Open charm enhancement by secondary interactions in relativistic nucleus-nucleus collisions?*

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Abstract

We calculate open charm production in $Pb+Pb$ reactions at SPS energies within the HSD transport approach - which is based on string, quark, diquark $(q, \bar{q}, qq, \bar{q}\bar{q})$ and hadronic degrees of freedom - including the production of open charm pairs from secondary 'meson'-'baryon' (or quark-diquark and antiquark-diquark) collisions. It is argued that at collision energies close to the $c\bar{c}$ pair threshold the dominant production mechanism is related to the two body (or quasi two body) reactions $\pi N \to \bar{D}(\bar{D}^*)\Lambda_c, (\Sigma_c)$. Estimates within the framework of the Quark-Gluon String model suggest cross sections of a few μb for $\pi N \to \bar{D}\Lambda_c$ in the region of 1 GeV above threshold. The dynamical transport calculations for $Pb+Pb$ at 160 A·GeV indicate that the open charm enhancement reported by the NA50 Collaboration might be due to such secondary reaction mechanisms.

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1 Introduction

In the last decade the interest in hadronic states with charm flavors ($c, \bar{c}$) has been rising continuously in line with the development of new experimental facilities [1]. This relates to the charm production cross section in pN and πN reactions as well as to their interactions with baryons and mesons which determine their properties (spectral functions) in the hadronic medium. The charm quark degrees of freedom play an important role especially in the context of a phase transition to the quark-gluon plasma (QGP) [2] where charmonium ($c\bar{c}$) states should no longer be formed due to color screening [3, 4]. However, the suppression of J/Ψ and Ψ' mesons in the high density phase of nucleus-nucleus collisions [5, 6] might also be attributed to inelastic comover scattering (cf. [7, 8, 9, 10, 11] and Refs. therein) provided that the corresponding J/Ψ-hadron cross sections are in the order of a few mb [12, 13, 14, 15, 16]. Present theoretical estimates here differ by more than an order of magnitude [17] especially with respect to J/Ψ-meson scattering such that the question of charmonium suppression is not yet settled. On the other hand, the enhancement of 'intermediate-mass dileptons' in $Pb+Pb$ collisions at the SPS has been tentatively attributed to an enhancement of 'open charm' in nucleus-nucleus collisions relative to pA reactions at the same invariant energy $\sqrt{s}$ [18]. Thus 'charmonium suppression' and 'open charm enhancement' are present facets of relativistic heavy-ion collisions, which provide a theoretical [15, 19, 20, 21, 22, 23] and experimental challenge for the future [24, 25].

In this letter we will argue that the open charm excess reported in Ref. [18] might be due to secondary meson-baryon (quark-diquark) interactions. We will employ the HSD transport approach [7, 10, 26] for the overall reaction dynamics of nucleus-nucleus collisions using parametrizations for the elementary production channels for the charmed hadrons $D, \bar{D}, D^*, \bar{D}^*, D_s, \bar{D}_s, D_s^*, \bar{D}_s^*$, $J/\Psi, \Psi(2S), \chi_{2c}$ from NN and πN collisions. We recall that in the HSD transport approach the initial stages of a πN, pp, pA or AA reaction (at high energy) are described by the excitation of color neutral strings, where the leading quarks and 'diquarks' in a baryonic string (or quarks and antiquarks in a mesonic string etc.) are allowed to rescatter again (in case of nuclear targets) with hadronic cross sections divided by the number of constituent quarks and antiquarks in the hadrons, respectively [27].

In order to explore the kinematical situation for secondary 'meson'-'baryon' interactions we show in Fig. 1 the distribution in the invariant collision energy $\sqrt{s}$ from such secondary interactions (solid histogram) for a central collision of $Pb + Pb$ at 160 A·GeV from the HSD approach. This distribution extends to about 15 GeV while the corresponding primary baryon-baryon collisions are centered around 17.3 GeV (dashed histogram) and become less frequent than the 'meson'-'baryon' collisions for $\sqrt{s} \leq 13$ GeV. Since the threshold for open charm production in meson-baryon collisions is $\sqrt{s_0} = m_D + m_{\Lambda_c} \approx$ 4.15 GeV there are a lot of secondary collisions above threshold. The crucial question now is the magnitude of the open charm cross section in 'meson'-'baryon interactions for 4.15 GeV $\leq \sqrt{s} \leq 15$ GeV, i.e from threshold up to roughly 10 GeV above threshold.

As argued in Refs. [20, 28] the creation of a $c\bar{c}$ pair at high $\sqrt{s}$ is due to a hard process and dominated by gluon-gluon fusion (cf. Fig. 2a) for an illustration of a pp reaction). On the other hand, the quark annihilation mechanism is found to contribute significantly or even to become dominant for πN reactions at lower $\sqrt{s}$ [29]. This mechanism is depicted

Table 1: The parameters a_x, α and β in Eq. (1) for inclusive D-meson production in πN reactions

πN				
Meson	$\sqrt{s_0}$ [GeV]	a_x [mb]	α	β
D^0	4.667	0.273	2.86	1.28
$\bar{D}^0$	4.150	0.247	3.80	1.26
D^+	4.671	0.255	3.22	1.28
D^-	4.154	0.286	3.50	1.22
D^{0*}	4.951	1.076	3.14	1.22
$\bar{D}^{0*}$	4.292	0.774	3.80	1.26
D^{+*}	4.955	0.719	2.86	1.32
D^{-*}	4.296	0.839	3.40	1.24
D_s^+	4.875	0.0932	3.62	1.22
D_s^-	4.435	0.0545	3.70	1.34
D_s^{+*}	5.162	0.284	3.42	1.24
D_s^{-*}	4.578	0.163	3.64	1.34

in Fig. 2b) for the particular final state $\bar{D}\Lambda_c$, where – by convention – $\bar{D}$ stands for a D-meson with a $\bar{c}$-quark. However, the perturbative $q\bar{q} \to 1$ gluon $\to c\bar{c}$ process is included in standard PYTHIA calculations [30] and drops very fast with decreasing $\sqrt{s}$ close to the threshold of $D-$meson production [28]. We recall that in Ref. [28] the open charm cross sections for pN and πN reactions have been calculated within PYTHIA using MRS G (next to leading order) structure functions from the PDFLIB package [31] for the gluon distribution of the proton, a bare charm quark mass $m_c = 1.5$ GeV and $k_T = 1$ GeV. The results from PYTHIA (scaled to the available data [28]) for $D, \bar{D}, D^*, \bar{D}^*, D_s, \bar{D}_s, D_s^*, \bar{D}_s^*$, as a function of $\sqrt{s} \geq 10$ GeV have been parametrized by an expression of the form,

$$\sigma_X(s) = a_X (1-Z)^{\alpha} \ Z^{-\beta}, \qquad (1)$$

with $Z = \sqrt{s_X^0}/\sqrt{s}$ where $\sqrt{s_X^0}$ denotes the threshold for the channel X in pN or πN reactions. The individual parameters a_X, α and β from this fit are given in Table 1 for πN reactions. As found in Ref. [28] the contribution to open charm production from 'secondary' interactions – employing the parametrizations (1) – are about ~ 9 % in central $Au + Au$ collisions at 160 A·GeV. This order of magnitude for the open charm enchancement is far below the observation of Ref. [18].

On the other hand, close to threshold, one would expect the exclusive reaction $\pi N \to \bar{D}\Lambda_c$ to dominate. In case of S -wave production this cross section then should rise as $\sim (1-Z)^{0.5}$ for a two-body final channel. Such a behaviour is well known experimentally [32] for the reactions $\pi^+ p \to \rho^+ p$, $\pi^- p \to \omega n$, $\pi^- p \to K^0 \Lambda$ or $\pi^- p \to \phi n$ as displayed in Fig. 3. These experimental cross sections can be described by the expression

$$\sigma_{\pi N \to XB}(\sqrt{s}) = a_X (1 - \frac{\sqrt{s_0}}{\sqrt{s}})^{0.5} (\frac{\sqrt{s_0}}{\sqrt{s}})^{\gamma_X} \qquad (2)$$

with $a_\rho = 15$ mb, $a_\omega = 12$ mb, $a_{K^0} = 2.5$ mb, $a_\phi = 0.2$ mb and $\gamma_\omega = \gamma_K = 6$, $\gamma_\rho = 5$ and $\gamma_\phi = 10$, respectively. In Eq. (2) $\sqrt{s_0}$ denotes the threshold for each reaction separately. For $\sqrt{s} - \sqrt{s_0} \geq m_\pi$ three-body final states (with an additional pion) become possible while multi-particle production dominates at high invariant energy. To demonstrate the relative importance of multi-particle final states the inclusive cross sections for ρ^+, ω and ϕ are shown in terms of the thick lines in Fig. 3 using the parametrizations from the review [7]. The inclusive yield for all open charm mesons with a $\bar{c}$ quark is shown in terms of the lower thick solid line in Fig. 3 where the parametrisations (1) have been employed with the parameters from Table 1 (cf. [28]). The related data (full squares) have been taken from the review of Tavernier [33]. We recall that for $\sqrt{s} - \sqrt{s_0} \geq 6$ GeV the parametrization reflects the PYTHIA results (scaled to the available data) and at lower energies lacks a more fundamental justification as pointed out in Ref. [28].

Since the binary exclusive reactions dominate the threshold behaviour for ρ, ω, K^0 and ϕ production, one can expect a similar relation to hold also for the channels $\bar{D}\Lambda_c$, $\bar{D}^*\Lambda_c$, $\bar{D}\Sigma_c$, $\bar{D}^*\Sigma_c$, *etc.* Here the reaction mechanism is expected to be dominated by D^*-meson or D^*-Reggeon exchange as illustrated in Fig. 2c). The question that remains is the size of a related parameter a_D in (2). Here we refer to the Regge model for an estimate.

In Ref. [34] the cross section for the reaction $\pi N \to \bar{D}(\bar{D}^*)\Lambda_c$ has been estimated within the framework of the Quark-Gluon String Model (QGSM) developed in Ref. [35]. The GGSM is a nonperturbative approach based on a topological $1/N_f$ expansion in QCD, where N_f denotes the number of flavors, and on the color-tube model. This approach can be considered as a microscopic model describing Regge phenomenology in terms of quark degrees of freedom. It provides the possibility to establish relations between many soft hadronic reactions as well as masses and partial widths of resonances with different quark contents (see e.g. the review [36]). Recently, this model also has been successfully applied to the description of the nucleon and pion electromagnetic form factors [37] and deuteron photodisintegration [38].

The amplitude of the reaction $\pi N \to \bar{D}(\bar{D}^*)\Lambda_c$ corresponding to the planar graph of Fig. 2c) with u and $\bar{c}$ quark exchange in the t channel – using the Mandelstam variables s and t – can be written as (see Ref. [34])

$$A_{\pi^- p \to \bar{D}\Lambda_c}(s,t) = \sqrt{2} g_0^2 F(t) (s/s_0^{u\bar{c}})^{\alpha_{u\bar{c}}(t)-1} (s/\bar{s}), \tag{3}$$

where $g_0 \simeq 5.8$ is a universal flavor independent coupling constant, $\alpha_{u\bar{c}}(t) = \alpha_{D^*}(t)$ is the D^* Regge trajectory, $\bar{s} = 1$ GeV^2, $s_0^{u\bar{c}} = 4.9$ GeV^2 is the flavor dependent scale factor and $F(t)$ is the form factor describing the t dependence of the residue. We have considered two forms of the D^* Regge trajectory, i.e.
i) a linear trajectory (set a from Ref. [34])

$$\alpha_{D^*}(t) = -0.86 + 0.5t \tag{4}$$

ii)a nonlinear trajectory, i.e. the square root trajectory from Ref. [39]

$$\alpha_{D^*}(t) = \alpha_{D^*}(0) - \gamma[\sqrt{T} - \sqrt{T-t}] \tag{5}$$

with $\alpha_{D^*}(0) = -1.02$, $\gamma = 3.65$ GeV^{-1}, $\sqrt{T}$ =3.91 GeV. Both choices lead to very similar total cross sections such that we do not discuss the two choices separately. The form factor $F(t)$ determining the t-dependence of the residue has been parametrized in Ref. [34] as

$$F(t) = \Gamma(1 - \alpha_D{}^*(t)) \tag{6}$$

and is motivated by dual models. The form factor (6) is convenient for an analytical continuation of the amplitude to the region of positive t, where the Γ function in (6) is an exponentially decreasing function of t. In particular, the form (6) was successfully used to relate the normalization of different planar graphs at t= 0 with the widths of the mesons lying on the corresponding Regge trajectories. For example, in Ref. [40] a width $\Gamma(D^{*+} \to D^0\pi^+ + D^+\pi^0) = (3/2)\Gamma(D^{*+} \to D^0\pi^+)$= 20 keV was found. This value is not very different from the result based on the QCD sum rules [41] giving $\simeq$ 48 keV, while the experimental upper limit is 131 keV.

However, in the region of negative t the parametrization (6) exhibits a factorial growth (which is faster than exponential) and therefore is not acceptable. For $t \leq 0$ we will use the convential parametrization

$$F(t) = \Gamma(1 - \alpha_D{}^*(0)) \exp(R^2 t) \tag{7}$$

with $R^2 = 0 \div 0.2$ GeV^{-2}.

The differential cross section for the reaction $\pi^- p \to \bar{D}\Lambda_c$ then is

$$\frac{d\sigma_{\pi^- p \to \bar{D}\Lambda_c}}{dt} = \frac{1}{64\,\pi s}\,\frac{1}{(p_\pi^{\rm cm})^2}\,\,|A_{\pi^- p \to \bar{D}\Lambda_c}(s,t)|^2, \tag{8}$$

where $p_\pi^{\rm cm}$ denotes the pion momentum in the cms, and the total cross section is obtained by integrating (8) over the kinematical allowed regime.

The result for the channel $\pi^- p \to \bar{D}\Lambda_c$ (using $R^2 = 0$) is shown in Fig. 3 by the lower solid line as a function of $\sqrt{s} - \sqrt{s_0}$, which can be well described by the function (2) using a_D = 0.027 mb and $\gamma_D = \gamma_\omega = \gamma_K = 6$ (lower dashed line). The ratio of the ω cross section to the 'estimated' $\bar{D}$ cross section close to threshold ($\sqrt{s} - \sqrt{s_0} \approx 0.4$ GeV) is $\sim$ 500; a similar ratio holds for the inclusive cross sections at $\sqrt{s} - \sqrt{s_0} \approx 30$ GeV where explicit data are available for the $\pi N \to D\bar{D} + X$ reaction. Thus our estimate in the Regge model sounds reasonable, however, has to be controlled by experiment in order to allow for definite conclusions.

We mention that similar exclusive cross sections can also be obtained from boson-exchange models with D^* or D_1 exchange (cf. Fig. 2c) employing monopole form factors at the vertices with cutoffs Λ ($\approx 1.6 - 1.9$ GeV) while fixing the couplings $g_{\bar{D}\pi\bar{D}^*}$ and $g_{\bar{D}^*\pi = D_1}$ to the $\pi\bar{D}$ and $\pi\bar{D}^*$ decay widths, respectively. Furthermore, the cross section for the reaction $NN \to \bar{D}(D^*)\Lambda_c N$ has been calculated within the Reggezied one-pion exchange model using the pion form factor $F_\pi = \exp(R_\pi^2 t)$ with $R_\pi^2 = 0.1(GeV/c)^{-2}$ as in Ref. [34]. Since the explicit cross sections for the NN reactions at low $\sqrt{s}$ are of no major importance for our present study, we refer the reader to a forthcoming publication on these issues [42].

For the transport calculations (to be discussed below) we estimate the cross section for charmed hadron production in πN reactions by employing the ansatz (2) for all charmed hadrons such as $\bar{D}, \bar{D}^*, \bar{D}_s, \bar{D}_s^*$ with associated charmed hyperons $\Lambda_c, \Sigma_c, \Lambda_c^s$.... We explicitly adopt $a_D = 1/3 a_{D^*} = a_{D_s^*} = 3 a_{D_s}$ (as in Ref. [28]) with $a_D \approx 0.027$ mb. These estimates, of cause, only have exploratory character as stated above.

We now turn to the results of transport calculations for the reaction $Pb + Pb$ at 160 A·GeV. A description of the transport approach is given in Refs. [7, 27] and the production and propagation of charmed mesons is described in Refs. [28, 43, 44]. The novel phenomenon addressed here with respect to Ref. [28] is the secondary production of open charm mesons by 'meson'-'baryon' collisions with the new parametrizations (2) for the low-energy $\pi N \to \bar{D}(\bar{D}^*)\Lambda_c(\Sigma_c)$ processes. We mention in passing that the role of secondary reactions on intermediate mass dilepton pairs via the $q\bar{q} \to \gamma \to l^+l^-$ (Drell-Yan) mechanism has been investigated in the UrQMD transport model in Ref. [45] for nucleus-nucleus collisions at SPS energies before.

In Fig. 4 we show the open charm multiplicity (all $D, \bar{D}, D^*, \bar{D}^*, D_s^*, \bar{D}_s^*, D_s, \bar{D}_s$) as a function of the impact parameter b from the HSD approach for $Pb + Pb$ at 160 A·GeV. Here the dashed line gives the yield from primary baryon-baryon collisions, which is essentially the yield from pn reactions at $\sqrt{s} \approx 17$ GeV times the number of 'hard' pN collisions (as given by Eq. (6) of Ref. [28]), while the solid line corresponds to the yield of open charm from secondary reactions as described above. Whereas for peripheral collisions the secondary production is slightly smaller than the direct channel, the yield from secondary meson-baryon channels becomes larger with decreasing impact parameter b. The tiny kinks in the curves in Fig. 4 are due to the limited statistics of the transport calculations. Without explicit representation we note that the final differential spectra of the D-mesons in transverse momentum and rapidity are very similar to those from primary and secondary channels, respectively, due to rescattering with the surrounding hadrons (cf. Ref. [28]).

In order to compare to the data from the NA50 Collaboration [18] we have to adopt a model to convert the number of participating nucleons A_{part} to the impact parameter b from the transport calculation. We use

$$A_{part} = 2A - N_0(b), \tag{9}$$

where $N_0(b)$ stands for the number of noninteracting nucleons (with no 'hard' collisions) from the transport code at impact parameter b while A is the target (projectile) mass number. Denoting the expected number of $D, \bar{D}$ mesons from primary BB collisions by $N_{prim.}$ and the number from secondary 'meson'-'baryon' interactions by $N_{sec.}$ this leads to the ratio

$$R(b) = \frac{N_{prim.} + N_{sec.}}{N_{prim.}}(b) = R(A_{part}(b)) = R(A_{part}), \tag{10}$$

which is displayed in Fig. 5 (solid histogram) in comparison to the data on the open charm enhancement from Ref. [18]. The calculated ratio first increases fast with A_{part} and becomes almost constant for $A_{part} \geq 100$. This is due to the fact that secondary semihard 'meson'-'baryon' reactions with 'wounded' nucleons, that have scattered at least once, already set in for large impact parameter b; their relative number then increases only slightly faster than $\sim A_{part}$. Obviously, the general trend of the data can be roughly described with increasing centrality for the secondary cross sections specified above. The present statistical uncertainty of the data [18] does not allow for a final conclusion.

In summary: in this letter we have argued that for 'low' energy 'meson'-'baryon' reactions the dominant $c\bar{c}$ production is related to the two-body (or quasi two-body) reactions $\pi N \to \bar{D}(\bar{D}^*)\ \Lambda_c(\Sigma_c)$. Estimates within the framework of the Quark-Gluon String model suggest cross sections of a few μb for $\pi N \to \bar{D}\Lambda_c$ in the region of about 1 GeV above threshold. The estimated order of magnitude for the open charm cross section (cf. lower part of Fig. 3) is found to be compatible with the 'open charm enhancement' claimed by the NA50 Collaboration at the SPS [18] without employing the assumption of thermal and chemical or statistical equilibrium as advocated in Refs. [46, 47, 48]. It should be stressed, however, that experimental investigations on open charm production in πN reactions at invariant energies of $4.2 \leq \sqrt{s} \leq 15$ GeV are mandatory to confirm or disprove our suggestion.

We, furthermore, note that the cross section for charmonia such as J/Ψ, χ_c or Ψ' are not substantially enhanced by such secondary reaction channels since their cross sections are small in πN collisions [8, 28] such that no substantial 'enhancement' of charmonia relative to the primary NN reaction channels is expected.

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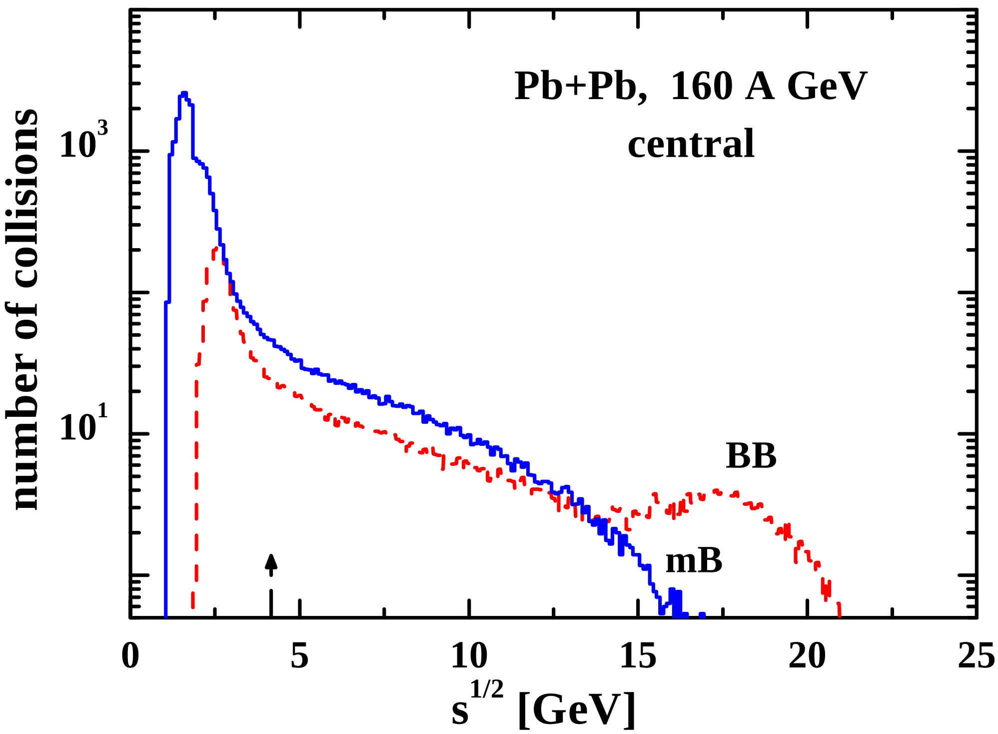

Figure 1: The distribution in the invariant collision energy $\sqrt{s}$ from primary baryon-baryon (dashed histogram; BB) and secondary 'meson'-'baryon' interactions (solid histogram; mB) for a central collision of $Pb + Pb$ at 160 A·GeV from the HSD transport approach. The arrow at $\sqrt{s} \approx 4.15$ GeV denotes the threshold for $\bar{D} + \Lambda_c$ production in secondary interactions. Note, that contrary to Fig. 13 in Ref. [10] 'meson' interactions with 'wounded' nucleons (or diquarks) are taken into account, too.

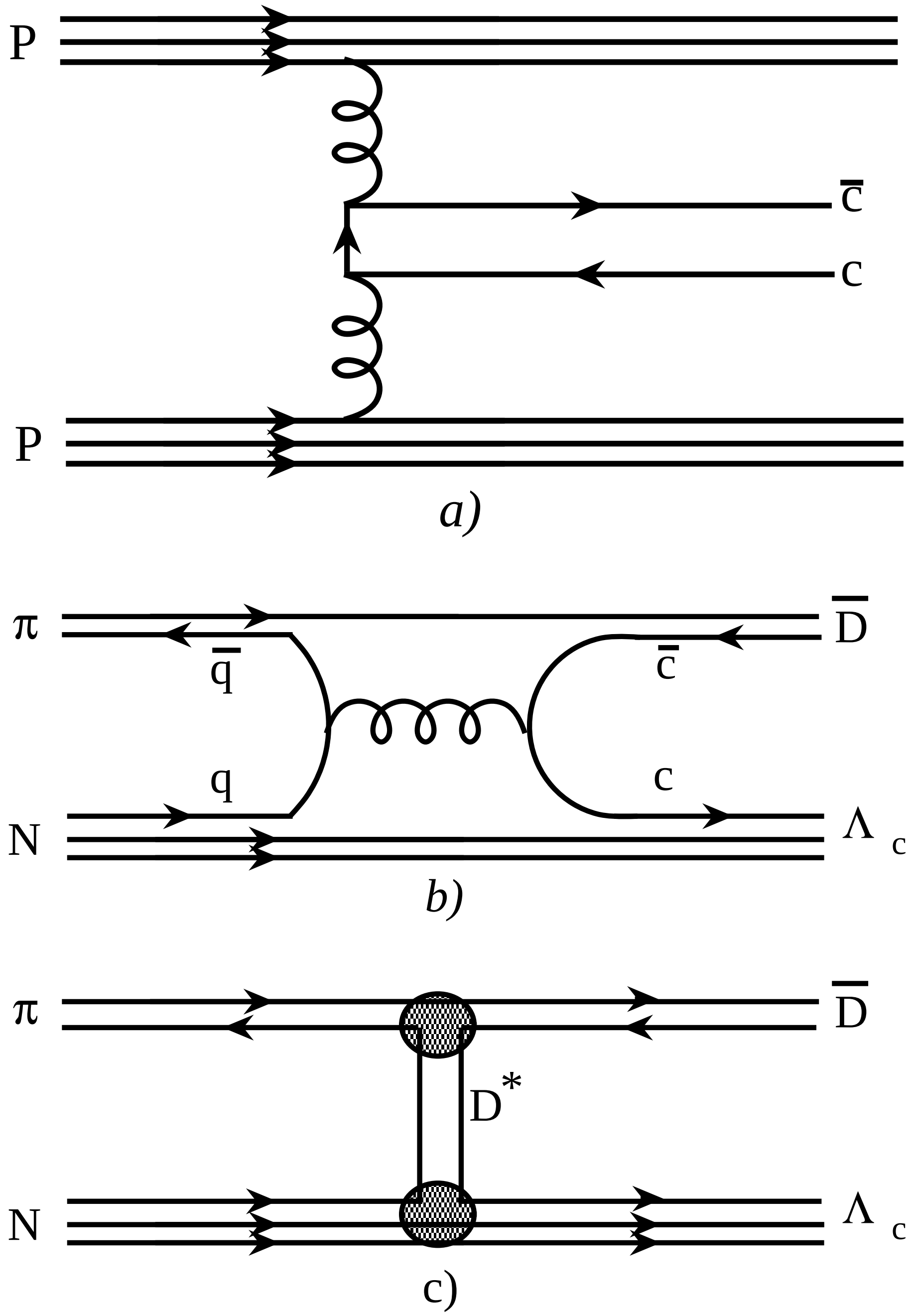

Figure 2: Diagrams for $c\bar{c}$ production in pp collisions via two-gluon fusion (a), for $\bar{D}\Lambda_c$ production in πN collisions via $q\bar{q}$ annihilation (b) and for $\bar{D}\Lambda_c$ production in πN collisions via D^*-exchange (c).

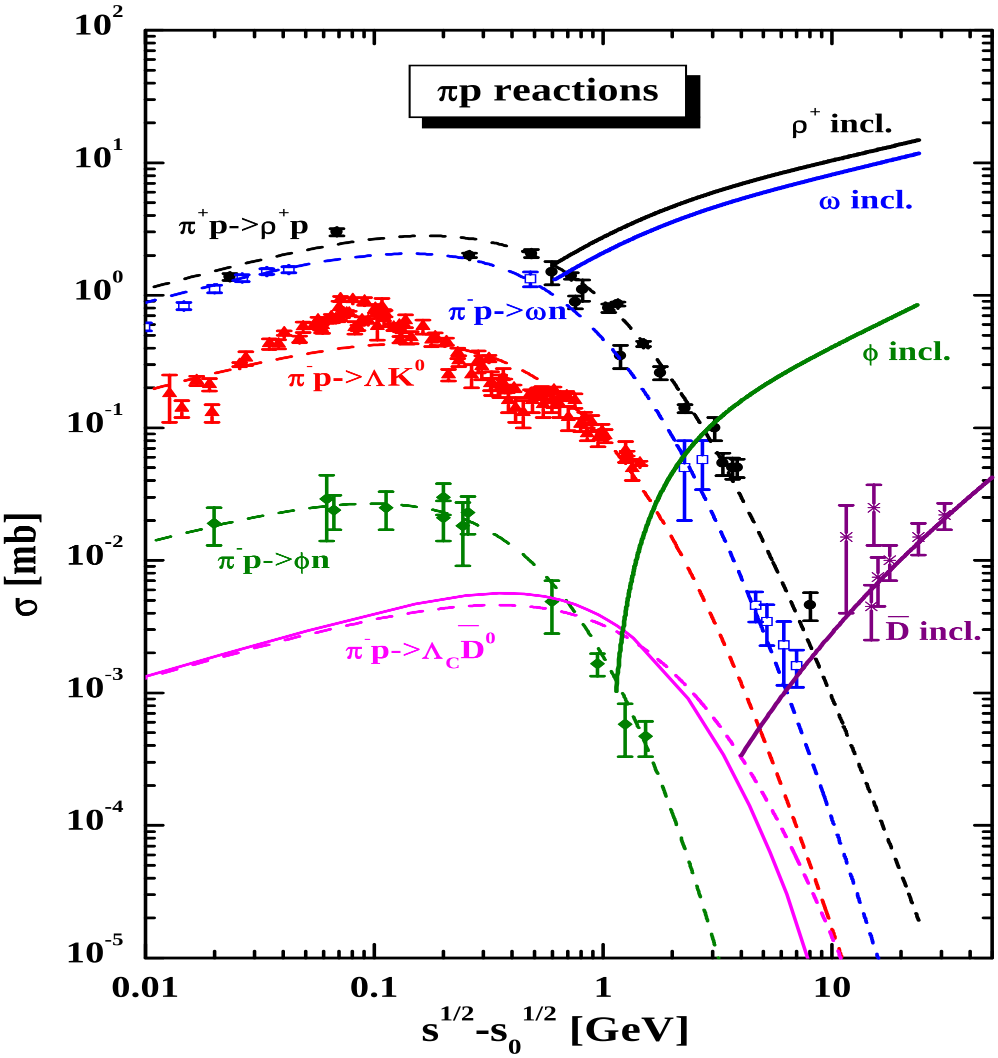

Figure 3: The exclusive cross sections for the reactions $\pi^+ p \rightarrow \rho^+ + p$, $\pi^- p \rightarrow \omega + n$. $\pi^- p \rightarrow K^0 + \Lambda$ and $\pi^- + p \rightarrow \phi + n$ from Ref. [32] in comparison to the parametrizations (2) (dashed lines). The inclusive cross sections for ρ^+, ω and ϕ mesons are displayed in terms of the upper thick solid lines, respectively, within the parametrizations from the review [7]. The lower solid line is the prediction for the process $\pi^- + p \rightarrow \bar{D}^0 + \Lambda_c$ within the Regge model; the lower dashed line is the corresponding parametrization by (2). The inclusive yield for all open charm mesons with a $\bar{c}$ quark ($\bar{D}$ incl.) is shown in terms of the lower thick solid line where the functions (1) have been employed with the parameters from Table 1. The related inclusive data ($*$) have been taken from Ref. [33].

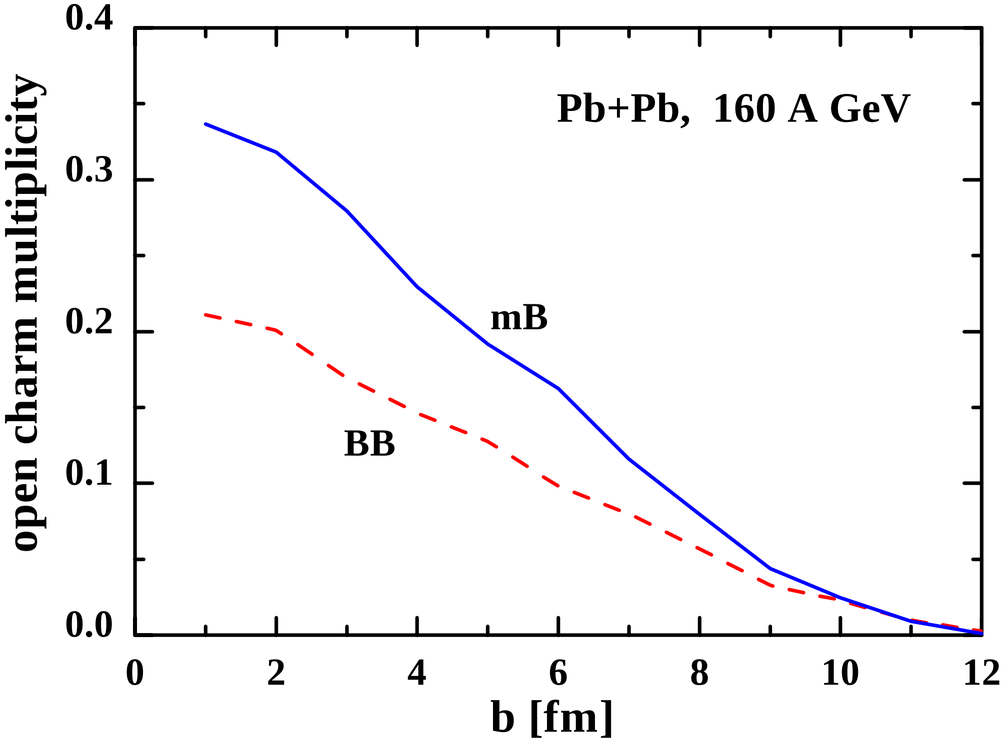

Figure 4: The multiplicity of all $D, \bar{D}$ mesons from the HSD transport approach for $Pb+Pb$ at 160 A·GeV as a function of impact parameter b. The dashed line stands for the yield from primary baryon-baryon collisions while the solid line denotes the contribution from secondary 'meson'-'baryon' collisions within the parametrization (2).

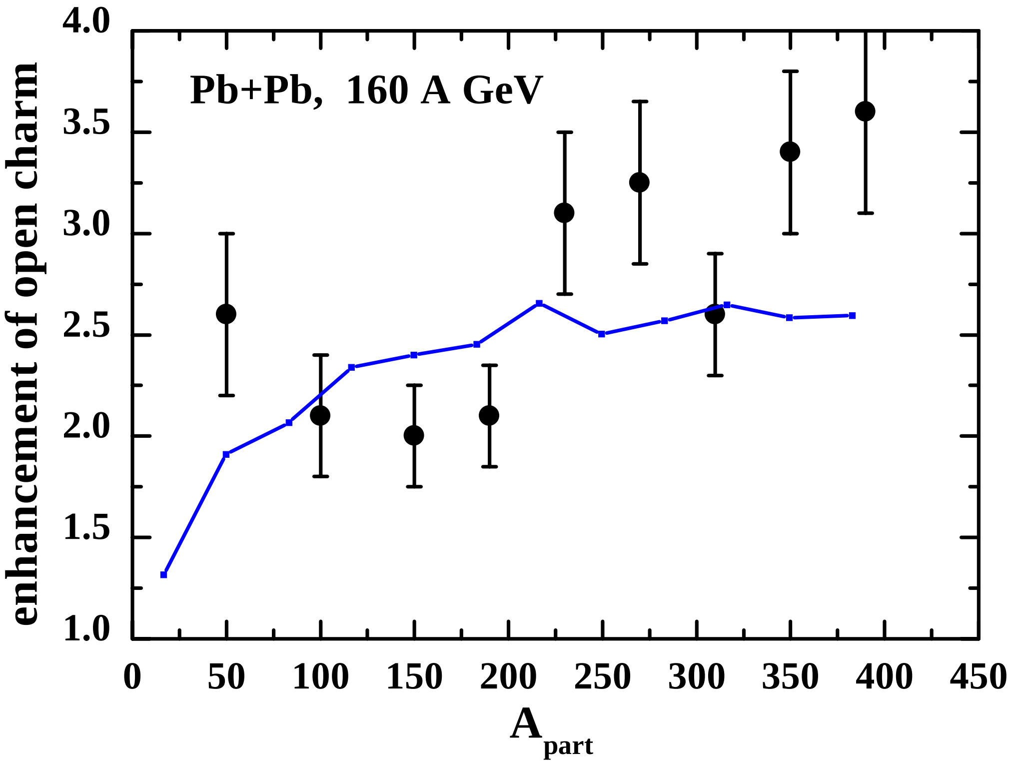

Figure 5: The enhancement factor (10) for the production of all $D, \bar{D}$ mesons from the HSD transport approach for $Pb + Pb$ at 160 A·GeV as a function of the number of participants A_{part} (see text) in comparison to the data from Ref. [18].