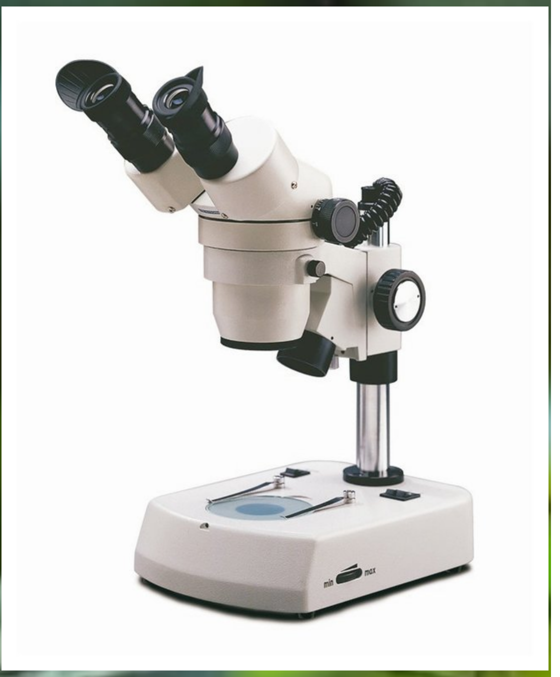


Nuclear structure from large to small distance scales

Mark Strikman, PSU

Polarized light ion physics with EIC

Outline

Open questions in microscopic nuclear structure

Four resolution scales in resolving structure of nuclei

Why high energies are necessary to probe short-range structure of nuclei

Δ-isobars in nuclei - towards direct observations

EMC effect: unambiguous evidence of non-nucleonic degrees of freedom in A; constrains on the mechanism, message from LHC pA collisions

Next ten years: JLAB, EIC, FAIR (PANDA, CBM,...), J-PARC, Dubna...

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

➟ Complexity of the problem

Four energy momentum transfer scales in structure (interactions with) nuclei with different role of low momentum nucleons ($k < k_F$ -naive estimate of the highest momenta in nuclei for non-interacting gas) *and high momentum nucleons due to local NN interactions (slow decrease with k distribution).*

① Nuclear observables at low energy scale: treat nucleus as a Landau-Migdal Fermi liquid with nucleons as quasiparticles (close connection to mean field approaches) - should work for processes with energy transfer $\lesssim E_F$ and momentum transfer $q \lesssim k_F$. Nucleon effective masses ~0.7 m_N, effective interactions - SRC are hidden in effective parameters. Similar logic in the chiral perturbation theory / effective field theory approaches - very careful treatment at large distances ~ $1/m_\pi$, exponential cutoff of high momentum tail of the NN potential

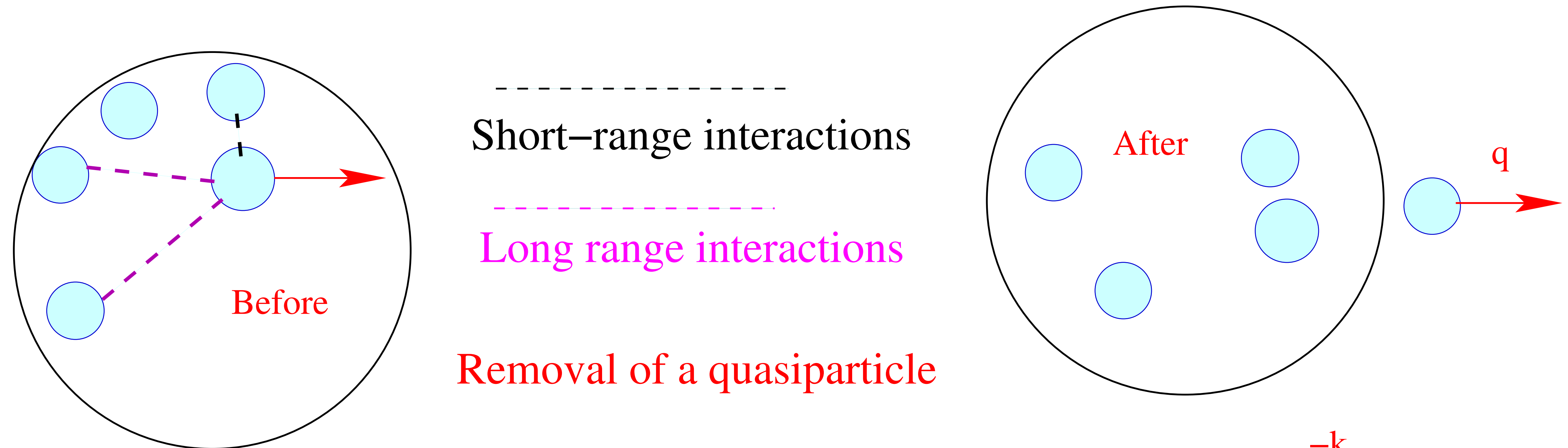
② Nuclear observables at intermediate energy scale: energy transfer < 1 GeV and momentum transfer q < 1 GeV. Transition from quasiparticles to bare nucleons - very difficult region - observation of the momentum dependence of quenching (suppression) factor Q for A(e,e'p) (Lapikas, MS, LF, Van Steenhoven, Zhalov 2000)

$$Q(q^2 = 0.2\mathrm{GeV}^2) \approx 0.5 \Rightarrow Q(q^2 = 1.0\mathrm{GeV}^2) > 0.85$$

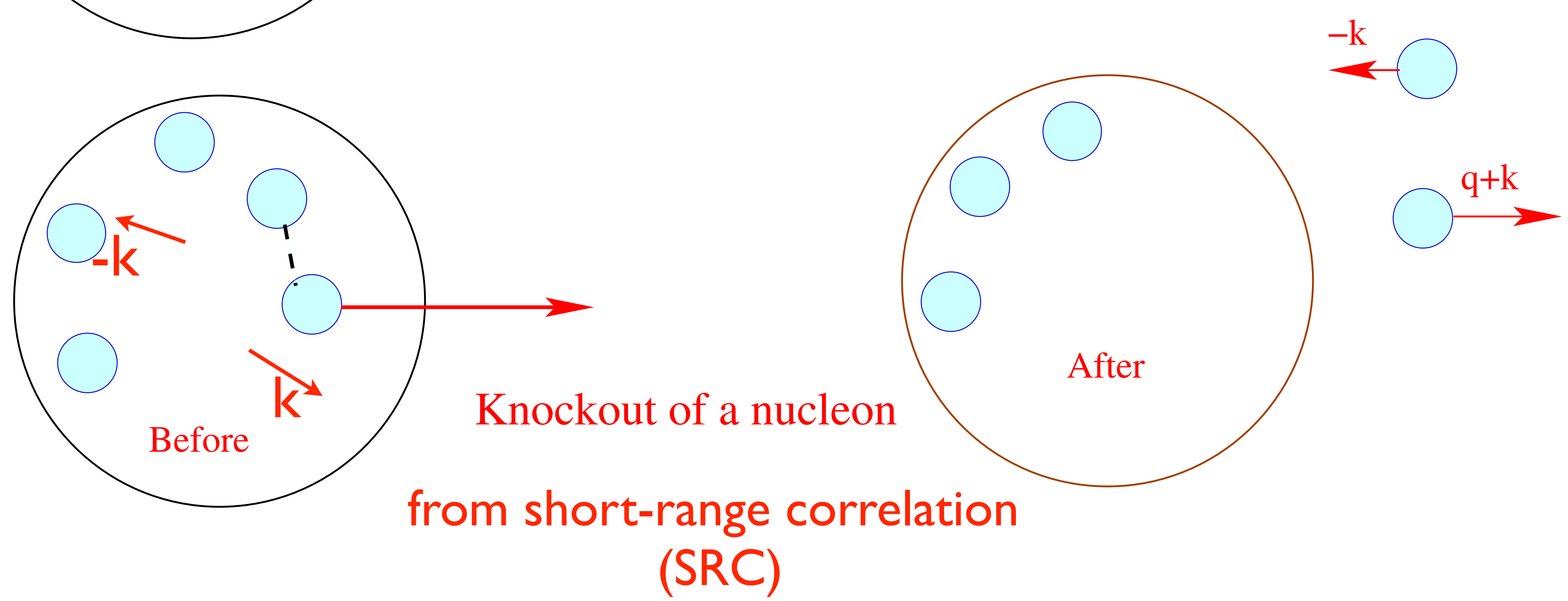
③ Hard nuclear reactions I: energy transfer > 1 GeV and momentum transfer q > 1 GeV. Resolve SRCs = direct observation of SRCs but not sensitive to quark-gluon structure of the bound states

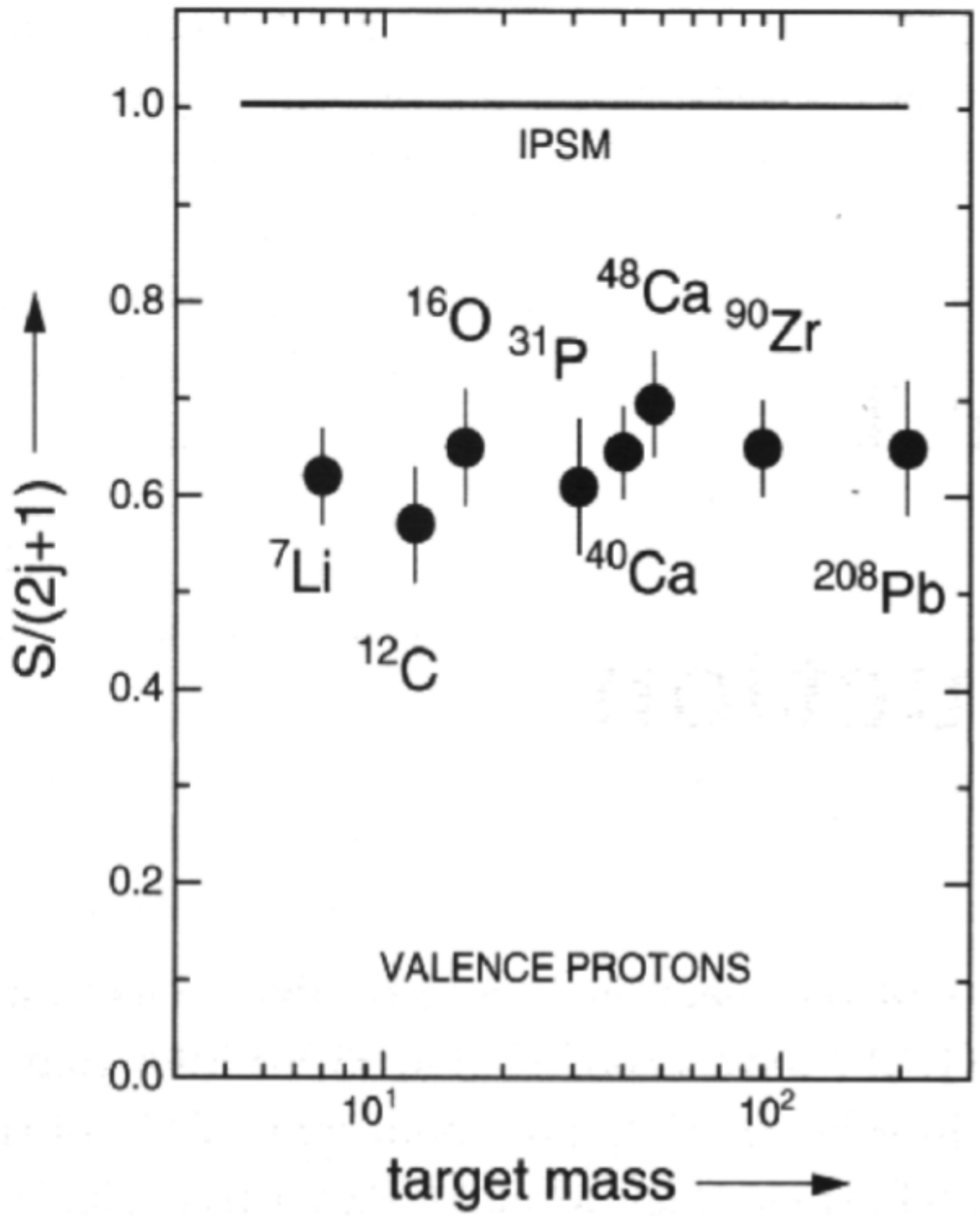
④ Hard nuclear reactions II: energy transfer ≫ 1 GeV and momentum transfer q ≫ 1 GeV. May involve nucleons in special (for example small size configurations). Allow to resolve quark-gluon structure of SRC: difference between bound and free nucleon wave function, exotic configurations

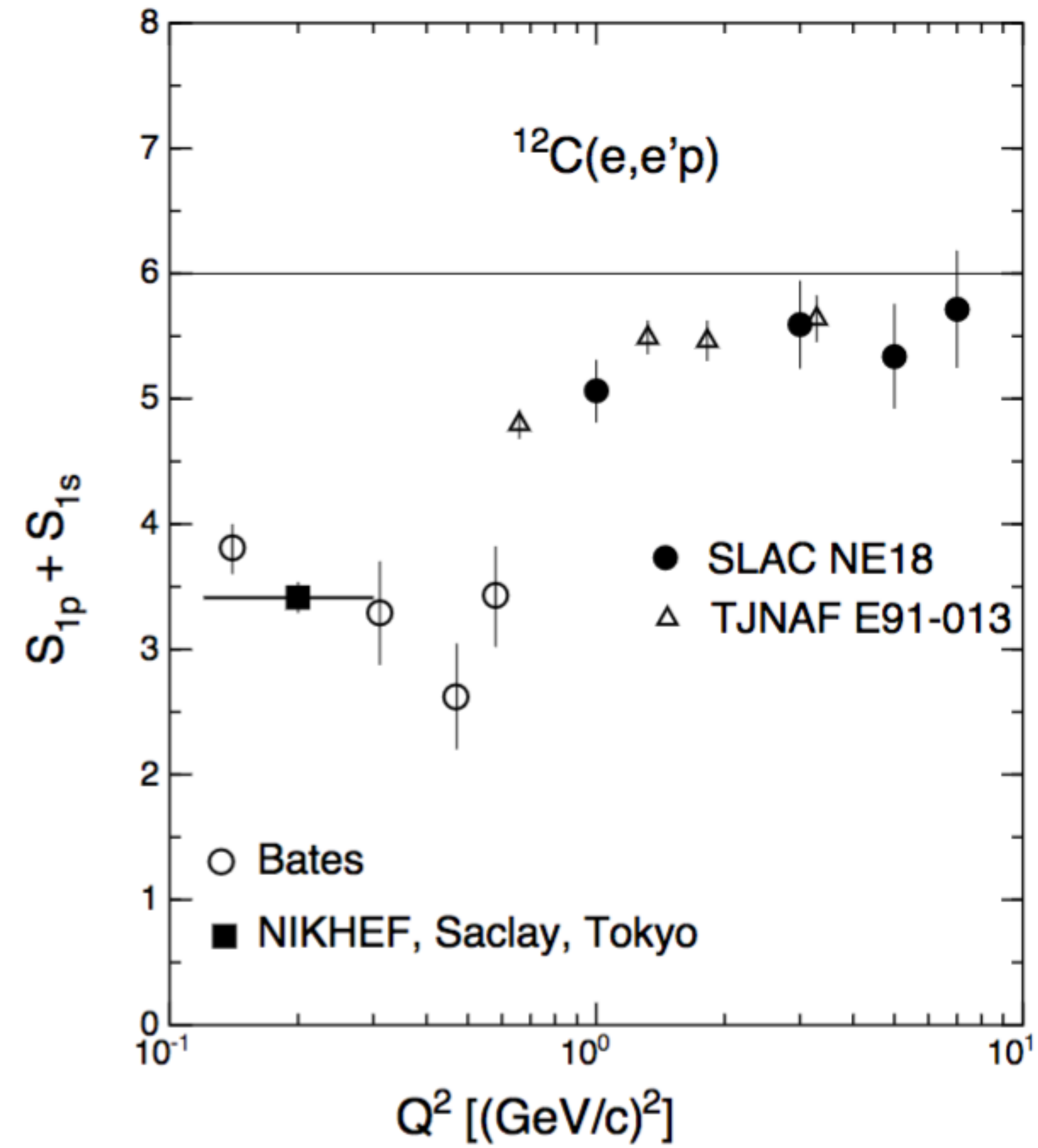
Low Q^2 scale



High Q^2 scale I

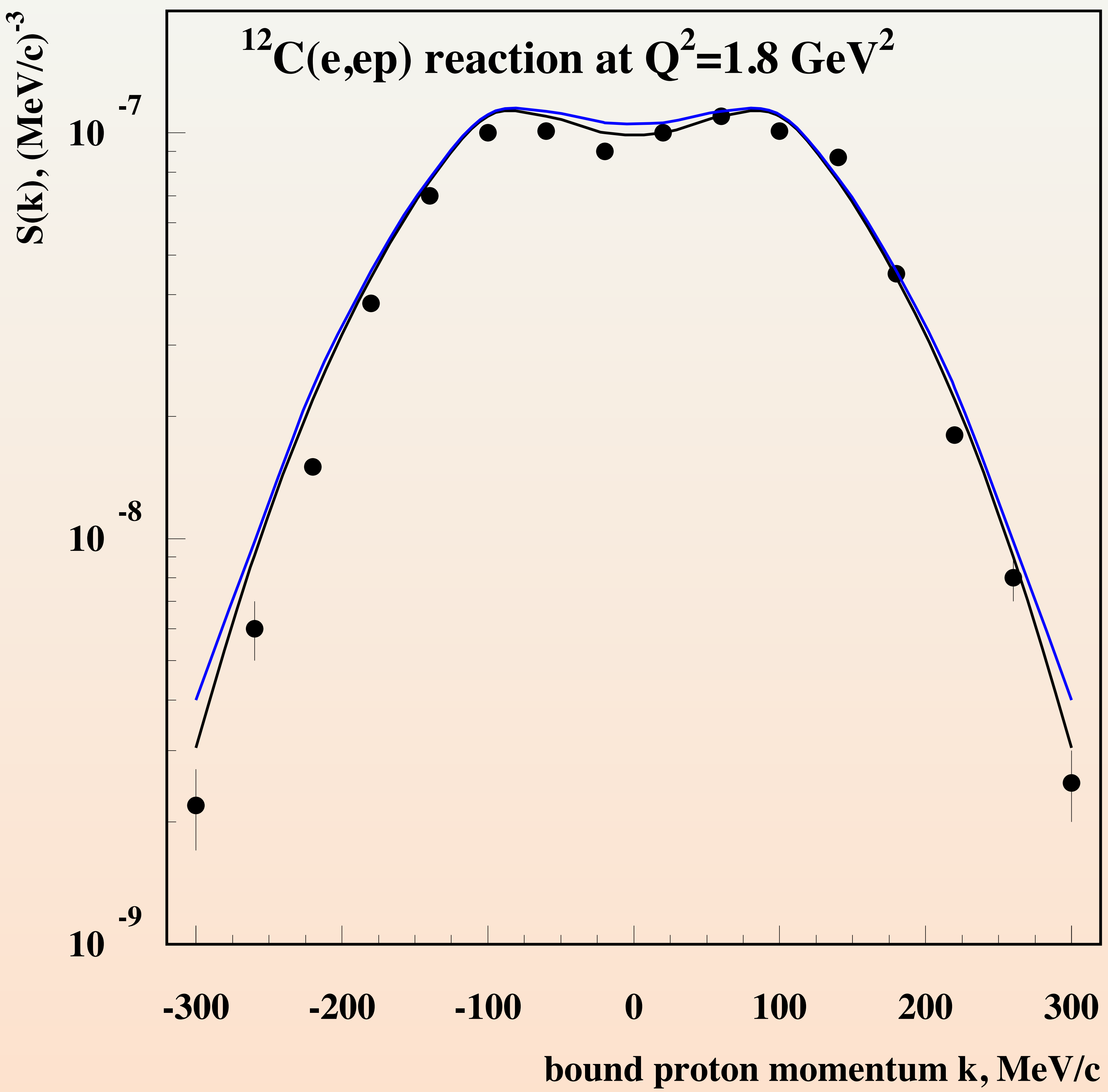


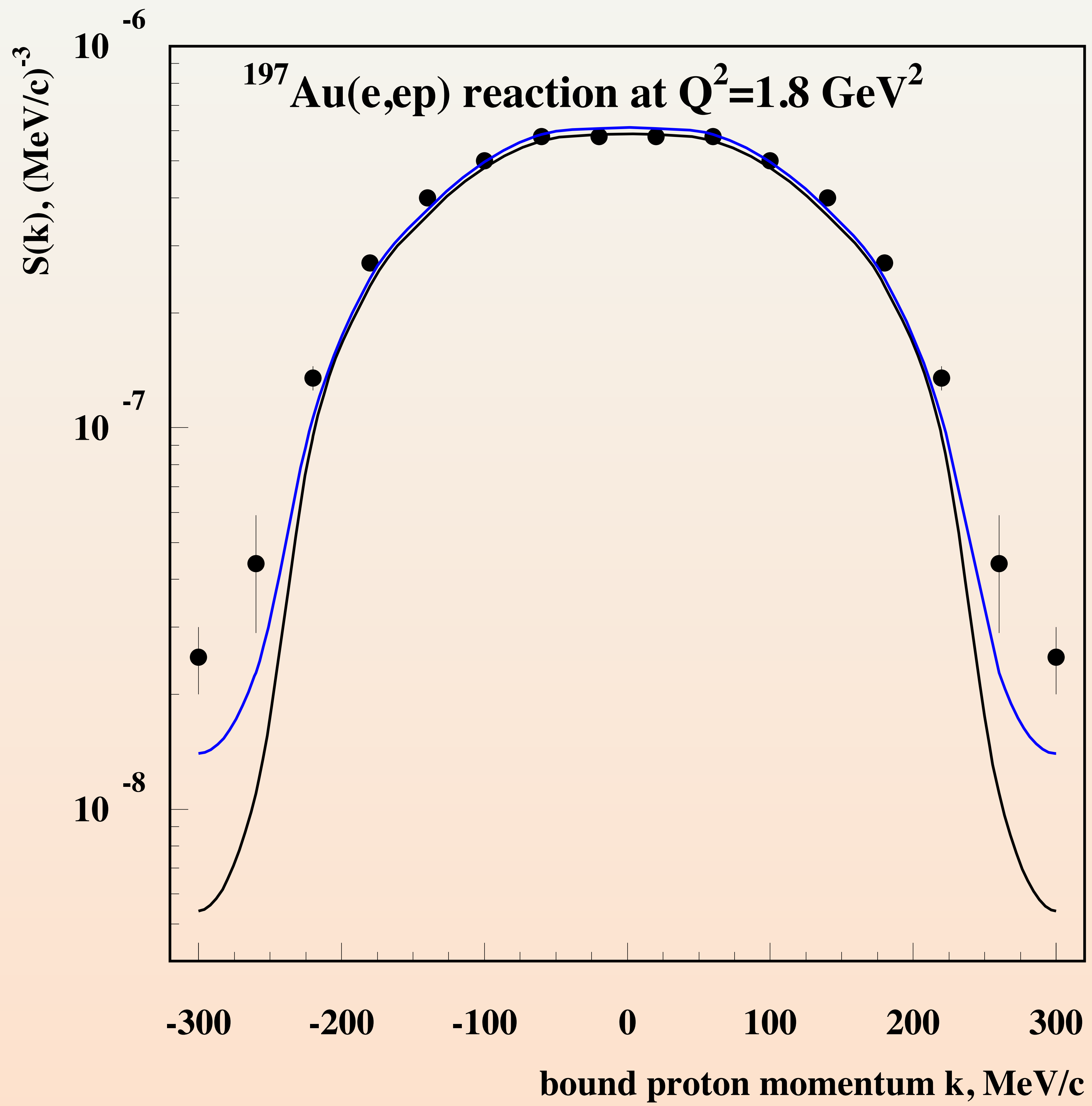




L. Lapikas, G. van der Steenhoven,\\
L. Frankfurt, M.~Strikman,
M. Zhalov, 99

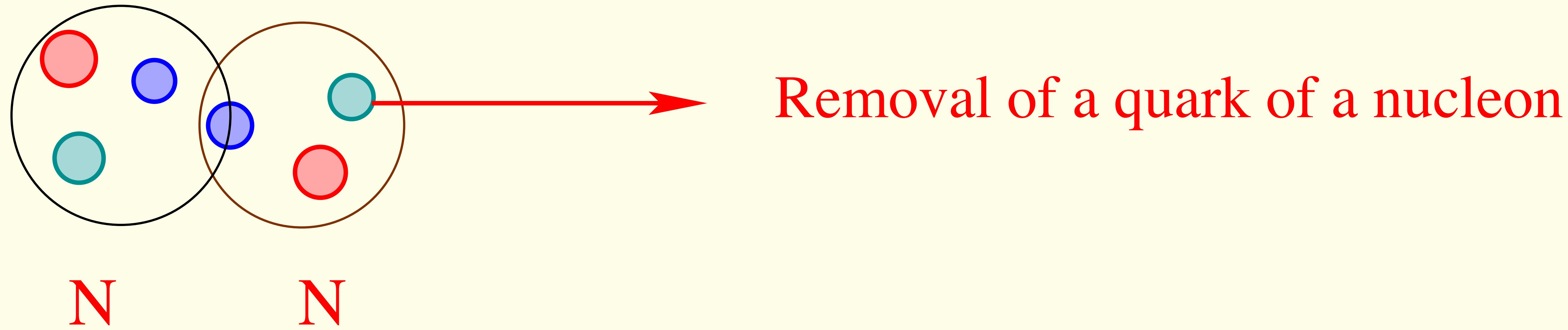
Eikonal approximation usually neglects change of the transverse nucleon momentum in the final state rescatterings. We checked that account of this effect leads to a small correction for k<200 MeV/c

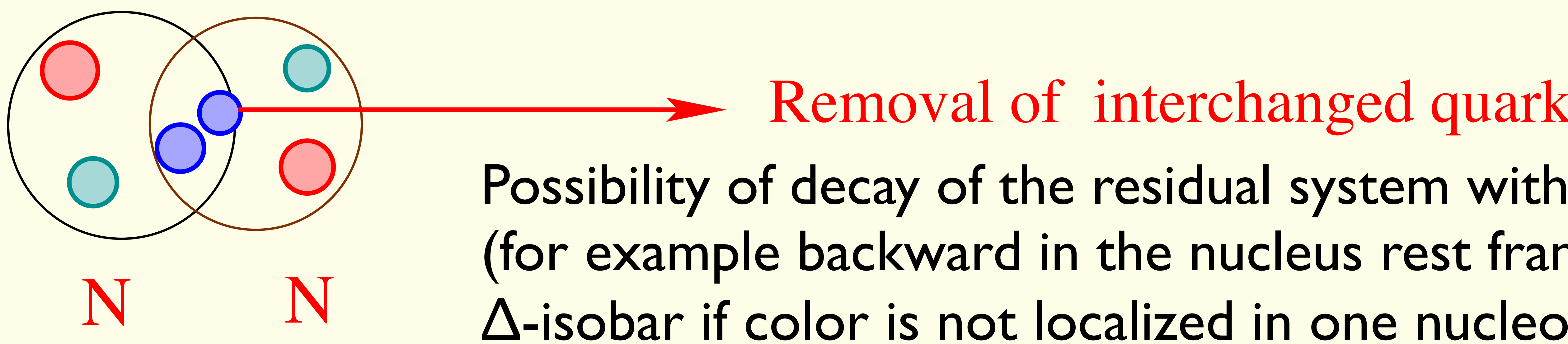




FSZ2000; data from D. Dutta et.al.

High Q^2 scale II Quark removal in the DIS kinematics



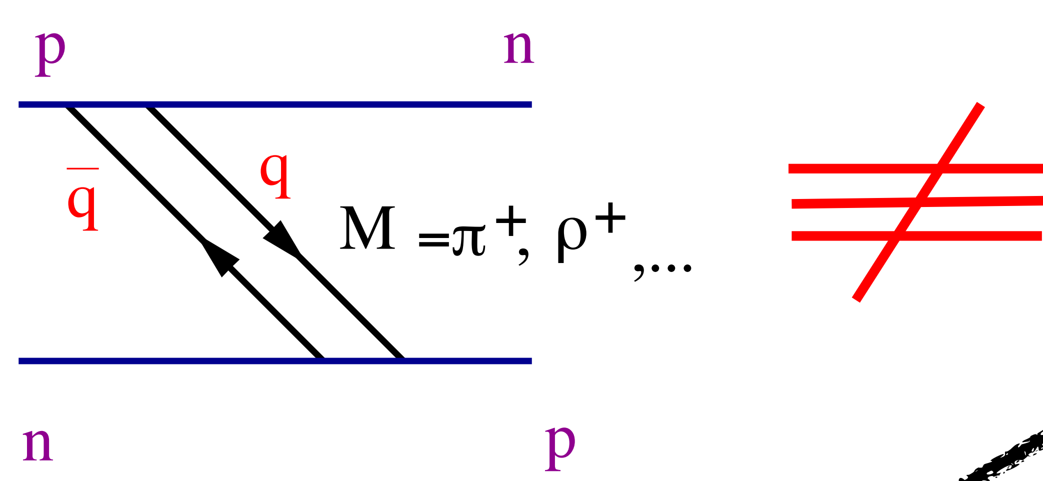


Possibility of decay of the residual system with production of slow (for example backward in the nucleus rest frame) baryons like N*, Δ-isobar if color is not localized in one nucleon.

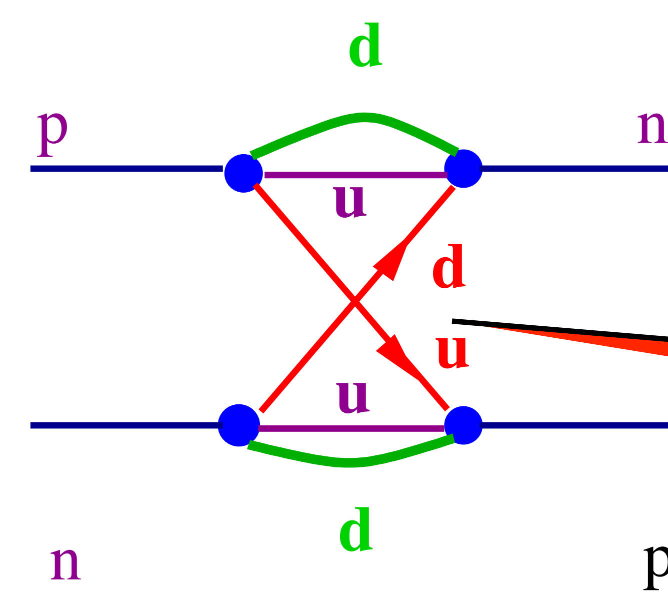
New effects if one would remove a valence gluon (EIC) ?

Interaction picture also depends on resolution: low scale instantaneous effective resolution, high Q scale non-static interaction: interaction time >> 1/Q

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



Meson Exchange

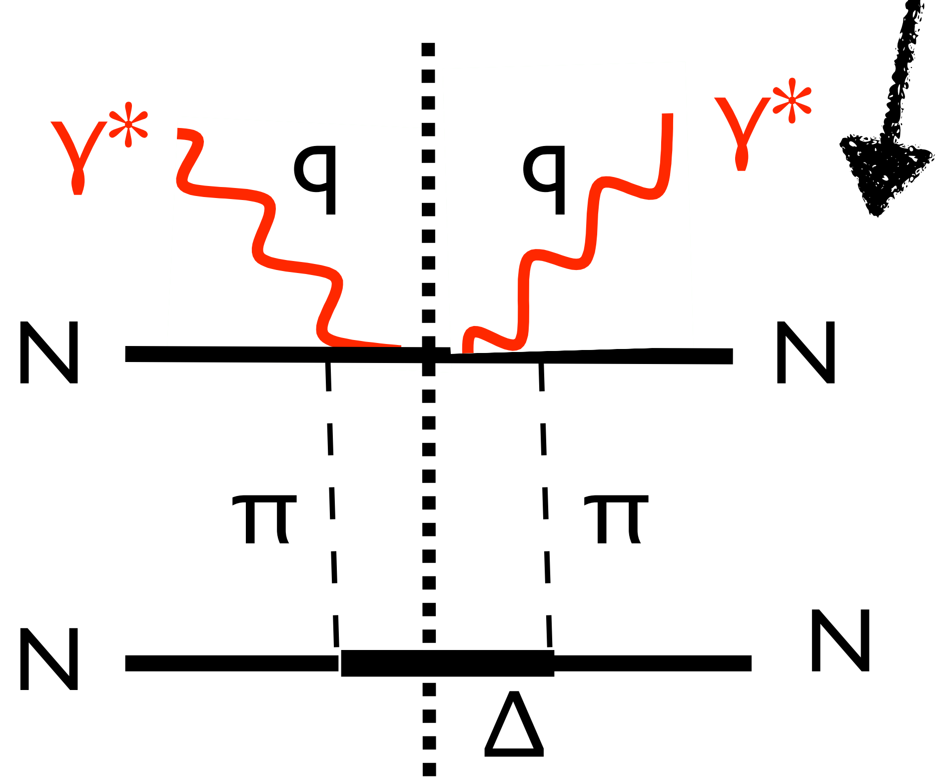


Quark interchange

Intermediate state may not be = pn, but say ΔN.

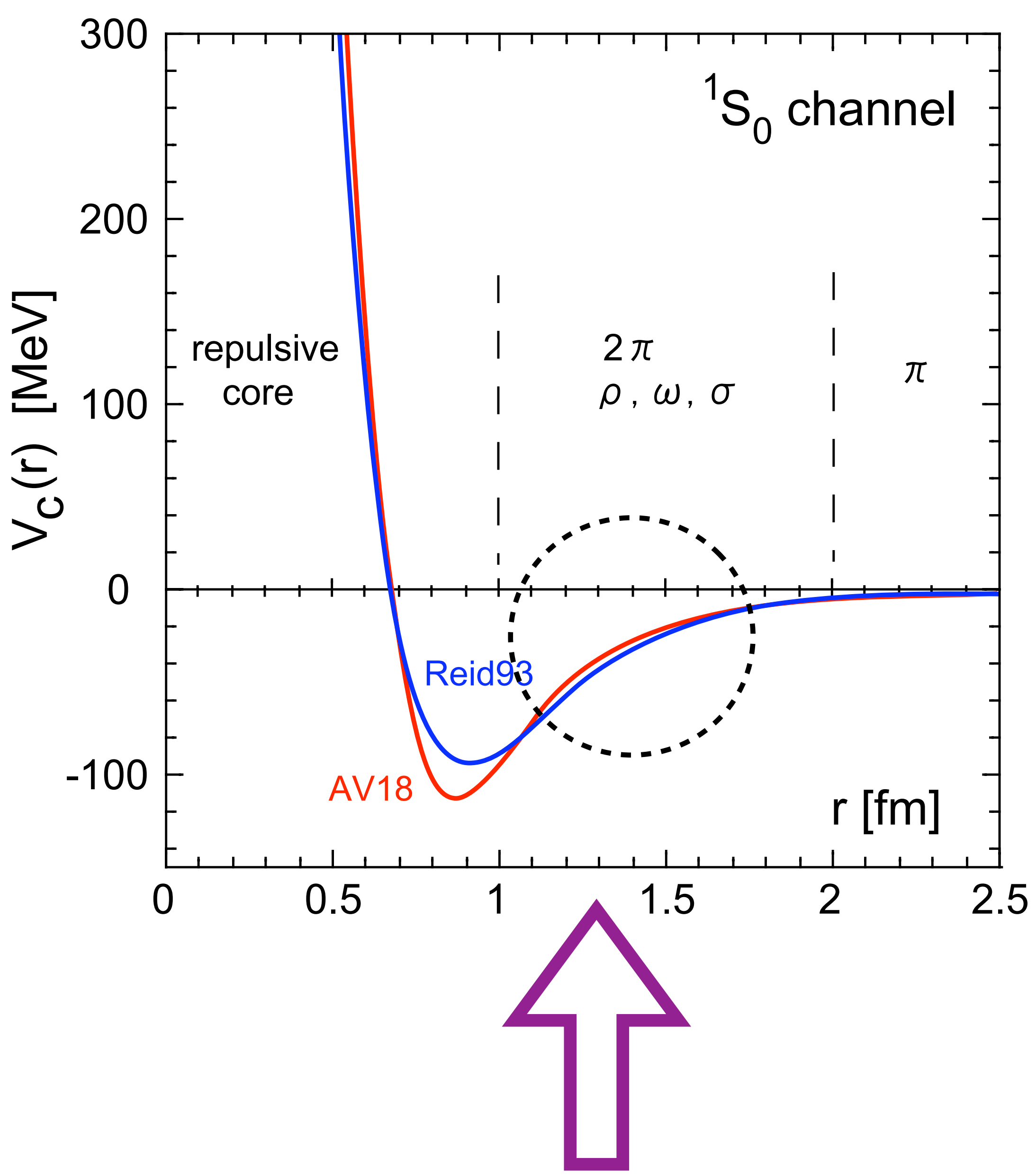
may correspond to a tower of meson exchanges with coherent phases - high energy example is Reggeon; pion exchange for low t special - due to small mass

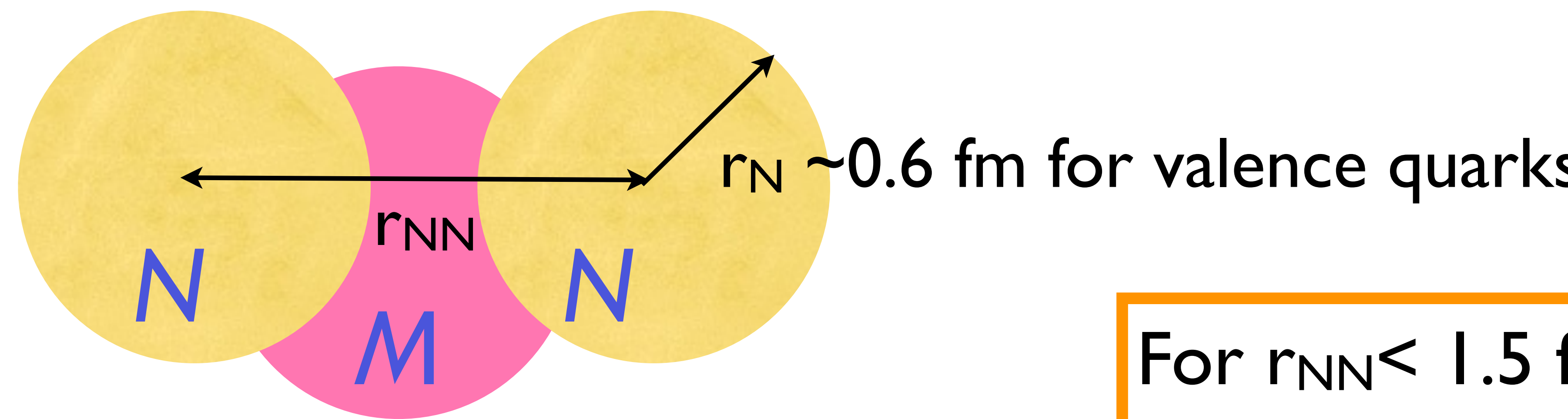
Two gluon interchange? Much higher mass scale in t -channel - very short distances



High frequency probe can resolve N Δ

QCD - medium and short distance forces are at distances where internal nucleon structure may play a role - nucleon polarization/ deformation





For r_{NN}< 1.5 fm difficult to exchange a meson; valence quarks of two nucleons start to overlap

quark, gluon interchanges?

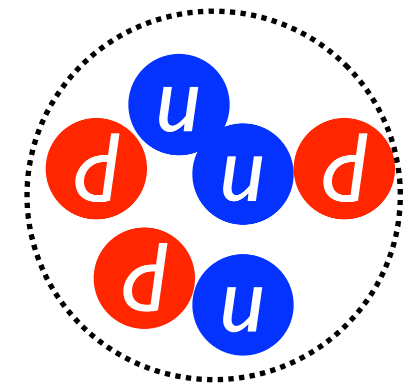
At average nuclear density, ρ_0 each nucleon has a neighbor at r_{NN}< 1.2 fm!!

Very different situation than for cold Fermi gasses where $r_{at} << r_{at-at}$

Natural expectation - deviations from many nucleon approximation are highest in SRC

Could nucleus be a quark soup?

quark kneading (FS75)



became popular under name six quark bags

suppressed - dynamical reasons discussed below

In the cores of neutron stars --$\rho_{core} \gg 2\rho_0$

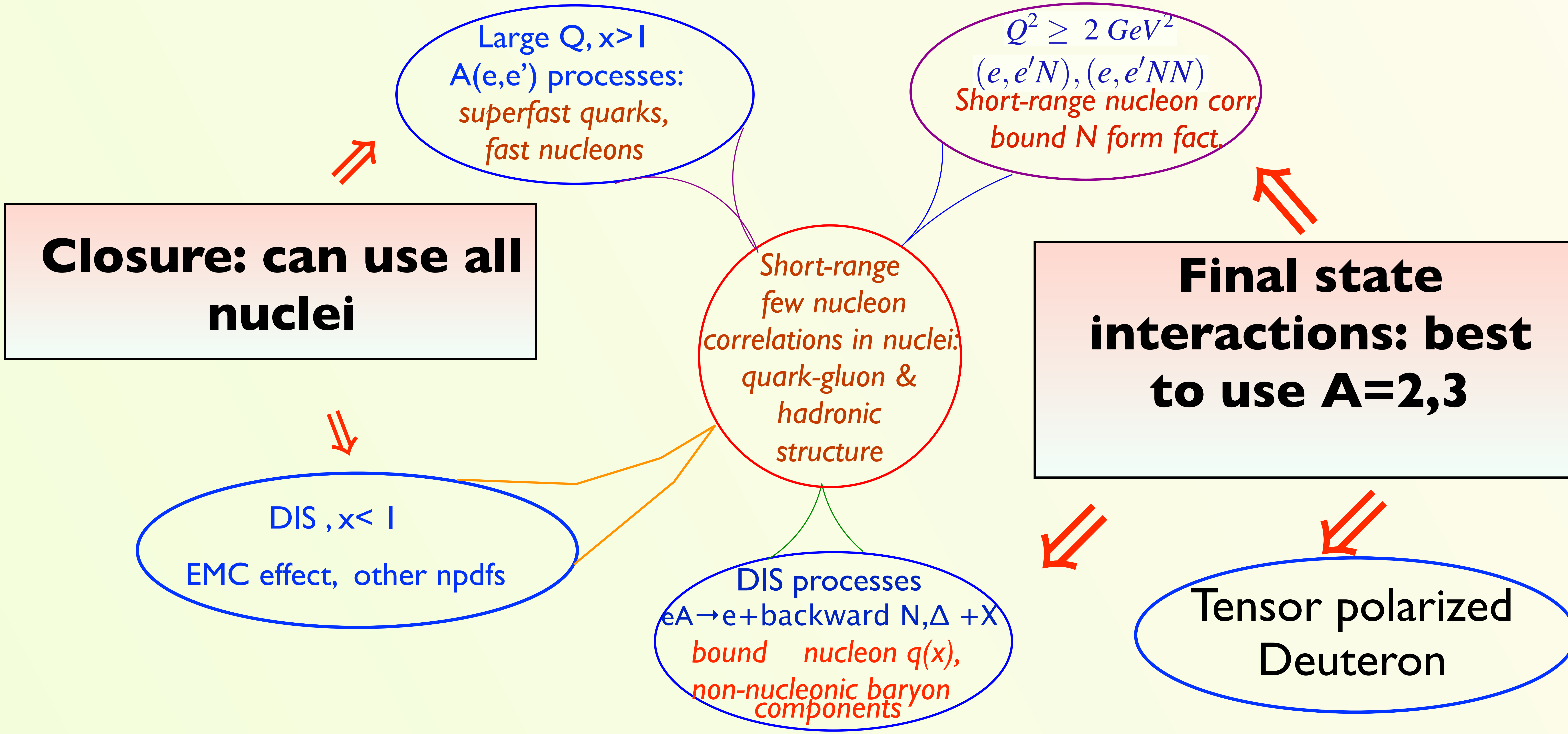
high sensitivity to microscopic dynamics of SRC

for density $2\rho_0$: protons surrounded by neutrons with density $4\rho_0$

No reasons to expect 3N SRC << 2N SRC

Sargsian’s talk

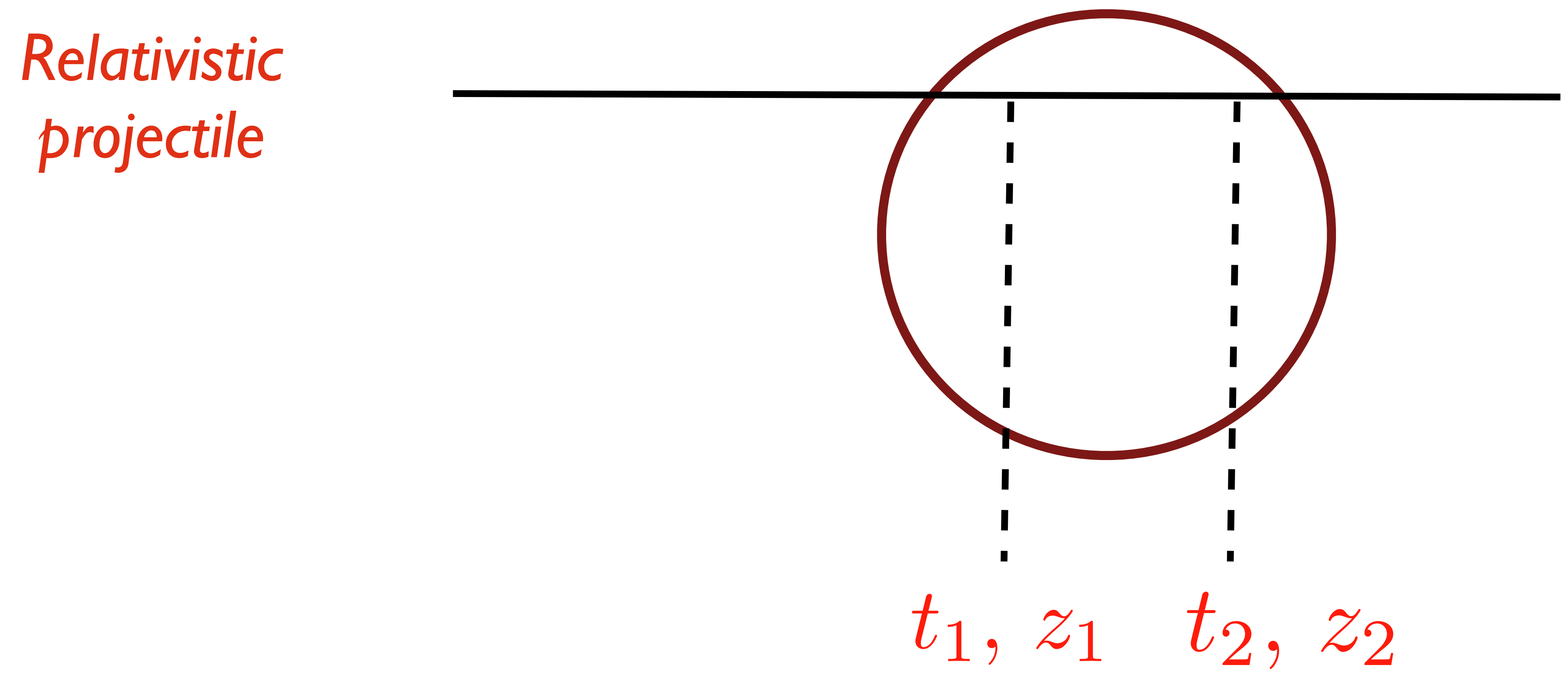
Multi prong approach to the study of SRC and their internal structure



Package deal - cannot cherry pick some of the processes - would result in a gross loss of information

Important to have complementary studies of large angle hadron/photon induced exclusive reactions: γ A→ π N (A-1) with A-1 decay; (anti) proton beams, GSI, J-PARC

⇒ All listed high energy processes develop along the light cone (LC) -- trivial for QCD community.



$$t_1 - z_1 = t_2 - z_2$$

Hence there is a price to pay for use of high energy processes:

the amplitudes of the processes are expressed through LC objects and in particular one actually probes LC wave functions, spectral functions,... of nuclei

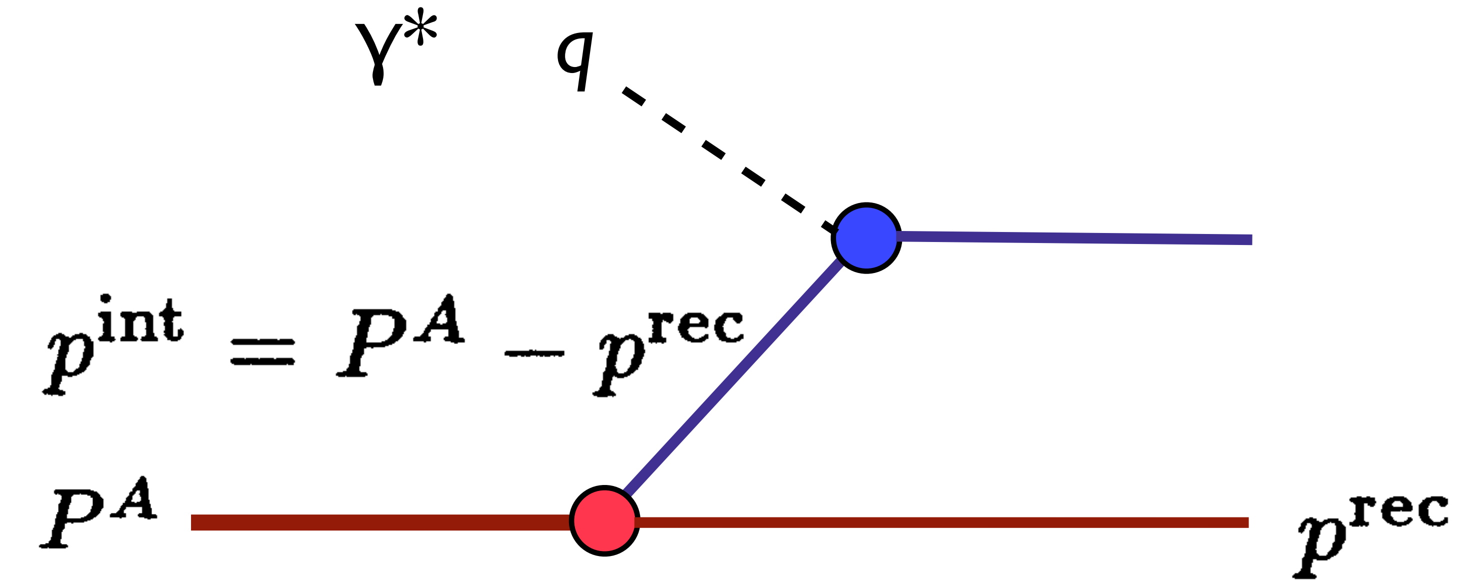
However for low momentum component in nuclei and for 2N SRC correspondence with nonrelativistic wave functions is unambiguous and rather simple due to angular condition FS76

Many features of NR QM hold - number of degrees of freedom, etc (but nonlinear relations with amplitudes). At the same time logic of quantum mechanics does not map easily to the language of virtual particles - transformational vacuum pairs → extra degrees of freedom.

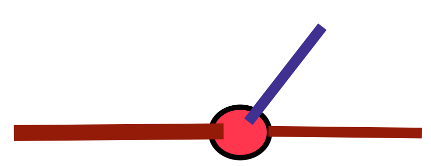
☝ *- Correspondence between NR and LC descriptions of nuclei is not applicable for the cases when the probe interacts with rare configurations in the bound nucleons e.g. EMC effect) due to the presence of an additional scale.*

Important example - onset of LC dominance in high Q^2A (e,e') processes

Consider example of high Q^2 (e,e') process at fixed large x >1 in the many nucleon approximation for the nucleus



The on-shell condition for the struck nucleon $(p^{\rm int} + q)^2 = m^2$



(Vertex function)^2 is the spectral function of the nucleus

$$P_A(k,E) = \langle \psi_A | a_{\rm N}^{+}(k) \delta(E + E_{\rm R} - E_{\rm fX}) a_{\rm N}(k) | \psi_A \rangle,$$

QCD analog - fully unintegrated parton density -

$$\tilde{m}^2 + q_+ p_-^{\rm int} + q_- p_+^{\rm int} + q^2$$

$$= \tilde{m}^2 + q_+ \frac{M_A}{A}\alpha + q_- \left(\frac{\tilde{m}^2 + p_t^2}{\alpha(M_A/A)}\right) + q^2 = m^2$$

Use the nucleus rest frame
$P_+^A = P_-^A = M_A.$

$\alpha \equiv A\frac{p_-^{int}}{P_-^A}$ light-cone fraction scaled to A

$$\Rightarrow \quad \frac{\partial \alpha}{\partial \tilde{m}^2} = -\left(\frac{1 + (q_-/\alpha)(M_A/A)}{(q_+ M^A/A) - [q_-(\tilde{m}^2 + p_t^2)]/\alpha^2 M_A/A}\right) \longrightarrow 0 \quad \propto 1/q_+$$

$Q^2 \to \infty, x = const$

$\Rightarrow$ In high energy limit σ depends only on the spectral function integrated over all variables but α - LC dominance, in particular no dependence on the mass of the recoil system. Relevant quantity is LC nucleon density matrix - $\rho_A^N(\alpha)$

$$\rho_A^N(\alpha) = \int \prod_{i=1}^{i=A} \frac{d\alpha_i}{\alpha_i} d^2 p_{t\,i} \psi_A^2(\alpha_i, p_{t\,i}) \delta(\alpha_1 - \alpha)$$

LC nuclear many nucleon wave function

Correspondence between LC density matrix and $n_A(k)$ nonrel. momentum distribution?

- Mean field: $\alpha=1+k_3/m_N$ for $k_3/m_N \ll 1$

- Deuteron: $\alpha = 1 + k_3/\sqrt{m_N^2 + k^2}$ $\psi_D^2(\alpha, k_t) = \sqrt{m_N^2 + k^2}\psi_D^{2\,(n.r.)}(k)$ FS76

No correspondence between asymptotic of the momentum distribution $n(k)$ for $k \to \infty$ and $\rho_A(\alpha \to A, p_t)$

Correspondence between $\rho_A(\alpha,p_t)$ and LC projection of nonrelativistic spectral function $P_A(k,E)$?

Some resemblance between structure of diagrams for high momentum dependence of various contributions to the spectral function $P_A(k,E)$ and $\rho_A(\alpha,p_t)$.

However n.r. $P_A(k,E)$ has wrong normalization (violates baryon & electric charge conservation) and when applied to DIS eA scattering --- violates the momentum sum rule. Final state overlapping integral satisfies closure in E_{rec} not in LC variable conjugated to α.

Expectation: $\rho_A^N(\alpha, k_t) \approx a_2(A)\rho_D^N(\alpha, k_t)\ \mathrm{for} 1.3 \leq \alpha \leq 1.6$

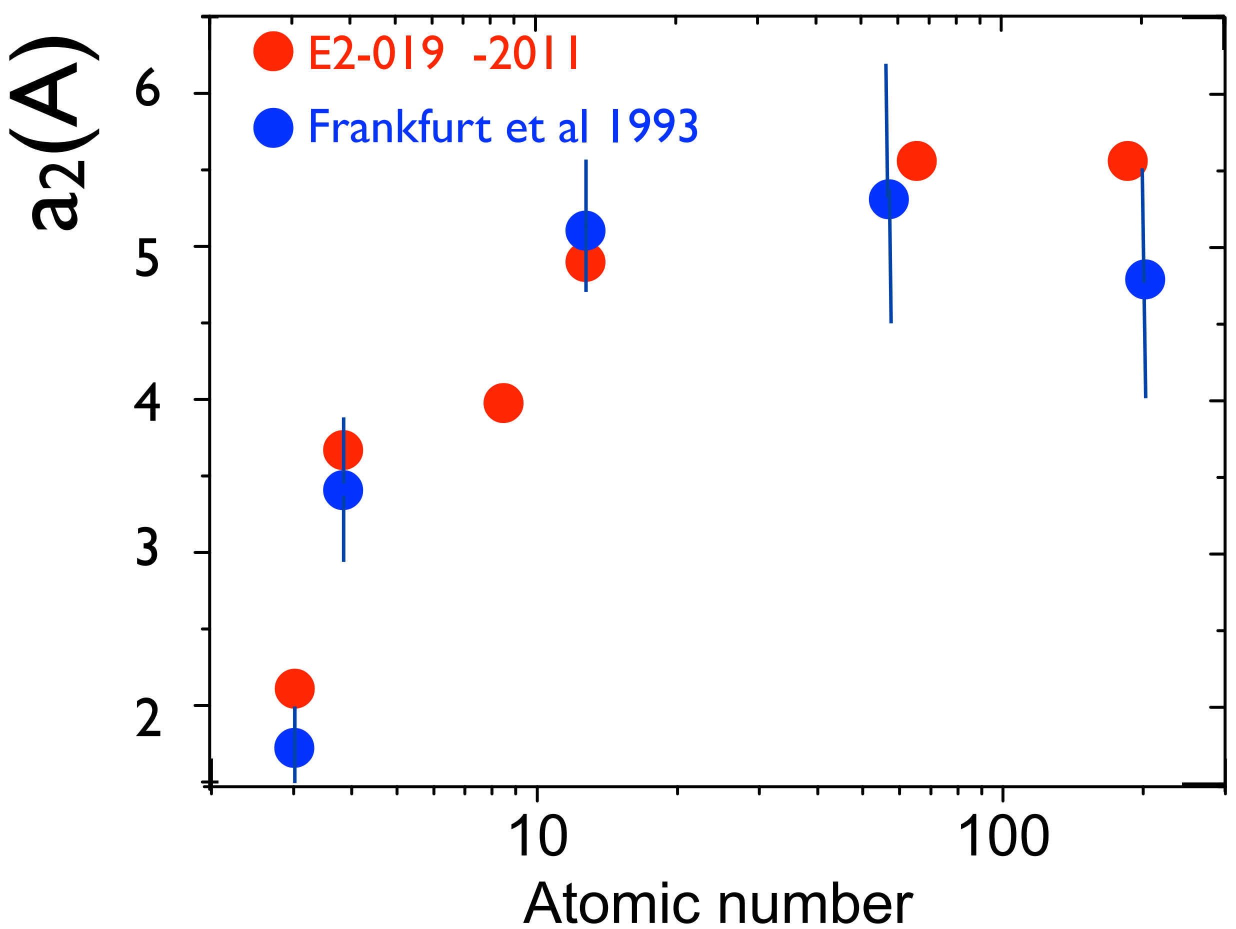
For larger α three nucleon correlations decreases slower with increase of α. Effects of 3N correlations can be seen in $P_A(k,E)$ but no simple relation is known (exists?) with $\rho_A(\alpha > 1.6, p_t)$ (Sargsian's talk)

Determine $\alpha(x,Q)$ based on dominance of two nucleon correlations in the recoil :

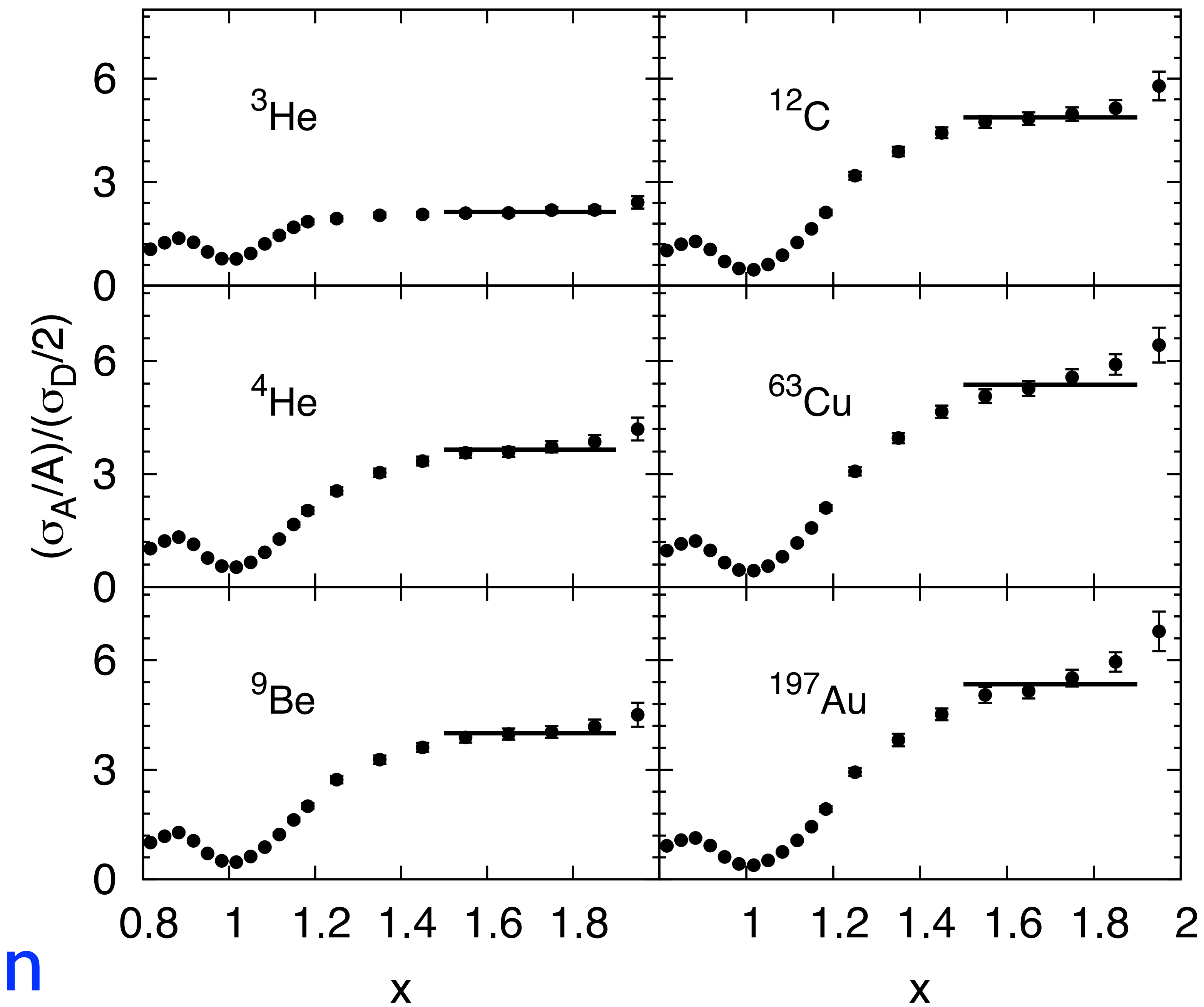
$$\alpha_{tn} = 2 - \frac{q_- + 2m}{2m_N}\left(1 + \frac{\sqrt{W^2 - 4m_N^2}}{W}\right) \qquad where\ q_- = q_0 - q_3,\ W^2 = 4m_N^2 + 4q_0 m_N - Q^2$$

At large momentum transfer answer is expressed through LC density matrix, while in nonrel. approach even in this limit — spectral function. No smooth matching with high energy limit.

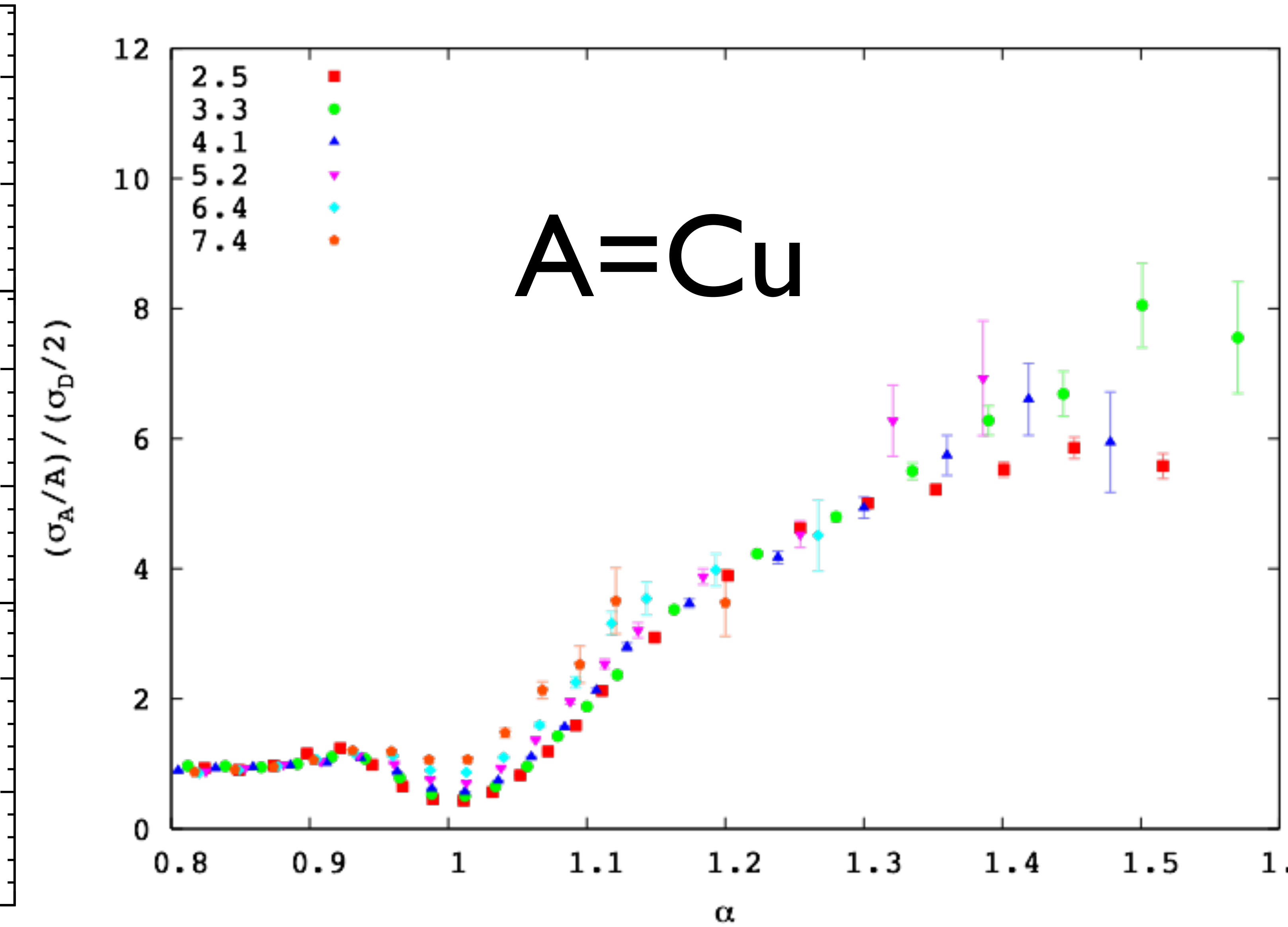
Universality of 2N SRC for .35 < k < .6 GeV/c is confirmed by Jlab experiments



Probability of the high momentum component in nuclei per nucleon, normalized to the deuteron wave function ($a_2(A)$)



Per nucleon cross section ratio at Q^2=2.7 GeV^2 - E2-019-2011



From N.Fomin thesis

E2-019-2011

Very good agreement between three (e,e') analyses for a_2 (A)

One of the consequences of LC dynamics - nonlinear relation between momenta of knocked out nucleon and spectator in

nuclear decay function (FS 77-88) - probability to emit a nucleon with momentum k_2 after removal of a fast nucleon with momentum k_1, leading to a state with excitation energy E_r (nonrelativistic formulation)

$$D_A(k_2, k_1, E_r) = |\langle \phi_{A-1}(k_2, ...) | \delta(H_{A-1} - E_r) a(k_1) | \psi_A \rangle|^2$$

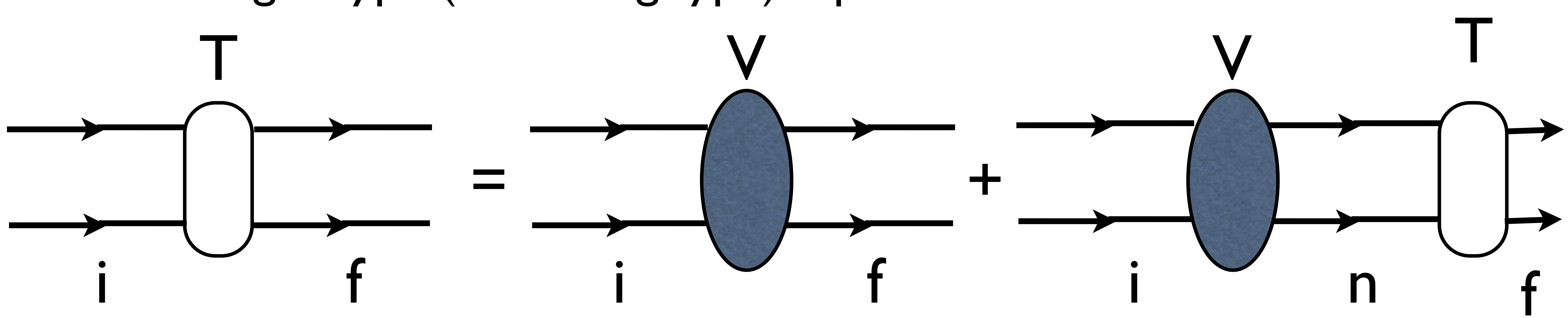
Present already in the case of 2N system. So can focus on the LC dynamics for two body case - more technical discussion

Light-cone Quantum mechanics of two nucleon system

Due to the presence of a small parameter (inelasticity of NN interactions) it makes sense to consider two nucleon approximation for the LC wave function of the deuteron.

Key point is presence of the unique matching between nonrelativistic and LC wave functions in this approximation. Proof is rather involved.

First step: include interactions which do not have two nucleon intermediate states into kernel V (like in nonrel. QM) to build a Lippman-Schwinger type (Weinberg type) equation.



Angular condition allows to reduce eqn to the form close to NR and results in theseteron wave function shown in previous slides

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

$$\frac{\mathrm{d}\sigma(\mathrm{e}+\mathrm{D}_\Omega \to \mathrm{e}+\mathrm{N}+\mathrm{X})}{(\mathrm{d}\alpha/\alpha)\,\mathrm{d}^2 p_\mathrm{t}} \Bigg/ \frac{\mathrm{d}\sigma(\mathrm{e}+\mathrm{D} \to \mathrm{e}+\mathrm{N}+\mathrm{X})}{(\mathrm{d}\alpha/\alpha)\,\mathrm{d}^2 p_\mathrm{t}}$$

$$= 1 + \left(\frac{3k_i k_j}{k^2}\,\Omega_{ij} - 1\right) \frac{\frac{1}{2}w^2(k) + \sqrt{2}u(k)w(k)}{u^2(k)+w^2(k)} \equiv P(\Omega, k)$$

Ω is the spin density matrix of the deuteron, $\mathrm{Sp}\Omega = 1$

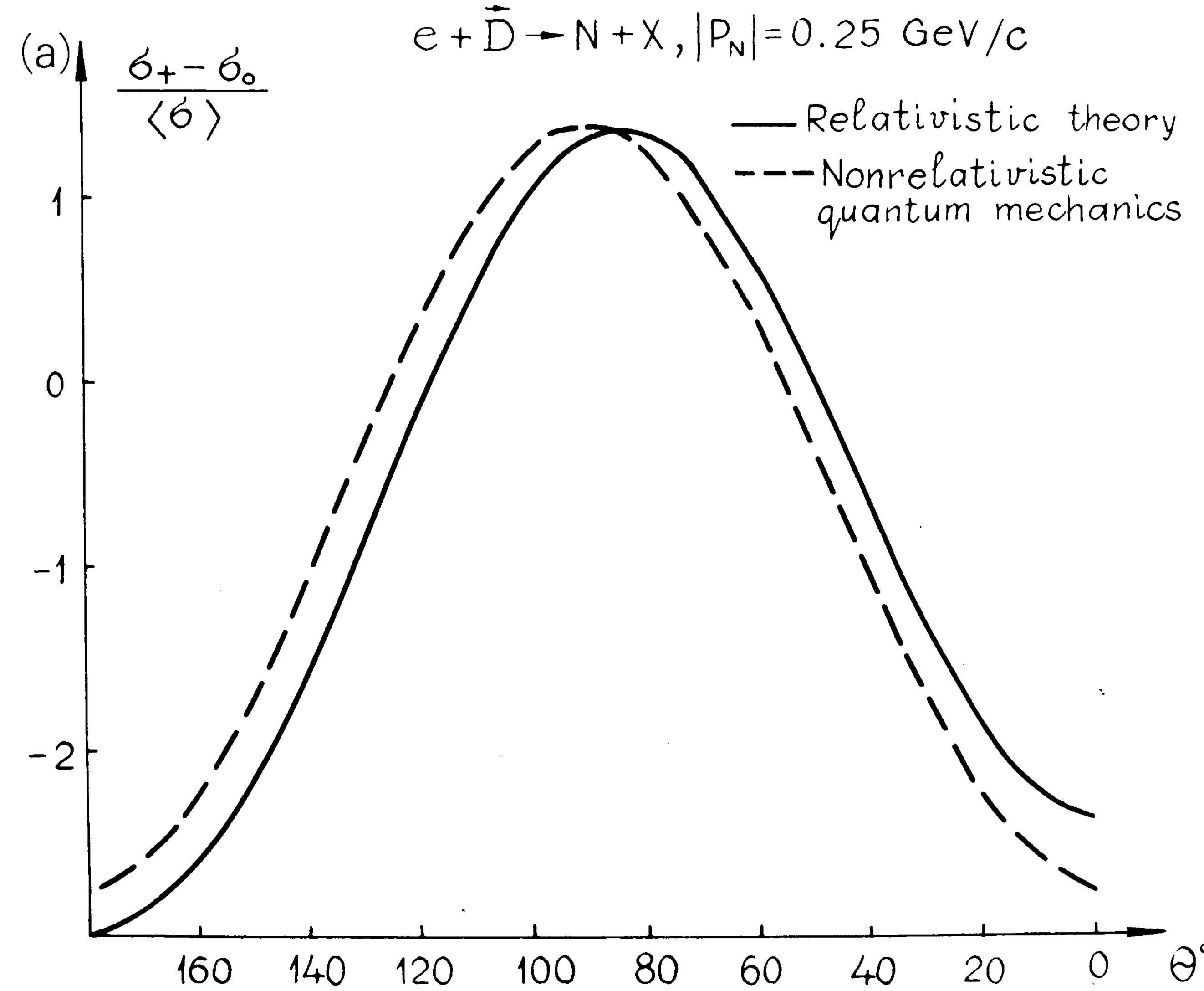
Consider

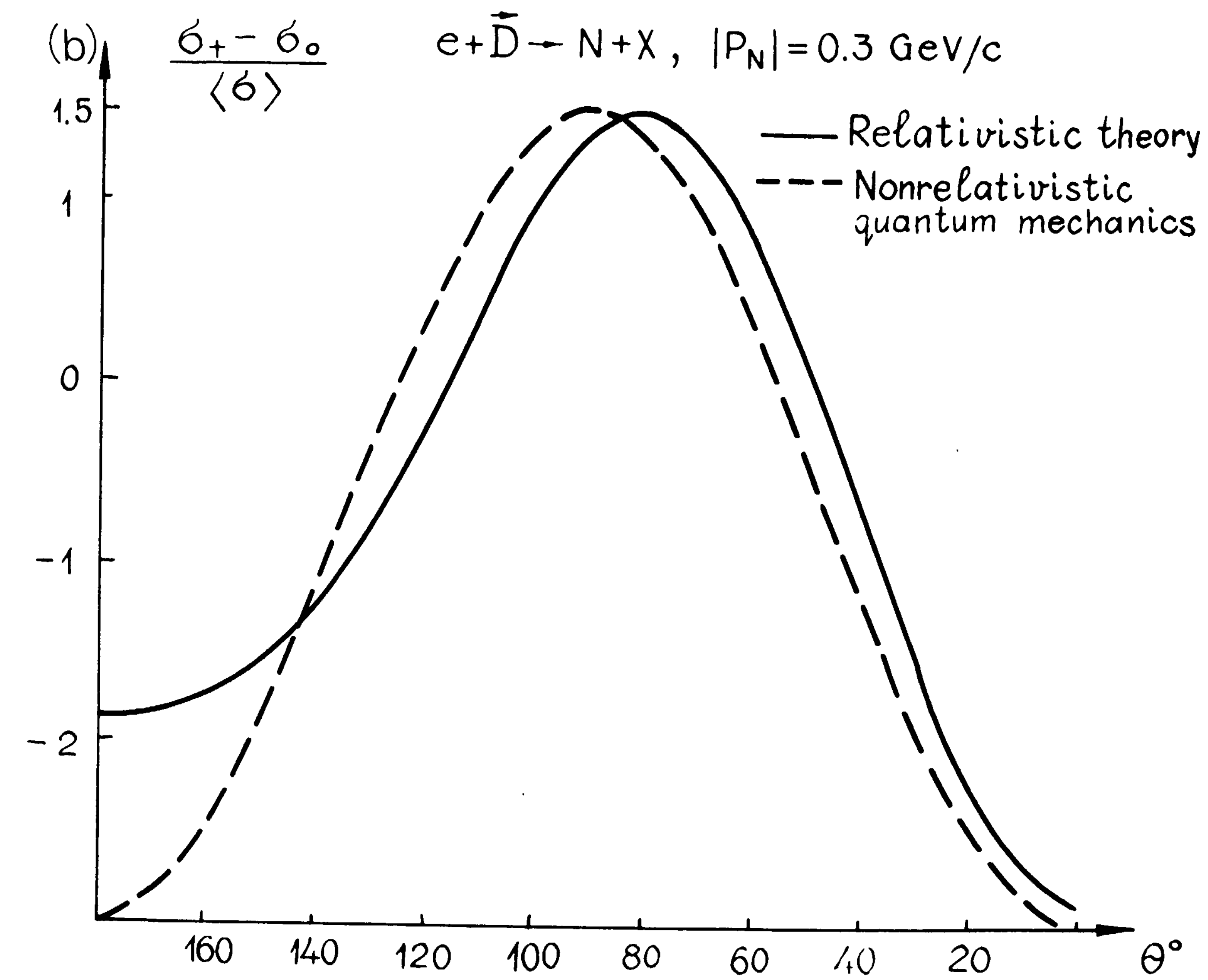
$$R = T_{20} = \left[\frac{1}{2}(\sigma_+ - \sigma_-) - \sigma_0\right] \Big/ \langle\sigma\rangle$$

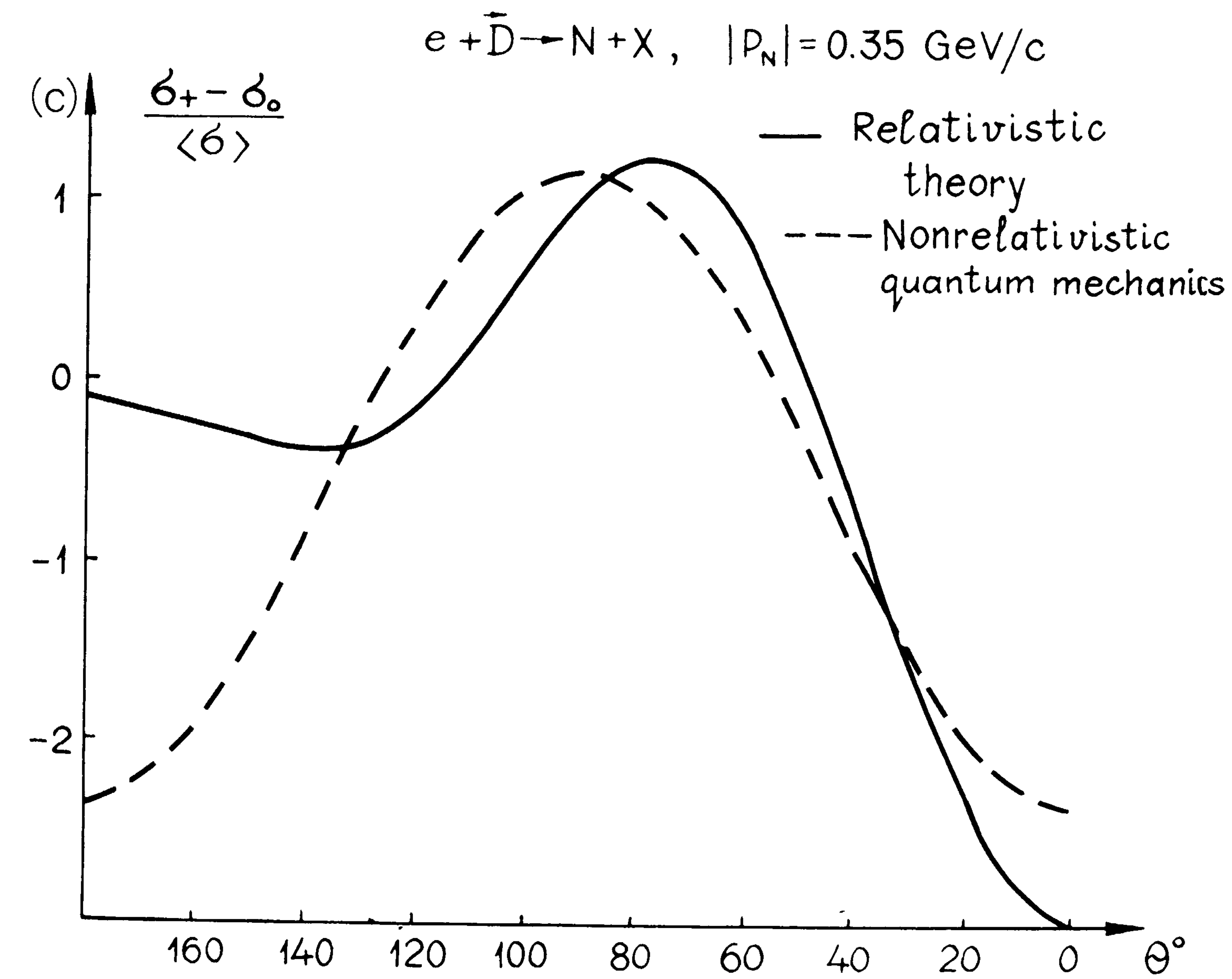
$$R^{lc}(p_s) = \frac{3(k_t^2/2 - k_z^2)}{k^2}\,\frac{u(k)w(k)\sqrt{2} + \frac{1}{2}w^2(k)}{u^2(k)+w^2(k)}$$

$$R^{\mathrm{nonrel}}(p_s) = \frac{3(p_t^2/2 - p_z^2)}{p^2}\,\frac{u(p)w(p)\sqrt{2} + \frac{1}{2}w^2(p)}{u^2(p)+w^2(p)}$$

trivial angular dependence for fixed p


(a)
$\frac{\sigma_+ - \sigma_0}{\langle\sigma\rangle}$
$e + \vec{D} \to N + X, |P_N| = 0.25$ GeV/c
Relativistic theory
Nonrelativistic quantum mechanics
1
0
-1
-2
160 140 120 100 80 60 40 20 0
θ°


(b)
$\frac{\sigma_+ - \sigma_0}{\langle\sigma\rangle}$
$e + \vec{D} \to N + X, |P_N| = 0.3$ GeV/c
Relativistic theory
Nonrelativistic quantum mechanics
1.5
1
0
-1
-2
160 140 120 100 80 60 40 20
θ°


$e + \vec{D} \to N + X, |P_N| = 0.35$ GeV/c
(c)
$\frac{\sigma_+ - \sigma_0}{\langle\sigma\rangle}$
Relativistic theory
Nonrelativistic quantum mechanics
1
0
-1
-2
160 140 120 100 80 60 40 20 0
θ°

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: *geometry 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

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

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

LC vs NR for A> 2 - two of key differences

- For large momentum transfer processes like DIS

LC - answer expires through LC density matrix

solution of LC Hamiltonian eqn

NR - answer expressed through spectral function - seems hopeless to calculate for A>3

- Very different characterization of 3N SRC - Misak's talk

Expectations

- pionic component is small due to chiral symmetry

Experimental evidence that there are fewer pions in nuclei than in free nucleons - a challenge for effective chiral models? willl discuss data later

- closest inelastic intermediate state is Δ- isobar - due to strong attraction potential enhancement as compared to a naive estimate

- non-nucleonic degrees of freedom are predominantly in SRC

< 10- 15 % of SRC

⬇

< 2 - 3 % per nucleon

Will discuss later

Intermediate states with Δ -isobars.

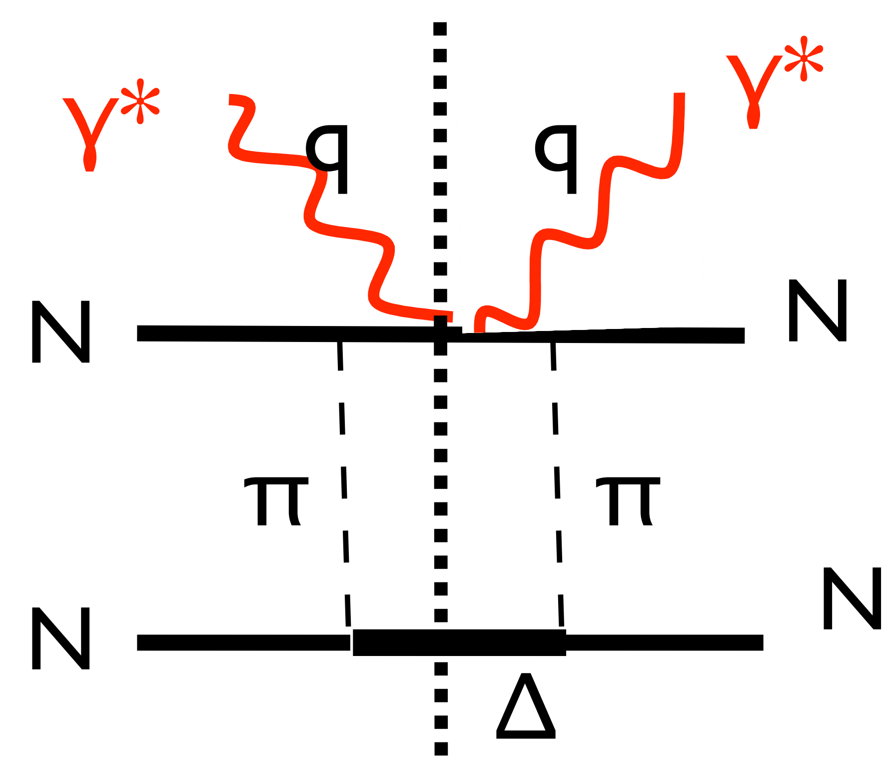
Often hidden in the potential. Probably OK for calculation of the energy binding, energy levels. However wrong for high Q^2 probes.

Explicit calculations of B.Wiringa - ~1/2 high momentum component is due to ΔN correlations, significant also ΔΔ . Tricky part - match with observables - momentum of Δ in the wf and initial state

Large Δ admixture in high momentum component

⇓

- Suppression of NN correlations in kinematics of BNL experiment
- Presence of large E_R tail (~ 300 MeV) in the spectral function



I do not discuss N*'s but they may contribute as well

Generic feature: distribution of ***ΔΔ over relative momenta in the deuteron wave function is broad similar trend for ΔN***

$$\frac{1}{2E_\Delta - m_d} = \frac{1}{2\sqrt{m_\Delta^2 + k^2} - m_d}$$

Reason: the energy denominator in difference from NN state is practically constant up to k ~ ***$m_\Delta/2$***

The same in the light cone formalism

$$\left[\frac{m_\Delta^2 + k_t^2}{\alpha(2-\alpha)} - m_d^2\right]^{-1}$$

α/2 is the light-cone fraction carried by isobar

Since difference is large small sensitivity to change of α: change of α from 0.7 to 1.3: α(2-α) --- 1 to 0.91

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 **much more important in I=1 (pp,nn) SRCs**

➡ Δ's **much broader distribution in momenta (α,k_t)**

Expectations during 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

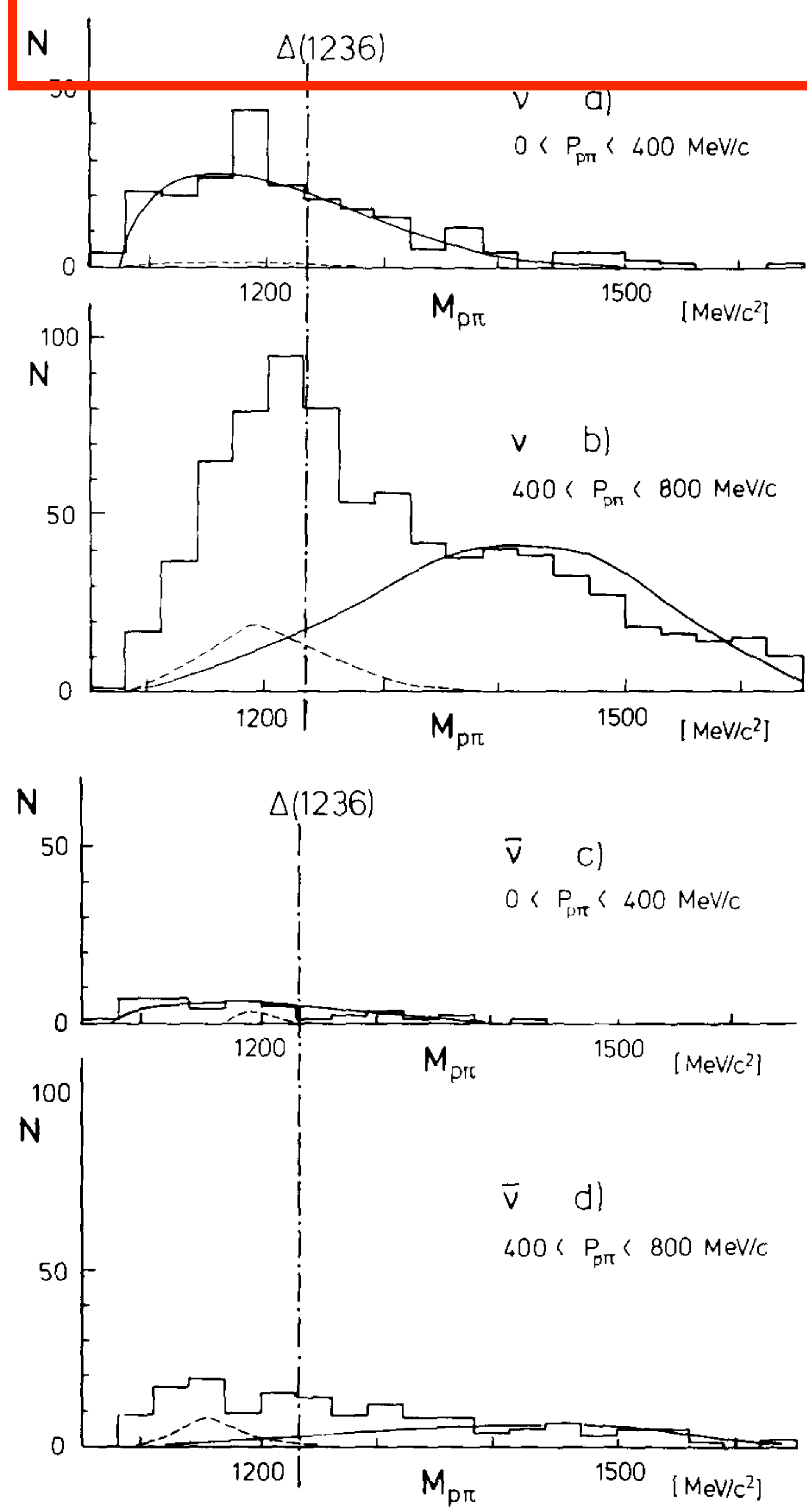
$$\frac{P(\Delta)}{P_{SRC}(N)} \sim \frac{0.04}{0.2} \sim 0.2$$

Too much ?

Volume 174, number 4 PHYSICS LETTERS B 17 July 1986

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

Based on the analysis of 15499 νD interactions
probability to find deuteron in Δ++Δ- state < 0.2% on 90% CL



$$\frac{P_D(\Delta\Delta)}{P_D(SRC)} < 0.1$$

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.

Possible evidence for Δ's in nuclei

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

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

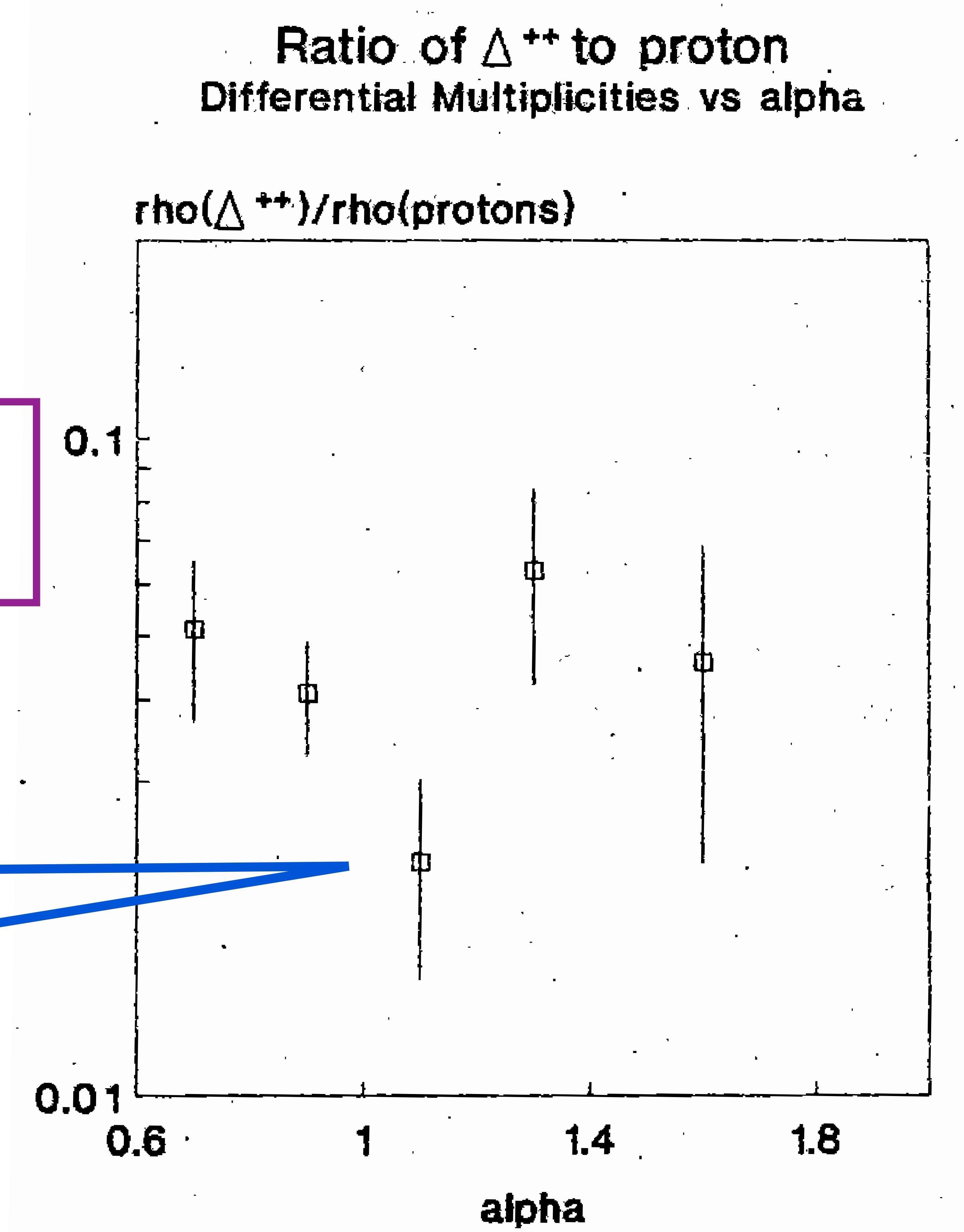
expect R=1 for isosinglet nucleus

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

$$\Downarrow$$

$$\frac{P(\Delta)}{P_{SRC}(N)}\sim\ 0.1$$

suppression at α~1



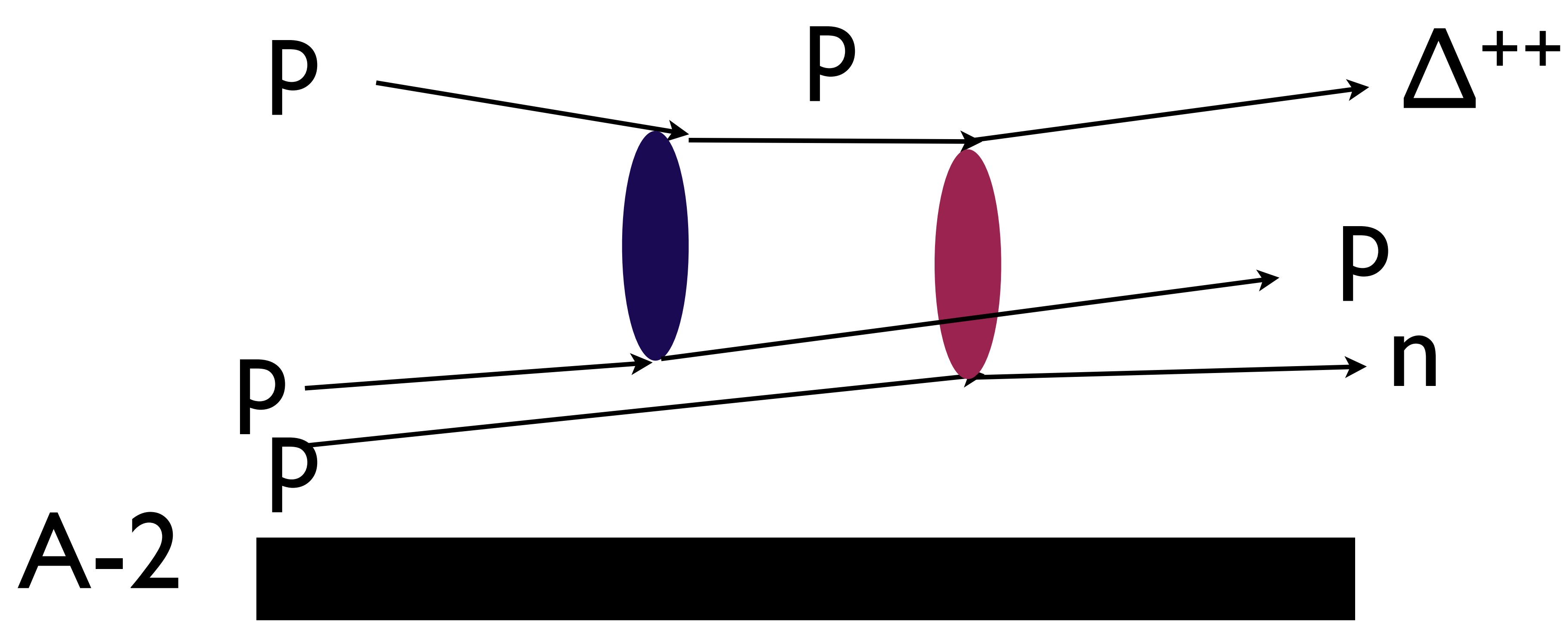
New data are necessary: many options in Jlab kinematics ? New Jlab experiments ?

Perfect kinematics for EIC in particular $\vec{e}+\vec{D}\to e+\Delta^{++}+X(or\,forward\,\pi^{\pm})$

☛ proton beams: look for channels forbidden for scattering off single nucleons but allowed for scattering off exotics: Δ's 6q... at large c.m. angles

$$p + A \rightarrow \Delta^{++} + p + (A-1)$$

Background: two step process with charge exchange at the second step (drops with p_{inc})



Important tool for the analysis: $\alpha_\Delta < 1$ cut as the α_Δ distribution is broader than α_N distribution. Measuring the strength of charge exchange using $\alpha_\Delta = 1$ range

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

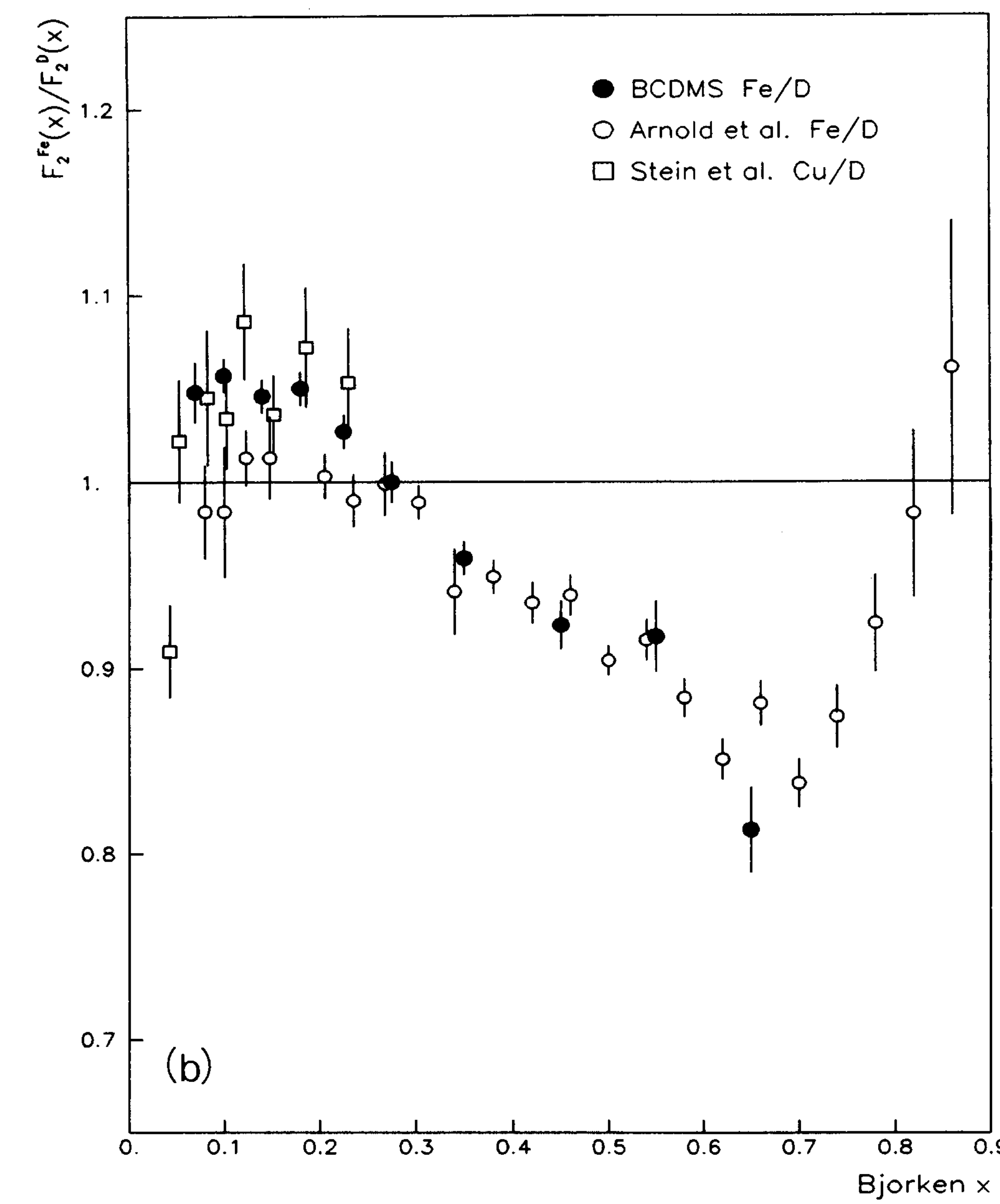
Reference point: nucleus is a collection of quasifree nucleons.

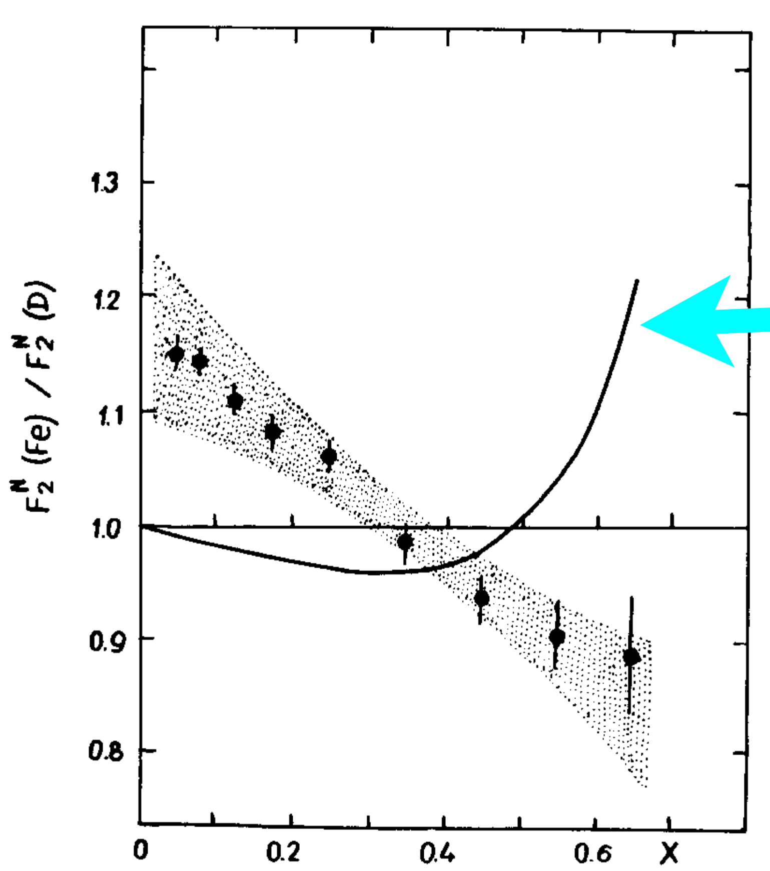
↓

A hard probe incoherently interacts with individual nucleons

↓

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





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

One should be surprised not 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.

How model dependent was the expectation?
EMC paper had many curves hence impression that curves could be moved easily.

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

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

$$P_A = \alpha_1 P_A/A,\ \alpha_2 P_A/A,\ \alpha_3 P_A/A \qquad \alpha_1 + \alpha_2 + \alpha_3 = 3$$

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 αP_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

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

λ_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)

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

Fermi motion

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

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

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

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 - what they are?

O.Nash: God in his wisdom made a 
But he forget to tell us why

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

- Pionic model: extra pions - $\lambda_\pi \sim 4\%$ -actually for fitting Jlab and SLAC data ~ 6%

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

- 6 quark configurations in nuclei with $P_{6q} \sim 20\text{-}30\%$

- *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

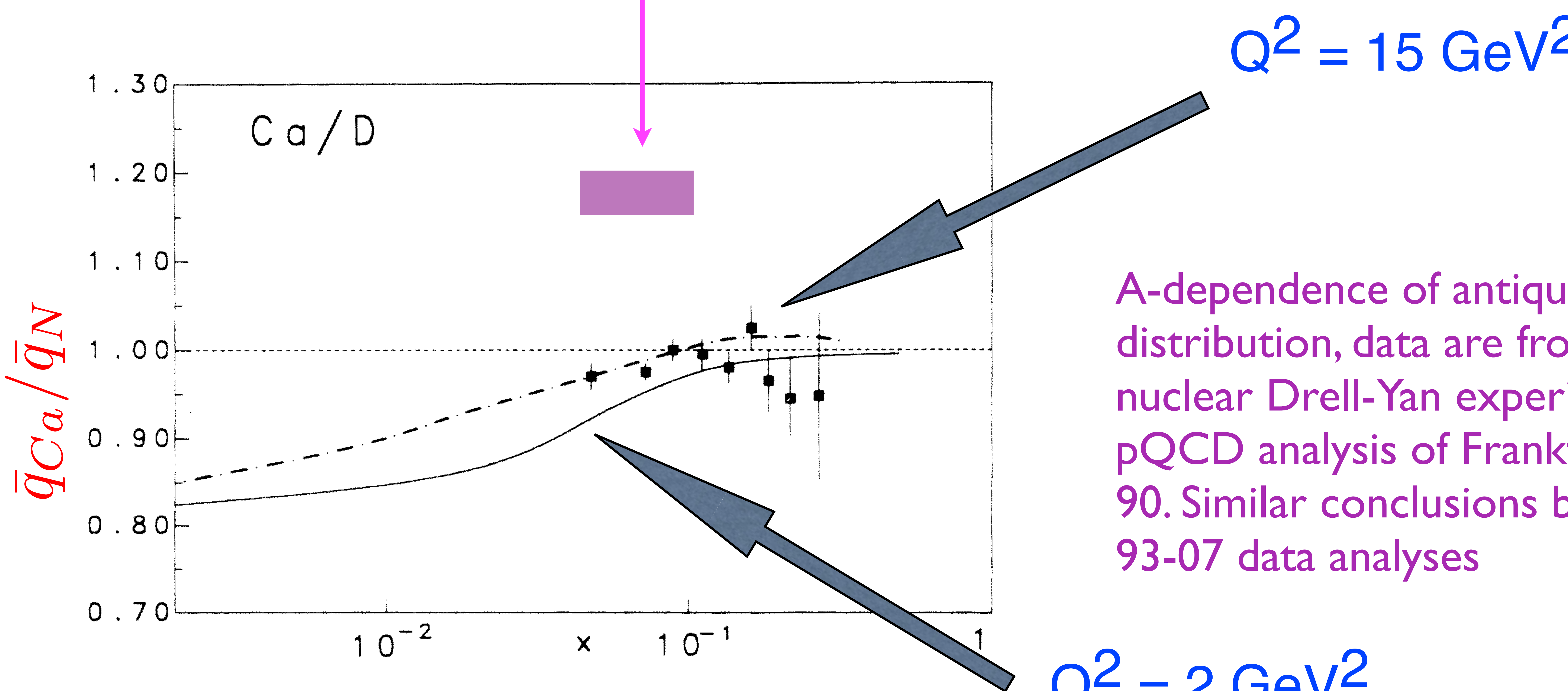
Third try (not always done) fix momentum sum rule by adding mesons

⇓

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

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

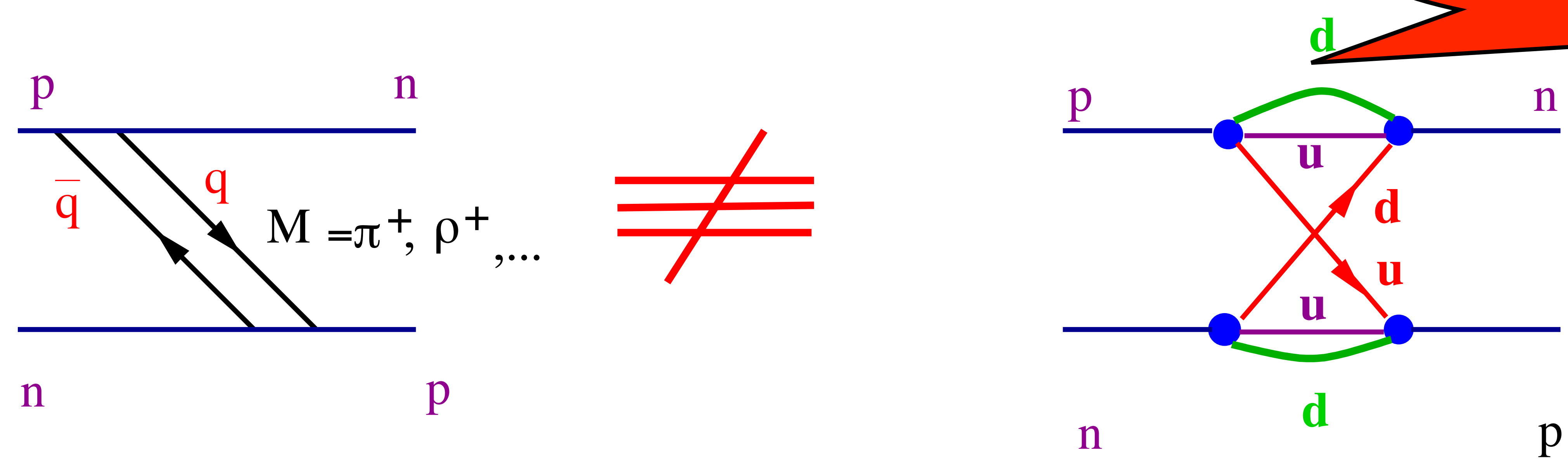
vs Prediction $\bar{q}_{Ca}(x)/\bar{q}_N = 1.1 \div 1.2_{|\,x=0.05\div0.1}$ in meson model (chiral models?)



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?

Better match to Drell Yan data



Meson Exchange
extra antiquarks in nuclei

Quark interchange
no extra antiquarks

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 20% swelling

Restrictions from the studies of SRCs to be presented later in the workshop

- Universality of 2N SRC for .35 < k < .6 GeV/c is confirmed by Jlab experiments

The second group of processes (both lepton and hadron induced) which led to the progress in the studies of SRC is investigation of the decay of SRC after one of its nucleons is removed via large energy- momentum transfer process.

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

- *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* $Q^2= 2GeV^2$

⇒ probability of exotics < 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?"

Rules out models with 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 (FS85)

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. So new pattern of x-dependence of the bound nucleon F_{2N} modification is a welcomed feature of new analysis

tests in pA LHC run in March 2013 & dAu at RHIC - will discuss briefly

In color screening model modification of average properties is small < 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 no better than 20%. But roughly it works (A.Schmidt's talk)

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 $p^2_{int}-m^2=0$. In this point modification should vanish. Our quantum mechanical treatment of 85 automatically took this into account.

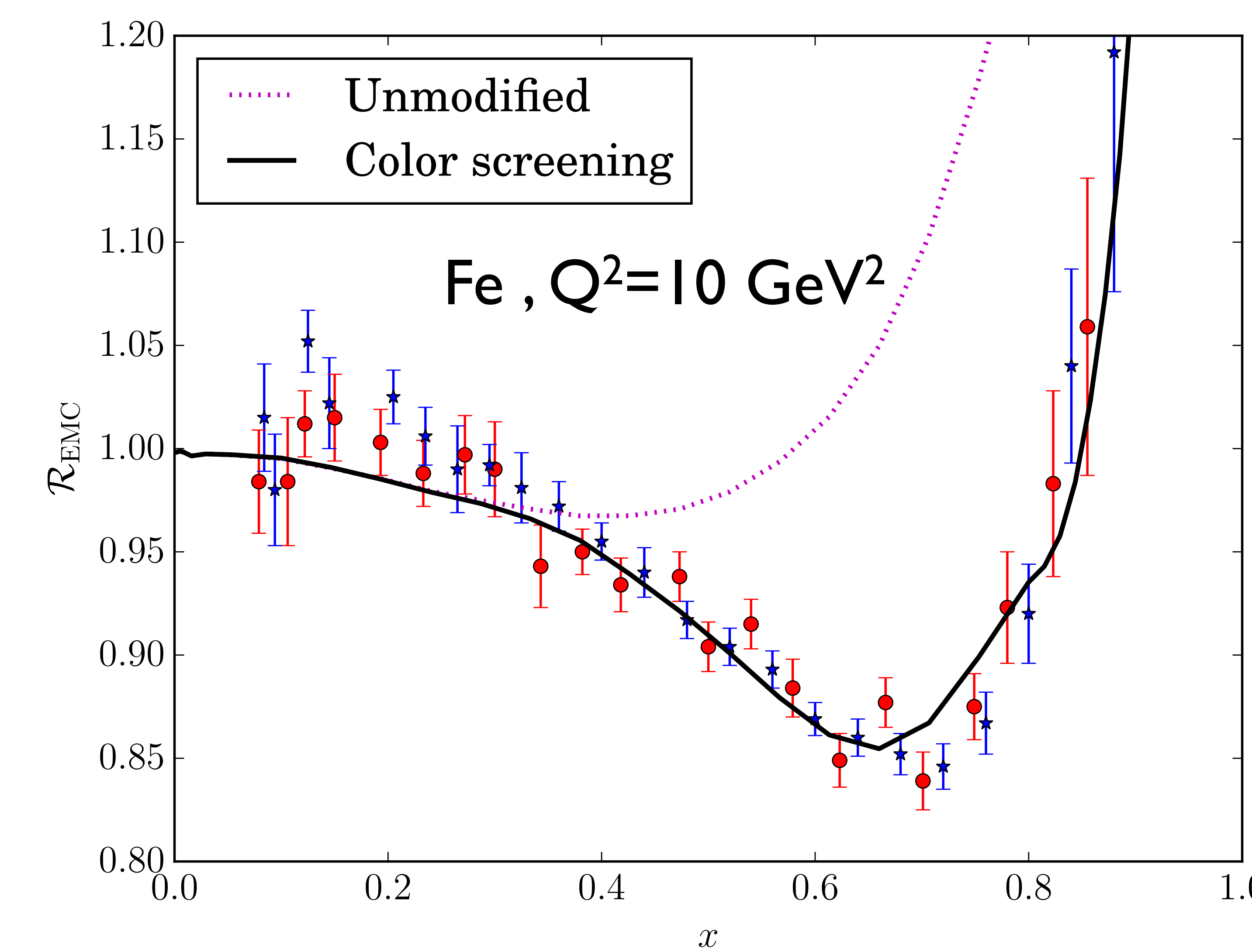
Our dynamical model for dependence of bound nucleon pdf on virtuality - explains why effect is large for large x and practically absent for x~ 0.2 (average configurations V(conf) ~ <V>)

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

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

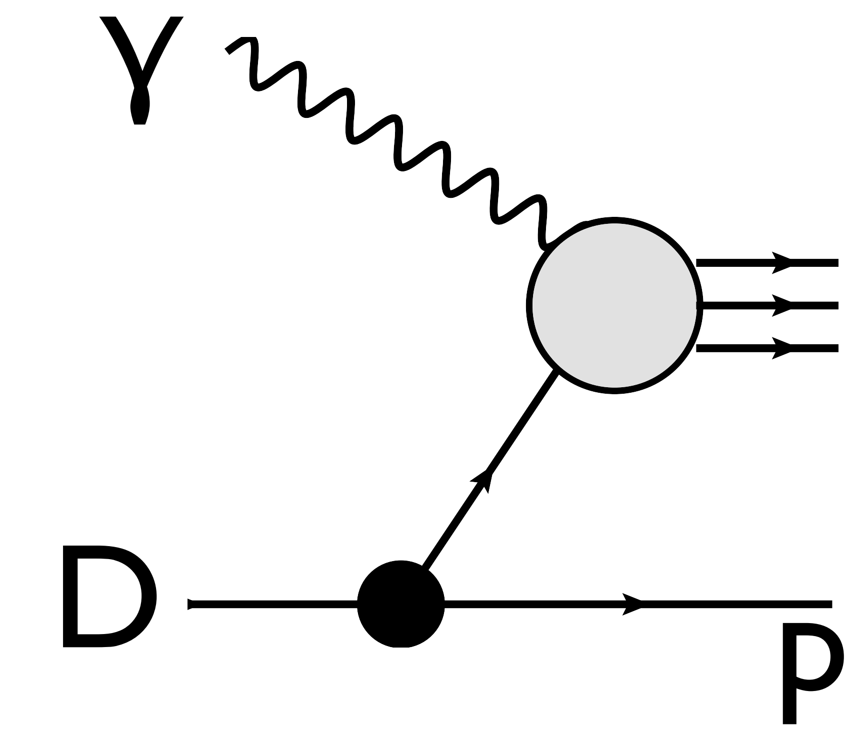
Freese, Sargsian, MS 14

28



"Gold plated test"

Tagging of proton and neutron in e+D→e+ backward N +X (lab frame). Collider kinematics -- nucleons with $p_N > p_D/2$



➡ *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 at say100 MeV/c - go to 200 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

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

A>2 -- motion of the pair, two step processes.

Interesting possibility - EMC effect maybe missing some significant deformations which are averaged 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

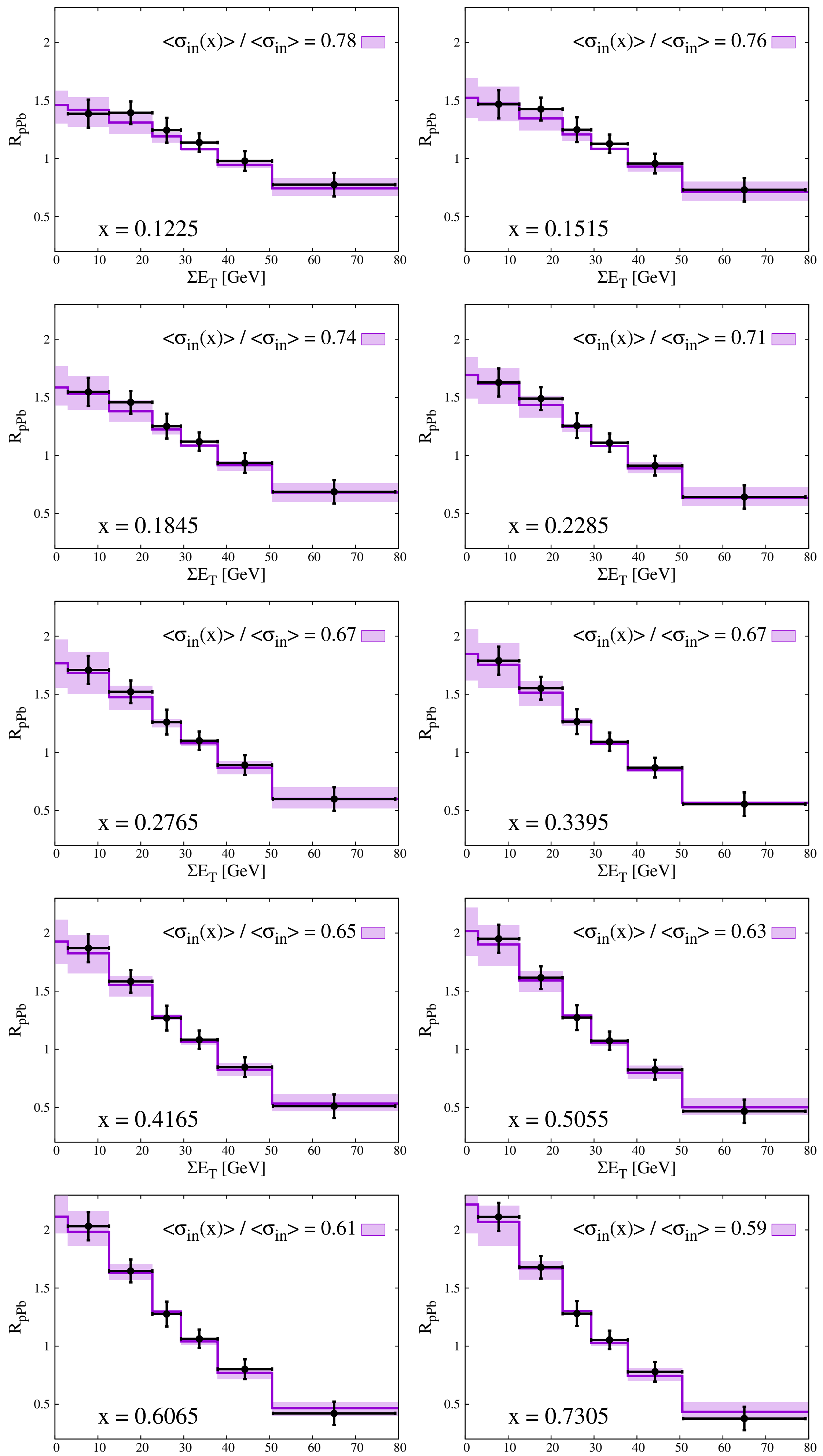
$$d\sigma/d\Omega/ < d\sigma/d\Omega >= 1 + c(p,q).$$

Here <σ> is cross section averaged over φ and dΩ 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.

we suggested a critical test 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 area of probed configurations is a factor of 2 smaller than average.



Deviations from Glauber model for production of dijets, described in the color fluctuation model as due to decrease of $<\sigma_{eff}(x)>/\sigma_{in}$ Data from pA ATLAS.

Consistent results from analysis of the deuteron - gold data from RHIC

At soft scale area of nucleon with x=0.6 is a factor of 4 smaller than average

Conclusions

Summary of the findings

Experiments at large momentum transfers produce strong constrains on the dynamics of the EMC effect

Meson degrees of freedom too small to produce a significant effect

Mean field logic with universal swelling of nucleons is ruled out by (e,e') data at x=1

Limits on exotics in SRC are very strong - exclude a significant trivial 6q like component

Effect grows roughly proportional to average kinetic energy / probability of SRCs

Dynamical mechanism satisfying these constrains is color screening model of suppression of small configurations in bound nucleons. It passed so far the LHC test suggested in 83 - suppression of jet production in central collisions at xp>0.5

Transition from Every Model Is Cool (G.Miller, 83) to Most models are not cool.

Next ten years

Discovery of non-nucleonic degrees of freedom in nuclei: Δ's , tagged structure function (testing origin of the EMC effect)

Direct observation of the 3N correlations

High statistic studies of 2N correlations: determining at what momenta SRC set in, node in pp SRC, S/D wave separation in deuteron, deviations from universality of SRC

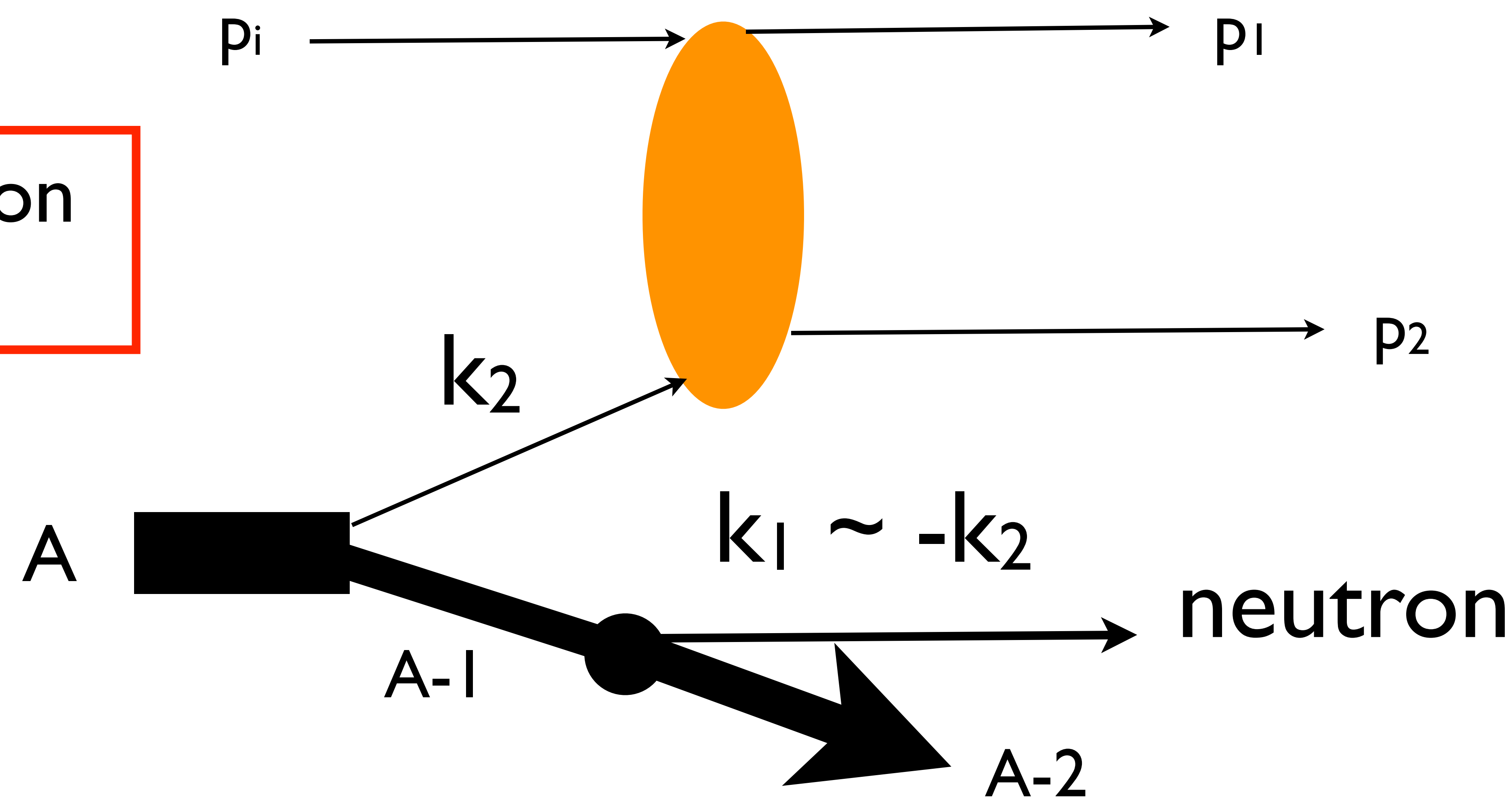
Factorization of manifestations of SRC at large $Q^2(t)$ - Jlab vs hadronic probes

Theory: FSI effects, calculation of the decay function, solving LC many body equations,...

Supplementary slides

Implications for (e,ep), (p, 2p) reactions at large momentum transfer

proton/electron scattering



$s' = (p_1 + p_2)^2$

$t = (p_1 - p_p)^2$

$k_2 = p_1 + p_2 - p_i$

Possible t -range for HADES at 90°:
2 GeV^2 ÷ 4 GeV^2

From measurement of p_1, p_2 $p_{neutron}$ choose small excitation energy of A-2 (< 100 MeV)

$\sigma = d\sigma_{pp\rightarrow pp}/dt(s',t) * D(k_1,k_2)$ (D= Decay function)

☛ *Factorization test of the reaction mechanism:*

$d\sigma(s',t,k_1,k_2) / d\sigma_{pp\rightarrow pp}/dt(s',t)$ = " independent of s', t Decay function"

☛ Detailed test of the reaction mechanism for scattering off 2N SRC

$p\,^2H \rightarrow ppn$

Reach Q^2 (for elastic eN scattering) where small size configurations are enhanced

$$\frac{D(Q^2 >> 2\ GeV^2, k_1, k_2)}{D(Q^2 = 2\ GeV^2, k_1, k_2)} = \delta_A(\kappa_1{}^2)$$

Breakdown of factorization

Indications from analysis of x>1 D(e,e') SLAC data at Q^2=6 GeV^2

Sargsian et al unpublished

Analogous effect for A(p,2p) at s,t where/ if color transparency sets   in

-t > 10 GeV^2 ?