Hadroproduction of $D$ and $B$ mesons in a massive VFNS

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Abstract. We present a calculation of the next-to-leading order cross section for the inclusive hadroproduction of $D$ and $B$ mesons as a function of the transverse momentum and the rapidity in a massive variable flavor number scheme. We compare our numerical results with recent data from the CDF Collaboration at the Fermilab Tevatron for the production of $D^0$, $D^{*+}$, $D^+$, and $D_s^+$ mesons at center-of-mass energy $\sqrt{S} = 1.96$ TeV and find reasonably good agreement with the measured cross sections.

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Various approaches for next-to-leading order (NLO) calculations in perturbative QCD have been applied to one-particle inclusive hadroproduction of $D$ or $B$ mesons. For definiteness, we shall consider here $D$ mesons. However, all results can easily be carried over to any other heavy-flavored hadron.

A basic approach is the fixed flavor number scheme (FFNS) [1], in which the number of active flavors in the initial state is fixed to $n_f = 3$ and the charm quark appears only in the final state. The charm mass $m$ is explicitly taken into account together with the transverse momentum $p_T$ of the observed meson. In this scheme the charm mass acts as a cutoff for the initial- and final-state collinear singularities and collinear logarithms $\ln(p_T^2/m^2)$ are kept in the hard scattering cross sections. However, for $p_T \gg m$, these logarithms become large and spoil the convergence of the perturbation series.

Therefore, in the regime $p_T \gg m$, it is more appropriate to treat charm quarks like massless partons and to absorb the collinear logarithms into scale dependent parton distribution functions (PDFs) and fragmentation functions (FFs). As is well-known, by this procedure the large logarithms $\ln(p_T^2/m^2)$ are summed via the DGLAP evolution equations and the hard scattering cross sections are finite (infrared safe) in the limit $m \to 0$. If the power-like charm mass terms $\mathcal{O}(m^2/p_T^2)$ are neglected this is just the conventional parton model or zero-mass variable flavor number scheme (ZM-VFNS). Usually, in the ZM-VFNS the charm mass is neglected from the beginning and the collinear singularities appear in dimensional regularization as poles in $\varepsilon$ where $d = 4 - 2\varepsilon$ is the number of space-time dimensions. Conventionally, these poles are removed in the modified-minimal-subtraction ($\overline{\text{MS}}$) scheme. If, on the other hand, the collinear singularities have been regularized with help of a mass $m$ it is necessary also to subtract finite terms along with the collinear logarithms $\ln m^2$ in order to recover the hard scattering cross sections in the $\overline{\text{MS}}$ scheme.
On top of these two basic approaches, schemes have been devised which combine the two features, non-zero charm mass and resummation of $\ln(p_T^2/m^2)$-terms. One such scheme, which has been applied already to inclusive charmed meson production for the Tevatron experiment is the so-called fixed-order next-to-leading-logarithm (FONLL) scheme. This scheme smoothly interpolates between the traditional cross section in the FFNS and a suitably modified cross section in the ZM-VFNS approach with perturbative FFs with the help of a $p_T$ dependent weight function $[2, 3]$. In both non-zero-charm-mass approaches, FFNS and FONLL, the theoretically calculated cross sections are convoluted with a scale-independent non-perturbative FF extracted from $e^+e^-$ data describing the transition from the produced charm quark to the observed $D$ meson.

Recently, a general mass variable flavor number scheme (GM-VFNS) has been worked out by us $[4, 5, 6, 7]$ which is closely related to the ZM-VFNS, but keeps all $m^2/p_T^2$ terms in the hard-scattering cross sections in order to achieve better accuracy in the intermediate region $p_T \geq m$. The massive hard scattering cross sections have been constructed in a way that the conventional hard scattering cross sections in the $\overline{MS}$ scheme are recovered in the limit $p_T \to \infty$ (or $m \to 0$). The requirement to adjust the massive theory to the ZM-VFNS with $\overline{MS}$ subtraction is necessary since all commonly used PDFs and FFs for heavy flavors are defined in this particular scheme. In this sense this subtraction scheme is a consistent extension of the conventional ZM-VFNS for including charm-quark mass effects. It should be noted that our implementation of a GM-VFNS is similar to the ACOT scheme which has been extended to 1-particle inclusive production of $B$ mesons a few years ago $[8]$. There are small differences concerning the collinear subtraction terms $[5]$. Further, in $[8]$, the resummation of the final state collinear logarithms has been performed only to leading logarithmic accuracy.

To calculate the cross section $d^2\sigma/dp_T dy$ for the reactions $p + \bar{p} \to D + X$, FFs are needed which describe the fragmentation of the charm quarks, the light quarks, and the gluon into the observed $D$ mesons. Fragmentation functions for the $D^*$ meson
For the charm mass we take
\[ m = 1.5 \text{ GeV} \]
and evaluate \[ \alpha_s^{(n_f)}(\mu_R) \] with \( n_f = 4 \) and scale parameter \( \Lambda_{MS}^{(4)} = 328 \text{ MeV} \), corresponding to \( \alpha_s^{(5)}(m_Z) = 0.1181 \). The results are presented in Figs. 1 and 2. The solid lines correspond to the central scale choice \( \mu_R = \mu_F = \mu_{f} = m_T = (p_T^2 + m_T^2)^{1/2} \), where \( \mu_R \) is the renormalization, \( \mu_F \) the initial-state and \( \mu_{f} \) the final-state factorization scale, respectively. To investigate the scale

\footnote{It should be noted that the results presented at the DIS05 have been obtained with the FFs from [10, 13].}
variation of our predictions, we independently vary the renormalization and factorization scales by a factor of two: $0.5 \leq \mu_R/m_T, \mu_F/m_T, \mu_F'/(2m_T) \leq 2$ while keeping their ratios $0.5 \leq \mu_F/\mu_R, \mu_F'/\mu_R, \mu_F'/\mu_F \leq 2$ [16]. Our theoretical results are compared with the experimental data from CDF [9]. As can be seen, the data are in good agreement with the upper curve of the uncertainty band whereas they are a factor of about 1.5(1.2) above our central prediction at low(high) $p_T$.

Residual sources of theoretical uncertainty include the variations of the charm mass and the assumed PDF and FF sets. A variation of the value of the charm-quark mass does not contribute much to the theoretical uncertainty. Also the use of other up-to-date NLO proton PDF sets produces only minor differences. Concerning the choice of the NLO FF sets we obtain results reduced by a factor of 1.2–1.3 when we use the NLO sets obtained by fitting with the initial scale choice $\mu_0 = 2m_c, 2m_b$.

In conclusion, we have presented a NLO perturbative QCD calculation of $D$ meson production at the Tevatron in a GM-VFNS [4, 5] which provides the best description of these experimental results obtained so far. It completes earlier work in this scheme on $D$ meson production in $\gamma\gamma$ and $\gamma p$ collisions [18]. This approach will be applied next to $B$ meson production at the Tevatron. Furthermore, it is planned to extend this scheme to heavy meson production in deep inelastic scattering.

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