Coherent phenomena in eA collisions

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Outline

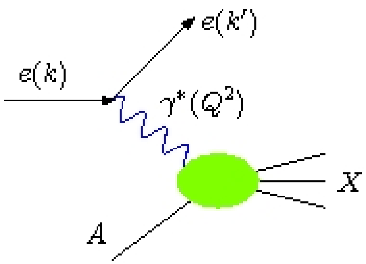
- Intro: Partonic structure of nuclei in eA collisions
- Leading twist nuclear shadowing and nuclear PDFs:
  - usual nuclear PDFs
  - nuclear generalized parton distributions (GPDs)
  - nuclear diffractive PDFs
- Summary

Partonic structure of nuclei in eA collisions

Accessed in hard (large Q²) processes with nuclei using QCD factorization theorems (= color transparency):

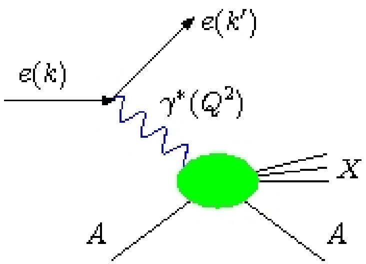
- **Usual** parton distributions

  from $F_{2A}(x,Q^2)$, $F_L(x,Q^2)$ in eA DIS



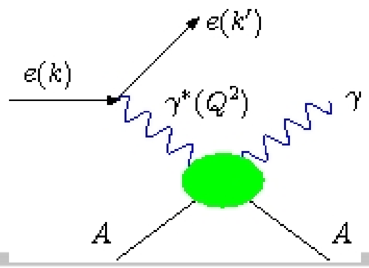
- **Diffractive** parton distributions

  from $F_{2A}{}^{D(3)}(x,Q^2,x_P)$ in diffraction in eA DIS



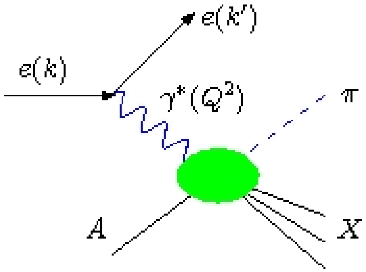
- **Generalized** parton distributions

  from DVCS and meson electroproduction



- **Transverse** moment. dependent

  from SIDIS



Partonic structure of nuclei in eA collisions

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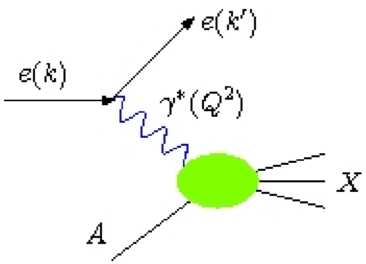
  from $F_{2A}(x,Q^2)$, $F_L(x,Q^2)$ in eA DIS



- **Diffractive** parton distributions

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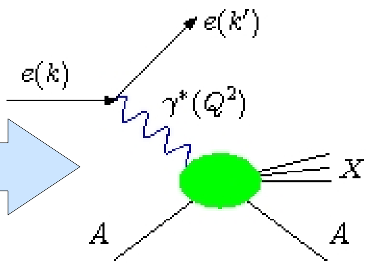
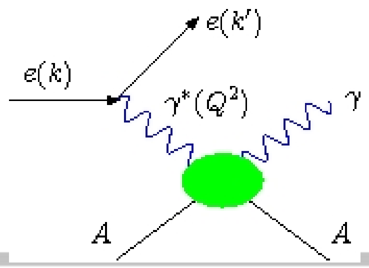


Coherent processes

- **Generalized** parton distributions

  from DVCS and meson electroproduction



- **Transverse** moment. dependent

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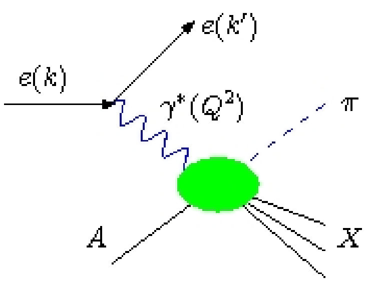


Partonic structure of nuclei in eA collisions-2

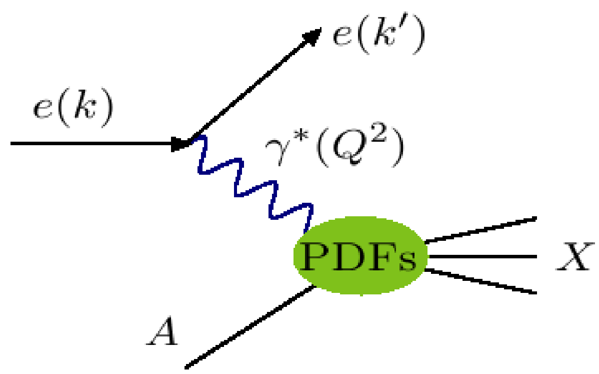
- Various PDFs contain fundamental information on different aspects of distribution/correlation of partons in nuclei.
- Modified (expected to be modified) in nuclei compared to free proton due to various nuclear effects,
- The dominant effect at small Bjorken x – nuclear shadowing

- **Diffractive parton distributions and structure functions**
  - never been measured
  - test for many approaches (LT vs. dipole models)
  - more sensitive to saturation than inclusive DIS

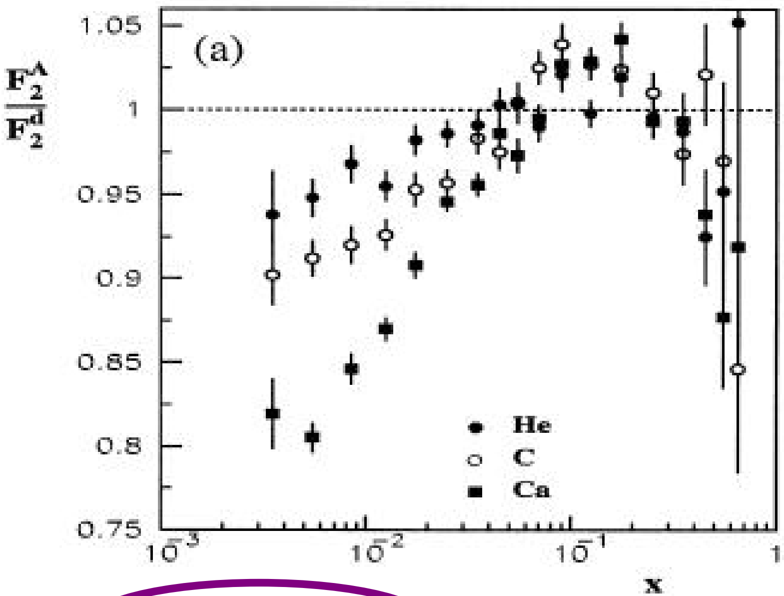
- **Generalized parton distributions and exclusive processes**
  - 3D correlations/distributions of partons
  - measured for ^{4}He at JLab 6 GeV, plans for 12 GeV; HERMES
  - standard nuclear effects enhanced: EMC, shadowing; sensitivity to saturation
  - non-standard effects also enhanced: bound nucleon medium modifications, non-nucleon degrees of freedom

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



shadowing

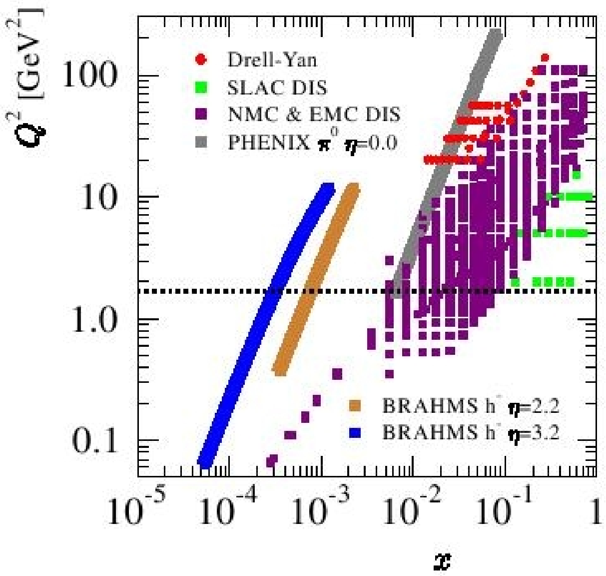
- Global fits to extract nuclear PDFs: lead to HUGE uncertainties at small x, especially for gluons

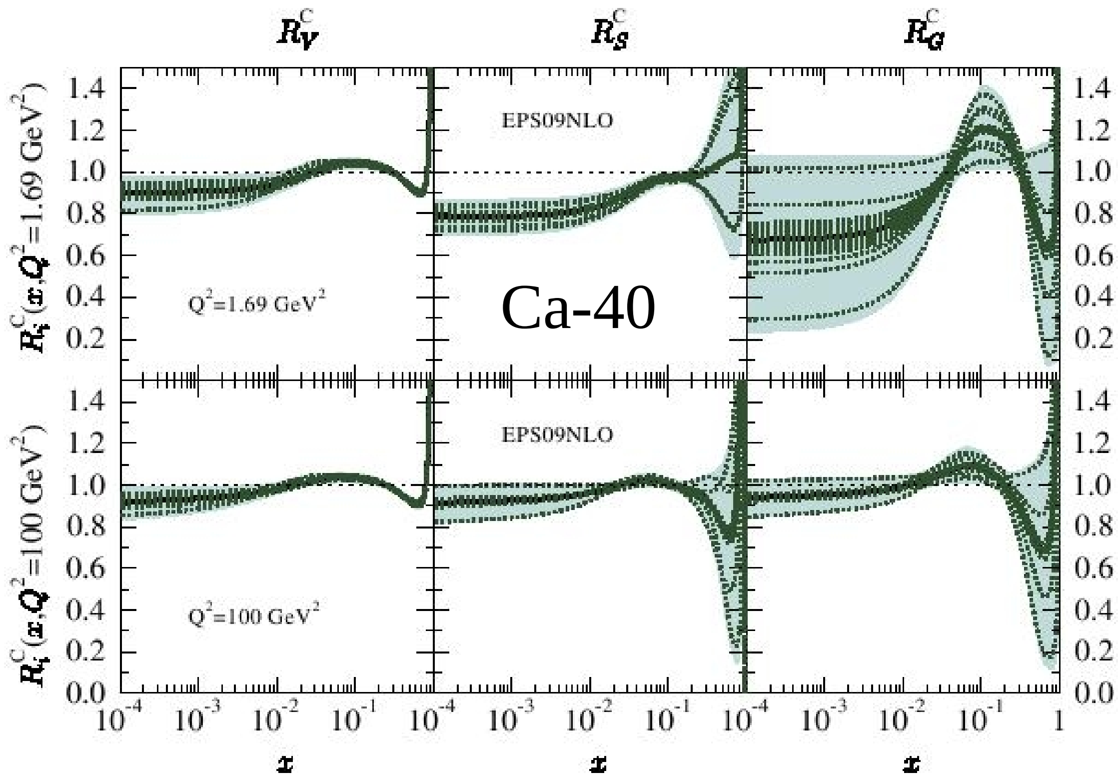
- Dynamical models of nuclear shadowing:
  - LT theory of nuclear shadowing
  - dipole models (LT + HT)
  - HT shadowing

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:

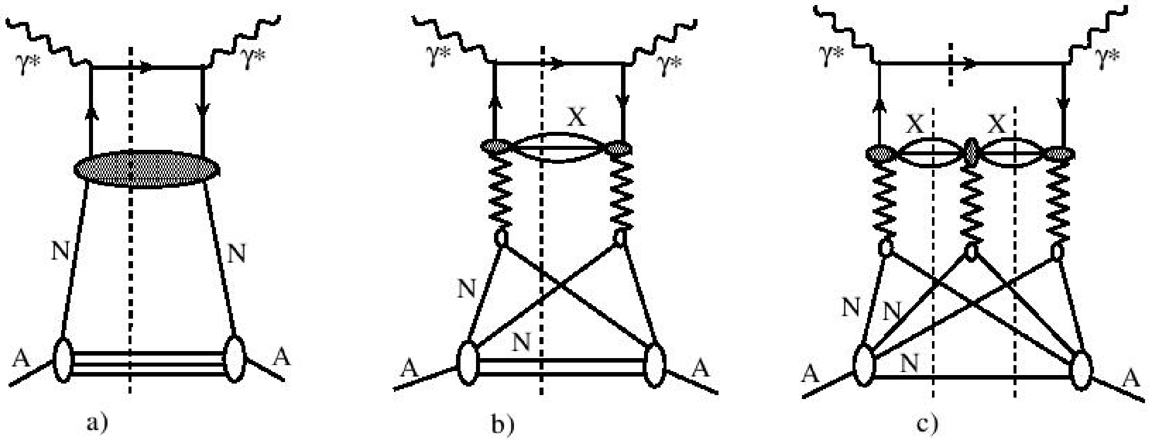
- generalization of Gribov's theory of nuclear shadowing to DIS and to arbitrary nuclei
  Frankfurt and Strikman, '88 and '98

- 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:



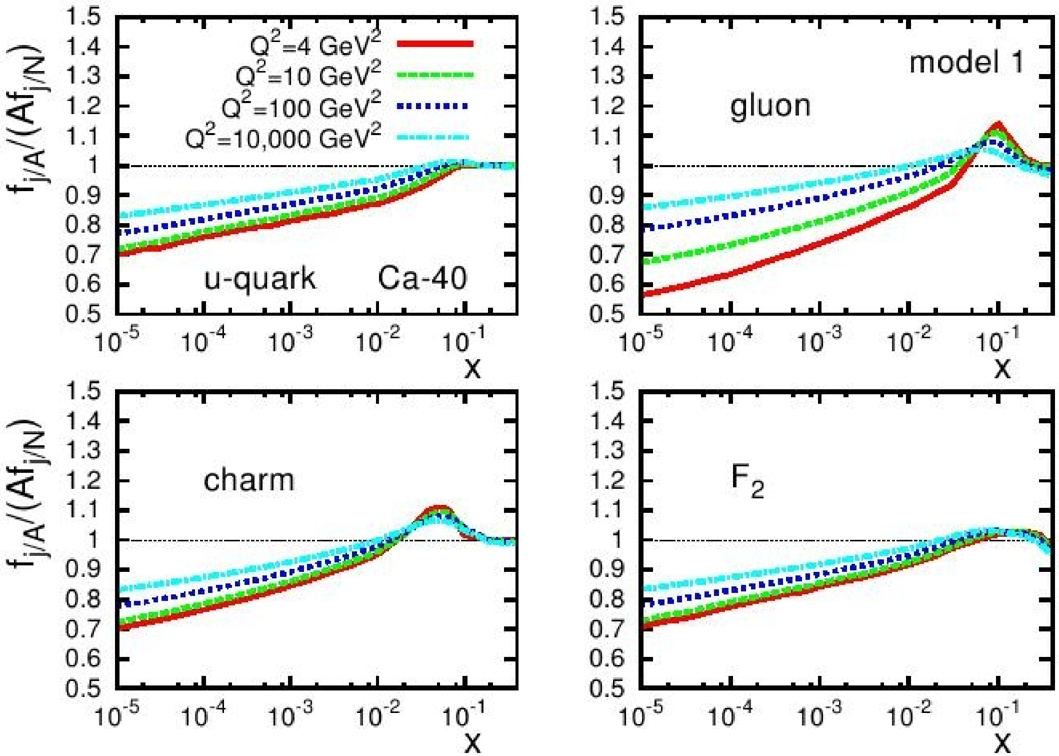
+ interaction with N > 3 nucleons

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

Input:

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

Predictions for nuclear PDFs

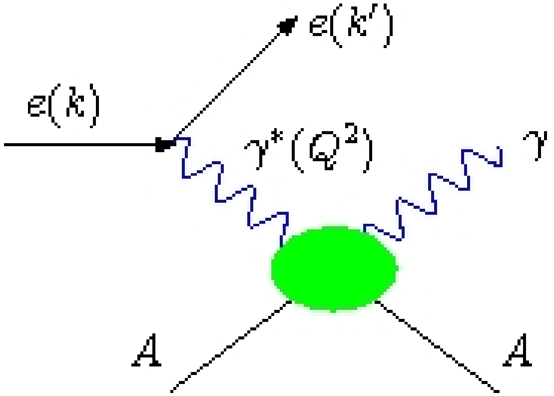


Frankfurt, VG, Strikman, 2010 (in preparation)

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

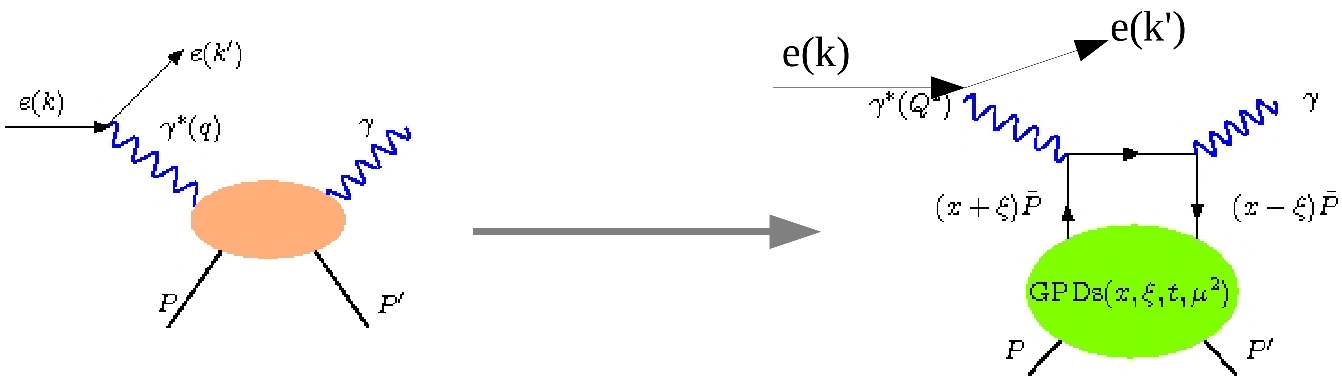
EIC is an ideal place to test these predictions!

- Nuclear shadowing and nuclear generalized parton distributions (GPDs)



Basics of generalized parton distributions

Can be accessed in hard exclusive reactions due to QCD factorization:



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

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

x and ξ : light-cone fractions

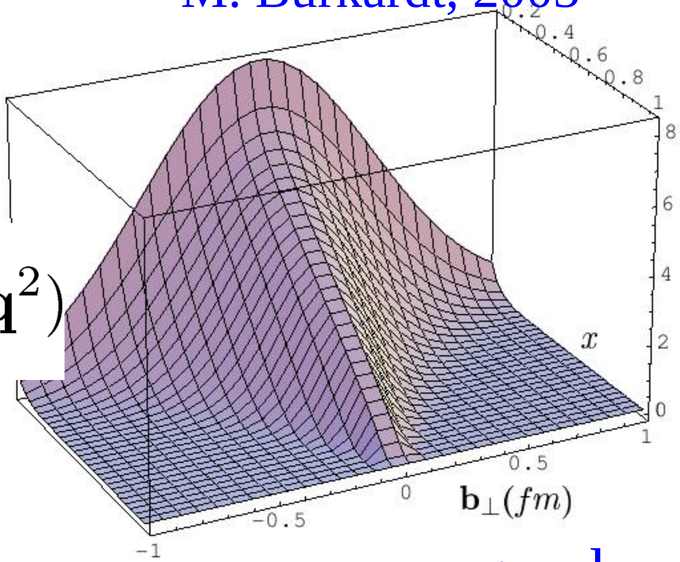
Properties of GPDs:

- reduced to usual PDFs in the forward limit ξ =t=0
- after integration over x give elastic form factors
- contain info on the parton contribution to total angular momentum of target
- give 3D (longitudinal x,xi+transverse impact param.) distribution of partons

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 (Align-jet model)

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

At small x, we study the transverse distribution of partons

Impact parameter dependence

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

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

• 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 and M. Siddikov, '09

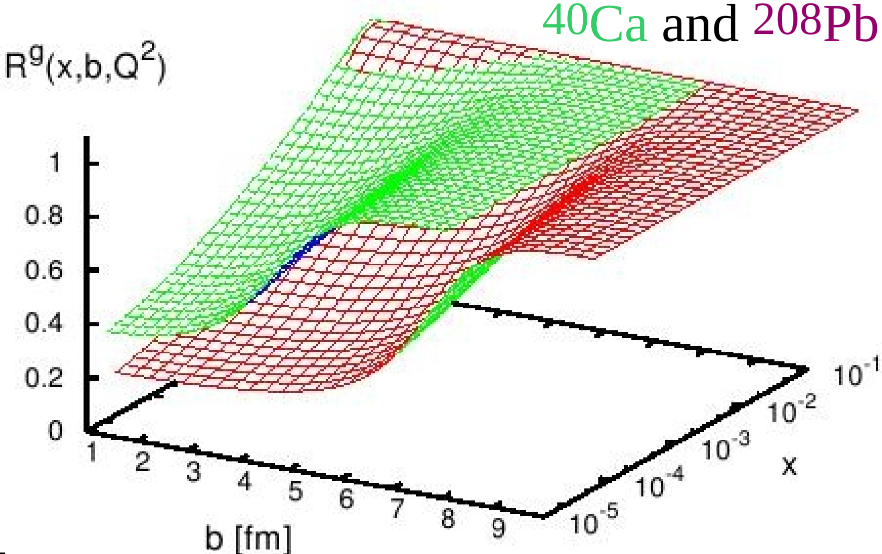
Nuclear GPDs at xi=0

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

Frankfurt, VG, Strikman, 2010 (in preparation)

Density of nucleons at given b

40Ca and 208Pb



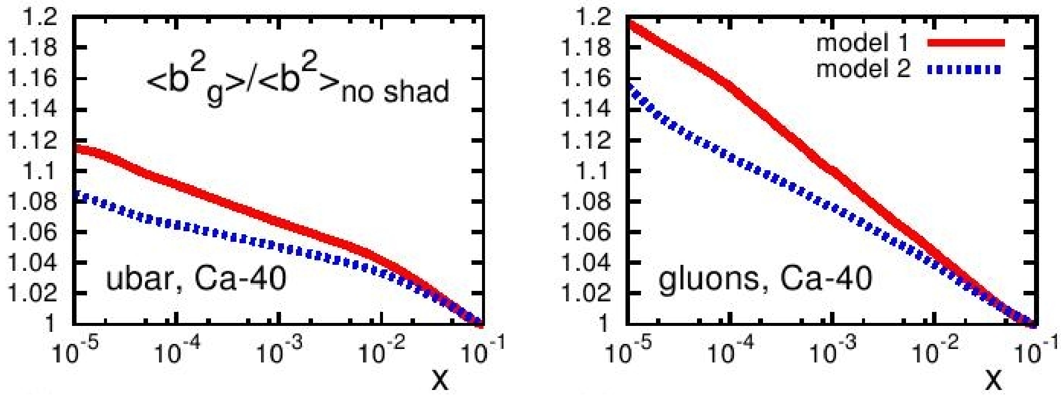
- Nuclear shadowing is larger at small b
- Shadowing introduces correlations between x and b, even if such correlations are absent for free nucleon

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

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

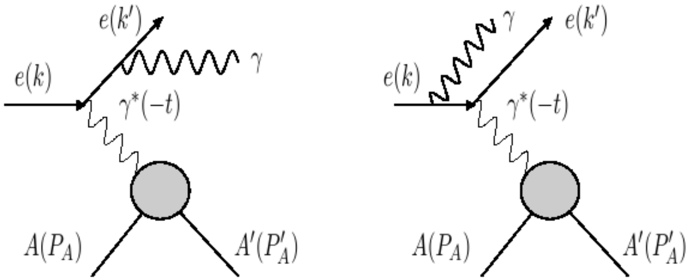


- *This has experimentally testable consequences*:
  -- position of the minima of DVCS cross section shifts towards smaller t
  -- dramatic oscillations of DVCS asymmetries

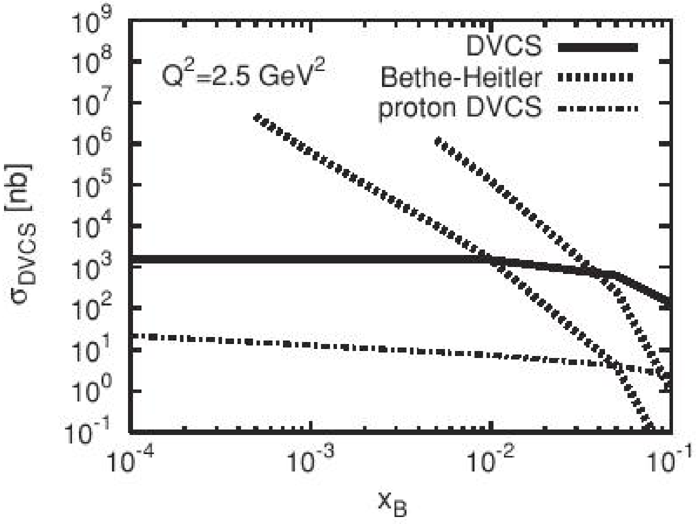
K. Goeke, VG, M. Siddikov, PRC 79 (2009) 035210

DVCS and BH cross sections

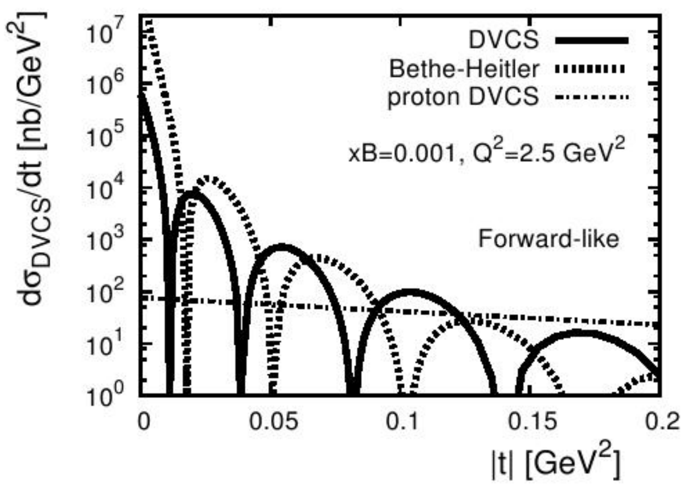
- DVCS interferes with Bethe-Heitler (BH) process, whose amplitude is real.



- DVCS and BH cross sections for 208Pb at Q^2=2.5 GeV²



need differential in t



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

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

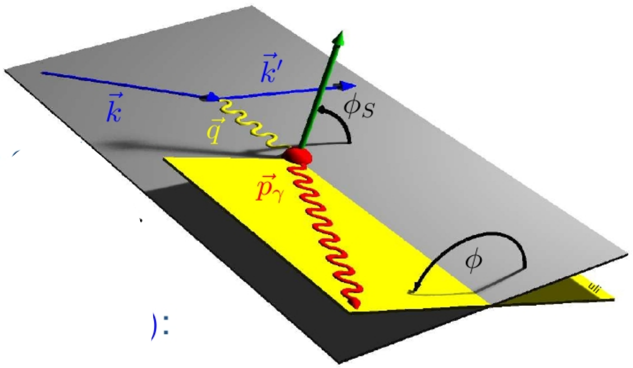
The shift is the measure of nuclear shadowing

(In the example, Δt=0.006 GeV2)

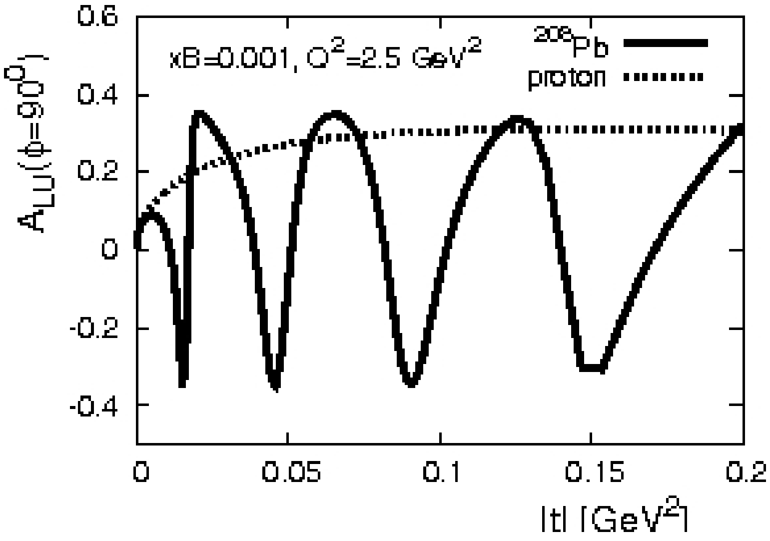
DVCS asymmetries

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

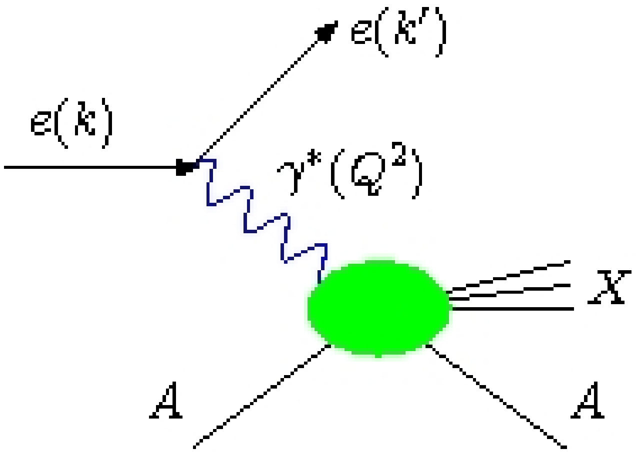


$$A_{\mathrm{LU}}(\phi) = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \propto \sin\phi \frac{H_A(\xi,\xi,t)F_A(t)}{F_A^2(t)}$$

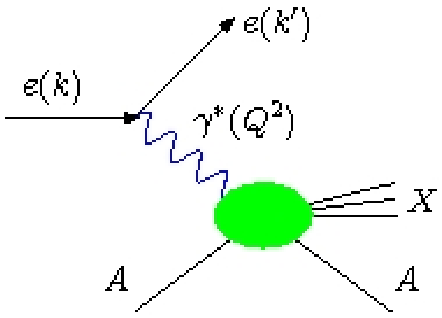


Oscillations are due to shadowing; position of nodes measures the strength of shadowing

- LT nuclear shadowing and nuclear diffractive parton distributions

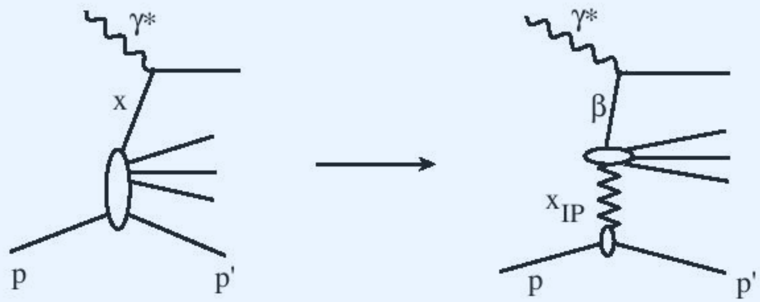


Basics of diffractive DIS



Diffractive structure function:

$$\frac{d^4\sigma^D_{eA}}{dx_{I\!P}\,dt\,dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(1+(1-y)^2\right)F^{D(4)}_{2A}(x,Q^2,x_{I\!P},t)$$



$$t = (p'-p)^2\,,$$

$$x_{I\!P} = \frac{q\cdot(p-p')}{q\cdot p} \approx \frac{M_X^2+Q^2}{W^2+Q^2}\,,$$

$$\beta = \frac{Q^2}{2q\cdot(p-p')} = \frac{x}{x_{I\!P}} \approx \frac{Q^2}{Q^2+M_X^2}\,,$$

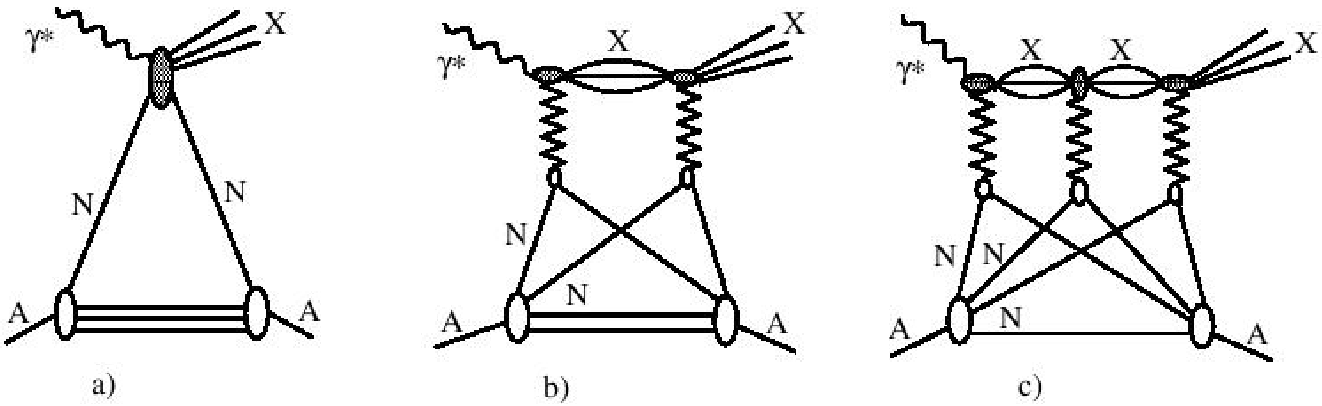
QCD factorization theorem for diffractions in DIS:

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

Nuclear diffractive PDFs

LT shadowing and eA coherent diffraction

Glauber-Gribov multiple rescattering series: Frankfurt, VG, Strikman, 2004



+ interaction with N > 3 nucleons

factorization theorem for diffraction

$$\beta f^{D(3)}_{j/A}(\beta, Q^2, x_{I\!P}) = 4\pi A^2 \beta f^{D(4)}_{j/N}(\beta, Q^2, x_{I\!P}, t_{\min}) \int d^2 b$$

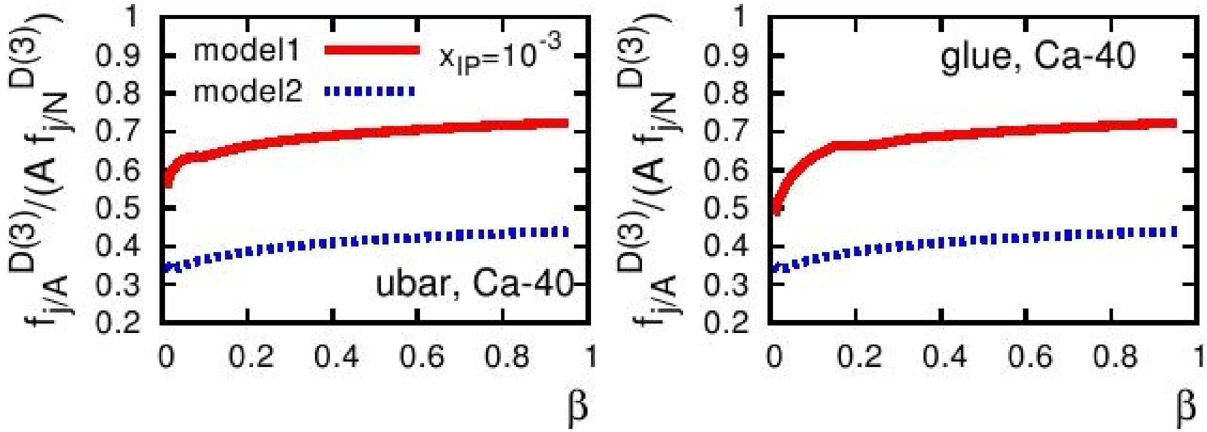
$$\times \left| \int_{-\infty}^{\infty} dz\, e^{i x_{I\!P} m_N z} e^{-\frac{A}{2}(1-i\eta)\sigma_3^j(x,Q^2)\int_z^{\infty} dz' \rho_A(b,z')} \rho_A(b,z) \right|^2 .$$

nuclear diffractive PDFs

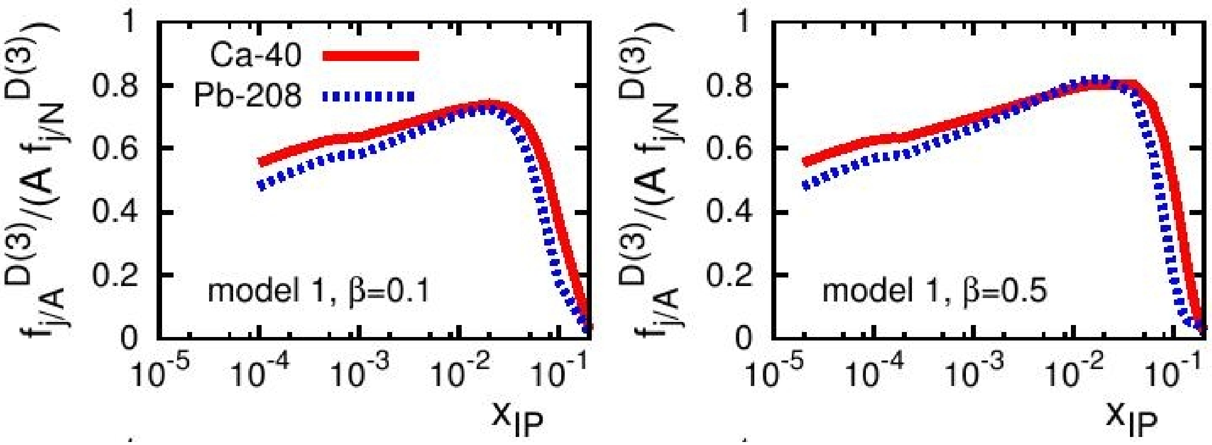
nucleon diffractive PDFs (input)

Predictions for nuclear diffractive PDFs

Frankfurt, VG, Strikman, 2010 (in preparation)

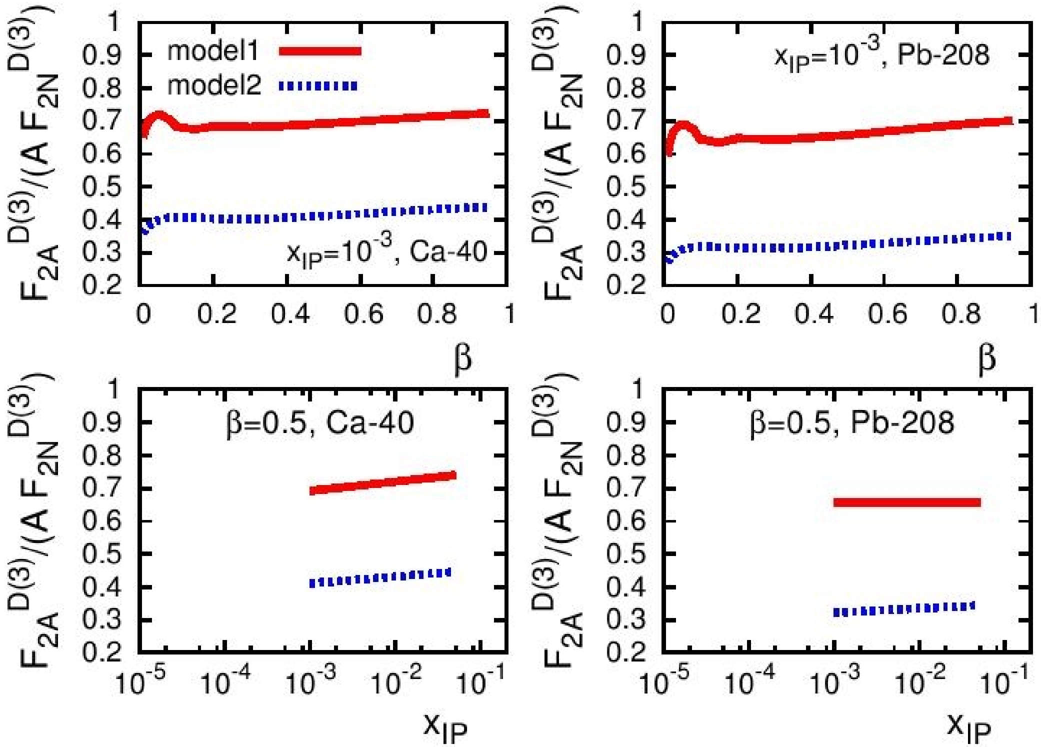


- weak dependence on beta
- weak flavor-dependence
- weak Q^2 dependence
- strong model-dependence (model 1 vs model 2)
- without shadowing, the ratio > 1

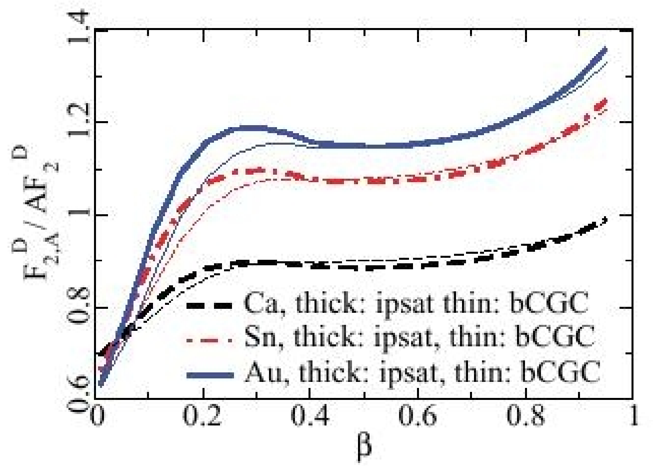


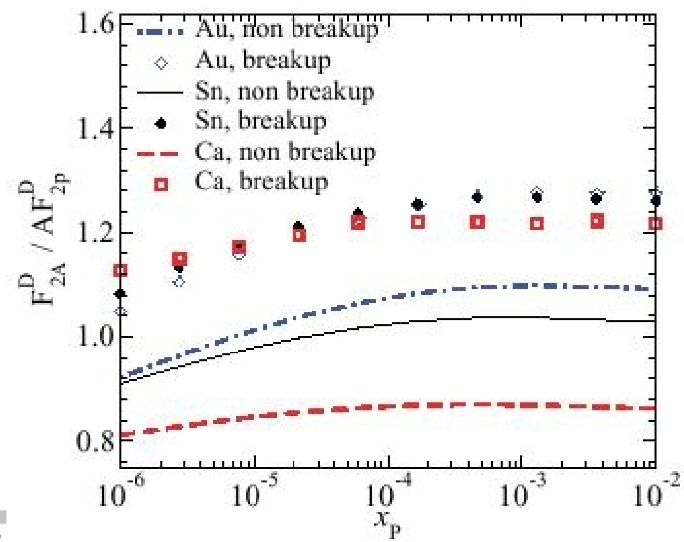
- at large $x_{P,}$ coherence is destroyed

Comparison to dipole formalism



H. Kowalski, at al., (2008)





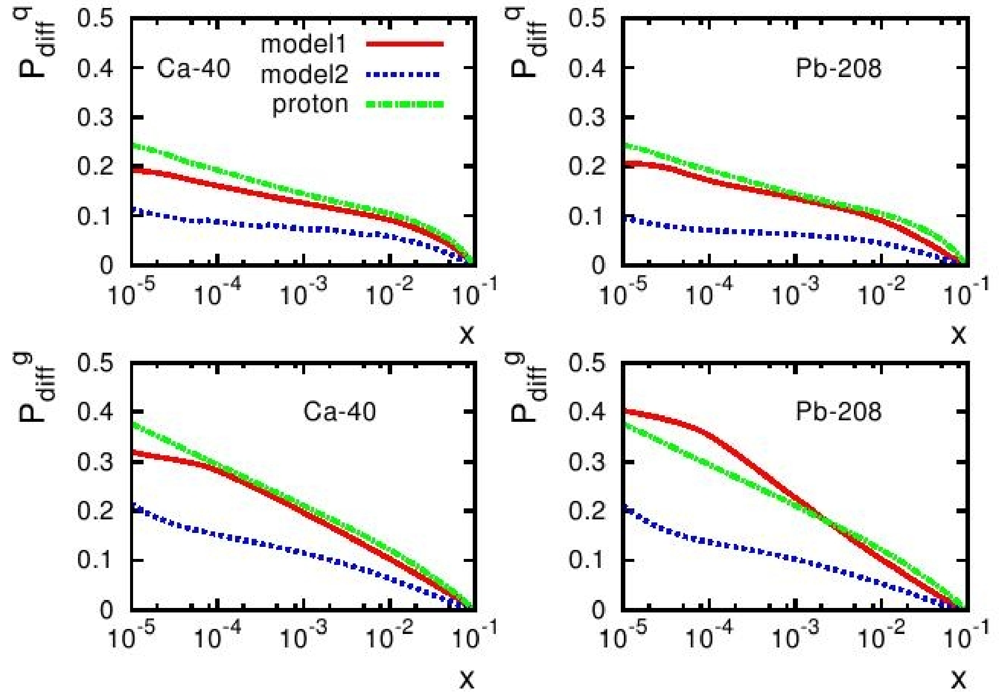
Shapes and absolute values (for ^{40}Ca) similar in two approaches

Bad news for LT vs. Saturation studies

Diffraction balance in eA DIS

Fraction of coherent diffraction:

$$P^{j}_{\mathrm{diff}} = \frac{\int_{x}^{0.1} dx_{I\!P}\, \beta f_j^{D(3)}(\beta, Q^2, x_{I\!P})}{x f_j(x, Q^2)}$$



Large shadowing slows down approach to Black Disk Regime when P=1/2

The formalism can be also used for incoherent* eA diffraction, eA->eXA' (A'≠A)

A/model	$F^{D(3)}_{2A,\mathrm{incoh}}/F^{D(3)}_{2A}$
^{40}Ca, model 1	0.35
^{40}Ca, model 2	0.43
^{208}Pb, model 1	0.12
^{208}Pb, model 2	0.20

Table 3
The $F^{D(3)}_{2A,\mathrm{incoh}}/F^{D(3)}_{2A}$ ratio at $x_{I\!P} = 10^{-3}$ and $Q_0^2 = 4$ GeV^2. The ratio is approximately β-independent.

significant!

Black Disk Regime

- So far relied on the LT QCD factorization (Color Transparency) and parton picture
- At ultra-high energies, the interaction of gamma* with A is maximal allowed by unitarity of S-matrix -> Black Disk Regime with definite predictions:

Frankfurt, VG, McDermott, Strikman, 2001

- Violation of Bjorken scaling and slow increase of SFs

$$F_T^A(x,Q^2) = \frac{2\pi R_A^2}{12\pi^3} Q^2 \rho(M_{\max}^2) \ln(M_{\max}^2/m_0^2) \propto \frac{2\pi R_A^2}{12\pi^3} Q^2 \rho(M_{\max}^2) \ln(x_0/x),$$

$$F_L^A(x,Q^2) = \frac{2\pi R_A^2}{12\pi^3} Q^2 \rho(M_{max}^2).$$

- Spectrum of diffractive final-states

$$\frac{dF_T^{D(3)}(x,Q^2,M^2)}{dM^2 d\cos\theta} = \frac{3}{8}(1+\cos^2\theta)\frac{\pi R_A^2}{12\pi^3}\frac{Q^2 M^2 \rho(M^2)}{(M^2+Q^2)^2},$$

$$\frac{dF_L^{D(3)}(x,Q^2,M^2)}{dM^2 d\cos\theta} = \frac{3}{4}\sin^2\theta\frac{\pi R_A^2}{12\pi^3}\frac{Q^4 \rho(M^2)}{(M^2+Q^2)^2}.$$

- Enhancement by Q4 of VM production

$$\frac{d\sigma^{\gamma_T^*+A\to V+A}}{dt} = \frac{M_V^2}{Q^2}\frac{d\sigma^{\gamma_L^*+A\to V+A}}{dt} = \frac{(2\pi R_A^2)^2}{16\pi}\frac{3\Gamma_V M_V^3}{\alpha(M_V^2+Q^2)^2}\frac{4\left|J_1(\sqrt{-t}R_A)\right|^2}{-tR_A^2},$$

Summary

• Fundamental nuclear PDFs are either poorly known or unknown at small values of Bjorken x, especially in the gluon channel.
Nuclear shadowing strongly suppresses all types of nPDFs: usual, diffractive, generalized.

• LT nuclear shadowing in nuclear DVCS and nuclear GPDs is large, and leads to an increase of transverse size of partons in nuclei.

• LT nuclear shadowing in nuclear diffractive PDFs is large, mimics/similar to predictions of the dipole formalism, and slows down approach to saturation.

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