Diffraction at EIC

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Outline

- Introduction
- Leading twist approach to diffraction
- Color dipole approach to diffraction
- Conclusions

Partonic structure of hadrons: Open questions

Decades of experiments at SLAC, CERN, Fermilab and HERA verified many predictions of QCD and explored the internal structure of hadrons in terms of quarks and gluons.

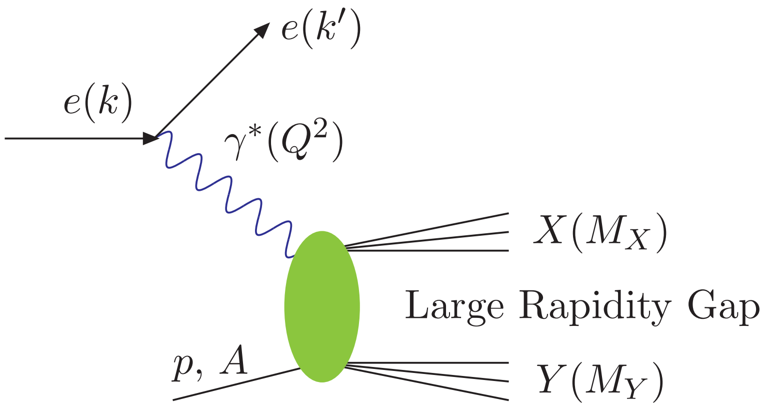
However, there are still many open questions:

- What is the gluon momentum distribution in nuclei?
- What are the properties of high-density gluon matter?
- How do fast quarks and gluons interact as they traverse nuclear matter?
- How do partons contribute to the spin of the nucleon?
- What is the spacial distribution of partons in the nucleon and in nuclei?

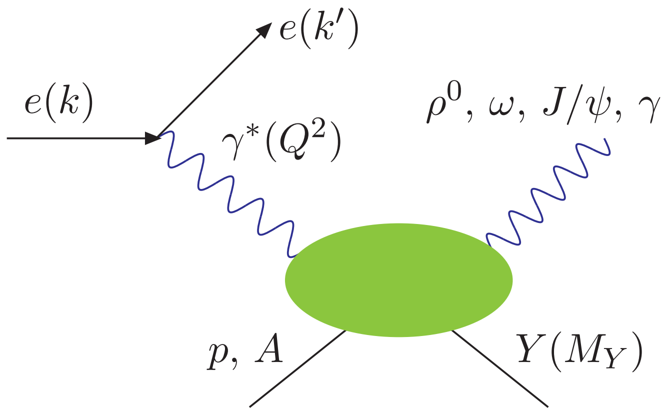
EIC and diffraction

The Electron-Ion Collider (EIC) is a proposed new facility to collide high-energy beams of electrons with with nuclei and polarized protons/light ions, which will attempt to address the above questions.

<u>All of the above</u> open questions can be experimentally studied in various hard diffractive processes in DIS:



INCLUSIVE DIFFRACTION

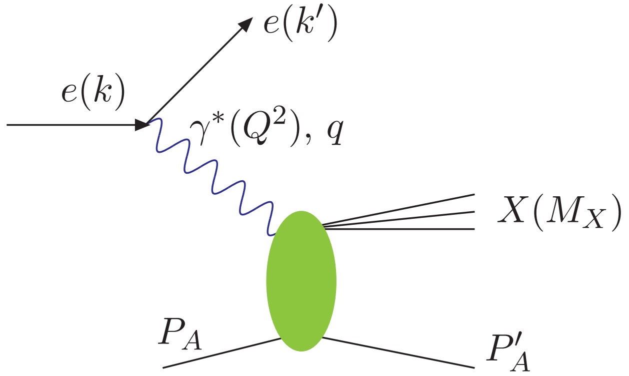


EXCLUSIVE PRODUCTION OF VECTOR MESONS

DVCS

Hard coherent inclusive diffraction in DIS

I will concentrate on hard inclusive diffraction in DIS.



$$x = \frac{Q^2}{2P_A q}$$

$$x_{I\!P} = \frac{q(P_A - P'_A)}{qP_A} \approx \frac{Q^2 + M_X^2}{Q^2} x$$

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

$$t = (P_A - P'_A)^2\,, \quad y = \frac{qP_A}{kP_A}$$

- The cross section in terms of diffractive structure functions $F_2^{D(4)}$ and $F_L^{D(4)}$

$$\frac{d^4\sigma^{eA\to eXA}}{dx\, dQ^2 dx_{I\!P}\, dt} = \frac{2\pi\alpha^2}{x\, Q^4}[1+(1-y)^2]\left(F_2^{D(4)}(x, Q^2, x_{I\!P}, t) - y^2 F_L^{D(4)}(x, Q^2, x_{I\!P}, t)\right)$$

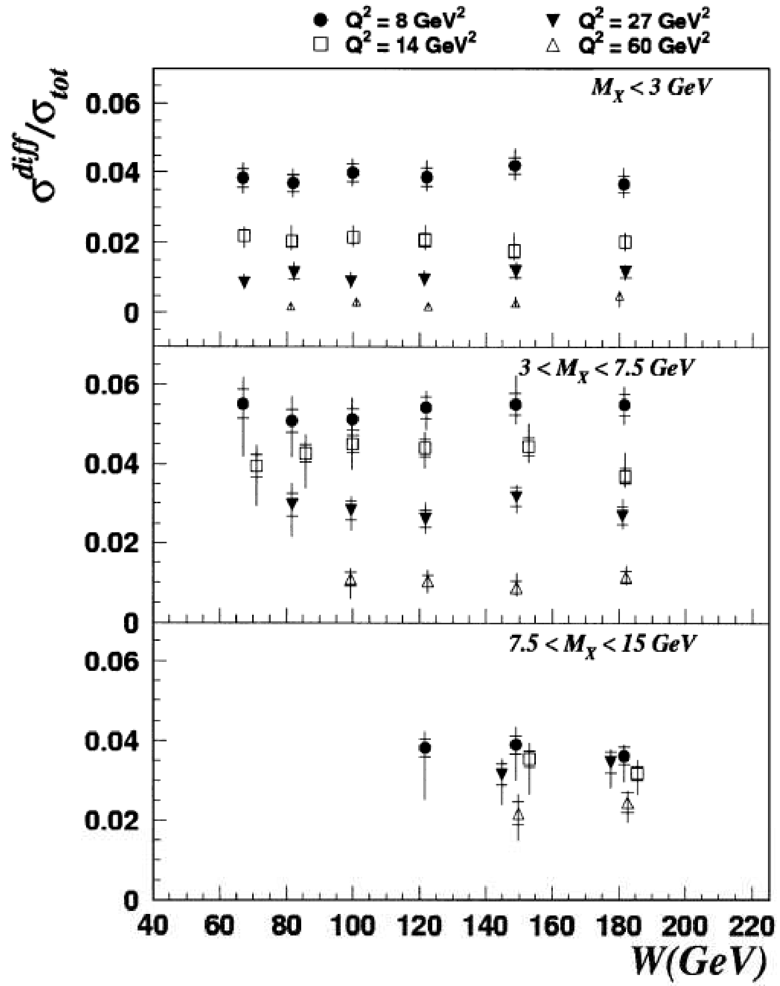
- One also often considers t-integrated $F_2^{D(3)}(x, Q^2, x_{I\!P}) = \int dt\, F_2^{D(4)}(x, Q^2, x_{I\!P}, t)$

Hard inclusive diffraction in DIS at HERA

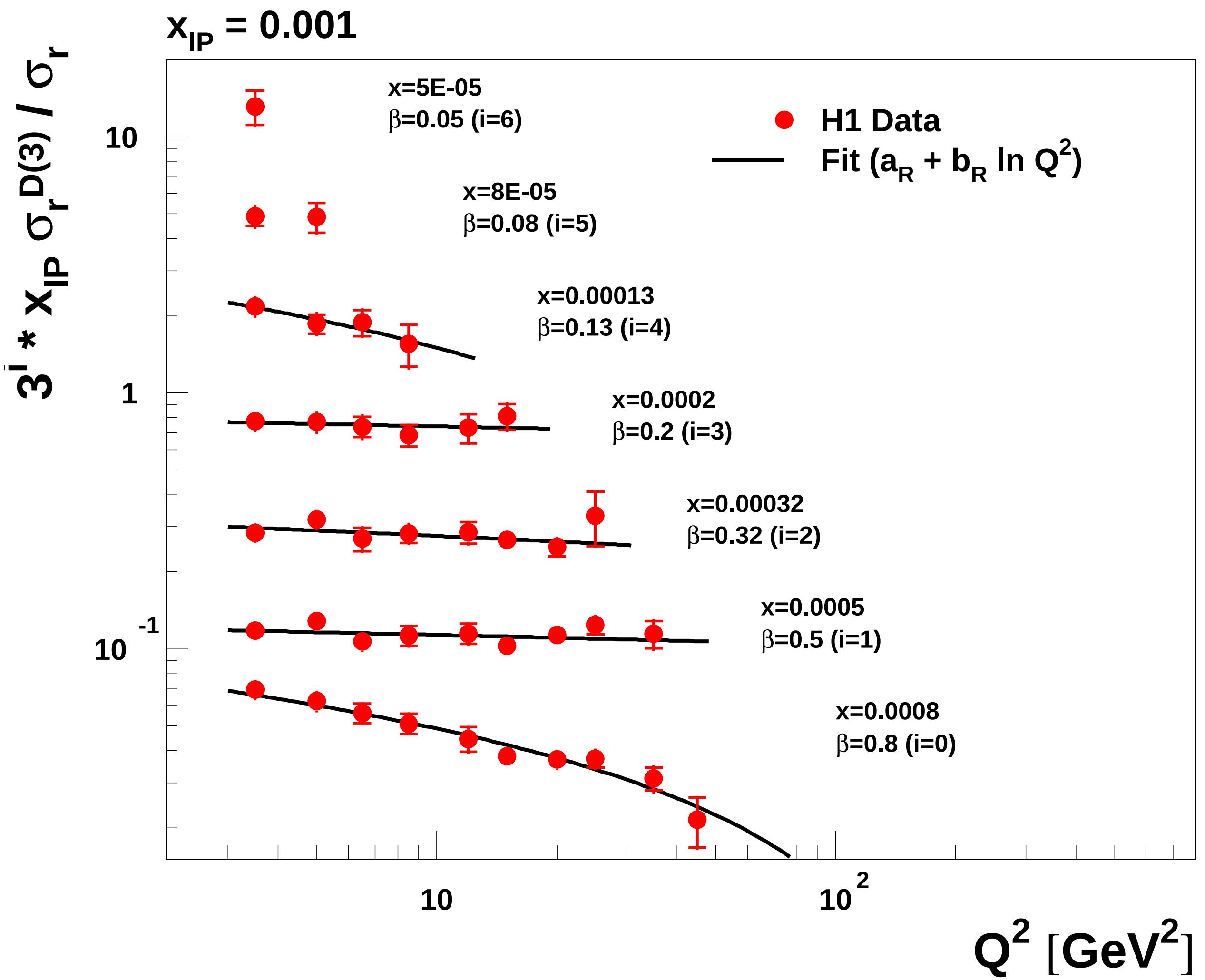
The discovery of the large cross section of hard inclusive diffraction in DIS is one of the major results of HERA. Several features came totally unexpected:

1) The fraction is diffraction $\approx 10-15\%$ of the total DIS cross section

2) The fraction of diffraction is energy-independent



3) Diffraction is a leading twist (LT) phenomenon
(not $1/Q^2$ suppressed to compared to the total DIS cross section)

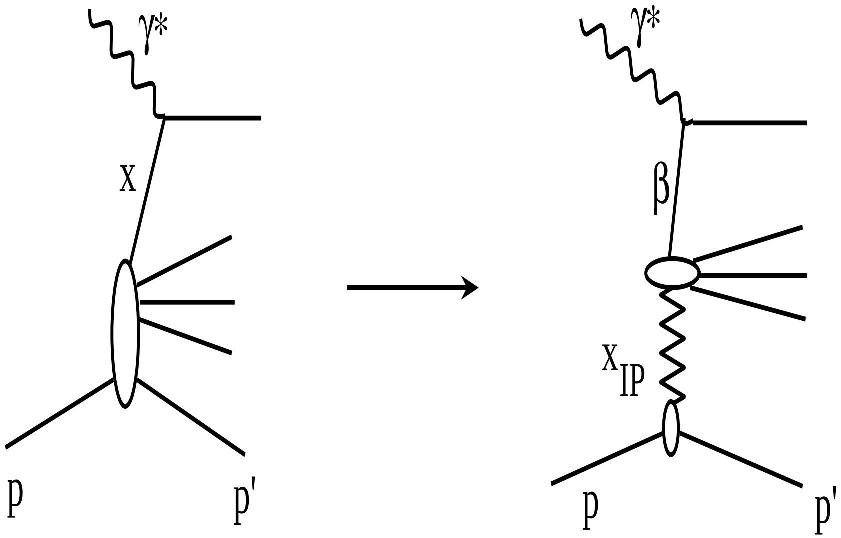


Two approaches to inclusive diffraction in DIS

1) Leading Twist (LT) approach based on the QCD factorization theorem, which allows to introduce universal diffractive PDFs $f_j^{D(3)}$ of the target:

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

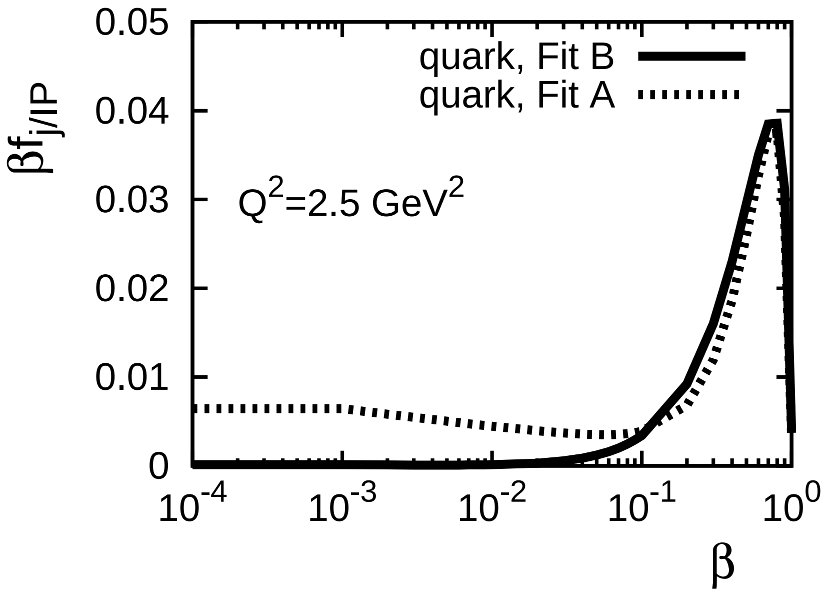
- One further uses Regge factorization assumption (supported by data)

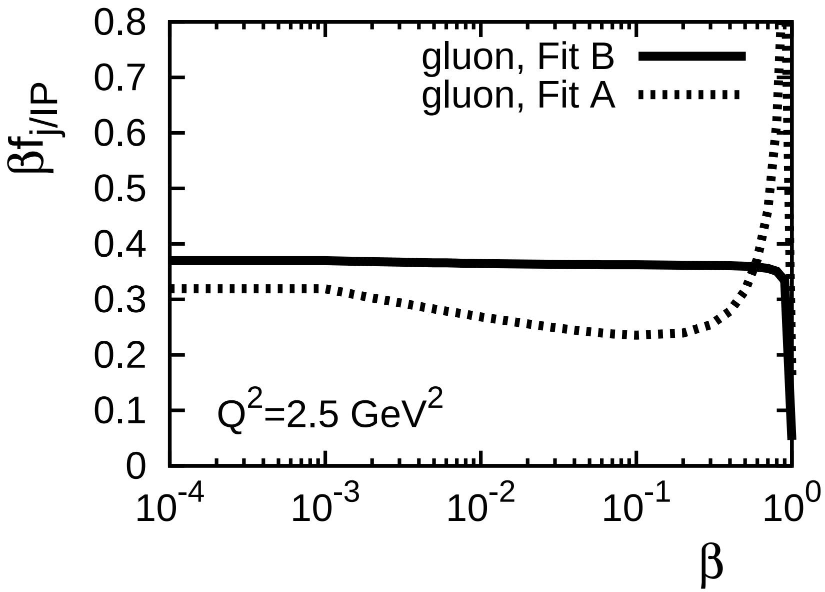


$$f_j^{D(3)}(x,Q^2,x_{I\!P}) = f_{I\!P/p}(x_{I\!P}) f_{j/I\!P}(\beta,Q^2) + n_{I\!R} f_{I\!R/p}(x_{I\!P}) f_{j/I\!R}(\beta,Q^2)$$

– $f_{I\!P/p}$ Pomeron flux
– $f_{j/I\!P}(\beta,Q^2)$ PDF of flavor j of the Pomeron
– The subleading Reggeon contribution is negligibly small for $x_{I\!P} < 0.01$.

- The QCD analysis of diffractive data (H1 and ZEUS) determines $f_{j/I\!P}(\beta, Q_0^2)$ from global fits to (mostly) $F_2^{D(3)}$ and $F_2^{D(4)}$.



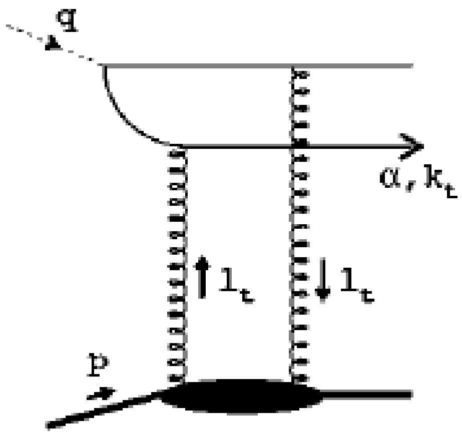


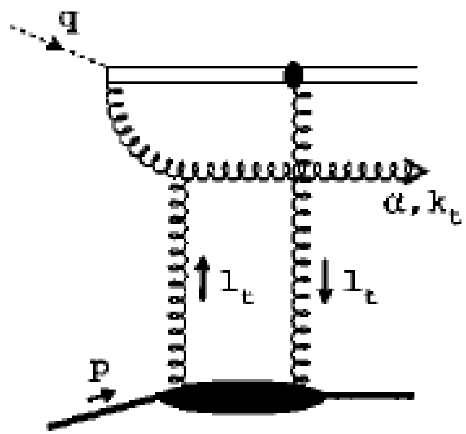
Important finding: $f_{g/I\!P}(\beta, Q_0^2) \gg f_{q/I\!P}(\beta, Q_0^2)$.

Two approaches to inclusive diffraction in DIS

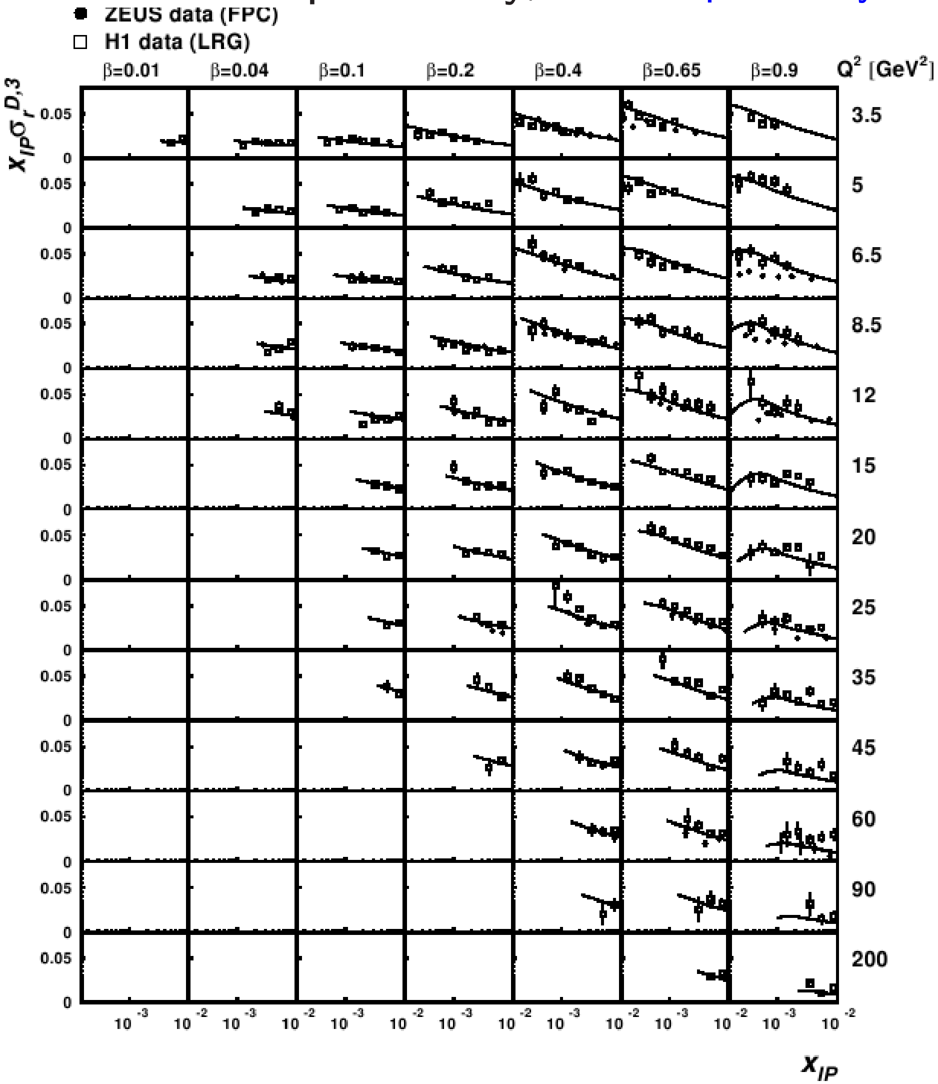
2) Color dipole framework: the main ingredient is the dipole cross section. It is an all-twist approach, which is equivalent to LT at LLA, but can naturally include saturation physics.

The formalism is based on the following space-time picture:
– the virtual photon fluctuates into $q\bar{q}$ and $q\bar{q}g$ dipoles
– the dipoles interact with the target with the dipole cross section
– the final state is formed





Once the dipole cross section is fixed by the inclusive DIS data, diffraction in DIS is described very well and model-independently, C. Marquet, Phys. Rev. D76, 094017 (2007)

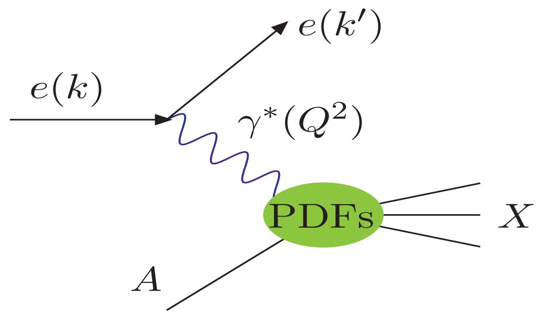


Important: The same model can predict diffraction in DIS with nuclei!

H. Kowalski, T. Lappi, C. Marquet, R. Venugopalan, arXiv:0805.4071

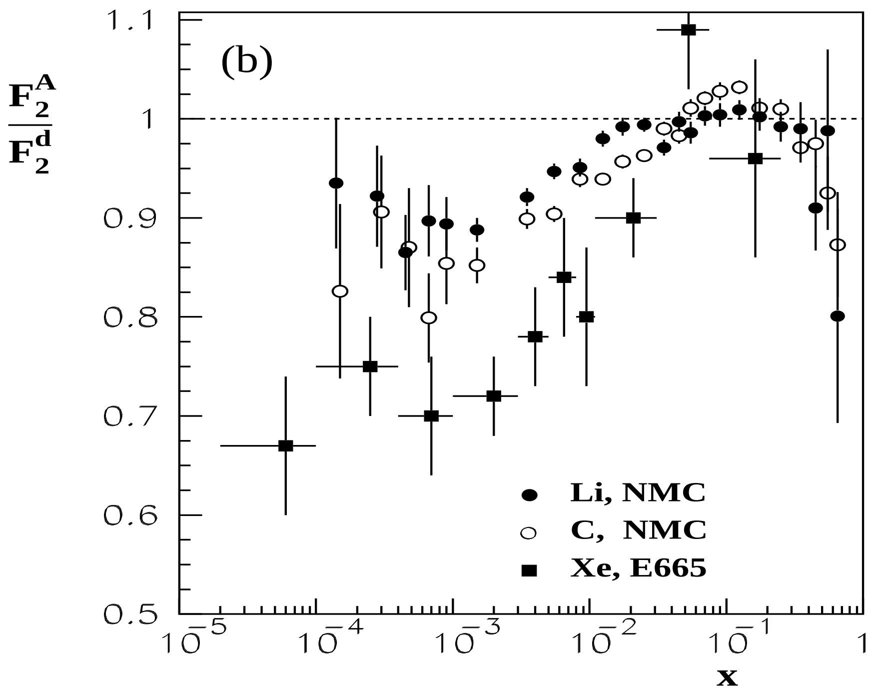
Nuclear shadowing

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

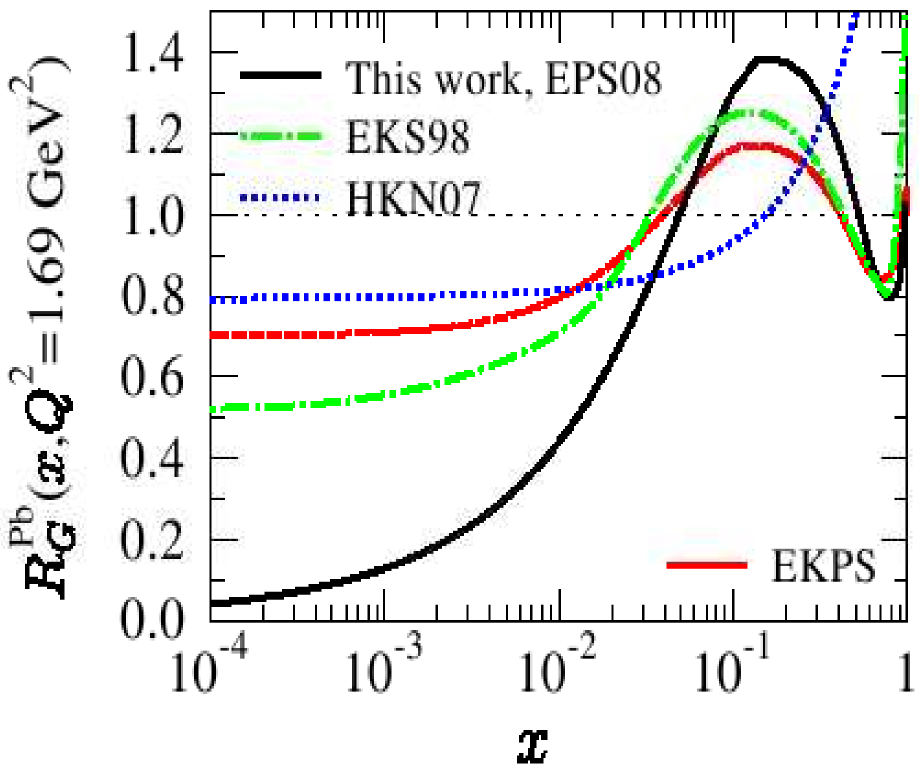


Using QCD factorization theorem, nuclear Parton Distribution functions (PDFs) can be extracted from $F_2^A(x, Q^2)$ and other data (DY, RHIC) by global fits.

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

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



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

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

LT approach to hard diffraction in DIS with nuclei

Leading twist theory of nuclear shadowing predicts **nuclear PDFs** – usual, diffractive, generalized – as functions of Bjorken x and the impact parameter b at some fixed scale Q_0.

The Q^2-dependence is given by DGLAP evolution equations.

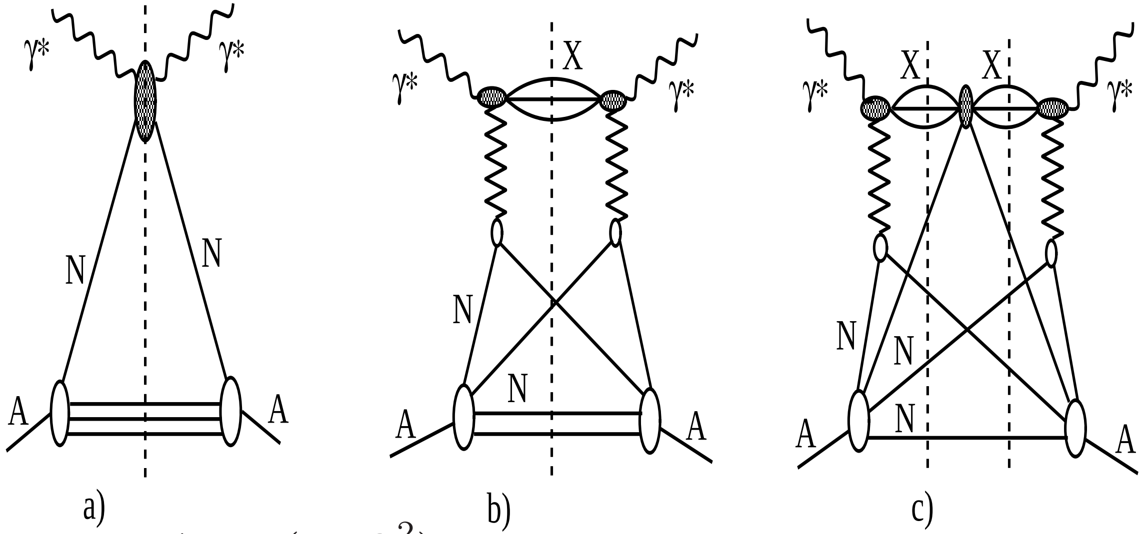
The theory is based on:

- Generalization of Gribov theory to DIS and to any nucleus
  Frankfurt, Strikman '88; '99

- Factorization theorem for hard diffraction in DIS
  Collins '98

- QCD fits to HERA data on hard diffraction
  ZEUS '99; H1 '97 and '06

Step 1.

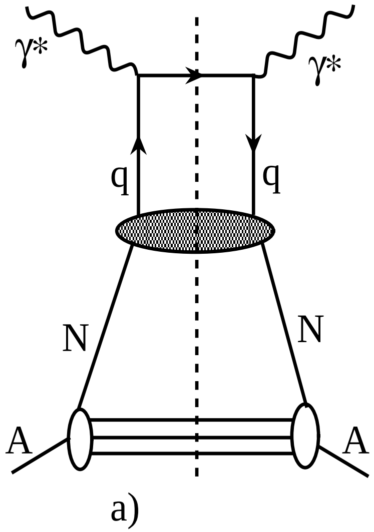


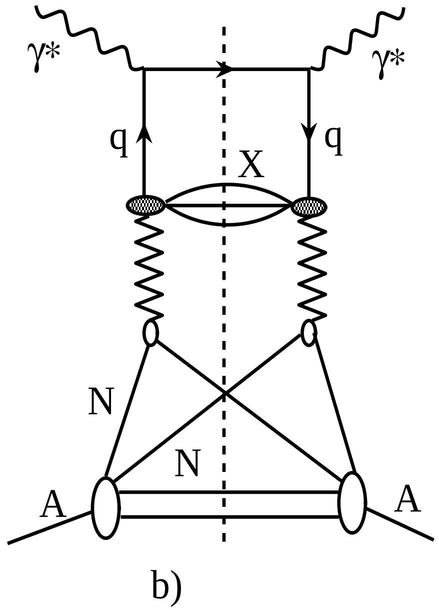
$$
\begin{aligned}
F_{2A}(x,Q^2) &= AF_{2N}(x,Q^2) \\
&- 8\pi A(A-1)\Re e\frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{I\!P} F_2^{D(4)}(x,Q^2,x_{I\!P},t_{\min}) \\
&\times \int d^2\vec{b}\int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2) e^{i(z_1-z_2)x_{I\!P}m_N}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

- $F_2^{D(4)}$ 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

Step 2. QCD factorization theorems for inclusive and diffractive DIS allows us to go from structure functions to parton distributions of given flavor j:

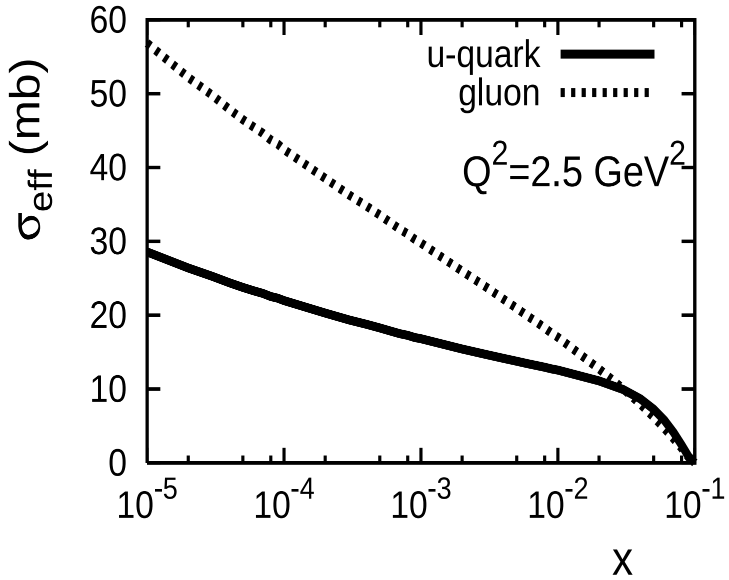
$$\begin{aligned} f_{j/A}(x,Q^2) &= A f_{j/N}(x,Q^2) \\ &- 8\pi A(A-1)\Re e\frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{I\!P} f_{j/N}^{D(4)}(x,Q^2,x_{I\!P},t_{\min}) \\ &\times \int d^2\vec{b}\int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2)e^{i(z_1-z_2)x_{I\!P}m_N}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





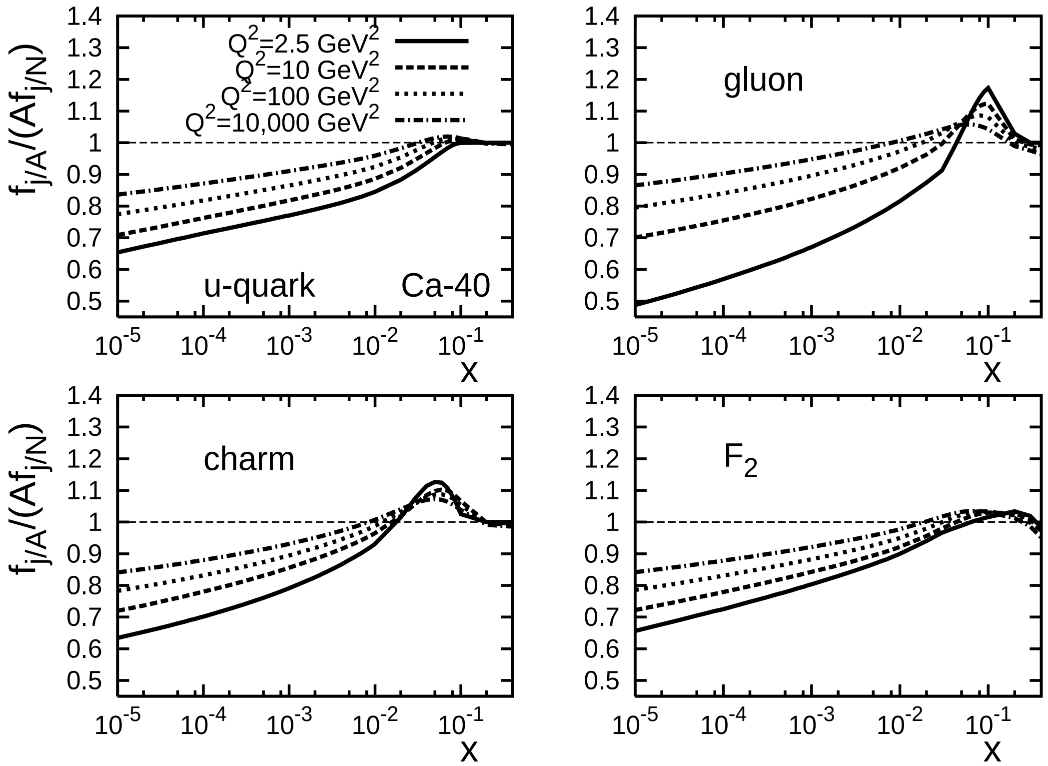
Step 3. The interaction with three and more nucleons is evaluated in the quasi-eikonal approximation: the produced diffractive state elastically rescatters on the target nucleons with the effective cross section $\sigma_{\rm eff}(x,Q^2)$:

$$\sigma^j_{\rm eff}(x,Q_0^2)=\frac{16\pi}{x f_{j/N}(x,Q_0^2)}\int_x^{0.1} dx_{I\!P}\,\beta f^{D(4)}_{j/N}(\beta,Q_0^2,x_{I\!P},t_{\rm min})$$



This leads to the attenuation factor $e^{-A\frac{1-i\eta}{2}\sigma^j_{\rm eff}\int_{z_1}^{z_2}dz'\rho_A(b,z')}$

$$
x f_{j/A}(x, Q_0^2) = A x f_{j/N}(x, Q_0^2)
$$
$$
- \frac{A(A-1)}{2} 16\pi \mathcal{R}e \left[\frac{(1-i\eta)^2}{1+\eta^2} \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_x^{0.1} dx_{I\!P} \right.
$$
$$
\left. \times \beta f_{j/N}^{D(4)}(\beta, Q_0^2, x_{I\!P}, t_{\min}) \rho_A(b, z_1) \rho_A(b, z_2) e^{i x_{I\!P} m_N (z_1 - z_2)} e^{-A \frac{1-i\eta}{2} \sigma_{\rm eff}^j \int_{z_1}^{z_2} dz' \rho_A(b, z')} \right]
$$

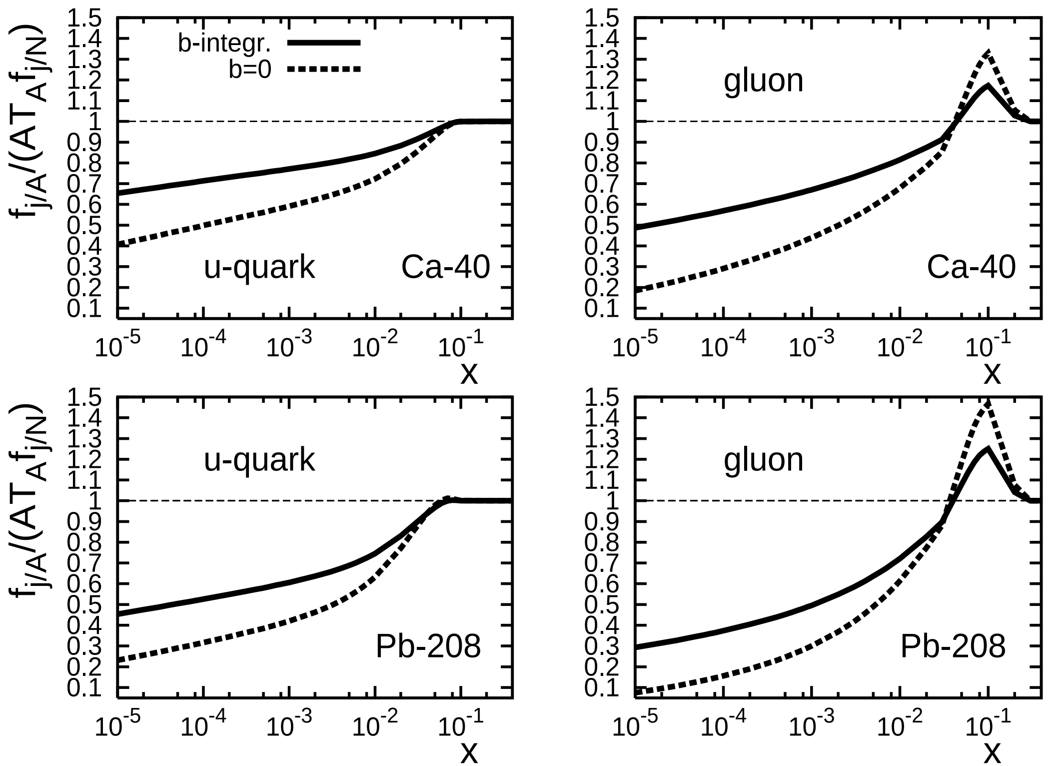


Impact parameter dependent nPDFs

$$xf_{j/A}(x,\mathbf{b},Q_0^2) = AT_A(\mathbf{b})xf_{j/N}(x,Q_0^2)$$

$$-\frac{A(A-1)}{2}16\pi\mathcal{R}e\left[\frac{(1-i\eta)^2}{1+\eta^2}\int_{-\infty}^{\infty}dz_1\int_{z_1}^{\infty}dz_2\int_x^{0.1}dx_{I\!P}\right.$$

$$\left.\times\beta f_{j/N}^{D(4)}(\beta,Q_0^2,x_{I\!P},t_{\min})\rho_A(\mathbf{b},z_1)\rho_A(\mathbf{b},z_2)e^{ix_{I\!P}m_N(z_1-z_2)}e^{-A\frac{1-i\eta}{2}\sigma_{\mathrm{eff}}^{j}\int_{z_1}^{z_2}dz'\rho_A(b,z')}\right]$$



Nuclear GPDs in the $\xi = 0$ limit

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)

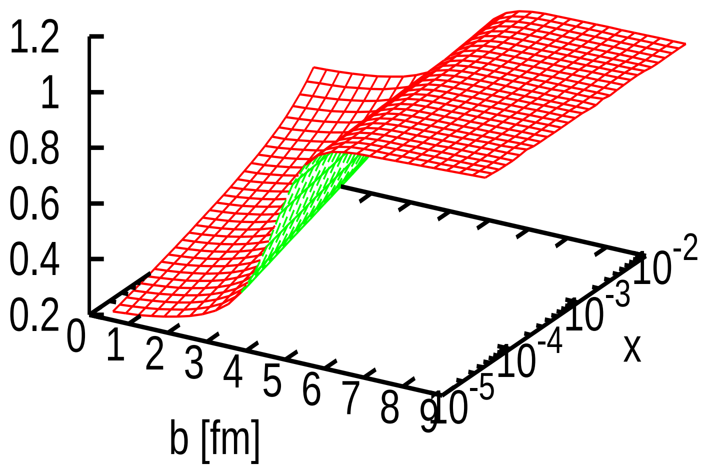
LT theory of NS gives nuclear GPDs at $\xi = 0$ "for free".

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

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

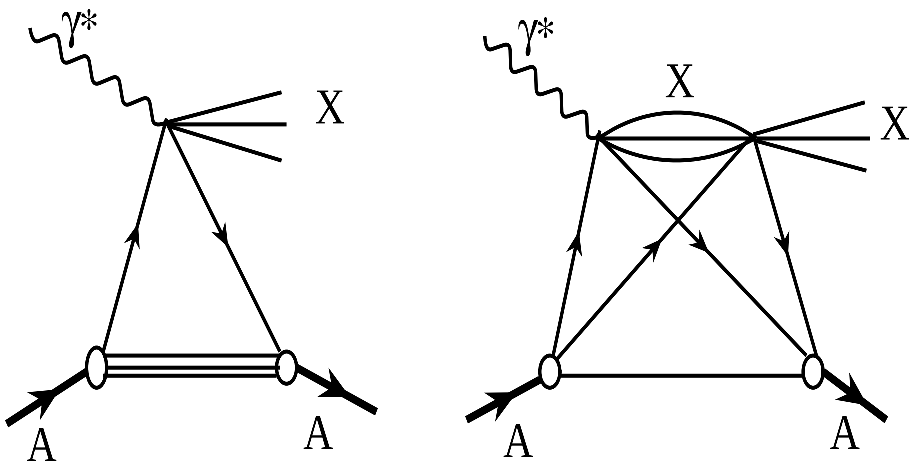
Interesting feature:

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



Nuclear diffractive PDFs

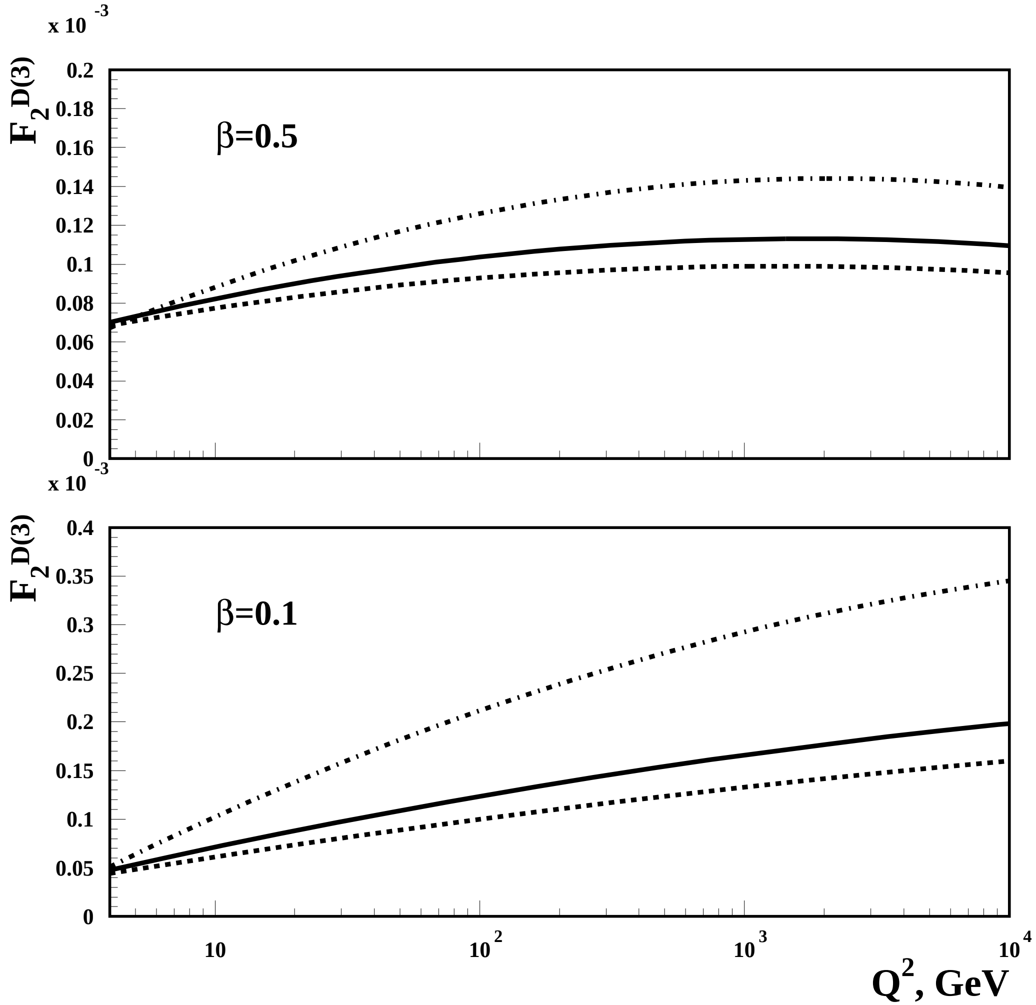
LT theory of nuclear shadowing can also be used to calculate nuclear diffractive PDFs which are measured in coherent inclusive diffraction in DIS on nuclei



$$x f_{j/A}^{D(3)}(x, Q_0^2, x_{I\!P}) = 4\,\pi A^2 \beta\, f_{j/N}^{D(4)}(x, Q_0^2, x_{I\!P}, t_{\min}) \int d^2 b \times \left| \int_{-\infty}^{\infty} dz\, e^{i x_{I\!P} m_N z} e^{-\sigma_{\rm eff}^{j}(x,Q_0^2)/2 \int_z^\infty dz' \rho_A(b,z')} \rho_A(b,z) \right|^2$$

The Q^2 evolution is by DGLAP.

Predictions for $F_2^{D(3)}$



$x_{I\!P} = 0.001$

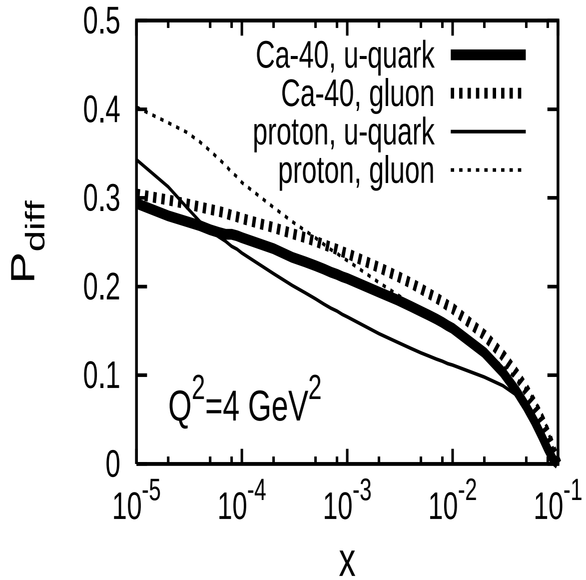
Solid – ^{40}Ca
Dotted – ^{208}Pb
Dot-dashed – proton

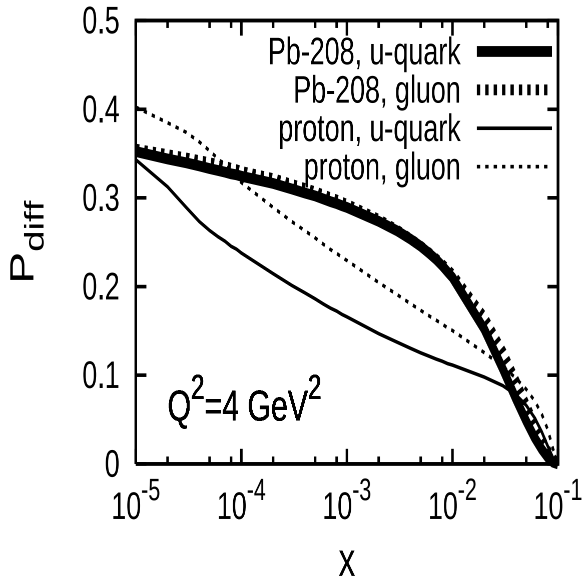
Arbitrary normalization!

L. Frankfurt, VG, M. Strikman, Phys. Lett. B 586 (2004) 41

Probability of diffraction

$$P^j_{\rm diff} = \frac{\int_x^{0.1} dx_{I\!P}\, x f_j^{D(3)}(x, Q_0^2, x_{I\!P})}{x f_j(x, Q_0^2)} \leq \frac{1}{2}$$





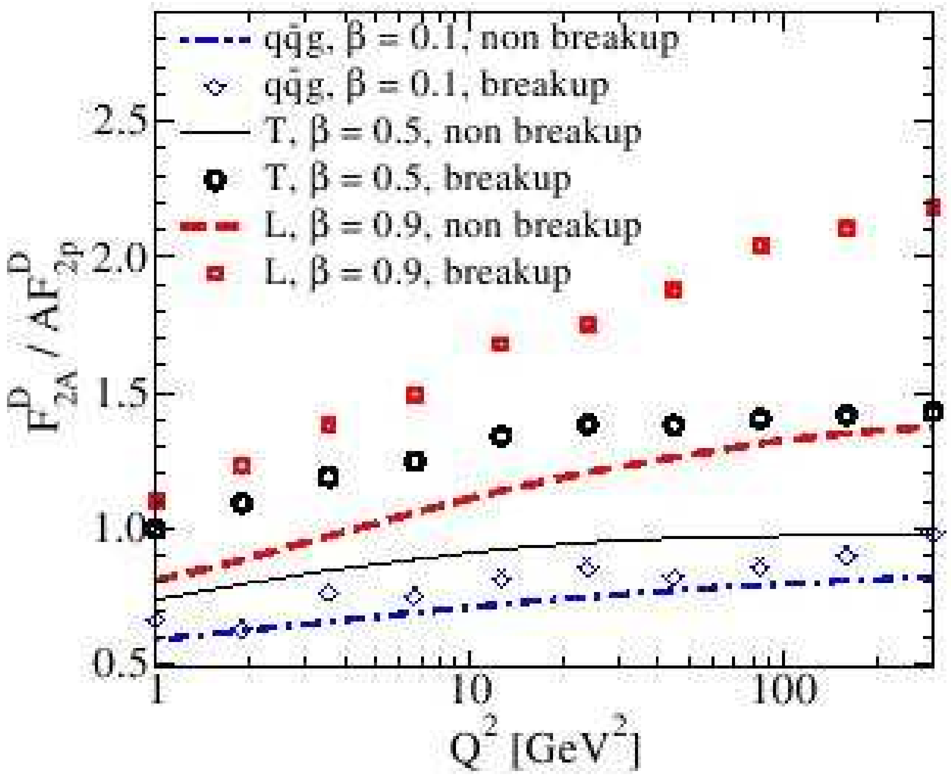
- Surprisingly, we do not observe nuclear enhancement of $P^j_{\rm diff}$ on nuclei.

- This is the effect of the (gray) nuclear surface; at central b, $P^j_{\rm diff} \approx 1/2$.

Color dipole approach to hard diffraction in DIS with nuclei

- The color dipole formalism (which describes diffraction at HERA) can be readily generalized to the nuclear case by working in the impact parameter space.
  H. Kowalski, T. Lappi, C. Marquet, R. Venugopalan, arXiv: 0805.4071 [hep-ph].

- Allows to consider coherent and incoherent diffraction.



$x_{I\!P} = 0.001$

Conclusions

- Studies of hard diffractive processes with nucleons and nuclei (inclusive, exclusive production of vector mesons, DVCS) is an integral part of the EIC physics program aiming to determine various distributions of partons in nuclei.

- The EIC will, for the first time, measure
  - the nuclear diffractive structure functions $F_{2,A}^{D(3)}$ and $F_{L,A}^{D(3)}$
  - the proton longitudinal diffractive structure function $F_L^{D(3)}$
  - other exclusive diffractive processes with nuclei

- In diffraction in DIS with nuclei, there are two different approaches: the LT theory of nuclear shadowing and the color dipole formalism.

  The LT approach uses the notion of nuclear diffractive PDFs, for which significant nuclear shadowing (suppression) is predicted.

The color dipole approach, which includes the physics of saturation and which describes very well the HERA diffractive data, makes definite, model-independent predictions for nuclear diffractive structure functions and for the pattern of nuclear shadowing and antishadowing.

- A comparison of the predictions of the LT and color dipole approaches for hard diffraction in DIS with nuclei will explore the transition to the regime of high parton densities and parton saturation.