Photo- and electroproduction of pions and eta mesons at twist-3

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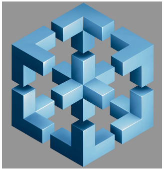
"Towards improved hadron femtography..."

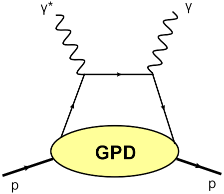
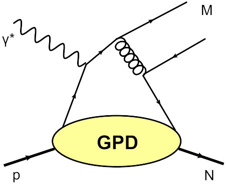


(Escher 3D, Al Borge)

Virginia Tech, July 18-22, 2022.

Outline

Handbag factorization

	DEEPLY VIRTUAL	WIDE ANGLE
 $\gamma^{(*)} N \to \gamma N$	DVCS (Compton scattering)	WACS
 $\gamma^{(*)} N \to M N'$	DVMP (meson production)	WAMP

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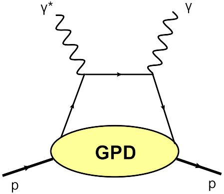

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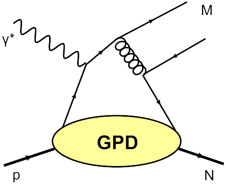
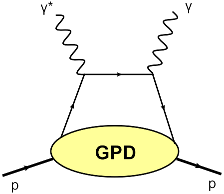


$\gamma^{(*)} N \to M N'$

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

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

Handbag factorization



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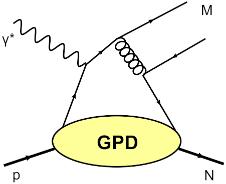

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- factorization
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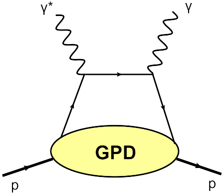

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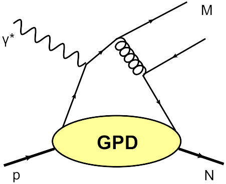

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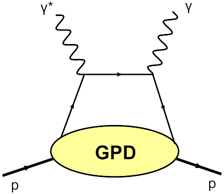

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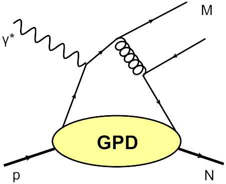

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Deeply virtual:

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

Wide angle:

- arguments for factorization $\mathcal{H}(1/x \otimes GPD(\xi = 0))$
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  - leading tw-2 theoretical predictions (γ_L^*) bellow the experimental data which indicate the importance of γ_T^*

  $\Rightarrow$ tw-3 calculations with transversity (chiral-odd) GPDs (H_T...) [Goloskokov, Kroll '10] (2-body, i.e, WW approximation), [Ahmad, Goldstein Liuti '09, Goldstein, Hernandez, Liuti '13]

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- WAπP:
  - tw-2 results [Huang, Kroll '00] well bellow the experimental data for photoproduction ($Q^2 = 0$)
  - tw-3 2-body contribution to pion photoproduction in WW approximation vanishes [Huang, Jakob, Kroll, P-K '03]
  - tw-3 (2- and 3-body) prediction to π_0 photoproduction calculated [Kroll, P-K '18] and fitted to CLAS data [CLAS '17]
  - tw-3 prediction for $\pi^{\pm}, \pi^0$ photo- and electroproduction ($Q^2 < -t$) analyzed [Kroll, P-K. '21]; extension to DVMP is straightforward
  - tw-3 prediction for photoproduction of η, η' mesons [Kroll, P-K. '22] (preliminary GlueX '20)

Helicity amplitudes $\mathcal{M}$ for WAMP

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

μ photon helicity, $\lambda\ldots$ quark helicities, $P\in\{\pi^\pm,\pi^0,\eta_8,\eta_1,\eta,\eta'\}$,

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μ photon helicity, $\lambda\ldots$ quark helicities, $P \in \{\pi^\pm, \pi^0, \eta_8, \eta_1, \eta, \eta'\}$,

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

$$a \in \{u, d\} \Rightarrow R^{\pi^\pm}_V = R^u_V - R^d_V,\; R^{\pi^0}_V = \frac{1}{\sqrt{2}}\left(e_u R^u_V - e_d R^d_V\right)$$
$$R^{\eta_8}_V \approx \frac{1}{\sqrt{2}} R^{\eta_1}_V \approx \frac{1}{\sqrt{6}}\left(e_u R^u_V + e_d R^d_V\right)$$

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

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

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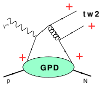
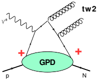
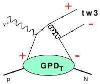
$\mathcal{H}^P_{0\lambda,\mu\lambda}$ ... non-flip subprocess amplitudes (twist-2)

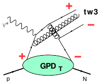


and 

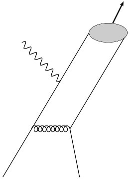
for η_1

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





Subprocess amplitudes $\mathcal{H}$



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

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

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

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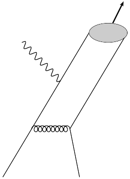

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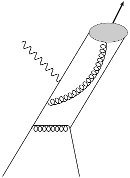
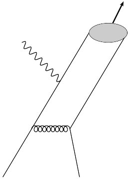


$q\bar{q}g \to \pi$ **projector** [Kroll, P-K '18]

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

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

Subprocess amplitudes $\mathcal{H}$



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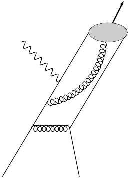

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$\mu_\pi = m_\pi^2/(m_u + m_d) \cong 2$ GeV, $f_{3\pi} \sim \mu_\pi$

distribution amplitudes (DAs):

twist-2 ($q\bar{q}$) : ϕ_π

2-body ($q\bar{q}$) twist-3 $\phi_{\pi p}$, $\phi_{\pi\sigma}$ 3-body ($q\bar{q}g$) 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
  $\phi_{\pi *}(\bar{\tau}) = \phi_{\pi *}(\tau), \phi_{3\pi}(\tau_a, \tau_b, \tau_g) = \phi_{3\pi}(\tau_b, \tau_a, \tau_g)$
  $\Rightarrow$ the subprocess amplitudes in terms of two twist-3 DAs and 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

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

Longitudinal photon polarization L

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

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

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

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

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

Subprocess amplitudes: twist-3

General structure:

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

- 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 $\hat{t} \neq 0$!

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

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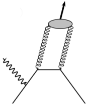
&= \left(\mathcal{H}^{P,\phi_{\pi p}} + \underbrace{\mathcal{H}^{P,\phi_{\pi 2}^{EOM}}\right) + \left(\mathcal{H}^{P,q\bar{q}g,C_F}}\, + \mathcal{H}^{P,q\bar{q}g,C_G}\right) \\
&= \mathcal{H}^{P,\phi_{\pi p}} + \mathcal{H}^{P,\phi_{3\pi},C_F} + \mathcal{H}^{P,\phi_{3\pi},C_G}
\end{aligned}$$

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

Subprocess amplitudes $\mathcal{H}^{\eta_8,\eta_1} \to \mathcal{H}^{\eta,\eta'}$

Novel features:

1.  $|gg\rangle$ states contribute to twist-2
   - $\mathcal{H}^{\pi,tw2} \Rightarrow \mathcal{H}^{\eta_8,tw2}, \mathcal{H}^{\eta_{1,q},tw2}$ $\qquad (\phi_\pi, f_\pi) \to (\phi_{\eta_8}, f_{\eta_8}), (\phi^q_{\eta_1}, f_{\eta_1})$

$\mathcal{H}^{\eta_1} = \mathcal{H}^{\eta_{1q},tw2} + \mathcal{H}^{\eta_{1g},tw2}$ $\qquad \phi^q_{\eta_1}$ and $\phi^g_{\eta_1}$ mix under evolution

   - $\mathcal{H}^{\pi,tw3} \Rightarrow \mathcal{H}^{P,tw3}$ $\qquad (\phi_{3\pi}, f_\pi, f_{3\pi}) \to (\phi_{3P}, f_P, f_{3P})$

2. flavour-mixing:
   - simplest: flavour-mixing embedded in the decay constants

$$f^8_\eta = f_8 \cos\theta_8 \qquad f^1_\eta = -f_1 \sin\theta_1$$

$$f^8_{\eta'} = f_8 \sin\theta_8 \qquad f^1_{\eta'} = f_1 \cos\theta_1$$

[review Feldmann '00]

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

η, η' distribution amplitudes

Twist-2 DA:

$$\phi_8(\tau,\mu_F) = 6\tau\bar{\tau}\left[1 + a_2^8(\mu_F)\, C_2^{3/2}(2\tau-1)\right]$$

$$\begin{aligned} \phi_{1,q}(\tau,\mu_F) &= 6\tau\bar{\tau}\left[1 + a_2^1(\mu_F)\, C_2^{3/2}(2\tau-1)\right] \\ \phi_{1,g}(\tau,\mu_F) &= 30\tau^2\bar{\tau}^2\left[1 + a_2^g(\mu_F)\, C_1^{5/2}(2\tau-1)\right] \end{aligned}$$

Twist-3 DAs:

assumption

$$\phi_{38}(\tau_a,\tau_b,\tau_g,\mu_F) = \phi_{31}(\tau_a,\tau_b,\tau_g,\mu_F) \approx \phi_{3\pi}(\tau_a,\tau_b,\tau_g,\mu_F)$$

Parameters:

- $a_2^8(\mu_0) = -0.039$, $a_2^1(\mu_0) = -0.057$, $a_2^g(\mu_0) = 0.038$ [Kroll, KPK '13], and other choices tested
- $f_{38}(\mu_0) = 0.86 f_{3\pi}(\mu_0) \Leftarrow$ [Ball '99; Braun, Filyanov '90]
- $f_{31}(\mu_0) = 0.86 f_{3\pi}(\mu_0) \Leftarrow \eta$ exp: [GlueX preliminary '20]
- mixing parameters from [Feldmann, Kroll, Stech '98]

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]
- $S_S(\leftarrow \tilde{H}_T) \cong \bar{S}_T/2$ $(\bar{E}_T = 2\tilde{H}_T + E_T)$

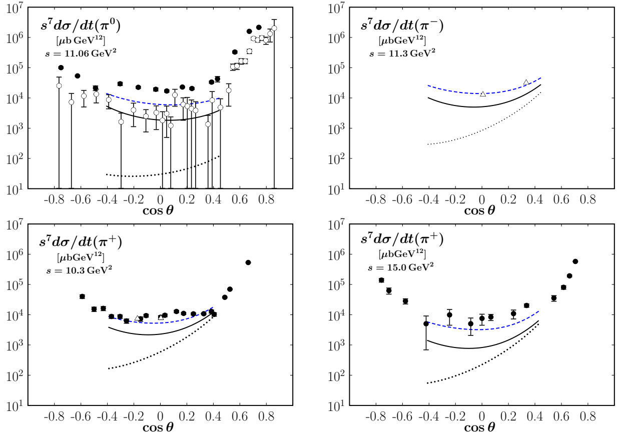
GPD parameterization [Diehl, Feldmann, Jakob, Kroll '04, Diehl, Kroll '13]

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

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

Photoproduction (π)

[Kroll, P-K '21]



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

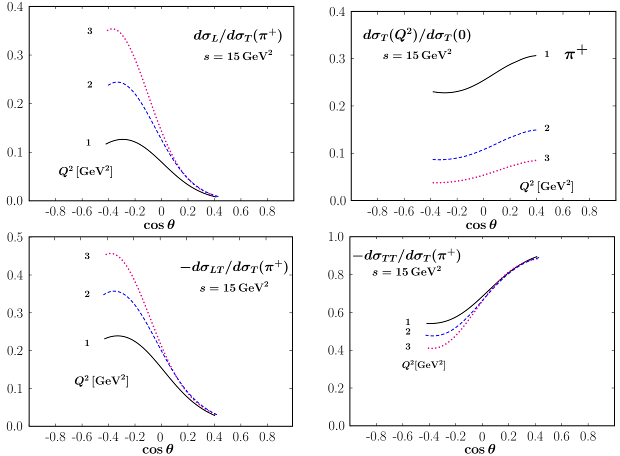
solid curves: complete twist-3
dotted curves: twist-2
dashed curves: $\omega_{20} = 10.3$
$\mu_R = \mu_F = 1$ GeV

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 (π)

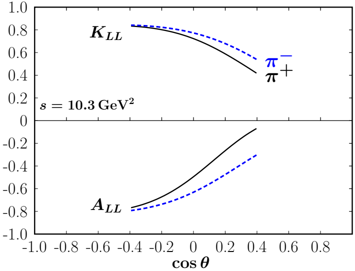
[Kroll, P-K '21]



- 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]: $\pi^{\pm}$



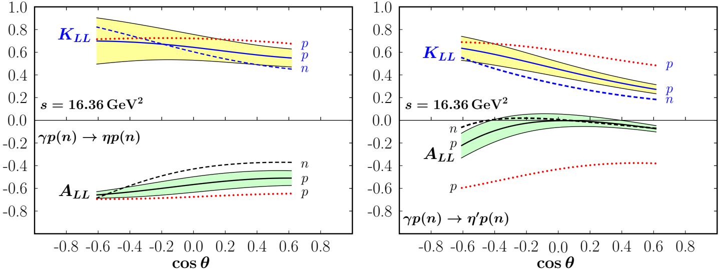
$A_{LL}(K_{LL})\ldots$ correlation of the helicities of the photon and incoming (outgoing) nucleon

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

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

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

[Kroll, P-K '22]: η, η'



$\rightarrow$ in contrast to π and η, for η' dominance of twist-2 and sensitivity to gluons

Conclusions, outlook...

- handbag factorization applied to wide-angle photo- and electroproduction of pions and etas $\rightarrow$ 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
- obtained twist-3 prediction includes both 2 and 3-body contributions
- π^0 photoproduction was fitted to the data
- helicity correlations show that twist-3 dominates for πs and η, while η' sensitive to twist-2 $\Rightarrow$ window to gg contributions
- different combinations of form factors $\Rightarrow$possibility of extraction $\Rightarrow$ large $-t$ behaviour of transversity GPDs
- application to DVMP underway

Conclusions, outlook...

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Thank you!