Neutrino induced hard exclusive $D_s$ production

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Abstract

Motivated by the possibility to use high intensity neutrino beams for neutrino–nucleon scattering experiments we analyze charged current induced exclusive meson production within the framework of generalized parton distributions. The cross section for hard exclusive $D_s$ production is estimated in this formalism to leading order in QCD. The integrated cross section proves to be sizable. It is shown that the considered process is well suited to provide novel information on the gluon structure of nucleons, which is contained in the generalized gluon parton distribution.

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The factorization theorem \cite{1, 2} states that up to power suppressed terms every contribution to the amplitude for hard exclusive meson production can be written as a convolution of a generalized parton distribution (GPD), a distribution amplitude, and a hard part. This has recently been applied for the investigation of electroproduction of single light mesons \cite{3} and meson pairs \cite{4}. The fact that in the near future also high intensity neutrino beams might be available for lepton–nucleon scattering experiments \cite{5, 6} motivates the present study extending the formalism to charged current induced processes.

We consider the example

$$\bar{\nu}_\mu + N \to \mu^+ + N + D_{s}^-.$$  

Similar processes have already been subject of experimental studies \cite{7}. For the analysis presented here, however, $Q^2$ has to be large compared to $-t$ and the squared masses of the involved particles. The leading order amplitude is given by the sum of three diagrams involving a gluon GPD (Fig. \[a\] and diagrams obtained by an interchange of vertices) and two diagrams with a contribution of the (polarized and unpolarized) strange quark GPD (Fig. \[b\] plus one diagram with changed order of vertices). It is important to note that the only dependence on quark distributions in the nucleon comes in via the strange sea. Therefore the considered process is a good probe for the gluon GPD, which dominates the amplitude. To leading order in the strong coupling constant $\alpha_s$ and neglecting terms of the order $m_{D_s}^4/(Q^2 + m_{D_s}^2)^2$ where $m_{D_s}$ is the mass of the $D_s$ meson the amplitude for the subprocess

$$W_L^{-\rm{charged}}(q) + N(p) \to D_{s}^-(q') + N(p')$$  

is given by

$$T = \langle N(p'), D_{s}^-(q')|J^{\rm{charged}} \cdot \varepsilon_L|N(p)\rangle$$
The differential cross section for leptoproduction is given in terms of this amplitude by

\[ \frac{\text{d} \sigma}{\text{d} x_{\text{Bj}} \text{d} Q^2 \text{d} t} = \frac{e^2}{2(4\pi)^3 \sin^2 \theta_W Q^2 (Q^2 + M_W^2)^2} \left( \frac{Q^2}{2x_{\text{Bj}} p \cdot t} \right) \sum_s |T|^2, \]

where the skewedness parameter \( \xi \) is related to the Bjorken variable by \( \xi = x_{\text{Bj}} (Q^2 + m_c^2)/(2Q^2 - x_{\text{Bj}} (Q^2 + m_c^2)) \). The mass of the charm quark \( m_c \) is understood as pole mass, in the following a value of \( m_c = 1.5 \text{ GeV} \) is used. For the GPD’s \( F_G(\tau, \xi, t) \), \( \tilde{F}_G(\tau, \xi, t) \), \( F_s(\tau, \xi, t) \), and \( \tilde{F}_s(\tau, \xi, t) \) the notation of Ref. \[8\] is used and the distribution amplitude for the \( D_s^+ \) meson is defined by

\[ \Phi_{D_s^+}(z) = \int \frac{\text{d} \lambda}{2\pi} e^{-i\lambda z(\bar{q} \cdot \bar{n})} \langle D_s^+ (q') | T \bar{\psi}^s(\lambda \bar{n}) \gamma_\lambda \bar{\psi}(0) | 0 \rangle. \]
where $l$ is the neutrino momentum.

For an numerical estimate of the cross section we model the distribution amplitude following [9] as

$$\Phi_{D_{s}^{-}}(z) = N_{D_{s}} \sqrt{z(1-z)} \exp \left[- \frac{m_{D_{s}}^{2}}{2\omega^{2}z^{2}} \right]$$  \hspace{1cm} (6)

taking for the parameter $\omega$ the value $\omega = 1.38$ GeV obtained in [10] as the best fit for the $D$ meson. The normalization constant $N_{D_{s}}$ has to be chosen such that the sum rule

$$\int_{0}^{1} dz \Phi_{D_{s}^{-}}(z) = f_{D_{s}}$$  \hspace{1cm} (7)

is satisfied, where we adopt for the decay constant $f_{D_{s}}$ the value $f_{D_{s}} = 270$ MeV as an average of the results obtained so far in lattice calculations [11], see also [12] for an earlier review.

The gluon and quark GPD’s are parameterized as in [4] combining Radyushkin’s model [2, 13] with the parameterizations of the usual (forward) parton distributions of Refs. [14] (MRS (A’)) and [15] (Gluon A (NLO)). For the $t$-dependence of the GPD’s we adopt the factorized ansatz $F(\tau, \xi, t) = F(\tau, \xi, 0) F_{0}(t) / F_{0}(0)$ and use the parameterization of [16] for the gluon form factor $F_{0}$. For the strong coupling constant the two loop result is taken with $N_{f} = 4$ and $\Lambda_{QCD}^{(4)} = 250$ MeV.

Figure 2 shows the results obtained for the differential cross sections $d\sigma/dx_{Bj}$ and $d\sigma/dQ^{2}$ where $t = (p - p')^{2}$ has been integrated over the interval $t_{\min} = m_{N}^{2} / (1 - \xi^{2}) < -t < 2$ GeV$^{2}$ and the neutrino energy has been chosen as $E_{\nu} = 34$ GeV. For the plot of the $x_{Bj}$-dependence $Q^{2}$ has been integrated from 12 GeV$^{2}$ to the upper bound given by
Figure 3: The differential cross sections from Fig. 2 compared with the results obtained for the asymptotic form of the distribution amplitude $\Phi_{D^-}$ (dashed lines) and by modeling the GPD's by their forward limit (dotted lines).

Figure 4: The result without mass corrections of the order $m_{D^-}^2/Q^2$. The very small difference to the complete result multiplied with a factor 10 is plotted with dotted lines.
the constraint \( y < 1 \), with \( y := p \cdot q / p \cdot l = Q^2 / (2x_{Bj} p \cdot l) \). The plot of \( d\sigma/dQ^2 \) is based on the \( x_{Bj} \)-dependent cross section integrated between \( x_{Bj} = 0.19 \) and \( x_{Bj} = 0.69 \) taking into account the same kinematical constraints. The dashed lines are obtained neglecting the contribution of the strange quark GPD and the polarized gluon GPD proving the dominance of the contribution of \( F_G(\tau, \xi, t) \). The negligible small contribution of the polarized gluon GPD multiplied with a factor 100 is plotted with dotted lines.

To illustrate the dependence of the cross section on the shape of the \( D_s \) distribution amplitude and the GPD’s we show in Fig. 3 the results obtained by modeling \( \Phi_{D_s^-} \) using its asymptotic form \( \Phi_{D_s^-}(z) = 6f_{D_s} z(1 - z) \) instead of the parameterization of Eq. 6 (dashed lines) and alternatively by replacing the models for the GPD’s \( F(\tau, \xi, 0) \) by their forward limit \( F(\tau, \xi, 0) \) (dotted lines). The latter choice corresponds to the approximation of the GPD’s for \( t = 0 \) by usual parton distributions. For comparison also the original result is plotted again in Fig. 3.

In Fig. 4 we finally show the result that is obtained if all corrections of the order \( m_{D_s}^2/Q^2 \) in the amplitude are neglected. The very small difference to the complete result multiplied with a factor 10 is plotted with dotted lines. The smallness of these corrections justifies the approach based on the factorization theorem, which is valid only up to terms of the order \( \mu^2/Q^2 \) with \( \mu \) being a typical mass scale of the process.

Integrating all variables \( Q^2, x_{Bj}, \) and \( t \) over the kinematical region specified above gives a value for the total cross section of \( \sigma = 2.45 \times 10^{-14} \text{ GeV}^{-2} = 9.5 \times 10^{-6} \text{ pb} \). Even given this small value the huge integrated luminosities of \( \int L dt > 10^{45} \text{ cm}^{-2} = 10^{9} \text{ pb}^{-1} \) available at a neutrino factory would lead to a sizable number of events of the order of magnitude \( 10^4 \). Larger total cross sections can be obtained for higher neutrino energies because of the larger available kinematical region.

Uncertainties of the rough estimate presented here result from the lack of knowledge about the exact form of the meson distribution amplitude as illustrated in Fig. 3. Also the predictions for the value of \( f_{D_s} \) differ by about 20\%. Up to now the experimental uncertainty for \( f_{D_s} \) is even larger [17]. It is worth noting, however, that experiments of the kind discussed in the present article can provide much more precise information on the \( D_s \) decay constant independently of the exact cross section for the process [12]. As discussed in [18] the relatively high production rate of \( D_s \) mesons allows to determine \( f_{D_s} \) by measuring the \( D_s \) branching ratios and its total width.

From the experimental point of view a difficulty arises from the fact that all three particles in the final channel need to be detected because the neutrino beam energy is not sharp and therefore an exclusive event can not be identified by reconstructing the momentum of an undetected particle via a missing momentum analysis.

It has been shown that the high intensity neutrino beams available at neutrino factories allow to study hard exclusive meson production also for weak interaction induced reactions opening a new possibility to study the nucleon structure and allowing to better test the theory of these exclusive processes. The production of charmed strange mesons proves to be of particular interest due to its high sensitivity to the gluon GPD’s.

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