"Quark-gluon dynamics of short-ranged nuclear correlations and how to observe it at the EIC"

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Short-range nuclear correlations at an Electron-Ion Collider
5-7 September 2018

Outline

- ☛ ***Introduction - nucleus wave function depends on resolution / momentum transfer scale***

- ☛ *High resolution —> High energy - dominance of light cone component of the wave function*

  why having polarized deuterons is very important

- ☛ *Expectations for non-nucleonic degrees of freedom*

- ☛ *Color screening and suppression of compact configurations in bound nucleons*

- ☛ *Challenges for explaining EMC effect as due to short-range correlations*

  Critical experiments - tagging, etc

- ☛ *Hunting for Δ - isobar like configurations in nuclei*

Experience of quantum field theory - interactions at different resolution (momentum transfer) scales resolve different degrees of freedom - renormalization,.... No simple relation between relevant degrees of freedom at different scales.

QCD: at large Q^2 DGLAP evolution of the nucleon wave function

at $Q^2 < 0.5\ \mathrm{GeV}^2$(?) spontaneously broken chiral symmetry regime

Transitional regime between these two regimes (e.g. set in of the gluon degrees of freedom) is still a challenge

Nuclei - even more resolution scales ➡ Complexity of the problem

Three important scales

① To resolve nucleons with $k < k_F$, one needs $Q^2 \geq 0.8$ GeV^2.

related effect: Q^2 dependence of quenching

② Hard nuclear reactions I: energy transfer > 1 GeV and momentum transfer q > 1 GeV.

$$q_0 \geq 1GeV \gg |V_{NN}^{SR}|, \vec{q} \geq 1GeV/c \gg 2\ k_F$$

Sufficient to resolve short-range correlations (SRCs) = direct observation of SRCs but not sensitive to quark-gluon structure of the constituents

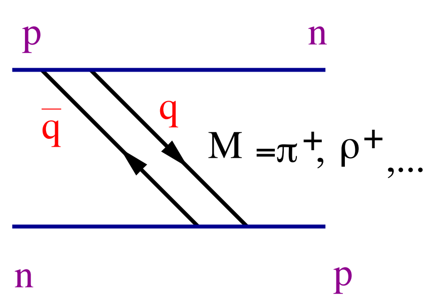
Principle of resolution scales was ignored in 70's leading to believe that SRC could not be unambiguously observed. Hence very limited data

③ Hard nuclear reactions II: energy transfer ≫ 1 GeV and momentum transfer q ≫ 1 GeV. May involve nucleons in special (for example small size configurations). Allow to resolve quark-gluon structure of SRC: difference between bound and free nucleon wave function, exotic configurations

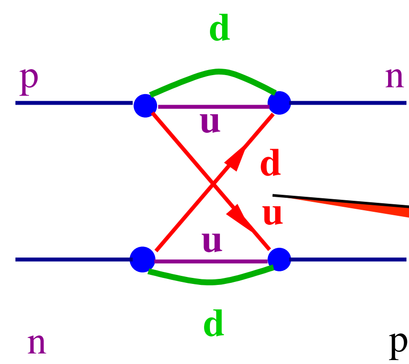
Major (chancy) discovery - the EMC effect - substantial difference of quark Bjorken x distributions at x > 0.25

Interaction picture also depends Q, and energy of the probe: at low scale instantaneous effective interaction, at high Q scale non-static interaction: interaction time >> 1/Q (part of the nucleus wave function)

Meson exchange forces: pions in the intermediate states, Δ-isobars



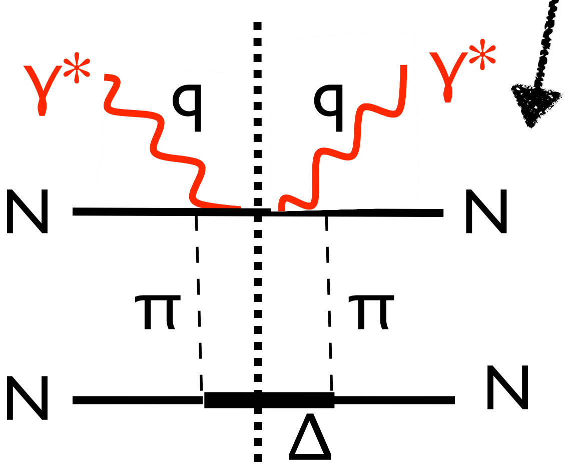
Meson Exchange



Quark interchange

Intermediate state could be ΔN rather than = pn,

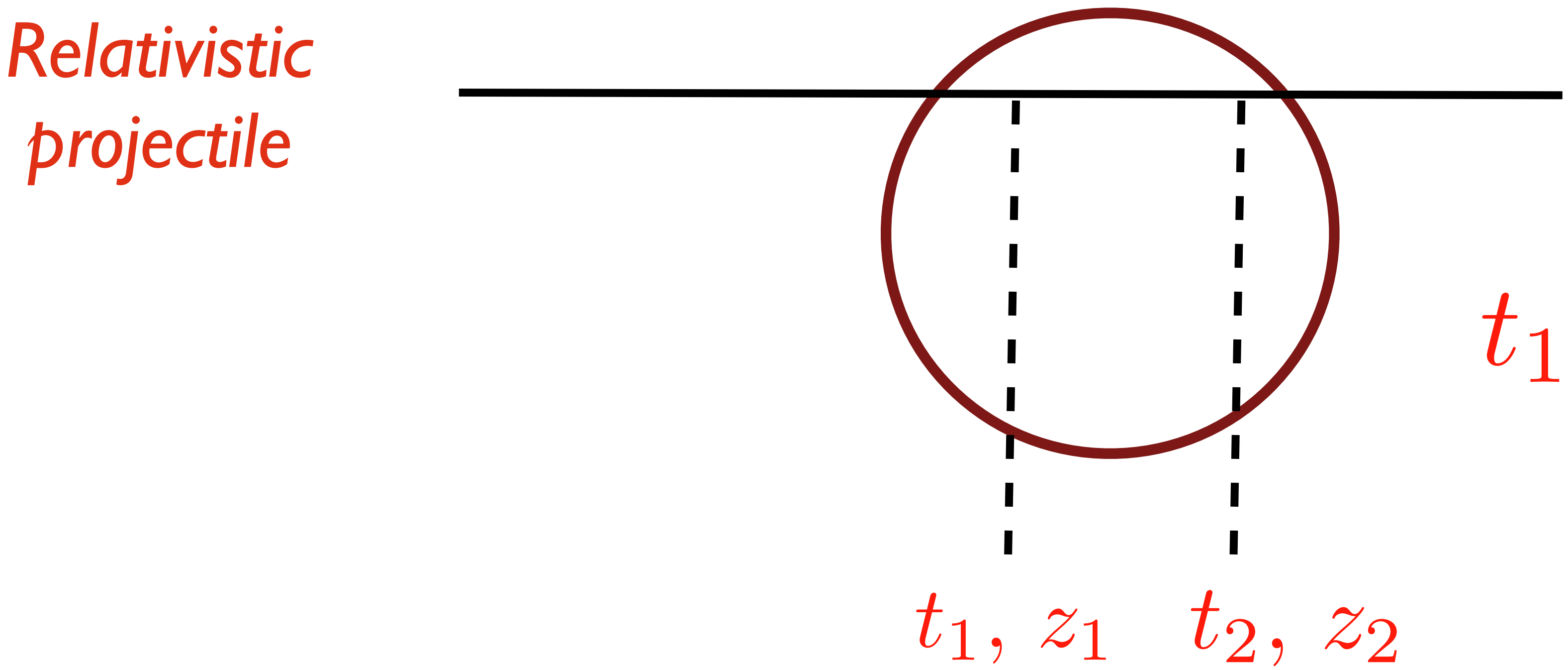
may correspond to a tower of meson exchanges with coherent phases - high energy example is Reggeon;
pion exchange for low t special - due to small mass
Two gluon interchange? Much larger mass scale in t -channel - very short distances



High frequency probe one can resolve N Δ, hence in this case intermediate Δ's cannot be included in NN potential

⟹ Price to pay for using high energy processes:

HE processes develops along the light cone.



$$t_1 - z_1 = t_2 - z_2$$

Similar to the perturbative QCD the amplitudes of the processes are expressed through the wave functions on the light cone. *Naturally satisfy baryon, energy sum rules,…*

Note: in general no benefit for using LC for low energy processes.

Hard nuclear reactions: energy transfer ≫ 1 GeV and momentum transfer q ≫ 1 GeV.

Objectives: direct observation of nonnucleonic degrees of freedom in nuclei (hadronic & quark-gluon)

Geometric reasoning - internucleon distance in 2N SRC < 2 r_N suggests 2N SRC is actually quark soup or has many non-nucleonic hadronic components.

FS76-81: *geometric reasoning is misleading* and nucleon degrees of freedom make sense for momenta well above Fermi momentum due to presence in QCD of

a hidden parameter (FS 75-81) : in NN interactions: direct pion production is suppressed for a wide range of energies due to chiral properties of the NN interactions:

$$\frac{\sigma(NN \to NN\pi)}{\sigma(NN \to NN)} \approx \frac{k_\pi^2}{16\pi^2 F_\pi^2}, \; F_\pi = 94 MeV$$

⇒ Main inelasticity for NN scattering for $T_p \leq 1$ GeV is single Δ-isobar

in the deuteron channel only 2 Δ's allowed

Correspondence argument: wave function - continuum ⇒ Small parameter for inelastic effects in the deuteron/nucleus WF, while relativistic effects are already significant since $p_N/m_N \leq 1$

Nucleons can come pretty close together without been excited / strongly deformed - dynamical parameter is nucleon momentum not the internucleon distance

Explains why data on scattering off 2N correlations indicate that 2N SRCs consists predominantly (> 90%) from nucleons

(Or Hen's talk)

Many nucleon light cone (LC) approximation

$$\psi_A(\alpha_i, p_{t,i})$$

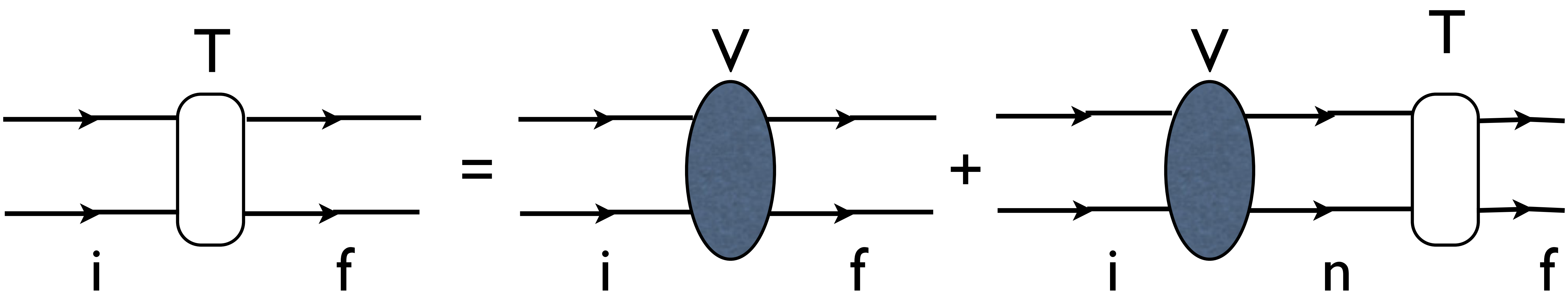
α/A -light cone momentum fraction
α=1 corresponds to a nucleon at rest

$$\sum_{i=1}^{A} \alpha_i = A, \sum_{i=1}^{A} p_{t,i}) = 0$$

First of these conditions cannot be implemented in virtual nucleon formalism

Deuteron: $\psi_D(\alpha, p_t)$

For two nucleon approximation we have in addition an angular condition that Lippman-Schwinger type equation for NN interaction



should lead to rotationally invariant scattering amplitudes (pretty lengthy proof) results in

$$\psi_D(\alpha, p_t) \to \psi_D(M_{NN}^2), M_{NN}^2 = 4\left(\frac{m^2 + p_t^2}{\alpha(2-\alpha)}\right)$$

Spin zero /unpolarized case

Relation between LC and NR wf.

$$\int \Psi^2_{NN}\left(\frac{m^2+k_t^2}{\alpha(2-\alpha)}\right)\frac{d\alpha d^2k_t}{\alpha(2-\alpha)} = 1 \qquad \int \phi^2(k)d^3k = 1$$

$$\Psi^2_{NN}\left(\frac{m^2+k_t^2}{\alpha(2-\alpha)}\right) = \frac{\phi^2(k)}{\sqrt{(m^2+k^2)}}$$

Similarly for the spin 1 case we have two invariant vertices as in NR theory:

$$\psi^D_\mu \epsilon^D_\mu = \bar{u}(p_1)\left(\gamma_\mu G_1(M^2_{NN}) + (p_1-p_2)_\mu G_2(M^2_{NN})\right)u(-p_2)\epsilon^D_\mu$$

hence there is a simple connection to the S- and D- wave NR WF of D

For two body system in two nucleon approximation

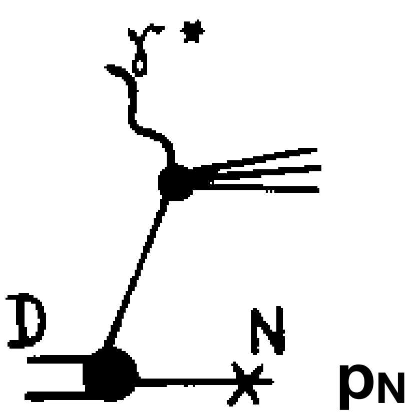
the biggest difference between NR and virtual nucleon approximation LC is in the relation of the wave function and the scattering amplitude

due to implicit presence of $N\bar{N}$ pairs in virtual nucleon approximation

$$\left(\frac{m^2+p_t^2}{\alpha(2-\alpha)}\right) = m^2+k^2 \to \alpha = 1+\frac{k_3}{\sqrt{m^2+k^2}}$$

$$\alpha = \left(\sqrt{m^2+p_N^2}+p_{3,N}\right)/m_D$$

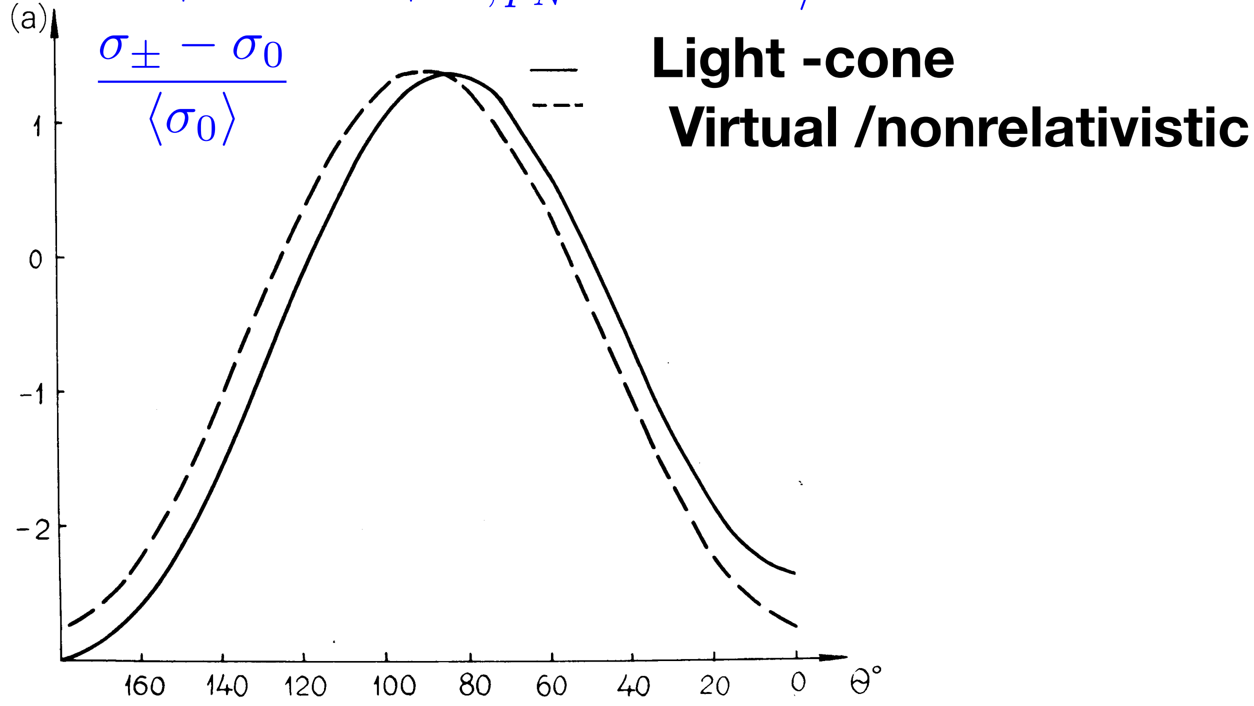
Nonlinear connection between momentum k in wave function and p_N - momentum of spectator in the deuteron rest frame



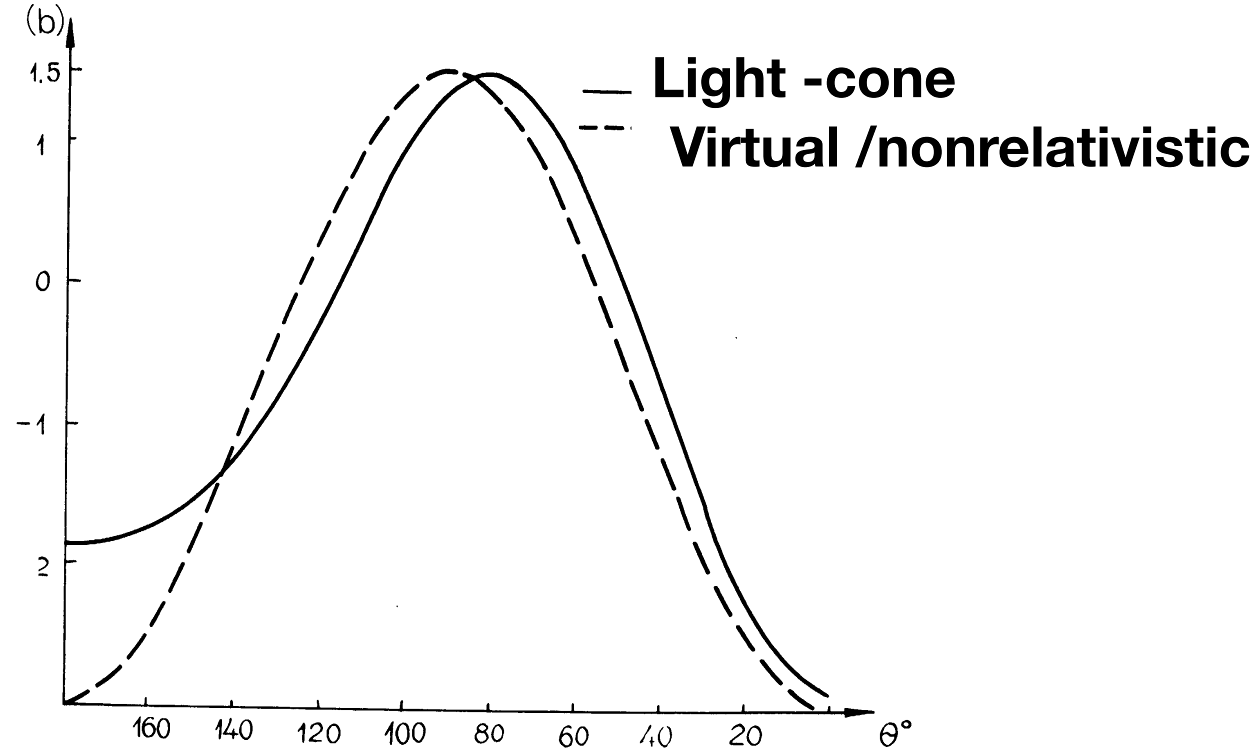
The spectator mechanism for the $\ell + \mathrm{D} \to \ell' + \mathrm{p} + \mathrm{X}$ reaction.

$e + \vec{D} \to N + X, p_N = .25 GeV/c$

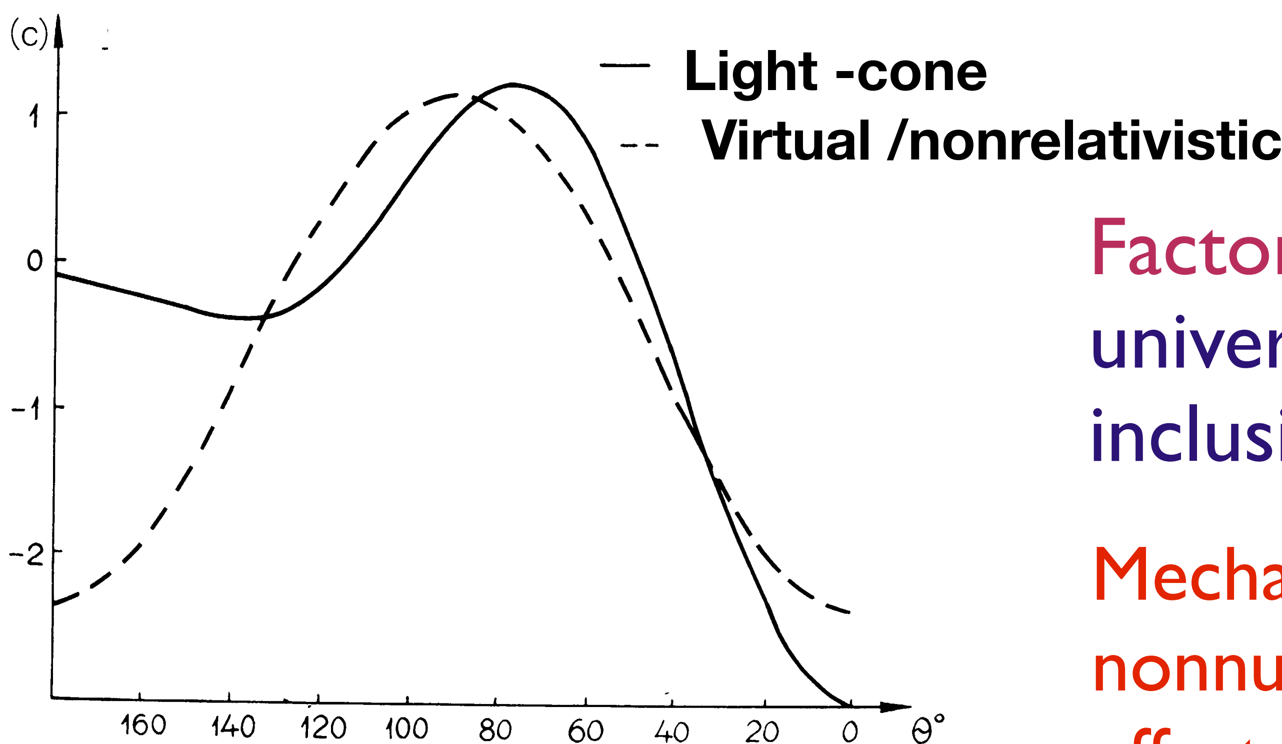
$\frac{\sigma_\pm - \sigma_0}{\langle \sigma_0 \rangle}$



$\frac{\sigma_\pm - \sigma_0}{\langle \sigma_0 \rangle}$ $e + \vec{D} \to N + X, p_N = .3 GeV/c$



$\frac{\sigma_\pm - \sigma_0}{\langle \sigma_0 \rangle}$ $e + \vec{D} \to N + X, p_N = .35 GeV/c$



Factorization test: T_{20} should be universal - the same for various hard inclusive and exclusive processes

Mechanisms of violation of factorization: nonnucleonic degrees of freedom in D /EMC effect, fsi

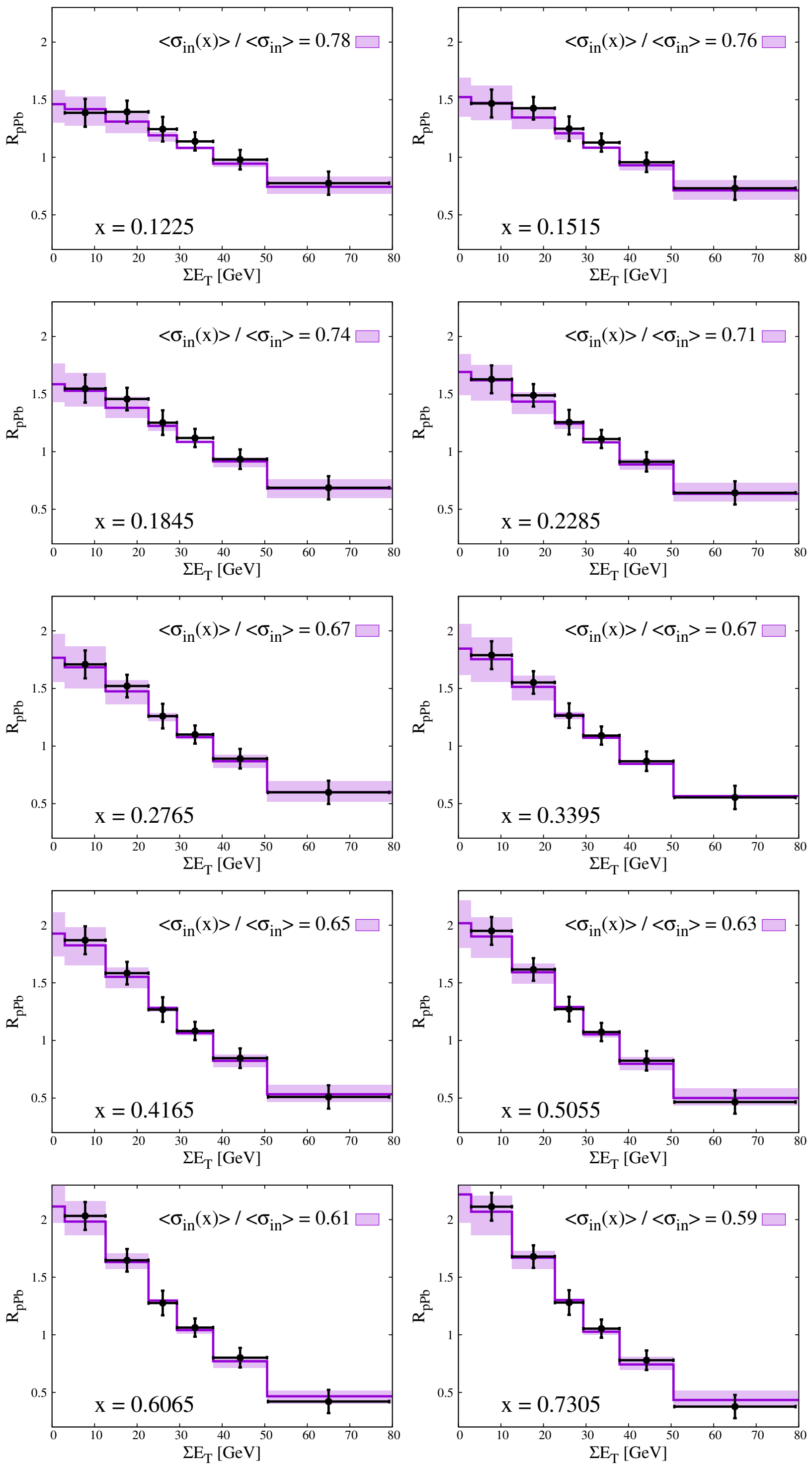
What are expectations for non-nucleonic degrees of freedom?

- Deformation of the bound nucleon wave function like for electrons in a molecule as compared to two independent atoms.

- Hadronic degrees of freedom - Δ-isobar - small probability but maybe important. Pions - very small effect.

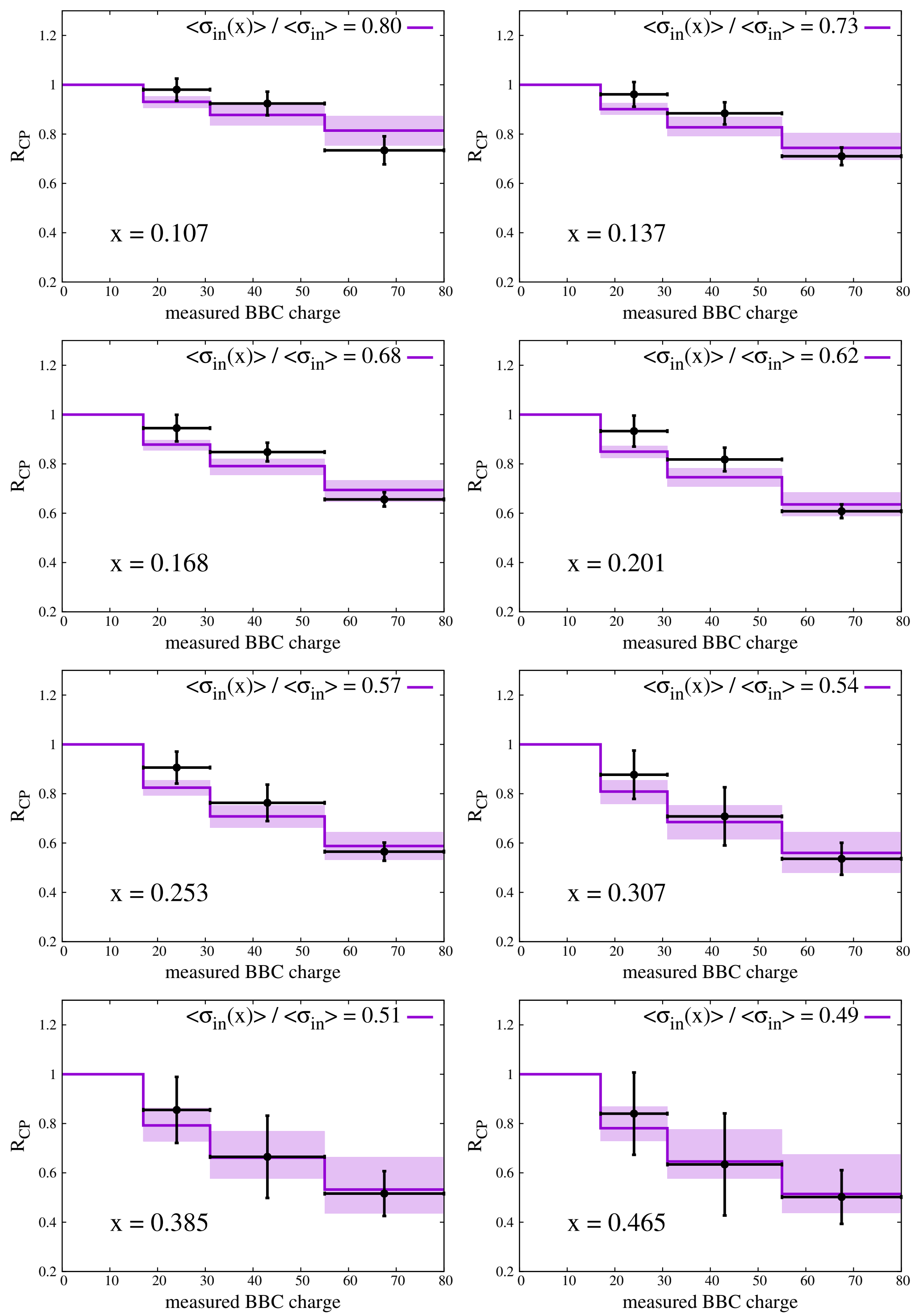
Let us first consider deformation effect

In QCD interaction depends on the size of hadron or configuration in the hadron
Quarks in nucleon with $x>0.5$ --0.6 belong to small size configurations with strongly suppressed pion & gluon fields (while pion exchange is critical for SRC especially D-wave.). Test we suggested in 83 is to measure number of wounded nucleons, ν, in pA collisions for hard trigger with large x.
Prediction: . drop of ν, with increase of x. Observed at LHC and RHIC.



Deviations from Glauber model for production of dijets, described in the color fluctuation model as due to decrease of $\langle\sigma_{eff}(x)\rangle/\sigma_{in}$

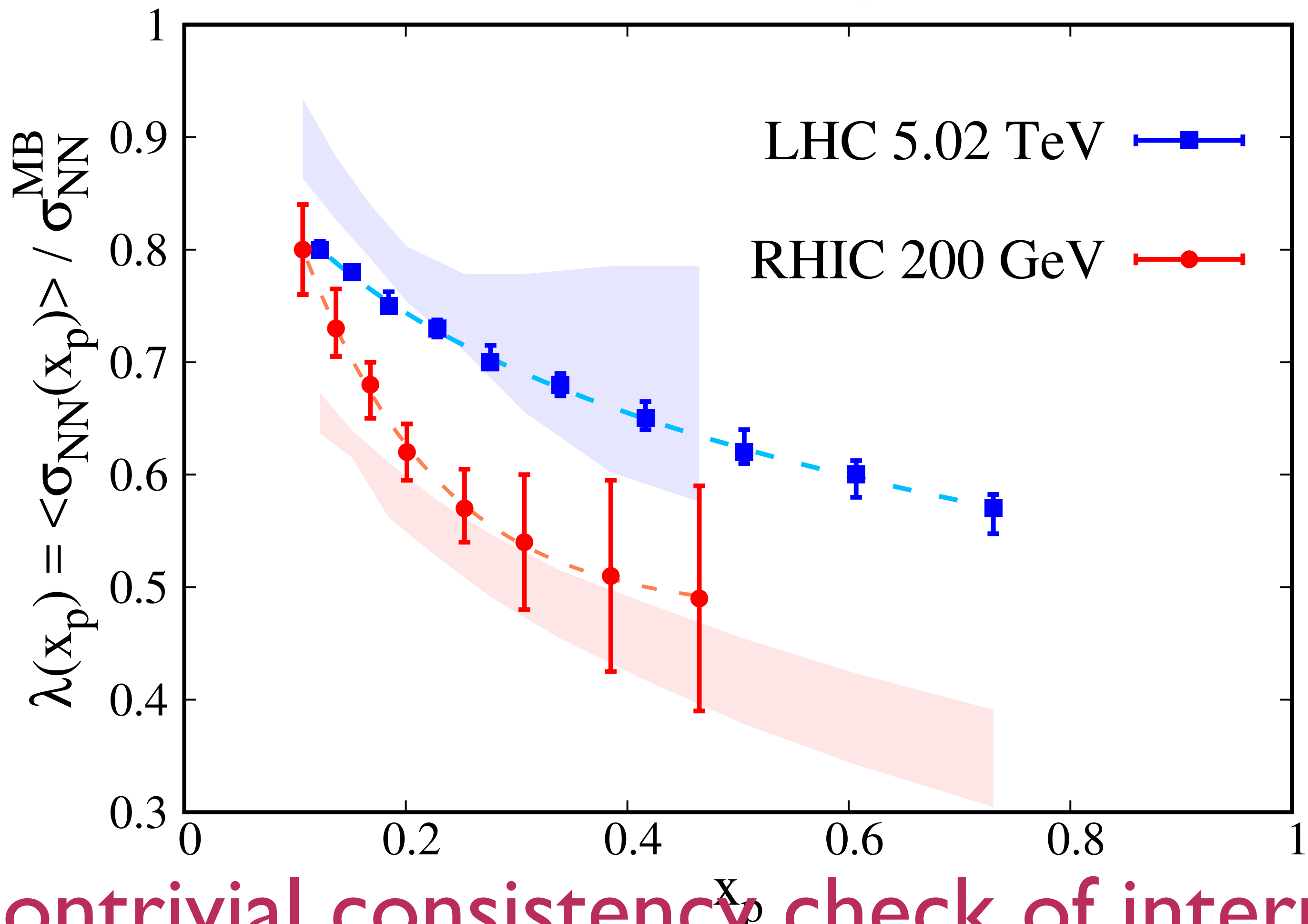
Data from pA ATLAS



Similar analysis with DAu RHIC jet production data at zero rapidity and high p_T.

Implicit eqn for relation of $\lambda(x_p, s_1)$ and $\lambda(x_p, s_2)$

$$\int_0^{\lambda(x_p;\sqrt{s_1})\sigma_{tot}(\sqrt{s_1})} d\sigma\, P_N(\sigma;\sqrt{s_1}) = \int_0^{\lambda(x_p;\sqrt{s_2})\sigma_{tot}(\sqrt{s_2})} d\sigma\, P_N(\sigma;\sqrt{s_2})$$



Highly nontrivial consistency check of interpretation of data at different energies and in different kinematics

suggests $\lambda(x_p$=0.5, low energy) ~1/4). Such a strong suppression results in the EMC effect of reasonable magnitude due to suppression of small size configurations in bound nucleons (Frankfurt & MS83)

Nucleon in quark configurations of a size << average size should interact much weaker than in average. Application of the variational principle indicates that probability of such configurations in bound nucleons should be suppressed
(as it leads to stronger overall attraction)

We estimated the effect in the perturbation theory over the difference of the configuration dependent and average potentials

Introducing in the wave function of the nucleus explicit dependence of the internal variables

$$\left[-\frac{1}{2m_{\rm N}}\sum_j \nabla_i^2 + {\sum_{i,j}}' V(R_{ij}, y_i, y_j) + \sum_i H_0(y_i)\right]\psi(y_i, R_{ij}) = E\psi(y_i, R_{ij}).$$

NR potential

$$U(R_{ij}) = \sum_{y_i, y_j, \tilde{y}_i, \tilde{y}_j} \langle \varphi_{\rm N}(y_i)\varphi_{\rm N}(y_j)|V(R_{ij}, y_i, y_j, \tilde{y}_i, \tilde{y}_j)|\varphi_{\rm N}(\tilde{y}_i)\varphi_{\rm N}(\tilde{y}_j)\rangle,$$

In the first order perturbation theory for V << U using closure we find

$$\delta = \left|\frac{\psi_0 + \delta\psi_0}{\psi_0}\right|^2 \simeq 1 + 2{\sum_j}' U(R_{ij})/\Delta E_A.$$

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

For average configurations in nucleon (V ≃ U) no deformations

modification of average properties of bound nucleons is < 2- 3 %

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

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

general case

$$p_{int} = M_A - p_{A-1}$$

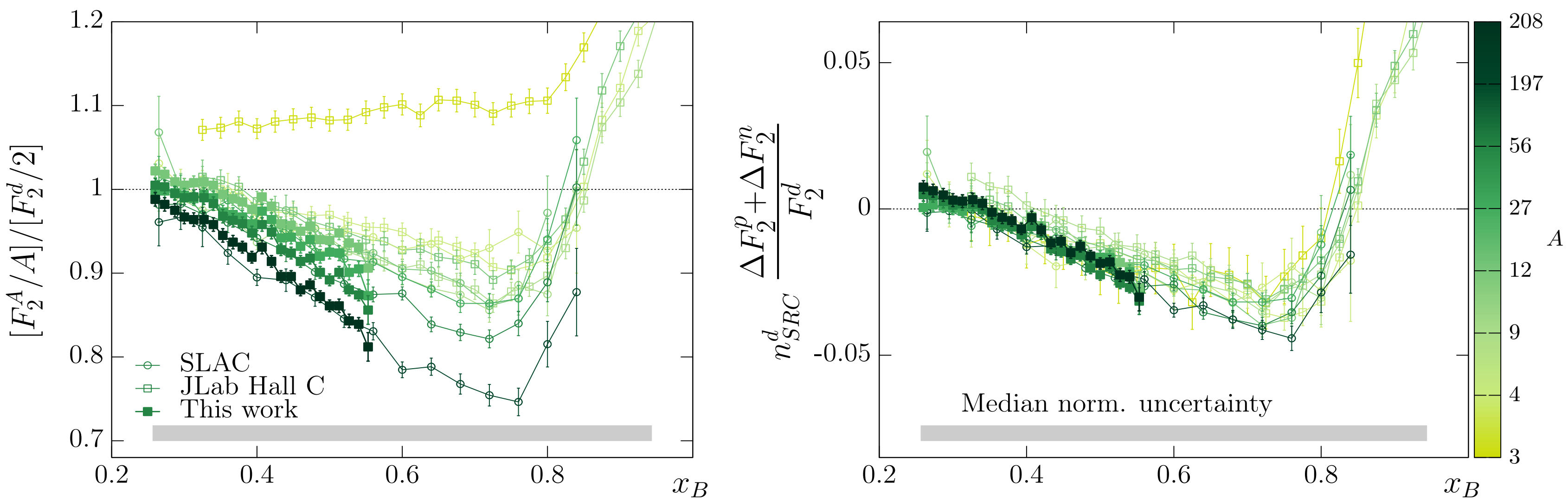
effect ∝ virtuality

Dependence of the modification of bound nucleon pdf on virtuality is a generic effect — the discussed mechanism - explains why effect is large for large x and practically absent for x~ 0.2 (average configurations V(conf) ~ <V>)

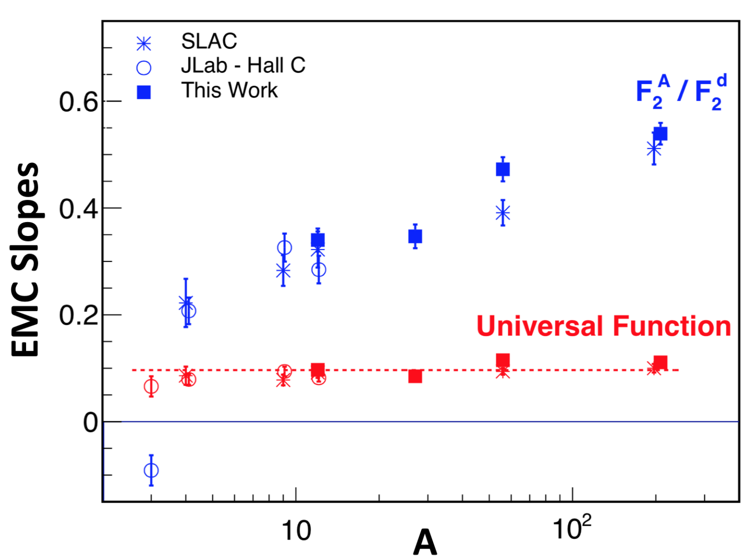
leads to universal shape and A-dependence of deviation of the EMC ratio from one

$$\sigma_{eA}(x,Q^2)/\sigma_{eD}(x,Q^2) - 1 = a_2(A) f(x,Q^2)$$

universality extend to x=0.8 where Fermi motion is important - another indication of dominance of SRCs as Fermi motion is dominated by SRC



(Or's talk)

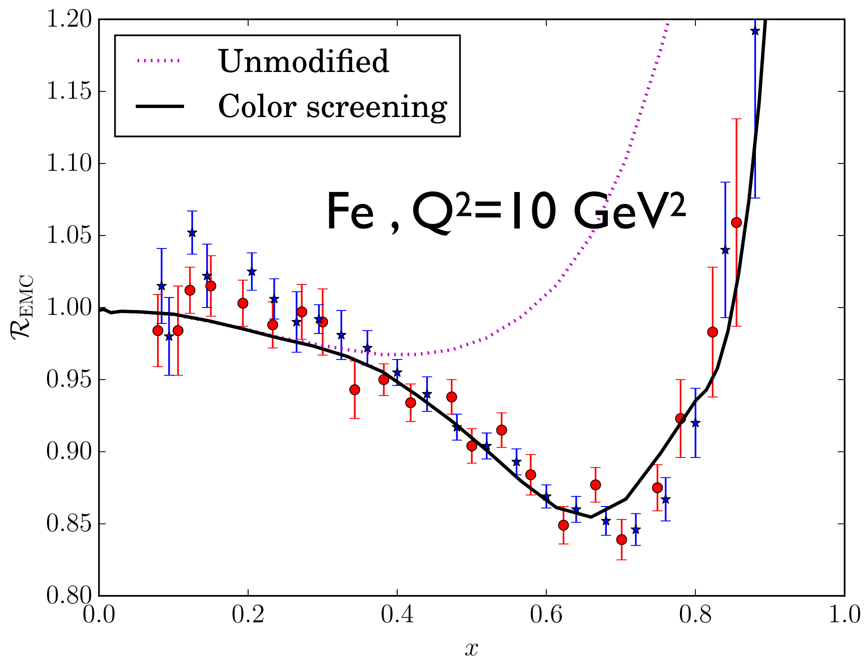


EMC ratio shows no Q^2 dependence: this indicates the presence of the EMC effect for high twist contribution to the EMC ratio

Model with modification of rare configurations in bound nucleons addresses the paradox: evidence that EMC effect is due to SRCs while SRC are at least 90% nucleonic, while the EMC effect for x=0.5 is $\geq$15% and there is no evidence for significant changes of the nucleon form factor for small nucleon momenta.

Very few models of the EMC effect survive when constraints due to the observations of the SRC, no enhancement of antiquarks, etc are included - essentially one generic scenario - strong deformation of rare configurations in bound nucleons increasing with nucleon momentum and with most of the effect due to the SRCs

Assuming that suppression is small for $x \leq 0.45$, grow linearly between $x=0.45$ and 0.65 and equal to $\delta_A(k)$ at larger x gives a reasonable description of the data



Freese, Sargsian, MS 14

Open questions to be studied at EIC

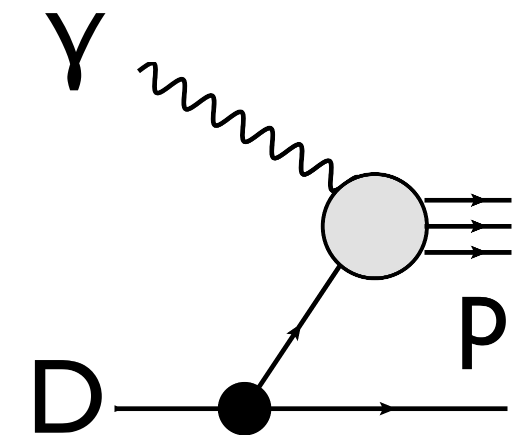
EMC effect for large Q where HT effects are negligible.

EMC effect for gluons: may expect squeezing of configurations with large x gluons and hence EMC effect

Direct measurement of the valence quark enhancement and antiquark suppression at x~ 0.1 (via semiinclusive processes - DIS with leading pions)

superfast quarks (x > 1)

“Gold plated test” FS 83



Tagging of proton and neutron in e+D→e+ backward N +X (lab frame).

Collider kinematics -- nucleons with $p_N > p_D/2$ - C.Weiss talk, Jlab experiments -L.Weinstein’s talk

➡ *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). If an effect is observed for say 200 MeV/c - go to 400 MeV/c and see whether the effect would increase by a factor of ~3-4.*

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

Here α is the light cone fraction of interacting nucleon

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

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

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

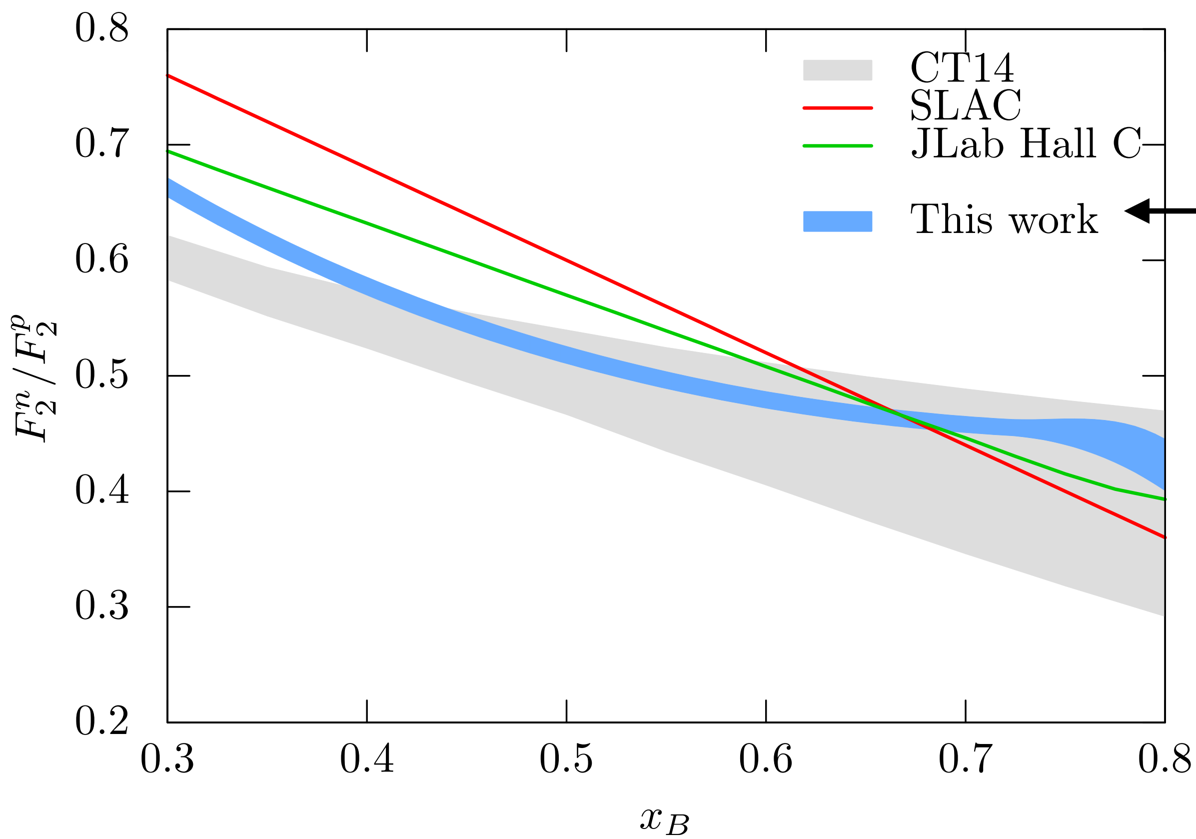
$$d\sigma/d\Omega/ < d\sigma/d\Omega >= 1 + c(p,q).$$

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)*. In difference from 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.

Tagging combined with detection of forward pions for flavor separation

⟹ **Separate EMC effect for u and d quarks in the proton/neutron.**
Maybe rather different as d/u strongly changes with x



correcting for the EMC effect based on pn src dominance

Tagging with polarized deuteron:

is the EMC effect the same for S and D waves? Different interactions in S and D wave —> different sensitivity to the size of configurations.

is the EMC effect the same for parallel and antiparallel helicities of quark and nucleon ?

Different EMC effect for

$$\lambda_u = \lambda_D/2 \qquad \lambda_d = \lambda_D/2$$

$$\lambda_u = -\lambda_D/2 \qquad \lambda_d = -\lambda_D/2$$

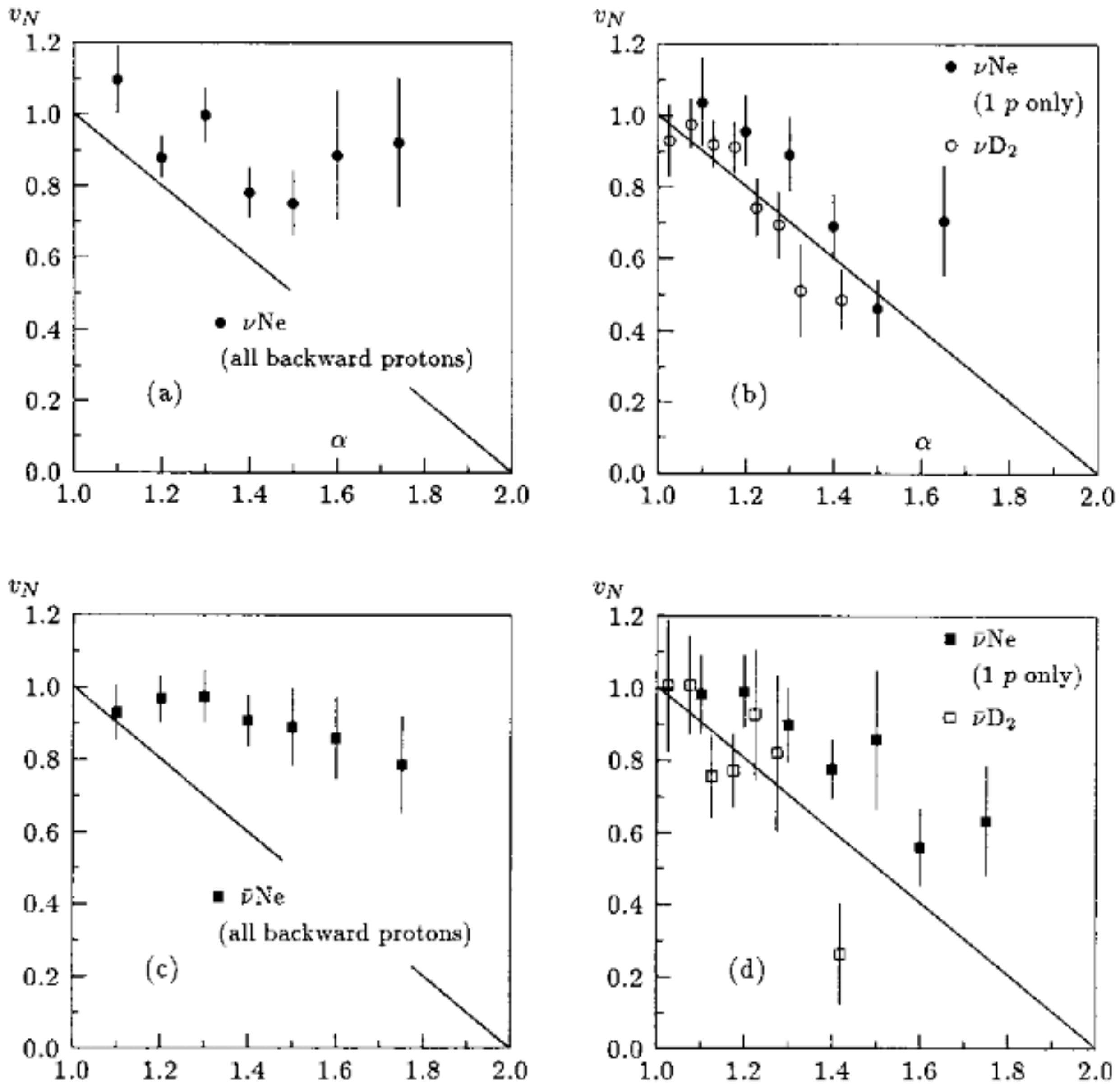
Topic for further exploration: pattern of f.s.i. - change of spectator rate, momentum distortions. Needs further studies (C.Weiss talk)

tagging for A>2 — can produce backward nucleon in a final state scattering off NN SRC.

example: neutrino experiment off Ne and D

$v_N = v / \langle v \rangle$

$v = xy$



Z. Phys. C Particles AND FIELDS, 44, 79 (1989) BEBC WA59

Fig. 6a–d. v_N versus α for neon and deuterium, **(a)** ν – Ne, **(b)** ν – Ne events with only one proton and $\nu - D_2$, **(c)** $\bar{\nu}$ – Ne, **(d)** $\bar{\nu}$ – Ne events with only one proton and $\bar{\nu} - D_2$. In **(a)** and **(c)** events with 2 backward protons are included twice. The lines show the prediction of the two-nucleon correlation model $v(\alpha) = \langle v \rangle (2 - \alpha)$

It is necessary to suppress cascades to observe SRC effect

Summary on the EMC effect

Possible explanations are very much constrained by

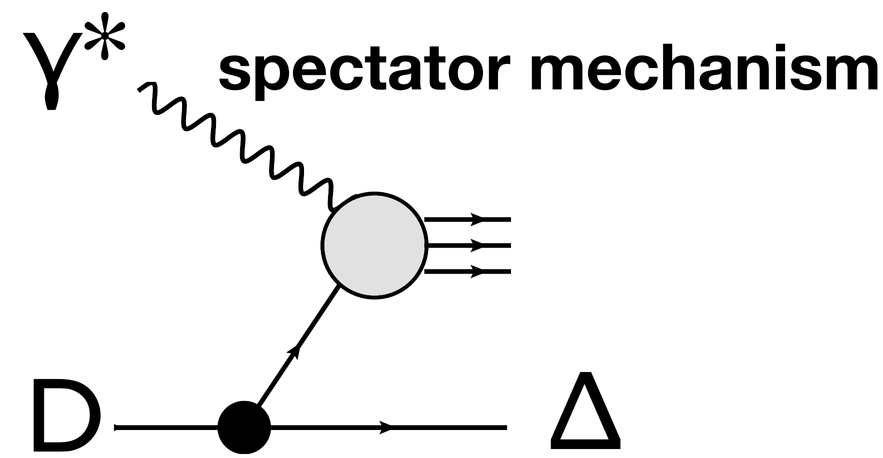
- $\bar{q}_A/\bar{q}_N \leq 1$
- bound nucleon at k< 200 MeV/c ≈ free nucleon
- presence of 20% universal 2N SRC build predominantly of nucleons
- evidence that SRCs give dominant contribution to the EMC effect
- Need to explain why effect is small at x≤ 0.4 and rapidly grows at larger x

explanation via mechanism of suppression of small size configurations in bound nucleons so far survives, with experimental indications of squeezing size at large x.

Other possible mechanism of suppression of rare large x components in far off shell nucleons?

EMC - many interesting directions for study/ Need to explore rates for x> 0.2 physics

Looking for Δ 's, 6q…. in DIS



$$\sigma_{eD\to e\Delta+X} = \sigma_{e\Delta\to X}(x/(2-\alpha), Q^2)\frac{\psi^2_{\Delta,\Delta}(\alpha, p_t)}{2-\alpha}$$

$$\alpha_\Delta = \frac{\sqrt{m_\Delta^2 + p^2} - p_3}{m_d/2}$$ p is target rest frame momentum of Δ isobar

Advantage σ(e Δ) can be estimated with a reasonable accuracy in difference from $e + {}^2H \to e +\ forward\ \Delta^{++} +\ slow\ \Delta^-$

$\alpha=1$, $p_t=0$ corresponds to $p_3 \sim 300$ MeV/c forward - for good acceptance in Jlab kinematics necessary to detect slow protons and pions. forward nucleon and pion (in the deuteron fragmentation) at EIC (Easy (?)).

Competing mechanism - Δ's from nucleon fragmentation =direct mechanism

$$\left.\frac{\sigma^{lD/\Delta}}{dx\ dy\ \frac{d\alpha}{\alpha}\ d^2k_t}\right|_{direct} = \int \frac{d\beta}{\beta}\ d^2p_t\ \rho_D^N(\beta, p_t)\ \times \tag{18}$$

$$\times\ \frac{d\sigma^{lN/\Delta}}{dx\ dy\ d\alpha/\alpha\ d^2k_t}\left(\beta E_l, x/\beta, y, Q^2, \frac{\alpha}{\beta - x}, k_t - \frac{\alpha}{\beta}p_t\right)$$

For scattering of stationary nucleon

$$\alpha_\Delta < 1 - x$$

Also there is strong suppression for production of slow Δ's - larger x stronger suppression

$$x_F = \frac{\alpha_\Delta}{1-x} \qquad \sigma_{eN\to e+\Delta+X} \propto (1-x_F)^n, n \geq 1$$

Numerical estimate for $P_{\Delta\Delta}$ =0.4%

$$\left.\frac{\sigma^{1D/\Delta}}{dx\ dy\ \frac{d\alpha}{\alpha}\ d^2k_t}\right|_{direct} \Bigg/ \left.\frac{\sigma^{1D/\Delta}}{dx\ dy\ \frac{d\alpha}{\alpha}\ d^2k_t}\right|_{spect} < 0.1$$

Tests possible to exclude rescattering mechanism: $\pi N\to\Delta$ FS90

For the deuteron one can reach sensitivity better than 0.1 % for ΔΔ especially with quark tagging *(FS 80-90)*

Δ-isobars are natural candidate for most important nonnucl. degrees of freedom

Large energy denominator for NN →NΔ transition ➡ Δ's **predominantly in SRCs**

Δ 's in 3He on 1% level from Bjorken sum rule for A=3 - Guzey &F&S 96

Expectations during the EMC effect rush

TABLE II. Pion excess and Δ fraction in nuclear matter (NM) and nuclei.

	$\langle \delta n^{\pi} \rangle / A$	$\langle n^{\Delta} \rangle / A$
NM, $k_F = 0.93$	0.08	0.03
NM, $k_F = 1.13$	0.12	0.04
NM, $k_F = 1.33$	0.18	0.06
^{2}H	0.024	0.005
^{3}He	0.05	0.02
^{4}He	0.09	0.04
^{27}Al	0.11	0.04
^{56}Fe	0.12	0.04
^{208}Pb	0.14	0.05

ruled out by Drell - Yan data

Friman, Pandharipande, WIringa 1983

$$\frac{P(\Delta)}{P_{SRC}(N)} \sim \frac{0.04}{0.2}$$ ~ 0.2

Too large ?

for x> 0.1 very strong suppression of two step mechanisms (FS80)

is confirmed by neutrino study of Δ-isobar production off D

Best limit on the probability of $\Delta^{++}\Delta^{-}$ component in the deuteron $< 0.2\%$. (however details of procedure are not available)

Side remark: Polarized deuteron extra bonus: $\Delta^{++}\Delta^{-}$ mostly in D-wave -- hence large spin effects

An analysis has been made of 15 400 ν–d interactions in order to find a $\Delta^{++}(1236)$–$\Delta^{-}(1236)$ structure of the deuteron. An upper limit of 0.2% at 90% CL is set to the probability of finding the deuteron in such a state.

SEARCH FOR A Δ(1236)–Δ(1236) STRUCTURE OF THE DEUTERON

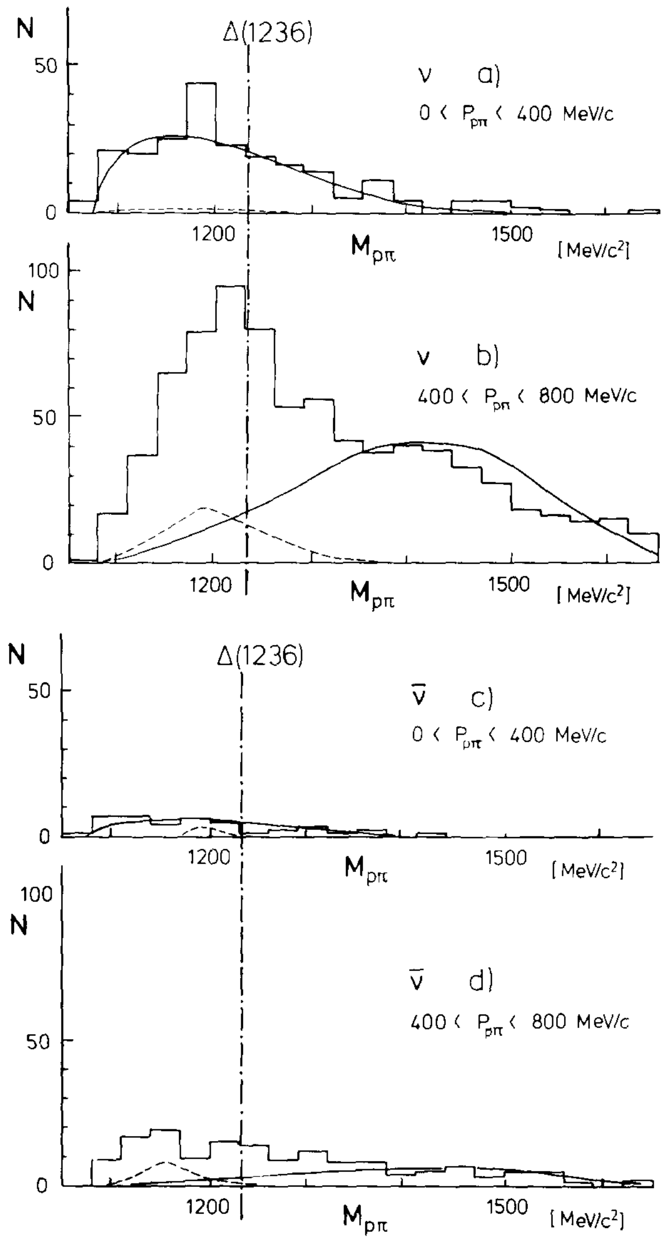


Fig. 1. Effective mass distributions of $p\pi^+$ combinations for ν (top) and $\bar{\nu}$ (bottom) interactions. The distributions are presented for two intervals of the combined $p\pi^+$ momentum: 0–400 and 400–800 MeV/c. The chosen bin size is 30 MeV/c^2 = $\Gamma(1235)/4$. The solid lines show the calculated background of combinations of a pion with a spectator proton. The dotted lines show prompt $p\pi^+$ production as obtained from $\nu/\bar{\nu}$–hydrogen data.

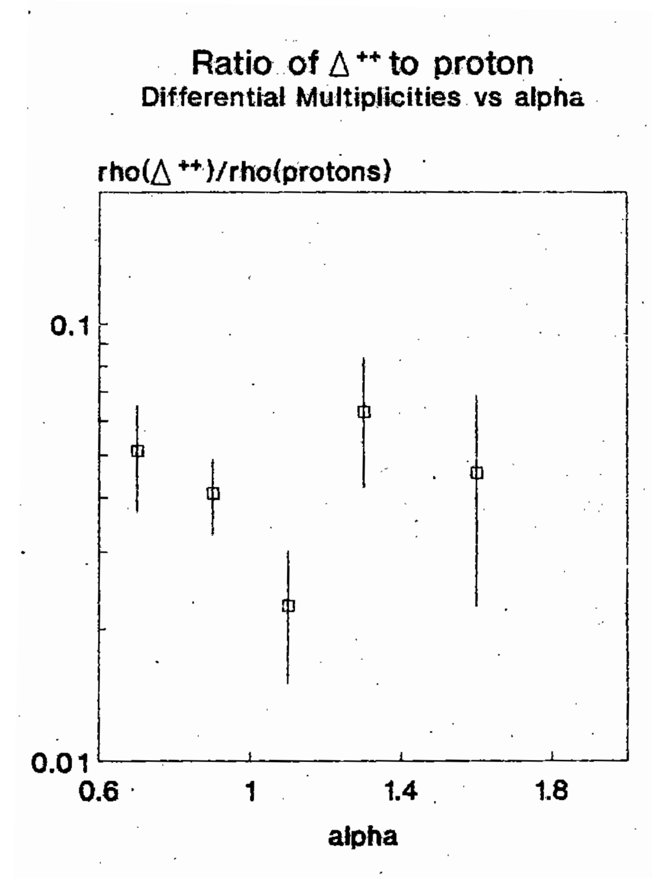
Is there a positive evidence for Δ's in nuclei?

- Indications from DESY AGRUS data (1990) on electron - air scattering at E_e=5 GeV (Degtyarenko et al).

  Measured Δ^{++}/p, Δ^0/p for the same light cone fraction alpha.

$$\frac{\sigma(e+A\to\Delta^0+X)}{\sigma(e+A\to\Delta^{++}+X)}=0.93\pm0.2\pm0.3$$

$$\frac{\sigma(e+A\to\Delta^{++}+X)}{\sigma(e+A\to p+X)}=(4.5\pm0.6\pm1.5)\cdot10^{-2}$$



- Bjorken sum rule for A=3

  One needs to include Δ's in the A=3 system on the level of 1% to remove the discrepancy with 3N model (Guzey, FS 94)

Perfect kinematics for EIC studies - Δ's along nucleus

Conclusions

Studying quark - gluon structure of SRCs is doable at EIC

prime kinematics is $x > 0.1 - 0.2$

at small $x < 0.1$ longitudinal distances become large ~ $1/2m_N x$ and much larger than R_{cor} ~ 1.2 fm and contribution of SRCs is usually suppressed.

Issues: acceptance in the forward direction

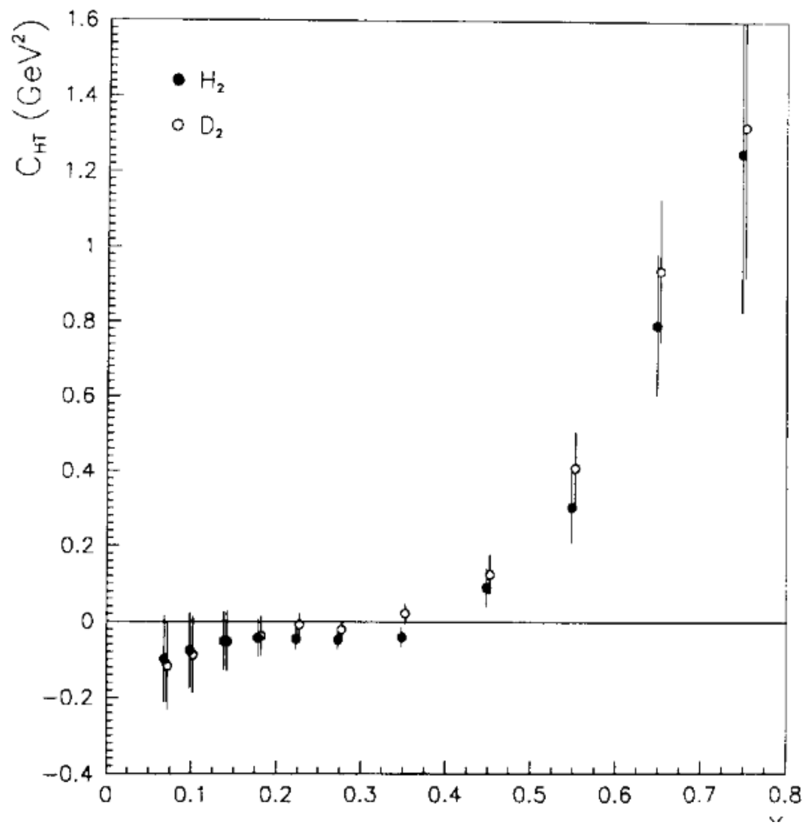
counting rates, optimal energies, resolution

polarized deuteron beam

Complications/distortions due to the f.s.i.

Use of complementary reactions (Jlab, EIC) - tests of factorization are very important

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



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

Marc Virchaux and Alain Milsztajn, 1992

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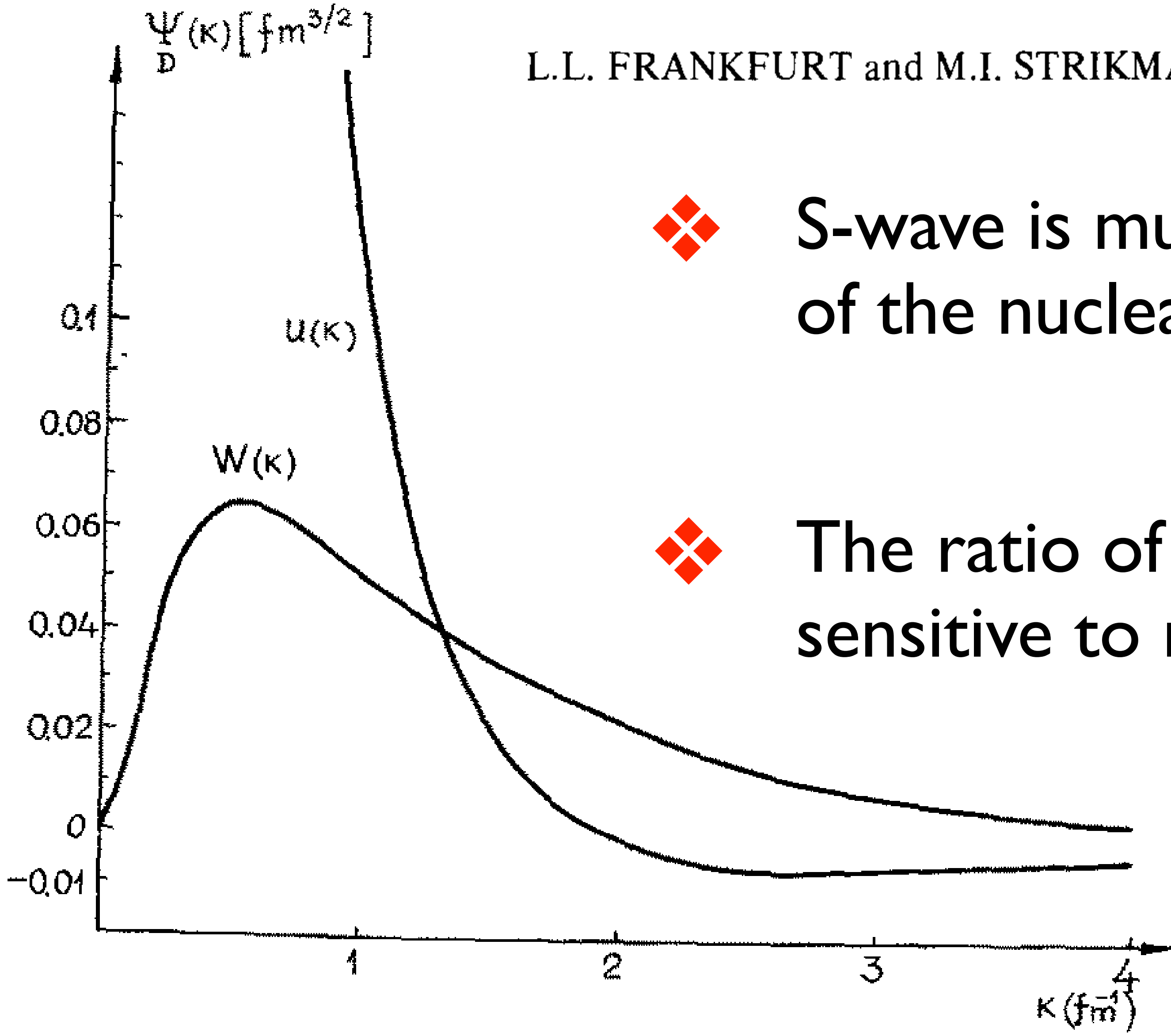
NEW DIRECT WAY OF CHECKING THE NUCLEAR CORE HYPOTHESIS IN INCLUSIVE HADRON SCATTERING OFF THE POLARIZED DEUTERON

L.L. FRANKFURT and M.I. STRIKMAN



- S-wave is much more sensitive of the presence of the nuclear core than $\psi^2_D(\kappa)$
- The ratio of S and D - waves is much more sensitive to relativistic effects than $\psi^2_D(\kappa)$

Fast variation of w(k)/u(k) with k $\Longrightarrow$

The best way to look for the difference between LC and NR/Virtual nucleon seems to be scattering off the polarized deuteron