Implementation of DVMP in PARTONS

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Chiral-even GPDs

- Chiral-even GPDs parametrize the following off-forward matrix elements of quark operators at a light-like separation
  D.Müller, D.Robaschik, B.Geyer, F.-M.Dittes, J.Hořejši, Fortsch. Phys. **42**, 101 (1994)
  X.D.Ji, PRL **78**, 610 (1997); PRD **55**, 7114 (1997).

  A.V.Radyushkin, PLB **380**, 417 & **385**, 333 (1996).

$$P^+ \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p', \lambda' | \bar{\psi}(-\frac{z}{2})\gamma^+ \psi(\frac{z}{2}) | p, \lambda \rangle \Big|_{z^+=0, \vec{z}_T=0}$$
$$= \bar{u}(p', \lambda') \left[H^q \gamma^+ + E^q \frac{i\sigma^{+\alpha}\Delta_\alpha}{2m} \right] u(p, \lambda)$$

$$P^+ \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p', \lambda' | \bar{\psi}(-\frac{z}{2})\gamma^+ \gamma_5 \psi(\frac{z}{2}) | p, \lambda \rangle \Big|_{z^+=0, \vec{z}_T=0}$$
$$= \bar{u}(p', \lambda') \left[\tilde{H}^q \gamma^+ \gamma_5 + \tilde{E}^q \frac{\gamma_5 \Delta^+}{2m} \right] u(p, \lambda)$$

- GPDs depend on three parameters

$$x, \qquad \xi = \frac{p^+ - p'^+}{p^+ + p'^+}, \qquad t = \Delta^2$$

where $\Delta = p' - p$ *and* $P^+ = (p' + p)^+/2$.

Chiral-even GPDs

- Chiral-even GPDs are accessible through Deeply Virtual Compton Scattering

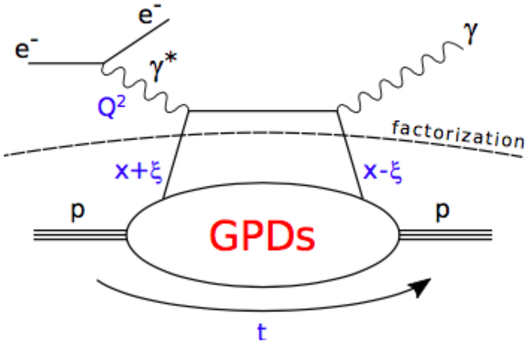


Fig: Eur. Phys. J. C78 (2018) 6, 478

Chiral-odd GPDs

- There are four chiral-odd GPDs $H_T, \tilde{H}_T, E_T, \tilde{E}_T$ at leading twist

M. Diehl, Eur. Phys. J. C **19**, 485 (2001)

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

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

where $i = 1, 2$ is the transversity index

Chiral-odd GPDs

- Accessible, if one assumes an effective handbag mechanism, through exclusive meson production processes

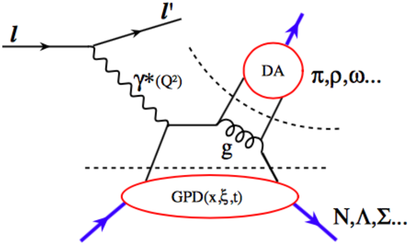


Fig: EPJ Web Conf. **137**, 01003 (2017)

Properties of GPDs

- In the forward limit $\Delta \to 0$, certain GPDs are related to PDFs

$$H^q(x,0,0) = f_1^q(x)$$
$$\tilde{H}^q(x,0,0) = g_1^q(x)$$
$$H_T^q(x,0,0) = h_1^q(x).$$

- Related to form factors via

$$\int_{-1}^{1} \left\{ H, E, \tilde{H}, \tilde{E} \right\}(x,\xi,t)dx = F_1(t), F_2(t), G_A(t), G_P(t)$$
$$\int_{-1}^{1} \left\{ H_T, \tilde{H}_T, E_T \right\}(x,\xi,t)dx = H_T(t), \tilde{H}_T(t), E_T(t)$$
$$\int_{-1}^{1} \left\{ \tilde{E}_T \right\}(x,\xi,t)dx = 0$$

- Polynomiality

Goloskokov-Kroll Model

- Goloskokov-Kroll(GK) model for pseudoscalar meson production is based on an effective handbag mechanism

S. V. Goloskokov, P. Kroll, Eur. Phys. J. C **65**, 137 (2010) & Eur. Phys. J. A **47**, 112 (2011)

- For π^0 production, contributions from longitudinally polarized photons read

$$\mathcal{M}_{0+,0+} = \sqrt{1-\xi^2}\frac{e}{Q}[\langle\tilde{H}\rangle - \frac{\xi^2}{1-\xi^2}\langle\tilde{E}\rangle]$$

$$\mathcal{M}_{0-,0+} = \frac{e}{Q}\frac{\sqrt{-t'}}{2m}[\xi\langle\tilde{E}\rangle]]$$

where $t' = t - t_0$ with $t_0 = -4M_N^2\xi^2/(1-\xi^2)$.

first index = helicity of the produced meson,
second index = helicity of the final particle,
third index = helicity of the virtual photon,
fourth index = helicity of the initial particle.

Goloskokov-Kroll Model

- Generically, $\langle F \rangle$ represents a convolution of a GPD F with an appropriate subprocess amplitude

$$\langle F \rangle = \sum_{\lambda} \int_{-1}^{1} dx\, \mathcal{H}_{0\lambda,0\lambda}(x, \xi, Q^2, t = 0)\, F(x, \xi, t)$$

where λ denotes unobserved helicities of the partons.

- Subprocesses are calculated in the so-called modified perturbative approach: Transverse momenta of the quark and the anti-quark in the meson are kept and gluon radiations are taken into account through Sudakov factor S
- For π^0 electroproduction, GPDs appear in the form of

$$(e_u\, F^u - e_d\, F^d)/\sqrt{2}$$

Goloskokov-Kroll Model

- In impact space

$$\mathcal{H}_\pi = \int d\tau d^2\vec{b}\, \hat{\Psi}_\pi(\tau, -\vec{b}) \hat{\mathcal{F}}_\pi(\bar{x}, \xi, \tau, Q^2, \vec{b}) \alpha_s(\mu_R)\, exp\big(- S(\tau, \vec{b}, Q^2)\big)$$

  where $\hat{\Psi}_\pi$ is the pion wave function and $\hat{\mathcal{F}}_\pi$ is the hard scattering kernel
- Contributions from transversely polarized photons are significant: Twist-3 effects
- For small $-t'$ and ξ, only H_T and $\bar{E}_T$ enter in twist-3 contributions

$$\mathcal{M}_{0-,++} = \sqrt{1-\xi^2} e \langle H_T \rangle$$
$$\mathcal{M}_{0+,\mu+} = -\frac{e}{4m}\sqrt{-t'}\langle \bar{E}_T \rangle$$

Goloskokov-Kroll Model - Cross Sections

- Partial cross sections

$$\frac{d\sigma_L}{dt} = \kappa[\mathcal{M}^2_{0+,0+} + \mathcal{M}^2_{0-,0+}]\,,$$
$$\frac{d\sigma_T}{dt} = \frac{\kappa}{2}[\mathcal{M}^2_{0-,-+} + \mathcal{M}^2_{0-,++} + \mathcal{M}^2_{0+,-+} + \mathcal{M}^2_{0+,++}]\,,$$
$$\frac{d\sigma_{TT}}{dt} = -\frac{\kappa}{2}Re[\mathcal{M}^*_{0-,++}\cdot\mathcal{M}_{0-,-+} + \mathcal{M}^*_{0+,++}\cdot\mathcal{M}_{0+,-+}]\,,$$
$$\frac{d\sigma_{LT}}{dt} = \frac{\kappa}{\sqrt{2}}Re[\mathcal{M}^*_{0-,0+}\cdot(\mathcal{M}_{0-,++} - \mathcal{M}_{0-,-+}) + \mathcal{M}^*_{0+,0+}\cdot(\mathcal{M}_{0+,++} - \mathcal{M}_{0+,-+})]\,.$$

Goloskokov-Kroll Model - GPDs

- GPDs are constructed from double distribution ansatz

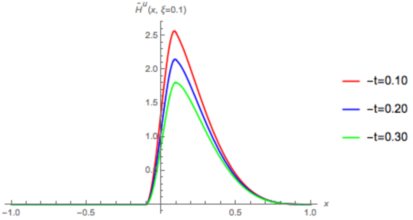
$$F_i^a(\bar{x}, \xi, t) = \int_{-1}^{1} d\rho \int_{-1+|\rho|}^{1-|\rho|} d\eta\, \delta(\rho + \xi\eta - \bar{x}) f_i^a(\rho, \eta, t)$$

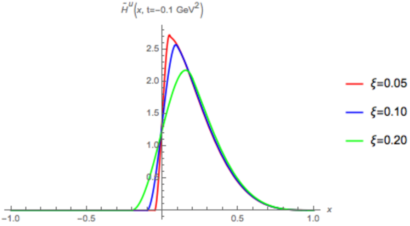
where for valence-quark GPDs;

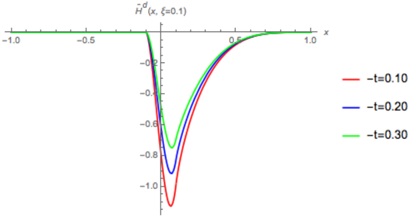
$$f_i(\rho, \eta, t) = exp[(b_i - \alpha_i' \, ln\, \rho)t]\, F_i^a(\rho, \xi = t = 0)\, \frac{3}{4} \frac{(1-\rho)^2 - \eta^2}{(1-\rho)^3} \Theta(\rho)$$

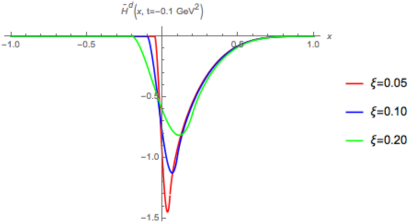
- Parameters of the forward limits
  - $\tilde{H}$: DSSV, Phys. Rev. D **80**, 034030 (2009)
  - H_T: ABM, Phys. Rev. D **86**, 054009 (2012) and DSSV, Phys. Rev. D **80**, 034030 (2009)
  - $\tilde{E}$: LHPC Collaboration, Phys. Rev. D **77**, 094502 (2008)
  - $\bar{E}_T$: QCDSF and UKQCD Collaborations, Phys. Rev. Lett. **98**, 222001 (2007)

Goloskokov-Kroll Model - GPDs

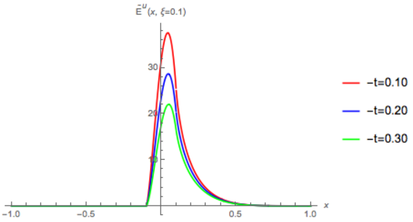


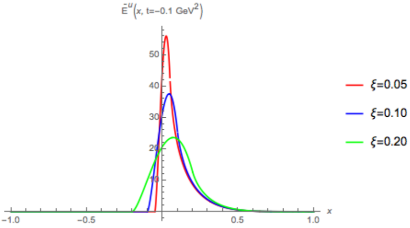


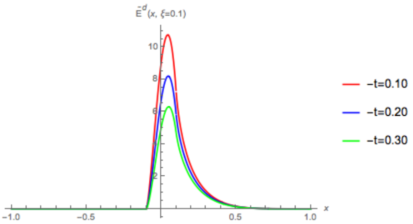


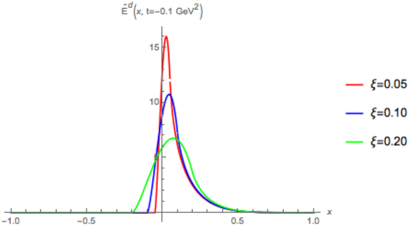


Goloskokov-Kroll Model - GPDs

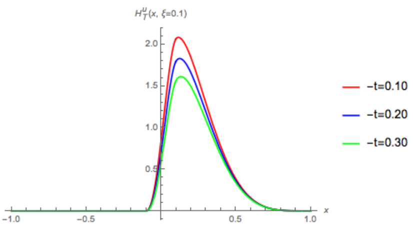


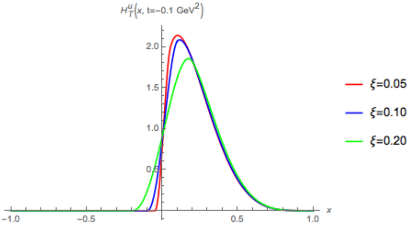


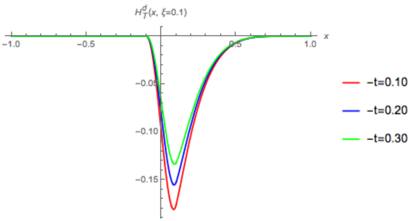


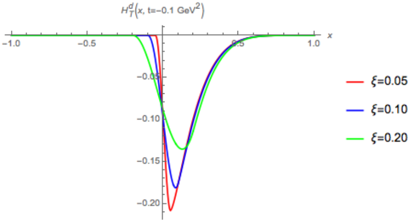


Goloskokov-Kroll Model - GPDs

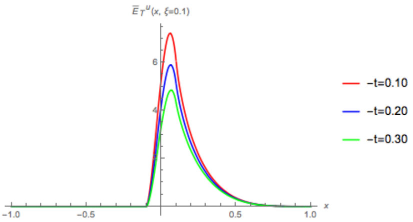


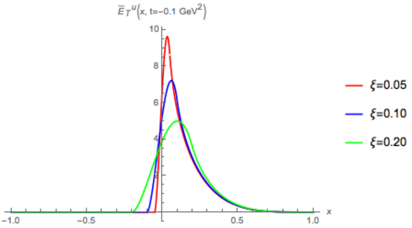


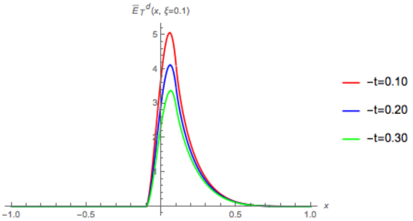


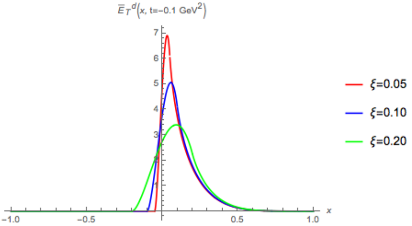


Goloskokov-Kroll Model - GPDs









Goloskokov-Kroll Model - π^0

- In π^0 electroproduction, $\bar{E}_T$ dominates the process since GPDs appear in the form of $(e_u \bar{E}_T^u - e_d \bar{E}_T^d)/\sqrt{2}$
- To compute longitudinally polarized photon amplitudes, we need: twist-2 meson wave function, kernel, running coupling, Sudakov factor and GPDs $\tilde{H}$ and $\tilde{E}$.
- To compute transversely polarized photon amplitudes, we need: twist-3 meson wave function, kernel, running coupling, Sudakov factor and GPDs H_T and $\bar{E}_T$.
- 3-dimensional integrals over $\bar{x}, \tau$ and b are performed in impact space
- In many different processes, such as vector meson or other pseudoscalar meson production, meson wavefunction as well as the Sudakov factor has the same structure

Goloskokov-Kroll Model - π^0

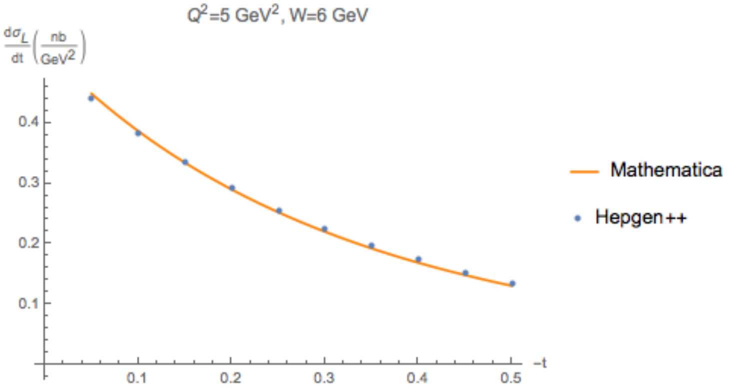
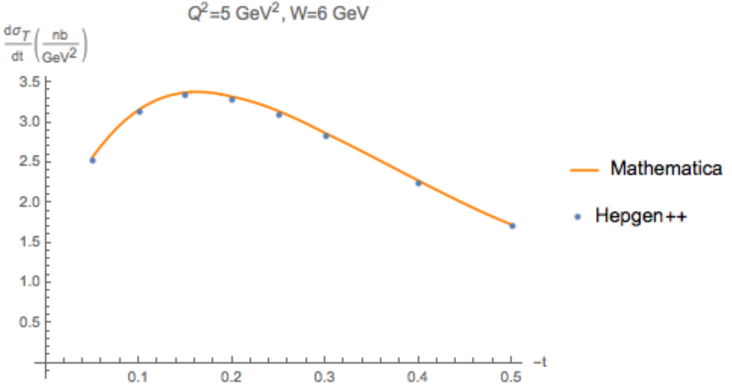
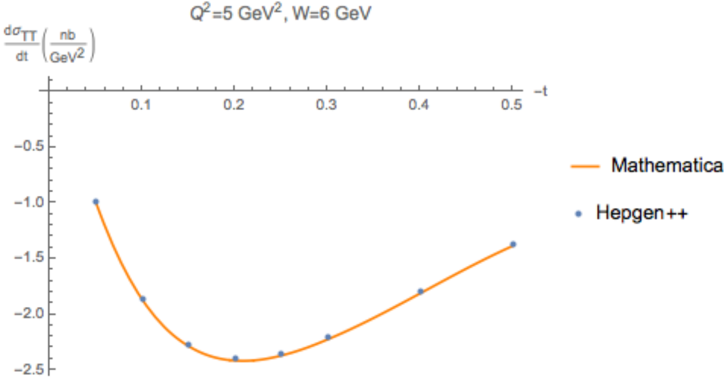


Figure: Comparison between our Mathematica results and $Hepgen++$ (see C. Regali's PhD thesis, https://freidok.uni-freiburg.de/data/11449)

Goloskokov-Kroll Model - π^0



Goloskokov-Kroll Model - π^0



Goloskokov-Kroll Model - π^+

- Contrary to π^0 production, GPDs appear in the form of $(F^u - F^d)$ in π^+ production
- H_T dominates the process due to the relative sign of up and down quark GPDs
- One also needs to consider pion-pole terms in π^+ production

PARTONS

B. Berthou et al., Eur.Phys.J. C78 (2018) 6, 478

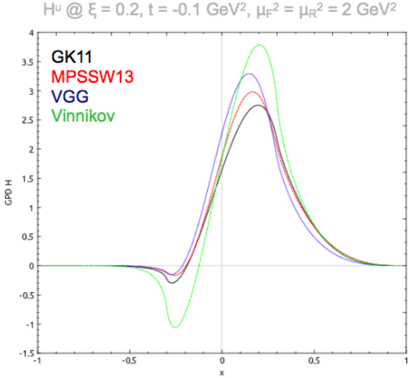
- PARtonic Tomography Of Nucleon Software (PARTONS) is a software framework dedicated to the phenomenology of GPDs
- Website: http://partons.cea.fr

PARTONS

- Bridge between models of GPDs and experimental data
- Written in C++: Inheritance and polymorphism
- XML interface for automated tasks
- Layered structure:
    - GPD Layer
    - CFF Layer
    - Process Layer
    - Observable Layer

PARTONS

- Existing modules:
  GPDs: GK, VGG, Vinnikov, MPSSW, MMS, HM
  Evolution: Vinnikov's code
  CFF (for DVCS): LO and NLO evaluation
  Cross Section (for DVCS): VGG, BMJ, GV



PARTONS

- Recent applications with PARTONS:
  "Border and skewness functions from a leading order fit to DVCS data",

  H. Moutarde, P. Sznajder, J. Wagner, Eur. Phys. J. C **78**, no. 11, 890 (2018)
  "Unbiased determination of Compton Form Factors",

  H. Moutarde, P. Sznajder, J. Wagner, Eur. Phys. J. C **79**, no. 7, 614 (2019)
- Adding new modules as easy as possible (see the website for tutorials)

Conclusions

- PARTONS: A comprehensive framework dedicated to the phenomenology of GPDs
- DVCS process is already implemented in PARTONS
- Easy addition of other partonic processes
- Implementation of DVMP processes is in progress
- First model to be implemented: Goloskokov-Kroll model of π^0 and π^+ production