# $\overset{(-)}{\nu}$ A scattering at moderate energies

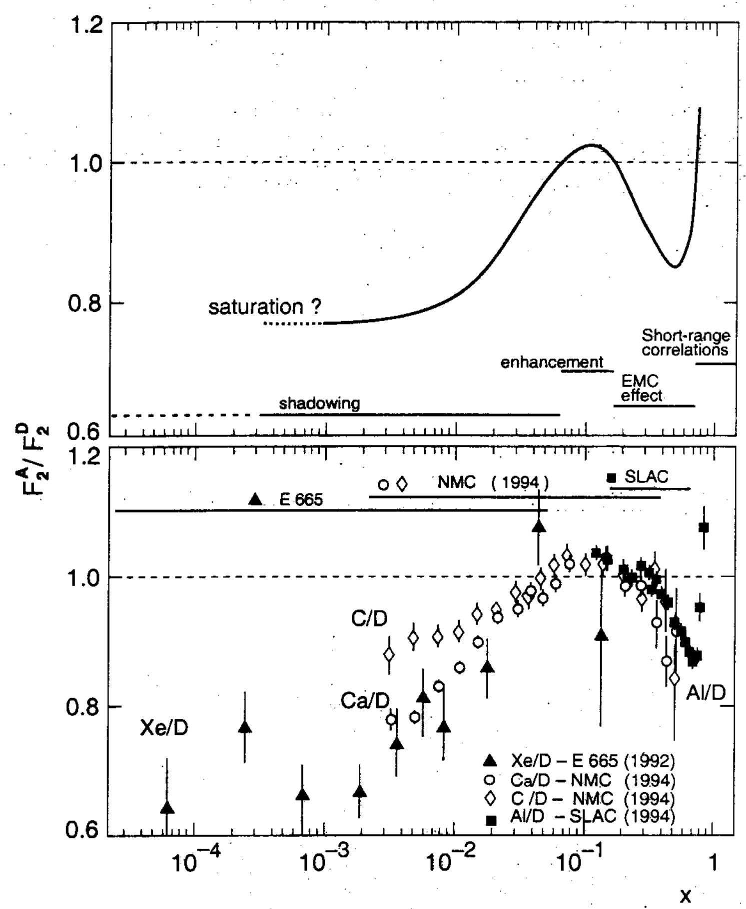
– what they can add to the studies/understanding of nuclear structure and strong interaction dynamics

M. Strikman (PSU)

1. A-dependence of parton densities
   – open questions.

2. Higher twists for $\nu$ scattering off nuclei
   – why they should be large.

# Summary of the current information on A-dependence of parton densities at $x \leq 0.2$




Results for $\boxed{R_A(x,Q^2) = \frac{2}{A}\frac{F_{2A}(x,Q^2)}{F_{2D}(x,Q^2)}}$:

- $x \sim 0.1$ enhancement: $R_{A=40}(x \sim 0.1) \sim 1.05$
- Shadowing for $x \leq 0.04$
- $Q^2$ scaling of $R_A(x,Q^2)$

all of EMC effect for $x \geq 0.5$

- new physics

Model independent statement

if
- baryon charge of nucleus carried by N's
- momentum of nucleus carried by N's

$$\Downarrow$$

$$F_{2A}(x,Q^2)/F_{2N}(x,Q^2)\Big|_{x\geq 0.5} > 1$$

FS 81-85

"binding" calculation of the EMC effect violates the momentum sum rule.

## Implications of the leading twist QCD momentum and baryon sum rules

Frankfurt, Liuti, MS 88-90

The momentum sum rule ($x_A = AQ^2/2q_0 m_A$):

$$\int_0^A dx_A \frac{x_A}{A}\left[\sum_{i=u,d,s,..}(q_A^i(x_A,Q^2)+\bar{q}_A^i(x_A,Q^2))+G_A(x_A,Q^2)\right]=1$$

The baryon sum rule:

$$\frac{1}{A}\int_0^A dx_N(q_A^i(x_A,Q^2)-\bar{q}_A^i(x_A,Q^2))=\int_0^1(q_N^i(x_N,Q^2)-\bar{q}_N^i(x_N,Q^2))$$

$+$ NMC data for $R_A(x,Q^2)$

$$\Downarrow$$

$$\frac{\int_0^A dx_A \frac{x_A}{A} G_A(x_A,Q^2)}{\int_0^1 dx_N x_N G_N(x_N,Q^2)} = 1-\epsilon(A), \quad \epsilon(A\sim 40)\sim 10^{-2}$$

QCD aligned jet model + sum rules for baryon charge + momentum



# Evidence for Enhancement of Gluon and Valence-Quark Distributions in Nuclei from Hard Lepton-Nucleus Processes

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Current data on deep-inelastic processes off nuclei are analyzed by using exact QCD sum rules for the total momentum and baryon charge of nuclei. Evidence for an overall enhancement of the gluon field in heavy nuclei ($\geq 4\%$) is found which, combined with the calculation of nuclear shadowing, yields a substantial enhancement of valence-quark and gluon distributions at $x \approx 0.1$, as well as a suppression of the sea for $x \leq 0.1$. It is also shown that scaling violations lead to a strong decrease of shadowing for the sea at $x \approx 0.05$. Implications for disentangling the origin of internuclear forces are further discussed.

PACS numbers: 25.30.Mr, 12.38.Lg, 13.60.Hb, 25.40.Ve

Wrong $g_A/g_N < \bar{q}_A/\bar{q}_N$ at small $x$ FS 98

The main aim of this Letter is to analyze the implications for the nuclear structure of current experimental results on parton distributions in nuclei at small values of $x$ obtained both in deep-inelastic muon-nucleus scattering[1,2] and in the Drell-Yan process.[3] We show that valence-quark and gluon distributions in nuclei are enhanced at $x \approx 0.1$, namely, for the kinematics where essential longitudinal distances in deep-inelastic processes, $l$ ($l \approx 1/2M_N x$ in the nucleus rest frame), are comparable with mean internucleon distances $r_{NN}$:

$$r_{NN} = 1.7\ \text{fm} > 1/2M_N x > r_N = 0.6\ \text{fm}\,, \tag{1}$$

$r_N$ being the nucleon radius (the nontrivial relationship between the nucleus-rest-frame and the infinite-momentum-frame descriptions at small $x$ is discussed at length in Ref. 4).

In the first step of our analysis we use only exact QCD sum rules for parton distributions in nuclei, while in the second step we add information from calculations of nuclear shadowing at small $x$.[4,5] The sum rules for the baryon-charge and total-momentum conservation in nucleus $A$ may be written as

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

and

$$\int_0^A \frac{1}{A}[G_A(x_A,Q^2)+V_A(x_A,Q^2)+S_A(x_A,Q^2)]x_A\,dx_A - \int_0^1 [G_N(x,Q^2)+V_N(x,Q^2)+S_N(x,Q^2)]x\,dx = 0\,, \tag{3}$$

where $V_A, G_A, S_A$ and $V_N, G_N, S_N$ represent the valence, gluon, and sea parton distributions in nucleus $A$ and in the free nucleon, respectively. Moreover, $x$ is the usual Bjorken variable, whereas $x_A = AQ^2/2M_A q_0 = AM_N/M_A x$. Equations (2) and (3) are valid for $Q^2 \geq Q_0^2 \approx 1\text{-}2\ \text{GeV}^2$, where the parton model seems to be applicable.

Since, for an isoscalar target,

$$\frac{F_2^{A(N)}(x,Q^2)}{x} = \frac{5}{18}[V_{A(N)}(x,Q^2)+S_{A(N)}(x,Q^2)] - \frac{s_{A(N)}(x,Q^2)+\bar{s}_{A(N)}(x,Q^2)}{6} \tag{4}$$

[$s_{A(N)}$ ($\bar{s}_{A(N)}$) being the strange-quark (-antiquark) distribution] and, experimentally, $\int_0^1 G_N(x,Q^2)x\,dx \approx 0.5$, one can define (neglecting contributions from the charm sea which are very small for the values of $Q^2$ of interest)

$$\gamma_G^A = \frac{\int_0^A (1/A) G_A(x_A,Q^2)x_A\,dx_A}{\int_0^1 G_N(x,Q^2)x\,dx} - 1 \tag{5a}$$

or, equivalently,

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

Equation (5b) can be calculated by using the New Muon Collaboration data[1] on the ratio between the second moments for $F_2^A$ in $^{40}$Ca and in the deuteron. By disregarding both the change of gluon momentum in the deuteron with respect to the free nucleon (i.e., by assuming $\gamma_G^D = 0$ for $A = 2 \equiv D$) and the possible change in the strange sea, we find for $^{40}$Ca,

$$\gamma_G^A = (2.18 \pm 0.28 \pm 0.50)\% , \tag{6a}$$

$$\gamma_G^A = (2.31 \pm 0.35 \pm 0.39)\% , \tag{6b}$$

corresponding to Ref. 1(a) [Eq. (6a)] and Ref. 1(b) [Eq. (6b)], respectively.

Nevertheless, it is natural to expect that $\gamma_G^D > 0$, though much smaller than $\gamma_G^A$ ($\gamma_G^D/\gamma_G^A \approx \frac{1}{10} - \frac{1}{5}$ for $A = 40$; cf. Ref. 4); moreover, accounting for the strange-quark term in Eq. (4) would somewhat increase the value of $\gamma_G^A$, provided the strange-sea distribution in nuclei has a dependence upon $A$ similar to the one found for the nonstrange distribution (for the nonstrange sea, both deep-inelastic muon data[1,2] and Drell-Yan data[3] show a decrease with $A$ of the momentum fraction). If the above corrections are taken into account, the value of $\gamma_G^A$ [Eqs. (6)] is enhanced by 0.2%–0.7%.

$\gamma_G^A$ should increase with $A$ due to the increase of the mean nuclear density $\langle \rho_A \rangle$ with $A$. In fact, an enhancement of the gluon field in nuclei is likely to arise in the range $x > 0.05$, where the gluon component of the virtual photon interacts mostly with two nucleons (see Ref. 5 and discussion below); thus for small nuclear densities, $\gamma_G^A \propto \langle \rho_A \rangle$, whereas in the case of nuclear matter (NM),

$$\gamma_G^{A \to \infty} \approx \gamma_G^A \rho_{\rm NM} / \langle \rho_A \rangle \approx 4\% , \tag{7}$$

where $\rho_{\rm NM}$, the nuclear-matter density, is taken equal to 0.17 fm$^{-3}$. Note that, due to scaling violations, $\gamma_G^A$ decreases with increasing $Q^2$, mostly because of the anomalous dimension of the difference between the second moments of $G_A$ and $G_N$ which is equal to $\frac{50}{81}$. $\gamma_G^A$ was evaluated in Eqs. (5)–(7) by using the experimental determination of the ratio between the second moments for $F_2^A$ and $F_2^N$, corresponding to $Q^2 \gtrsim 3$ GeV$^2$;[1] accounting for scaling violations thus leads to a 20% increase of $\gamma_G^A$ at $Q_0^2 \approx 1$ GeV$^2$ (for $\Lambda = 200$ MeV), with respect to the values given in Eqs. (6) and (7).

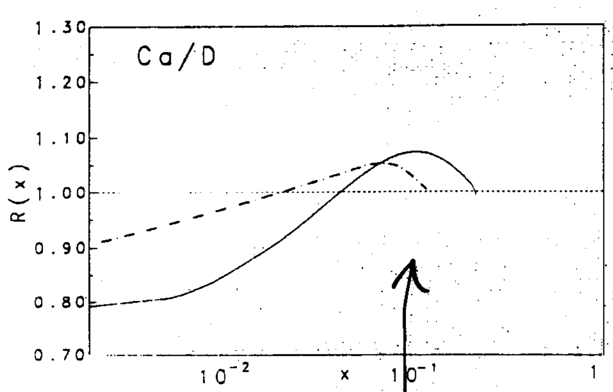


FIG. 1. Ratio $R \equiv R_G(x,Q^2) = (2/A) G_A(x,Q^2)/G_D(x,Q^2)$ plotted vs $x$, for different values of $Q^2$: solid line, $Q^2 = 2$ GeV$^2$; dot-dashed line, $Q^2 = 15$ GeV$^2$.

Therefore, we conclude that in the nonperturbative parton wave function for nuclear matter, the gluon field is enhanced by about 5%, whereas the momentum carried by charged partons is depleted by the same amount.

The second question we want to address concerns the value of $x$ at which the enhancement of the gluon field is concentrated. In Ref. 5 it was demonstrated that shadowing of the soft component of the nuclear wave function is responsible for the nuclear shadowing of $F_2^A$ which was observed in Refs. 1 and 2. Similarly, we expect shadowing of the gluon field $G_A(x,Q_0^2)$ to be of the same magnitude as for $F_2^A(x,Q_0^2)$, since the essential longitudinal distances for small $x$ are practically equivalent in both the gluon and quark channels (cf. discussion in Ref. 4). Thus, one may write

$$\frac{G_A(x,Q_0^2)}{A G_N(x,Q_0^2)} \approx \left. \frac{F_2^A(x,Q_0^2)}{A F_2^N(x,Q_0^2)} \right|_{x < x_{\rm sh} = 0.01-0.02} . \tag{8}$$

At the same time, the positive contribution to $\gamma_G^A$ should arise from the region of relatively small $x$ where both Eq. (1) and the requirement that the virtual-photon components can interact with two nucleons are satisfied ($x \le 0.15$). Thus, it is natural to expect the positive contribution to $\gamma_G^A$ to be localized in the region $x_0 < x < x_1$, where $x_0 \approx 0.05$ ($x > x_{\rm sh}$) and $x_1 \le 0.15$. The mean value of the enhancement factor in this $x$ range is given by

$$c_G(A) = \frac{\int_{x_0}^{x_1} [(1/A) G_A(x,Q_0^2) - G_N(x,Q_0^2)] x\, dx}{\int_{x_0}^{x_1} G_N(x,Q_0^2) x\, dx} . \tag{9}$$

For $^{40}$Ca we find, based on the above value of $\gamma_G^A$, $c_G(A) = 0.06$ when the negative contribution in Eq. (3) in the $x < x_0$ region is neglected, whereas $c_G(A) = 0.10$ when such contribution is taken into account by using Eq. (8). The corresponding estimates for nuclear matter are $c_G(\rm NM) = 0.10$ and 0.20, respectively. Therefore, quite a significant gluon enhancement is expected for heavy nuclei at $x = 0.1$ and $Q^2 \approx Q_0^2$. As $Q^2$ increases, such an enhancement shifts to smaller values of $x$, due to scaling violations (see Fig. 1). In our calculations we neglect higher-twist corrections to the QCD evolution equations, since it was demonstrated in Ref. 6 that they lead to negligible corrections for the $x$ and $Q^2$ range of interest in this Letter.

The enhancement of $G_A$ in the range $x_0 < x < x_1$ leads to a significant scaling violation for the sea distribution $S_A$ at $x \simeq 0.05$, for which shadowing was recently observed in the Drell-Yan process at $Q^2 > 16$ GeV$^2$ (note that the data of Ref. 3 refer to the $\bar u$ and $\bar d$ distributions only; therefore, in the following, $S_A$ will represent the $\bar u$ and $\bar d$ contributions to the sea-quark distribution). By using QCD evolution equations and the above estimates of the gluon enhancement [Eqs. (7) and (8)],



Gluon enhancement washes away
need to look at $Q^2 \sim 2$ GeV$^2$

we find that the difference $R_S(x,Q^2)-1\equiv S_A(x,Q^2)/AS_N(x,Q^2)-1$, evaluated at $x=0.05$, increases by a factor of 2 as $Q^2$ varies between $Q^2=3$ and 25 GeV$^2$. In particular, if we use the QCD aligned-jet model (QAJM) of Refs. 4 and 5 (which is a QCD extension of the well-known parton logic of Bjorken) to calculate $R_S(x,Q^2)$, we find, in the case of $^{40}$Ca, $R_S(x=0.04, Q^2=3\ \mathrm{GeV}^2)=0.9$ and $R_S(x=0.04, Q^2=25\ \mathrm{GeV}^2)=0.97$. The last number is in good agreement with Drell-Yan data[3] (see Fig. 2). Thus, we conclude that the small shadowing for $S_A$ observed in Ref. 3 for $x\simeq 0.04$ and $Q^2>16$ GeV$^2$ corresponds to a much larger shadowing for $Q^2=Q_0^2$.

Shadowing in the sea-quark distribution at $x=0.04$ $[R_S(x=0.04, Q^2=3\ \mathrm{GeV}^2)=0.9]$, combined with the experimental data for $F_2^A(x,Q^2)/AF_2^N(x,Q^2)$ at the same value of $x$ $[F_2^A(x,Q^2)/AF_2^N(x,Q^2)>1]$, unambiguously implies an enhancement of the valence quarks, i.e., $R_V(x,Q^2)\equiv V_A(x,Q^2)/AV_N(x,Q^2)>1$. For $^{40}$Ca, $R_V(x=0.04\text{-}0.1, Q^2=3\ \mathrm{GeV}^2)\approx 1.1$, whereas for infinite nuclear matter, we find $R_V(x=0.04\text{-}0.1, Q^2=3\ \mathrm{GeV}^2)\gtrsim 1.2$. By applying the baryon-charge sum rule [Eq. (2)], we conclude that experimental data require the presence of shadowing for valence quarks at small values of $x$ [i.e., $R_V(x,Q^2)<1$ for $x_{\mathrm{sh}}<0.01\text{-}0.03$]. Moreover, the amount of shadowing for $R_V(x,Q^2)$ is about the same (somewhat larger) as the shadowing for the sea-quark channel (see Fig. 3). The overall change of the momentum carried by valence and sea quarks at $Q^2=1$ GeV$^2$ is

$$\gamma_V^A(Q_0^2)=1.3\%\,,\quad \gamma_S^A(Q_0^2)=-4.6\%\,.$$

To summarize, the present data are consistent with the parton-fusion scenario first suggested in Ref. 7: All parton distributions are shadowed at small $x$, while at larger $x$, only valence-quark and gluon distributions are enhanced. At the same time, other scenarios inspired by the now popular (see, e.g., Ref. 8) idea of parton fusion, which assume that the momentum fraction carried by sea quarks in a nucleus remains the same as in a free nucleon,[9] are hardly consistent with deep-inelastic and Drell-Yan data.

Let us briefly consider dynamical ideas that may be consistent with the emerging picture of the small-$x$ ($x\le 0.1$) parton structure of nuclei. In the nucleus rest frame the $x\approx 0.1$ region corresponds to a possibility for the virtual photon to interact with two nucleons which are at distances of about 1 fm [cf. Eq. (1)]. But at these distances quark and gluon distributions of different nucleons may overlap. So, in analogy with the pion model of the European Muon Collaboration effect, the natural interpretation of the observed enhancement of gluon and valence-quark distributions is that intermediate-range internucleon forces are a result of interchange of quarks and gluons. Within such a model, screening of the color charge of quarks and gluons would prevent any significant enhancement of the meson field in nuclei. Such a picture of internucleon forces does not necessarily contradict the experience of nuclear physics. Really, in the low-energy processes where quark and gluon degrees of freedom cannot be excited, the exchange of quarks (gluons) between nucleons is equivalent, within the dispersion representation over the momentum transfer, to the exchange of a group of a few mesons. Another

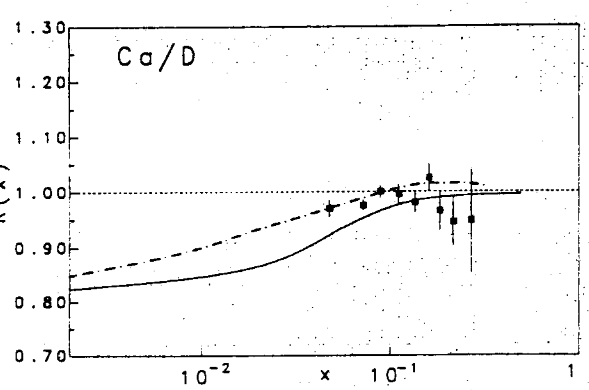


FIG. 2. Ratio $R=(2/A)\bar u_A(x,Q^2)/\bar u_D(x,Q^2)$ plotted vs $x$, for different values of $Q^2$. Notations as in Fig. 1. Experimental data from Ref. 3.

$V_A/V_N$

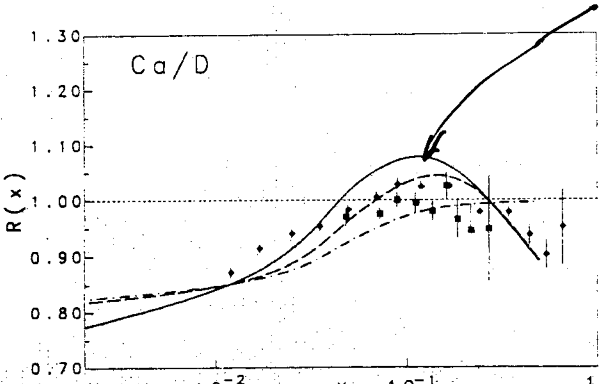


FIG. 3. Ratios $R(x,Q_0^2)=(2/A)F_2^A(x,Q_0^2)/F_2^D(x,Q_0^2)$ (dashed line), $R\equiv R_V(x,Q_0^2)=(2/A)V_A(x,Q_0^2)/V_D(x,Q_0^2)$ (solid line), and $R\equiv R_S(x,Q_0^2)=(2/A)S_A(x,Q_0^2)/S_D(x,Q_0^2)$ (dot-dashed line) in $^{40}$Ca. All curves have been obtained at $Q_0^2=2$ GeV$^2$. The low-$x$ behavior ($x\le x_{\mathrm{sh}}$) corresponds to the predictions of the QAJM of Refs. 4 and 5; the antishadowing pattern (i.e., a 10% enhancement in the valence channel whereas no enhancement in the sea, leading to a less than 5% increase of $F_2^A$ at $x\approx 0.1\text{-}0.2$) has been evaluated within the present approach by requiring that sum rules (2) and (3) are satisfied. Experimental data are from Ref. 1 (diamonds) and Ref. 3 (squares), the latter representing the sea-quark ratio $R_S$ (cf. Fig. 2). The theoretical curves are located below the data at small $x$, due to the high experimental values of $Q^2$: $\langle Q^2\rangle=14.5$ GeV$^2$ in Ref. 1 and $\langle Q^2\rangle=16$ GeV$^2$ in Ref. 3, respectively.

(the same?) option is that the discussed change of parton distributions is a consequence of the difference between structure functions of bound and free nucleons. Both options suggest "melting" of nucleon degrees of freedom with the increase of the nucleon density, i.e., the tendency to a phase transition in superdense nuclear matter. It is also worth emphasizing that the comparatively large ($\geq 20\%$) enhancement deduced above of valence quarks and gluons in infinite nuclear matter for $x \approx 0.1$ should lead to a comparable change of some bound-nucleon properties, for example, to a change of bound-nucleon elastic form factors at intermediate $Q^2$ (though not to a noticeable change of the radii or to large-$Q^2$ asymptotic behavior). Obviously, even larger effects of the same kind may be expected in the cores of neutron stars.

It seems necessary, therefore, to perform further experimental studies of parton distributions in nuclei aimed at a direct determination of the $A$ dependence of the valence-quark and gluon distributions at small values of $x$, which could be obtained from $\mu$-$\bar{\mu}$ pair production in $\pi A$ scattering, by carefully analyzing final states in $\mu A$ scattering, the $A$ dependence of $\sigma_L/\sigma_T$, etc. (see the list of suggestions given in Ref. 4). Another interesting opportunity would be the comparison of hard processes in peripheral and central high-energy heavy-ion collisions at BNL Relativistic Heavy Ion Collider energies, which would allow a direct measurement of the parton structure of nuclear matter.

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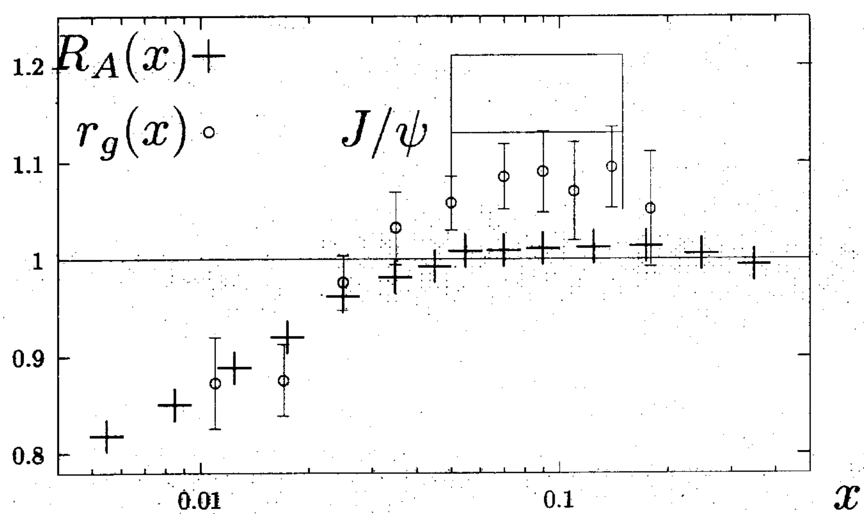
Theory expectations: **gluon shadowing** at small $x$ at least as large as for $F_{2A}$.

$\Rightarrow$ Gluon enhancement at $x \sim 0.1$: $\frac{G_A(x,Q_0^2)}{AG_N(x,Q_0^2)} \sim 1.1$ for $A \sim 40$ ( $\sim 1.2$ for A=200) to keep gluon fraction practically $A$-independent.

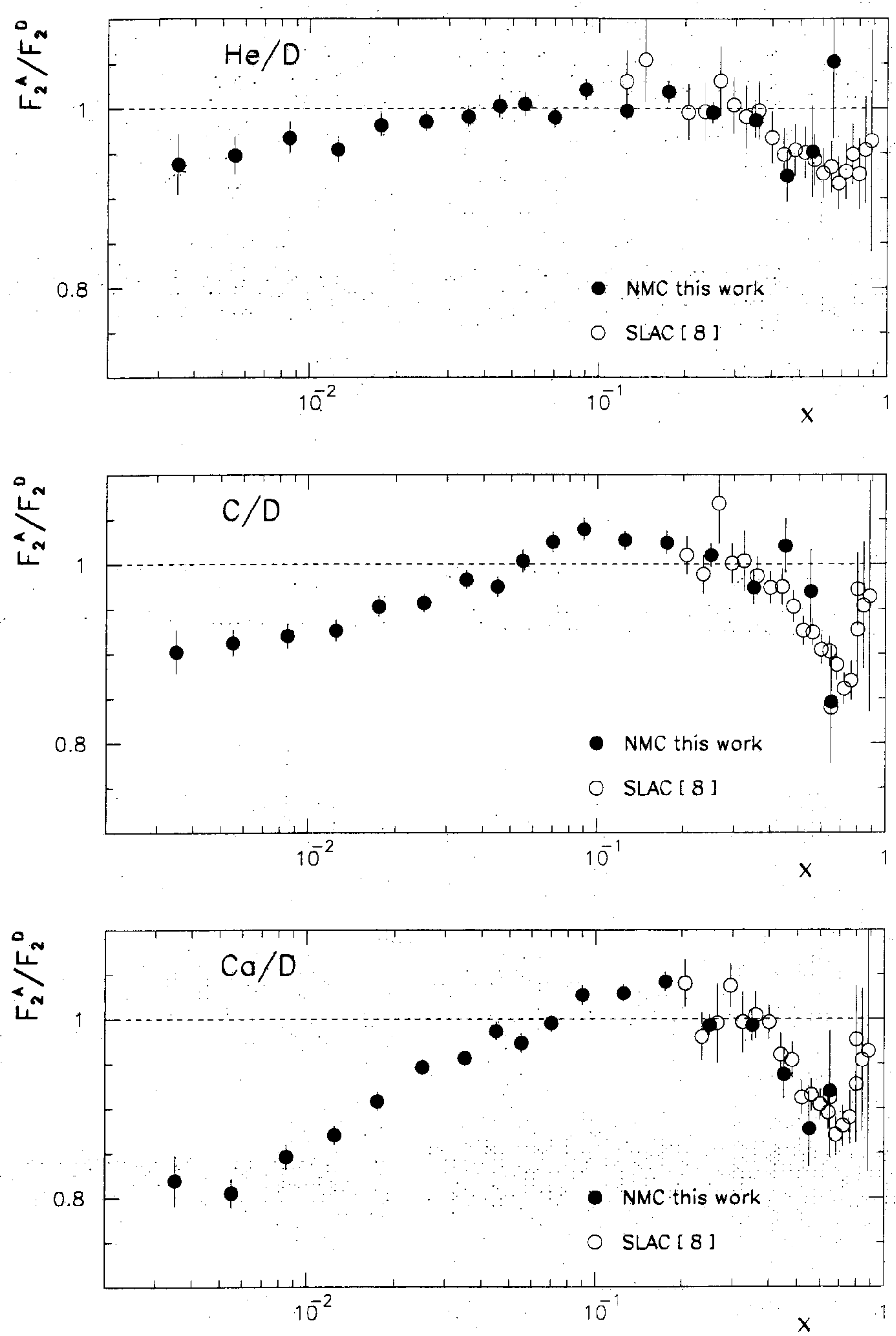
$\Rightarrow$ Small positive scaling violation for $R_A(x \sim 0.05 - 0.1)$. Observed by NMC in the high precision $Sn/C$ measurements.

T. Gousset and H.J. Pirner have demonstrated that $r_g(x) = G_{\mathrm{Sn}}(x)/G_{\mathrm{C}}(x)$ can be extracted from the data in a model independent way since $R_A(x) = \left|F_2^{\mathrm{Sn}}(x)/F_2^{\mathrm{C}}(x) - 1\right| \leq 0.02$ for $0.05 < x < 0.2$.
The box is the $r_g$ extracted using the gluon fusion model from the NMC $\mu + A \to \mu + J/\psi + X$ data.




Consistent with FLS 90 prediction.

Warning: ≈ same effect of scaling violation for C/D and Sn/C is expected NMC does not see it : A. Brull.

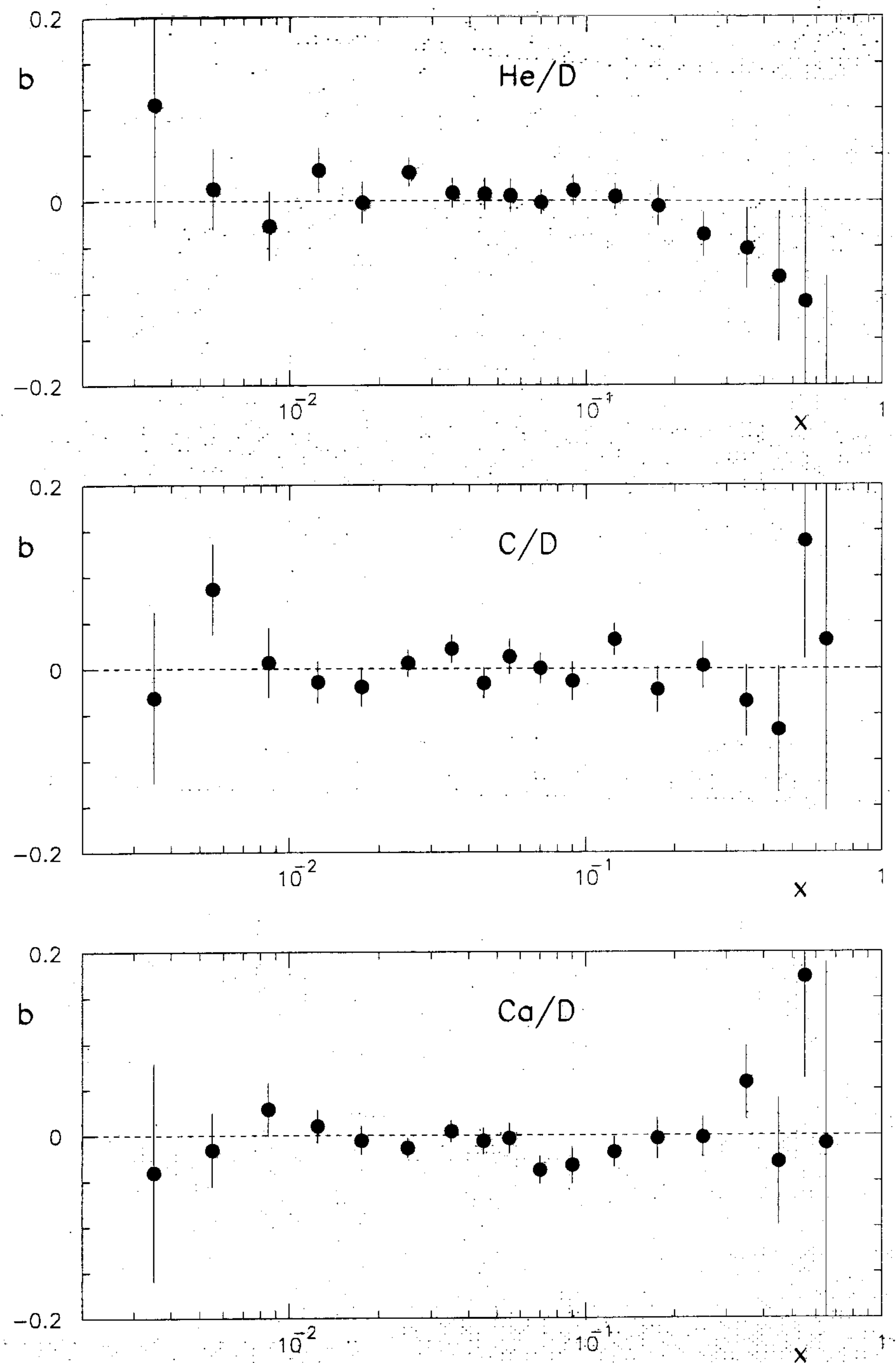



High-precision NMC 1995 data for the shadowing region.

however for $x < 0.01$ $Q^2 \le 1 GeV^2$

— higher twist not negligible —

dangerous to use in global fits

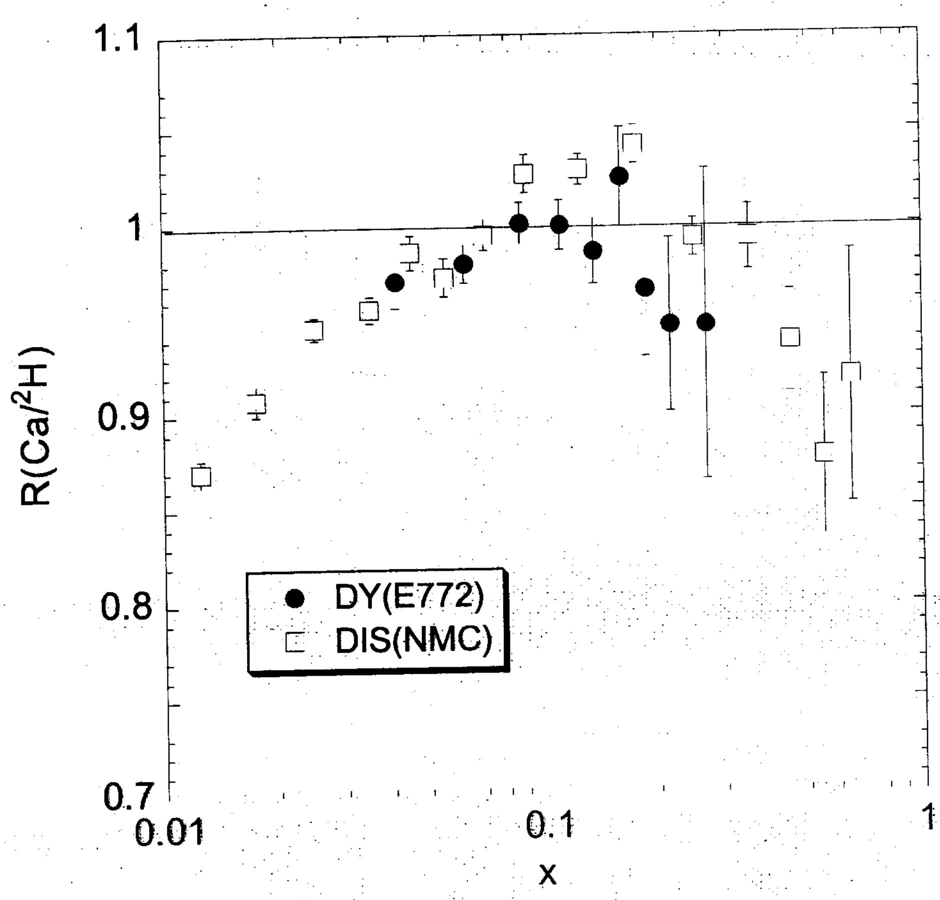


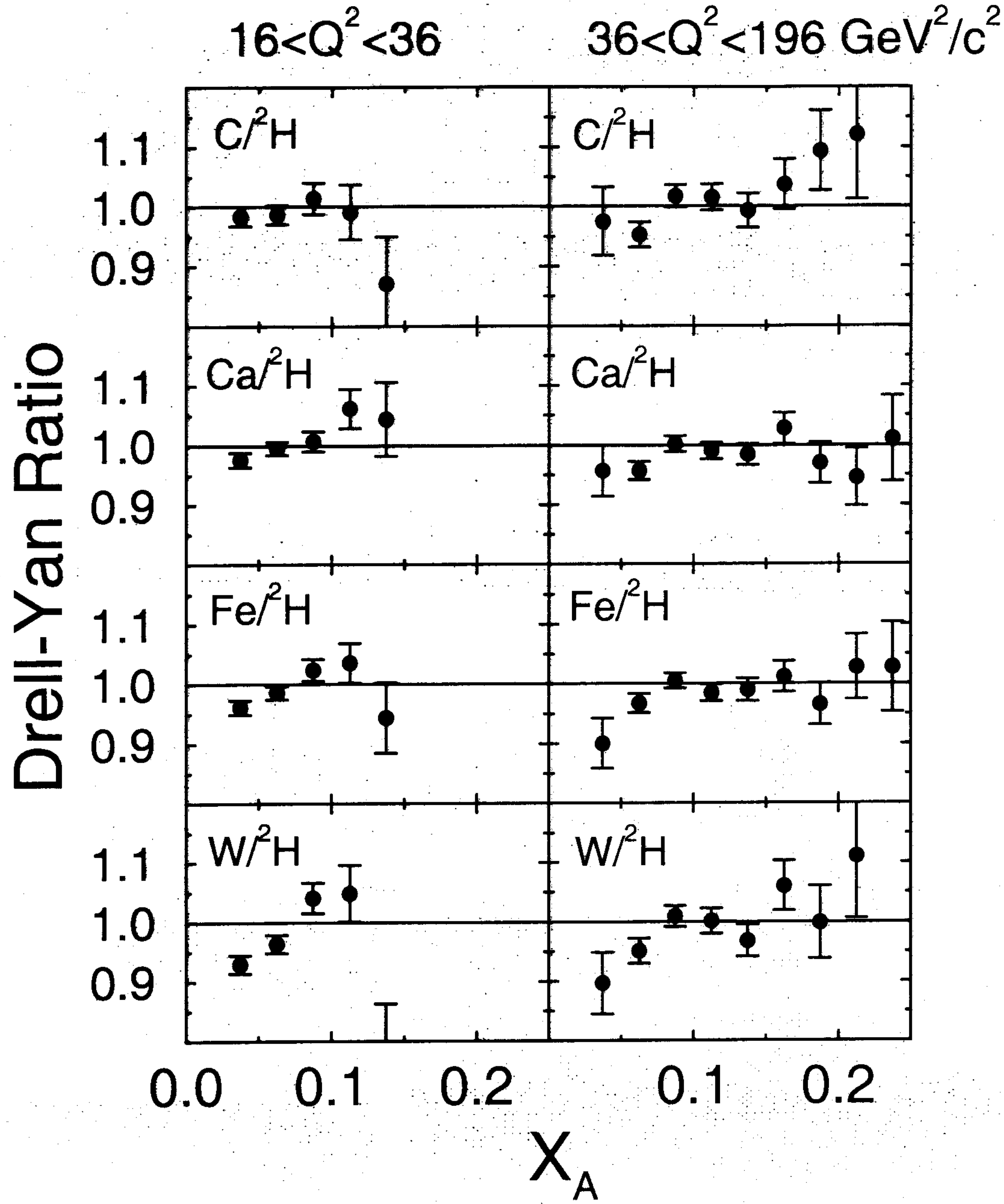

C fit of the scaling violation of $\dfrac{\partial \frac{2F_{2A}(x,Q^2)}{AF_{2D}(x,Q^2)}}{\partial \ln Q^2} = b(x)$

## Antiquarks in Nuclei - Drell-Yan results

Measurements of the Drell-Yan process at $M^2_{\mu^+\mu^-} \geq 16 GeV^2$ at FNAL established:

- $R_{\bar{q}}(x < M^2) \equiv \frac{2\bar{q}_A(x,M^2)}{Aq_D(x,M^2)} \leq 1$ for $x \leq 0.2$
- $R_{\bar{q}}(x, M^2)$ is shadowed for $x \leq 0.05$
- $M^2$ dependence of $R_{\bar{q}}(x, M^2)$ is consistent with pQCD.





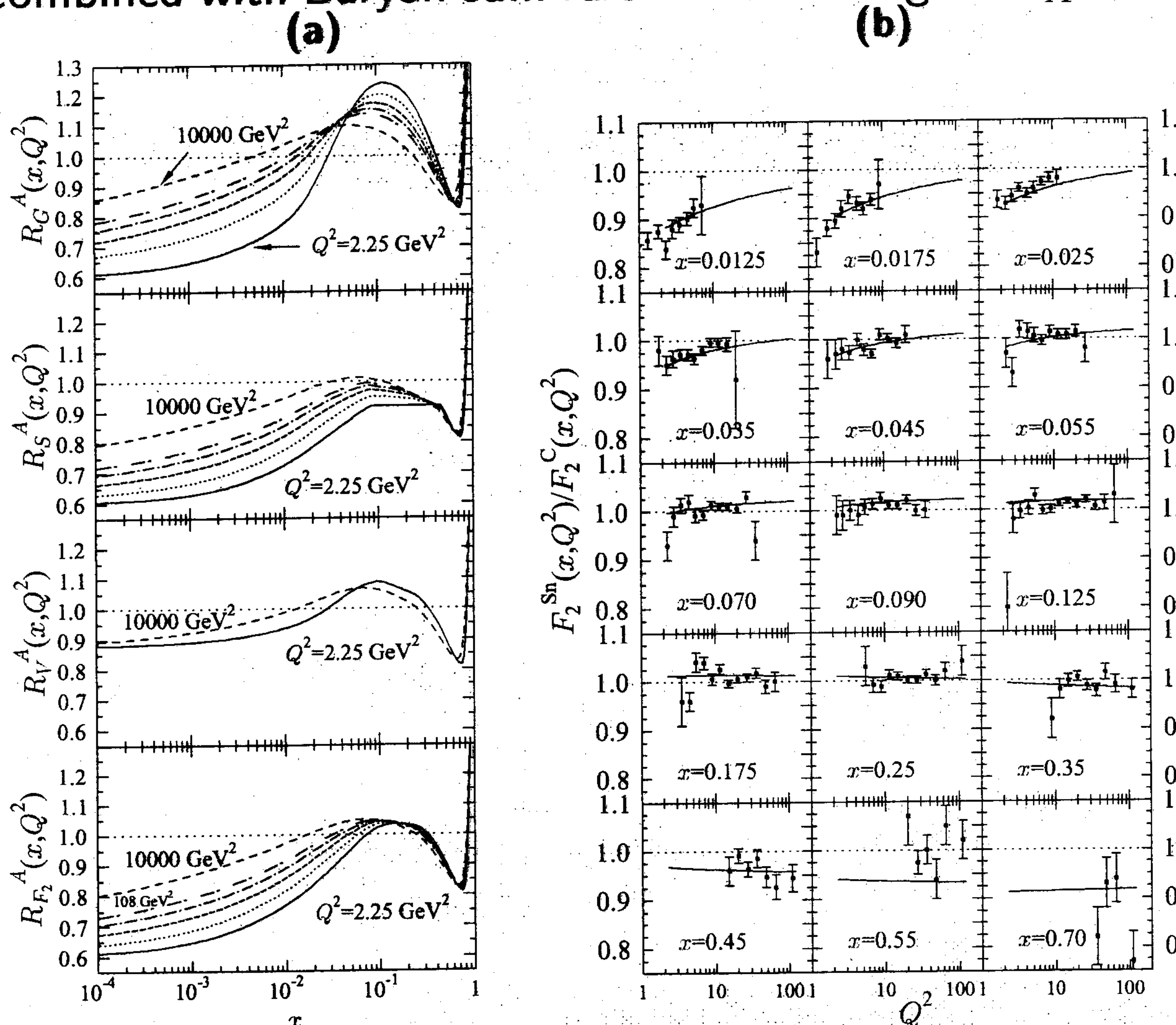

o Corrections from energy loss effects are neglegible [HERMES data rule out model discussed by Kopeliovich group + group]

oo Pion/binding models of the EMC effect are in big trouble.

Scaling violation $\Longrightarrow$ Smaller $R_{\bar{q}}$ for the NMC $Q^2$ range

$\Longrightarrow$ $F_{2A}(x \sim 0.1, Q^2 = 4GeV^2) > 1$ is due to $V_A/V_N > 1$

Combined with Baryon sum rule $\rightarrow$ shadowing for $V_A$ (FLS 90)




Global fit of the DIS & DY nuclear data Eskola et al (1998) + guess for $x < 0.01$.

(a) The scale evolution of the ratios $xG_A/xG_N$, $xS_A/xS_N$, $xV_A/xV_N$, and $F_2^A/F_2^D$ for an isoscalar nucleus $A = 208$. (b) The calculated $Q^2$ dependence of $F_2^{\rm Sn}/F_2^{\rm C}$ compared with the NMC data.

Smaller shadowing for $xV_A/xV_N$ than FLS. - more accurate data



- to get larger $xV_A$ shadowing necessary to change the shape or trust data less.

**Summary of information on A-dependences of parton densities**

**Nuclear shadowing is directly observed for $\bar{q}$, indirectly for $G_A, V_A$.**

**Nuclear enhancement (antishadowing) for $x \sim 0.1$ is directly observed for $q_V$. Indications of a large enhancement for gluons. Enhancement is absent for antiquarks**

systematic errors are high.

**Reminder** The $x \sim 0.1$ region corresponds to distances $\sim 1-2fm$ relevant for the quark-gluon nature of internuclear forces. *The observed A dependence of $R_g, R_{\bar{q}}$ is hardly consistent with the meson picture of the short-range nuclear forces which predicted a 10-20% enhancement of $\bar{q}_A/\bar{q}_N$.*

**AA connection** Significant modifications of parton densities (largest for the central impact parameters) have to be accounted for in interpreting nucleus-nucleus collisions at RHIC.

Where $\nu$ experiments can help

Directly measure

$\bar{q}_A / \bar{q}_N$ at $Q^2 \sim 2\,GeV^2$

larger shadowing, possible to push to higher $x$? Scaling violation - window to gluons.

Is strange sea the same?

$\bar{s} \to \bar{c}$ studies

- Directly measure $V_A / V_N$ — $x \lesssim 0.15$ is most interesting.

  Warning: A-dependence is weak for $A > 12$ $\Rightarrow$ need C/D data.

  $x > 1$? — resolution? $\exp -8x$ is very steep.

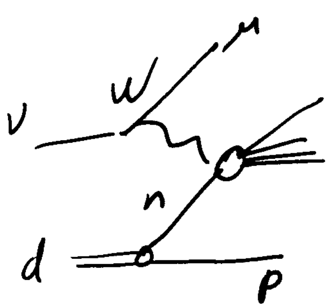
- $x \sim 0.5$ No advantages for inclusive experiments

Semiinclusive experiments with deuteron
- new physics as compared to eD

$$\nu(\bar{\nu}) + D \to \mu + (\text{backward } p) + X$$

study of the EMC effect with bound nucleon [tagged structure functions FS85]

$$\frac{u_{bound}(x,Q^2,p_{spect})}{u(x,Q^2)} \quad vs \quad \frac{d_{bound}(x,Q^2,p_{spect})}{d(x,Q^2)}$$




Since physics of d & u at large x is different effects could differ

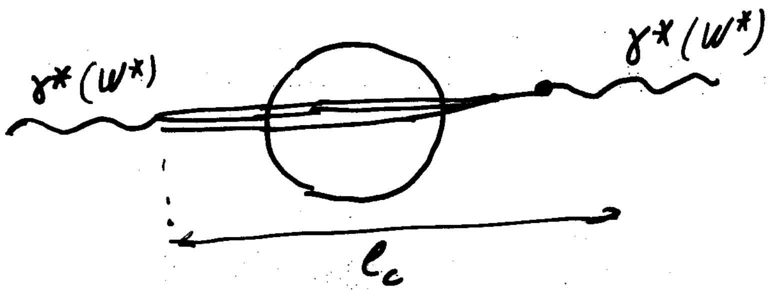
[First naturally studies at Jlab will give some idea of dynamics]

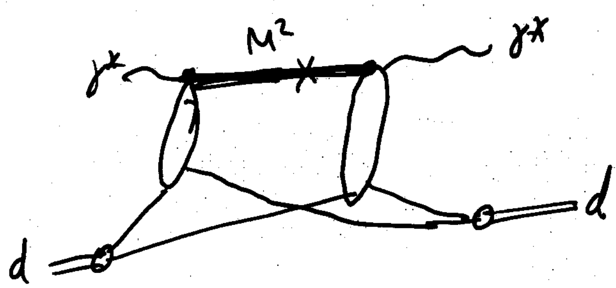
## Theory: Shadowing for intermediate $Q^2 \lesssim$ few $GeV^2$

General theory – Gribov – connection to presence of diffractive-like state in $\ell N \to \ell' X N$ scattering where

$$x_F^N = 1 - \varepsilon \qquad \varepsilon \lesssim \frac{k_F}{m_N}$$

Key element: large coherence length $l_c \sim \frac{1}{2 m_N x}$



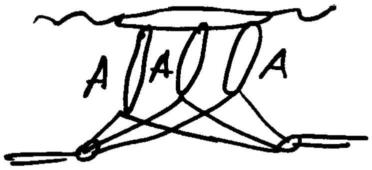

For $A > 2$ need to include also multiple rescatterings.

low $Q^2$, $M^2 \sim m_V^2$ — shadowing

$$\frac{A_{eff}}{A} \simeq \frac{1}{A\,\sigma_{VN}} \cdot \int d^2b \left(2 - 2\exp - \frac{T(b)\sigma}{2}\right)$$

$$T(b) = \int_{-\infty}^{\infty} dz\, \rho(z,b).$$

Gives a reasonable description of $\sigma_{\gamma A}/\sigma_{\gamma N}$



$A = IP + R$

$\sigma_{RN}$ vs $\sigma_{RA}$

like $R = \dfrac{\sigma_{\bar{p}A} - \sigma_{p A}}{\sigma_{\bar{p}N} - \sigma_{pN}}$

If $(\sigma_{\bar{p}N} - \sigma_{pN}) / \sigma_{pN} \ll 1$

$$R = \frac{1}{A} \frac{\partial}{\partial \sigma_{NN}} \sigma_{pA}(\sigma_{NN}) = \frac{1}{A} \int T(b) \cdot \exp - \frac{\sigma T(b)}{2} d^2b$$

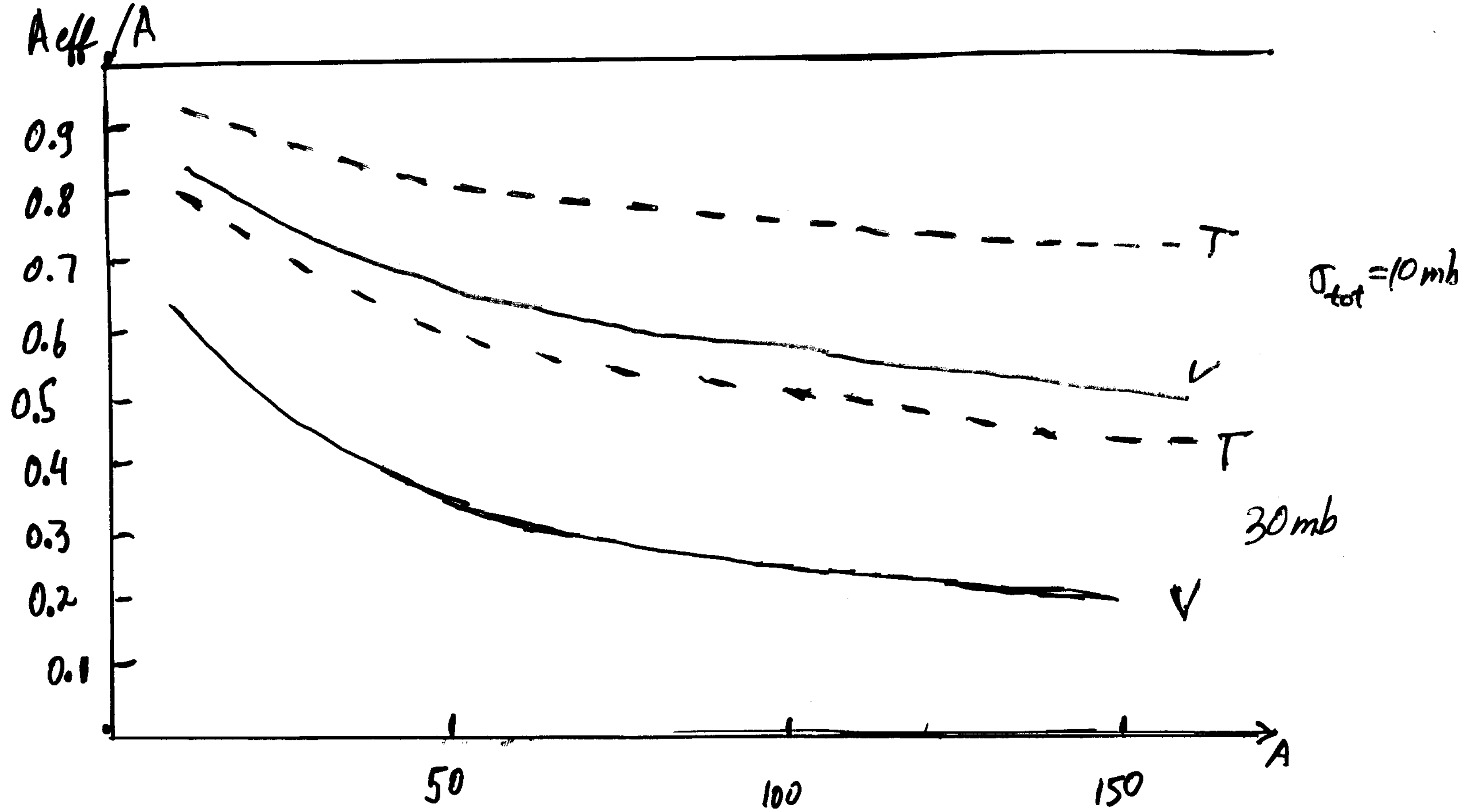
$\boxed{\text{FS 85-88}}$

Larger shadowing than for $\sigma_{pA}$.

Physics: Scattering from the center (black) does not contribute to the difference.

≡ Exchange of N-identical Reggeons : $\frac{1}{N!}$

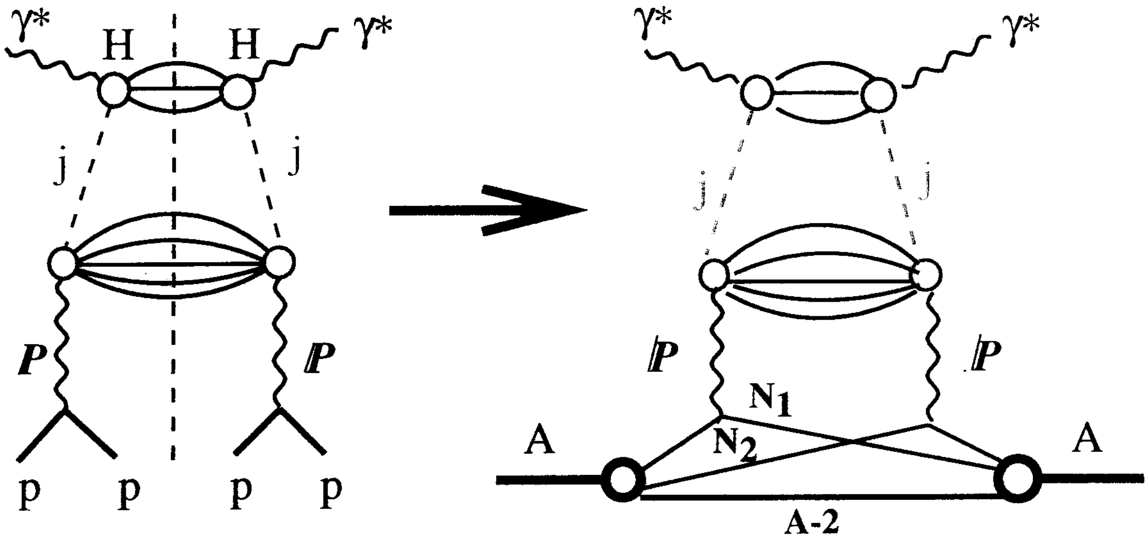
If $R \otimes \underbrace{IP \times IP \times IP}_{N-1} \longrightarrow \frac{1}{(N-1)!}$



Aeff /A
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
T
σtot =10mb
V
T
30mb
V
50
100
150
A

$\Rightarrow$ In the valence channel for soft physics - valence quark channel like $F_3(x, Q^2)$ larger shadowing than for $F_2(x, Q^2)$.

**Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the diffractive parton densities $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$ of ep scattering.** FS 98




**Hard diffraction off parton "j"**

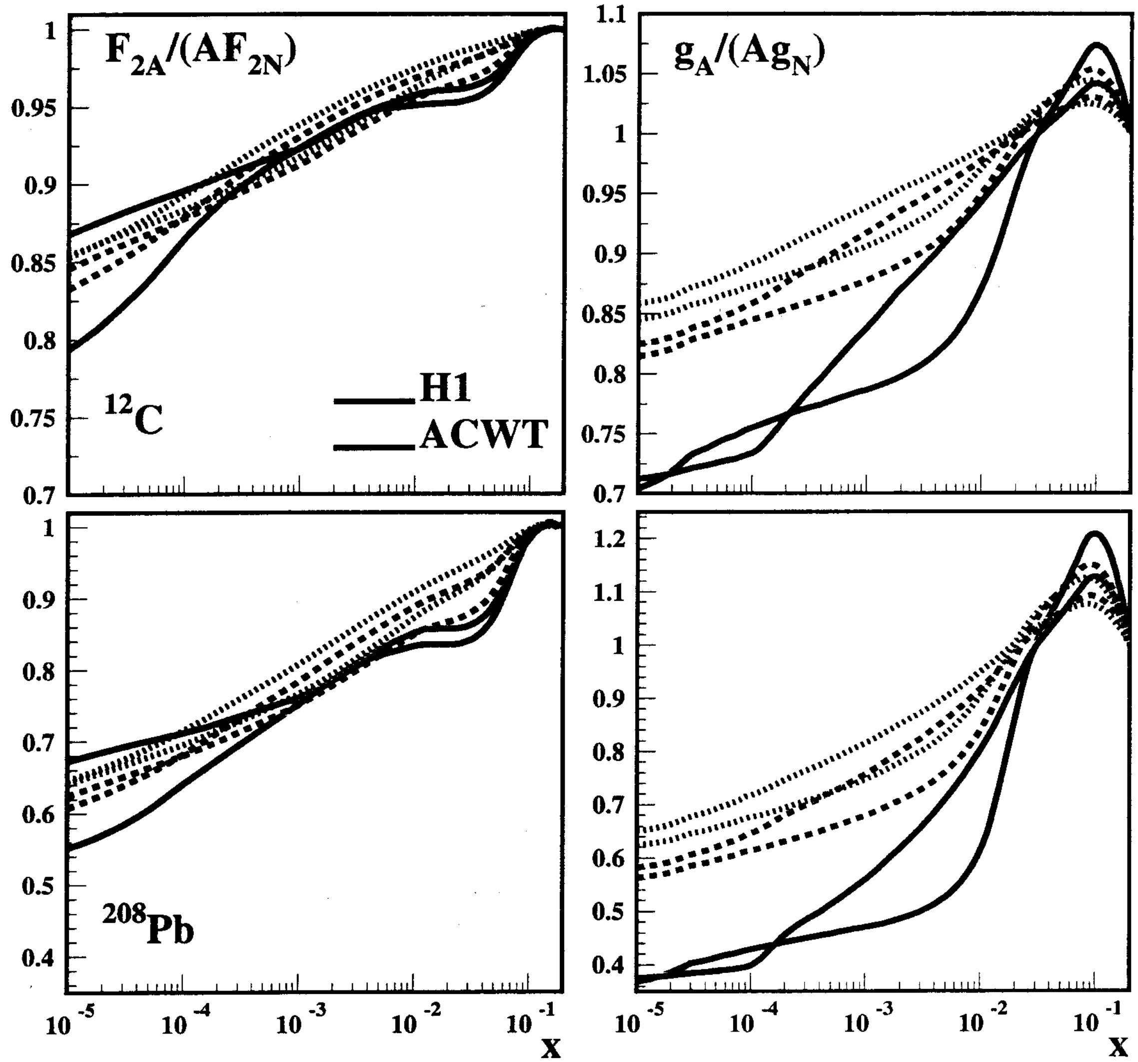
**Leading twist contribution to the nuclear shadowing for structure function $f_j(x,Q^2)$**

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

$$\cdot f_{j/N}^D\left(\beta, Q^2, x_{I\!P}, t\right)_{|k_t^2=0}\, \rho_A(b,z_1)\rho_A(b,z_2)\cos(x_{I\!P} m_N(z_1-z_2)),$$

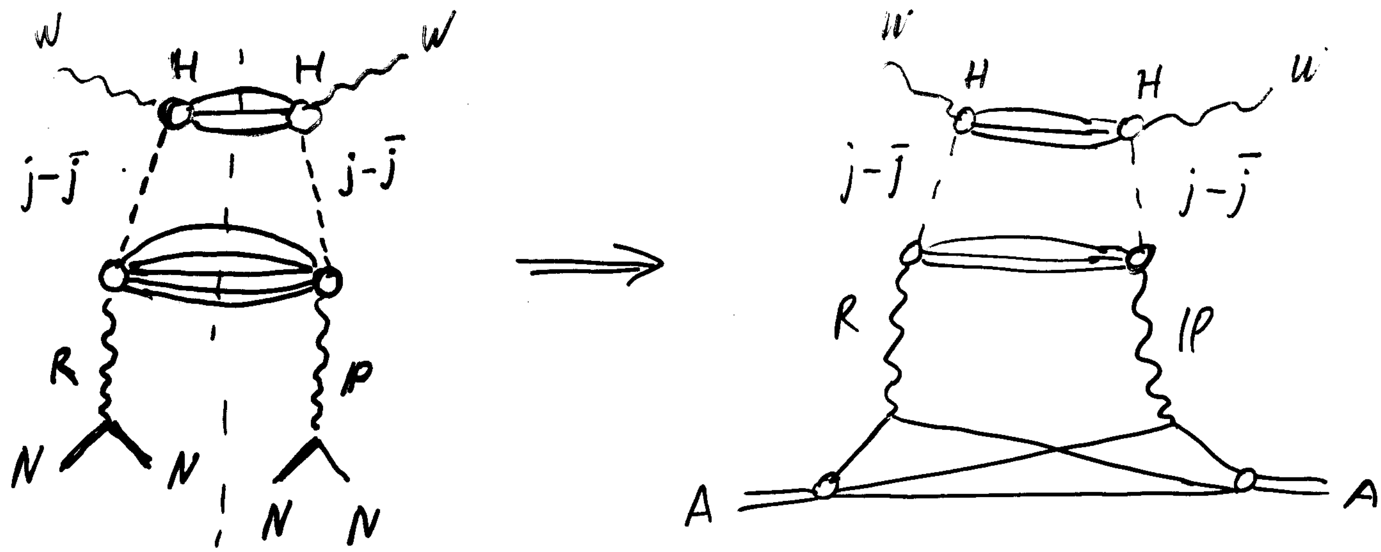
where $f_{j/A}(x,Q^2)$, $f_{j/N}(x,Q^2)$, are inclusive parton densities; $\rho_A(r)$ is the nucleon density in the nucleus, $\eta = \left(1-\left(\frac{Re}{Im}\right)^2\right)/\left(1+\left(\frac{Re}{Im}\right)^2\right)$

## Predictions for $F_2^A$ and $g_A$




- NLO calculation (with CTEQ5M for $f_{j/N}$)
- Valence quarks are shadowed as the sea quarks; charm quarks are **not** modified at the input scale $Q_0 = 2$ GeV
- Predictions with H1 and ACWT are virtually the same for $10^{-4} < x < 10^{-2}$: $F_2^D$ is measured in this range and fitted well by both parameterizations

Extension of FS factorization relation to valence channel diffraction




Diffraction in the valence channel for large $Q^2$ not studied experimentally – smaller than for vacuum channel ??

Would suppress LT valence quark shadowing.

Since at low $Q^2$ shadowing for $F_{3A}$ should be large, while at $Q^2 \gtrsim 2\,GeV^2$ where LT dominates it is small (if the current data on $F_{2A}/F_{2N}$, $\bar{q}_A/\bar{q}_N$ stand)

\+ weak $Q^2$ evolution for $F_3$ in LT

$$\Downarrow$$

Large higher twist effects for $F_3$ for $x \lesssim 0.03$.

What about HT effect for $F_2$ in $\nu A$ scattering?

Also should be large though for different reasons.

Consider $F_2$ in $\nu$ scattering for

$Q^2 \to 0$, fixed $E_\nu$.

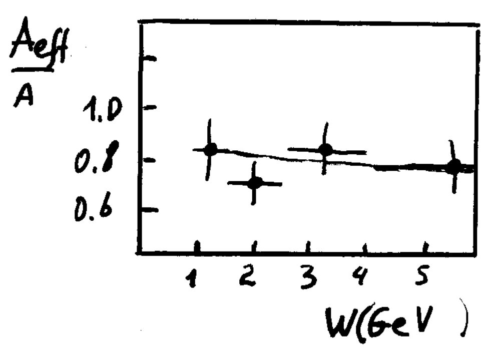
Adler theorem implies

$$R^\nu \equiv \left.\frac{\sigma_{\nu A}(Q^2, E_\nu)}{\sigma_{\nu N}(Q^2, E_\nu)}\right|_{Q^2\to 0} = \frac{\sigma_{\pi A}(E_\nu)}{\sigma_{\pi N}(E_\nu)}.$$

Consistent with $\nu$ Ne data

Kopeliovich & Marage 93

$(\nu+\bar{\nu})$ Ne data




— Bell optical model

– mass of hadronic system

Differences between $R^\gamma$ & $R^\nu$

(a) $R^\nu < R^\gamma$ for large $E$

(b) Onset of shadowing for $\gamma$'s at $E_\gamma \sim$ few GeV

for $\nu$'s already at $E_\nu \sim 0.5$ GeV

Conclusions.

Several promising topics for inclusive $\overset{(-)}{\nu} A$ studies.

- $V_A/V_N$ enhancement at $x \sim 0.05-0.15$

  if $\sigma_A/\sigma_N \geq 1$

  is smaller at $Q^2 \sim 2.0\ GeV^2$ than in DY

  – much more sensitive to nuclear structure

  High precision data may probe $\sigma_A/\sigma_N \sim 1.2$ for $x \sim 0.1$

- Low $Q^2$ physics of higher twist effects specific for nuclei

  Difference between $F_{2A}^{\gamma^*}/F_{2N}^{\gamma^*}$ and $F_{2A}^{\nu}/F_{2N}^{\nu}$, and between $F_{2A}^{\nu}/F_{2N}^{\nu}$ & $F_{3A}^{\nu}/F_{3A}^{\nu}$.

  – probes of dynamics of nuclear shadowing & [illegible] PCAC

- Need deuteron targets:

  if A's are $\geq 12$ – nuclear effects are reduced by at least a factor of 2.