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# Charmed Meson Fragmentation Functions

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Fragmentation functions for heavy-light mesons, like the charmed $D$, $D^*$ mesons, are proposed. They rest on next-to-leading QCD perturbative fragmentation functions for heavy quarks, with the addition of a nonperturbative term describing phenomenologically the quark $\rightarrow$ meson transition. The cross section for production of large $p_T$ $D$, $D^*$ mesons at the Fermilab Tevatron is evaluated in this framework. [S0556-2821(97)01205-8]

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## I. INTRODUCTION

Much experimental and theoretical work has been recently devoted to the study of heavy flavor production in hadronic collisions. Theoretically, because the heavy quark mass sets the scale in the perturbative expansion of QCD, acting as a cutoff for the infrared singularities, the most relevant features of this process are calculable within perturbation theory. Indeed the calculation in perturbative QCD of the differential and total cross sections to order $\alpha_s^3$ has been performed [1], thus providing a firm basis for a detailed study of the properties of the bottom and charm quarks.

The next-to-leading order (NLO) one particle inclusive differential distribution will, however, contain terms of the kind $\alpha_s \ln(p_T/m)$ which, in the large-$p_T$ limit, will become large and will spoil the perturbative expansion of the cross section. This is reflected in a large sensitivity to the choice of the renormalization or factorization scales and hence in a large uncertainty in the theoretical prediction. In Ref. [2] this problem was tackled by introducing the technique of the perturbative fragmentation functions (PFF's) through which these terms were resummed to all orders and the cross section was shown to display a milder scale sensitivity.

When considering heavy meson inclusive production, nonperturbative effects are also quite important, especially for charmed mesons (being $m_c \approx 1.5$ GeV), and so they have to be estimated as well as possible for a reliable calculation of the production cross sections. They are normally introduced within the formalism of FF's and indeed a NLO analysis of FF's into charmed mesons (in particular $D,D^*$) including nonperturbative effects has been performed in Ref. [3] for $e^+e^-$ annihilation processes up to energies reached at the CERN $e^+e^-$ collider LEP. In this analysis, however, the charm component in the FF's is considered only, the other components giving a small contribution to the $e^+e^-$ production cross section.

On the other hand, the contribution of gluon-gluon and quark-gluon scattering subprocesses to the production cross section is relevant in hadronic collisions, and the gluonic component can no longer be neglected.

Thus we proceed in this paper to the construction of a set of NLO fragmentation functions for $D,D^*$ mesons, including gluon, light, and anticharm quark contributions. This set can therefore be used in the calculation of large-$p_T$ inclusive production cross sections for any hard collision process.

## II. THEORETICAL FRAMEWORK

The general framework of this analysis is the following: We will consider the fragmentation into a charm quark of any parton produced at large transverse momentum $p_T \gg m_c$, followed by the hadronization of the charm quark into a meson. Exploiting the difference in time scales of the two processes, short for the perturbative fragmentation of the parton into the charm quak and longer for the nonperturbative hadronization of the charm quark in a meson, we can factor the overall fragmentation function of the parton $i$ into the meson $H$ in the following way:

$$D_i^H(z,\mu,m_c) = D_i^c(z,\mu,m_c) \otimes D_{\rm np}^H(z), \tag{1}$$

the $\otimes$ symbol meaning the usual convolution operation. This expression represents our ansatz for the fragmentation of a

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parton into a charmed meson. The nonperturbative part of the fragmentation is taken to be universal, i.e., independent of the parton which produced the charm quark via perturbative cascade. It is also independent of the scale at which the fragmentation function is taken: All the evolution effects are dumped into the perturbative part.

The first part of the process can be calculated with purely perturbative techniques at an initial scale of the order of the charm quark mass, while we have to rely on phenomenological inputs to extract the hadronization nonperturbative effects at a fixed scale. Then using the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations at NLO accuracy we can evaluate fragmentation functions at the appropriate scale $O(p_T)$, assuming that no scaling violation effects arise in the nonperturbative part of the fragmentation function.

The calculation of the perturbative part of the process has been carried out in Ref. [4]. For the reader's convenience we shall briefly report the main results of this analysis. Using the factorization property, the charm quark production cross section in $e^+e^-$ collisions can be written as

$$\frac{d\sigma}{dx}(x,Q,m_c)=\sum_i \int_x^1 \frac{d\hat{\sigma}_i}{dx}\left(\frac{x}{z},Q,\mu\right) D_i^c(z,\mu,m_c)\frac{dz}{z}, \tag{2}$$

where $x$ is the energy fraction of the charm quark, $Q$ is the center-of-mass energy, and $m_c$ is the charm quark mass. Equation (1) shows that the cross section is factorized into a short-distance term $d\hat{\sigma}_i/dx$ for the production of the massless parton $i$ and a parton FF $D_i^c$ into a charm quark, evaluated at a scale $\mu$. When $\mu$ is taken to be of the order of $m_c$, $D_i^c(x,\mu,m_c)$ is expressed in a perturbative expansion in powers of $\alpha_s$:

$$D_i(z,\mu,m_c)=d_i^{(0)}(z)+\frac{\alpha_s}{2\pi}d_i^{(1)}(z,\mu,m_c)+O(\alpha_s^2). \tag{3}$$

Then using the perturbative expansion of the left-hand side (LHS) of Eq. (2) one obtains the explicit expression of $d_i^{(0)}$ and $d_i^{(1)}$ coefficients.

This has been explicitly done in Ref. [4], obtaining the following set of NLO initial conditions in the modified minimal subtraction $\overline{\text{MS}}$ scheme for the fragmentation function of a charm quark, gluon, and light quarks, respectively, into a charm quark:

$$D_c^c(x,\mu_0)=\delta(1-x)+\frac{\alpha_s(\mu_0)C_F}{2\pi}\left[\frac{1+x^2}{1-x}\left(\ln\frac{\mu_0^2}{m_c^2}-2\ln(1-x)-1\right)\right]_+, \tag{4}$$

$$D_g^c(x,\mu_0)=\frac{\alpha_s(\mu_0)T_f}{2\pi}[x^2+(1-x)^2]\ln\frac{\mu_0^2}{m_c^2}, \tag{5}$$

$$D^c_{q,\bar{q},\bar{c}}(x,\mu_0)=0, \tag{6}$$

where $\mu_0$ is taken of the order of the charm quark mass, which we fix in our analysis at 1.5 GeV. As obvious, $D_g^c$ is of order $\alpha_s$, and $D^c_{q,\bar{q},\bar{c}}$ is zero in the NLO approximation, being of the order of $\alpha_s^2$. Nonetheless, this component is generated at higher scales through the evolution with DGLAP equations, which involve a mixing of all parton components of FF's.

TABLE I. Collection of parameters which describe the nonperturbative part of the fragmentation functions. In the Colangelo-Nason paper [3], these $\alpha$ and $\beta$ where obtained with $\Lambda_5$ = 100 MeV.

| Meson | $\alpha$ | $\beta$ | $\langle n_H\rangle$ | $\langle n_H\rangle$ |
|---|---|---|---|---|
| $D^0$ | 1.0 | 3.67 | 0.58 | 0.58 |
| $D^{*0}$ | 0.6 | 5.4 | 0.3 | 0.29 |
| | Colangelo-Nason | | HERWIG | JETSET |

The PFF initial conditions (4), (5), and (6), evolved up to the appropriate scale $O(p_T)$ with NLO accuracy, can be used to evaluate the open charm quark production cross section in the large-$p_T$ region. Indeed this allows the resummation of potentially large logarithms of the kind $\alpha_s\ln(p_T/m_c)$, arising from quasicollinear configurations, thus recovering a more reliable prediction of the $p_T$ spectrum at large transverse momentum than the fixed order $O(\alpha_s)$ calculation. This is discussed in detail in Ref. [2] in the case of $b$ quarks and in Ref. [5] for charm quark photoproduction.

In order to obtain the inclusive production of $D,D^*$ mesons, one has to take into account further the hadronization of the charm quark into the final charmed meson. The perturbative fragmentation functions (4), (5), and (6) can be convoluted with a nonperturbative part, which we parametrize as

$$D^H_{\rm np}(z)=\langle n_H\rangle A(1-z)^\alpha z^\beta,$$
$$\frac{1}{A}=\int_0^1(1-z)^\alpha z^\beta dz, \tag{7}$$

where the parameters $\alpha$, $\beta$, and $\langle n_H\rangle$ have to be extracted from a comparison with experimental data at a fixed scale. Indeed $\alpha$ and $\beta$ have been obtained by Colangelo and Nason in Ref. [3] by fitting ARGUS data [6] for $D,D^*$ meson fragmentation functions in $e^+e^-$ collisions at a center-of-mass energy of 10.6 GeV. They are reported in Table I. We will use their determination, on the ground of our universality assumption for the nonperturbative part of the fragmentation functions. It is worth mentioning that we have challenged this universality assumption by comparing our fragmentation functions (1), evolved up to 90 GeV and using the ARGUS parameters of Table I, with LEP data by OPAL [7]. Reasonable agreement has been found, giving support to our hypothesis. It is also worth noting that Colangelo and Nason's original work [3] gives a subset of our fragmentation functions only, since they were addressing the nonsinglet component, by far the dominant one in the large-$z$ region. We deal instead with the whole set, including mixings with gluons and antiquarks. A more complete analysis of $D$ meson production in $e^+e^-$ collisions at LEP with the full set, extending also down to small-$z$ values, will be presented elsewhere [8].

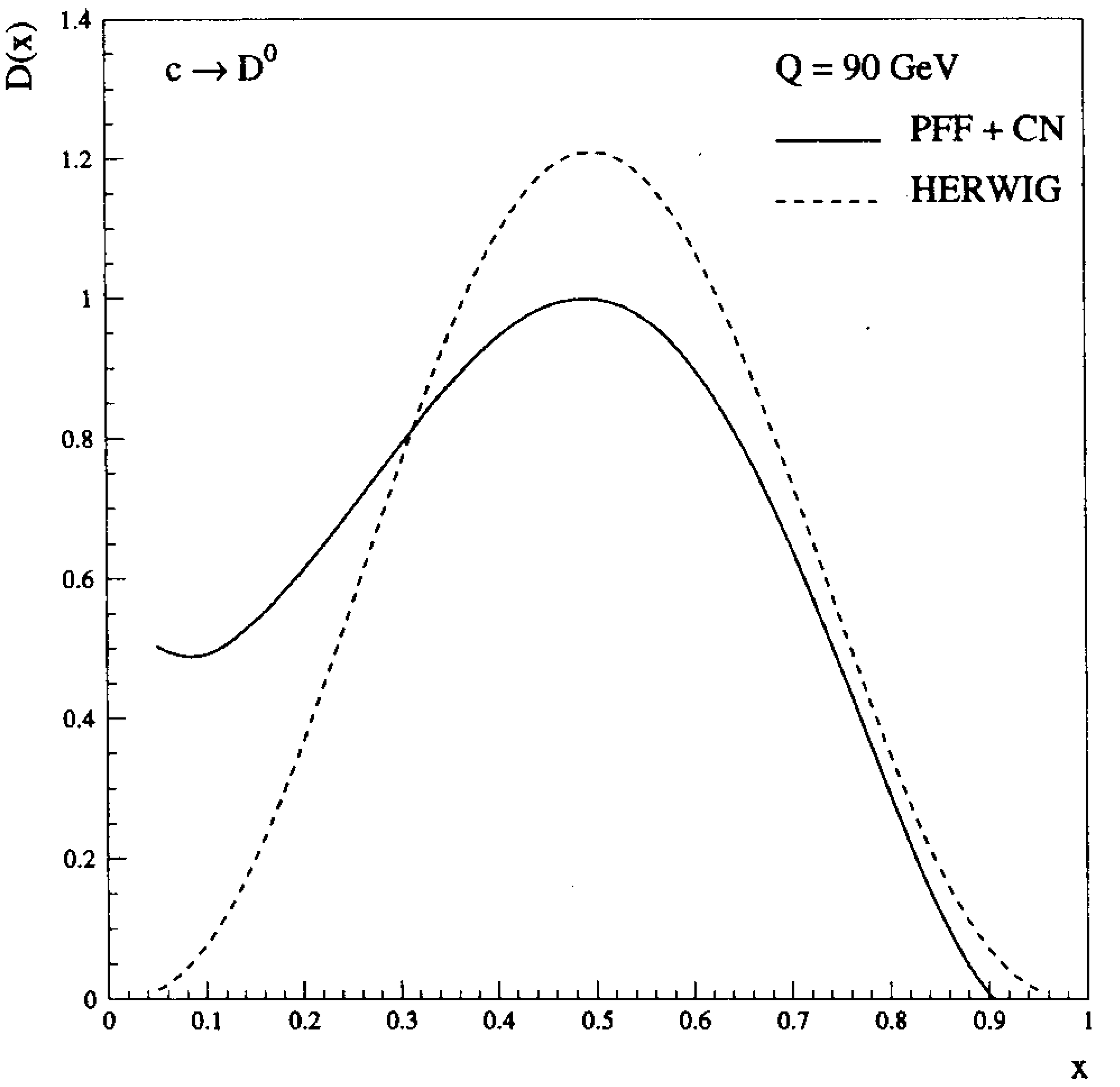


FIG. 1. Comparison between the $D_c^{D^0}$ fragmentation function produced by HERWIG at 90 GeV and the one given by our ansatz (1) with the nonperturbative parameters by Colangelo and Nason (see Table I).

The parameter $\langle n_H \rangle$ in Eq. (7) is the mean multiplicity of charmed mesons produced in the process, i.e., how many mesons the nonperturbative fragmentation of a $c$ quark produces. In the analysis of Ref. [3] the normalization condition fixed by $\langle n_H \rangle$ has not been determined. We have therefore used the mean multiplicity simulated by the HERWIG [9] generator in the process $e^+e^- \to c\bar{c}$ at 90 GeV. This provides us with the last missing parameter for fully defining the nonperturbative part of the fragmentation function. The values we used are summarized in Table I: They describe either the nonperturbative fragmentation of a charm quark into a $D^0$ or a $D^{*0}$ or, alternatively, of an charm antiquark into a $\bar{D}^0$ or a $\bar{D}^{*0}$. As a double check, the same multiplicities have also been extracted from JETSET [10], by fragmenting a charm quark of 5.3 GeV energy. They are also reported in Table I and can be seen to agree well. It must be noted that the $D$ meson multiplicities include feeddown from the $D^*$ decays. It is also worth noticing that the nonperturbative fragmentation function (7), with the parameters shown in Table I, compares nicely with a Peterson fragmentation function with $\epsilon = 0.06$, used, for instance, in [12] to describe the transition from $c$ quarks to $D$ mesons.

TABLE II. Collection of parameters which describe the fragmentation functions produced by HERWIG at 90 GeV, parametrized as $D_i^H(z) = N_H^i(1-z)^{\alpha_i} z^{\beta_i}$. It also holds that $\langle n \rangle = NB(\alpha+1, \beta+1)$, $B$ being the Euler $\beta$ function representing the normalization integral of the FF's. Note that the parameters $\alpha$ and $\beta$ do not have to coincide with those of Eq. (7), because they include also the perturbative component of the FF's.

| | $\alpha$ | $\beta$ | $N_H^i$ | $\langle n_H^i \rangle$ |
|---|---|---|---|---|
| $c \to D^0$ | 2.75 ± 0.08 | 2.72 ± 0.03 | 53.6 | 0.58 |
| $g \to D^0$ | 1.12 ± 0.51 | 0.36 ± 0.19 | 0.0045 | 0.0013 |
| $c \to D^{*0}$ | 2.01 ± 0.06 | 2.42 ± 0.08 | 12.4 | 0.30 |
| $g \to D^{*0}$ | 0.16 ± 0.08 | 0.016 ± 0.03 | 0.008 | 0.007 |

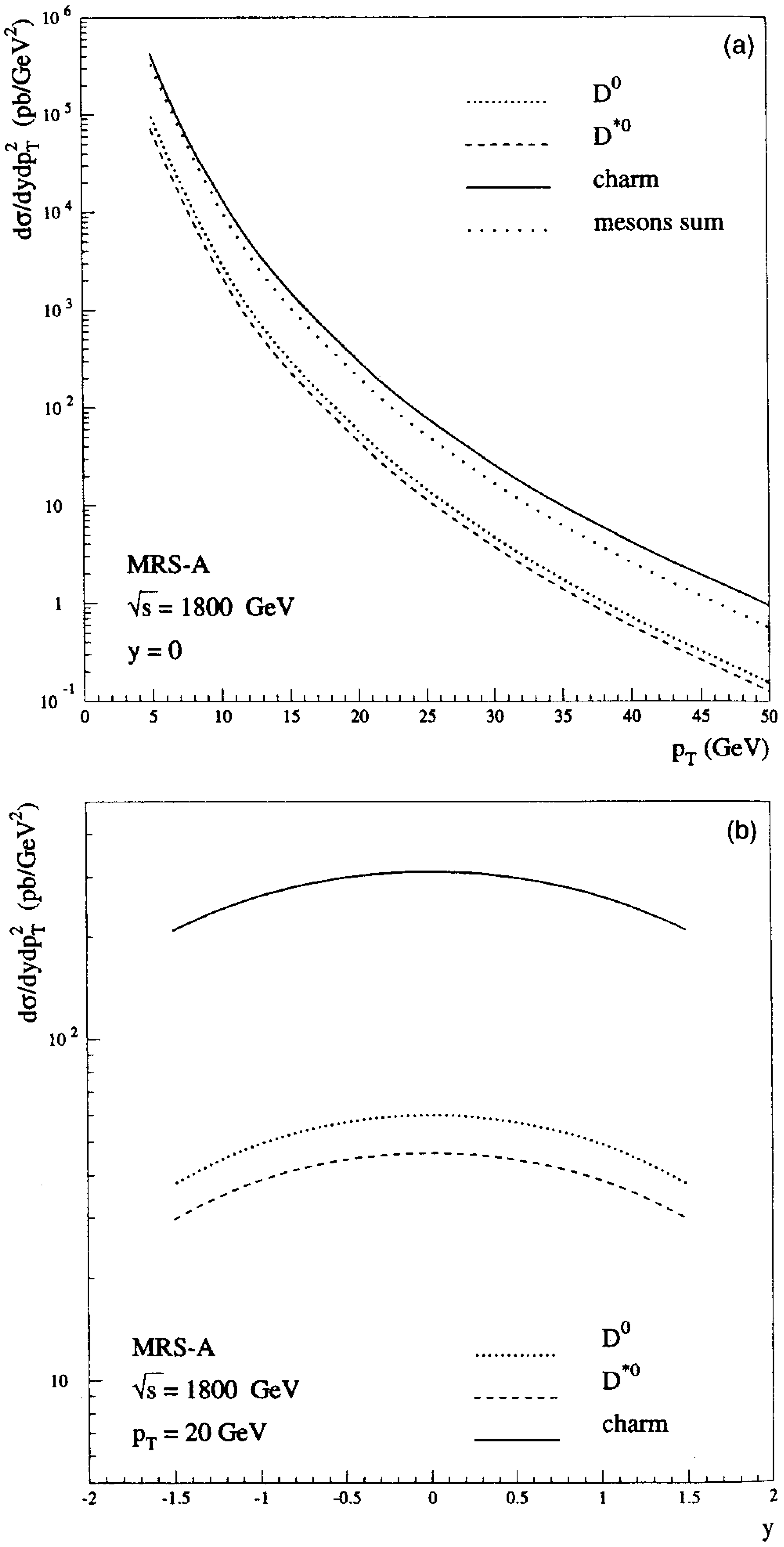


FIG. 2. Cross sections for mesons production at the Tevatron, as predicted by our fragmentation function approach. Comparison with the pure charm quark cross section is also shown. The meson sum also includes $D^+$ and $D^{*+}$ contributions.

The use of an explicit parametrization for the FF's at a given scale extracted from HERWIG has been successfully made in the past for the case of the inclusive production of light and strange mesons [13]. In these papers not only the multiplicity but also parameters $\alpha$ and $\beta$ dictating the shape of the FF's (see Table II) were extracted from HERWIG at some large scale. We have refrained from doing so in this work, since the large mass of the charm quark provides us with a solid ground for evaluating in perturbative QCD (PQCD) at least the perturbative part of the fragmentation function; see Eq. (1). For the sake of completeness we do, however, provide in Fig. 1 a comparison between the fragmentation function which we obtain by evolving the ansatz of Eq. (1) and that we get using the HERWIG parametrization given in Table II, at a scale of 90 GeV. The value of $\Lambda_5 = 100$ MeV has been used in the evolution, for consistency with the Colangelo-Nason fits [3]. The Sudakov form factor [4] has also been included, as it was taken into account in Ref. [3]. Its effects are, however, small, of the order of a few percent, both on the fragmentation function itself and on the cross sections which will follow.

A number of comments about this plot are in order. The discrepancy in the small-$x$ region is due to the PFF's being enhanced by mixing with the gluon-splitting kernel, while the HERWIG result is suppressed by phase space constraints. This difference is, however, of no practical importance in the evaluation of hadronic cross sections, since such small-$x$ values probe the very large-$p_T$ tail of the kernel cross section, where the latter is small. The discrepancy around the maximum can instead be considered as a normalization offset, which could be eliminated by a fine-tuning of both FF's to some experimental data. It is, however, worth noticing that the present accuracy of the data is not better than the uncertainty originating from the difference of the two FF's. Moreover, the consequences on the observable hadronic cross section are small.

### III. RESULTS

Using the perturbative initial conditions (4), (5), and (6) and the nonperturbative parametrization (7) with the parameters summarized in Table I, we have a NLO evaluation of the parton FF's in $D,D^*$ mesons at a scale $\mu_0 \approx m_c$. Then using the DGLAP evolution equations to NLO accuracy one can evaluate the fragmentation function set at any desired factorization scale $\mu$. By convoluting this set with the NLO kernel cross sections for massless parton scattering [11] one gets a prediction for $D$ and $D^*$ production at large $p_T$ at a hadron collider. Figures 2(a) and 2(b) show the $p_T$ and rapidity spectra for the Tevatron. Also shown (solid line) is the pure charm quark NLO cross section, as predicted by the perturbative fragmentation function approach. These results have been obtained with the Martin-Roberts-Stirling set A (MRS-A) structure functions set [14] and with a $\Lambda_5$ value of 100 MeV. The Sudakov form factor [4] has also been included: We notice here once more that its effects are numerically small, below 10%, in the $p_T$-rapidity range we have considered.

As expected the $D$ meson cross sections lie below the charm quark one. It can, however, be checked that summing them up and introducing an additional factor of 2 to allow for $D^+$ and $D^{*+}$ states (which are assumed to fragment like the neutral ones) the charm quark cross section is almost reproduced (wide-dotted line). The small residual gap is given by the meson FF's being softer and therefore producing a smaller cross section.

Many uncertainties do of course affect this result, though not shown in the plots. First of all, the mesons fragmentation functions will share all the uncertainties related to the heavy quark PFF's on which they are built. Factorization scale and initial scale dependences, of the kind studied in [2], will also appear here with a similar behavior, leading to an uncertainty of order 20–30 %. These fragmentation functions will also share the same shortcomings of the PFF's. This means that their description is not accurate at low $p_T$ and at the edges of phase space (see also [5] for a discussion of this point), where unresummed higher order corrections and nonperturbative effects play an important role. This leads to the impossibility of performing a meaningful comparison with the $D^*$ photoproduction data collected at DESY $ep$ collider HERA, since the minimum $p_T$, of the order of 2–3 GeV, is too low and the edges of phase space in rapidity are probed.

A second kind of uncertainty is related to the determination of the nonperturbative parameters $\alpha$, $\beta$, and $\langle n_H \rangle$. The set we have chosen was fitted to ARGUS data, and has been picked mainly for illustrative purposes, although, as stated above, it reproduces fairly well the actual OPAL data from LEP. An analysis of all LEP data, when available, will certainly lead to a more precise determination of these parameters. Of course also a detailed measurement of the $D$, $D^*$ inclusive cross sections at the Tevatron would be very helpful and give complementary information on the FF's, particularly for the gluon terms.

To conclude, we have presented a model for the $D$ and $D^*$ fragmentation functions based on PFF's for heavy quarks complemented by a factorized nonperturbative term describing the quark-meson transition. Predictions have been given for large-$p_T$ charmed mesons production at the Tevatron.

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