Hard Meson Electroproduction

P. Kroll
Fachbereich Physik, Univ. Wuppertal and Univ. Regensburg
Seattle, September 2009

Outline:

• Introduction
• Handbag factorization for meson electroproduction
• Transversely polarized photons matter
• Vector mesons
• Results for vector mesons
• Pions (pion pole, \( \tilde{H} \), \( \tilde{E} \), twist-3, results)
• Summary

based on work done in collaboration with S. Goloskokov
Electroproduction of mesons

rigorous proof of collinear factorization for $Q^2 \to \infty$
(Radyushkin (96); Collins et al (97))

hard subprocesses
$\gamma^* g \to V g$, $\gamma^* q \to V, Pq$

and GPDs and meson w.f.
(encode the soft physics)

dominant transition $\gamma^*_L \to V_L, P$
other transitions power suppressed

As compared to DVCS:
disadvantage: two soft functions
advantages: diff. mesons ($\rho^0, \phi, \omega, \rho^+, K^{*0}, J/\Psi$) allow for flavor separation
wealth of good data for $Q^2$ up to $\simeq 100$ GeV$^2$ and $W$ up to $\simeq 200$ GeV
Transverse photon polarization matters

\[ R = \sigma_L / \sigma_T \quad \text{(HERA } W \simeq 80 \text{ GeV)} \]
\[ \gamma^* \rightarrow V_T \text{ transitions substantial} \]
\[ \text{power corr. and/or higher twist needed} \]

Various moments of \( \pi^+ \) cross section measured with trans. pol. target
\[ \sin \phi_s \text{ moment very large} \]
\[ \text{does not seem to vanish for } t' \rightarrow 0 \]
\[ A_{UT}^{\sin \phi_s} \propto \text{Im} M_{0^+,0^+,0^-,-++} \]
\[ \text{requires n-f. ampl. } M_{0^-,++} \]
\[ \gamma^* \rightarrow P \text{ transitions substantial} \]

HERMES prel.
\[ Q^2 \simeq 2.5 \text{ GeV}^2, \ W = 3.99 \text{ GeV} \]
Corrections to the l.-t. amplitudes?

vector-meson electroproduction:
predictions for $\sigma_L$ exceed data by a large factor
(HERA $W = 75\text{GeV}$ $\rho$)
power corr. and/or higher orders of pQCD?
(Diehl-Kugler 07, Ivanov 07)

$\pi^+$ electroproduction:
contribution from pion exchange
requires $\pi$ elm form factor
(it is measured there)
lead. twist only about a third of exp. value
fails with cross section by order of magnitude
additional contributions required

new data on $F_{\pi\gamma}$ may change our understanding of pion DA and of hard exclusive processes
The $\gamma^* p \to VB$ amplitudes

consider large $Q^2$, $W$ and small $t$;
kinematics fixes skewness: $\xi \simeq \frac{x_{Bj}}{2-x_{Bj}} [1 + m_V^2/Q^2] \simeq x_{Bj}/2 + \text{m.m.c.}$

$$
\mathcal{M}_{\mu+,\mu+}(V) = \frac{e_0}{2} \left\{ \sum_a e_a C_V^{aa} \langle H_{eff}^g \rangle V_\mu + \sum_{ab} C_V^{ab} \langle H_{eff}^{ab} \rangle V_\mu \right\},
$$

$$
\mathcal{M}_{\mu-,\mu+}(V) = -\frac{e_0}{2} \frac{\sqrt{-t}}{M + m} \left\{ \sum_a e_a C_V^{aa} \langle E^g \rangle V_\mu + \sum_{ab} C_V^{ab} \langle E^{ab} \rangle V_\mu \right\},
$$

$C_V^{ab}$ flavor factors, $M(m)$ mass of $B(p)$, $H_{eff} = H - \xi^2/(1 - \xi^2)E$
contributions from $\tilde{H}$ to T-T amplitude not shown

electroproduction with unpolarized protons at small $\xi$:
$E$ not much larger than $H$ (see below) $\implies$ $H_{eff} \to H$ for small $\xi$
$|M_{\mu-,\mu+}|^2 \propto t/m^2$ neglected $\implies$ probes $H$ (exception $\rho^+$)
trans. polarized target: probes $Im[\langle E \rangle^* \langle H \rangle]$ interference
polarized beam and target: probes $Re[\langle H \rangle^* \langle \tilde{H} \rangle]$ interference
Subprocess amplitudes

\( F = H, E \) \( \lambda \) parton helicities

\[
\langle F \rangle_{V\mu}^{ab(g)} = \sum_{\lambda} \int d\bar{x} \mathcal{H}_{\mu\lambda,\mu\lambda}^{Vab(g)}(\bar{x}, \xi, Q^2, t = 0) F^{ab(g)}(\bar{x}, \xi, t)
\]

\( F^{aa} = F^a, \quad F^{ab} = F^a - F^b \quad (a \neq b) \) (with flavor symmetry)

\[
\gamma^* \begin{array}{c}
\text{..} \\
\text{..} \\
\text{..}
\end{array} V
\]

\[ \mathcal{H}_{\mu\lambda,\mu\lambda}^{Vab} = \int d\tau d^2\vec{b} \hat{\Psi}_{V\mu}(\tau, -\vec{b}) \exp[-S(\tau, \vec{b}, Q^2)] \times \hat{\mathcal{F}}_{\mu\lambda,\mu\lambda}^{ab}(\bar{x}, \xi, \tau, Q^2, \vec{b}) \]

LO pQCD

+ quark trans. mom.

+ Sudakov supp.

\( \Rightarrow \) lead. twist for \( Q^2 \to \infty \)

in collinear appr:

\[
TT : \int_0^1 d\tau \frac{\Phi_V(\tau)}{\tau} \frac{1}{(1 - \tau)t + \tau Q^2} \quad \text{IR singular for large } Q^2
\]

\[
\text{regular for large } -t \quad \text{(wide-angles)}
\]
\[ \exp[-s(\xi, \tilde{b}, Q)] \]

\[ \xi = \tau \text{ or } 1 - \tau, \quad \tilde{b} = b, \quad Q = 30\Lambda_{QCD} \]

\[ Q^2 \to \infty: \text{ all partons scatter within small space-time region} \]

\[ \text{accumulation profile} \]

\[ \text{reasonable values of } \alpha_s \]

\[ \text{at } Q^2 = 4(40) \text{ GeV}^2 \]

\[ W = 75 \text{ GeV} \]
Double distributions

integral representation \((i=\text{valence, sea quarks, gluons})\)

\[
H_i(\bar{x}, \xi, t') = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(\beta + \xi \alpha - \bar{x}) f_i(\beta, \alpha, t') + D_i \Theta(\xi^2 - \bar{x}^2)
\]

\(f_i\) double distributions \(\text{Mueller et al.}(94), \text{Radyushkin}(99)\)

advantage - polynomiality automatically satisfied

\(D_i(\bar{x}, t)\) \((i = \text{gluon, sea})\) additional free function, support \(-\xi < \bar{x} < \xi\)

useful ansatz with relation to PDFs (reduction formula respected)

\[
f_i(\beta, \alpha, t') = h_i(\beta) \exp[(b_i + \alpha' \ln(1/\beta))t] \frac{\Gamma(2n_i + 2)}{2^{2n_i+1}\Gamma^2(n_i + 1)} \frac{[(1 - |\beta|)^2 - \alpha^2]^{n_i}}{(1 - |\beta|)^{2n_i+1}}
\]

\[
h_g(t = 0) = |\beta|g(|\beta|), \quad n_g = 2 \quad \alpha_g' = 0.15 \text{ GeV}^{-2}
\]

\[
h_{\text{sea}}^q(t = 0) = q(|\beta|)\text{sign}(\beta), \quad n_{\text{sea}} = 2 \quad \alpha_{\text{sea}} = \alpha_g
\]

\[
h_{\text{val}}^q(t = 0) = q_{\text{val}}(\beta) \Theta(\beta), \quad n_{\text{val}} = 1 \quad \alpha'_{\text{v}} = 0.9 \text{ GeV}^{-2}
\]

sea quarks mix with gluons under evolution
Numerical results

Goloskokov-K. 06, 07, 08

GPDs constructed from CTEQ6 PDFs through the double distr. ansatz
\(D = 0\), sum rules and positivity bounds checked numerically

Gaussian wave fcts for the mesons
\[\Psi_{V_j}(\tau, k_\perp) \propto \exp[-a_{V_j}^2 k_\perp^2 / (\tau \bar{\tau})]\]

L an T different, free parameters - \(a_{V,L,T}^2\) (transverse size \(\langle k_\perp^2 \rangle^{1/2} \propto 1 / a_{V,L,T}^2\))

meson wf. provides effects of order \(\langle k_\perp^2 \rangle / Q^2\) separation of both GPDs mainly influence the \(\xi(x_{Bj})\) dependence effects possible

fit to all data from HERMES, COMPASS, E665, H1, ZEUS
cover large range of kinematics
\[Q^2 \simeq 3 - 100 \text{ GeV}^2\]
\[W \simeq 5 - 180 \text{ GeV}\]
A few results on cross sections

\[ W = 75, 90 \text{ GeV} \quad \text{dashed line: lead. twist suppression due to } a, \]
\[ \text{full symbols: H1, open ZEUS} \quad \text{SU(3) breaking in sea, valence quarks} \]

\[ Q^2 = 3.8 \text{ GeV}^2, \quad \text{glue+sea, glue, valence + interf.} \quad R \text{ at } W = 90 \text{ GeV} \]
\[ \text{data: H1, ZEUS, E665, HERMES} \]
$\rho^0$ and $\phi$ cross sections

![Graphs showing cross sections vs. W (GeV) for $\rho$ and $\phi$](image)

at $Q^2 = 4(3.8) \text{ GeV}^2$

E665 (△), HERMES (●), CORNELL (▲)

ZEUS (□), H1 (■), CLAS (○)

Goloskokov-K (09)

double distribution model too simple for valence quarks for large $\xi$?
breakdown of handbag physics? Lacking nucleon resonances? (Mueller)

$\omega$, $\rho^+$ large at small $W$ too? JLAB12 may explore region close to minimum
What do we know about $E_v$?

analysis of Pauli FF for proton and neutron at $\xi = 0$ Diehl et al (04):

$$F_2^{p(n)} = \int_0^1 dx \left[ e_{u(d)} E_v^u(x, \xi = 0, t) + e_{d(u)} E_v^d(x, \xi = 0, t) \right]$$

ansatz for small $-t$: $E_v^u = e_v^u(x) \exp \left\{ t(\alpha'_v \ln(1/x) + b^e_v) \right\}$

forward limit: $e_v^a = N_a x^{-\alpha_v(0)} (1 - x)^{\beta^a_v}$ (analogously to PDFs)

$N_a$ fixed from $\kappa_a = \int_0^1 dx E_v^a(x, \xi = 0, t = 0)$

fitting FF data provides: $\beta^u_v = 4$, $\beta^d_v = 5.6$

(other powers not excluded in 04 analysis)

new JLab data on $G_{E,M}^n$ up to 3.5(5.0) GeV$^2$ favor $\beta^u_v < \beta^d_v$

Input to double distribution model
$E$ for gluons and sea quarks

**sum rule** (Ji’s s.r. and momentum s.r. of DIS) at $t = \xi = 0$

$$\int_0^1 dx x e_g(x) = e_{20}^g = -\sum e_{20}^{a_v} - 2\sum e_{20}^{\bar{a}}$$

valence term very small, in particular if $\beta_v^u \leq \beta_v^d$

$\Rightarrow$ gluon and sea quark moments cancel each other almost completely

parameterization (flavor symm. sea for $E$ assumed)

$$e^i = N_i x^{-\alpha_g(0)} (1 - x)^{\beta^i}$$

and exponential $t$ dependence:

$$\propto \exp \left\{ t(\alpha'_i \ln(1/x) + b_i^e) \right\}$$

input to double distribution model for $E$

positivity bound forbids large sea $\Rightarrow$ gluon small too
Solutions for $E$ and Ji’s sum rule

\[
\langle J^a \rangle = \frac{1}{2} \left[ q_{20}^a + e_{20}^a \right] \quad \langle J^g \rangle = \frac{1}{2} \left[ g_{20} + e_{20}^g \right]
\]

$(\xi = 0)$ \quad $\langle J \rangle$ means average value of three component of $J$

<table>
<thead>
<tr>
<th>var.</th>
<th>$\beta^u_{\text{val}}$</th>
<th>$\beta^d_{\text{val}}$</th>
<th>$\beta^g$</th>
<th>$\beta^s$</th>
<th>$N_g$</th>
<th>$N_s$</th>
<th>$J^u$</th>
<th>$J^d$</th>
<th>$J^s$</th>
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<td>-</td>
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<td>0.000</td>
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<td>0.214</td>
</tr>
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<td>2</td>
<td>4</td>
<td>5.6</td>
<td>6</td>
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<tr>
<td>4</td>
<td>10</td>
<td>5</td>
<td>7</td>
<td>-</td>
<td>0.523</td>
<td>0.000</td>
<td>0.209</td>
<td>0.013</td>
<td>0.015</td>
<td>0.257</td>
</tr>
</tbody>
</table>

$J^i$ quoted at scale 4 GeV$^2$ \quad (spread indicates uncertainties of present knowledge)

$\sum J^i = 1/2$, the spin of the proton

characteristic, stable pattern: for all variants $J^u$ and $J^g$ are large, others small
Results for $A_{UT}(V)$

Goloskokov-K (08)

preliminary data: HERMES (07)

$W = 5 \text{ GeV} \quad Q^2 = 3 \text{ GeV}^2$

variant 1, 2, 3, 4

variant 1 for $\omega, \rho^+, K^{*0}$

$t$ dependence controlled by trivial factor $\sqrt{-t'}$

except for $\rho^+$: since $H_u^v - H_d^v$ small and $E_u^v - E_d^v$ large

$E$ non-negligible in cross section, contribution from helicity flip ampl. $\propto t'$

more data on $\rho^0, \omega, \phi$ from HERMES and COMPASS will come
Cross sections for $\omega$, $\rho^+$ and $K^{*0}$

results for HERMES and COMPASS ($W = 5, 10 \text{ GeV}$) $\rho^0$, $\omega$, $\rho^+$, $K^{*0}$

$W$ dependence controlled by Regge behaviour $\sigma \propto W^{4(\alpha(0) - 1)}$ at fixed $Q^2$

$\rho^0$, $\omega$: $\alpha - 1 = \delta \simeq 0.1$ diffractive (gluon + sea)

$\rho^+$: $\alpha - 1 \simeq -0.5$ $K^{*0}$ intermediate

valence quark contributions die out quickly with increasing $W$ at small $\xi$
**Exclusive electroproduction of pions**

as for vector-mesons with replacement \( H \rightarrow \tilde{H} \) and \( E \rightarrow \tilde{E} \)

for \( \pi^+ \) production: only \( \tilde{H}^{(3)} = \tilde{H}_v^u - \tilde{H}_v^d \) and \( \tilde{E}^{(3)} = \tilde{E}_v^u - \tilde{E}_v^d \) contribute

and pion pole

Mankiewicz et al (98), Vanderhaeghen et al (99), Belitsky-Mueller (01),...
leading-twist calculation with double distr. model for \( \tilde{H} \) input \( \Delta q \) and
\[
\tilde{E}_v^u = -\tilde{E}_v^d = \frac{1}{\sqrt{2}} \Theta(\bar{x} \leq \xi) \frac{\Phi_{\pi}(\tau)}{\xi} \frac{m g_{\pi NN} f_{\pi}}{m_{\pi}^2 - t} F_{\pi NN}(t)
\]
provides l.t. result for pion FF

( about 1/3 of exp. value measured in same reaction CLAS (06))
fails with cross section by order of magnitude

full pion FF needed and extra \( \tilde{E} \), see Goloskokov-K(09),Bechler-Mueller (09)
The pion pole contribution

\[ M_{0+,0+}^{\text{pole}} = -e_0 \frac{2m \xi Q}{\sqrt{1 - \xi^2}} \frac{\rho_\pi}{t - m_\pi^2}, \]

\[ M_{0-,0+}^{\text{pole}} = +e_0 Q \sqrt{-t'} \frac{\rho_\pi}{t - m_\pi^2}, \]

\[ M_{0+,\pm}^{\text{pole}} = \pm 2\sqrt{2}e_0 \xi m \sqrt{-t'} \frac{\rho_\pi}{t - m_\pi^2}, \]

\[ M_{0-,\pm}^{\text{pole}} = \pm \sqrt{2}e_0 t' \sqrt{1 - \xi^2} \frac{\rho_\pi}{t - m_\pi^2}. \]

amps. for transv. pol. photons disappear for forward scattering cross section for \( \gamma p \to \pi^+ n \) (or \( p\bar{p} \to n\bar{n} \)), should show forward dip but exhibit pronounced spike experimentally (width \( O(m_\pi^2) \))

ways out: conspirator (Phillips(67)), poor man’s absorption model (Williams(70)), Regge cuts (Rhanama-Storrow(82)), nucleon exchange (gauge invariance) modifies non-flip amplitude

\[ M_{0-,++}^{\text{pole}} \implies \sqrt{2}e_0 (t_0 - m_\pi^2) \sqrt{\frac{1 + \xi}{1 - \xi}} \frac{\rho_\pi}{t - m_\pi^2} \]

too small
Can $\mathcal{M}_{0-,++}$ be fed by ordinary GPDs?

lead. twist pion wave fct. $\propto q' \cdot \gamma \gamma_5$ (perhaps including $k_\perp$)

$\mathcal{M}_{0-,++} \propto t'$

$\mathcal{M}_{0-,++} \propto \text{const}$

helicity flip GPDs ($H_T$, $E_T$, $\tilde{H}_T$, $\tilde{E}_T$) required

Hoodbhoy-Ji (98), Diehl (01)
A twist-3 contribution

\[ \mathcal{M}^{\text{twist-3}} = e_0 \sqrt{1 - \xi^2} \int_{-1}^{1} d\bar{x} \left\{ \mathcal{H}_{0-,\mu^+} \left[ H_T^{(3)} - \frac{\xi}{1 - \xi^2} (\xi E_T^{(3)} - \tilde{E}_T^{(3)}) \right] \right\} + \mathcal{O} \left( \frac{t'}{m^2} \right) \]

\[ \mathcal{M}^{\text{twist-3}} \propto t' \]

(3-part. contr. neglected: \( \tau \Phi_P = \Phi_\sigma/N_c - \tau \Phi'_\sigma/(2N_c) \))

solution: \( \Phi_P = 1, \Phi_\sigma = \Phi_{AS} \) (Braun-Halperin (90))

\[ \sim q' \cdot \gamma_5 \Phi + \mu_\pi \gamma_5 \left[ \Phi_P - i\sigma_{\mu\nu} (\ldots \Phi'_\sigma + \ldots \Phi_\sigma \partial/\partial k_{\perp\nu}) \right] \]

Beneke-Feldmann (01)

\( \mathcal{H}_{0-,++} \neq 0, \Phi_P \) dominant, \( \Phi_\sigma \) contr. \( \propto t'/Q^2 \)

\( \mu_\pi = m_\pi^2/(m_u + m_d) \simeq 2 \text{ GeV at scale } 2 \text{ GeV} \)

in coll. appr.: \( \mathcal{H}_{0-,++} \) infr. sing. and double pole \( 1/(x - \xi)^2 \) m.p.a. regular

small \( \xi \): \( H_T \) should dominate; take transversity PDF from Anselmino et al (07)

\[ \delta^a = 7.46 N_T^a (1 - x)^5 [q(x) + \Delta q(x)] \]

\( N_T^u = 0.5 \quad N_T^d = -0.6 \)

input to double distr. ansatz
Results on unseparated $\pi^+$ cross section

data from HERMES 07
magenta lines: pion pole contr. (unseparated and transverse cross sections)
new data on $F_{\pi\gamma}$ may change our understanding of pion DA
Target asymmetries in electroproduction

<table>
<thead>
<tr>
<th>observable</th>
<th>dominant interf. term</th>
<th>( \gamma^* p \rightarrow MB ) amplitudes</th>
<th>low ( t' ) behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_{UT} \sin(\phi - \phi_s) )</td>
<td>LL</td>
<td>( \text{Im} [M_{0-}^* 0+, 0+] )</td>
<td>( \propto \sqrt{-t'} )</td>
</tr>
<tr>
<td>( A_{UT} \sin(\phi_s) )</td>
<td>LT</td>
<td>( \text{Im} [M_{0-}^* 0+, 0+] )</td>
<td>const.</td>
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<tr>
<td>( A_{UT} \sin(2\phi - \phi_s) )</td>
<td>LT</td>
<td>( \text{Im} [M_{0-}^* 0+, 0+] )</td>
<td>( \propto t' )</td>
</tr>
<tr>
<td>( A_{UT} \sin(\phi + \phi_s) )</td>
<td>TT</td>
<td>( \text{Im} [M_{0-}^* 0+, 0+] )</td>
<td>( \propto \sqrt{-t'} )</td>
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<td>( A_{UT} \sin(2\phi + \phi_s) )</td>
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<tr>
<td>( A_{UT} \sin(3\phi - \phi_s) )</td>
<td>TT</td>
<td>( \text{Im} [M_{0-}^* 0+, 0+] )</td>
<td>( \propto (-t')^{3/2} )</td>
</tr>
<tr>
<td>( A_{UL} \sin(\phi) )</td>
<td>LT</td>
<td>( \text{Im} [M_{0-}^* 0+, 0+] )</td>
<td>( \propto \sqrt{-t'} )</td>
</tr>
</tbody>
</table>

\( \phi \) azimuthal angle between lepton and hadron plane; \( \phi_s \) orientation of target spin vector; \( \theta_\gamma \) rotation from direction of incoming lepton to virtual photon one

Holds for vector and pseudoscalar mesons. Detailed info. on amplitudes

\( \pi^+ \): all measured; \( \rho^0, \phi \): only \( \sin(\phi - \phi_s) \) asymmetry; for \( \omega \) all (prel.)
Results on target asymmetries

Goloskokov-K (09)

\[ Q^2 = 2.5 \text{ GeV}^2 \]
\[ W = 3.99 \text{ GeV} \]

prel. data on \( A_{UT} \) HERMES (08); \( A_{UL} \) HERMES(02)

upper (lower) blue: without twist-3 contr. (only LL)

other asym.: \(|A_{UT}| < 0.1\) agree with exp.
**Summary of GPDs**

**INPUT:** NLO CTEQ6M at scale 4 GeV$^2$ \( t = 0 \)

\( H^g \) dominant at small and intermediate \( x \)
other look similar but probably valence quark dominated
(\( \Delta g \simeq 0 \), sum rule and positivity bound for \( E^g, \tilde{E}^g \)?)
\( H^u_v, H^d_v \) same sign, for other GPDs opposite signs
What is probed by experiments:

imaginary parts $\propto$ GPDs at $\xi = x$

real parts - convolutions, dominated by $x$ near $\xi$ (see also disp. rel.)

$\xi \approx 10^{-3}$ HERA
$\approx 10^{-2}$ COMPASS
$\approx 10^{-1}$ HERMES
$\approx 0.1 - 0.4$ JLab

$x \geq 0.6$ not probed

large $x$ region important

$\gamma$ production: valence + sea (to LO)

$\rho^0, \omega$: gluon+sea+valence

$\phi$: gluon +sea

$J/\Psi$: gluon

$\rho^+, \pi^+$: valence
Summary

- phenomenology of DVME within the handbag approach is complicated, many GPDs contribute, extension to large $\xi$ still to be done
- GPDs modeled through reggeized double distributions and subprocess calculated within mod. pert. approach few free parameters ($a_V$)
- fair agreement with cross section data for vector mesons at small $\xi$ for $Q^2 \simeq 3\ldots100$ GeV$^2$, $W \simeq 5\ldots180$ GeV (only $H$ matters)
- $E$ constructed with the help of Pauli FF, sum rules and positivity bounds
- data on $A_{UT}$ will fix $E$ and hence details on parton angular momenta better
- first attempts to understand $\pi^+$ electroproduction, is complicated required are GPDs $\tilde{H}$ and $\tilde{E}$, pion exchange and a twist-3 effect for transversely pol. photons (helicity-flip GPD $H_T$ and twist-3 pion wave fct.)