Status of DVCS, DVMP and GPDs

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Outline:

- **The handbag, power corrections and GPDs**
- **Analysis of meson electroproduction**
- **DVCS**
- **The GPD $\widetilde{H}$**
- **The GPD E**
- **Ji's sum rule**
- **Summary**

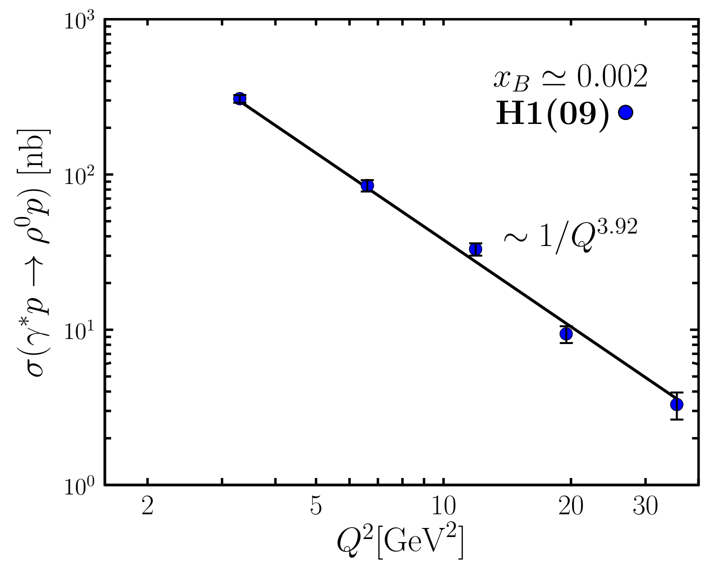
Can we apply the asymp. fact. formula ?

rigorous proofs of collinear factorization in generalized Bjorken regime:
for $\gamma_L^* \to V_L(P)$ and $\gamma_T^* \to \gamma_T$ amplitudes $\big(Q^2, W \to \infty,\, x_{\rm Bj}$ fixed$\big)$
$\mathcal{K} = \int dx K(x,\xi,t)\mathcal{H}(x,\xi,Q^2)$ Radyushkin, Collins et al, Ji et al

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 $x_{\rm Bj}$
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 (11,13): absorb effects into GPDs

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

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

- can this be extended to lower W?

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

Goloskokov-K (06): take into account transverse size of meson,

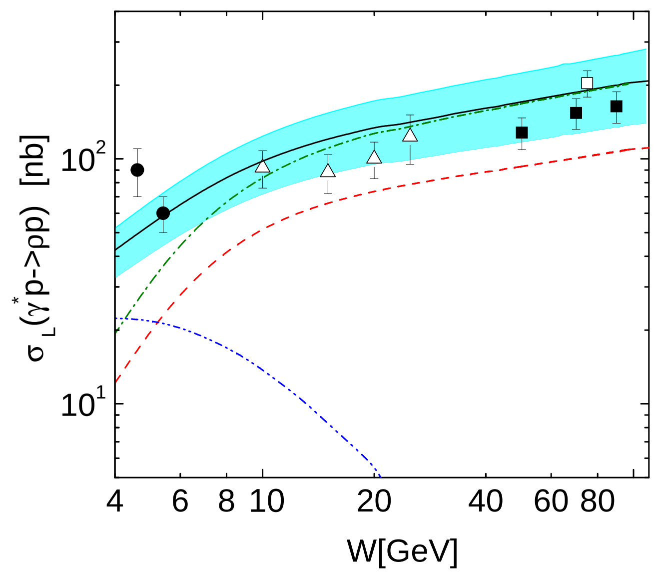
i.e. power corrections $1/Q^n$ to subprocess $\gamma_L^* q(g) \to V_L\, q(g)$

H for gluon, sea and valence

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

gluon + sea, gluon

valence + (gluon + sea)-valence interference

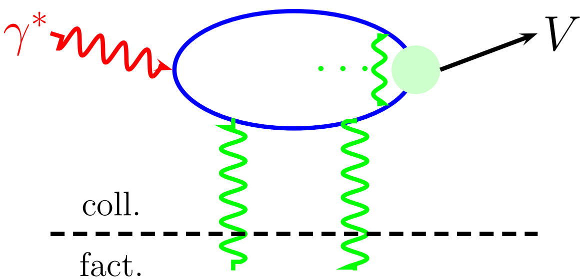


The subprocess amplitude for DVMP

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)

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

resummed gluon radiation to NLL $\Rightarrow \exp[-S]$

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

LO pQCD

+ quark trans. mom.

+ Sudakov supp.

$\Rightarrow$ asymp. fact. formula (lead. twist) for $Q^2 \to \infty$

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 $k_\perp$ in wave fct: series $\sim (\langle k_\perp^2\rangle/Q^2)^n$ (from all τ)

Parametrizing the GPDs

double distribution representation — 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.), D-term neglected

advantage: polynomiality and reduction formulas automatically satisfied

positivity bounds respected (checked numerically)

$H_{\rm val}$, $E_{\rm val}$ and $\widetilde{H}_{\rm val}$ at $\xi = 0$ from GPD analysis of nucleon form factors (sum rules) — Diehl et al(04), Diehl-K (13)

Ansätze for zero-skewness GPDs

simplest ansatz: VGG(98), Freund et al (01)

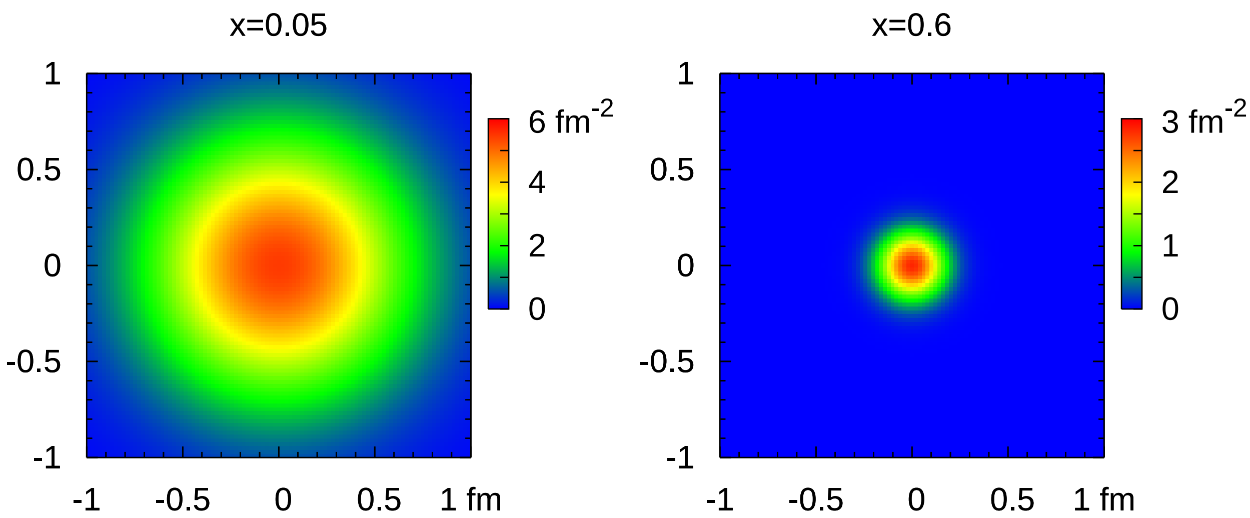
e.g. $H^q(x, \xi = 0, t) = c_q q(x) F_1^q(t)$ PDF times form factor

respects reduction formula and sum rules $\int dx H^q(x, \xi = 0, t) = F_1^q(t)$

Burkhardt(00,03): $q(x, \mathbf{b}) = \int \frac{d^2 \mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}\mathbf{\Delta}_\perp} H^q(x, \xi = 0, t = -\Delta_\perp^2)$

density interpretation $\mathbf{b}$ transverse distance between struck parton and hadron's center of momentum $\sum x_i \mathbf{b}_i = 0$;

partons with large (small) x_i must (can) have small (large) $\mathbf{b}_i$



$x - b$ $(x - t)$

correlation required

improvement: Regge-like ansatz (frequently used now)

$$H^q(x,\xi=0,t) = q(x)e^{tf_q(x)} \qquad f_q(x) = B_q + \alpha'_q \ln(x)$$

at small x: $q \sim x^{-\alpha(0)} \Longrightarrow H^q \sim x^{-\alpha(t)}$

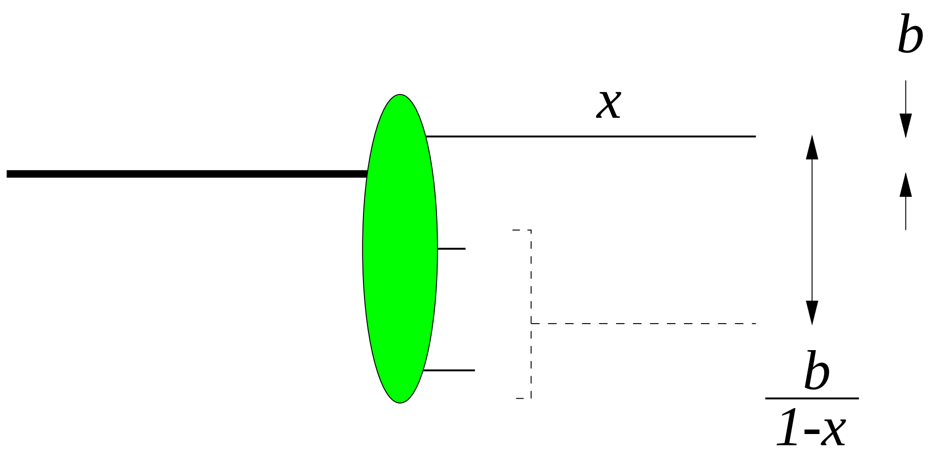
standard Regge trajectory - $H^q \sim 1/\sqrt{x}$ at $t \simeq 0$ (fact. ansatz for all t)

$\sim \sqrt{x}$ at $t \simeq -1\,\mathrm{GeV}^2$

FT: $q(x,\mathbf{b}) = \frac{1}{4\pi}\frac{q(x)}{f_q(x)} \exp\left[-b^2/4f_q(x)\right]$ and $< b^2 >^q_x = 4f_q(x)$

distance between active parton and cluster of spectators

(rough estimate of proton radius) $d_q(x) = \frac{\sqrt{<b^2>^q_x}}{1-x} \sim 1/(1-x)$ for $x \to 1$!



Regge-like ansatz only suitable at small x, i.e. at small $-t$

further improvement: DFJK04, Diehl-K(13)

used in analysis of form factors for proton and neutron at $\xi = 0$

$$F_1^{p(n)} = e_{u(d)} \int_{-1}^{1} dx H_i^u(x, \xi = 0, t) + e_{d(u)} \int_{-1}^{1} dx H_i^d(x, \xi = 0, t)$$

Pauli form factor $\quad H \to E$

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

profile fct: $f_q = (B_q + \alpha_q' \ln 1/x)(1-x)^3 + A_q x(1-x)^2$

fixes valence quark GPDs $H, E, \widetilde{H}$ at $\xi = 0$

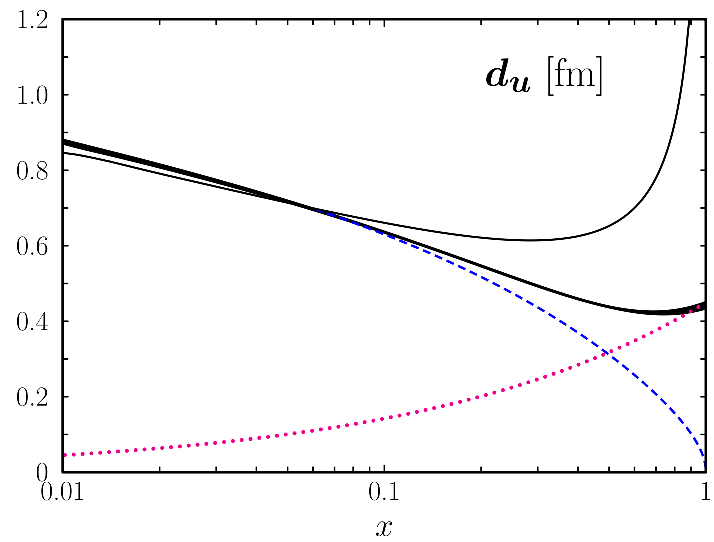
$$d_q(x) = \frac{2\sqrt{f_q(x)}}{1-x} \to 2\sqrt{A_q}$$

for $x \to 1$

Regge-like profile fct can (only) be used

at small x (small $-t$)

its FT not meaningful at large x



Analysis of hard exclusive meson leptoproduction

- analysis of nucleon form factor data DFJK(04), Diehl-K(13)
  fixes GPDs H, E and $\widetilde{H}$ for valence quarks at zero skewness

- fit to all available long. cross section data for ρ^0 and ϕ production
  from HERMES, COMPASS, E665, H1, ZEUS
  cover large range of kinematics $Q^2 \simeq 3 - 100\,\mathrm{GeV}^2$ $W \simeq 4 - 180\,\mathrm{GeV}$
  but small $-t'(\simeq -t)$, skewness $\xi(\simeq x_B/2) \lesssim 0.1$
  fixes the GPD H for gluons and sea quarks GK (05,07,08,13)

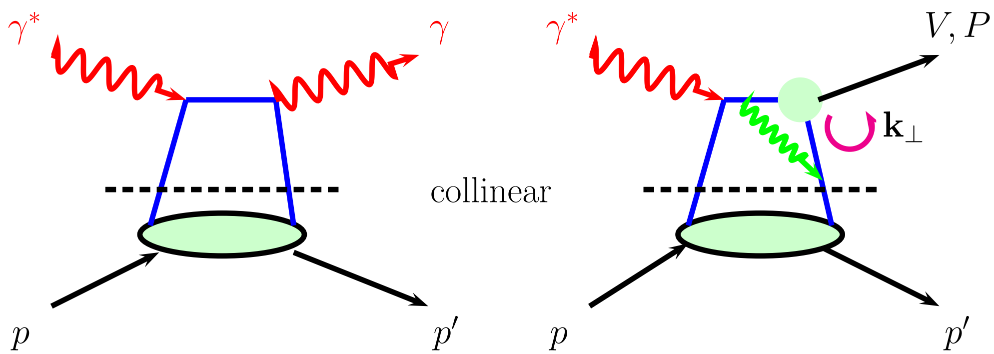
- analysis of transverse cross sections, SDMEs, asymmetries for ρ^0, ϕ from
  HERMES, COMPASS and HERA
  analysis of cross section and asymmetries for π^+ from HERMES
  typically $2\,\mathrm{GeV}^2 \lesssim Q^2 \lesssim 5\,\mathrm{GeV}^2$
  provides information on $\widetilde{H}$, E, H_T, $\bar{E}_T$ (mainly for val. quarks)
  and on pion pole
  typically of lesser quality than that of H GK (10,11)
  (requires extension of handbag appr. to $\gamma_T^* \to M$ transitions)

Exploiting universality

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

- $\nu_l p \to l P p$ Kopeliovich et al (13)
  V-A structure leads to different combinations of GPDs no data
- timelike DVCS Pire et al (13) no data
- $\gamma^* p \to \omega p$ GK(14)
  compared with SDMEs from HERMES(14)
  prominent role of pion pole
- DVCS K-Moutarde-Sabatie(13)

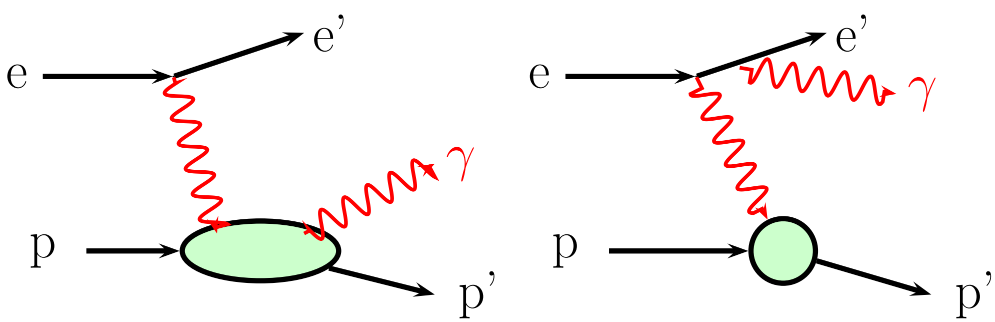
DVCS



leading-twist, LO accuracy

collinear for consistency

NLO: gluon GPDs contribute as well



$$d\sigma(lp \to lp\gamma) = d\sigma_{BH} + d\sigma_I + d\sigma_{DVCS}$$

$$d\sigma_i \propto \sum_{n=0}^{3} \left[c_n^i \cos(n\phi) + s_n^i \sin(n\phi) \right]$$

DVCS convolutions

$$\mathcal{K} = e_u^2 \mathcal{K}^u + e_d^2 \mathcal{K}^d + e_s^2 \mathcal{K}^s$$

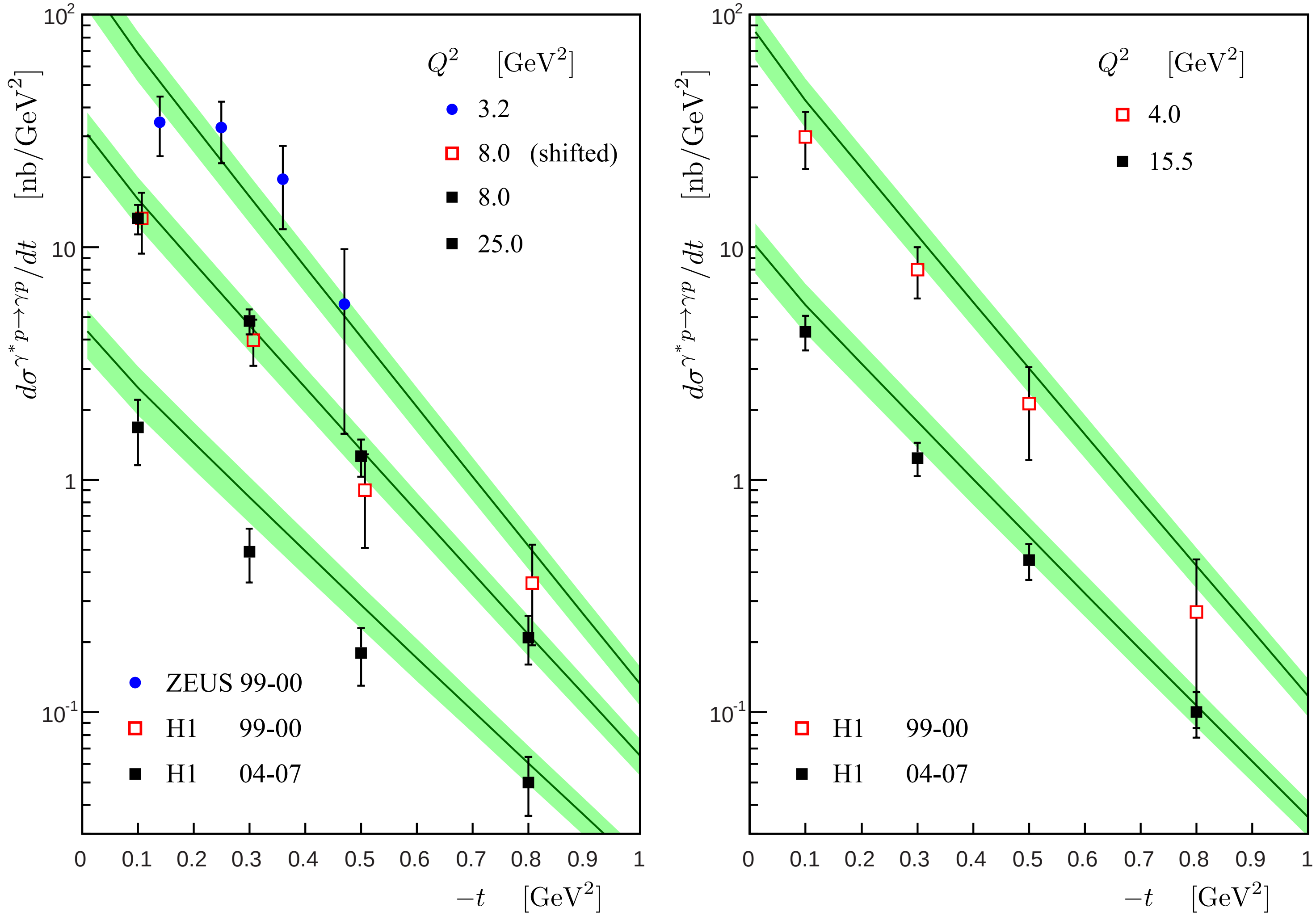
GPD contributions to DVCS observables

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

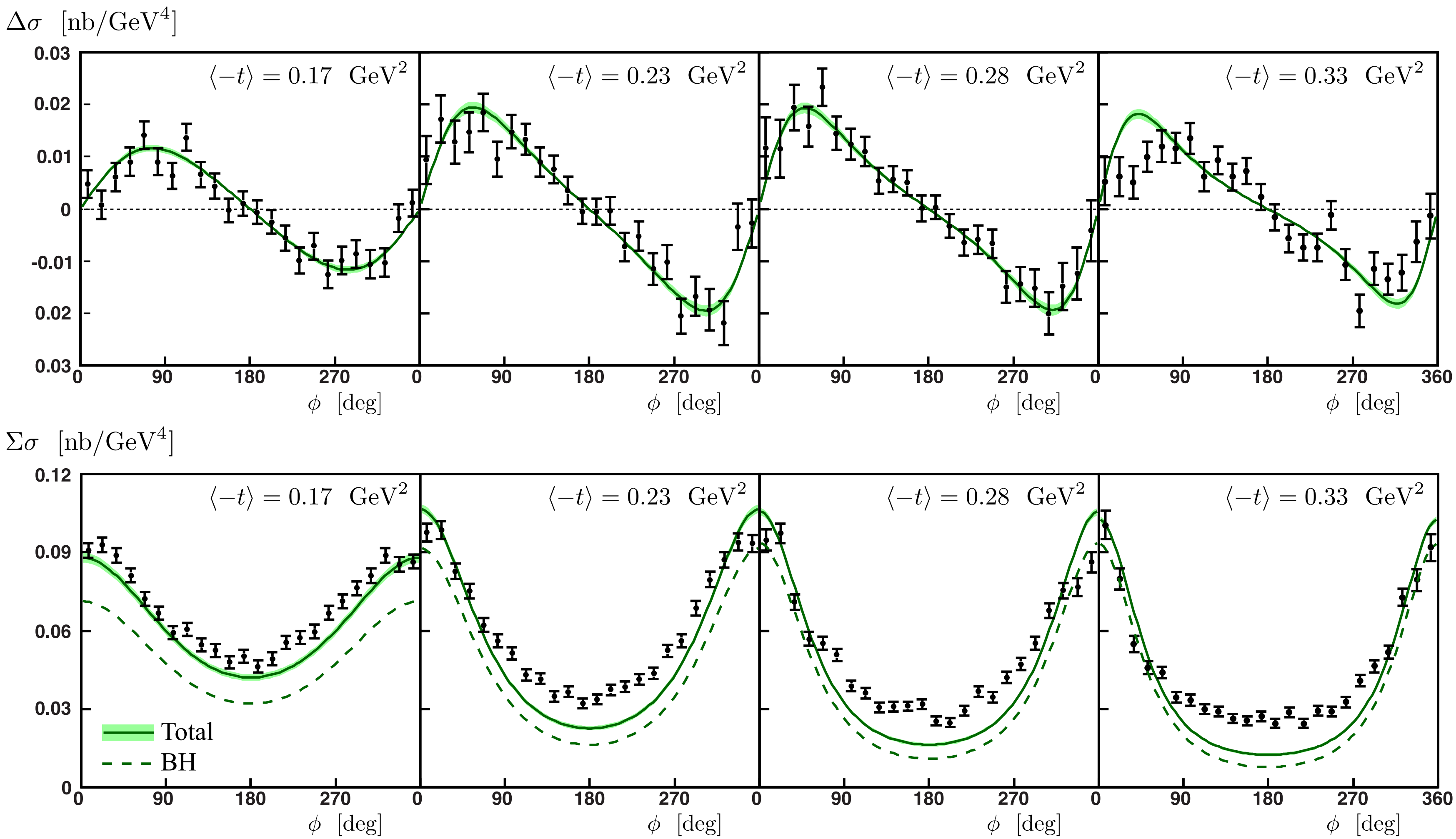
with H most of the DVCS observables can be computed

DVCS at HERA



$W \simeq 90\,\mathrm{GeV}$ data from ZEUS, H1

DVCS at JLAB

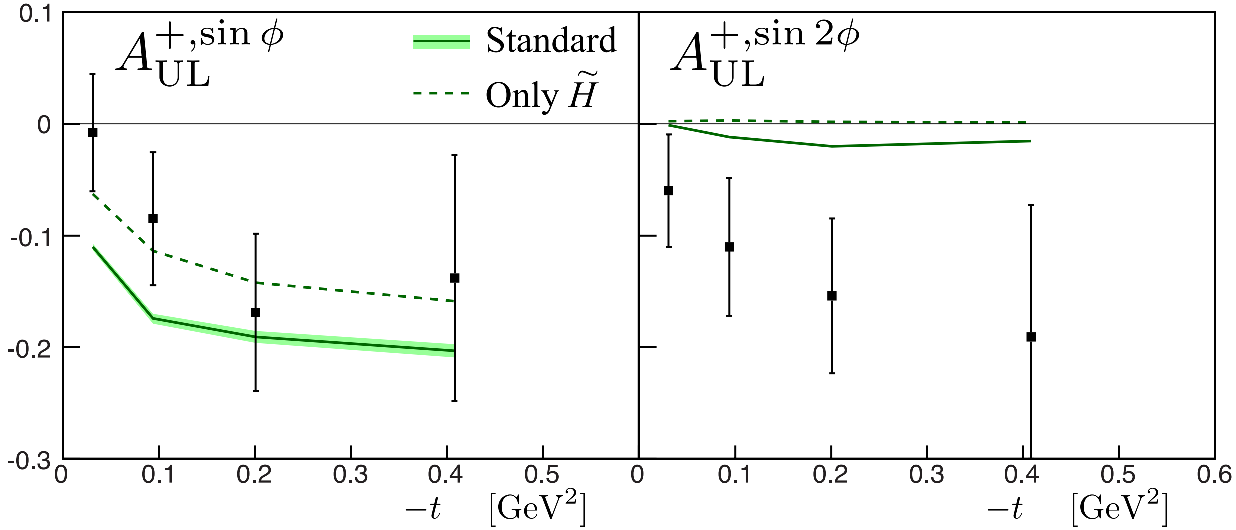


Hall A data $x_{\mathrm{Bj}} = 0.36$ $Q^2 = 2.3\,\mathrm{GeV}^2$ dashed lines: BH

difference and sum of electron-helicity cross section

less satisfactory description of JLAB data (large skewness, small W)

Long. polarized target asymmetry



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

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

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

E for gluons and sea quarks

E for valence quarks from FF analysis Diehl-K(13)

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

$\Rightarrow$ 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 FTs forbids large sea $\Longrightarrow$ gluon small too

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

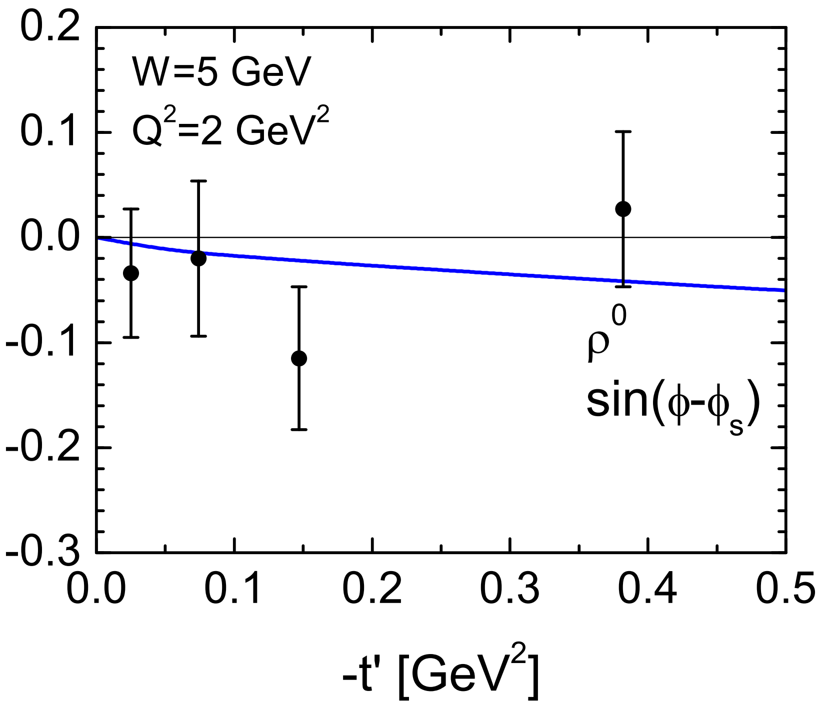
parameterization as described: $\beta_e^s = 7$, $\beta_e^g = 6$ Regge-like parameters as for H

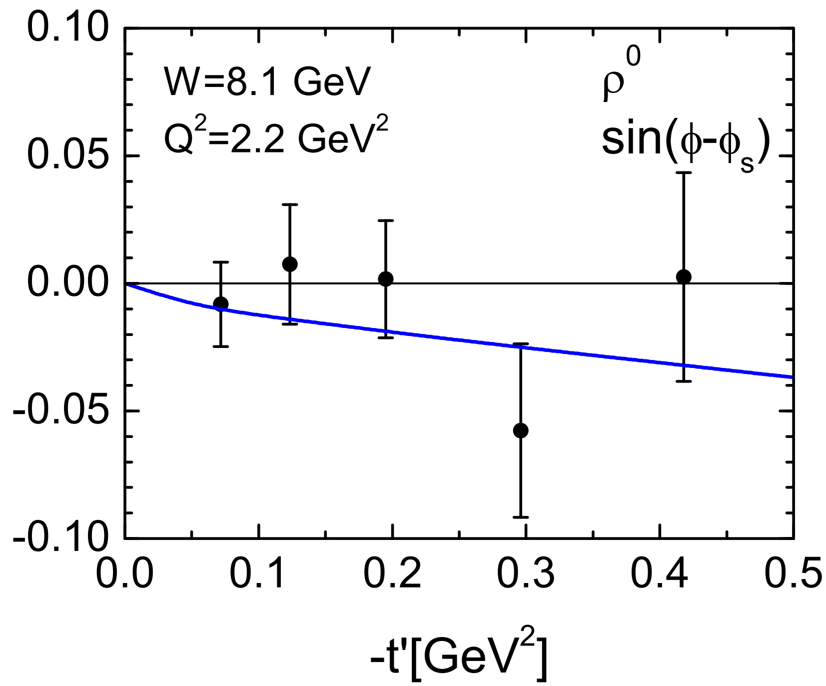
$e_i = N_i x^{-\alpha_g(0)}(1-x)^{\beta_i}$ flavor symm. sea for E assumed

N_s fixed by saturating 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)

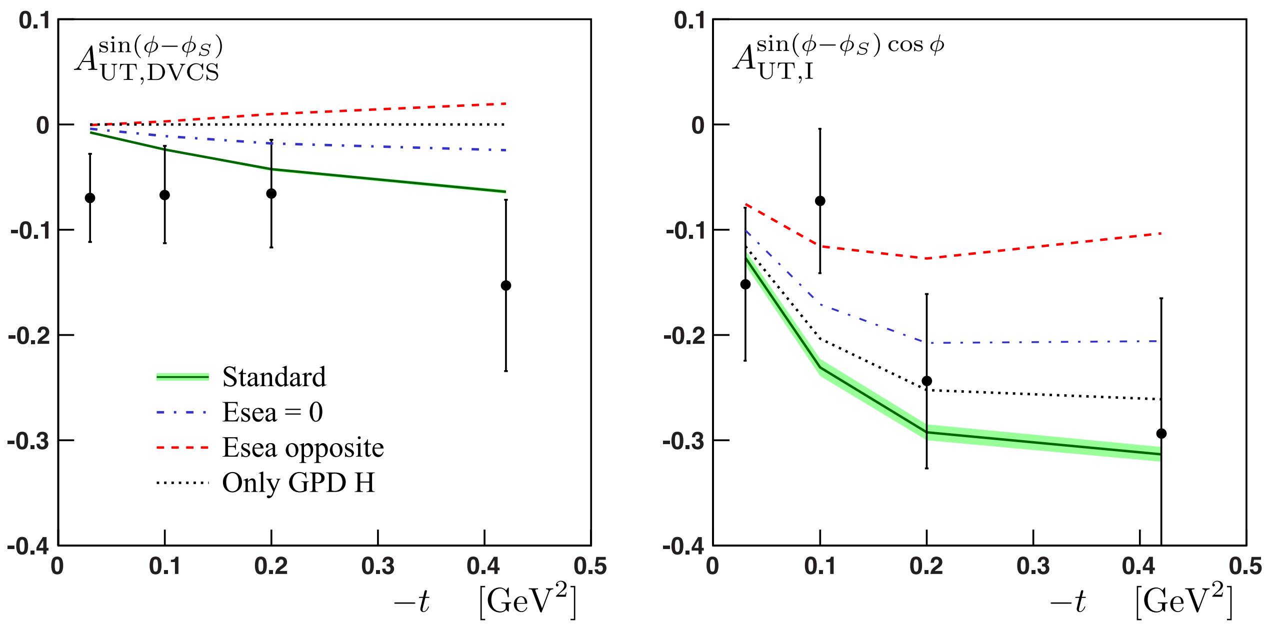
theor. result: Goloskokov-K(09)

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

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)

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

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

theory: KMS(12)

$A_{UT,DVCS}^{\sin(\phi-\phi_s)} \sim \mathrm{Im}\left[\mathcal{E}^*\mathcal{H}\right]$

no cancellation between

sea and gluon

$\Rightarrow \mathcal{E}^{\mathrm{sea}}$ seen

from BH-DVCS interference

separate contr. from

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

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

$\mathcal{E}^g \geq 0$ 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):

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

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

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

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

$$(N_s = -0.155)$$

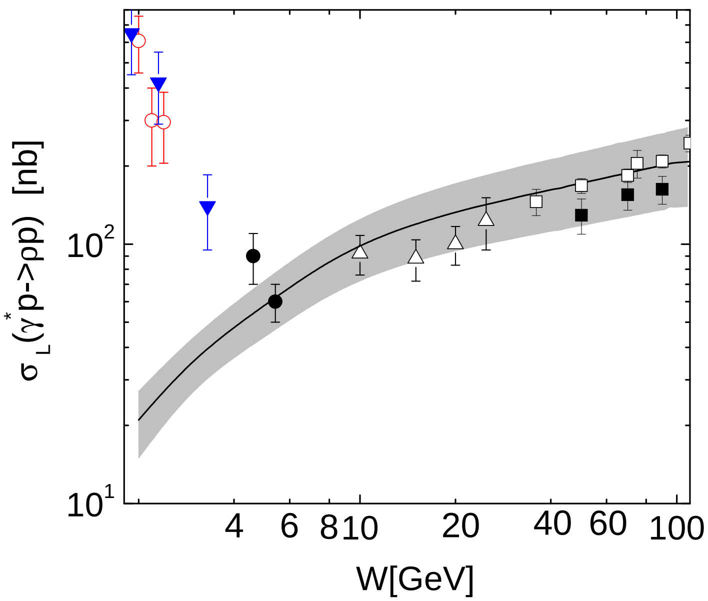
need better determ. of E^s (smaller errors of A_{UT} in DVCS)

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

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_{Bj} (small W)

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

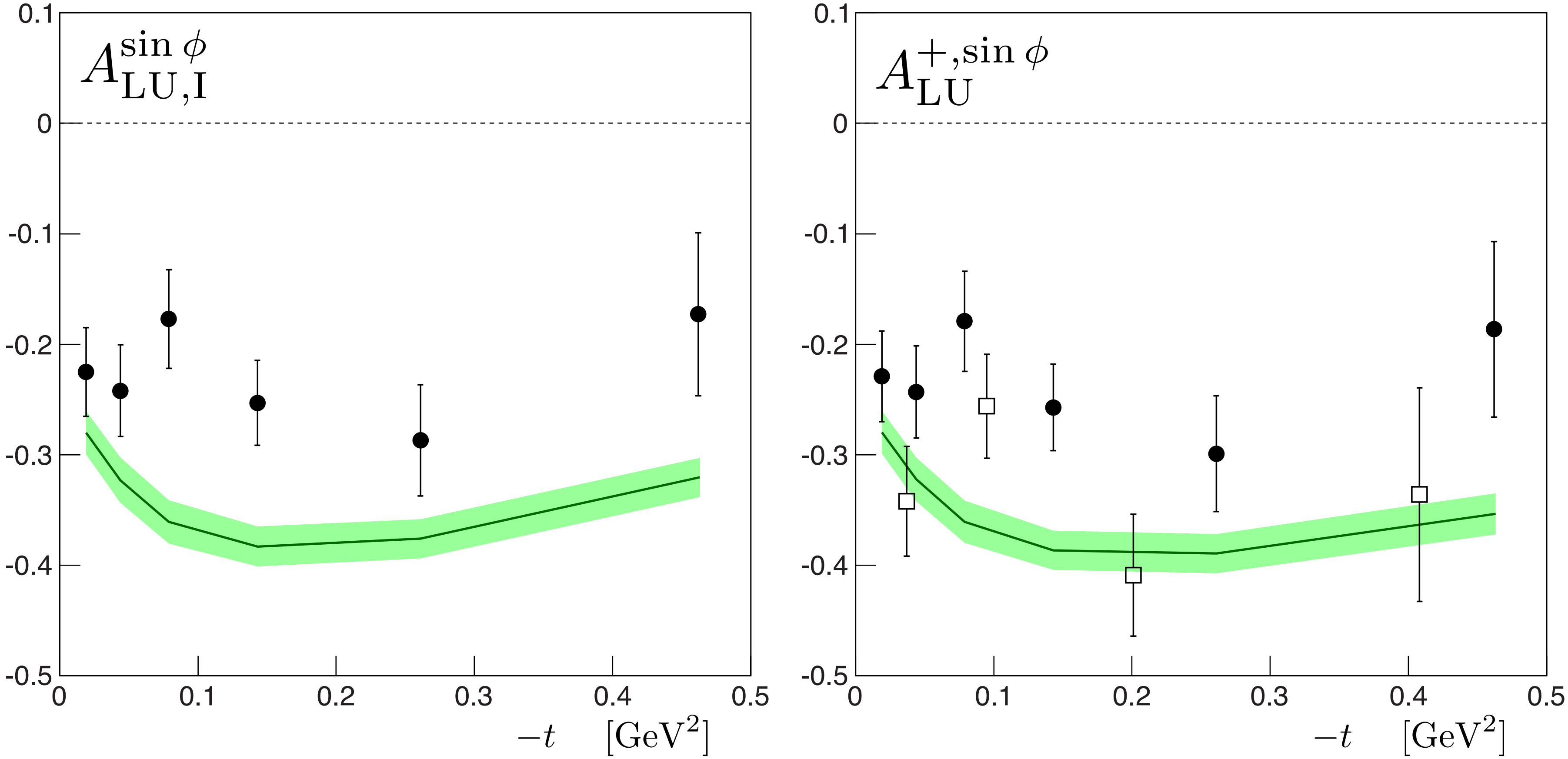
$$\xi \simeq \frac{x_{\mathrm{Bj}}}{2-x_{\mathrm{Bj}}}\left[1+\frac{1}{(1-x_{\mathrm{Bj}}/2)Q^2}(m_M^2 - x_{\mathrm{Bj}}^2 m^2 - x_{\mathrm{Bj}}(1-x_{\mathrm{Bj}})t')\right]$$

- GPD parameterization can be applied to large skewness region but success is not guaranteed

$t_0 = -4m^2\xi^2/(1-\xi^2)$ large probes GPD in different region of t ($W = 2\,\mathrm{GeV}$, $Q^2 = 4\,\mathrm{GeV}^2$: $t_0 = -0.86\,\mathrm{GeV}^2$)

Summary

- exclusive electroproduction of mesons allows to extract the GPDs $H, E, \widetilde{H}, H_T, \bar{E}_T$ at small ξ and $W \gtrsim 4\,\mathrm{GeV}$
- with exception of H little is known about the gluon and sea-quark sector, experimental information insufficient as yet
- double distr. ansatz is 'flexible' enough to account for all small ξ data; constraints from positivity, PDFs, form factors used
- these GPDs allow to calculate DVCS free of parameters, to study transverse localization of partons (at least for valence quarks) and to evaluate Ji's sum rule
- future improvements: use of new PDFs, more complicated profile fcts. for all GPDs, D-term, kinematical corrections at low Q^2, low W, large ξ and new data from COMPASS, JLAB12 and EIC?



HERMES 1203.6287 (solid circles)
and recoil data HERMES 1206.5683 (open squares)

$$x_B \simeq 0.097 \qquad Q^2 = 2.51\,\mathrm{GeV}^2$$