# D-MESON PRODUCTION IN THE GM-VFN SCHEME

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We study the inclusive hadrodroduction of  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and  $D_s^+$  mesons at nextto-leading order in the parton model of quantum chromodynamics endowed with universal non-perturbative fragmentation functions (FFs) 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 FFs 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.

# 1. Introduction

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.<sup>1</sup> Until recently, the most advanced theoretical predictions,<sup>2,3</sup> based on quantum chromodynamics (QCD) at next-to-leading order (NLO), consistently undershot 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 existed. Especially 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, it is 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. Here, we report on recent progress in this direction.<sup>4</sup>

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# 2. General-Mass Variable-Flavor-Number Scheme

We wish to advocate the general-mass variable-flavor-number (GM-VFN) scheme, which has recently been elaborated for the photoproduction<sup>5</sup> and hadroproduction<sup>6</sup> of heavy-flavored hadrons. In this approach, one starts from the  $p_T \gg m_c$  region and absorbs the large logarithms  $\ln(p_T^2/m_c^2)$ into the parton density function (PDF) of the c-quark in the incoming hadrons and the fragmentation functions (FFs) for the  $c \to X_c$  transitions. After factorizing the  $\ln m_c^2$  terms, the cross section is infrared safe in the limit  $m_c \rightarrow 0$ , and  $n_f = 4$  is taken in the strong-coupling constant  $\alpha_s$ and the DGLAP evolution equations. The remaining  $m_c$  dependence, i.e. the  $m_c^2/p_T^2$  power terms, is retained in the hard-scattering cross sections. These terms are important in the intermediate  $p_T$  region, where  $p_T \gtrsim m_c$ , 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 non-singular terms. This is done by requiring that, in the limit  $p_T \to \infty$ , the known hardscattering cross sections of the zero-mass variable-flavor-number (ZM-VFN) scheme are recovered. To achieve this, subtraction terms are derived by comparing the fixed-flavor-number (FFN) theory in the limit  $m_c \rightarrow 0$  with the ZM-VFN theory, implemented in the  $\overline{\text{MS}}$  factorization scheme.<sup>5,6</sup> 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.

## 3. Numerical Results

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,<sup>1</sup> which come as distributions  $d\sigma/dp_T$  at c.m. energy  $\sqrt{S} = 1.96$  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.<sup>1</sup> We set  $m_c = 1.5$  GeV and evaluate  $\alpha_s^{(n_f)}(\mu_R)$ , where  $\mu_R$  is the renormalization scale, with  $\Lambda_{\overline{\text{MS}}}^{(4)} = 328$  MeV,<sup>8</sup> corresponding to  $\alpha^{(5)}(m_Z) = 0.1181$ . We employ proton PDF set CTEQ6.1M from the CTEQ Collaboration<sup>8</sup> and the NLO FFs<sup>7</sup> that were recently fitted to LEP1 data taking the starting scales for the DGLAP evolution to be  $\mu_0 = m_c, m_b$ . We distinguish between the initial- and final-state factorization scales,  $\mu_F$  and  $\mu'_F$ , so that we have three unphysical mass scales altogether. Our default choice is  $\mu_R = \mu_F =$  $\mu'_F = m_T$ , where  $m_T = \sqrt{p_T^2 + m_c^2}$  is the transverse mass. In order to conservatively estimate the theoretical error due to the scale uncertainty, we independently vary the values of  $\mu_R/m_T$ ,  $\mu_F/m_T$ , and  $\mu'_F/m_T$  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 in Fig. 1. The four frames 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 mentioned in Sec. 1 has disappeared. In fact, our theoretical predictions provide the best description of the CDF data obtained so far.

### 4. Conclusions

In conclusion, the GM-VFN scheme resums large logarithms by the DGLAP evolution of non-perturbative FFs, guarantees the universality of the latter as in the ZM-VFN scheme, and simultaneously retains the  $m_c$ -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<sup>7</sup> to LEP1 data, we managed for the first time to reconcile the CDF data on the production of these mesons in Tevatron run II<sup>1</sup> with QCD within errors and thus eliminated a worrisome discrepancy. Furthermore, we presented the first NLO predictions for the  $D_s^+$  data.<sup>1</sup>

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Figure 1. Comparison of the CDF data<sup>1</sup> with our NLO predictions for  $X_c = D^0, D^+, D^{*+}, D^{*+}_s$ . The solid lines represent our default predictions, while the dashed lines indicate the unphysical-scale uncertainty.

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