Nuclear pdfs - summary of what we know and open questions

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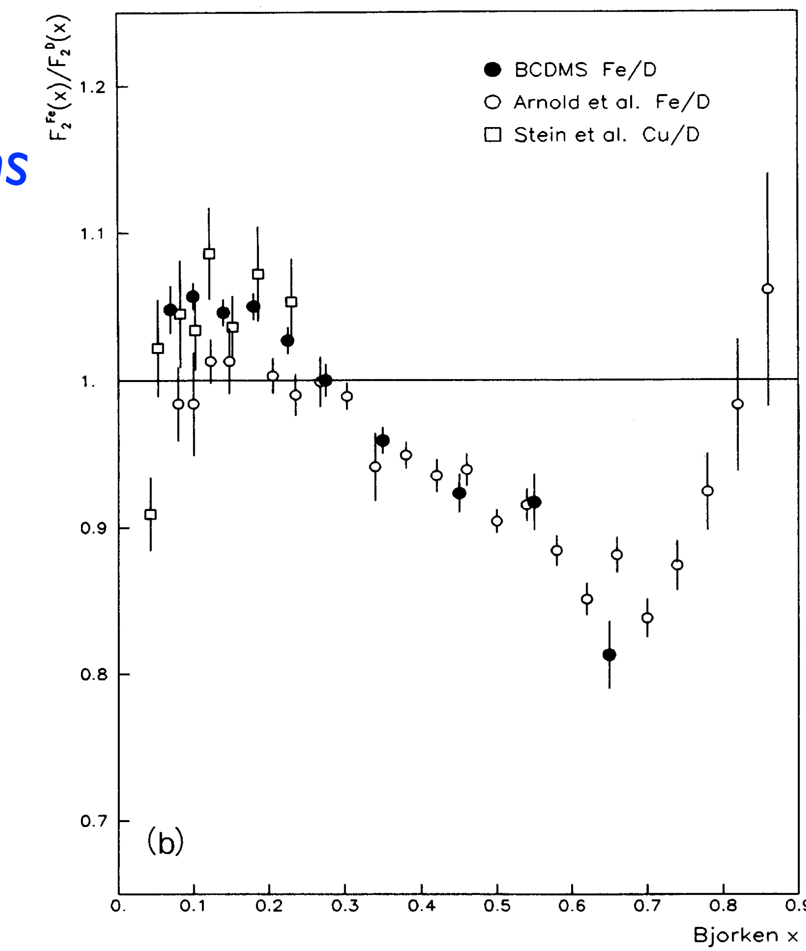
LDRD Nuclear gluons with charm, November 03

DIS (and other hard inclusive processes) = The highest resolution possible for probing the distribution of constituents in hadrons is deep inelastic scattering

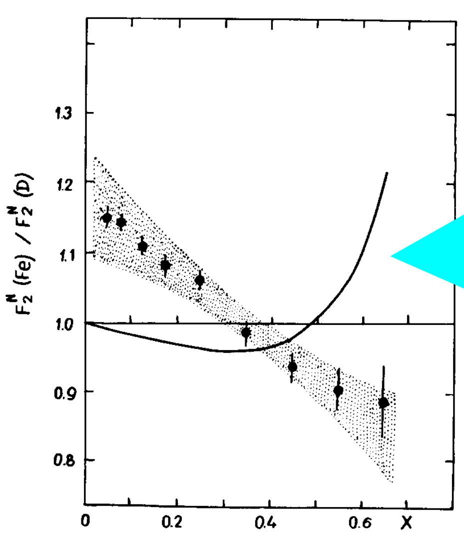
Reference point: nucleus is a collection of quasifree nucleons.

A hard probe incoherently interacts with individual nucleons



EMC ratio

$$R_A(x,Q^2) \equiv \frac{\sigma_A(x,Q^2)}{Z\sigma_p(x,Q^2) + N\sigma_n(x,Q^2)} = 1$$



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

One should not be surprised by presence of the effect but by its smallness for x<0.35 where bulk of quarks are. Since distances between nucleons are comparable to the radii of nucleons.

Large effects for atoms in this limit.

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

$$\overrightarrow{P_A} = \begin{array}{l} \longrightarrow \alpha_1 P_A/A \\ \longrightarrow \alpha_2 P_A/A \\ \rightarrow \alpha_3 P_A/A \end{array} \qquad \alpha_1 + \alpha_2 + \alpha_3 = 3$$

Fermi motion: $\alpha_i \neq 1$

In this case probability to find a quark with momentum xP_A/A in nucleon with momentum $\alpha P_A/A$ is $f_N(x/\alpha)$

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

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

≡probability to find a nucleon with longitudinal momentum $\alpha P_A/A$

Can account of Fermi motion describe the EMC effect?

YES : If one violates baryon charge conservation or momentum conservation or both

Many nucleon approximation:

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

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

fraction of nucleus momentum NOT carried by nucleons

=0 in many nucl. approx

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

Fermi motion - actually SRCs

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

$F_{2N} \propto (1-x)^n, n \approx 2(JLAB)$

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

$n \approx 3(Leading\, twist)$

$n(Jlab) \approx 2(LT + HT)$

R_A for x <(n+1)/2 slightly below and rapidly growing for x > (n+1)/2

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

Traditional nuclear physics:

EMC effect is trivial

λ_A ---fraction of momentum carried by pions is few %

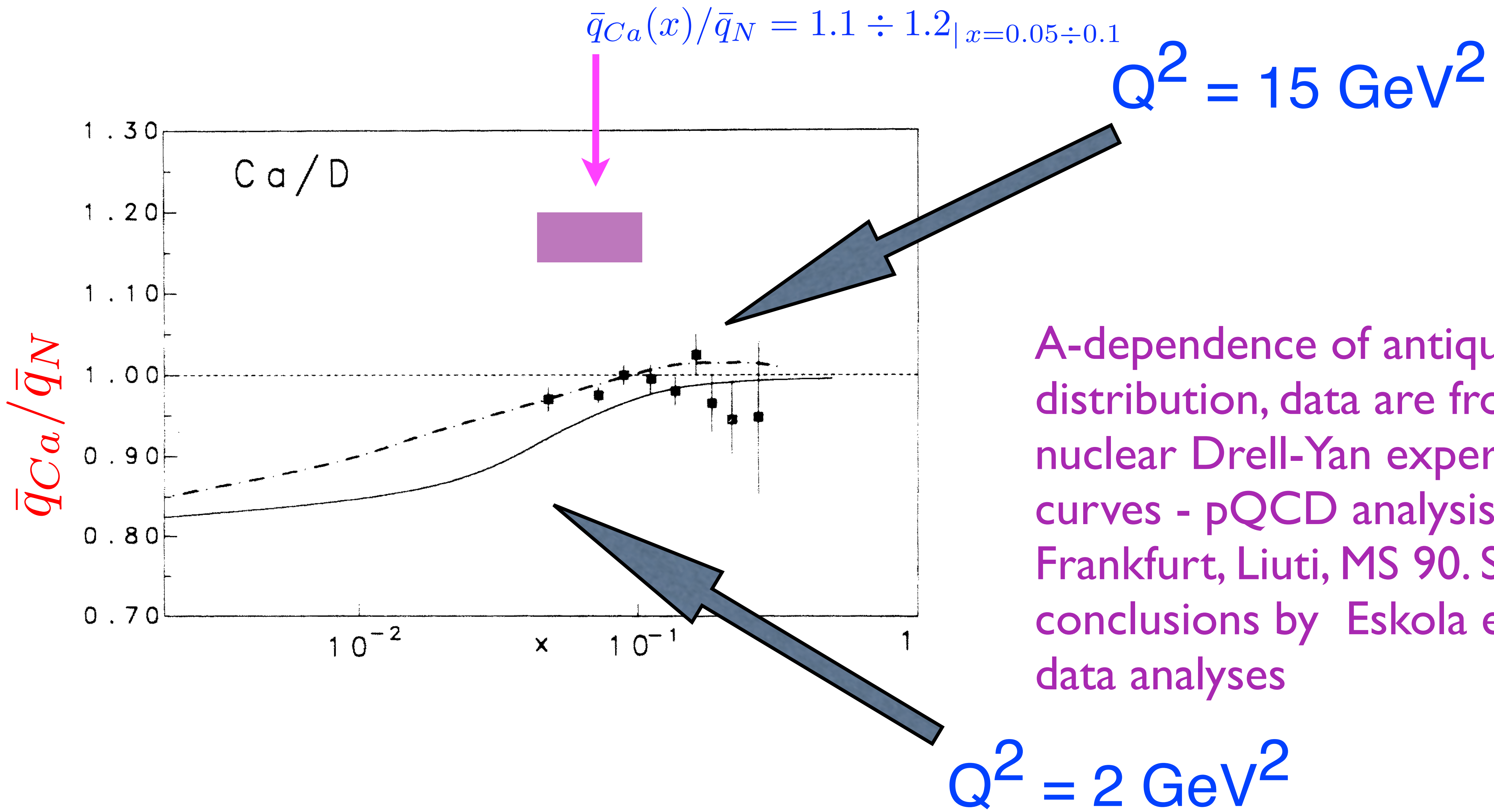
$$R_A(x, Q^2) = 1 - \frac{\lambda_A n x}{1-x}$$

Drell-Yan experiments:

1989 $\bar{q}_{Ca}/\bar{q}_N \approx 0.97$

vs pion model
Prediction

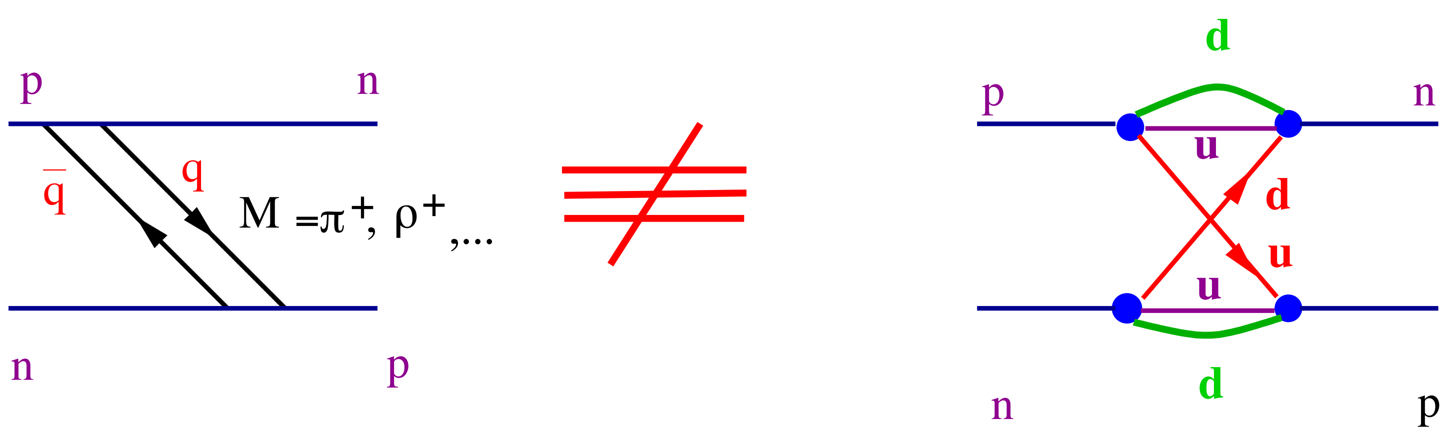
$\bar{q}_{Ca}(x)/\bar{q}_N = 1.1 \div 1.2_{|\,x=0.05 \div 0.1}$



A-dependence of antiquark distribution, data are from FNAL nuclear Drell-Yan experiment, curves - pQCD analysis of Frankfurt, Liuti, MS 90. Similar conclusions by Eskola et al 93-07 data analyses

Pion model addresses a deep question - what is microscopic origin of intermediate and short-range nuclear forces - do nucleons exchange mesons or quarks/gluons? Duality?

A better match to Drell Yan data



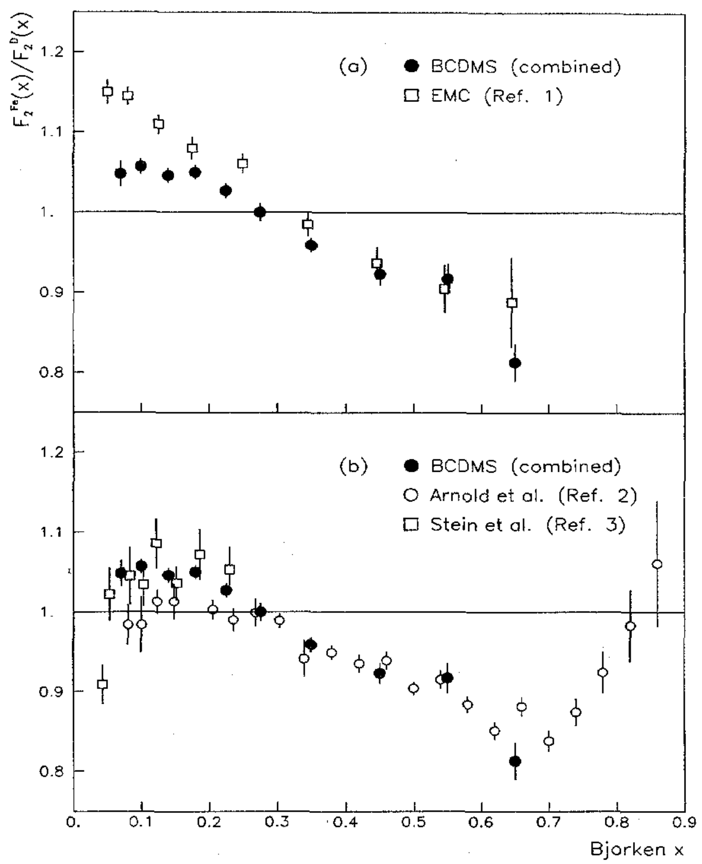
Meson Exchange | ***Quark interchange***

extra antiquarks in nuclei | no extra antiquarks

Before going to theoretical ideas - let us review what can be concluded about pdfs based on DIS and DY data + exact QCD sum rules

Open question is the role of HT - experimentally - good scaling of the ratios at SLAC And Jlab - still x -dependence of HT and LT nucleon pdf is different.

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



DY + DIS → enhancement at x~ 0.1 is due to valence quarks

Bj scaling within 30% accuracy - caveat - HT effects maybe large in SLAC kinematics for x≥ 0.5. Differences of $R_A(x>0.5)$ reported by EMC, NMC and BCDMS are too large for making firm conclusions

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 $\Rightarrow$ enhancement of V_A(x~ 0.1) at least partially

reflection of the EMC effect - some room for contribution compensating valence quark shadowing. FGS12 have an argument now why shadowing for V_A is suppressed.

Comment: the best way to measure V_A/V_N is semi inclusive π^+- π^-

LC momentum sum rule

$$\int_0^A \frac{1}{A} [G_A(x_A, Q^2) + V_A(x_A, Q^2) + S_A(x_A, Q^2)] x_A dx_A \qquad (2)$$

$$- \int_0^1 [G_N(x, Q^2) + V_N(x, Q^2) + S_N(x, Q^2)] x\, dx = 0$$

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

Frankfurt, Liuti, MS90

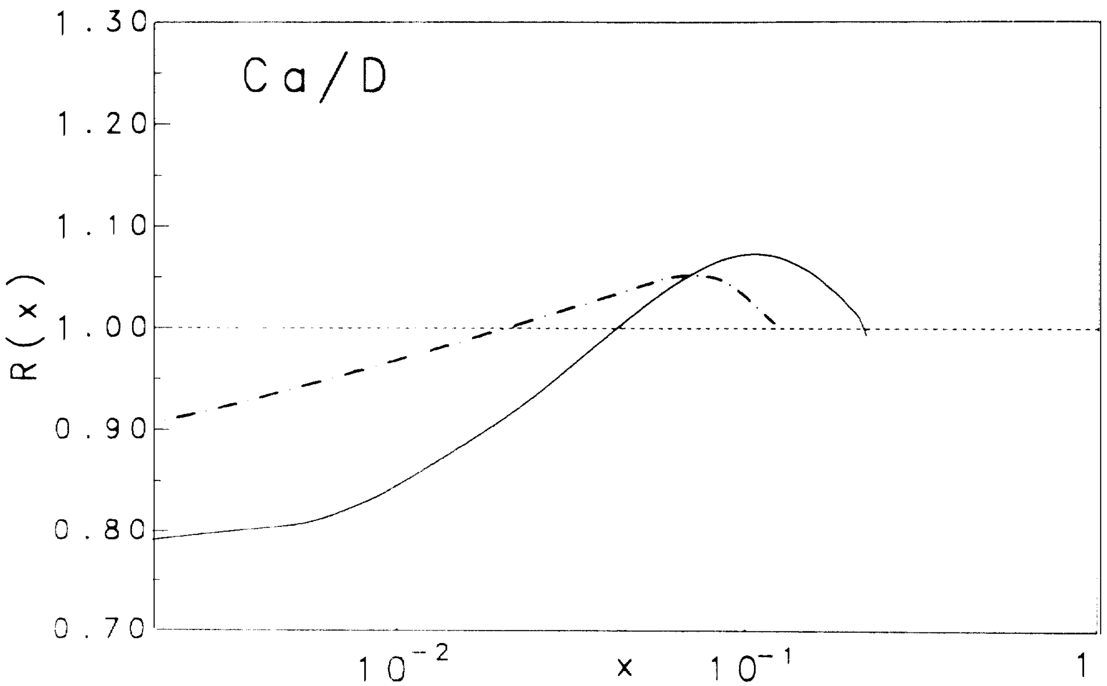
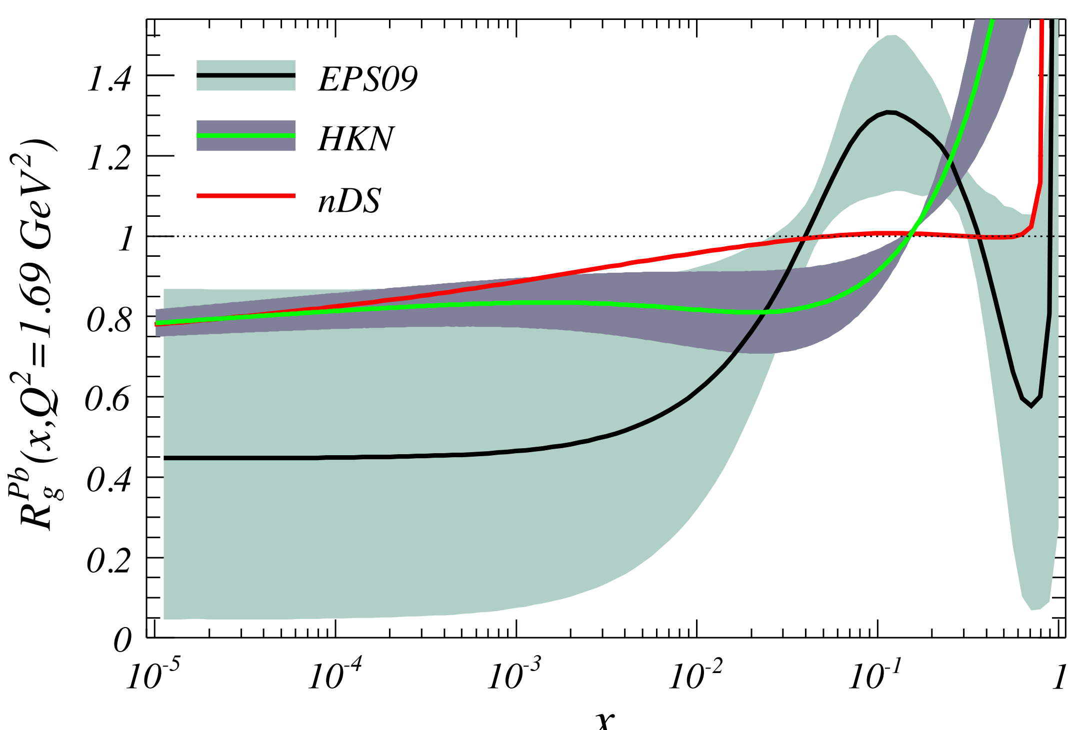


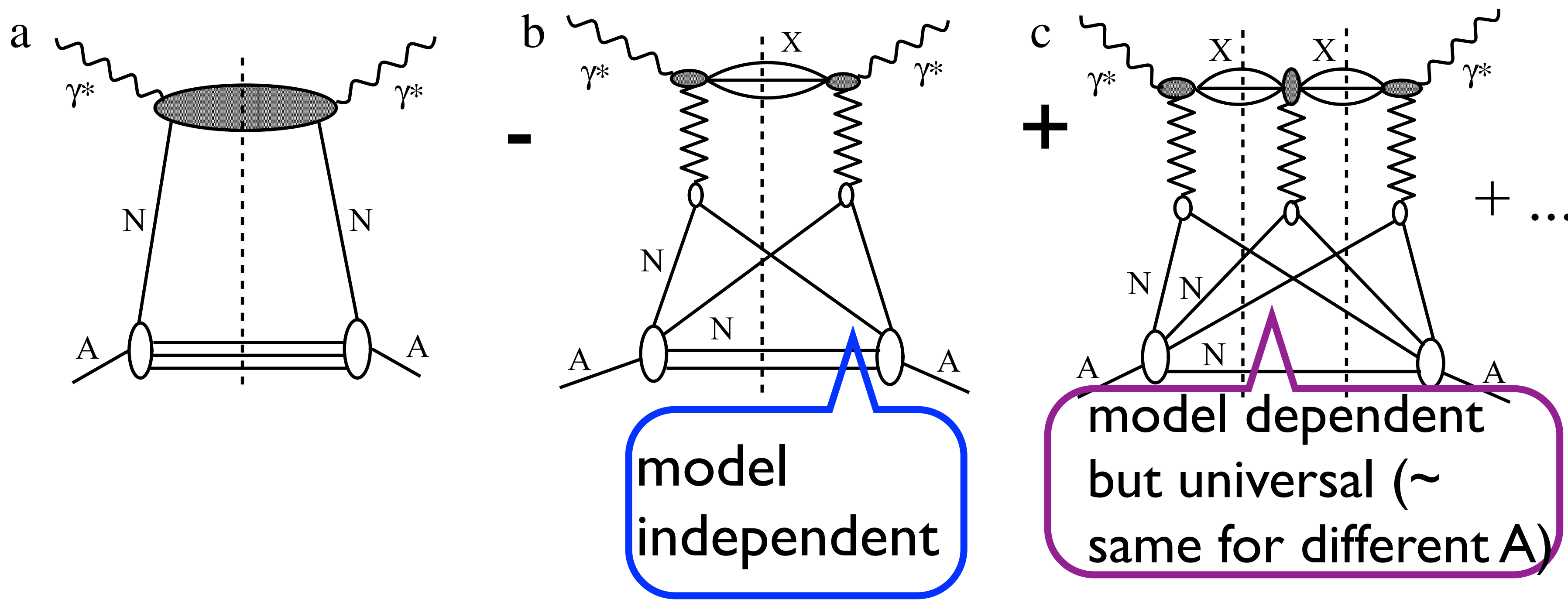
FIG. 1. Ratio $R \equiv R_G(x,Q^2) = (2/A)G_A(x,Q^2)/G_D(x,Q^2)$ plotted vs x, for different values of Q^2: solid line, $Q^2 = 2$ GeV^2; dot-dashed line, $Q^2 = 15$ GeV^2.



Before LHC, g_A/g_N was practically not constrained. Only exception are NMC data on scaling violation at x~0.1 (Sn/C) and J/psi A-dependence (but systematic errors are too large

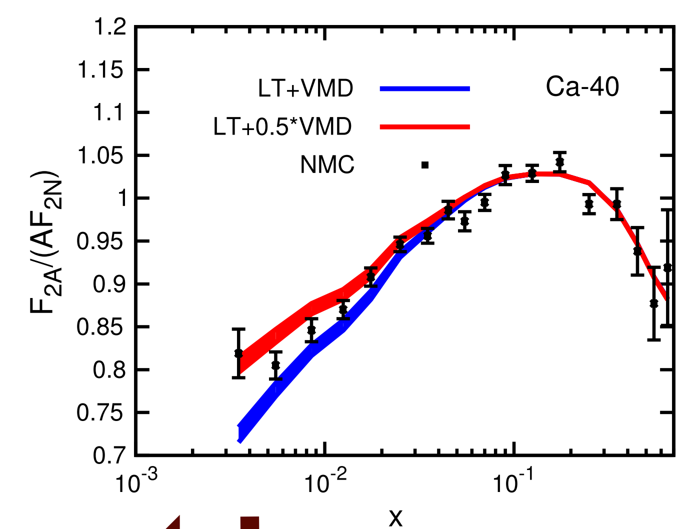
Need theory to calculate small x pdfs

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



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

Before HERA one had to model ep diffraction to calculate shadowing for σ_{γ^*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 γ A scattering without free parameters.



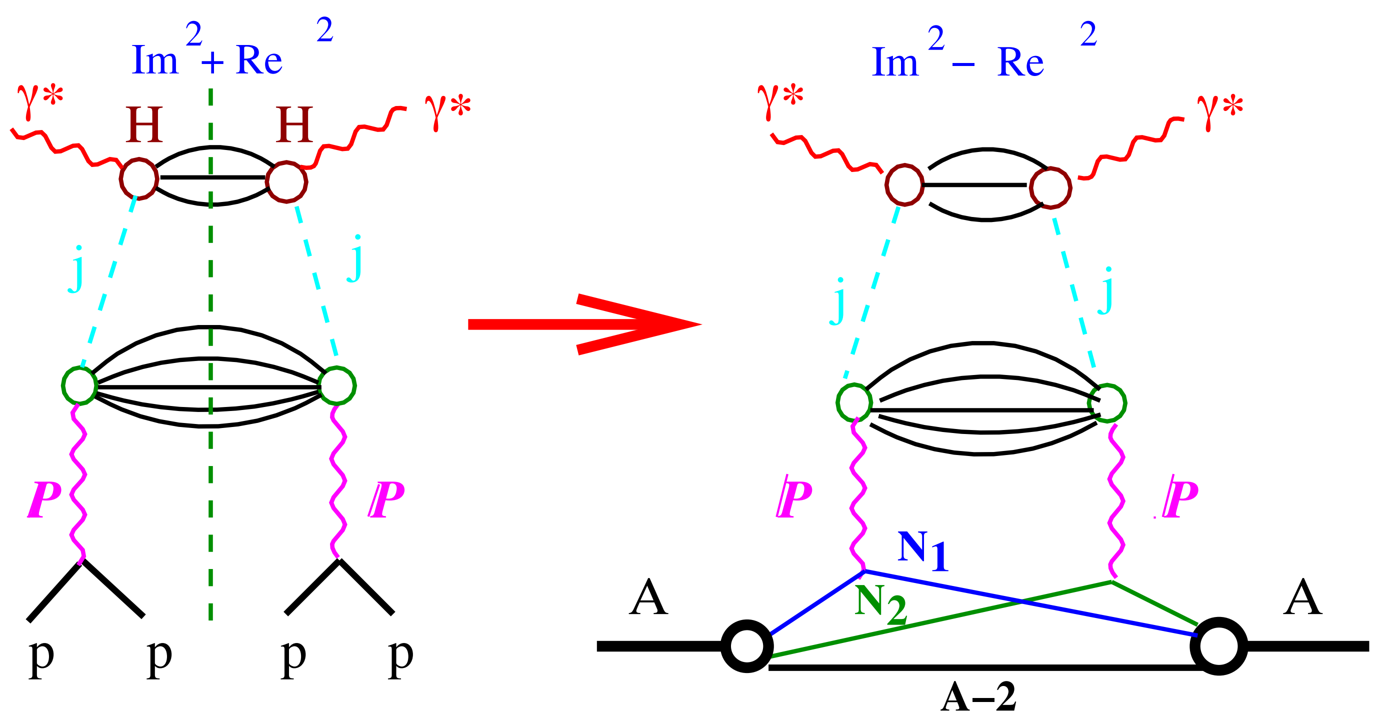
$Q^2 \leq 2\,GeV^2$

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 $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$:



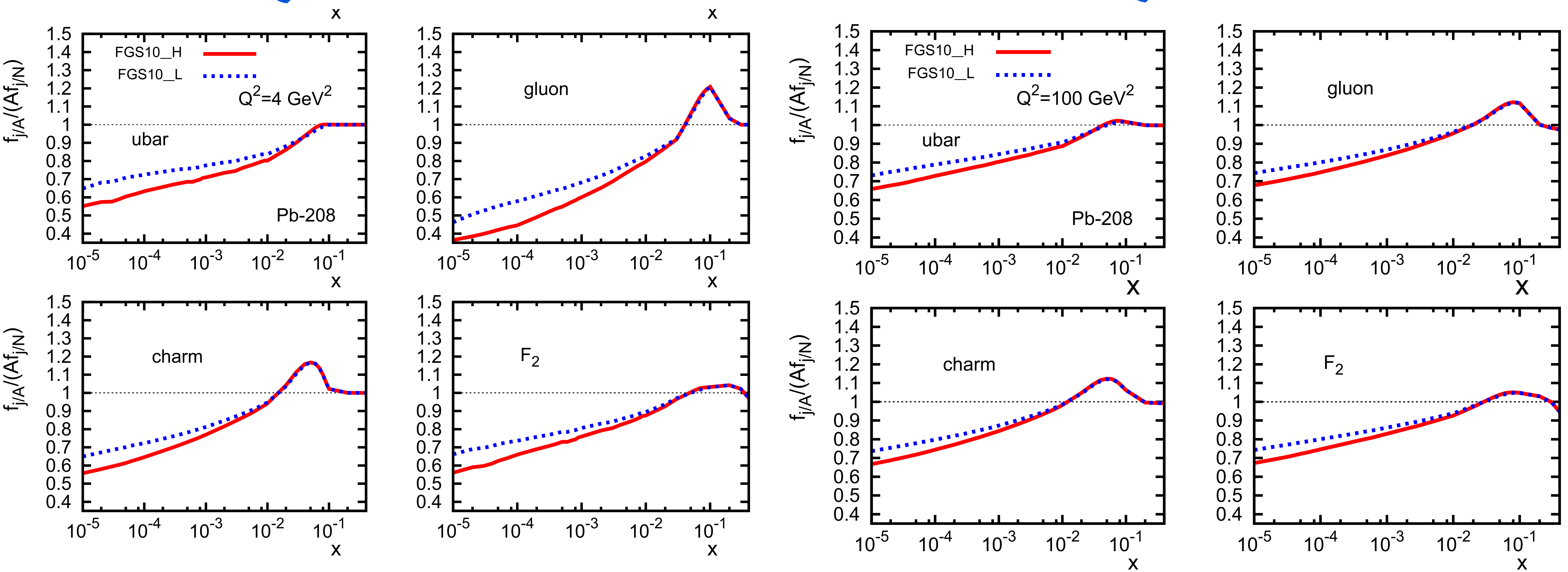
Hard diffraction
off parton "j"

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 $\qquad$ Q^2 = 100 GeV^2

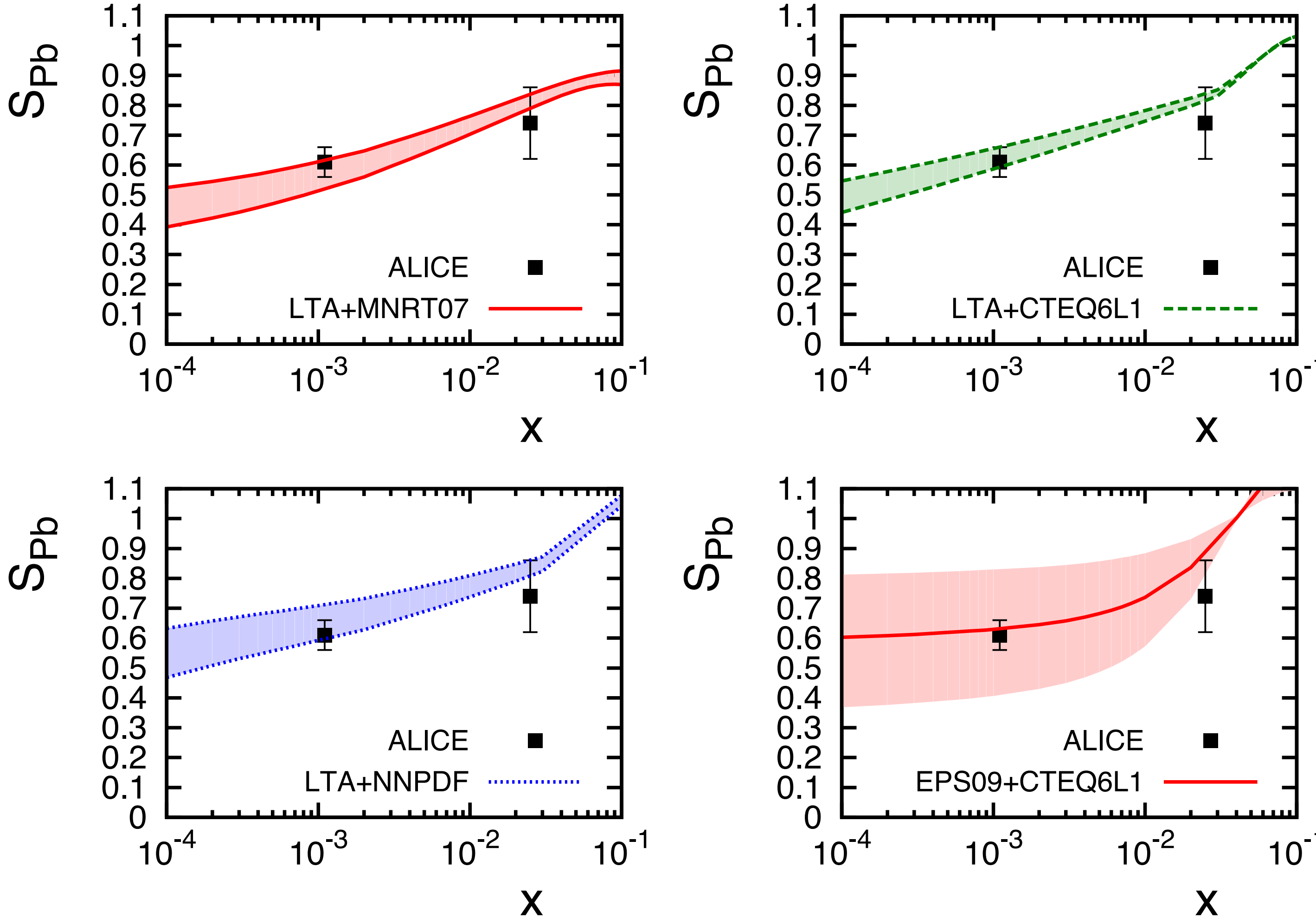


Predictions for nuclear shadowing at the input scale Q^2 = 4 GeV^2. and = 100 GeV^2. The ratios R_j ($\bar{u}$ and c quarks and gluons) and R_{F2} as functions of Bjorken x. Two sets of curves correspond to models FGS10_H and FGS10_L.

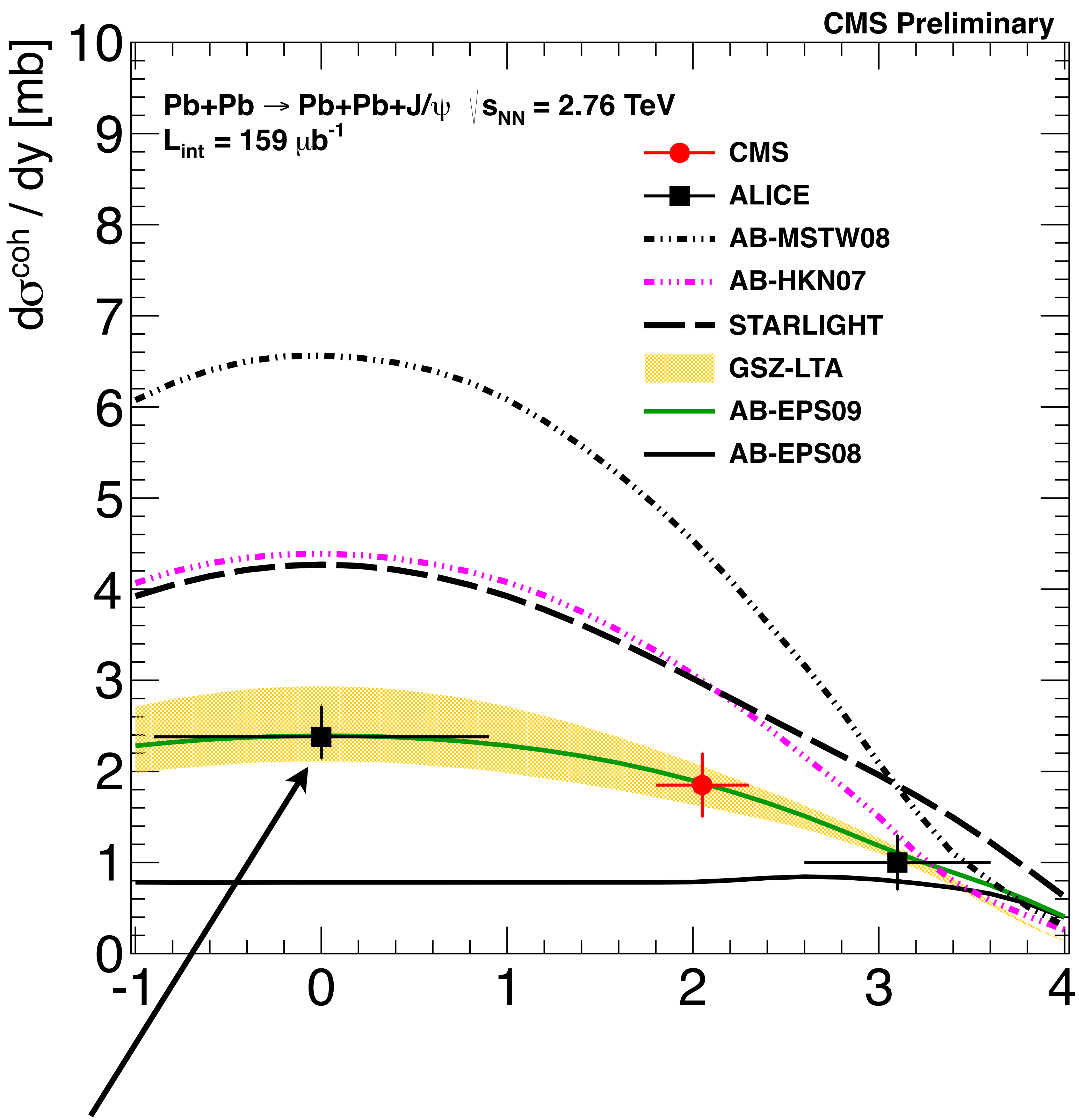
Sum rules require large gluon antishadowing

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.



$\chi = 10^{-3}$ minimal x for EIC

Dijets in p+Pb collisions and their quantitative constraints for nuclear PDFs

Hannu Paukkunen[a,b], Kari J. Eskola[a,b], Carlos Salgado[c]

Nuclear Physics A 00 (2014) 1–4

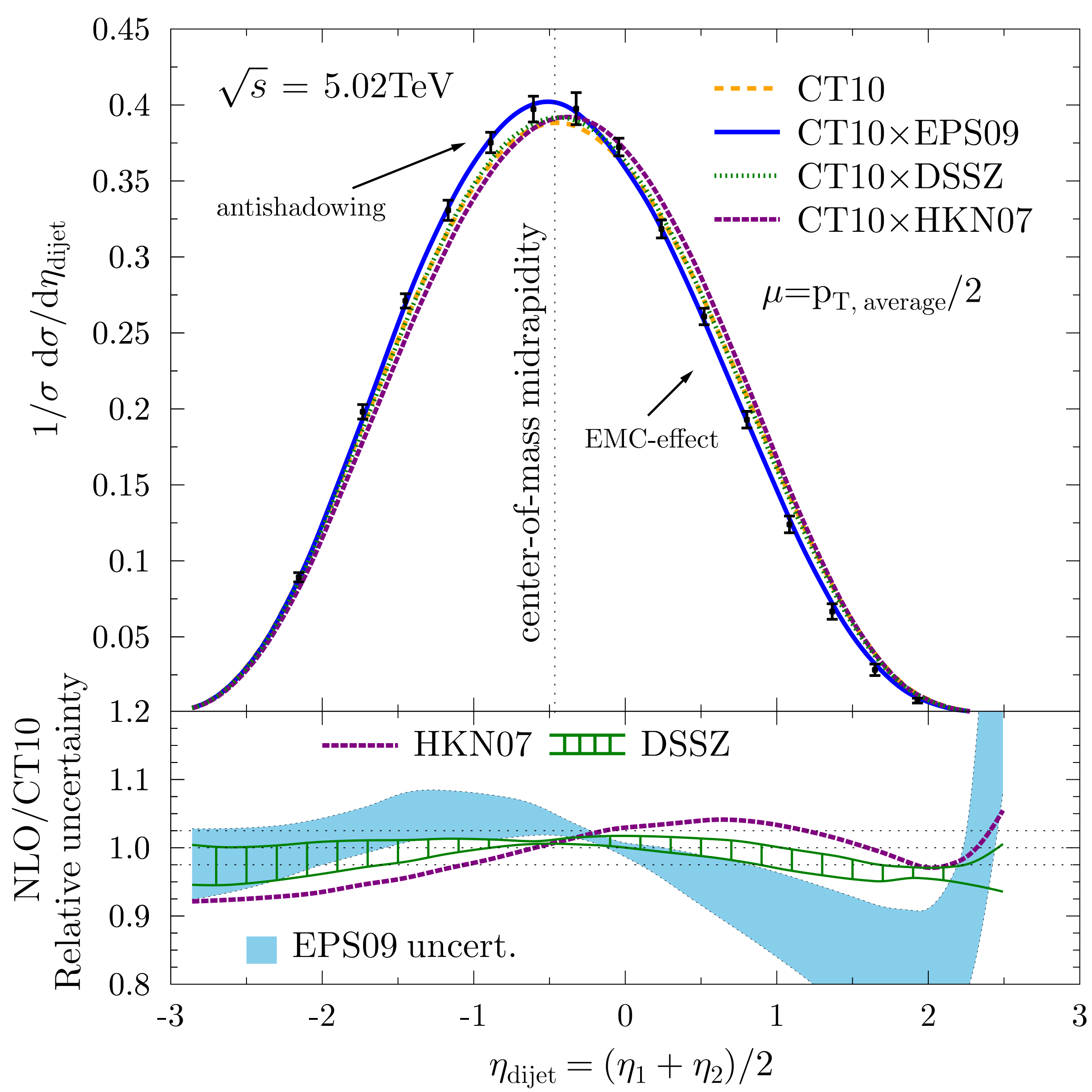


Figure 3. The preliminary CMS dijet data [11] compared to predictions with different PDFs. Figure adapted from [12].

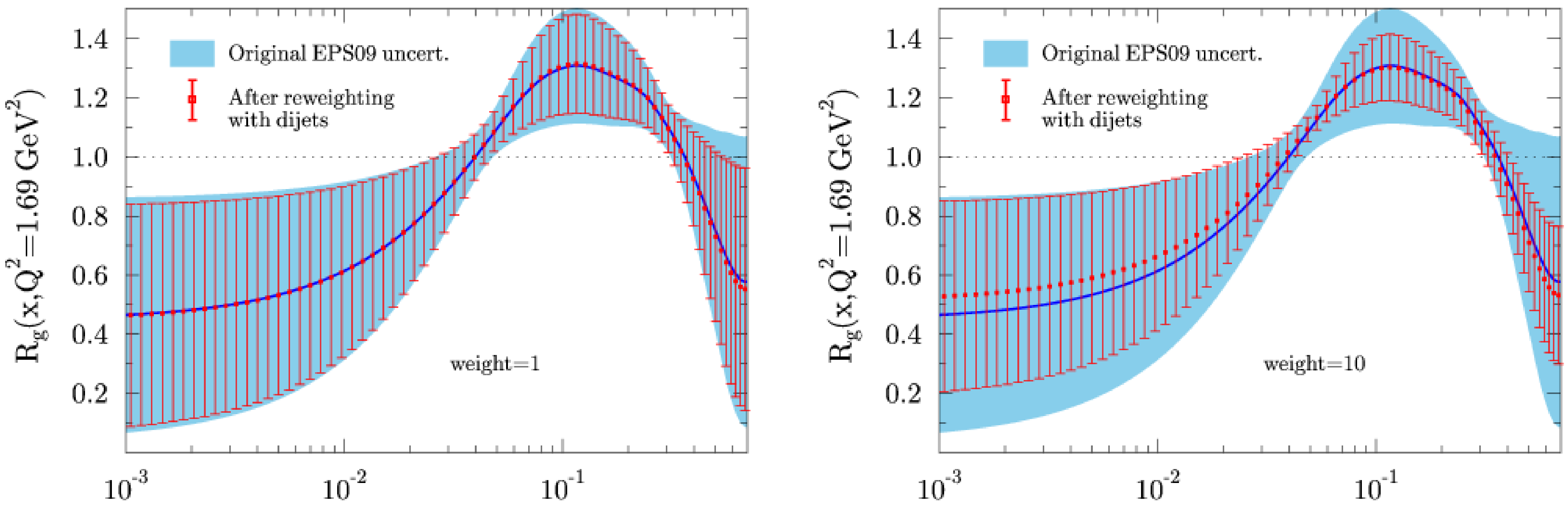


Figure 4. **Left-hand panel:** The EPS09 nuclear modification $R_G(x, Q^2 = 1.69\,\mathrm{GeV}^2)$ before and after the reweighting with CMS p+Pb dijet da
Right-hand panel: As the left-hand panel but giving the dijet data an extra weight of 10.

LHC data are sensitive to antishadowing, EMC effect for gluons is build into parametrization - not constrained by the data

Back to EMC effect at x >0.3

First explanations/models of the EMC effect (no qualitatively new models in 30 years)

- Pionic model: extra pions - λ_π ~ 4% -actually for fitting Jlab and SLAC data ~ 6% for A> 40

  + enhancement from scattering off pion field with α_π~ 0.15

  $$R_A(x,Q^2) = 1 - \frac{\lambda_A n x}{1-x}$$

  killed by DY data

- 6 quark configurations in nuclei with P_{6q}~ 20-30%

- *Nucleon swelling - radius of the nucleus is 20--15% larger in nuclei. Color is significantly delocalized in nuclei*

  Larger size →fewer fast quarks - possible mechanism: gluon radiation starting at lower Q^2

  $$(1/A)F_{2A}(x,Q^2) = F_{2D}(x, Q^2\xi_A(Q^2))/2$$

- Mini delocalization (color screening model) - small swelling - enhancement of deformation at large x due to suppression of small size configurations in bound nucleons + valence quark antishadowing with effect roughly $\propto$ k_{nucl}^2

Traditional nuclear physics strikes back:

EMC effect is just effect of nuclear binding : account for the nucleus excitation in the final state: $e + A \to e' + X + (A-1)^*$

First try: baryon charge violation because of the use of non relativistic normalization

Second try: fix baryon charge ➔ violate momentum sum rule

Third try (not always done) fix momentum sum rule by adding mesons

⇓

version of pion model

Do we know that properties of nucleons in nuclei the same as for free nucleons?

Cannot use info from low momentum transfer processes - quasiparticles, complicated interactions of probe with nucleons: Nucleon effective masses ~0.7 m_N, strong quenching for A(e,e'p) processes: suppression factor Q~0.6 practically disappears at Q^2=1 GeV^2 .

Analysis of (e,e') SLAC data at x=1 -- tests Q^2 dependence of the nucleon form factor for nucleon momenta k_N < 150 MeV/c and Q^2 > 1 GeV^2 :

☛ $$r_N^{bound}/r_N^{free} < 1.036$$

Similar conclusions from combined analysis of (e,e'p) and (e,e') JLab data

Analysis of elastic pA scattering $|r_N^{\rm bound}/r_N^{\rm free} - 1| \lesssim 0.04$

Problem for the nucleon swelling models of the EMC effect which need 20% swelling

Theoretical analysis of the (p,ppn), (e,e'pN) data: Very strong correlation - removal of proton with $k > 250$ MeV/c - leads in 90% cases to emission of neutron, in 10% - proton.

Combined analysis of (e,e') and knockout data

Structure of 2N correlations - probability ~ 20% for A>12

→ dominant but not the only term in kinetic energy

90% pn + 10% pp < 10% exotics ⇒ probability of exotics < 2%

- *EVA BNL 5.9 GeV protons (p,2p)n* $-t = 5\ GeV^2;\ t = (p_{in} - p_{fin})^2$

- *(e,e' pp), (e,e'pn) Jlab* $Q^2 = 2 GeV^2$

Different probes, different kinematics - the same pattern of very strong correlation - Universality is the answer to a question: "How to we know that (e,e'pN) is not due to meson exchange currents?"

One cannot introduce large exotic component in nuclei - 20 % 6q, Δ's

Very few models of the EMC effect survive when constraints due to the observations of the SRC are included as well as lack of enhancement of antiquarks and Q^2 dependence of the quasielastic (e,e') at x=1

- essentially one scenario survives - strong deformation of rare configurations in bound nucleons increasing with nucleon momentum and with most of the effect due to the SRCs .

<u>A-dependence of R_A</u> $1 - R_A(x,Q^2) = f(A) \cdot g(x,Q^2)$ for x <0.7

$$f(A) \propto < k^2 >, \, average \, excitation \, energy, \, a_2$$

$$f(A) \propto < \rho(r_1)\rho(r_2)\theta(r_0 - |r_1 - r_2|), \; r_0 \sim 1.2 \, fm$$

At x > 0.7 graduate transition to regime $R_A(x,Q^2) \propto a_2(A)$

Dynamical model - color screening model of the EMC effect

(FS 83-85)

Combination of two ideas:

(a) Quark configurations in a nucleon of a size << average size (PLC) should interact weaker than in average. Application of the variational principle indicates that probability of such configurations in nucleons is suppressed.

(b) Quarks in nucleon with $x>0.5$ --0.6 belong to small size configurations with strongly suppressed pion field - while pion field is critical for SRC especially D-wave.

test was possible in pA LHC run in March 2013

In color screening model modification of **average** properties is < 2- 3 %.

Introducing in the wave function of the nucleus explicit dependence of the internal variables we find for weakly interacting configurations in the first order perturbation theory using closer we find

$$\tilde{\psi}_A(i) \approx \left(1 + \sum_{j \neq i} \frac{V_{ij}}{\Delta E}\right) \psi_A(i)$$

where $\Delta E \sim m_{N^*} - m_N \sim 600 - 800\, MeV$ average excitation energy in the energy denominator. Using equations of motion for ψ_A the momentum dependence for the probability to find a bound nucleon, $\delta_A(p)$ with momentum p in a PLC was determined for the case of two nucleon correlations and mean field approximation. In the lowest order $\delta_A(p) = 1 - 4(p^2/2m + \epsilon_A)/\Delta E_A$

After including higher order terms we obtained for SRCs and for deuteron:

$$\delta_D(\mathbf{p}) = \left(1 + \frac{2\frac{\mathbf{p}^2}{2m} + \epsilon_D}{\Delta E_D}\right)^{-2}$$

Accordingly $$\frac{F_{2A}(x,Q^2)}{F_{2N}(x,Q^2)} - 1 \propto \langle\delta(p)\rangle - 1 = -4\left\langle\frac{\frac{\mathbf{p}^2}{2m}+\epsilon_A}{\Delta E_A}\right\rangle$$

which to the first approximation is proportional the average excitation energy and hence roughly to $a_2(A)$, which proportional to $<\rho^2(r)>$ for A>12 (FS85).
Accuracy is probably not better than 20%.But roughly it works - see Jlab studies

We extended calculations to the case of scattering off A=3 for a final state with a certain energy and momentum for the recoiling system FS & Ciofi Kaptari 06.
Introduce formally virtuality of the interacting nucleon as

$$p_{int}^2 - m^2 = (m_A - p_{spect})^2 - m^2.$$

Find the expression which is valid both for A=2 and for A=3(both NN and deuteron recoil channels):

$$\delta(p, E_{exc}) = \left(1 - \frac{p_{int}^2 - m^2}{2\Delta E}\right)^{-2}$$

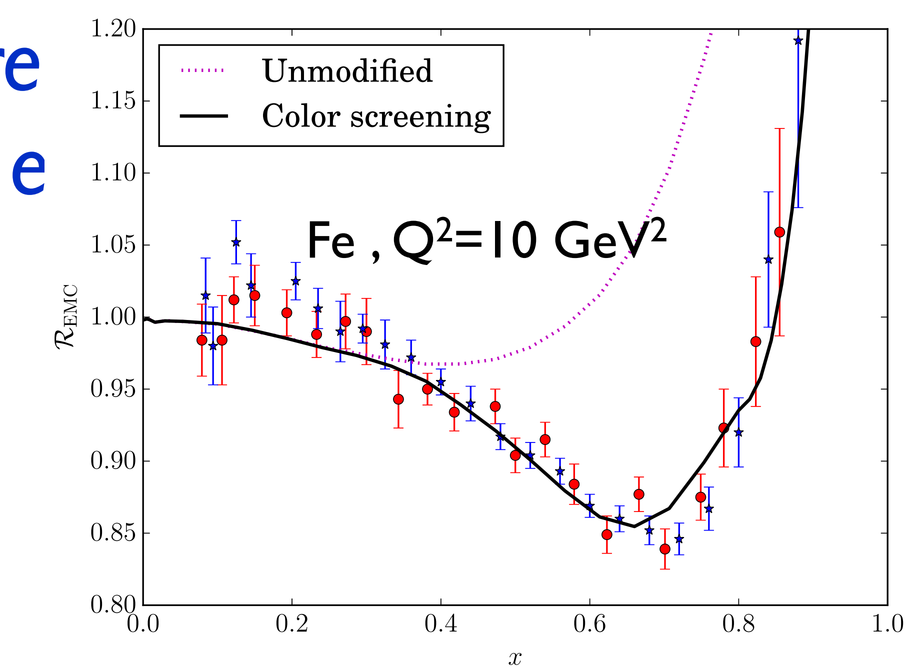
Dependence of suppression we find for small virtualities: $1-c(p^2_{int}-m^2)$

seems to be very general for the modification of the nucleon properties. Indeed, consider analytic continuation of the scattering amplitude to $p^2_{int}-m^2=0$. For this point modification should vanish. Our quantum mechanical treatment of 85 automatically took this into account.

Our dynamical model for dependence of bound nucleon pdf on virtuality - explains why effect is large for large x and practically absent for $x \sim 0.2$ (average configurations $V(conf) \sim \langle V \rangle$)

This generalization of initial formula allows a more accurate study of the A-dependence of the EMC e

Simple parametrization of suppression: no suppression $x \leq 0.45$, by factor $\delta_A(k)$ for $x \geq 0.65$, and linear interpolation in between

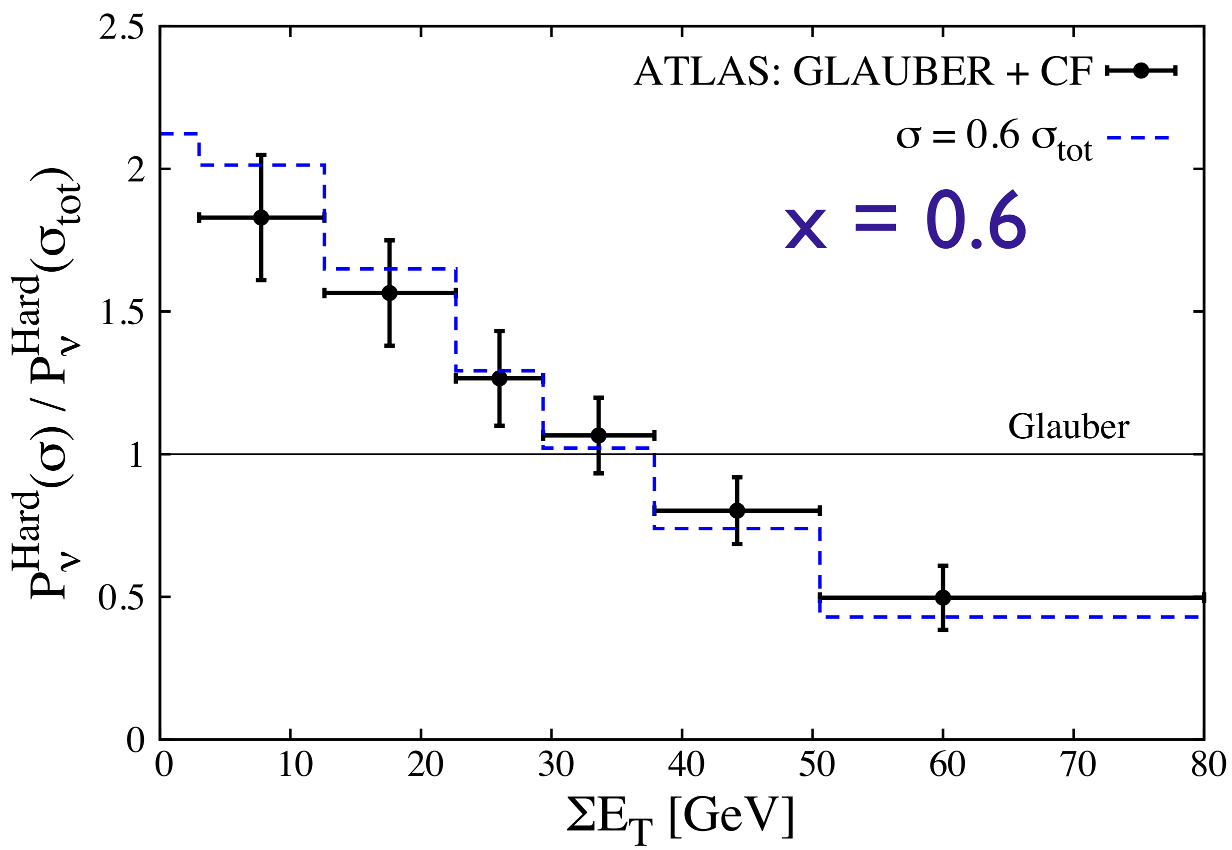


Freese, Sargsian, MS 14

Critical test we suggested in 1983:

pA scattering with trigger on large x hard process. If large x corresponds to small sizes hadron production will be suppressed. In other words - trigger for large activity - suppression of events with large x.

ATLAS and CMS report the effect of such kind. Our analysis (M.Alvioli, B.Cole. LF, . D.Perepelitsa, MS) suggests that for x~ 0.6 the transverse size of probed configurations is a factor of 0.6 smaller than average.



Relative probability of hard processes corresponding to a small σ selection as a function of ΣE_T . ATLAS data are for x = 0.6 with black crosses taking into account the difference between number of wounded nucleons calculated in the Glauber and CF approaches

Expectations for gluon EMC ratio for x >0.2

$$xG_N(x,Q^2 \sim 5\,GeV^2) \propto (1-x)^n,\, n \approx 5$$

If no EMC effect for gluons the crossover point from small suppression to enhancement is

$$x_{cross} = \frac{2}{n+1} = 0.33$$

In the color screening model squeezing of size of configuration with valence gluon likely already for x >0.2 - so suppression may show up effect. Does not contradict the LHC pA centrality data, but more detailed analysis is necessary.

In the rescaling model -- suppression already at x=0.1. Antishadowing?

Overall - my impression is that G_A/G_N suppression is likely at large x, but whether it starts already at x ~ 0.2 is an open question. If suppression starts only at x=0.3 it maybe masked by the Fermi motion and one would need nucleon tagging to look for this effect.

Conclusions

Well grounded expectations for enhancement of gluons in nuclei at $x \sim 0.1$ and of shadowing at $x < 10^{-2}$

Realistic to measure with charm tagging

Possible EMC effect at $x > 0.2$ - challenging measurement even with charm (but potential prize is high). All alternative methods are even less promising.