Dual parameterization update
(Minimal model)

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References:

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- H. Avakian *et al.*, JLab proposal PR-08-021 (2008);
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Outline

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Introduction

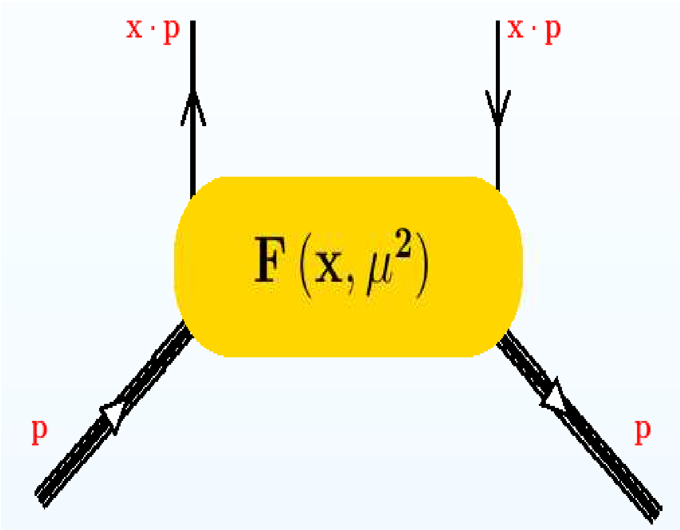
Generalized Parton Distributions (GPDs) of a hadron (nucleon, pion, nucleus) parameterize response of the target to well-defined QCD quark and gluon operators (probes) on the light-cone.

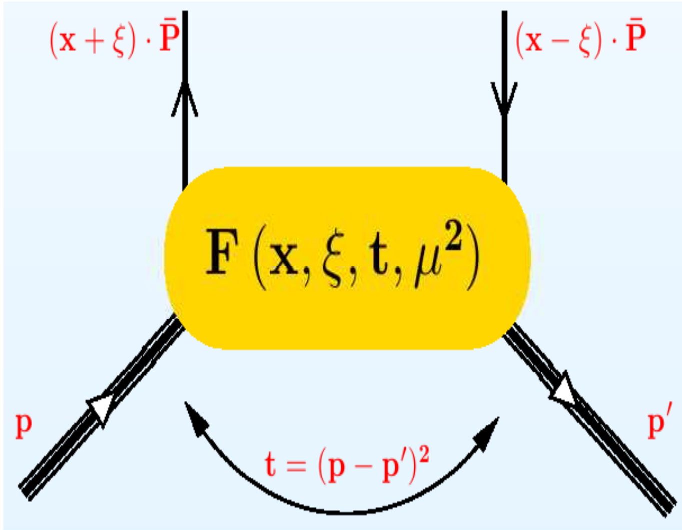
Quark GPDs of the nucleon:

$$\bar{P}^+ \int \frac{dz^-}{2\pi} e^{ix\bar{P}^+ z^-} \langle P'|\bar{\psi}(-\frac{z^-}{2})\gamma_+\psi(\frac{z^-}{2})|P\rangle_{z^+=0,\, z_\perp=0} = H^q(x,\xi,t)\bar{N}(P')\gamma^+ N(P) + E^q(x,\xi,t)\bar{N}(P')\frac{i\sigma^{+\mu}\Delta^\mu}{2m_N}N(P)$$

$$\bar{P}^+ \int \frac{dz^-}{2\pi} e^{ix\bar{P}^+ z^-} \langle P'|\bar{\psi}(-\frac{z^-}{2})\gamma_+\gamma_5\psi(\frac{z^-}{2})|P\rangle_{z^+=0,\, z_\perp=0} = \tilde{H}^q(x,\xi,t)\bar{N}(P')\gamma^+\gamma_5 N(P) + \tilde{E}^q(x,\xi,t)\bar{N}(P')\frac{\gamma_5\Delta^+}{2m_N}N(P)$$

It is instructive to compare GPDs to usual parton distributions (PDFs):



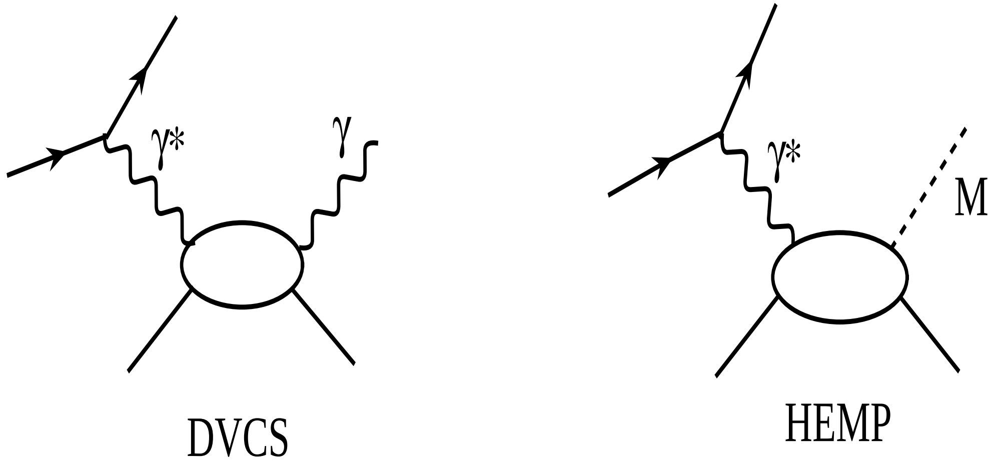


x longit. momentum fraction, $x = x_B$
μ^2 factorization scale

$\bar{P} = (P + P')/2$
$x \pm \xi$ longit. momentum fractions
$\xi = x_B/(2 - x_B)$
$t = (P' - P)^2$
enters via convolution !

GPDs contain more microscopic information about the parton structure of the target than PDFs and form factors.

GPDs can be accessed in hard exclusive reactions such as Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP):



- QCD factorization theorems for DVCS and HEMP allow to express the corresponding scattering amplitudes as convolution of coefficient functions with the GPDs

$$
\begin{aligned}
T^{\mu\nu}_{\rm DVCS}(\xi, t, Q^2) = & - \frac{1}{2} g^{\mu\nu}_{\perp} \int_{-1}^{1} dx \, C^{+}(x,\xi) [H(x,\xi,t,Q^2) \bar{N}(p') \hat{n} N(p) \\
& + E(x,\xi,t,Q^2) \bar{N}(p') i\sigma^{k\lambda} \frac{n_k \Delta_\lambda}{2m_N} N(p)] + \ldots
\end{aligned}
$$

- Corollaries of factorization
  - GPDs are universal (process-independent)
  - GPDs have a well-defined dependence on the factorization scale (virtuality Q^2)

- DVCS experimental observables (cross section, asymmetries) expressed in terms of the Compton Form Factors

$$\mathcal{H}(\xi, t, Q^2) = \sum e_q^2 \int_0^1 dx\, H^q(x, \xi, t, Q^2) \left(\frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right)$$

- Since GPDs enter via convolution and depend on three variables, extraction from the data is difficult/impossible

- At the present stage, models of GPDs are necessary

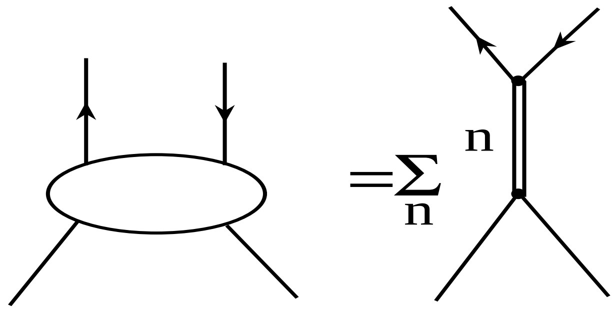
Dual parameterization of nucleon GPDs

- The essence of the dual parameterization of GPDs is the assumption of duality between the s and t-channel description of the quark-hadron scattering amplitude

- In hadronic physics, duality is realized by the Veneziano model. The dual Veneziano amplitude is given as an infinite series of infinitely narrow resonances in either s or t channel.

  The series is formally divergent to provide singularities of the amplitude $\Rightarrow$ same in the dual parameterization of GPDs.

- In the dual parameterization, a GPD is given by infinite series of generalized light-cone distribution amplitudes in the t-channel



- **Derivation**:
  - Two-pion distribution amplitude $\Phi^I(z,\xi,w^2)$ is expanded in terms of eigenfunctions of QCD evolution and in partial waves of produced pions

$$\Phi^I(z,\zeta,w^2,\mu^2) = 6z(1-z)\sum_{n=0}^{\infty}\sum_{l=0}^{n+1} B^I_{nl}(w^2,\mu^2)\, C_n^{3/2}(2z-1)\; P_l\,(2\zeta-1)$$

    * $I = 0,1$ isospin
    * p_1 and p_2 momenta of final pions, $P = p_1 + p_2$
    * $z = k^+/P^+$ quark light-cone fraction
    * $\zeta = p_1^+/P^+$ distribution of light-cone momenta between pions
    * $w^2 = (p_1+p_2)^2$

– Consider Mellin moments of Φ^I

$$\int_0^1 dz(2z-1)^{N-1}\Phi^I(z,\zeta,w^2) = \frac{1}{[p_1^+ + p_2^+]^N}\langle p_1 p_2|\bar{\psi}\gamma^+(\overleftrightarrow{\nabla}^+)^{N-1}\psi|0\rangle$$

– As matrix elements of a local operator, the Mellin moments can be continued to the crossed, GPD channel,

$$\langle p_1 p_2|\bar{\psi}\gamma^+(\overleftrightarrow{\nabla}^+)^{N-1}\psi|0\rangle = \langle p_2|\bar{\psi}\gamma^+(\overleftrightarrow{\nabla}^+)^{N-1}\psi|-p_1\rangle$$

– Changing appropriately the kinematic variables, we have

$$\xi^N \sum_{n=0}^{N-1}\sum_{l=0}^{n+1} B^I_{nl}(t)\, P_l\left(\frac{1}{\xi}\right)\int_0^1 dx\frac{3}{4}(1-x^2)x^{N-1}C_n^{3/2}(x) = \int_0^1 dx x^{N-1} H^I(x,\xi,t)$$

– The quark GPDs of the pion are reconstructed as a formal divergent series

$$H^I(x,\xi,t,\mu^2) = \sum_{n=0}^{\infty}\sum_{l=0}^{n+1} B^I_{nl}(t,\mu^2)\,\theta\left(\xi-|x|\right)\left(1-\frac{x^2}{\xi^2}\right) C_n^{3/2}\left(\frac{x}{\xi}\right) P_l\left(\frac{1}{\xi}\right)$$

- Shuvaev and Polyakov (2002) postulated similar dual parameterization for nucleon GPDs,

$$H^i(x,\xi,t,\mu^2) = \sum_{\substack{n=1 \\ \text{odd}}}^{\infty} \sum_{\substack{l=0 \\ \text{even}}}^{n+1} B^i_{nl}(t,\mu^2)\,\theta\left(\xi - |x|\right) \left(1 - \frac{x^2}{\xi^2}\right) C_n^{3/2}\left(\frac{x}{\xi}\right) P_l\left(\frac{1}{\xi}\right)$$

$$E^i(x,\xi,t,\mu^2) = \sum_{\substack{n=1 \\ \text{odd}}}^{\infty} \sum_{\substack{l=0 \\ \text{even}}}^{n+1} C^i_{nl}(t,\mu^2)\,\theta\left(\xi - |x|\right) \left(1 - \frac{x^2}{\xi^2}\right) C_n^{3/2}\left(\frac{x}{\xi}\right) P_l\left(\frac{1}{\xi}\right)$$

- i the quark flavor

- B^i_{nl} and C^i_{nl} unknown form factors

- Formula is written for singlet combinations of the GPDs, $H^i(x,\xi,t) \equiv H^i(x,\xi,t) - H^i(-x,\xi,t)$ and $E^i(x,\xi,t) \equiv E^i(x,\xi,t) - E^i(-x,\xi,t)$

- The important property of polynomiality is by construction

Main features of dual parameterization

- Easy QCD evolution to leading order accuracy

$$B^i_{nl}(\mu^2) = B^i_{nl}(\mu_0^2)\left(\frac{\ln(\mu_0^2/\Lambda^2)}{\ln(\mu^2/\Lambda^2)}\right)^{\gamma_n/B}$$

  - γ_n anomalous dimension
  - $B = 11 - (2/3)n_{\text{flav}}$

- Simple expression for the Compton Form Factors to the LO accuracy (see later) $\longrightarrow$ use the dual parameterization of the GPDs as a **LO parameterization**.

- The formal series diverge $\longrightarrow$ cannot be used in this form to study GPDs themselves. However, the series can be decomposed over other orthogonal polynomials on $x \in [-1, 1]$ (Belitsky *et al.*, 1997) or it can actually be summed using the trick of Polyakov and Shuvaev.

Polyakov-Shuvaev trick

Let us introduce of a set of generating functions Q_k^i and R_k^i

$$B^i_{n\,n+1-k}(t,\mu^2) = \int_0^1 dx\, x^n Q_k^i(x,t,\mu^2)$$

$$C^i_{n\,n+1-k}(t,\mu^2) = \int_0^1 dx\, x^n R_k^i(x,t,\mu^2) \rightarrow$$

$$H^i(x,\xi,t,\mu^2) = \sum_{\substack{k=0\\ \text{even}}}^{\infty} \Big[\frac{\xi^k}{2}\left(H^{i\,(k)}(x,\xi,t,\mu^2) - H^{i\,(k)}(-x,\xi,t,\mu^2)\right)$$

$$+ \quad \left(1-\frac{x^2}{\xi^2}\right)\theta\left(\xi-|x|\right)\sum_{\substack{l=1\\ \text{odd}}}^{k-3} C^{3/2}_{k-l-2}\left(\frac{x}{\xi}\right)P_l\left(\frac{1}{\xi}\right)\int_0^1 dy\, y^{k-l-2}\, Q_k^i(y,t,\mu^2)\Big]$$

$$H^{i\,(k)}(x,\xi,t,\mu^2) = \frac{1}{\pi}\int_0^1 \frac{dy}{y}\left[\left(1-y\frac{\partial}{\partial y}\right)Q_k^i(y,t,\mu^2)\right]\int_{-1}^1 ds \frac{x_s^{1-k}}{\sqrt{2x_s - x_s^2 - \xi^2}}\theta(2x_s - x_s^2 - \xi^2)$$

$$- \quad \lim_{y\rightarrow 0} Q_k^i(y,t,\mu^2)\int_{-1}^1 ds \frac{x_s^{1-k}}{\sqrt{2x_s - x_s^2 - \xi^2}}\theta(2x_s - x_s^2 - \xi^2)$$

Minimal model of the dual parameterization ($t = 0$)

Essence of the minimal model: GPDs H^i and E^i are expressed in terms of the forward parton distributions, unknown forward limit of E^i and Gegenbauer moments of the D-term.

- Keep only Q_0^i and Q_2^i for H^i and R_0^i and R_2^i for E^i.
  In the HERA kinematics ($\xi < 0.005$), the contribution of Q_k^i and R_k^i with $k \geq 2$ is kinematically suppressed by ξ^k.
  In HERMES kinematics ($\xi < 0.1$), we keep Q_2^i and R_2^i as a first correction.

- Relation between Mellin moments of H^i and form factors B_{nl}^i in the $\xi \to 0$ limit

$$B_{n\,n+1}^i(t,\mu^2) = \frac{2n+3}{2n+4}\int_{-1}^{1} dx\, x^n H^i(x,0,t,\mu^2) \equiv \frac{2n+3}{2n+4}\int_{0}^{1} dx\, x^n \left(q^i(x,t,\mu^2) + \bar{q}^i\right)$$

$$C_{n\,n+1}^i(t,\mu^2) = \frac{2n+2}{2n+4}\int_{-1}^{1} dx\, x^n E^i(x,0,t,\mu^2) \equiv \frac{2n+3}{2n+4}\int_{0}^{1} dx\, x^n \left(e^i(x,t,\mu^2) + \bar{e}^i\right)$$

- Since all B^i_{nn+1} and C^i_{nn+1} are fixed, the generating functions Q^i_0 and R^i_0 can be restored

$$Q^i_0(x,t,\mu^2) = q^i(x,t,\mu^2) + \bar{q}^i(x,t,\mu^2) - \frac{x}{2}\int_x^1 \frac{dz}{z^2}\Big(q^i(z,t,\mu^2) + \bar{q}^i(z,t,\mu^2)\Big)$$

$$R^i_0(x,t,\mu^2) = e^i(x,t,\mu^2) + \bar{e}^i(x,t,\mu^2) - \frac{x}{2}\int_x^1 \frac{dz}{z^2}\Big(e^i(z,t,\mu^2) + \bar{e}^i(z,t,\mu^2)\Big)$$

In $t \rightarrow 0$ limit , $q^i(x,t,\mu^2) + \bar{q}^i(x,t,\mu^2)$ become the singlet singlet combination of forward quark distribution and $e^i(x,t,\mu^2) + \bar{e}^i(x,t,\mu^2)$ become the unknown forward limit of the singlet combination GPDs E^i

Therefore, up to the t-dependence, the leading functions Q^i_0 and R^i_0 are completely constrained by the forward parton distributions and the forward limit of the GPDs E^i.

- Since the GPDs E^i decouple in the forward limit, the functions $e^i + \bar{e}^i$ are unconstrained. We followed the simple model of Goeke *et al.*, 2001

$$e^i(x,\mu^2) = A_i(\mu^2)\, q^i_{\mathrm{val}}(x,\mu^2) + \frac{B_i(\mu^2)}{2}\,\delta(x)$$
$$\bar{e}^i(x) = \frac{B_i(\mu^2)}{2}\,\delta(x)$$

where

$$A_i(\mu^2) = \frac{\mathbf{2J^i}(\mu^2) - M_2^i(\mu^2)}{M_2^{i,\mathrm{val}}}$$
$$B_u(\mu^2) = k_u - 2\,A_u(\mu^2)\,, \quad B_d(\mu^2) = k_d - A_d(\mu^2)$$

- Similarly to the construction of the GPD H, the GPD $\tilde{H}^q$ can be constructed using the forward polarized PDFs Δq.

- Functions Q_2^i and R_2^i are not so well-constrained, only their Mellin moments are known. From

$$B^i_{nn-1}(t,\mu^2) = \frac{n}{n+1} B^i_{nn+1}(t,\mu^2) + \frac{d^i_n(t,\mu^2)}{P_{n-1}(0)} \,,$$

  where d_n are Gegenbauer moments of the D-term, we find

$$Q_2^i(x,t,\mu^2) = Q_0^i(x,t,\mu^2) - \int_x^1 \frac{dz}{z} Q_0^i(z,t,\mu^2) + \tilde{Q}_2^i(x,t,\mu^2)$$

  where

$$\int_0^1 dx\, x^n\, \tilde{Q}_2^i(x,t,\mu^2) = \frac{d^i_n(t,\mu^2)}{P_{n-1}(0)}$$

  The Gegenbauer moments d_n^i are taken from the chiral quark soliton model.

- Since the D-term contribution to the GPDs E^i and H^i are equal and opposite in sign,

$$R_2^i(x,t,\mu^2) = R_0^i(x,t,\mu^2) - \int_x^1 \frac{dz}{z} R_0^i(z,t,\mu^2) - \tilde{Q}_2^i(x,t,\mu^2)$$

Models of t-dependence

- Factorized exponential t-dependence

$$H^i(x,\xi,t,\mu^2) = \exp\left(\frac{B(\mu^2)\,t}{2}\right) H^i(x,\xi,t=0,\mu^2)$$

$$E^i(x,\xi,t,\mu^2) = \exp\left(\frac{B(\mu^2)\,t}{2}\right) E^i(x,\xi,t=0,\mu^2)$$

with Q^2-dependent slope

$$B(\mu^2) = 7.6\,\left(1 - 0.15\,\ln(\mu^2/2)\right)\ \mathrm{GeV}^2$$

- The value of the slope is chosen to reproduce the only measurement of differential DVCS cross section by H1 at HERA fitted to the exponential form: $B(\mu^2 = 8\ \mathrm{GeV}^2) = 6.02 \pm 0.35 \pm 0.39$ GeV^{-2}, Aktas *et al.*, 2005.
- The slight decrease of the slope is expected on general grounds.

- Non-factorizable Regge-motivated t-dependence

$$q^i(x,t,\mu_0^2) - \bar{q}^i(x,t,\mu_0^2) = q^i_{\mathrm{val}}(x,t,\mu_0^2) = \left(\frac{1}{x^{\alpha'_{\mathrm{val}}t}}\right) q^i_{\mathrm{val}}(x,\mu_0^2)$$

$$q^i(x,t,\mu_0^2) + \bar{q}^i(x,t,\mu_0^2) = \left(\frac{1}{x^{\alpha' t}}\right) \left[q^i(x,\mu_0^2) + \bar{q}^i(x,\mu_0^2)\right]$$

$$g(x,t,\mu_0^2) = \left(\frac{1}{x^{\alpha'_g t}}\right) g(x,\mu_0^2)$$

$$\boxed{\alpha'_{\mathrm{val}} = 1.1(1-x)\ \mathrm{GeV}^{-2}\,, \quad \alpha' = 0.9\ \mathrm{GeV}^{-2}\,, \quad \alpha'_g = 0.5\ \mathrm{GeV}^{-2}}$$

Note that the data on σ_{DVCS} forces us to take $\alpha', \alpha'_g > \alpha_{I\!P} = 0.25\ \mathrm{GeV}^{-2}$.

- For the D-term, we use the results of the lattice calculations, Gockeler *et al.*, 2003

$$d_i^{u,d}(t) = d_i^{u,d}(t=0)\frac{1}{(1-t/M_D^2)^2}\,, \quad M_D = 1.11 \pm 0.20\ \mathrm{GeV}$$

Improved model of t-dependence (due to M. Diehl)

The value $\alpha'_g = 0.5$ GeV^{-2} is unrealistically large. It probably comes from the too rigid model of the Regge-motivated t-dependence.

A more general form:

$$g(x, t, \mu_0^2) = e^{B_g t} \left(\frac{1}{x^{\alpha'_g t}} \right) g(x, \mu_0^2)$$

with $B_g \sim 1$ GeV^{-2}, should lead to a much smaller α'_g.

DVCS cross section in HERA kinematics

- The DVCS cross section on the photon level

$$\sigma_{\rm DVCS}(x_B, Q^2) = \frac{\pi\alpha^2 x_B^2}{Q^4\sqrt{1+4m_N^2 x^2/Q^2}} \int_{t_{\rm min}}^{t_{\rm max}} dt\, |\mathcal{A}_{\rm DVCS}(\xi, t, Q^2)|^2$$

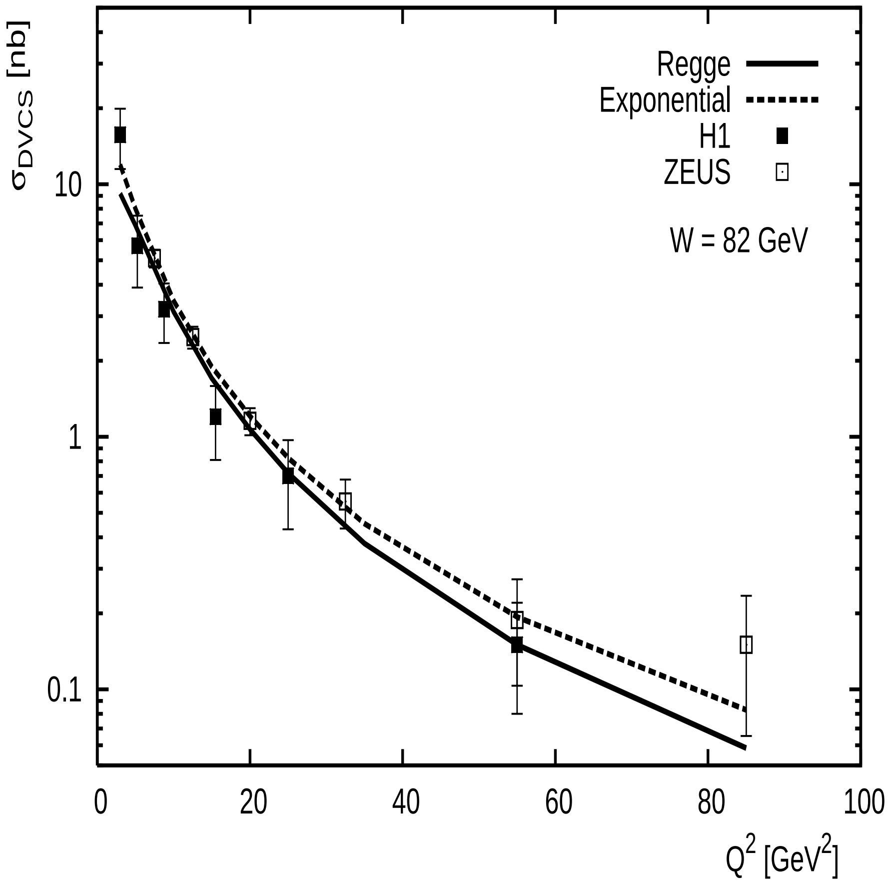
  - In the small-ξ limit, $|\mathcal{A}_{\rm DVCS}(\xi, t, Q^2)|^2 \approx |\mathcal{H}|^2(1-\xi^2)$
  -

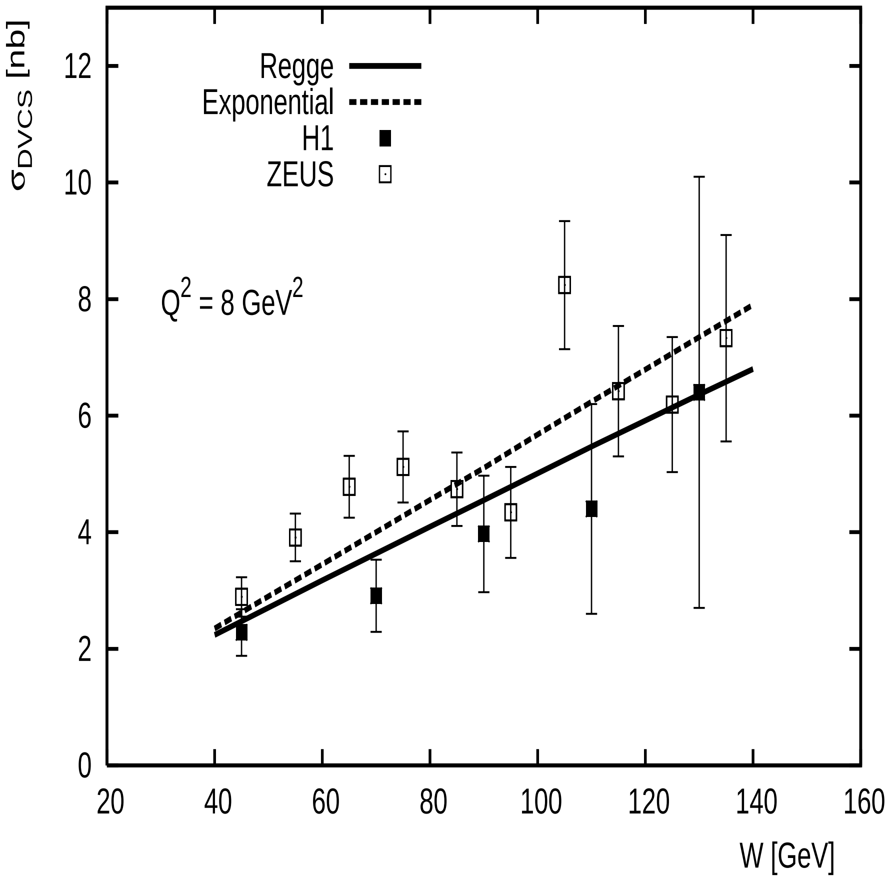
$$\mathcal{H}(\xi, t, Q^2) = \sum_i e_i^2 \int_0^1 dx\, H^i(x, \xi, t, Q^2)\left(\frac{1}{x-\xi+i0} + \frac{1}{x+\xi-i0}\right)$$

- One appealing feature of the dual parameterization is that the convolution integral can be easily taken

$$\mathcal{H}(\xi, t, Q^2) = -\sum_i e_i^2 \int_0^1 \frac{dx}{x} \sum_{k=0}^{\infty} x^k Q_k^i(x, t, Q^2)\left(\frac{1}{\sqrt{1-\frac{2x}{\xi}+x^2}} + \frac{1}{\sqrt{1+\frac{2x}{\xi}+x^2}} - 2\delta_{k0}\right)$$

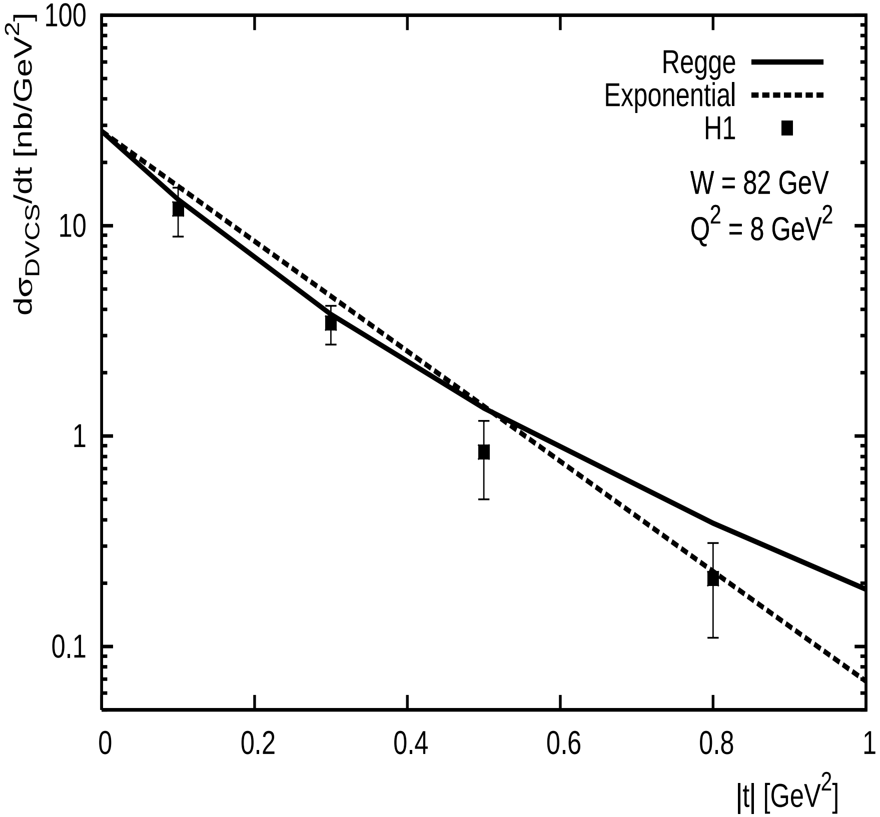
- Moreover, in the HERA kinematics, only Q_0^i which is given by forward PDFs, is important $\rightarrow$ **parameter-free*** predictions for the DVCS cross section.





- The differential DVCS cross section

$$\frac{d\sigma_{\rm DVCS}(x_B,t,Q^2)}{dt} = \frac{\pi\alpha^2 x_B^2}{Q^4\sqrt{1+4m_N^2 x^2/Q^2}}|\mathcal{A}_{\rm DVCS}(\xi,t,Q^2)|^2$$



Beam-spin asymmetry in HERMES kinematics

- The approximate expression for the $\sin\phi$-moment of the beam-spin asymmetry, Belitsky *et al.*, 2001

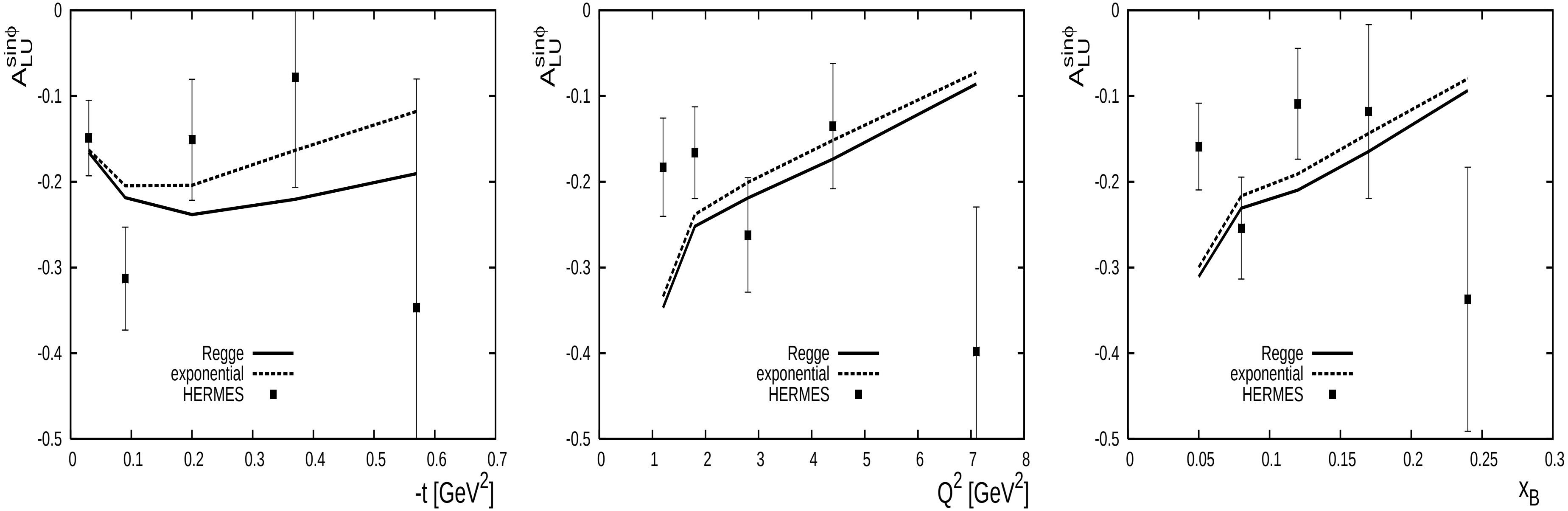
$$A_{LU}^{\sin\phi} \approx \left(\frac{x_B}{y}\right) 8\, K\, y\,(2-y)(1+\epsilon^2)^2 \, \frac{\left[F_1(t)\, Im\,\mathcal{H}(\xi,t) + \frac{|t|}{4m_N^2} F_2(t)\, Im\,\mathcal{E}(\xi,t)\right]}{c_{0,\mathrm{unp}}^{\mathrm{BH}}}$$

- The dual parameterization predictions compare very well to the HERMES measurement at $\langle x_B\rangle = 0.11$, $\langle Q^2\rangle = 2.6$ GeV^2 and $\langle t\rangle = -0.27$ GeV^2

$$A_{LU}^{\sin\phi} = -0.22\ldots-0.24\,, \quad \text{exponential } t-\text{dependence}$$
$$A_{LU}^{\sin\phi} = -0.27\ldots-0.29\,, \quad \text{Regge } t-\text{dependence}$$
$$A_{LU}^{\sin\phi} = -0.23\pm0.04\pm0.03\,, \quad \text{HERMES (Airapetian, 2001)}$$

The range of theoretical prediction comes from varying $0 \le J_u \le 0.4$.

- Comparison of the dual parameterization predictions for the $A_{LU}^{\sin\phi}$ dependence on t, Q^2 and x_B in the HERMES kinematics, F. Ellinghaus, Ph.D. thesis, 2004.



- The calculation is done with $J_u = J_d = 0$, but the sensitivity to the model for the GPD E is weak.

- Apart from the last point, the data is described by both models fairly well.

Beam-spin asymmetry in CLAS kinematics

The 2001 average kinematic point of the CLAS kinematics: $E = 4.25$ GeV, $\langle Q^2 \rangle = 1.25$ GeV^2, $\langle x_B \rangle = 0.19$ and $\langle t \rangle = -0.19$ GeV^2, experimental value,

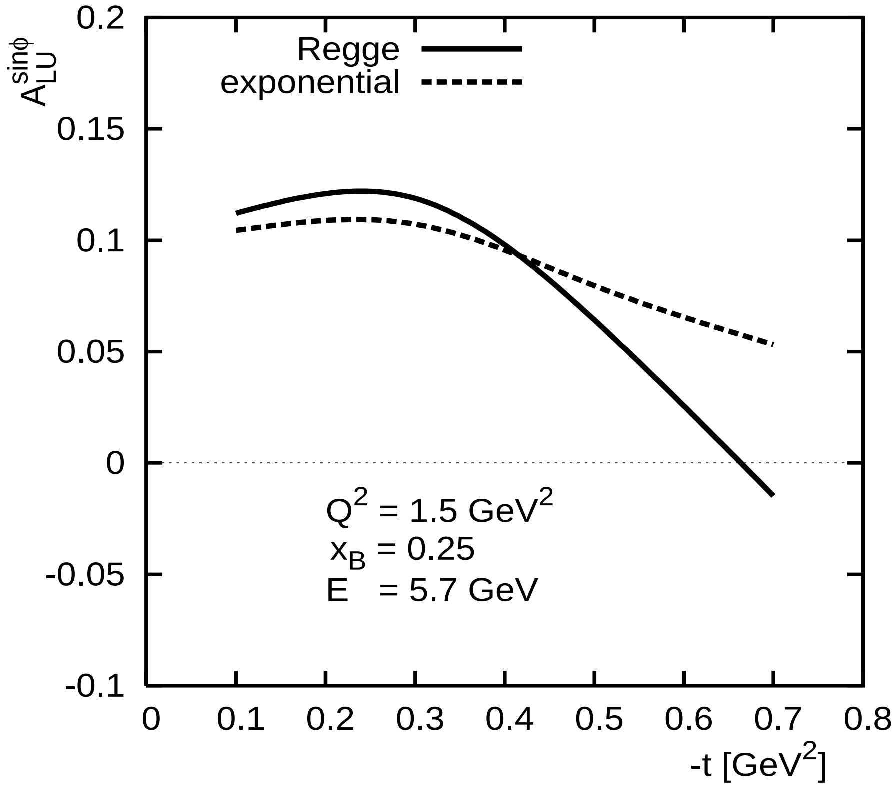
$$A_{LU}^{\sin\phi} = 0.15 \ldots 0.17\,, \quad \text{exponential } t - \text{dependence}$$

$$A_{LU}^{\sin\phi} = 0.18 \ldots 0.20\,, \quad \text{Regge } t - \text{dependence}$$

$$A_{LU}^{\sin\phi} = 0.202 \pm 0.028\,, \quad \text{CLAS (Stepanyan, 2001)}$$

The range of theoretical prediction comes from varying $0 \leq J_u \leq 0.4$.

Calculations of $A_{LU}^{\sin\phi}$ in the present CLAS kinematics: $E = 5.7$ GeV, $Q^2 = 1.5$ GeV^2 and $x_B = 0.25$.



Note that our model becomes unstable starting from $x_B = 0.2 - 0.3$.

Beam-charge asymmetry in HERMES kinematics

- The approximate expression for the $\cos\phi$-moment of the beam-charge asymmetry, Belitsky *et al.*, 2001

$$A_C^{\cos\phi} \approx \left(\frac{x_B}{y}\right) 8\,K\,(2-2y+y^2)\,\left(1+\epsilon^2\right)^2 \frac{\left[F_1(t)\,Re\,\mathcal{H}(\xi,t) + \frac{|t|}{4m_N^2} F_2(t)\,Re\,\mathcal{E}(\xi,t)\right]}{c_{0,\mathrm{unp}}^{\mathrm{BH}}}$$

- The dual parameterization predictions in the average HERMES kinematics, $\langle x_B\rangle = 0.12$, $\langle Q^2\rangle = 2.8$ GeV^2 and $\langle t\rangle = -0.27$ GeV^2

$$A_C^{\cos\phi} = 0.010\ldots 0.030\,, \quad \text{exponential } t-\text{dependence}$$

$$A_C^{\cos\phi} = 0.19\ldots 0.23\,, \quad \text{Regge } t-\text{dependence}$$

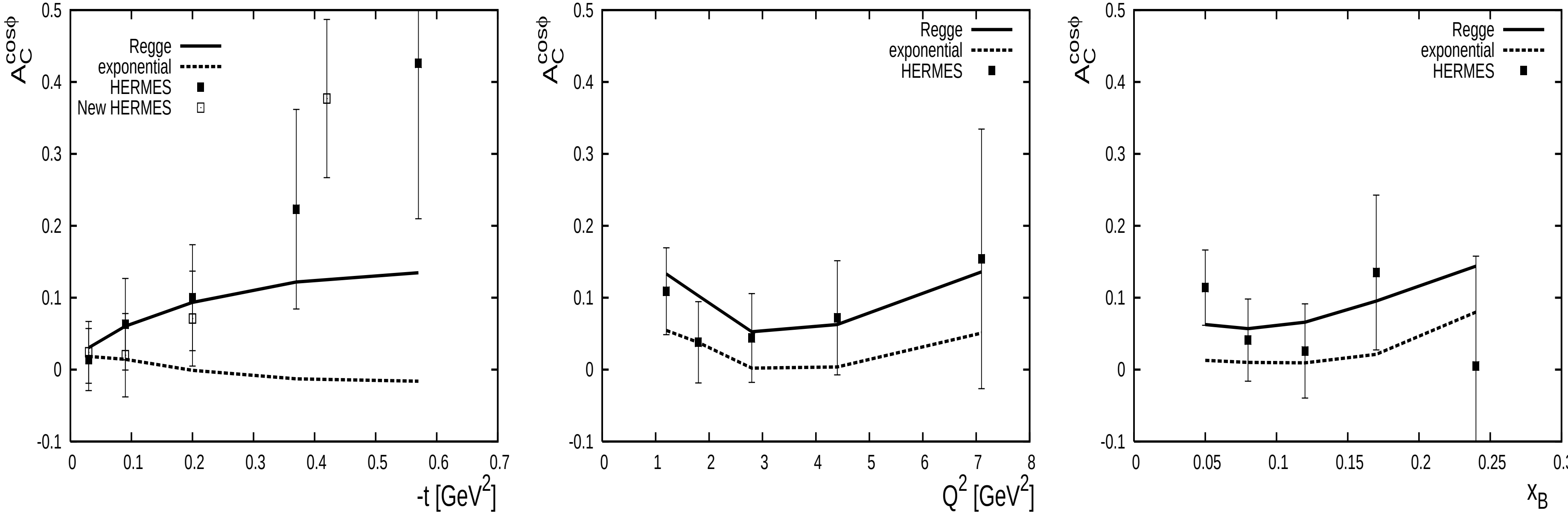
$$A_C^{\cos\phi} = 0.11 \pm 0.04 \pm 0.03\,, \quad \text{HERMES (2002, unpub.)}$$

The range of theoretical prediction comes from varying $0 \le J_u \le 0.4$.

- Also for the 2006 HERMES kinematics: $\langle x_B \rangle = 0.10$, $\langle Q^2 \rangle = 2.5$ GeV^2 and $\langle t \rangle = -0.12$ GeV^2

$$A_C^{\cos\phi} = 0.013 \ldots 0.022\,, \quad \text{exponential } t-\text{dependence}\,,$$
$$A_C^{\cos\phi} = 0.080 \ldots 0.092\,, \quad \text{Regge } t-\text{dependence}\,,$$
$$A_C^{\cos\phi} = 0.063 \pm 0.029 \pm 0.026\,, \quad (\text{HERMES}, 2006)$$

- Comparison of the dual parameterization predictions for the $A_C^{\cos\phi}$ dependence on t, Q^2 and x_B to the analysis (F. Ellinghaus, Ph.D. thesis, 2004) and to new HERMES data (Airapetian, 2006).



- The calculation is done with $J_u = J_d = 0$.

- The Regge model of the t-dependence gives a much better description of the data.

Transversely-polarized target asymmetry in HERMES kinematics

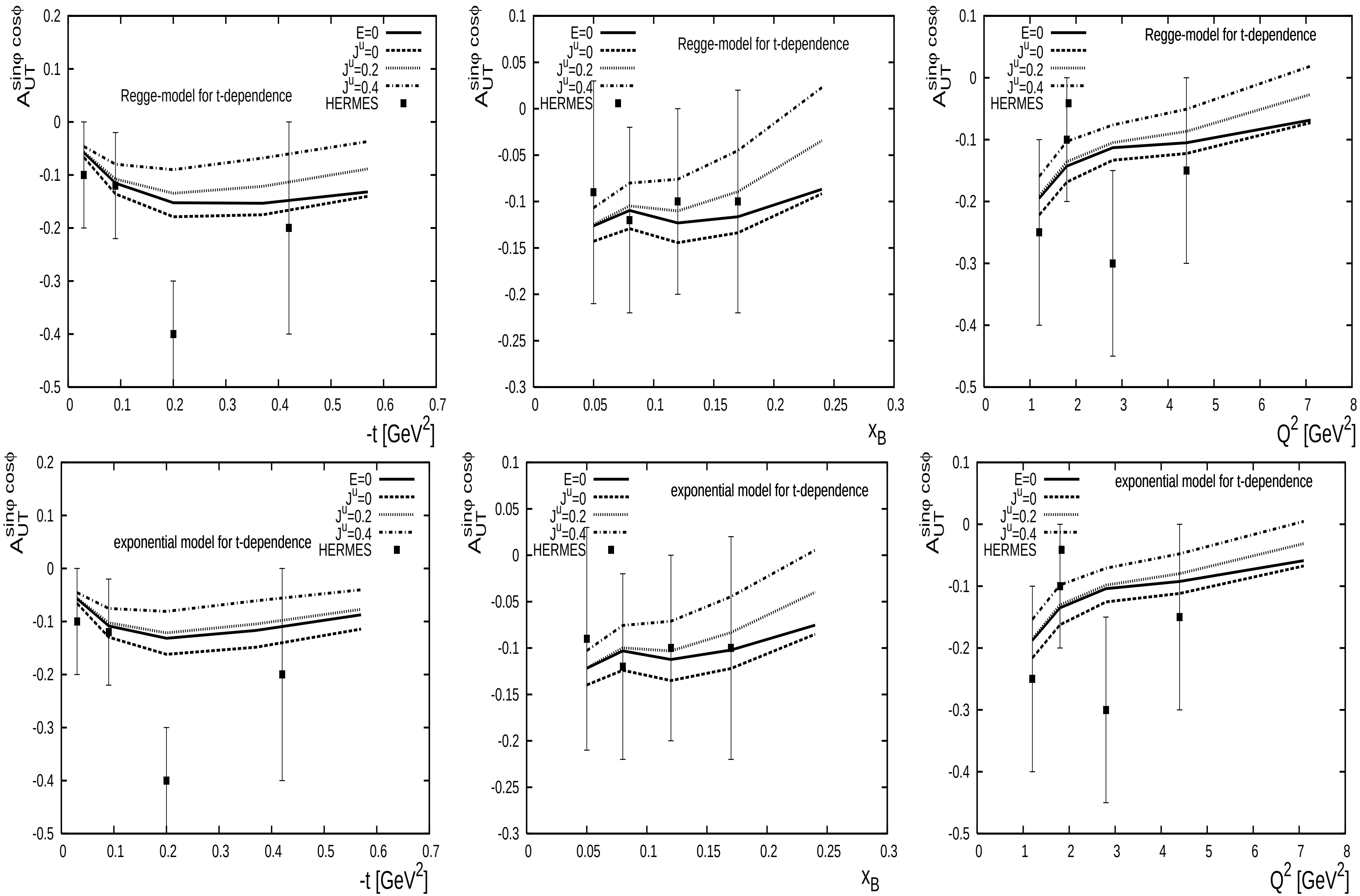
- The $\sin\phi$-$\cos\varphi$-moment of the transversely-polarized target (unpolarized beam) asymmetry is sensitive to the GPD E, Belitsky *et al.*, 2001

$$A_{UT}^{\sin\phi\ \cos\varphi} = A_{UT}^{\sin(\phi-\phi_S)\ \cos\phi} \propto F_2(t)\, Im\,\mathcal{H}(\xi,t) - F_1(t)\, Im\,\mathcal{E}(\xi,t)$$

- Can be used to discriminate between different models of the GPD E

- Can be used to determine the total angular momentum carried by quarks, Ellinghaus, Nowak, Vinnikov, Ye, 2005.

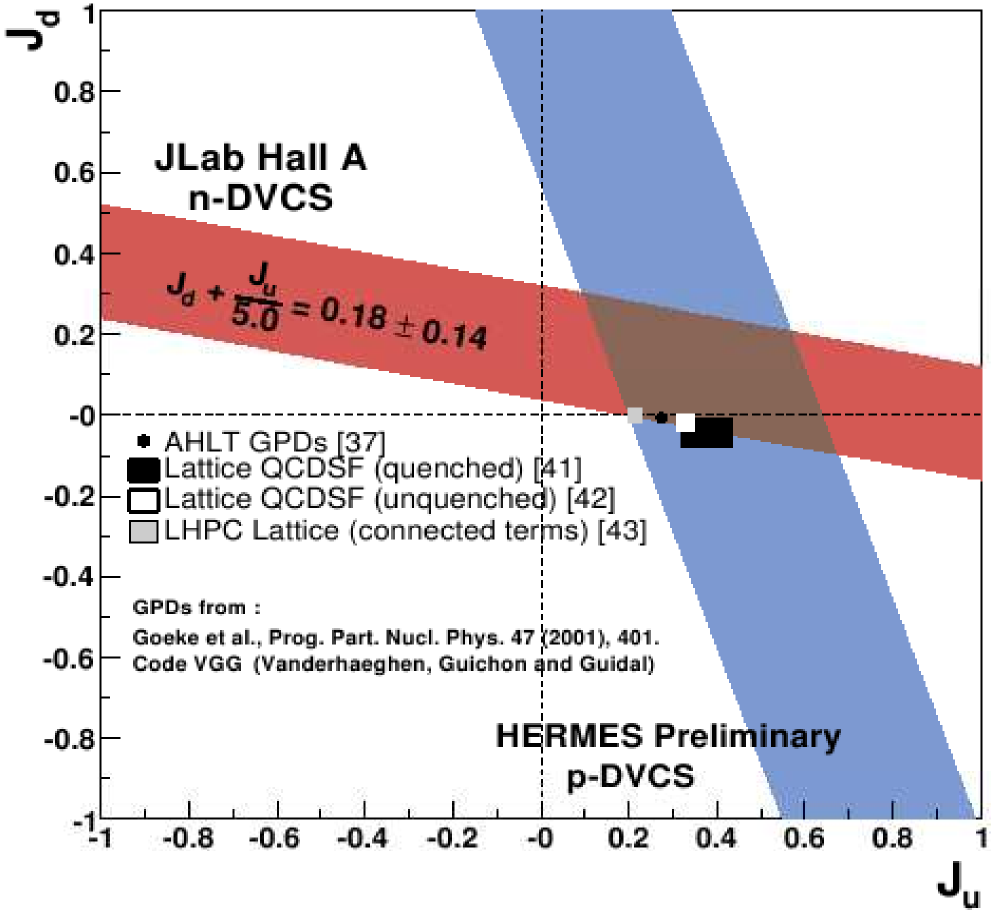
- The dual parameterization predictions for $A_{UT}^{\sin(\phi-\phi_S)\ \cos\phi}$ can be compared to the preliminary HERMES data, Ye, 2005. However, because of large experimental errors, no quantitative conclusion from the comparison can be made.



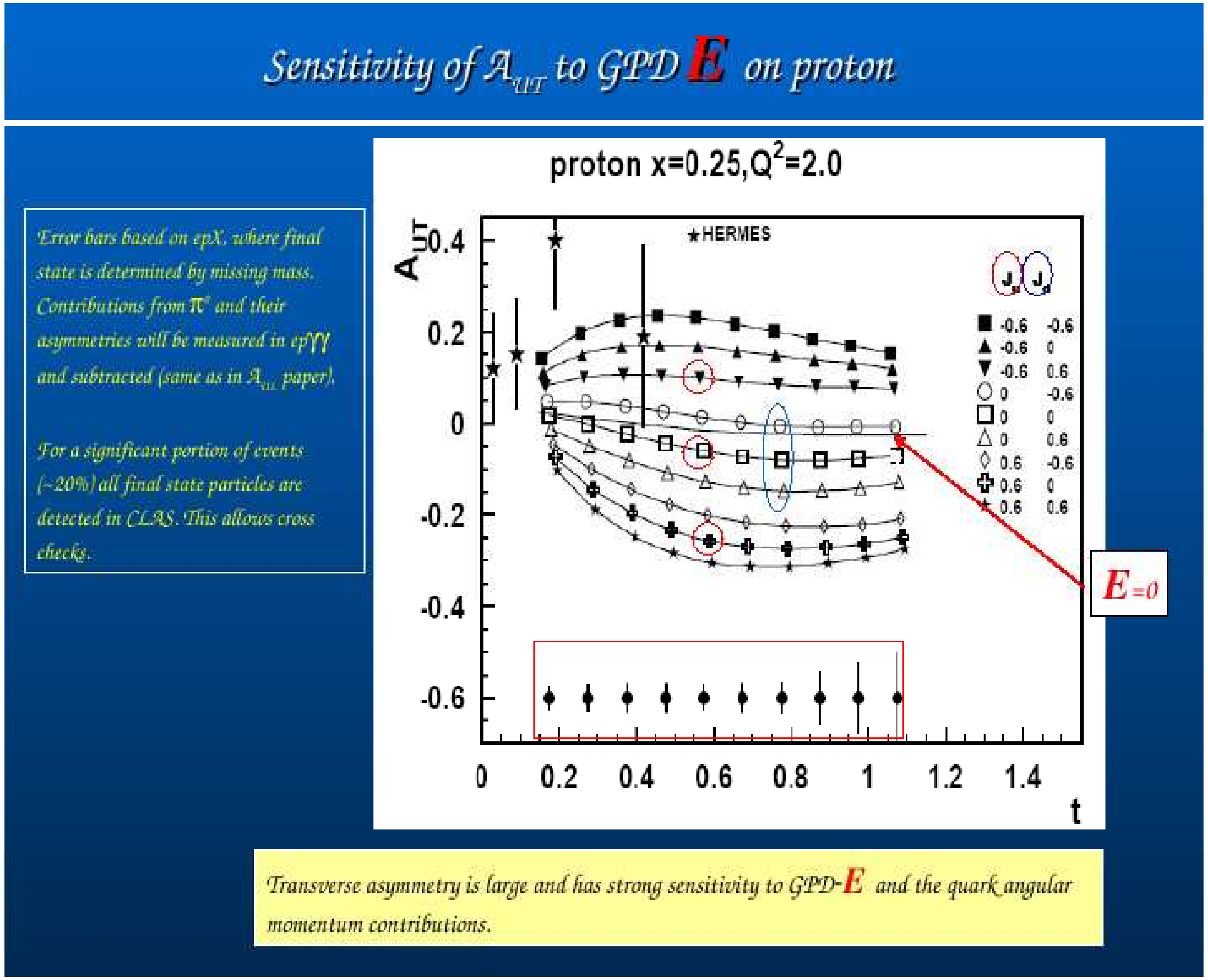
$A_{UT}^{\sin\varphi\cos\phi}$
E=0
J^u=0
J^u=0.2
J^u=0.4
HERMES
Regge-model for t-dependence
exponential model for t-dependence
-t [GeV^2]
x_B
Q^2 [GeV^2]

GPDs and the proton spin crisis

$$\frac{1}{2} = J^q + J^g = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$



Future GPD measurements with transverse target at JLab
H. Avakian *et al.*, JLab proposal PR-08-021 (2008)



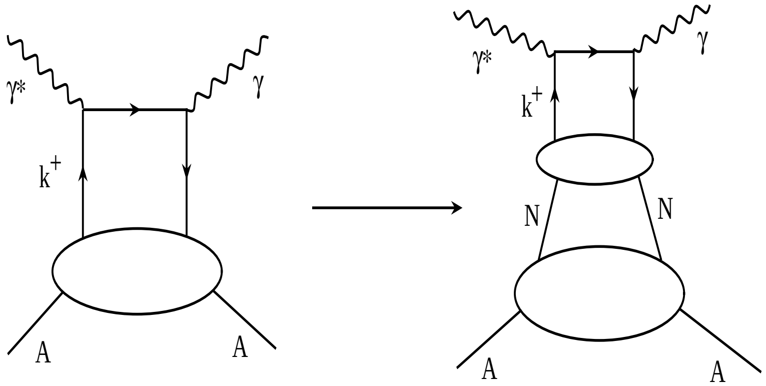
Dual parameterization of nuclear GPDs

Three roles of nuclear GPDs and nuclear DVCS:

- To give information of the nucleon GPDs (neutron) complimentary to experiments on the protons
- To access novel nuclear effects not present in DIS and in elastic scattering on nuclei
  - Non-nucleonic degrees of freedom
  - Off-forward EMC effect
  - Nuclear shadowing and antishadowing in the real and imaginary parts of the nuclear DVCS amplitude
- To provide constraints on theoretical models of nuclear structure
  - Relativistic description is important for polynomiality

A simple constituent model for nuclear GPDs

- Assume that the nuclear GPDs is a sum of the free nucleon GPDs (spin-0 nucleus)
  A. Kirchner and D. Mueller, Eur. Phys. J. C **32** (2003) 347 [arXiv:hep-ph/0302007].



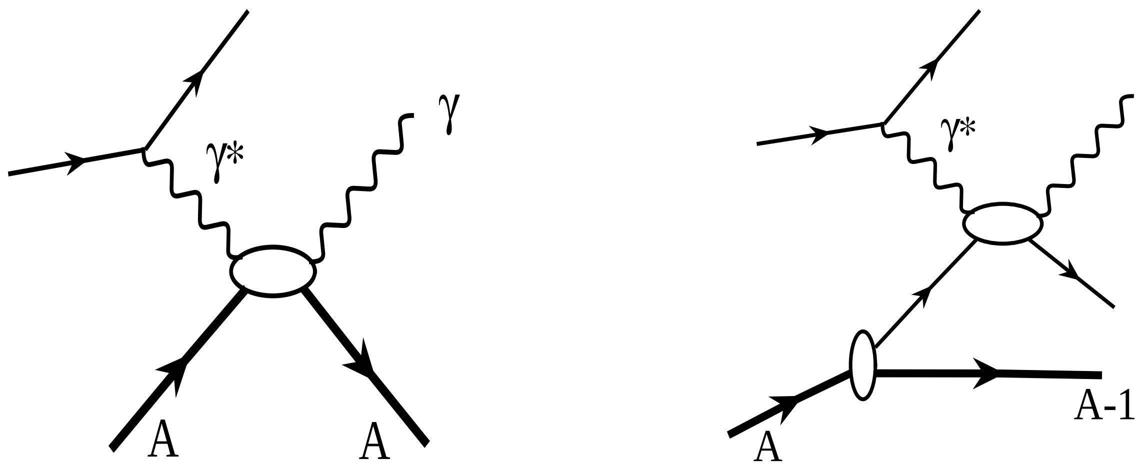
$$\begin{aligned} H_A^q(x, \xi_A, Q^2, t) &= \left|\frac{dx_N}{dx}\right| \left[Z \left(H^{q/p}(x_N, \xi_N, Q^2, t) + \frac{t}{4m_N^2} E^{q/p}(x_N, \xi_N, Q^2, t) \right) \right. \\ &+ \left. N \left(H^{q/n}(x_N, \xi_N, Q^2, t) + \frac{t}{4m_N^2} E^{q/n}(x_N, \xi_N, Q^2, t) \right) \right] F_A(t) \end{aligned}$$

The simple model of nuclear GPDs

- Ignores nuclear modifications and uses free nucleon GPDs (dual parameterization)
- Has the correct forward limit and the nuclear form factor
- Does not satisfy polynomiality

Coherent and incoherent contributions

- When the recoiled nucleus not detected, DVCS observables receive coherent and incoherent contributions.



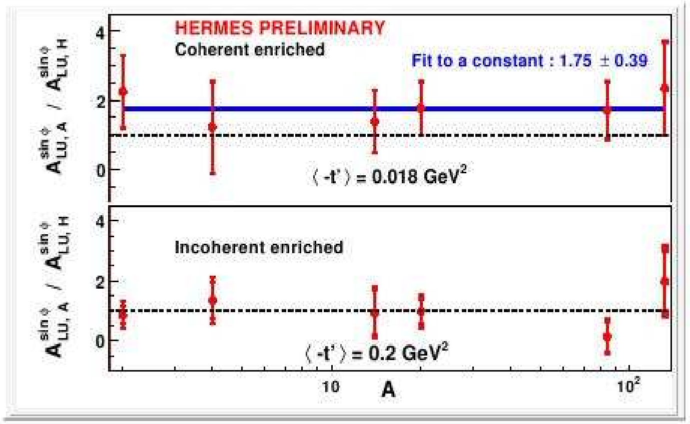
- Coherent dominates at small t; Incoherent dominates at large t

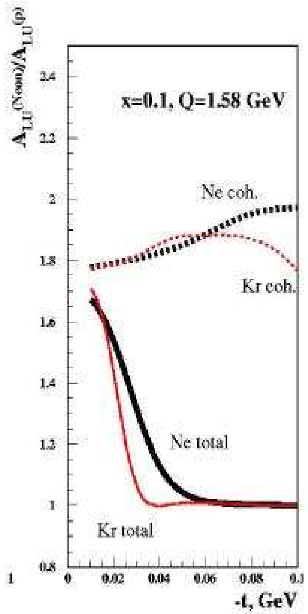
- One can write an interpolation formula between the two regimes
  V. Guzey and M. Strikman, Phys. Rev. C68 (2003) 015204

Nuclear beam-spin asymmetry A_{LU}

$$A_{LU}(\phi) = \frac{Z(A-1)F_A^2(t)\{\mathcal{I}_A\} + F_N(t)\left(Z\{\mathcal{I}_p\} + N\{\mathcal{I}_n\}\right)}{Z(Z-1)\{\mathrm{BH}_A\} + Z(A-1)\{\mathcal{I}_A\} + A(A-1)\{\mathrm{DVCS}_A\} + Z\{\mathrm{BH}_N\} + Z\{\mathcal{I}_N\} + A\{\mathrm{DVCS}_N\}}$$

Ratio A_{LU}^A / A_{LU}^p (Method 1)

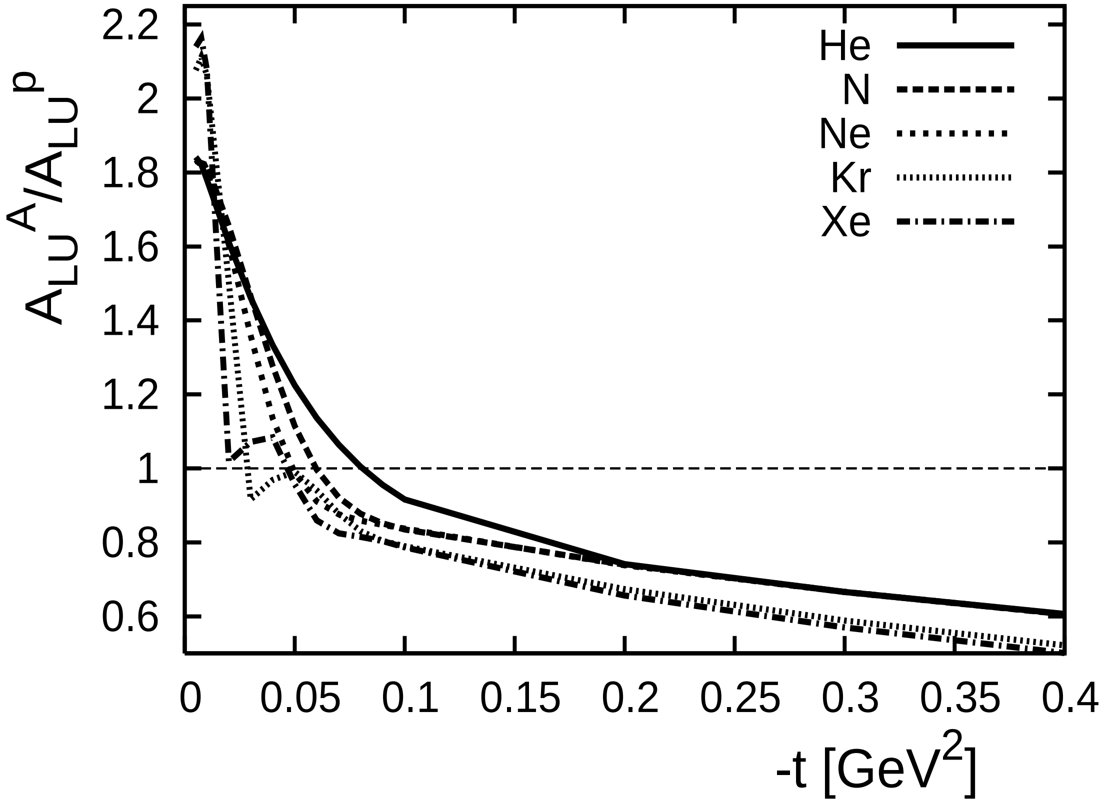




- Coherent enriched: mean ratio deviates from unity by 2σ. Consistent with predictions between 1.8 and 1.95: Guzey/Strikman Phys.Rev.C 68 (2003)
- Incoherent enriched: Consistent with unity as naively expected

Frank Ellinghaus, University of Maryland, October 2006 6

Nuclear beam-spin asymmetry A_{LU} (keep the neutron)

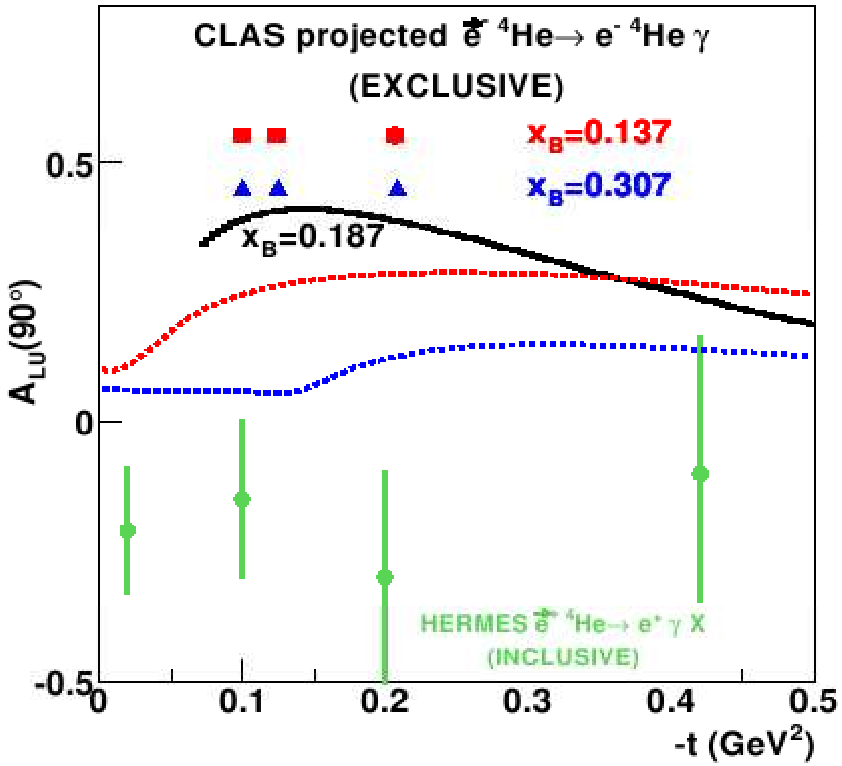


V. Guzey, ArXiv:0801.3235 [nucl-th] (2008)

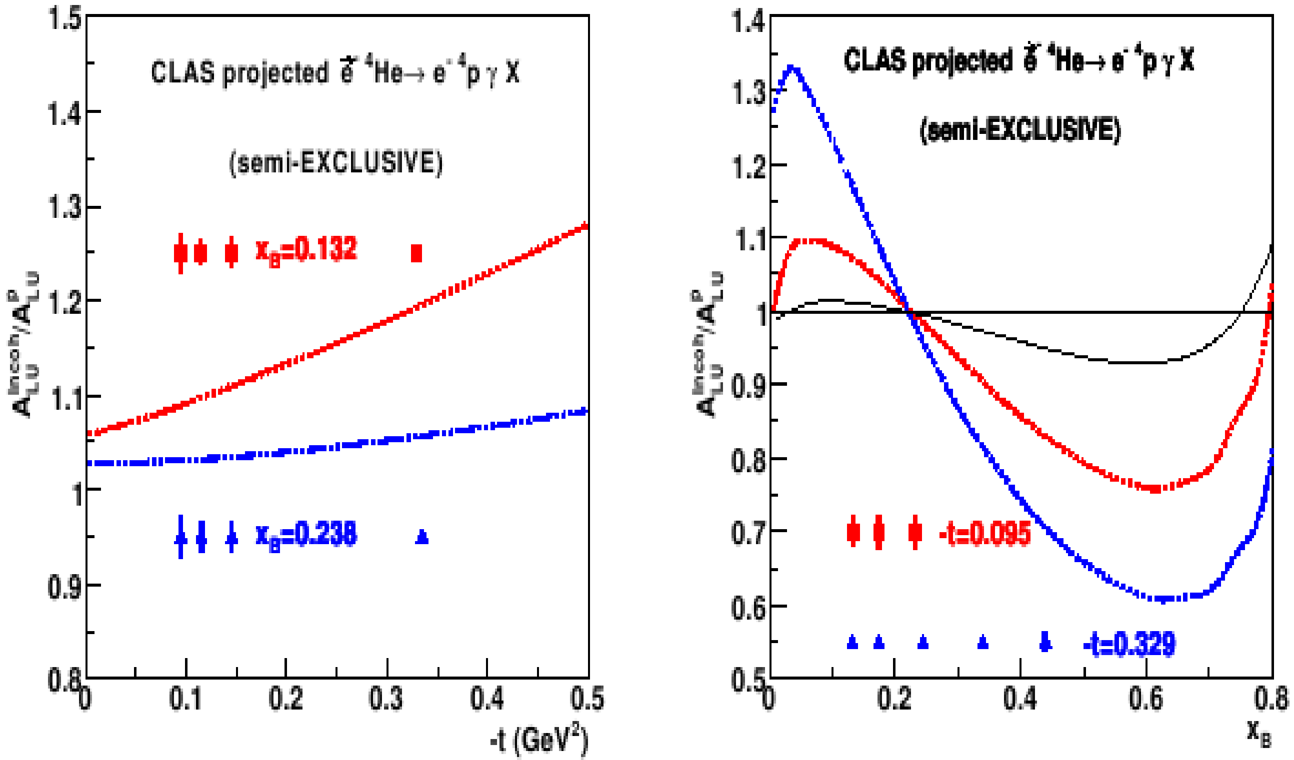
- Use incoherent DVCS to measure the neutron GPDs

Nuclear DVCS on ^{4}He at JLab
K. Hafidi *et al.*, JLab proposal PR-08-024 (2008)

- Measure coherent DVCS on ^{4}He using the BoNuS Detector; for the first time and with large accuracy



- In addition, the incoherent measurement $\vec{e}\,^4\mathrm{He} \to epX$ will probe nuclear modifications of the proton GPDs.



S. Liuti and S. K. Taneja (2005)

Conclusions and discussion

- Dual parameterization of nucleon GPDs is a new LO parameterization of GPDs H and E which
  - Has a simple QCD evolution
  - Allows for an economical and good description of all available data on DVCS
  - Works best for $x_B < 0.1 - 0.2$

- Recent theoretical and phenomenological work on the dual parameterization: twist-3, reconstruction of GPDs using the DVCS amplitude, dispersion relations.

- Nuclear DVCS is a new tool to study microscopic structure of nucleons and nuclei.
  - A wide-open field for theorists (relativistic description of nuclear structure, small-x nuclear GPDs, FSI)
  - The future high-precision JLab data on DVCS on ^{4}He will be an important step