EMC effect & SRC

Observations and challenges

Mark Strikman, Feb. 3 2023

DIS off nuclei, Drell Yan processes measures LT effect —> no FSI

Hadron production in DIS maybe sensitive to final state interaction.

Dominance of LT makes even small deviations of the EMC ratio from one meaningful

EMC effect cannot be explained in many nucleon approximation without introducing baryon charge and / or momentum non-conservation using convolution approximation:

Still some skeptics

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

Nucleon light cone density matrix.

A> α > 0 - light cone density matrix

≡probability to find a nucleon having momentum αP_A

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

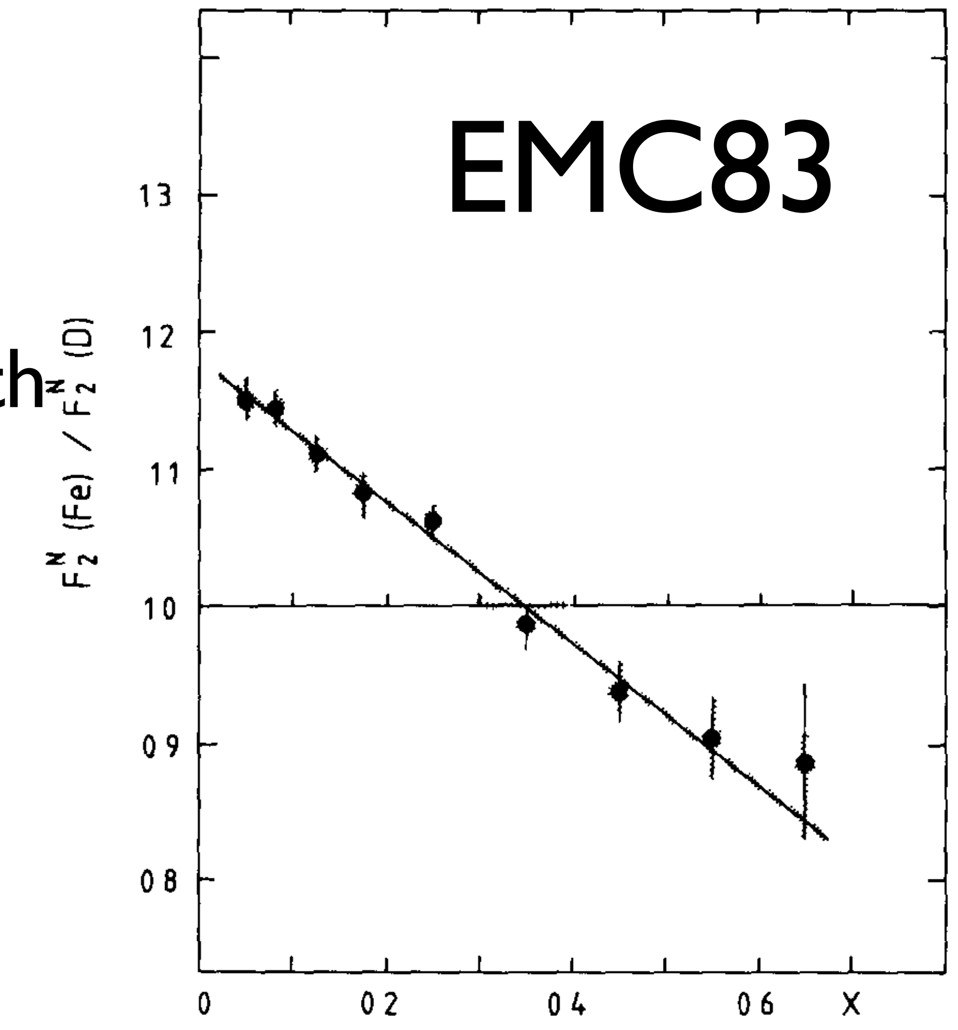
$$\frac{1}{A}\int \alpha\rho_A^N(\alpha,p_t)\frac{d\alpha}{\alpha}d^2p_t = 1 - \lambda_A$$

fraction of nucleus momentum NOT carried by nucleons

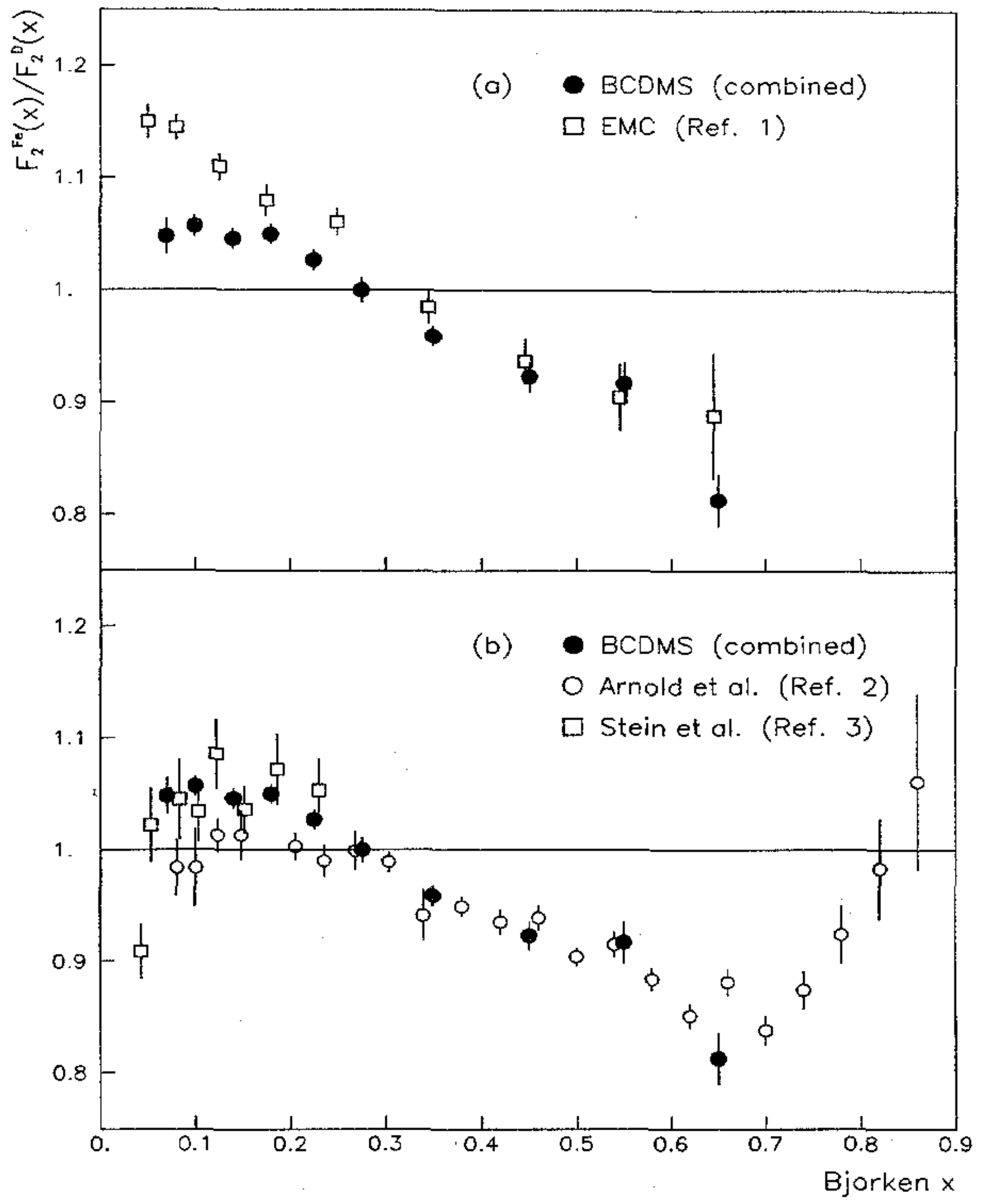
$R_A(x,Q^2) = 2F_{2A}(x,Q^2)/AF_{2D}(x,Q^2)$ from one

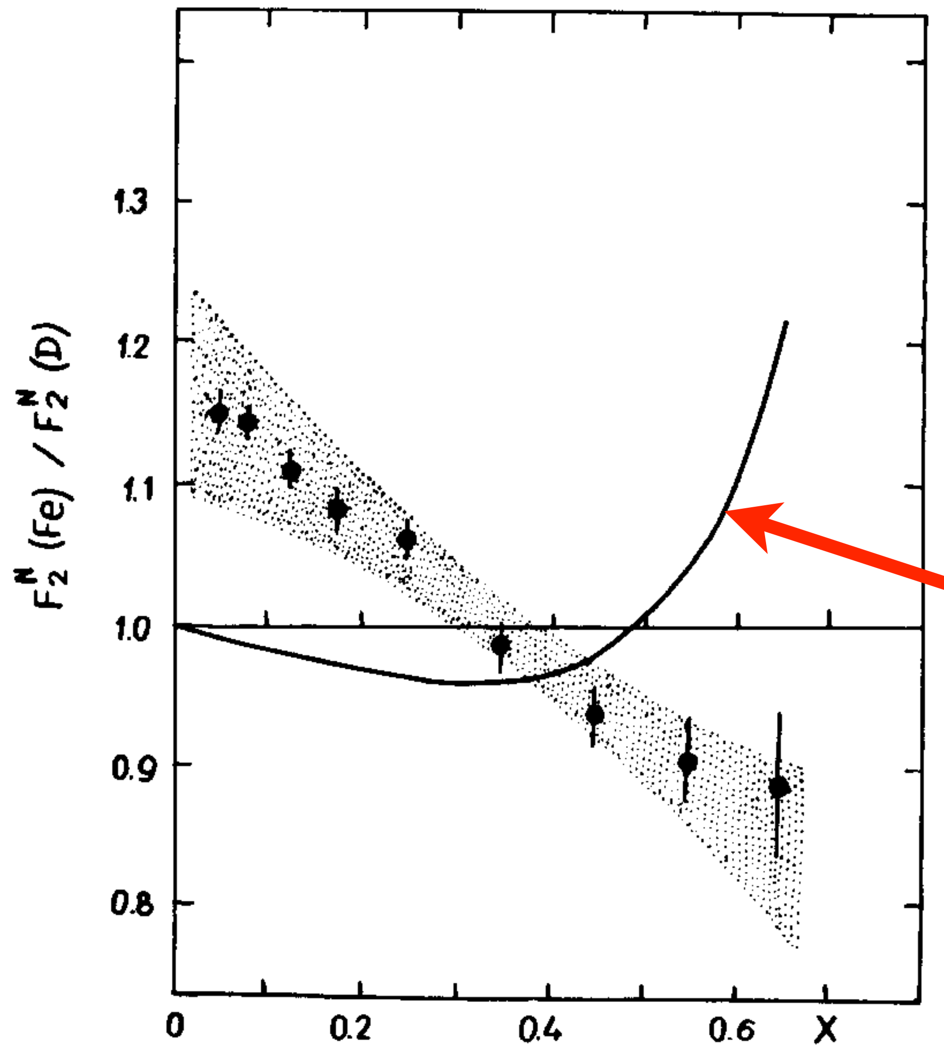
$$q_\nu = (q_0, \vec{q}), x = x_{Bj} = -q^2/2q_0 m_p \quad q_\nu = p_{\gamma^*}$$

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



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





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

Bjorken scaling within 30% accuracy - caveat - HT effects are large in SLAC kinematics for x≥ 0.5. Even more so at Jlab energies

Can account of Fermi motion describe the EMC effect?

YES

If one violates baryon charge conservation
or momentum conservation or both

Many nucleon approximation:

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

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

≡probability to find a nucleon having momentum αP_A

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

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

In nucleus rest frame $x=AQ^2/2m_Aq_0$

Since spread in α due to Fermi motion is modest ⇒ do Taylor series expansion in convolution form

in (1- α): α= 1+ (α-1)

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

Fermi motion

$$+\frac{xF_{2N}'(x,Q^2) + (x^2/2)F_{2N}''(x,Q^2)}{F_{2N}(x,Q^2)} \cdot \frac{2(T_A - T_{{}^2H})}{3m_N}$$

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

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

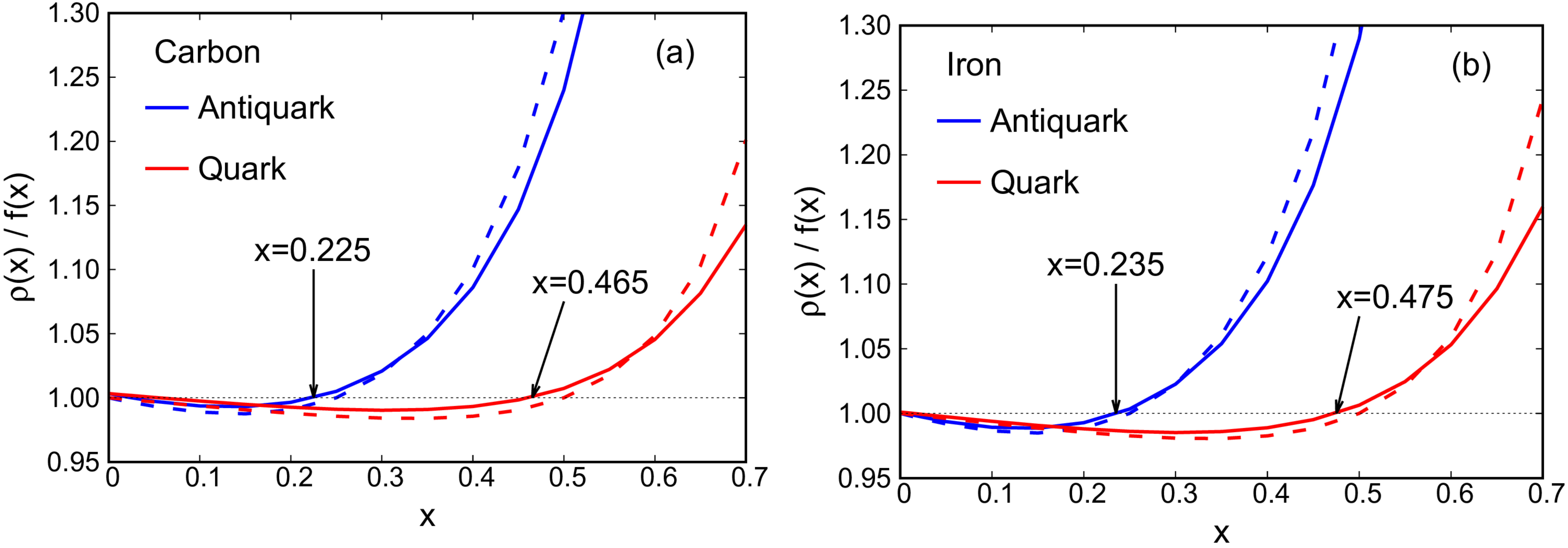
small negative for x <(n+1)/2

> 0 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 - what are they?

God in his wisdom made a fly
But he forget t o tell us why

Ogden Nash



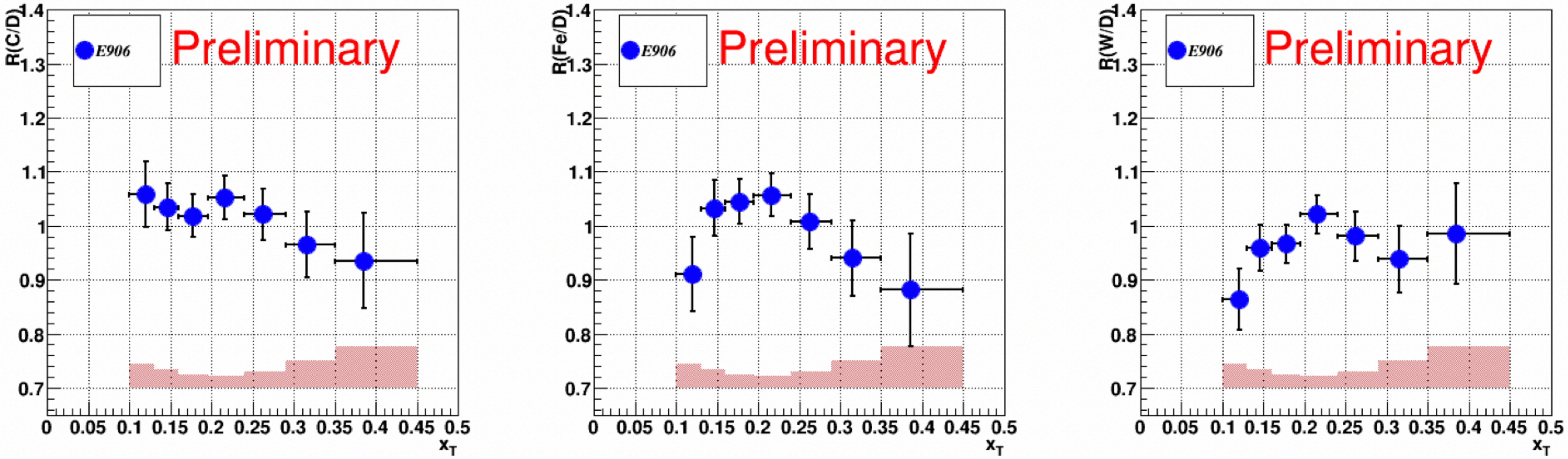
Solid lines are expectation s of exact convolution formula, dashed - Taylor series expansion.

➡ Correction for Fermi motion is small but not negligible and can be calculated with good accuracy especially if one includes (e,e') x> 1 information.

Alvioli and MS, 2023

SEAQUEST RESULTS

Present by Arun Tadepalli



EMC effect like pattern?

R(Fermi motion) ~1.2

EMC effect for antiquarks ?

MS + Alvioli analysis of preliminary Drell Yan data.

Can energy losses explain the observed pattern? Does not work. Is effect propto a2(A).

A shtetl dweller asked the rabbi: –What shall I do, my chickens are sick! –Draw a red circle on the wall of the poultry house. Next day: –Rabbi, my chickens have started dying. –Draw a green triangle around the circle. Next day again: –Rabbi, in the poultry house only corpses are left. –Pity, I had so many other patterns in reserve.

Anonymous

5. Models of the EMC effect

A shtetl dweller asked the rabbi:
—What shall I do, my chickens are sick!
—Draw a red circle on the wall of the poultry house.
Next day:
—Rabbi, my chickens have started dying.
—Draw a green triangle around the circle.
Next day again:
—Rabbi, in the poultry house only corpses are left.
—Pity, I had so many other patterns in reserve.

First explanations/models of the EMC effect

- Pionic model: extra pions - $\lambda_\pi \sim 4\%$

$$R_A(x,Q^2) = 1 - \frac{\lambda_A n x}{1-x}$$ + enhancement from scattering off pion field with $\alpha_\pi \sim 0.15$

- 6 quark configurations in nuclei with $P_{6q} \sim$ 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 - 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

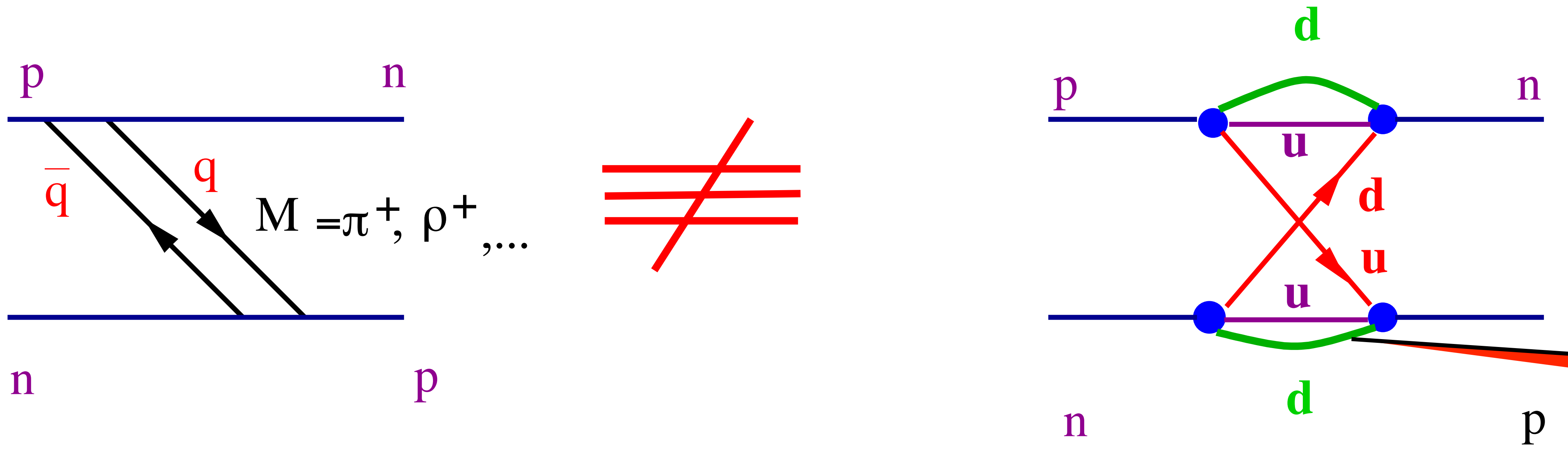
Second try: fix baryon charge ➔ violate momentum sum rule

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

⇓

version of pion model

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?



Intermediate state may not be = pn

Meson Exchange
extra antiquarks in nuclei

Quark interchange
no extra antiquarks

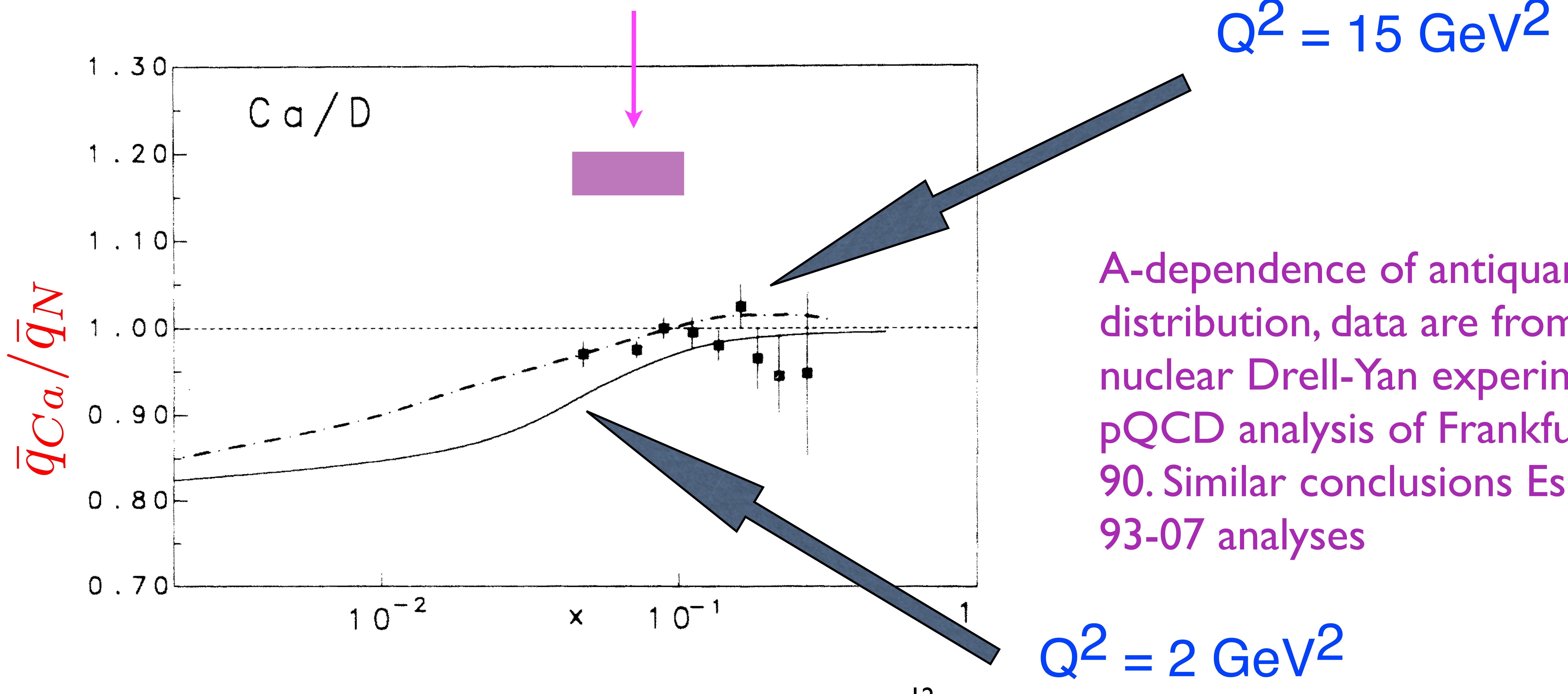
may correspond to a tower of meson exchanges with coherent phases - high energy example is Reggeon; pion exchange for low t special - due to small mass

Question to Lattice QCD: is there a big difference between NN interactions with and without quenching?

Drell-Yan experiments: $\bar{q}_{Ca}/\bar{q}_N \approx 0.97$
1989

vs Prediction $\bar{q}_{Ca}(x)/\bar{q}_N = 1.1 \div 1.2_{|\, x=0.05\div0.1}$

meson model expectation
$\bar{q}_{Ca}(x)/\bar{q}_N = 1.1 \div 1.2_{|\, x=0.05\div0.1}$



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

More DY data is needed. Can DIS help - study K- production

Does similar pattern holds for gluons? Open charm at 22 GeV probes a right kinematics? LHC diets..

Study total cross section for charm reduction off D, 4He, C to reduce effects of f.s.i.

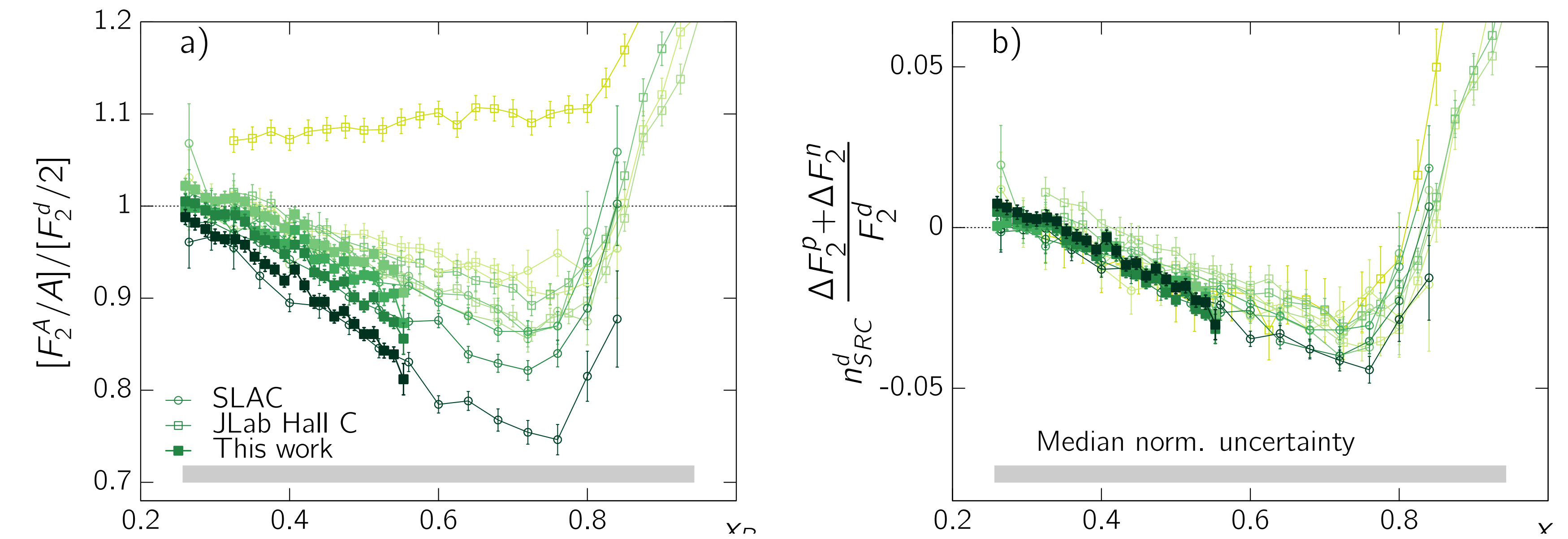
If confirmed with a better precision DY measurement would be a second critical contribution of DY studies into understanding of quark- gluon nuclear structure (the first one was ruling out enhancement of antiquarks due to scattering off pions).

General pattern : Softening of x distribution of quarks and antiquarks (and gluons?) in bound nucleons; effect manifested at smaller x.

Suppression for say carbon / nucleon is 12% at x=0.5— 0.6, and SCRC probability for C is 15%

Could the EMC effect be solely due to SRCs? Difficult - indeed in this scenario nucleons with momenta > k_F practically do should not have quarks with x> 0.5.

Questions (a)straight line fit does not include x -range where 1-R reaches maximum. Approximate similarity of R_A was demonstrated in 1985. Is it better than 10%?



(b) Need to correct definition of x, snd c) take into account that Coulomb field carries finite fraction of the nucleus momentum — 1% effects but all together EMC effect is 10%.

It appears that essentially one generic scenario survives <u>strong deformation of rare configurations in bound nucleons increasing with nucleon momentum and with most (though not all) of the effect due to the SRCs .</u>

Dynamical model - color screening model of the EMC effect

(FS 83-85)

Combination of two ideas:

(a) QCD: Quark configurations in a nucleon of a size << average size should interact weaker than in average. Application of the variational principle indicates that probability of such configurations in bound nucleons should be 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.

small admixture of nonnucleonic degrees of freedom due to small probability of configurations with $x>0.\underline{5}$ (~0.02) - hence no contradictions with soft physics)

In 83 we proposed a test of (b) in hard pA collisions. Finally became possible using data from pA LHC data then in 2013 on forward jet production confirmed our expectations that a nucleon with large x quark has smaller than average size

For small virtualities: $1\text{-}c(p^2_{int}\text{-}m^2)$

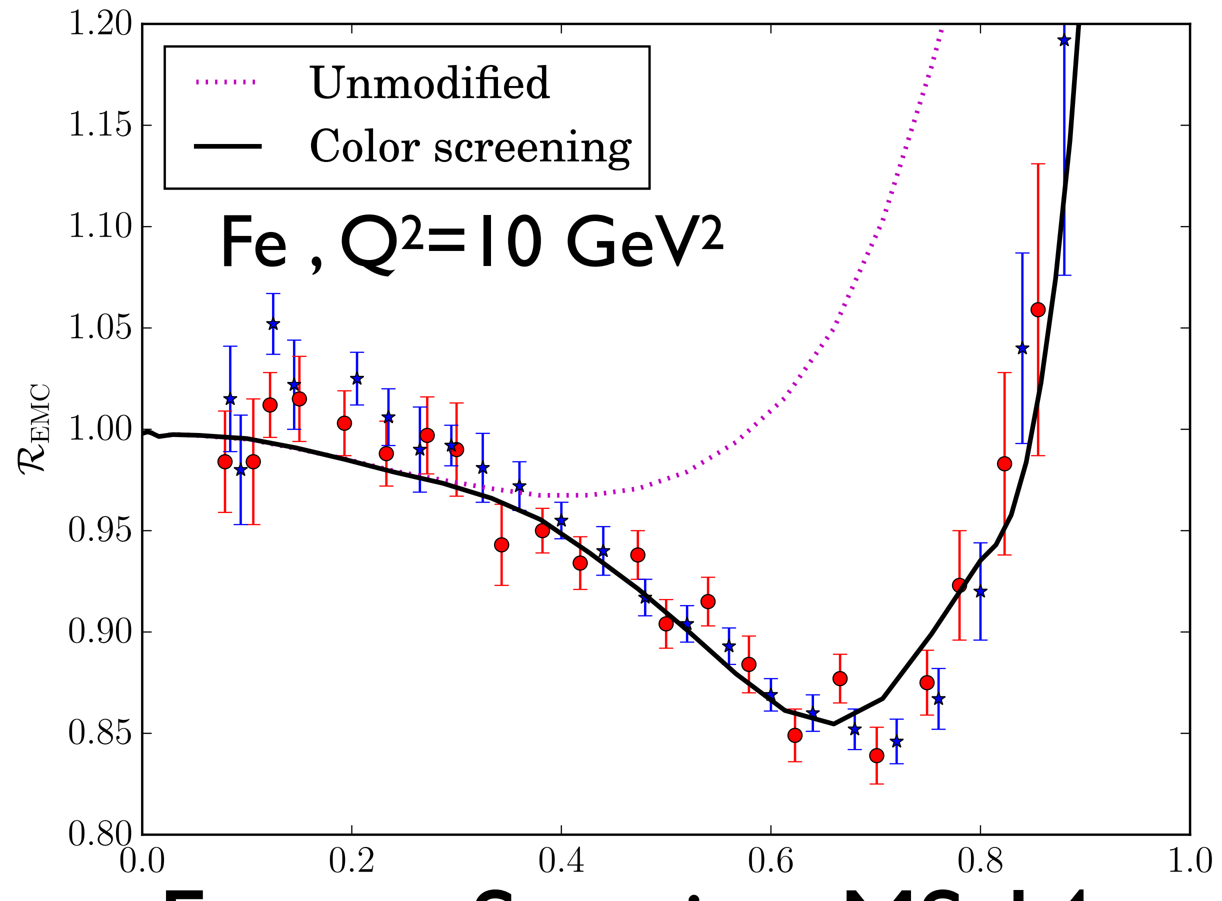
seems to be very general for the modification of the nucleon properties. Indeed, consider analytic continuation of the scattering amplitude to $p^2_{int}\text{-}m^2=0$. In this point modification should vanish. Still modification for S- and D- wave maybe different

Our dynamical model for dependence of bound nucleon pdf on virtuality - explains why effect is large for large x and practically absent for x~ 0.2 (average configurations V(conf) ~ <V>)

In the lowest order of perturbation over fluctuation the EMC effect is proportional to<V> in which SRC give dominant contribution but mean field is still significant - 30 -40%,

A-dependence of <V> is similar to that of the EMC effect (I.Sick)

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

Estimating the effect of suppression of small configurations. Introducing in the wave function of the nucleus explicit dependence of the internal variables we find that probability of small size configuration is smaller by factor

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

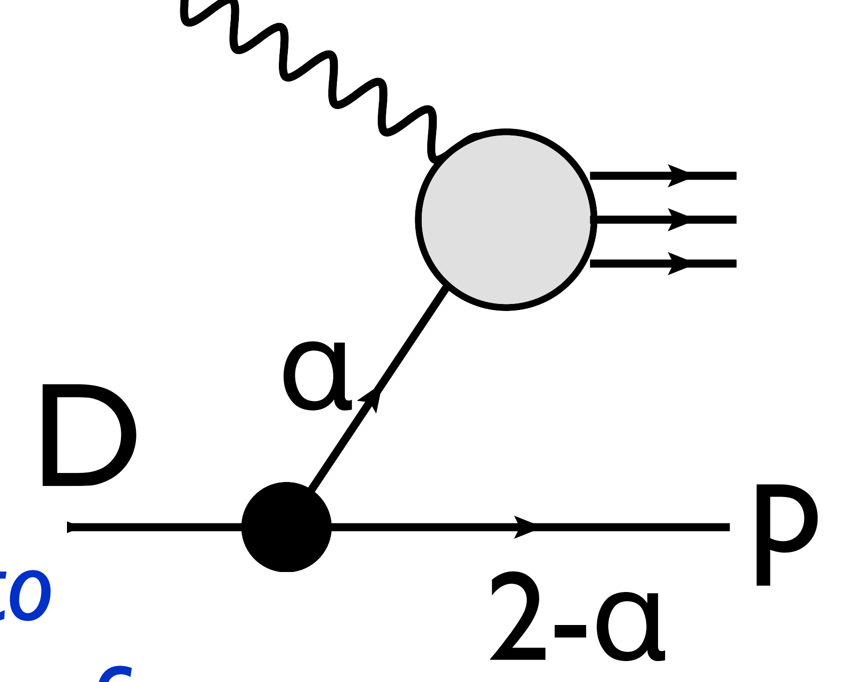
effect $\propto$ virtuality

$$p_{int} = p_A - p_{recoil}$$

Four vectors

$$\Delta E = m_{N^*} - m_N$$

Tagging of proton and neutron in e+D→e+ backward N +X as a probe of the origin of the EMC effect (FS 85)



interesting to measure tagged structure functions where modification is expected to increase quadratically with tagged nucleon momentum. It is applicable for searches of the form factor modification in (e,e'N).

$$1 - F_{2N}^{bound}(x/\alpha, Q^2)/F_{2N}(x/\alpha, Q^2) = f(x/\alpha, Q^2)(m^2 - p_{int}^2)$$

Here α is the light cone fraction of interacting nucleon

$$\alpha_{spect} = (2 - \alpha) = (E_N - p_{3N})/(m_D/2)$$

In practice, small background for 2- α >1, and in this kinematics one expects an EMC like effect already for smaller spectators momenta, since x/α > x.

Importance caveat: for large nucleon momenta nucleons closer to each other and chances of f.s.i maybe larger. Not the case in semi exclusive case eD—>e +p + "resonance". But maybe relevant for larger W. Need dedicate studies of f.s.i. in DIS in the nucleus fragmentation region.

SMALLER X' MORE HADRONS PRODUCED , MA ULT IN STRONGER

Optimistic possibility - EMC effect maybe missing some significant deformations which average out when integrated over the angles

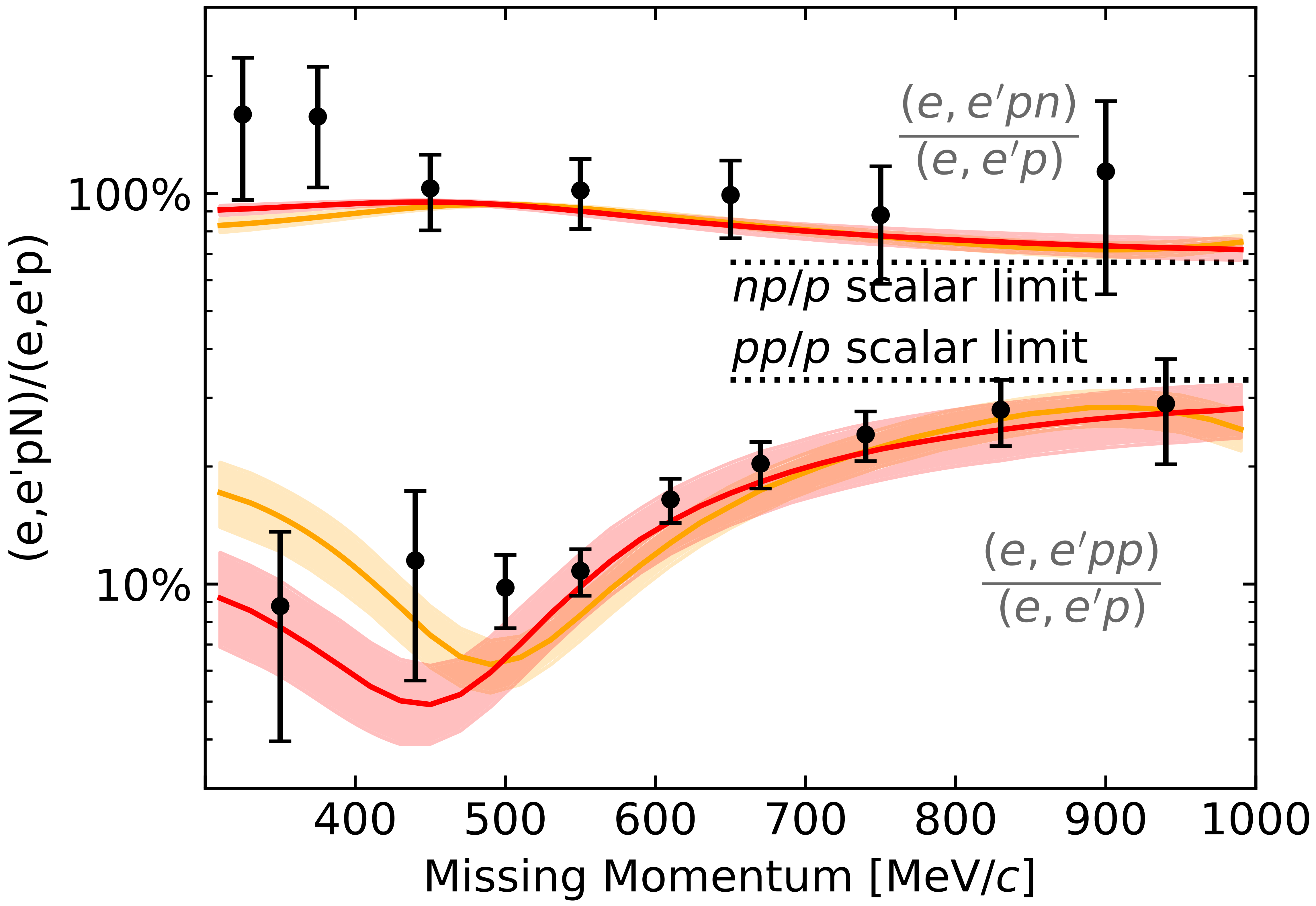
A priori, deformation of a bound nucleon can also depend on the angle ϕ between the momentum of the struck nucleon and the reaction axis as

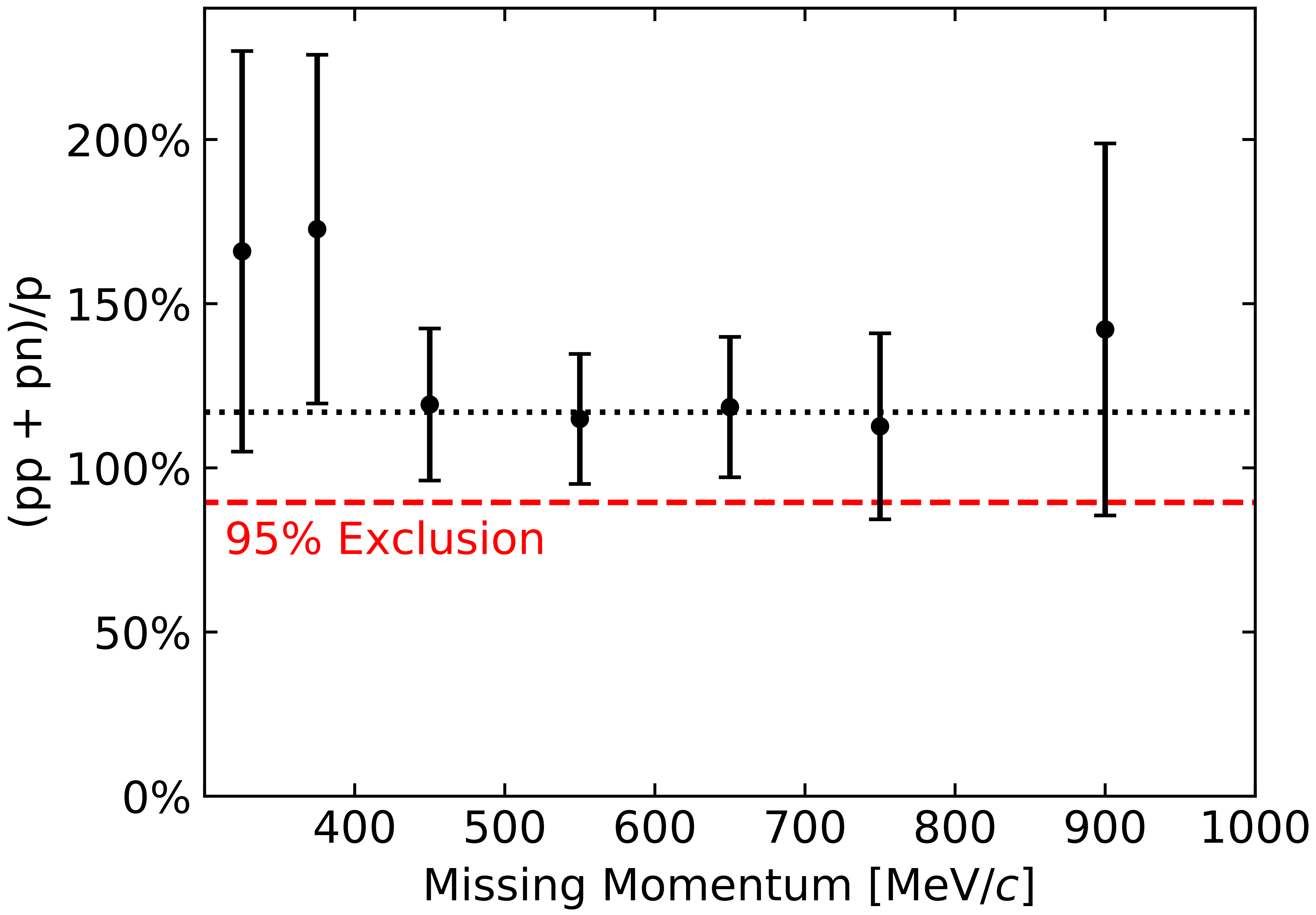
$$d\sigma/d\Omega/ < d\sigma/d\Omega >= 1 + c(p, q).$$

Here $<\sigma>$ is cross section averaged over ϕ and $d\Omega$ is the phase volume and the factor c characterizes non-spherical deformation.

Such non-spherical polarization is well known in atomic physics *(discussion with H.Bethe)*. Contrary to QED detailed calculations of this effect are not possible in QCD. However, a qualitatively similar deformation of the bound nucleons should arise in QCD. One may expect that the deformation of bound nucleon should be maximal in the direction of radius vector between two nucleons of SRC.

New challenge





The fraction of high-momentum protons with a measured recoil partner nu-cleon for ^{12} C: the measured ratio of $(e, e'\ pp) + (e, e'\ pn)$ events to $(e, e'\ p)$ events as a function Z of $\vec{p}$miss.

EXCLUDES PRESENCE OF MORE THAN 5% OF NONUCLEONIC DEGREES OF FREEDOM IN SRC

To do list for EMC related topics

- ☞ Leading / HT separation in the EMC effect —- especially at x ~ 0.6 where Fermi motion effect is very different for LT & HT
- ☞ Tagged structure functions in eD
- ☞ Direct searches for non-nucleonic degrees of freedom like Δ-isobars
- ☞ Dedicated studies of f.si. in light nuclei

Finalizing DY data

Conclusions

Last decade - impressive progress in understanding SRC in nuclei

☞☞ Next few years: tagged structure functions in eD to test critically the origin of the EMC effect , probing ultra high momenta in nuclei, three nucleon correlations, determining optimal formalism for description of relativistic dynamics.

☞ Two nucleon SRC - going from discovery to precision measurements