Nuclear GPDs and coherent nuclear processes

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Exclusive Reactions at High Momentum Transfer
Jefferson Lab, May 18-21, 2010

Outline

- Intro: Nuclear generalized parton distributions (GPDs)
- Nuclear GPDs at medium $x_{B,}$ $x_B > 0.05$:
  - comparison to Hermes data; new JLab experiment
  - off-diagonal EMC effect
- Leading twist nuclear shadowing and nuclear GPDs at small x_B, $x_B < 0.05$
- Summary

Summary of generalized parton distributions

Deeply virtual Compton scattering (DVCS)

Timelike Compton scattering

Exclusive meson production,
deep virtual/ large t

Wide angle Compton scattering,
$p\bar{p} \longrightarrow \gamma\gamma$

GPDs

Form factors

3D picture of hadrons, parton angular momentum

Parton distributions, DIS

Generalized parton distributions in nuclei

Complimentary to proton GPDs

- nuclear GPDs involve proton and neutron GPDs -> access to different spin/flavor combinations
- 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

- off-diagonal EMC effect
- nuclear shadowing

New nuclear effects more prominent

- medium modifications of bound nucleon GPDs
- non-nucleon degrees of freedom;
- fast A-dependence of D-term

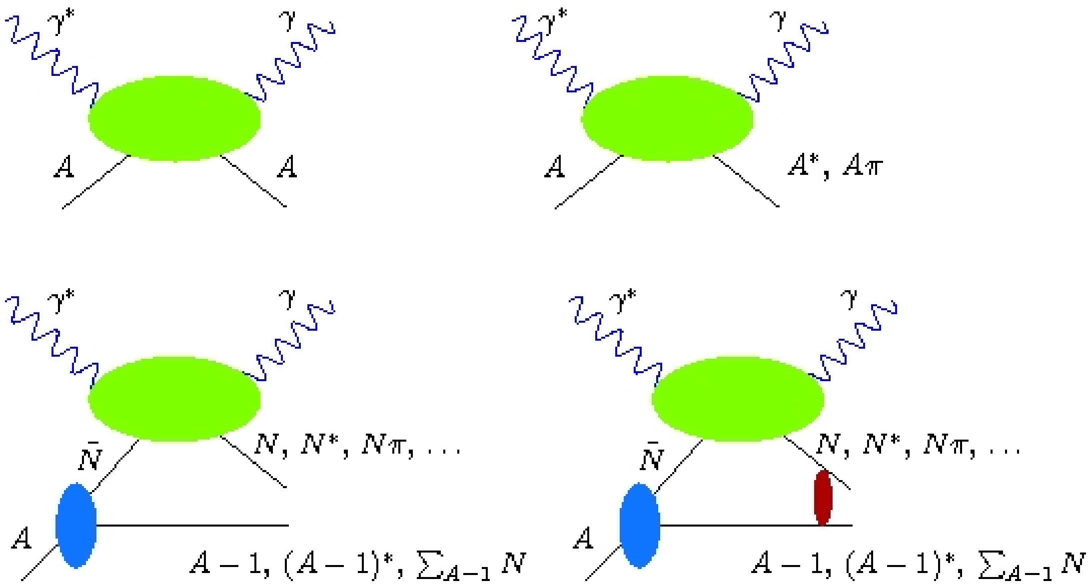
- Nuclear GPDs at medium x_B, $x_B > 0.05$

Nuclear DVCS

The cleanest process to study GPD is deeply virtual Compton scattering (DVCS).

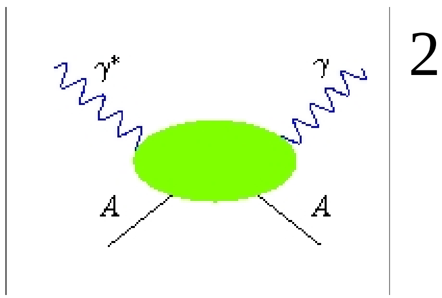
Nuclear DVCS is more complex and versatile than DVCS on protons:

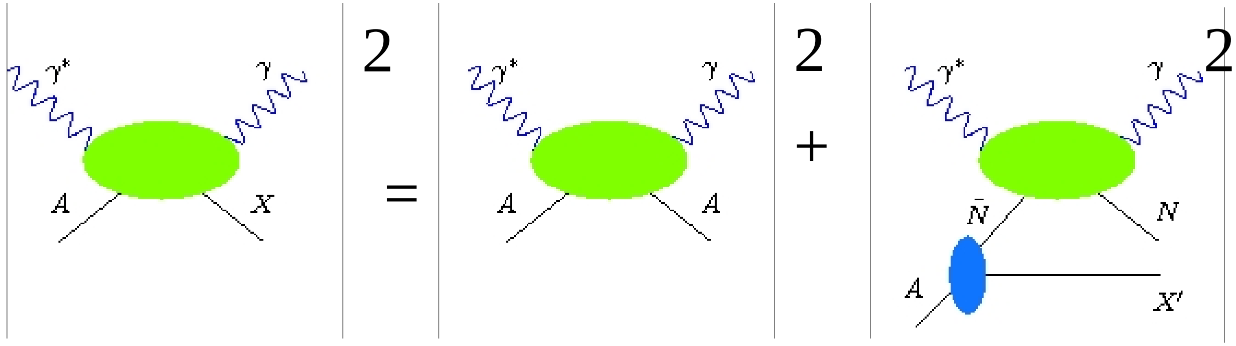
- many more final states can be excited
- targets with different spin and isospin



Coherent and incoherent nuclear DVCS

The theoretical analysis of nuclear DVCS is simplest when the final state is either elastic or forms a complete set of states:





Coherent nuclear DVCS:

- dominates at small t
- cross sect. ~ $A^2 F_A^2(t)$
- JLab with ^{4}He

"Coherent" and Incoherent nuclear DVCS:

- "coh." dominates at small t, incoherent at large t

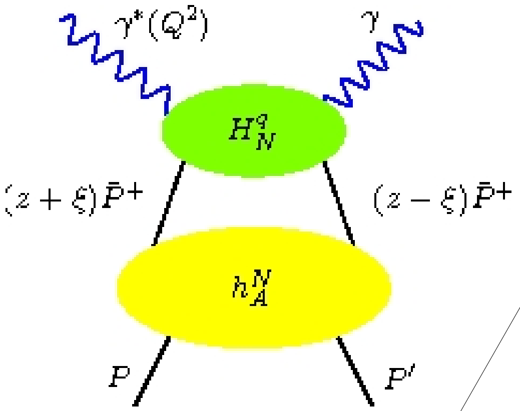
cross sect. ~ $A(A-1)F_A^2(t')|T_N|^2 + AF_N^2(t)|T_N|^2$

VG, M. Strikman, 2003

- similarly for Bethe-Heitler and Interference
- Hermes measurement

Convolution approximation for nGPDs

Both coherent and incoherent nuclear DVCS take place on (medium-modified) bound nucleons:



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

z is nucleon LC fraction

Ignoring convolution:

$T_{coh} = F_A(t)(ZT_p(t) + NT_n(t))$

A. Kirchner, D. Mueller, 2003

$|T_{coh\text{-}enr}|^2 = A(A-1)F_A^2(t')|T_n(t)|^2$

$|T_{incoh}|^2 = Z|T_p(t)|^2 + N|T_n(t)|^2$

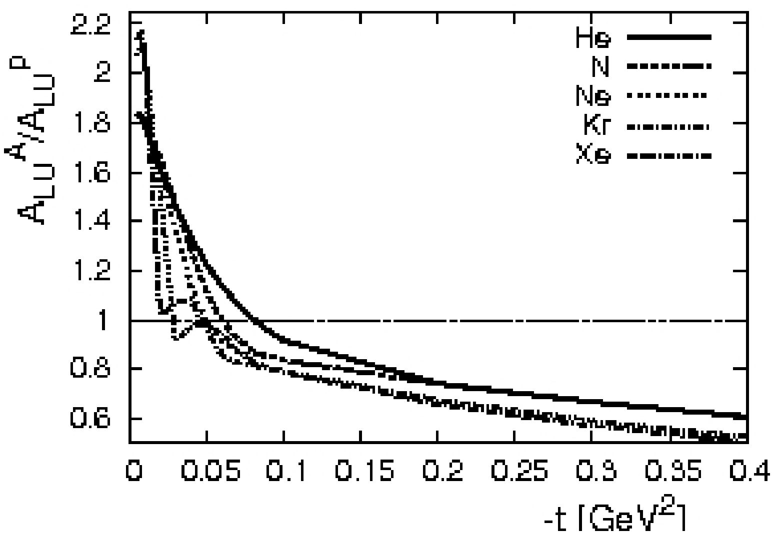
Convolution over z and p_t:

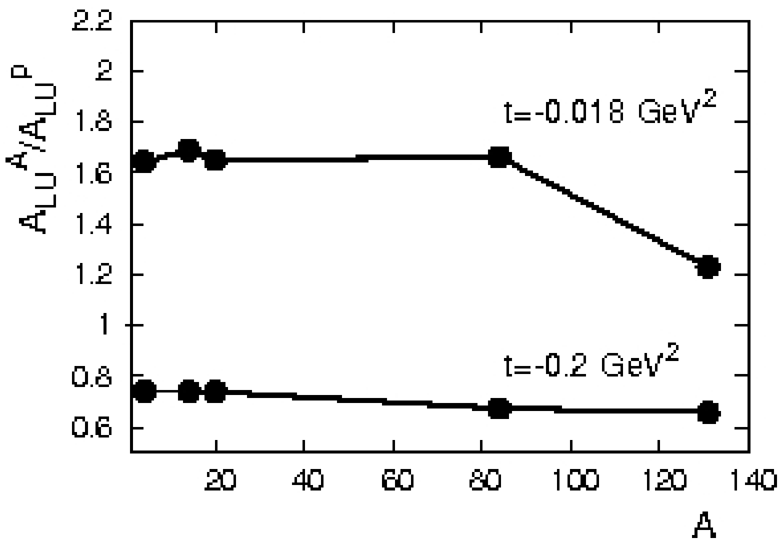
S. Liuti and K. Taneja,
PRC 72, 032201 and 034902 (2005)

Beam-spin DVCS asymmetry

Predictions for the ratio of the nuclear to proton beam-spin DVCS asymmetries, A_{LU}^{A}/A_{LU}^{p}, in Hermes kinematics, x_B=0.065, Q^2=1.7 GeV2

VG and M. Strikman, PRC 68, 015204 (2003); VG, PRC 78, 025211 (2008)





- Enhancement at small is combinatoric:

$$A_{LU}^{A}/A_{LU}^{p} \approx 1 + \frac{N}{Z}\frac{I_n}{I_p} \approx 1.65 - 1.85$$

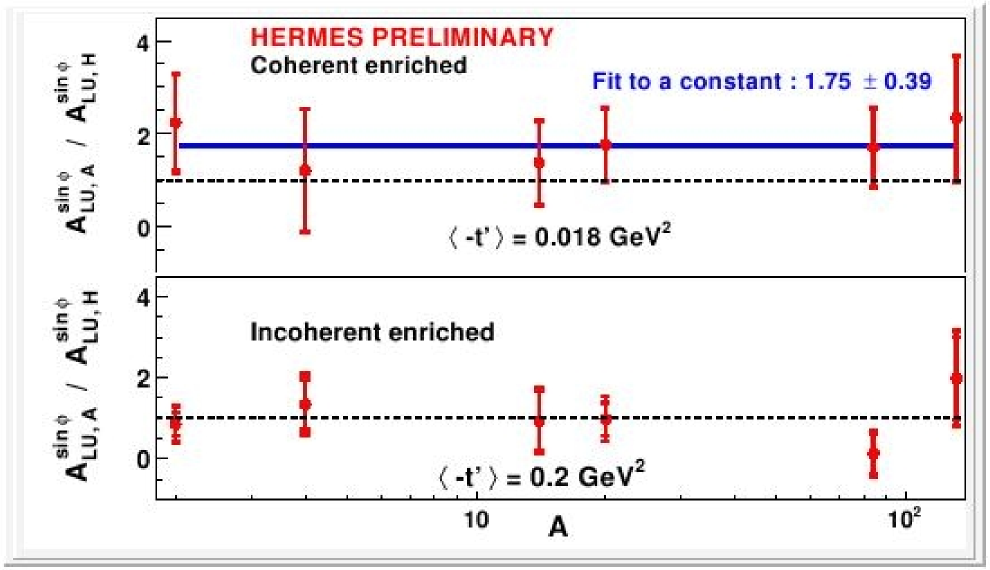
- Suppression of incoh. DVCS at large t is due to neutron contribution

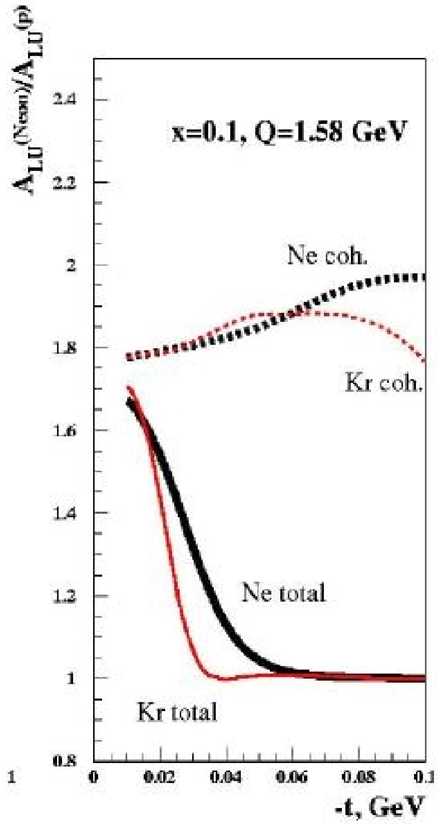
Also A. Kirchner and D.Mueller, EPJ C 32, 347 (2003)

Beam-spin DVCS asymmetry-2

Hermes 2006

RATIO A^A_{LU}/A^p_{LU} (METHOD 1)





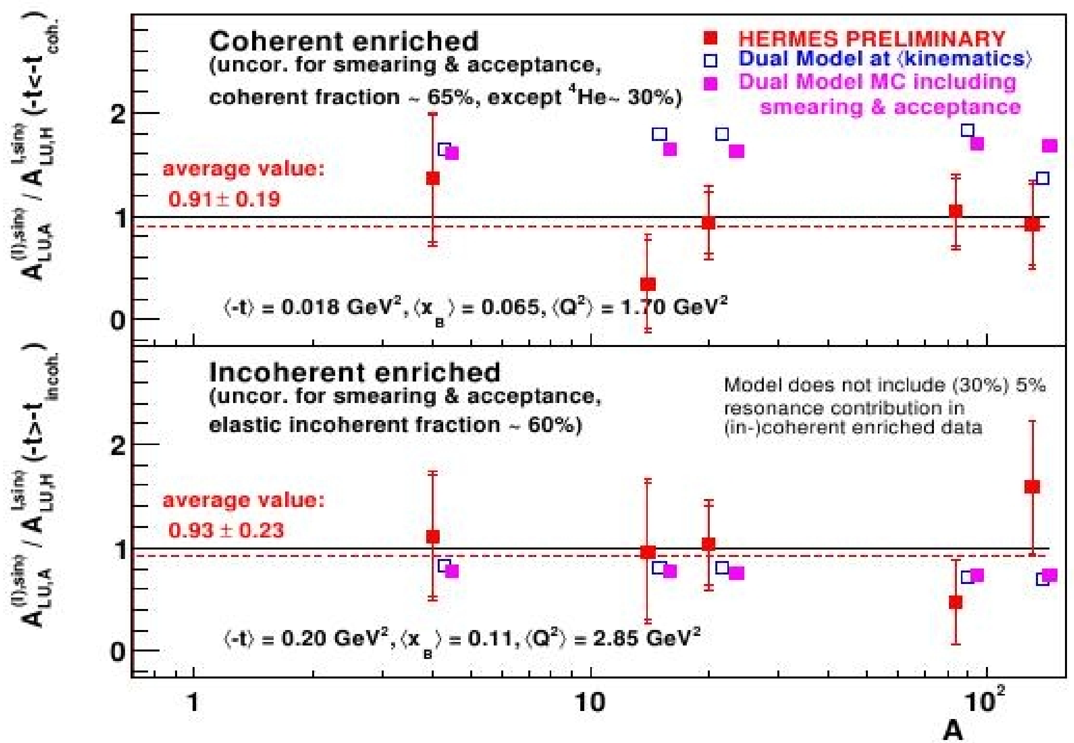
- COHERENT ENRICHED: MEAN RATIO DEVIATES FROM UNITY BY 2σ. CONSISTENT WITH PREDICTIONS BETWEEN 1.8 AND 1.95: GUZEY/STRIKMAN PHYS.REV.C 68 (2003)
- INCOHERENT ENRICHED: CONSISTENT WITH UNITY AS NAIVELY EXPECTED

Beam-spin DVCS asymmetry-3

Hermes 2009 final

Airapetian, PRC 81, 2010

Ratio of Leading BSA Amplitude: $A_{LU,A}^{(I),\sin\phi}/A_{LU,H}^{I,\sin\phi}$



- The measured ratio of $A_{LU,A}^{(I),\sin\phi}/A_{LU,H}^{I,\sin\phi}$ is comparable with unity in both (in-)coherent enriched sample
- The results have been corrected for the background and other experimental effects, but not for the smearing (small effect, $\sim$0.01) and acceptance effect

Puzzle!

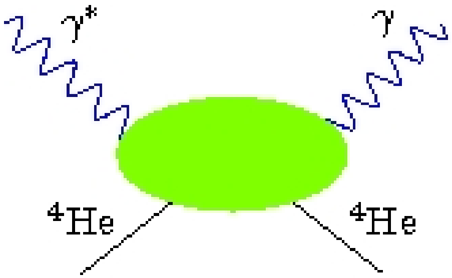
The JLab experiment on DVCS on 4He

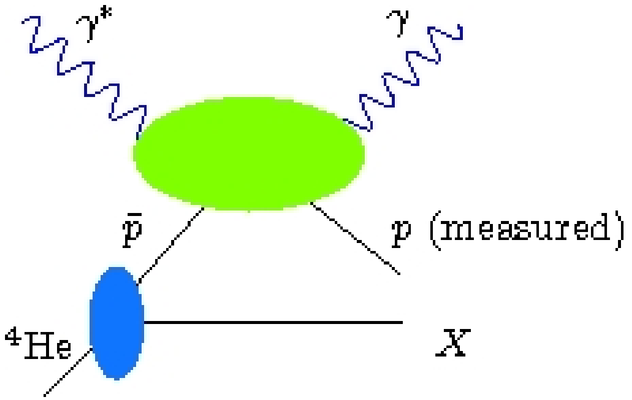
The analysis of new JLab data (CLAS) on DVCS on 4He will clarify the situation (data taken in Fall 2009)

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

The analysis will extract:

- purely coherent DVCS on 4He (final nucleus detected with BoNuS)
- DVCS on the bound proton (possible nuclear modifications of bound proton GPDs, VG, A.W. Thomas, K. Tsushima, 2009)





Also LoI for 12 GeV

Off-diagonal EMC effect

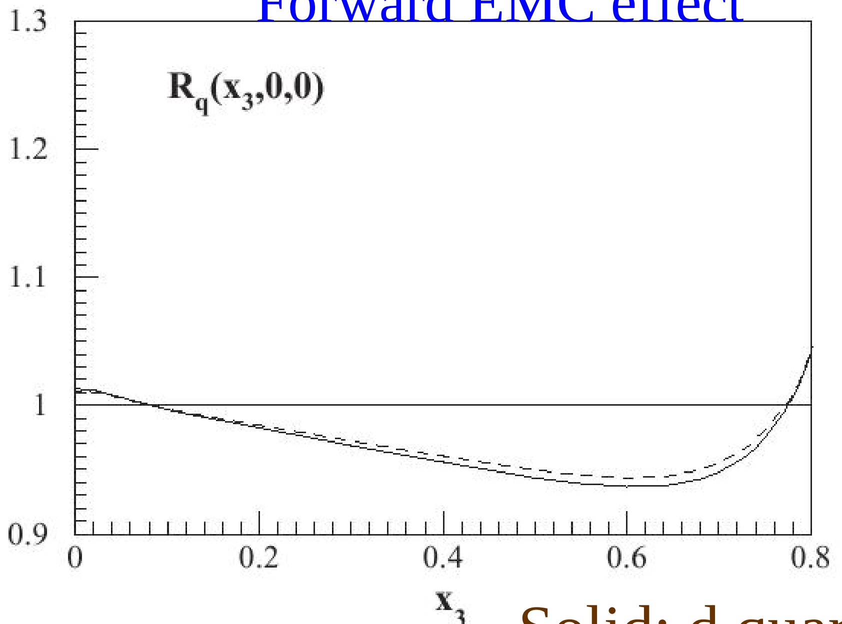
Calculations for ^{3}He using off-diagonal light-cone distribution h_A obtained with off-diagonal spectral function and realistic NN potential

S. Scopetta, PRC 79, 025207 (2009)

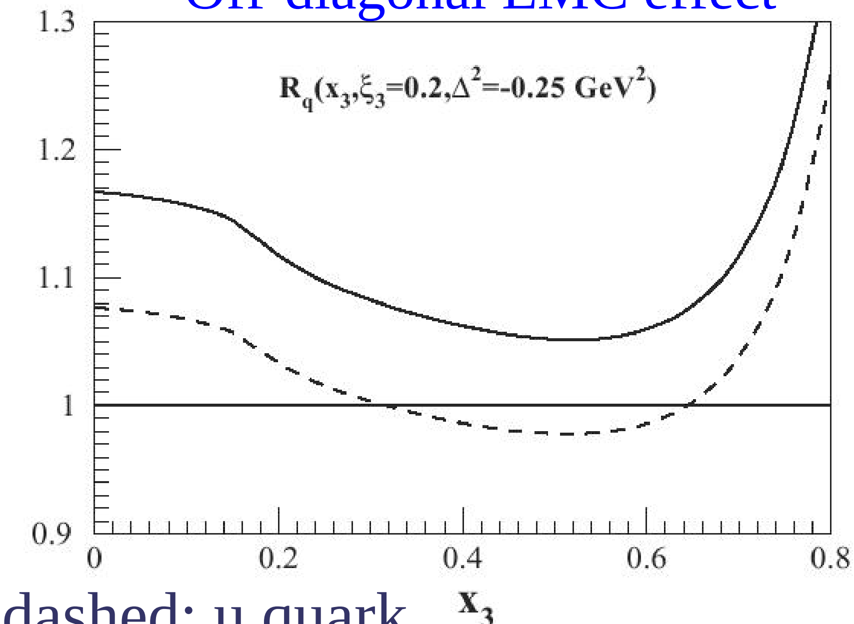
$$R_q(x,\xi,t) = \frac{H^q_{^3\mathrm{He}}(x,\xi,t)}{H^{q,(0)}_{^3\mathrm{He}}(x,\xi,t)}$$

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

Forward EMC effect



"Off-diagonal EMC effect"

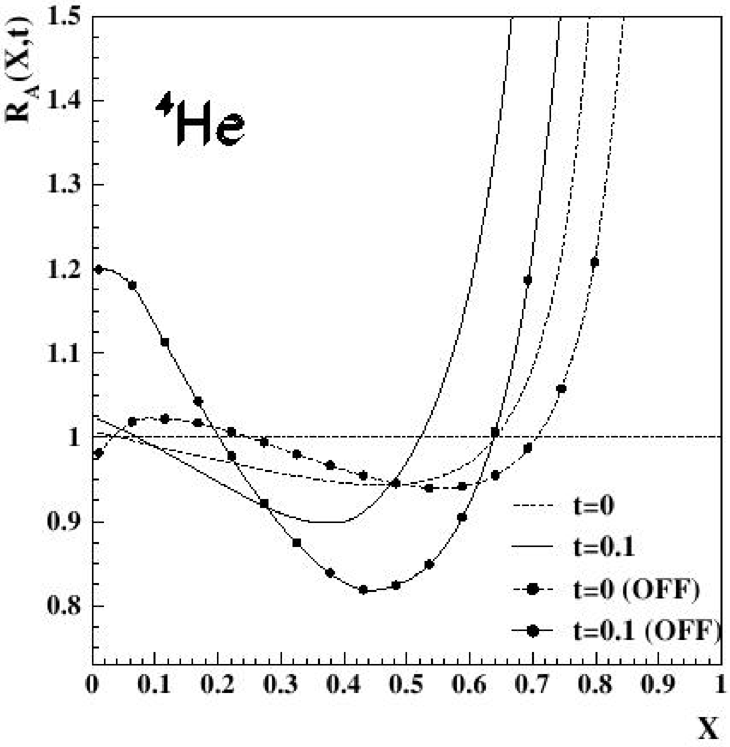


Solid: d quark; dashed: u quark

Off-diagonal EMC effect-2

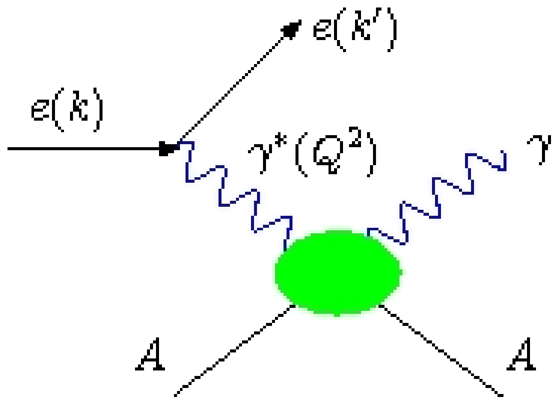
Convolution over z and pt and effects of off-shellness,

S. Liuti and S.K. Taneja , 2005



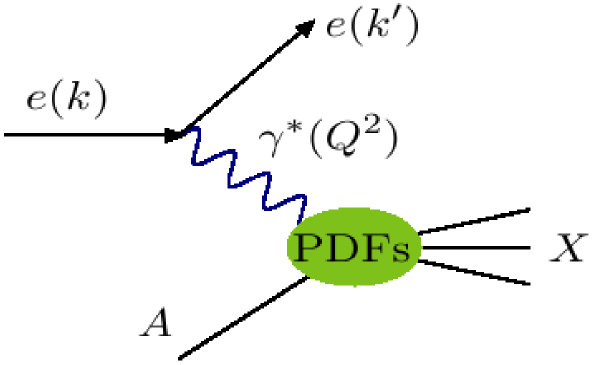
Enhanced off-diagonal EMC effect

- Nuclear shadowing and nuclear generalized parton distributions (GPDs)

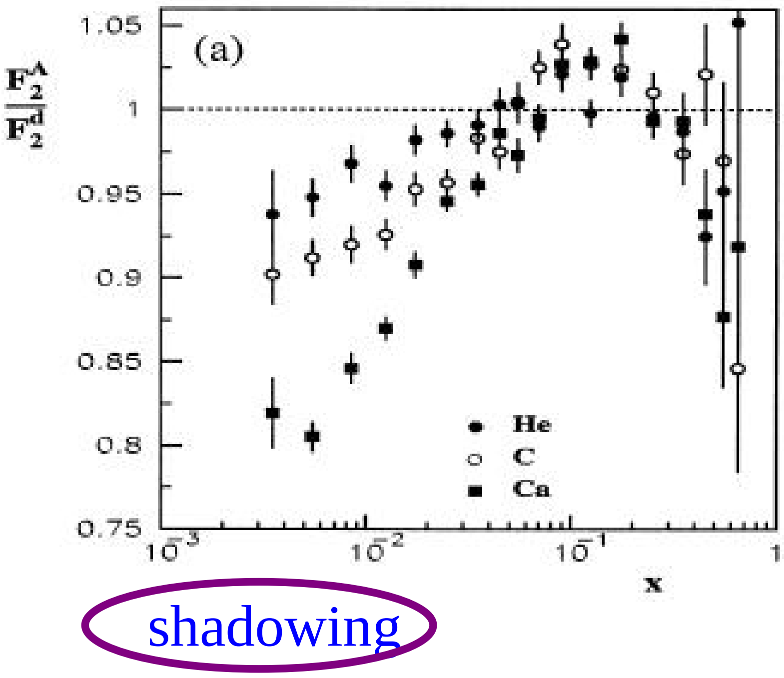


Nuclear shadowing in DIS with nuclei

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



Ratio of nuclear to deuteron structure functions



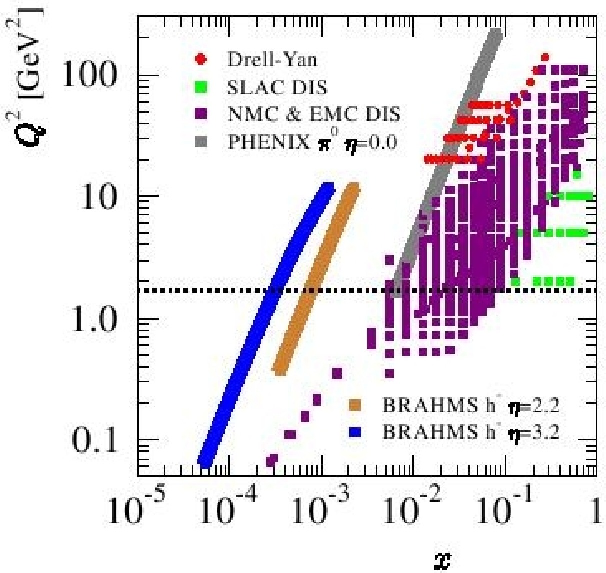
- Global fits to extract nuclear PDFs: lead to HUGE uncertainties at small x, especially for gluons

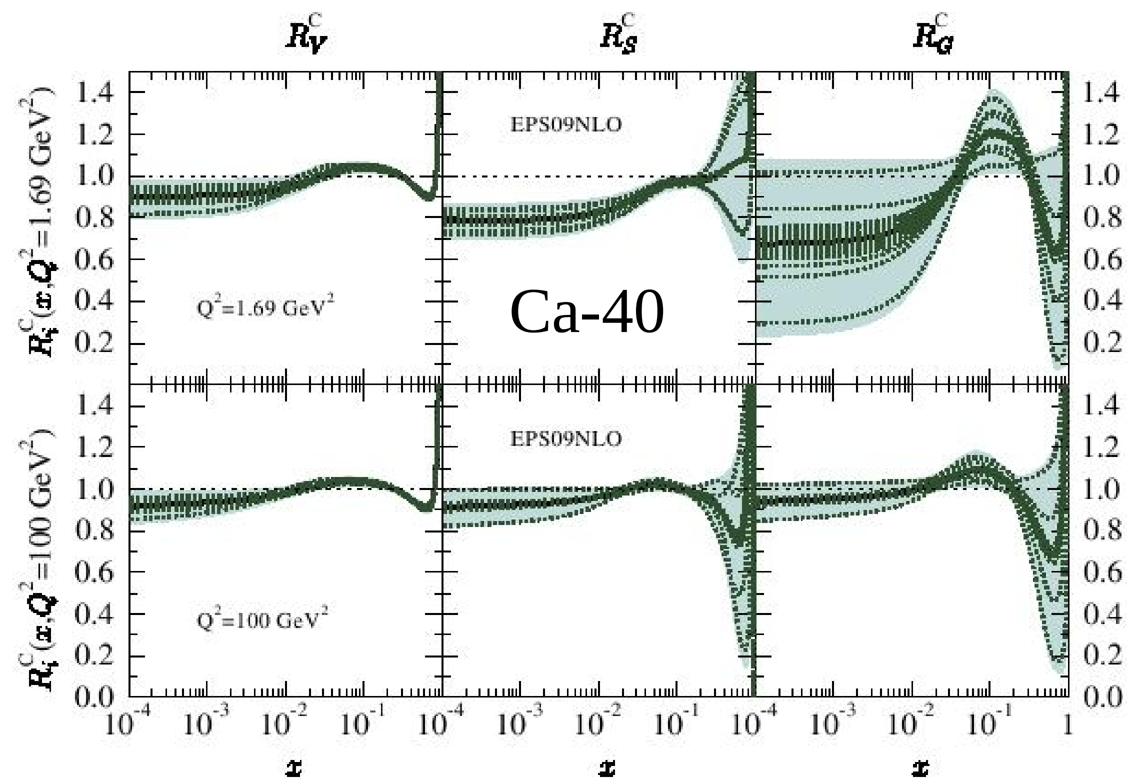
- Dynamical models of nuclear shadowing:
  - LT theory of nuclear shadowing
  - dipole models (LT + HT)
  - HT shadowing

J.-w. Qiu and I. Vitev, PRL 93 (2004) 262301

EPS09 nuclear PDFs

Example of extraction of NLO nuclear PDFs and their uncertainties from available data, Eskola, Puukkunen, Salgado, JHEP 04 (2009) 065





Before EIC, pA scattering at LHC should help to better constrain nPDFs and resolve discrepancy between different scenarios (shadowing and EMC for glue) Quiroga-Arias, Milhano, Wiedermann, arXiv: 1002:2537

Leading twist theory of nuclear shadowing

The leading twist theory of nuclear shadowing is an approach to calculate nuclear parton distributions (PDFs) as functions of x and b at some scale Q_0^2.

The Q^2 dependence is given by DGLAP.

The approach is based on:

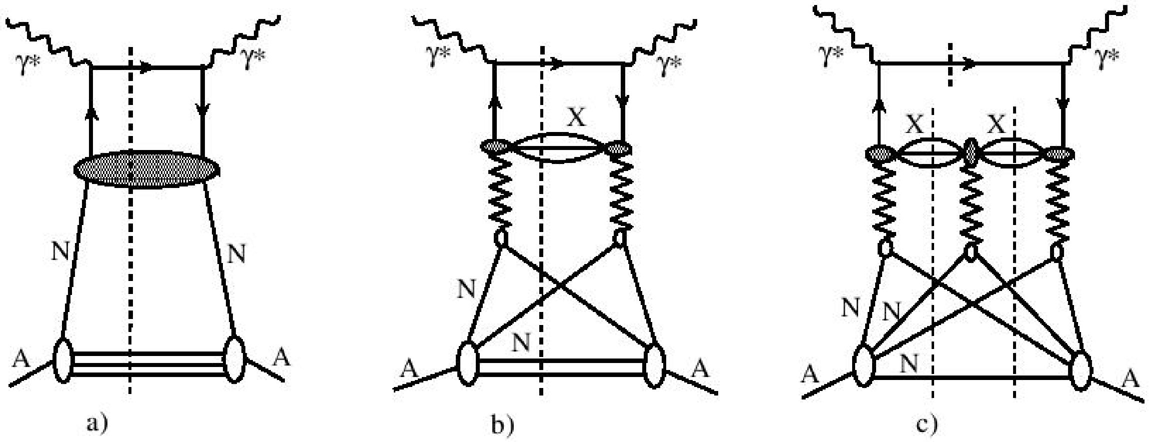
- generalization of Gribov's theory of nuclear shadowing to DIS and to arbitrary nuclei
  Frankfurt and Strikman, '88 and '98

- collinear factorization theorem for inclusive and diffractive DIS
  J. Collins '98

- QCD fits to HERA measurement of diffraction in ep DIS
  H1 and ZEUS Collab. 2006

Leading twist theory of nuclear shadowing-2

Graphical representation for nuclear quark PDFs:

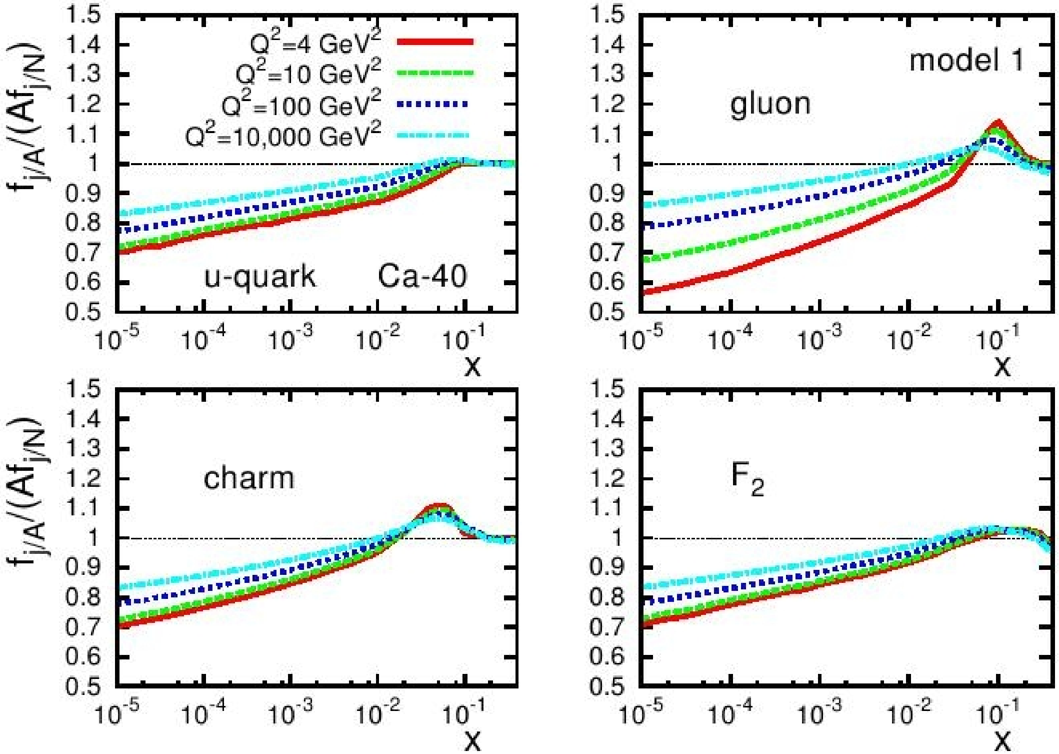


+ interaction with N > 3 nucleons

$$x f_{j/A}(x,Q^2) = A x f_{j/N}(x,Q^2)$$
$$- x f_{j/N}(x,Q^2) 8\pi A(A-1)\, \Re e \frac{(1-i\eta)^2}{1+\eta^2} B_{\rm diff} \int_x^{0.1} dx_{I\!P} \beta f_j^{D(3)}(\beta,Q^2,x_{I\!P})$$
$$\times \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2) e^{i(z_1-z_2)x_{I\!P} m_N} e^{-\frac{A}{2}(1-i\eta)\sigma_3^j(x,Q^2)\int_{z_1}^{z_2} dz' \rho_A(\vec{b},z')}, \quad (57)$$

Input:
- diffractive PDFs and slope B
- nuclear density
- rescattering cross section for N ≥ 3 nucleons

Predictions for nuclear PDFs



Frankfurt, VG, Strikman, 2010 (in preparation)

- shadowing is large
- gluon shadowing > quark shadowing
- large shadowing in $F_L^A(x,Q^2)$
- same approach for nuclear GPDs and diffractive PDFs

EIC is an ideal place to test these predictions!

Impact parameter dependence

- LT theory of nuclear shadowing also gives impact parameter *b* dependence of nuclear PDFs:

$$x f_{j/A}(x,Q^2,b) = A T_A(b) x f_{j/N}(x,Q^2)$$
$$- 8\pi A(A-1) B_{\text{diff}} \, \Re e \frac{(1-i\eta)^2}{1+\eta^2} \int_x^{0.1} dx_{I\!P} \beta f_j^{D(3)}(\beta,Q^2,x_{I\!P})$$
$$\times \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \, \rho_A(\vec{b},z_1) \rho_A(\vec{b},z_2) \, e^{i(z_1-z_2)x_{I\!P} m_N} e^{-\frac{A}{2}(1-i\eta)\sigma_3^j(x,Q^2) \int_{z_1}^{z_2} dz' \rho_A(\vec{b},z')} ,$$

- Impact parameter dependent nuclear PDFs=nuclear GPDs in the xi=0 limit:

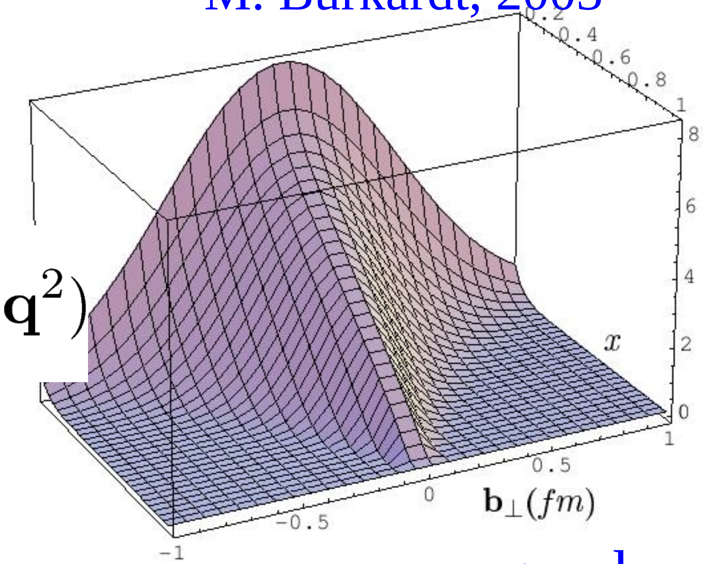
$$f_{j/A}(x,Q^2,b) = H_A^j(x,\xi=0,b,Q^2) .$$

Intuitively clear – M. Strikman
Formal proof – K. Goeke, VG, M. Siddikov, '09

Basics of generalized parton distributions-2

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:

M. Burkardt, 2003



u quark

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

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

For small skewness ξ (small Bjorken x), the skewness can be neglected at Q^2=few GeV^2

Freund, McDermott, Strikman, 2003 (QCD-imp. align-jet model)

K. Kumericki, D. Mueller, 2009 (QCD fits to data)

At small x_B, we study the transverse distribution of partons

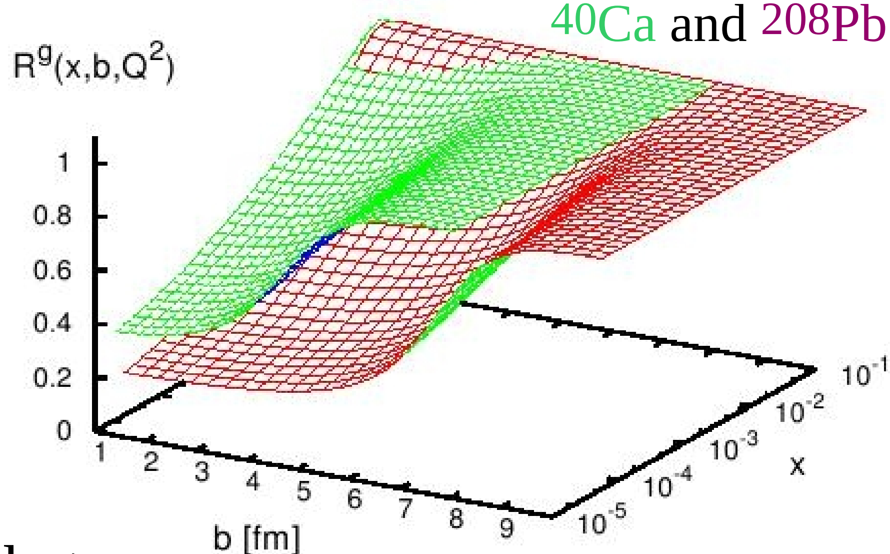
Nuclear GPDs at xi=0

$$R^j(x,b,Q^2) = \frac{f_{j/A}(x,Q^2,b)}{A\,T_A(b) f_{j/N}(x,Q^2)} = \frac{H_A^j(x,\xi=0,b,Q^2)}{A\,T_A(b) f_{j/N}(x,Q^2)}.$$

Frankfurt, VG, Strikman, 2010 (in preparation)

Density of nucleons at given b

40Ca and 208Pb



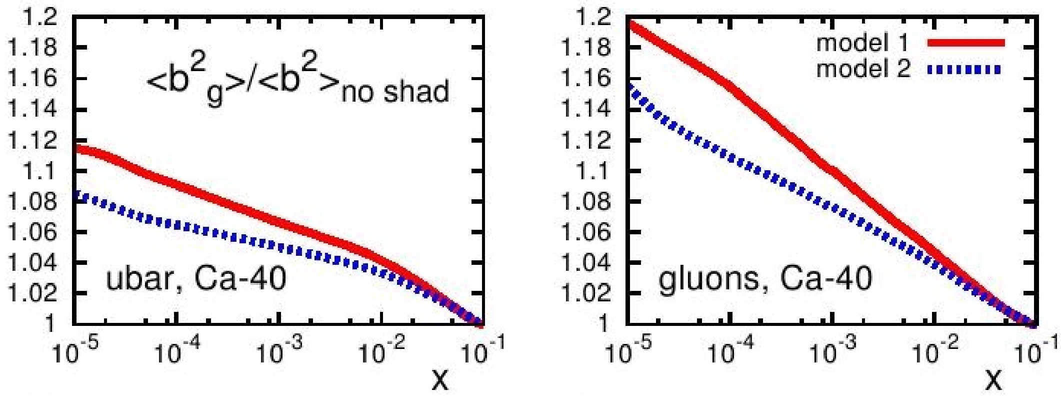
- Nuclear shadowing is larger at small b
- Shadowing introduces correlations between x and b, even if such correlations are absent for free nucleon

Spacial image of nuclear shadowing can be studied using coherent exclusive reactions with nuclei (DVCS, VM production)

Increase of parton transverse size

- Impact-parameter dependent nuclear shadowing leads to an **increase** of transverse size of partons (quarks and gluons) in nuclei

$$\langle b_g^2 \rangle = \frac{\int d^2b\, b^2 g_A(x,Q^2,b)}{\int d^2b\, g_A(x,Q^2,b)} . \qquad \langle b^2 \rangle_{\text{no shad}} = \frac{\int d^2b\, b^2 A T_A(b) f_{j/N}(x,Q^2)}{\int d^2b\, A T_A(b) f_{j/N}(x,Q^2)} = \int d^2b\, b^2 T_A(b) .$$

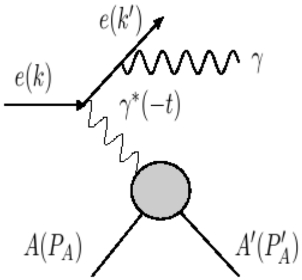


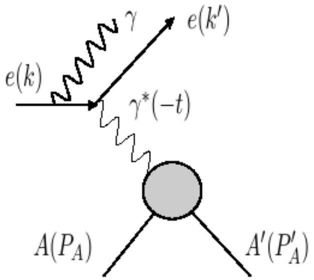
- *This has experimentally testable consequences*:
  -- position of the minima of DVCS cross section shifts towards smaller t
  -- dramatic oscillations of DVCS asymmetries

K. Goeke, VG, M. Siddikov, PRC 79 (2009) 035210

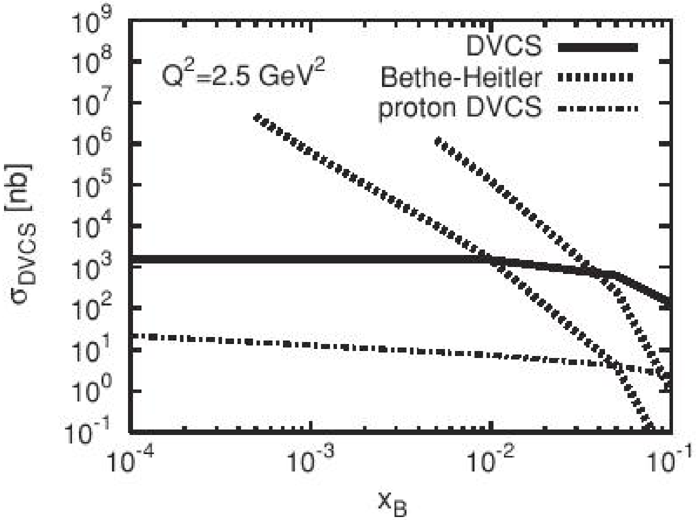
DVCS and BH cross sections

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

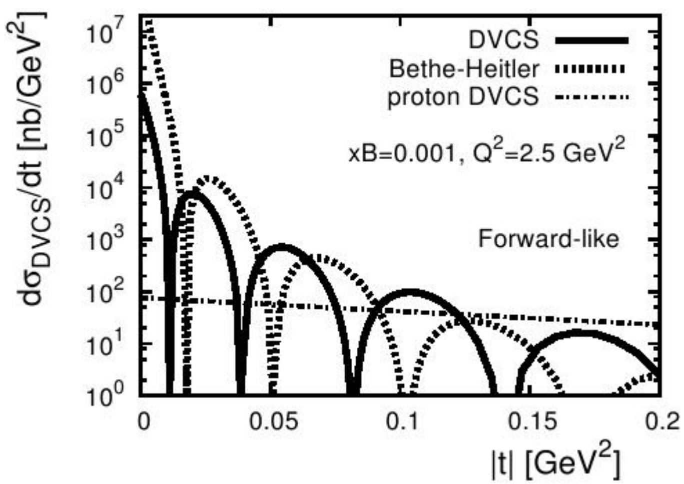




- DVCS and BH cross sections for ^{208}Pb at Q^2=2.5 GeV^2



need differential in t



$d\sigma^{BH}/dt \sim 1/(tQ^2)$

$d\sigma^{DVCS}/dt \sim 1/Q^4$

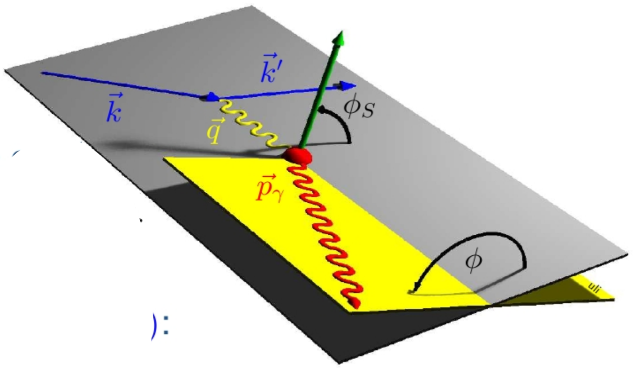
The shift is the measure of nuclear shadowing

(In the example, Δt=0.006 GeV^2)

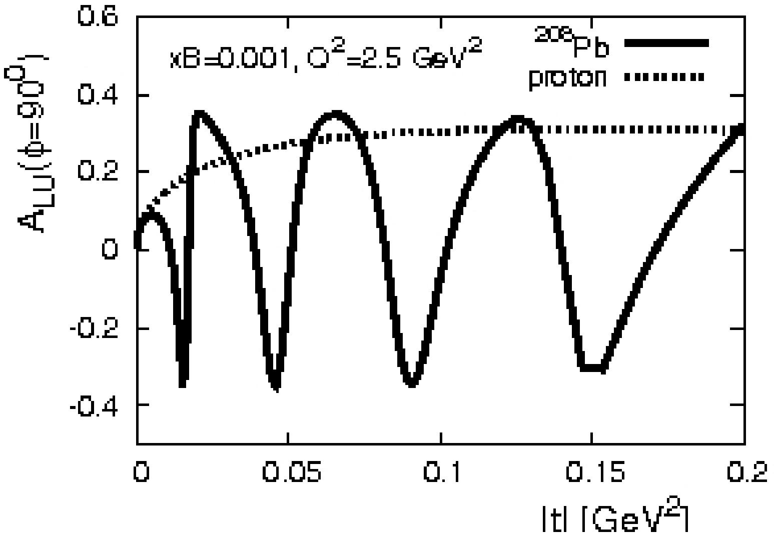
DVCS asymmetries

One extracts separately real and imaginary parts of DVCS amplitude through the interference between DVCS and BH amplitudes

Beam-spin asymmetry: pol. beam, unpol.target



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



Oscillations are due to shadowing; position of nodes measures the strength of shadowing

Summary

- Nuclear GPDs are interesting because of enhancement of traditional nuclear effects (EMC, nuclear shadowing) and sensitivity to novel nuclear effects (medium modifications, fast A-dependence of D-term), see my summary slide.

- LT nuclear shadowing in nuclear GPDs and DVCS is large, and leads to an increase of transverse size of partons in nuclei with measurable consequences.
Large shadowing in nDVCS also confirmed in dipoles models,
Kopeliovich, Schmidt, Siddikov, arXiv:1003:4188; Machado, arXiv:0810.3665

EIC in an ideal (only) machine to study LT nuclear shadowing in various nuclear parton distributions.