Coherent nuclear processes at high energies

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EIC Collaboration Meeting at Stony Brook University
January 11, 2010

Outline

- Introduction: Nuclear parton distributions
- Leading twist (LT) theory of nuclear shadowing
- LT nuclear shadowing and coherent inclusive diffraction with nuclei, nuclear diffractive parton distributions
- LT nuclear shadowing and coherent exclusive processes with nuclei, nuclear generalized parton distributions
- Summary

Introduction: Nuclear parton distributions

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

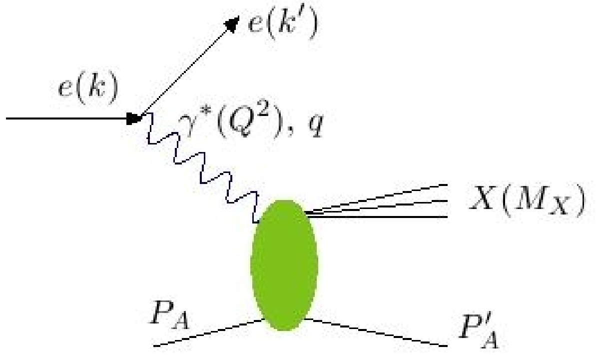
- Collinear factorization theorems enable one to introduce universal (process-independent) distributions of partons in the target and to study their Q^2 dependence (DGLAP).

- There are several kinds of PDFs: usual PDFs, diffractive PDFs, and generalized parton distributions

- In my talk, I will focus on the nuclear PDFs that can be studied in coherent scattering – nuclear diffractive PDFs and nuclear generalized parton distributions (GPDs).

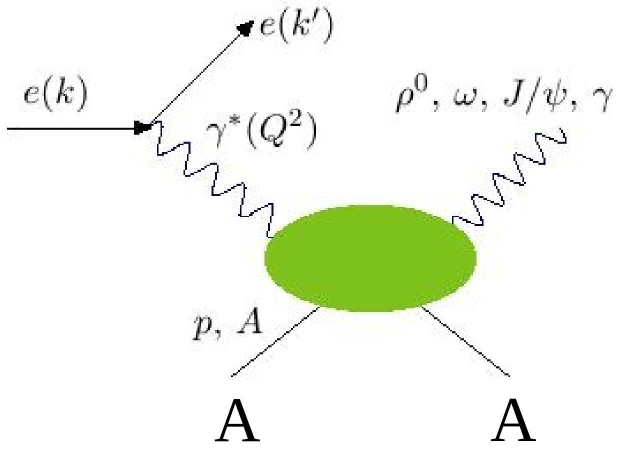
Introduction: Coherent nuclear processes

Coherent inclusive diffraction,
measures nuclear diffractive PDFs



$$F_2^{D(3)}(x, Q^2, x_{I\!P}) = \frac{x}{x_{I\!P}} \sum_{j=q,\bar{q},g} \int_{x/x_{I\!P}}^{1} \frac{d\beta'}{\beta'} C_j\left(\frac{x}{x_{I\!P}\beta'}, Q^2\right) f_j^{D(3)}(\beta', Q^2, x_{I\!P})$$

Coherent exclusive scattering,
measures nuclear GPDs



$$\sigma_{\mathrm{DVCS}}(x_B, Q^2) = \frac{\pi \alpha_{\mathrm{em}}^2 x_B^2}{Q^4 \sqrt{1 + 4m_N^2 x_B^2 / Q^2}} \times \int_{t_{\min}}^{t_{\max}} dt |\mathcal{A}_{\mathrm{DVCS}}(\xi, t, Q^2)|^2, \quad (37)$$

where

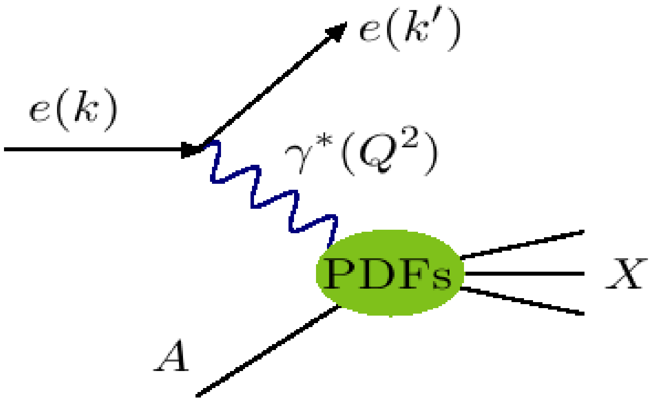
$$|\mathcal{A}_{\mathrm{DVCS}}(\xi, t, Q^2)|^2 = |\mathcal{H}|^2(1 - \xi^2) - \xi^2(\mathcal{H}^*\mathcal{E} + \mathcal{H}\mathcal{E}^*) - |\mathcal{E}|^2\left(\frac{t}{4m_N^2} + \xi^2\right) \quad (38)$$

Introduction: Coherent nuclear processes-2

Naturally, before one measures nuclear coherent scattering, the first measurement at an EIC should be inclusive (incoherent) scattering:

- usual nuclear parton distributions, fundamental
- essentially unknown in small-x region

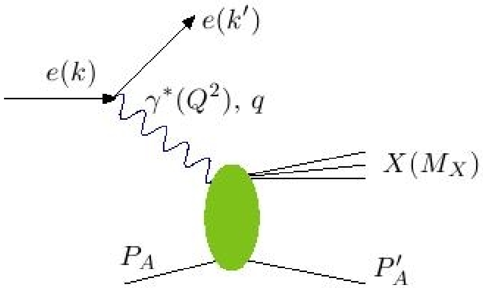
(N. Armesto's lecture, A. Stasto's talk)



The measurements of nuclear coherent processes will

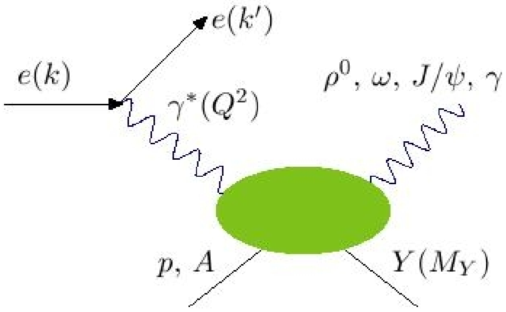
1) *be complimentary to inclusive measurements*

- more sensitive nuclear shadowing
- more sensitive to parton saturation



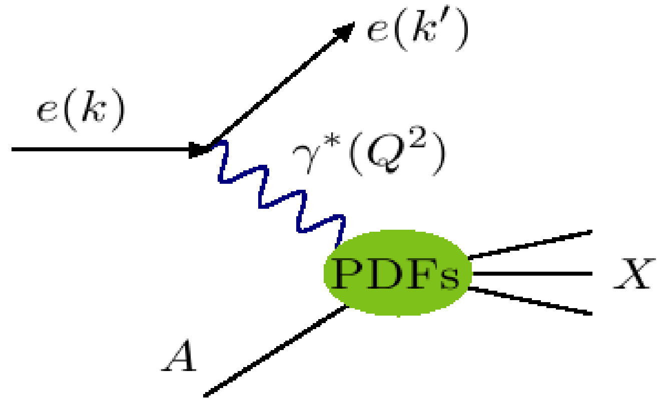
2) *probe the physics inaccessible in inclusive measurements*

- non-perturbative nature of the Pomeron
- 3D imaging of partons in nuclei

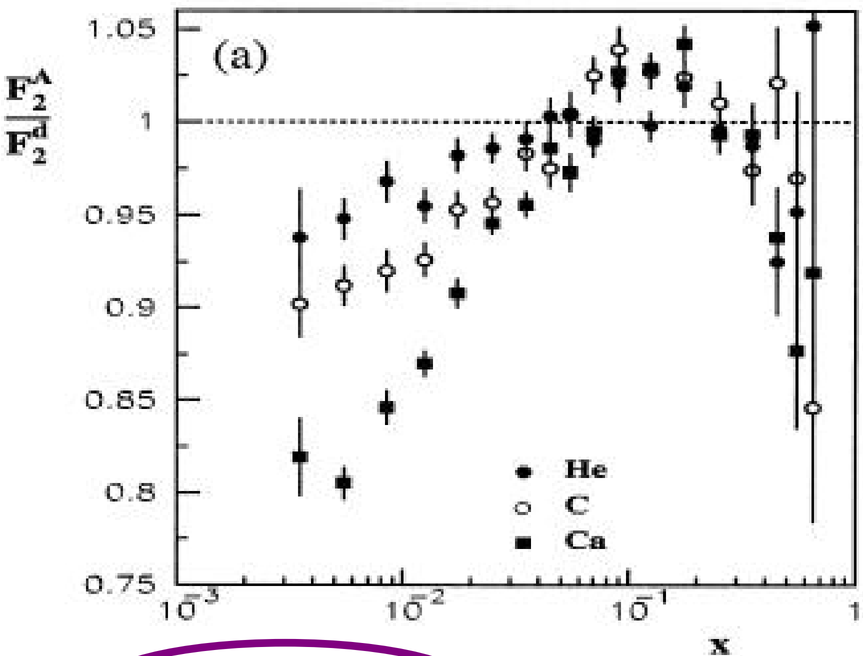


Nuclear shadowing in DIS with nuclei

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



Ratio of nuclear to deuteron structure functions



shadowing

- Global fits to extract nuclear PDFs lead to large uncertainties at small x
  N. Armesto's lecture

- Alternative to fitting: dynamical models of nuclear shadowing:
  -- LT theory of nuclear shadowing
  -- dipole models and CGC

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.

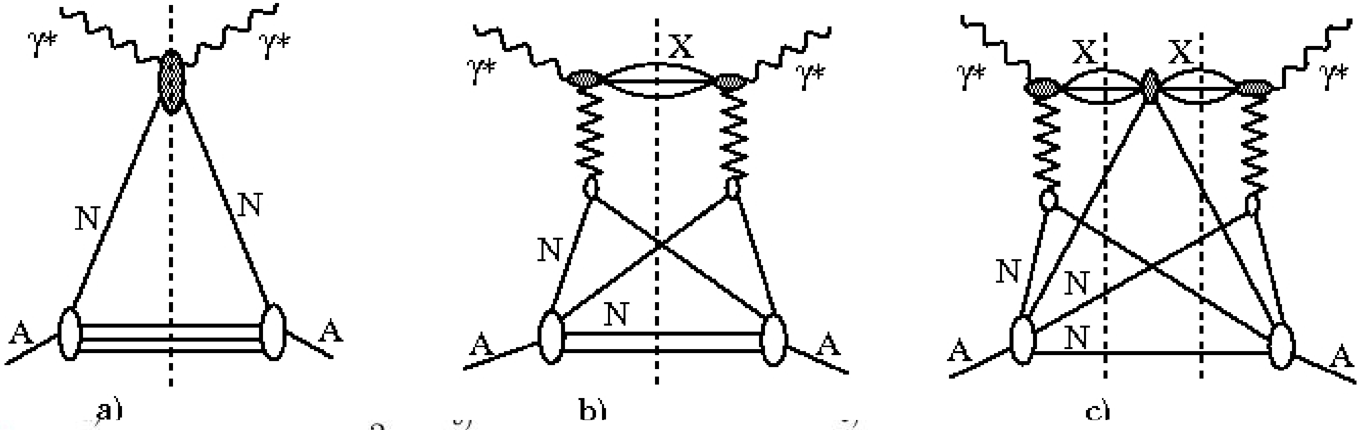
The Q^2 dependence is given by DGLAP.

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

LT theory of nuclear shadowing-2

At high energies (small Bjorken x), the virtual photon interacts with many (all) nucleons of the nuclear target:



$$F_{2A}(x,Q^2) = AF_{2N}(x,Q^2)$$
$$- 8\pi A(A-1)\Re e\frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{I\!P} F_2^{D(4)}(x,Q^2,x_{I\!P},t_{\min})$$
$$\times \int d^2\vec{b}\int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2)e^{i(z_1-z_2)x_{I\!P}m_N}$$
$$+ \ \ldots$$

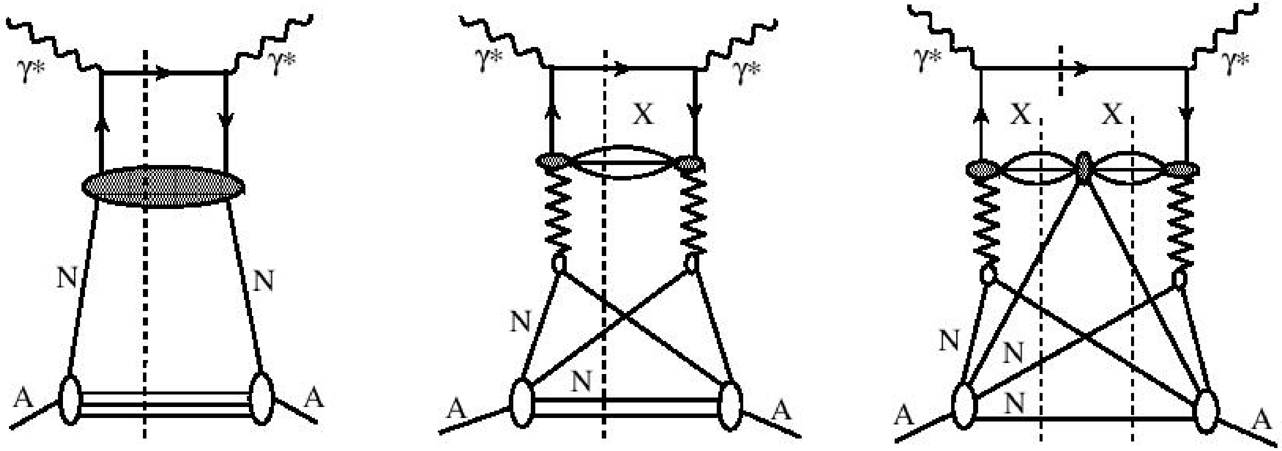
*In this formula, only the interaction with one and two nucleons

- $F_2^{D(4)}$ diffractive structure function
- ρ_A nuclear density
- $\eta = ImA/ReA$
- $e^{i(z_1-z_2)x_{I\!P}m_N}$ effect of coherence length

LT theory of nuclear shadowing-3

Use factorization theorem to replace the structure functions by the parton distributions:

$$
\begin{aligned}
f_{j/A}(x,Q^2) &= A f_{j/N}(x,Q^2) \\
&- 8\pi A(A-1)\Re e\frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{I\!P} f_{j/N}^{D(4)}(x,Q^2,x_{I\!P},t_{\min}) \\
&\times \int d^2\vec{b}\int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2)e^{i(z_1-z_2)x_{I\!P}m_N}
\end{aligned}
$$



LT theory of nuclear shadowing-4

Model the interaction with N ≥3 nucleons: color fluctuation approximation

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

Strong points:

- NLO nuclear PDFs
- nuclear shadowing for indiv. flavor
- impact parameter dependent nuclear PDFs (*Nuclear GPDs in the xi=0 limit)
- same approach to nuclear diffractive PDFs and nuclear GPDs*

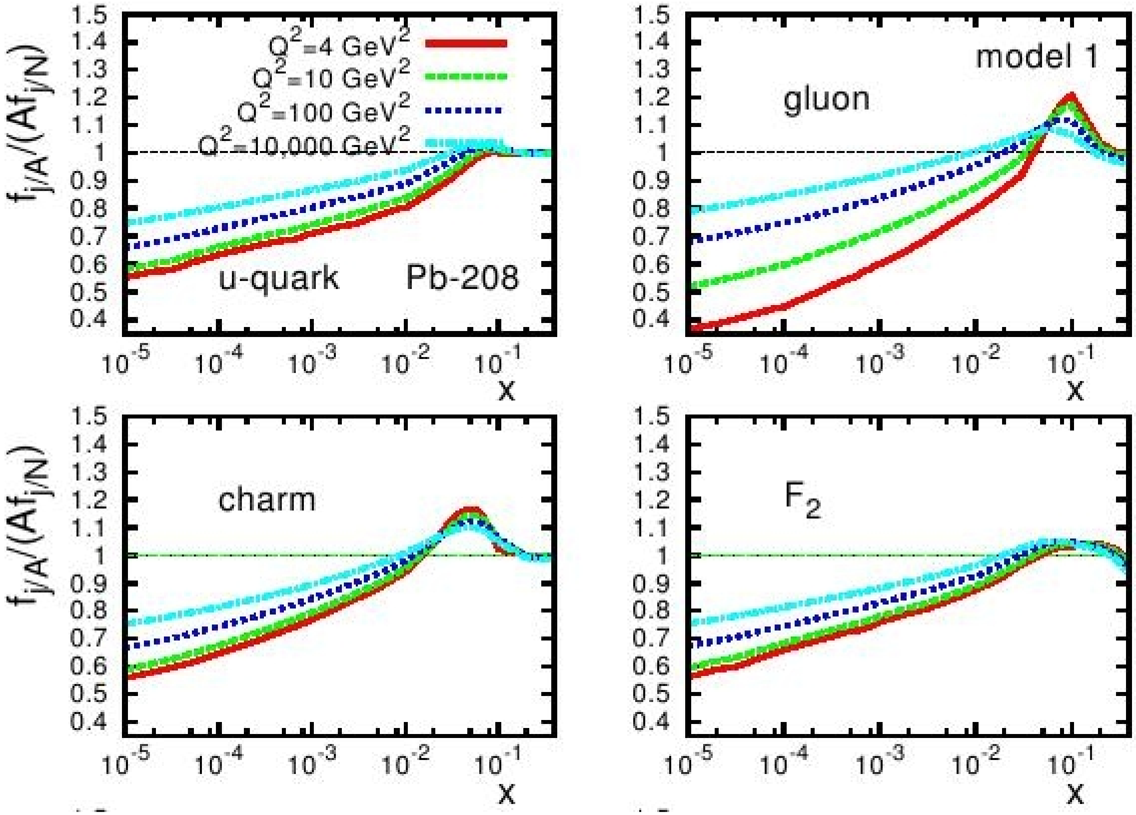
Weak points:

- modeling of multiple interactions
- significant uncertainty due to uncertainty in $B_{\rm diff}$
- requires certain extrapolations of diffractive PDFs
- only vacuum channel (gluons and anti-q)

LT theory of nuclear shadowing-5

Predictions for nuclear PDFs for Pb-208

Frankfurt, Guzey, Strikman, 2010

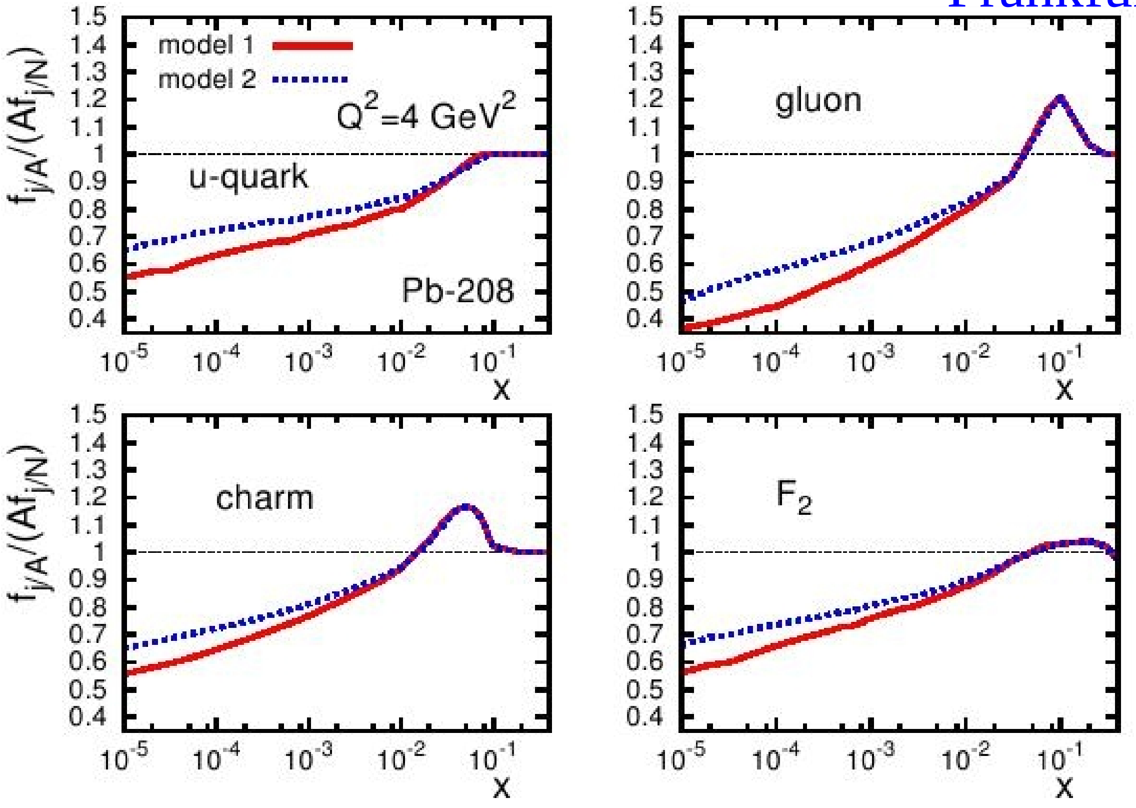


- At the input scale, gluon shadowing > quark shadowing
- Antishadowing is by hand using momentum sum rule
- Shadowing for valence quarks from Eskola

LT theory of nuclear shadowing-6*

Uncertainty due to modeling of the interaction with N ≥3 nucleons

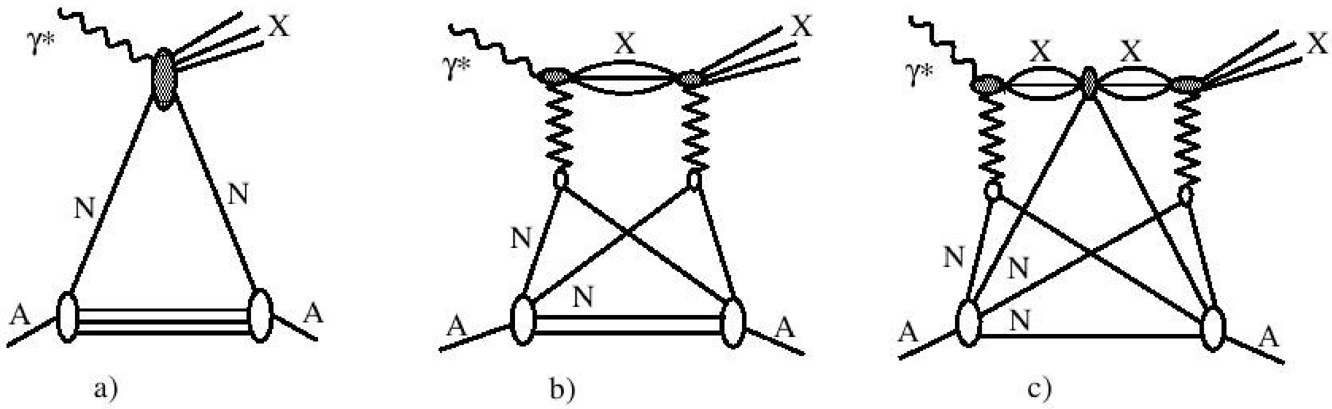
Frankfurt, Guzey, Strikman, 2010



The difference decreases with increasing Q2.

LT nuclear shadowing and nuclear diffractive PDFs

The leading twist theory of nuclear shadowing can be generalized to inclusive diffraction and corresponding *nuclear diffractive PDFs*:

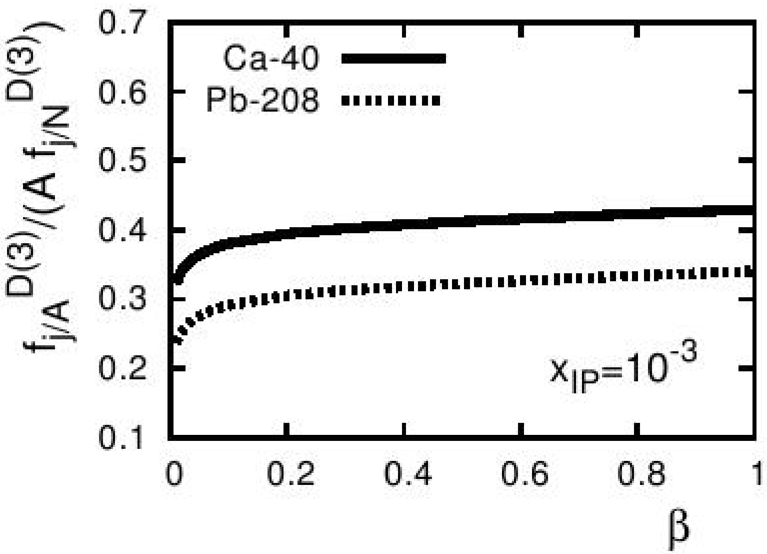


$$\beta f_{j/A}^{D(3)}(\beta,Q^2,x_{I\!P}) = 4\pi A^2 B_{\rm diff}\,\beta f_{j/N}^{D(3)}(\beta,Q^2,x_{I\!P})\int d^2b$$
$$\times \left|\int_{-\infty}^{\infty} dz\, e^{i x_{I\!P} m_N z}\, e^{-\frac{A}{2}(1-i\eta)\sigma_{\rm soft}(x,Q^2)\int_z^\infty \rho_A(b,z')}\rho_A(b,z)\right|^2 .$$

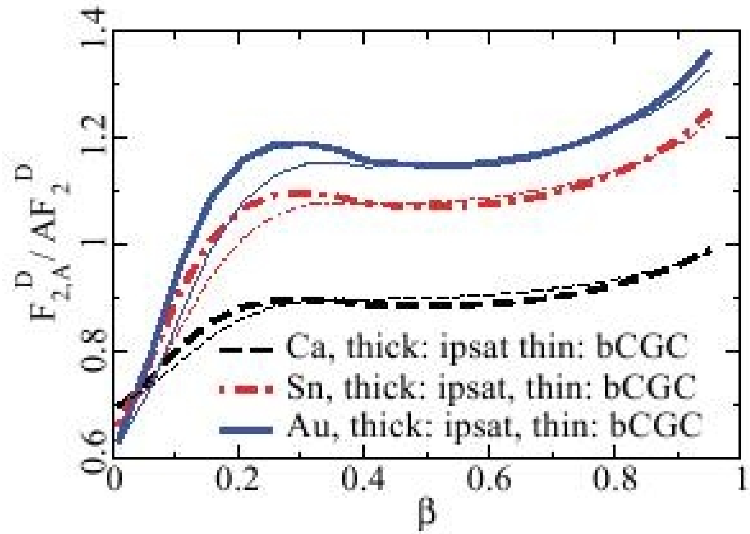
LT nuclear shadowing and nuclear diffractive PDFs-2

Comparison of the LT nuclear shadowing and color dipole predictions

Frankfurt, Guzey, Strikman, 2010



H. Kowalski, T. Lappi, C. Marquet, R. Venugopalan, PRC 78, 045201 (2008)

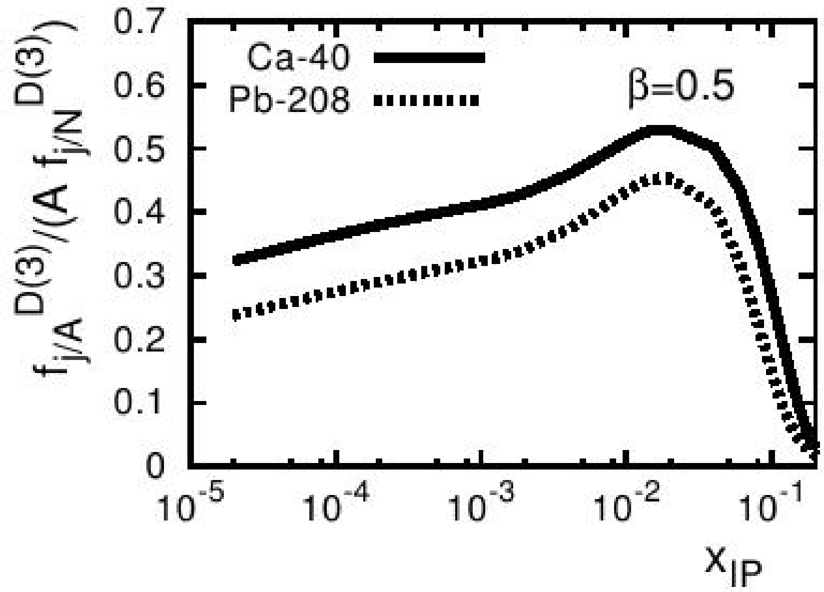


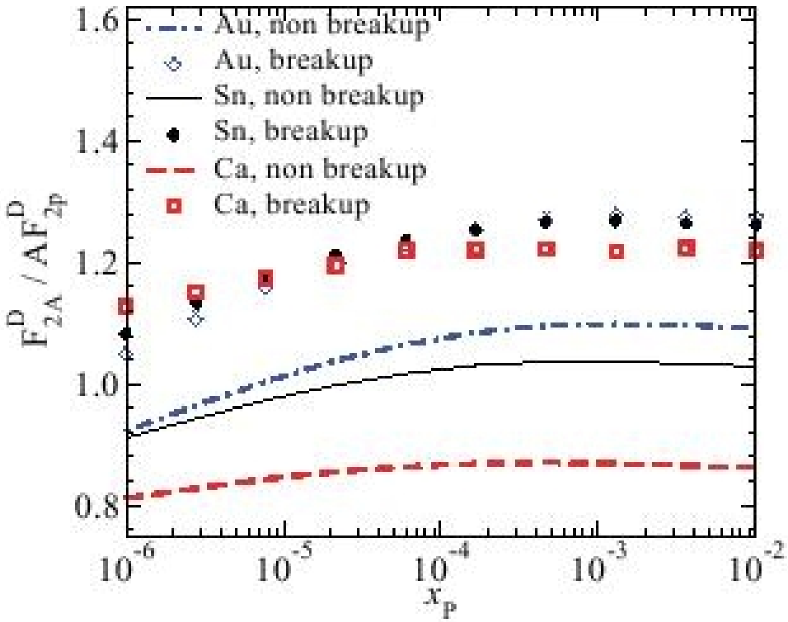
- Shapes are similar -> no dramatic difference between "no-saturation" and saturation approaches.
- Preliminary and will be updated: calculation with a different model for N≥3 will give larger ratios (in our LT approach)
- Will the Q2 evolution be dramatically different in two approaches?

LT nuclear shadowing and nuclear diffractive PDFs-3*

H. Kowalski, T. Lappi, C. Marquet,
R. Venugopalan, PRC 78, 045201 (2008)

Frankfurt, Guzey, Strikman, 2010

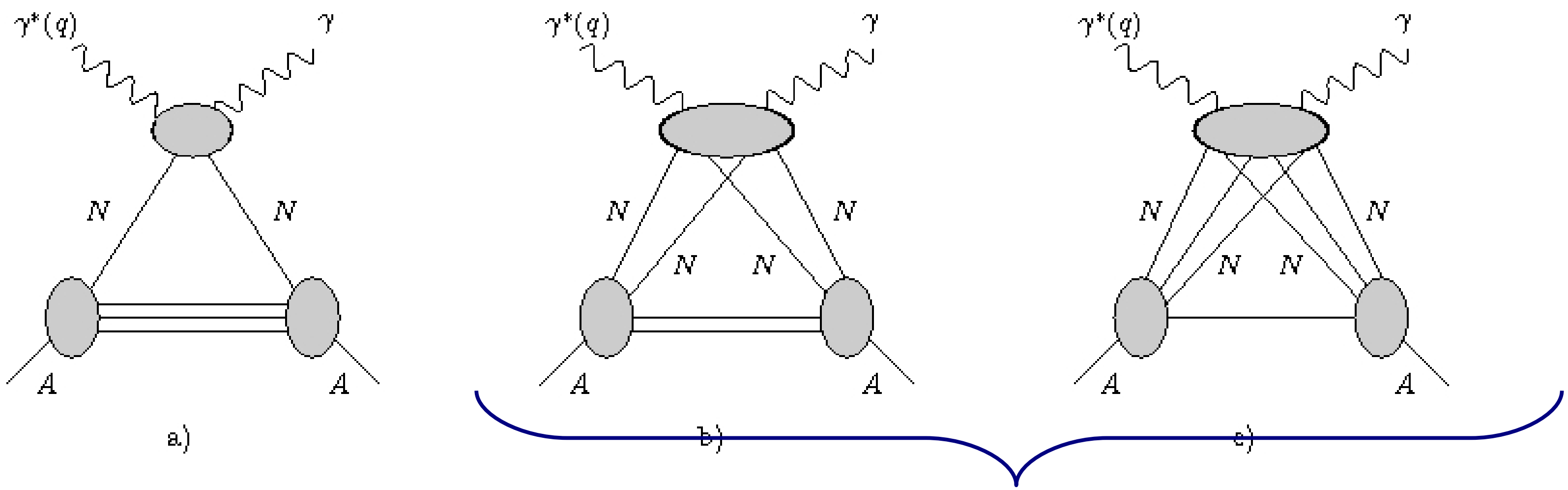




LT nuclear shadowing and nuclear GPDs

Formalism of LT nuclear shadowing can be generalized to non-forward kinematics of DVCS and nuclear GPDs at small x_B

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



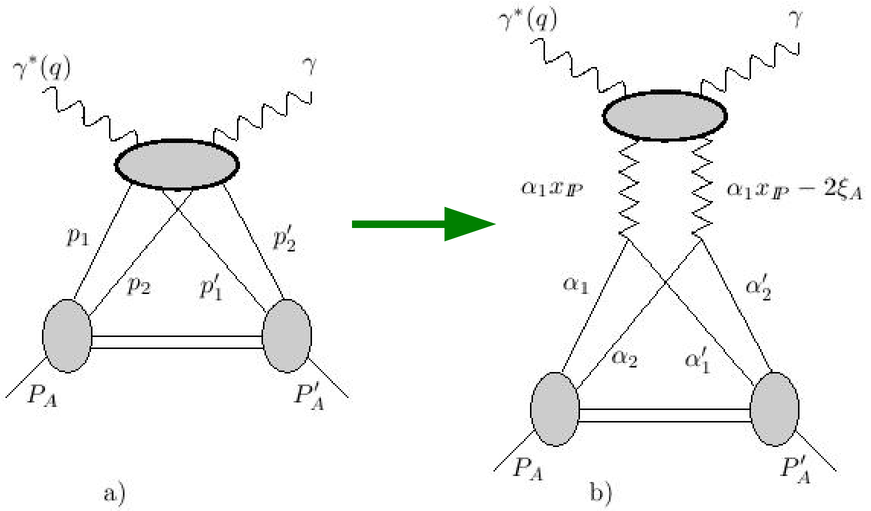
Born term

Shadowing correction

- The lower nuclear part is straightforward (Glauber formalism)
- The upper part is difficult and model-dependent– we used a particular model
- Only the xi=0 case is model-independent (impact parameter dependent PDFs)

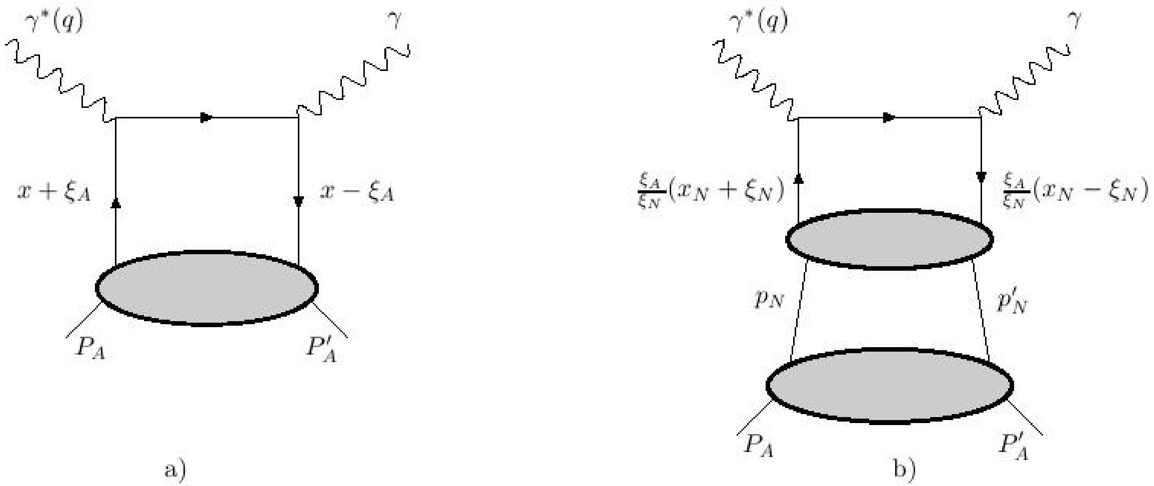
LT nuclear shadowing and nuclear GPDs-2

- Modeled double rescattering by DVCS on the “Pomeron”



- Used QCD factorization for DVCS to express DVCS amplitude in terms of GPDs

- Used light-cone coordinates to calculate the nuclear part



LT nuclear shadowing and nuclear GPDs-3

Final expression for nuclear GPDs in the presence of shadowing:

$$\begin{aligned} H_A^j(x_N,\xi_A,t,Q^2) &= F_A(t)\sum_N H_N^j(x_N,\xi_N,t,Q^2) \\ &- \frac{A(A-1)}{2}\,16\pi B_{\rm diff}\,\Re e\Big\{\int d^2\vec{b}\,e^{i\vec{\Delta}_\perp\cdot\vec{b}}\int_\infty^\infty dz_1\int_{z_1}^\infty dz_2\int_{x_{I\!P}^{\rm min}}^{0.1} dx_{I\!P} \\ &\times \rho_A(b,z_1)\rho_A(b,z_2)\,k_\eta\,e^{-im_N z_2(x_{I\!P}-2\xi_N)+im_N z_1 x_{I\!P}}\,e^{-\frac{A}{2}(1-i\eta)\sigma_{\rm eff}^j(x_B,Q^2)\int_{z_1}^{z_2}dz'\rho_A(\vec{b},z')} \\ &\times \phi_{I\!P/N}(x_{I\!P})\phi_{I\!P/N}(x_{I\!P}-2\xi_N)\Big\}\frac{1}{x_{I\!P}}H_{I\!P}^j\Big(\frac{\xi_{I\!P}}{\xi_N}x_N,\xi_{I\!P},t_{\rm min},Q^2\Big)\,. \qquad (65) \end{aligned}$$

Pomeron probability amplitude

Pomeron GPD

- This expression has correct forward limit – reproduces nuclear PDF
- In the xi=0 limit, it is model-independent and gives
  the impact parameter dependent nuclear PDFs (after the FT)

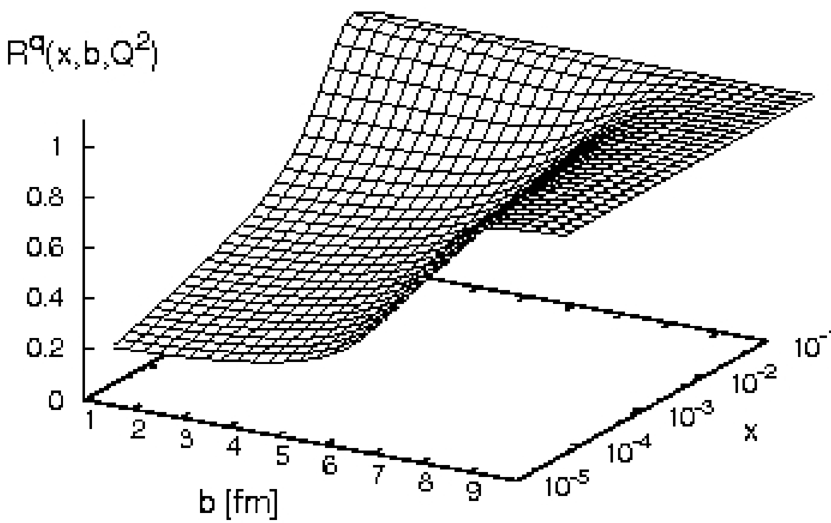
LT nuclear shadowing and nuclear GPDs-4

In the $\xi = 0$ limit, $t = -q^2$, and GPDs have the probabilistic interpretation in the impact parameter **b** space.

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

Density of nucleons at given b

208Pb



- 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

LT nuclear shadowing and nuclear GPDs-5

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

$$\langle b_g^2 \rangle = \frac{\int d^2b\, b^2 g_A(x,Q^2,b)}{\int d^2b\, g_A(x,Q^2,b)} .$$

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

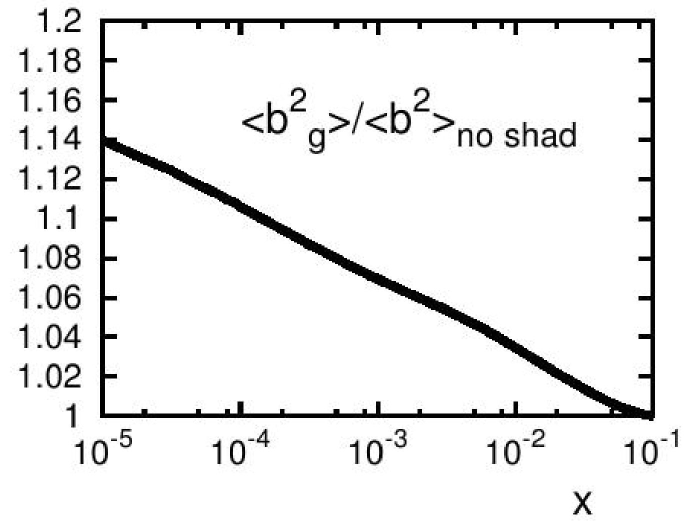


Fig. 41. The ratio $\langle b_g^2 \rangle / \langle b^2 \rangle_{\text{no shad}}$ for ^{208}Pb as a function of Bjorken x at $Q^2 = 4$ GeV^2.

- This has experimentally testable consequences:

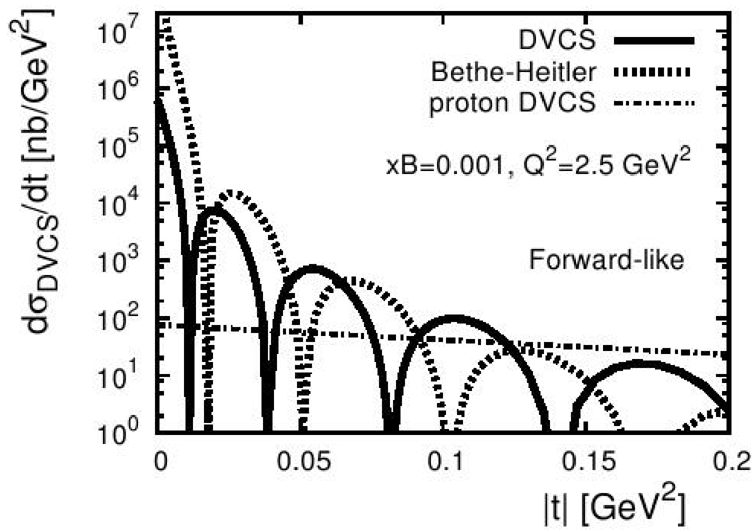
-- position of the minima of DVCS cross section shifts towards smaller t
-- dramatic oscillations of DVCS asymmetries

LT nuclear shadowing and nuclear GPDs-6

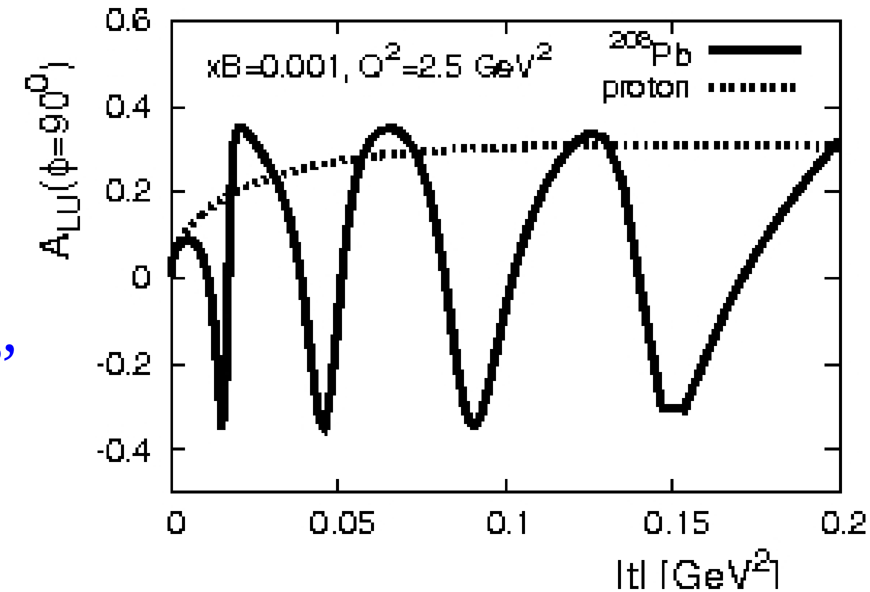
• The DVCS and BH cross sections for Pb-208 integrated over phi

The shift is the measure of nuclear shadowing

(In the example, Δt=0.006 GeV2)



Similar pattern also for diffractive VM production



• The beam-spin DVCS asymmetry

The reason for the oscillations is shadowing, position of nodes measures the strength of shadowing

Summary

• An EIC is an ideal machine to study nuclear shadowing in nuclear PDFs, and more generally, to test the transition from the linear to non-linear parton dynamics.

• Coherent nuclear processes are complimentary to inclusive measurements and at the same time more sensitive to nuclear shadowing and saturation.

• Nuclear shadowing in nuclear GPDs is large, and leads to an increase of transverse size of partons in nuclei which is measurable -- the shift of the minima of DVCS cross section and oscillations of DVCS asymmetries.

• More theoretical work is still required to explore the full potential of coherent nuclear processes at an EIC.