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Charm cross sections for the Tevatron Run II

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Abstract: We present a calculation of the D^{*+}, D^+ and D^0 meson single inclusive production cross section for the Tevatron Run II. We use the FONLL approach in perturbative QCD, which, besides including the known next-to-leading order corrections, also provides for the resummation at the next-to-leading logarithmic level of terms enhanced at large p_{T} by powers of $\log(p_{\mathrm{T}}/m)$, where m is the charm mass and p_{T} is its transverse momentum. Non-perturbative effects in charm hadronization are extracted, in moment space, from recent ALEPH data for D^* fragmentation in e^+e^- collisions.

Keywords: QCD, NLO Computations, Phenomenological Models, Hadronic Colliders.

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1. Introduction

Heavy flavour production at hadron colliders has been mostly studied for bottomed hadrons so far, due to the possibility of using muons or J/Ψ to tag the B hadrons. At CDF, thanks to the development of the silicon vertex trigger, charm production studies have become possible. This opens up the interesting possibilities of comparing QCD predictions for charm production with experimental results, much in the same way as one does for bottomed hadrons. One is then especially interested in seeing whether the predicted charm cross section bears the same relationship with respect to data as the bottom cross section.

In the present work, we provide cross sections for charm production for the Tevatron Run II. The calculation of the cross section is performed according to the FONLL prescription [1], and the effect of a non-perturbative fragmentation function is included in full analogy with the work of ref. [2], where a prediction for B production at the Tevatron Run I is given. We will thus not review the FONLL framework, and the moment space method for the extraction of the non-perturbative fragmentation function, rather referring the reader to refs. [1, 2].[1] The only novel aspect of the present work that needs to be discussed is the phenomenological extraction of the non-perturbative D-meson fragmentation function, which will serve as input to our calculation of the D spectrum. Good data on D^* fragmentation have been published by the ALEPH collaboration [3], together with a study yielding the relative fraction of directly produced D and D^* mesons. Other experiments [4, 5] have provided valuable results relevant to charm production, in particular for the D^* production properties. We prefer however to use here ALEPH data only, since it

[1] Suffice here to say that the perturbative FONLL calculation includes the full next-to-leading order calculation for heavy quark production (and therefore also the power suppressed m/p_T terms, all important in the $p_T \sim m$ region), plus the resummation to next-to-leading logarithmic accuracy of the $\log(p_T/m)$ terms, which are large where $p_T \gg m$. The moment space method, on the other hand, takes care of properly extracting from experimental data, and importing in the process at hand, the relevant non-perturbative information.

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addresses in a single context all the production issues that are relevant for our purposes. In section 2, we will first describe how we have constructed the D^0 and D^+ fragmentation functions in terms of the D^* one and of the relative fractions of directly produced vector and pseudoscalar states. In section 3 we discuss how the D^* non-perturbative fragmentation function itself was extracted from the ALEPH data. In section 4 we present our phenomenological predictions, and in section 5 we give our conclusions.

2. Construction of the D^0 and D^+ non-perturbative fragmentation functions

Non-perturbative information concerning the hadronization of the charm quarks into the observed D mesons must be extracted from experimental data. High quality data at present only exist for fragmentation into the vector state D^*, as measured by the ALEPH collaboration [3] at LEP. The extraction of this non-perturbative fragmentation function (FF from now on) will be described in the next section. In the present one we show how this FF can be suitably modified in order to describe the production of the pseudoscalar states D^0 and D^+ too.

The D^0 FF has been postulated to be a linear combination of D^0's coming from the decays of the D^{*0}'s and D^{*+}'s, and D^0's not coming from D^* decays, that we call here "primary" D^0's :

$$F(c \to D^0) = F_p(c \to D^0) + F(c \to D^{*+}) \otimes F(D^{*+} \to D^0) + F(c \to D^{*0}) \otimes F(D^{*+} \to D^0)\,,$$

where $F_p(c \to D^0)$ is the fragmentation function for primary D^0 production, $F(c \to D^{*0})$ and $F(c \to D^{*+})$ are the fragmentation functions for D^* states production, $F(D^{*0} \to D^0)$ and $F(D^{*+} \to D^0)$ describe the decay of a D^* into a D^0.

We assume that the production of primary D and D^* is flavour independent, and the only flavour dependencies arise in the decay of the D^*. In other words, one assumes as usual that isospin is a good symmetry, except that, due to the known fact that the $D\pi$ decay mode is barely accessible to the D^*, small isospin violations are amplified in the decay. Under this assumption, we can extract from the ALEPH paper [3] the primary D^0 fraction and the D^{*+} and D^{*0} fraction:[2]

$$\mathrm{BR}(c \to D^0_p) = 0.168, \quad \mathrm{BR}(c \to D^*) = 0.233\,. \tag{2.1}$$

Observe that these values conflict with the naive assumption of spin counting, that would predict a ratio of the D to D^* states equal to the ratio of the number of spin states, 1/3.

We now need a model for the D^* FF. For sake of definiteness, we have taken the analytic forms of ref. [6] for the fragmentation into pseudoscalar (P) and vector (V) states. Such FF's will be denoted by $D^{(P)}_{BCFY}(z;r)$ and $D^{(V)}_{BCFY}(z;r)$ respectively, and understood to be normalized to one. A single non-perturbative parameter r describes both pseudoscalar

[2]Here and in the following, the branching fractions are presented and used without an associated experimental uncertainty. While such errors are in principle available from the experimental papers, we have refrained from quoting them as their contribution to the total uncertainty will turn out to be negligible.

and vector production in this formulation, and we can thus use the parameter fitted to D^* production as input in the pseudoscalar (D^0 and D^+) fragmentation functions. We will comment in the following about the influence of this choice on our result.

The D^* decay into a D^0 could be calculated exactly using the known decay chains. However, since the decay $D^* \to \pi D^0$ is dominant and the decay products are nearly at rest in the decay frame, the effect of this decay is simply modeled as a rescaling of the longitudinal momentum by a factor m_D/m_{D^*} in the FF for D^* production:

$$\begin{aligned} \tilde{D}^{(V)}_{BCFY}(z;r) &= \int dy\, dz_{D^*}\, \delta(z - y z_{D^*}) D^{(V)}_{BCFY}(z_{D^*};r)\, \delta\left(y - \frac{m_D}{m_{D^*}}\right) \\ &= \Theta\left(\frac{m_D}{m_{D^*}} - z\right) D^{(V)}_{BCFY}\left(\frac{m_{D^*}}{m_D} z; r\right) \frac{m_{D^*}}{m_D}\,, \end{aligned} \tag{2.2}$$

$\Theta(x)$ being the Heaviside step function. We can therefore write

$$\begin{aligned} D^{c\to D^0}(z;r) &= \mathrm{BR}(c \to D^0_p) D^{(P)}_{BCFY}(z;r) + \\ &\quad + \mathrm{BR}(c \to D^*)(\mathrm{BR}(D^{*0} \to D^0) + \mathrm{BR}(D^{*+} \to D^0)) \tilde{D}^{(V)}_{BCFY}(z;r)\,, \end{aligned} \tag{2.3}$$

where [7]

$$\mathrm{BR}(D^{*0} \to D^0) = 1\,, \qquad \mathrm{BR}(D^{*+} \to D^0) = 0.677\,. \tag{2.4}$$

Putting in numbers, eq. (2.3) reads

$$D^{c\to D^0}(z;r) = 0.168 D^{(P)}_{BCFY}(z;r) + 0.39 \tilde{D}^{(V)}_{BCFY}(z;r) \tag{2.5}$$

showing that about 2/3 of the fragmentation function depends in a precise way on the D^* fragmentation.

The FF for D^+ production can be constructed along similar lines. Since D^{*0} cannot decay to D^+ we only have

$$F(c \to D^+) = F_p(c \to D^+) + F(c \to D^{*+}) \otimes F(D^{*+} \to D^+) \tag{2.6}$$

and therefore

$$\begin{aligned} D^{c\to D^+}(z;r) &= \mathrm{BR}(c \to D^+_p) D^{(P)}_{BCFY}(z;r) + \\ &\quad + \mathrm{BR}(c \to D^*) \mathrm{BR}(D^{*+} \to D^+) \tilde{D}^{(V)}_{BCFY}(z;r) \end{aligned} \tag{2.7}$$

with[3] [3, 7]

$$\mathrm{BR}(c \to D^+_p) = 0.162, \qquad \mathrm{BR}(D^{*+} \to D^+) = 0.323\,. \tag{2.8}$$

Numerically

$$D^{c\to D^+}(z;r) = 0.162 D^{(P)}_{BCFY}(z;r) + 0.07153 \tilde{D}^{(V)}_{BCFY}(z;r)\,. \tag{2.9}$$

For the sake of completeness, we now write down the FF for production of D^* states:

$$D^{c\to D^*}(z;r) = \mathrm{BR}(c \to D^*) D^{(V)}_{BCFY}(z;r) = 0.233 D^{(V)}_{BCFY}(z;r)\,. \tag{2.10}$$

[3] Note that $\mathrm{BR}(c \to D^+_p) = 0.162$ is actually to be considered equal to $\mathrm{BR}(c \to D^0_p) = 0.168$ within the experimental uncertainties and consistently with our flavour-independence hypothesis.

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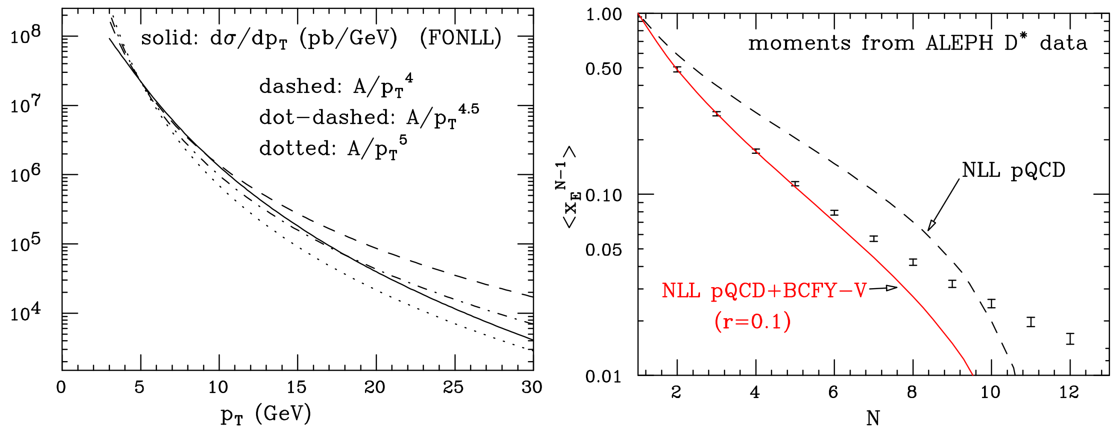

Figure 1: *a*) Left plot: p_T spectrum of the charm cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1960\,\mathrm{GeV}$, compared to A/p_T^n behaviours. *b*) Right plot: Mellin moments of D^* fragmentation distribution as calculated from ALEPH data [3], compared to pure perturbative QCD and to pQCD convoluted with the non-perturbative form $D^{(V)}_{BCFY,N}(r = 0.1)$.

The non-perturbative parameter r, which in the model of ref. [6] can be interpreted as the ratio of the constituent mass of the light quark to the mass of the meson, will be more precisely determined in the next section by a comparison with the ALEPH D^* data.

It is worth noting now that, in the present work, the model of ref. [6] is needed in order to compensate for the lack of an explicit measurement of the direct component of the $D^{+/0}$ fragmentation function. In the case of the D^0 production the influence of the model is marginal, since most D^0 are produced through D^* decays. In the case of D^+ production we have the opposite situation. Therefore, our D^+ spectrum will strongly reflect this model dependence. New data on D^+ fragmentation may eventually help in reducing this uncertainty in the future.

3. Extraction of the D^* non-perturbative fragmentation function

The non-perturbative fragmentation function has been extracted from D^* fragmentation data from the ALEPH collaboration [3]. We assume the measured energy fraction (x_E) distribution (normalized to one) to be described by a convolution (a product, in Mellin moments space) of a perturbative contribution (which describes the production of a c quark in the hard interaction) and the BCFY non-perturbative form describing its hadronization into the D^*:

$$\sigma_N(c \to D^*)(r) = D_N^{pQCD} D^{(V)}_{BCFY,N}(r)\,. \tag{3.1}$$

The non-perturbative parameter r is then determined by comparing σ_N to the measured $\langle x_E^{N-1}\rangle$ values.

According to the discussion published in [2] about B meson production at CDF, we have taken care that the fitted non-perturbative fragmentation function properly describes the Mellin moments of the D^* spectrum in e^+e^- experimental data around $N = 4, 5$ rather than the whole x_E shape, as this information is the most relevant one when calculating

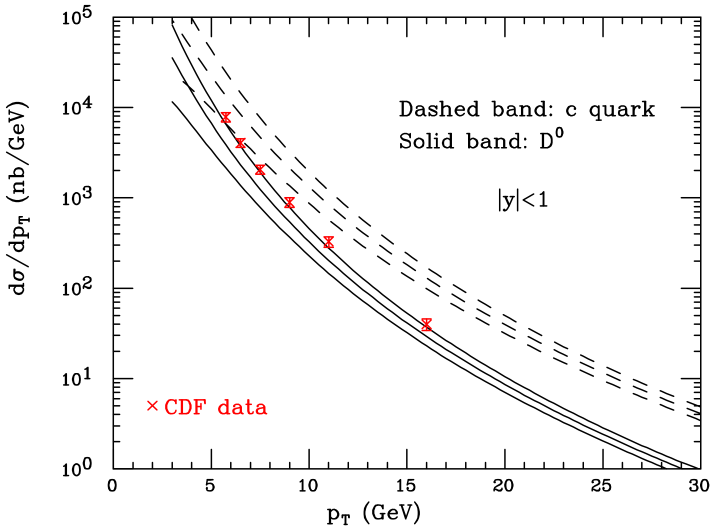

Figure 2: QCD predictions for the D^0 differential cross section at the Tevatron Run II. CDF data are also shown for comparison.

the hadronic production. Indeed, as shown in figure 1a, in the region of interest between $p_T = 5$ and $p_T = 20\,\mathrm{GeV}$, the charm transverse momentum distribution predicted by the FONLL calculation falls off like A/p_T^n, with n between 4 and 5.

Figure 1b shows a comparison of the Mellin moments calculated from the D^* fragmentation data of the ALEPH Collaboration [3] with the result of a convolution of a perturbative and a non-perturbative distribution. The perturbative component D_N^{pQCD} resums to all orders and to next-to-leading logarithmic [8] accuracy the large $\alpha_s^n \log^k(Q^2/m^2)$ $(k \leq n)$ terms (Q being the e^+e^- centre-of-mass energy, and m the heavy quark mass) which appear in the fixed order calculation. This resummation is analogous to the one performed in the FONLL result, where $\alpha_s^n \log^k(p_T^2/m^2)$ terms are resummed. For the non-perturbative distribution, the functional form for vector states given by Braaten et al. [6] has been chosen. Though no rigorous fit[4] of its free parameter r has been performed, one can see from figure 1b that the choice $r = 0.1$ gives a good description of the relevant moments around $N = 4, 5$. The failure of the curve to describe higher-N moments is of course related to unaccounted-for sub-leading logarithms related to soft-gluon emission becoming more important. Resummation of these terms would improve the picture but, though available [9, 10], it has not been included since it would not affect this phenomenological application.[5]

[4]The choice of not performing a rigorous fit of the moments is related to the fact that their errors have been only naively estimated from the errors of each x_E bin, a full correlation matrix being unavailable. Lacking a rigorous calculation for the errors on the moments and the correlations between the various moments, a fit would yield results of little significance as far as the errors on the fitted parameters are concerned.

[5]By tweaking the factorization scales which appear in the resummed perturbative calculation one could improve the behaviour of the curve in the $N > 6$ region even without resumming the soft-gluon logarithms. This implies a different value for the non-perturbative parameter r when fitting the experimental moments. We have checked that the differences compensate, and the predictions for D meson production in $p\bar{p}$ collisions remain identical within a few percent.

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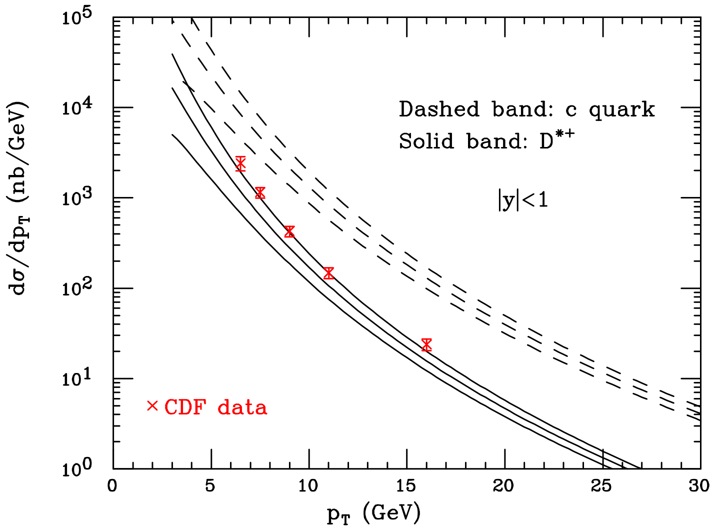

Figure 3: Same as figure 2, but for D^{*+} production.

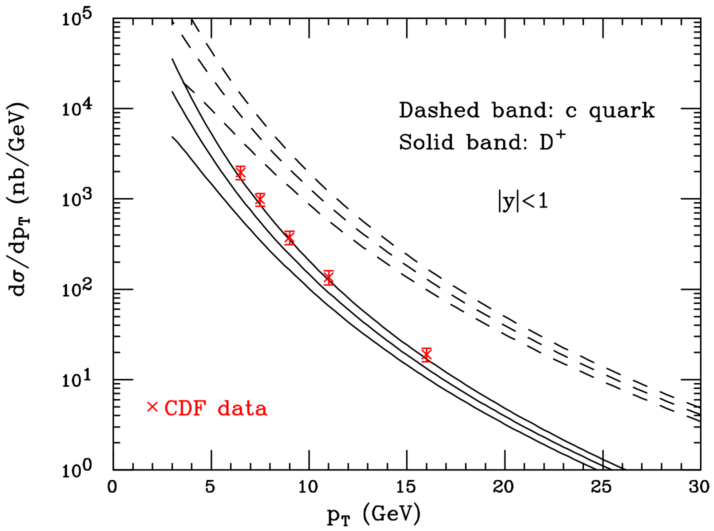

Figure 4: Same as figure 2, but for D^{+} production.

4. Phenomenological results

We show in figures 2, 3 and 4 our predictions for the $d\sigma/dp_{\rm T}$ ($|y| < 1$) cross sections for D^0, D^{*+} and D^+ production at the Tevatron Run II, obtained with the FONLL perturbative result combined with the non-perturbative fragmentation functions given in eqs. (2.10), (2.9) and (2.5) respectively. The perturbative calculation is consistent with the one employed in calculating e^+e^- fragmentation when fitting the D^* non-perturbative FF, and it is also shown for comparison. The three curves in each plot are the lower, central and upper values of an uncertainty band produced by varying independently the factorization and renormalization scales in the transverse mass region $m_{\rm T}/2$ and $2m_{\rm T}$. The charm mass has been fixed here to $m = 1.5\,{\rm GeV}$, and the CTEQ6M parton distribution functions set,

p_T (GeV)	$d\sigma/dp_T$ ($\|y\| < 1$) (nb/GeV)		
	D^0	D^{*+}	D^+
5.75	$.385^{+.266}_{-.171}\ \times 10^4$	$.192^{+.140}_{-.089}\ \times 10^4$	$.170^{+.120}_{-.076}\ \times 10^4$
	7837±220±884	-	-
6.5	$.232^{+.142}_{-.095}\ \times 10^4$	$.117^{+.076}_{-.050}\ \times 10^4$	$.103^{+.065}_{-.043}\ \times 10^4$
	4056±93±441	2421±108±424	1961±69±332
7.5	$.124^{+.067}_{-.046}\ \times 10^4$	$.634^{+.359}_{-.245}\ \times 10^3$	$.554^{+.304}_{-.209}\ \times 10^3$
	2052±58±227	1147±48±145	986±28±156
9	$.539^{+.242}_{-.173}\ \times 10^3$	$.279^{+.132}_{-.093}\ \times 10^3$	$.242^{+.111}_{-.079}\ \times 10^3$
	890±25±107	427±16±54	375±9±62
11	$.203^{+.075}_{-.057}\ \times 10^3$	$.107^{+.041}_{-.031}\ \times 10^3$	$.917^{+.346}_{-.263}\ \times 10^2$
	327±15±41	148±8±18	136±4±24
16	$.292^{+.078}_{-.062}\ \times 10^2$	$.157^{+.044}_{-.035}\ \times 10^2$	$.133^{+.036}_{-.029}\ \times 10^2$
	39.9±2.3±5.3	23.8±1.3±3.2	19.0±0.6±3.2

Table 1: Theoretical predictions, with uncertainties, for the differential cross sections of D^0, D^{*+} and D^+ meson production in $p\bar{p}$ collisions at the Tevatron Run II. The experimental measurements by the CDF Collaboration [11, 12] are also shown in the second lines at each p_T value. The statistical and systematic errors have been added in quadrature in the figures.

corresponding to $\Lambda^{(5)} = 0.226\,\mathrm{GeV}$, has been used. We have verified that accounting also for the effects of varying the QCD scale in the range $0.192 < \Lambda^{(5)} < 0.241\,\mathrm{GeV}$ and the charm mass in the range $1.2 < m < 1.8\,\mathrm{GeV}$ does not produce a larger band than the one given by factorization and renormalization scale variations.[6]

The data measured by the CDF Collaboration [11, 12] are also presented in the plots, superimposed to the theoretical curves. They can be seen to be in fair agreement with the predictions. The slopes in particular are very well described, and they differ from that of the QCD prediction for charm quarks, pointing to a correct determination of the softening effects related to the non-perturbative fragmentation functions. Explicit numerical values for the theoretical predictions are given in table 1, and the Data/Theory ratios are shown in figure 5 together with the theoretical uncertainty bands, here defined as upper/lower theoretical prediction divided by the central value.

The bands shown in the plots of figures 2, 3 and 4 do not account for all the possible uncertainties. Besides the effects of renormalization/factorization scales, mass and QCD scale variations, previously discussed, one could also consider changing the Parton Distribution Function set and/or modifying the model describing the hadronization of the charm quark into the mesons. At the present level of accuracy, however, we do not expect these issues to change significantly the picture presented in the figures.

[6]An explanation of the limited sensitivity to the value of m is that the effects of mass variations are largely compensated by the need to also fit a different non-perturbative parameter r from the e^+e^- ALEPH D^* data, as m also enters the evolution of the perturbative calculation. It should also be stressed that the variation of either the mass or the QCD scale is not computed fully consistently, because we are not in a position to determine the effect of these variations on the parton densities. We therefore content ourselves with computing them at fixed parton densities.

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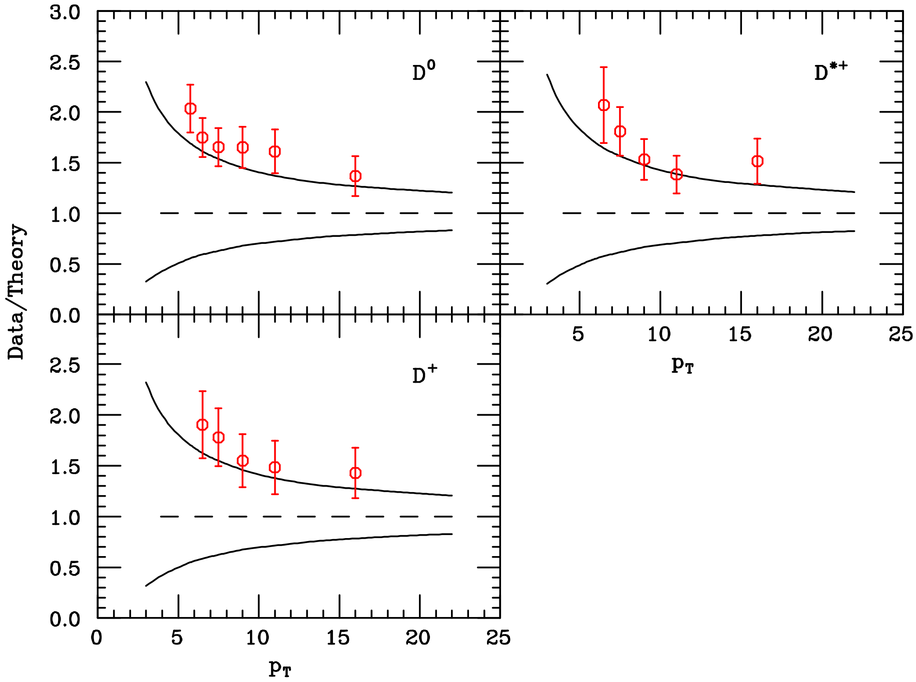

Figure 5: The ratios between the CDF experimental results and the central theoretical predictions. Theoretical uncertainty bands are also shown, defined as the ratio between the upper (lower) theoretical prediction and the central value.

5. Conclusions

We have presented predictions for D^{*+}, D^+ and D^0 transverse momentum distributions as measured by the CDF Collaboration at the Fermilab Tevatron Run II in $p\bar{p}$ collisions at a centre-of-mass energy of 1960 GeV.

The calculation consists of next-to-leading log resummed QCD (matched to a fixed next-to-leading order result) combined with non-perturbative information describing the charm hadronization into the mesons, and determined from moment-space analysis of D^{*+} data measured by the ALEPH Collaboration in e^+e^- collisions.

The overall agreement is good, with the data lying on the upper limit of the theoretical uncertainty band. This behaviour is similar to what observed in B mesons [13, 2] and b-jets [14, 15] production at the Tevatron. This consistency is encouraging, and many improvements, like tuning of scales and/or quark mass, adding higher order perturbative contributions, or a more accurate determination of non-perturbative effects, could easily conspire to bring the theoretical prediction in even better agreement with the experimental data. It has been speculated that new physics mechanisms may be needed in order to explain the measured excess in the b cross section [16]. The presence of 'new physics' effects cannot certainly be ruled out at this stage. However, the fact that both charm and bottom production data bear similar relationship to the theoretical prediction gives an indication that uncalculated QCD effects are a more likely explanation of the discrepancy.

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