GPDs from exclusive meson leptoproduction

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Outline:

- **Exclusive processes, GPDs, parametrizations**
- **What did we learn about GPDs?**
- **Transverse target asymmetries for DVCS**
- π^0 **cross section and/or** η/π^0 **cross section ratio**
- **Beam spin asymmetry for** π **production**
- **Summary**

Hard exclusive scattering - GPDs

DVCS and meson electroproduction

rigorous proofs of collinear factorization in generalized Bjorken regime:

Radyushkin, Collins et al, Ji et al $(Q^2, W \to \infty,\ x_{Bj}$ fixed)

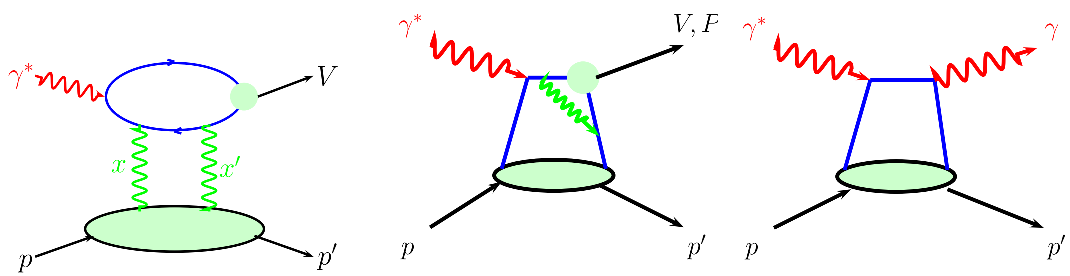
possible power corrections not under control $\Longrightarrow$

unknown at which Q^2 asymptotic result can be applied

hard subprocesses

$\gamma^* g \to V g\,,$

$\gamma^* q \to V(P,\gamma) q$



and GPDs and meson w.f.

(encode the soft physics)

$$\langle K \rangle = \int_{-1}^{1} d\bar{x}\, \mathcal{H}(\bar{x},\xi,t) K(\bar{x},\xi,t)$$

dominant transitions $\gamma_L^* \to V_L(P)$, $\gamma_T^* \to \gamma_T$

other transitions power suppressed but often non-negligible (e.g. $\gamma_T^* \to V_T, \pi^+$)

GPDs

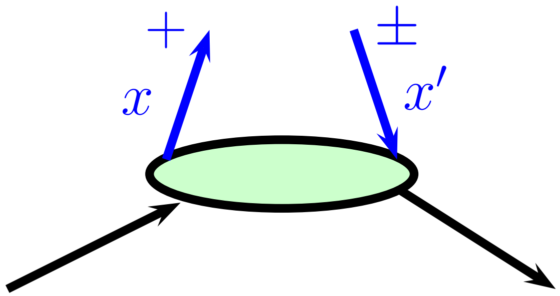
D. Müller et al (94), Ji(97), Radyushkin (97)

GPDs: $K = K(\bar{x}, \xi, t)$ $\quad x = \frac{\bar{x}+\xi}{1+\xi}$ $\quad x' = \frac{\bar{x}-\xi}{1-\xi}$

defined by FT of $\langle p'|\bar{\Psi}(-z/2)\Gamma\Psi(z/2)|p\rangle$

$\Gamma = \gamma^+, \gamma^+\gamma_5$ $\qquad K = H, E, \widetilde{H}, \widetilde{E}$ (non-flip)

$\quad = \sigma^{+j}$ $\qquad H_T, E_T, \widetilde{H}_T, \widetilde{E}_T$ (flip)



for quarks ($\xi < \bar{x} < 1$) and gluons

(antiquarks for $-1 < \bar{x} < -\xi$, $q\bar{q}$ pairs $-\xi < \bar{x} < \xi$)

reduction formula $H^q(\bar{x}, \xi = t = 0) = q(\bar{x})$, $\widetilde{H}^q \to \Delta q(\bar{x})$, $H_T^q \to \delta^q(\bar{x})$

sum rules (proton form factors): $F_1^q(t) = \int d\bar{x} H^q(\bar{x}, \xi, t)$, $F_1 = \sum e_q F_1^q$

$E \to F_2$, $\widetilde{H} \to F_A$, $\widetilde{E} \to F_P$

polynomiality, universality, evolution, positivity constraints

Ji's sum rule $\quad J_q = \frac{1}{2}\int_{-1}^{1} d\bar{x}\, \bar{x}\, [H^q(\bar{x}, \xi, t = 0) + E^q(\bar{x}, \xi, t = 0)]$

Parameterizing the GPDs

needed in order to extract GPDs from data

double distribution ansatz (Mueller *et al* (94), Radyushkin (99))

$$K_i(\bar{x},\xi,t) = \int_{-1}^{1} d\rho \int_{-1+|\rho|}^{1-|\rho|} d\eta\, \delta(\beta+\xi\alpha-\bar{x})\, K_i(\rho,\xi=0,t) w_i(\rho,\eta) + D_i\, \Theta(\xi^2-\bar{x}^2)$$

DD: zero-skewness GPD $\times$ weight fct w_i (generates ξ dep.)

$K_i(\rho,\xi=0,t) = k_i(\rho)\exp\left[(b_i+\alpha_i'\ln(1/\rho))t\right]$

$k_i = q, \Delta q, \delta^q$ for $H, \widetilde{H}, H_T$ or $c\bar{x}^{-\alpha_f(0)}(1-\bar{x})^{\beta_f}$ for $E, \widetilde{E}, \bar{E}_T$

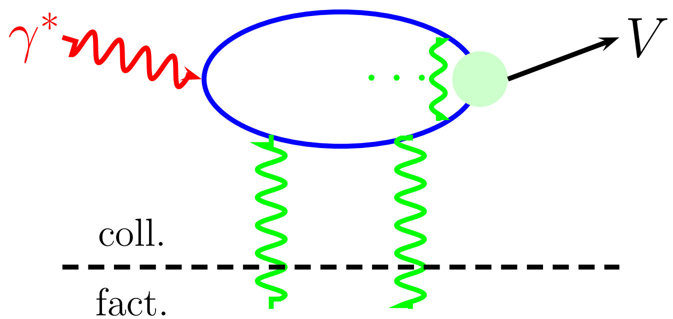
Regge-like t dep. (for small ξ and small $-t$ reasonable appr.)

advantage: polynomiality and reduction formulas automatically satisfied

D-term neglected

The subprocess amplitude for DVMP

mod. pert. approach - quark trans. momenta in subprocess
(emission and absorption of partons from proton collinear to proton momenta)
transverse separation of color sources $\Longrightarrow$ gluon radiation
(Sudakov factor Sterman et al(93))



LO pQCD
+ quark trans. mom.
+ Sudakov supp.
$\Rightarrow$ asymp. fact. formula (lead. twist)
for $Q^2 \to \infty$

gluon part bears similarity to color dipole model

What has been done?

- analysis of FF (Diehl et al, (04), update: Diehl-K 1302.4604)
  using ABM11 PDFs, fixes $H, E, (\widetilde{H})$ for valence quarks
- analysis of $d\sigma_L/dt$ for ρ^0 and ϕ production Goloskokov-K, hep-ph/0611290
  for $Q^2 \gtrsim 3\,\mathrm{GeV}^2$ and $W \gtrsim 4\,\mathrm{GeV}$ ($\xi \lesssim 0.1,\ -t \lesssim 0.5\,\mathrm{GeV}^2$)
  data from H1, ZEUS, E665, HERMES
  fixes H for sea quarks and gluons for given H^{val} (E negligible)
  update with ABM11 required
- analysis of π^+ production, Goloskokov-K, 0906.0460
  $d\sigma/dt$ and A_{UT} data from HERMES
  evidence for strong contr. from γ_T^* (H_T)
  fixes $\widetilde{H}$, pion pole and H_T (no clear signal for $\widetilde{E}_{\mathrm{non-pole}}$)
- SDME and A_{UT} for ρ^0 production,
  π^0 cross section and η/π^0 from CLAS (large skewness!),
  lattice QCD QCDSF and UKQCD, hep-lat/0612032
  hints at strong contributions from $\bar{E}_T = 2\widetilde{H}_T + E_T$ needs confirmation

Applications

our set of GPDs allows for parameter free calculations of other hard exclusive reactions

- $\gamma^* p \to \omega p$ Goloskokov-K, 1407.1141
  compared to SDMEs from HERMES(14) good agreement
  prominent role of pion pole

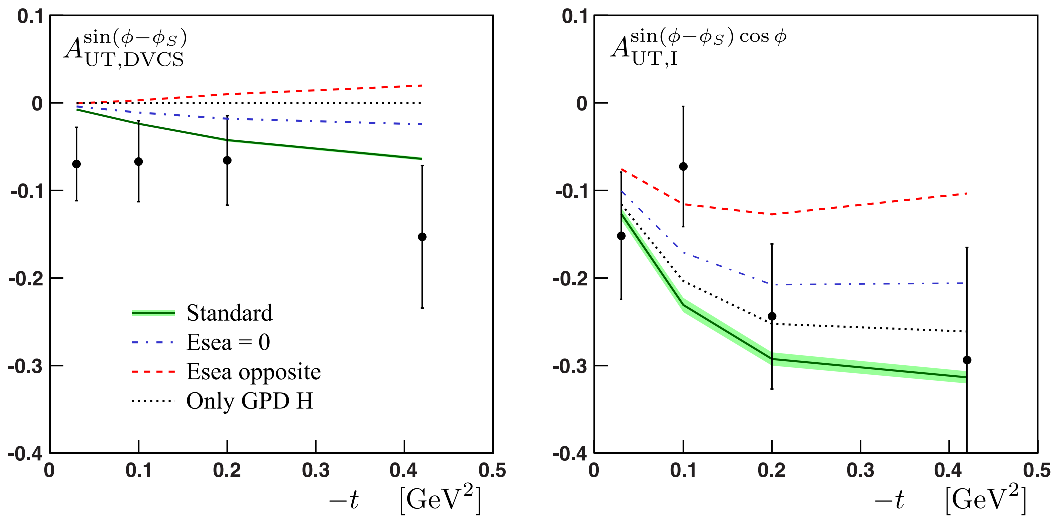
- DVCS K-Moutarde-Sabatie, 1210.6975
  compared to data from Jlab, HERMES,H1,ZEUS
  good agreement with small skewness data
  less good agreement with Jlab data

What future data from HERA and HERMES

will provide additional constraints and tests

of this set of GPDs?

Target asymmetry in DVCS



data: HERMES 06

$\langle Q^2 \rangle \simeq 2.7\,\mathrm{GeV}^2$

$\langle x_{\mathrm{B}} \rangle \simeq 0.1$

K.-Moutarde-Sabatie

$$A_{UT,DVCS}^{\sin(\phi-\phi_s)} \sim \mathrm{Im}\Big[\langle E\rangle^* \langle H\rangle\Big] \qquad\qquad A_{UT,I} \sim \mathrm{BH-DVCS\ interference}$$

negative $\langle E^s \rangle$ favored

(flavor symmetric sea for E assumed)

E^s restricted by positivity bound for FT of zero-skewness GPDs Burkardt

$(\vec{\Delta}_\perp \to \vec{b}_\perp;\, t = -\Delta_\perp^2)$ $\qquad \frac{b_\perp^2}{m^2}\left(\frac{\partial e_s(\bar{x},\vec{b}_\perp)}{\partial b_\perp^2}\right)^2 \leq s^2(\bar{x},\vec{b}_\perp) - \Delta s^2(\bar{x},\vec{b}_\perp)$

Parton angular momenta

Ji's sum rule (for $\xi = 0$, $t = 0$): $(q = u, \bar{u}, d, \ldots)$

$$J^q = \frac{1}{2}\left[q_{20} + e^q_{20}\right] \qquad J^g = \frac{1}{2}\left[g_{20} + e^g_{20}\right]$$

$q_{20}(= \int_0^1 dx x q(x))$, g_{20} from ABM11

e_{20} for valence quarks from form factor analysis

$e^s_{20} = 0 \div -0.026$ (from A_{UT} for DVCS and saturation of positivity bound)

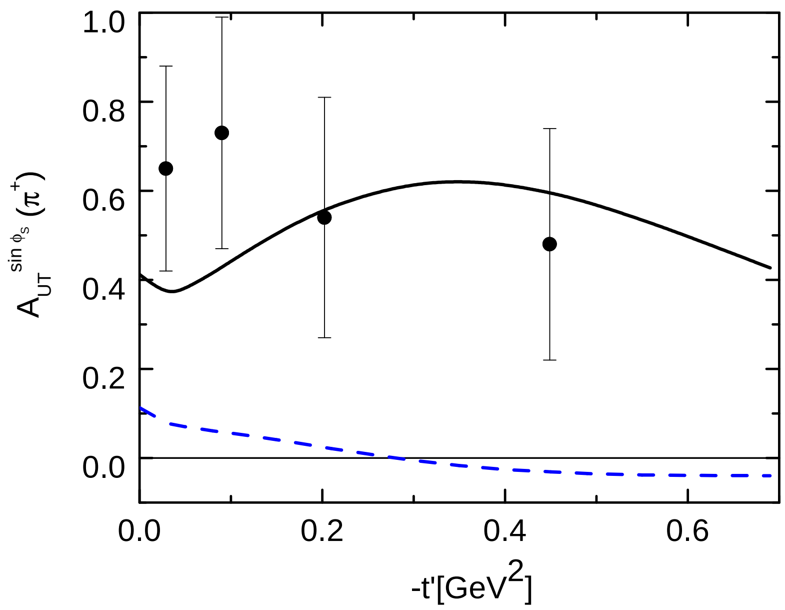
e^g_{20} from sum rule: $e^g_{20} = -\sum e^{q_v}_{20} - 2\sum e^{\bar{q}}_{20}$

$$\begin{aligned} J^{u+\bar{u}} &= 0.261 \div 0.235 \qquad & J^{s+\bar{s}} &= 0.017 \div -0.009 \\ J^{d+\bar{d}} &= 0.035 \div 0.009 \qquad & J^g &= 0.187 \div 0.265 \end{aligned}$$

at scale $2\,\mathrm{GeV}$ uncertainties due to E^s (l.h.s. $e^s_{20} = 0$, r.h.s. $e^s_{20} = -0.026$)

need for smaller errors of A_{UT} for DVCS

Transversity GPDs



HERMES(09) π^+

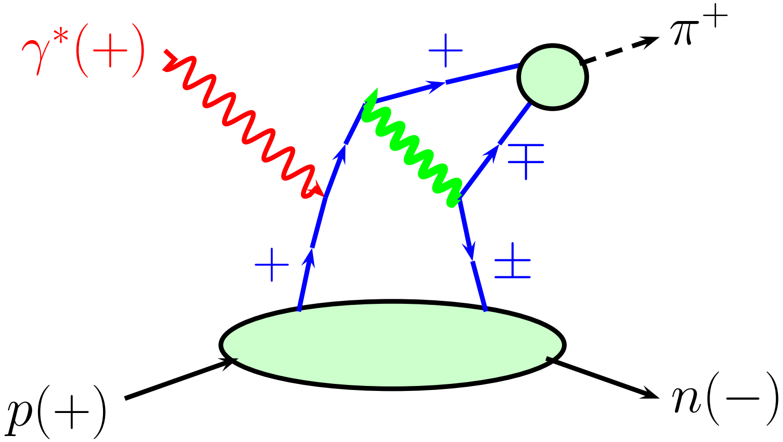
$Q^2 \simeq 2.5\,\mathrm{GeV}^2$, $W = 3.99\,\mathrm{GeV}$

ϕ_s orientation of target spin vector

large, does not vanish for $t' \to 0$

$$A_{UT}^{\sin\phi_S} \sim \mathrm{Im}\Big[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,0+}\Big]$$

large n-f. ampl. $\mathcal{M}_{0-,++}$ required, non-vanishing in forward direction



usual GPDs: $\mathcal{M}_{0-,++} \sim t'$

transversity GPDs: $\mathcal{M}_{0-,++} \to \mathrm{c}$

go along with twist-3 pion w.f.

suppressed by μ_π/Q

as compared to leading-twist ampl.

$\mu_\pi = m_\pi^2/(m_u + m_d) \simeq 2\,\mathrm{GeV}$

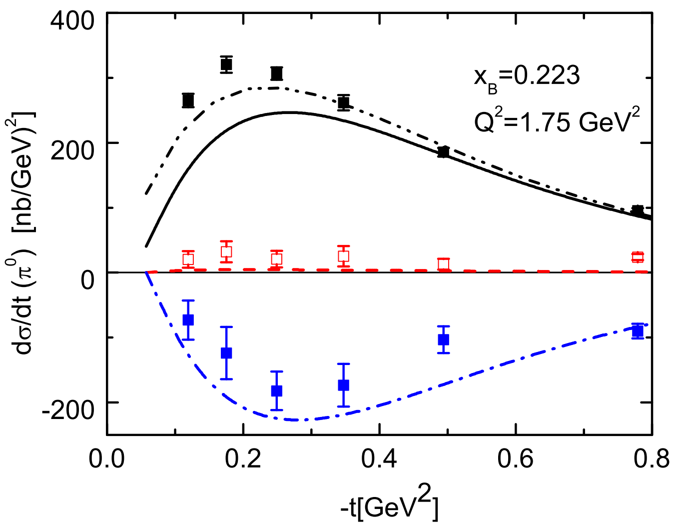
at scale $2\,\mathrm{GeV}$ (Braun-Filianov (90))

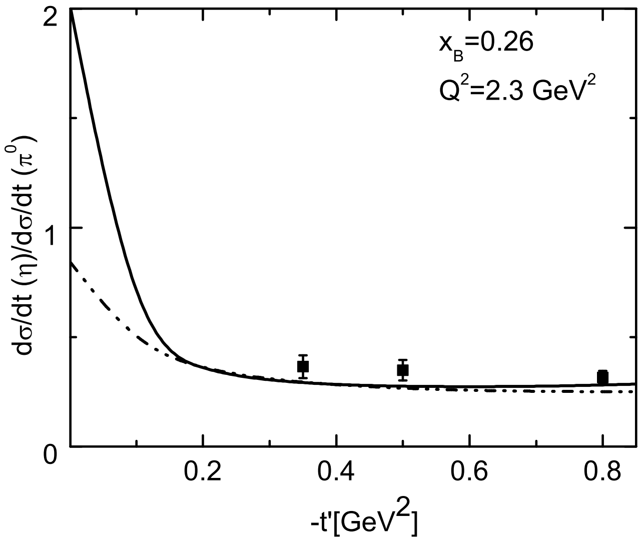
$$\mathcal{M}_{0-,++} = e_0\sqrt{1-\xi^2}\int d\bar{x}\mathcal{H}^{\mathrm{twist-3}}_{0-,++}H_T \quad \mathcal{M}_{0+,\pm+} = -e_0\frac{\sqrt{-t'}}{2m}\int d\bar{x}\mathcal{H}^{\mathrm{twist-3}}_{0-,++}\bar{E}_T$$

H_T constrained by δ_q (Anselmino et al(09)) or lattice QCD

$\bar{E}_T$ constrained by lattice QCD QCDSF-UKQCD

CLAS data on π^0 cross section and η/π^0 ratio





estimates, not fits (large skewness, small W) $\widetilde{H}$ contribution only about 10%

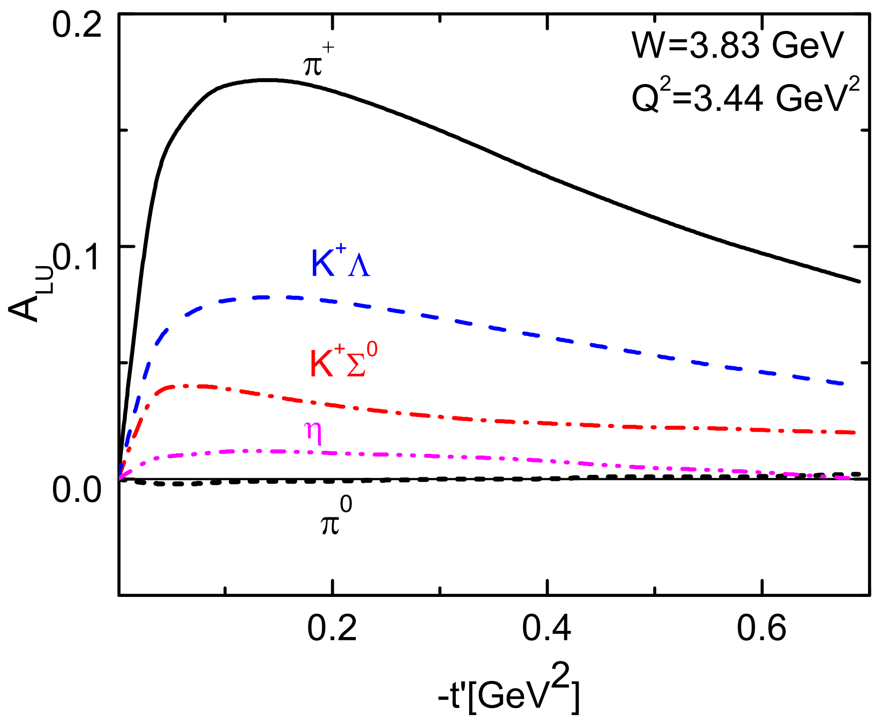
$$\frac{d\sigma(\eta)}{d\sigma(\pi^0)} \simeq \left| \frac{\langle e_u K^u + e_d K^d \rangle_\eta}{\langle e_u K^u - e_d K^d \rangle_{\pi^0}} \right|^2$$

$\widetilde{H}^u, H_T$ opposite sign for u and d quarks, $\bar{E}_T$ same sign

η/π^0 ratio larger than 1 less than 1

small skewness data would confirm this interpretation and allow to learn more about the transversity GPDs

The beam spin asymmetry for π production



Goloskokov-K, 1106.4897

$$A_{LU} \sim \mathrm{Im}\Big[\big(\mathcal{M}^*_{0+,++} - \mathcal{M}^*_{0+,-+}\big)\mathcal{M}_{0+,0+} + \big(\mathcal{M}^*_{0-,++} - \mathcal{M}^*_{0-,-+}\big)\mathcal{M}_{0-,0+}\Big]$$

if H_T and $\bar{E}_T$ are the dominant transversity GPDs:

$$A_{LU} \sim \mathrm{Im}\Big[\mathcal{M}^*_{0-,++}\mathcal{M}_{0-,0+}\Big] \sim \mathrm{Im}\Big[\langle H_T\rangle^*\langle\widetilde{E}\rangle\Big]$$

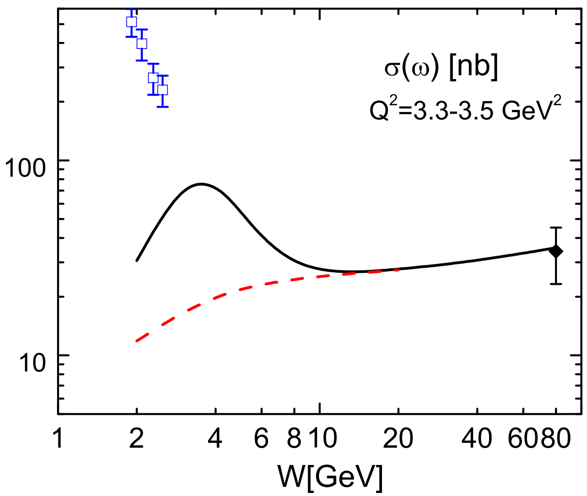
additional information on H_T and, for π^0, on $\widetilde{E}_{\mathrm{non-pole}}$

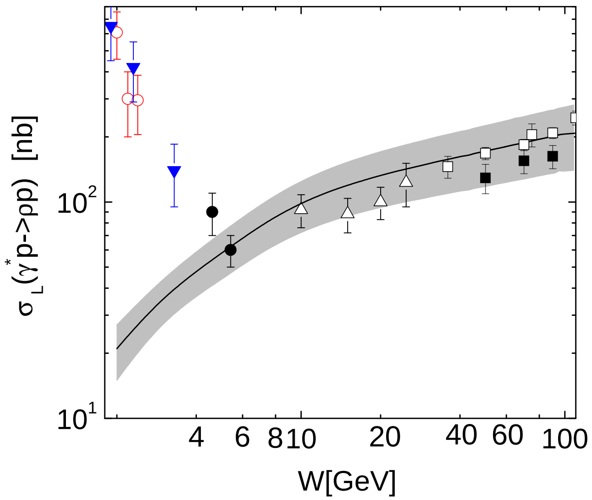
Summary

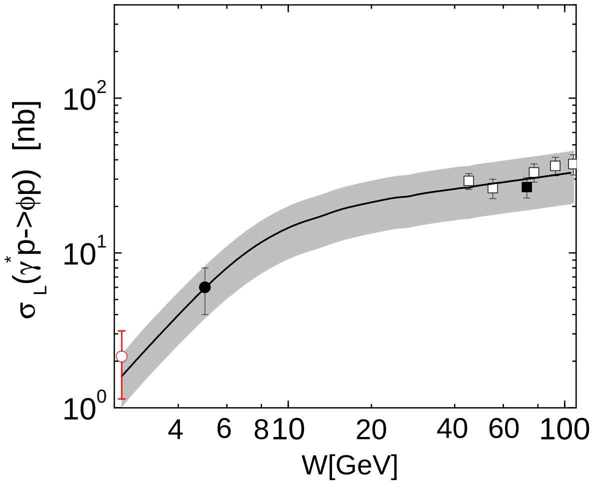
- more accurate data on A_{UT} for DVCS and data on π^0 leptoproduction as well as the η/π^0 ratio would help fo fix $E^{\rm sea}$ and the transversity GPDs
- of interest are also data on
  $A_{UL}(\pi)$: $\bar{E}_T$ important
  any information on strangness production, e.g
  $A_{UT}(K^+\Lambda, K^+\Sigma)$: sensitive to H_T^s
  $\sigma(\omega)$: may answer question whether $H^{\bar{u}} = H^{\bar{d}}$ or not

BACK-UP

The ω cross section







at $Q^2 = 3.5\,\mathrm{GeV}^2$ $\qquad$ $4\,\mathrm{GeV}^2$ $\qquad$ $3.8\,\mathrm{GeV}^2$

data from H1, ZEUS, E665, HERMES, CORNELL, CLAS

Goloskokov-K, hep-ph/0611290, 1407.1141

decreasing W at fixed $Q^2 \Longrightarrow$ increasing x_B, ξ and $-t_0 = 4m^2\xi^2/(1-\xi^2)$

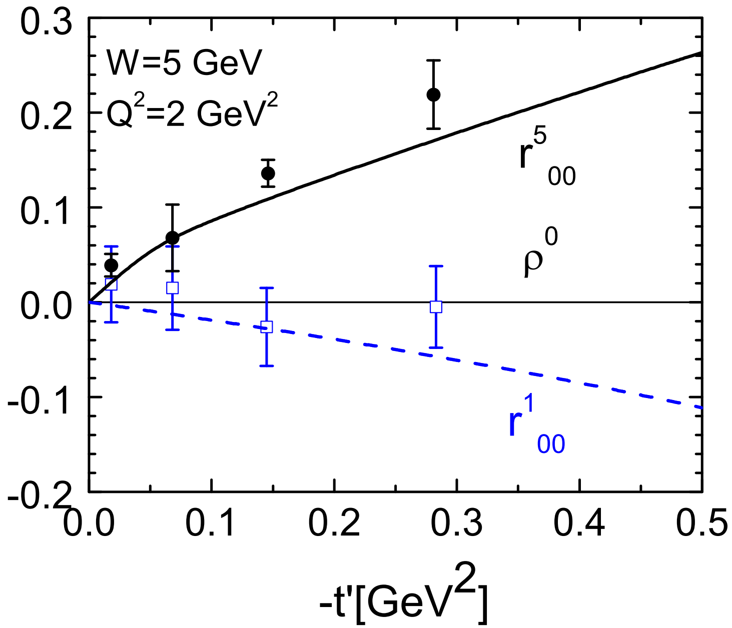
Handbag: GPDs decrease with increasing $-t$, decrease of c.s. related to $-t_0$

large ρ^0, ω cross sections at low W not understood, probably not hard physics

$\sigma \sim |gluon + sea|^2$: $\qquad$ $\sigma(\omega)/\sigma(\rho^0) = 1/9$ for $H^{\bar{u}} = H^{\bar{d}}$ $\qquad$ true?

(up to wave function effects, e.g. $f_\rho = 209$ MeV, $f_\omega = 187$ MeV)

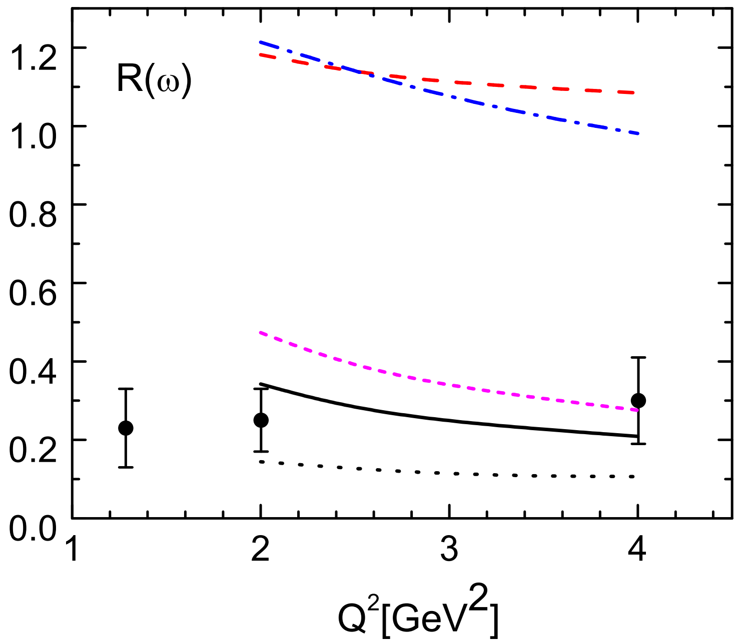
$\bar{E}_T$ in ρ^0 production



$$r^1_{00} \sim -|\langle \bar{E}_T \rangle|^2 \qquad\qquad r^5_{00} \sim \mathrm{Re}\Big[\langle \bar{E}_T \rangle^* \langle H \rangle\Big]$$

Goloskokov-K. 1310.1472

ω production



data from HERMES 1407.2119

$W = 4.8\,\text{GeV}$, $t' = -0.08\,\text{GeV}^2$

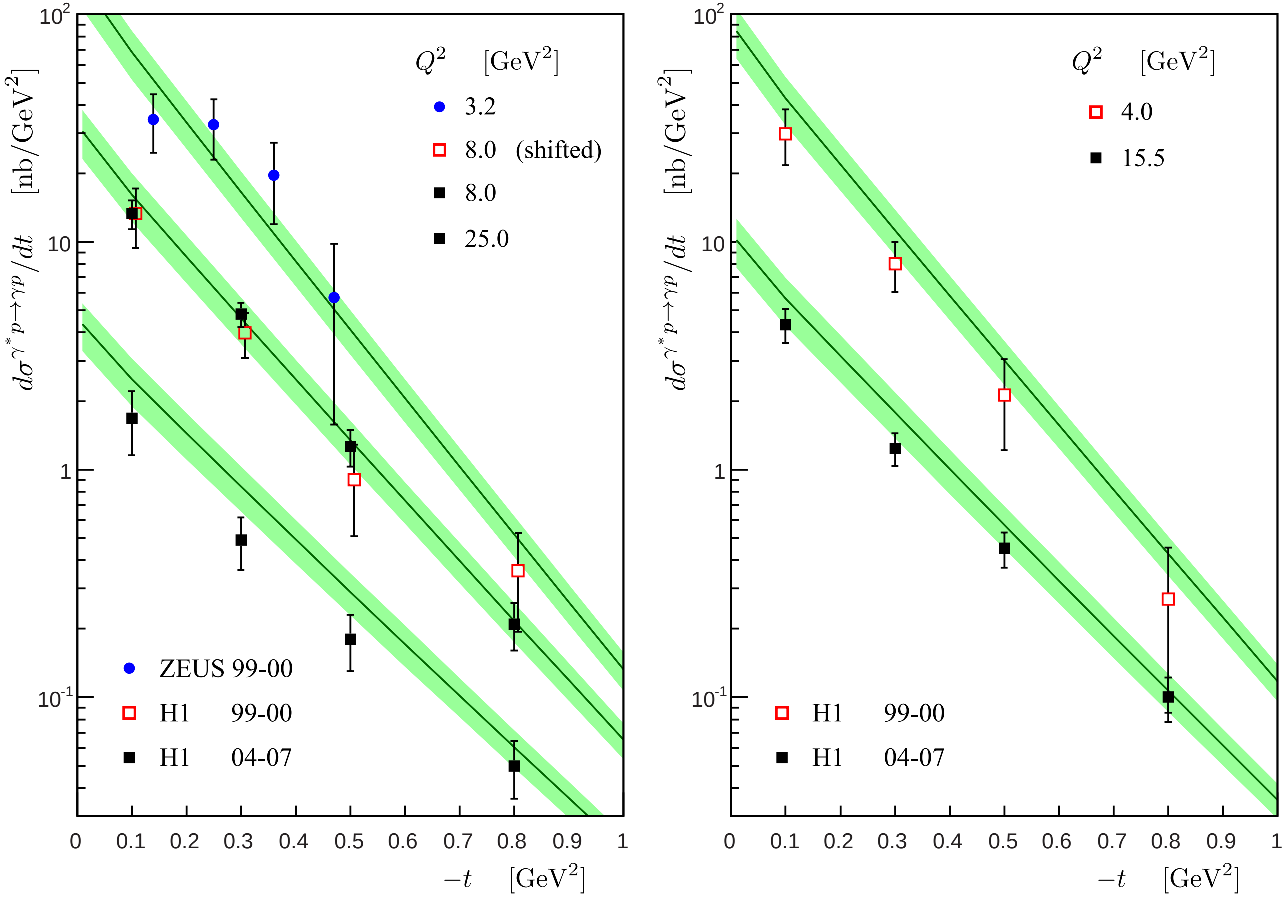
Goloskokov-K, 1407.1141

$R = \frac{1}{\varepsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}} = d\sigma(\omega_L)/d\sigma(\omega_T)$ (full result: black line)

red line: without pion pole, magenta line: $R = d\sigma_L/d\sigma_T$

blue (dotted) line: predictions at $W = 8(3.5)\,\text{GeV}$

DVCS predictions



K-Moutarde-Sabatie, 1210.6975