PRODUCTION AND MEASUREMENT OF *D*-MESONS IN NUCLEUS–NUCLEUS COLLISIONS AT THE CERN SPS

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We argue that the measurement of open charm gives a unique opportunity to test the validity of pQCD-based and statistical models of nucleus–nucleus collisions at high energies. We show that various approaches used to estimate D-meson multiplicity in central Pb+Pb collisions at 158 A GeV give predictions which differ by more than a factor of 100. Finally we demonstrate that decisive experimental results concerning the open charm yield in $A+A$ collisions can be obtained using data of the NA49 experiment at the CERN SPS.

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1. Introduction

The measurement of production of D-mesons in nucleus–nucleus collisions at CERN SPS energies is a challenging experimental adventure. This is due to the short life time and expected low multiplicity of D-mesons which cause the small experimental signal originating from D decays to be hidden in the large background composed of combinations of 'non-signal' tracks.

There is, however, an increasing interest in results on charm production in nucleus–nucleus ($A+A$) collisions which motivates various experimental groups to design upgrades of the existing experiments or to build new experiments, which should allow to measure open charm production in $A+A$ collisions [1–3].

The aim of this paper is twofold. In the first sections we present a new motivation for the experimental study of the open charm production in nuclear collisions. We show that this measurement should allow to establish a boarder of applicability of pQCD-based and statistical models of strong interactions.

In the second part of the paper we demonstrate that the first measurement of D-meson production may be even possible using the current set-up of the NA49 experiment [4]. In particular we estimate the statistical resolution of D-meson measurement which can be achieved using the data of the NA49 experiment. Summary and conclusions (Section 5) close the paper.

2. Physics beyond QGP: pQCD *vs* thermodynamics

The main motivation for a broad experimental program in which nucleus–nucleus collisions at high energies are studied is the search for the Quark Gluon Plasma [5, 6]. An impressive set of data was collected during the last decades and many unexpected phenomena were discovered [7]. However, the question whether a transient QGP state is created in the early stage of the collisions is still under vivid discussion. In our opinion this situation is due to the fact that there is no consensus on which models of high energy hadronic and nuclear collisions should be used to interpret experimental results.

The data are in qualitative and quantitative agreement with the hypothesis of QGP creation in $A+A$ collisions at the CERN SPS if a statistical model of the early stage is used for their interpretation [8]. This model is, however, considered a non-orthodox approach to hadronic and nuclear collisions as its basic assumptions can not be derived from the commonly accepted theory of strong interaction, QCD. Its validity is, therefore, more surprising than the conclusions reached within this model concerning QGP creation at the CERN SPS.

On the other hand it is difficult to use QCD for the interpretation of the experimental results. Problems arise because almost all effects intuitively expected in the case of a transition to QGP are in the domain of so-called soft processes in which experimentally testable strict predictions of QCD are not possible. Attempts to build phenomenological QCD-inspired models of soft processes are not very successful [9]. Conclusive interpretation of the data within these models seems to be impossible as one can not estimate the uncertainties introduced by the used approximations.

As a possible solution one tries to identify phenomena sensitive to the early stage in which so-called hard QCD processes are believed to prevail [10]. In this case one hopes to obtain testable QCD predictions using perturbative methods. A well known example is the analysis of J/ψ production in $A+A$ collisions performed under the assumption that the initial production of

$c\bar{c}$ pairs is described by pQCD. However the limits of the applicability of pQCD are theoretically not well defined. Therefore any assumption based on validity of pQCD calculations and used to interpret the data should be tested experimentally. In the case of the J/ψ example this test can be done by the measurement of the open charm yield and its comparison to pQCD predictions.

In connection with the above discussion of QCD-based models it is interesting to consider a hypothetical model in which, due to technical problems, strict experimentally testable predictions can not be obtained. The model gives approximate predictions, however, the error made due to the approximations is difficult to estimate. Experimental results which are in agreement with the predictions of the model can be treated as a 'proof' of its validity. On the other hand any disagreement between the model and the data can be interpreted as due to the used approximations. Therefore the model can not be falsified [11] before a substantial improvement in its predictive power. This example illustrates the logical problem which one may encounter discussing the validity of QCD-based models.

In the summarized exciting situation concerning our understanding of strong interactions the role of the experimental results on open charm production in $A + A$ collisions is unique.

- Data on open charm should allow to test limits of applicability of the perturbative QCD methods.
  It is often assumed that the charm quark is heavy enough for pQCD treatment [12]. Based on this hypothesis results on J/ψ production in $A + A$ collisions are interpreted in the so-called 'suppression' models [10,13], in which the suppression is calculated relative to the J/ψ yield expected from the pQCD factorization theorem [14] and data on J/ψ production in $p + p$ interactions. It was, however, recently shown that the J/ψ multiplicity is, in good approximation, proportional to pion multiplicity [15]. Thus the J/ψ yield shows an A-dependence which is characteristic of soft QCD processes. This experimental observation motivates the question whether pQCD can be used as a model of charm quark production in hadronic and nuclear collisions.

- Data on open charm should allow to test the validity of a non-orthodox statistical model of the early stage of $A + A$ collisions [8].
  In this model charm quark multiplicity is large enough to justify the use of the thermodynamical approximation. Consequently not only the absolute yield of open charm but also its A-dependence are very different for the statistical and the pQCD-based models. For detailed discussion see the following section.

3. Multiplicity of D-mesons in nuclear collisions

This section starts with a review of the data on D^0 and $\overline{D}^0$ production in proton–nucleon interactions, which leads to an estimate of the mean multiplicity of $D^0 + \overline{D}^0$ mesons, $\langle D^0 + \overline{D}^0 \rangle$, in nucleon–nucleon, $N + N$, interactions at 158 A GeV. This result is needed for the further discussion of the multiplicity of $D^0 + \overline{D}^0$ mesons in nuclear collisions at 158 A GeV which is estimated using four different approaches.

3.1. $\langle D^0 + \overline{D}^0 \rangle$ in $N + N$ interactions

There are six measurements of D-meson production cross section at various collision energies ranging from 200 GeV to 800 GeV, which allow to estimate the mean multiplicity of $D^0 + \overline{D}^0$ in $p + N$ interactions [16–21]. In $p + p$ interactions $\sigma(D^0 + \overline{D}^0)$ is measured at 360 GeV [18], 400 GeV [19] and at 800 GeV [20]. At 200 GeV [16], 250 GeV [17] and 800 GeV [21] the cross section in $p + N$ interactions is estimated based on measured cross section for $p + A$ interactions assuming that $\sigma(D^0 + \overline{D}^0)$ is proportional to A. We note here that this assumption is not fully justified by the experimental results [15] and may lead to an additional systematic error in estimating $\sigma(D^0 + \overline{D}^0)$ in $p + N$ interactions. In addition a symmetry of the x_F distribution of $D^0 + \overline{D}^0$ mesons with respect to $x_F = 0$ is assumed for the calculation of the integrated cross section using measurements at $x_F > 0$. In the case of the measurement at 200 GeV [16] only results for the sum of all D-mesons are published; in this case we assume that 50% of them are $D^0 + \overline{D}^0$ mesons.

The mean multiplicity of $D^0 + \overline{D}^0$ mesons in $p+p$ and $p+N$ interactions is calculated as a ratio $\sigma(D^0 + \overline{D}^0)/\sigma$, where σ is the inelastic cross section for $p+p$ interaction at the corresponding energy. The values of $\langle D^0 + \overline{D}^0 \rangle_{NN}$ are given in Table I and plotted as a function of $\sqrt{s}$ in Fig. 1. The results at $\sqrt{s} = 19.4$ GeV and $\sqrt{s} = 21.7$ GeV differ by a factor of about 8, which suggests a possible large systematic uncertainty of the measurements at low energy not accounted for in the quoted errors. Taking this into account we estimate the mean multiplicity of $D^0 + \overline{D}^0$ at $\sqrt{s} = 17.3$ GeV ($E_{\rm LAB}$ = 158 GeV) in nucleon–nucleon interactions by an arithmetic average of the measurements at $\sqrt{s} = 19.4$ GeV and $\sqrt{s} = 21.7$ GeV, which gives:

$$\langle D^0 + \overline{D}^0 \rangle_{NN} = 2.0 \times 10^{-4}. \tag{1}$$

A large systematic error up to several times the estimated value should be kept in mind.

TABLE I

The results on mean multiplicity of $D^0 + \overline{D}^0$ mesons produced in $p+p$ and $p+N$ interactions. The multiplicity for $p+N$ interactions was estimated from the data on $p+A$ interactions (used reactions are listed in the third column) assuming that cross section for D–meson production is proportional to A. For detailed discussion of the data see text.

$p_{\rm LAB}$ [GeV]	$\sqrt{s}$ [GeV]	Reactions	$\langle D^0 + \overline{D}^0 \rangle \times 10^4$	Reference
200	19.4	p+Si	0.47 ± 0.23	[16]
250	21.7	p+(Be,Al,Cu,W)	3.6 ± 0.9	[17]
360	26.0	$p+p$	6.2 ± 1.9	[18]
400	27.4	$p+p$	5.6 ± 0.8	[19]
800	38.8	$p+p$	6.5 ± 2.4	[20]
800	38.8	p+(Be,Au)	5.2 ± 1.0	[20]

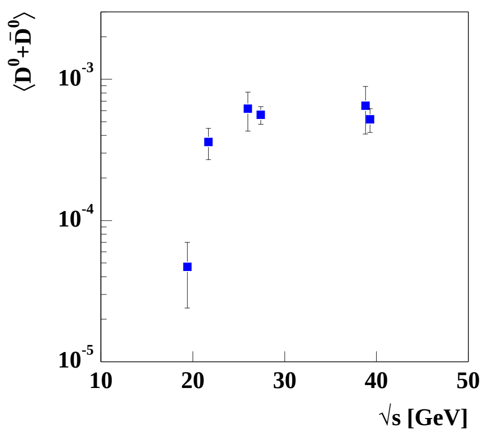

Fig. 1. The mean multiplicity of $D^0 + \overline{D}^0$ mesons in proton–nucleon interactions as a function of collision energy in the c.m. system.

3.2. $\langle D^0 + \overline{D}^0 \rangle$ *in central Pb+Pb collisions at 158 A GeV*

We discuss here four approaches which allow to predict A-dependence of the open charm yield and the mean multiplicity of D^0 and $\overline{D}^0$ mesons in central Pb+Pb collisions, $\langle D^0 + \overline{D}^0 \rangle_{\rm PbPb}$, at 158 A GeV. It is assumed that the central collisions are selected by accepting only events with a low number of spectator nucleons from the projectile nucleus and that the typical trigger conditions of the NA49 experiment are used [4]. This results in a mean number of participant nucleons, $\langle N_{\rm P} \rangle$, of about 350 [22].

A. Model of soft A-dependence. It was recently observed [15] that the mean multiplicity of J/ψ mesons increases proportionally to the mean multiplicity of negatively charged hadrons (more than 90% π^- mesons) when $p+p$, $p+A$ and $A+A$ collisions are considered (see Fig. 2). It may be

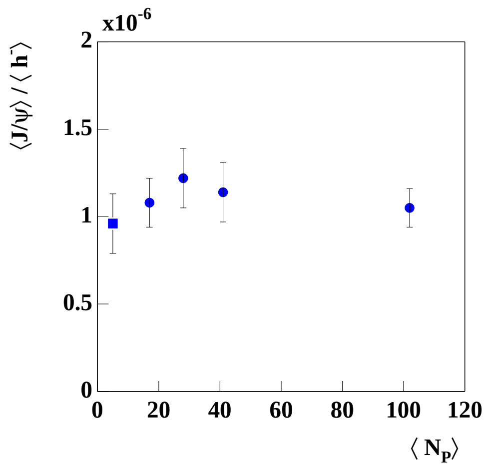

Fig. 2. The ratio of the mean multiplicities of J/ψ mesons and negatively charged hadrons for inelastic nucleon–nucleon (square) and inelastic O+Cu, O+U, S+U and Pb+Pb (circles) interactions at 158 A GeV plotted as a function of the mean number of participant nucleons. For clarity the $N+N$ point is shifted from $\langle N_{\rm P}\rangle = 2$ to $\langle N_{\rm P}\rangle = 5$.

therefore assumed that a similar dependence on the size of the colliding objects is also valid for D-mesons. This assumption yields the following dependence of a mean multiplicity of $D^0 + \overline{D}^0$ mesons:

$$\langle D^0 + \overline{D}^0\rangle \sim \langle h^-\rangle \sim \langle N_{\rm P}\rangle, \tag{2}$$

For central Pb+Pb collisions at 158 A GeV the model results in:

$$\langle D^0 + \overline{D}^0\rangle_{\rm PbPb} = \langle D^0 + \overline{D}^0\rangle_{NN} \frac{\langle h^-\rangle_{\rm PbPb}}{\langle h^-\rangle_{NN}} = 2\times 10^{-4}\,\frac{700}{3.1} \approx 4.5\times 10^{-2}\,, \tag{3}$$

where the values of $\langle h^-\rangle_{\rm PbPb}$ and $\langle h^-\rangle_{NN}$ are taken from Ref. [22] and Ref. [23], respectively.

B. pQCD-based approach. It is usually assumed that due to the large mass of the charm quark, production of charm can be calculated using perturbative QCD methods [12]. This assumption leads to the expectation that the cross section for charm production increases as A^2 for all inelastic $A+A$

collisions and that the mean multiplicity of open charm increases as $\langle N_{\rm P}\rangle^{4/3}$ for central $A+A$ collisions. Thus for central Pb+Pb collisions we get:

$$\langle D^0 + \overline{D}^0 \rangle_{\rm PbPb} = \langle D^0 + \overline{D}^0 \rangle_{NN} \, (\langle N_{\rm P}\rangle/2)^{4/3} \approx 2 \times 10^{-1}. \tag{4}$$

This estimate agrees with a previously published prediction for charm production based on pQCD inspired models [24].

C. The NA50 estimate. The NA50 Collaboration found recently [25] that a model based on pQCD can not describe the dimuon invariant mass spectrum between the ϕ and J/ψ peaks in central Pb+Pb collisions. The spectrum, however, can be reproduced when the contribution from open charm decays is scaled up by a factor of about 3. Based on this analysis one may expect that:

$$\langle D^0 + \overline{D}^0 \rangle_{\rm PbPb} \approx 6 \times 10^{-1}, \tag{5}$$

i.e. it is equal to the multiplicity calculated in **B** multiplied by a factor of 3.

D. Statistical approach. The production of entropy and strangeness in $A+A$ collisions at the CERN SPS can be described by a statistical model which assumes the creation of a Quark Gluon Plasma in the early stage of the collision [8]. This fact triggered the hypothesis that also charm production can be described by the same statistical approach. For a large enough number of participant nucleons ($\langle N_{\rm P}\rangle > 50$) the calculated multiplicity of charm quarks appears to be significantly larger than one and therefore grand canonical volume dependence of the charm yield is predicted:

$$\langle c + \bar{c} \rangle \sim \langle N_{\rm P} \rangle. \tag{6}$$

Strong canonical suppression is expected for the low number of participants. It can be estimated [8], that the mean number of c and $\overline{c}$ quarks produced in central Pb+Pb collisions at 158 $A\,$GeV is about 17. Based on $p+p$ data [19] we assume here that about one third of them hadronize as D^0 and $\overline{D}^0$ mesons which gives:

$$\langle D^0 + \overline{D}^0 \rangle_{\rm PbPb} \approx 6. \tag{7}$$

We summarize this section by observing that the dependence of the mean multiplicity of open charm on the size of the colliding objects as well as its absolute value are very different for discussed here models. The mean multiplicity of $D^0 + \overline{D}^0$ mesons in central Pb+Pb collisions at 158 $A\,$GeV ranges from 4.5×10^{-2} to about 6 showing more than a factor 100 difference between the minimum and the maximum values. Thus measurement of the open charm yield in $A+A$ collisions may serve as a critical test of the various theoretical approaches. In particular it should allow to establish a boarder of the applicability of pQCD-based and statistical models.

4. *D*-meson measurement in NA49

We consider here the possibility of a measurement of D^0 and $\overline{D}^0$ production in $A+A$ collisions at 158 $A\,$GeV using the current set-up of the NA49 experiment at the CERN SPS [4]. We start from an introductory discussion on the means to distinguish D^0 decays from combinatorial background and on the calculation of the statistical error on D^0 multiplicity. We continue with a brief summary of the relevant properties of the NA49 experiment and finally we present results of a simulation which yield an estimate of the statistical resolution of $D^0 + \overline{D}^0$ measurement in central Pb+Pb collisions using the NA49 data.

Our analysis is based on the study of the two body decay channels of D^0 and $\overline{D}^0$ mesons:

$$D^0 \to K^- + \pi^+ \qquad \text{and} \qquad \overline{D}^0 \to K^+ + \pi^- \tag{8}$$

for which the branching ratio is measured to be $(3.85 \pm 0.09)\%$ [26]. The mass and the proper life time of D^0 and $\overline{D}^0$ mesons are $m_{D^0} = (1864.6 \pm 0.5)$ MeV/c^2 and $c\tau = 0.01244$ cm, respectively [26].

4.1. Introductory remarks

Let us consider a central Pb+Pb collision at CERN SPS energy in which among thousands of produced particles are also D^0 mesons. The D^0 mesons decay after a typical flight distance of about 0.1 cm ($\approx \gamma\, c\tau$) from the collision point. There are many decay channels possible, but for the reasons discussed at the end of this paper we consider only decays of a single type, $D^0 \to K^- + \pi^+$, which happen only in 3.85 % of all cases of D^0 decays.

For simplicity of the initial discussion we assume that an ideal detector is placed around the collision point, *i.e.* for all charged particles electric charge, mass and momentum vector at a given reference plane are measured.

For all (K^-, π^+) pairs originating from D^0 decays (signal pairs) the following conditions have to be approximately (within experimental resolution) fulfilled:

1. the trajectories of K^- and π^+ intersect at a point (decay point) which is different from the Pb+Pb collision point,
2. the distribution of the D^0 life time in its own c.m.s. frame is an exponential distribution with a mean value equal to $c\tau = 0.0124$ cm,
3. energy and momentum conservation laws are fulfilled at the decay point when D^0 decay hypothesis is assumed,
4. the angular distribution of the decay products in the D^0 c.m.s. is isotropic.

Conditions 1–4 can be fulfilled (within experimental resolution) by a set of (K^-, π^+) pairs which do not originate from the same D^0 decay (background pairs) only by chance. The probability of this happening decreases with increasing experimental resolution.

As a useful example we consider the condition 3 of energy momentum conservation at the decay vertex. For practical reasons one often quantifies deviations from energy momentum conservation, assuming the D^0 decay hypothesis, by calculating the invariant mass, $M(K^-, \pi^+)$, for a pair of negatively and positively charged particles and comparing it to the known mass of the D^0 meson. Almost all signal pairs are expected to be distributed in a narrow interval ΔM centered around m_{D^0}. The M distribution for background pairs is significantly broader and it has no characteristic peak structure at m_{D^0}. The smearing of the M distribution for signal pairs results from the finite resolution of momentum measurement. With increasing resolution the size of the interval ΔM in which almost all signal pairs are included decreases consequently resulting in a lower number of accepted background pairs.

In the high resolution limit almost only signal pairs (and almost no background pairs) are selected when taking pairs from ΔM. In this case the total number of signal pairs, $N_{\rm S}$, in $N_{\rm EV}$ events can be approximated by the measured number of pairs in the ΔM interval, $N_{\Delta M}$. An estimate of the mean multiplicity of signal pairs is therefore given by

$$\langle N_{\rm S}^{\rm E} \rangle = \frac{N_{\Delta M}}{N_{\rm EV}} \tag{9}$$

and its statistical error can be calculated as

$$\sigma(\langle N_{\rm S}^{\rm E} \rangle) = \frac{\sqrt{\langle N_{\Delta M} \rangle}}{\sqrt{N_{\rm EV}}} \approx \frac{\sqrt{\langle N_{\rm S}^{\rm E} \rangle}}{\sqrt{N_{\rm EV}}} \tag{10}$$

assuming a Poissonian distribution of the pair multiplicity in the interval ΔM.

In the limit of poor resolution the number of background pairs, $N_{\rm B}$, in the interval ΔM is much larger than the number of signal pairs. Therefore in order to estimate the number of signal pairs, $N_{\rm S}^{\rm E}$, an estimate of the number of background pairs, $N_{\rm B}^{\rm E}$ is needed:

$$N_{\rm S}^{\rm E} = N_{\Delta M} - N_{\rm B}^{\rm E}\,. \tag{11}$$

The estimate of $N_{\rm B}^{\rm E}$ is model dependent and therefore it has a systematic error which however will not be discussed here. Various models can be used. As an example let us mention a 'mixed event' model of the background in which background pairs are constructed by selecting particles from different events. Independent of the model used it is reasonable to assume that the statistical error of $N_{\mathrm{B}}^{\mathrm{E}}$ can be made much smaller than the statistical error of $N_{\Delta M}$. Thus the statistical error of $\langle N_{\mathrm{S}}^{\mathrm{E}}\rangle$ can be calculated as

$$\sigma(\langle N_{\mathrm{S}}^{\mathrm{E}}\rangle) = \frac{\sqrt{\langle N_{\Delta M}\rangle}}{\sqrt{N_{\mathrm{EV}}}} \approx \frac{\sqrt{\langle N_{\mathrm{B}}^{\mathrm{E}}\rangle}}{\sqrt{N_{\mathrm{EV}}}}, \tag{12}$$

assuming Poissonian distribution of pair multiplicity in the interval ΔM.

We observe that in the limit of high resolution the statistical error of the signal is almost fully defined by the number of signal pairs, whereas in the limit of poor resolution it is defined by the number of background pairs.

One can define the statistical significance of the measurement as the ratio $\langle N_{\mathrm{S}}^{\mathrm{E}}\rangle/\sigma(\langle N_{\mathrm{S}}^{\mathrm{E}}\rangle)$ which in the case of the poor resolution limit is given by

$$\frac{\langle N_{\mathrm{S}}^{\mathrm{E}}\rangle}{\sigma(\langle N_{\mathrm{S}}^{\mathrm{E}}\rangle)} = \frac{\langle N_{\mathrm{S}}^{\mathrm{E}}\rangle}{\sqrt{\langle N_{\mathrm{B}}^{\mathrm{E}}\rangle}}\sqrt{N_{\mathrm{EV}}}. \tag{13}$$

Thus in order to maximize the statistical significance of the result one should select the acceptance (in the example above the size of the ΔM interval) such that the ratio $\langle N_{\mathrm{S}}^{\mathrm{E}}\rangle/\sqrt{\langle N_{\mathrm{B}}^{\mathrm{E}}\rangle}$ reaches a maximum.

4.2. The NA49 experiment

The NA49 experiment [4] at the CERN SPS was designed and constructed to search for signals of the Quark Gluon Plasma created at the early stage of nucleus–nucleus collisions. Basic detectors of the NA49 set-up are four Time Projection Chambers (TPC's), which allow for a precise tracking of charged particles. Two medium size TPC's of 3 m^3 gas volume each are located inside of two magnets with up to 1.5 T field strength each. Two large size TPC's of 20 m^3 gas volume each are positioned downstream of the magnets for high precision energy loss measurement and acceptance coverage in the forward direction. Overall the TPC's acceptance coverage amounts to up to 80% of all produced charged particles (this number depends on the reaction studied and magnetic field — target configuration).

The TPC's measure up to 234 space points on tracks of up to 13 m length. This allows a precise determination of the sign of electric charge, momentum vector ($\sigma(p)/p^2 \approx 10^{-4}$ (GeV/ $c)^{-1}$) and energy loss ($\approx$ 4% relative resolution) for all accepted particles. These measurements yield information on particle mass which results in large acceptance (limited resolution) particle identification. Four Time-of-Flight walls ($\approx$ 60 ps resolution) complement the particle identification capabilities of the NA49 detector.

A typical resolution in reconstruction of the distance between the collision point and the secondary vertex of a two body decay near the target is of the order of 1 cm and is mainly due to the long extrapolation length needed from the first TPC detector.

4.3. Statistical error on $\langle D^0 + \overline{D}^0 \rangle_{\rm PbPb}$ *in NA49*

In order to estimate the statistical resolution of a $\langle D^0 + \overline{D}^0 \rangle_{\rm PbPb}$ measurement in NA49 we performed a simulation of signal and background pairs as expected in this experiment for central Pb+Pb collisions at 158 $A\,$GeV. In the simulation the standard geometry and magnetic field of NA49 are assumed [4]. We define the geometrical acceptance of the NA49 TPC's by the requirement that the particle trajectories cross more than 20 TPC padrows, at least one of which has to be in a TPC located inside the magnetic field. A parametrization of the momentum resolution as measured by NA49 is included in the simulation. Concerning particle identification we consider two extreme cases. In the first one we assume that no information on particle mass is available, whereas ideal particle identification is assumed in the second case. For the background calculation spectra of charged hadrons produced in central Pb+Pb collisions at 158 $A\,$GeV as measured by NA49 [22] are parametrized in rapidity (y) and transverse momentum ($p_{\rm T}$). The signal simulation is done assuming a Gaussian ($\sigma = 0.6$) rapidity distribution and an exponential spectrum in transverse mass ($T = 300$ MeV) for both D^0 and $\overline{D}^0$ mesons. The total multiplicity of D^0 and $\overline{D}^0$ mesons of 6 as predicted by the statistical model (see point 3.2.**D**) is assumed (if needed). In Fig. 3 we show the $y - p_{\rm T}$ distribution of D^0 mesons for which both decay products are in the geometrical acceptance of the NA49 TPC's.

Before further presentation of results of the simulation we note that conditions 1 and 2 (see Section 4.1), which require an accurate measurement of the decay vertex, can not be used in the existing NA49 set-up to distinguish signal from background pairs. This is due to the poor resolution in the reconstruction of the secondary vertex from two body decays of the order of 1 cm, which is much larger than the typical flight path of D^0 and $\overline{D}^0$ of about 1 mm. Therefore background rejection has to be done using conditions 3, energy-momentum conservation, and 4, isotropy of the decay, only. We quantify these conditions by studying $M(K^-,\pi^+)$ (or $M(K^+,\pi^-)$) distribution and cosΘ distribution, where Θ is the angle between D and π meson directions calculated in D-meson c.m. system.

The results of the simulation shown below are obtained for the D^0 decay, without using information on particle mass. An improvement of the statistical resolution of charm measurement due to the addition of $\overline{D}^0$ decays and particle mass information is considered at the end of this section.

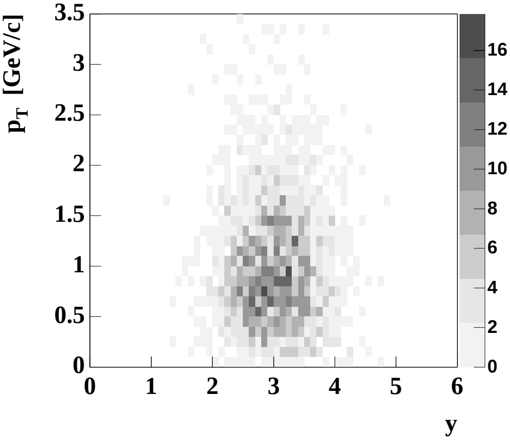

Fig. 3. The simulated distribution in transverse momentum and rapidity of D^0 mesons for which both decay products ($D^0 \rightarrow K^- + \pi^+$) are reconstructed in the NA49 TPC's. The distribution is given in arbitrary units.

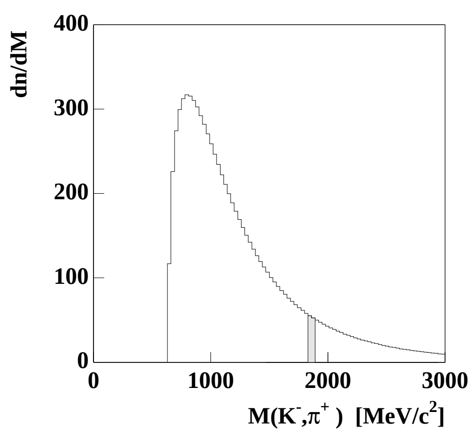

Fig. 4. The simulated invariant mass distribution for all combinations of positively and negatively charged hadrons accepted by the NA49 TPC's. Masses of positively and negatively charged hadrons are assumed to be kaon and pion masses, respectively. The calculation is performed for central Pb+Pb collisions at 158 A GeV. The spectrum is normalized per event and it is in $(\mathrm{MeV}/c^2)^{-1}$ units. The shadowed area indicates the invariant mass region around D^0 mass further used for detailed analysis.

In Fig. 4 we show an invariant mass distribution $M(K^-,\pi^+)$ for background pairs obtained using the geometrical acceptance of NA49. It is seen that the D^0 meson mass is located in the region of the monotonously decreasing tail of the distribution, well beyond the position of its maximum. The $M(K^-,\pi^+)$ distributions for signal and background pairs in the interval of M around m_{D^0} are shown in Figs. 5a and 5c, respectively. For pairs from the interval $\Delta M = 4$ MeV$/c^2$ around m_{D^0} we plot also the cosΘ distributions in Figs. 5b and 5d.

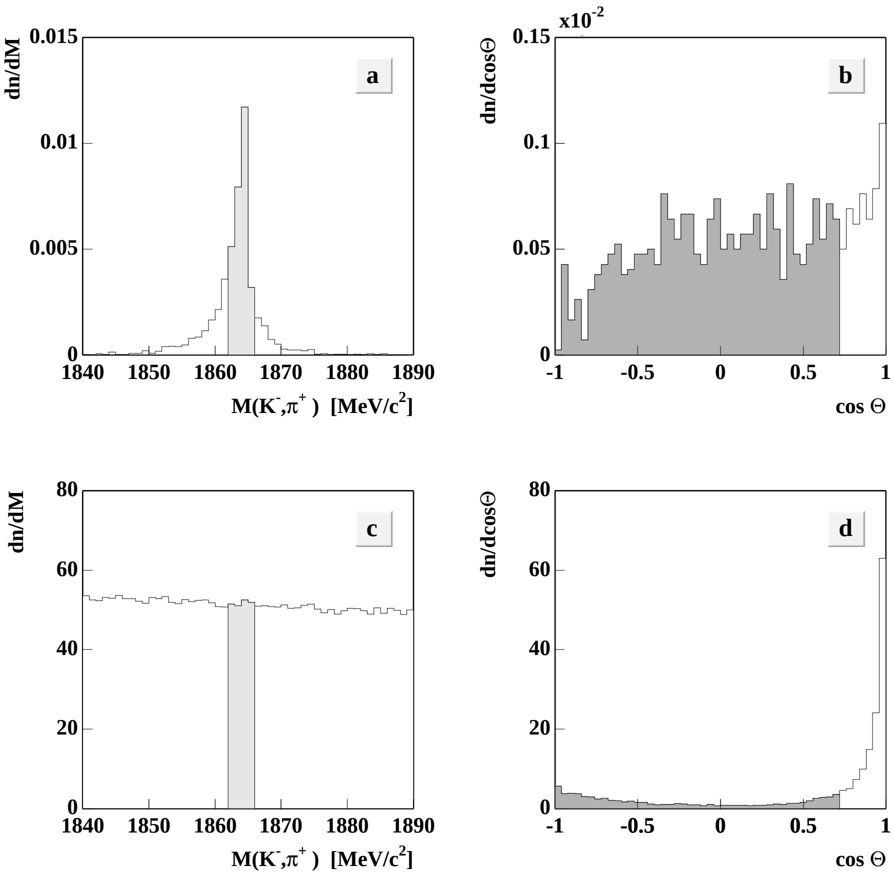

Fig. 5. The invariant mass and cosΘ distributions for D^0 decays (plots **a** and **b**) and background (plots **c** and **d**) pairs. The cosΘ distributions are plotted for pairs from the interval $\Delta M = 4$ MeV$/c^2$ around m_{D^0}. Shadowed areas indicate regions selected for final analysis (see text for details). The spectra are normalized per event, the invariant mass spectra are in (MeV$/c^2)^{-1}$ units.

We observe that in the case of D^0 measurement by NA49 we are in the poor resolution limit *i.e.* the statistical resolution of signal measurement is determined by the number of background pairs and is independent of the signal multiplicity. It is also clear that rejection of pairs with high $\cos\Theta$ values should result in an improvement of statistical significance of the signal measurement. We estimate that the maximum significance can be achieved by accepting pairs with $\cos\Theta < 0.7$ and inside an interval of $\Delta M = 4$ MeV$/c^2$ (background cuts). The mean multiplicity of background pairs for this selection is

$$\langle N_{\rm B}\rangle_{\rm NOID} \approx 80, \tag{14}$$

where the subscript $_{\rm NOID}$ is used to underline that the number is obtained without using information on particle identification. This yields an estimate of the statistical resolution of $\langle N_{\rm S}^{\rm E}\rangle$

$$\sigma_{\rm NOID}(\langle N_{\rm S}^{\rm E}\rangle) = \frac{\sqrt{\langle N_{\rm B}\rangle_{\rm NOID}}}{\sqrt{N_{\rm EV}}} \approx \frac{9}{\sqrt{N_{\rm EV}}}. \tag{15}$$

The resulting correction factors needed to obtain $\langle D^0\rangle$ from the estimated signal multiplicity $\langle N_{\rm S}^{\rm E}\rangle$ in the acceptance are:

- $w_{\rm BR} = 26.0$, for the branching ratio,
- $w_{\rm GA} = 2.4$, for the geometrical acceptance,
- $w_{\rm BC} = 2.3$, for the background cuts.

Therefore the statistical resolution of $\langle D^0\rangle$ can be estimated as:

$$\sigma_{\rm NOID}(\langle D^0\rangle) = w_{\rm BR}\, w_{\rm GA}\, w_{\rm BC}\, \frac{\sqrt{\langle N_{\rm B}\rangle_{\rm NOID}}}{\sqrt{N_{\rm EV}}} \approx \frac{1300}{\sqrt{N_{\rm EV}}}. \tag{16}$$

In the case of ideal particle identification background multiplicity can be reduced by about a factor of 10, which results in $\sigma_{\rm ID}(\langle D^0\rangle) \approx 400/\sqrt{N_{\rm EV}}$. Therefore for 10^6 central Pb+Pb collisions at 158 A GeV $\sigma(\langle D^0\rangle) \approx 0.4$–$1.3$ in comparison to $\langle D^0\rangle \approx 3$ expected in the case of the statistical model. Statistical significance of measurement of $\langle D^0 + \overline{D}^0\rangle$ is approximately by a factor of $\sqrt{2}$ better than significance of separate measurements for D^0 or $\overline{D}^0$.

In Fig. 6 we plot $\sigma_{\rm NOID}(\langle D^0+\overline{D}^0\rangle)$ and $\sigma_{\rm ID}(\langle D^0+\overline{D}^0\rangle)$ as a function of the number of central Pb+Pb collisions at 158 A GeV registered by NA49. The different predictions concerning $\langle D^0+\overline{D}^0\rangle$ discussed in Section 3 are also indicated in Fig. 6 for comparison.

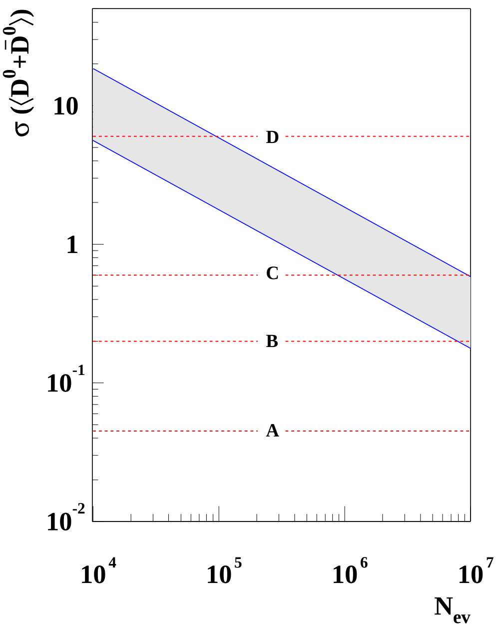

Fig. 6. The statistical resolution of the measurement of mean multiplicity of $D^0+\overline{D}^0$ mesons in central Pb+Pb collisions at 158 A GeV as a function of the number of analyzed events. The calculation is performed for the current NA49 set-up assuming no information on particle mass (upper solid line) and an ideal particle identification (lower solid line). The mean multiplicity of $D^0+\overline{D}^0$ mesons estimated in four different approaches (**A**–**D**, see Section 3) is indicated by dashed lines.

Finally in Fig. 7 we show $M(K^-,\pi^+)$ distributions obtained using the $\cos\Theta$ cut for signal and background pairs for 100 central Pb+Pb collisions. In this case the number of generated D^0 decays was scaled up by a factor of 100 and therefore the statistical significance of the observed signal peak corresponds to the significance expected for 10^6 events.

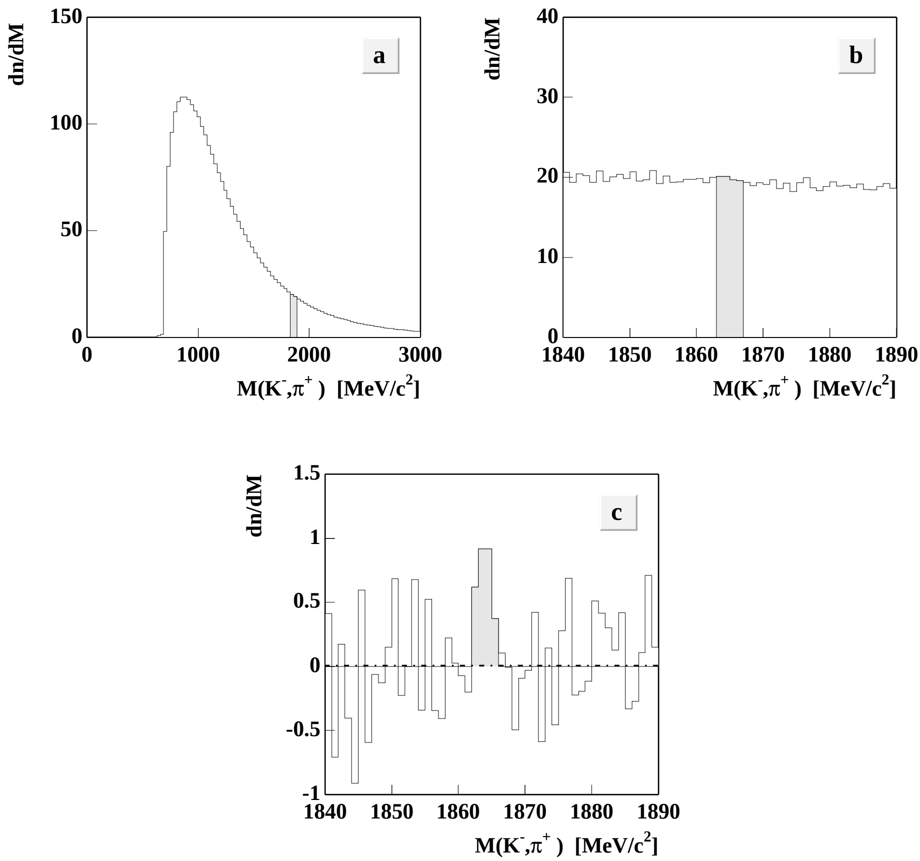

Fig. 7. The invariant mass distribution for the sum of signal (D^0 decays) and background pairs simulated for 100 central Pb+Pb collisions at 158 A GeV (plots **a** and **b**). In the simulation the current NA49 set-up was used and the number of signal pairs expected in the statistical model (see 3.2.**D**) was increased by a factor of 100. Thus the statistical significance of the result corresponds to the significance expected for 10^6 central Pb+Pb collisions. The difference of the distribution for the sum of signal and background pairs (shown in plot **b**) and the distribution for background pairs calculated within the 'mixed event' model of the background is shown in plot **c**. For all plots only pairs with $\cos\Theta < 0.7$ are selected. All spectra are normalized per event and they are given in $(\mathrm{MeV}/c^2)^{-1}$ units.

4.4. Discussion

The experiment NA49 registered up to now about 10^6 central Pb+Pb collisions at 158 A GeV. As follows from the results of simulation presented in Fig. 5 already the analysis of this data should yield significant results concerning open charm production in Pb+Pb collisions. This encouraging conclusion is reached mainly due to three factors:

- there are expectations of a significant enhancement of open charm production in $A+A$ collisions,
- a significant fraction of produced D-mesons is covered by the large geometrical acceptance of NA49,
- the good momentum resolution of NA49 allows for a significant reduction of background even without reconstructing the D-meson decay vertex.

The results presented in this paper are obtained by a simple analysis of simulated data. This scheme was selected in order to underline the main concepts and to build intuition concerning basic ingredients of the problem of D-meson measurement in $A+A$ collisions. The use of more sophisticated statistical methods of data analysis (see Ref. [27]), which *e.g.* include explicitly the statistical errors of the measured momentum vector by using a kinematical fit, may lead to an improvement of the achieved resolution.

We studied also the statistical resolution of open charm measurement using three and four body decays of neutral and charged D-mesons. We found that due to high combinatorial background the statistical resolution is much lower than in the case of the two body decay channel.

5. Summary and conclusions

The main results presented in this paper can be summarized as follows.

- The measurement of open charm production in $A+A$ collisions gives a unique possibility to establish the boarders of applicability of the statistical and pQCD-based models.
- Various approaches used to estimate the D-meson multiplicity in central Pb+Pb collisions at 158 A GeV give predictions which differ by more than a factor 100.
- Experimental data already registered by NA49 should allow to obtain a significant result on open charm production in Pb+Pb collisions. The analysis can yield the first observation of open charm signal or it will lead to an estimate of the upper limit of open charm multiplicity which should significantly narrow the range of allowed models.

It is obvious that a significant increase of statistics of $A+A$ collisions at maximum SPS energy registered by NA49 is required for a continuation of the open charm program. This can be achieved during the already scheduled heavy ion run at the CERN SPS in the year 2000 and the possible runs beyond. It is also clear that for a precise measurement of open charm production an upgrade of the NA49 set-up by a vertex detector, which allows for an accurate reconstruction of D-meson decay vertices, is needed.

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REFERENCES

[1] J. Bächler *et al.* (NA49 Collab.), Status and Future Programme of the NA49 Experiment, CERN/SPSC 98–4, CERN/SPSLC/P264 Add. 2.

[2] J. Bächler *et al.* (NA49 Collab.), Status and Future Programme of the NA49 Experiment, CERN/SPSC 99–4, CERN/SPSLC/P264 Add. 3.

[3] M.C. Abreu *et al.* (NA50 Collab.), Low Mass Dimuon Physics in NA50 Upgraded by Adding a Pixel Vertex Spectrometer, CERN/SPSC 97–22, SPSC/P265 Add. 1.

[4] S. Afanasjev *et al.* (NA49 Collab.), *Nucl. Instrum. Methods* **A430**, 210 (1999).

[5] J.C. Collins, M.J. Perry, *Phys. Rev. Lett.* **34**, 151 (1975).

[6] E.V. Shuryak, *Phys. Rep.* **C61**, 71 (1980) and **C115**, 995 (1984).

[7] For recent review see Proceedings of the Thirteenth International Conference on Ultra-Relativistic Nucleus–Nucleus Collisions, Tsukuba, Japan, December 1–5, 1997, *Nucl. Phys.* **A638** (1998).

[8] M. Gaździcki, M.I. Gorenstein, hep–ph/9803462, *Acta Phys. Pol.* **B30**, 2705 (1999) and references therein.

[9] G. Odyniec, *Nucl. Phys.* **A638**, 135c (1998).

[10] H. Satz, Colour Deconfinement and J/ψ Suppresion in High Energy Nuclear Collisions, hep–ph/9711289 (1997).

[11] K.R. Popper, *The Logic of Scientific Discovery*, Hutichson (1959).

[12] *Hard Processes in Hadronic Interactions*, eds. H. Satz and X.-N. Wang, Special Issue of *Int. J. Mod. Phys.* **10**, 2881 (1995).

[13] C. Gerschel, J. Hüfner, Charmonium Suppression in Heavy–Ion Collisions, hep–ph/9802245 (1998).

[14] J.C. Collins, Hard-Scattering Factorization with Heavy Quarks: A General Treatment, hep–ph/9806259.

[15] M. Gaździcki, *Phys. Rev.* **C60**, 054903 (1999).

[16] S. Berlag *et al.* (NA32 Collab.), *Z. Phys.* **C39**, 451 (1988).

[17] G.A. Alves *et al.* (E768 Collab.), *Phys. Rev. Lett.* **77**, 2388 (1996).

[18] M. Aguilar-Benitez *et al.* (LEBC–EHS Collab.), *Phys. Lett.* **B135**, 237 (1984).

[19] M. Aguilar-Benitez *et al.* (LEBC–EHS Collab.), *Z. Phys.* **C40**, 321 (1988).

[20] R. Ammar *et al.* (LEBC–MPS Collab.), *Phys. Rev. Lett.* **61**, 2185 (1988).

[21] M.J. Leitch *et al.* (E789 Collab.), *Phys. Rev. Lett.* **72**, 2542 (1994).

[22] H. Appelshauser *et al.* (NA49 Collab.), *Phys. Rev. Lett.* **82**, 2471 (1999).

[23] M. Gaździcki, D. Röhrich, *Z. Phys.* **C65**, 215 (1995).

[24] P. Braun-Munzinger *et al.*, *Eur. Phys. J.* **C1**, 123 (1998).

[25] E. Scomparin *et al.* (NA50 Collab.), CERN–EP/98–188.

[26] C. Caso *et al.* (Particle Data Group Collab.), *Eur. Phys. J.* **C3**, 1 (1998).

[27] M. Gaździcki, J. Pluta, W. Retyk, Search for Short Lived Particles in High Multiplicity Enviroment, nucl-ex/9904008.