Charm Production and Fragmentation in Charged Current DIS

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In charged current deep inelastic scattering charm is dominantly produced in scattering events on strange quarks, thereby allowing for an experimental determination of the nucleon’s strange sea density. A measurement of the energy spectrum of final state charm fragments (D-mesons) determines the charm fragmentation function at spacelike scales considerably below typical $e^+e^-$ c.m.s. energies. NLO corrections to the naive $s \rightarrow c$ parton model production picture are important and well understood.

1. Parton Model Expectations

Charm production in CC DIS is dominated by an $s \rightarrow c$ transition at the virtual $W$-boson vertex. The $d \rightarrow c$ background is sizable at large $x$ where the Cabibbo suppression is balanced by the valence enhancement of $d_v$. Since $d_v$ is well known I will not consider $d \rightarrow c$ and assume a vanishing Cabibbo angle for simplicity. The results presented here are, however, not affected by this choice. The LO production cross section of charmed hadrons

$$\frac{d\sigma_{LO}}{dx \, dy \, dz} \propto s(\chi)D_c(z)$$

manifests the obvious possibility to extract the nucleon’s strange sea density $s(\chi)$ and the charm fragmentation function $D_c(z)$ from experimental data [1]. In Eq. (1) $x$ and $y$ are the standard inclusive DIS observables and $z \equiv p_{H_c} \cdot p_N / q \cdot p_N$ being the momentum of the charmed hadron, the target nucleon and the mediated gauge boson, respectively. In the target rest frame $z$ reduces to the charmed hadron energy $E_{H_c}$, scaled to its maximal value $\nu = q_0$. In the massless parton model the fractional momentum $\chi$ of the struck strange quark reduces to the Bjorken variable $x$. For theoretical predic-

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tions to be reliable one has of course to consider the NLO of the QCD perturbation series where $W^* s \rightarrow cg$ (incl. virtual corrections) and $W^* g \rightarrow c\bar{s}$ contributions enter the game. The NLO terms mix quark and gluon initiated contributions and induce a scheme dependence due to the necessity of handling collinear divergencies arising from on-shell strange quark propagators. Most prominent choices are the dimensionally regularized ($m_s = 0$) $\overline{MS}$ scheme and the massive ($m_s \neq 0$) ACOT formalism [2] for heavy quarks.

In principle also $\Delta s$ seems measurable at a polarized HERA setup [3] and the corresponding NLO framework is underway [4].

2. NLO framework

At NLO the production cross section is no longer of the simple factorized form of Eq. (1) and double convolutions (symbol $\otimes$ below) have to be considered [5]. However, to a reasonable approximation

$$d\sigma_{NLO} = (s \otimes d\sigma_s + g \otimes d\sigma_g) \otimes D_c(x, z, Q^2)$$

$$\equiv d\sigma_{LO} \, K(x, z, Q^2)$$

$$\propto s(\chi) \, D_c(z) \, K(x, z, Q^2)$$

$$\simeq s(\chi) \, D_{x,Q^2}[D_c](z)$$

holds also at NLO accuracy within experimental errors and for the limited kinematical range of present data on neutrino production of charm. In Eq. (2) the approximate multiplicative factor $D$ absorbs the precise $K$-factor $K(x, z, Q^2)$ obtained...
Figure 1. $s_{\text{eff}}$ equals the charm production cross section in Eq. (2) up to a constant of normalization. The shaded band represents a parametrization of CCFR data and the curves show theoretical predictions using GRV94 (solid) and CTEQ4 (dashed). For the dot-dashed curves the normalization of the CTEQ4 prediction has been changed by the factor given in the legend. From a full NLO QCD calculation, $D$ is not a simple universal fragmentation function but a nontrivial process-dependent functional which is, however, mainly sensitive on $D_c$ and shows little sensitivity on the exact parton distributions considered. The occurrence of $x, Q^2$ and $z$ in Eq. (2) as indices and as a functional argument, respectively, reflects the fact that the dependence on $x$ and $Q^2$ is much weaker than on $z$. Eq. (2) tells us that $s(\chi)$ fixes the normalization of $d\sigma$ once $K$ is known. On the other hand $K$ (or $D$) can be computed from $D_c$ with little sensitivity on $s(\chi)$, such that $s(\chi)$ and $D_c(z)$ decouple in the production dynamics and can be simultaneously extracted. This point can be clearly inferred from Fig. 1 where it is shown for CCFR (fixed target) kinematics that the NLO calculations using GRV94 (solid) and CTEQ4 (dashed) strange seas can be brought into good agreement by a mere change of the normalization given by the ratio $s_{\text{GRV}}(\chi)/s_{\text{CTEQ4}}(\chi)$ (dot-dashed). The freedom in realizing Eq. (2) in distinct NLO schemes, e.g. MS or ACOT, might a priori lead to an ambiguity in measuring the nucleon’s strangeness. From Fig. 2 one can, however, see that the scheme dependence is small for the inclusive ($z$-integrated) charm structure function $F^c_2$. This result does also hold for the semi-inclusive structure functions entering Eq. (2), as can be judged comparing the $m_s = 0$ and $m_s = 500\text{MeV}$ curves in the upper half of Fig. 4 below.

3. Strange Sea

The wide spread of available strange sea densities is illustrated by some of its representatives in Fig. 3. It is especially interesting to note the difference between the NLO (MS) and ACOT predictions.

Figure 2. The inclusive structure function $F^c_2$ for charm production in CC DIS (solid lines) within MS (thick lines) and ACOT (thin lines) using $m_s = 500\text{MeV}$. Also shown are the individual quark scattering and gluon fusion components which contribute to the structure function and which are regularized by subtraction terms. $\mu$ is the arbitrary factorization scale.
but also in shape- of the characteristically steep strange sea of GRV94 which builds up entirely through a renormalization group resummation of $g \rightarrow s \bar{s}$ splittings from a low resolution scale $\mu^2 \sim 0.3\text{GeV}^2$ and the conventional strange seas of CTEQ4 and CCFR which comprise an additional nonperturbative input component at larger $x \sim 0.1$. Comparing the solid (GRV94) and the dashed (CTEQ4) curves in Fig. 1 with the parametrization $[5]$ of CCFR production data a purely radiative strange sea seems to be favored over larger nonperturbative inputs which overshoot data at larger $x$. This conclusion is awaiting further experimental analyses and it would be helpful to have published production data at hand for future investigations.

4. Charm Fragmentation Function (FF)

Since the cross section in Eq. (1) is directly proportional to $D_c$ at LO accuracy neutrino-production of charm can give valuable information on the charm FF complementary to that from one charmed hadron inclusive $e^+e^-$ annihilation. Especially a test of the universality of the charm fragmentation function is an important issue $[10]$. In Fig. 1 a scale-independent Peterson $[11]$ FF with a hardness parameter of $\varepsilon_c = 0.06$ has been used. This choice seems to be compatible with the neutrino data band. On the other hand a distinctly harder value of $\varepsilon_c = 0.02$ has been obtained in $[12]$ from LEP and ARGUS $e^+e^-$ data, see also $[13]$ for related analyses. If the fit of $[12]$ is evolved down to fixed target energies it is incompatible with the parametrized neutrino data in Fig. 1. A point which might influence the extraction of a universal FF from neutrino-production is the scheme dependence in handling final state quasi-collinear logarithms $\ln(Q^2/m_c^2)$. Along the lines of $[14]$ they may be resummed into a running of the fragmentation function as has been done in $[12]$ or they may be kept at fixed order as in $[5]$ using a scale-independent FF. In Fig. 4 we examine such resummation effects for CCFR kinematics. We use the same Peterson FF with $\varepsilon_c = 0.06$ once for...
a fixed order calculation \[\text{solid lines}\] and once as the nonperturbative input part of the running \(c \rightarrow D\) FF \[\text{dashed curves}\]. We note that towards intermediate scales around \(Q^2 \sim 20\text{GeV}^2\) one begins to see the softening effects of the resummation which are enhanced as compared to the fixed order calculation. However, as one would expect at these scales, the resummation effects are moderate and cannot explain the discrepancy between the \(\varepsilon_c\) values. However, charm fragmentation at LEP has been measured by tagging on \(D^*\)’s, whereas neutrinoproduction experiments observe mainly \(D\)’s through their semileptonic decay-channel \(\text{dimuon events}\). ARGUS \[\text{Ref. 15}\] and CLEO \[\text{Ref. 16}\] data at \(\sqrt{s} \simeq 10\text{GeV}\) indeed show \[\text{Ref. 17}\] a harder energy distribution of \(D^*\)’s compared to \(D\)’s. It seems therefore to be possible within experimental accuracy to observe a nondegeneracy of the charm fragmentation functions into the lowest charmed pseudoscalar and vector mesons. We note that an \(\varepsilon_c\) value around 0.06 which is in agreement with neutrino data on \(D\)-production is also compatible with the \(D\) energy spectrum measured at ARGUS where the evolution may be performed either using fixed order expressions in \[\text{Ref. 18}\] or via a RG transformation along the lines of \[\text{Ref. 14, 12}\]. If forthcoming experimental analyses should confirm our findings the lower decade \(m_c(\sim 1\text{GeV}) \rightarrow \text{ARGUS}(10\text{GeV})\) may be added to the evolution path ARGUS(10GeV) \[\text{Ref. 12}\] paved in \[\text{Ref. 12}\] for the charm FF.

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REFERENCES

1. H. Abramowicz \textit{et al.}, CDHSW collab., Z. Phys. \textbf{C15}, 19 (1982); S. A. Rabinowitz \textit{et al.}, CCFR collab., Phys. Rev. Lett. \textbf{70}, 134 (1993); A. O. Bazarko \textit{et al.}, CCFR collab., Z. Phys. \textbf{C65}, 189 (1995); A. O. Bazarko, Ph. D. thesis, Columbia University, Nevis-285 (1994); J. Yu, talks given at the \textit{33rd Rencontres de Moriond: QCD and High Energy Hadronic Interactions}, Les Arcs, March 1998; \textit{6th International Workshop on Deep Inelastic Scattering and QCD (DIS98)}, Brussels, April 1998.

2. M. A. G. Aivazis, F. I. Olness and W.- K. Tung, Phys. Rev. \textbf{D50}, 3085 (1994); M. A. G. Aivazis, J. C. Collins, F. I. Olness and W.- K. Tung, Phys. Rev. \textbf{D50}, 3102 (1994); J. C. Collins, PSU-TH/198, \texttt{hep-ph 9806259}.

3. M. Maul, A. Schäfer, Phys. Lett. \textbf{B390}, 437 (1997).

4. S. Kretzer, M. Stratmann, paper in preparation.

5. M. Glück, S. Kretzer and E. Reya, Phys. Lett. \textbf{B398}, 381 (1997); Erratum \textbf{B405}, 392 (1997).

6. S. Kretzer and I. Schienbein, DO-TH 98/05, \texttt{hep-ph 9805233}, to appear in Phys. Rev. \textbf{D}.

7. S. Kretzer and I. Schienbein, DO-TH 98/14, \texttt{hep-ph 9808375}, submitted to Phys. Rev. \textbf{D}.

8. M. Glück, E. Reya and A. Vogt, Z. Phys. \textbf{C67}, 433 (1995).

9. H. L. Lai \textit{et al.}, CTEQ collab., Phys. Rev. \textbf{D55}, 1280 (1997).

10. K. Kleinknecht and B. Renk, Z. Phys. \textbf{C17}, 325 (1983).

11. C. Peterson et al., Phys. Rev. \textbf{D27}, 105 (1983).

12. M. Cacciari and M. Greco, Phys. Rev. \textbf{D55}, 7134 (1997).

13. J. Binnewies, B. A. Kniehl and G. Kramer, Phys. Rev. \textbf{D58}, 014014 (1998); Z. Phys. \textbf{C76}, 677 (1997).

14. B. Mele and P. Nason, Nucl. Phys. \textbf{B361}, 626 (1991).

15. H. Albrecht \textit{et al.}, ARGUS collab., Z. Phys. \textbf{C52}, 353 (1991).

16. D. Bortoletto \textit{et al.}, CLEO collab., Phys. Rev. \textbf{D37}, 1719 (1988).

17. This point is well illustrated in Fig. 36.13 in the 1996 \textit{Review of particle Physics}, R. M. Barnett \textit{et al.}, Phys. Rev. \textbf{D54}, 1 (1996).

18. P. Nason and B. R. Webber, Nucl. Phys. \textbf{B421}, 473 (1994); Erratum \textbf{480}, 755 (1996).