite is assumed, i.e., all the created gluons interact and produce heavy quark pairs. In this hypothesis, the excess measured in the previous NA38 analysis of the 200 A GeV/c SU system can be fairly well described, as shown in fig.7.9; the calculated enhancement shows a marked E_T dependence which qualitatively agrees with the results of the present work.

The same calculation is being performed for the 158 A GeV/c PbPb system[12], but since the results are still not known, no conclusive comparison can be drawn with the results of the present thesis.

7.4.4 Secondary DY production at SPS

In ref.[16] the role of secondary DY production in nucleus-nucleus collisions at SPS energy is studied. Secondary DY production is due to the electro-magnetic annihilation of the valence quarks of the secondary hadrons created in the collision. The dimuon yield from the secondary DY process is calculated as the sum of the contributions from all the possible hadron-hadron collisions, weighted by the inverse of the total hadron-hadron cross-section. Clearly, valence quark annihilation is most important in pion-nucleon, nucleon-antinucleon and pion-pion collisions. If only interactions between fully formed final state hadrons are allowed, the expected dimuon yield from secondary DY is found to be negligible in p-A interactions ($\approx$ 2%). In the same hypothesis, the predicted enhancement in 200 A GeV/c S-U and 160 GeV/c Pb-Pb amounts to 25% and 45% respectively for M$\simeq$1.5 GeV/c^2.

Next the authors include the contribution of DY dimuon from the annihilation of

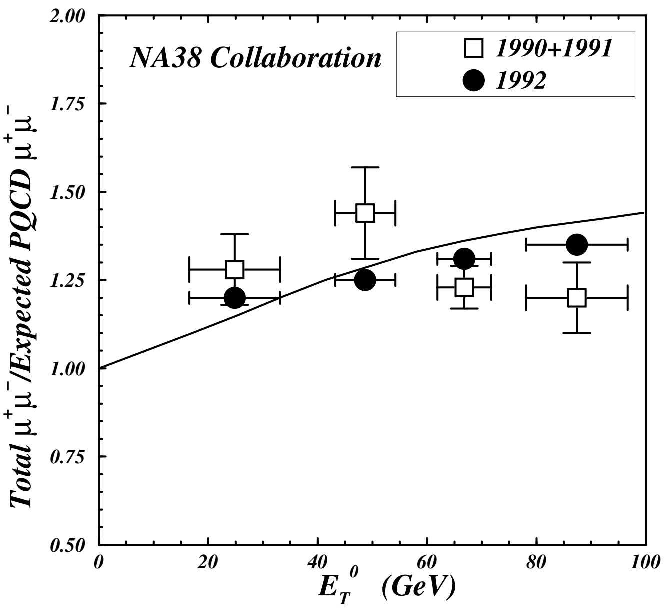

Figure 7.9: *Ratio of the total opposite-dimuon yield in 200 A GeV/c S-U collisions as measured by NA38 and expected from pQCD. The full line represents the same ratio as calculated in the frame of the model developed in ref.[15]. The ratio is plotted against the transverse energy E_T of the collision.*

partons which still have to hadronise, the so called primordial or pre-resonance $q\overline{q}$ annihilation. This is done considering that the secondary DY production can take place before the hadron formation time $\tau_F \approx$ 1 fm has elapsed. If secondary interactions are allowed for τ >0.5 fm, the predicted enhancement in the mass range 1.5< M <2 GeV/c^2 is in quite good agreement with the excess measured in the IMR region.

The authors point out that perturbative calculations cease to be totally reliable for M<2 GeV/c^2 and should not be trusted when M<1 GeV/c^2.

In the above described model the meson-baryon interactions are responsible for a fraction ≥90% of the produced secondary DY. Therefore, as the authors themselves conclude, the relative importance of this secondary dilepton source should *linearly increase* with the multiplicity of pions produced in the collision, in clear disagreement with the finding of the present work.

7.4.5 Comparison with the HELIOS/3 results

The HELIOS/3 experiment[17] at the CERN SPS has measured the dimuon production in the low and intermediate mass regions in 200 A GeV/c p-W and S-W

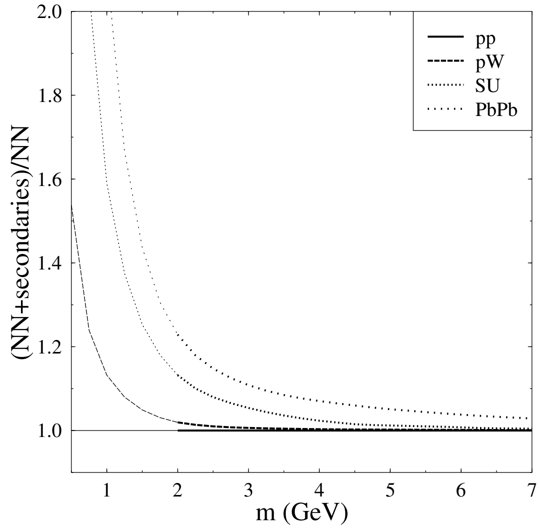

Figure 7.10: *Mass spectra of the dilepton produced in primary and secondary hadronic collisions normalized to the dileptons produced in primary nucleon-nucleon scattering only. The ratio is shown for different colliding systems, pp, 200 GeV/c p-W, 200 A GeV/c S-U and 160 A GeV/c Pb-Pb and for y_{cms}=0.5. The thinner parts of the lines indicate the mass region where perturbative calculations cease to be completely reliable[16].*

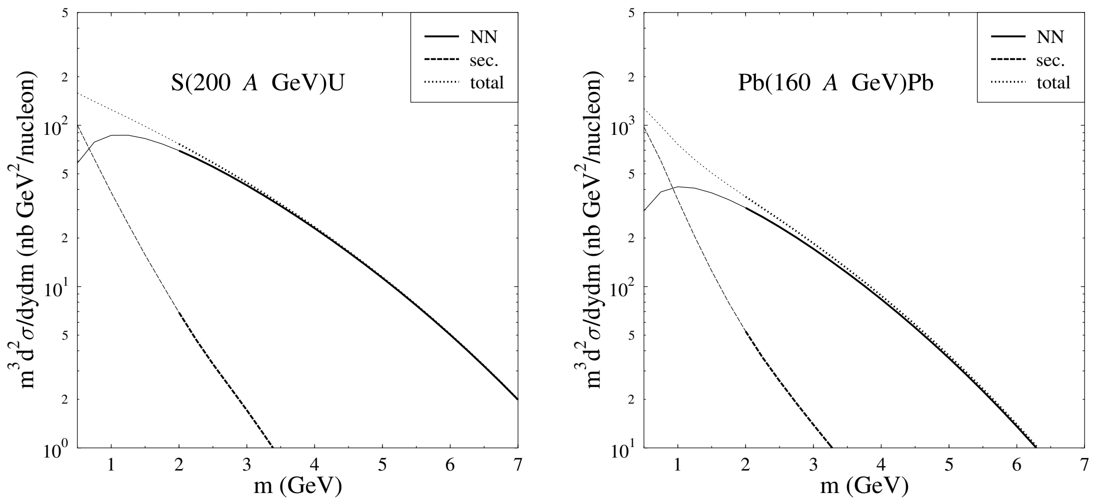

Figure 7.11: *Differential DY cross section per unit rapidity at y_{cms}=0.5. The calculation has been performed for the 200 A GeV/c S-U (left) and 160 A GeV/c Pb-Pb (right) 10% most central collisions. The shape of the different contributions to the total DY cross section are shown. The contribution of the pre-resonance DY production is not shown. The thinner part of the lines indicated the mass region where perturbative calculation cease to be completely reliable[16].*

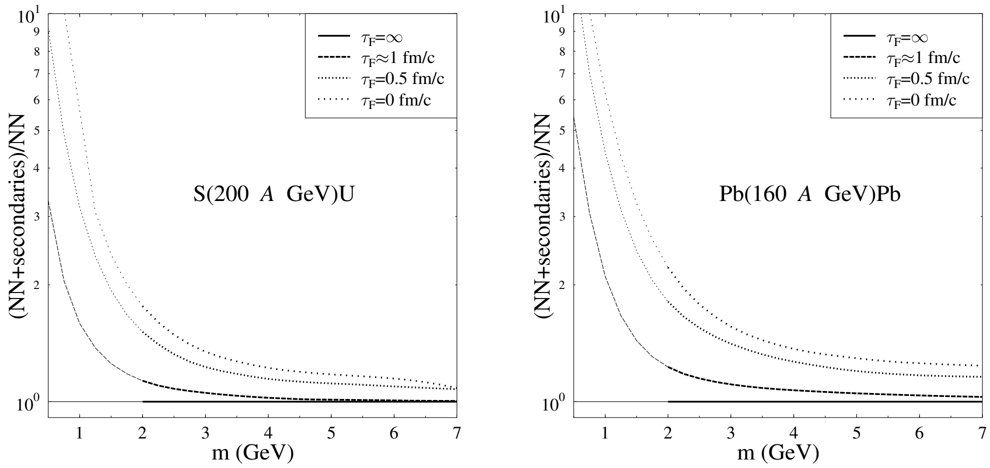

Figure 7.12: *Mass spectra of the dilepton produced in primary and secondary hadronic collisions normalized to the dileptons produced in primary nucleon-nucleon scattering only. Preresonance DY production is also taken into account varying the hadron formation time. The ratio is shown for 200 A GeV/c S-U (left) and 160 A GeV/c Pb-Pb (right) collisions and for y_{cms}=0.5. When τ_F=0.5, the dilepton enhancement amounts to a factor 3 in Pb-Pb collisions and to a factor 2 in S-U collisions. The thinner parts of the lines indicate the mass region where perturbative calculations cease to be totally reliable[16].*

collisions. The experiment was not originally designed to measure the dimuon production in the IMR region, but the amount of data collected in that region of mass were large enough to motivate the search for a dimuon enhancement both in the low and in the intermediate mass regions. The experiment covers the rapidity interval 3.0< y <7.0. The SW data have been grouped in 6 different classes corresponding to different values of the charged particle multiplicity. The charged particle multiplicity was measured in the pseudorapidity range 3.7< η <5.5. Three more classes have also been defined, the minimum bias class, constructed from all multiplicy classes, the peripheral event class, corresponding to the sum of classes 1 and 2, and the central event one, corresponding to the multiplicity classes 3÷6. The combinatorial background contribution has been determined similarly to what has been done in the present work. For 200 A GeV/c S-W and p-W collisions the calculated R_{BCK} factors are R_{BCK}=1.14±0.02 and R_{bck}=1.57±0.10 respectively. Both values are large if compared to the result of the present thesis; this difference is due to the different acceptance of the spectrometer; furthermore, the apparatus of HELIOS/3 presented different acceptances for positive and negative muons and no image cut was implemented[23].
The intermediate mass region has been analysed in two different ways. First, a direct comparison has been drawn between the p-W and the S-W data normalized to their respective charged particle multiplicities. In the second type of analysis, only

the IMR has been studied and reproduced with the superposition of the known contributing processes. No fit was performed. This second approach is somewhat more similar to the approach we used in the present work. The expected contributions are the tails of the low mass vector mesons, ρ, ϕ, ω, the DY muon pairs and dimuons from the semi-leptonic decay of charmed mesons. The open charm dimuon mass spectrum has been determined using PYTHIA 5.6, whilst the expected open charm dimuon contribution in S-W interactions has been computed from the cross section measured by NA38 in p-W collisions at 200 GeV/c, $\sigma^{c\bar{c}}$=(8.2±0.2) $\mu b/nucleon$. The DY mass shape was determined with PYTHIA 5.6, tuning the intrinsic k_T value in order to get the best reproduction of the experimental p_T distribution. The DY cross section expected in p-W and S-W collisions at 200 GeV/c has been calculated in the frame of the naif parton model, i.e., no dependence on the scale Q^2 has been included (see chapter 1), and then multiplied by a common K_{DY}=2.5±0.5. The cross section for DY production has been calculated in the kinematic range defined by -1< x_F <1 and 1≤ M ≤4 GeV/c^2; this implies that no additional cuts on $cos\theta$ has been applied. Notice that a direct extrapolation of the DY contribution from the high mass region was not feasible because of lack of data. The expected dimuon contribution from the above listed sources have then been normalized to the charged multiplicity, as done for the experimental data.

The excess is then given as the ratio D/S of measured and expected sources in the two mass regions 1.35< M <2.5 and 1.6< M <2.5 GeV/c^2. Only the multiplicity classes 3,4,5,6 are used, because of the little statistics collected in the more peripheral ones. Of the total error on the D/S ratio, 70-80% comes from the data whilst 20% comes from the calculated expected sources. The D/S ratio is affected by a ≈ 20%-30% incertitude for the mass region 1.6< M <2.5 GeV/c^2 and 10%-20% incertitude for the wider mass region range. In fig.7.13 the measured D/S ratio is plotted against the charged multiplicity for the two indicated IMR ranges.

The ratio D/S is not immediatly comparable with the open charm enhancement given in the present work. In fact it is in general very difficult to compare the D/S ratios measured by experiments covering different kinematic domains. The comparison between our results and HELIOS/3 can thus be only qualitative. The HELIOS/3 Collaboration concludes that the measured excess linearly depends on the charged particle multiplicity. It is actually difficult to agree with such conclusion, since only the most central bins have been analyzed and the bin number 3, although included in the final analysis, still presents a large statistical incertitude. On the overall, it is reassuring that the HELIOS/3 Collaboration indipendently measures an excess in the IMR region, qualitatively confirming the results of the NA38/NA50 Collaboration.

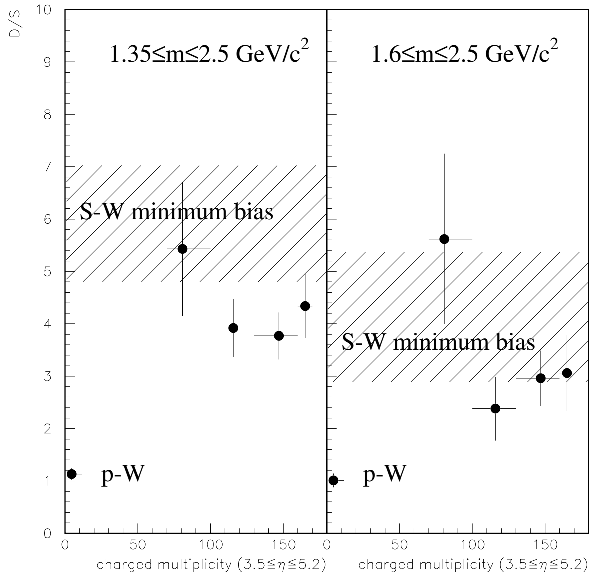

Figure 7.13: *The HELIOS/3 D/S ratio as a function of the charged multiplicity. The charged multiplicty has been measured in the pseudorapidity interval 3.5≤ η ≤5.2. The shaded area corresponds to D/S=5.91±1.11 and 4.13±1.24 as measured on the minimum bias class of events.*

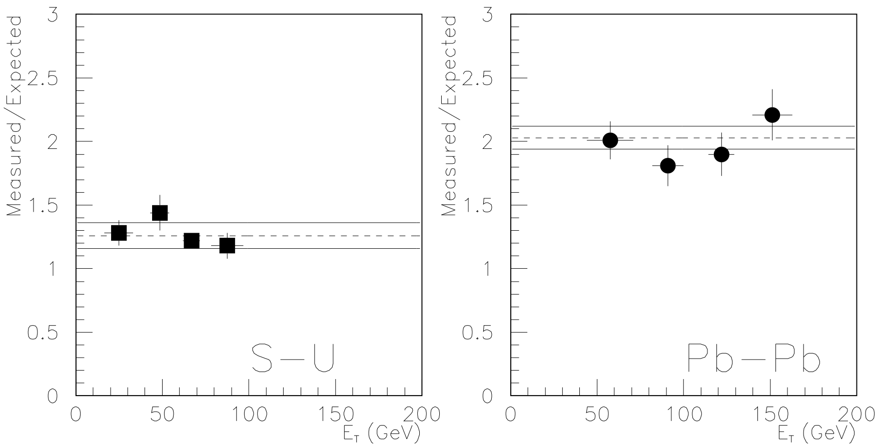

Figure 7.14: *Centrality dependence of the excess in 200 A GeV/c S-U (1992, NA38) and 158 A GeV/c Pb-Pb collisions (1995, NA50) as presented at QM'96 by the NA38/NA50 Collaboration[18].*

7.4.6 Comparison with the NA38/NA50 previous results

The NA38/NA50 Collaboration at QM'93[22] presented the results of the analysis of the 200 A GeV/c SU data whereas the results of the analysis of the low statistics 158 A GeV/c PbPb (1995) data were presented at QM'96[18]. The excess was measured in the form of the D/S ratio and plotted as a function of the transverse energy E_T, as shown in fig.7.14 Qualitatively, the QM'96 data do not disagree with the present finding when the main differences in the two performed analysis are taken into account. When the SU and PbPb sets of data were analysed, a common R_{BCK} factor equal to 1 for all centrality bins and both systems was assumed. We now know that this is not correct. If, for instance, a larger R_{BCK} factor had been assumed for the more peripheral PbPb bin, the quadratical dependence of the excess on the collision centrality would have been more evident. Notice however that the D/S presented at QM'96 for the PbPb set of data already suggested a stronger than linear increase of the excess with centrality.

7.5 Conclusion

The NA38/NA50 data collected in 450 GeV/c p-A, 200 A GeV/c S-U and 158 A GeV/c Pb-Pb collisions have been analysed. The dimuon mass spectra in the IMR are well described by a superposition of dimuons from charmed meson (and baryon) semi-leptonic decays and DY, after combinatorial background subtraction. The combinatorial background subtraction has been performed calculating the contribution of the charge correlated background with the help of a specifically developed Monte-Carlo chain. The dimuon production from open charm in S-U and Pb-Pb interactions, normalized to the pA results, is enhanced with respect to leading order pQCD calculations, where the open charm production is assumed to scale with $A \times B$. A factor $\simeq 1.6$ enhancement is found in central S-U collisions and a factor $\simeq 3$ in central Pb-Pb. The analysis of the intermediate mass region p_T spectra provides further support to the hypothesis that the excess dimuons originate from open charm decays. The measured excess shows a marked quadratical dependence on the collision centrality. A clear theoretical understanding of the underlying physical process is still lacking but the measured centrality dependence of the excess could rule out some of the proposed interpretations.

This work, which was only very recently presented[25, 24, 26], triggered a considerable interest from the heavy-ion community, both from the theoretical and the experimental side. An example is the report prepared after the Meeting on Heavy Ion Physics at the SPS, held in September 1998, which was meant to assess the present status of the field, to list the remaining open questions and to evaluate the physics issues for which the SPS fixed target programme remains competitive in the near future. In the resulting final report, the following lines can be read : "[...] we would like to mention open charm as an area presently not covered by any of the existing experiments. Open charm production is closely related to charmonium production. There are indirect indications (by NA50) for an enhancement (compared to A^2 scaling of pp results) in open charm production. A direct measurement is needed for confirmation, and the feasibility should be seriously studied"[27].

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