Deeply Virtual Compton Scattering with nuclei at small-x at EIC

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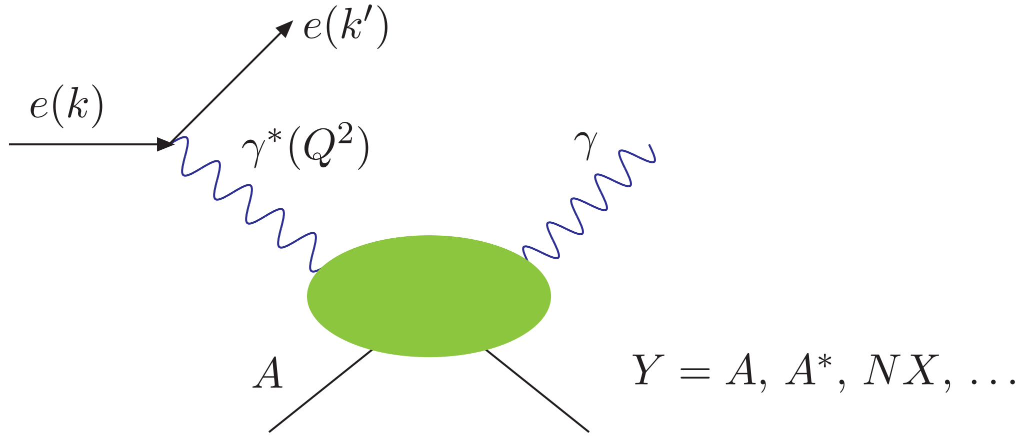
Outline

- Introduction: Roles and importance of nuclear DVCS
- LT approach to nuclear DVCS
- Color dipole approach to nuclear DVCS
- Conclusions

Introduction

Deeply Virtual Compton Scattering (DVCS) is the cleanest example of hard exclusive process.

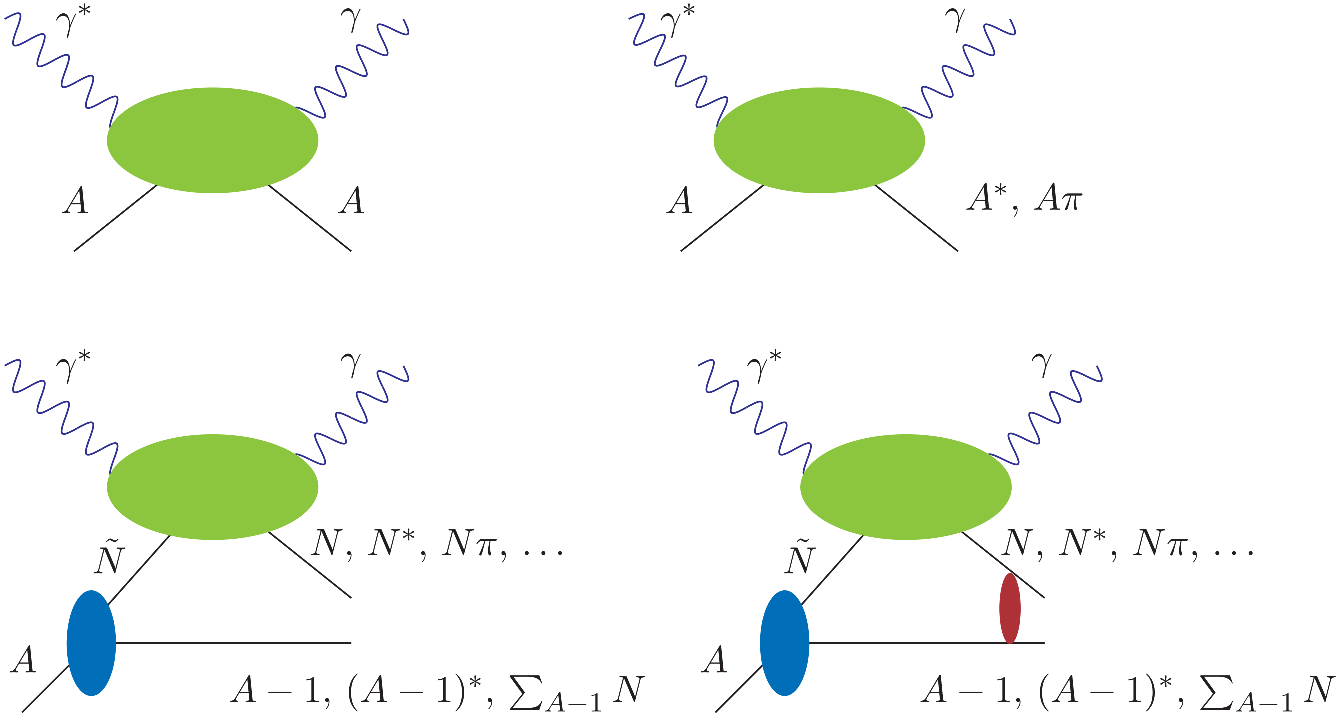


At the future Electron-Ion Collider (EIC), DVCS and related hard exclusive processes with nuclei will address:

- Interaction of small-size $q\bar{q}$ dipoles with nuclear matter, related to the phenomenon of Color Transparency
- Sea quark and gluon 3D (transverse) imaging through the studies (extraction) of generalized parton distributions (GPDs)
- Approach to the regime of high parton densities (saturation)

Nuclear DVCS is more complex and versatile than DVCS on the free proton since:

- many more final states can be excited (coherent and incoherent DVCS)
- the reaction mechanism is more complex (final-state interactions)
- different spin and isospin of the target are available (important for parton imaging)



Important roles of nuclear DVCS:

Nuclear DVCS (with light nuclei) gives the information on the nucleon GPDs complimentary to DVCS on the free proton:

- theoretical description of nuclear GPDs requires GPDs of the (bound) proton and neutron as input
  VG and Strikman '03, VG '08;S. Scopetta '04; S. Liuti and S.K. Taneja '05
- incoherent DVCS on deuteron accesses almost-on-shell neutron GPDs
  M. Mazouz *et al.* (JLab Hall A), Phys. Rev. Lett. **99**, 242501 (2007)
- DVCS on polarized ^{3}He will probe GPDs of the neutron
- electroduction of pseudoscalar mesons on deuteron is sensitive to non-pole contribution to the GPD $\tilde{E}$
  F. Cano and B. Pire, Eur. Phys. J. A **19**, 423 (2004)
- electroproduction of pseudoscalar mesons on ^{3}He at small t probes GPDs of the neutron ($\gamma_L^* + {}^3\text{He} \to \pi^0 + {}^3\text{He}$) or proton ($\gamma_L^* + {}^3\text{He} \to \pi^+ + {}^3\text{H}$)
  L. Frankfurt *et al.*, Phys. Rev. D **60**, 014010 (1999)

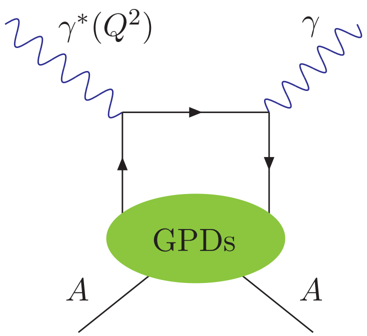
Nuclear DVCS is interesting in its own right:

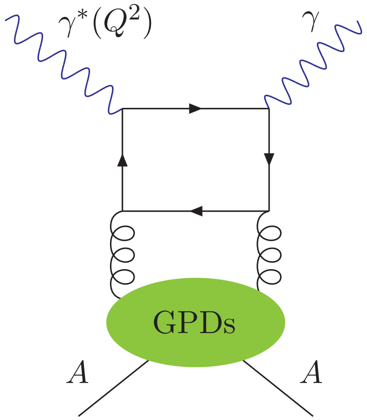
- Might access nuclear effects not present in DIS and elastic scattering with nuclei:
  - contribution of non-nucleon (meson) degrees of freedom to the real part of the DVCS amplitude
    M.V. Polyakov, Phys. Lett. B **555**, 57 (2003); VG and M. Siddikov, J. Phys. G **32**, 251 (2006)
  - unexpected pattern of nuclear shadowing for the real part of the DVCS amplitude at high-energies
    A. Freund and M. Strikman, Phys. Rev. C **69**, 015203 (2004)
- Puts stringent constaints on theoretical models of the nuclear structure: covariant description is more important than for nuclear DIS and nuclear form factors
- Will provide constraints on nuclear PDFs at small x complimentary to the inclusive measurements of F_2^A and F_L^A and diffractive F_2^D and F_L^D.
- Nuclear DVCS is more sensitive to the physics of high parton densities and the parton saturation than inclusive scattering
  M.V.T. Machado, arXiv:0810.3665 [hep-ph]

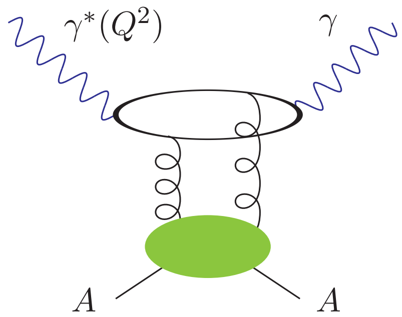
Two approaches to nuclear DVCS at small x:

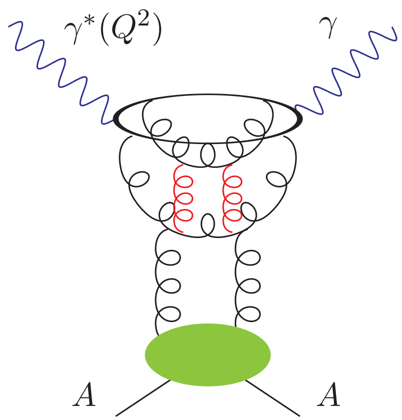
1) Leading Twist (LT) approach based on the QCD factorization theorem, which allows to introduce universal generalized parton distributions (GPDs) of the target

2) Color dipole framework: the main ingredient is the dipole cross section. The approach is equivalent to LT at the LLA, but can naturally include saturation physics.





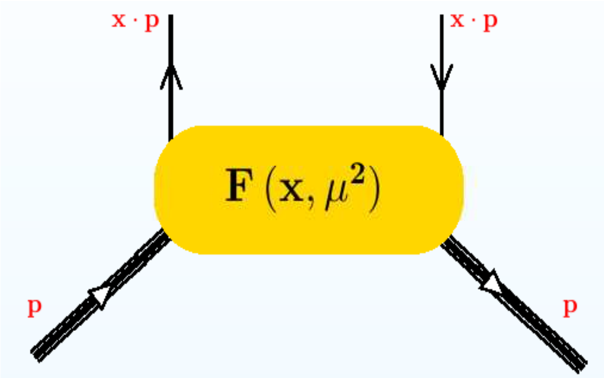


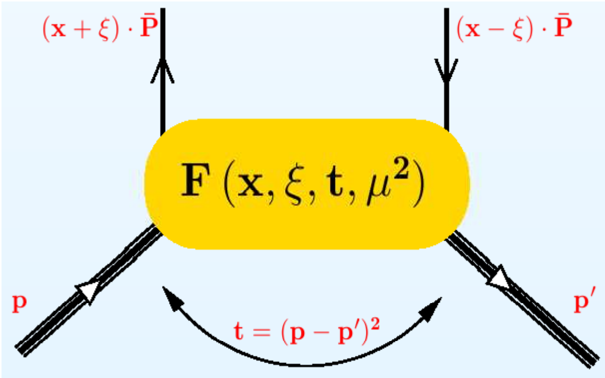


LT approach to nuclear DVCS

The central objects of the LT approach are nuclear generalized parton distributions (GPDs). GPDs interpolate between parton distributions and elastic form factors:

$$H^q(x,\xi,t,\mu^2) = \int \frac{dz^-}{4\pi} e^{ix\bar{P}_A^+ z^-} \langle P'_A | \bar{\psi}\left(-\frac{z^-}{2}\right) \gamma^+ \psi\left(\frac{z^-}{2}\right) | P_A \rangle_{|z^+, \vec{z}_\perp = 0}$$





- x longit. momentum fraction
- μ^2 factorization scale

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

How to construct nuclear GPDs? Two possible ways:

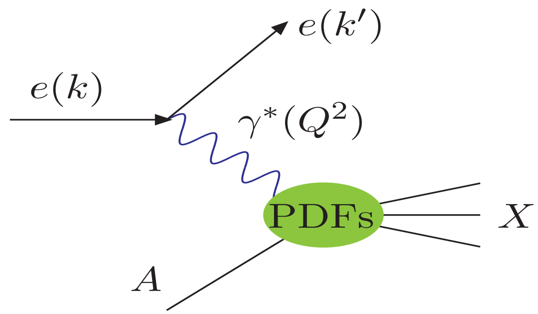
- Use experience with modeling nucleon GPDs in terms of nucleon PDFs and relate nuclear GPDs to nuclear PDFs
  - Double Distribution
    A. Radyushkin, Phys. Rev. D 56, 5524 (1997)
  - Align-jet model motivated
    A. Freund, M. McDermott, M. Strikman, Phys. Rev. D 67, 036001 (2003)
  - Dual parameterization
    V.G. and T. Teckentrup, Phys. Rev. D 74, 054027 (2006)

  Pros: Large sensitivity to poorly known nuclear PDFs at small x
  Cons: Is there a good model of small-x nucleon GPDs?

- Generalize the LT theory of nuclear shadowing to the case of off-forward kinematics
  V.G and M. Siddikov, in progress

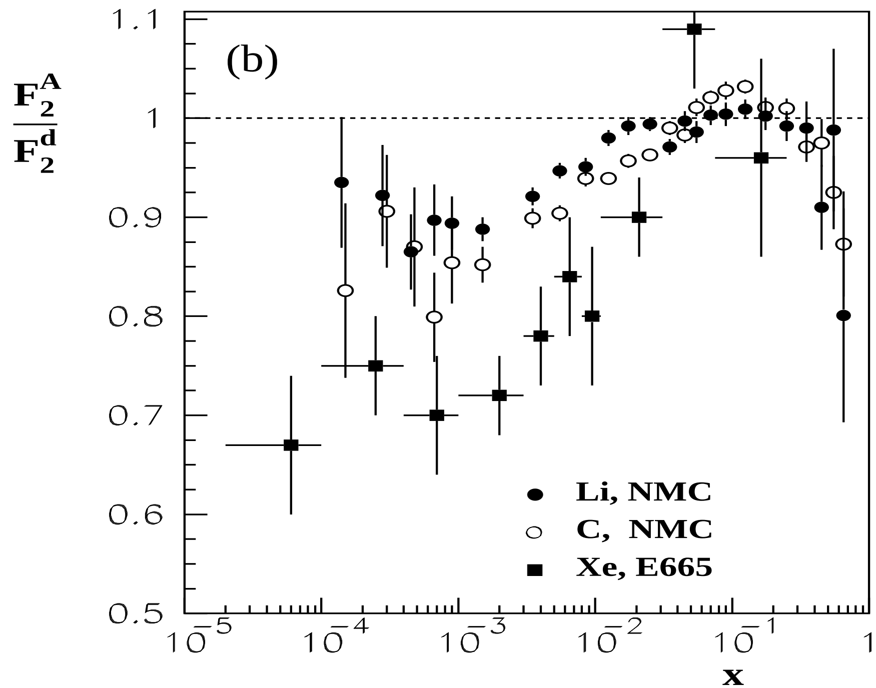
Provided we have a reliable model for nuclear GPDs in terms of nuclear PDFs, how do we know the latter?

Unpolarized Inclusive Deep Inelastic Scattering (DIS) measures the structure function $F_2^A(x,Q^2)$



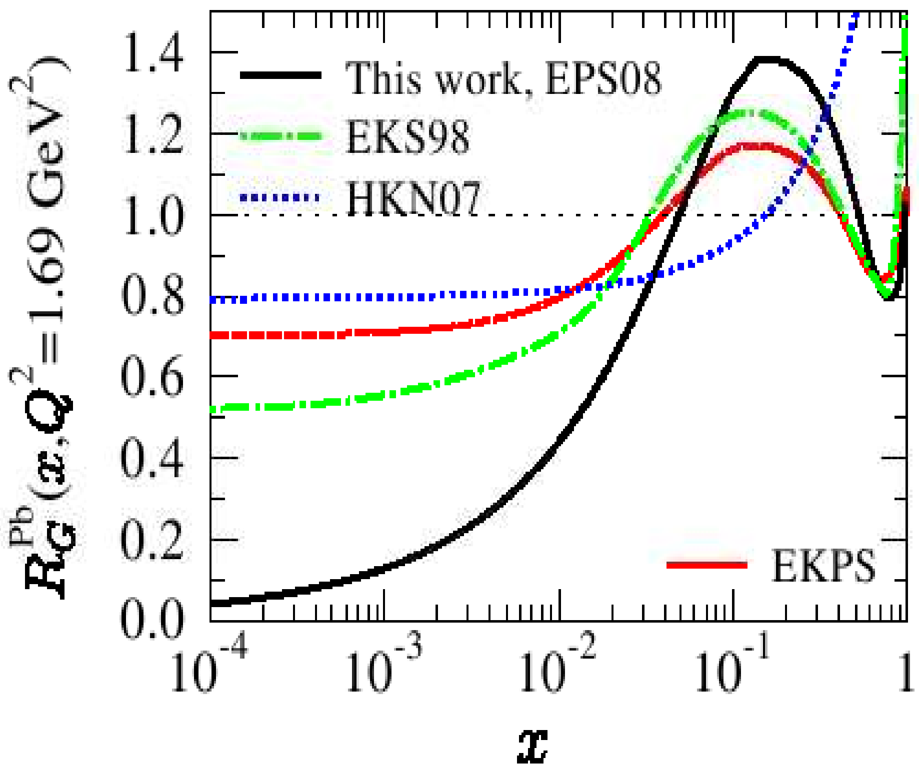
DIS on fixed nuclear targets, $R_{F_2} = F_2^A(x,Q^2)/F_2^D(x,Q^2)$

– nuclear shadowing
– antishadowing
– EMC effect



Using QCD factorization theorem, nuclear Parton Distribution functions (PDFs) can be extracted from $F_2^A(x,Q^2)$ and other data (DY, RHIC) by global fits.

$$R_G = g_A(x,Q^2)/[A g_N(x,Q^2)]$$



K. Eskola *et al.*, arXiv:0802.0139 [hep-ph]

Main drawbacks:

– insufficient kinematic coverage;
– small x correspond to small Q^2. Hence, small-x is either excluded from fits or contain large uncertainty (HT corrections)
$\rightarrow$ large uncertainties at small-x

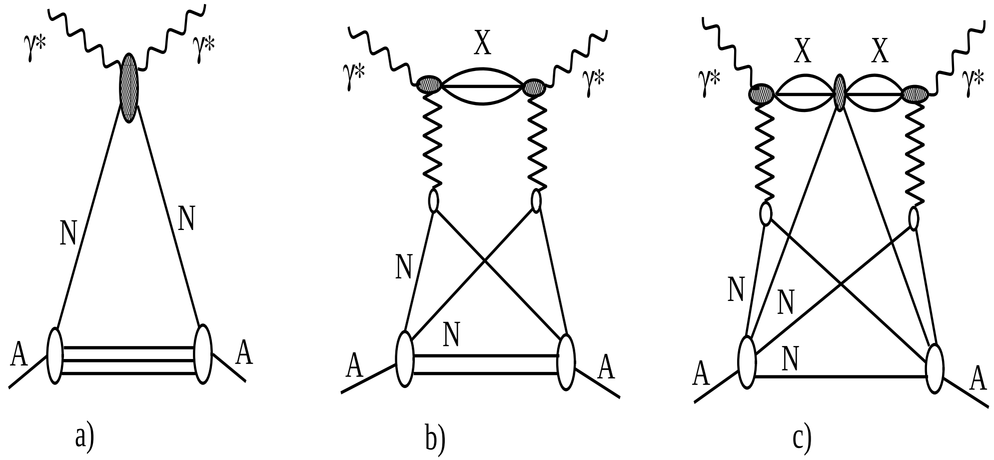
The future EIC will measure nuclear PDFs down to $\approx 5 \times 10^{-4}$.

An alternative to fitting is the leading twist (LT) model of nuclear shadowing (NS)

L. Frankfurt, V.G, M. Strikman, Phys. Rev. D71, 054001 (2005)

LT model of NS is based on:

- connection between NS and diffraction due to V. Gribov
- QCD factorization theorem for inclusive and hard diffractive scattering in DIS
- QCD analysis of the HERA diffractive data by H1 and ZEUS



$$x f_{j/A}(x, Q_0^2) = A\, x f_{j/N}(x, Q_0^2)$$

$$- 8\pi A(A-1)\Re e \frac{(1-i\eta)^2}{1+\eta^2} \int_x^{0.1} dx_{I\!P}\, \beta f_j^{D(4)}(\beta, Q_0^2, x_{I\!P}, t_{\min})$$

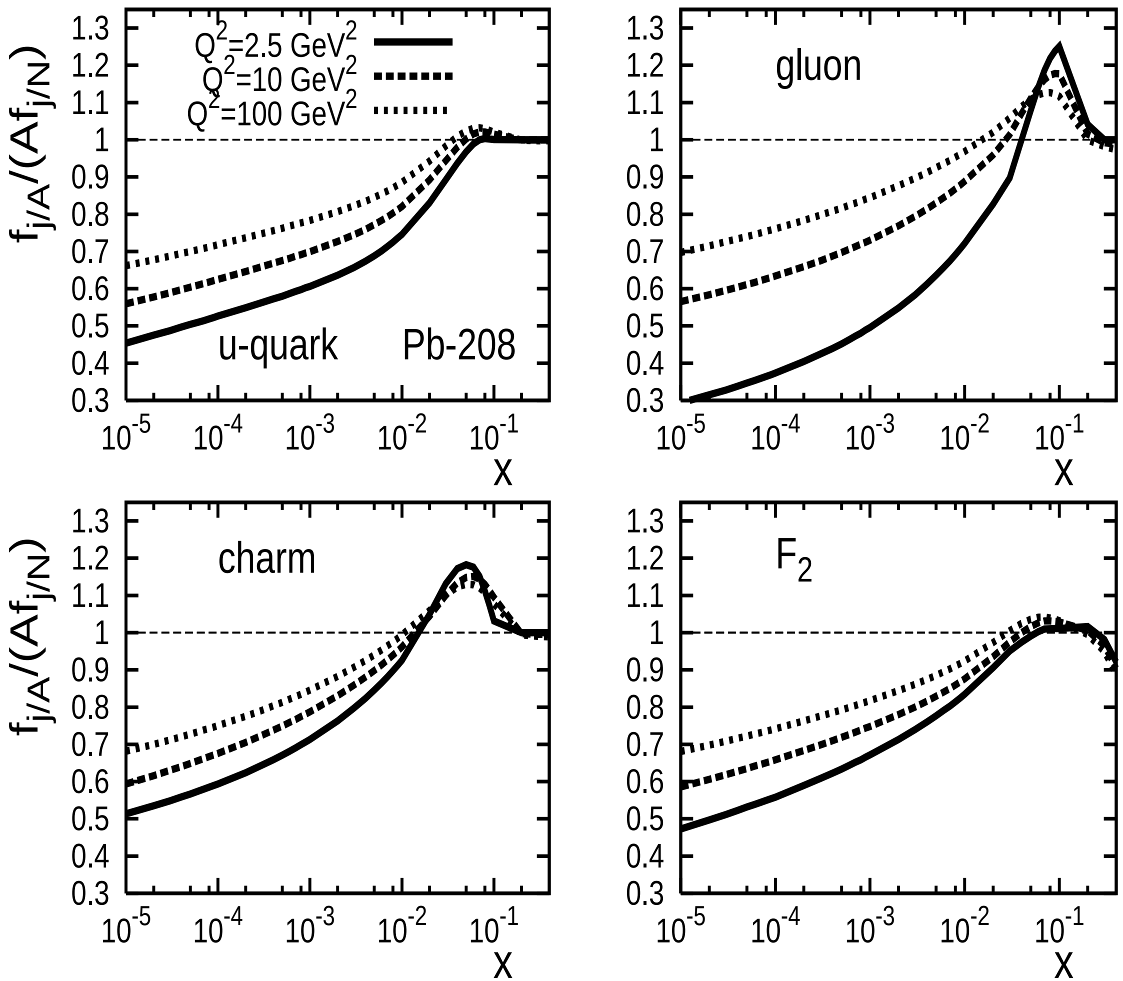
$$\times \int d^2\vec{b} \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b}, z_1) \rho_A(\vec{b}, z_2) e^{i(z_1 - z_2) x_{I\!P} m_N}$$

$$\times\, e^{-\frac{A}{2}(1-i\eta)\sigma_{\rm eff}^j(x,Q^2) \int_{z_1}^{z_2} dz' \rho_A(\vec{b},z')}$$

Predictions of LT model of NS,

L. Frankfurt, V.G, M. Strikman, in preparation,

based on 2006 H1 analysis of diffraction at HERA



LT model of NS also predicts:

– nuclear diffractive PDFs

– impact parameter dependent PDFs

Nuclear impact parameter dependent PDFs are nuclear GPDs at $\xi = 0$
(from the definition and from the fact that $\vec{b}$ is conjugate to $\vec{\Delta}_\perp$,
M. Burkardt, Int. J. Mod.Phys. A 18, 173 (2003) for proton)

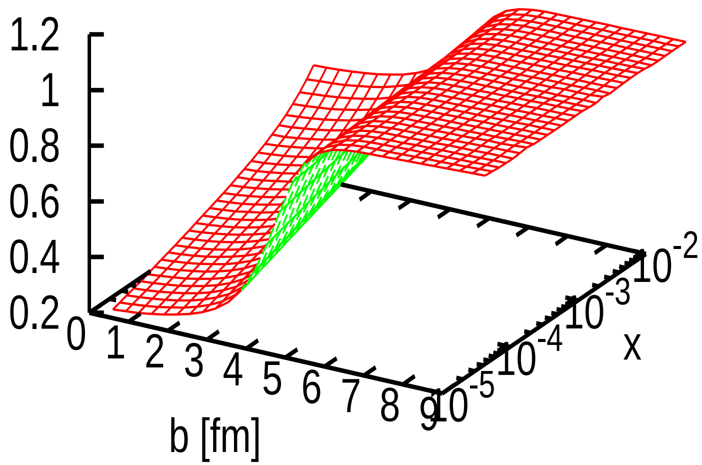
LT theory of NS gives nuclear GPDs at $\xi = 0$ "for free".

$$R_q = q_A(x,b)/[AT_A(b)q_N(x)] \sim H_A^q(x,\xi=0,b)$$

for ^{208}Pb at $Q_0^2 = 2.5$ GeV^2

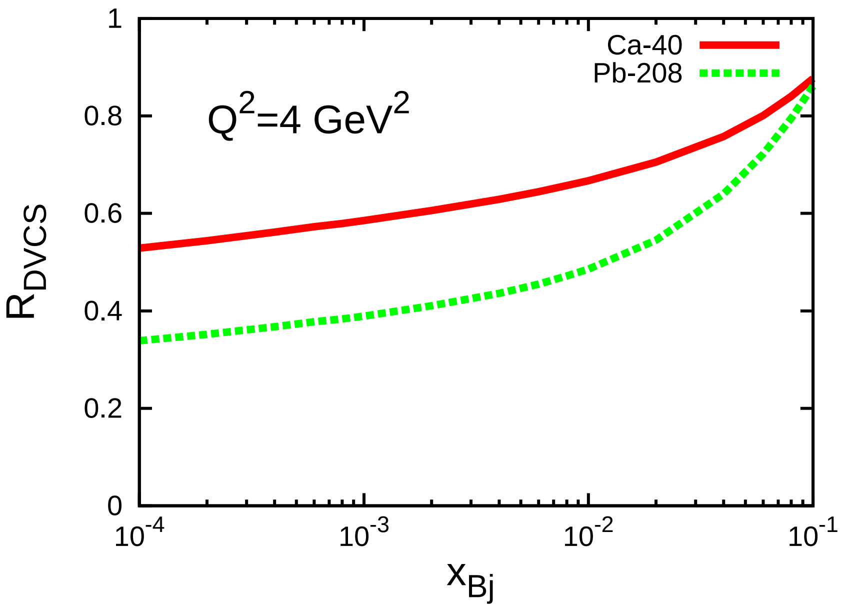
Interesting feature:

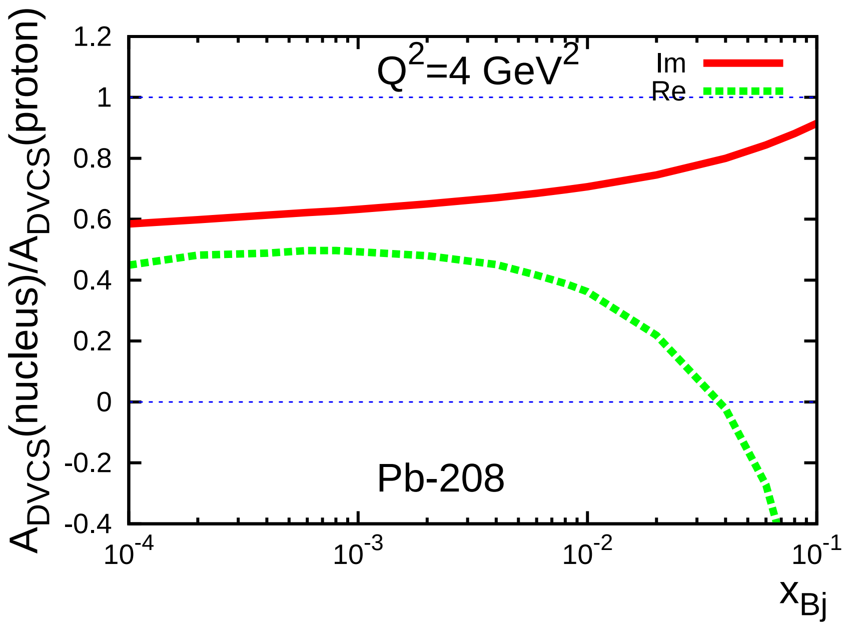
– NS introduces correlations between x and b
– Such correlations are absent in the nucleon GPDs at small x



LT approach predictions for coherent nuclear DVCS

Use the dual parameterization of nucleon GPDs with nuclear PDFs from the LT theory of nuclear shadowing.



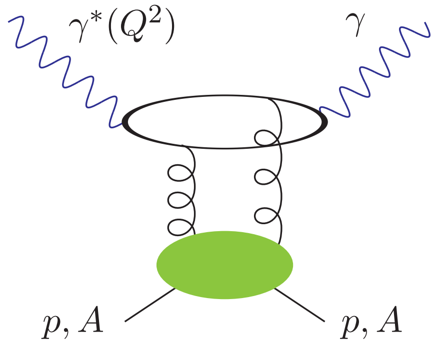


Ratio of t-integrated DVCS cross sections, Ratio of nucleus/proton DVCS amplitudes

$$R_{\mathrm{DVCS}} = \frac{\sigma_{\mathrm{DVCS}}}{\sigma_{\mathrm{DVCS}}(\mathrm{no\ NS})} \propto \frac{\left[\sum_q e_q^2 H_A^q(\xi,\xi,Q^2)\right]^2}{\left[A \sum_q e_q^2 H_N^q(\xi,\xi,Q^2)\right]^2} \qquad R = \frac{\mathcal{A}^A_{\mathrm{DVCS}}(t_{\min})}{\mathcal{A}^p_{\mathrm{DVCS}}(t_{\min})}$$

The future EIC will probe nuclear DVCS down to $\approx 5 \times 10^{-4}$.

Color dipole approach to nuclear DVCS



The scattering proceeds in three steps:
– the virtual photon fluctuates into $q\bar{q}$ dipole
– the dipole interacts with the target
– the $q\bar{q}$ dipole recombines into the final real photon

$$\mathcal{A}^{\gamma^* T \to \gamma T}(x, Q^2, \Delta) = \int d^2 r \int dz\, \Psi^*_{\gamma}(r, z, 0) \mathcal{A}_{q\bar{q}}(x, r, \Delta) \Psi_{\gamma^*}(r, z, Q^2)$$

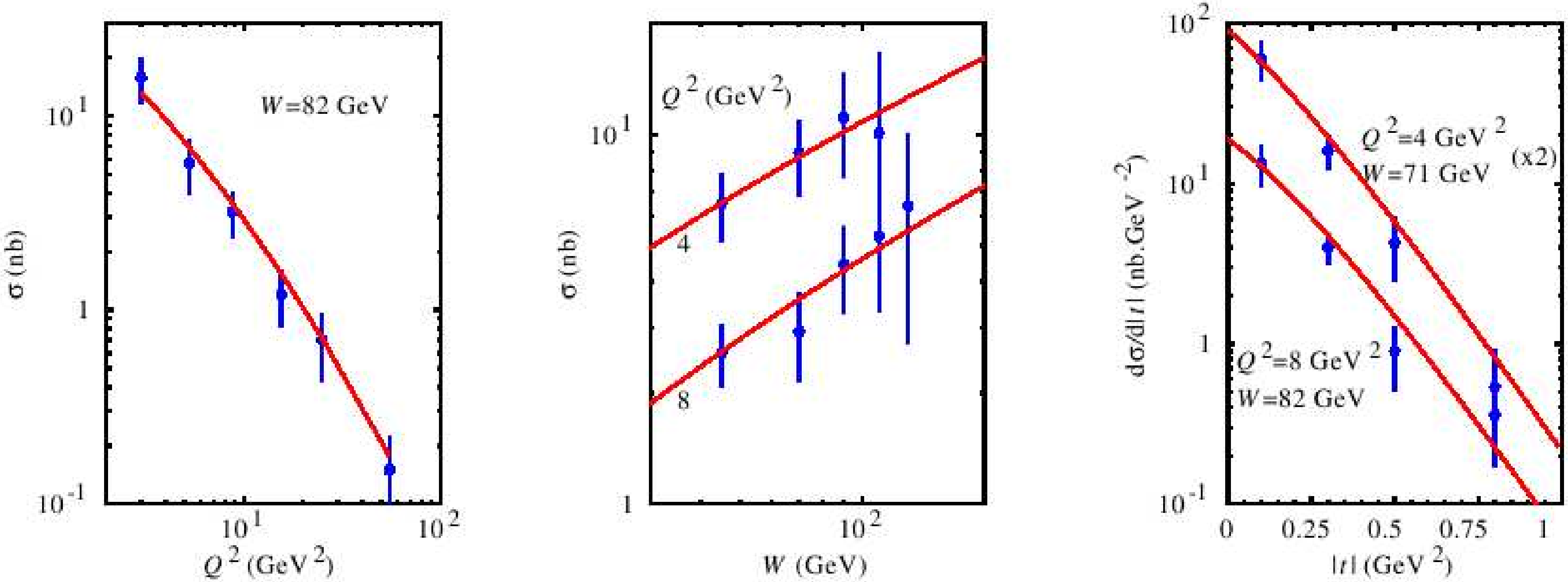
– r is the transverse size of the dipole; z is the light-cone fraction of one of quarks
– Ψ^*_{γ} and Ψ_{γ^*} are probability amplitudes known from QED
– $\mathcal{A}_{q\bar{q}}(x, r, \Delta)$ is the dipole amplitude, which can be modelled in several ways:

- by including the Δ-dependence of the saturation scale Q_s
  C. Marquet, R.B. Peschanski, G. Soyez, Phys. Rev. D76, 034011 (2007)

- by considering the impact-parameter dependent dipole amplitude
  H. Kowalski, L. Motyka, G. Watt, Phys. Rev. D74, 074016 (2006)

The resulting model provides a good description of HERA data on DVCS and exclusive electroproduction of VM on the proton

C. Marquet, R.B. Peschanski, G. Soyez, Phys. Rev. D76, 034011 (2007)



(a) $\gamma^* p \to \gamma p$ at fixed W

(b) $\gamma^* p \to \gamma p$ at fixed Q^2

(c) Differential cross-section

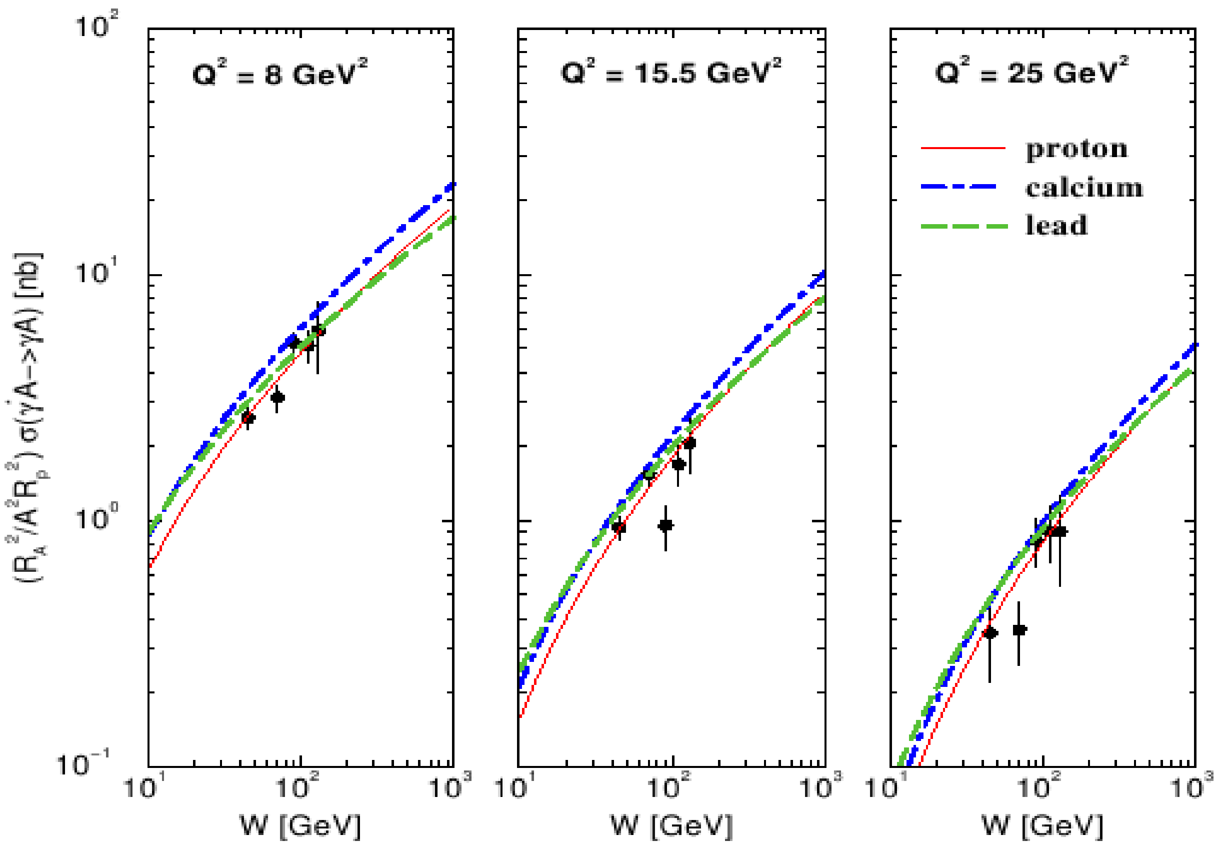
The dipole amplitude can be generalized to the scattering on a nucleus

M.V.T. Machado, arXiv:0810.3665

$$\mathcal{A}_{q\bar{q}}(x,r,\Delta) = 2\pi R_p^2 e^{-B|t|} N(rQ_s(x,\Delta),x) \to 2\pi R_A^2 F_A(t) N(rQ_{s,A}(x,0),x)$$

Predictions for coherent DVCS on nuclei

M.V.T. Machado, arXiv:0810.3665



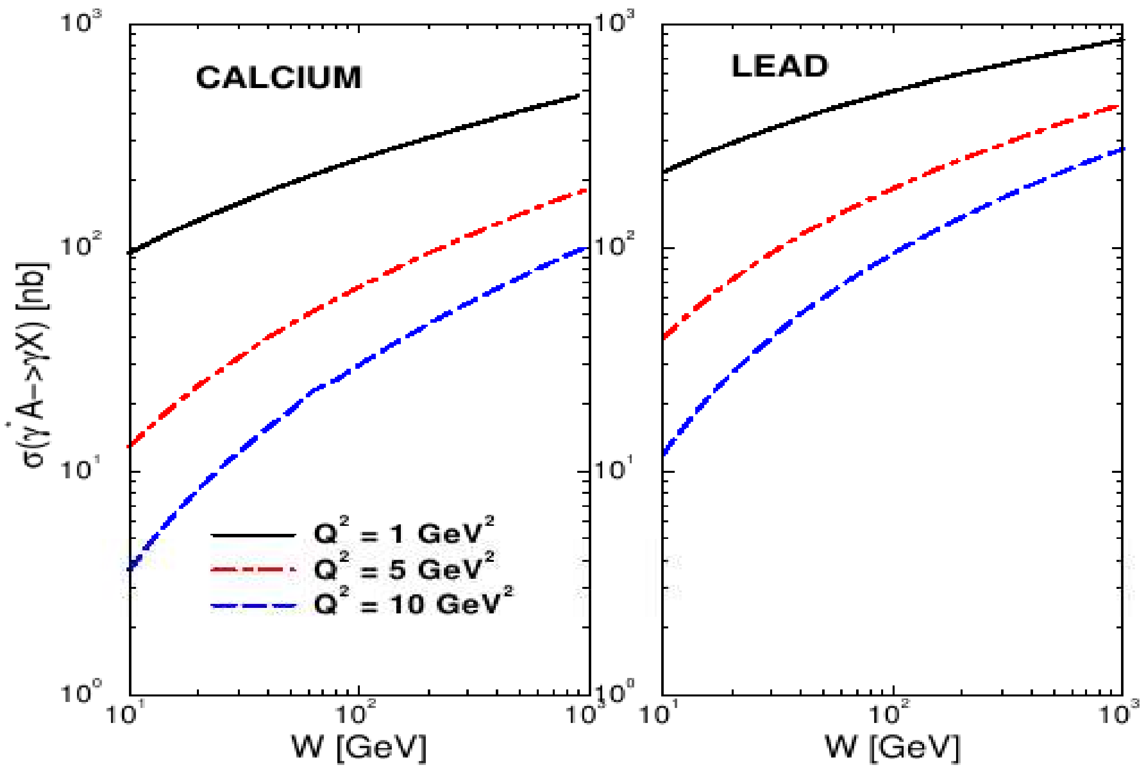
Predictions for incoherent DVCS on nuclei, $\gamma^* A \to \gamma N X$

M.V.T. Machado, arXiv:0810.3665

$$|\mathcal{A}^{\gamma^* A\to\gamma NX}(x,Q^2,t=0)|^2 = \int d^2b T_A(b) \left| \int d^2r \int dz\, \Phi_{\gamma^*\gamma}\sigma_{q\bar{q}}(x,r) \exp\left[-\frac{1}{2}\sigma_{q\bar{q}}(x,r)T_A(b)\right] \right|^2$$

– $\Phi_{\gamma^*\gamma}$ is the Ψ^*_γ and Ψ_{γ^*} overlap

– $\sigma_{q\bar{q}}(x,r) = \mathcal{A}_{q\bar{q}}(x,r,\Delta=0)$



Conclusions

- Studies of DVCS and other hard exclusive processes with nuclei is an integral part of the EIC physics program aiming to determine distributions of partons in nuclei.

- On the one hand, the extraction of nuclear GPDs is a natural continuation of studies of nuclear parton distributions at small-x with fixed nuclear targets.

  In particular, DVCS is very sensitive to LT nuclear shadowing at small-x. This is observed both in the DVCS cross section and in DVCS cross section asymmetries.

- On the other hand, studies of nuclear DVCS and other hard exclusive processes with nuclei at the EIC are promising reactions to explore the regime of high parton densities and parton saturation.