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Charm Production in the Firetube Model

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Abstract

It is shown that the non-perturbative Schwinger mechanism can account for the charm production data in hadron-hadron collisions. This result comes from the fact that, due to a multiple exchange of gluons, the string constant in a hadron-hadron collision can be much larger than that of the usually quoted value for an elementary color triplet string.

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The firetube model [1] for hadron-hadron collisions provides a very simple description for the mechanism of hadron production, reproducing the main features of the observed particle spectra. Generally speaking, the firetube model assumes that a classical thick string (firetube) is formed in between the hadrons during the collision. Then this firetube fragments into several fireballs which subsequently decay into observed hadrons. The model shares many similar aspects with the commonly used models based on the fragmentation of a classical string, such as the LUND model [2]. However, there exist basic differences. First, in the firetube model, the string tension can be much larger than that of an elementary string between a quark-antiquark pair. Second, most of the final hadrons come from the thermal decay of fireballs. These points bring quite a new aspect into the mechanism of hadron production. For example, in a common string fragmentation model, the production of hadrons comes directly from the string breakup which, in turn, is related to the creation of quark-antiquark pairs via a Schwinger-like mechanism. In such an image, the so-called K/π ratio would be strictly related to the string constant κ. In contrast to this, the mechanism responsible for the production of pions in the firetube model is the decay of fireballs and has nothing to do with the production of $q\overline{q}$-pairs via Schwinger mechanism. In this sense, the K/π ratio does not necessarily represent the string tension. Furthermore, if the string constant is as small as the standard value ~ 1 GeV/fm, the Schwinger mechanism cannot account for the observed rate of charmed particles [2]. However, in the firetube model, the classical string in between the colliding hadrons is supposed to be formed by the exchange of multiple sea partons (assumed to be gluons in this note). Therefore, the strength of the string constant for hadron–hadron collision is not necessarily the same as that of the $q\bar{q}$-string created, for example, in the electron-positron annihilation process. Since the heavy quark production rate is extremely sensitive to the value of the string constant, a slight increase of this quantity drastically changes the situation and can easily account for a significant part of the observed charm production rate.

In this work, we show that in hadron-hadron collision processes the effective string constant can be much greater than that of the elementary string. We calculate the hadron production rates and spectra for proton-proton collisions in the framework of the firetube model and show that they are quite consistent with the experimental data. In particular, the non-perturbative charm production via Schwinger mechanism is found to be in good agreement with the observed data. The Feynman x_F dependence of charmed particles extends to large values of x_F , showing an effect similar to that of the so-called *intrinsic charm* model advocated by Brodsky and colleagues [3].

It is of special interest to extend the above idea to hadron-nucleus collisions. In our model, it is found that the production rate of charmed particles by a nuclear target has a linear dependence in A if we restrict to the positive x_F region. However, for negative x_F, the production cross section increases more rapidly than linearly in A, which is not the case in perturbative QCD (PQCD) models.

Firetube Model - When two hadrons collide, several gluons are exchanged between them. As a result, these hadrons become colored objects joined by a color flux tube, which we call the firetube. Let S be the cross section of this firetube (~ geometrical size of the colliding hadrons), and Q be the color charge at the end points of the firetube, measured in units of the elementary charge q_o of a quark. Ignoring the contribution from the chromomagnetic field, the chromoelectric field E is given by Gauss' theorem, $E = q_oQ/S$, and the force which acts on an elementary charge inside the firetube will be q_oE. On the other hand, the string constant κ is related to the field energy density as $\kappa = E^2S/2$. From this, we get

$$\kappa = \kappa_o Q^2 \tag{1}$$

$$q_oE = 2\kappa_o Q \tag{2}$$

where we denoted the quantity $q_o^2/2S$ by κ_o. We identify the constant κ_o as the string constant of an "elementary string ".

For each collision process, the chromoelectric charge Q fluctuates if the number of exchanged gluons is greater than one. Assuming that each gluon exchange is a step of a random walk in color space [4], it can be shown that the charges generated on the hadrons after the exchange of n gluons distribute sharply around the mean value $3/2\sqrt{n}$, where the 3/2 factor accounts for the gluonic octet charge. Thus we get $\kappa \simeq 9/4\kappa_o n$ and $q_oE \simeq 3\kappa_o\sqrt{n}$, showing that the exchange of a few gluons can generate string constants and chromoelectric fields significantly larger than the elementary ones.

To determine completely the string constant, we simply assume that the probability distribution of n is given by a truncated Poisson distribution, $P_n \sim \nu^n/n!$ for $n \geq 1$, where ν is a parameter. Once the string constant κ is determined, we proceed the firetube fragmentation mechanism explained in Ref.[1]. For proton-proton collision at $\sqrt{s} = 21$ GeV, we show in Fig.1 the calculated charged particle pseudo-rapidity distribution together with the experimental data [5]. The parameter values for this Monte Carlo simulation are $\nu = 1.3$, $\kappa_o = 1$ GeV/fm, $S = 2.2$ fm^2, $\omega = 0.3$ fm^{-2}, $\alpha_o = 0.22$, $m_s = 450$ MeV, and $m_c = 1150$ MeV, where ω is the breakup rate of the firetube and α_0 is a parameter related to the longitudinal hydrodynamical expansion of fireballs [1]. The masses m_s and m_c of the s and c quarks will be needed in the calculation of the production rates as we show below.

Strangeness and Charm Production - Let us suppose that the production rate of s and c quarks is given by

$$\mathcal{R} = \sum_{n=1}^{\infty} \frac{(q_oE)^2}{4\pi^3 n^2} \exp\left\{-\frac{n\pi m^2}{q_oE}\right\} \tag{3}$$

similar to the Schwinger mechanism of electron-positron pair creation in QED. In this formula, m is the quark mass and $q_oE = \kappa_o(2Q-1)$, taking into account the charge shielding effect due to the pair production. As we see, the production rate is extremely sensitive to the value of $q_o E$ for heavy particles. For example if $q_o E$ were of the order of 1 GeV/fm as usually quoted in the string model, the dominant exponential factor in Eq.(3) would be of the order of 10^{-12} and no reasonable interaction volume and time scale for hadron-hadron collision would account for the observed charmed particle production cross section. On the other hand, in our model, if gluons are exchanged between the colliding hadrons according to the SU(3) random walk distribution, the average value of the exponential factor for charm quark pair becomes as large as $\sim 10^{-4}$ for the parameter values given above.

In order to calculate the charmed particle spectra we proceed as follows. First, we calculate the space-time volume VT for a given firetube fragmentation into fireballs as the total area swept by the firetube in the x-t plane times the firetube cross section S. The total number of charmed quarks is then twice the value $VT \times \mathcal{R}$. We assume that each fireball carries these quarks with a probability proportional to its mass. The charmed particles are emitted from the fireballs following their longitudinal expansion and thermal decay, in the same way as other mesons. In Fig.2, we show a x_F distribution of charmed mesons calculated with the model (solid line) together with the experimental data for $D/\bar{D}$ production [6]. The agreement is quite satisfactory. Note that our x_F distribution is wider than that of PQCD predictions with fragmentation function taken from electron-positron experiments, giving a result similar to that of the intrinsic charm model [3]. The transverse momentum distribution predicted by the model is also in excellent agreement with experimental data [6], as is shown in Fig.3.

In addition to the central fireballs of the firetube fragmentation, there is a contribution from the leading particles. The mechanism for firetube fragmentation into fireballs assumes a homogeneous constant probability rate of firetube breaking. There is no a priori reason for this mechanism to remain the same for the two end-point particles which contain valence quarks, because of the different boundary condition. In order to reproduce the observed proton leading particle spectra, we suppose that the two incident hadrons detach from the firetube with a constant probability rate on its trajectory. When the incident hadrons separate from the firetube, there exists a probability that they turn into charmed particles (such as Λ_c) since we suppose that the leading particle detaching mechanism is due to the color screening effect caused by the production of $q\bar{q}$-pairs. Thus, it is reasonable to assume that this probability is given as the ratio of the production rate of charmed quarks to that of any type of quarks. We calculate these production rates according to Eq.(3) for each quark. One of the charmed quarks is distributed into the detached hadron turning it into a charmed baryon, and the other quark is associated to the adjacent fireball. The dotted line in Fig.2 indicates the spectrum of the leading charmed baryons.

As we have seen, the large string tension in between two colliding hadrons can accommodate both the pion and charmed meson spectra quite satisfactorily. At this point, one may worry about the strange meson production. In the usual argument, the K/π ratio is accounted for in terms of the Schwinger mechanism, too. If so, the large string tension would give a too high K/π

ratio. However, in our model, pions are not produced in the string fragmentation process, but they emerge from the thermal decay of fireballs. In fact, if we calculate the number of strange mesons (kaons) in the same way as the charmed mesons and divide it by the total number of pions, we get a K/π ratio quite consistent with the experimental data[7], as is shown in Fig.4. The slight overestimate of $\sim 15\%$ might be corrected by considering processes we have not taken into account here, such as $s\bar{s}$ annihilation. It is worthwhile to note the apparent change of the energy dependence near $\sqrt{s} \simeq 50$ GeV.

Hadron – Nucleus Collisions - The idea that multiple gluon exchange enhances the charm production rate in hadron-nucleus collisions has been discussed for some time [8]. To simulate the hadron-nucleus collision in our model, we assume that the incident particle passes through the target on a straight line and collides with those nucleons within a transverse distance $\sqrt{\sigma_{inel}/\pi}$, where σ_{inel} is the total inelastic hadron-nucleon cross section. For each event, we can calculate the total number of exchanged gluons n as $n = \sum_{i=1}^{N} n_i$, where N is the number of hadron-nucleon collisions and n_i is the number of gluons exchanged in the i-th collision. From this, we can generate the color charge Q by the random walk described before.

The other important quantity to be considered is the transversal area S. It is natural to assume that the transversal area of the firetube increases as a function of N, since generally these collisions will occur in a different place of the incident hadron. However, it will saturate for large N values due to the total transverse area σ_{inel} available for the incident hadron. We parametrize the area after N independent collisions S_N as

$$S_N = S + (\sigma_{inel} - S)(1 - e^{-(N-1)/\beta})$$

and the value of β is estimated as 1.2 after a Monte Carlo simulation.

In order to see the A-dependence of the charm production cross section, we plotted in Fig. 5 the cross section of forward ($x_F > 0$) and backward moving ($x_F < 0$) charmed hadrons as a function of A. It is found that the forward production cross section increases almost linearly in A, while the backward rate goes faster, almost quadraticaly with A. The positive x_F pion-nucleus data of Ref.[9] is shown in Fig.5 and the agreement with our calculations is seen to be quite reasonable (note however that the data normalization is arbitrary). Although our calculations are performed for p-A collisions we expect that the π-A cross section will behave qualitatively in the same way. The linear dependence in the target mass number of the forward charm production is consistent with the PQCD prediction. On the other hand, if we look at the backward moving charmed particles, the situation is quite different. The $\sim A^2$ dependence is quite different from the PQCD results. Although this asymmetry is not expected on the usual perturbative mechanism of charm production, it is easy to understand its origin in our model. The center-of-mass of the firetube has smaller rapidity compared to that of the center-of-mass of the proton-proton system when $N > 1$. This causes the asymmetry in the calculated spectra.

To summarize, we have discussed the possibility that gluon exchange produces an intense chromoelectric flux in between colliding hadrons. This picture is consistent with a non-perturbative Schwinger mechanism for charm production. The model describes very well the experimental data for pions, kaons and charmed particles produced in proton-proton collisions. When extended to hadron-nucleus collisions, we find that the charm production cross section for positive x_F is essentially proportional to the target mass number A. However, for *negative* x_F the charm production rate increases more rapidly than linear in A, contrary to the PQCD prediction. It would be quite interesting to check this asymmetry experimentally, analyzing the charm production in hadron-nucleus collisions for $x_F < 0$.

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Figure Captions

Fig.1 Charged particle pseudorapidity distribution in p+p collisions at $\sqrt{s}$ = 21 GeV. Experimental data are taken from Ref.[5]. The solid line is the result of the firetube model.

Fig.2 Feynman x_F distribution of charmed particles for p+p reaction at P_{inc} =400 GeV/c. The solid curve corresponds to the charmed mesons and the dotted one to the leading charmed baryons. Experimental data for $D/\bar{D}$ are taken from Ref.[6].

Fig.3 Transverse momentum distribution of charmed particles for the same reaction as in Fig.2.

Fig.4 Kaon to pion ratio as a function of energy in proton-proton collisions. The solid line represents our calculation. Data are taken from Ref.[7].

Fig.5 Charm production cross section for proton-nucleus collisions as a function of the target mass number. The upper and lower lines correspond to backward and forward moving charmed particles, respectively. The experimental points (pion-nucleus data) are taken from Ref.[9] with an arbitrary normalization.

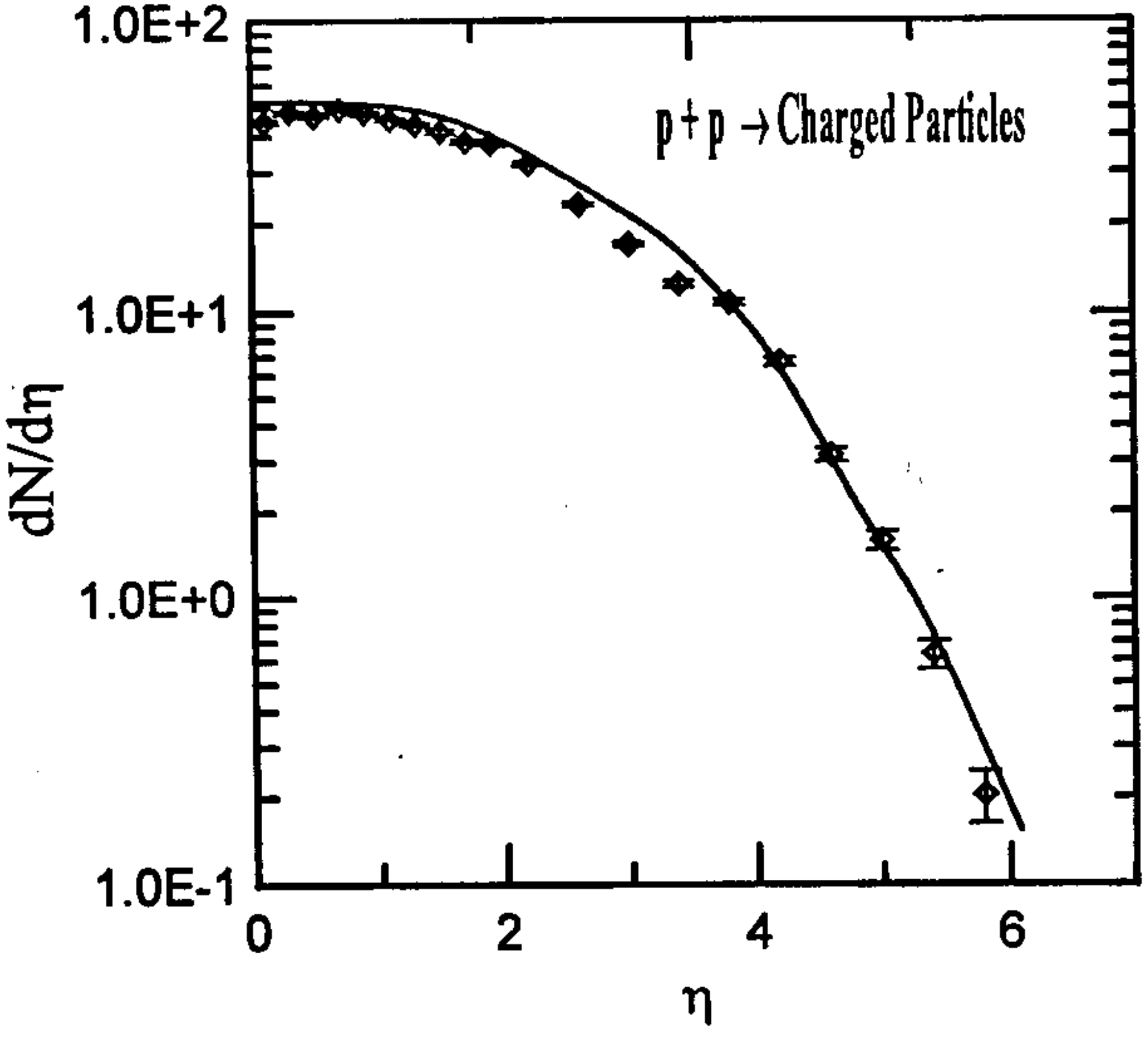

Fig. 1

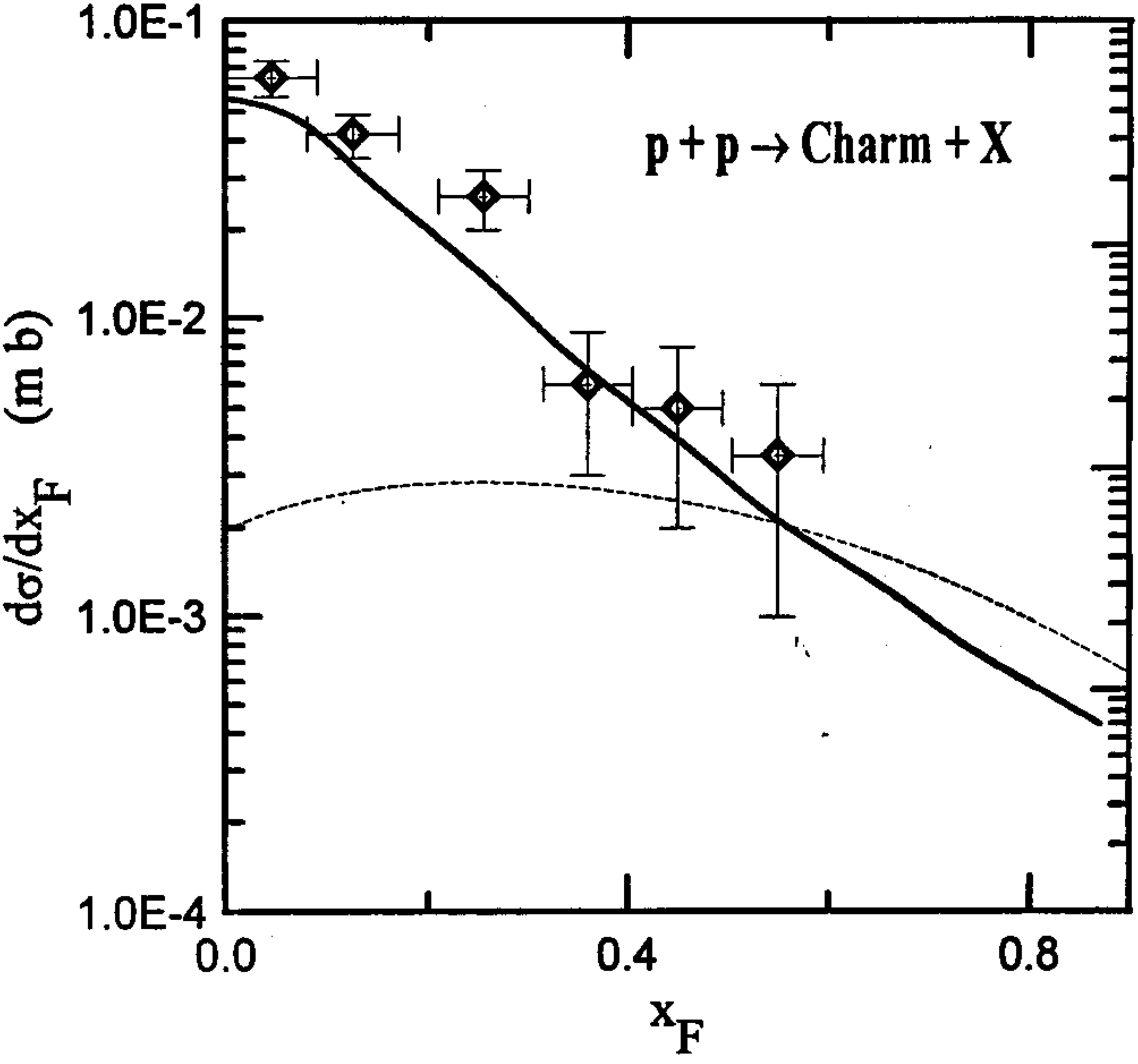

Fig. 2

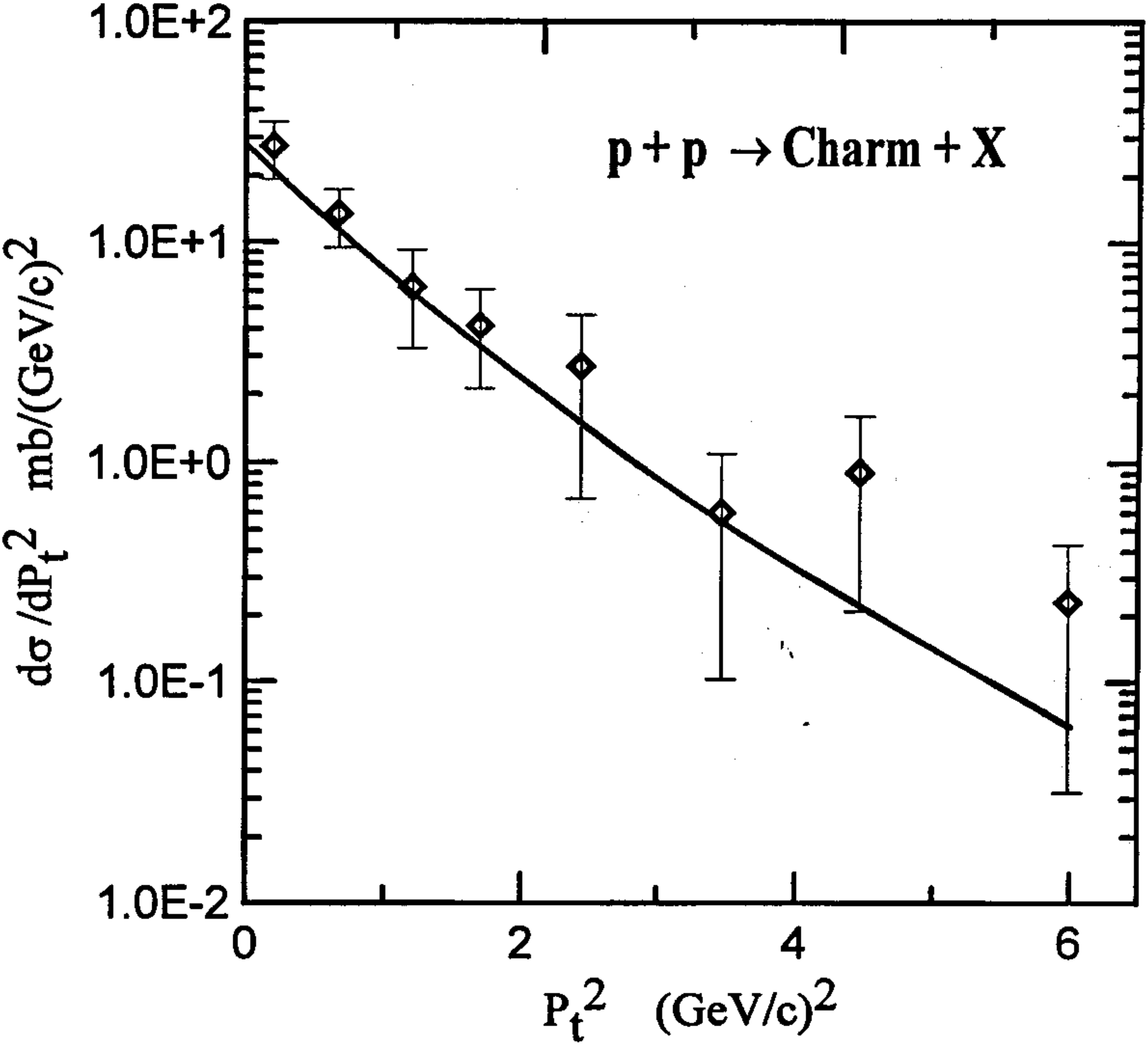
p + p → Charm + X
$d\sigma / dP_t^2$ mb/(GeV/c)^2
1.0E+2
1.0E+1
1.0E+0
1.0E-1
1.0E-2
0
2
4
6
P_t^2 (GeV/c)^2

Fig. 3

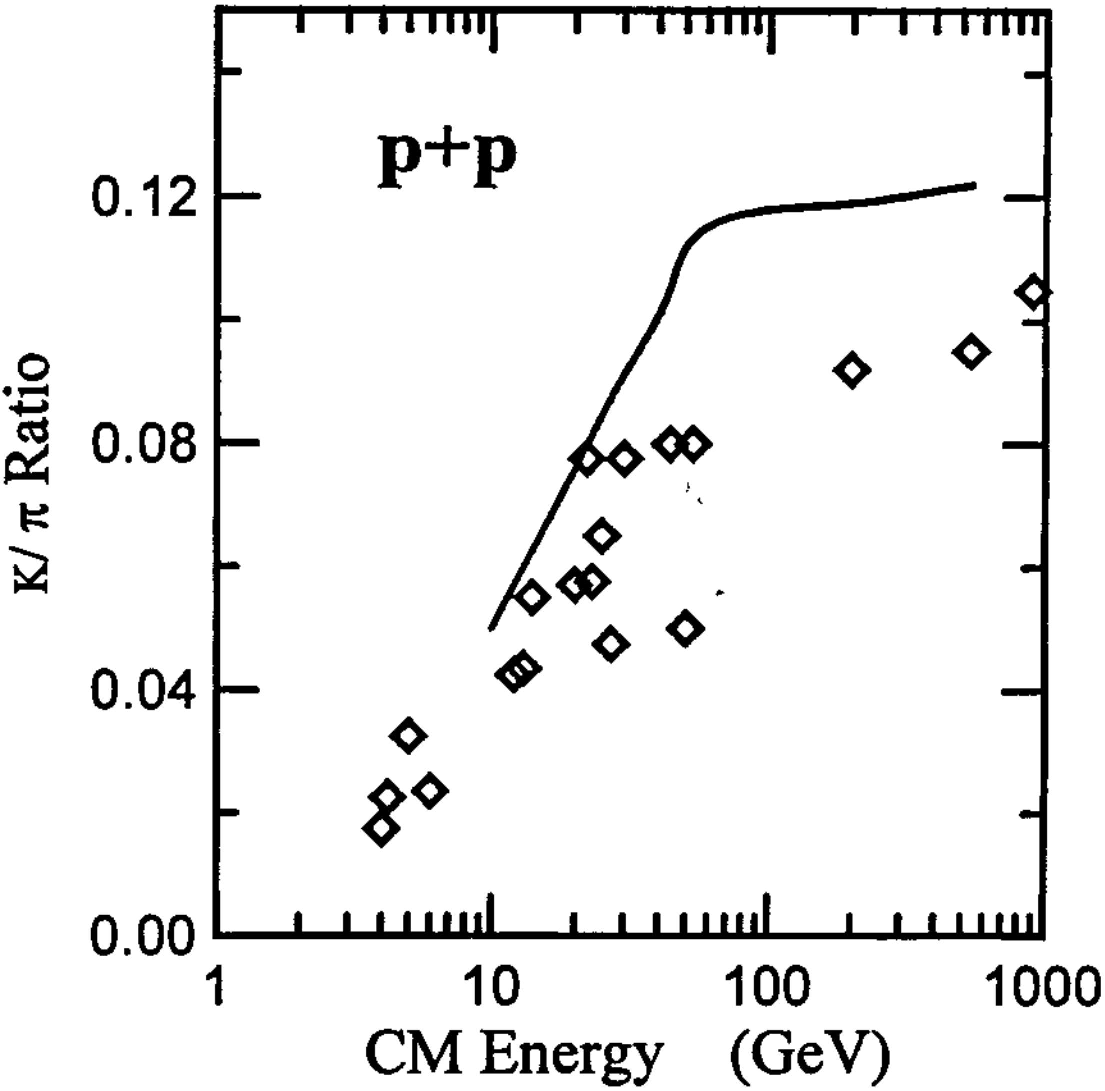

Fig. 4

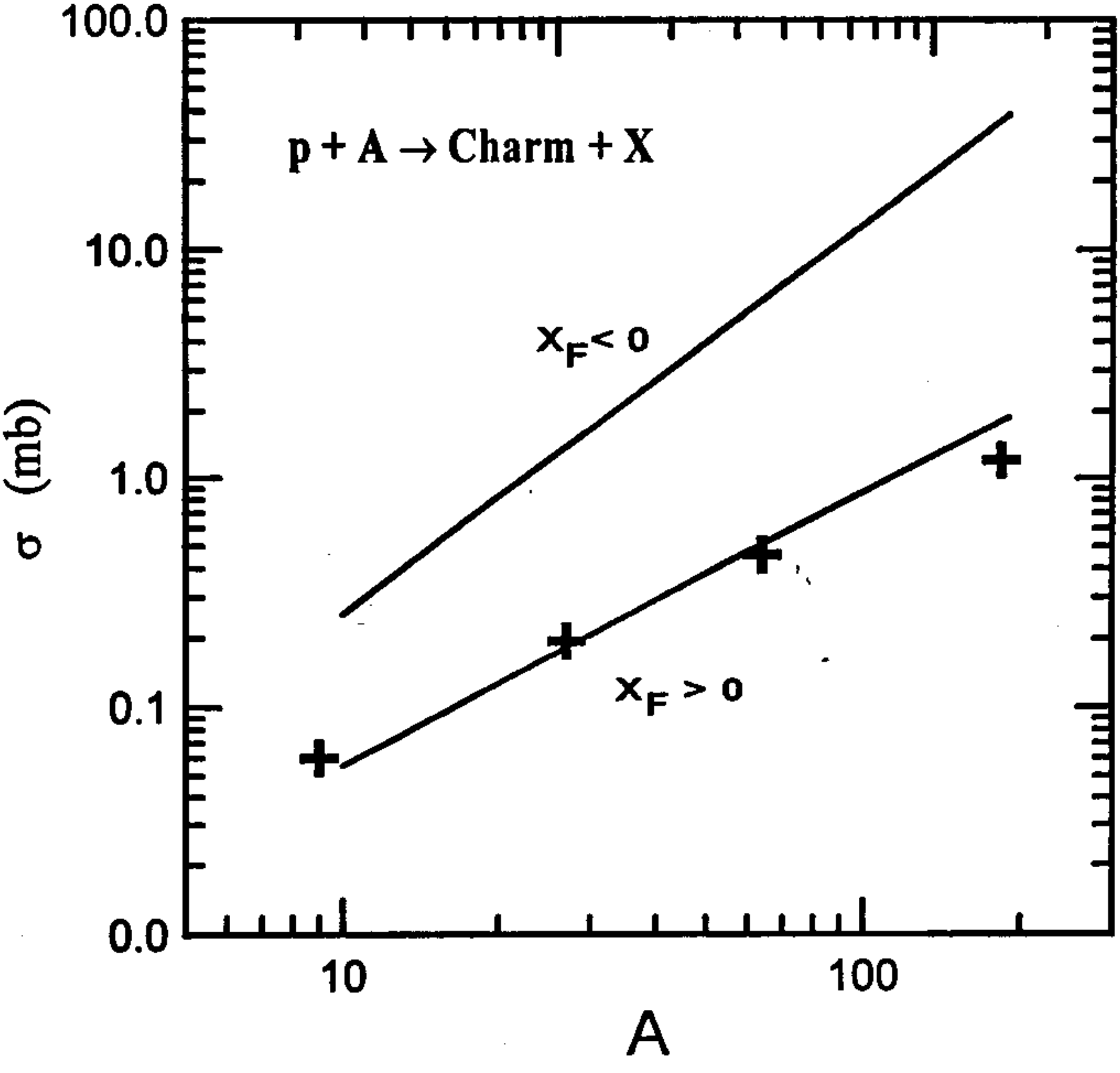

Fig. 5

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