Generalized parton distributions in nuclei

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• One of key objective of nuclear physics is to understand the structure of the nucleon and nuclei in terms of quarks and gluons (partons) – the fundamental degrees of freedom of Quantum Chromodynamics, the theory of the strong interactions.

• The partonic structure of hadrons is studied in high energy scattering with a large momentum transfer that enables one to resolve short-distance parton structure of the target.

• Main theoretical tool – factorization theorems that enable to introduce universal (process-independent) distributions of partons in the target.

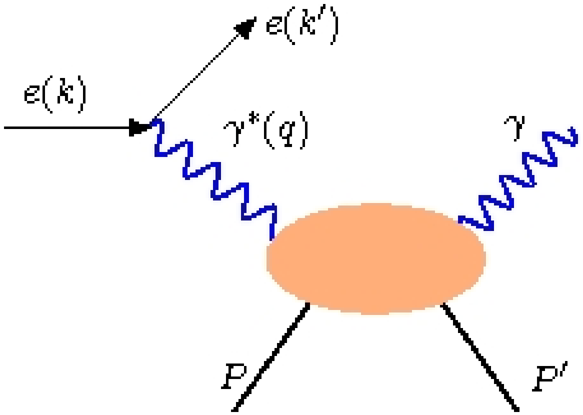
• Generalized parton distributions (GPDs) is an example of such distributions that can be probed in hard exclusive processes.

Outline

- Introduction: basics of generalized parton distributions (GPDs)
- Motivation to study generalized parton distributions in nuclei
- Three examples of nuclear effects in nuclear GPDs:
  - off-diagonal EMC effect
  - nuclear shadowing for nuclear GPDs
  - medium modifications of bound nucleon GPDs

Deeply virtual Compton scattering

Best process to study generalized parton distributions (GPDs) is deeply virtual Compton scattering (DVCS)



$$\mathcal{A}_{\mathrm{DVCS}}(\xi, t, Q^2)$$

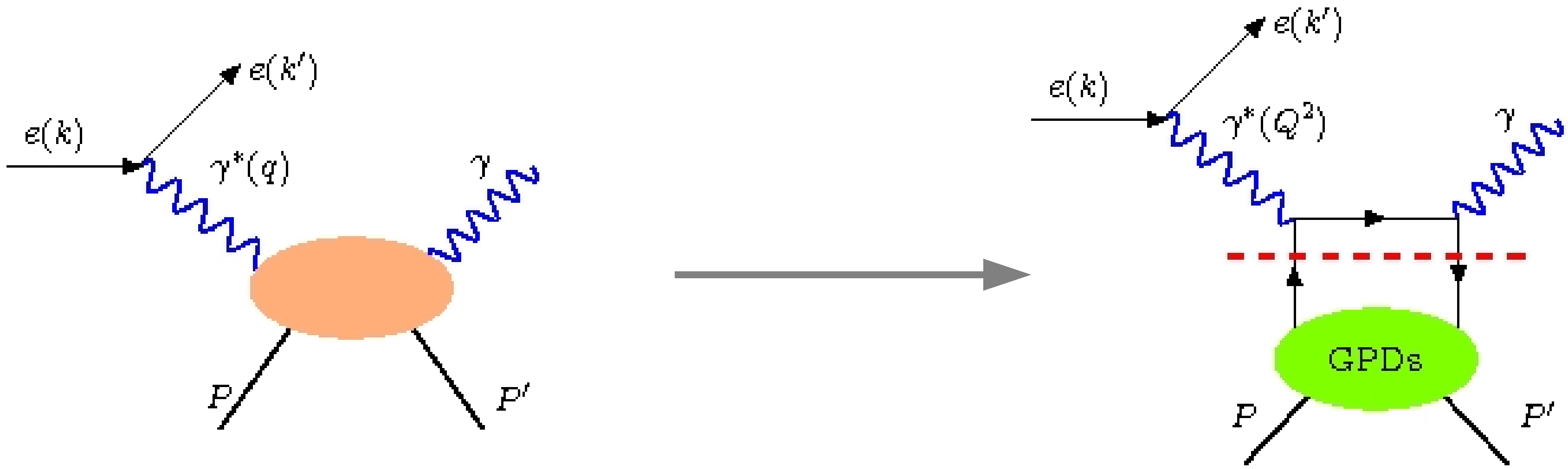
$$\begin{aligned} \xi &\approx \frac{x_B}{2 - x_B} \\ t &= (P - P')^2 \\ Q^2 &= -q^2 \\ x_B &= \frac{Q^2}{2(P \cdot q)} \end{aligned}$$

DVCS: factorization

In Bjorken limit: Q^2 and $W^2 = (P+q)^2$ large

x_B and t fixed

DVCS amplitude factorizes:



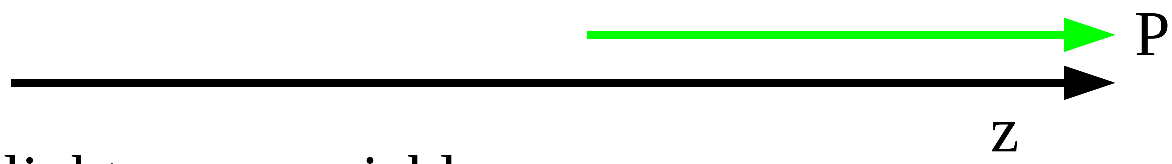
$$\mathcal{A}_{\mathrm{DVCS}}(\xi, t) = \text{Hard Part} \otimes \text{GPDs} = \sum_{\pm} \int_{-1}^{1} dx \frac{\text{GPDs}(x, \xi, t)}{x \mp \xi \pm i\epsilon}$$

x and ξ : light-cone fractions

Light-cone fractions*

For the parton interpretation of high energy scattering, it is convenient to

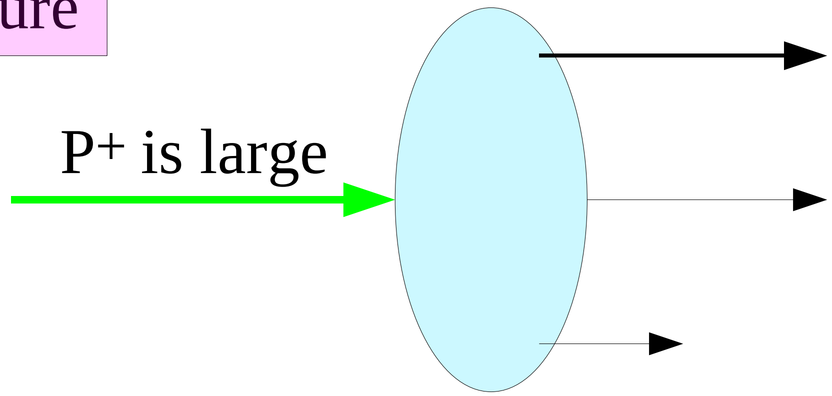
- consider the hadron moving very fast, e.g., in the +z-direction



- and introduce light-cone variables:

$$a^+ = \frac{1}{\sqrt{2}}(a^0 + a^3)\,, \qquad a^- = \frac{1}{\sqrt{2}}(a^0 - a^3)$$

Collinear picture



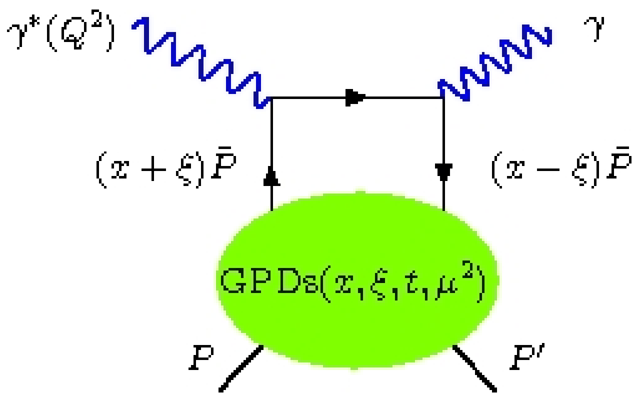
$$x = \frac{k^+}{P^+}$$

R. Feynman, 1969

DVCS vs. DIS

Deeply virtual Compton scattering

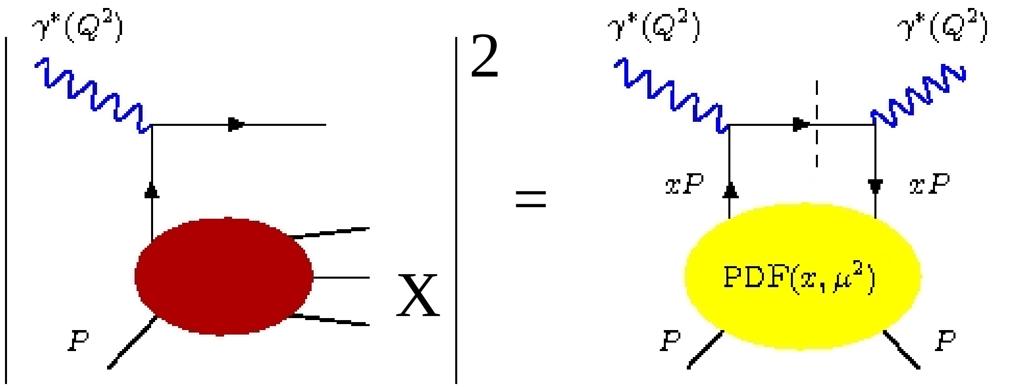
$$\gamma^* p \rightarrow \gamma p$$



- depends on 4 variables: two independent LC fractions x and ξ , t and μ^2
- ξ is fixed by kinematics
- enters amplitude integrated over x!

Deep Inelastic scattering (DIS)

$$\gamma^* p \rightarrow X$$



- depends on one LC fraction x and μ^2
- at leading order, enters amplitude at $x = x_B$

$$\bar{P} = (P + P')/2$$

Definition of GPDs

The number of GPDs depends on the spin of the target:

- 4 quark and 4 gluon GPDs for spin-1/2 (the nucleon, ^{3}He)
- 1 quark and 1 gluon GPD for spin-0 (^{4}He)
- 9 quark and 9 gluon GPDs for spin-1 (deuterium)

In this talk, I will consider only quark GPDs.

The nucleon unpolarized quark GPDs (of flavor q):

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}^+ z^-} \langle P' | \bar{\psi}(-\frac{z^-}{2}) \gamma^+ \psi(\frac{z^-}{2}) | P \rangle_{|z^+, \vec{z}_\perp = 0}$$

$$= \frac{1}{2\bar{P}^+} [H^q(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m} u(p)]$$

Properties of GPDs

1) Forward limit (ξ =t=0):

$$H^q(x,0,0) = q(x)\,, \quad x > 0$$

$$H^q(x,0,0) = -\bar{q}(-x)\,, \quad x > 0$$

• GPD H reduces to usual PDFs

• GPD E decouples

2) Connection to elastic form factors:

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$ Dirac

$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$ Pauli

Light-cone fraction x "slicing" of elastic form factors

Properties of GPDs (Cont.)

3) Polynomiality -- consequence of Lorentz invariance
4) Positivity -- consequence of unitarity

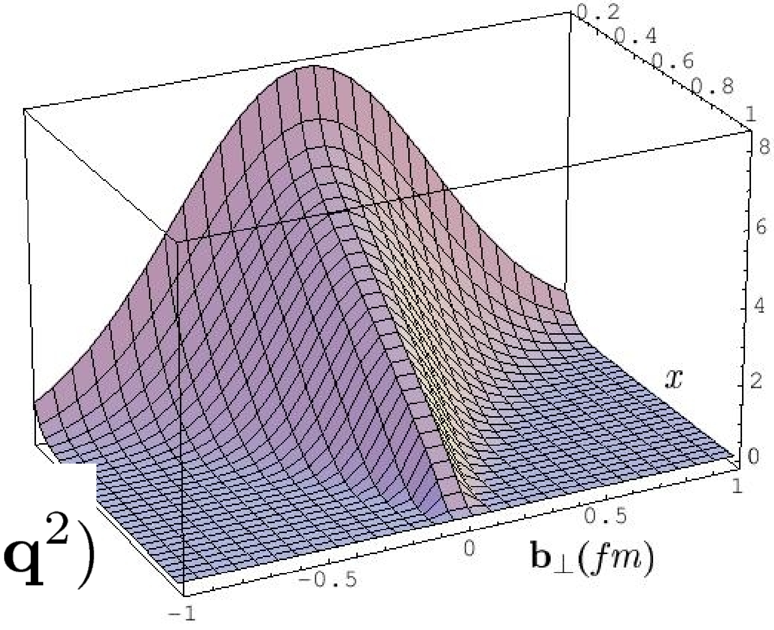
5) Probabilistic interpretation

In the $\xi = 0$ limit ($t = -\mathbf{q}^2$), the partons carry equal light-cone fractions x and GPDs have probabilistic interpretation in x-b space:

$$q(x, \mathbf{b}) = \int \frac{d^2\mathbf{q}}{(2\pi)^2} e^{-i\mathbf{b}\cdot\mathbf{q}} H^q(x, \xi = 0, t = -\mathbf{q}^2)$$

Probability to find a quark with LC fraction x and at transverse distance **b**.

M. Burkardt, 2003



u quark

Properties of GPDs (Cont.)

6) Spin sum rule and relation to the spin crisis

X. Ji, 1997

$$\frac{1}{2}\int_0^1 dx x(H^q(x,\xi,t=0)+E^q(x,\xi,t=0)) = J^q$$

$$\frac{1}{2}\int_0^1 dx x(H^g(x,\xi,t=0)+E^g(x,\xi,t=0)) = J^g$$

$$\sum_q J^q + J^g = \frac{1}{2}$$

Quark and gluon contributions to target total angular momentum

Decomposition into helicity and orbital momentum contributions:

$$\sum_q J^q = \frac{1}{2}\Delta\Sigma + L^q$$

From polarized DIS and SIDIS: $\Delta\Sigma \approx 0.33$

"Proton spin crisis"

Planed measurements of GPDs, especially E, should clarify the situation with the spin balance of the proton.

Properties of GPDs (Cont.)

7) Connection to form factors of the QCD energy-momentum tensor

$$\langle P'|T^{\mu\nu}_{q,g}|P\rangle = A_{q,g}(t)\bar{u}P^{(\mu}\gamma^{\nu)}u + B_{q,g}(t)\bar{u}\frac{P^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2m}u$$

$$+ C_{q,g}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{m}\bar{u}u + \bar{C}_{q,g}(t)mg^{\mu\nu}\bar{u}u$$

- Form factors A(t) and B(t) related to the angular momentum:

$$\frac{1}{2}(A_q(0) + B_q(0)) = J^q \qquad \frac{1}{2}(A_g(0) + B_g(0)) = J^g$$

- Form factor C(t) describes the distribution of shear forces experienced by quarks and gluons in the hadron.

M.V. Polyakov, 2003

The theoretical and experimental interest to generalized parton distibutions is fueled by the facts that GPDs:

- provide a proper theoretical framework for the description of hard exclusive processes (DVCS, electroproduction of mesons, etc.)
- extend the traditional 1D picture of hadrons to full 3D image
- have the potential to address the proton spin crisis.

What do we learn additionally from GPDs of nuclei?

Generalized parton distributions of nuclei

Complimentary to proton GPDs

- nuclear GPDs involve proton and neutron GPDs, i.e. indirect info on nucleon GPDs
- DVCS on quasi-free nucleon in nuclei (incoherent DVCS) probes the nucleon GPDs
- The only way to measure neutron GPDs,

JLab, DVCS on deuteron, 2007

Traditional nuclear effects enhanced

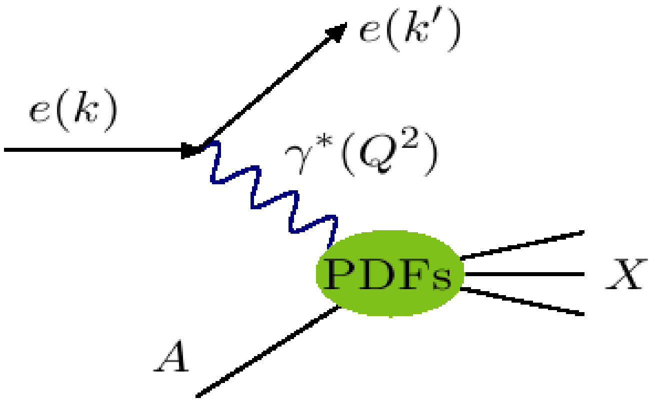
- nuclear binding and off-diagonal EMC effect
- nuclear shadowing

New nuclear effects

- non-nucleon degrees of freedom
- medium modifications of bound nucleon GPDs

Off-diagonal EMC effect

Inclusive DIS with nuclear targets measures nuclear PDFs and structure function $F_{2A}(x,Q^2)$



European Muon Collaboration (EMC), CERN
J.J. Aubert et al. Phys. Lett. B123, 275 (1983)

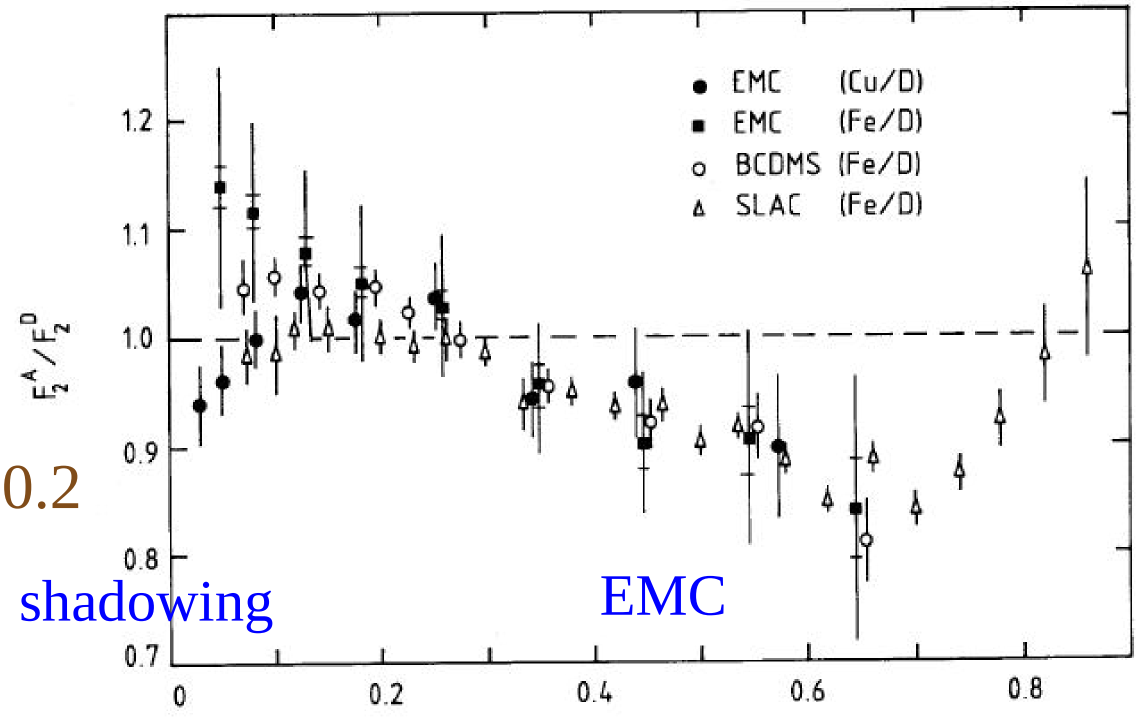


FIG. 3

The EMC effect:

$F_{2A}(x,Q^2) < AF_{2N}(x,Q^2)$ for $0.7 > x > 0.2$

Naive expectation: $F_{2A}(x,Q^2)=AF_{2N}(x,Q^2)$ since Q^2 » nuclear scales

Off-diagonal EMC effect (Cont.)

There is no universally accepted explanation of the EMC effect:

- conventional nuclear binding underestimates the EMC effect

L. Frankfurt and M. Strikman, 1988

- models with explicit non-nucleon degrees of freedom (pion excess models) seem to contradict the nuclear Drell-Yan data

*However, this is under debate

- models involving both nuclear binding and modifications of the bound nucleon structure function *can* explain the EMC effect, but these are models

K. Saito and A.W. Thomas, 1994

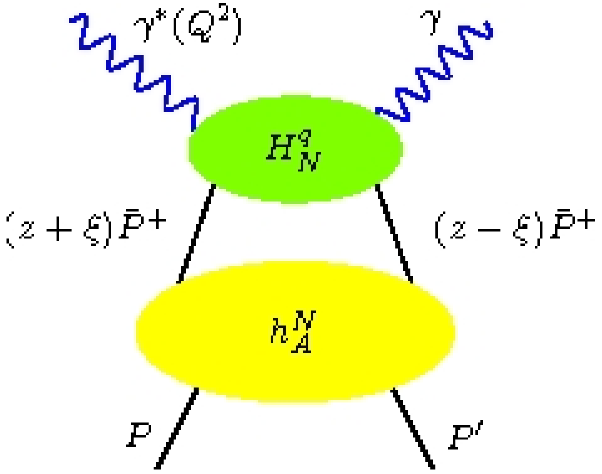
Studies of the EMC effect in off-diagonal kinematics may shed some light on the origin of the EMC effect.

Off-diagonal EMC effect (Cont.)

Traditional nuclear binding effects in nuclear GPDs can be taken into account using the impulse approximation,

VG and M. Siddikov, 2006

S. Scopetta, 2004 and 2009



$$H_A^q(x,\xi,t) = \sum_N \int_x^1 \frac{dz}{z} h_A^N(z,\xi,t) H_N^q\left(\frac{x}{z},\frac{\xi}{z},t\right)$$

$$z = \frac{\bar{p}_N^+}{\bar{P}^+}$$

LC fraction of the interaction nucleon

Off-diagonal light-cone distribution

Nucleon GPDs

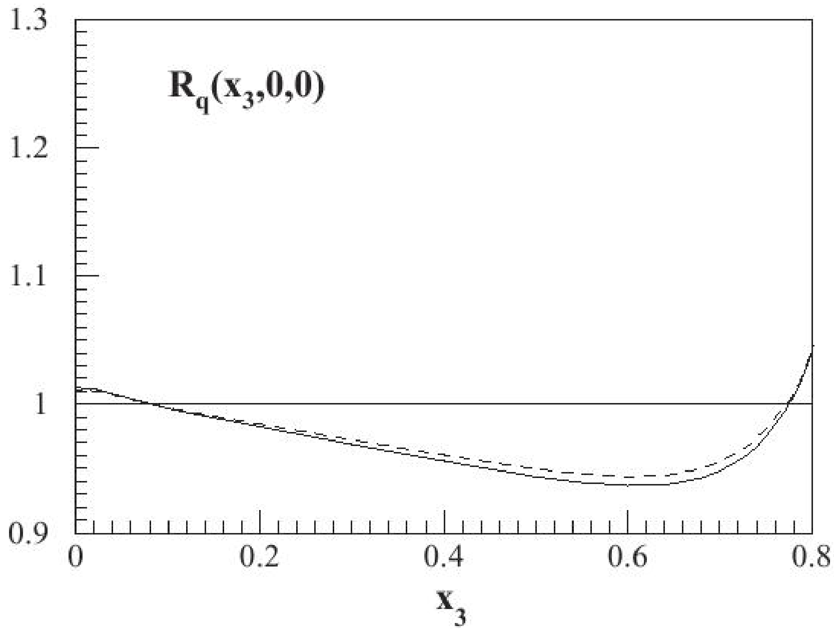
Off-diagonal EMC effect (Cont.)

Calculations for ^{3}He using off-diagonal light-cone distribution h_A obtained with off-diagonal spectral function and realistic NN potential, S. Scopetta, 2009

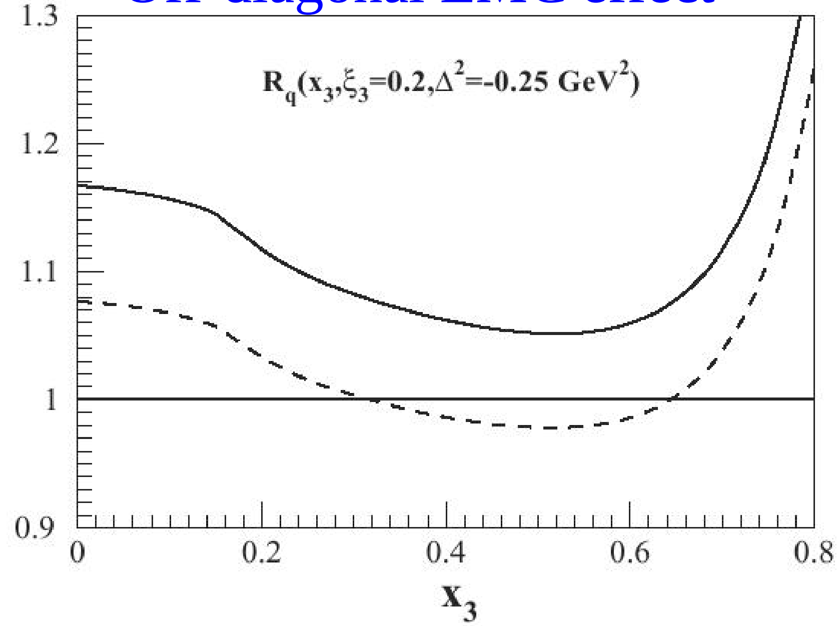
$$R_q(x,\xi,t) = \frac{H^q_{^3\mathrm{He}}(x,\xi,t)}{H^{q,(0)}_{^3\mathrm{He}}(x,\xi,t)}$$

$$H^{q,(0)}_{^3\mathrm{He}} = F_A(t)(2H^q_p + H^q_n)$$

Forward EMC effect



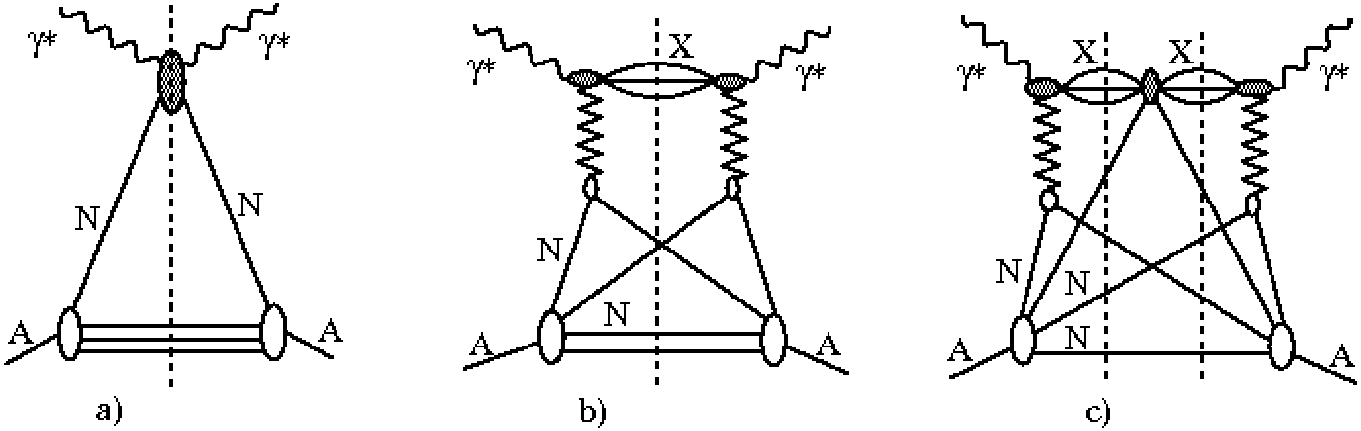
Off-diagonal EMC effect



Solid: u quark; dashed: d quark

Nuclear shadowing for nuclear GPDs

In DIS with nuclei, nuclear shadowing, $F_{2A}(x,Q^2)<AF_{2N}(x,Q^2)$ for $x < 0.1$, is explained by the observation that at small x_B, γ^* *simultaneously* interacts with all nucleons:



\+ - +

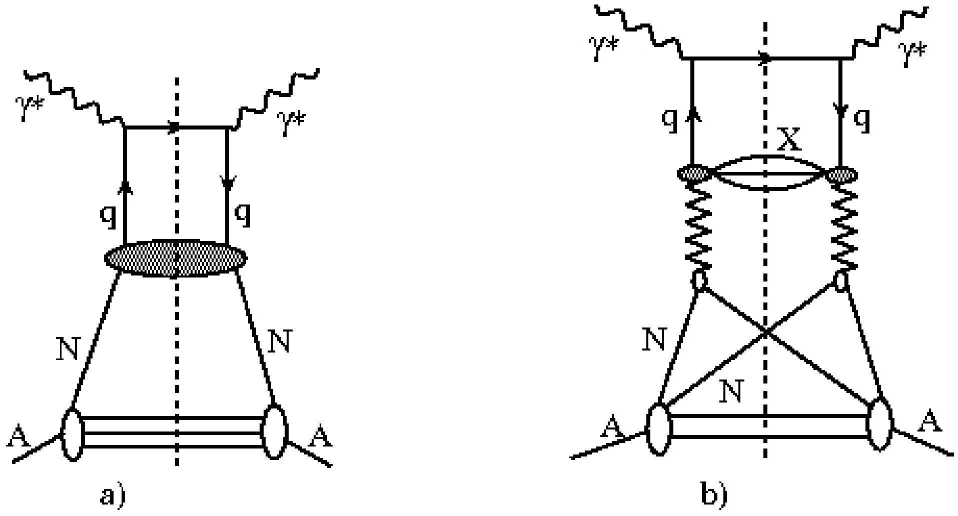
- Since the γ^*N scattering amplitude is predominantly imaginary, the graphs shown above contribute with an alternating relative sign, i.e. b) decreases a). Geometric picture: one nucleon *shadows* the other one, R. Glauber, 1959

- γ^*N interaction is diffractive: shadowing driven by diffraction.

V.N. Gribov, 1969

Shadowing for nuclear GPDs (Cont.)

- The next important step is the *factorization theorem*, which allows to derive nuclear shadowing for nuclear parton distributions in terms of diffractive parton distributions of the proton measured at HERA.



+ other terms

$$q_A(x) = A\,q_N(x) - q_N^{D(3)} \otimes \text{Nuclear Part} + \ldots$$

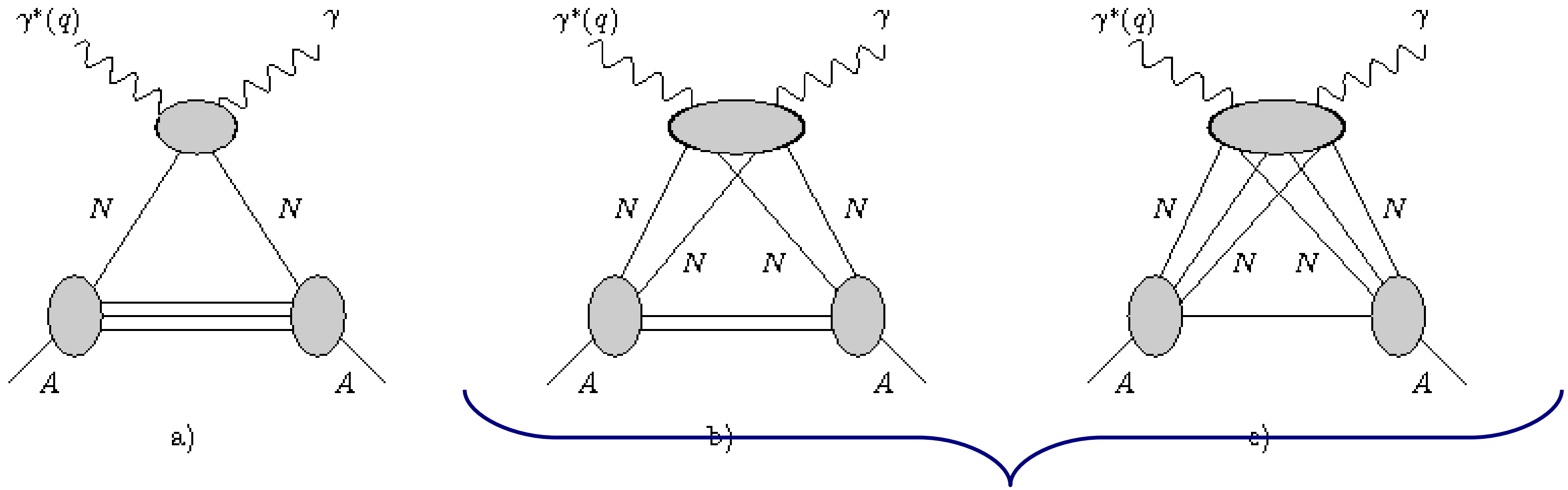
Leading twist theory of nuclear shadowing, M. Strikman and L. Frankfurt, 1989

L. Frankfurt, VG, M. Strikman, 2007

Shadowing for nuclear GPDs (Cont.)

The formalism of leading twist nuclear shadowing can be generalized to DVCS and nuclear GPDs at small x_B

K. Goeke, VG, M. Siddikov, 2009



Born term

Shadowing correction

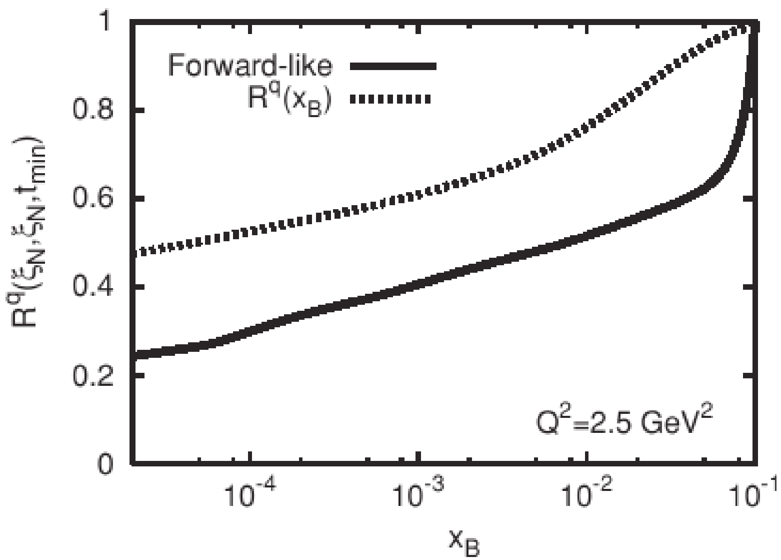
$$H_A^{q,g}(x,\xi,t) = AF_A(t)H_N^{q,g}(x,\xi,t) \qquad -H_{IP}^{q,g} \otimes \text{Nucl. Part}$$

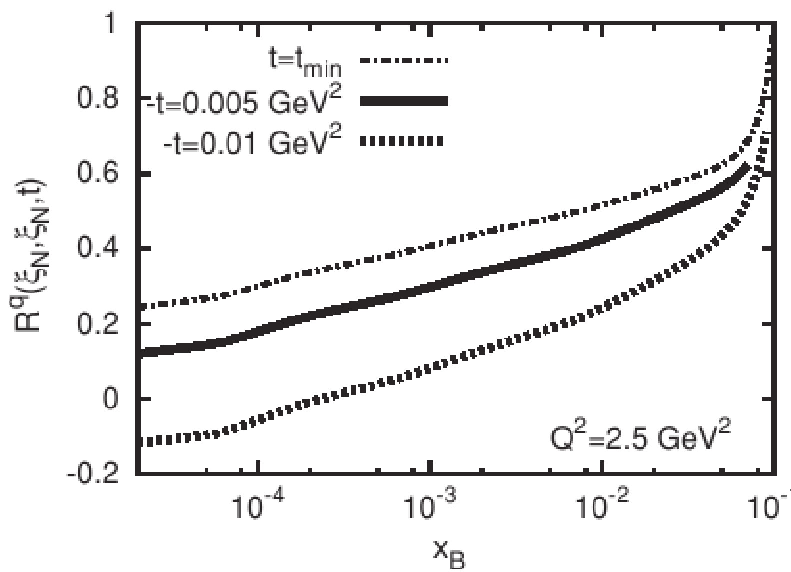
"quark or gluon GPD of the Pomeron"

Shadowing for nuclear GPDs (Cont.)

$$R^q(x,\xi,t) = \frac{H_A^q(x,\xi,t)}{AF_A(t)H_N^q(x,\xi,t)}$$ at $x = \xi = x_B/(2-x_B)$

K. Goeke, VG, M. Siddikov, 2009





208Pb

Shadowing for GPDs is larger than for forward nuclear PDFs.

Shadowing increases with increasing |t|

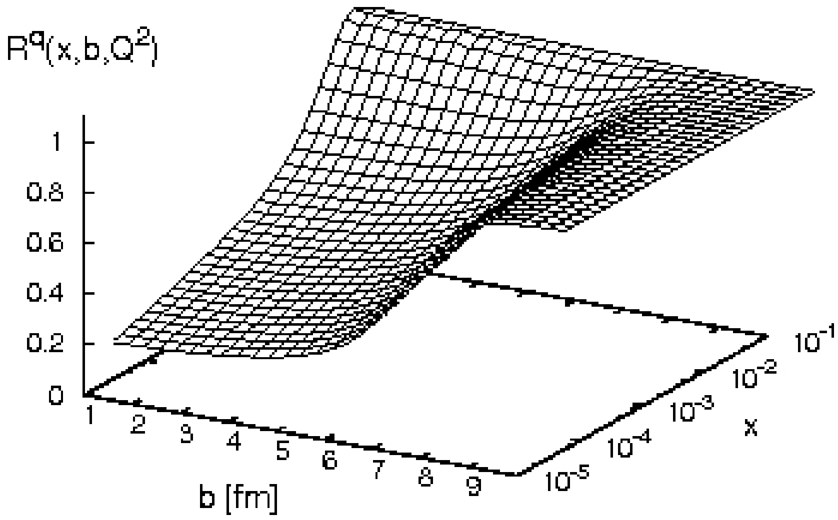
*Used forward-like model for GPDs

Shadowing for nuclear GPDs (Cont.)

In the ξ =0 limit, t=-**q²**, and GPDs have the probabilistic interpretation in the impact parameter **b** space.

$$R^q(x,b) = \frac{H_A^q(x,\xi=0,b)}{AT_A(b)H_N^q(x,\xi=0,b)}$$

208Pb



Density of nucleons at given b

- Nuclear shadowing is larger at small b

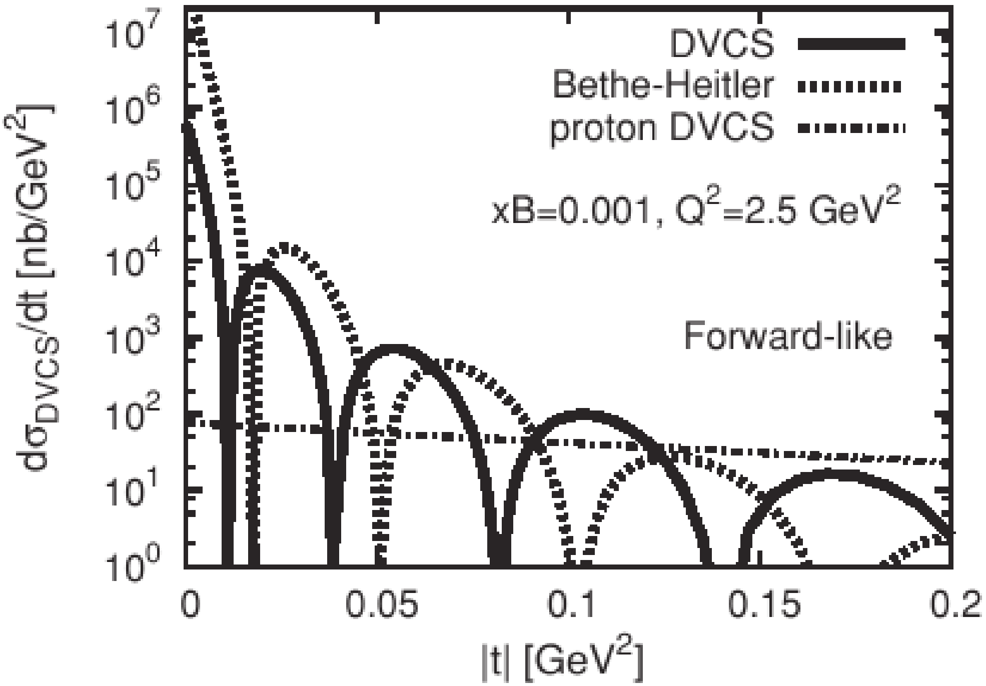
- Nuclear shadowing introduces *correlations between x and b*, even if such correlations are absent for the free nucleon GPDs

Shadowing for nuclear GPDs (Cont.)

Predictions for DVCS cross section $\gamma^* A \to \gamma A$

$$\frac{d\sigma_{\rm DVCS}}{dt} = \frac{\pi^3 \alpha_{\rm em}^2 x_B^2}{Q^4} |H_A(\xi,\xi,t)|^2$$

K. Goeke, VG, M. Siddikov, 2009



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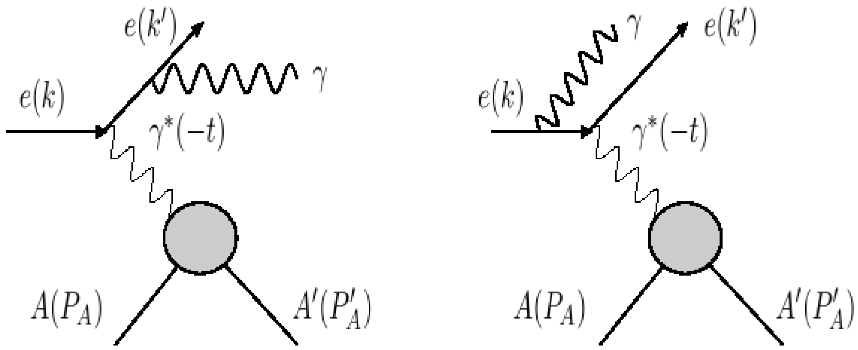
Shadowing for nuclear GPDs (Cont.)

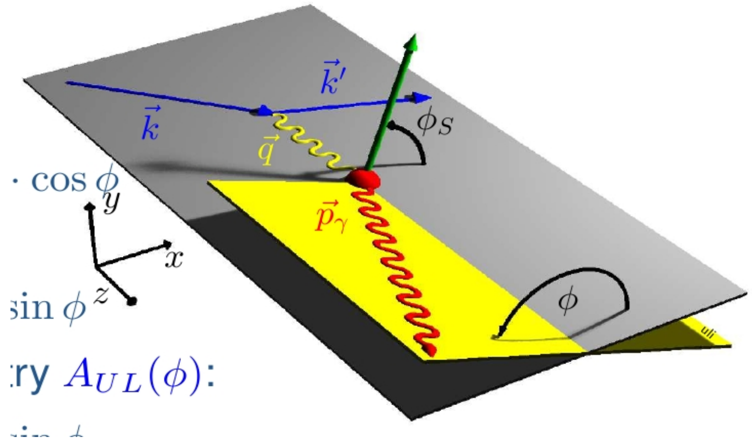
DVCS interferes with Bethe-Heitler (BH) process, whose amplitude is real.



One extracts real and imaginary parts of DVCS amplitude by measuring cross section asymmetries, which are proportional to the interference between DVCS and BH amplitudes.

Beam-spin asymmetry (polarized beam)

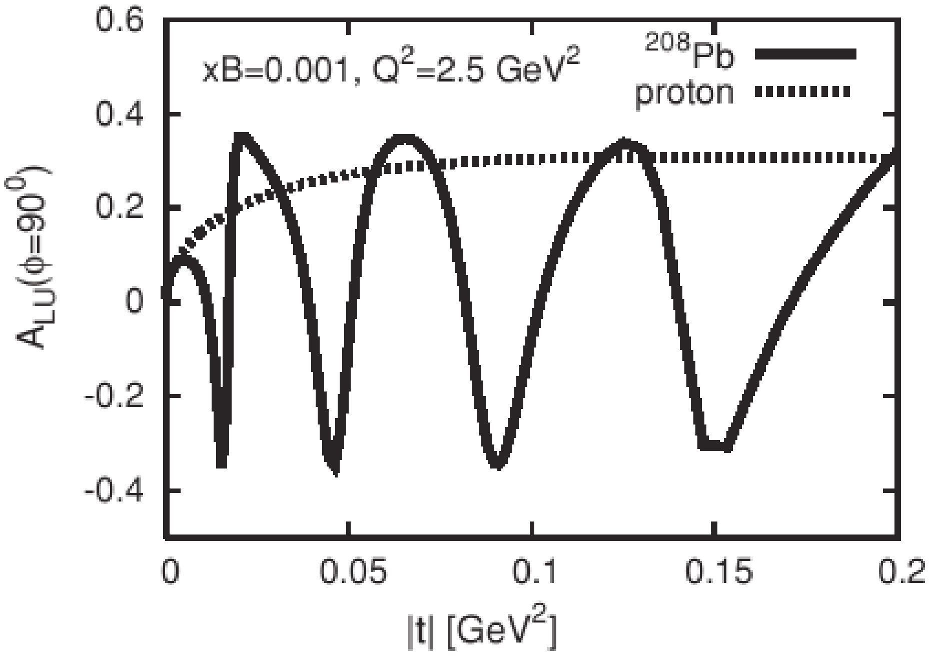
$$A_{\rm LU}(\phi) = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \propto \sin\phi \frac{H_A(\xi,\xi,t)F_A(t)}{F_A^2(t)}$$



Shadowing for nuclear GPDs (Cont.)

Predictions for beam-spin DVCS asymmetry

K. Goeke, VG, M. Siddikov, 2009



208Pb

Nuclear shadowing leads to dramatic oscillations.

Medium modifications of bound nucleon GPDs

Properties of bound nucleons in a nuclear medium are expected to be modified:

- structure function $F_{2N}^*(x,Q^2) \neq F_{2N}(x,Q^2)$ in DIS with nuclei

- elastic form factors $F_{1,2}^*(t) \neq F_{1,2}(t)$ in quasi-elastic scattering on nuclei

  Recoil polarization in $^4He(\vec{e}, e'\vec{p})^3H$

  S. Strauch et al. PRL 91, 052301 (2003)
  S. Malace at al, 0807.2252 [nucl-ex]

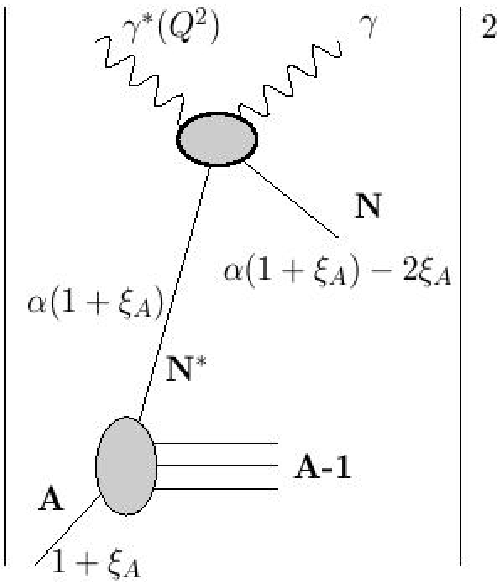
- axial coupling constant $g_A^* < g_A$ in nuclear beta decay

- various static properties (masses, magnetic moments)

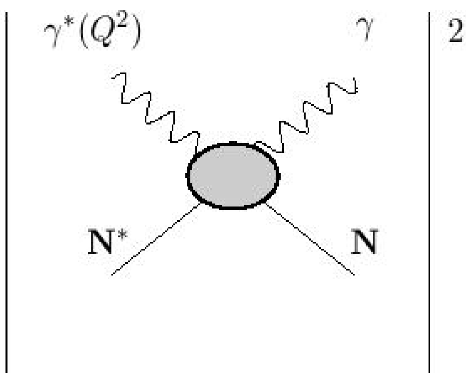
> It is natural to expect that bound nucleon GPDs should also be modified by the nuclear medium.

Medium modifications of bound nucleon GPDs (Cont.)

GPDs of the bound nucleon can be probed in *incoherent* DVCS with nuclei



$$= \int \frac{d\alpha}{\alpha} \rho_A^N(\alpha,\lambda) \sum_\lambda$$



Ignoring Fermi motion:

$$|\mathcal{T}^{^4\mathrm{He}}_{\mathrm{DVCS}}|^2 = \sum_\lambda |\mathcal{T}^{p^*}_{\mathrm{DVCS}}|^2$$

Nuclear DVCS, example for 4He

Bound proton

proton polarization

Medium modifications of bound nucleon GPDs (Cont.)

Recalling the connection of GPDs and elastic form factors, one can propose a simple model for the *bound nucleon GPDs*, which leads to correct form factors of the bound nucleon:

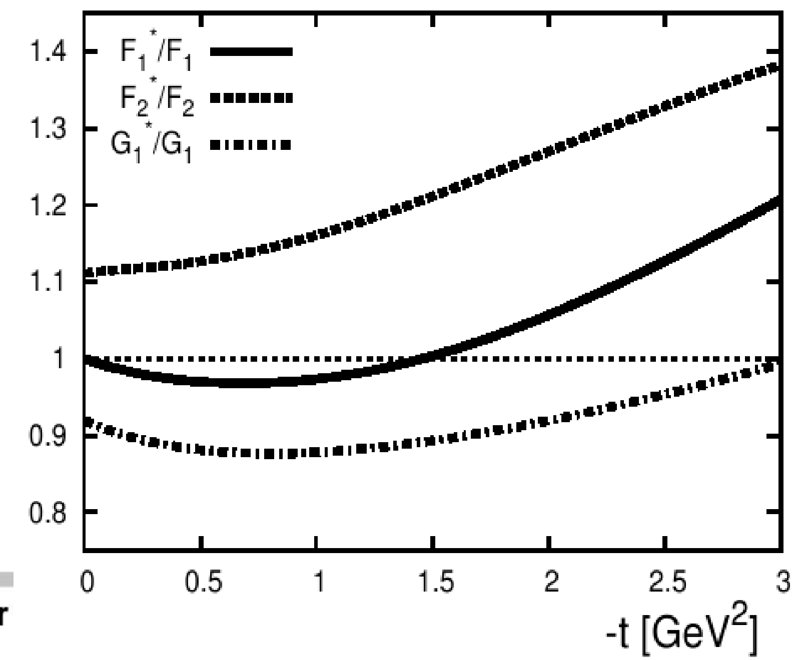
VG, A.W. Thomas, K. Tsushima, 2009

$$H^{q/N^*}(x,\xi,t) = \frac{F_1^{q/N^*}(t)}{F_1^{q/N}(t)} H^{q/N}(x,\xi,t)$$

$$E^{q/N^*}(x,\xi,t) = \frac{F_2^{q/N^*}(t)}{F_2^{q/N}(t)} E^{q/N}(x,\xi,t)$$

Double distribution for free GPDs
M. Guidal et al, 2005

Results of Quark-Meson Coupling (QMC) model for bound proton in ^{4}He
K. Saito, A.W. Thomas, K. Tsushima, 2007.
Consistent with the data on recoil polarization in $^4He(\vec{e},e'\vec{p})^3H$



Medium modifications of bound nucleon GPDs (Cont.)

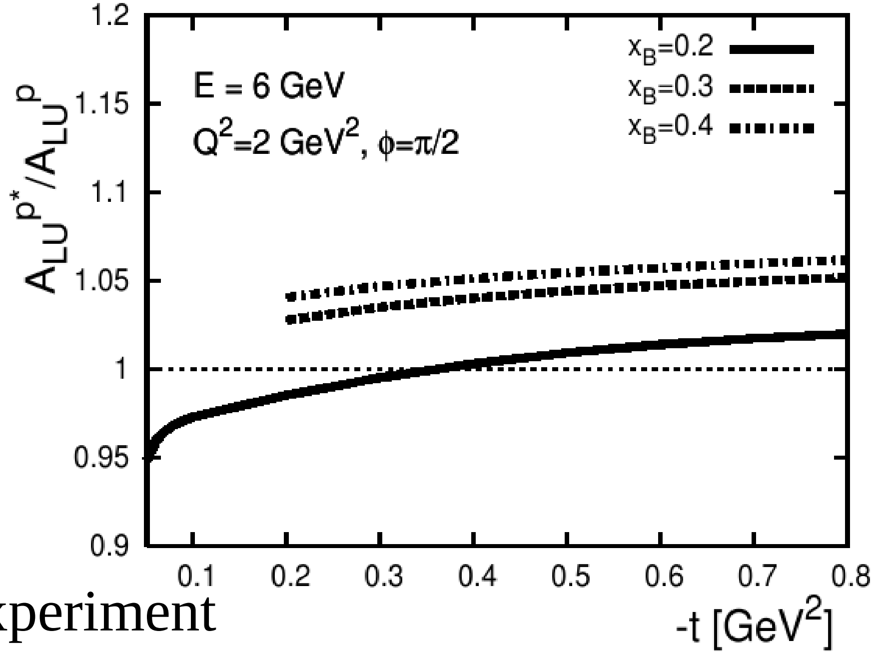
Prediction for the ratio of the beam spin DVCS asymmetries for the nucleon bound in ^{4}He and free nucleon

$$A_{LU}^{p^*}(\phi) \propto \mathrm{Im}\left(F_1^{p^*}\mathcal{H}^{p^*} - \frac{t}{4m_N^2} F_2^{p^*}\mathcal{E}^{p^*}\right) \Big/ f(F_1^{p^*}, F_2^{p^*}) \sin\phi$$

VG, A.W. Thomas, K. Tsushima, 2009

enhancement because $F_2^*(t) > F_2(t)$

suppression because $F_1^*(t) < F_1(t)$



- will be tested by the approved JLab at 6 GeV experiment

H.Egyian, F.Girod, K.Hafidi, S.Liuti, E.Voutier, E08-024 (2008)

- our predictions are very different from the only other existing model

S.Liuti and S.K.Taneja, 2005

Summary of generalized parton distributions of nuclei

Complimentary to proton GPDs

- nuclear GPDs involve proton and neutron GPDs, i.e. indirect info on nucleon GPDs
- DVCS on quasi-free nucleon in nuclei (incoherent DVCS) probes the nucleon GPDs
- The only way to measure neutron GPDs,

JLab, DVCS on deuteron, 2007

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- nuclear shadowing

New nuclear effects

- non-nucleon degrees of freedom
- medium modifications of bound nucleon GPDs