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Reconciling Open-Charm Production at the Fermilab Tevatron with QCD

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We study the inclusive hadroproduction of D^0, D^+, D^{*+}, and D_s^+ mesons at next-to-leading order in the parton model of quantum chromodynamics endowed with universal nonperturbative fragmentation functions fitted to e^+e^- annihilation data from CERN LEP1. Working in the general-mass variable-flavor-number scheme, we resum the large logarithms through the evolution of the fragmentation functions and, at the same time, retain the full dependence on the charm-quark mass without additional theoretical assumptions. In this way, the cross section distributions in transverse momentum recently measured by the CDF Collaboration in run II at the Fermilab Tevatron are described within errors.

Recently, there has been much interest in the study of charmed-hadron (X_c) production at hadron colliders, both experimentally and theoretically. The CDF Collaboration measured the differential cross sections $d\sigma/dp_T$ for the inclusive production of D^0, D^+, D^{*+}, and D_s^+ mesons (and their antiparticles) in $p\bar{p}$ collisions at the Fermilab Tevatron (run II) as functions of transverse momentum (p_T) in the central rapidity (y) region [1]. Unfortunately, the most advanced theoretical predictions available so far [2,5], based on quantum chromodynamics (QCD) at next-to-leading order (NLO), consistently undershoot all the D^0, D^+, and D^{*+} data by significant amounts, as is evident from Fig. 3 of Ref. [1], while no predictions for D_s^+ mesons exist yet. It is presently an open question if this discrepancy is related to an experimental problem, a technically deficient QCD prediction, or the appearance of new physics beyond the standard model. Such a situation is familiar from inclusive bottom-flavored-hadron (X_b) production in run I, where a long-standing discrepancy between CDF data [6] and certain NLO predictions of QCD were, in fact, interpreted as an indication for low-energy supersymmetry [7]. It is, therefore, an urgent task to deepen our understanding of the inclusive hadroproduction of charmed hadrons on the basis of QCD in order to render the theoretical predictions as reliable as possible, so as to establish a sturdy anchor for new-physics searches. This is even more important in view of future physics at the CERN Large Hadron Collider, where the continuum production of charmed hadrons will provide important backgrounds for numerous new-physics signals. This is the main motivation of this Letter. Moreover, we provide the first NLO prediction for the CDF D_s^+ data [1]. Prior to explaining our improved theoretical framework and describing our updated input, for the reader's quick orientation, we present a brief survey of the various NLO approaches adopted so far in the literature.

In the so-called massless scheme, also known as the zero-mass variable-flavor-number (ZM-VFN) scheme [4,8], the conventional parton model approach imple-mented in the modified minimal subtraction ($\overline{\text{MS}}$) scheme is adopted, assuming that the charm (c) quark can be treated as massless, although its mass m is certainly larger than the asymptotic scale parameter Λ_{QCD}. In this approach, the c quark occurs as an incoming parton, leading to contributions in addition to those where it is produced by an incoming gluon g or a light u, d, or s quark. The c quark fragments into the charmed hadron similarly as the gluon and the light quarks with a fragmentation function (FF), which must be known from other processes. The well-known factorization theorem provides a straightforward procedure for systematic higher-order perturbative calculations. Because of the assumption that $m = 0$, the predictions are reliable only for large values of p_T, with $p_T \gg m$, where powers of m^2/p_T^2 can be neglected. This approach has the advantage, however, that the potentially large logarithms of the type $\ln(p_T^2/m^2)$ are absorbed into the c-quark parton distribution functions (PDFs) of the colliding hadrons and into the FF for the transition $c \to X_c$. These logarithms are resummed through the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations. Still, m appears in the initial conditions of the c-quark PDF and FF. In this respect, the c-quark PDF and FF differ from the PDFs of the gluon and the light quarks.

In the so-called massive scheme, also called the fixed-flavor-number (FFN) scheme [9], the number of active quark flavors in the initial state is fixed to $n_f = 3$, and the c quark appears only in the final state. The physical value of m is explicitly taken into account together with the variable p_T, as if the two were of the same order. In this scheme, m acts as a cutoff for the initial- and final-state collinear singularities. However, in NLO, terms proportional to $\ln(p_T^2/m^2)$ arise at large p_T values from collinear gluon emission off c quarks or from almost collinear branchings of gluons into $c\bar{c}$ pairs. For $p_T \gg m$, these terms spoil the convergence of the perturbative series. The FFN approach with $n_f = 3$ is, thus, limited to a narrow p_T range, reaching up to a few times m. The advantage of

this scheme is that the m^2/p_T^2 power terms are fully taken into account.

Obviously, the ZM-VFN and FFN schemes are valid in complementary p_T regions, and it is desirable to combine them in a unified approach that enjoys the virtues of both schemes and, at the same time, is bare of their flaws, i.e., one that resums the large logarithms, retains the full finite-m effects, and preserves the universality of the FFs. This is vital for a reliable and meaningful interpretation of the CDF data [1], which populate mostly the transition region. A first attempt to implement such an interpolating scheme is the so-called fixed-order next-to-leading-logarithm (FONNL) scheme, in which the conventional cross section in the FFN approach is linearly combined with a suitably modified cross section in the ZM-VFN approach with perturbative FFs, using a certain p_T-dependent weight function [5,10]. In both finite-mass approaches, FFN and FONNL, the FFN cross sections are convoluted with a nonperturbative c-quark FF, adjusted to e^+e^- data, that is not subject to DGLAP evolution.

Here we wish to advocate an approach that is much closer in spirit to the ZM-VFN scheme but keeps all m^2/p_T^2 power terms in the hard-scattering cross sections, namely, the general-mass variable-flavor-number (GM-VFN) scheme, which has recently been elaborated for the photoproduction [11] and hadroproduction [12,13] of heavy-flavored hadrons. In this approach, one starts from the $p_T \gg m$ region and absorbs the large logarithms $\ln(p_T^2/m^2)$ into the c-quark PDF of the incoming hadrons and the FF for the $c \to X_c$ transition. After factorizing the $\ln m^2$ terms, the cross section is infrared safe in the limit $m \to 0$, and $n_f = 4$ is taken in the strong-coupling constant α_s and the DGLAP evolution equations. The remaining m dependence, i.e., the m^2/p_T^2 power terms, is retained in the hard-scattering cross sections. These terms are important in the intermediate p_T region, where $p_T \gtrsim m$, and are expected to improve the precision of the theoretical predictions. The large logarithms are absorbed into the PDFs and FFs by subtraction of the collinearly (mass) singular terms. However, in order to define a unique factorization prescription, one also has to specify nonsingular terms. This is done by requiring that, in the limit $p_T \to \infty$, the known ZM-VFN hard-scattering cross sections are recovered. To achieve this, subtraction terms are derived by comparing the FFN theory in the limit $m \to 0$ with the ZM-VFN theory, implemented in the $\overline{\text{MS}}$ factorization scheme. This matching procedure is useful, since all commonly used c-quark PDFs and FFs are defined in the ZM-VFN scheme. The latter can then be used consistently together with hard-scattering cross sections calculated in the GM-VFN scheme. The derivation of the subtraction terms is described in Ref. [13].

We note that our implementation of the GM-VFN scheme is similar to the Aivazis-Collins-Olness-Tung [14] scheme formulated for the initial state of fully inclusive deep-inelastic scattering. The extension of this scheme

to the inclusive production of heavy partons was considered in Ref. [15], where the resummation of the final-state collinear logarithms was performed only to leading order (LO) and parton-to-hadron FFs were not included. A comprehensive discussion of the differences between our approach and Ref. [15] concerning the collinear-subtraction terms may be found in Ref. [13].

We now describe our calculation of the differential cross section $d^2\sigma/(dp_T dy)$ of $p + \bar{p} \to X_c + X$, where $X_c = D^0, D^+, D^{*+}, D_s^+$ and X comprises the residual final-state hadrons, at NLO in the GM-VFN scheme. A crucial ingredient entering this calculation are the non-perturbative FFs for the transitions $a \to X_c$, where $a = g, u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}$. For $X_c = D^{*+}$, such FFs were extracted at LO and NLO in the $\overline{\text{MS}}$ factorization scheme with $n_f = 5$ massless quark flavors several years ago [4] from the scaled-energy (x) distributions $d\sigma/dx$ of the cross section of $e^+ + e^- \to D^{*+} + X$ measured by the ALEPH [16] and OPAL [17] Collaborations at CERN LEP1. Two of us [18] recently extended the analysis of Ref. [4] to include $X_c = D^0, D^+, D_s^+, \Lambda_c^+$ by exploiting appropriate OPAL data [19]. Besides the total X_c yield, which receives contributions from $Z \to c\bar{c}$ and $Z \to b\bar{b}$ decays as well as from light-quark and gluon fragmentation, the ALEPH and OPAL Collaborations separately specified the contribution due to tagged $Z \to b\bar{b}$ events yielding X_b hadrons, which then weakly decay to X_c hadrons. The contribution due to the fragmentation of primary c quarks into X_c hadrons approximately corresponds to the difference of these two measured distributions. To test the scaling violations of these FFs and also the separation of the $c \to X_c$ component, these FFs were employed to interpret the x distributions of $e^+ + e^- \to X_c + X$ for center-of-mass energy $\sqrt{S} = 10.55$ GeV measured by the CLEO Collaboration [20] at the Laboratory of Elementary Particle Physics at Cornell University Cornell Electron Storage Ring, with very encouraging results. Further details may be found in Ref. [18].

In Refs. [4,12], the starting scales μ_0 for the DGLAP evolution of the $a \to X_c$ FFs in the factorization scale μ_F' are taken to be $\mu_0 = 2m$, with $m = 1.5$ GeV, for $a = g, u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}$ and $\mu_0 = 2m_b$, with $m_b = 5$ GeV, for $a = b, \bar{b}$. The FFs for $a = g, u, \bar{u}, d, \bar{d}, s, \bar{s}$ are assumed to be zero at $\mu_F' = \mu_0$ and are generated through the DGLAP evolution to larger values of μ_F'. For consistency with the $\overline{\text{MS}}$ prescription for PDFs, we repeated the fits of the X_c FFs for the choice $\mu_0 = m, m_b$. This changes the c-quark FFs only marginally but has an appreciable effect on the gluon FF, which is important at Tevatron energies, as was found for D^{*+} production in Ref. [12]. For shortage of space, these new FFs will be presented elsewhere.

The calculation of the cross section $d^2\sigma/(dp_T dy)$ proceeds as outlined in Ref. [12]. The full cross section consists of three contributions. The first one contains all the channels with only gluons or light quarks in the initial state and c-quark fragmentation. Only this contribution carries

explicit m dependence. Second, this contribution must be extended by allowing for c quarks in the initial state. The third contribution is due to gluon or light-quark fragmentation. The second and third contributions are calculated in the ZM-VFN scheme using the hard-scattering cross sections derived in Ref. [21]. A certain part of these contributions is due to Feynman diagrams with internal c-quark lines; another one is due to diagrams with external c-quark lines and contains m-dependent logarithms, which are resummed. Thus, in the FFN scheme, the m dependence of these contributions would enter only beyond NLO, which is reflected in the ZM-VFN scheme by the generic suppression of the c-quark PDF relative to the gluon and light-quark ones and of the gluon and light-quark FFs relative to the c-quark one. This entitles us to omit this m dependence by calculating the c-quark-initiated contributions and those involving the fragmentation of gluons or light quarks in the ZM-VFN scheme. It turns out that the light-quark fragmentation contributions are negligible. However, gluon fragmentation contributes approximately 40% to the cross section, almost independent of p_T. For the D^{*+} case, we showed in Ref. [12] that the effect of the m-dependent terms is much reduced in the full cross section, since those parts that have to be calculated with $m = 0$ dominate. In fact, this observation carries over to the other charmed mesons considered here.

We are now in a position to present our numerical results for the cross sections of inclusive D^0, D^+, D^{*+}, and D_s^+ hadroproduction to be directly compared with the CDF data [1], which come as distributions $d\sigma/dp_T$ at $\sqrt{S} = 1.96$ TeV with y integrated over the range $|y| \leq 1$. For each X_c species, the particle and antiparticle contributions are averaged. We work in the GM-VFN scheme with $n_f = 4$, thus excluding X_c hadrons from X_b-hadron decays, which are vetoed in the CDF analysis [1]. We set $m = 1.5$ GeV and evaluate $\alpha_s^{(n_f)}(\mu_R)$, where μ_R is the renormalization scale, with $\Lambda_{\overline{\text{MS}}}^{(4)} = 328$ MeV [22], corresponding to $\alpha_s^{(5)}(m_Z) = 0.1181$. We employ proton PDF set CTEQ6.1M from the CTEQ Collaboration [22] and the FFs introduced above. We distinguish between the initial- and final-state factorization scales μ_F and μ_F', so that we have three unphysical mass scales altogether. Our default choice is $\mu_R = \mu_F = \mu_F' = m_T$, where $m_T = \sqrt{p_T^2 + m^2}$ the transverse mass. In order to conservatively estimate the theoretical error due to the scale uncertainty, we independently vary the values of μ_R/m_T, μ_F/m_T, and μ_F'/m_T

between $1/2$ and 2 and determine the maximum upward and downward deviations from our default predictions.

Our theoretical predictions are compared with the CDF data on an absolute scale in Fig. 1 and in the data-over-theory representation with respect to our default results in Fig. 2. The four frames in each figure refer to D^0, D^+, D^{*+}, and D_s^+ mesons. In all cases, we find good agreement in the sense that the theoretical and experimental errors overlap; i.e., the notorious discrepancy between experiment and theory [1] mentioned in the introduction has disappeared. In fact, our theoretical predictions provide the best description of the CDF data obtained so far.

As for the D^0, D^{*+}, and D_s^+ mesons, many of the central data points fall into the theoretical error band, while those for the D^+ mesons lie somewhat above it. With the exception of the D_s^+ case, the experimental results are gathered on the upper side of the theoretical error band, corresponding to a small value of μ_R and large values of μ_F and μ_F', the μ_R dependence being dominant in the upper p_T range. As is evident from Fig. 2, in these cases, the central data points tend to overshoot the central QCD predictions by a factor of about 1.5 at the lower end of the considered p_T range, where the errors are largest, however. This factor is rapidly approaching unity as the value of p_T is increased. The tendency of measurements of inclusive hadroproduction in Tevatron run II to prefer smaller renormalization scales is familiar from single jets, which actually favor $\mu_R = p_T/2$ [23].

The overwhelming bulk of the theoretical error stems from the scale uncertainty discussed above. Residual sources of theoretical uncertainty include the variations in the value of m and the adopted PDF and FF sets. We now quantitatively study the impact of these variations relative to the typical example of our default prediction for D^{*+} mesons. The generous variation of m by $\pm 20\%$, from 1.2 to 1.8 GeV, induces a shift in cross section of only $\pm 2\%$ at $p_T = 5$ GeV, which rapidly decreases towards larger values of p_T because the m-dependent terms are themselves reduced in size. Switching to the NLO proton PDF set MRST2004 of Martin, Roberts, Stirling, and Thorne [24], with $\Lambda_{\overline{\text{MS}}}^{(4)} = 347$ MeV and a more physical parametrization of the gluon distribution to produce a better description of the Tevatron inclusive jet data, produces a reduction ranging from -15% at $p_T = 5$ GeV to -1% at $p_T = 20$ GeV. The theoretical uncertainty due to the FFs was estimated in Ref. [12] to be of order 10% or less in the p_T range considered here, by comparing FF sets
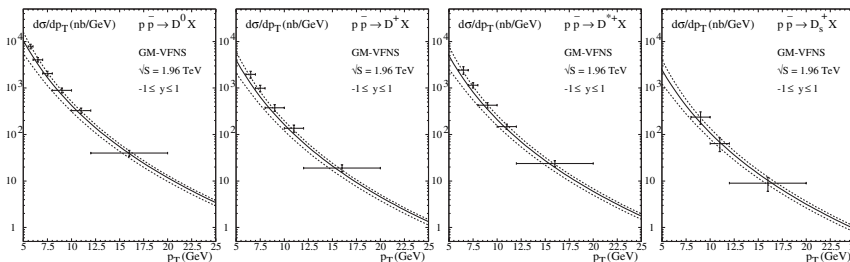

FIG. 1. Comparison of the CDF data [1] with our NLO predictions for $X_c = D^0$, D^+, D^{*+}, D_s^+. The solid lines represent our default predictions, while the short-dashed lines indicate the scale uncertainty (see text).
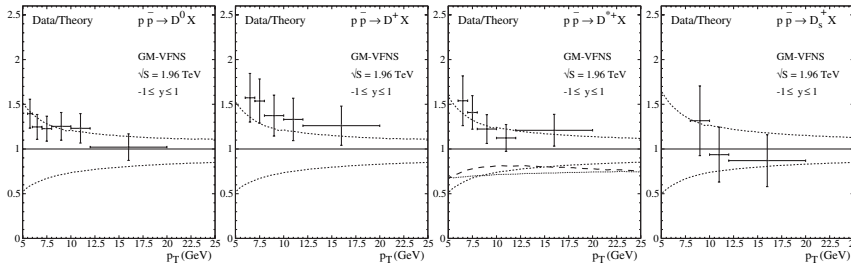
FIG. 2. Data-over-theory representation of Fig. 1 with respect to our default predictions. In the third frame, the central predictions from Refs. [2,5] are indicated for comparison, by the dotted and long-dashed lines, respectively.

[4] fitted separately to slightly incompatible ALEPH [16] and OPAL [17] data.

For comparison, the central D^{*+} prediction of Ref. [2] evaluated in the ZM-FVN scheme with $\mu_R = \mu_F = \mu'_F = 2m_T$ and $\mu_0 = 2m$, and the one of Ref. [5] evaluated in the FONLL scheme with $\mu_R = \mu_F = \mu'_F = m_T$ and $\mu_0 = m$, both shown in Fig. 3 of Ref. [1], are also included in the third frame in Fig. 2. Our default prediction exceeds the one of Ref. [2] because of the incorporation of the finite-m effects through the scheme upgrade from ZM-VFN to GM-VFN and the adjustment of the value of μ_0 necessitated by formal consistency with Refs. [22,24]. The effect of the former change alone is quantitatively discussed in Ref. [12]; the effect of the latter change is even more important and ultimately responsible for the agreement with the CDF data [1]. On the other hand, the conceptual differences between the GM-VFN and FONLL schemes are so multifarious and complex that the source of the respective deviation exhibited in Fig. 2 cannot be quantitatively broken down into specific items at this point. These two schemes substantially differ, e.g., in the implementation of the FFs and the matching of the ZM-VFN and FFN results.

In conclusion, the GM-VFN scheme, which we elaborated at NLO for the inclusive photoproduction [11] and hadroproduction [12,13] of heavy-flavored hadrons, resums large logarithms by the DGLAP evolution of nonperturbative FFs and guarantees the universality of the latter as in the ZM-VFN scheme and simultaneously retains the m-dependent terms of the FFN scheme without additional theoretical assumptions. Adopting this framework in combination with new fits of D^0, D^+, D^{*+}, and D_s^+ FFs to OPAL data from LEP1 [17,19], we managed for the first time to reconcile the CDF data on the production of these mesons in Tevatron run II [1] with QCD within errors and, thus, eliminated a worrisome discrepancy. Furthermore, we presented the first NLO predictions for the D_s^+ data [1].

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