Exclusive electro-weak production
of a charmed meson at high energy

B. Pire[1], L. Szymanowski[2] and J. Wagner[2⋆]

1 CPHT, CNRS, École Polytechnique, I.P. Paris, 91128 Palaiseau, France
2 National Centre for Nuclear Research (NCBJ), Pasteura 7, 02-093 Warsaw, Poland

⋆ Jakub.Wagner@ncbj.gov.pl

Abstract

Exclusive electro-weak processes have peculiar features which make them complementary to usually discussed deeply virtual electroproduction processes such as deep virtual Compton scattering or meson production (and the corresponding crossed reactions). They allow in particular single charmed meson production, which we study in two different contexts : electroproduction at an electron ion collider and neutrino-production at a medium energy neutrino facility. We rely on the QCD collinear factorization framework where generalized parton distributions allow physicists to perform a nucleon tomography.

1 Introduction

The very high luminosity anticipated at planned high energy electron ion colliders will open the physics domain of charged current events in exclusive electroproduction processes to a detailed investigation of various interesting channels. Inspired by the pioneering works of [1, 2] we calculate the leading order amplitude for the following reactions :

$$e^-(k) + N(p_1) \quad \rightarrow \quad \nu_e(k') + D_s^-(p_D) + N'(p_2), \tag{1}$$

$$e^-(k) + N(p_1) \quad \rightarrow \quad \nu_e(k') + D_s^{*-}(p_D, \epsilon_D) + N'(p_2), \tag{2}$$

on a nucleon N (proton or neutron) target, and demonstrate that these processes may be accessed at future electron-ion colliders [3–5].

This study is much related to the reactions one may access in neutrino experiments, namely

$$\nu_e(k) + N(p_1) \quad \rightarrow \quad e^-(k') + D^+(p_D) + N'(p_2), \tag{3}$$

$$\nu_e(k) + N(p_1) \quad \rightarrow \quad e^-(k') + D^{*+}(p_D, \epsilon_D) + N'(p_2), \tag{4}$$

which we discussed some time ago [6, 7] but have not yet been confronted to experimental data.

2   Neutrino-production of a heavy meson

Although hadronic physics is not today the main purpose of neutrino experiments which focus mostly on the study of neutrino oscillations, let us stress that data collected at the near detectors contain very valuable information which should be analyzed with care. For instance, it has been noticed [8] that the elusive chiral-odd quark transversity GPDs contribute to the exclusive D meson production, thanks to the charmed mass effect in the quark propagators. Moreover, the gluon transversity GPDs contribute to the vector meson D^* production when this charmed meson is transversely polarized [7]. A complete study [6] showed that the cross sections were small but yet sufficient for a dedicated study to be performed with an hopefully successful output, at least for the longitudinal contributions related to vector and axial GPDs. Without entering into details, we illustrate our results by showing in Fig. 1 the differential cross-section $\frac{d\sigma(\nu N \to l^- N D^+)}{dy\, dQ^2\, dt}$. Note that the gluonic contribution is enhanced by a factor $\frac{V_{cs}^2}{V_{cd}^2}$ if one considers D_s^+ rather than D^+ production, with V_{cq} the relevant CKM matrix elements.
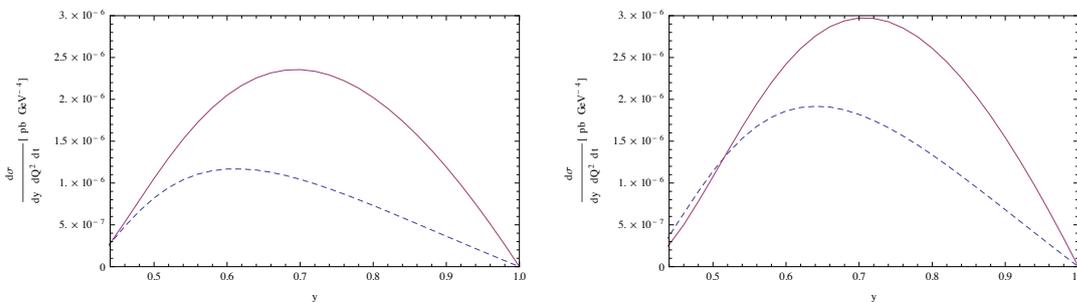
Figure 1: The y dependence of the longitudinal contribution to the cross section $\frac{d\sigma(\nu N \to l^- N D^+)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for $Q^2 = 1$ GeV^2, $\Delta_T = 0$ and $s = 20$ GeV^2 for a proton (left panel) and neutron (right panel) target : total (quark and gluon, solid curve) and quark only (dashed curve) contributions.

3   Prospects for EIC

Exclusive charged current reactions in high luminosity electron accelerators have been studied with optimistic results [1, 2]. We enlarged [9] this study by considering the production of charmed meson. Since the scattering amplitude is proportional to the relevant CKM matrix element, the dominant production process involves a $D_s^-(1968)$ or $D_s^{*-}(2112)$ charmed and strange meson. The $D_s^{*-}(2112)$ decays mostly in a $D_s^-(1968)\gamma$ pair. Neglecting the strange quark content of the nucleon, the exclusive production of these mesons occur in the kinematical domain where collinear factorization allows a description of the scattering amplitude as a convolution of gluon GPDs and the D_s^- or D_s^{*-} meson distribution amplitude (DA),

Our results, shown on Fig. 2 and 3 for the pseudoscalar D_s meson and on Fig. 4 for the two polarization modes of the vector D_s^* meson are quite encouraging. Note that the kinematics of the solid curve on the left pannel of Fig. 2 (resp.Fig. 3 corresponds to $\xi = 0.012$ (resp. $\xi = 0.1$). The cross-section for the production of the transverse polarization mode of the D_s^* is suppressed. As it may have been anticipated the Q^2 dependence is quite modest at small $Q^2 << M_D^2$. The y-dependence is quite strong resulting in the dominance of the moderate skewness region. The dependence of our results with respect to the choice of the gluon GPDs
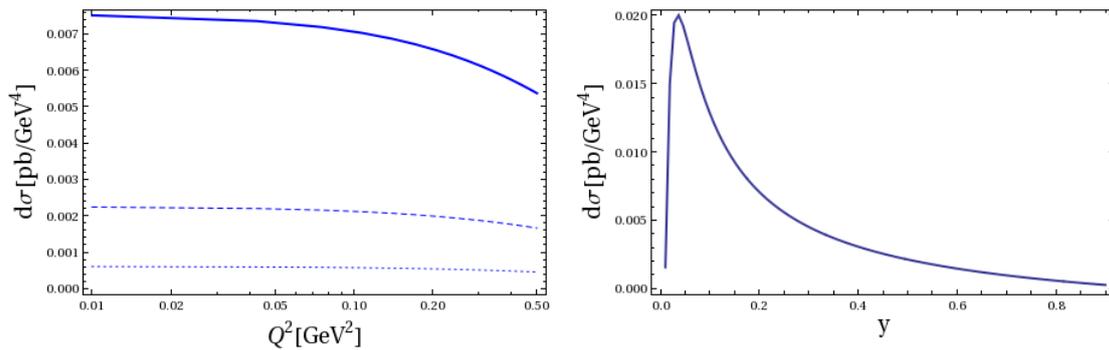
Figure 2: Left panel : The Q^2 dependence of the cross section $\frac{d\sigma(e^- N \to \nu N D_s^-)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for $\Delta_T = 0$ and $s = 820$ GeV^2 and $y = .2$ (solid curve) , $y = .5$ (dashed curve) and $y = .8$ (dotted curve). Right panel : The y dependence of the cross section $\frac{d\sigma(e^- N \to \nu N D_s^-)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for $Q^2 = 0.1$ GeV^2, $\Delta_T = 0$ and $s = 820$ GeV^2.

and heavy meson DAs is discussed in [9].

4 Conclusion

The hadronic physics opportunities opened by high luminosity and medium energy neutrino facilities have definitely be underexploited up to now. We demonstrated that the study of exclusive channels like D or D^* charmed meson production are very complementary to the hadronic program of electron facilities such as JLab, by giving access to elusive quantities like the quark or gluon transversity GPDS. We believe that planned high energy neutrino experiments such as Minerve and Minos+ [10, 11] which have their scientific program oriented toward the understanding of neutrino oscillations will collect more statistics and will thus allow some nice progress in the realm of hadronic physics.

On the other hand, we have shown that the production cross-sections for charged current exclusive D_s charmed strange mesons, although small, are in the reach of future high luminosity electron-ion colliders making them another potential source of information for future programs aiming at the extraction of GPDs. The rate for the longitudinally polarized D_s^* vector meson is of the same order of magnitude as the one for the pseudoscalar D_s meson. Both are in fact of the same order of magnitudes as the rates for light mesons at a Q^2 value of the order a few GeV^2 [2]. A full feasibility study is much needed, since detecting a D_s meson is not a trivial goal in a charged current event where the momentum of the outgoing neutrino cannot be measured.

Acknowledgements
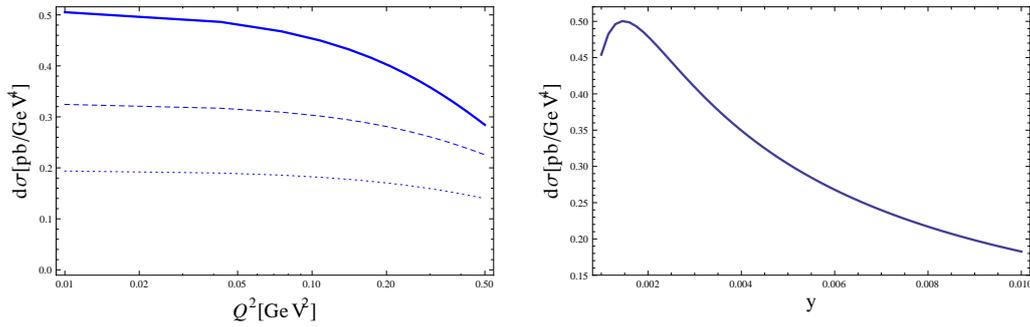
Figure 3: Left panel : The Q^2 dependence of the cross section $\frac{d\sigma(e^- N \to \nu N D_s^-)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for $\Delta_T = 0$ and $s = 20000$ GeV^2 and $y = 10^{-3}$ (solid curve) , $y = 5 \cdot 10^{-3}$ (dashed curve) and $y = 10^{-2}$ (dotted curve). Right panel : The y dependence of the cross section $\frac{d\sigma(e^- N \to \nu N D_s^-)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for $Q^2 = 0.1$ GeV^2, $\Delta_T = 0$ and $s = 20000$ GeV^2.
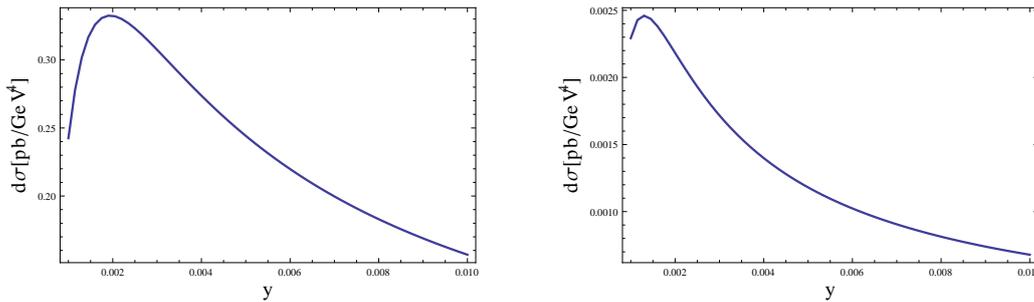
Figure 4: Left panel : The y dependence of the longitudinal cross section $\frac{d\sigma(e^- N \to \nu N D_s^{-*})}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for $\Delta_T = 0$ and $s = 20000$ GeV^2 and $Q^2 = .1$ GeV^2 . Right panel : idem for the production cross-section of a transversely polarized D_s^{-*}.

References

[1] M. Siddikov and I. Schmidt, *Generalized parton distributions from charged current meson production in ep experiments*, Phys. Rev. D **96**, 096006 (2017), doi:10.1103/PhysRevD.96.096006.

[2] M. Siddikov and I. Schmidt, *Generalized parton distributions from charged current meson production*, Phys. Rev. D **99**, 116005 (2019), doi:10.1103/PhysRevD.99.116005.

[3] A. Accardi et al., *Electron-Ion Collider: The next QCD frontier*, Eur. Phys. J. A **52**, 268 (2016), doi:10.1140/epja/i2016-16268-9.

[4] D. P. Anderle et al., *Electron-ion collider in China*, Front. Phys. **16**, 64701 (2021), doi:10.1007/s11467-021-1062-0.

[5] R. Abdul Khalek et al., *Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report*, arXiv:2103.05419.

[6] B. Pire, L. Szymanowski and J. Wagner, *Exclusive neutrino production of a charmed meson*, Phys. Rev. D **95**, 094001 (2017), doi:10.1103/PhysRevD.95.094001.

[7] B. Pire and L. Szymanowski, *Exclusive neutrino production of a charmed vector meson and transversity gluon generalized parton distributions*, Phys. Rev. D **96**, 114008 (2017), doi:10.1103/PhysRevD.96.114008.

[8] B. Pire and L. Szymanowski, *Neutrino Production of a Charmed Meson and the Transverse Spin Structure of the Nucleon*, Phys. Rev. Lett. **115**, 092001 (2015), doi:10.1103/PhysRevLett.115.092001.

[9] B. Pire, L. Szymanowski and J. Wagner, *Charged current electroproduction of a charmed meson at an electron-ion collider*, Phys. Rev. D **104**, 094002 (2021), doi:10.1103/PhysRevD.104.094002.

[10] L. Aliaga et al., *Design, calibration, and performance of the MINERvA detector*, Nucl. Instrum. Meth. A **743**, 130 (2014), doi:10.1016/j.nima.2013.12.053.

[11] D. S. Ayres et al., *NOvA Proposal to Build a 30 Kiloton Off-Axis Detector to Study Neutrino Oscillations in the Fermilab NuMI Beamline*, arXiv:hep-ex/0503053.