Results on open charm from NA50

M.C. Abreu, B. Alessandro, C. Alexa, R. Arnaldi, M. Atayan, C. Baglin, A. Baldit, M. Bedjidian, S. Beole, V. Boldea, et al.

Results on open charm from NA50

M Masera[5*] for the NA50 Collaboration: M C Abreu[6†], B Alessandro[10], C Alexa[3], R Arnaldi[10], M Atayan[12], C Baglin[1], A Baldit[2], M Bedjidian[11], S Beolè[10], V Boldea[3], P Bordalo[6‡], A Bussière[1], L Capelli[11], L Casagrande[6§], J Castor[2], T Chambon[2], B Chaurand[9], I Chevrot[2], B Cheynis[11], E Chiavassa[10], C Cicalò[4], T Claudino[6], M P Comets[8], N Constans[9], S Constantinescu[3], A De Falco[4], N De Marco[10], G Dellacasa[13], A Devaux[2], S Dita[3], O Drapier[11], L Ducroux[11], B Espagnon[2], J Fargeix[2], P Force[2], M Gallio[10], Y K Gavrilov[7], C Gerschel[8], P Giubellino[10], M B Golubeva[7], M Gonin[9], A A Grigorian[12], J Y Grossiord[11], F F Guber[7], A Guichard[11], H Gulkanyan[12], R Hakobyan[12], R Haroutunian[11], M Idzik[10‖], D Jouan[8], T L Karavitcheva[7], L Kluberg[9], A B Kurepin[7], Y Le Bornec[8], C Lourenço[5], P Macciotta[4], M Mac Cormick[8], A Marzari-Chiesa[10], M Masera[5*], A Masoni[4], S Mehrabyan[12], M Monteno[10], A Musso[10], P Petiau[9], A Piccotti[10], J R Pizzi[11], F Prino[10], G Puddu[4], C Quintans[6], S Ramos[6‡], L Ramello[13], P Rato Mendes[6], L Riccati[10], A Romana[9], I Ropotar[5], P Saturnini[2], E Scomparin[10] S Serci[4], R Shahoyan[6¶], S Silva[6], M Sitta[13], C Soave[10], P Sonderegger[5‡], X Tarrago[8], N S Topilskaya[7], G L Usai[4], E Vercellin[10], L Villatte[8] and N Willis[8].

[1] LAPP, CNRS-IN2P3, Annecy-le-Vieux, France
[2] LPC, Univ. Blaise Pascal and CNRS-IN2P3, Aubière, France
[3] IFA, Bucharest, Romania
[4] Università di Cagliari/INFN, Cagliari, Italy
[5] CERN, CH-1211 Geneva 23, Switzerland
[6] LIP, Lisbon, Portugal
[7] INR, Moscow, Russia
[8] IPN, Univ. de Paris-Sud and CNRS-IN2P3, Orsay, France
[9] LPNHE, Ecole Polytechnique and CNRS-IN2P3, Palaiseau, France
[10] Università di Torino/INFN, Torino, Italy
[11] IPN, Univ. Claude Bernard and CNRS-IN2P3, Villeurbanne, France
[12] YerPhI, Yerevan, Armenia
[13] Università del Piemonte Orientale, Alessandria and INFN-Torino, Italy

* on leave of absence from Università di Torino/INFN, Torino, Italy
† also at UCEH, Universidade de Algarve, Faro, Portugal
‡ also at IST, Universidade Técnica de Lisboa, Lisbon, Portugal
§ now at CERN
‖ now at Faculty of Physics and Nuclear Techniques, University of Mining and Metallurgy, Cracow, Poland
¶ on leave of absence from YerPhI, Yerevan, Armenia

Abstract. The NA50 and NA38 experiments have studied muon pair production in p-A and nucleus–nucleus collisions at the CERN SPS. Results on dimuons in the invariant mass region between the ϕ and the J/ψ masses (IMR) are presented. The standard sources of muon pairs in the IMR are the Drell-Yan process and the semileptonic decay of charmed mesons. A new four dimensional unfolding method is applied to the data. The p–A results are well described in terms of these known sources, which, on the contrary, fail to explain nucleus-nucleus data: an extra–yield of muon pairs is observed. Although this excess is compatible with an enhanced production of charmed hadrons, other possible sources cannot be excluded. In particular, a comparison between data and predictions from a theoretical model which calculates the production of thermal dimuons is presented in this paper.

1. Introduction

The invariant mass distribution of dimuons ($M_{\mu\mu}$) produced in hadronic interactions at SPS energies is characterized by a continuous spectrum and by peaks from two–body decays of vector mesons (ρ, ω, ϕ, J/ψ and ψ'). The study of the non–resonant part of the spectrum leads to several experimental challenges: the cross section at high mass is very low and muon pairs are produced by the overlap of various sources. Moreover the major source of muon pairs at low masses ($M_{\mu\mu} < 2\,GeV/c^2$) is the combinatorial background from charged pions and kaons decays. In this paper an analysis of dimuons in the mass interval between the ϕ and the J/ψ masses is presented. The study is performed on data collected by the NA50 and NA38 collaborations at the CERN SPS, namely p–A collisions at $450\,GeV$, S–U (NA38) at $200\,A\,GeV$ and Pb–Pb at $158\,A\,GeV$. The relevance of this intermediate mass region (IMR) arises from the fact that a thermal radiation from early and hot stages of the collision could give a detectable signal under the form of muon pairs of relatively low mass. In the IMR the contribution of low mass resonances is negligible and the other known sources are hard processes for which an evaluation is possible.

An excess of dimuons in the IMR for nucleus–nucleus collisions with respect to a linear extrapolation of the standard sources in proton induced collisions has been already demonstrated by a previous analysis of these data[1]. Moreover, the kinematical distributions of the observed excess turned out to be compatible with those expected from semileptonic decays of charmed mesons. An excess in the IMR was also found in S-W collisions by the Helios–3 experiment[2].

The analysis presented here differs from the previous one in the unfolding method. The unfolding, i.e. the procedure to go from measured quantities to physical ones, was done separately for each kinematical variable ($M_{\mu\mu}$, p_{T} Y_{CM} and $\cos\Theta_{CS}$ +). In the present analysis a 4–dimensional approach[4] allowing for correlations among the kinematical variables is adopted.

In the following, we will focus on the peculiarities of this analysis. The description of the apparatus and the data reduction together with the discussion of the charge correlation effects on the normalization of the combinatorial background can be found in ref. [1].

+ Θ_{CS} is the polar angle of one of the muons in a particular rest frame of the muon pair, known as Collins–Soper reference frame[3]

2. The analysis

Measured distributions are affected by detector effects such as acceptance and resolution. In more quantitative terms, let us define x as the set of kinematical variables used to describe a dimuon and $\Phi(x)$ as the physical distribution that has to be determined experimentally. The measurement is a finite sampling of the distribution D defined as:

$$D(x') = \int S(x'|x)A(x)\Phi(x)dx \tag{1}$$

where $A(x)$ is the acceptance and $S(x'|x)$ is the smearing function. $S(x'|x)dx'$ is the probability that a dimuon characterised by x is mapped by the apparatus in an elementary cell of size dx' centred at x'. The unfolding procedure consists in the resolution of the integral equation (1). To solve equation (1), both the smearing and the acceptance must be known. The solution of the equation (1) is based on a method proposed by W.H. Richardson[5] and, independently, by L.B. Lucy[6]. Equation (1) can be rewritten as:

$$D(x') = \int S(x'|x)A(x)\Phi(x)dx = \int S(x'|x)\Psi(x)dx \tag{2}$$

with $\Psi(x) = A(x)\Phi(x)$. The *inverse* conditional probability density $Q(x|x')dx$ can be related to $S(x'|x)$ through the Bayes theorem:

$$Q(x|x') = \Psi(x)\frac{S(x'|x)}{D(x')} \Longrightarrow \Psi(x) = \int D(x')Q(x|x')dx' \tag{3}$$

The determination of the physical distribution Ψ can be achieved iteratively. At the r^{th} iteration, the physical distribution is approximated by $\Psi_r(x)$. The next step is computed as follows:

$$\Psi_{r+1}(x) = \int D_0(x)Q_r(x|x')dx' = \int D_0(x)\frac{\Psi_r(x)S(x'|x)}{D_r(x')}dx'$$

where

$$D_r(x') = \int \Psi_r(x)S(x'|x)dx$$

and $D_0(x') \equiv D(x')$ is the measured distribution. To speed up the procedure of convergence, the starting value $\Psi_0(x)$ is chosen to be the measured distribution. This procedure leaves the normalization of the distributions unchanged at each iteration. The number of iterations needed to get the physical distribution has to be determined with care, as described in reference [4], since noise in the distributions appears when the number of steps is too large. For mass distributions, the width of the J/ψ meson decreases with the number of steps in the procedure and flattens when the number of iterations is ~ 50. In order to avoid amplifications of the fluctuations, this number of steps has not been exceeded. The smearing function and the acceptance are computed by means of a detailed Monte Carlo simulation as a function of the four kinematical variables. The computation is done on a 4-dimensional grid, hence the integrals in the iterative procedure are replaced by discrete sums. The computation of the errors by means of the iterative method is practically impossible given the high number of elements of the matrices involved ($\sim 10^{13}$). Therefore, the errors of the data, corrected for the acceptance, are used. This assumption has been checked with a complete 1-d error matrix calculation for the mass spectrum. The combinatorial background from

π and K meson decays is more than 85% of the total $\mu^+\mu^-$ yield. The number of background muon pairs is calculated starting from the number of like sign pairs as

$$N_{bkg}^{+-} = 2R\sqrt{N^{++}N^{--}} \tag{4}$$

where R expresses the effects of charge correlations and is equal to 1 in the limit of high multiplicities. Its proper value has been determined as described in reference[1]. In a 4-dimensional analysis, however, detected like sign pairs are not enough, many cells of the 4-d grid being empty. As a solution, equation (4) is still used to normalize the integrated $\mu^+\mu^-$ background, but the 4-d grid is filled by means of the so called Fake Opposite Sign method (FOS). An exhaustive combination among muons coming from different like sign pairs is used to increase the population of the grid. The deconvolution is applied to data after the background subtraction.

The kinematical region used for this analysis has been chosen in order to have an acceptance relatively high for each cell of the grid ($\geq 5\%$):

$$M_{\mu\mu} \geq 1.6\, GeV/c^2 \qquad 0.2 \leq Y_{CM} \leq 0.8 \qquad |\cos\Theta_{CS}| \leq 0.3$$

For p–A data $-0.2 \leq Y_{CM} \leq 0.4$. The standard sources contributing to the dimuon production in the IMR are the Drell–Yan process (DY) and the semileptonic decays of pairs of charmed hadrons ($D\bar{D}$). In the selected kinematical region, the contribution of the tails of the low mass resonances is negligible. The mass spectra have been fitted in the range $1.6 \leq M_{\mu\mu} \leq 8 GeV/c^2$ assuming a gaussian shape for the J/ψ and ψ' mesons and taking the shapes of the mass distributions for DY and $D\bar{D}$ processes from the Pythia 6.1 generator[7], with the MRS A set of parton distribution functions[8], $m_c = 1.5\, GeV/c^2$, $\sigma_{k_T}^{DY} = 0.8\, GeV/c$ and $\sigma_{k_T}^{D\bar{D}} = 1.0\, GeV/c^2$. The normalizations of the various contributions have been determined from the fit.

3. Results

The four p–A samples (where A stands for Al, Cu, Ag and W) were fitted together, imposing the same ratio $D\bar{D}/DY$, since, as hard processes, both DY and open charm are expected to scale linearly with the target mass. The ratio between the semileptonic decays of charmed particles and the DY process in the IMR ($1.6 \leq M_{\mu\mu} \leq 2.5 GeV/c^2$) has been found to be (statistical errors only):

$$\left(\frac{D\bar{D}}{DY}\right)_{p-A,\,450} = 4.13 \pm 0.15$$

From the measured cross section for the DY process, the total open charm production cross section in p–p collisions can be indirectly estimated. Our result is compared to direct measurements in figure 1. The S–U and Pb–Pb data samples have been subdivided respectively in 5 and 7 centrality bins defined in terms of the measured electromagnetic transverse energy. In order to compare the experimental mass distributions with the predicted ones, it is necessary to determine an expected value for the open charm cross section in nucleus–nucleus collisions. To this purpose the p–A cross section was extrapolated to nucleus–nucleus collisions assuming a linear dependence on the colliding nuclei masses and using the $\sqrt{s}$ dependence given by Pythia. This extrapolation, together with the measurement of the number of DY events from the high mass data (where DY is the only known source) allowed us to determine both the expected ratio ($D\bar{D}/DY$) and the number of $D\bar{D}$ events for each centrality bin. The total measured dimuon yield compared to the expected one in

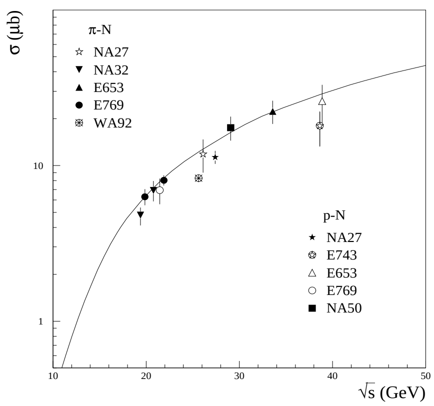

Figure 1. $\sigma_{c\bar{c}}$ $(x_F > 0)$

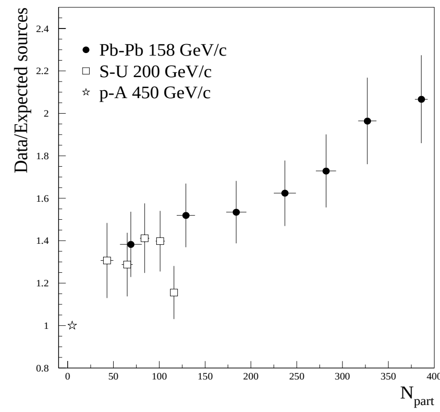

Figure 2. D/E vs. N_{part}

the IMR is shown in figure 2. There is clearly an excess of dimuons in the IMR that increases monotonically with the number of participants in the collision, reaching a value of the order of 2 for central Pb–Pb collisions. The observed excess cannot be ascribed to a bad evaluation of the combinatorial background, since the shape of the data cannot be reproduced by varying the normalization of the background as discussed in detail in ref. [1]. Mass spectra can be fitted well if the normalization of the open charm contribution is taken as a free parameter of the fit. Moreover also the $p_{\rm T}$ spectra can be well reproduced by a combination of DY and $D\bar{D}$ provided that the latter is left free to fit the data. The double ratio

$$E = \frac{D\bar{D}/DY\big|_{meas.}}{D\bar{D}/DY\big|_{expected}}$$

can be taken as a measure of the excess. The charm enhancement needed to reproduce data is of the order of 3 for central Pb–Pb events.

The fact that data can be understood in terms of an extra production of open charm with respect to a linear extrapolation from p–A collision does not imply necessarily that the excess is actually due to this source. Other possible phenomena that could lead to this *charm–like* excess in the IMR have been proposed. Spieles *et al* [9] evaluated the role of secondary DY processes in hadronic rescatterings by means of the UrQMD model and found a $\sim$ 10% enhancement of the primordial DY for $M_{\mu\mu} \simeq 2\,GeV/c^2$. Lin and Wang[10] investigated the role of final state rescattering of charmed mesons, which broadens their m_T spectra leading to an enriched $\mu^+\mu^-$ yield in the acceptance of the NA50 spectrometer. The degree of thermalization is parametrized in terms of the temperature T of the environment in which D mesons thermalize. This temperature is a local parameter and should not be confused with the inverse slope parameter T_{eff} of m_T distributions. The open charm enhancement E is related by the model to the temperature T $[E(T=0)=1]$ so it is possible to assign a temperature to each centrality bin and to calculate the $M_{\mu\mu}$ distribution for dimuons originating from $D\bar{D}$ decays keeping into account the rescattering effects. In figure 3 (a) the IMR mass spectrum for central Pb-Pb collision is fitted with DY and $D\bar{D}$ contributions, with the latter taken as a free parameter, while in figure 3 (b) the open charm contribution is evaluated with the rescattering model. The D meson rescattering is not sufficient to account for the observed excess.

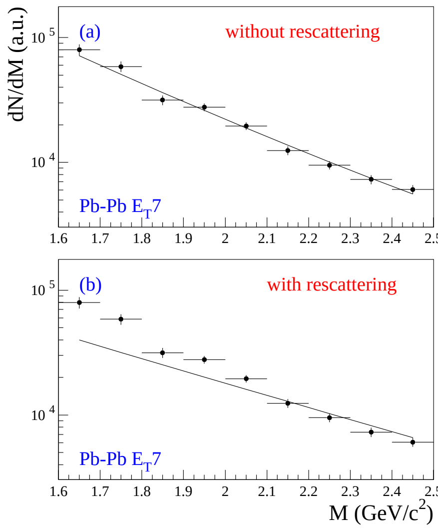

Figure 3. (a) fit with DY and $D\bar{D}$ contribution as a free parameter; (b) $D\bar{D}$ contribution given by the rescattering model

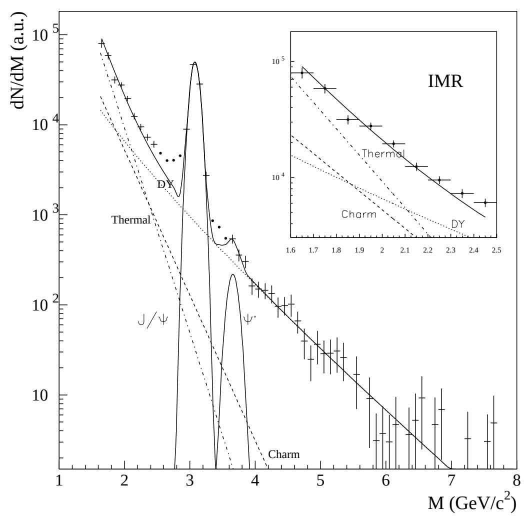

Figure 4. Central Pb–Pb mass spectrum with the estimated contributions.

Theoretical work on thermal dilepton radiation from an expanding fireball is in progress[11, 12, 13]. In figure 4 a comparison between central Pb–Pb data and the predictions of the thermal model from Rapp and Shuryak[13] is presented. The model is based on the assumption that the fireball formed in a Pb–Pb collision is in local thermal equilibrium. The dimuon yield is evaluated starting from the production rate that in the IMR is given by the perturbative QCD result for the $q\bar{q}$ annihilation process for both the QGP initial phase and the subsequent hadron gas phase. This rate has to be integrated over the space–time evolution of the collision. Here a simplified thermal fireball model that includes the most relevant features of a complete hydrodynamical simulation is used. The parameters applied for the comparison are the following: initial temperature $T_i = 192\, MeV$, fireball lifetime equal to $14\, fm/c$ and critical temperature for the QGP $T_c = 175\, MeV$. The impact parameter for the Pb–Pb collision is $b \leq 1\, fm$, so the comparison is made with the most central bin of the data sample. The thermal contribution rapidly drops when $M_{\mu\mu}$ increases and it is completely negligible at the J/ψ mass. The agreement with data is rather good, even though the comparison is limited to a single centrality bin and the p_{T} analysis is still in progress.

4. Conclusions

The use of a new method for the data unfolding leads to results that are in quantitative agreement with the already published ones[1]. The advantages of the method consist in the fact that it accounts for correlations among kinematical variables and does not imply the assumption of specific shapes for their distributions. On the other hand, the method can be applied only to a relatively restricted kinematical region with high acceptance. Moreover local small distortions of the distribution appear near the the narrow J/ψ peak . This is a known drawback of the unfolding method (the so called Gibbs ring effect): data points affected by this problem have been replaced by dots in figure 4. The p–A dimuon yield in the IMR has been described as a combination of semileptonic decays of charmed hadrons and Drell–Yan. An indirect measurement for charm hadroproduction has been performed and the result is in good agreement with direct measurements. For nucleus–nucleus collisions, the dimuon yield is underestimated by a linear extrapolation of the processes that describe p–A data. The excess cannot be explained as a bad evaluation of the background and a local open charm enhancement due to the rescattering of charmed hadrons is insufficient to account for the measured yield. Mass and p_{T} distributions are consistent with a combination of DY and open charm semileptonic decays, with a ratio $(D\bar{D})/(DY)$ up to 3 times higher than the expected value. The explicit introduction of thermal dimuons leads to results that are compatible with the data, even if a more systematic comparison is needed.

These results suggest that only a direct measurement of the open charm production in nucleus–nucleus collisions at SPS energies would allow to draw final conclusions on the nature of the dimuon production in the intermediate mass region.

References

[1] M C Abreu *et al Eur. Phys. J.* **C 14**, 443-455 (2000)
[2] A L S Angelis *et al Eur. Phys. J.* **C 13**, 433-452 (2000)
[3] J C Collins and D E Soper *Phys. Rev.* **D 16**,2219-2225 (1977)
[4] M C Abreu *et al Nucl. Instrum. Methods* **A 405**, 139 (1996)
[5] W H Richardson *J. Opt. Soc. of Am.* **62**, 55-59 (1972)
[6] L B Lucy, *Astron. J.***79**, 745-754 (1974)
[7] T Sjöstrand *Computer Phys. Commun.* **82**, 74 (1994) and hep-ph/0001032.
[8] A Martin *et al Phys. Rev.* **D51**, 4756 (1995)
[9] C Spieles *et al Eur. Phys. J.* **C 5**, 349-355 (1998)
[10] Z Lin and X N Wang *Phys. Lett.* **B 444**, 246-251 (1998)
[11] P Huovinen *et al* Nucl. Phys. **A 650**, 227-244 (1999)
[12] K Gallmeister *et al hep-ph/9908269* (1999)
[13] R Rapp and E Shuryak *Phys. Lett.* **B 473**, 13-19 (2000)