Accessing GPDs in neutrinoproduction of heavy mesons

Jakub Wagner

Theoretical Physics Division
National Center for Nuclear Research, Warsaw

DIS2017, April 6th

in collaboration with:
B. Pire (CPhT Ecole Polytechnique, Palaiseau)
L. Szymanowski (NCNR, Warsaw)

based on:

B. Pire, L. Szymanowski, JW arXiv:1702.00316

Exclusive processes and GPDs

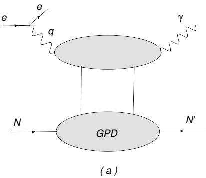


Figure : DVCS

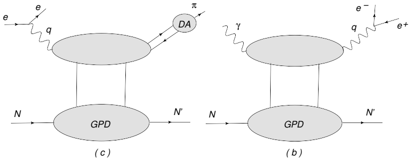


Figure : DVMP and TCS

- Various exclusive processes give information about GPDs: DVCS, TCS, DDVCS, DVMP, HVMP
- Also neutrino production of light mesons considered: allows for flavour separation, different combination of GPDs due to the charged current coupling structure. Smaller cross sections, less intense beams but process in the reach of the i.e. MINERVA experiments
  → [Kopeliovich,Schmidt, Siddikov] PRD 86

Neutrino production of charmed meson

- Here we consider D pseudo scalar charmed meson production - heavy quark production allows to extend the range of validity of collinear factorization, the heavy quark mass playing the role of the hard scale.

- Factorization theorem with HEAVY quark: $\rightarrow$ [J. C. Collins, PRD58]
  - Independently of the relative sizes of the heavy quark masses and Q
  - Size of the errors is a power of $\Lambda/\sqrt{Q^2+M_D^2}$ when $\sqrt{Q^2+M_D^2}$ is the large scale.

- Sensitivity to transversity GPDs. $\rightarrow$ [Pire,Szymanowski] PRL 115

Transversity

- The transverse spin structure of the nucleon - that is the way quarks and antiquarks spins share the polarization of a nucleon, when it is polarized transversely to its direction of motion - is almost completely unknown. Poorly known PDF, TMDs, GPDs.
- Lattice result and SIDIS analysis suggest that transversity distributions are not small $\rightarrow$ [M. Radici talk]
- Transversity GPDs coupled to chiral-odd twist 3 pi-meson DA may explain π electroproduction data at JLab [Goloskokov, Kroll], [Ahmad, Goldstein, Liuti] $\rightarrow$ [F.Sabatié talk]
- One can consider a 3-body final state process [Ivanov, Pire, Szymanowski, Teryaev], [Enberg, Pire, Szymanowski], [El Beiyad et al.], [Boussarie, Pire, Szymanowski, Wallon]

  $\rightarrow$ Leading twist process $\rightarrow$ [R.Boussarie talk]

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

Neutrino-production of charmed meson

We consider the exclusive production of a pseudoscalar $D-$meson through the reactions on a proton (p) or a neutron (n) target:

$$
\begin{aligned}
\nu_l(k)p(p_1) &\to l^-(k')D^+(p_D)p'(p_2)\,, \\
\nu_l(k)n(p_1) &\to l^-(k')D^+(p_D)n'(p_2)\,, \\
\nu_l(k)n(p_1) &\to l^-(k')D^0(p_D)p'(p_2)\,, \\
\bar{\nu}_l(k)p(p_1) &\to l^+(k')D^-(p_D)p'(p_2)\,, \\
\bar{\nu}_l(k)p(p_1) &\to l^+(k')\bar{D}^0(p_D)n'(p_2)\,, \\
\bar{\nu}_l(k)n(p_1) &\to l^+(k')D^-(p_D)n'(p_2)\,,
\end{aligned}
$$

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 subprocesses:

$$W^+d \to D^+d \quad , \quad W^+d \to D^0u \quad , \quad W^-\bar{d} \to D^-\bar{d} \quad , \quad W^-\bar{d} \to \bar{D}^0\bar{u}\,,$$

convoluted with chiral-even or chiral-odd quark GPDs, and the hard subprocesses:

$$W^+g \to D^+g \quad , \quad W^-g \to D^-g\,,$$

convoluted with gluon GPDs.

Feynman diagrams

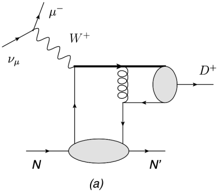


Figure : Feynman diagrams for the factorized amplitude for the $\nu_\mu N \to \mu^- D^+ N'$ process; the thick line represents the heavy quark.

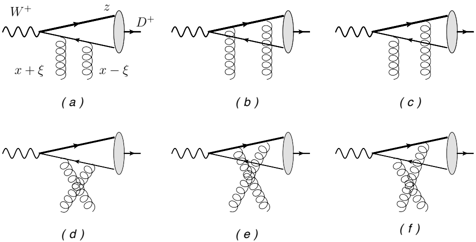


Figure : Feynman diagrams for the factorized amplitude for the $W^+ N \to D^+ N'$ process involving the gluon GPDs; the thick line represents the heavy quark.

Neutrino-production of charmed meson

Standard notations of deep exclusive leptoproduction:

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

- $\nu N \to \mu^- D^+ N$ differential cross section:

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

with

$$\tilde{\Gamma} = \frac{G_F^2}{(2\pi)^4}\frac{1}{32y}\frac{1}{\sqrt{1+4x_B^2 m_N^2/Q^2}}\frac{1}{(s-m_N^2)^2}\frac{Q^2}{1-\epsilon},$$

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.

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

GPD Models

- Chiral even GPDs: Goloskokov-Kroll model

- Transversity GPDs

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-}\,\langle p_2,\lambda'|\,\bar\psi(-\tfrac{1}{2}z)\,i\sigma^{+i}\,\psi(\tfrac{1}{2}z)\;|p_1,\lambda\rangle\Big|_{z^+=\mathbf{z}_T=0}$$

$$= \frac{1}{2P^+}\bar u(p_2,\lambda')\left[H_T^q\,i\sigma^{+i} + \tilde H_T^q\,\frac{P^+\Delta^i-\Delta^+P^i}{m_N^2} + E_T^q\,\frac{\gamma^+\Delta^i-\Delta^+\gamma^i}{2m_N} + \tilde E_T^q\,\frac{\gamma^+P^i-P^+\gamma^i}{m_N}\right]u(p_1,\lambda).$$

The GPD $H_T(x,\xi,t)$ is equal to the transversity PDF in the $\xi=t=0$ limit. G-K provide parametrization (with some lattice input) for $H_T(x,\xi,t)$ and for the combination $\bar E_T(x,\xi,t) = 2\tilde H_T(x,\xi,t) + E_T(x,\xi,t)$. Since $\tilde E_T(x,\xi,t)$ is odd under $\xi\to-\xi$, most models find it vanishingly small. We will put it to zero. We consider 3 models:

- model 1 : $\tilde H_T(x,\xi,t) = 0; E_T(x,\xi,t) = \bar E_T(x,\xi,t)$.
- model 2 : $\tilde H_T(x,\xi,t) = H_T(x,\xi,t); E_T(x,\xi,t) = \bar E_T(x,\xi,t) - 2H_T(x,\xi,t)$.
- model 3 : $\tilde H_T(x,\xi,t) = -H_T(x,\xi,t); E_T(x,\xi,t) = \bar E_T(x,\xi,t) + 2H_T(x,\xi,t)$.

Distribution amplitudes

- Usual heavy-light meson DA reads :

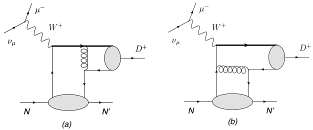
$$\langle D^+(P_D)|\bar{c}_\beta(y)d_\gamma(-y)|0\rangle \quad = \quad i\frac{f_D}{4}\int_0^1 dz e^{i(z-\bar{z})P_D\cdot y}[(\hat{P}_D - M_D)\gamma^5]_{\gamma\beta}\phi_D(z)\,,$$

with $z = \frac{P_D^+ - k^+}{P_D^+}$, $\int_0^1 dz\ \phi_D(z) = 1$, $f_D = 0.223$ GeV, $\bar{z} = 1 - z$ and $\hat{p} = p_\mu\gamma^\mu$.

- We will parametrize $\phi_D(z)$:

$$\phi_D(z) = 6z(1-z)(1 + C_D(2z-1))$$

with $C_D \approx 1.5$, which has a maximum around $z = 0.7$.
→ [T. Kurimoto, H. n. Li and A. I. Sanda, Phys. Rev. D 65]



The transverse amplitude is then written as ($\tau = 1 - i2$):

$$T_T = \frac{-i2C_q\xi(2M_D - m_c)}{\sqrt{2}(Q^2 + M_D^2)} \bar{N}(p_2)\left[\mathcal{H}_T i\sigma^{n\tau} + \tilde{\mathcal{H}}_T \frac{\Delta^\tau}{m_N^2} + \mathcal{E}_T \frac{\hat{n}\Delta^\tau + 2\xi\gamma^\tau}{2m_N} - \tilde{\mathcal{E}}_T \frac{\gamma^\tau}{m_N}\right] N(p_1),$$

with $C_q = \frac{2\pi}{3} C_F \alpha_s V_{dc}$, in terms of transverse form factors that we define as :

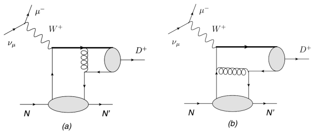
$$\mathcal{F}_T = f_D \int \frac{\phi_D(z)dz}{\bar{z}} \int \frac{F_T^d(x,\xi,t)dx}{(x - \xi + \beta\xi + i\epsilon)(x - \xi + \alpha\bar{z} + i\epsilon)},$$

where F_T^d is any d-quark transversity GPD, $\alpha = \frac{2\xi M_D^2}{Q^2 + M_D^2}$, $\beta = \frac{2(M_D^2 - m_c^2)}{Q^2 + M_D^2}$.

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

For chiral-even GPDs due to the collinear kinematics and the leading twist CF

For chiral-odd GPDs due to the odd number of γ matrices in the Dirac trace.



The quark contribution to longitudinal amplitude of leading twist is a slight modification of the calculation in:

B. Z. Kopeliovich, I. Schmidt and M. Siddikov, Phys. Rev. D **86** and D **89**
G. R. Goldstein, O. G. Hernandez, S. Liuti and T. McAskill, AIP Conf. Proc. **1222**

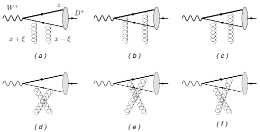
$$T_L^q = \frac{-iC_q}{2Q}\bar{N}(p_2)\left[\mathcal{H}_L\hat{n} - \tilde{\mathcal{H}}_L\hat{n}\gamma^5 + \mathcal{E}_L\frac{i\sigma^{n\Delta}}{2m_N} - \tilde{\mathcal{E}}_L\frac{\gamma^5\Delta.n}{2m_N}\right]N(p_1),$$

with the chiral-even form factors defined by

$$\mathcal{F}_L = f_D\int\frac{\phi_D(z)dz}{\bar{z}}\int dx\frac{F^d(x,\xi,t)}{x-\xi+\alpha\bar{z}+i\epsilon}\left[\frac{x-\xi+\gamma\xi}{x-\xi+\beta\xi+i\epsilon}+\frac{Q^2}{Q^2+zM_D^2}\right],$$

with $\gamma = \frac{2M_D(M_D-2m_c)}{Q^2+M_D^2}$, $\beta = \frac{2(M_D^2-m_c^2)}{Q^2+M_D^2}$

Neutrino-production of charmed meson — Longitudinal W



The gluonic contribution to the amplitude reads:

$$
\begin{aligned}
T_L^g \quad &= \quad \frac{iC_g}{2} \int_{-1}^{1} dx \frac{-1}{(x+\xi-i\epsilon)(x-\xi+i\epsilon)} \int_0^1 dz f_D \phi_D(z) \cdot \\
&\Big[\bar{N}(p_2)[H^g \hat{n} + E^g \frac{i\sigma^{n\Delta}}{2m}] N(p_1) \mathcal{M}_H^S \\
&+ \bar{N}(p_2)[\tilde{H}^g \hat{n}\gamma^5 + \tilde{E}^g \frac{\gamma^5 n.\Delta}{2m}] N(p_1) \mathcal{M}_H^A \Big] \\
\equiv \quad &\frac{-iC_g}{2Q} \bar{N}(p_2) \left[\mathcal{H}^g \hat{n} + \mathcal{E}^g \frac{i\sigma^{n\Delta}}{2m} + \tilde{\mathcal{H}}^g \hat{n}\gamma^5 + \tilde{\mathcal{E}}^g \frac{\gamma^5 n.\Delta}{2m} \right] N(p_1) \, ,
\end{aligned}
$$

where the last line defines the gluonic form factors $\mathcal{H}^g$, $\tilde{\mathcal{H}}^g$, $\mathcal{E}^g$, $\tilde{\mathcal{E}}^g$ and $C_g = T_f \frac{\pi}{3} \alpha_s V_{dc}$ with $T_f = \frac{1}{2}$ and the factor $\frac{-1}{(x+\xi-i\epsilon)(x-\xi+i\epsilon)}$ comes from the conversion of the strength tensor to the gluon field.

The longitudinal cross section σ_{00}

$$\sigma_{00} = \frac{1}{Q^2}\Big\{ \quad [\,|C_q\mathcal{H}_L + C_g\mathcal{H}_g|^2 + |C_q\tilde{\mathcal{H}}_L - C_g\tilde{\mathcal{H}}_g|^2](1-\xi^2)$$
$$+\frac{\xi^4}{1-\xi^2}[\,|C_q\tilde{\mathcal{E}}_L - C_g\tilde{\mathcal{E}}_g|^2 + |C_q\mathcal{E}_L + C_g\mathcal{E}_g|^2]$$
$$-2\xi^2\mathcal{R}e[C_q\mathcal{H}_L + C_g\mathcal{H}_g][C_q\mathcal{E}_L^* + C_g\mathcal{E}_g^*]$$
$$-2\xi^2\mathcal{R}e[C_q\tilde{\mathcal{H}}_L - C_g\tilde{\mathcal{H}}_g][C_q\tilde{\mathcal{E}}_L^* - C_g\tilde{\mathcal{E}}_g^*]\Big\}.$$

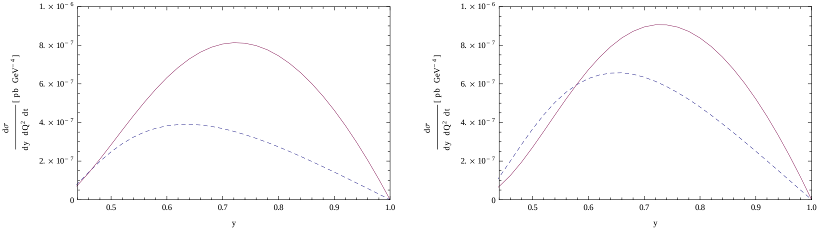


Figure : The y dependence of the longitudinal contribution to the cross section $\frac{d\sigma(\nu N \to l^- N D^+)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for $Q^2 = 1$ GeV^2, $\Delta_T = 0$ and $s = 20$ GeV^2 for a proton (left panel) and neutron (right panel) target : total (quark and gluon, solid curve) and quark only (dashed curve) contributions. GLUONS IMPORTANT!!!

The transverse cross section σ_{--}

$$\sigma_{--} = \frac{16\xi^2 C_q^2 (m_c - 2M_D)^2}{(Q^2 + M_D^2)^2} \left\{ (1-\xi^2)|\mathcal{H}_T|^2 + \frac{\xi^2}{1-\xi^2}|\mathcal{E}'_T|^2 - 2\xi \mathcal{R}e[\mathcal{H}_T \mathcal{E}'^*_T] \right\}$$

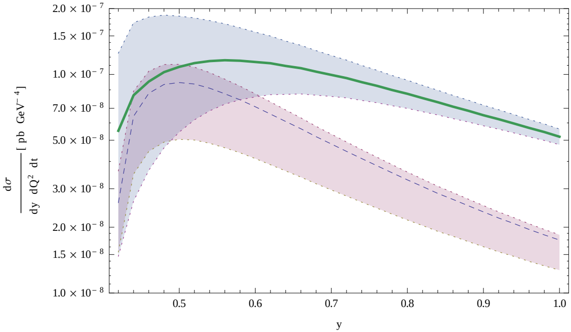


Figure : The y dependence of the transverse contribution to the cross section $\frac{d\sigma(\nu N \to l^- N D^+)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for $Q^2 = 1$ GeV^2, $\Delta_T = 0$ and $s = 20$ GeV^2 for a proton (dashed curve) and neutron (solid curve) target.

The interference cross section σ_{-0}

Vanishes at zeroth order in Δ_T, the term linear in Δ_T/m_N reads
$\lambda = \tau^* = 1 + i2$

$$
\begin{aligned}
\sigma_{-0} &= \frac{\xi\sqrt{2}C_q}{m}\frac{2M_D - m_c}{Q(Q^2+M_D^2)}\Bigg\{ \\
&- i\mathcal{H}_T^*[C_q\tilde{\mathcal{E}}_L - C_g\tilde{\mathcal{E}}_g]\xi\epsilon^{pn\Delta\lambda} + i{\mathcal{E}'}_T^*\epsilon^{pn\Delta\lambda}[C_q\tilde{\mathcal{H}}_L - C_g\tilde{\mathcal{H}}_g] \\
&+ 2\tilde{\mathcal{H}}_T^*\Delta^\lambda\{C_q\mathcal{H}_L + C_g\mathcal{H}_g - \frac{\xi^2}{1-\xi^2}[C_q\mathcal{E}_L + C_g\mathcal{E}_g]\} \\
&+ \mathcal{E}_T^*\Delta^\lambda\{(1-\xi^2)[C_q\mathcal{H}_L + C_g\mathcal{H}_g] - \xi^2[C_q\mathcal{E}_L + C_g\mathcal{E}_g]\} \\
&- \mathcal{H}_T^*\Delta^\lambda[C_q\mathcal{E}_L + C_g\mathcal{E}_g] + {\mathcal{E}'}_T^*\Delta^\lambda\xi[C_q\mathcal{H}_L + C_g\mathcal{H}_g + C_q\mathcal{E}_L + C_g\mathcal{E}_g]\Bigg\}
\end{aligned}
$$

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

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

- with $K_\epsilon = \frac{\sqrt{1+\varepsilon}+\sqrt{1-\varepsilon}}{2\sqrt{\epsilon}}$
- Simple approximate results:

$$
\begin{aligned}
< cos\varphi > &\approx \frac{K\mathcal{R}e[\mathcal{H}_D(2\tilde{\mathcal{H}}_T^\phi + \mathcal{E}_T^\phi + \bar{\mathcal{E}}_T^\phi)^* - \mathcal{E}_D \mathcal{H}_T^{\phi *}]}{8|\mathcal{H}_D^2| + |\tilde{\mathcal{E}}_D^2|}\ , \\
< sin\varphi > &\approx \frac{K\mathcal{I}m[\mathcal{H}_D(2\tilde{\mathcal{H}}_T^\phi + \mathcal{E}_T^\phi + \bar{\mathcal{E}}_T^\phi)^* - \mathcal{E}_D \mathcal{H}_T^{\phi *}]}{8|\mathcal{H}_D^2| + |\tilde{\mathcal{E}}_D^2|}\ , \\
K &= -\frac{\sqrt{1+\varepsilon}+\sqrt{1-\varepsilon}}{2\sqrt{\epsilon}}\ \frac{2\sqrt{2}\xi m_c}{Q}\ \frac{\Delta_T}{m_N}
\end{aligned}
$$

Azimuthal dependence

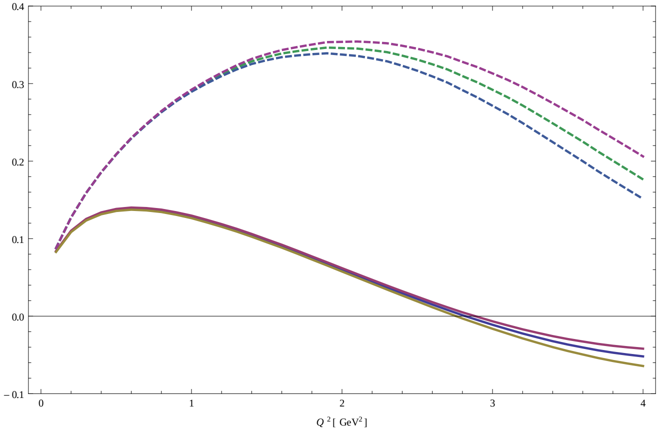


Figure : The Q^2 dependence of the $< cos\ \varphi >$ (solid curves) and $< sin\ \varphi >$ (dashed curves) moments normalized by the total cross section, for $\Delta_T = 0.5$ GeV, $y = 0.7$ and $s = 20$ GeV^2. The three curves correspond to the three models explained in the text, and quantify the theoretical uncertainty of our estimates.

Light meson production - importance of gluon contribution.

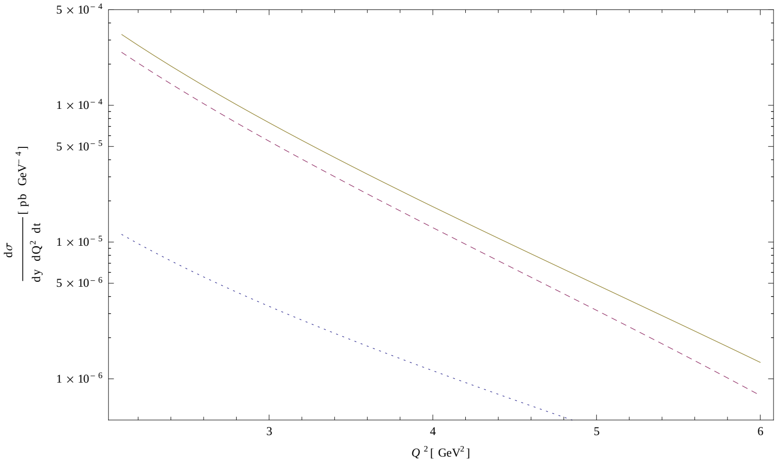


Figure : The Q^2 dependence of the quark (dashed curve) contribution compared to the total (quark and gluon, solid curve) longitudinal cross section $\frac{d\sigma(\nu N \to l^- N \pi^+)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for π^+ production on a proton target for $y = 0.7, \Delta_T = 0$ and $s = 20$ GeV^2.

Summary

- Collinear QCD factorization allows to calculate neutrino production of $D-$mesons in terms of GPDs down to $Q^2 = 0$.
- 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
- The behaviour of the proton and neutron target cross sections for D^+, D^- and D^0 production with ν and $\bar{\nu}$ enables to separate the u and d quark contributions.
- Within the reach of planned medium and high energy neutrino facilities and experiments such as Minerνa and MINOS+.
- Gluon contribution very important -> consequences for light mesons!

  $\rightarrow$ C. Andreopoulos talk