Intermediate mass dimuons as a probe of open charm production in heavy-ion collisions at the SPS

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- Introduction
- Data analysis and results
- The combinatorial background
- Conclusions

Open charm in a dimuon experiment

- NA38/NA50: $\mu\mu$ production in p–A, S–U, Pb–Pb collisions
- Open charm as a dimuon source
- $D\overline{D}$
  $\to \mu^{-}$+X
  $\to \mu^{+}$+X
- Only correlated $D\overline{D}$ production at SPS energies
- Sizeable contribution in the IMR only (HMR : DY + charmonia, LMR: hadronic resonance decays)

- Problems
  - Unfold in a "safe" way the various contributions to the IMR dimuon M and p_T spectra
  - From $D\overline{D} \to \mu^{+}\mu^{-}X$ to $\sigma_{c\bar{c}}$
  - IMR = DY ($\sim$5%) + $D\overline{D}$ ($\sim$5%) + π,$K \to$ uncorrelated $\mu\mu$ ($\sim$90%)

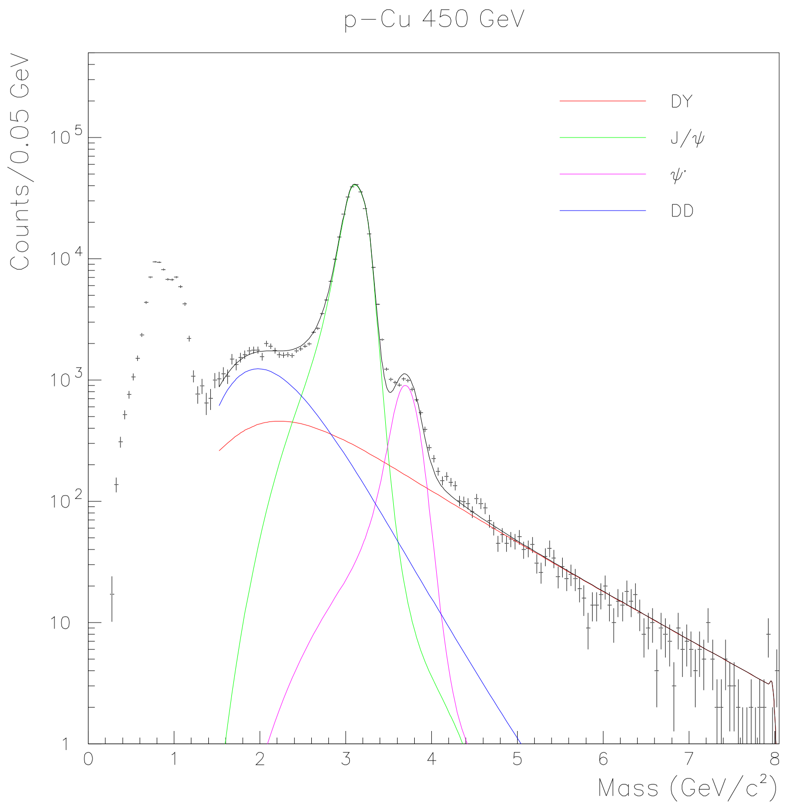
- If the background is correctly estimated
  $\to$ IMR - comb. backgr. = DY ($\sim$50%) + $D\overline{D}$ ($\sim$50%)
- IMR analysis is (mainly) a combinatorial background analysis

The analysis

- The IMR: 1.5<$M_{\mu\mu}$<2.5 GeV/c^2
  - Calculate the shapes of the invariant mass distributions for DY and open charm ($D\overline{D}$) dimuons;
  - Describe the IMR as a superposition of such shapes;
  - Constraints:
    - High mass (M>4.5 GeV/c^2) region: DY is the only dimuon source at SPS energy
    - DY scaling law is well known both in p–A and A–B collisions:
      * $\sigma^{DY}_{pA} = \sigma^{DY}_{pN} \cdot (A)^{\alpha}$
      * $\sigma^{DY}_{AB} = \sigma^{DY}_{NN} \cdot (AB)^{\alpha}$
      * NA38/NA50 have measured α=1.002±0.011 (Abreu et al., Phys. Lett. B410(1997) 337)
    - DY (hard process) can be used as a reference when studying $D\overline{D} \to \mu^+\mu^-$ in p–A and A–B collisions
  - Adjust the normalization of the calculated DY mass shape to reproduce the data in the high mass region → fix the DY contribution to the IMR;
  - Normalize the $D\overline{D}$ contribution fitting the measured IMR mass spectra;
  - Compare with expectations, based on the direct measurements of CERN and FNAL experiments.

The p–A data

- High–statistics pA data on four nuclear targets (Al, Cu, Ag, W), at 450 GeV incident energy.
- DY and $D\overline{D}$ production in p–A collisions are known to scale as A^{α}, with α_{DY}=$\alpha_{D\overline{D}}$=1 $\rightarrow$ $\sigma_{D\overline{D}}/\sigma_{DY}$ = *const.* vs A
- After background subtraction, perform a simultaneous fit of the IMR for the four p–A data samples:
  - Impose $\sigma_{D\overline{D}}/\sigma_{DY} = const.$ from p–Al to p–W;
  - Fit the data in the zone $1.5 < M < 8.0$ GeV/c^2, including the high mass region $\rightarrow$ calculate J/ψ and ψ' mass shapes.

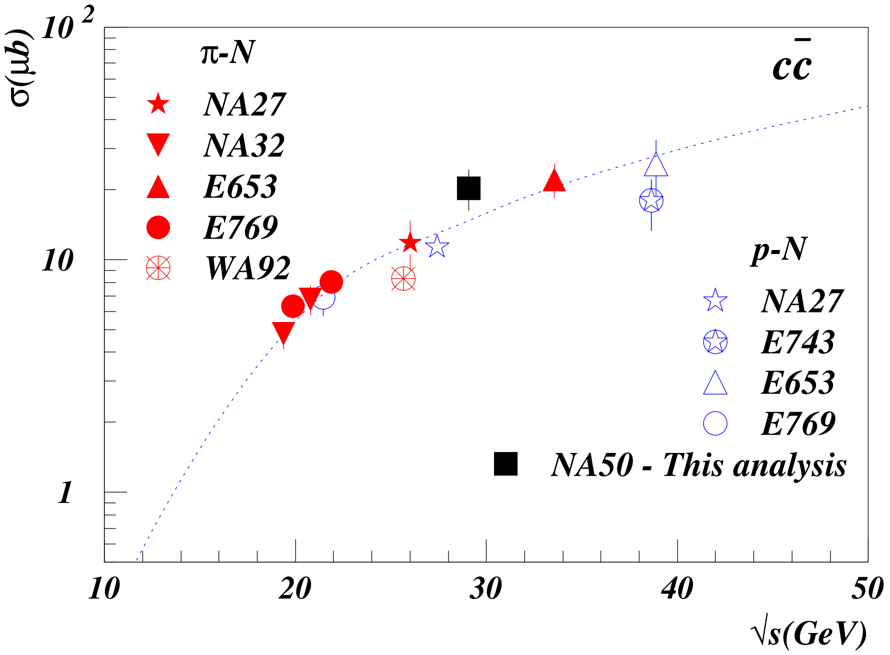


Open charm cross section

- PYTHIA has been used in this analysis to calculate the $D\overline{D}$ dimuon mass shape;
- PYTHIA reproduces, at CERN and FNAL energies (see Braun–Munzinger et al., Eur. Phys. J. C1(1998)123):
  - the open charm hadro-production $\sqrt{s}$-dependence;
  - the D-meson differential distributions;
  - the lepton distributions from D-meson semi–leptonic decays.
- Derive, from the yield of open charm decays estimated in the p–A analysis, the open charm cross section at 450 GeV;

$\sigma_{c\overline{c}}^{NN} = \frac{N_{\mu^+\mu^-}^{D\overline{D}}}{\mathcal{L}\cdot\mathcal{A}_{D\overline{D}}} \cdot (phasespace fact.) \cdot \frac{1}{B.R.(D \to \mu)^2} \cdot \frac{1}{A}$

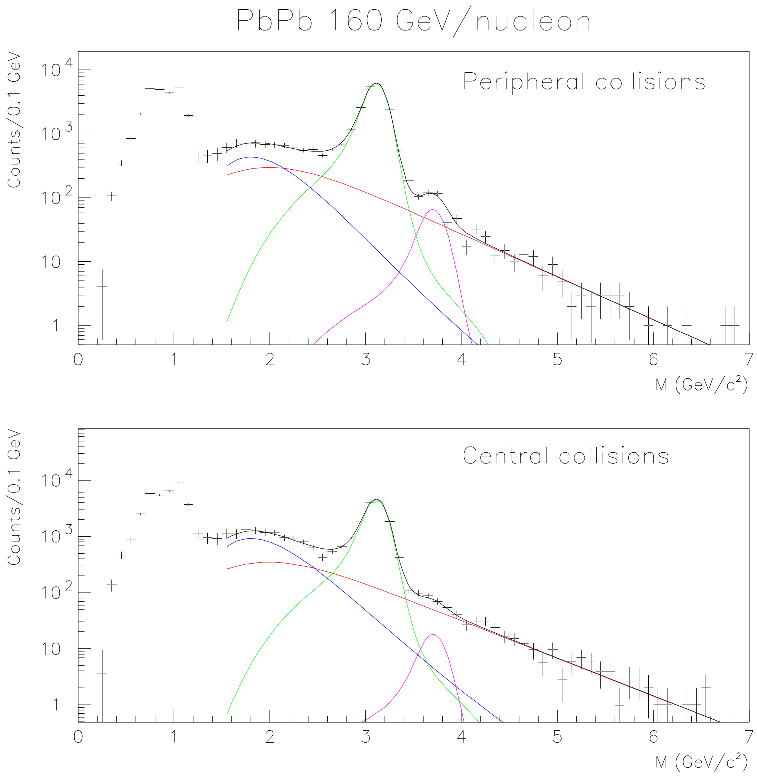
- Compare with other experiments



- The NA50 value is compatible with the results of the other experiments

S–U and Pb–Pb collisions

- Fit the mass spectra with the same procedure adopted for the p–A data samples
- No constraint on $\sigma_{D\overline{D}}/\sigma_{DY}$
- Background normalization fixed
- The DY exhibits no anomalous behaviour from p–p to Pb–Pb collisions (see Abreu et al., Phys. Lett. B410(1997)337)
- We would expect: $\sigma_{D\overline{D}}/\sigma_{DY} = const.$ vs E_T

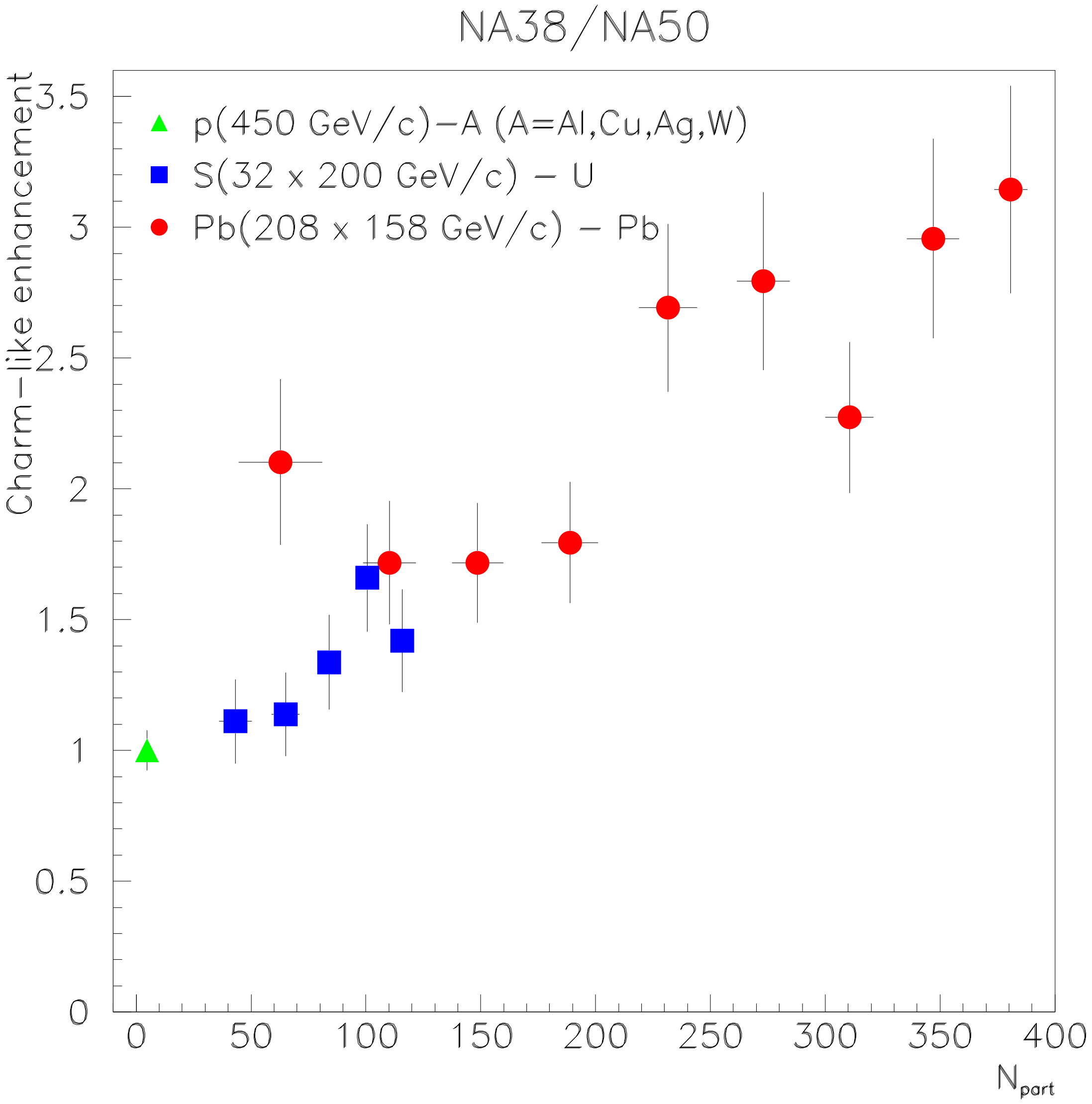


In central Pb–Pb collisions an enhancement of the open charm component, with respect to DY, is necessary in order to describe the mass spectrum $\rightarrow$ **charm–like** enhancement.

The charm–like enhancement

- Nine centrality bins for Pb–Pb and five for S–U;
- All the IMR Pb–Pb and S–U mass spectra are satisfactorily described by a superposition of DY and $D\overline{D}$ dimuons;
- For both systems the number of $D\overline{D}$ dimuons is found to increase with the centrality of the collision, with respect to DY, which is known to behave normally;
- Use the DY reference process to quantify the enhancement:
  - Calculate, for S–U and Pb–Pb, the expected $\sigma_{c\bar{c}}$, using the PYTHIA $\sqrt{s}$–dependence of the cross section, upscaled to match the NA50 p–A point;
  - Calculate, for the centrality integrated spectra, the ratio $(D\overline{D}/DY)_{expected}$, which should be a constant as a function of the centrality;
  - When looking at data for the various centrality bins:
    * $(D\overline{D}/DY)_{measured}$ is found to be always larger than $(D\overline{D}/DY)_{expected}$;
    * The ratio $\frac{(D\overline{D}/DY)_{measured}}{(D\overline{D}/DY)_{expected}}$ gives, for the various centrality bins, the enhancement E in the open charm cross section needed to describe the data.

Charm–like enhancement vs N_{part}: p–A, S–U, Pb–Pb

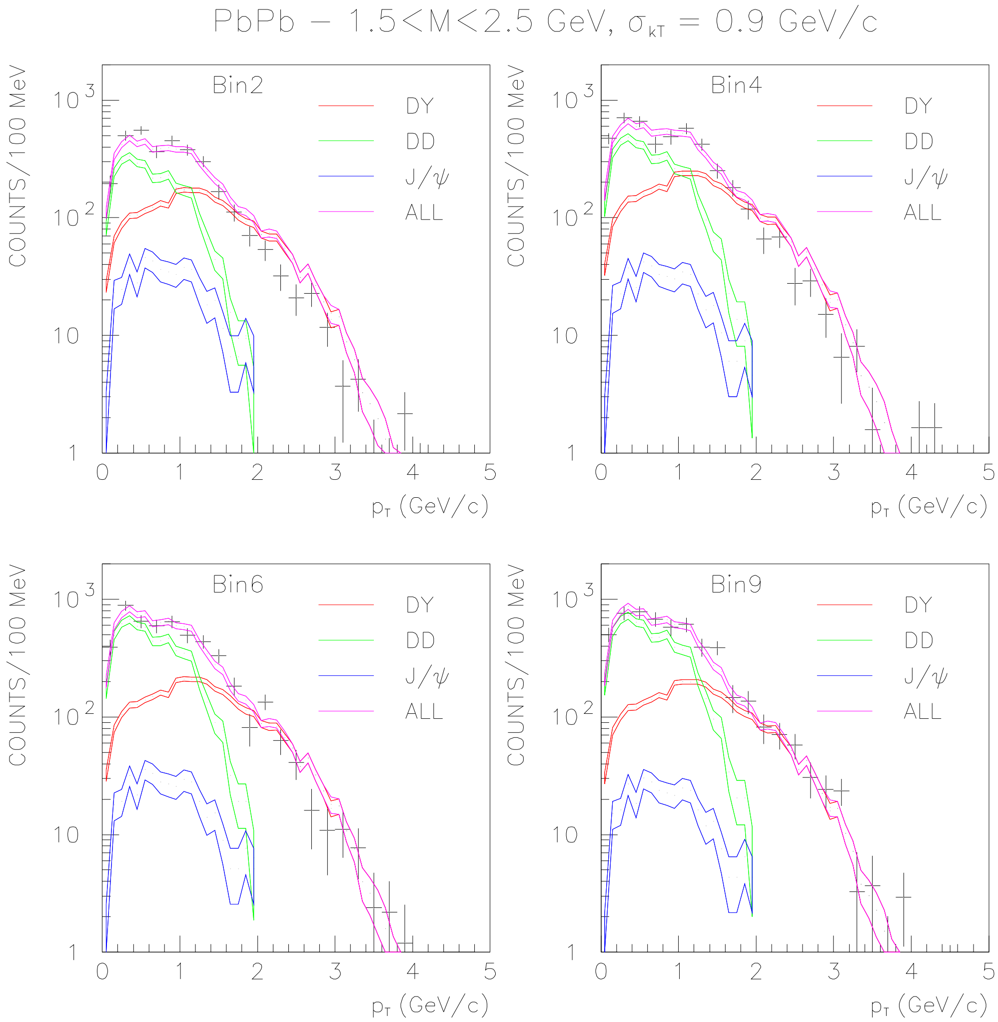


(E.Scomparin et al., NA50 coll., CERN-EP/98-188)

- Charm–like enhancement: a factor 3 in central Pb–Pb with respect to p–A
- Linear increase with N_{part}

p_T distributions of the Pb–Pb IMR events

• Are the distributions of the other kinematical variables of the IMR dimuons compatible with the hypothesis of open charm enhancement ?

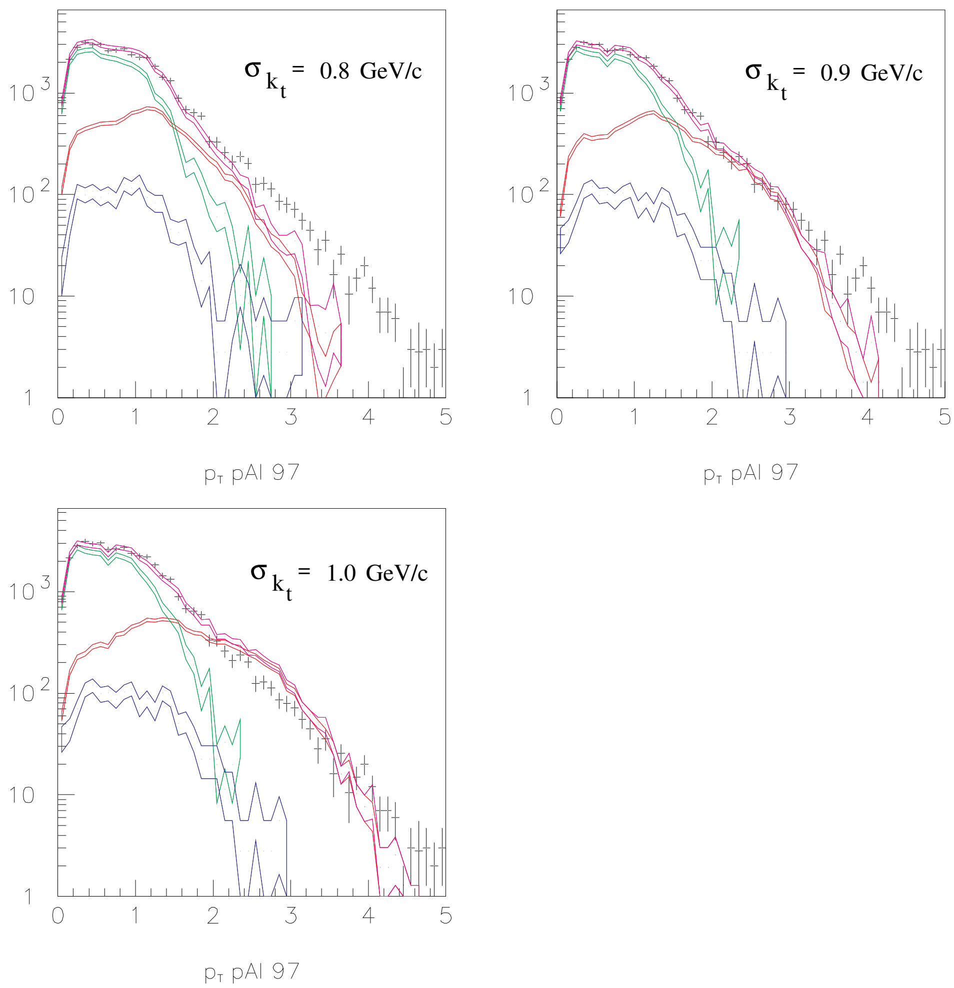


• p_T shapes for DY, $D\overline{D}$, J/ψ from PYTHIA + simulation of the detector;

• Absolute normalizations from the fit of the mass spectra;

• Independent evidence that the enhancement is due to a charm–like component.

p_T distributions of the p–A IMR events



• p_T shapes for DY, $D\overline{D}$, J/ψ from PYTHIA + simulation of the detector (DY=red, $D\overline{D}$=green, J/ψ=blue, $DY + D\overline{D} + J/\psi$=magenta);

• Absolute normalizations of the various sources from the fit of the mass spectra;

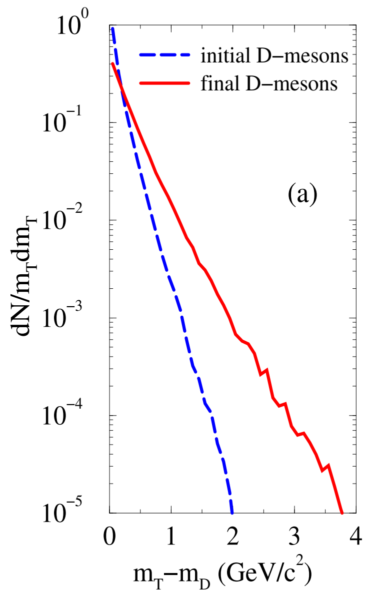
• Tuning the σ_{k_T} in PYTHIA to 0.9 GeV/c we get a good description of the p–A p_T spectra up to $p_T \sim 4$ GeV/c

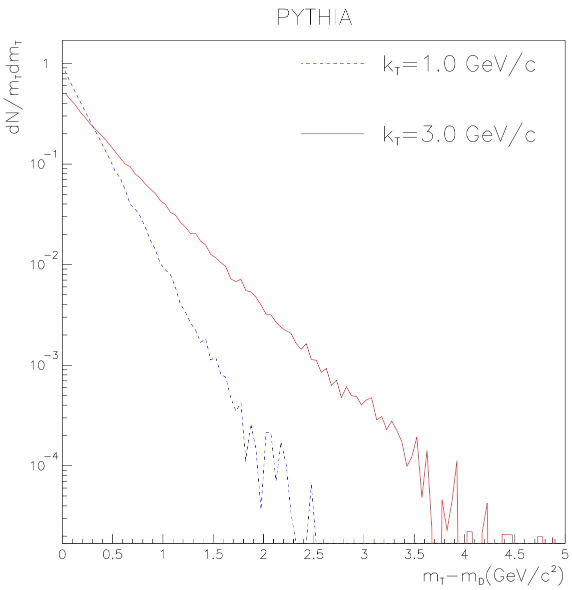
D-meson rescattering and differential distributions

• It has been claimed (Z.Lin and X.N. Wang, Phys.Lett. B444(1998) 245) that D-meson rescattering in nuclear matter can broaden the m_T spectrum of charmed mesons, enriching the part of the phase space covered by NA50, without modifying too much the shape of the $D\overline{D}$ mass spectra.

• Are our p_T spectra sensitive to the strong D-meson m_T broadening foreseen by these authors?

• Introduce in the analysis, when simulating the open charm dimuon p_T spectrum, the m_T broadening by a proper increase, inside PYTHIA, of the intrinsic transverse momentum of the incoming partons

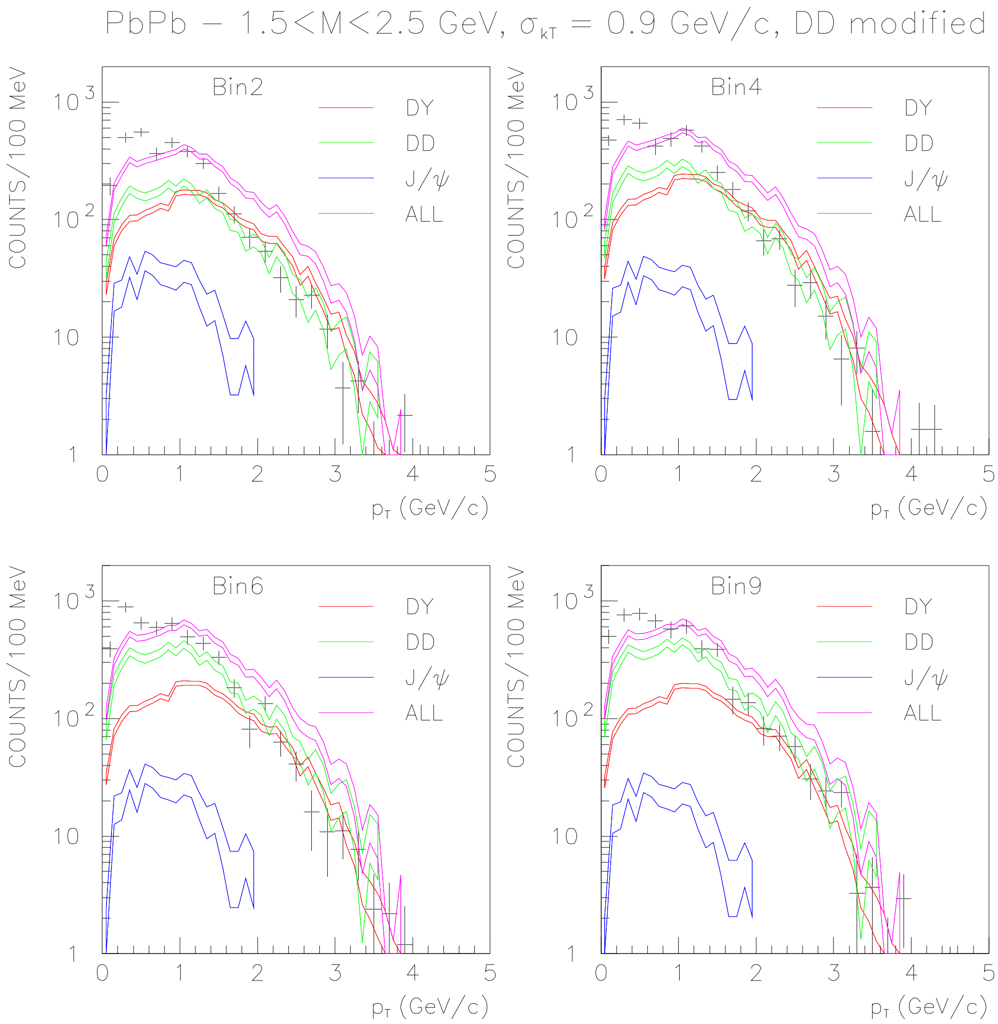




• Calculate, starting from the broadened D-meson distribution, the mass and p_T spectrum of $D\overline{D}$ dimuons in the acceptance of the apparatus

p_T distributions of the Pb–Pb IMR events (2)

- p_T shapes for $D\overline{D}$ include now the possible effect of a strong rescattering of D-mesons in nuclear matter

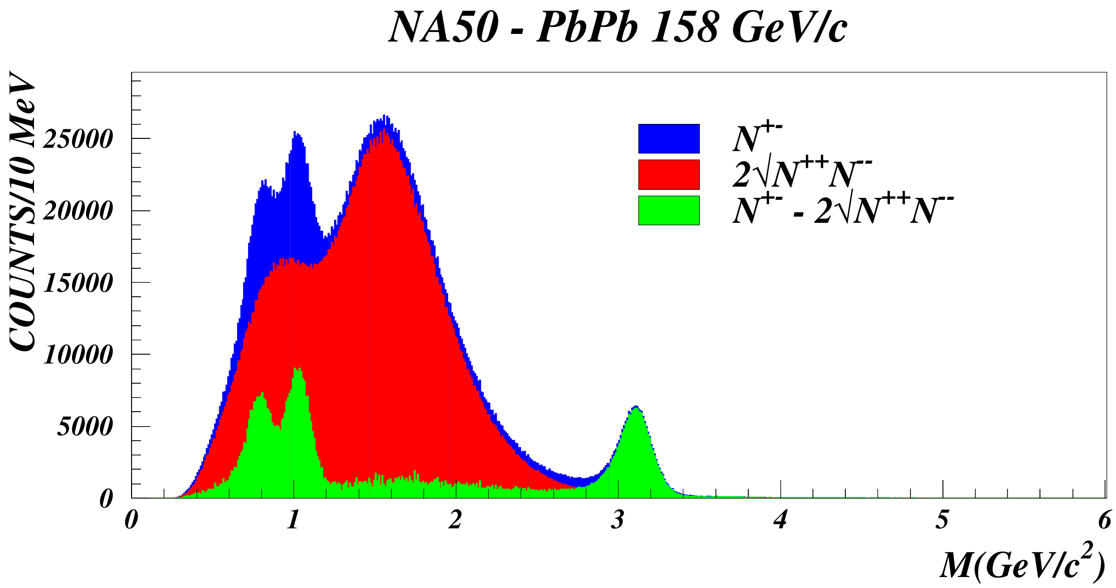


- The data exclude any significant modification of $D\overline{D}$ spectra in PbPb collisions in any centrality bin.

The combinatorial background

- Can in principle be estimated through the simple formula:

$$\frac{dN^{bck}}{dM} = 2R\sqrt{\frac{dN^{++}}{dM}\frac{dN^{--}}{dM}}$$



Difficulties:

- R=1 only if π,K multiplicity is high and no charge correlation exists

$\longrightarrow$ p–A or peripheral A–B could yield $R > 1$

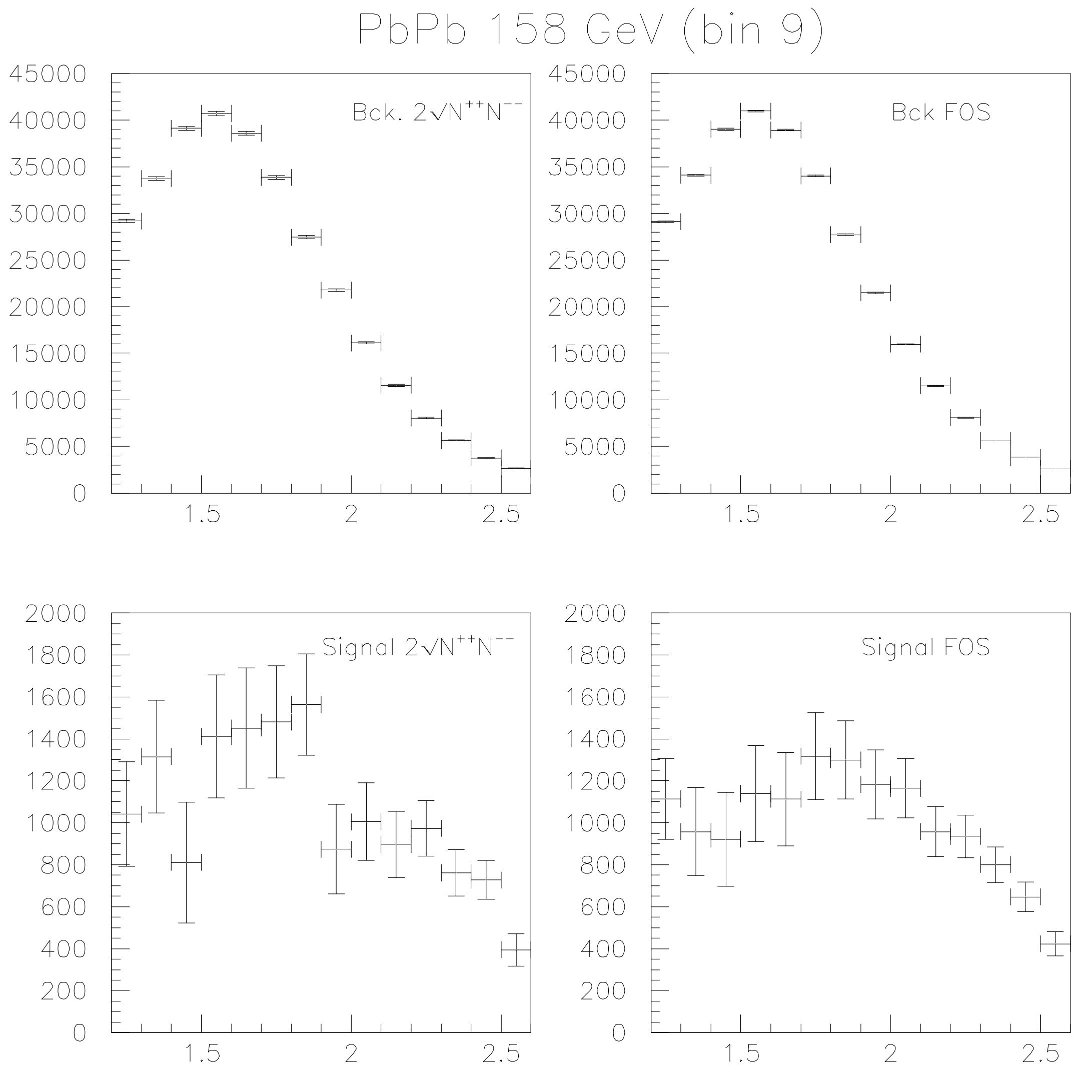
- $N^{bck}/N^{+-} \sim 80\% - 95\%$ (pA – PbPb) ("CERES-like" situation)

The combinatorial background: strategy

- We need:
  - An accurate knowledge of the mass shape of the combinatorial background, to avoid large errors on the background subtracted spectra
    - We can use a mixed event method, i.e.:
      - Store, for like-sign events, the single muon distributions for separated subclasses of the data set (magnetic field, position of subtarget, centrality bin);
      - Get the mass shape of the background combining positive and negative muons making all the possible pairs
  - An estimation of the charge correlation effects which can affect the absolute normalization of the background (expressed through the R-factor).
    - We can use a Monte-Carlo simulation, i.e.:
      - Use an event generator (VENUS) to generate p–A, S–U and Pb–Pb collisions;
      - Let produced π and K decay to muons;
      - Calculate decay probability, within the experimental set–up, for each meson
      - Make *all* possible $\mu\mu$ combinations (dimuons), assigning a *weight* to each of them, proportional to the decay probability
      - Introduce detector effects, to reject dimuons out of the experiment acceptance
      - Get R as: $R = \frac{N^{+-}_{sim}}{2\sqrt{N^{++}_{sim} N^{--}_{sim}}}$
  - How to perform a check of the Monte-Carlo results ?
    - NA38 has *measured* the R-factor for pW collisions at 200 GeV incident energy; try to compare the results there.

The mixed event method: results

- Useful when background level is very high, as in central PbPb collisions



- The mixed-event method (FOS, Fake-Opposite-Sign) gives a smoother mass shape for the background subtracted spectrum

Can one measure the background R-factor?

• Compare, for the same reaction, the mass spectra obtained with two set-up, very different in what concerns their hadron absorption properties

→ The signal does not change

→ The combinatorial background is higher in the set–up with the shorter hadron absorber

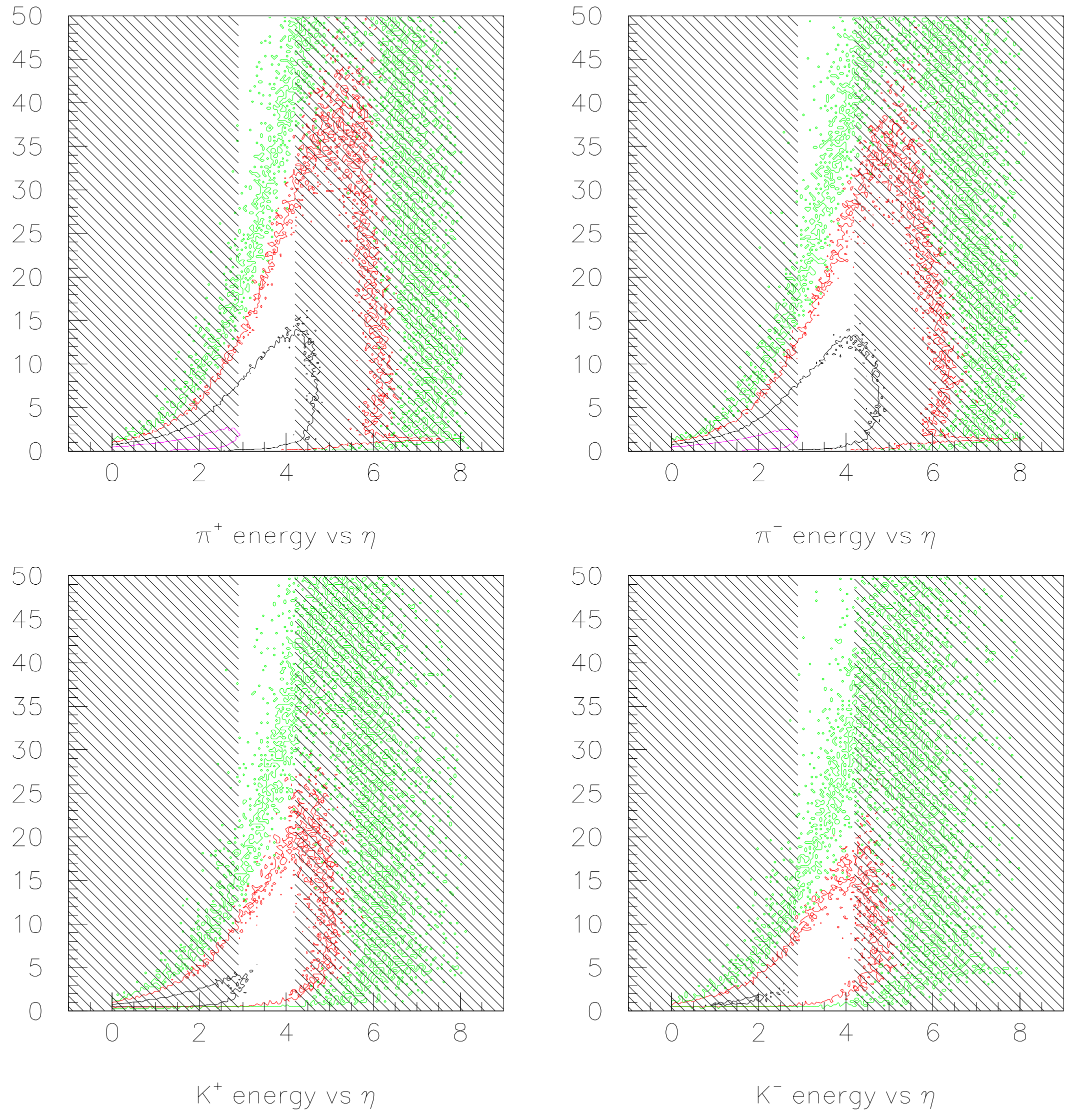
• Fit simultaneously the mass distributions, leaving the R-factor as a free parameter

→ NA38 gets, for pW collisions at 200 GeV, R=1.19±0.04
(C. Lourenço, PHD thesis, Lisbon 1995)

• Can the Monte-Carlo reproduce this result?

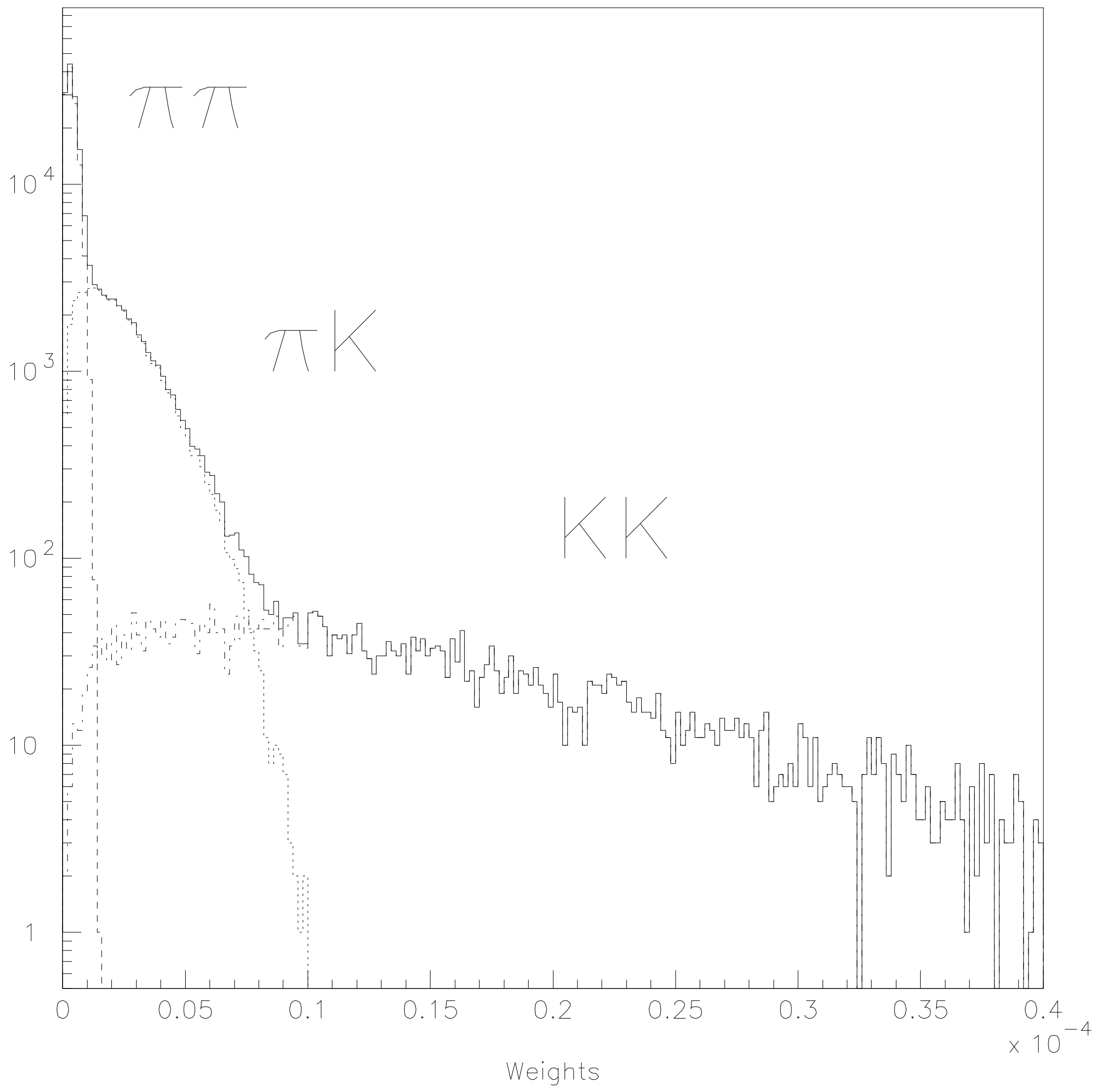
The R-factor (1)

- Event generation: VENUS
- NA50 geometrical acceptance $\sim 3 < \eta < 4$



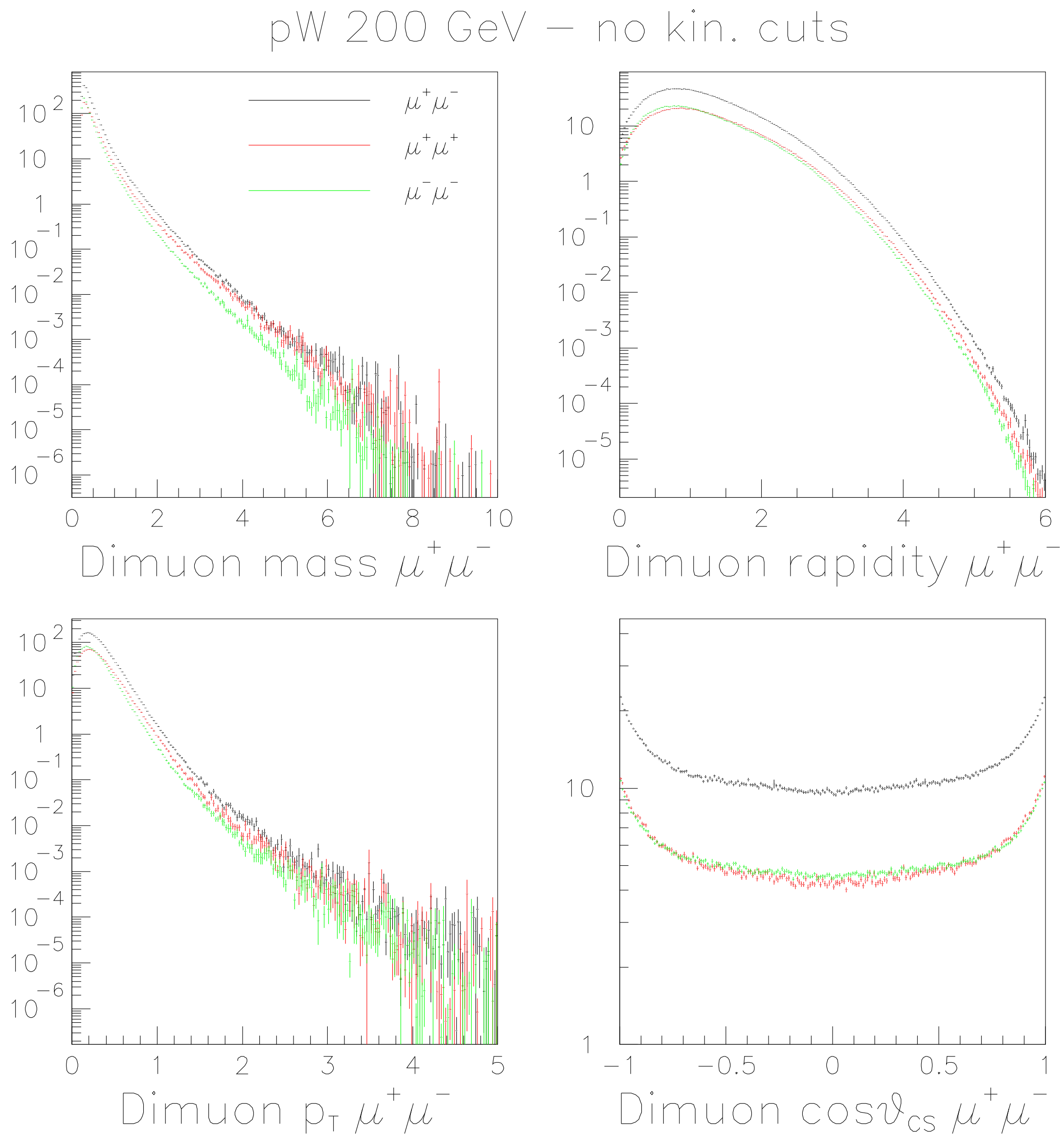
The R-factor (2)

- Decay probability to muons for meson pairs: $P_{\mu_1\mu_2} = P_{\mu_1} \cdot P_{\mu_2}$
- $P_{\mu_i}(x_0) = 1 - e^{M\,x_0\,\Gamma/|\overrightarrow{p}_i|}$



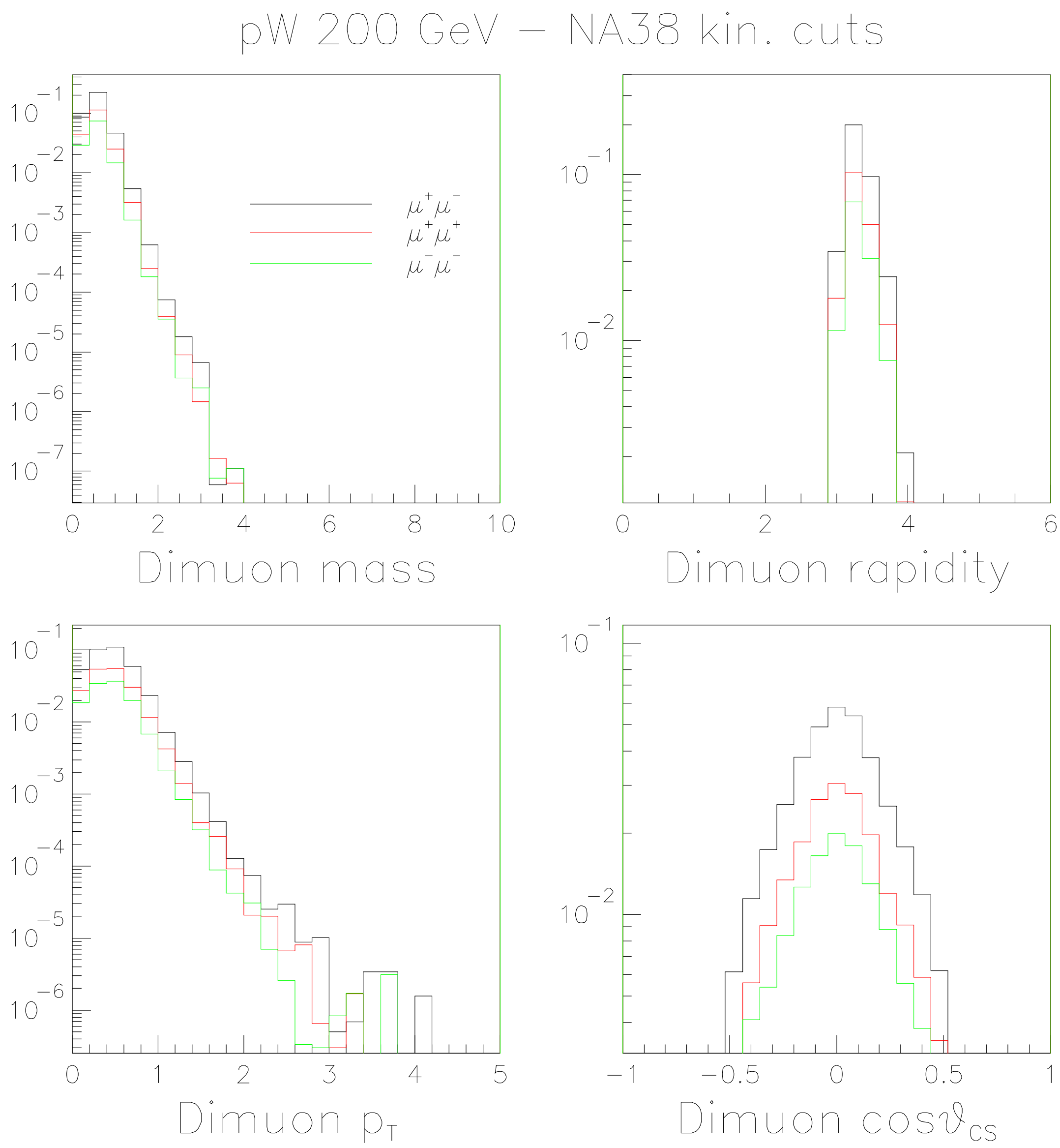
The R-factor (3)

- Simulated mass spectra for like-sign and opposite-sign background dimuons, before applying detector cuts



The R-factor (4)

• Simulated mass spectra for like-sign and opposite-sign background dimuons, after applying detector cuts

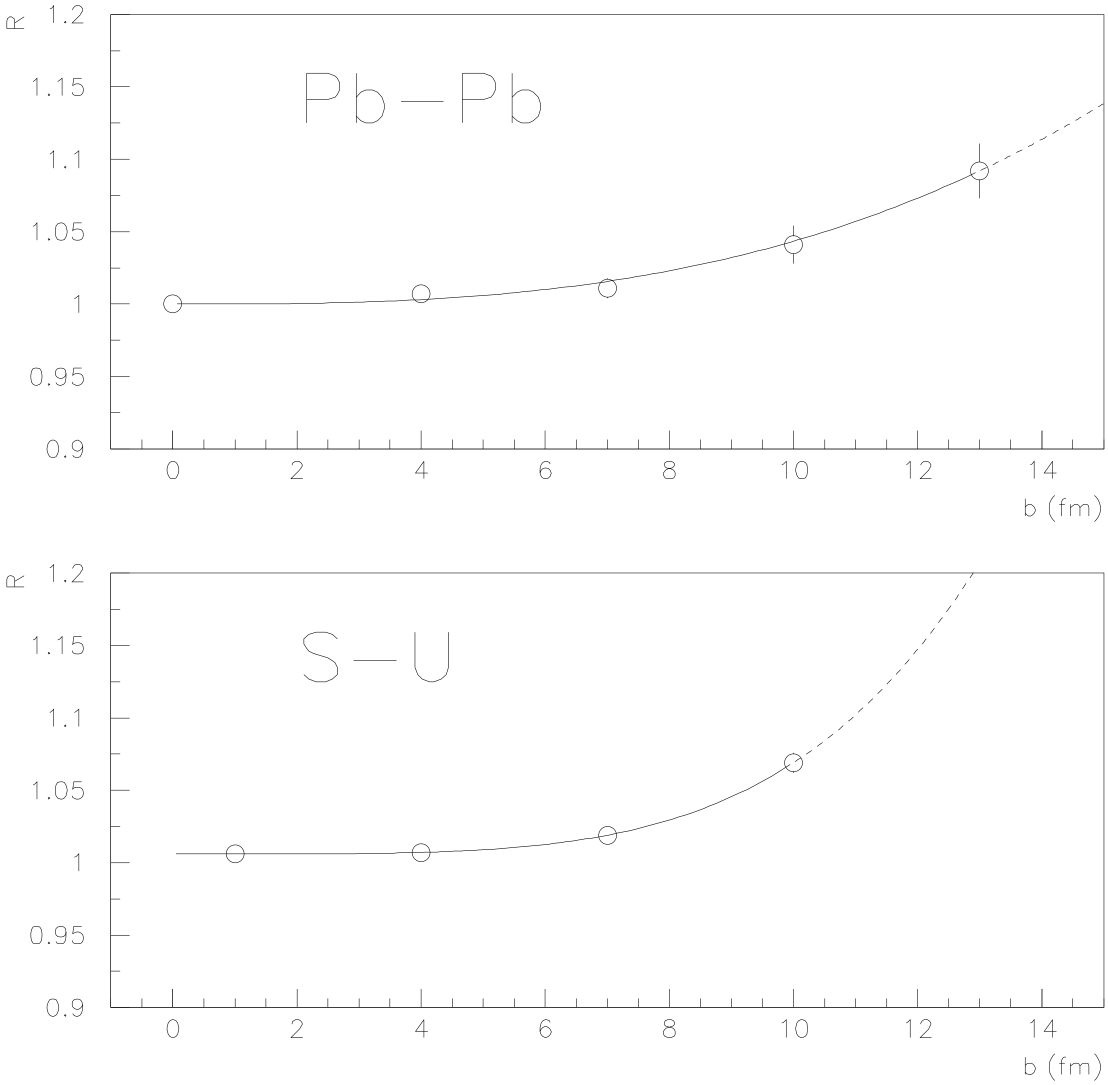


Get R as:

$$R_{sim} = \frac{N^{+-}_{sim}}{2\sqrt{N^{++}_{sim} N^{--}_{sim}}}$$

We get: $R_{sim} = 1.21 \pm 0.02$ to be compared with $R_{meas} = 1.19 \pm 0.04$

R vs impact parameter b in AB collisions



- Get for each centrality class, containing N events:

$$\langle R\rangle = \frac{1}{N}\int \frac{dN}{db}R(b)db$$

- $\langle R\rangle$>1 for peripheral collisions: e.g. $\langle R\rangle$=1.035 for Pb–Pb bin 1 ($\langle b\rangle$=10.7 fm)

R-factor: summary of results

System	Energy (GeV/c)	$R \pm \sigma_R$ (low intensity)	$R \pm \sigma_R$ (I=2.5·10^9p/burst)	$R \pm \sigma_R$ (measured)
pW	200	1.21±0.02		1.19±0.04
pAl	450	1.19±0.05	1.06±0.02	
pCu	450	1.26±0.04	1.06±0.02	
pAg	450	1.21±0.04	1.06±0.01	
pW	450	1.21±0.03	1.05±0.01	

System	Energy (A GeV/c)	N_{part} bin	N_{part}	$R \pm \sigma_R$
PbPb	158	1	63 ± 18	1.035 ± 0.011
PbPb	158	2	110 ± 11	1.017 ± 0.003
PbPb	158	3	149 ± 11	1.010±0.002
PbPb	158	4	189 ± 12	1.006±0.001
PbPb	158	5	231 ± 13	1.003±0.000
PbPb	158	6	273 ± 11	1.001±0.000
PbPb	158	7	310 ± 10	1.001±0.000
PbPb	158	8	347 ± 11	1.000±0.000
PbPb	158	9	381 ± 7	1.000±0.000
SU	200	1	43 ± 7	1.023 ± 0.005
SU	200	2	65 ± 6	1.013 ± 0.002
SU	200	3	84 ± 5	1.009 ± 0.001
SU	200	4	101 ± 5	1.007 ± 0.000
SU	200	5	116 ± 3	1.006 ± 0.000

- For proton–nucleus and peripheral nucleus-nucleus collisions R >1

Background subtraction: discussion

• All the fits to the mass spectra have been performed keeping the background contribution fixed:

$$\frac{dN^{bck}}{dM} = 2R_{sim}\sqrt{\frac{dN^{++}}{dM}\frac{dN^{--}}{dM}}$$

with R_{sim} calculated with the above described Monte–Carlo simulation

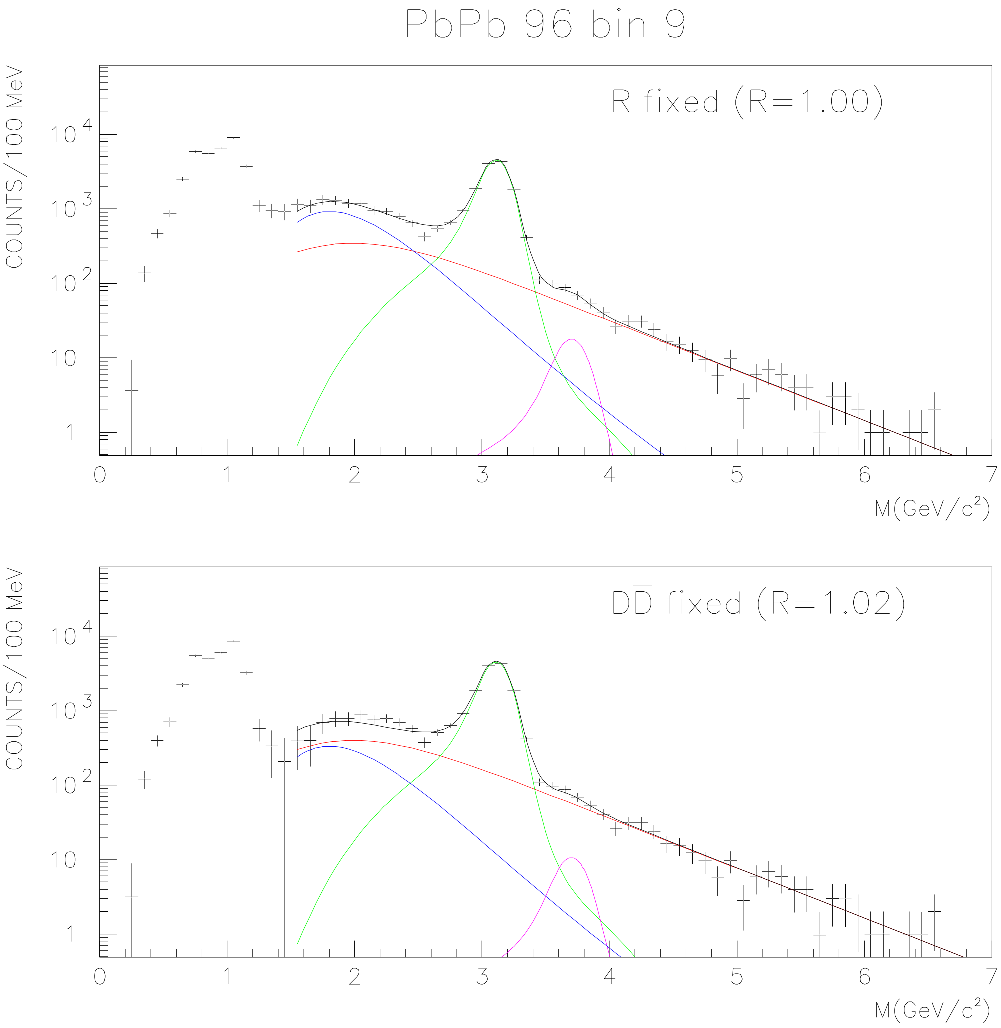
• How much are our results sensitive to the choice of the R-factor?

• Could the open charm enhancement even be due to an uncorrect subtraction of the background?

- Two possible tests:
  - Assume there is no $D\overline{D}$ enhancement, leave the background normalization free and try to fit the mass spectra, i.e. try to see if we can account for the $D\overline{D}$ enhancement by an increase of the background level
  - Assume that the multiplicity of secondary particle in peripheral S–U and Pb–Pb collisions is so large that charge correlation effects can be neglected, i.e. set all the R-factors to 1. Is the $D\overline{D}$ enhancement still there?

The unsubtracted background hypothesis

- Assume there is no $D\overline{D}$ enhancement, i.e. fix the open charm contribution at the expected level
- Leave the background normalization free, i.e. let combinatorial background account for the excess dimuons

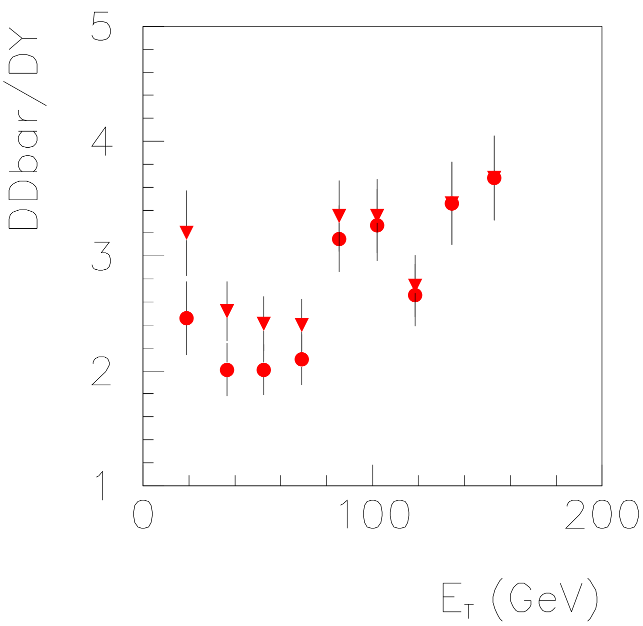


→ Background becomes too high around M=1.4 GeV/c^2

→ Worse description of the IMR: χ^2 higher by a factor ∼5

The R=1 hypothesis

• Compare, for Pb–Pb collisions, the $D\overline{D}/DY$ values (which are proportional to the $D\overline{D}$ enhancement factor), as a function of centrality, for the standard analysis (R obtained by simulation, circles) and when fixing R=1 everywhere (triangles)



(C. Soave, PHD thesis, Torino 1999)

When R=1 everywhere, there is, for Pb-Pb, a larger (by about 20%) $D\overline{D}$ contribution for peripheral collisions, leading to a modest flattening of the centrality dependence of the enhancement. For S–U collisions the effect is even smaller, due to the smaller background level.

Conclusions

• The NA50 IMR p–A data allow to indirectly derive an open charm cross section which agrees with other (direct) measurements, performed at CERN and FNAL in the same energy range.

• A description of S–U and Pb–Pb spectra (both in mass and p_T) can be achieved supposing that open charm production is enhanced in nucleus–nucleus collisions.

• A strong rescattering of the charmed mesons in the nucleus seems to be excluded by our p_T data.

• The combinatorial background contribution can be safely estimated and subtracted.

• The results of this indirect measurement of open charm production in nucleus–nucleus collisions motivate more accurate measurements, to be performed either in a limited background environment and/or by directly reconstructing the D-meson decay.