New exclusive processes and the PARTONS project

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based on:
B. Pire, L. Szymanowski, JW, Phys.Rev. D95 (2017) no.9, Phys.Rev. D95 (2017) no.11
A. Pedrak, B. Pire, L. Szymanowski, JW, arXiv:1708.01043

PARTONS collaboration

Exclusive processes and GPDs

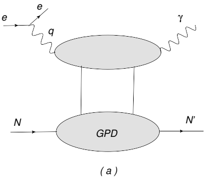


Figure: DVCS

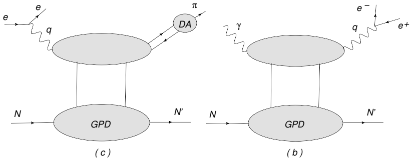


Figure: DVMP and TCS

- Various exclusive processes give information about GPDs: DVCS, TCS, DDVCS, DVMP, HVMP
- Also neutrino-production of light mesons considered: allows for flavour separation, different combinations of GPDs due to the charged current coupling structure. Much smaller cross sections, but process in the reach of the i.e. MINERVA experiments

  $\rightarrow$ [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, antiquarks and gluons 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.
- Quark transversity is a chiral odd quantity; to observe it need another chiral odd quantity (another PDF in Drell Yan, another fragmentation funcion in SIDIS, a heavy quark mass effect in coefficient function, a 3-body final state)
- Lattice result and SIDIS analysis suggest that transversity distributions are not small
- Transversity GPDs coupled to chiral-odd twist 3 pi-meson DA may explain π electroproduction data at JLab [Goloskokov, Kroll], [Ahmad, Goldstein, Liuti]
- 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

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

Neutrino-production of charmed meson

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

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

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 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

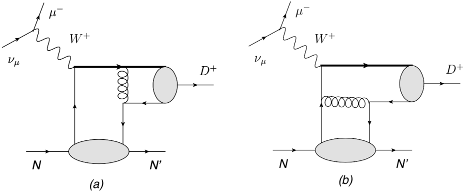


Figure: Feynman diagrams for the factorized amplitude for the $\nu_\mu N \to \mu^- D^+ N'$ process; the **thick** line represents the heavy quark.

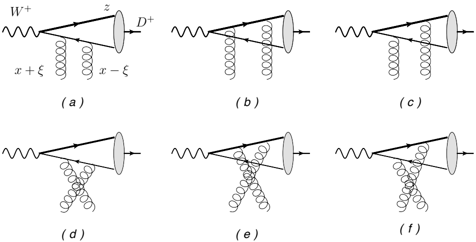


Figure: Feynman diagrams for the factorized amplitude for the $W^+ N \to D^+ N'$ process involving the gluon GPDs; the thick line represents the heavy quark.

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 $\epsilon \simeq 2(1-y)/[1+(1-y)^2]$.

- Similarly to DDVCS we can introduce two variables:

$$\xi = -\frac{(p_2 - p_1).n}{2} \quad , \quad \xi' = -\frac{q.n}{2} \, . \tag{1}$$

where n is the light-cone vectors

$$\xi \approx \frac{Q^2 + M_D^2}{4p_1.q - Q^2 - M_D^2} \quad , \quad \xi' \approx \frac{Q^2}{4p_1.q - Q^2 - M_D^2} \, . \tag{2}$$

- 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:

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

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

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

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

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 :

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

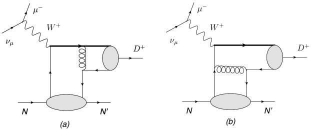
with $z = \frac{P_D^+ - k^+}{P_D^+}$, $\int_0^1 dz\ \phi_D(z) = 1$, $f_D = 0.223$ GeV, $\bar{z} = 1 - z$ and $\hat{p} = p_\mu\gamma^\mu$.

- 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]

Neutrino-production of charmed meson   Transverse W



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

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

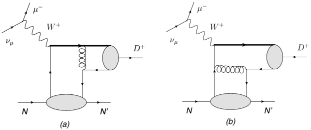
with $C_q = \frac{2\pi}{3} C_F \alpha_s V_{dc}$, in terms of transverse form factors that we define as :

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

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:

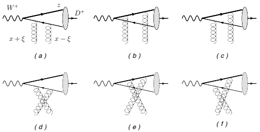
B. Z. Kopeliovich, I. Schmidt and M. Siddikov, Phys. Rev. D **86** and D **89**
G. R. Goldstein, O. G. Hernandez, S. Liuti and T. McAskill, AIP Conf. Proc. **1222**

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

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



The gluonic contribution to the amplitude reads:

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

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}

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

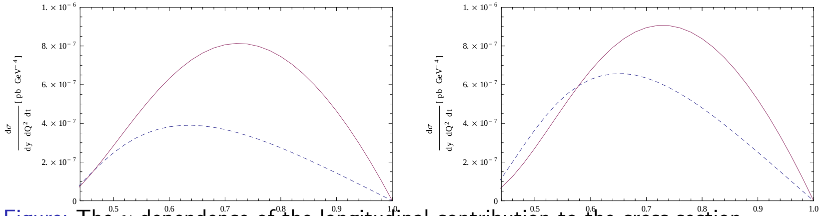


Figure: The y dependence of the longitudinal contribution to the cross section $\frac{d\sigma(\nu N \to l^- N D^+)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for $Q^2 = 1$ GeV^2, $\Delta_T = 0$ and $s = 20$ GeV^2 for a proton (left panel) and neutron (right panel) target : total (quark and gluon, solid curve)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

The transverse cross section σ_{--}

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

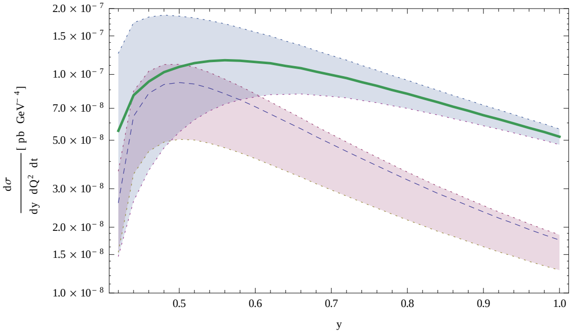


Figure: The y dependence of the transverse contribution to the cross section $\frac{d\sigma(\nu N \to l^- N D^+)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for $Q^2 = 1$ GeV^2, $\Delta_T = 0$ and $s = 20$ GeV^2 for a proton (dashed curve) and neutron (solid curve) target.

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

$$< cos\ \varphi > \; = \; \frac{\int cos\ \varphi\ d\varphi\ d^4\sigma}{\int d\varphi\ d^4\sigma} = K_\epsilon \frac{\mathcal{R}e\sigma_{-0}}{\sigma_{00}} ,$$

$$< sin\ \varphi > \; = \; K_\epsilon \frac{\mathcal{I}m\sigma_{-0}}{\sigma_{00}}$$

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

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

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

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

Azimuthal dependence

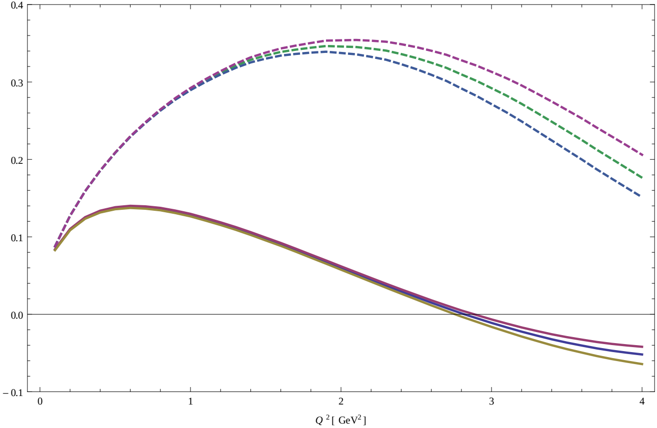


Figure: The Q^2 dependence of the $< cos\ \varphi >$ (solid curves) and $< sin\ \varphi >$ (dashed curves) moments normalized by the total cross section, for $\Delta_T = 0.5$ GeV, $y = 0.7$ and $s = 20$ GeV^2. The three curves correspond to the three, and quantify the theoretical uncertainty of our estimates.

Light meson production - importance of gluon contribution.

$$\nu N \to l^- N \pi^+$$

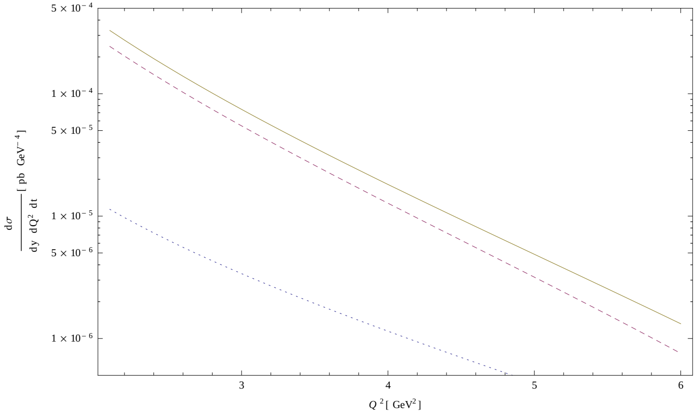


Figure: The Q^2 dependence of the quark (dashed curve) contribution compared to the total (quark and gluon, solid curve) longitudinal cross section $\frac{d\sigma(\nu N \to l^- N \pi^+)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for π^+ production on a proton target for $y = 0.7, \Delta_T = 0$ and $s = 20$ GeV^2.

Light meson production - importance of gluon contribution.

Two models for E_g from [Koempel, Kroll, Metz and Zhou] Phys. Rev. D 85

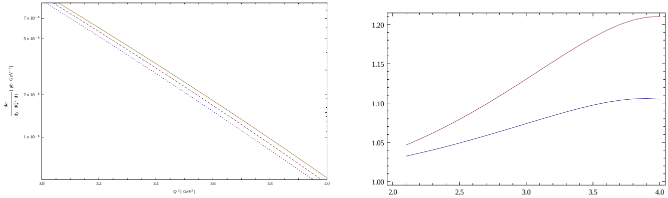


Figure: The Q^2 dependence of the cross section $\frac{d^3\sigma(\nu N \to l^- N \pi^+)}{dy\, dQ^2\, dt}$ (in pb GeV^{-4}) for $y = 0.5, \Delta_T = 0$ and $s = 13$ GeV^2, on a proton (left panel). The dotted line corresponds to $E^g(x, \xi, t) = 0$, the dashed (resp. solid) one uses V2 (resp. V4) parametrization of $E^g(x, \xi, t)$. On the right panel we show the ratio of the cross section calculated with V4 of E_g (upper line) and V2 of E_g (lower line) to the cross section calculated with $E_g = 0$.

Summary - neutrinos

Charmed meson production:

- 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 quark transversity 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+.
- TODO: NLO calculation, showing how factorization works with one light and one heavy quark

Light meson production:

- Gluon contribution very important
- Simple relation between π and longitudinal ρ production - useful in studying meson DA's

Hard photoproduction of a diphoton with a large invariant mass

A. Pedrak, B. Pire, L. Szymanowski, JW, arXiv:1708.01043

$$\gamma(q,\epsilon) + N(p_1, s_1) \to \gamma(k_1,\epsilon_1) + \gamma(k_2,\epsilon_2) + N'(p_2, s_2)$$

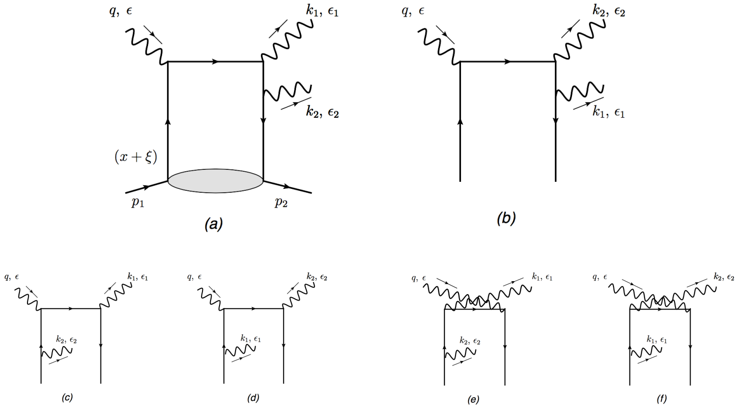


Figure: Feynman diagrams contributing to the coefficient function of the process $\gamma N \to \gamma\gamma N'$

Hard photoproduction of a diphoton with a large invariant mass

- Purely electromagnetic process at Born order - as are deep inelastic scattering (DIS), deeply virtual Compton scattering (DVCS) and timelike Compton scattering (TCS).
- Insensitive to gluon GPDs.
- No contribution from the badly known chiral-odd quark distributions.
- This study enlarges the range of $2 \to 3$ reactions analyzed in the framework of collinear QCD factorization. Simplest - great tool to study factorization.

Coefficient functions and generalized Form Factors

$$
\begin{aligned}
iCF_q^V &= Tr[i\mathcal{M}\ \not{p}] = \\
&- ie_q^3 \Big[\ A^V \left(\frac{1}{D_1(x)D_2(x)} + \frac{1}{D_1(-x)D_2(-x)} \right) \\
&\qquad + B^V \left(\frac{1}{D_1(x)D_3(x)} + \frac{1}{D_1(-x)D_3(-x)} \right) \\
&\qquad + C^V \left(\frac{1}{D_2(x)D_3(-x)} + \frac{1}{D_2(-x)D_3(x)} \right) \Big] , \\
iCF_q^A &= Tr[i\mathcal{M}\gamma^5\ \not{p}] = \\
&-ie_q^3 \Big[\ A^A \left(\frac{1}{D_1(x)D_2(x)} - \frac{1}{D_1(-x)D_2(-x)} \right) \\
&\qquad + B^A \left(\frac{1}{D_1(x)D_3(x)} - \frac{1}{D_1(-x)D_3(-x)} \right) \Big]
\end{aligned}
$$

where $A^V, \dots, A^A, \dots$ depend on photons polarizations and final photons p_T.
Denominators read:

$$
D_1(x) = s(x + \xi + i\varepsilon), \quad D_2(x) = s\alpha_2(x - \xi + i\varepsilon), \quad D_3(x) = s\alpha_1(x - \xi + i\varepsilon)
$$

Generalized form factors

The scattering amplitude is written in terms of generalized Compton form factors $\mathcal{H}^q(\xi)$, $\mathcal{E}^q(\xi)$, $\tilde{\mathcal{H}}^q(\xi)$ and $\tilde{\mathcal{E}}^q(\xi)$ as

$$\mathcal{T} = \frac{1}{2s}\left[\left(\mathcal{H}(\xi)\bar{U}(p_2)\not{n}U(p_1) + \mathcal{E}(\xi)\bar{U}(p_2)\frac{i\sigma^{\mu\nu}\Delta_\nu n_\mu}{2M}U(p_1)\right) + \left(\tilde{\mathcal{H}}(\xi)\bar{U}(p_2)\not{n}\gamma^5 U(p_1) + \tilde{\mathcal{E}}(\xi)\bar{U}(p_2)\frac{i\gamma_5(\Delta\cdot n)}{2M}U(p_1)\right)\right]$$

$$\mathcal{H}(\xi) = \sum_q \int_{-1}^{1} dx\, CF_q^V(x,\xi)H^q(x,\xi), \quad \tilde{\mathcal{H}}(\xi) = \sum_q \int_{-1}^{1} dx\, CF_q^A(x,\xi)\tilde{H}^q(x,\xi),$$

$$\mathrm{Re}\,\mathcal{H}(\xi) \sim \sum_q e_q^3 P.V. \int_{-1}^{1} dx \frac{H^q(x,\xi)+H^q(-x,\xi)}{x-\xi}$$

$$\mathrm{Im}\,\mathcal{H}(\xi) \sim \sum_q e_q^3 \left[H^q(\xi,\xi)+H^q(-\xi,\xi)\right]$$

$$\mathrm{Re}\,\tilde{\mathcal{H}}(\xi) \sim 0$$

$$\mathrm{Im}\,\tilde{\mathcal{H}}(\xi) \sim \sum_q e_q^3 \left[\tilde{H}^q(\xi,\xi)-\tilde{H}^q(-\xi,\xi)\right]$$

Differential cross section

Choosing as independent kinematical variables $\{t, u', M^2_{\gamma\gamma}\}$, the fully unpolarized differential cross section reads

$$\frac{d\sigma}{dM^2_{\gamma\gamma}dtd(-u')} = \frac{1}{2}\frac{1}{(2\pi)^3 32 S^2_{\gamma N} M^2_{\gamma\gamma}} \sum_{\lambda,\lambda_1\lambda_2,s_1,s_2} \frac{|\mathcal{T}|^2}{4}$$

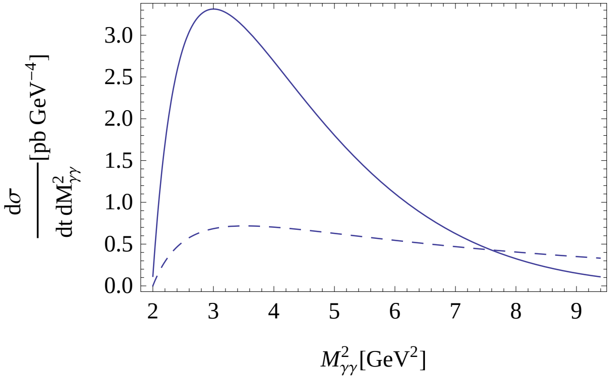


Figure: the $M^2_{\gamma\gamma}$ dependence of the unpolarized differential cross section on a proton at $t = t_{min}$ and $S_{\gamma N} = 20 GeV^2$ (full curves) and $S_{\gamma N} = 100 GeV^2$ (dashed curve). The bounds in u' are chosen so that both $-u'$ and $-t'$ are larger than 1 GeV^2.

Polarization asymmetries

- **Circular** initial photon polarization cross-section difference reads:

$$\mathcal{T}_+\mathcal{T}_+^* - \mathcal{T}_-\mathcal{T}_-^* \sim |\Delta_t||p_t|\,,$$

so circular polarization asymmetry is of $O(\frac{\Delta_T}{Q})$.

- **Linear** initial photon polarization defines the x axis:

$$\epsilon(q) = (0, 1, 0, 0)$$

and hence the azimuthal angle ϕ through

$$p_T^\mu = (0,\; p_T\; cos\phi,\; p_T\; sin\phi, 0).$$

Azimuthal dependence

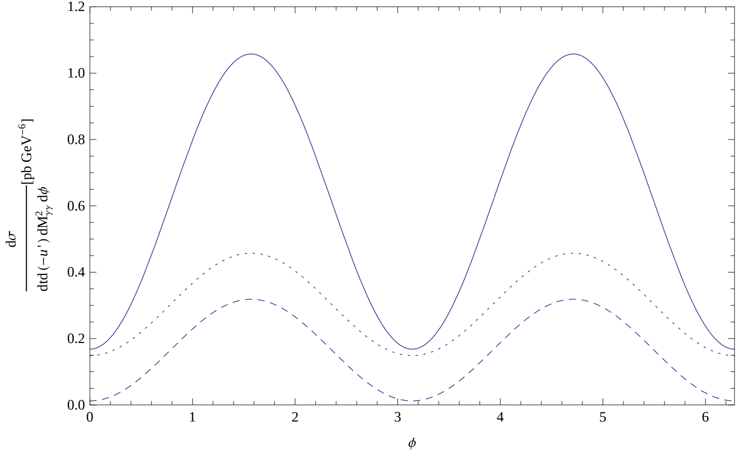


Figure: the azimuthal dependence of the differential cross section $\frac{d\sigma}{dM^2_{\gamma\gamma}dtdu'd\phi}$ at $t = t_{min}$ and $S_{\gamma N} = 20$ GeV^2. $(M^2_{\gamma\gamma}, u') = (3, -2)$ GeV^2 (solid line), $(M^2_{\gamma\gamma}, u') = (4, -1)$ GeV^2 (dotted line) and $(M^2_{\gamma\gamma}, u') = (4, -2)$ GeV^2 (dashed line). ϕ is the angle between the initial photon polarization and one of the final photon momentum in the transverse plane.

Summary - diphoton photoproduction

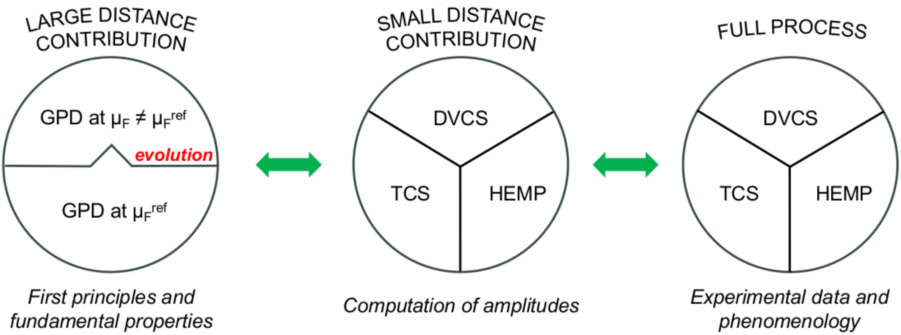
- Purely electromagnetic process at Born order
- Insensitive to gluon GPDs
- Cross section of the order of TCS which is measurable at JLAB
- Strong azimuthal dependence for linearly polarized photon beam

To be done:

- The $O(\alpha_s)$ corrections to the amplitude need to be calculated.They are particularly interesting since they open the way to a perturbative proof of factorization.
- Importance of the timelike vs spacelike nature of the probe with respect to the size of the NLO corrections; since the hard scales at work in our process are both the timelike one $M^2_{\gamma\gamma}$ and the spacelike one u', we are facing an intermediate case between timelike Compton scattering (TCS) and spacelike DVCS.
- Leptoproduction needs to be complemented by the analysis of the Bethe Heitler processes where one or two photons are emitted from the lepton line. Probably dominating and leading to interesting interference effects.

- New precise experiments
- Various models, schemes, processes, observables
- Extraction of GPDs is complicated - various channels needed
- Various approaches: local and global CFF fitting, GPDs fitting...,
- Extrapolation for tomography (uncerteinties propagation),
- Various groups doing usually one chain

based on the talks and material from
H. Moutarde, P. Sznajder, L. Colaneri, N.Chouika
$\rightarrow$ C.Mezrag talk



Tasks and challenges:

- Physical models
- Perturbative approximations
- Many observables
- Numerical methods
- Accuracy and speed
- Fits

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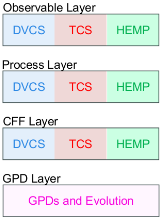
Layers



Layered structure:

- Layer - collection of objects designed for common purpose
- One module - one physical developenement
- Operation on modules provided by services
- Automation
- Features improving calculation speed (some layer services store previously calculated values)

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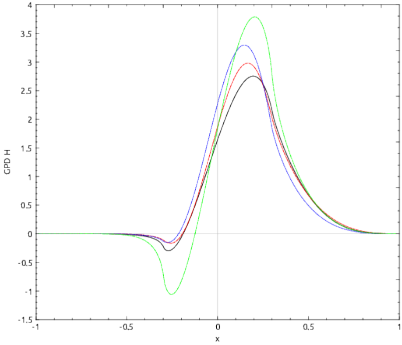
Existing modules

- GPD models: Goloskokov-Kroll, VGG, Vinnikov, MPSSW13, MMS13,
- Evolution: Vinnikov,
- Compton Form Factors (generally: convolution of GPDs or DA with coefficient functions): LO, NLO, NLO + heavy quarks (Noritsch)
- Cross section (DVCS + BH): VGG, BMJ, GV
- Observables: A_{LU}, A_{UL}, A_{LL}, A_C, fourier moments, ...
- Running coupling: 4-loop PDG expression, constant value



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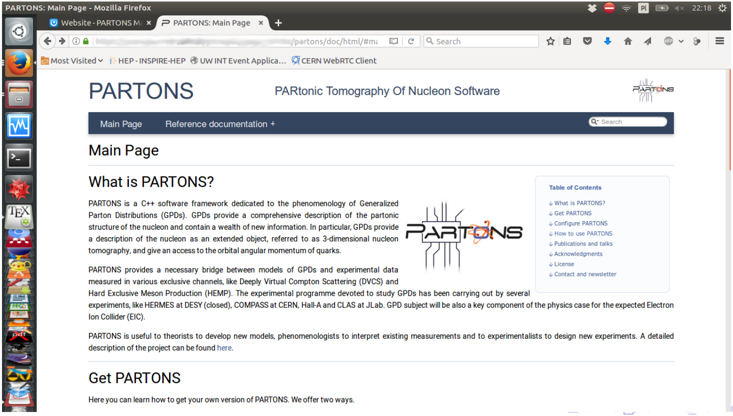
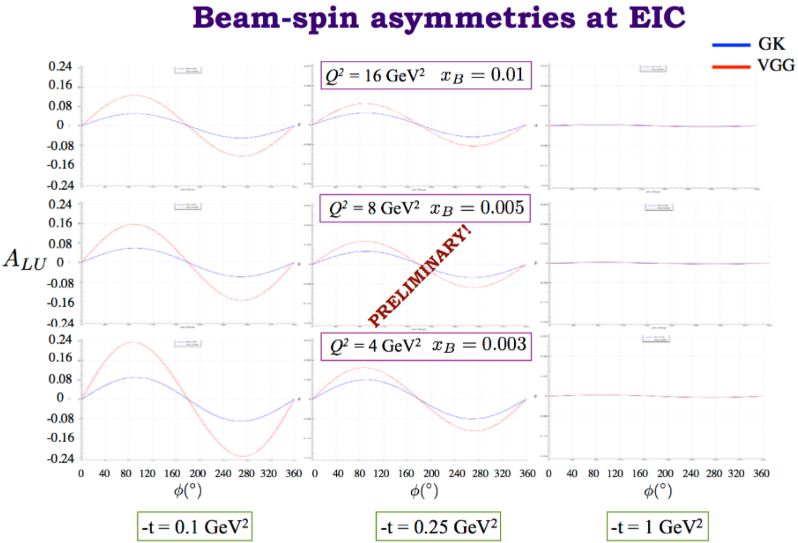
Release

Release expected soon (September 2017)

- Open source
- Virtual Machine with out-of-the-box running PARTONS (also possible to install on your own Linux or Mac)
- Examples: xml, c++ codes
- preprint arXiv:1512.06174v1 (new description to appear soon !)
- Website with detailed manual



N.Chouika, L.Colaneri



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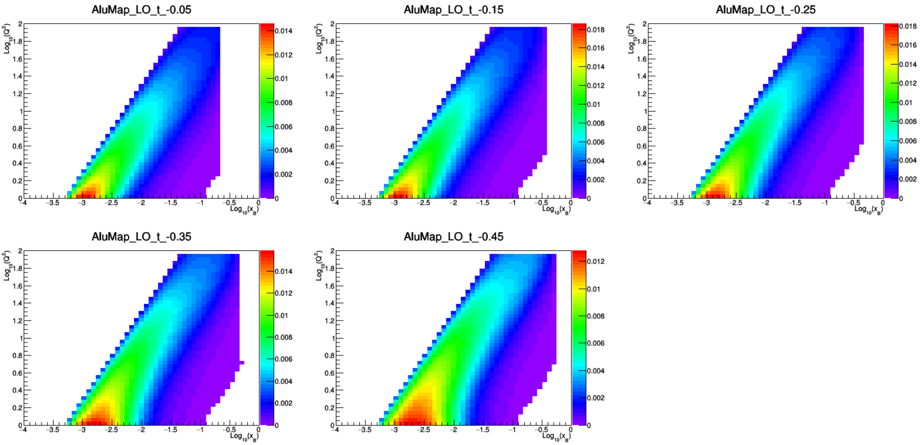
Examples

L.Colaneri

Beam spin asymmetry at $\phi = \pi/2$ for EIC



$\rightarrow$ Paweł Sznajder DIS2017, IPNO2017

Asumptions:

- Leading order, Leading twist, with dispersion relations:

$$\Im m\mathcal{H}(\xi,t,Q^2) = \pi \sum_q e_q^2 \left[H^q(\xi,\xi,t,Q^2) - H^q(-\xi,\xi,t,Q^2)\right]$$

$$\Re e\mathcal{H}(\xi,t,Q^2) = \frac{1}{\pi}\text{P.V.}\int_0^1 d\xi' \left(\frac{1}{\xi-\xi'} - \frac{1}{\xi+\xi'}\right) \Im m\mathcal{H}(\xi',t,Q^2) + \mathcal{C}_\mathcal{H}(t,Q^2)$$

- Border function (a_{val} fitted to F_1)

$$H^q(x,x,t,Q^2) = H^q(x,0,t,Q^2) \times r^q(x)$$
$$H^q(x,0,t,Q^2) = q(x) \times x^{-a_q t}$$
$$r^q(x) = \frac{C_q}{(1-x^2)^2}$$

- Substraction constant,

$$\mathcal{C}_\mathcal{H}(t,Q^2) = C_{\text{sub}} \times \exp\left(a_{\text{sub}} t\right)$$

- CFF $\mathcal{E}$ and $\tilde{\mathcal{E}}$ prop to GK:

$$\mathcal{E}(\xi,t,Q^2) = N_E \times \mathcal{E}_{\text{GK}}(\xi,t,Q^2)$$
$$\widetilde{\mathcal{E}}(\xi,t,Q^2) = N_{\widetilde{E}} \times \widetilde{\mathcal{E}}_{\text{GK}}(\xi,t,Q^2)$$

→ Paweł Sznajder

Results of fit to new CLAS and HALL A data:

- cuts: $Q^2 > 1.5\,\mathrm{GeV}^2$, $-t/Q^2 < 0.25$
- free parameters: $a_{H_{sea}}$, $a_{\tilde{H}_{val}}$, $a_{\tilde{H}_{sea}}$, C_{sub}, a_{sub}, N_E, $N_{\tilde{E}}$.
- $\chi^2/\mathrm{ndf} = 3272.6/(3433-7) \approx 0.96$
- Datasets

  [1] Phys.Rev.C92 (2015), [2] Phys.Rev.Lett.115 (2015), [3] Phys.Rev.D91 (2015)

Experiment	Reference	Observables	N points all	N points selected	chi2	chi2 / ndf
Hall A	[1] KINX2	σUU	120	120	135.0	1.19
Hall A	[1] KINX2	ΔσLU	120	120	98.9	0.88
Hall A	[1] KINX3	σUU	108	108	274.8	2.72
Hall A	[1] KINX3	ΔσLU	108	108	107.3	1.06
CLAS	[2]	σUU	1933	1333	1089.2	0.82
CLAS	[2]	ΔσLU	1933	1333	1171.9	0.88
CLAS	[3]	AUL, ALU, ALL	498	305	338.1	1.13

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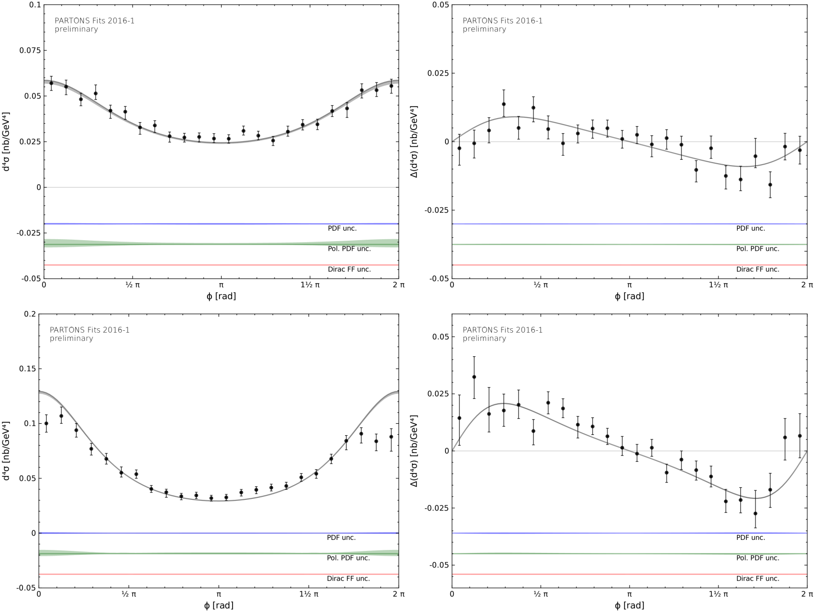
Examples: FITS



C++:

```
// Retrieve GPD service
GPDService* pGPDService =
        Partons::getInstance()->getServiceObjectRegistry()->getGPDService();
// Load GPD module with the BaseModuleFactory
GPDModule* pGPDModel =
    Partons::getInstance()->getModuleObjectFactory()->newGPDModule(GK11Model::classId);
// Create a GPDKinematic(x, xi, t, MuF, MuR) to compute
GPDKinematic gpdKinematic(0.1, 0.00050025, -0.3, 8., 8.);
// Compute data and store results
GPDResult gpdResult = pGPDService->computeGPDModel(gpdKinematic, pGPDModel, List<GPDType>());
// Print results
std::cout << gpdResult.toString() << std::endl;
```

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How to use it?

XML:

```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>
<scenario date="2016-03-25" description="Example : computation of one GPD model (GK11) without evolution">
  <task service="GPDService" method="computeGPDModel" storeInDB="0">
      <kinematics type="GPDKinematic">
         <param name="x" value="0.1" />
         <param name="xi" value="0.00050025" />
         <param name="t" value="-0.3" />
         <param name="MuF2" value="8" />
         <param name="MuR2" value="8" />
      </kinematics>
      <computation_configuration>
         <module type="GPDModule">
            <param name="className" value="GK11Model" />
         </module>
     </computation_configuration>
  </task></scenario>
```

- Modern platform devoted to study GPDs
- Design to support the effort of GPD community
- Can be used by both theoreticians and experimentalists
- Come with number of available physics developments implemented
- Modular - addition of new developments as easy as possible
- Release of the code in September 2017 out-of-the-box running PARTONS with examples and documentation
- Coming soon: Study of DVCS Observables at EIC kinematics (NLO effects, heavy flavours)
- Coming soon: Local fits of CFFs, neural networks, ...
- We are looking forward to your input and feedback