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Generalized parton distributions of spin-0 nuclei

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1. Motivation
2. D-term and its A-dependence
3. Evaluation of nuclear GPDs
4. Results for asymmetries

I. Motivation

- Generalized parton distributions (GPDs) became a standard tool for the parameterization of the nonperturbative hadronic structure in hard processes. The standard definition for spin-0 target is

$$\frac{1}{2}\int\frac{dz^-}{2\pi}\langle P'|\bar{\psi}(0)\gamma_+\psi(z)|P\rangle e^{ix\bar{P}^+z^-} = H(x,\xi,t)$$

- The theoretical study of GPDs was initiated in 1996 (Ji 1996, Radyushkin 1996)

- Experimental study - through the Deeply Virtual Compton Scattering (DVCS) and meson electroproduction. Experiments are being held by HERMES, H1, CLAS collaborations.

- Nuclear DVCS - sensitivity both to the nuclear forces and distortion of the nucleon in the nuclei.

- A first experiment on nuclear DVCS-measurement of DVCS asymmetries with Deuterium and Neon nuclei at HERMES (DESY). Another experiment is planned at the future Electron Ion Collider (EIC) (Deshpande 2002).

- Study of the forward limit (DIS)-shadowing, antishadowing, EMC-effect etc.

- DVCS cross-section-possibly new nuclear effects ?

- Current approach to the study of the nuclear DVCS- *sum* of the free nucleon GPDs (Kirchner, Mueller 2003, Freund *et. al.* 2003, Guzey, Strikman 2003).

- The assumption is *good but not universal* - "pathological" A-dependence $d_A(0) \propto A^{7/3}$ (M. Polyakov 2002).

II. $d_A(0)$ and its A-dependence

- The framework for our analysis - field-theoretical Walecka model. (Walecka, Serot 1984)

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + \frac{1}{2}(\partial_\mu\phi\partial^\mu\phi - m_s^2\phi^2)$$
$$+\bar{\psi}(i\hat{\partial} - M - g_v\hat{V} + g_s\phi)\psi$$

- D-term -introduced to supplement double distribution parametrization (Polyakov, Weiss, 1999). Formal definition-through its moments:

$$d_n(t) = \frac{1}{(n+1)!}\frac{\partial}{\partial\xi^{n+1}}\int dx\ x^n H(x,\xi,t)$$
$$D(z) = (1-z^2)\sum_{n\ odd} d_n(t)C_n^{3/2}(z)$$

- (Ji 1996): Connection of the GPD first moments with energy-momentum tensor form factors $M_A(t)$ and $d_A(t)$:

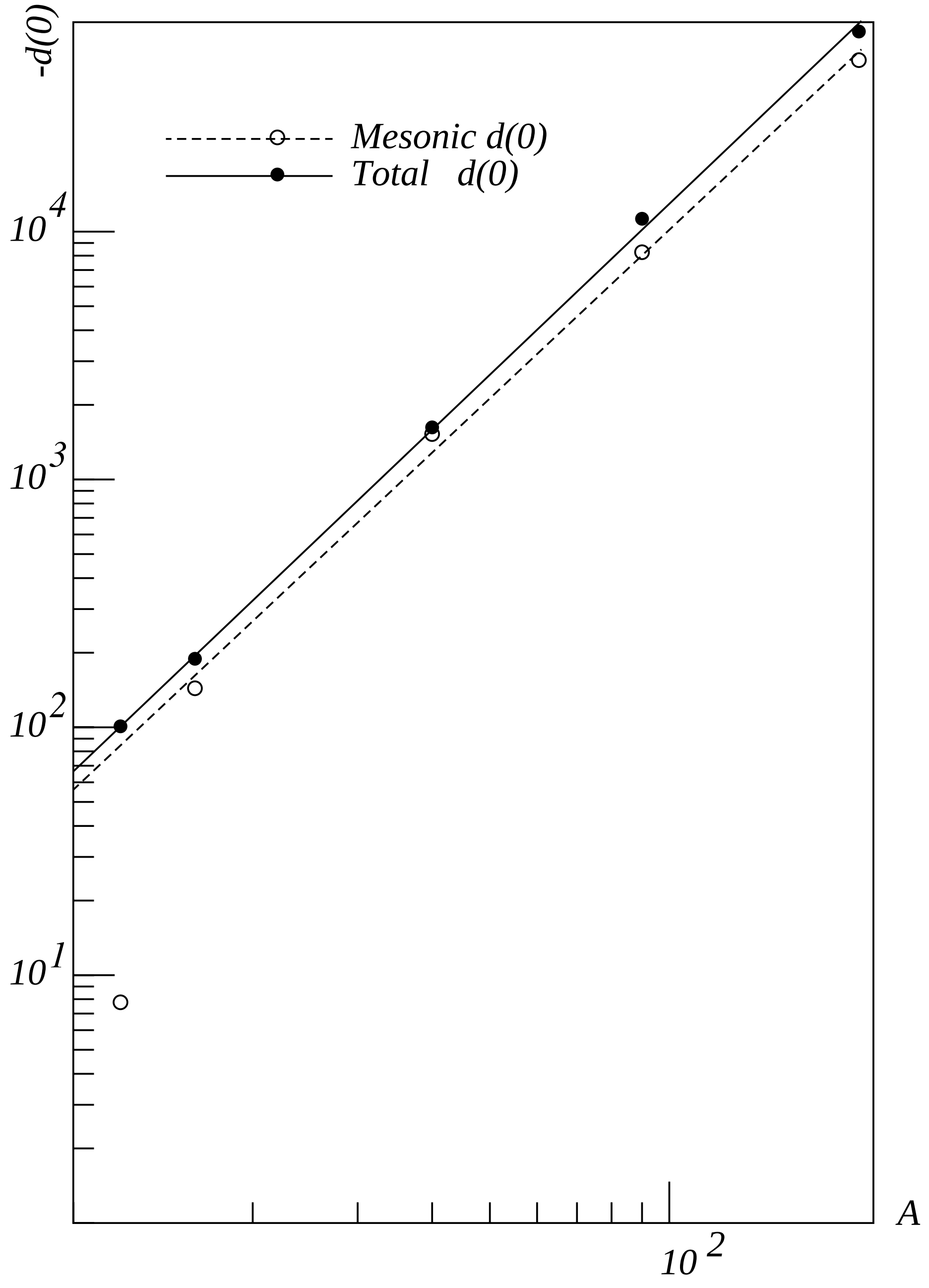
$$\langle P'|\hat{T}_{\mu\nu}(0)|P\rangle = M_A(t)\bar{P}_\mu\bar{P}_\nu + \frac{1}{5}d_A(t)(\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2)$$

$$d_A(0) \approx \; -0.3\; A^{2.26}.$$

- Liquid drop model (M. Polyakov 2002):

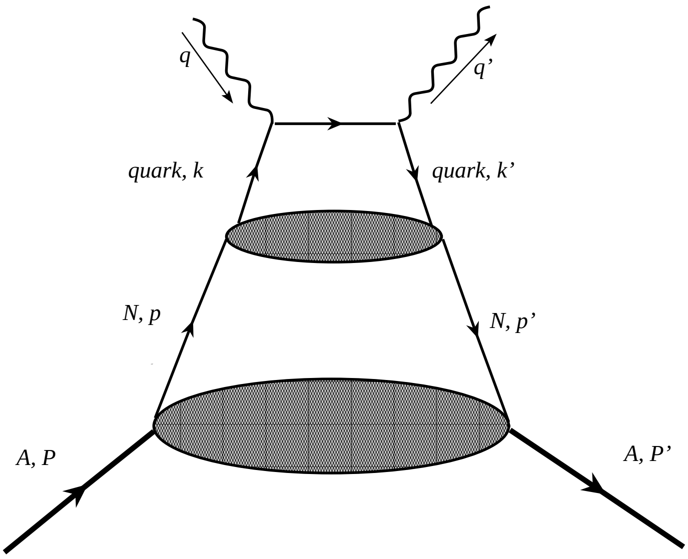
$$d_A(0) \approx -0.2\, A^{7/3}.$$

- Dominant contribution from the mesons



III. Evaluation of nuclear GPDs

- The natural assumption in study of the nuclear hard processes-separation into the nucleonic and nuclear parts.

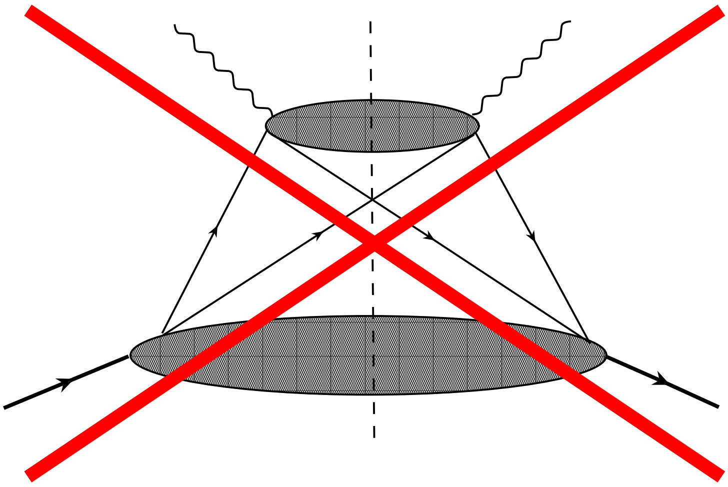


- Convolution formula

$$H_{q/A}(x,\xi,t) = \sum_i \int_x^1 \frac{dy}{y} H_{i/A}(y,\xi,t) H_{q/i}\left(\frac{x}{y},\frac{\xi}{y},t\right),$$

- Forward case-(Jaffe 1985, Berger 1983)

- The convolution approximation neglects the simultaneous coherent interaction of the virtual photon with several nuclear constituents. Inapplicable for $x < 0.1$.



- Definition of the nuclear parts $H_{i/A}$:

$$H_{N/A}(x,\xi,t) = \frac{1}{2}\int \frac{dz^{-}}{2\pi} e^{ixP^{+}z^{-}} \langle P'|\bar{\psi}\left(\frac{z}{2}\right) e^{i\int_{-z/2}^{z/2} V(\lambda)\cdot d\lambda} \gamma_{+}\psi\left(-\frac{z}{2}\right)|P\rangle,$$

$$H_{\phi/A}(x,\xi,t) = \frac{1}{2}\int \frac{dz^{-}}{2\pi} e^{ixP^{+}z^{-}} \langle P'|\phi\left(\frac{z}{2}\right) i\overleftrightarrow{\partial}_{+}\phi\left(-\frac{z}{2}\right)|P\rangle,$$

$$H_{V/A}(x,\xi,t) = \frac{1}{4x\bar{P}^{+}}\int \frac{dz^{-}}{2\pi} e^{ixP^{+}z^{-}} \langle P'|V_{+\alpha}\left(\frac{z}{2}\right) V_{+}^{\alpha}\left(-\frac{z}{2}\right)|P\rangle$$

$$+\frac{m_V^2}{4x\bar{P}^{+}}\int \frac{dz^{-}}{2\pi} e^{ixP^{+}z^{-}} \langle P'|V_{+}\left(\frac{z}{2}\right) V_{+}\left(-\frac{z}{2}\right)|P\rangle\,.$$

- Final result:

$$H_{N/A}(x,\xi,t) = \frac{m_A}{2\pi}\int \frac{dz^-}{2\pi} e^{ix\bar{P}^+ z^-} \int d^3X \sum_n \bar{\Phi}_n\left(\frac{z}{2} - \vec{X}\right) \times$$

$$\times P\, e^{i\int_{-z/2}^{z/2} V(\lambda)\cdot d\lambda} \gamma_+ \Phi_n\left(-\frac{z}{2} - \vec{X}\right),$$

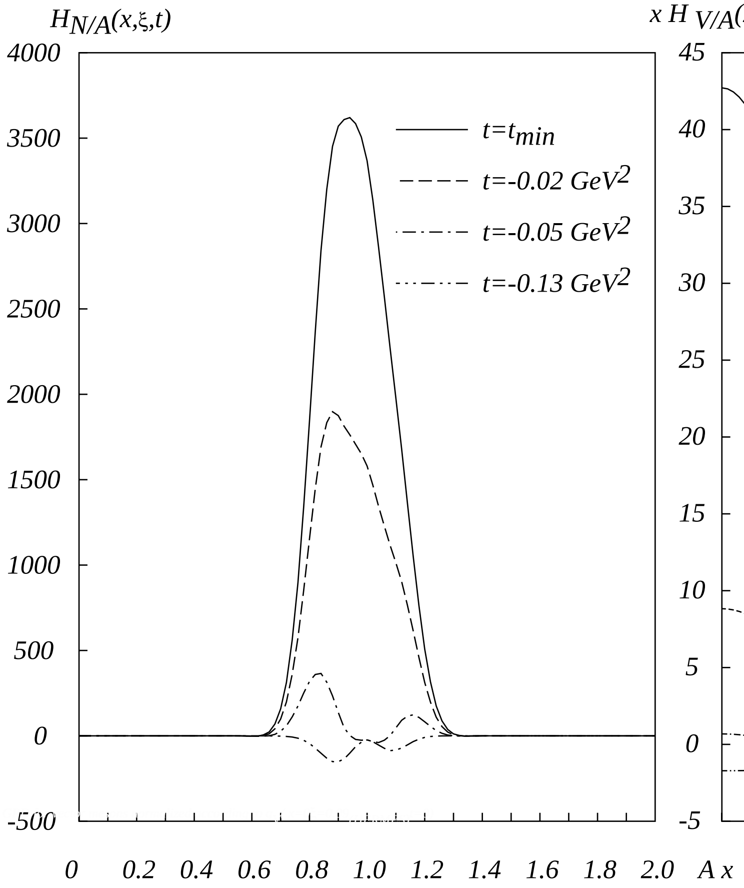
$$H_{\phi/A}(x,\xi,t) =$$

$$\int \frac{d\bar{p}^+ d^2\bar{p}_\perp}{(2\pi)^3}\delta\left(x - \frac{\bar{p}^+}{\bar{P}^+}\right)\bar{p}^+ \phi\left((x-\xi), \bar{p}_\perp + \frac{\Delta_\perp}{2}\right)\phi\left((x+\xi), \bar{p}_\perp - \frac{\Delta_\perp}{2}\right),$$

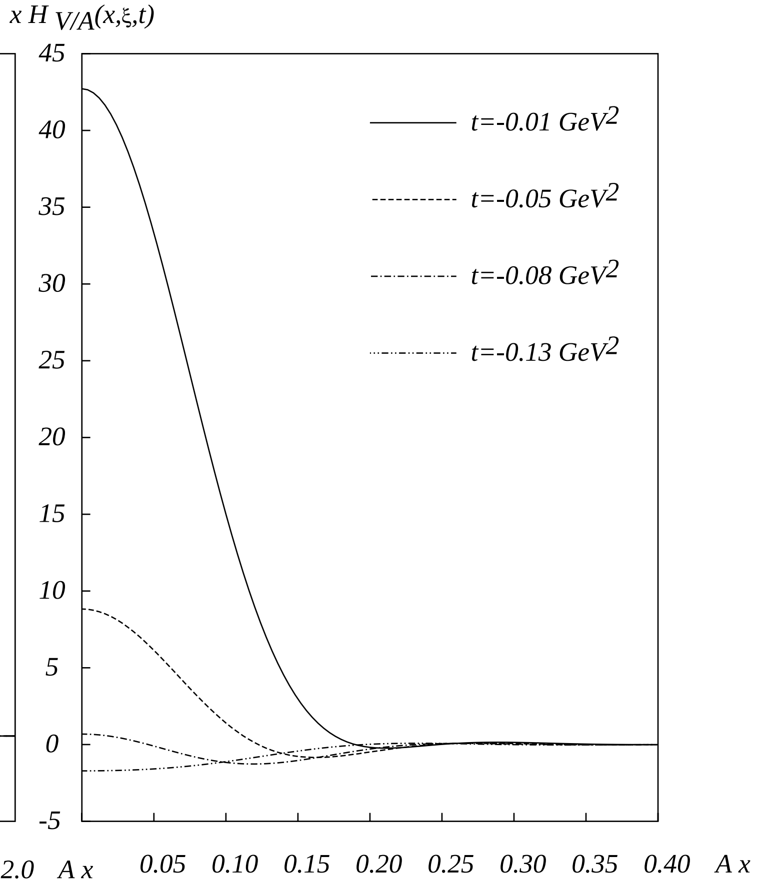
$$H_{V/A}(x,\xi,t) = \int \frac{d\bar{p}^+ d^2\bar{p}_\perp}{(2\pi)^3}\delta\left(x - \frac{\bar{p}^+}{\bar{P}^+}\right)\frac{\bar{p}_\perp^2 - \Delta_\perp^2/4 + m_V^2}{4x\bar{P}^+} \times$$

$$\times V_+\left((x-\xi), \bar{p}_\perp + \frac{\Delta_\perp}{2}\right) V_+\left((x+\xi), \bar{p}_\perp - \frac{\Delta_\perp}{2}\right).$$

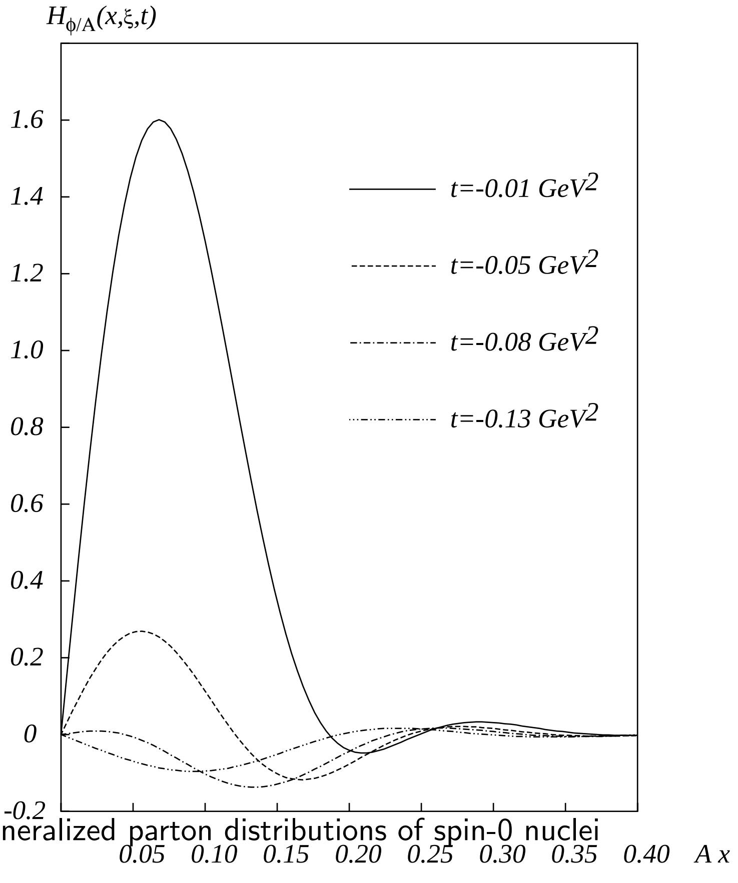
- We can see that similarly to the gluonic GPD, the vector off-forward distribution is singular at $x = 0$.



$H_{N/A}(x,\xi,t)$
4000
3500
3000
2500
2000
1500
1000
500
0
-500
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 A x
$t=t_{min}$
t=-0.02 GeV^2
t=-0.05 GeV^2
t=-0.13 GeV^2



$x\,H_{V/A}(x,\xi,t)$
45
40
35
30
25
20
15
10
5
0
-5
0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 A x
t=-0.01 GeV^2
t=-0.05 GeV^2
t=-0.08 GeV^2
t=-0.13 GeV^2



$H_{\phi/A}(x,\xi,t)$
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
-0.2
0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 A x
t=-0.01 GeV^2
t=-0.05 GeV^2
t=-0.08 GeV^2
t=-0.13 GeV^2

IV. Predictions for physical observables

- Model for the nucleon GPDs $H_{q/N}(x,\xi,t)$ (Radyushkin 2000; N. Kivel, M. V. Polyakov and M. Vanderhaeghen 2000)

$$H_N(x,\xi,t) \equiv \sum e_q^2 H_{q/N} =$$

$$= F_N(t)\int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\delta(x-\beta-\alpha\xi)h(\beta,\alpha)q_N(\beta) + \theta\left(1-\frac{x^2}{\xi^2}\right) D_N\left(\frac{x}{\xi},t\right),$$

$$h(\beta,\alpha) = \frac{3}{4}\frac{(1-|\beta|)^2-\alpha^2}{(1-|\beta|)^3}, \qquad \mathrm{D}_N(z,t) = -\sum_q e_q^2/N_f\, d_1(t)\,(1-z^2)C_1^{3/2}(z)$$

CTEQ5L parameterization for nucleon PDFs.

- Models of meson GPDs $H_{q/mes}(x,\xi,t)$

$$H_V(x,\xi,t) = H_\phi(x,\xi,t) = H_{mes}(x,\xi,t) \equiv \sum_q e_q^2 H_{q/mes}(x,\xi,t) \approx q_{mes}(x)$$

$$q_{mes}(x) = \frac{x^\alpha(1-x)^\beta}{B(\alpha+1,\beta)}$$

$$\int_{-1}^{1}\sum_q x\,dx\,H_{q/mes}(x,0,0) = 1$$

We have neglected possible ξ-dependence for the *meson* GPDs $H_{mes}(x,\xi,t)$ since in the kinematics of nuclear DVCS $\xi \ll 1$, $t\langle r_{mes}^2\rangle \ll 1$, and give only small corrections compared to the forward case.

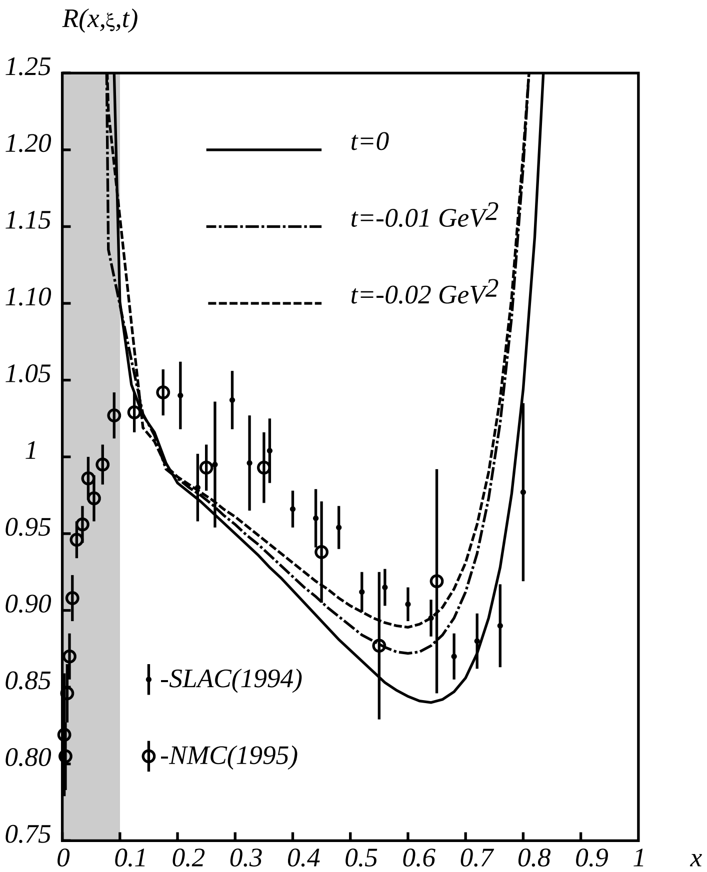
- Similar parametrization was used for description of the π-mesons (Owens 1984).

- Consider now the ratio

$$R(x,\xi,t) = \frac{\sum_q e_q^2 H_{q/A}(x_A,\xi,t)}{F_{N/A}(t) H_N(x,\xi,t)},$$

$$R(x,0,0) \approx R(x) \equiv \frac{F_{2\,A}(x_A)}{A\,F_{2\,N}(x)},$$

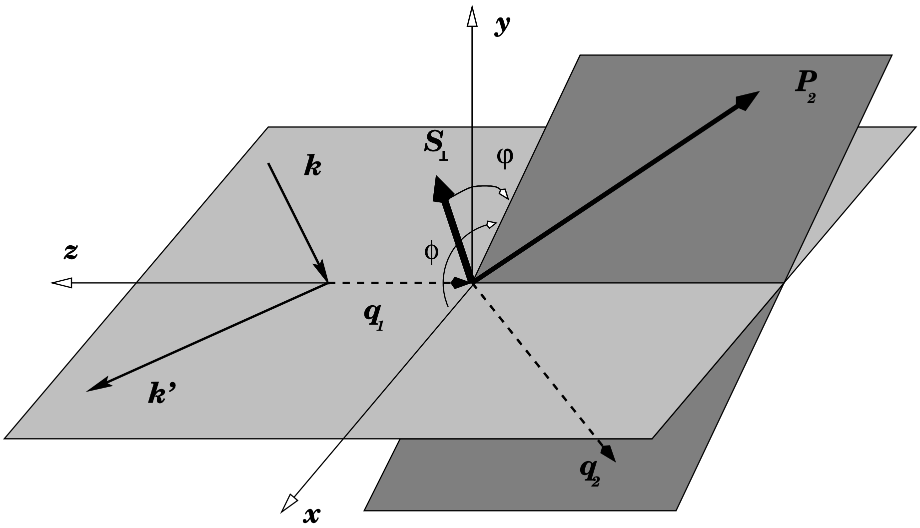
(the last equality is valid to the leading order in α_S)



Data for the ratio $R(x)$ are from the SLAC (Gomez *et.al.*, 1993) and NMC (Amaudruz *et. al.*, 1995).

- Beam-charge and beam-spin asymmetries:

$$A_C(\phi) = \frac{\sigma^+(\phi) - \sigma^-(\phi)}{\sigma^+(\phi) + \sigma^-(\phi)}, \qquad A_{LU}(\phi) = \frac{\overrightarrow{\sigma}(\phi) - \overleftarrow{\sigma}(\phi)}{\overrightarrow{\sigma}(\phi) + \overleftarrow{\sigma}(\phi)},$$



$\sigma^{\pm}$ and $\overrightarrow{\sigma}, \overleftarrow{\sigma}$ -cross-sections of unpolarized electron/positron and longitudinally polarized leptons, respectively (Belitsky 2001).

- Choice of the kinematics-HERMES on Neon (Ellinghaus 2002): $\langle x_{Bj} \rangle_{per\,nucleon} = 0.09, \langle Q^2 \rangle = 2.2\,GeV^2, \langle t \rangle = -0.01\ GeV^2$.

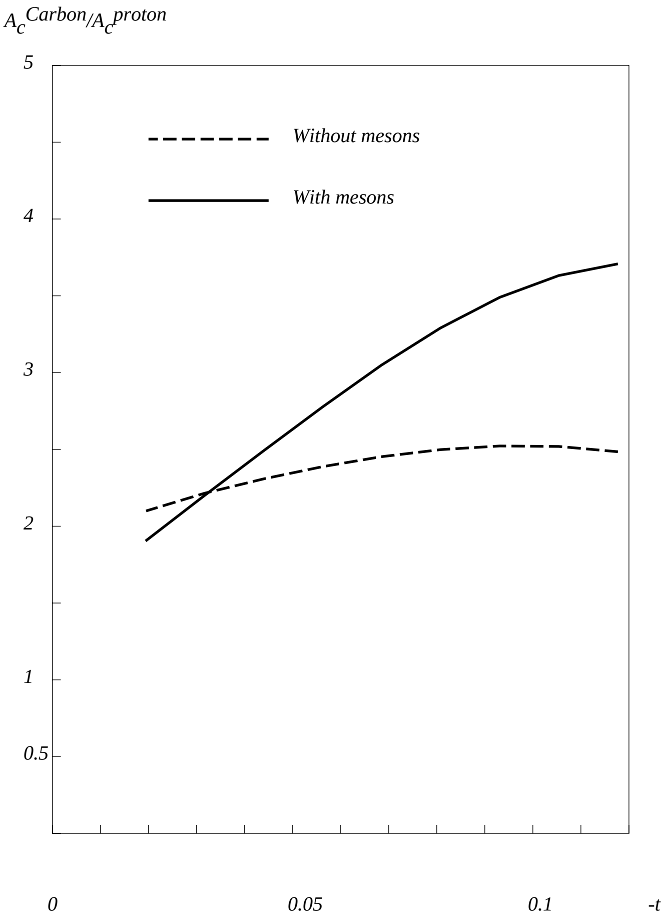
$$A_C^{cos} = \frac{1}{\pi} \int_0^{2\pi} d\phi\ \cos\phi\, A_C(\phi); \qquad A_{LU}^{sin} = \frac{1}{\pi} \int_0^{2\pi} d\phi\ \sin\phi\, A_{LU}(\phi)\,.$$

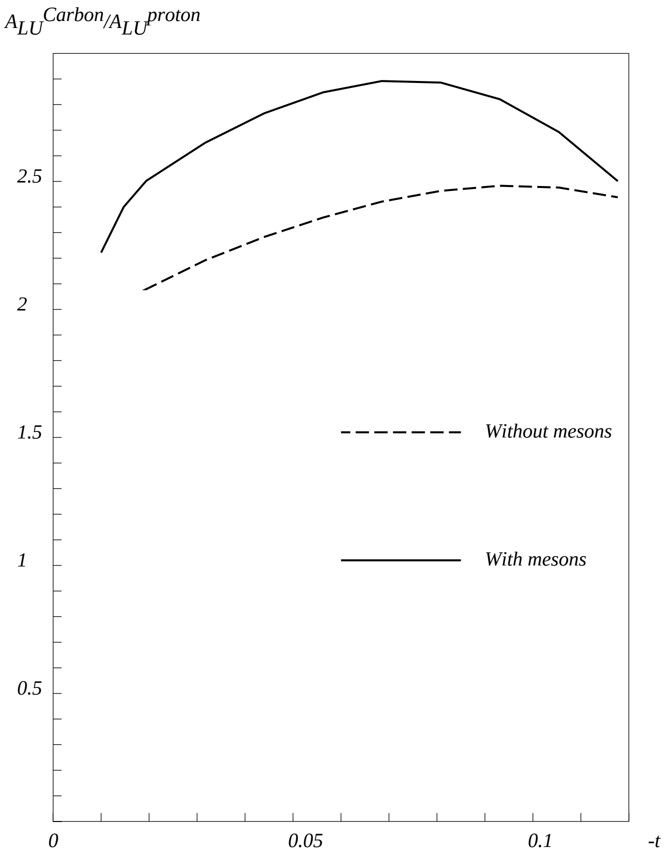
- Sensitivity to mesons of the values A_C^{cos}, A_{LU}^{sin}.

Nucleus	$A_{C\ A}^{cos}/A_{C\ N}^{cos}$	$A_{LU\ A}^{sin}/A_{LU\ N}^{sin}$	$A_{C\ A}^{cos}/A_{C\ N}^{cos}$	$A_{LU\ A}^{sin}/A_{LU\ N}^{sin}$
^{12}C	2.45	1.85	1.573	2.222
^{16}O	2.43	1.83	1.905	2.270
^{40}Ca	2.38	1.89	3.276	2.180
^{90}Zr	2.59	1.93	4.879	2.104

Table 1: The ratios of the nuclear to the free proton asymmetries for different nuclei. The second and third columns correspond to the calculation without the nuclear mesons; the fourth and fifth columns correspond to the full calculation including the meson contribution.

- A least-square fit gives the following approximate A-dependence: $A_{C\ A}^{cos}/A_{C\ N}^{cos} \propto A^{0.5}$; $A_{LU\ A}^{sin}/A_{LU\ N}^{sin} \propto A^{-0.03}$ for all A; the ratio of the DVCS amplitudes squared $|A_{DVCS\,A}/A_{DVCS\,N}|^2 \propto A^{4.29}$.





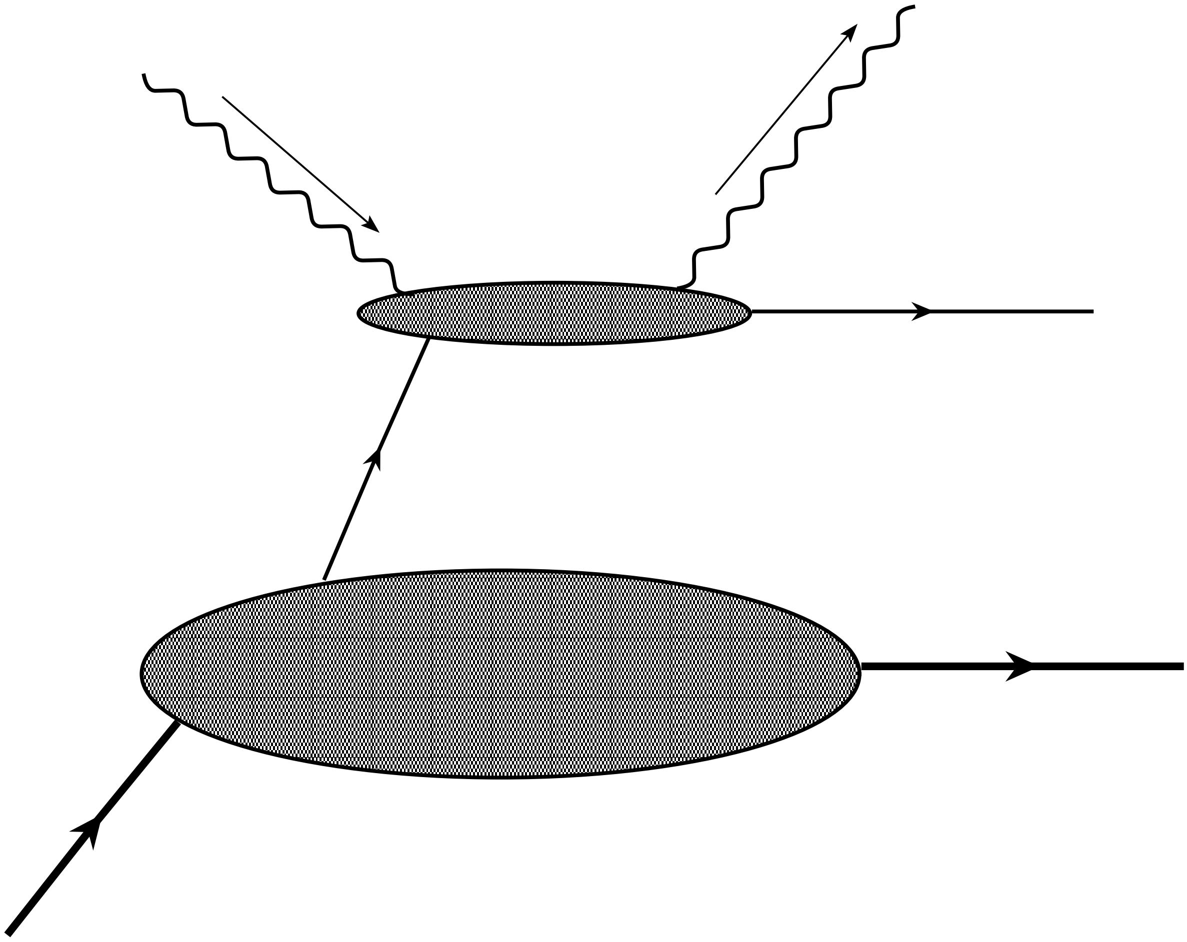
- Comparison with experimental data for Neon ($A = 20$)

$$\left(\frac{A_{LU\ A}^{sin}}{A_{LU\ N}^{sin}} \right)_{exp} = 1.22 \pm 0.26 \,,$$

Interpolation of our results gives

$$\left(\frac{A_{LU\ A}^{sin}}{A_{LU\ N}^{sin}} \right)_{th} \approx 2.1 \pm 0.2 \,.$$

- One of the possible explanations of the discrepancy- contribution of incoherent nuclear scattering (with nucleus break-up) (V. Guzey and M. Strikman, 2003) (Ratio $= 1$ for both asymmetries).



V. Summary

- A microscopic evaluation of nuclear GPDs (for spin-0 nuclei).
- Meson (non-nucleonic) degrees of freedom might be not negligible.
- We studied the A and t-dependence of the beam-charge and beam-spin DVCS asymmetries.