Neutrino-production of a charmed meson and the transverse spin structure of the nucleon

Lech Szymanowski

National Centre for Nuclear Research (NCBJ)
Warsaw, Poland

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in collaboration with B. Pire (Ecole Polytechnique, CPhT, Palaiseau)

Recent progresses in Transversity partonic distributions

What is transversity?

- Transverse spin content of the proton:

$$|\uparrow\rangle_{(x)} \sim |\rightarrow\rangle + |\leftarrow\rangle$$
$$|\downarrow\rangle_{(x)} \sim |\rightarrow\rangle - |\leftarrow\rangle$$

spin along x helicity states

- Observables which are sensitive to helicity flip thus give access to transversity partonic distributions: Poorly known PDF, TMDs, GPDs.

- SIDIS analysis

  $\rightarrow$ transversity distributions are not small

  M. Radici et al ,JHEP 1505 (2015) 123

- Lattice calculations

  QCDSF and UKQCD Coll. Phys.Rev.Lett. 98 (2007) 222001

- Theoretical models

  $\rightarrow$ cross-channel analysis,

  K Semenov et al, Eur.Phys.J.A50 (2014) 90

- Transversity is a chiral-odd quantity

  $\rightarrow$ the chiral odd quantities one wants to measure appear in pairs

Accessing Transversity GPDs of the nucleon

How to get access to transversity GPDs?

- At twist 3 chiral odd GPDs may couple to chiral-odd twist 3 meson DAs [Goloskokov, Kroll], [Ahmad, Goldstein, Liuti]

  $\rightarrow$ π electroproduction data at JLab consistent with this scenario

  $\rightarrow$ However processes involving twist 3 DAs may face problems with factorization (end-point singularities)

- One can consider a 3-body final state process [Ivanov, Pire, LSz, Teryaev], [Enberg, Pire, LSz], [El Beiyad et al.], [Boussarie, Pire, LSz, Wallon]

  $\rightarrow$ Leading twist process

  $\rightarrow$ more tailored to EIC kinematics

$$\gamma N \rightarrow \rho\rho N' \qquad \gamma N \rightarrow \pi\rho N' \qquad \gamma N \rightarrow \gamma\rho N'$$

Neutrino-production of charmed meson

We consider the exclusive reactions

$$\begin{aligned} \nu_l(k)N(p_1) &\rightarrow l^-(k')D^+(p_D)N'(p_2)\,, \\ \bar{\nu}_l(k)N(p_1) &\rightarrow l^+(k')D^-(p_D)N'(p_2)\,, \end{aligned}$$

in the kinematical domain where collinear factorization leads to a description of the scattering amplitude in terms of nucleon GPDs and the $D-$meson distribution amplitude, with the hard subprocess ($q = k' - k; Q^2 = -q^2$):

$$W^+(q)d \rightarrow D^+d' \qquad W^-(q)u \rightarrow D^-u'\,,$$

described by the handbag Feynman diagrams

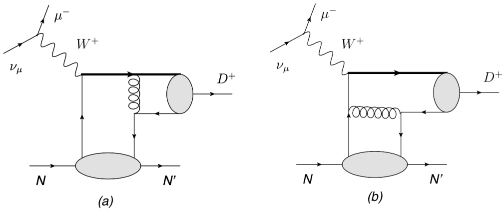


Figure : Feynman diagrams for the factorized amplitude for the $\nu_\mu N \rightarrow \mu^- D^+ N'$ process; the thick line represents the heavy quark.

Neutrino-production of charmed meson

Our aim:

• to show that the transverse amplitude $W_T q \to D q'$ gets its leading term in the collinear QCD framework as a convolution of chiral odd leading twist GPDs with a coefficient function of order $\frac{m_c}{Q^2}$ (to be compared to the $O(\frac{1}{Q})$ longitudinal amplitude)

• to show how to access these GPDs through the azimuthal dependence of the $\nu N \to \mu^- D^+ N$ differential cross section

$$\frac{d^4\sigma(\nu N \to l^- N' D)}{dx_B\, dQ^2\, dt\, d\varphi} = \tilde{\Gamma}\Big\{\frac{1+\sqrt{1-\varepsilon^2}}{2}\sigma_{--} + \varepsilon\sigma_{00}$$
$$+\sqrt{\varepsilon}(\sqrt{1+\varepsilon}+\sqrt{1-\varepsilon})(\cos\varphi\, \mathrm{Re}\sigma_{-0} + \sin\varphi\, \mathrm{Im}\sigma_{-0})\Big\},$$

with

$$\tilde{\Gamma} = \frac{G_F^2}{(2\pi)^4}\frac{1}{16 x_B}\frac{1}{\sqrt{1+4x_B^2 m_N^2/Q^2}}\frac{1}{(s-m_N^2)^2}\frac{Q^2}{1-\epsilon},$$

and the "cross-sections" $\sigma_{lm} = \epsilon_l^{*\mu} W_{\mu\nu}\epsilon_m^{\nu}$ are product of amplitudes for the process $W(\epsilon_l)N \to DN'$, averaged (summed) over the initial (final) hadron polarizations.

T. Arens, O. Nachtmann, M. Diehl and P. V. Landshoff, Z. Phys. C **74**, 651 (1997).

Neutrino-production of charmed meson

Standard notations of deep exclusive leptoproduction:

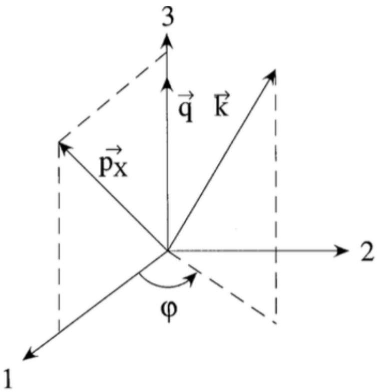
- $P = (p_1 + p_2)/2, \qquad \Delta = p_2 - p_1, \qquad t = \Delta^2, \qquad x_B = Q^2/2p_1.q,$
- $y = p_1.q/p_1.k$ and $\epsilon \simeq 2(1-y)/[1+(1-y)^2]$.
- n are light-cone vectors and $\xi = -\Delta.n/2P.n$ is the skewness variable.

Neutrino-production of charmed meson

The azimuthal angle φ is defined in the initial nucleon rest frame as:

$$sin\ \varphi = \frac{\vec{q}\cdot[(\vec{q}\times\vec{p}_D)\times(\vec{q}\times\vec{k})]}{|\vec{q}||\vec{q}\times\vec{p}_D||\vec{q}\times\vec{k}|},$$

while the final nucleon momentum lies in the $1-3$ plane $(\Delta^y = 0)$



Neutrino-production of charmed meson

Theoretical input:

- D-meson distribution amplitude

A. Szczepaniak, E. M. Henley and S. J. Brodsky, Phys. Lett. B **243**, 287 (1990);
T. Kurimoto, H. n. Li and A. I. Sanda, Phys. Rev. D **65**, 014007 (2002);
S. Descotes-Genon and C. T. Sachrajda, Nucl. Phys. B **650**, 356 (2003);
V. M. Braun, D. Y. Ivanov and G. P. Korchemsky, Phys. Rev. D **69**, 034014 (2004);
T. Feldmann, B. O. Lange and Y. M. Wang, Phys. Rev. D **89**, no. 11, 114001 (2014);
V. M. Braun and A. Khodjamirian, Phys. Lett. B **718**, 1014 (2013).

$$\langle 0|\bar{d}(y)\gamma^{\mu}\gamma^{5}c(-y)|D(p_D)\rangle = if_D P^{\mu}\int_0^1 e^{i(2z-1)p_D\cdot y}\phi_D(z)\,,$$

where $\int_0^1 dz\ \phi_D(z) = 1$ and $f_D = 0.223$ GeV. twist-2 DA

CLEO meaurement : M Artuso et al prl 95,251801 (2005)

Neutrino-production of charmed meson

Theoretical input ctnd:

- Transversity GPDs

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p_2,\lambda'|\,\bar{\psi}(-\tfrac{1}{2}z)\, i\sigma^{+i}\, \psi(\tfrac{1}{2}z)\; |p_1,\lambda\rangle\Big|_{z^+=\mathbf{z}_T=0}$$
$$= \frac{1}{2P^+}\bar{u}(p_2,\lambda')\Big[H_T^q\, i\sigma^{+i} + \tilde{H}_T^q\,\frac{P^+\Delta^i-\Delta^+P^i}{m_N^2} + E_T^q\,\frac{\gamma^+\Delta^i-\Delta^+\gamma^i}{2m_N} + \tilde{E}_T^q\,\frac{\gamma^+P^i-P^+\gamma^i}{m_N}\Big]u(p_1,\lambda). \quad (1)$$

The leading GPD $H_T(x,\xi,t)$ is equal to the transversity PDF in the $\xi = t = 0$ limit

The transversity PDF has recently been argued by M. Radici et al [JHEP 1505 (2015) 123] to be sizable for the $d-$quark, which is contributing to our process.

Neutrino-production of charmed meson — Longitudinal W

The longitudinal amplitude of leading twist:

slight modification of the calculation in

B. Z. Kopeliovich, I. Schmidt and M. Siddikov,
Phys. Rev. D **86**, 113018 (2012) and D **89**, 053001 (2014);
G. R. Goldstein, O. G. Hernandez, S. Liuti and T. McAskill,
AIP Conf. Proc. **1222** (2010) 248.

with usual chiral-even GPDs:

$$T_L = \frac{-iC}{Q} \qquad \bar{N}(p_2)\left[\mathcal{H}_D\hat{n} + \frac{1}{2m_N}\mathcal{E}_D i\sigma^{n\Delta} - \tilde{\mathcal{H}}_D\hat{n}\gamma_5 - \frac{\Delta.n}{2m_N}\tilde{\mathcal{E}}_D\gamma_5\right] N(p_1)\,,$$

with $C = \frac{8\pi}{9}\alpha_s V_{dc}$ and $(\bar{z} = 1 - z)$:

$$\mathcal{F}_D(\xi,t) = f_D \int dz \frac{\phi_D(z)}{\bar{z}} \int dx \frac{F^d(x,\xi,t)}{x-\xi+i\epsilon},$$

for any chiral even $d-$quark GPD in the nucleon $F^d(x,\xi,t)$; g is the weak interaction coupling constant and V_{dc} the CKM matrix element.

Neutrino-production of charmed meson — Transverse W

The transverse amplitude T_T up to $O(m_c/Q^2)$

- T_T vanishes when $m_c = 0 = m_d$.

For chiral-even GPDs due to the colinear kinematics and the leading twist CF
For chiral-odd GPDs due to the odd number of γ matrices in the Dirac trace.

- $T_T \neq 0$ due to $m_c \neq 0$ in the hard CF

Fact. thm with HEAVY quark: J. C. Collins, Phys. Rev. D **58**, 094002 (1998)

- hard-scattering factorization of meson leptoproduction

Fact. thm with LIGHT quark: J. C. Collins, L. Frankfurt, M. Strikman, Phys. Rev. D **56**

valid at leading twist with the inclusion of heavy quark masses in the hard CF

- The proof is applicable independently of the relative sizes of m_c and Q
- the error is a power of Λ/Q
- in our case, this means including $\frac{m_c}{k_c^2-m_c^2}$ in the off-shell heavy quark propagator in the leading twist CF
- inclusion $\frac{m_c}{k_c^2-m_c^2}$ in T_L has no effect

odd number of γ's in trace

Neutrino-production of charmed meson   Transverse W

T_T reads: $\tau = 1 - i2$

$$T_T = \frac{iC\xi m_c}{\sqrt{2}Q^2}\bar{N}(p_2)\left[\mathcal{H}_T^{\phi} i\sigma^{n\tau} + \tilde{\mathcal{H}}_T^{\phi}\frac{\Delta^{\tau}}{m_N^2} + \mathcal{E}_T^{\phi}\frac{\hat{n}\Delta^{\tau} + 2\xi\gamma^{\tau}}{2m_N} - \tilde{\mathcal{E}}_T^{\phi}\frac{\gamma^{\tau}}{m_N}\right]N(p_1),$$

in terms of transverse form factors defined as :

$$\mathcal{F}_T^{\phi} = f_D \int \frac{\phi(z)dz}{\bar{z}} \int \frac{F_T^d(x,\xi,t)dx}{(x-\xi+i\epsilon)(x-\xi+\alpha\bar{z}+i\epsilon)},$$

- F_T^d is any d-quark transversity GPD,
- $\alpha = \frac{2\xi m_c^2}{Q^2+m_c^2}$
- $\bar{\mathcal{E}}_T^{\phi} = \xi\mathcal{E}_T^{\phi} - \tilde{\mathcal{E}}_T^{\phi}$.
- $\mathcal{F}_T^{\phi}$ has legitimate limit for small α, $\Rightarrow$ the dependence on the heavy meson DA effectively factorizes

Neutrino-production of charmed meson

Observables

$$\frac{d^4\sigma(\nu N \to l^- N' D)}{dx_B\, dQ^2\, dt\, d\varphi} = \tilde{\Gamma}\Big\{ \frac{1+\sqrt{1-\varepsilon^2}}{2}\sigma_{--} + \varepsilon\sigma_{00}$$
$$+\sqrt{\varepsilon}(\sqrt{1+\varepsilon}+\sqrt{1-\varepsilon})(\cos\varphi\ \mathrm{Re}\sigma_{-0} + \sin\varphi\ \mathrm{Im}\sigma_{-0})\ \Big\},$$

with

$$\tilde{\Gamma} = \frac{G_F^2}{(2\pi)^4}\frac{1}{16x_B}\frac{1}{\sqrt{1+4x_B^2 m_N^2/Q^2}}\frac{1}{(s-m_N^2)^2}\frac{Q^2}{1-\epsilon}\,,$$

the "cross-sections" $\sigma_{lm} = \epsilon_l^{*\mu} W_{\mu\nu} \epsilon_m^{\nu}$ are product of amplitudes for the process $W(\epsilon_l)N \to DN'$, averaged (summed) over the initial (final) hadron polarizations

Neutrino-production of charmed meson — Observables

The longitudinal cross section σ_{00} is obtained by squaring the amplitude T_L;

at zeroth order in Δ_T, it reads :

$$\sigma_{00} = \frac{C^2}{2Q^2}\left\{8(|\mathcal{H}_D^2| + |\tilde{\mathcal{H}}_D^2|)(1-\xi^2) + |\tilde{\mathcal{E}}_D^2|\frac{1+\xi^2}{1-\xi^2}\right\}$$

The transverse cross section σ_{--} is obtained by squaring the amplitude T_T;

at zeroth order in Δ_T, it reads :

$$\sigma_{--} = \frac{4\xi^2 C^2 m_c^2}{Q^4} \left\{ (1-\xi^2)|\mathcal{H}_T^\phi|^2 + \frac{\xi^2}{1-\xi^2}|\bar{\mathcal{E}}_T^\phi|^2 - 2\xi \mathcal{R}e[\mathcal{H}_T^\phi \bar{\mathcal{E}}_T^{\phi *}] \right\}$$

Neutrino-production of charmed meson — Observables

The interference cross section σ_{-0} vanishes at zeroth order in Δ_T.

The term linear in Δ_T/m_N reads $\lambda = \tau^* = 1 + i2$

$$\sigma_{-0} = \frac{-\xi\sqrt{2}C^2}{m_N}\frac{m_c}{Q^3}\Big\{-i\mathcal{H}_T^{*\phi}\tilde{\mathcal{E}}_D\xi(1+\xi)\epsilon^{pn\Delta\lambda}$$

$$+\mathcal{H}_T^{*\phi}\Delta^\lambda[-(1+\xi)\mathcal{E}_D] + \tilde{\mathcal{H}}_T^{*\phi}\Delta^\lambda[2\mathcal{H}_D - \frac{2\xi^2}{1-\xi^2}\mathcal{E}_D]$$

$$+\mathcal{E}_T^{*\phi}\Delta^\lambda[(1-\xi^2)\mathcal{H}_D - \xi^2\mathcal{E}_D]$$

$$+\bar{\mathcal{E}}_T^{\phi *}[\Delta^\lambda[(1+\xi)\mathcal{H}_D + \xi\mathcal{E}_D] + i(1+\xi)\epsilon^{pn\Delta\lambda}\tilde{\mathcal{H}}_D]\Big\}.$$

Neutrino-production of charmed meson — Observables

$$
\begin{aligned}
< cos\ \varphi > &= \frac{\int cos\ \varphi\ d\varphi\ d^4\sigma}{\int d\varphi\ d^4\sigma} = K_\epsilon \frac{\mathcal{R}e\sigma_{-0}}{\sigma_{00}}\ , \\
< sin\ \varphi > &= K_\epsilon \frac{\mathcal{I}m\sigma_{-0}}{\sigma_{00}}
\end{aligned}
$$

- with $K_\epsilon = \frac{\sqrt{1+\varepsilon}+\sqrt{1-\varepsilon}}{2\sqrt{\epsilon}}$
- we neglected the $O(\frac{m_c^2}{Q^2})$ contribution of σ_{--} in the denominator.
- the dependence on the heavy meson DA effectively factorizes in the transverse FFs $\mathcal{H}_T^\phi$, $\mathcal{E}_T^\phi$, $\tilde{\mathcal{H}}_T^\phi$, $\tilde{\mathcal{E}}_T^\phi$ as it does in longitudinal FF $\mathcal{F}_D$

$\Longrightarrow$ heavy meson DA disappears in the ratios

Neutrino-production of charmed meson

Observables

- The complete formula for $< cos\ \varphi >$, $< sin\ \varphi >$ is quite long
- Plausible assumptions:

$$\tilde{\mathcal{H}}(\xi,t) << \mathcal{H}(\xi,t)$$

known smallness of the ratio of the helicity dependent to the helicity independent $d-$quark DF

ξ sufficiently small

neglect $\xi*$FFs

- Simple approximate results:

$$< cos\varphi > \approx \frac{K\mathcal{R}e[\mathcal{H}_D(2\tilde{\mathcal{H}}_T^{\phi} + \mathcal{E}_T^{\phi} + \bar{\mathcal{E}}_T^{\phi})^* - \mathcal{E}_D \mathcal{H}_T^{\phi *}]}{8|\mathcal{H}_D^2| + |\tilde{\mathcal{E}}_D^2|},$$

$$< sin\varphi > \approx \frac{K\mathcal{I}m[\mathcal{H}_D(2\tilde{\mathcal{H}}_T^{\phi} + \mathcal{E}_T^{\phi} + \bar{\mathcal{E}}_T^{\phi})^* - \mathcal{E}_D \mathcal{H}_T^{\phi *}]}{8|\mathcal{H}_D^2| + |\tilde{\mathcal{E}}_D^2|},$$

$$K = -\frac{\sqrt{1+\varepsilon} + \sqrt{1-\varepsilon}}{2\sqrt{\epsilon}} \frac{2\sqrt{2}\xi m_c}{Q} \frac{\Delta_T}{m_N}$$

In our kinematics, $\Delta^1 = \Delta^x = \Delta_T$, $\Delta^y = 0$, $\epsilon^{pn\Delta\lambda} = -i\Delta_T$.

- Collinear QCD factorization allows to calculate neutrino production of $D-$mesons in terms of GPDs.

- Chiral-odd and chiral-even GPDs contribute to the amplitude for different polarization states of the W

- The azimuthal dependence of the cross section allows to get access to chiral-odd GPDs

- There is no small factor preventing the measurement from being feasible, provided ξ, $\frac{m_c}{Q}$, $\frac{\Delta_T}{m_N}$ are not too small.

- The observables that we propose are certainly not a 1% effect.
  K is not small ($K = 0(\frac{.3}{\sqrt{\epsilon}})$) if we focus on Q in the range of $2-3$ GeV and $\Delta_T/m_N \approx 0.5$ (this conclusion is unchanged if we include terms of order $(\Delta_T/m_N)^2$).

THANK YOU FOR YOUR ATTENTION