# OVERVIEW OF NUCLEAR PDFS

**Mark Strikman, PSU**

**EMC EFFECT FOR ANTIQUARKS???**

**HT in DIS**

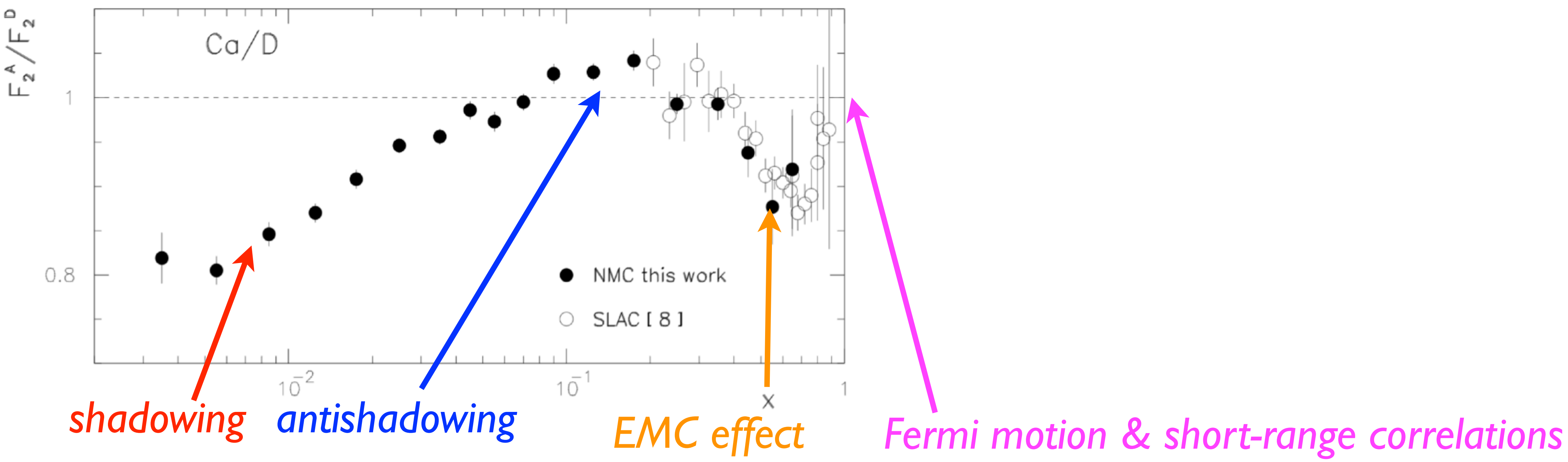
**Correct definition of x in eA**

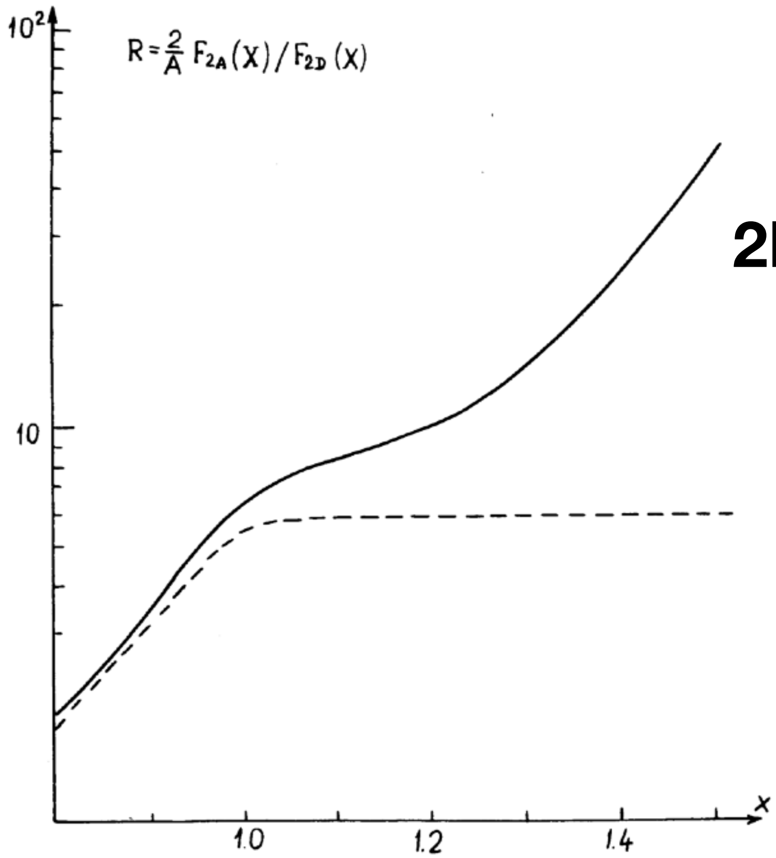
**Shadowing and anti shadowing**

## *Outline: from large to small x*

Nuclear effect for pdfs: deviation of

$R_j(x,Q^2) = 2f_{j/A}(x,Q^2)/Af_{j/N}(x,Q^2)$ from 1





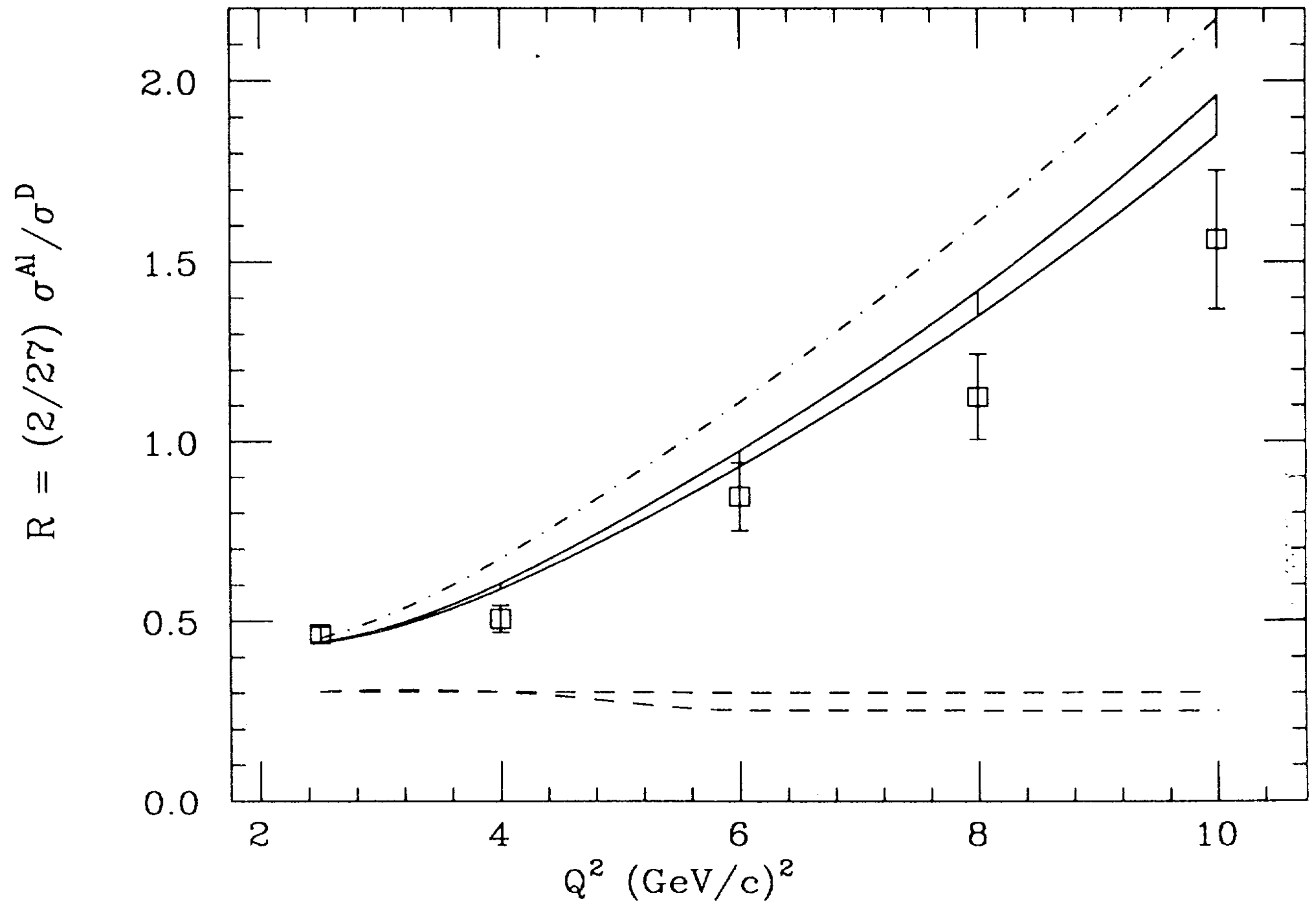




FIG. 7. $\frac{2\sigma^{Al}}{27\sigma^{D}}$ as a function of $Q^2$ for $x = 1$. Data is from [5,3]. The dash-dotted curve is a calculation including inelastic channels but without consideration of the EMC effect. The solid curve encloses a range of values that are possible (due to uncertainties in the model) in the color minidelocalization model of the EMC effect [7]. The two dashed curves are the results of a calculation without inelastic contributions with the lower of these including the effect of nucleon swelling.

**Scaling limit $Q^2 > 20$ GeV$^2$ ?**

**Broad integral over LC fraction α**

**Early sensitivity to 3 src**

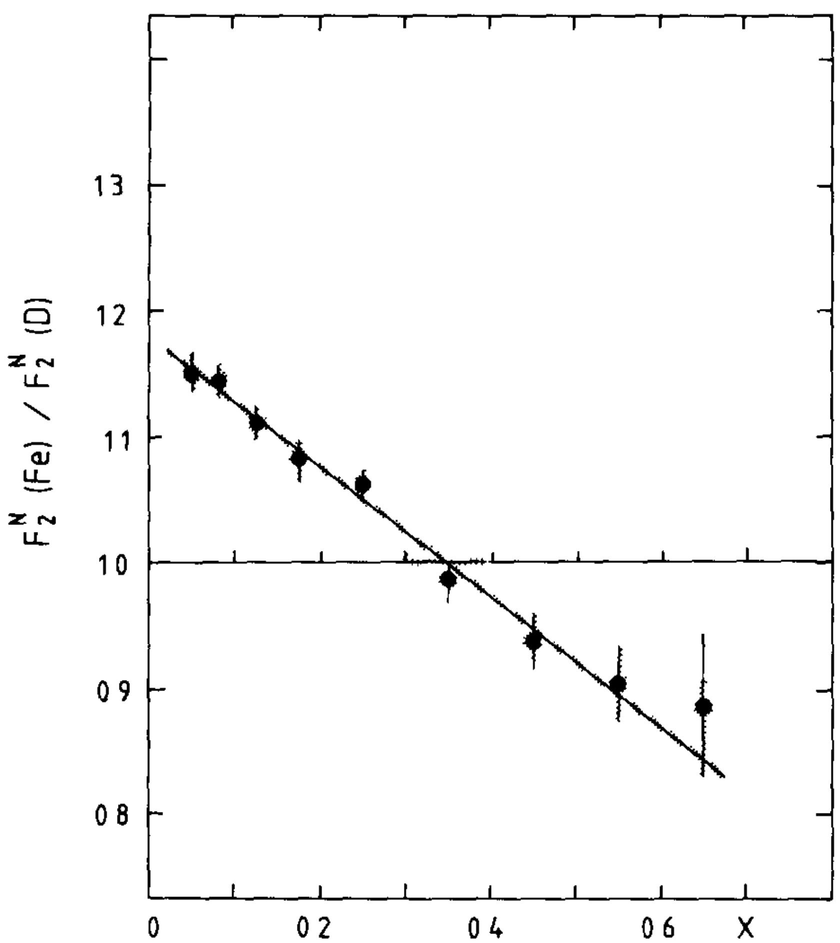
Volume 123B, number 3,4 PHYSICS LETTERS 31 March 1983

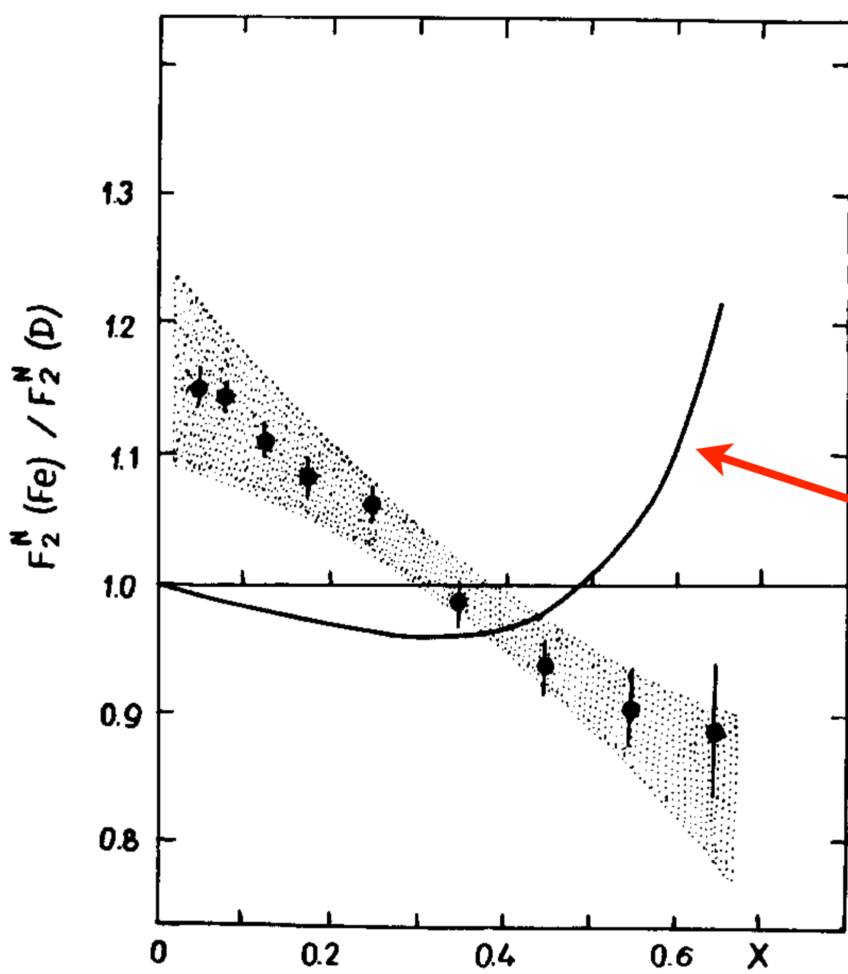
## THE RATIO OF THE NUCLEON STRUCTURE FUNCTIONS $F_2^N$ FOR IRON AND DEUTERIUM

The European Muon Collaboration

Received 19 January 1983

First reported at the Rochester conference Paris, 1982



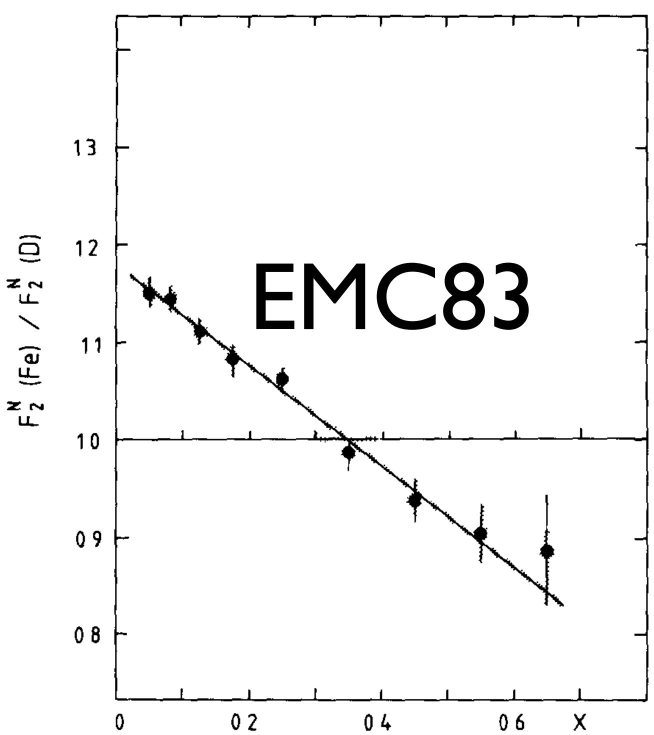




*Theoretical expectation under assumption that nucleus consists only of nucleons FS 81*

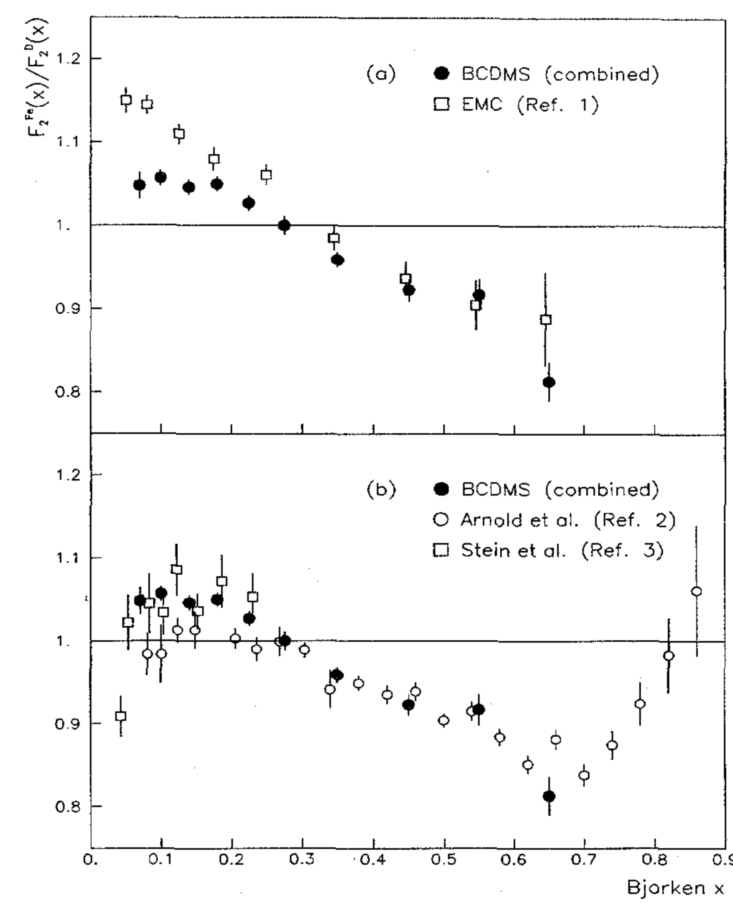
Major discovery (by chance) - the European Muon Collaboration effect - substantial difference of quark Bjorken x distributions at x > 0.25 in A>2 and a=2 nuclei : large deviation of the EMC ratio

**$R_A(x,Q^2) = 2F_{2A}(x,Q^2)/AF_{2D}(x,Q^2)$ from one**

$$q_\nu = (q_0, \vec{q}), x = x_{Bj} = -q^2/2q_0 m_p \quad q_\nu = p_{\gamma^*}$$




*1987 - effect is significantly smaller and has more complicated x -dependence*




straight line fit - suggested universal mechanism. Fermi motion very small effect with R(x>0.5) >1

Bjorken scaling within 30% accuracy - caveat - HT effects are large in SLAC kinematics for x≥ 0.5

## How model dependent was the expectation?

EMC paper had many curves hence impression that curves could be moved easily.

*Why the effect cannot be described in the approximation: nucleus = A nucleons?*

consider a fast nucleus with momentum $P_A$ as a collection of nucleons with momenta $P_A/A$

$P_A$ → = → $\alpha_1 P_A/A$, → $\alpha_2 P_A/A$, → $\alpha_3 P_A/A$

$\alpha_1 + \alpha_2 + \alpha_3 = 3$

If no Fermi motion: $\alpha_i = 1$

*In this case probability to find a quark/antiquark with momentum $xP_A/A$ is*

$$F_q^A(x) = A f_q^N(x)$$

$$\Rightarrow \quad R_A(x) \equiv F_q^A(x) / A f_q^N(x) = 1$$

Deviation of $R_A(x)$ from one is refereed to as EMC effect - 1983

*Why it is interesting to study a 10% effect - most of reactions*
*Agreement with nuclear theory is not good to even 20%*
*Can account of Fermi motion describe the EMC effect?*

*Many nucleon approximation:*

Need to use

Light cone nuclear nucleon density (light cone projection of the nuclear spectral function

$$\rho_A^N(\alpha, p_t)$$

≡probability to find a nucleon having momentum $\alpha P_A$

**to satisfy QCD sum rules**

$$\int \rho_A^N(\alpha, p_t)\frac{d\alpha}{\alpha}d^2p_t = A$$

baryon charge sum rule

momentum sum rule

$$\frac{1}{A}\int \alpha\rho_A^N(\alpha, p_t)\frac{d\alpha}{\alpha}d^2p_t = 1 - \lambda_A$$

**$\lambda_A$=0 in nucleus = collection of nucleons**

fraction of nucleus momentum NOT carried by nucleons

$$F_{2A}(x, Q^2) = \int \rho_A^N(\alpha, p_t)F_{2N}(x/\alpha)\frac{d\alpha}{\alpha}d^2p_t$$

Since spread in α due to Fermi motion is modest ⇒ do Taylor series expansion in (1- α): α= 1+ (α-1)

Fermi motion

$$R_A(x,Q^2) = 1 - \frac{\lambda_A x F'_{2N}(x,Q^2)}{F_{2N}(x,Q^2)} + \frac{xF'_{2N}(x,Q^2) + (x^2/2)F''_{2N}(x,Q^2)}{F_{2N}(x,Q^2)} \cdot \frac{2(T_A - T_{^2H})}{3m_N}$$

$$xf_N(x,Q^2) \propto (1-x)^n \qquad R_A(x,Q^2) = 1 - \frac{\lambda_A n x}{1-x} + \frac{xn\left[x(n+1)-2\right]}{(1-x)^2} \cdot \frac{(T_A - T_{^2H})}{3m_N}$$

small negative $R_A$-1 for $x_{cr}$= 2/(n+1) and rapidly growing for x > $x_{cr}$

$x_{cr}$=0.5 for quarks, $x_{cr}$=0.25 for antiquarks [$n_{antiquarks}$ =7 - quark counting rules]

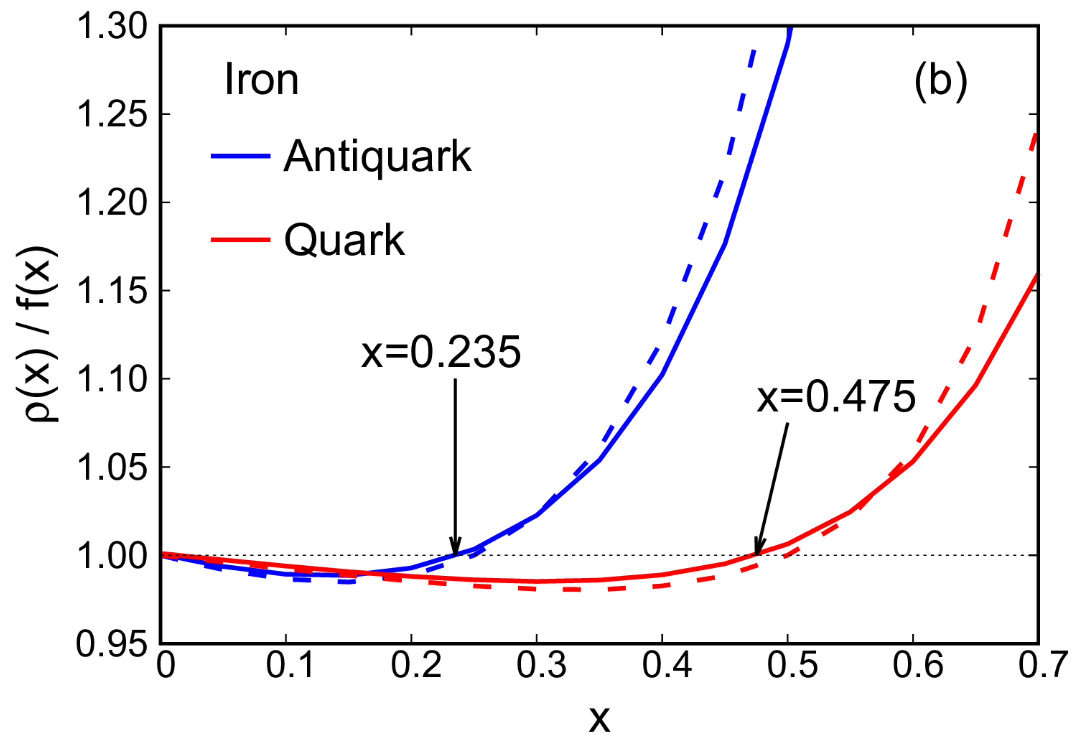
EMC effect is unambiguous evidence for presence of non nucleonic degrees of freedom in nuclei. The question - what they are?

**Fermi motion expectations - no nonnucleonic degrees of freedom**

**$R_{A/D}(x)$**

$$x\bar{q}(x) \propto (1-x)^n, n = 7.$$

$q_A(x)/q_D(x)$ **n=3**




**crossover (R=1) point**

$$R_{cr} = 2/(n+1)$$

**Recent DY the highest x~ 0.4**

**Solid curves exact calculation, dashed curves-Taylor expansion - perfect agreement.**

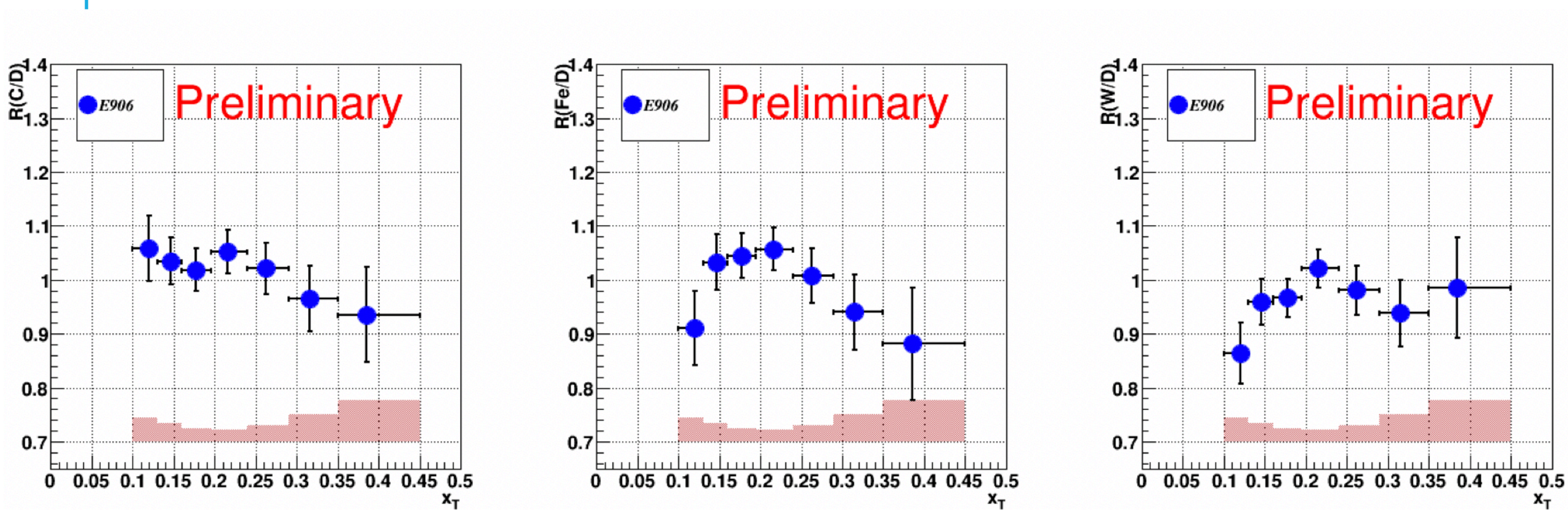
**Region of crossover a sweet spot for looking for nonnucleonic effects**

*EMC effect CANNOT BE explained without introducing non-nucleonic degrees of freedom - just due to Fermi motion.*

Claims to the opposite are due violation of the baryon charge conservation or momentum conservation or both

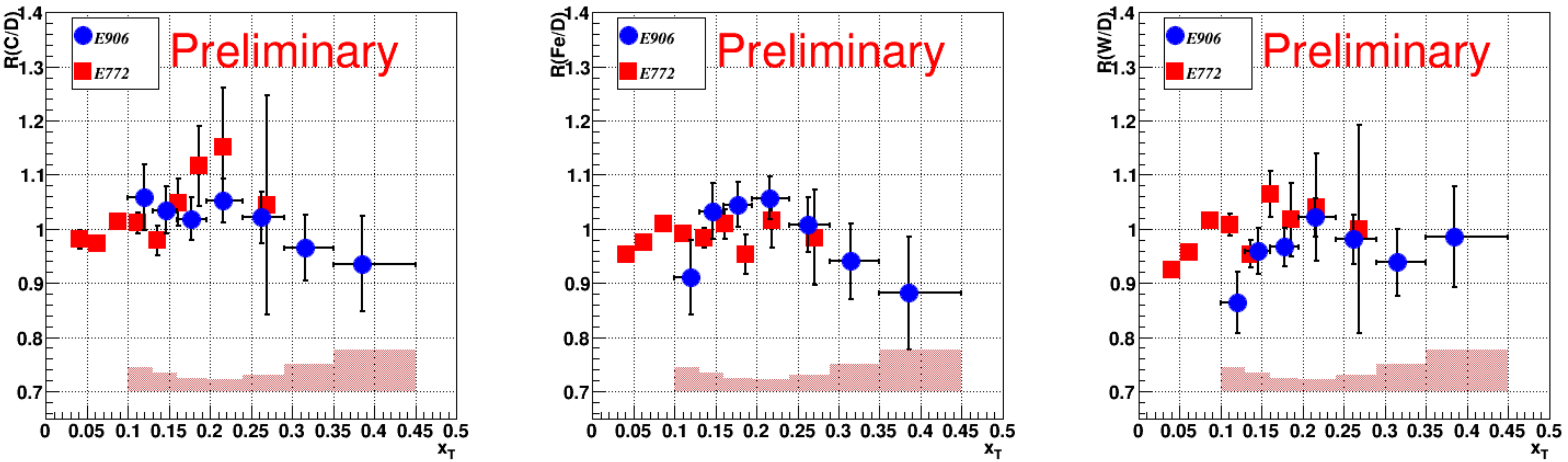
**For antiquarks no evidence for enhancement for x> 0.25 expected due to Fermi motion**

# SEAQUEST RESULTS



# SEAQUEST COMPARISON WITH E772

*E772 systematics not shown




**Softening of x distribution of quarks and antiquarks (and gluons?) in bound nucleons**

Seaquest data indicate that deviations from naive many nucleon model are even larger for antiquarks than for quarks

R (x=0.4,data) ~ 0.9 ±0.1, Fermi motion R= 1.2

Qualitatively new information about quark - gluon structure of nuclei

Complements the studies of the EMC effect by Jlab & MIT groups which find experimental indications that the EMC effect is proportional to the probability of the “pn” short range correlations in nuclei

Both quarks and antiquarks are softer in SRCs?

Challenge: probability of SRC in nuclei is 25% and 90% of SRC are nucleons - how to get 15% effect for EMC ratio

If the origin of antiquark effect is the same - modification of parton structure of SRCs - weak A-dependence for A≥ 12.

The data seem to be consistent with weak A-dependence except W/D highest point ? (correction for N=1.5 Z for W seems to be small)

**If confirmed with a better precision,… this measurement would be a second critical contribution of DY studies into understanding of quark- gluon nuclear structure (the first one was ruling out enhancement of antiquarks due to scattering off pions).**

## Moderate x ~0.5 for eA- standard EMC effect

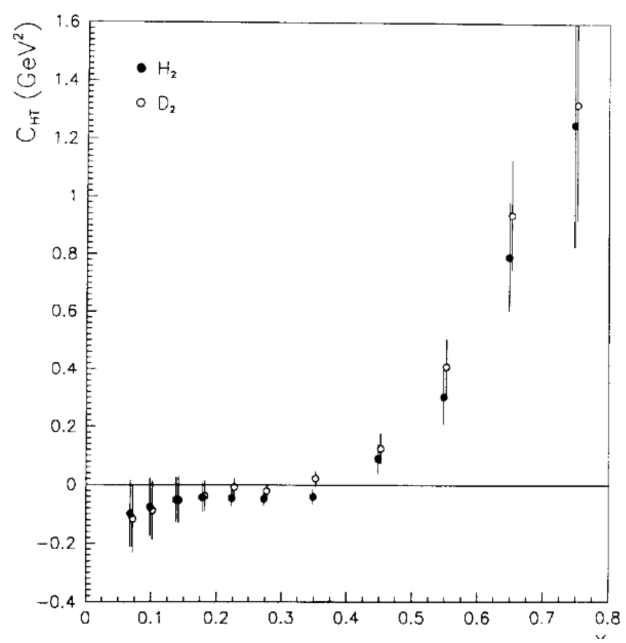
**Two problems for precision analysis necessary since dynamical quantity**

**1-R which for for a wide rage of nuclei does not exceed 10%for wide range of A**

**A) HT effects**

**B) QCD consistent definition of Bjorken x**

$$F_{2N}(x, Q^2) = F_{2N}^{LT}(x, Q^2)(1 + C/Q^2)$$




The higher-twist coefficients C, as a function of x. Full (open) circles are for H2 (D2) data

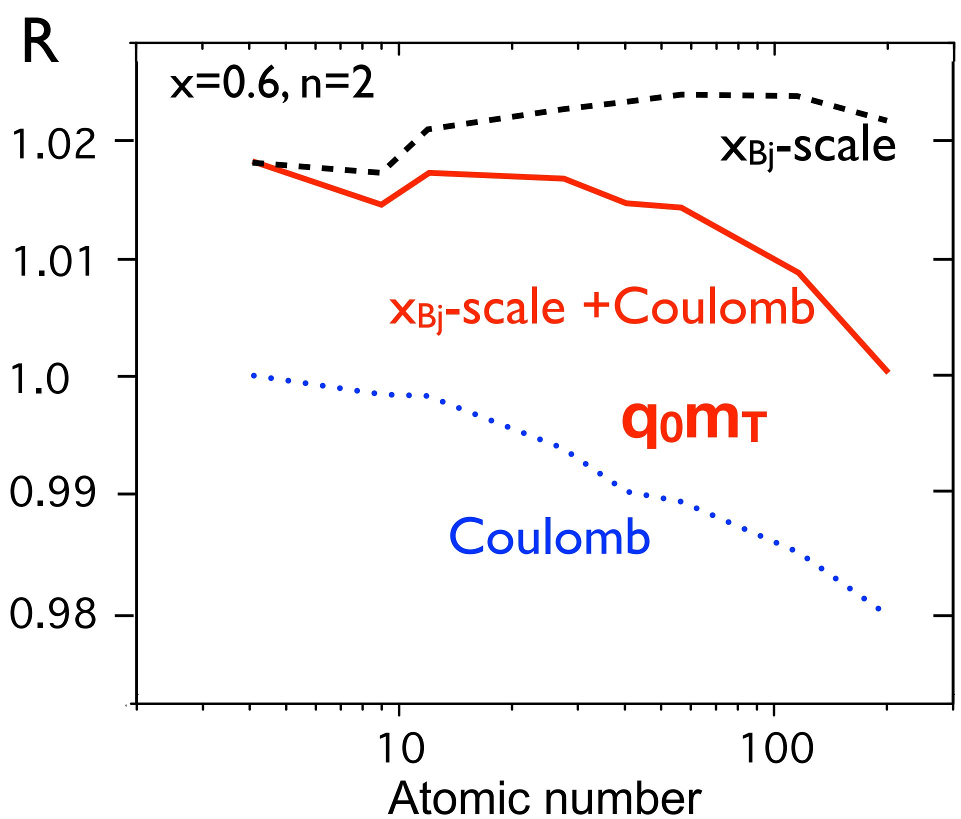
Marc Virchaux and Alain Milsztajn, 1992

Bjorken scaling within 30% accuracy - caveat - HT effects are quite large in Jlab and SLAC kinematics for x≥ 0.65.

Example: for x=0.65, $Q^2$ = 2GeV$^2$, HT/LT =0.3 !!!

**Also, the high Q BCDMS point at x=0.65, is much lower than SLAC and Jlab measurements to be reproduced by DGLAP evolution.**

**Bj x - light cone fraction** **$x_T = Q^2/2q_0m_T$** **Not $x_p$ used in all data analyses**




**: Change of R due to account for correct x-scale( dashed line), contribution of equivalen photons (dotted line) and combined effect (solid line) as a function of atomic number fo $x = 0.6$ and $F_{2N}(x) \propto (1-x)^2$**

# Baryon charge sum rule

$$\int_0^A \frac{1}{A} V_A(x_A,Q^2)dx_A - \int_0^1 V_N(x,Q^2)dx = 0 \qquad (1)$$

From (1) + EMC effect ⇒ enhancement of $V_A(x\sim 0.1)$ at least partially reflection of the EMC effect - some room for contribution compensating smallish valence quark shadowing. FGS12 presented an argument now why shadowing for $V_A$ is suppressed.

*Comment: the best way to measure $V_A/V_N$ is semi inclusive $\pi^+ - \pi^-$*

$$\frac{D^{A/\pi^+}(x,x_F,Q^2) - D^{A/\pi^-}(x,x_F,Q^2)}{D^{N/\pi^+}(x,x_F,Q^2) - D^{N/\pi^-}(x,x_F,Q^2)} = \frac{F_{2N}(x,Q^2)}{F_{2A}(x,Q^2)}\,\frac{u_v^A(x,Q^2) - \frac{1}{4}d_v^A(x,Q^2)}{u_v^N(x,Q^2) - \frac{1}{4}d_v^N(x,Q^2)}$$

$$= \frac{F_{2N}(x,Q^2)}{F_{2A}(x,Q^2)}\,\frac{V_A(x,Q^2)}{V_N(x,Q^2)}\Bigg|_{N,A=\text{isosinglet}}$$

*right hand side does not depend of $x_F$. Perhaps better to measure*

*$(\pi^+ - \pi^-)/(\pi^+ + \pi^-)$*

Consider isoscalar target

$$\frac{F_2^{A(N)}(x,Q^2)}{x} = \frac{5}{18}[V_{A(N)}(x,Q^2)+S_{A(N)}(x,Q^2)] - \frac{s_{A(N)}(x,Q^2)+\bar{s}_{A(N)}(x,Q^2)}{6}$$

and use $\int_0^1 G_N(x,Q^2)x\,dx \approx 0.5$

define $$\gamma_G^A = \frac{\int_0^A (1/A) G_A(x_A,Q^2) x_A\,dx_A}{\int_0^1 G_N(x,Q^2)x\,dx} - 1$$

$$\gamma_G^A \approx \frac{\int_0^1 F_2^N(x,Q^2)dx - \int_0^A (1/A) F_2^A(x_A,Q^2)dx_A}{\int_0^1 F_2^N(x,Q^2)dx} - \frac{6}{5}\frac{\int_0^A (1/A)\bar{s}_A(x_A,Q^2)x_A\,dx_A - \int_0^1 \bar{s}_N(x,Q^2)x\,dx}{\int_0^1 G_N(x,Q^2)x\,dx}$$

Use NMC data (the smallest relative normalization error)

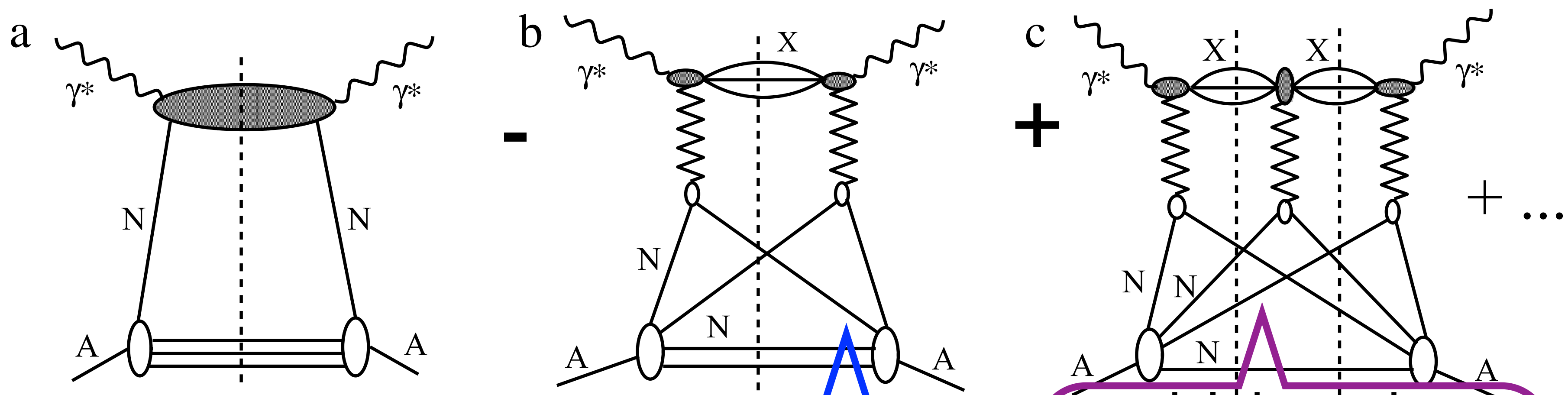
$\gamma_G^A = (2.18 \pm 0.28 \pm 0.50)\%$,

$\gamma_G^A = (2.31 \pm 0.35 \pm 0.39)\%$,

for $^{40}$Ca

The Gribov theory of nuclear shadowing relates shadowing in $\gamma^* A$ and diffraction in the elementary process: $\gamma^* + N \to X + N$.

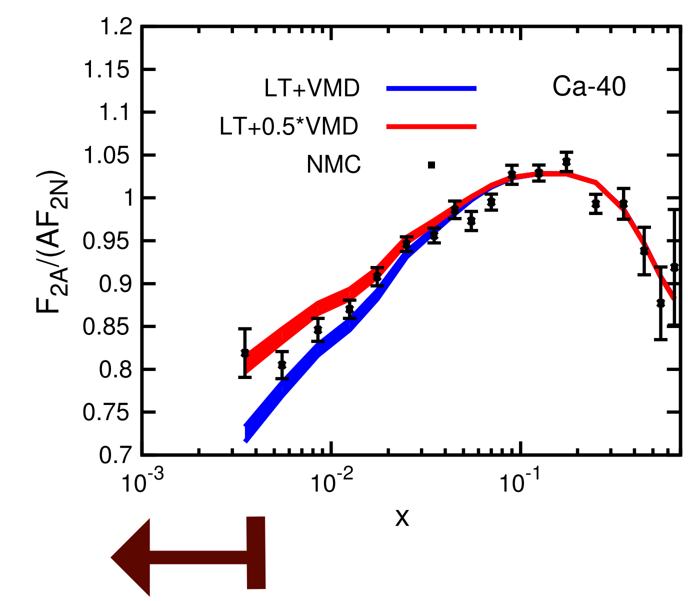
four fold rescattering a small correction for $x > 10^{-3}$




model independent

model dependent but universal (~ same for different A)

Before HERA one had to model ep diffraction to calculate shadowing for $\sigma_{\gamma^* A}$ (FS88-89, Kwiecinski89, Brodsky & Liu 90, Nikolaev & Zakharov 91). More recently several groups (Capella et al) used the HERA diffractive data as input to obtain a reasonable description of the NMC data (however this analysis made several simplifying assumptions). Also the diffractive data were used by several groups to describe shadowing in $\gamma A$ scattering without free parameters.




$Q^2 \leq 2\, GeV^2$

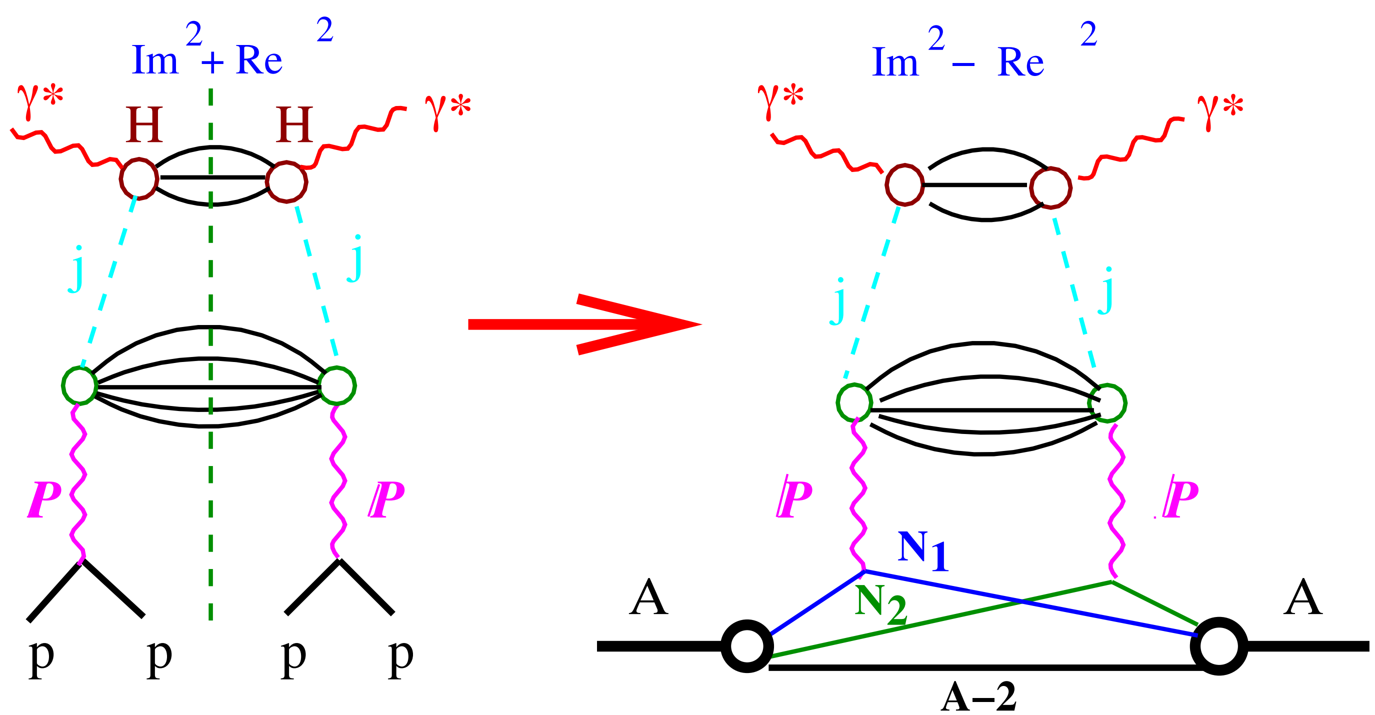
Does not allow to calculate gluon pdfs and even quark pdfs

# 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)*

(instead of calculating $F_{2A}$ only)

Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the nucleon diffractive parton densities $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$ :



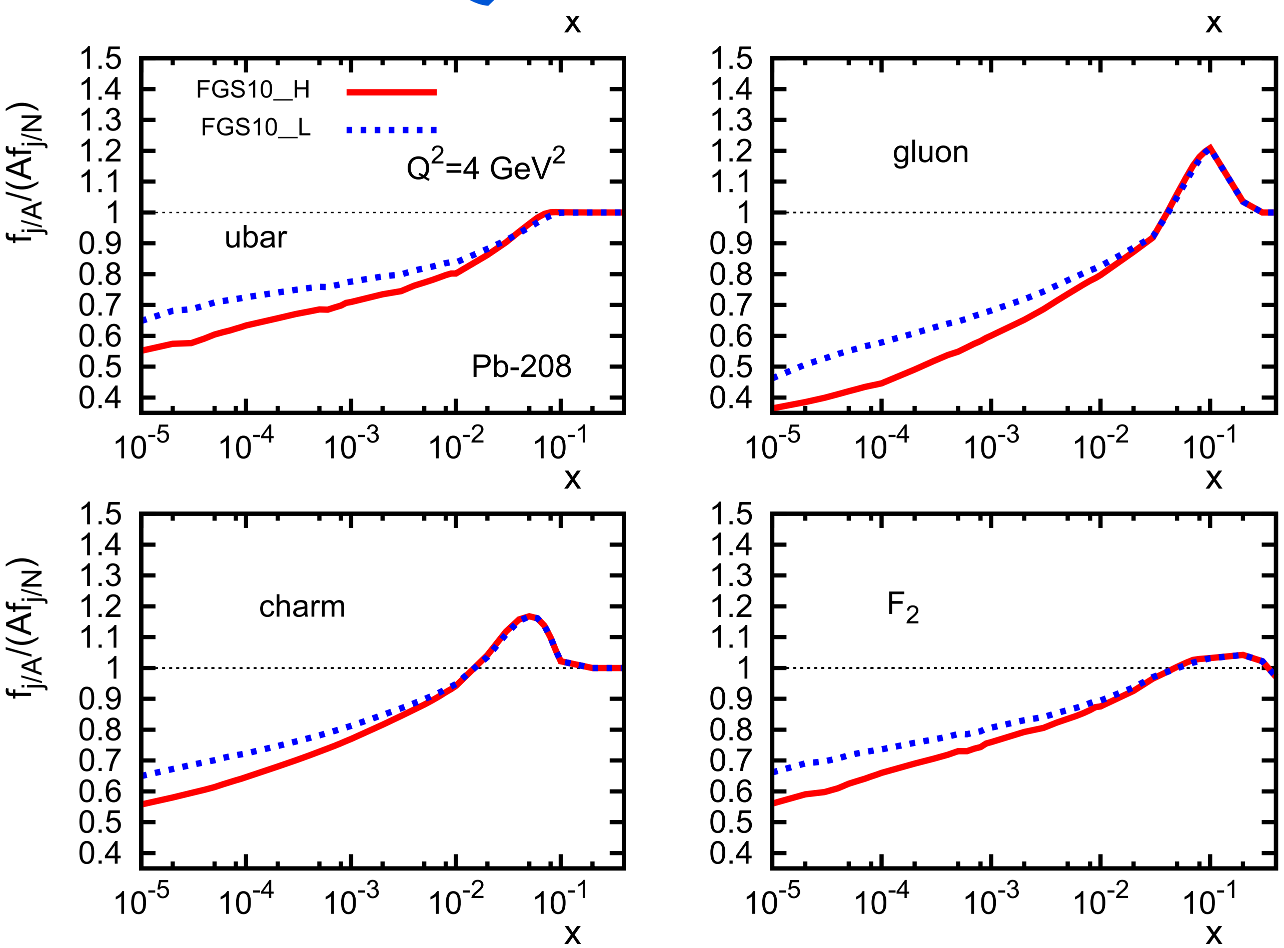

**Hard diffraction off parton "j"**

**Leading twist contribution to the nuclear shadowing for structure function $f_j(x,Q^2)$**

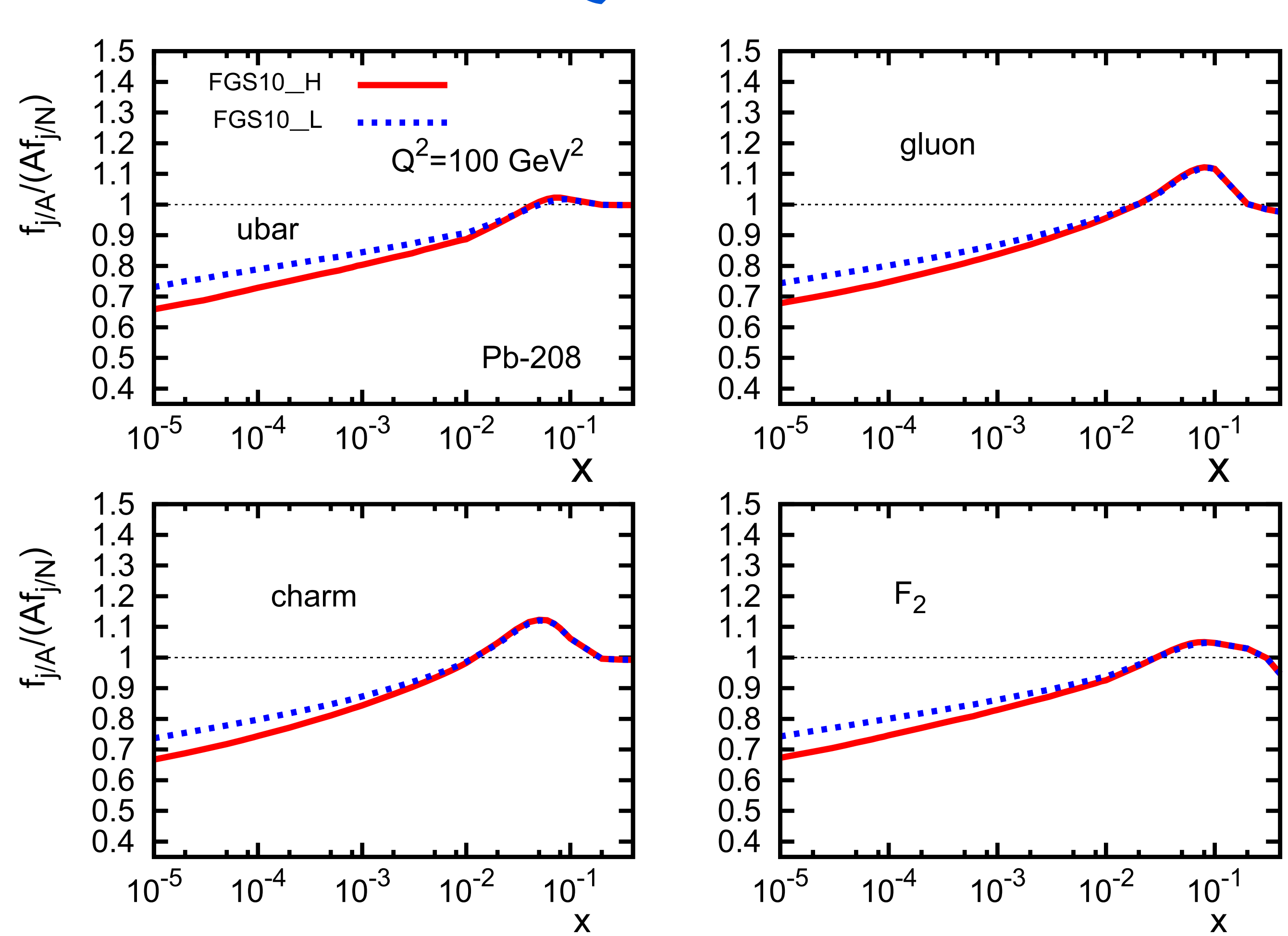
Numerical studies impose antishadowing to satisfy the sum rules for baryon charge and momentum (LF + MS + Liuti 90) - sensitivity to model of fluctuations (interaction with N>2 nucleons) is rather weak. At the moment uncertainty from HERA measurements is comparable.

NLO pdfs - as diffractive pdfs are NLO

## $Q^2$ = 4 GeV$^2$




## $Q^2$ = 100 GeV$^2$

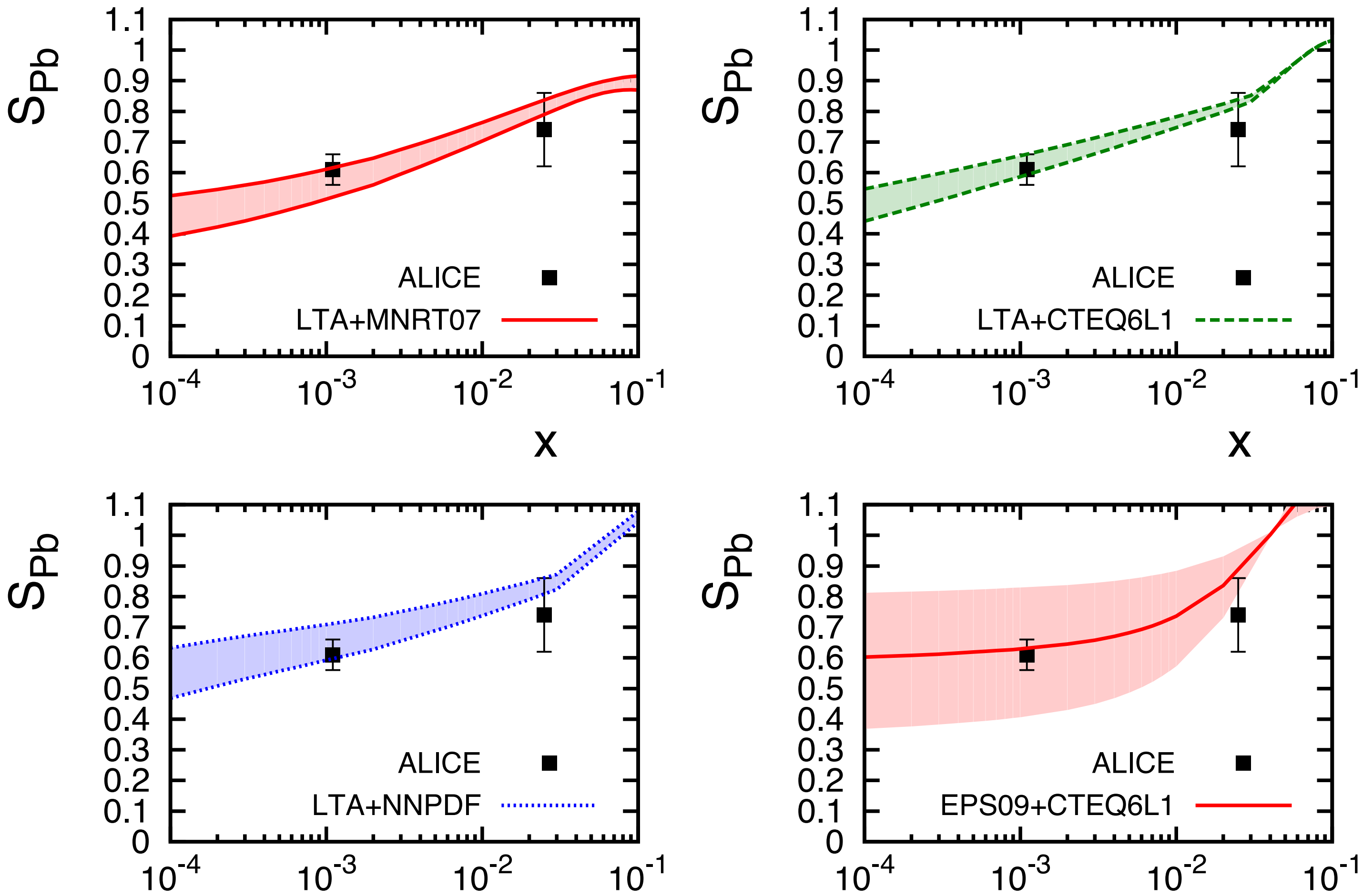



Predictions for nuclear shadowing at the input scale $Q^2$ = 4 GeV$^2$. and = 100 GeV$^2$. The ratios $R_j$ ($\bar{u}$ and c quarks and gluons) and $R_{F2}$ as functions of Bjorken x. Two sets of curves correspond to models FGS10_H and FGS10_L.

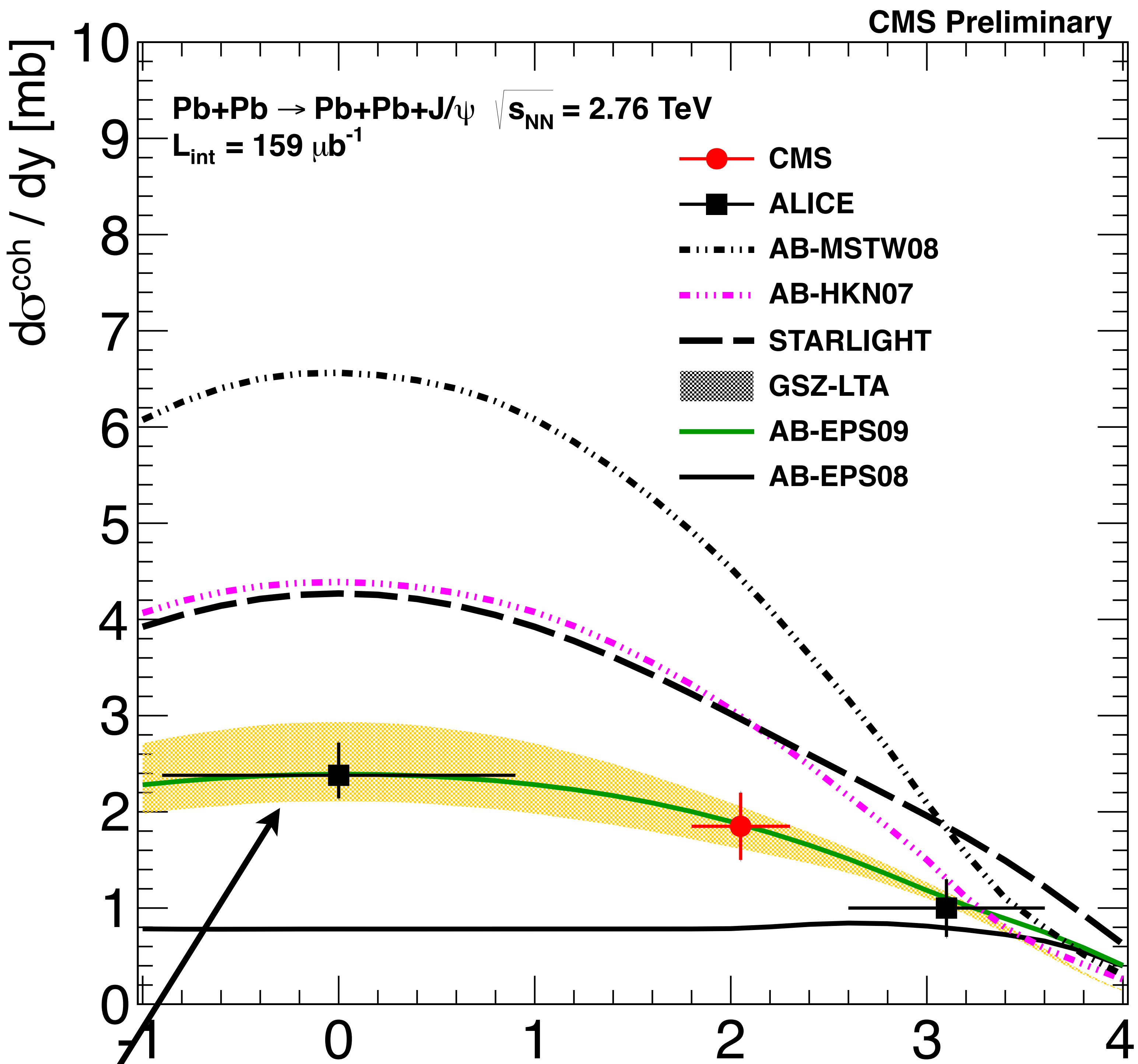
Sum rules require pretty large gluon antishadowing

# Gluon shadowing from J/ψ photoproduction

$$S_{Pb} = \left[ \frac{\sigma(\gamma A \to J/\psi + A)}{\sigma_{imp.approx.}(\gamma A \to J/\psi + A)} \right]^{1/2} = \frac{g_A(x,Q^2)}{g_N(x,Q^2)}$$




Points - experimental values of S extracted by Guzey et al (arXiv:1305.1724) from the ALICE data; Curves - analysis with determination of Q -scale by Guzey and Zhalov arXiv:1307.6689; JHEP 1402 (2014) 046.




$\chi=10^{-3}$

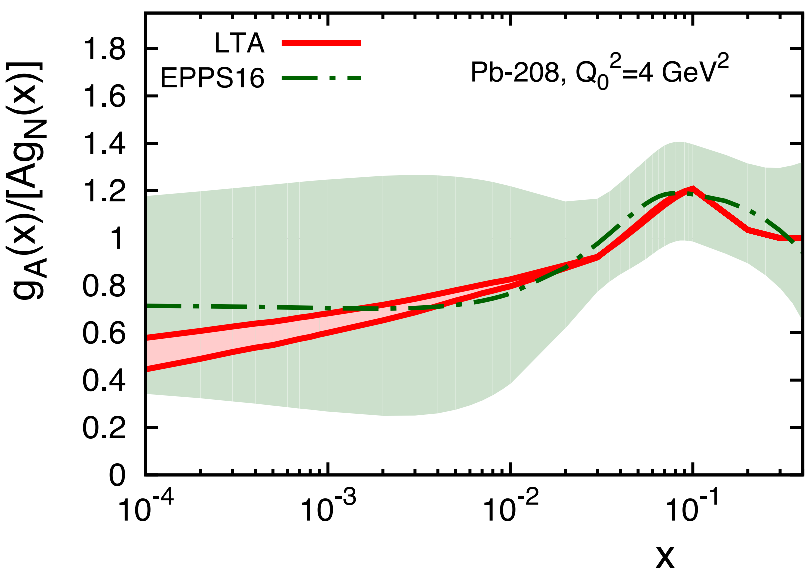
GOOD AGREEMENT WITH PREDICTIONS OF LTA.

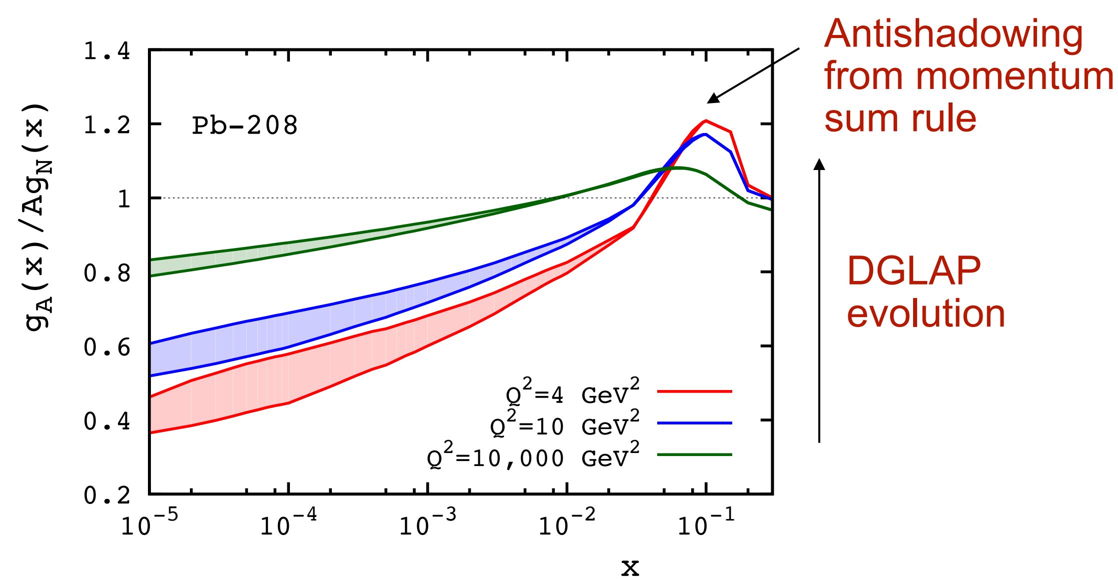
**DOWN TO X~ 10-5**

**LARGE REDUCTION OF GLUON DENSITY**

# LTA predictions for nPDFs

- HERA analysis: perturbative Pomeron is made mostly of gluons → LTA model naturally predicts large gluon nuclear shadowing, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255




- Alternative, complementary point of view: shadowing is mixture of leading and higher twist (HT) effects in dipole picture with saturation, Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303, or a purely HT effect, Qiu, Vitev, PRL 93 (2004) 262301.

- Electron-Ion Collider has potential to discriminate models of NS due to:

- wide x-$Q^2$ coverage
- measurements of the longitudinal structure function $F_L^A(x,Q^2)$ sensitive to gluons
- measurements of diffraction in eA DIS

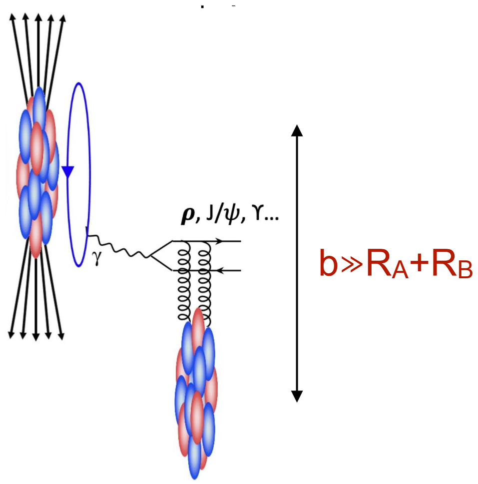
Plenary talks on EIC, 23.06.



**Antishadowing in LTA not in dipole models.**

# Nuclear shadowing in UPC at LHC

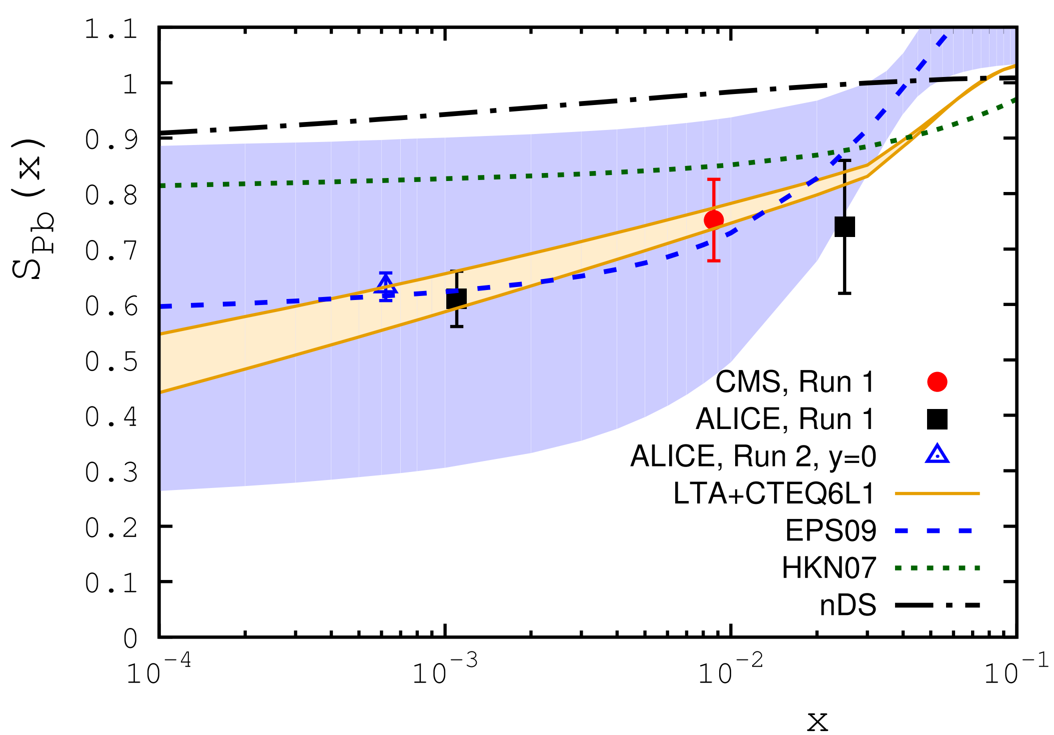
• Before EIC, models of NS can be tested in ultraperipheral collisions (UPCs) of heavy ions at LHC and RHIC, Plenary talks on UPCs, 21.06; Nystrand, 20.06




A. Stahl, LPCC CERN Seminar, 6.12.2022

• Measured cross section converted nuclear suppression factor $S_{Pb}$, Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; [CMS] PLB 772 (2017) 489; Acharya et al [ALICE], EPJC 81 (2021) 8, 712

$$S_{Pb}(W) = \left[\frac{\sigma^{\gamma A\to J/\psi A}(W)}{\sigma_{\rm IA}^{\gamma A\to J/\psi A}(W)}\right]^{1/2} = \frac{g_A(x,\mu^2)}{A g_p(x,\mu^2)}$$



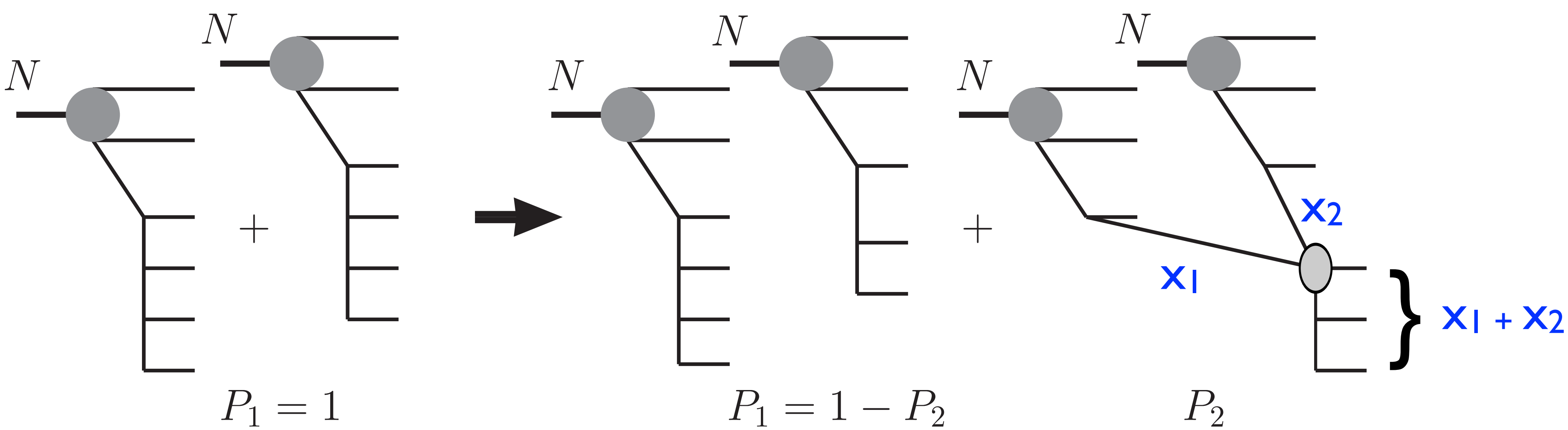

• Direct evidence of large gluon shadowing, $R_g(x=6\times10^{-4} - 0.001) \approx 0.6$ in agreement with LTA model and EPS09/EPPS16 nPDFs, Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290, Guzey, Zhalov, JHEP 1310 (2013) 207

• NLO pQCD challenges this interpretation due strong cancellation between LO and NLO gluon terms, Eskola, plenary talk on 21.06.

# Dynamical model of antishadowing

Guzey et al 16

At a soft scale one can consider small x infinite momentum frame nucleon wave function as a soft ladder - consistent with HERA observation of $\alpha_{IP}$(diff) =1.12 -soft. In the diffusion ladders belonging to two nucleons can overlap and merge into one ladder.

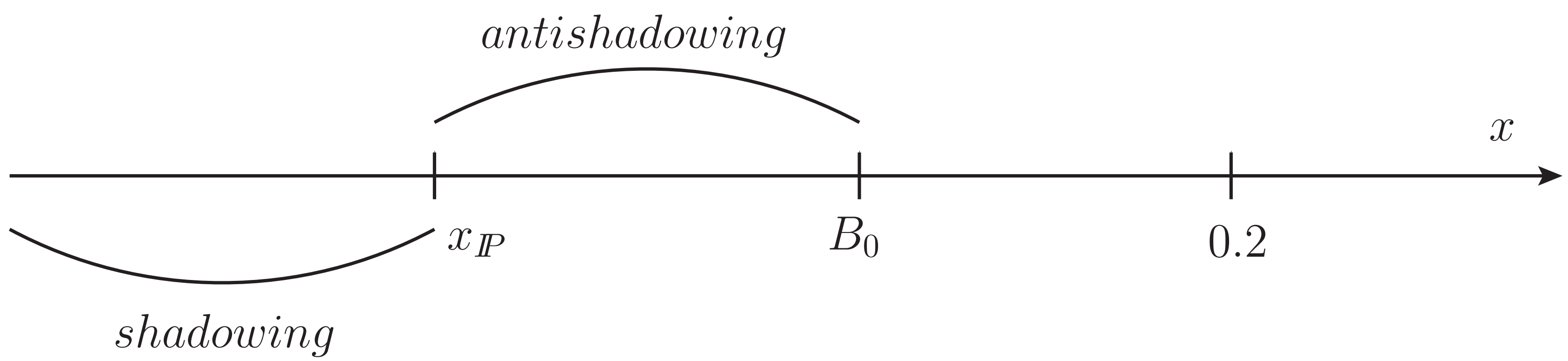



*Merging of two ladders coupled to two different nucleons in the 2IP → IP process in the nucleus infinite momentum frame. This process corresponds both to*

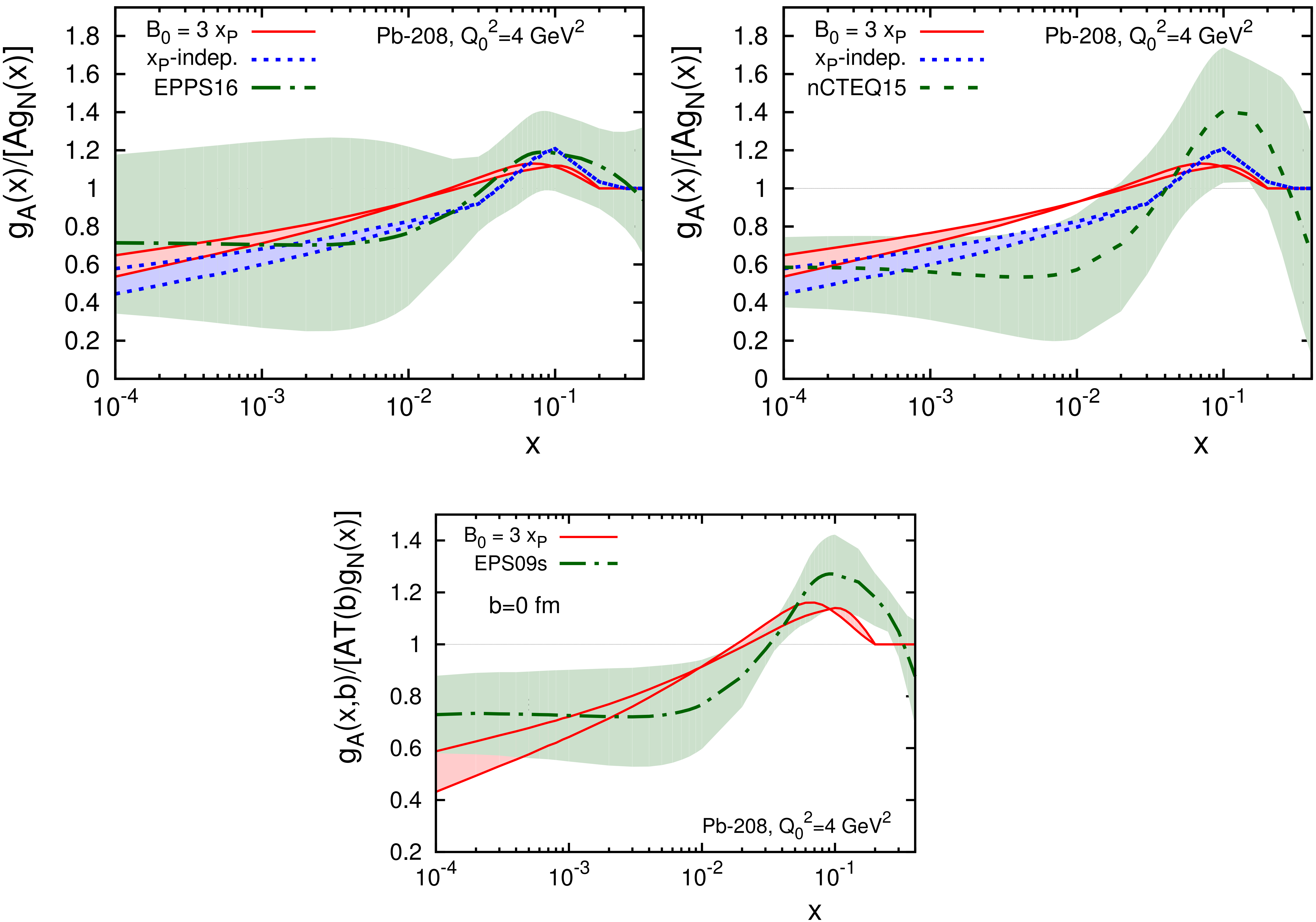
- *nuclear shadowing: fewer partons at small x by factor 2-* $P_2$
- *antishadowing: more partons at* $x \sim x_1 + x_2$

*Total light cone momentum carried in the merged configuration is the same as for two free nucleons, hence the momentum sum rule is automatically concerned*

Soft process ⇒ for a merger leading to shadowing at given x the compensating antishadowing should occur at nearby rapidities: Δy ≤1 $\rightarrow B_0/x_{I\!P} \sim 3$




I do not have time to discuss details of modeling which includes accurate definition of x for the nucleus and account for a small fraction of the momentum carried by coherent photons (0.8% for Pb)



B0 = 3 xP
xP-indep.
EPPS16
Pb-208, Q0^2=4 GeV^2
gA(x)/[AgN(x)]
x
B0 = 3 xP
xP-indep.
nCTEQ15
Pb-208, Q0^2=4 GeV^2
gA(x)/[AgN(x)]
x
B0 = 3 xP
EPS09s
b=0 fm
Pb-208, Q0^2=4 GeV^2
gA(x,b)/[AT(b)gN(x)]
x

## Gluon nuclear pdf - goof chances to discover EMC effect for gluons,

## antishadowing,what are best tools at EIC?

## Scaling violation for R(x), charm

Ss

1) The “latest” results from our project were reported in Yulia’s talk at INT 2018 and are described in the proceedings (page 289): https://inspirehep.net/literature/1782665

This proceedings article was quoted in the EIC Yellow Report: https://inspirehep.net/literature/1851258

2) Charm impact study by the Berkley group: https://inspirehep.net/literature/1882506
(they refer to our project)

2) Earlier study of nuclear PDFs by the BNL group, including impact of charm:
https://inspirehep.net/literature/1616727