Dual parameterization of nucleon and nuclear GPDs

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References:

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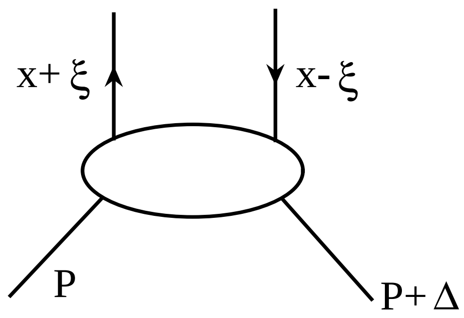
Introduction

- Generalized Parton Distributions (GPDs) of a hadron (nucleon, pion, nucleus) describe correlations of partons in the target. For the nucleon

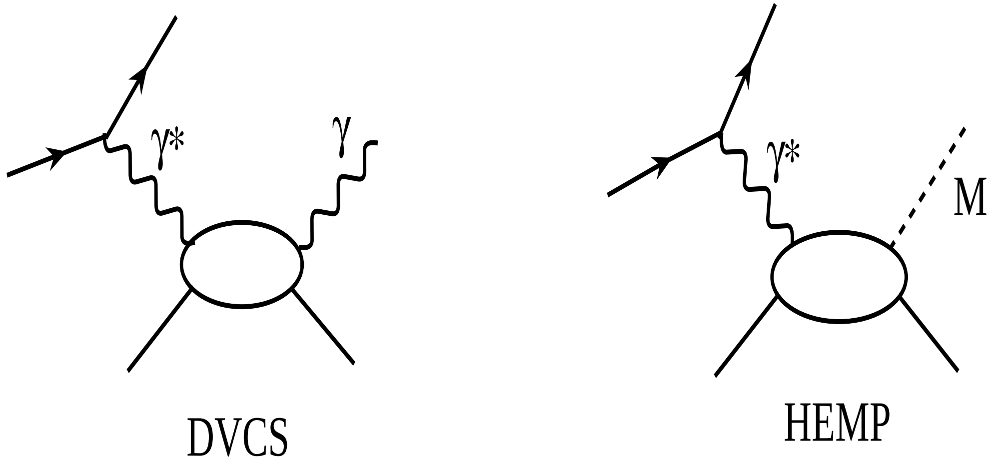
$$\bar{P}^+ \int \frac{dz^-}{2\pi} e^{ix\bar{P}^+ z^-} \left\langle P' | \bar{\psi}\left(-\frac{z^-}{2}\right) \gamma_+ \psi \left(\frac{z^-}{2}\right) | P \right\rangle = H(x,\xi,t)\bar{N}(P')\gamma^+ N(P) + E(x,\xi,t)\bar{N}(P')\frac{i\sigma^{+\mu}\Delta^\mu}{2m_N}N(P)$$

- Schematically



- GPDs contain more microscopic information about the parton structure of the target than usual parton distributions 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

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

- 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

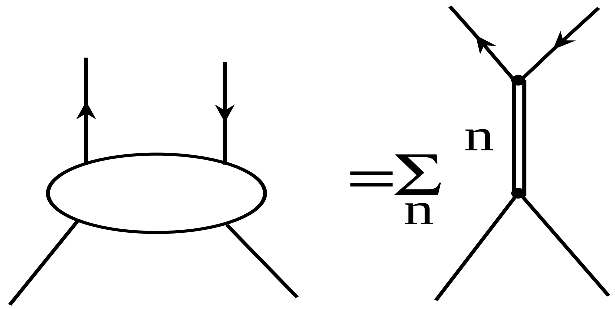
$$\mathcal{H}(\xi, t, Q^2) = \sum e_q^2 \int_0^1 dx\, H^q(x, \xi, t, Q^2) \left(\frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right)$$

- 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



- Duality in hadronic physics – 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.

- The dual representation of quark GPDs of the pion is a formal solution reproducing Mellin moments of the pion GPDs, M. Polyakov, 1998.

- **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

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

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

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

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

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

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

- 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
  - $B = 11 - (2/3)n_{\mathrm{flav}}$

- 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

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

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

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

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

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

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

Minimal model of the dual parameterization

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

$$B^i_{n n+1}(t,\mu^2) = \frac{2n+3}{2n+4}\int_{-1}^{1} dx\, x^n H^i(x,0,t,\mu^2) \equiv \frac{2n+3}{2n+4}\int_0^1 dx\, x^n \left(q^i(x,t,\mu^2) + \bar{q}^i\right)$$

$$C^i_{n n+1}(t,\mu^2) = \frac{2n+2}{2n+4}\int_{-1}^{1} dx\, x^n E^i(x,0,t,\mu^2) \equiv \frac{2n+3}{2n+4}\int_0^1 dx\, x^n \left(e^i(x,t,\mu^2) + \bar{e}^i\right)$$

- 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 $t \to 0$ 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.

The $t \to 0$ limit

- Forward quark PDFs are taken from CTEQ5L at $\mu_0 = 1$ GeV.

- 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

$$A_i(\mu^2) = \frac{\mathbf{2J^i(\mu^2)} - M_2^i(\mu^2)}{M_2^{i,\mathrm{val}}}$$

$$B_u(\mu^2) = k_u - 2\, A_u(\mu^2)\,, \quad B_d(\mu^2) = k_d - A_d(\mu^2)$$

- 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^i_n 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,

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

Two 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

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

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

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

with

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

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

- Since the D-term does not have a partonic interpretation, we cannot use the Regge model.
  Instead, we use the results of the lattice calculations, Gockeler *et al.*, 2003

$$d_i^{u,d}(t) = d_i^{u,d}(t=0)\frac{1}{(1-t/M_D^2)^2}$$

where $M_D = 1.11 \pm 0.20$ GeV in the continuum limit.

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

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

Contains both real and imaginary parts

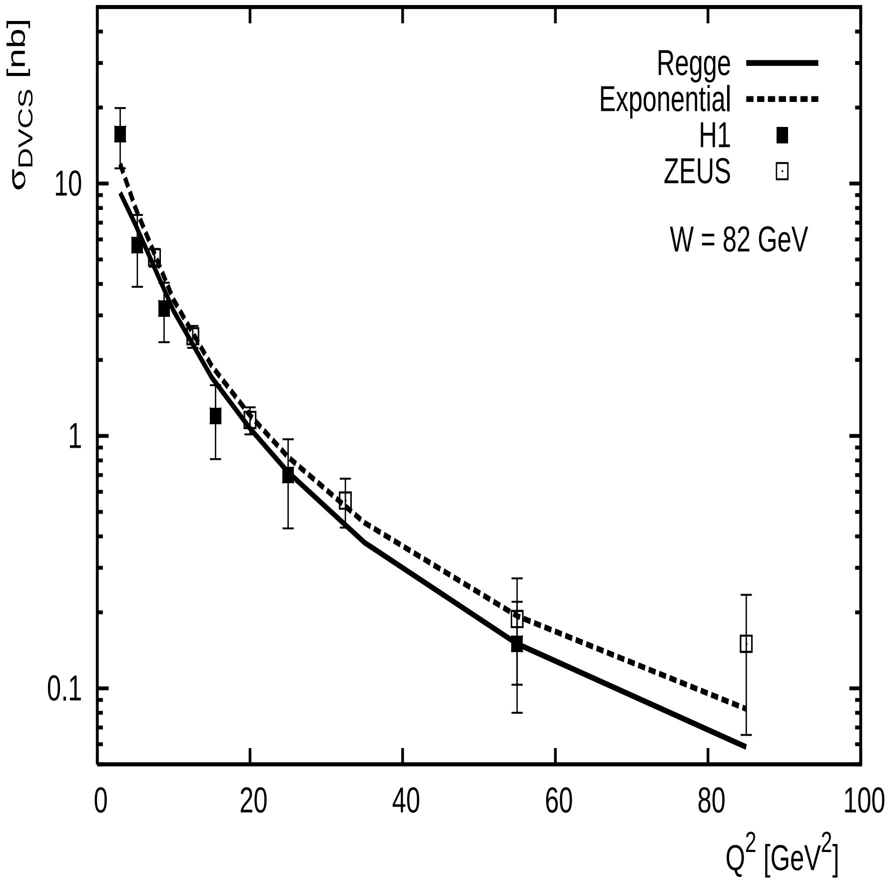
$$Im\,\mathcal{H}(\xi,t) = -\sum_i e_i^2 \int_a^1 \frac{dx}{x}\frac{1}{\sqrt{2x/\xi - x^2 - 1}} \sum_{\text{even}\,k} x^k Q_k^i(x,t)\,,$$

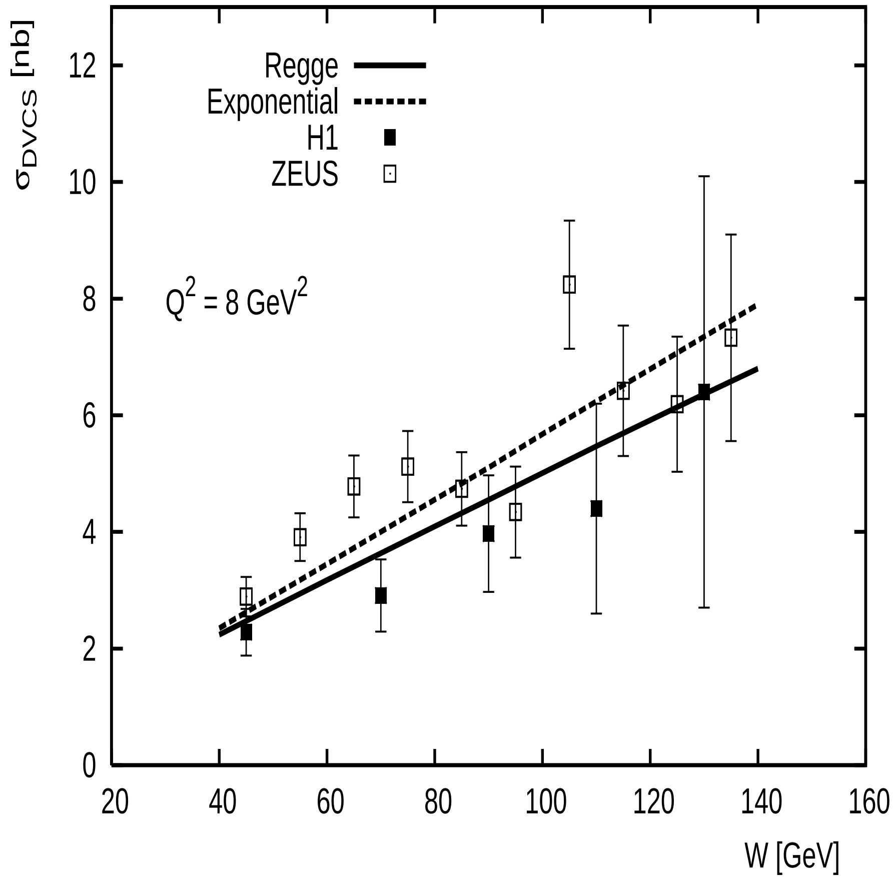
$$Re\,\mathcal{A}^i(\xi,t) = -\sum_i \int_a^1 \frac{dx}{x} \sum_{\text{even}\,k} x^k Q_k^i(x,t)\Big(\frac{1}{\sqrt{1+2x/\xi+x^2}} - 2\delta_{k0}\Big)$$

$$-\sum_i e_i^2 \int_0^a \frac{dx}{x} \sum_{even\,k} x^k Q_k(x,t)\Big(\frac{1}{\sqrt{1-2x/\xi+x^2}} + \frac{1}{\sqrt{1+2x/\xi+x^2}} - 2\delta_{k0}\Big)$$

where $a = (1-\sqrt{1-\xi^2})/\xi \approx \xi/2$ at small ξ.

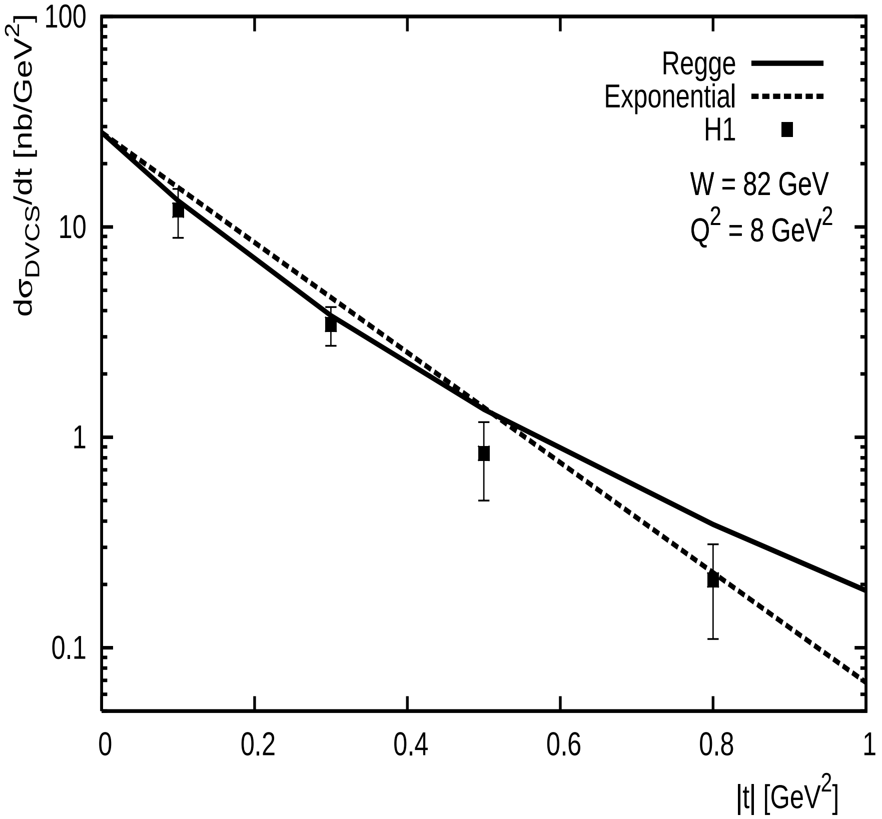
- Moreover, in the HERA kinematics, only Q_0^i which is given by forward PDFs, is important → **parameter-free*** predictions for the DVCS cross section.





- 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

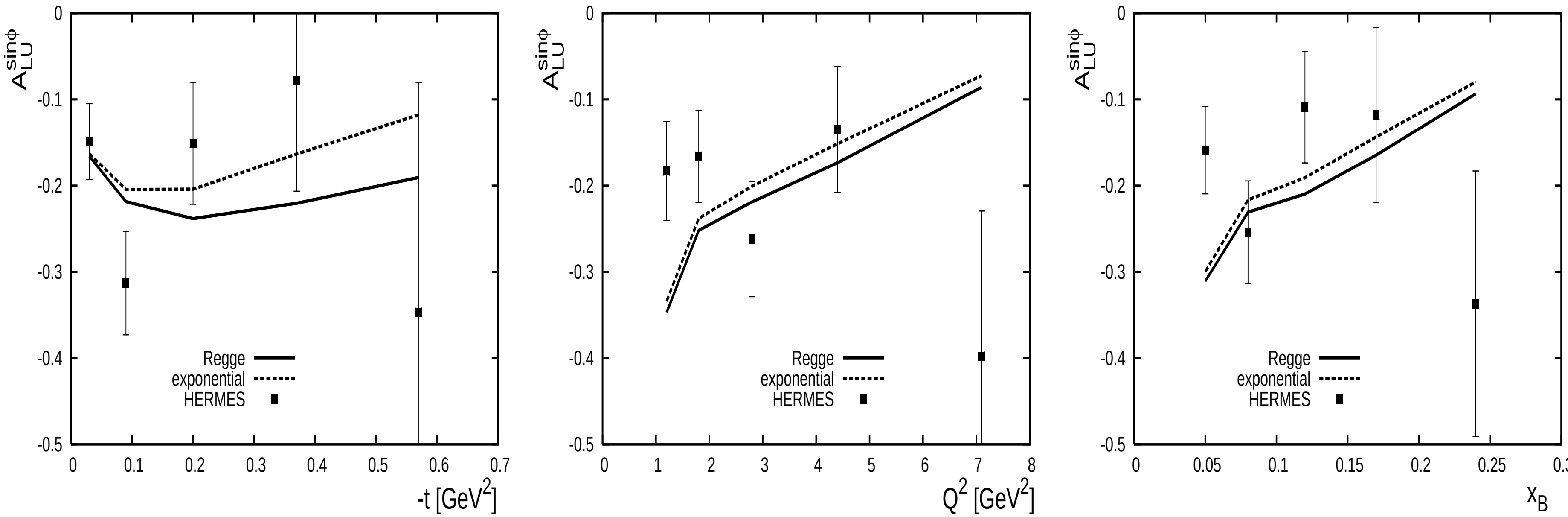
$$A_{LU}^{\sin\phi} \approx \left(\frac{x_B}{y}\right) 8\,K\,y\,(2-y)(1+\epsilon^2)^2 \frac{\left[F_1(t) Im\,\mathcal{H}(\xi,t) + \frac{|t|}{4m_N^2} F_2(t) Im\,\mathcal{E}(\xi,t)\right]}{c_{0,\mathrm{unp}}^{\mathrm{BH}}}$$

- 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,

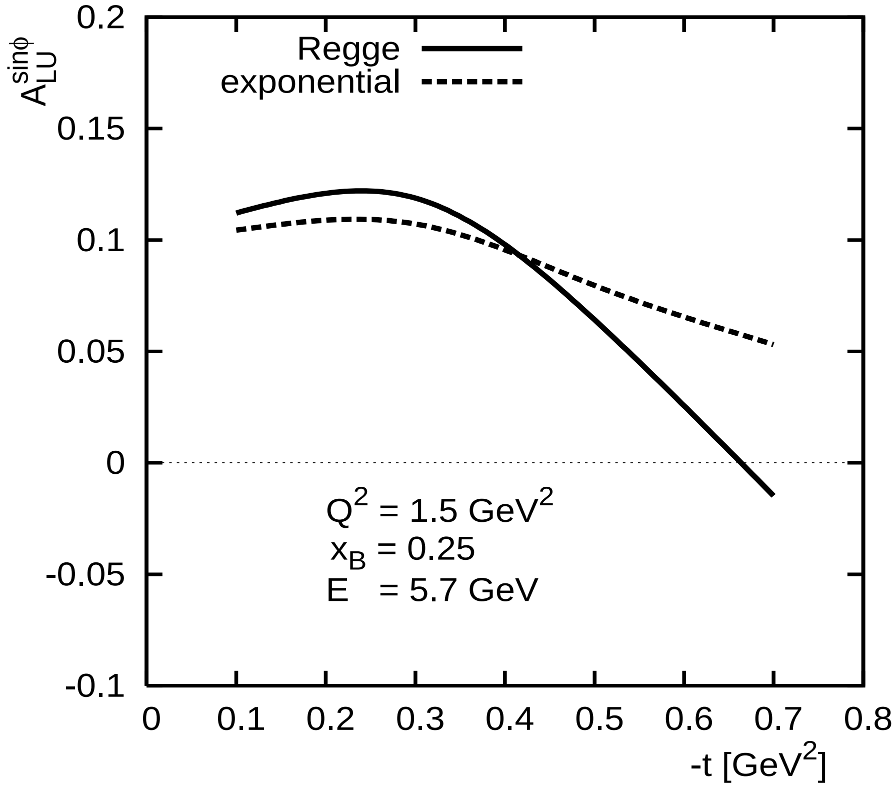
$$A_{LU}^{\sin\phi} = 0.15 \ldots 0.17\,, \quad \text{exponential } t - \text{dependence}$$

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

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

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

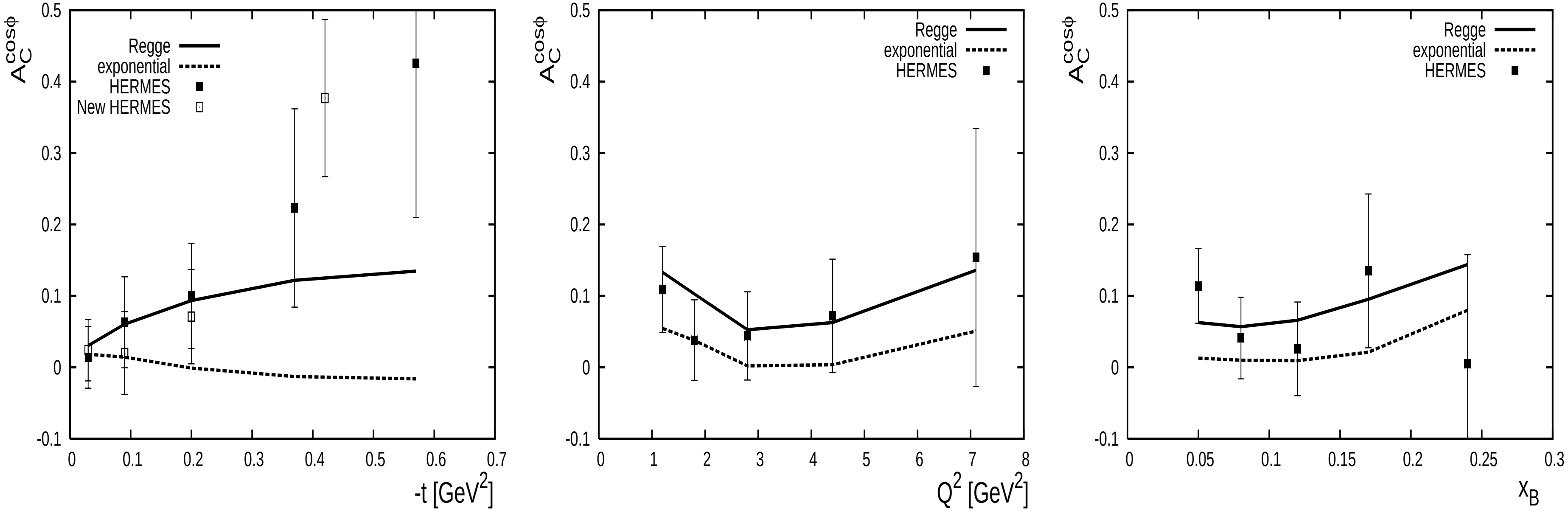
$$A_C^{\cos\phi} = 0.010\ldots0.030\,, \quad \text{exponential } t-\text{dependence}$$
$$A_C^{\cos\phi} = 0.19\ldots0.23\,, \quad \text{Regge } t-\text{dependence}$$
$$A_C^{\cos\phi} = 0.11\pm0.04\pm0.03\,, \quad \text{HERMES (2002, unpub.)}$$

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

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

- 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

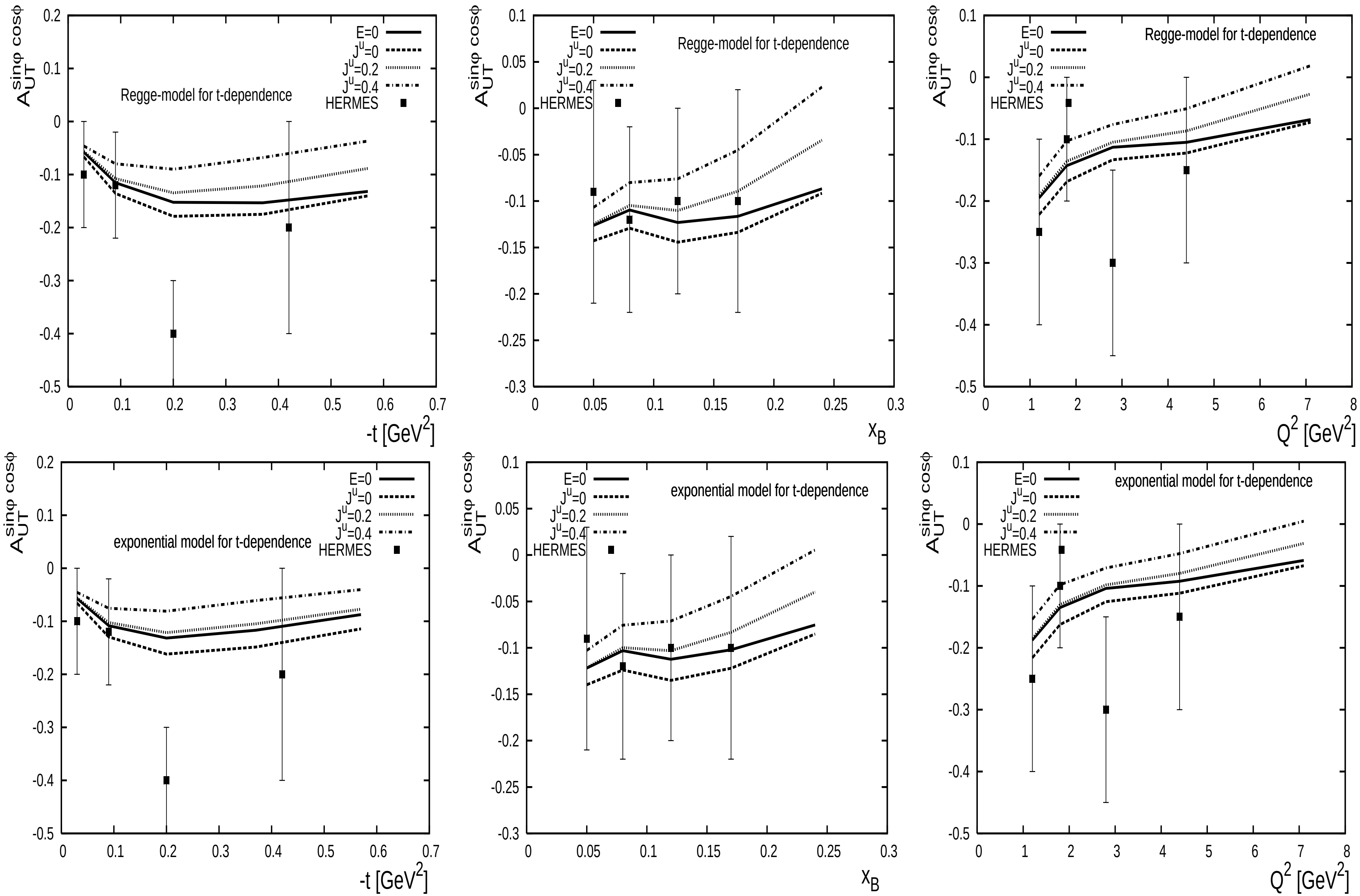
- The $\sin\phi$-$\cos\varphi$-moment of the transversely-polarized target (unpolarized beam) asymmetry is sensitive to the GPD E, Belitsky *et al.*, 2001

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

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

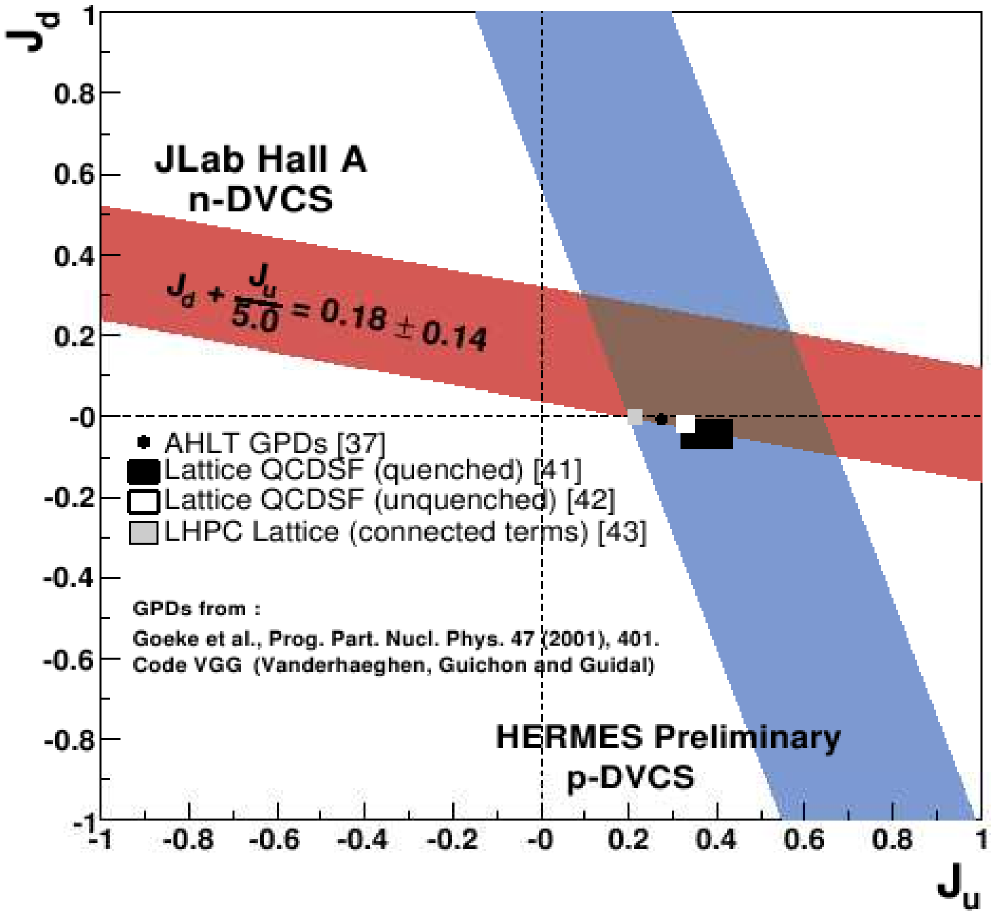
- Can be used to determine the total angular momentum carried by quarks, Ellinghaus, Nowak, Vinnikov, Ye, 2005.

- 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.

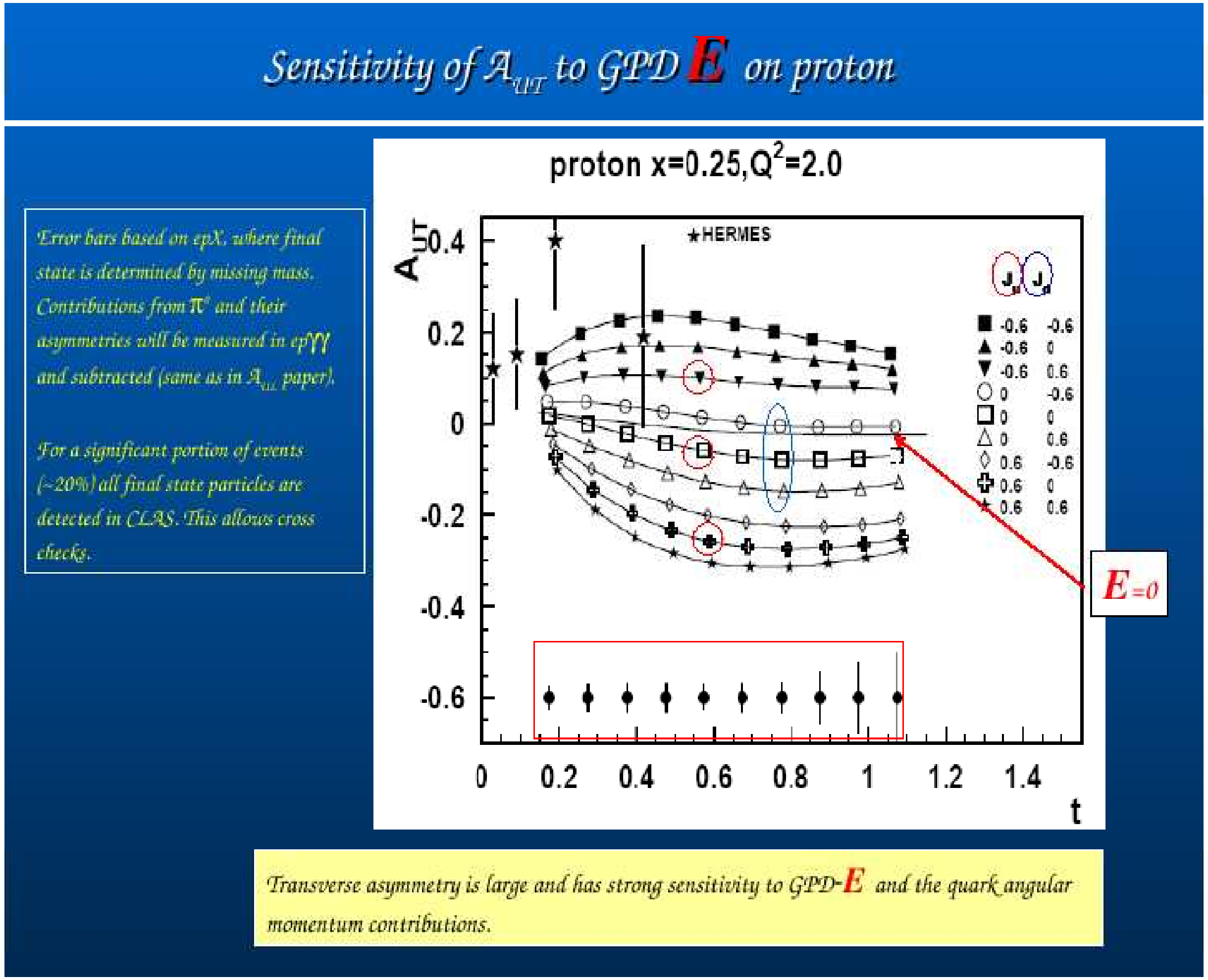

$A_{UT}^{\sin\varphi\cos\phi}$
E=0
J^u=0
J^u=0.2
J^u=0.4
HERMES
Regge-model for t-dependence
exponential model for t-dependence
-t [GeV^2]
x_B
Q^2 [GeV^2]

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)



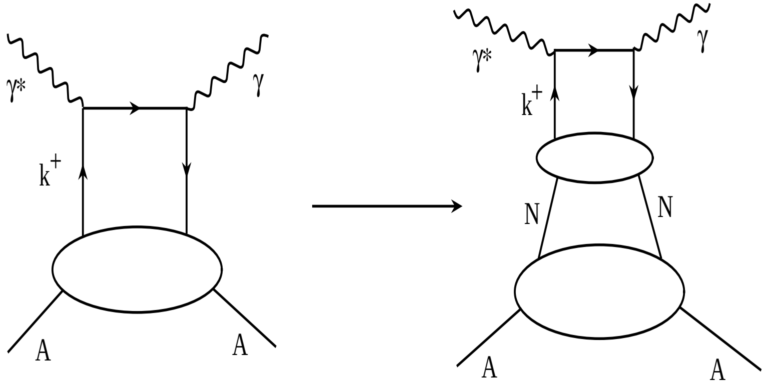
Dual parameterization of nuclear GPDs

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].



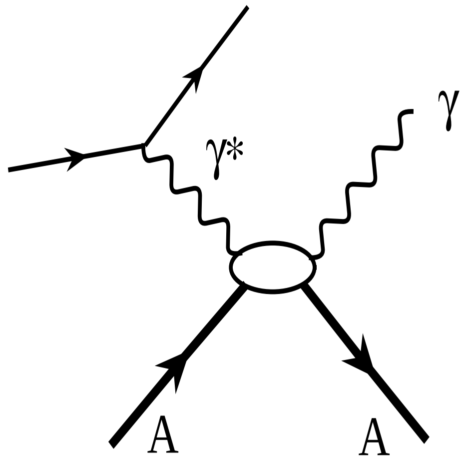
$$
\begin{aligned}
H_A^q(x,\xi_A,Q^2,t) \quad &= \quad \left|\frac{dx_N}{dx}\right| \Bigg[Z \left(H^{q/p}(x_N,\xi_N,Q^2,t) + \frac{t}{4m_N^2} E^{q/p}(x_N,\xi_N,Q^2,t) \right) \\
&+ \quad N \left(H^{q/n}(x_N,\xi_N,Q^2,t) + \frac{t}{4m_N^2} E^{q/n}(x_N,\xi_N,Q^2,t) \right) \Bigg] F_A(t)
\end{aligned}
$$

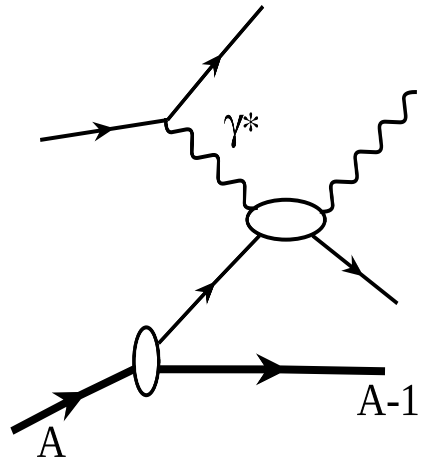
The simple model of nuclear GPDs

- 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.





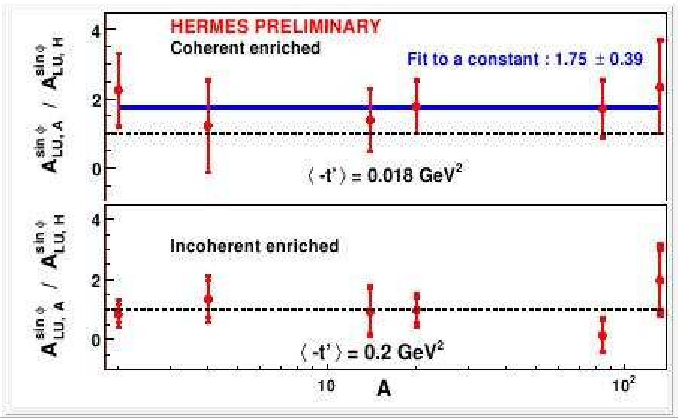
- Coherent dominates at small t; Incoherent dominates at large t

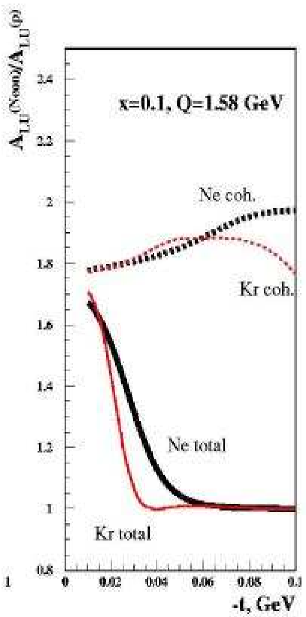
- One can write an interpolation formula between the two regimes
  V. Guzey and M. Strikman, Phys. Rev. C68 (2003) 015204

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^A_{LU}/A^p_{LU} (Method 1)

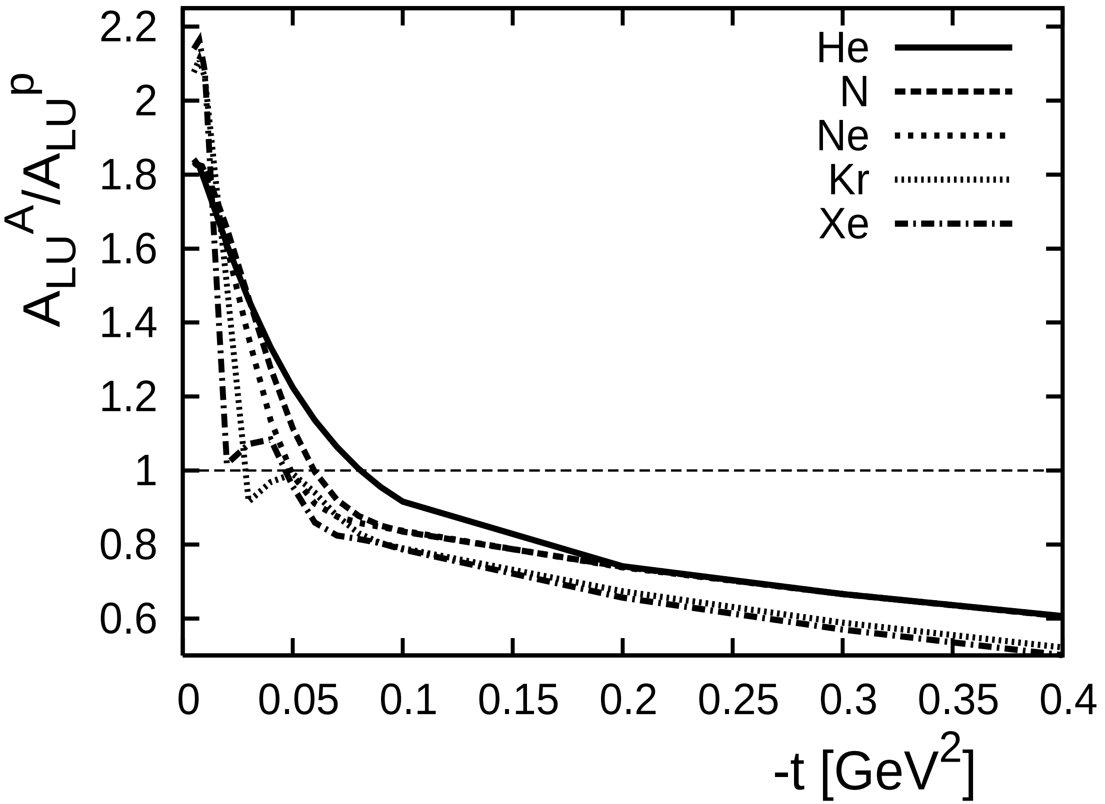




- Coherent enriched: mean ratio deviates from unity by 2σ. Consistent with predictions between 1.8 and 1.95: Guzey/Strikman Phys.Rev.C 68 (2003)
- Incoherent enriched: Consistent with unity as naively expected

Frank Ellinghaus, University of Maryland, October 2006 6

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

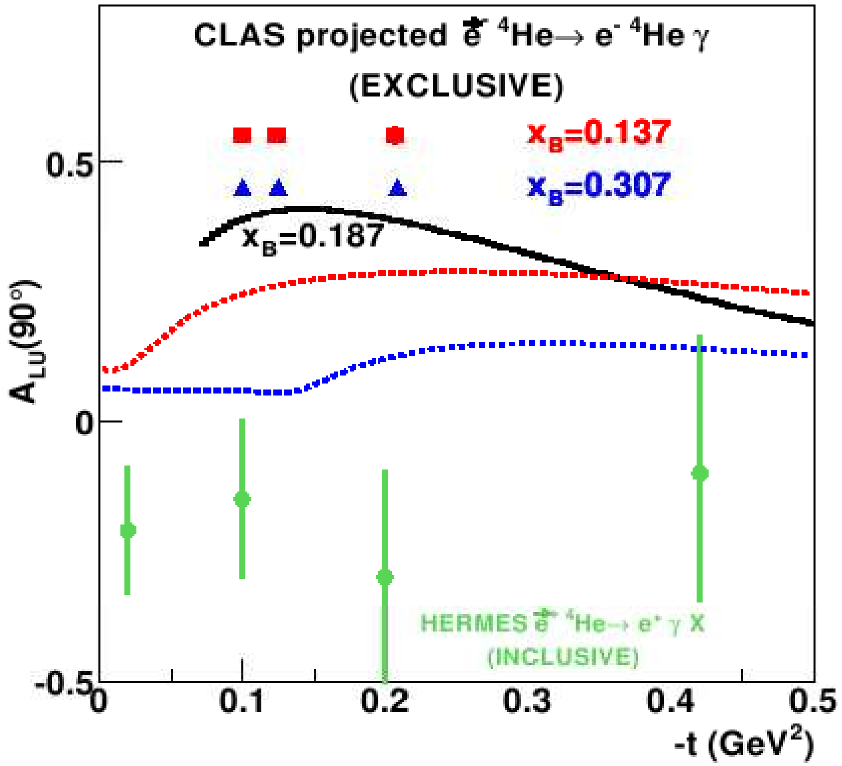


V. Guzey, ArXiv:0801.3235 [nucl-th] (2008)

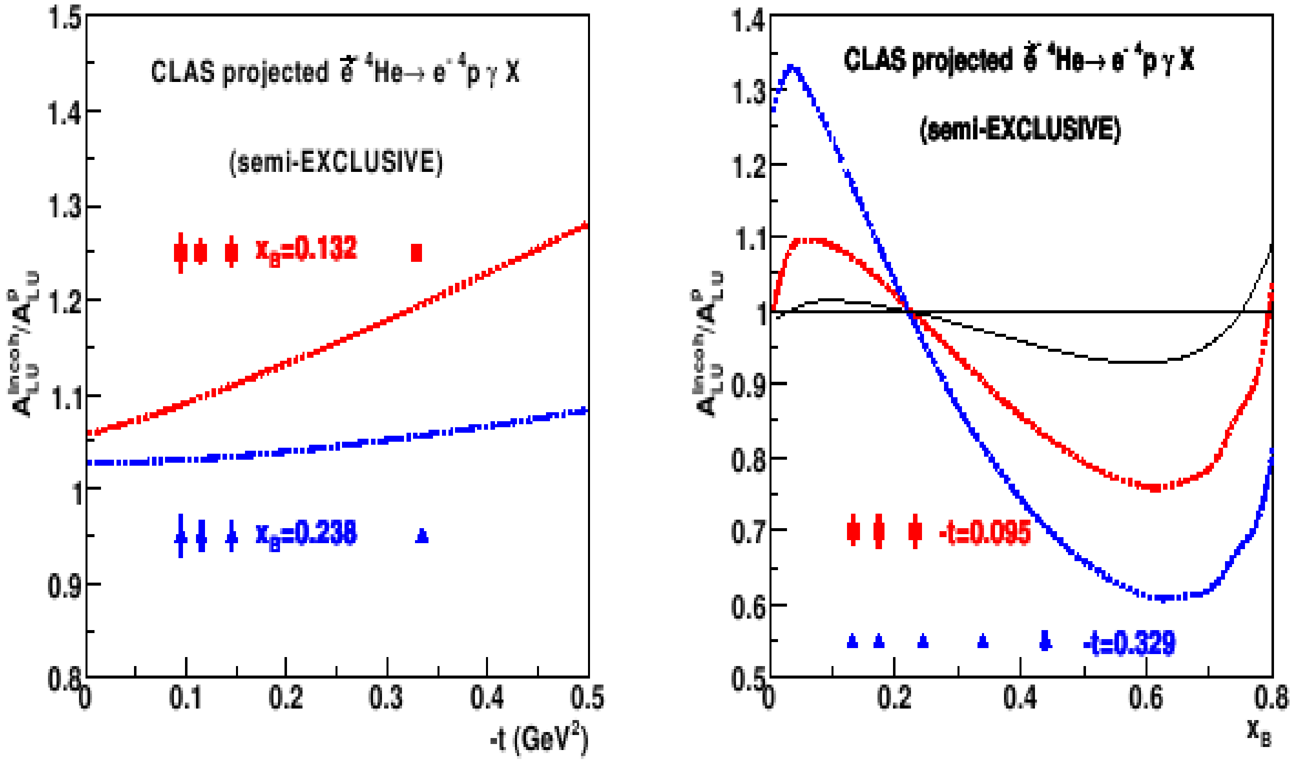
- Use incoherent DVCS to measure the neutron GPDs

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 $x_B < 0.1 - 0.2$
  - Can be systematically improved, M. Polyakov (2007)
- 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