GPDs from meson electroproduction

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Outline:

- **Exclusive processes, handbag, GPDs and power corrections**
- **Analysis of meson electroproduction**
- **DVCS**
- **The GPD E**
- **The GPDs $\widetilde{H}$ and $\widetilde{E}$**
- **Summary: improving the GPDs; what new data?**

Can we apply the asymp. fact. formula ?

rigorous proofs of collinear factorization in generalized Bjorken regime:
for $\gamma_L^* \to V_L(P)$ and $\gamma_T^* \to \gamma_T$ amplitudes $\big(Q^2, W \to \infty$, x_{Bj} fixed$\big)$

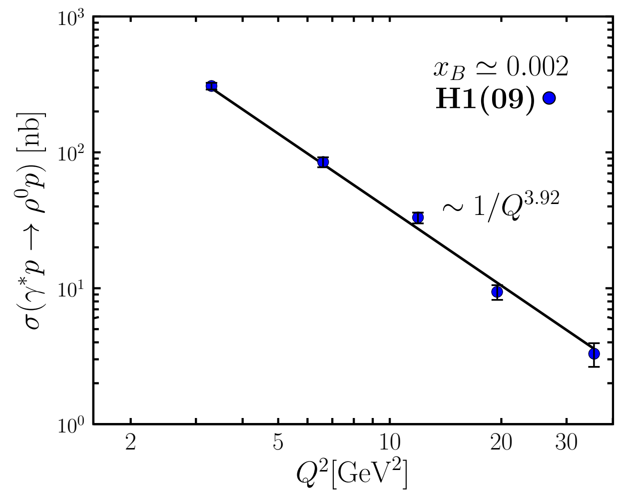
Radyushkin, Collins et al, Ji-Osborne

possible power corrections not under control $\Longrightarrow$
unknown at which Q^2 asymptotic result can be applied

e.g. ρ^0 production: $\sigma_L/\sigma_T \propto Q^2$
experiment: $\simeq 2$ for $Q^2 \leq 10\,\mathrm{GeV}^2$
$\gamma_T^* \to V_T$ transitions substantial

$\sigma_L \propto 1/Q^6$ at fixed x_B
modified by $ln^n(Q^2)$

experiment:



Two concepts to solve problem with $\gamma_L^* \to V_L$ ampl.:

at small x_B only GPD H relevant

Mueller et al (1112.2597,1312.5493): absorb effects into GPDs

$\Longrightarrow$ strong $\ln^n(Q^2)$ from evolution of GPDs

only shown for HERA data with $H^{g,sea}$ (i.e. at $W \simeq 90\,\mathrm{GeV}$)

- can it be extended to lower W?

fits to only DVCS or to DVCS+DVMP data from HERA lead to different GPDs

Goloskokov-K (hep-ph/0611290): take into account transverse size of meson,

i.e. power corrections $1/Q^n$ to subprocess $\gamma_L^* q(g) \to V_L\, q(g)$

H for gluon, sea and valence

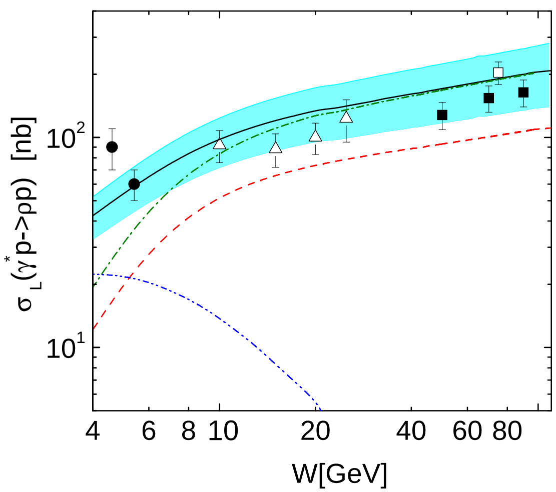
$W \geq 4\,\mathrm{GeV}$

GK hep-ph/0611290 $Q^2 = 4\,\mathrm{GeV}^2$

gluon + sea, gluon

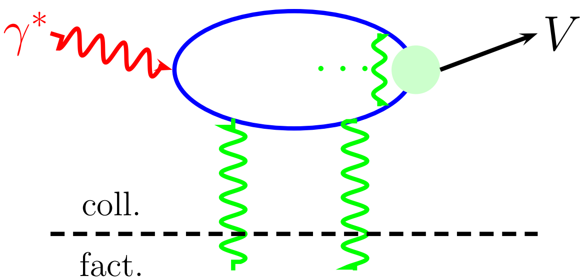
(gluon + sea)-valence + valence

Errors: CTEQ6 errors and other PDFs



The subprocess amplitude for DVMP

Goloskokov-K. (06) 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



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

resummed gluon radiation to NLL
Sudakov factor Sterman et al(93)

$$S(\tau, \mathbf{b}, Q^2) \propto \ln \frac{\ln(\tau Q/\sqrt{2}\Lambda_{\rm QCD})}{-\ln(b\Lambda_{\rm QCD})} + \text{NLL}$$

provides rather sharp cut-off at $b = 1/\Lambda_{\rm QCD}$

$$\mathcal{H}^M_{0\lambda,0\lambda} = \int d\tau d^2b\, \hat\Psi_M(\tau, -\vec b)\, e^{-S}\, \hat{\mathcal{F}}_{0\lambda,0\lambda}(\bar x, \xi, \tau, Q^2, \vec b)$$

$\hat\Psi_M \sim \exp[\tau\bar\tau b^2/4a_M^2]$ LC wave fct of meson
$\hat{\mathcal{F}}$ FT of hard scattering kernel
e.g. $\propto 1/[k_\perp^2 + \tau(\bar x + \xi)Q^2/(2\xi)] \Rightarrow$ Bessel fct

Sudakov factor generates series of power corr. $\sim (\Lambda^2_{\rm QCD}/Q^2)^n$
(from region of soft quark momenta $\tau, \bar\tau \to 0$)
from intrinsic transv. momenta (wave fct) series $\sim (\langle k_\perp^2\rangle/Q^2)^n$ (from all τ)

Parametrizing the GPDs

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

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

weight fct $w_i(\rho,\eta) \sim [(1-|\rho|)^2-\eta^2]^{n_i}$ $(n_g = n_{\rm sea} = 2, n_{\rm val} = 1$, generates ξ dep.)

zero-skewness GPD $K^i(\rho,\xi=0,t) = k^i(\rho)\exp\left[(b_{ki}+\alpha'_{ki}\ln(1/\rho))t\right]$

$k = q, \Delta q, \delta^q$ for $H, \widetilde{H}, H_T$ or $N_{ki}\rho^{-\alpha_{ki}(0)}(1-\rho)^{\beta_{ki}}$ for $E, \widetilde{E}, \bar{E}_T$

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

advantages: polynomiality and reduction formulas automatically satisfied

$H_{\rm val}$, $E_{\rm val}$ and $\widetilde{H}_{\rm val}$ from analysis of form factors (sum rules)

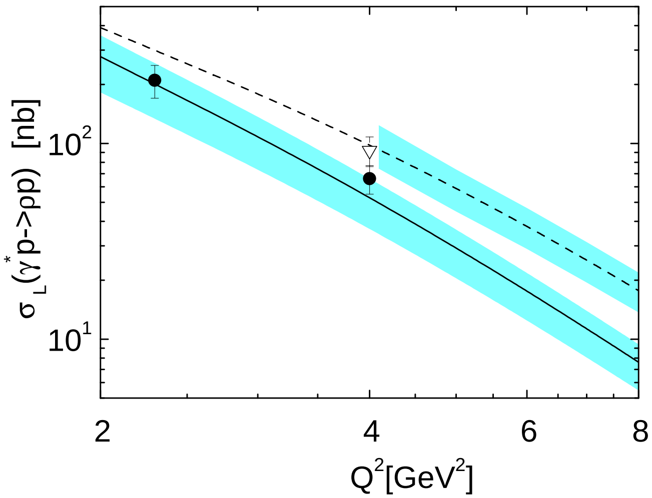
positivity bounds respected DFJK(04), Diehl-K (13)

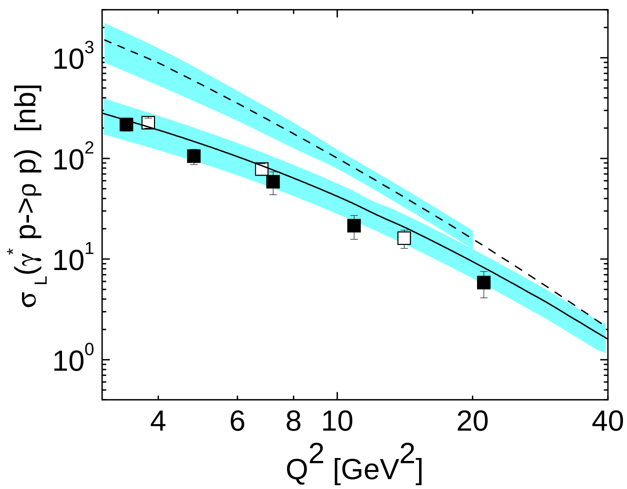
D-term neglected

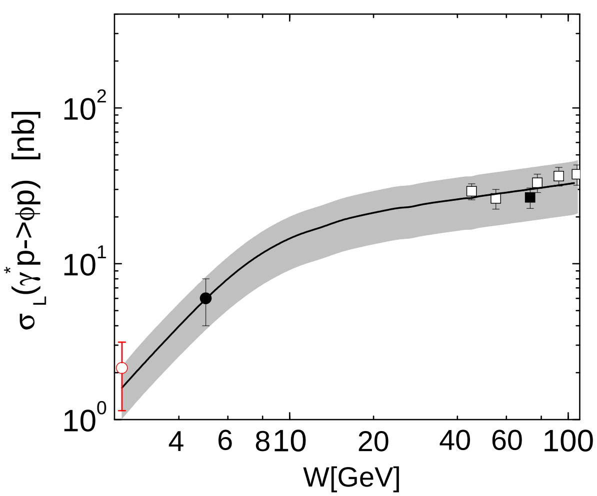
Extraction of the GPD H

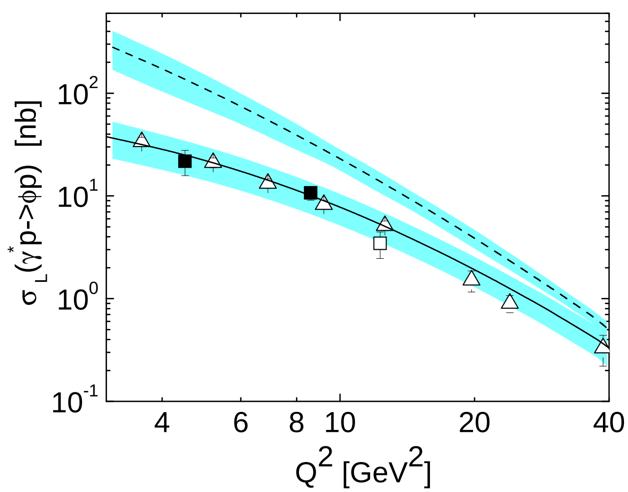
long. cross sections fix H; constrained by PDFs and Dirac FF GK(06)

fit to available data for $Q^2 \simeq 3 - 100\,\mathrm{GeV}^2$, $W \simeq 4 - 180\,\mathrm{GeV}$, small ξ and $-t$









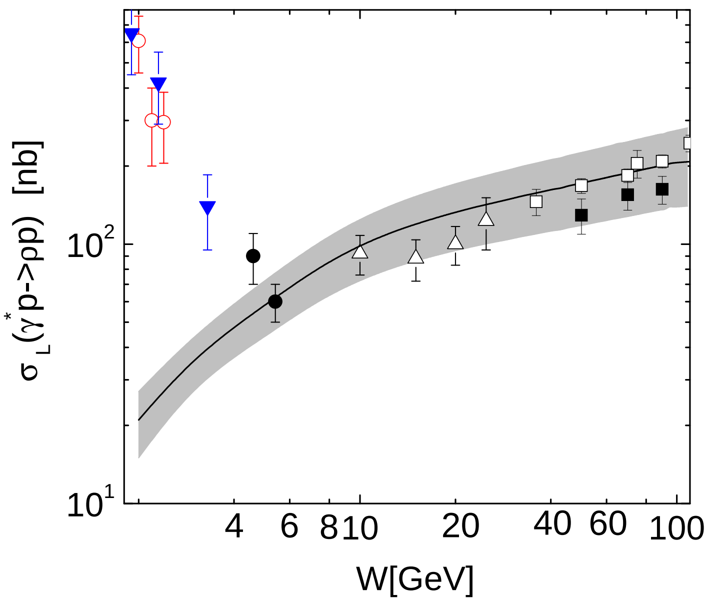
dashed lines:
asymp. formula

right:
$W = 75\,\mathrm{GeV}$
H1, ZEUS

left:
$W = 5(10)\,\mathrm{GeV}$
HERMES (E665)

$Q^2 = 3.8\,\mathrm{GeV}^2$
CLAS, HERMES, HERA

Why restriction to small skewness data?



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

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

breakdown of handbag physics?

at large $x_{\rm Bj}$ (small W)

- power corrections are strong at least in some cases
- kinematic corrections strong, e.g.

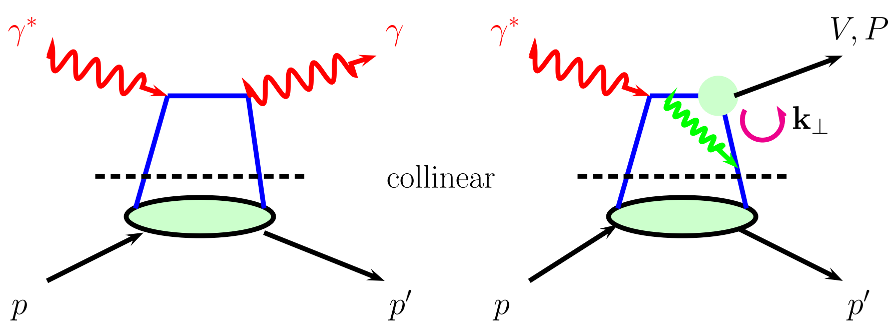
$$\xi \simeq \frac{x_{\rm Bj}}{2-x_{\rm Bj}}\Big[1 + \frac{1}{(1-x_{\rm Bj}/2)Q^2}(m_M^2 - x_{\rm Bj}^2 m^2 - x_{\rm Bj}(1-x_{\rm Bj})t')\Big]$$

- double distribution ansatz close to other parameterizations
- GPD parameterization can be applied to large skewness region but success is not guaranteed

DVCS

Exploiting universality: applying a given set of GPDs determined either from DVCS or meson electroproduction to the other process predictions

K.-Moutarde-Sabatié (13): use GK GPDs to predict DVCS to leading-twist, LO accuracy (collinear for consistency)



reasonable agreement with HERMES, H1 and ZEUS data
less satisfactory description of Jlab data
(large skewness, small W)

NLO: gluon GPDs contribute

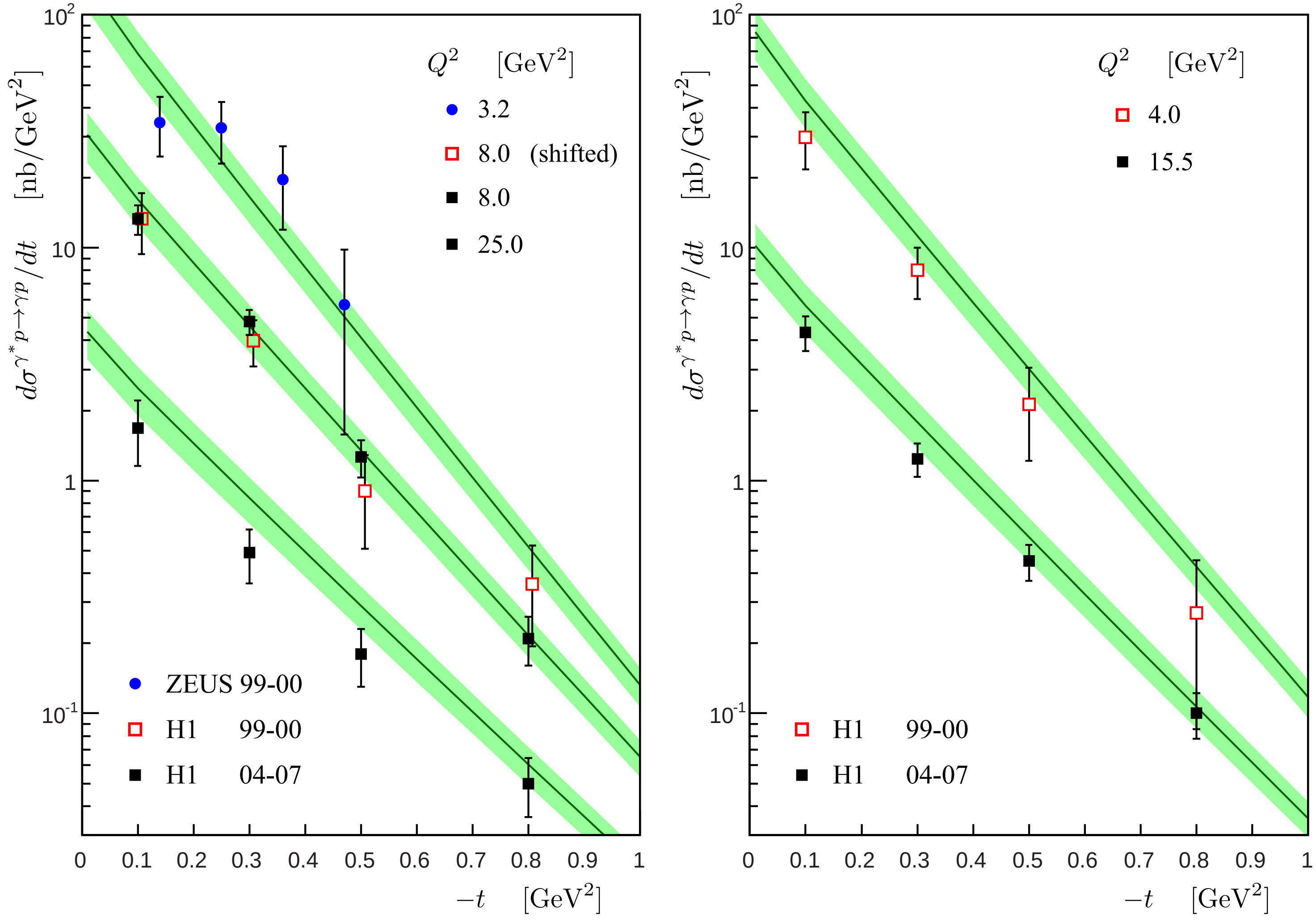
Moutarde et al (14)

convolutions: $\mathcal{K}_C = \int_{-1}^{1} dx [e_u^2 K^u + e_d^2 K^d + e_s^2 K^s] \left[\frac{1}{\xi - x - i\epsilon} - \epsilon_f \frac{1}{\xi + x - i\epsilon}\right]$

$(K = H, E \;\; \epsilon_f = 1 \qquad K = \widetilde{H}, \widetilde{E} \;\; \epsilon_f = -1)$

more reactions? e.g. $\nu_l p \to l P p$ Kopeliovich et al (13)

DVCS cross section



HERA $W \simeq 90\,\mathrm{GeV}$ under control of H KMS(13)

E for valence quarks

analysis of Pauli FF for proton and neutron at $\xi = 0$ DFJK(04), Diehl-K(13):

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

parametrization as described

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

profile fct: $g_h = (b_h + \alpha' \ln 1/x)(1-x)^3 + Ax(1-x)^2$

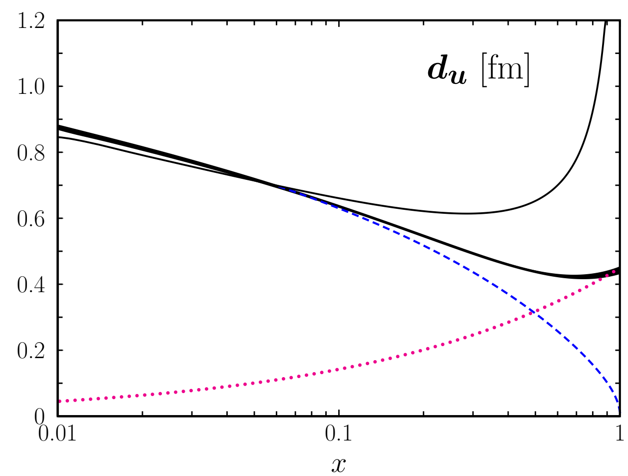
strong $x \leftrightarrow t$ correlation, small x (small $-t$): $g_h \to$ Regge profile fct

fits to FF data: (Diehl-K(13))

powers of $(1-\rho)^\beta$

$\beta_v^u \simeq 4.65$, $\beta_v^d \simeq 5.25$

$\xi \neq 0$: input to double distribution ansatz



avr. distance: spectators – active quark

$\langle b^2 \rangle_x^u = 4 g_u(x)$: $d_u(x) = \frac{\sqrt{\langle b^2 \rangle_x^u}}{1-x}$

E for gluons and sea quarks

Teryaev(99)

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 $\beta_v^u \leq \beta_v^d$ (DK(13): $\sum e_{20}^{a_v} = 0.041^{+0.011}_{-0.053}$)

$\Rightarrow$ 2nd moments of gluon and sea quarks cancel each other almost completely

(holds approximately for other moments too provided GPDs don't have nodes)

positivity bound for FT forbids large sea $\Longrightarrow$ gluon small too

$\frac{b^2}{m^2}\left(\frac{\partial e_s(x,b)}{\partial b^2}\right)^2 \leq s^2(x,b) - \Delta s^2(x,b)$

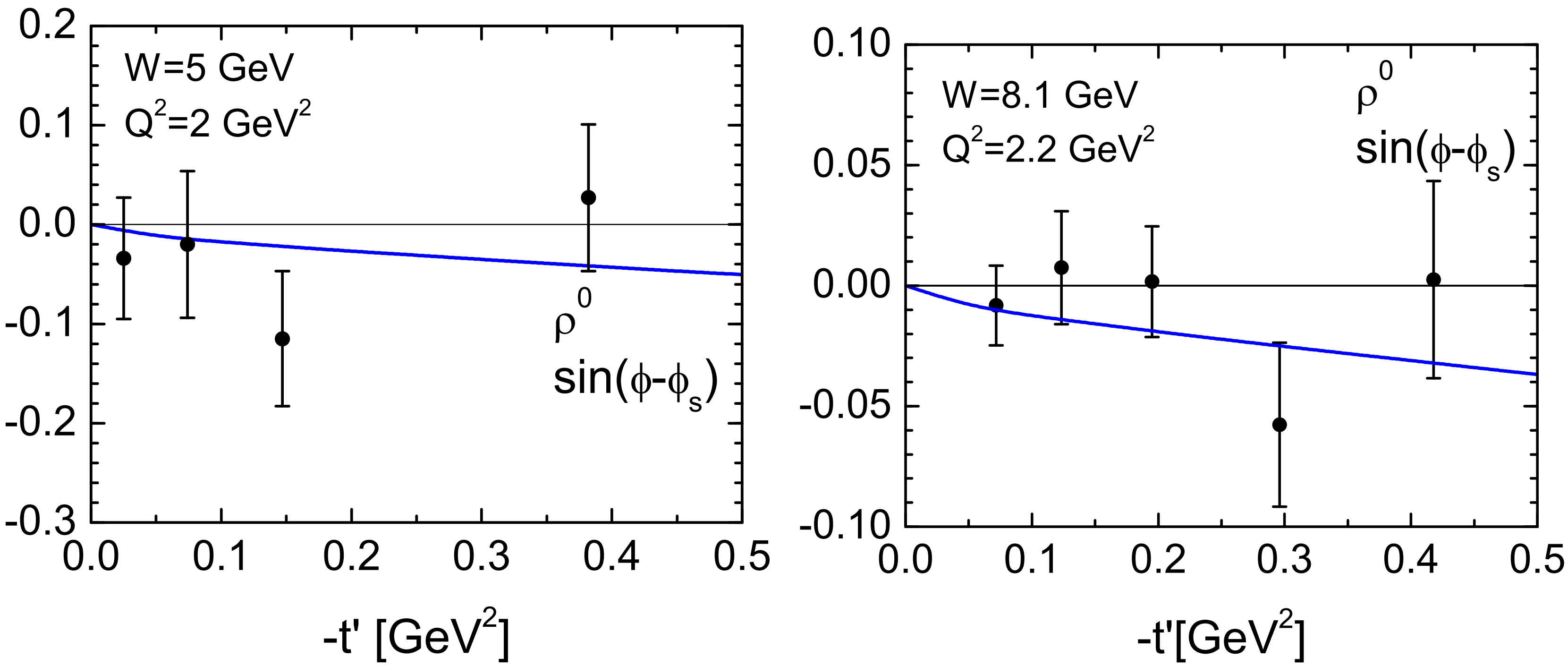
parameterization as described: $\beta_e^s = 7$, $\beta_e^g = 6$ Regge-like parameters as for H

flavor symm. sea for E assumed

N_s fixed by saturating the bound ($N_s = \pm 0.155$), N_g from sum rules

for $\xi \neq 0$ input to double distribution ansatz

$A_{UT}^{\sin(\phi-\phi_s)}$ for ρ^0 production



data: HERMES(08) COMPASS(12)

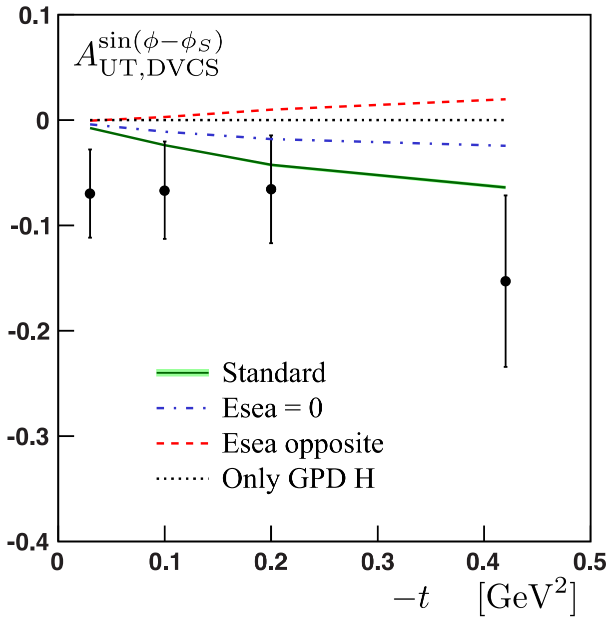
theor. result: Goloskokov-K(09)

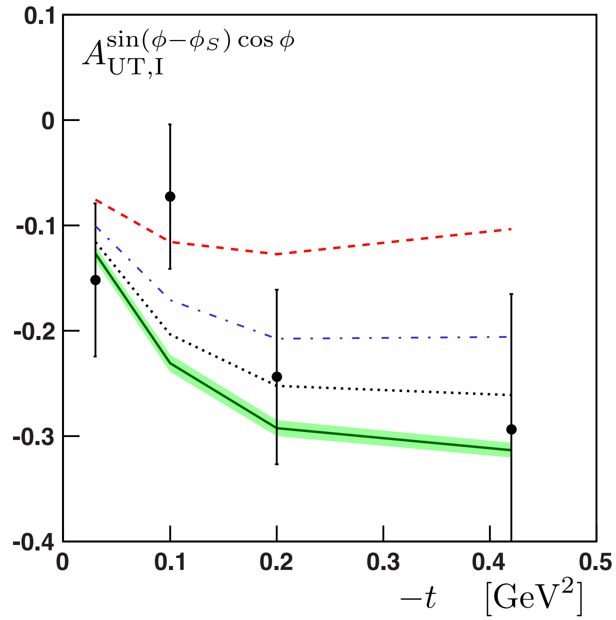
$$A_{UT}^{\sin(\phi-\phi_s)} \sim \mathrm{Im}\big[\mathcal{E}_M^* \mathcal{H}_M\big]$$

gluon and sea contr. from E cancel to a large extent

dominated by valence quark contr. from E

Target asymmetry in DVCS





data: HERMES(08)

$\langle Q^2 \rangle \simeq 2.5\,\mathrm{GeV}^2$

$\langle x_{\rm Bj} \rangle \simeq 0.09$

theory:

KMS(13)

$A^{\sin(\phi-\phi_s)}_{UT,DVCS} \sim \mathrm{Im}\big[\mathcal{E}^*_C \mathcal{H}_C\big]$

no cancellation between

sea and gluon

$\Rightarrow \mathcal{E}^{\rm sea}_C$ seen

from BH-DVCS interference

separate contr. from

$\mathrm{Im}\mathcal{H}_C$ and $\mathrm{Im}\mathcal{E}_C$

negative $\mathcal{E}^{\rm sea}_C$ favored in both cases

$\mathcal{E}^g_C \geq 0$ Koempel et al(11) transverse target polarisation in J/Ψ photo- and electroproduction, dominated by gluonic GPDs

Application: Angular momenta of partons

$$J^a = \frac{1}{2}\Big[q^a_{20} + e^a_{20}\Big] \qquad J^g = \frac{1}{2}\Big[g_{20} + e^g_{20}\Big] \qquad (\xi = t = 0)$$

q^a_{20}, g_{20} from ABM11 (NLO) PDFs

$e^{a_v}_{20}$ from form factor analysis Diehl-K. (13):

$$J^u_v = 0.230^{+0.009}_{-0.024} \qquad J^d_v = -0.004^{+0.010}_{-0.016}$$

e^s_{20}, e^g_{20} from analysis of A_{UT} in DVMP and DVCS

$$J^{u+\bar{u}} = 0.261\,;\, J^{d+\bar{d}} = 0.035\,;\, J^{s+\bar{s}} = \quad 0.018\,;\, J^g = 0.186 \quad (E^s = 0)$$

$$= 0.235\,; \qquad = 0.009\,; \qquad = -0.008\,; \qquad = 0.263 \quad (E^s < 0,\ E^g > 0)$$

$$(N_s = -0.155)$$

need better determ. of E^s (smaller errors of A_{UT})

J^i quoted at scale $2\,\mathrm{GeV}$

$\sum J^i = 1/2$ spin of the proton (Ji's sum rule)

there is no spin crisis

What do we know about $\widetilde{H}, \widetilde{E}$?

Obvious place to study them is leptoproduction of pions

$\widetilde{H}$: parametrized with DD ansatz, constrained by polarized PDFs and axial form factor

DSSV(09) parametrization of $x\Delta q(x) \sim x^{\alpha}(1-x)^{10}(1-\eta x)$ with $\eta > 1$ for gluon and sea quarks at scale $2\,\mathrm{GeV}$

$\Longrightarrow$ $\widetilde{H}$ very small for gluons and sum of sea quarks (with opposite signs)

$\widetilde{E}$: pion pole contribution

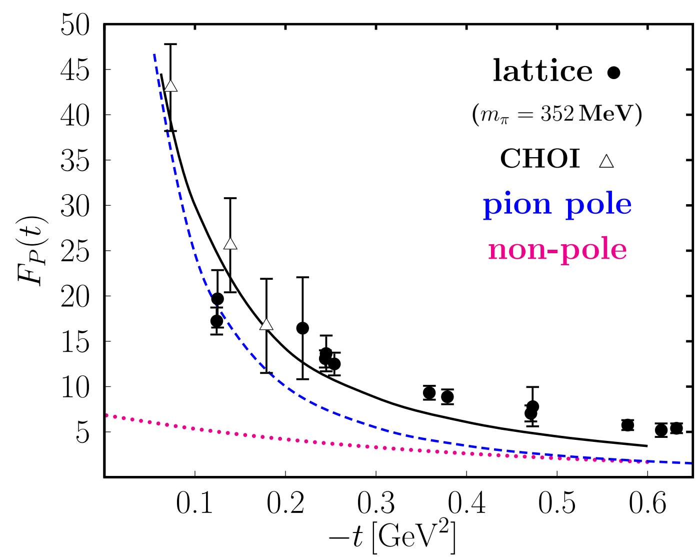
VGG99, Penttinen et al (99)

$$\widetilde{E}^u_{\rm pole} = -\widetilde{E}^d_{\rm pole} = \frac{\Theta(|x| \le \xi)}{4\xi}\,\frac{F_P(t)}{m_\pi^2 - t}\,\Phi_\pi\Big(\frac{x+\xi}{2\xi}\Big)$$

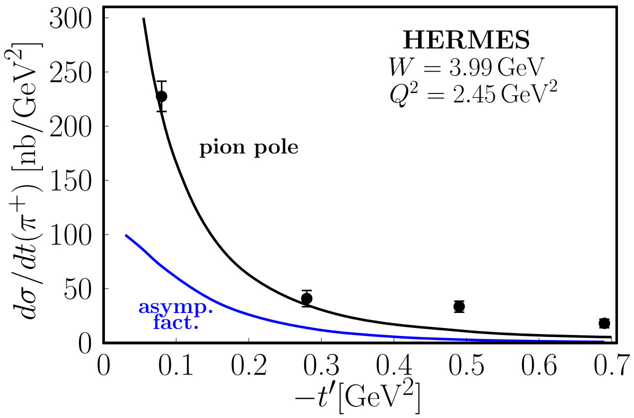
$$F_P = 2\sqrt{2} m f_\pi g_{\pi NN} F_{\pi NN}(t)$$

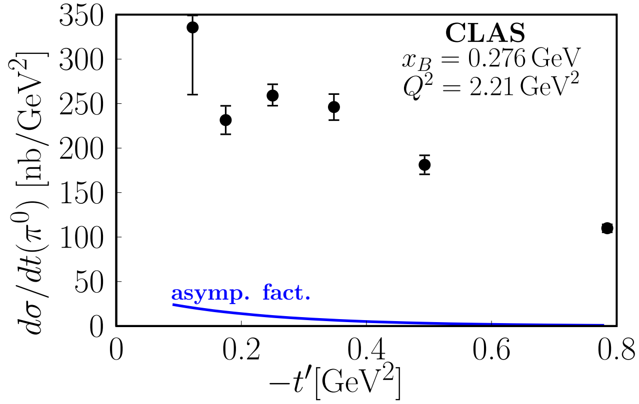
non-pole contribution to $\widetilde{E}$?

hardly known, probably small



Difficulties with pion production



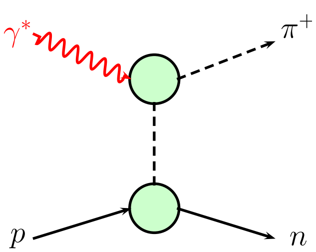


asymp. factorization formula fails by order of magnitude

$$\Longrightarrow \frac{d\sigma_L^{\text{pole}}}{dt} \sim \frac{-tQ^2}{(t-m_\pi^2)^2}\left[\sqrt{2}e_0 g_{\pi NN} F_{\pi NN}(t) F_\pi^{\text{pert}}(Q^2)\right]^2$$

handbag understimates pion FF $F_\pi^{\text{pert.}} \simeq 0.3 - 0.5 F_\pi^{\text{exp.}}$

(F_π measured in π^+ electroproduction at Jlab)



$\Longleftarrow$ Goloskokov-K(09): $F_\pi^{\text{pert}} \to F_\pi^{\text{exp}}$

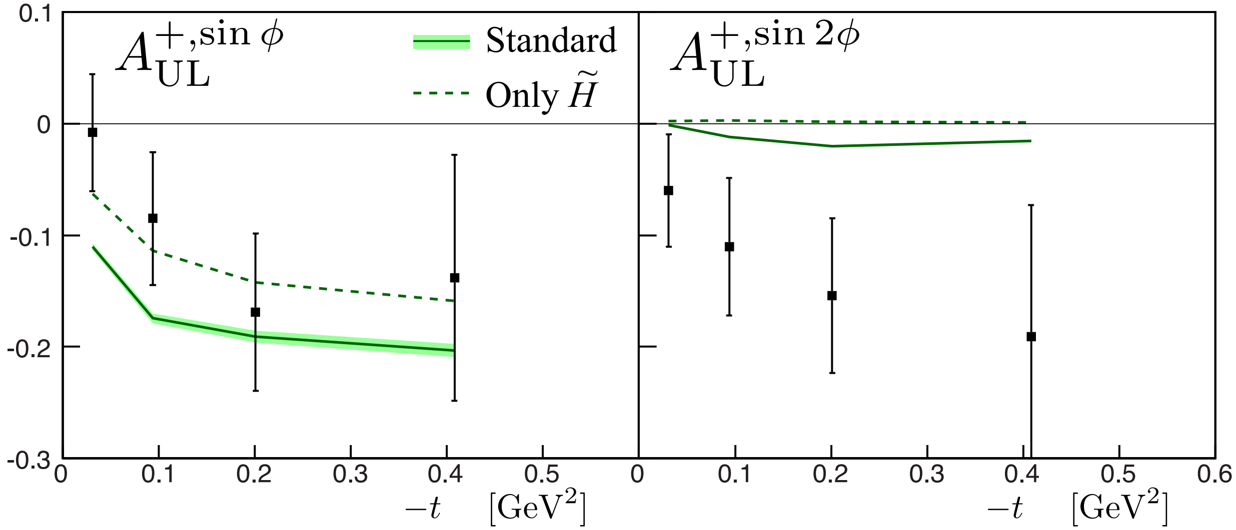
knowledge of the sixties suffices to explain HERMES data

Bechler-Mueller(09): consider α_s as a free parameter $\to \alpha_s \simeq 1$

in addition - need for contributions from $\gamma_T^* \to P$ transitions for π^+ and π^0

Moments of long. pol. target asymmetry

sensitive to $\widetilde{H}$ KMS(13)



Data from HERMES(10) $x_B = 0.1$, $Q^2 = 2.46\,\mathrm{GeV}^2$ with positron beam dominated by DVCS-BH interference

surprisingly strong $\sin 2\phi$ harmonic; theor. strongly suppressed
the only small-ξ observable which we don't fit

Improving the GPDs

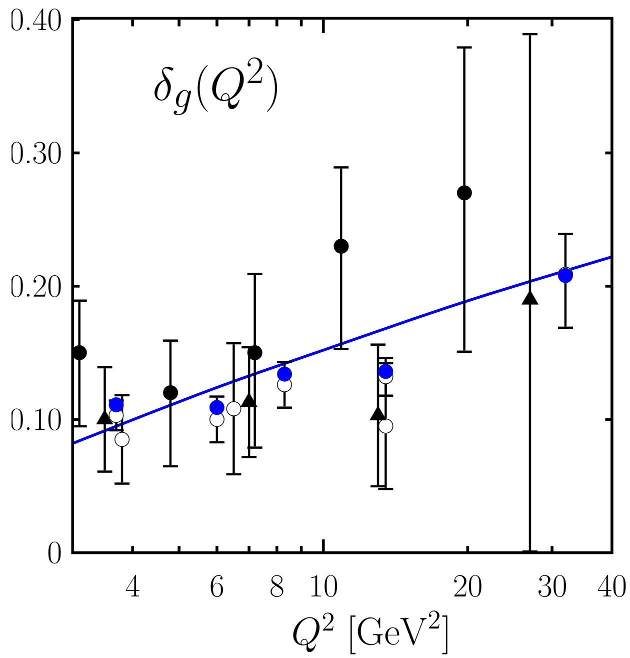
for valence quarks: H, E and $\widetilde{H}$ from DFJK(04)
(based on CTEQ6(02) and Blümlein-Böttcher(02))
to be replaced by results from Diehl-K(13) (based on ABM(12) and DSSV(09))
partially done; only little changes at small $-t$

gluon and sea quarks for $\widetilde{H}$: constrained by pol. PDFs from DSSV(09)
but very small (see above) almost negligible

gluon and sea quarks for H: change from CTEQ6(02) to ABM(12) not simple
at small x, see next page

Evolution: all this is input at initial scale $4\,\mathrm{GeV}^2$
for other scales: Vinnikov code
probably we will still use a parametrization of resulting Q^2 dependence

Gluon PDFs at small x



cross section for ρ^0 and ϕ electroproduction H1, ZEUS

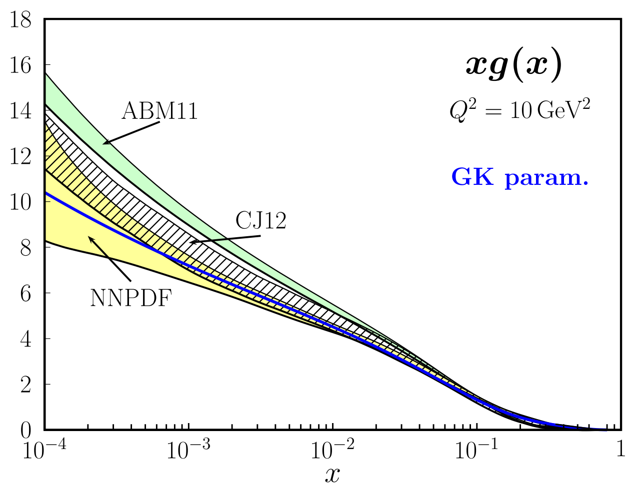
$\sigma \propto W^{4\delta_g(Q^2)}$ (real part neglected)

$\delta_g = 0.1 + 0.06\ln\left(Q^2/4\,\mathrm{GeV}^2\right)$

$\sigma \sim |H^g(\xi,\xi)|^2 \qquad H^g \sim (2\xi)^{-\delta_g(Q^2)}$

in DD ansatz need $xg(x) \sim x^{-\delta_g(Q^2)}$

(note: in agreement with CTEQ6M (NLO))



comparison of various gluon PDFs

ABM11, CJ12, NNPDF

large uncertainites for $x \lesssim 10^{-2}$

Goloskokov-K parametrization

$xg(x) = x^{-\delta_g}(1-x)^5 \sum_j c_j x^{j/2}$

will be kept

What new data do we need?

π^0 cross section, ideally with long.-trans. separation
(may confirm dominance of contributions from γ_T^* and at the end may lead to a better determination of $\widetilde{H}$

ω production cross section - check of pion pole contribution

J/Ψ production - probes H^g independent of $H^{\rm sea}$

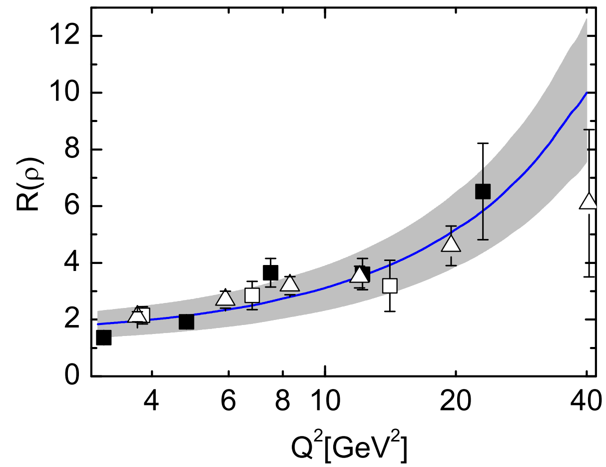
DVCS - look at observables sensitive to E and $\widetilde{H}$
of particular interest — $A_{UT,DVCS}^{\sin(\phi-\phi_s)}$ and $A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi}$
with smaller errors than HERMES
we may learn about $E^{sea} \Longrightarrow E^g \Longrightarrow J^{sea}, J^g$

Generalization of handbag approach

extension to $\gamma_T^* \to V_T$ transitions: $H_{\mu\lambda,\mu\lambda}(x,\xi,Q^2,t\simeq 0)$
suppressed by $\langle k_\perp^2\rangle^{1/2}/Q$
related to GPDs H, E and $\widetilde{H}, \widetilde{E}$
$k_\perp$ regularizes infrared singularity occuring in coll. approach

used to fit transverse cross sections,
SDME and spin asymmetries
not relevant for DVCS

bears resemblance to color dipole model:
Frankfurt et al (95) Nikolaev et al(11),
Kowalski et al(13)



GK(08)
HERA data; $W \simeq 75\,\mathrm{GeV}$

extension to $\gamma_T^* \to V_L(P)$ transitions:

$$\mathcal{M}_{0+\pm+} = \kappa_M \frac{e_0}{2} \frac{\sqrt{-t'}}{2m} \sum_a e_a \mathcal{C}_M^a \int dx H_{0-++} \bar{E}_T$$

$$\mathcal{M}_{0-++} = e_0 \sqrt{1-\xi^2} \sum_a e_a \mathcal{C}_M^a \int dx H_{0-++} H_T$$

$\kappa_V = \pm 1$, $\kappa_P = 1$

subprocess amplitude $H_{0-\lambda,\mu\lambda}(x,\xi,Q^2,t \simeq 0)$ is non-flip

suppressed by m_V/Q or μ_P/Q

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

requires opposite helicities of emitted and reabsorbed quarks

related to transversity GPDs H_T, $\bar{E}_T = 2\widetilde{H}_T + E_T$

and twist-3 meson wave functions

also regularized by $k_\perp$

GPD contributions to DVCS observables

Experiment	Observable	Normalized convolutions
HERMES	$A_{\rm C}^{\cos 0\phi}$	${\rm Re}\mathcal{H} + 0.06{\rm Re}\mathcal{E} + 0.24{\rm Re}\widetilde{\mathcal{H}}$
	$A_{\rm C}^{\cos\phi}$	${\rm Re}\mathcal{H} + 0.05{\rm Re}\mathcal{E} + 0.15{\rm Re}\widetilde{\mathcal{H}}$
	$A_{\rm LU,I}^{\sin\phi}$	${\rm Im}\mathcal{H} + 0.05{\rm Im}\mathcal{E} + 0.12{\rm Im}\widetilde{\mathcal{H}}$
	$A_{\rm UL}^{+,\sin\phi}$	${\rm Im}\widetilde{\mathcal{H}} + 0.10{\rm Im}\mathcal{H} + 0.01{\rm Im}\mathcal{E}$
	$A_{\rm UL}^{+,\sin 2\phi}$	${\rm Im}\widetilde{\mathcal{H}} - 0.97{\rm Im}\mathcal{H} + 0.49{\rm Im}\mathcal{E} - 0.03{\rm Im}\widetilde{\mathcal{E}}$
	$A_{\rm LL}^{+,\cos 0\phi}$	$1 + 0.05{\rm Re}\widetilde{\mathcal{H}} + 0.01{\rm Re}\mathcal{H}$
	$A_{\rm LL}^{+,\cos\phi}$	$1 + 0.79{\rm Re}\widetilde{\mathcal{H}} + 0.11{\rm Im}\mathcal{H}$
	$A_{\rm UT,DVCS}^{\sin(\phi-\phi_S)}$	${\rm Im}\mathcal{H}{\rm Re}\mathcal{E} - {\rm Im}\mathcal{E}{\rm Re}\mathcal{H}$
	$A_{\rm UT,I}^{\sin(\phi-\phi_S)\cos\phi}$	${\rm Im}\mathcal{H} - 0.56{\rm Im}\mathcal{E} - 0.12{\rm Im}\widetilde{\mathcal{H}}$
CLAS	$A_{\rm LU}^{-,\sin\phi}$	${\rm Im}\mathcal{H} + 0.06{\rm Im}\mathcal{E} + 0.21{\rm Im}\widetilde{\mathcal{H}}$
	$A_{\rm UL}^{-,\sin\phi}$	${\rm Im}\widetilde{\mathcal{H}} + 0.12{\rm Im}\mathcal{H} + 0.04{\rm Im}\mathcal{E}$
	$A_{\rm UL}^{-,\sin 2\phi}$	${\rm Im}\widetilde{\mathcal{H}} - 0.79{\rm Im}\mathcal{H} + 0.30{\rm Im}\mathcal{E} - 0.05{\rm Im}\widetilde{\mathcal{E}}$
HALL A	$\Delta\sigma^{\sin\phi}$	${\rm Im}\mathcal{H} + 0.07{\rm Im}\mathcal{E} + 0.47{\rm Im}\widetilde{\mathcal{H}}$
	$\sigma^{\cos 0\phi}$	$1 + 0.05{\rm Re}\mathcal{H} + 0.007\mathcal{H}\mathcal{H}^*$
	$\sigma^{\cos\phi}$	$1 + 0.12{\rm Re}\mathcal{H} + 0.05{\rm Re}\widetilde{\mathcal{H}}$
HERA	$\sigma_{\rm DVCS}$	$\mathcal{H}\mathcal{H}^* + 0.09\mathcal{E}\mathcal{E}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*$

coeff. are normalized to the largest one, only relative coeff. larger than 1% are kept.

KMS(13) with H most of the DVCS observables can be computed

What did we learn about GPDs from DVMP?

GPD	probed by	constraints	status
H	ρ^0_L, ϕ_L cross sections	PDFs	***
$\widetilde{H}$	$A_{LL}(\rho^0)$	polarized PDFs	*
E	-	sum rule for 2^{nd} moments	*
$\widetilde{E}, H_T, \ldots$	-	-	-
H	ρ^0_L, ϕ_L cross sections	PDFs, Dirac ff	***
$\widetilde{H}$	π^+ data	pol. PDFs, axial ff	**
E	$A_{UT}^{\sin(\phi-\phi_s)}(\rho^0, \phi)$	Pauli ff	**
$\widetilde{E}^{n.p.}$	π^+ data	pseudoscalar ff	*
$H_T, \bar{E}_T$	π^+ data, $A_{UT}^{\sin(\phi_s)}(\rho^0)$	transversity PDFs	*
$\widetilde{H}_T, \widetilde{E}_T$	-	-	-

Status of small-skewness GPDs as extracted from meson electroproduction data. The upper (lower) part is for gluons and sea (valence) quarks. Except of H for gluons and sea quarks all GPDs are probed for scales of about $4\,\mathrm{GeV}^2$

PDFs *****