Hadrons in nuclear matter - what will be interesting/important to measure ten years from now at electron-nucleus collider

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Prime directions of studies of hard nuclear reactions at EIC energies

- *Quark-gluon structure of nuclei. Origin of EMC effect, microscopic origin of medium/short-range nuclear forces.*

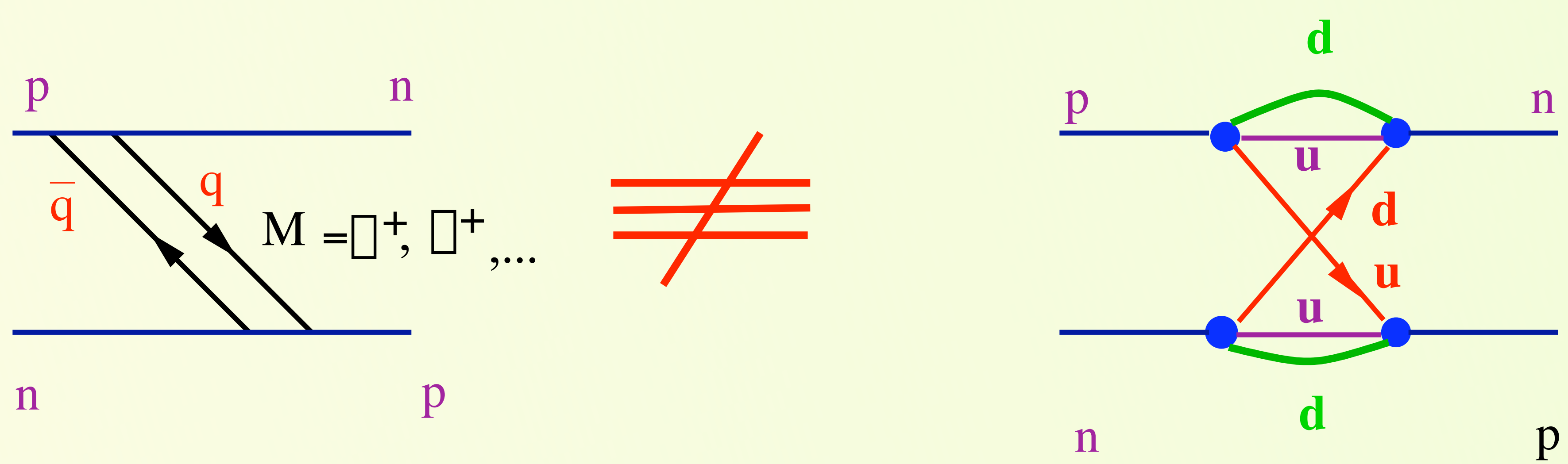
- *Onset of regime of large longitudinal distances: interplay of the leading twist and higher twist nuclear shadowing, "Pomeron - Pomeron" interactions.*

- *Onset of regime of* the leading twist/color transparency regime in hard exclusive processes.

- *Final state interactions - from medium x to small x, large field dynamics. Unfortunately will not have time to discuss.*

Fundamental questions of microscopic quark-gluon structure of nuclei and nuclear forces

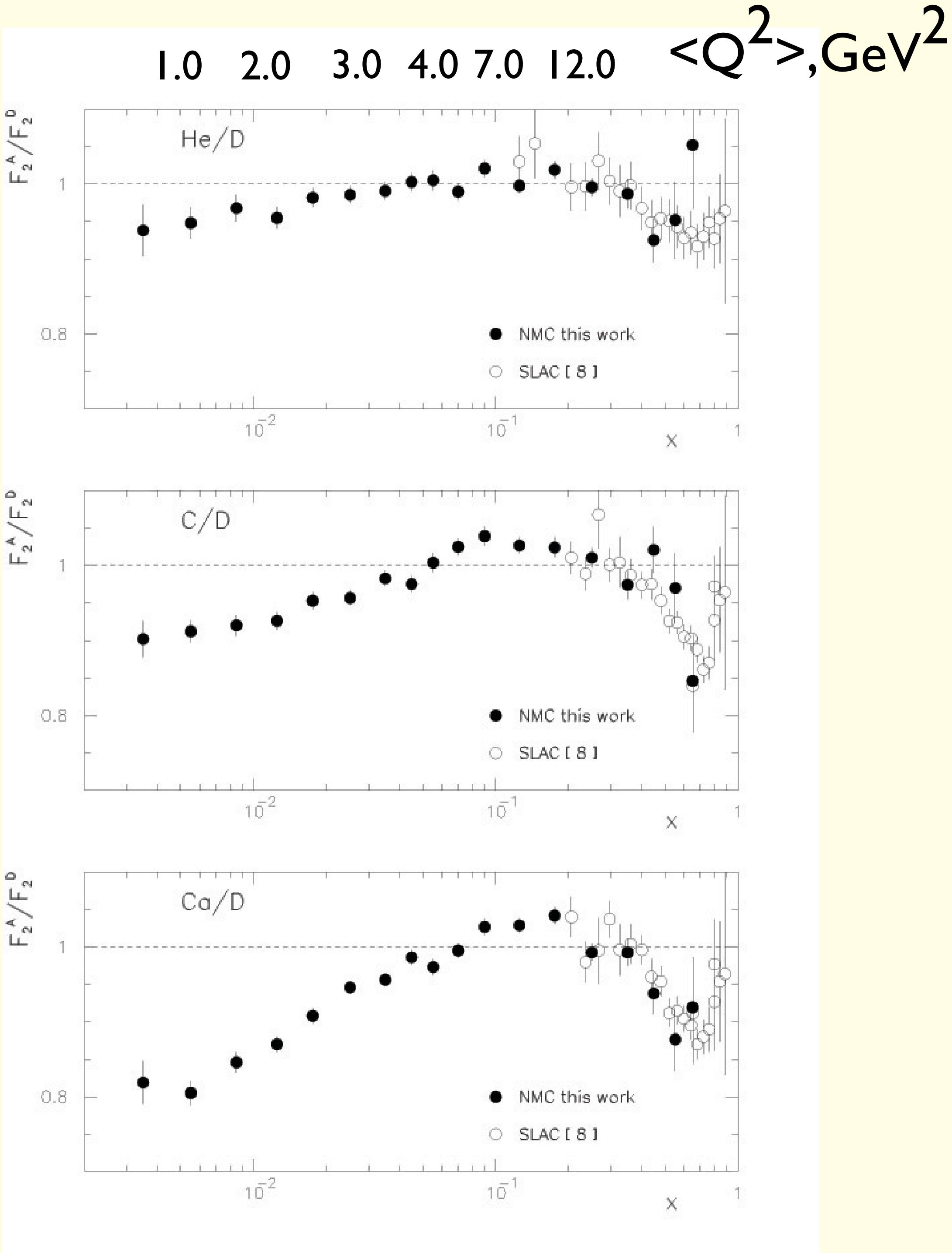
- Are nucleons good nuclear quasiparticles?
- Origin of intermediate and short-range nuclear forces: Do nucleons exchange mesons or quarks (gluons) ?



Meson Exchange $\neq$ *Quark interchange*

Lessons from DIS and Drell-Yan experiments with nuclei

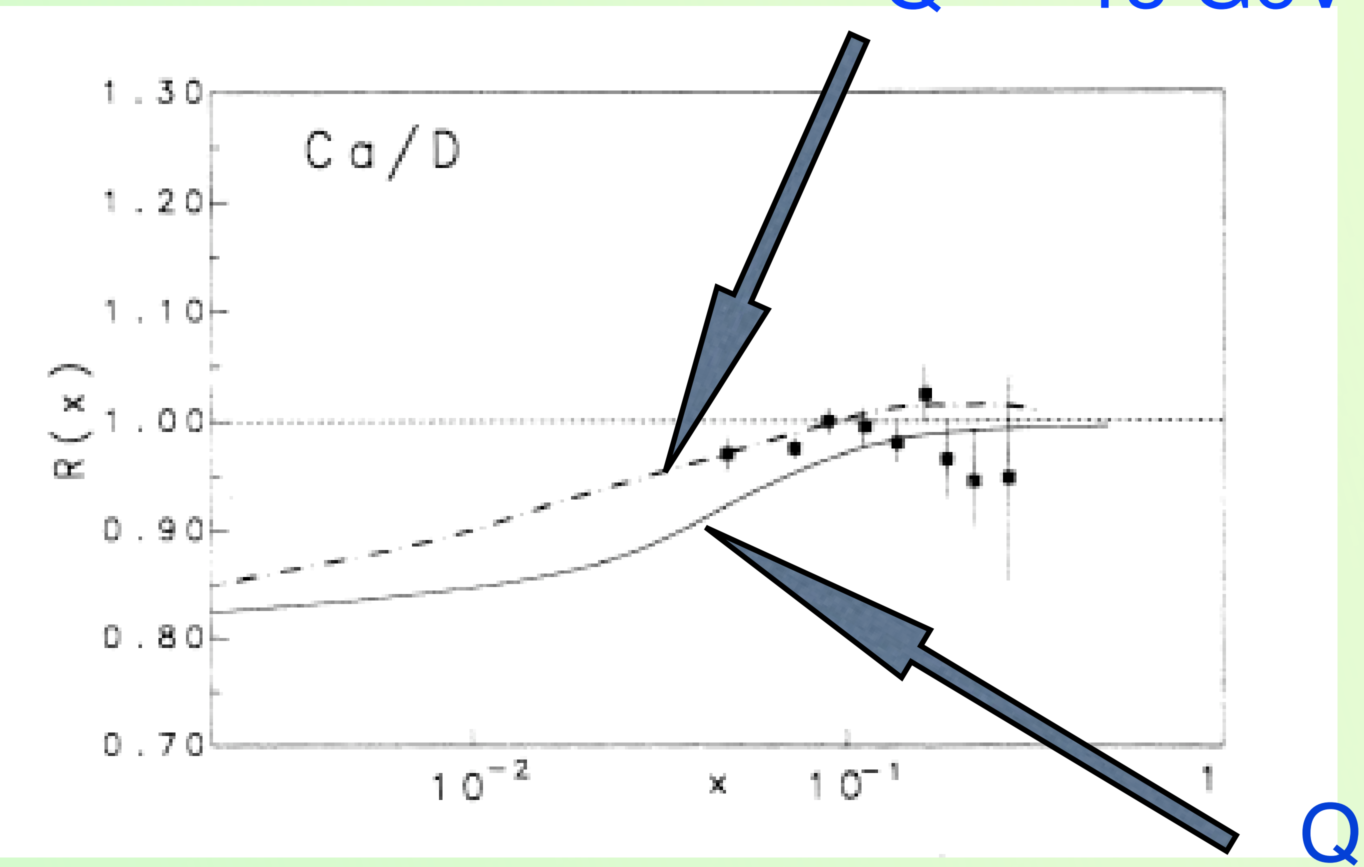
- Suppression of valence quarks at $0.7 \geq x \geq 0.4$ (EMC effect)



The current high precision data on the nuclear dependence of F_2 are definitely in the scaling region for x>0.1. However for x<0.01 they correspond to $Q^2 < 7$ GeV^2 where higher twist effects might be important, see discussion of shadowing.
For most of nuclei, the range is even smaller.

No enhancement/ Suppression of antiquarks at 0.15≥ x
(Drell -Yan process - FNAL)

$\bar{q}_A/\bar{q}_N$



$Q^2 = 15$ GeV^2

$Q^2 = 2$ GeV^2

A-dependence of antiquark distribution, data are from FNAL nuclear Drell-Yan experiment, curves - pQCD analysis of Frankfurt, Liuti, MS 90

☛ The EMC effect at $0.7 \geq x \geq 0.4$ is ***unambiguous signature of the presence of nonnucleonic degrees of freedom in nuclei.*** *Claims to the opposite are due to the violation of baryon or energy-momentum conservation or both.*

☛ The lack of the enhancement of antiquarks - *a serious problem for the models where nucleus is described as a system of nucleons and mesons which predict*

$\bar{q}_A/\bar{q}_N \sim 1.1\text{-}1.2$ for $x=0.1$ and $A=40$.

Open questions of nuclear parton structure at $x \geq 0.03$:

Are gluons enhanced around $x \sim 0.1$?

From QCD momentum sum rule and F_{2A}/F_{2D} data: gluons in nuclei carry the same light-cone fraction as in free nucleon within 1 % FS88.

→ Combined with gluon shadowing leads to suggestion of gluon enhancement at $x \sim 0.05 - 0.1$ (10–20% effect for large A)

Evidence of J/ψ enhancement in DIS inclusive scattering at similar x.

2σ effect. Mechanism of J/ψ production.

The scaling violation for the Sn/C ratio consistent with the FLS 90 prediction based on the enhancement of the gluons in nuclei.

2σ effect. No effect for C/D. Higher twist effects can mimic the effect.

☝ How big is the valence quark enhancement at $x \sim 0.1$?

$V_A/V_N > 1$ (~1.05 - 1.1) follows from enhancement of F_{2A} and suppression of antiquarks. However errors are large due to systematic errors of NMC and DY experiment and need to subtract numbers close to one.

Qualitatively, the observed flavor pattern favors quark, gluon exchanges vs meson exchanges.

Precision measurement of A-dependent parton densities is of fundamental importance for understanding microscopic dynamics of nuclei, for building a realistic approach to description of cores of the neutron stars. *Meson forces based models predict more antiquarks in heavy nuclei, while in nature there are less antiquarks in heavy nuclei.*

The only project which may be able to perform such measurements is EIC. For $x \geq 0.05$ one needs $W \geq 25$ GeV.

Ways to measure nuclear gluons

♥ A-dependence of leading open charm and J/ψ production in DIS

♥♥ A-dependence of photoproduction of leading dijets.

♥♥♥ A-dependence of σ_L -doable due variable energy of EIC

♥♥♥♥ Scaling violation of F^A_2 / F^D_2 ratio at large $Q^2 \geq 10$ GeV^2 to avoid HT effects.

A.Bruell talk

The ways to measure valence quarks and antiquarks

Valence quarks: measure difference of the inclusive spectra of positive and negative pions:

$$\frac{\dfrac{d\sigma\,(e+A\to e+\pi^{+}+X)}{dz\,dx\,dQ} - \dfrac{d\sigma\,(e+A\to e+\pi^{-}+X)}{dz\,dx\,dQ}}{\dfrac{d\sigma\,(e+N\to e+\pi^{+}+X)}{dz\,dx\,dQ} - \dfrac{d\sigma\,(e+N\to e+\pi^{-}+X)}{dz\,dx\,dQ}} = \frac{V_A(x,Q)}{V_N(x,Q)}$$

$$= V_A(x,Q)/V_N(x,Q)$$

Sea quarks:

Direct method: measurement of the production of leading K^--mesons

Indirect method: comparison of the F_2 and valence quark A-dependence

Gaining understanding of the EMC effect (extending current and future JLab studies)

- Is EMC effect the same for u- and d-quarks? *Use ^{3}He beams and pion tagging of knocked out quarks.*

- How EMC effect depends on the virtuality/off-energy-shellness of the nucleon? Is dependence the same for u- and d- quarks?

  Tagging of proton and neutron in $e+D \to e+ N +X$.

- Are baryonic non-nucleonic degrees of freedom present in nuclei?

  Mesonic models (like Argonne- Urbana potential) -few % Δ -isobars per nucleon (>0.3 for large momenta)

Study of $x_F \geq 0.5$ production of $\Delta-$ isobars in $e+D(A) \to e+ \Delta +X$. For the deuteron one can reach sensitivity better than 0.1 % for $\Delta\Delta$ (FS 80)

$\Sigma\Sigma$ ***EIC will provide qualitatively new insight into quark-gluon structure of nuclei and nuclear matter.***

Inclusive small x dynamics

Decade from now: LHC ≥ five years of running including ion-ion, and nucleon - nucleus runs, further data from RHIC. Will focus on LHC since RHIC results at small x depend on upgrades of the detectors which are under discussion. Numbers are for the current configuration of the CMS, ... - currently discussed upgrades are likely to extend the x-range.

Main tools:

- Ultraperipheral ion- ion collisions :

  γ - A scattering up to W= 1 TeV;

- Nucleon- ion collisions at W= 5 TeV.

Will measure A-dependence of gluons in several reactions and quarks in a couple of processes for

$10^{-2} \geq x \geq 10^{-5}$, $Q \geq 5$ GeV

EIC x-range in eA mode for the highest discussed W= 65 GeV for Q=2 GeV is $x_{min}=Q^2/W^2 = 10^{-3}$

EIC vs LHC - onset of the regime of strong gluon fields.

The key parameter is $xG_A(x,Q^2)/Q^2$. For $x=10^{-3}$, Q=2 GeV it is 2-3 times smaller than for LHC case of $x=10^{-5}$, Q=5 GeV. Another advantage of LHC is direct coupling to gluon channel where nonlinear effects are stronger. At EIC direct coupling to gluons would require Q~ 4 GeV and hence $x_{min}=Q^2/W^2 = 4*10^{-3}$. Thus EIC can hardly compete with LHC in terms of going deep into nonlinear regime. However it has a number of advantages in terms of exploration of the onset of the shadowing regime and as well as onset of nonlinear regime.

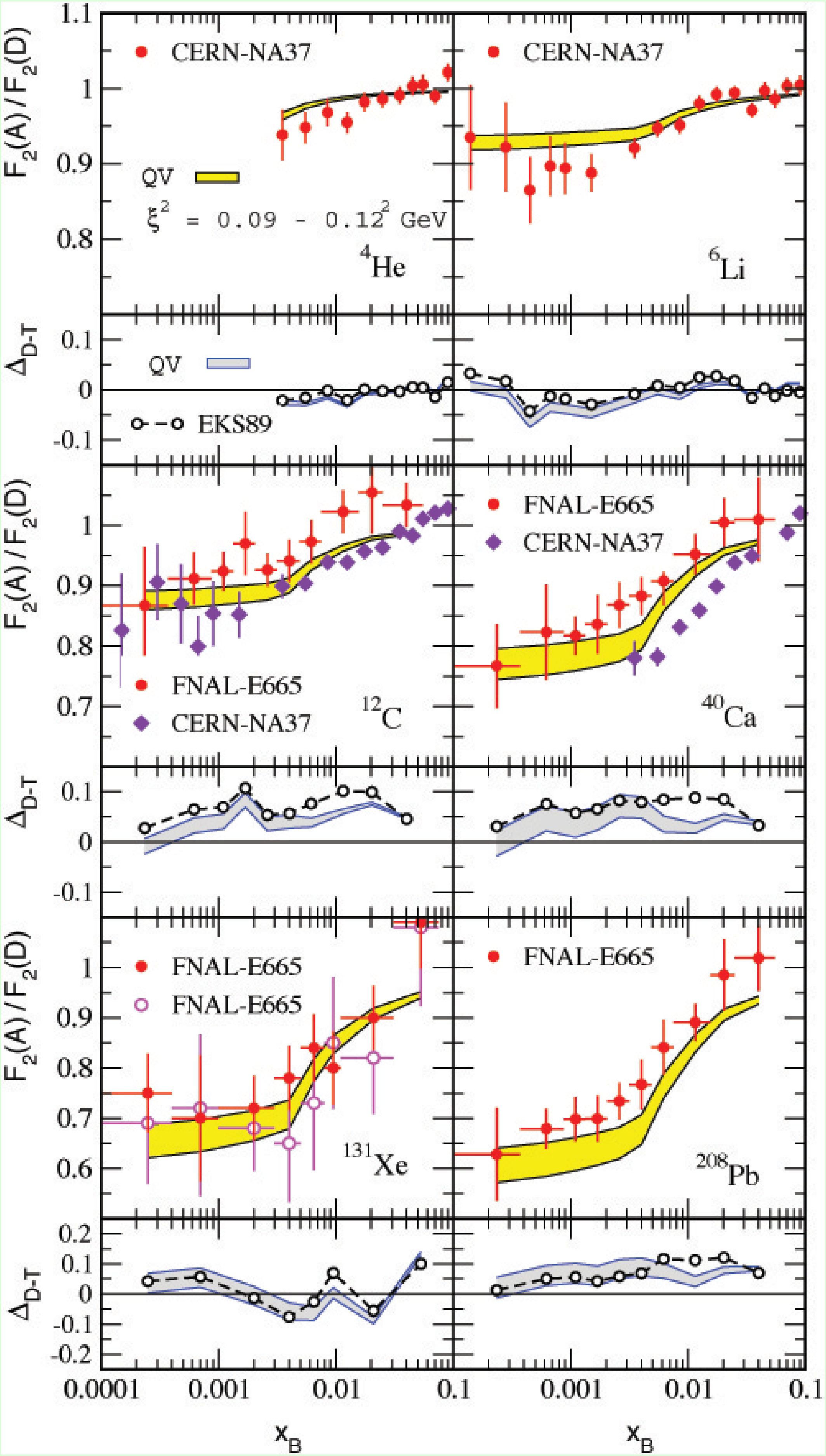
Minimal requirement for onset of shadowing regime:

$x \ll 1/(2 r_{NN} m_N)$, where r_{NN} average internucleon distance ~ 2fm. Hence shadowing effects may become noticeable for $x \leq 0.03$ which is indeed the case experimentally.

Several approaches to the analysis of the data:

★ Global analysis of DIS assuming validity of DGLAP equations at $Q^2 \geq 2\ \mathrm{GeV}^2$ and making a number of guesses about gluon shadowing for all x and x dependence of quark shadowing for small x where there is no data (Eskola et al, Kumano et al). A reasonable fits to the data with very different magnitude of gluon shadowing were obtained.

★ Due to small values of Q one can question validity of assumption that leading twist is the dominant source of shadowing - possible HT mechanisms are vector dominance model contribution (Bodalek & Kwiczinski, Piller & Weise, Thomas & Melnitchouk), quark rescatterings - Qiu and Vitev.



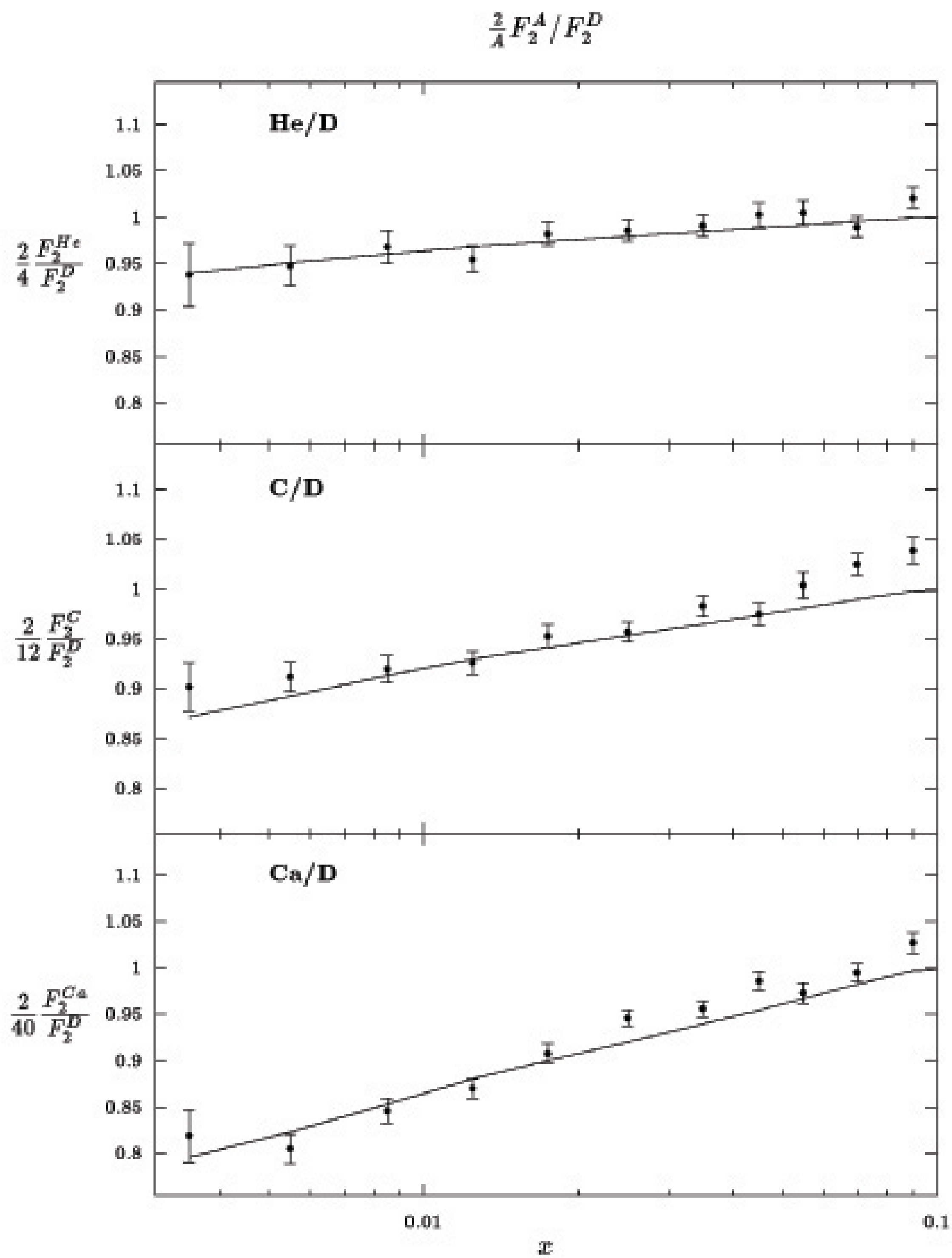
Higher twist model calculation of F_{2A}/F_{2D} by Qiu and Vitev versus CERN-NA37 and FNAL-E665 data on DIS on nuclei. Δ_{D-T} is a comparison of the higher twist calculation to the EKS98 scale-dependent leading twist shadowing parametrization

★ An alternative is to start with the Gribov theory of nuclear shadowing which relates shadowing and diffraction in the elementary process:

$$\gamma^* + N \to X + N.$$

Before HERA one had to model diffraction to calculate shadowing for $\sigma_{\gamma^* A}$ (FS88-89, Kwiecinski89, Brodsky & Liu 90, Nikolaev & Zakharov).

More recently several groups (Capella et al) used the HERA diffractive data as input to obtain a reasonable description of the NMC data.

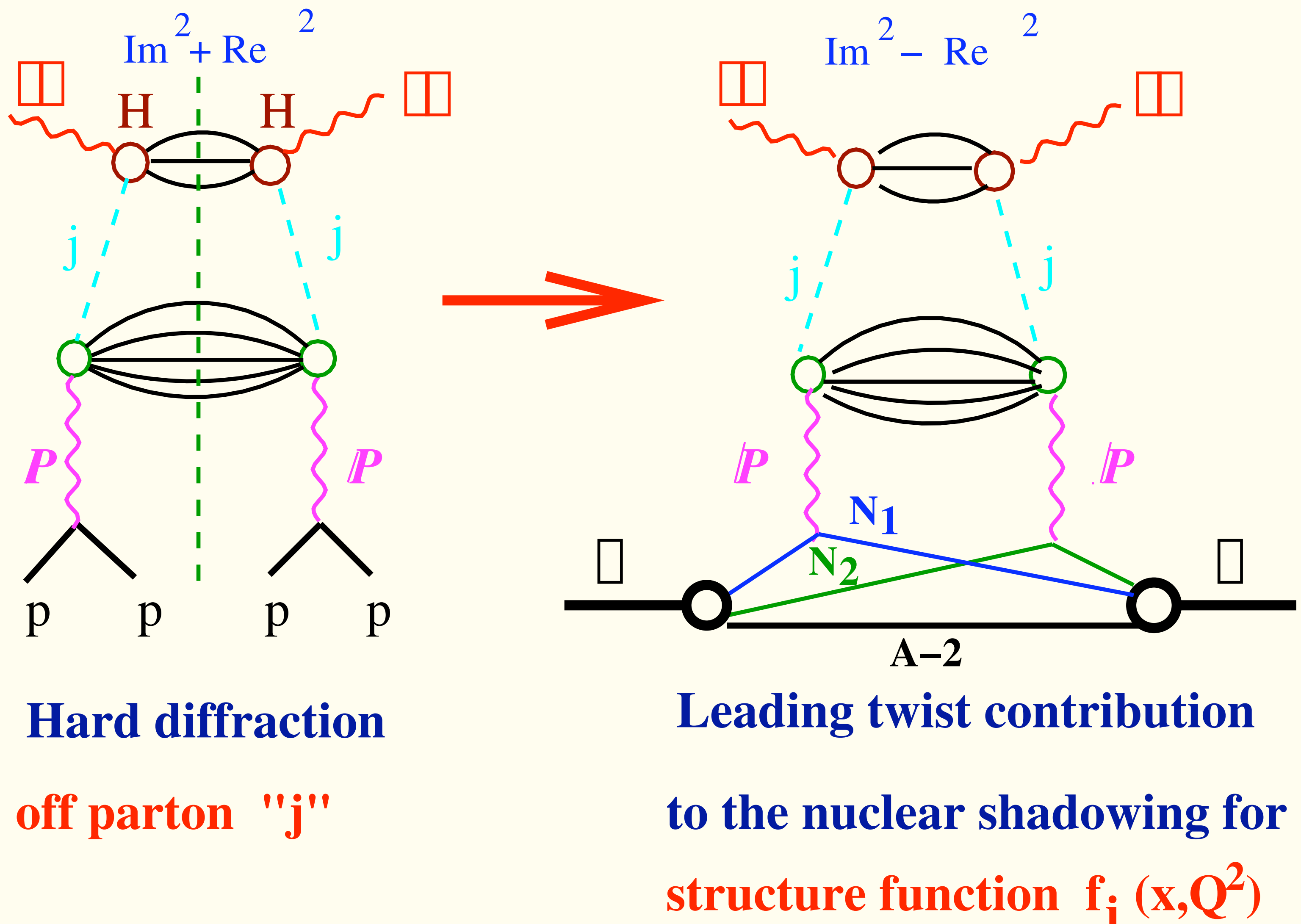


Comparison of the NMC data with the calculation within the Gribov theory by Capella, Kaidalov, Merino, Pertermann, Tran Thanh Van (97)

Theoretical expectations for shadowing in the LT limit

Combining Gribov theory of shadowing and pQCD factorization theorem for diffraction in DIS allows to calculate LT shadowing for all parton densities (FS98)

Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the nucleon diffractive parton densities $f^D_j(x/x_P, x_P, x, Q^2)$:



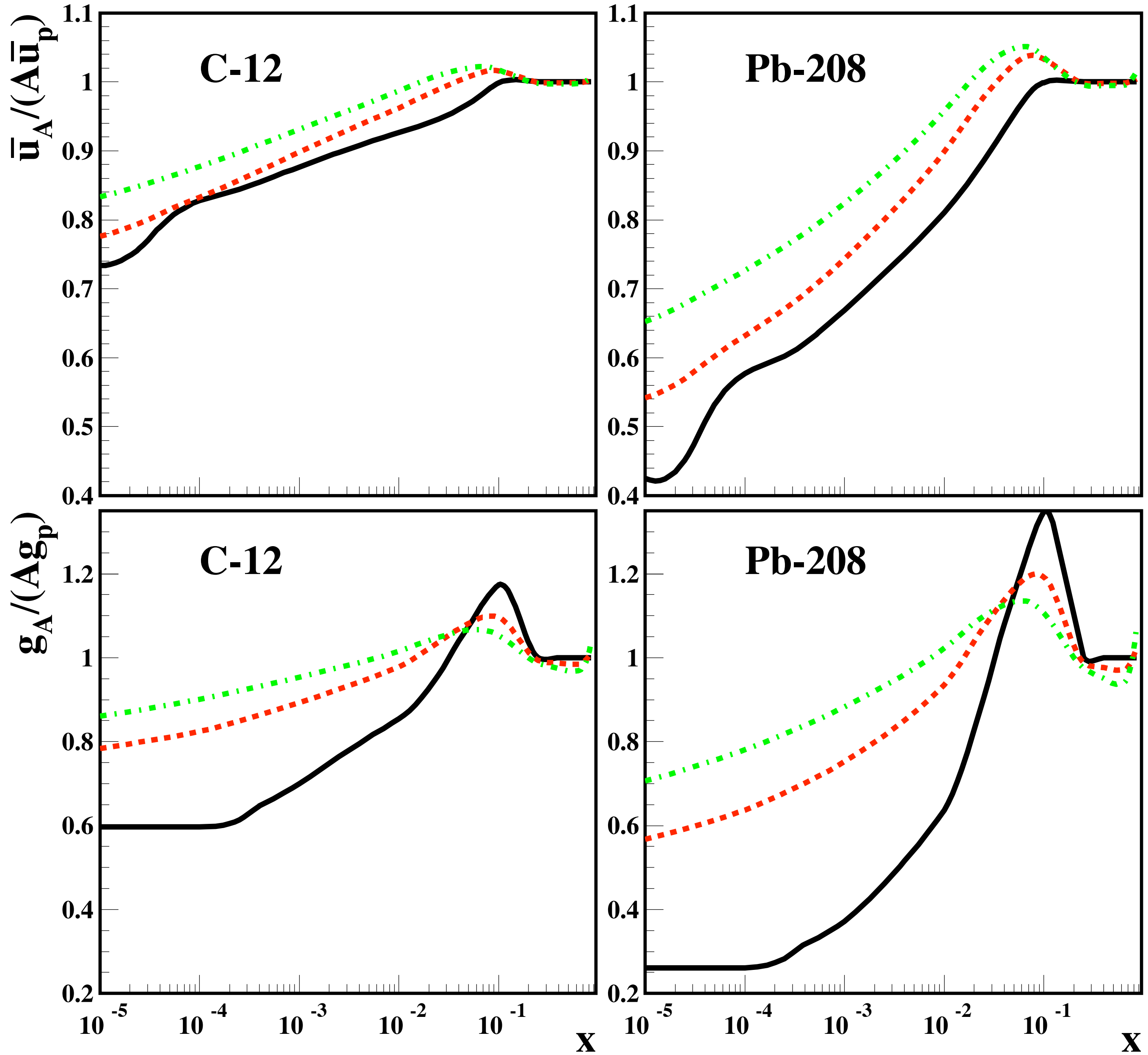
Theorem: in the low thickness limit (or for x>0.005)

$$f_{j/A}(x,Q^2)/A = f_{j/N}(x,Q^2) - \frac{1}{2+2\eta^2}\int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_x^{x_0} dx_{I\!P} \cdot$$

$$\cdot f^D_{j/N}\left(\beta, Q^2, x_{I\!P}, t\right)_{|k_t^2=0} \rho_A(b,z_1)\rho_A(b,z_2) Re\left[(1-i\eta)^2 \exp(i x_{I\!P} m_N (z_1 - z_2))\right],$$

where $f_{j/A}(x,Q^2), f_{j/N}(x,Q^2),$ are nucleus(nucleon) pdf's, $f^D_{j/N}$, - diffractive pdf's; $\eta = ReA^{diff}/ImA^{diff} \approx 0.3$, $\rho_A(r)$ is the nucleon density in the nucleus; $x_0 \sim 0.1$ for quarks and $x_0 \sim 0.03$ for gluons.

Detailed analysis in Guzey, FS & McDermott. Numerical studies include higher order rescattering terms and HERA measurements of diffractive quark and gluon PDFs which indicate dominance of the gluon-induced diffraction to calculate gluon and quark shadowing.



Dependence of G_A/AG_N and $\bar{q}_A/A\bar{q}_N$ on x for Q=2 (solid), 10 (dashed), 100 GeV (dot-dashed) curves calculated using diffractive parton densities extracted from the HERA data, the quasieikonal model for $N \geq 3$, and assuming validity of the DGLAP evolution.

Large gluon shadowing at x~ 0.003 agrees semiquantitatively with dA RHIC data: PHENIX data on J/ψ production and the leading pion (y~3) production by BRAHMS.

Connection to leading twist shadowing in Color Glass Condensate model.

In CGC main contribution comes from diffraction into large masses, such that $\beta = x/x_P \ll \langle\beta\rangle \sim 0.5$. This is indeed the case in LT approach for $x \ll 10^{-3}$. However dominance of this regime occurs for very small x only. We find that in the EIC kinematics average β are of the order 0.3.

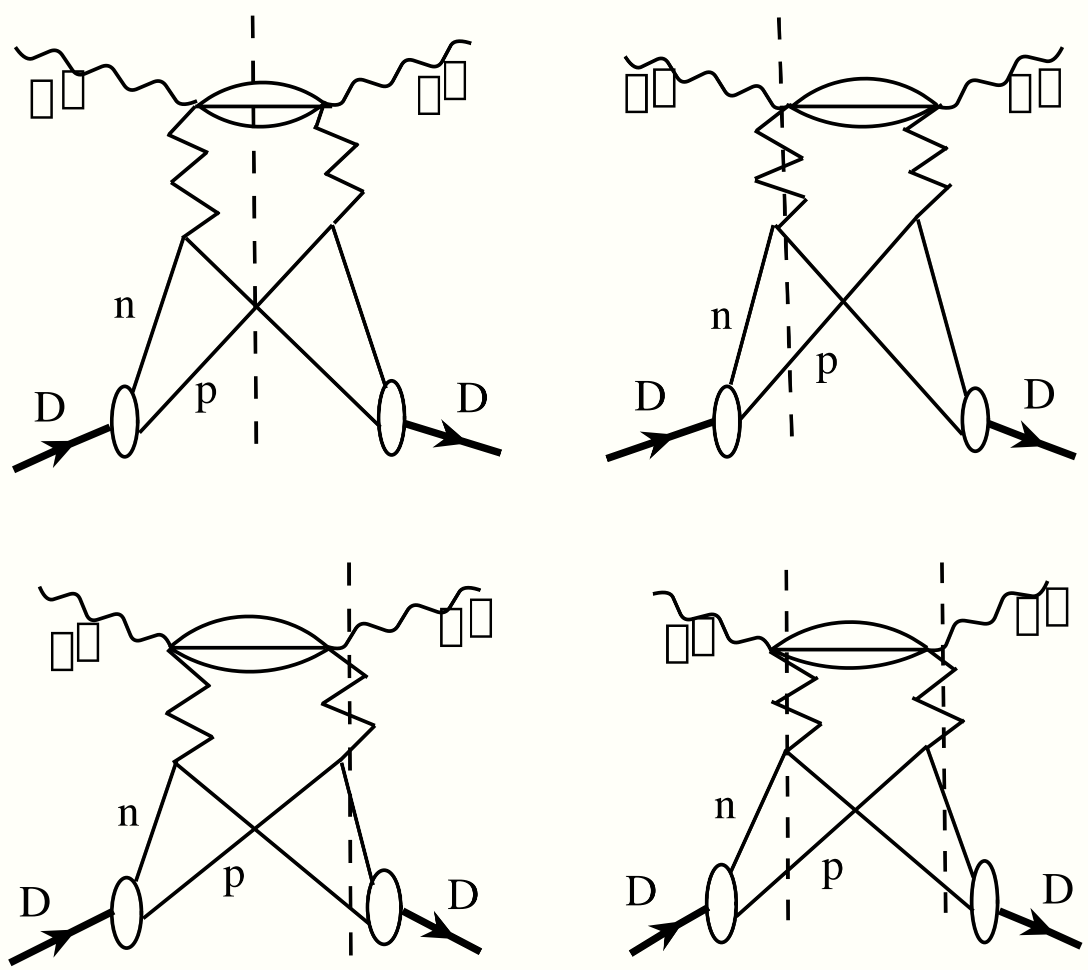
LT vs HT contributions in the NMC kinematics.

Recently we analyzed relative contributions of LT and HT for the kinematics of NMC. For $x \sim 0.005$ and $Q^2 = 2\ \text{GeV}^2$ about 40-50% of shadowing is due to the HT contribution, mostly due to enhancement of diffraction to low masses - the lightest vector mesons. (No local duality in this case !!!). So indeed HT is significant though it does not dominate like in the Qiu and Vitev fit, while EKS98 fits which assume dominance of the LT at such Q^2 appear to be an oversimplification.

Important advantages of EIC is possibility to measure shadowing as function of nuclear thickness - number of involved nucleons, and cross checks of the dynamics using diffractive channels.

Coherent interactions with two nucleons.

The basic interaction with two nucleons can be explored using deuteron beams. Although for the total cross sections the shadowing effect is just few %, it can be enhanced using tagging kinematics (Guzey & FS PRL 2003).

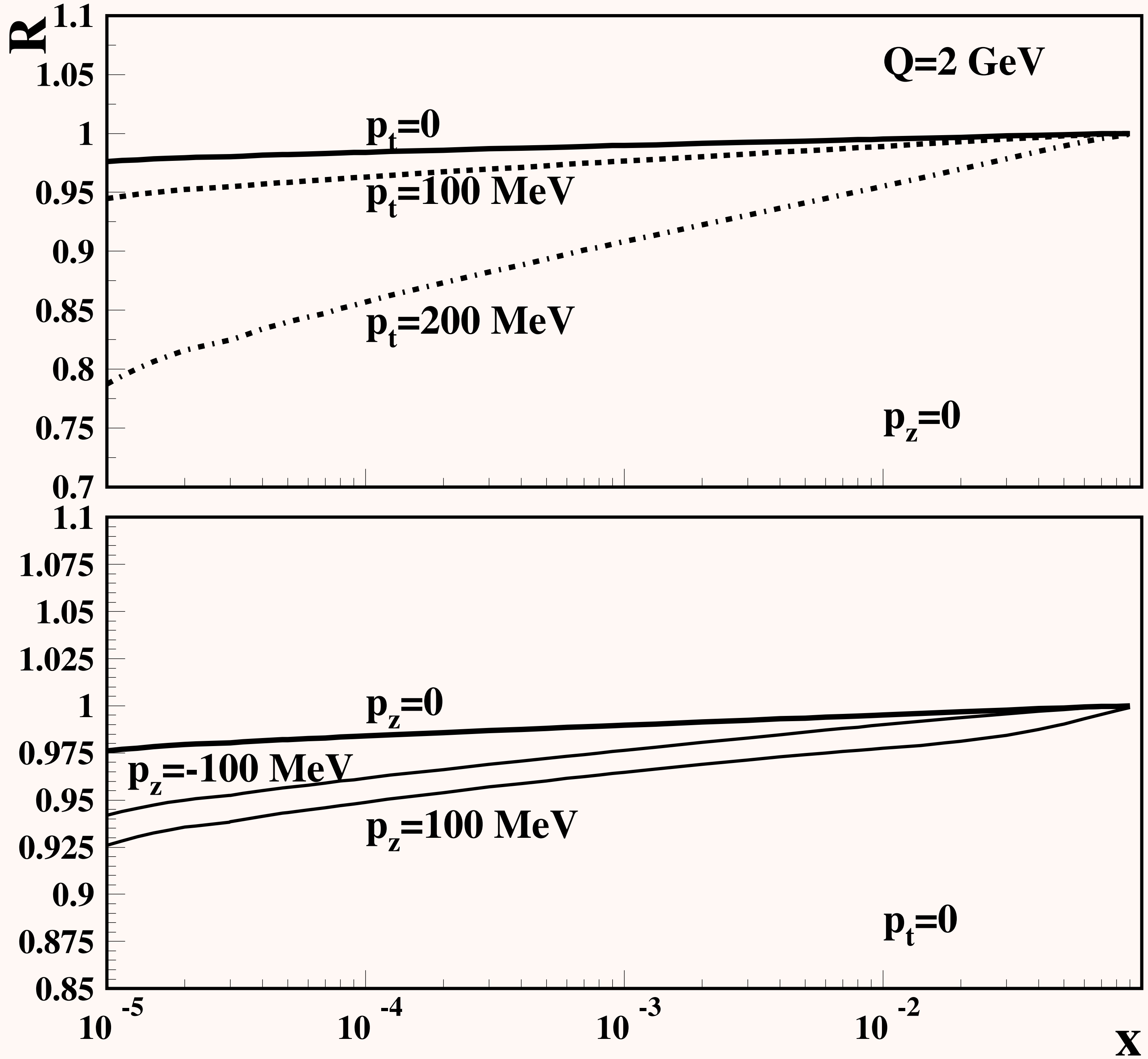


Relevant diagrams for the simultaneous interactions with two nucleons with production of a spectator (a nucleon with a small momentum in the deuteron rest frame).

We find for the complete cross section

$$\frac{d\sigma^{\gamma^* D \to pX}}{d^3p} = \sigma^{\gamma^* n}(2-2x_L)(u^2(p)+w^2(p)) - \frac{3-\eta^2}{1+\eta^2}$$
$$\times \int_x^{x_0} dx_{I\!P} \int \frac{d^2q_t}{\pi} F_2^{D(4)}\left(\beta, Q^2, x_{I\!P}, t\right) \Big[u(p)u(p')$$
$$+ w(p)w(p')(\frac{3}{2}\frac{(p\cdot p')^2}{p^2p'^2} - \frac{1}{2}) \Big],$$

where $p' = p + q_t + (x_{I\!P} m_N)e_z$, $x_L = E_p/E_D \approx (1 - p_z/m_N)/2$ is the Feynman x of the spectator proton; $p = (p_t, p_z)$ is the three-momentum of the detected (spectator) proton in the deuteron rest frame; u and w are the S-wave and D-wave components of the deuteron momentum space wave function normalized as $4\pi \int dp\, p^2(u(p)^2 + w(p)^2) = 1$; the factor $2 - 2x_L$ is the Müller flux factor.



The suppression of the proton spectrum by the nuclear shadowing correction. Top panel: The solid curve corresponds to p_t=0; the dashed curve corresponds to p_t=100 MeV; the dash-dotted curve corresponds to p_t=200 MeV. Bottom panel: p_t=0 and p_z=(0, -100, +100) MeV/c.

Even bigger effects in the case of the polarized deuteron.

Diffraction and semiexclusive reactions.

Motivations:

♥ Establishing the Q^2 range where QCD factorization is valid for exclusive processes.

At what Q^2 nucleon GPD's can be measured.

♥ Comparison of nuclear GPDs and nuclear pdfs.

♥ Much deeper understanding of small x nuclear dynamics via measurement of Pomeron- Pomeron interactions, nuclear diffractive pdfs.

☛Exclusive diffraction - photon & vector meson production. $x \geq 0.02$ Parton densities practically A-independent. Leading twist expectation for the amplitudes:

$$M(\gamma^* + A \to \gamma(V) + A) = A F_A(t)\, M(\gamma^* + A \to \gamma(V) + A)$$

Observed for the J/ψ photoproduction at FNAL.

At what Q^2 LT works for vector mesons? Leading twist dominates in the elementary reaction for $Q^2 \geq 10$ - $15\ \mathrm{GeV}^2$ only. However, squeezing may work already for $Q^2 \geq 5\ \mathrm{GeV}^2$ (FKS95) leading to the color transparency phenomenon for much larger range of Q and hence to a possibility to measure the ratios of nucleon GPDs for a broad range of reactions.

Alternative probe: incoherent exclusive processes for $|t| \geq 0.1\ \mathrm{GeV}^2$:

$$d\sigma(\gamma^* + A \to \gamma(V,\pi,K..) + A')/dt =$$
$$= Z\, d\sigma(\gamma^* + p \to \gamma(V,\pi,K..) + N)/dt + (A-Z)\, d\sigma(\gamma^* + n \to \gamma(V,\pi,K..) + N)/dt$$

☛Exclusive diffraction - γ & VM production for $x \leq 0.02$.

- DVCS on nuclei is doable - possible to measure both imaginary and real part. Large nuclear effects extend to x~0.1 for the real part. (Freund and MS 03)

- Onset of perturbative color opacity:

$$M(\gamma^*+A\to V+A)=AF_A(t)\,M(\gamma^*+A\to V+A)G_A(x,Q^2)/G_N(x,Q^2)$$

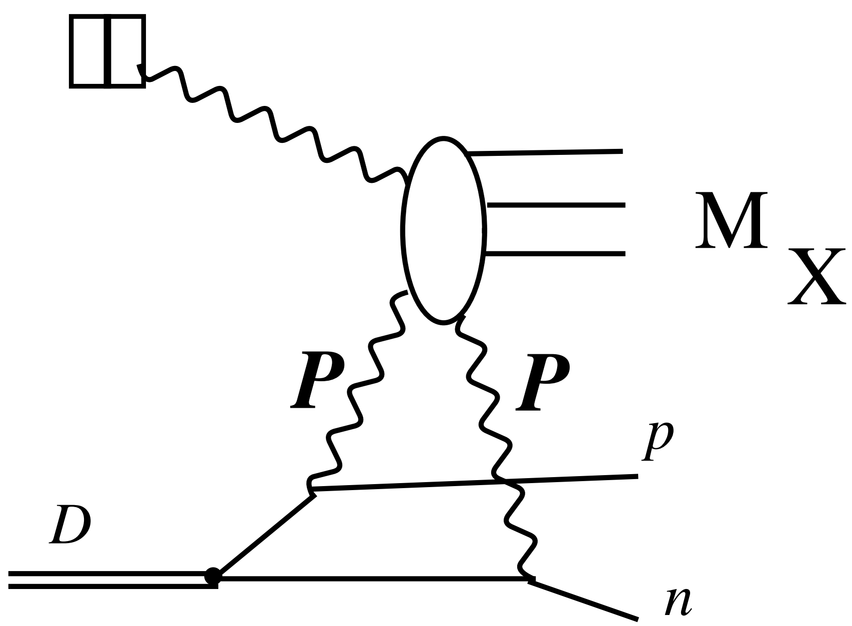
First checks via ultraperipheral ion-ion collisions at LHC -

J/ψ photoproduction off nuclei – at $x \geq 10^{-3}$

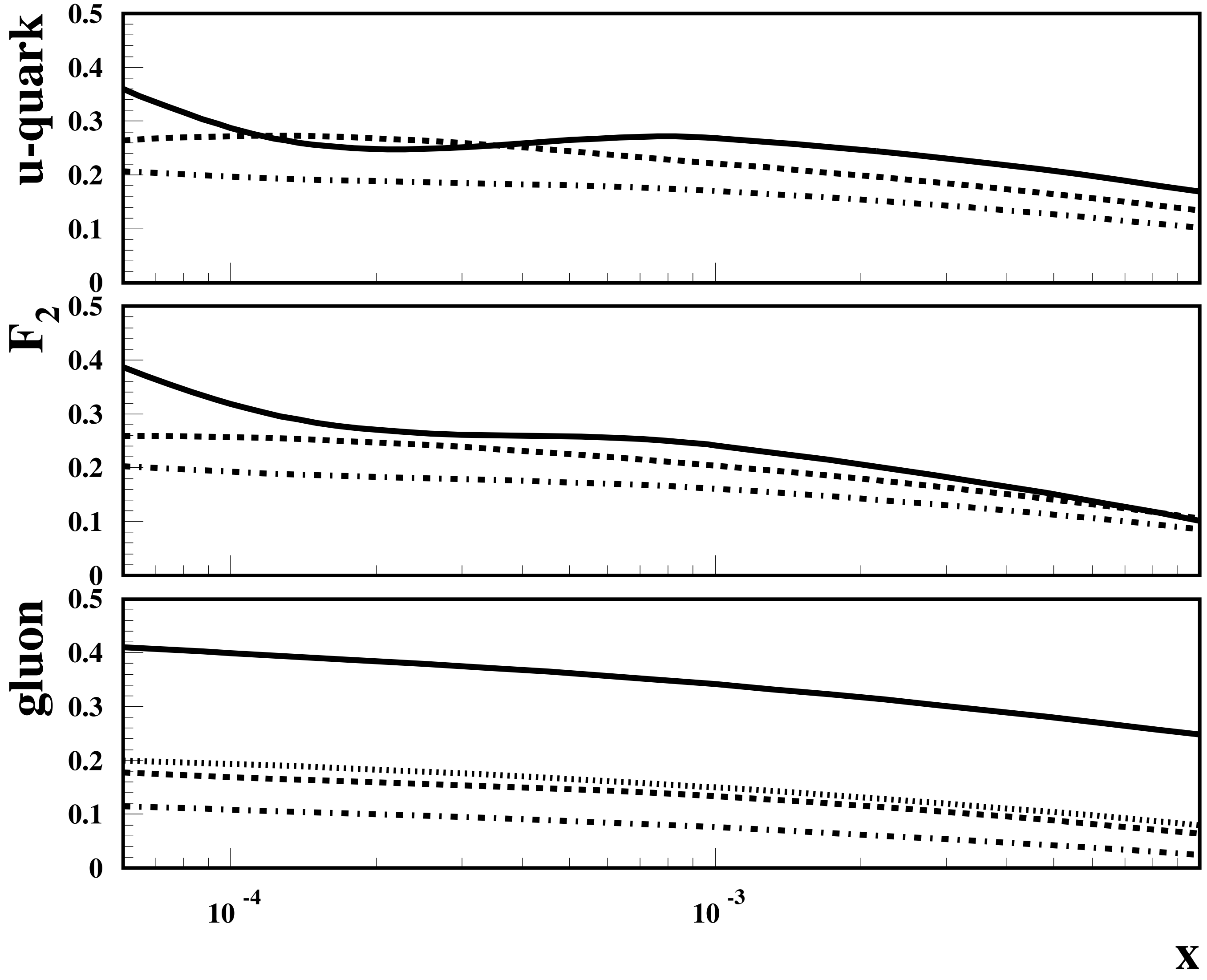
EIC will be able to measure nuclear GPDs via DVCS and next to measure VM to see whether suppression is similar, and study it as a function of Q^2 - interplay of HT and LT shadowing.

☛ Inclusive diffraction at x≤ 0.02.

☝ *Double tagging for the deuteron in special kinematics - measure of "Pomeron-Pomeron" interactions.*

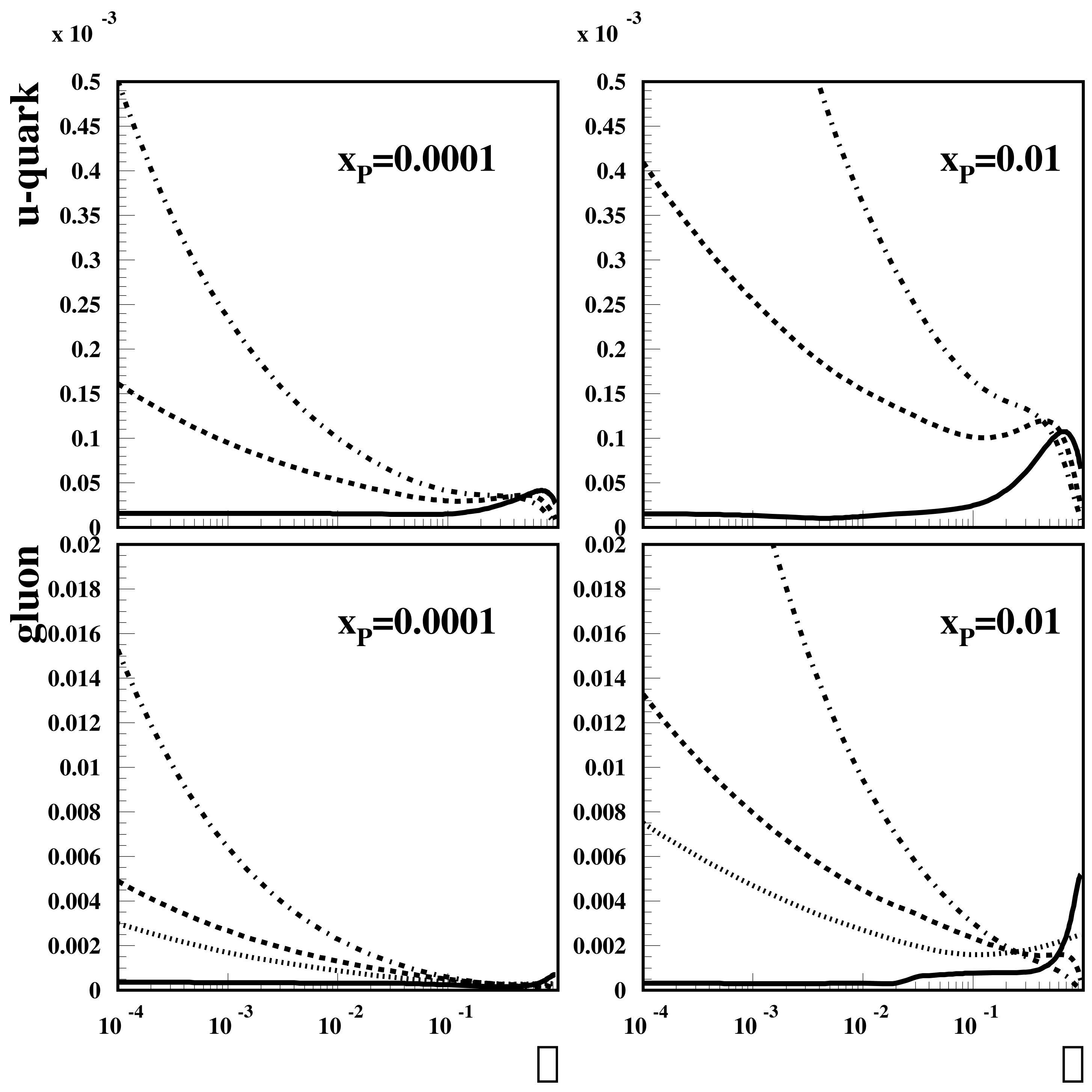


Measurement of the leading twist inclusive diffraction off nuclei - expected to be a significant fraction of the cross section for x<0.01



The ratios of diffractive and inclusive pdfs for the u-quarks and gluons and NLO F_{2A}'s for Pb. The solid curves correspond to Q=2 GeV; the dashed curves correspond to Q=10 GeV; the dot-dashed curves correspond to Q=100 GeV. In addition, for the gluons the dotted curve correspond to Q=5 GeV (Guzey, FS -03)

One also predicts a complicated dependence of the distribution on the diffractive mass as a function of flavor, Q, and $\beta = Q^2/(M^2+Q^2)$.



Conclusions

- ☺ EIC would allow to establish quark-gluon structure of nuclei at x> 0.01 - link to neutron stars
- ☺ Study of the interplay of leading twist and HT shadowing in many channels, starting with very low Q^2 - together with LHC achieve nearly complete coverage in virtuality for $x>10^{-3}$.
- ☺ Various experimental tests of conjectured connection between diffraction in the scattering off nucleon/nuclei and nuclear shadowing
- ☺ Color transparency/opacity phenomena, first determinations of nuclear GPDs, establishing the Q^2 range for studies of GPDs of nucleon in hard exclusive processes.

Many of the discussed measurements though doable from the angle of luminosity and kinematics are a challenge for detector design, systematics, etc.