On wide-angle photo- and electroproduction of pions to twist-3 accuracy

Kornelija Passek-Kumerički

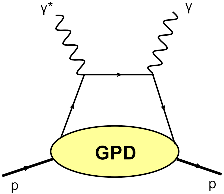
Rudjer Bošković Institute, Croatia

HADRON2021, Mexico City - online, 26-31 July 2021.

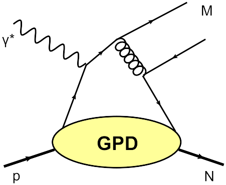
Outline

Handbag factorization

	DEEPLY VIRTUAL	WIDE ANGLE
	DVCS (Compton scattering)	WACS
	DVMP (meson production)	WAMP

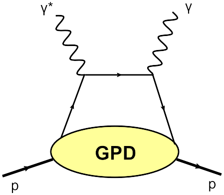
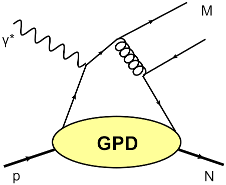


$$\gamma^{(*)} N \to \gamma N$$



$$\gamma^{(*)} N \to M N'$$

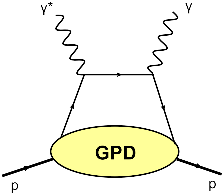
Handbag factorization

	DEEPLY VIRTUAL	WIDE ANGLE
	$Q^2 >>,\ -t <<$	$-t,\ -u,\ s >>$
	DVCS (Compton scattering)	WACS
$\gamma^{(*)} N \to \gamma N$		
	DVMP (meson production)	WAMP
$\gamma^{(*)} N \to M N'$		

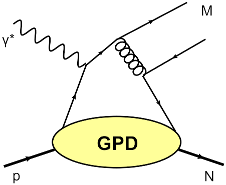
$q + p = q' + p'$ $\quad Q^2 = -q^2, s = (q+p)^2, t = (p-p')^2, u$ → parent process

$q + k_j = q' + k'_j$ $\quad Q^2, \hat{s}, \hat{u}, \hat{t}$ → active parton

Handbag factorization



$$\gamma^{(*)} N \to \gamma N$$



$$\gamma^{(*)} N \to M N'$$

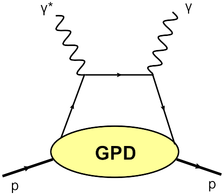
	DEEPLY VIRTUAL	WIDE ANGLE
	$Q^2 >>,\ -t <<$	$-t,\ -u,\ s >>$
$\gamma^{(*)} N \to \gamma N$	DVCS (Compton scattering) [Collins, Freund '99]	WACS
$\gamma^{(*)} N \to M N'$	DVMP (meson production) [Collins, Frankfurt, Strikman '97]	WAMP

- factorization
  $\mathcal{H} \otimes GPD$

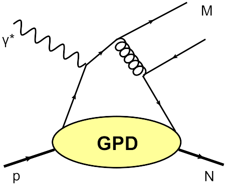
$q + p = q' + p'$ $\quad Q^2 = -q^2, s = (q+p)^2, t = (p-p')^2, u$ $\quad \to$ parent process

$q + k_j = q' + k_j'$ $\quad Q^2, \hat{s}, \hat{u}, \hat{t}$ $\quad \to$ active parton

Handbag factorization



$$\gamma^{(*)} N \to \gamma N$$



$$\gamma^{(*)} N \to M N'$$

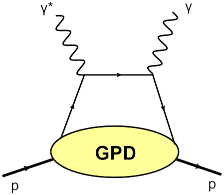
DEEPLY VIRTUAL	WIDE ANGLE
$Q^2 >>,\ -t <<$	$-t,\ -u,\ s >>$
DVCS (Compton scattering)	WACS
[Collins, Freund '99]	[Radyushkin '98]
	[Diehl, Feldman, Kroll, Jakob '98]
DVMP (meson production)	WAMP
[Collins, Frankfurt, Strikman '97]	[Huang, Kroll '00]

- factorization $\mathcal{H} \otimes GPD$
- arguments for factorization $\mathcal{H}(1/x \otimes GPD(\xi = 0))$

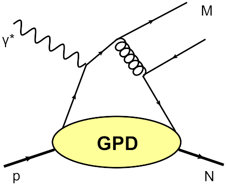
$q + p = q' + p'$ $\quad Q^2 = -q^2, s = (q+p)^2, t = (p-p')^2, u$ $\rightarrow$ parent process

$q + k_j = q' + k_j'$ $\quad Q^2, \hat{s}, \hat{u}, \hat{t}$ $\rightarrow$ active parton

Handbag factorization



$$\gamma^{(*)} N \to \gamma N$$



$$\gamma^{(*)} N \to M N'$$

$q + p = q' + p'$
$q + k_j = q' + k'_j$

DEEPLY VIRTUAL

$Q^2 >>, -t <<$

DVCS (Compton scattering)

[Collins, Freund '99]

DVMP (meson production)

[Collins, Frankfurt, Strikman '97]

- factorization
  $\mathcal{H} \otimes GPD$
- GPDs at small $(-t)$

WIDE ANGLE

$-t, -u, s >>$

WACS

[Radyushkin '98]

[Diehl, Feldman, Kroll, Jakob '98]

WAMP

[Huang, Kroll '00]

- arguments for factorization
  $\mathcal{H}(1/x \otimes GPD(\xi = 0))$
- GPDs at large $(-t)$

$Q^2 = -q^2, s = (q+p)^2, t = (p-p')^2, u$ → parent process
$Q^2, \hat{s}, \hat{u}, \hat{t}$ → active parton

Status and motivation

- DVCS, WACS: widely investigated, good description using handbag (NNLO, NLO...)

Status and motivation

- DVCS, WACS: widely investigated, good description using handbag (NNLO, NLO...)
- DVπP:
  - leading twist-2 theoretical predictions (γ_L^*) bellow the experimental data which indicate the importance of γ_T^*

  $\Rightarrow$ twist-3 calculations with transversity (chiral-odd) GPDs (H_T...) [Goloskokov, Kroll '10] (2-body, i.e, WW approximation), [Goldstein, Hernandez, Liuti '13]

Status and motivation

- DVCS, WACS: widely investigated, good description using handbag (NNLO, NLO...)
- DVπP:
  - leading twist-2 theoretical predictions (γ_L^*) bellow the experimental data which indicate the importance of γ_T^*
  - $\Rightarrow$ twist-3 calculations with transversity (chiral-odd) GPDs (H_T...) [Goloskokov, Kroll '10] (2-body, i.e, WW approximation), [Goldstein, Hernandez, Liuti '13]
- WAπP:
  - twist-2 results [Huang, Kroll '00] well bellow the experimental data for photoproduction ($Q^2 = 0$)
  - twist-3 2-body contribution to pion photoproduction in WW approximation vanishes [Huang, Jakob, Kroll, P-K '03]
  - twist-3 (2- and 3-body) prediction to π_0 photoproduction calculated [Kroll, P-K '18] and fitted to CLAS data [CLAS '17]
  - [Kroll, P-K. '21, arXiv:2107.04544]: twist-3 prediction for $P = \pi^{\pm}, \pi^0$ photo- and electroproduction analyzed ($Q^2 < -t$); extension to other PS mesons and well as DVMP is straightforward

Helicity amplitudes $\mathcal{M}$ for WAMP

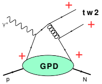
$$\mathcal{M}^P_{0+,\mu+} = \frac{e_0}{2}\sum_\lambda \Big[\mathcal{H}^P_{0\lambda,\mu\lambda}\,\Big(R^P_V(t) + 2\lambda\, R^P_A(t)\Big) - 2\lambda\,\frac{\sqrt{-t}}{2m}\,\mathcal{H}^P_{0-\lambda,\mu\lambda}\,\bar{S}^P_T(t)\Big]$$

$$\mathcal{M}^P_{0-,\mu+} = \frac{e_0}{2}\sum_\lambda \Big[\frac{\sqrt{-t}}{2m}\,\mathcal{H}^P_{0\lambda,\mu\lambda}\,R^P_T(t) - 2\lambda\,\frac{t}{2m^2}\,\mathcal{H}^P_{0-\lambda,\mu\lambda}\,S^P_S(t)\Big] + e_0\mathcal{H}^P_{0-,\mu+}\,S^P_T(t)$$

μ photon helicity, $\lambda\ldots$ quark helicities, $P = (\pi^\pm, \pi^0)$,

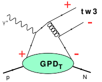
form factors: $R^a_V(t) = \int \frac{dx}{x}\, H^a(x, \xi = 0, t)$

$$R^{\pi^\pm}_V = R^u_V - R^d_V,\; R^{\pi^0}_V = \frac{1}{\sqrt{2}}\left(e_u R^u_V - e_d R^d_V\right)$$



$\mathcal{H}^P_{0\lambda,\mu\lambda}$ ... non-flip subprocess amplitudes (twist-2)

$$R_V \to H,\; R_A \to \tilde{H},\; R_T \to \tilde{E}$$



$\mathcal{H}^P_{0-\lambda,\mu\lambda}$ ... flip subprocess amplitudes (twist-3)

$$S_T \to H_T,\; \bar{S}_T \to \bar{E}_T,\; S_S \to \tilde{H}_T$$ (transversity GPDs)

Helicity amplitudes $\mathcal{M}$ for WAMP

μ photon helicity, $\lambda\ldots$ quark helicities, $P=(\pi^{\pm},\pi^0)$,

Transverse photon polarization ($\mu=\pm 1$)

$$\mathcal{M}^P_{0+,\mu+} = \frac{e_0}{2}\sum_\lambda \Big[\mathcal{H}^P_{0\lambda,\mu\lambda}\left(R^P_V(t)+2\lambda\,R^P_A(t)\right) \quad \to \text{twist-2}$$

$$-2\lambda\,\frac{\sqrt{-t}}{2m}\,\mathcal{H}^P_{0-\lambda,\mu\lambda}\,\bar{S}^P_T(t)\Big] \quad \to \text{twist-3}$$

$$\mathcal{M}^P_{0-,\mu+} = \frac{e_0}{2}\sum_\lambda \Big[\frac{\sqrt{-t}}{2m}\,\mathcal{H}^P_{0\lambda,\mu\lambda}\,R^P_T(t) \quad \to \text{twist-2}$$

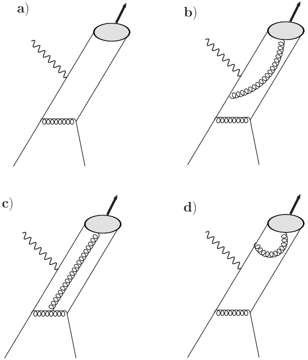
$$-2\lambda\,\frac{t}{2m^2}\,\mathcal{H}^P_{0-\lambda,\mu\lambda}\,S^P_S(t)\Big] + e_0\mathcal{H}^P_{0-,\mu+}\,S^P_T(t) \quad \to \text{twist-3}$$

Longitudinal photon polarization

$$\mathcal{M}^P_{0+,0+} = e_0\mathcal{H}^P_{0+,0+}\,R^P_A(t) \quad \to \text{twist-2}$$

$$\mathcal{M}^P_{0-,0+} = e_0\mathcal{H}^P_{0-,0+}\,S^P_T(t) \quad \to \text{twist-3}$$

Subprocess amplitudes $\mathcal{H}$

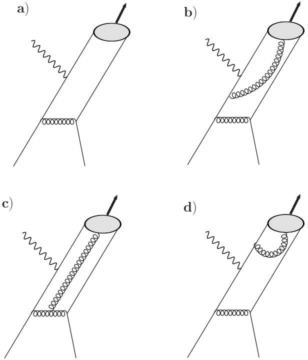


$q\bar{q} \to \pi$ projector (a) [Beneke, Feldmann '00]

$$(\tau q' + k_\perp) + (\bar{\tau} q' - k_\perp) = q'$$

$$\mathcal{P}_2^P \sim f_\pi \Big\{ \gamma_5 \, \not{q}' \phi_\pi(\tau, \mu_F) + \mu_\pi(\mu_F) \Big[\gamma_5 \, \phi_{\pi p}(\tau, \mu_F) - \frac{i}{6} \gamma_5 \, \sigma_{\mu\nu} \, \frac{q'^\mu n^\nu}{q' \cdot n} \, \phi'_{\pi\sigma}(\tau, \mu_F) + \frac{i}{6} \gamma_5 \, \sigma_{\mu\nu} \, q'^\mu \phi_{\pi\sigma}(\tau, \mu_F) \frac{\partial}{\partial k_{\perp\nu}} \Big] \Big\}_{k_\perp \to 0}$$

Subprocess amplitudes $\mathcal{H}$



$q\bar{q} \to \pi$ projector (a) [Beneke, Feldmann '00]

$$(\tau q' + k_\perp) + (\bar{\tau} q' - k_\perp) = q'$$

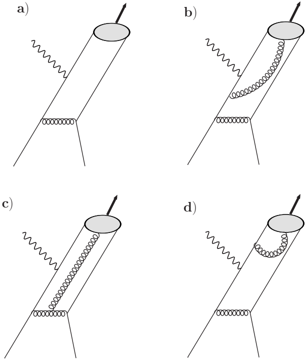
$$\mathcal{P}_2^P \sim f_\pi \Big\{ \gamma_5 \not{q}' \phi_\pi(\tau, \mu_F) + \mu_\pi(\mu_F) \Big[\gamma_5\, \phi_{\pi p}(\tau, \mu_F) - \frac{i}{6}\, \gamma_5\, \sigma_{\mu\nu}\, \frac{q'^\mu n^\nu}{q' \cdot n}\, \phi'_{\pi\sigma}(\tau, \mu_F) + \frac{i}{6}\, \gamma_5\, \sigma_{\mu\nu}\, q'^\mu \phi_{\pi\sigma}(\tau, \mu_F) \frac{\partial}{\partial k_{\perp\nu}} \Big] \Big\}_{k_\perp \to 0}$$

$q\bar{q}g \to \pi$ projector (b, c) [Kroll, P-K '18]

$$\tau_a q' + \tau_b q' + \tau_g q' = q'$$

$$\mathcal{P}_3^P \sim f_{3\pi}(\mu_F)\, \frac{i}{g}\, \gamma_5\, \sigma_{\mu\nu} q'^\mu g_\perp^{\nu\rho}\, \frac{\phi_{3\pi}(\tau_a, \tau_b, \tau_g, \mu_F)}{\tau_g}$$

Subprocess amplitudes $\mathcal{H}$



$q\bar{q} \to \pi$ projector (a) [Beneke, Feldmann '00]

$$(\tau q' + k_\perp) + (\bar{\tau} q' - k_\perp) = q'$$

$$\mathcal{P}_2^P \sim f_\pi \Big\{ \gamma_5\, q\!\!\!/' \phi_\pi(\tau,\mu_F) + \mu_\pi(\mu_F) \Big[\gamma_5\, \phi_{\pi p}(\tau,\mu_F) - \frac{i}{6}\gamma_5\, \sigma_{\mu\nu}\, \frac{q'^\mu n^\nu}{q'\cdot n}\, \phi'_{\pi\sigma}(\tau,\mu_F) + \frac{i}{6}\gamma_5\, \sigma_{\mu\nu}\, q'^\mu \phi_{\pi\sigma}(\tau,\mu_F) \frac{\partial}{\partial k_{\perp\nu}} \Big] \Big\}_{k_\perp\to 0}$$

$q\bar{q}g \to \pi$ projector (b, c) [Kroll, P-K '18]

$$\tau_a q' + \tau_b q' + \tau_g q' = q'$$

$$\mathcal{P}_3^P \sim f_{3\pi}(\mu_F)\, \frac{i}{g}\, \gamma_5\, \sigma_{\mu\nu} q'^\mu g_\perp^{\nu\rho}\, \frac{\phi_{3\pi}(\tau_a,\tau_b,\tau_g,\mu_F)}{\tau_g}$$

$\mu_\pi = m_\pi^2/(m_u+m_d) \cong 2$ GeV
distribution amplitudes (DAs):

twist-2: ϕ_π

2-body twist-3 $\phi_{\pi p}$, $\phi_{\pi\sigma}$ 3-body twist-3 $\phi_{3\pi}$

$\to$ connected by equations of motion (EOMs)

DAs and EOMs

$$\tau\phi_{\pi p}(\tau) + \frac{\tau}{6}\,\phi'_{\pi\sigma}(\tau) - \frac{1}{3}\,\phi_{\pi\sigma}(\tau) = \phi^{EOM}_{\pi 2}(\bar\tau)$$

$$\bar\tau\phi_{\pi p}(\tau) - \frac{\bar\tau}{6}\phi'_{\pi\sigma}(\tau) - \frac{1}{3}\phi_{\pi\sigma}(\tau) = \phi^{EOM}_{\pi 2}(\tau)$$

$$\phi^{EOM}_{\pi 2}(\tau) = 2\frac{f_{3\pi}}{f_\pi \mu_\pi}\int_0^{\bar\tau}\frac{d\tau_g}{\tau_g}\,\phi_{3\pi}(\tau, \bar\tau - \tau_g, \tau_g)$$

- EOMs and symmetry properties $\phi_{\pi *}(\bar\tau) = \phi_{\pi *}(\tau)$ $\phi_{3\pi}(\tau_a, \tau_b, \tau_g) = \phi_\pi(\tau_b, \tau_a, \tau_g)$ $\Rightarrow$ the subprocess amplitudes in terms of two twist-3 DAs, 2- and 3-body contributions combined
- combined EOMs $\rightarrow$ first order differential equation $\Rightarrow$ from known form of $\phi_{3\pi}$ [Braun, Filyanov '90] one determines $\phi_{\pi p}$ (and $\phi_{\pi\sigma}$)

  Note: $q\bar q g$ projector and EOMs were derived using light-cone gauge for constituent gluon

Subprocess amplitudes: twist-2

Transverse photon polarization ($\mu = \pm 1$) T

$$\mathcal{H}^{P,tw2}_{0\lambda,\,\mu\lambda} \sim f_\pi\, C_F\, \alpha_s(\mu_R)\, \frac{\sqrt{-\hat{t}}}{\hat{s}+Q^2} \int_0^1 d\tau\, \phi_\pi(\tau) \Bigg[(2\lambda\mu+1)\left(\frac{(\hat{s}\tau+Q^2)(\hat{s}+Q^2)-\hat{u}Q^2\bar{\tau}}{\hat{s}\bar{\tau}(Q^2\bar{\tau}-\hat{t}\tau)}\, e_a + \frac{(\hat{s}\tau-Q^2)(\hat{s}+Q^2)-\hat{u}Q^2\bar{\tau}}{\hat{u}\tau(Q^2\tau-\hat{t}\bar{\tau})}\, e_b\right) + (2\lambda\mu-1)\left(\frac{\hat{u}\, e_a}{(Q^2\bar{\tau}-\hat{t}\tau)} + \frac{\hat{s}\bar{\tau}\, e_b}{\tau(Q^2\tau-\hat{t}\bar{\tau})}\right)\Bigg]$$

Longitudinal photon polarization L

$$\mathcal{H}^{P,tw2}_{0\lambda,\,0\lambda} \sim f_\pi\, C_F\, \alpha_s(\mu_R)\, \lambda\, \frac{Q\sqrt{-\hat{u}\hat{s}}}{\hat{s}+Q^2} \int_0^1 d\tau\, \phi_\pi(\tau) \left(\frac{\hat{u}\, e_a}{\hat{s}(Q^2\bar{\tau}-\hat{t}\tau)} - \frac{(\hat{t}+\tau\hat{u})\, e_b}{\tau\hat{u}(Q^2\tau-\hat{t}\bar{\tau})}\right)$$

Subprocess amplitudes: twist-2

Transverse photon polarization ($\mu = \pm 1$) T

$$\mathcal{H}^{P,tw2}_{0\lambda,\,\mu\lambda} \sim f_\pi\, C_F\, \alpha_s(\mu_R)\, \frac{\sqrt{-\hat{t}}}{\hat{s}+Q^2} \int_0^1 d\tau\, \phi_\pi(\tau) \Big[(2\lambda\mu+1)\Big(\frac{(\hat{s}\tau+Q^2)(\hat{s}+Q^2)-\hat{u}Q^2\bar{\tau}}{\hat{s}\bar{\tau}(Q^2\bar{\tau}-\hat{t}\tau)}\, e_a + \frac{(\hat{s}\tau-Q^2)(\hat{s}+Q^2)-\hat{u}Q^2\bar{\tau}}{\hat{u}\tau(Q^2\tau-\hat{t}\bar{\tau})}\, e_b\Big) + (2\lambda\mu-1)\Big(\frac{\hat{u}\, e_a}{(Q^2\bar{\tau}-\hat{t}\tau)} + \frac{\hat{s}\bar{\tau}\, e_b}{\tau(Q^2\tau-\hat{t}\bar{\tau})}\Big)\Big]$$

Longitudinal photon polarization L

$$\mathcal{H}^{P,tw2}_{0\lambda,\,0\lambda} \sim f_\pi\, C_F\, \alpha_s(\mu_R)\, \lambda\, \frac{Q\sqrt{-\hat{u}\hat{s}}}{\hat{s}+Q^2} \int_0^1 d\tau\, \phi_\pi(\tau) \Big(\frac{\hat{u}\, e_a}{\hat{s}(Q^2\bar{\tau}-\hat{t}\tau)} - \frac{(\hat{t}+\tau\hat{u})\, e_b}{\tau\hat{u}(Q^2\tau-\hat{t}\bar{\tau})}\Big)$$

→ photoproduction ($Q \to 0$): $\mathcal{H}^{P,tw2}_{L}\Big|_{Q\to 0} = 0$

$$\mathcal{H}^{P,tw2}_{T}\Big|_{Q\to 0} \sim f_\pi\, C_F\, \alpha_s(\mu_R)\, \frac{1}{\sqrt{-\hat{t}}} \int_0^1 \frac{d\tau}{\tau}\, \phi_\pi(\tau)\, \big((1+2\lambda\mu)\,\hat{s} - (1-2\lambda\mu)\,\hat{u}\big)\Big(\frac{e_a}{\hat{s}} + \frac{e_b}{\hat{u}}\Big)$$

Subprocess amplitudes: twist-2

Transverse photon polarization ($\mu = \pm 1$) T

$$\mathcal{H}^{P,tw2}_{0\lambda,\,\mu\lambda} \sim f_\pi\, C_F\, \alpha_s(\mu_R)\, \frac{\sqrt{-\hat{t}}}{\hat{s}+Q^2} \int_0^1 d\tau\, \phi_\pi(\tau) \Big[(2\lambda\mu+1)\Big(\frac{(\hat{s}\tau+Q^2)(\hat{s}+Q^2)-\hat{u}Q^2\bar{\tau}}{\hat{s}\bar{\tau}(Q^2\bar{\tau}-\hat{t}\tau)}\, e_a + \frac{(\hat{s}\tau-Q^2)(\hat{s}+Q^2)-\hat{u}Q^2\bar{\tau}}{\hat{u}\tau(Q^2\tau-\hat{t}\bar{\tau})}\, e_b\Big) + (2\lambda\mu-1)\Big(\frac{\hat{u}\, e_a}{(Q^2\bar{\tau}-\hat{t}\tau)} + \frac{\hat{s}\bar{\tau}\, e_b}{\tau(Q^2\tau-\hat{t}\bar{\tau})}\Big)\Big]$$

Longitudinal photon polarization L

$$\mathcal{H}^{P,tw2}_{0\lambda,\,0\lambda} \sim f_\pi\, C_F\, \alpha_s(\mu_R)\, \lambda\, \frac{Q\sqrt{-\hat{u}\hat{s}}}{\hat{s}+Q^2} \int_0^1 d\tau\, \phi_\pi(\tau) \Big(\frac{\hat{u}\, e_a}{\hat{s}(Q^2\bar{\tau}-\hat{t}\tau)} - \frac{(\hat{t}+\tau\hat{u})\, e_b}{\tau\hat{u}(Q^2\tau-\hat{t}\bar{\tau})}\Big)$$

$\rightarrow$ photoproduction ($Q \rightarrow 0$): $\mathcal{H}^{P,tw2}_{L}\Big|_{Q\rightarrow 0} = 0$

$$\mathcal{H}^{P,tw2}_{T}\Big|_{Q\rightarrow 0} \sim f_\pi\, C_F\, \alpha_s(\mu_R)\, \frac{1}{\sqrt{-\hat{t}}} \int_0^1 \frac{d\tau}{\tau}\, \phi_\pi(\tau)\, ((1+2\lambda\mu)\,\hat{s} - (1-2\lambda\mu)\,\hat{u}) \Big(\frac{e_a}{\hat{s}} + \frac{e_b}{\hat{u}}\Big)$$

$\rightarrow$ DVMP ($\hat{t} \rightarrow 0$): $\mathcal{H}^{P,tw2}_{T}\Big|_{\hat{t}\rightarrow 0} = 0$

$\mathcal{H}^{P,tw2}_{L}\Big|_{\hat{t}\rightarrow 0}$: $\hat{s} = -\frac{\xi - x}{2\xi}\, Q^2\,,\ \hat{u} = -\frac{\xi + x}{2\xi}\, Q^2$ $\Rightarrow$ well known LO result for DVMP

Subprocess amplitudes: twist-3

General structure:

$$\begin{aligned}\mathcal{H}^{P,tw3} &= \mathcal{H}^{P,tw3,q\bar{q}} + \mathcal{H}^{P,tw3,q\bar{q}g} \\ &= \left(\mathcal{H}^{P,\phi_{\pi p}} + \underbrace{\mathcal{H}^{P,\phi_{\pi 2}^{EOM}}\right) + \left(\mathcal{H}^{P,q\bar{q}g,C_F}}_{} + \mathcal{H}^{P,q\bar{q}g,C_G}\right) \\ &= \mathcal{H}^{P,\phi_{\pi p}} \quad + \qquad \mathcal{H}^{P,\phi_{3\pi},C_F} \qquad + \mathcal{H}^{P,\phi_{3\pi},C_G}\end{aligned}$$

- 2-body twist-3 $\sim C_F$; 3-body C_F and C_G proportional parts
- C_G part is separately gauge invariant
- the sum of 2- and 3-body C_F parts is gauge invariant (QED and QCD)
- no end-point singularities for finite $\hat{t}$

Subprocess amplitudes: twist-3 at $Q <<$ or $\hat{t} <<$

General structure:

$$\begin{aligned}
\mathcal{H}^{P,tw3} &= \mathcal{H}^{P,tw3,q\bar{q}} + \mathcal{H}^{P,tw3,q\bar{q}g} \\
&= \left(\mathcal{H}^{P,\phi_{\pi p}} + \underbrace{\mathcal{H}^{P,\phi_{\pi 2}^{EOM}}\right) + \left(\mathcal{H}^{P,q\bar{q}g,C_F}}\, + \mathcal{H}^{P,q\bar{q}g,C_G}\right) \\
&= \mathcal{H}^{P,\phi_{\pi p}} \quad + \qquad \mathcal{H}^{P,\phi_{3\pi},C_F} \qquad + \mathcal{H}^{P,\phi_{3\pi},C_G}
\end{aligned}$$

- $\mathcal{H}_L^{P,tw3} \sim Q\sqrt{-t}$ vanishes both for $Q \to 0$ and $\hat{t} \to 0$
- photoproduction ($Q \to 0$): $\mathcal{H}^{P,\phi_{\pi p}} = 0$ [Kroll, P-K '18], $\mathcal{H}_T^{P,tw3}$ proportional to $(2\lambda - \mu)$
- DVMP ($\hat{t} \to 0$): $\mathcal{H}^{P,\phi_{\pi 2}^{EOM}} = 0$, end-point singularities in $\mathcal{H}^{P,\phi_{\pi p}}$ [Goloskokov, Kroll '10], $\mathcal{H}_T^{P,tw3}$ proportional to $(2\lambda + \mu)$

Pion distribution amplitudes

Twist-2 DA: $\phi_\pi(\tau,\mu_F) = 6\tau\bar{\tau}\left[1 + a_2(\mu_F)\, C_2^{3/2}(2\tau-1)\right]$

Twist-3 DAs:

$$\begin{aligned}\phi_{3\pi}(\tau_a,\tau_b,\tau_g,\mu_F) &= 360\tau_a\tau_b\tau_g^2\Big[1+\omega_{1,0}(\mu_F)\,\frac{1}{2}(7\tau_g-3)\\ &+ \omega_{2,0}(\mu_F)\,(2-4\tau_a\tau_b-8\tau_g+8\tau_g^2)\\ &+ \omega_{1,1}(\mu_F)\,(3\tau_a\tau_b-2\tau_g+3\tau_g^2)\Big]\end{aligned}$$

[Braun, Filyanov '90]

using EOMs [Kroll, P-K '18]:

$$\begin{aligned}\phi_{\pi p}(\tau,\mu_F) &= 1+\frac{1}{7}\frac{f_{3\pi(\mu_F)}}{f_\pi\mu_\pi(\mu_F)}\Big(7\,\omega_{1,0}(\mu_F)-2\,\omega_{2,0}(\mu_F)-\omega_{1,1}(\mu_F)\Big)\\ &\times\Big(10\,C_2^{1/2}(2\tau-1)-3\,C_4^{1/2}(2\tau-1)\Big)\,,\quad \phi_{\pi\sigma}(\tau)=\ldots\end{aligned}$$

Parameters:

- $a_2(\mu_0) = 0.1364 \pm 0.0213$ at $\mu_0 = 2$ GeV [Braun et al '15] (lattice)
- $\omega_{10}(\mu_0) = -2.55\,, \omega_{10}(\mu_0) = 0.0$ and $f_{3\pi}(\mu_0) = 0.004\ \mathrm{GeV}^2$. [Ball '99]
- $\omega_{20}(\mu_0) = 8.0$ [Kroll, P-K '18] fit to π^0 photoproduction data [CLAS '17]

Evolution of the decay constants and DA parameters taken into account.

Choice of scales: ${\mu_R}^2 = {\mu_F}^2 = \hat{t}\hat{u}/\hat{s}$

Form factors and GPDs

$R_i \ldots 1/x$ moment of $\xi = 0$ GPD (K_i)

- $R_V(\leftarrow H)$, $R_T(\leftarrow E)$ from nucleon form factor analysis [Diehl, Kroll '13]
- $R_A(\leftarrow \tilde{H})$ form factor analysis and WACS KLL asymmetry [Kroll '17]
- $S_T(\leftarrow H_T)$, $\bar{S}_T(\leftarrow \bar{E}_T)$ low $-t$ from DVMP analysis [Goloskokov, Kroll '11]
- $S_S(\leftarrow \tilde{H}_T) \cong \bar{S}_T/2$ ($\bar{E}_T = 2\tilde{H}_T + E_T$)

Form factors and GPDs

$R_i \ldots 1/x$ moment of $\xi = 0$ GPD (K_i)

- $R_V(\leftarrow H)$, $R_T(\leftarrow E)$ from nucleon form factor analysis [Diehl, Kroll '13]
- $R_A(\leftarrow \tilde{H})$ form factor analysis and WACS KLL asymmetry [Kroll '17]
- $S_T(\leftarrow H_T)$, $\bar{S}_T(\leftarrow \bar{E}_T)$ low $-t$ from DVMP analysis [Goloskokov, Kroll '11]
- $S_S(\leftarrow \tilde{H}_T) \cong \bar{S}_T/2$ $(\bar{E}_T = 2\tilde{H}_T + E_T)$

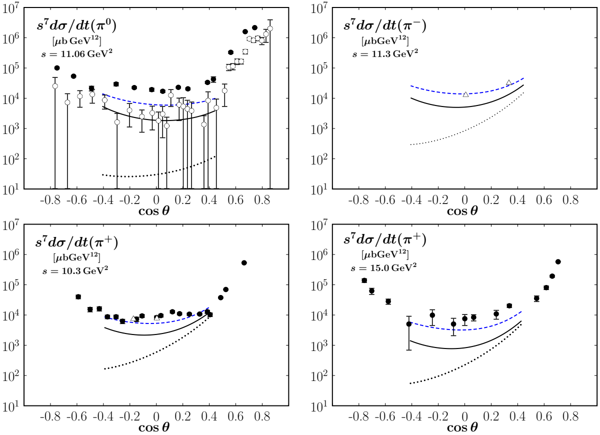
GPD parameterization [Diehl, Feldmann, Jakob, Kroll '04, Diehl, Kroll '13]

$$K_i^a = k_i^a(x) \exp\left[t f_i^a(x)\right], \; f_i^a(x) = \left(B_i^a - \alpha_i'^a \ln x\right)(1-x)^3 + A_i^a x(1-x)^2$$

- strong $x - t$ correlation
- power behaviour for large $(-t)$
- choice for transversity GPDs $A = 0.5$ GeV^{-2}

Photoproduction

[Kroll, P-K '21]



theoretical predictions with parameters from [Kroll, P-K '18] (fit of π^0 twist-3 prediction to [CLAS '17] data)

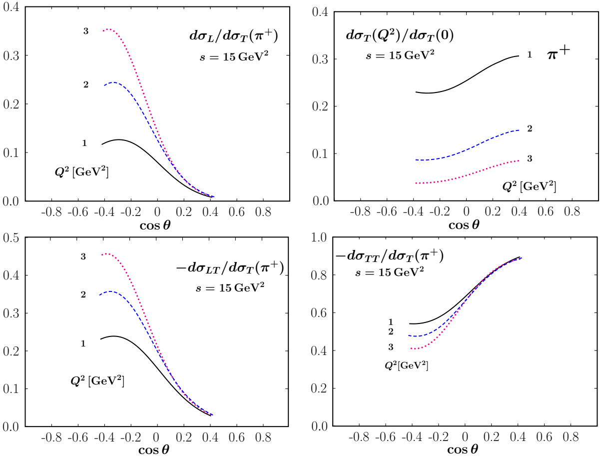
solid curves: complete twist-3
dotted curves: twist-2
dashed curves: $\omega_{20} = 10.3$
$\mu_R = \mu_F = 1$ GeV

exp data:
full circles [SLAC '76]
open circles [CLAS '17]
triangles [JLab, Hall A '05]

- twist-2 prediction well beyond the data [Huang, Kroll '00]
- scaling: s^{-7} (s^{-8}) twist-2 (twist-3) $\rightarrow$ effective s^{-9} $\rightarrow$ too strong

Electroproduction

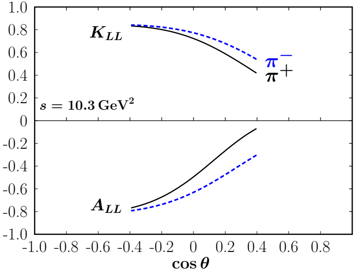
[Kroll, P-K '21]



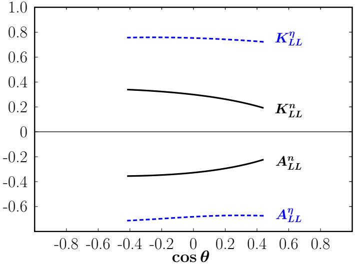
- both for σ_L and σ_{LT} no twist-2 and twist-3 interference $\Rightarrow$ information on S_T (H_T)
- information on S_S ($\tilde{H}_T$) from σ_{TT} (suppressed for DVMP)

Spin effects - photoproduction

[Kroll, P-K '21]



[Kroll, P-K '18]



$A_{LL}(K_{LL})\ldots$ correlation of the helicities of the photon and incoming (outgoing) nucleon

$$A_{LL}^{P,tw2} = K_{LL}^{P,tw2}$$
$$A_{LL}^{P,tw3} = -K_{LL}^{P,tw3}$$

$\rightarrow$ characteristic signature for dominance of twist-3 (like $\sigma_T \gg \sigma_L$ in DVMP)

$A_{LL}(K_{LL})$ for π^0 photoproduction on neutron and η photoproduction

Conclusions, questions, outlook...

- handbag factorization applied to wide-angle photo- and electroproduction of pions $\rightarrow$ WAMP
- in contrast to WACS, but like DVMP, the leading twist-2 analysis (helicity non-flip GPDs) for wide-angle photoproduction fails by order of magnitude
- twist-3 prediction for WAMP obtained, both 2 and 3-body contributions included
- π^0 photoproduction was fitted to the data
- interesting helicity correlations show that twist-3 dominates
- different combinations of form factors along with available data should allow to extract the form factors and to learn about large $-t$ behaviour of transversity GPDs important for parton tomography
- extension to other pseudoscalar mesons straightforward

Conclusions, questions, outlook...

- handbag factorization applied to wide-angle photo- and electroproduction of pions $\rightarrow$ WAMP
- in contrast to WACS, but like DVMP, the leading twist-2 analysis (helicity non-flip GPDs) for wide-angle photoproduction fails by order of magnitude
- twist-3 prediction for WAMP obtained, both 2 and 3-body contributions included
- π^0 photoproduction was fitted to the data
- interesting helicity correlations show that twist-3 dominates
- different combinations of form factors along with available data should allow to extract the form factors and to learn about large $-t$ behaviour of transversity GPDs important for parton tomography
- extension to other pseudoscalar mesons straightforward

Thank you!

Subprocess amplitudes: twist-3 at $Q \to 0$, $t \to 0$

photoproduction

$$\mathcal{H}^{P,tw3}_{0-\lambda,\,\mu\lambda}|_{Q^2\to 0} \sim (2\lambda-\mu)\, f_{3\pi}\, \alpha_S(\mu_R)\sqrt{-\hat{u}\hat{s}} \int_0^1 d\tau \int_0^{\bar{\tau}} \frac{d\tau_g}{\tau_g}\, \phi_{3\pi}(\tau,\bar{\tau}-\tau_g,\tau_g)$$
$$\times \left[C_F \left(\frac{1}{\bar{\tau}^2} - \frac{1}{\bar{\tau}(\bar{\tau}-\tau_g)}\right)\left(\frac{e_a}{\hat{s}^2}+\frac{e_b}{\hat{u}^2}\right) + \right.$$
$$\left. -C_G\, \frac{2}{\tau\tau_g}\, \frac{\hat{t}}{\hat{s}\hat{u}} \left(\frac{e_a}{\hat{s}}+\frac{e_b}{\hat{u}}\right)\right]$$

DVMP

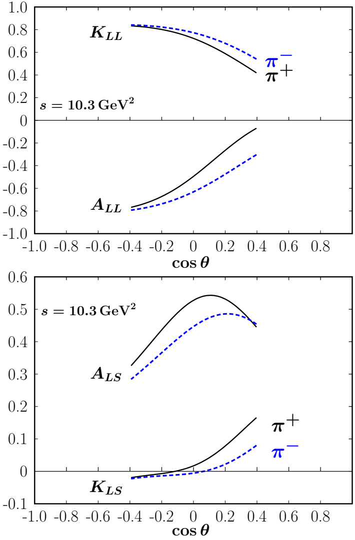
$$\mathcal{H}^{P,\phi_{\pi p}}_{0-\lambda,\mu\lambda}|_{\hat{t}\to 0} \sim (2\lambda+\mu)\; f_\pi \mu_\pi C_F \alpha_S(\mu_R)\sqrt{-\frac{\hat{u}}{\hat{s}}}\left[\frac{e_a}{\hat{s}} + \frac{\hat{s}}{\hat{u}}\frac{e_b}{\hat{u}}\right] \int_0^1 \frac{d\tau}{\bar{\tau}}\phi_{\pi p}(\tau)$$

$$\mathcal{H}^{P,C_F,\phi_{3\pi}}_{0-\lambda,\mu\lambda}|_{\hat{t}\to 0} \sim -(2\lambda+\mu)\, f_{3\pi}\, C_F \alpha_S(\mu_R)\sqrt{-\frac{\hat{u}}{\hat{s}}}\left(\frac{e_a}{\hat{s}} + \frac{\hat{s}}{\hat{u}}\,\frac{e_b}{\hat{u}}\right)$$
$$\times \int_0^1 \frac{d\tau}{\bar{\tau}^2} \int_0^{\bar{\tau}} \frac{d\tau_g}{\tau_g(\bar{\tau}-\tau_g)}\,\phi_{3\pi}(\tau,\bar{\tau}-\tau_g,\tau_g)$$

$$\mathcal{H}^{P,qqg,C_G}_{0-\lambda,\mu\lambda}|_{\hat{t}\to 0} \sim (2\lambda+\mu)\; f_{3\pi}\, C_G \alpha_S(\mu_R)\frac{Q^2}{\sqrt{-\hat{s}\hat{u}}}\left(\frac{e_a}{\hat{s}}+\frac{e_b}{\hat{u}}\right)$$
$$\times \int_0^1 \frac{d\tau}{\bar{\tau}} \int_0^{\bar{\tau}} \frac{d\tau_g}{\tau_g(\bar{\tau}-\tau_g)}\,\phi_{3\pi}(\tau,\bar{\tau}-\tau_g,\tau_g)$$

Spin effects - photoproduction

[Kroll, P-K '21]



$A_{LL}(K_{LL})\ldots$ correlation of the helicities of the photon and incoming (outgoing) nucleon

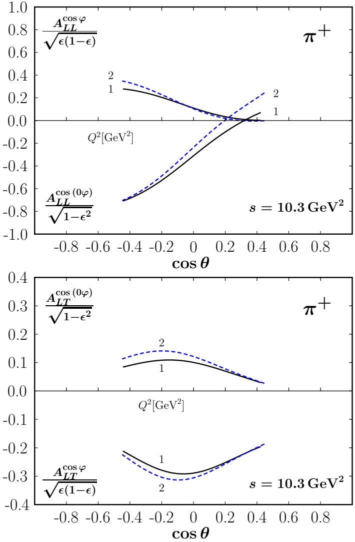
$$A_{LL}^{P,tw2} = K_{LL}^{P,tw2}$$
$$A_{LL}^{P,tw3} = -K_{LL}^{P,tw3}$$

$\rightarrow$ characteristic signature for dominance of twist-3 (like $\sigma_T \gg \sigma_L$ in DVMP)

$A_{LS}(K_{LS})\ldots$ correlation of the helicities of the photon and sideway polarization of the incoming (outgoing) nucleon

Spin effects - electroproduction

[Kroll, P-K '21]



$A_{LL}(K_{LL})$ have two modulations for electroproduction

(→ measured for DVMP [CLAS '15])

$A_{LT}(K_{LT})\ldots$ correlation between the lepton helicity and transversal target polarization