Close nucleon encounters: Short range correlations, EMC effect,…

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Hall C meeting, February 2022

Fundamental questions about microscopic quark-gluon structure of nuclei and nuclear forces

- Are nucleons good nuclear quasiparticles?
- Probability and structure of the short-range correlations in nuclei
  How to describe relativistic effects in a many nucleon bound states
- Microscopic origin of intermediate and short-range nuclear forces
- What are most important non-nucleonic degrees of freedom in nuclei?

Experience of quantum field theory - interactions at different resolutions (momentum transfer) resolve different degrees of freedom - renormalization,.... Describe the effects of the Dirac sea… No simple relation between relevant degrees of freedom at different resolution (virtuality)scales.

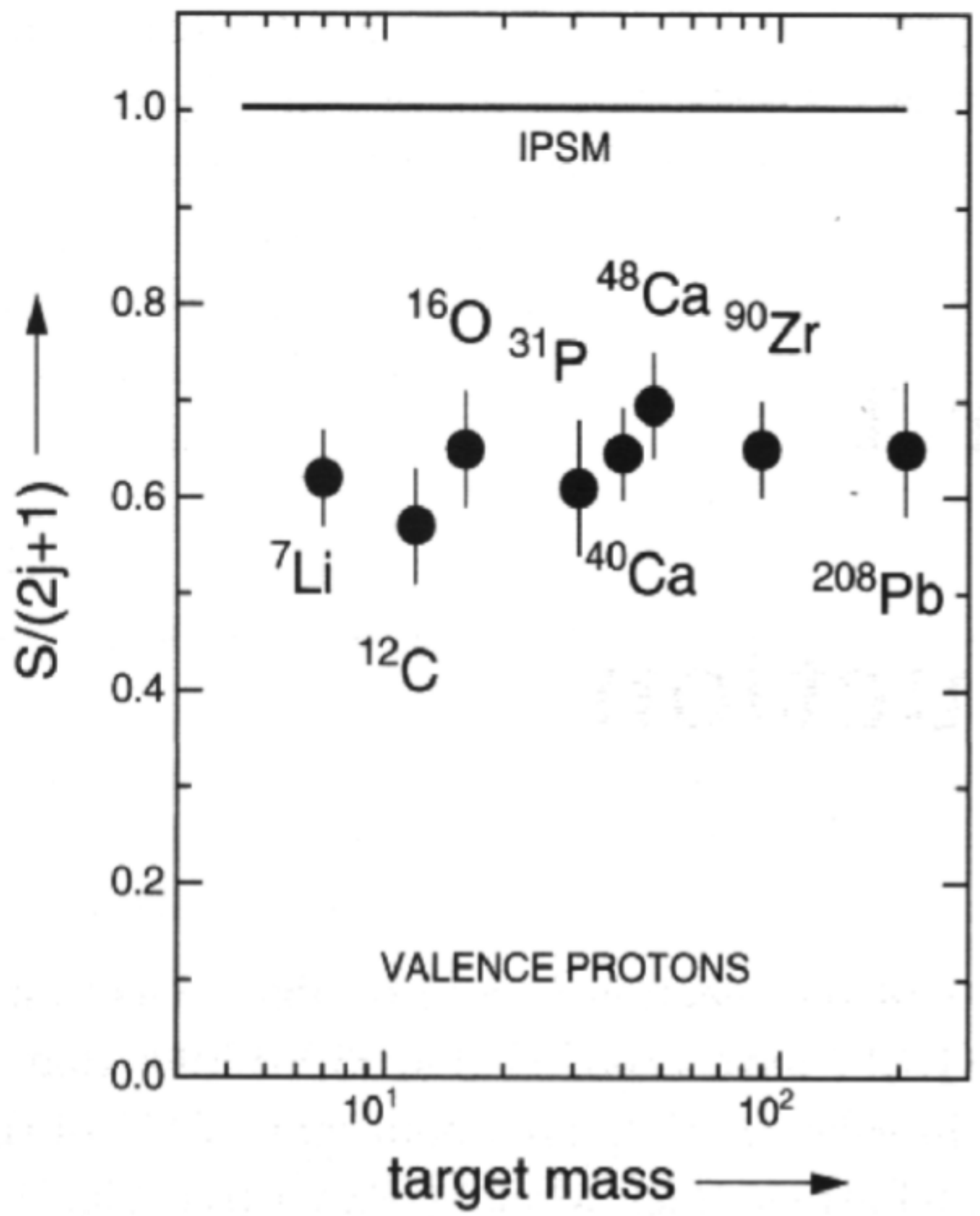
$\boxed{\Rightarrow \text{Complexity of the problem}}$

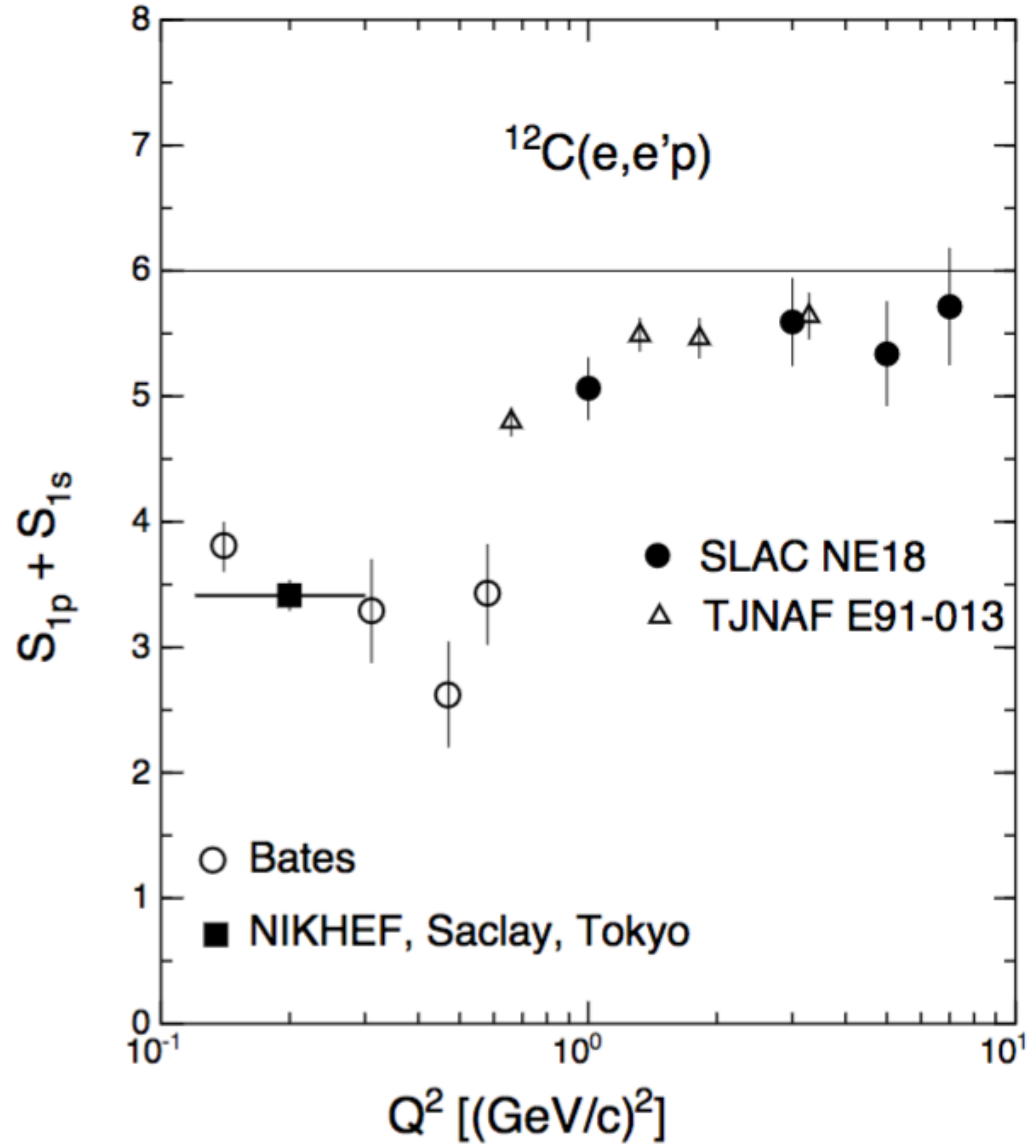
Three important scales

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

related effect: Q^2 dependence of quenching, Q

related to the rate of eA—> e’p(A-1) process



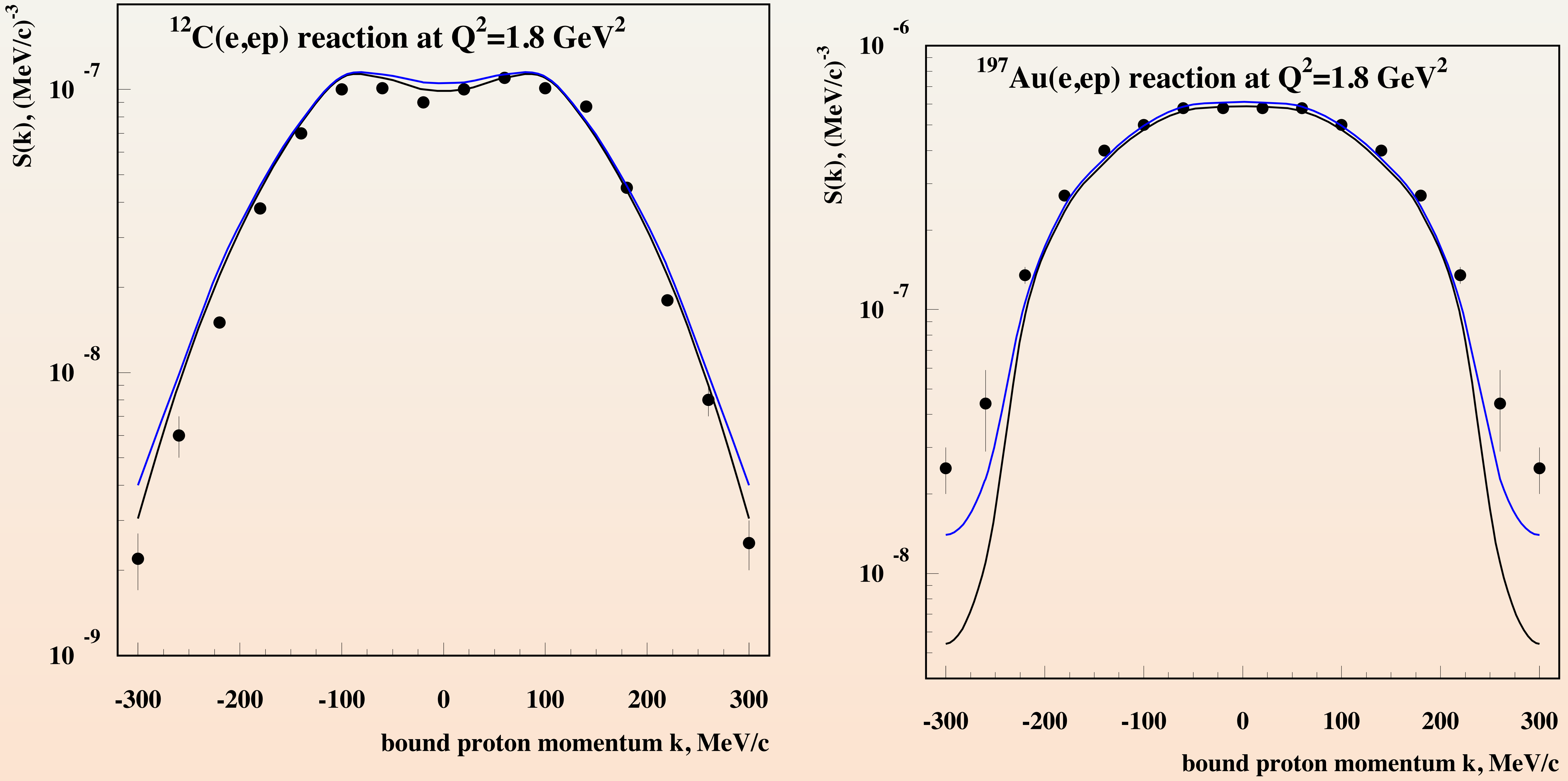


L. Lapikas, G. van der Steenhoven,
L. Frankfurt, M.~Strikman, M. Zhalov, 99

Quenching practically disappears ($\leq$ 10%) for $Q^2 \geq 1.5$ GeV^2

More data are highly desirable.

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.

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 (FS 76) was ignored in 70's, leading to believe SRC could not be unambiguously observed. Hence, very limited data

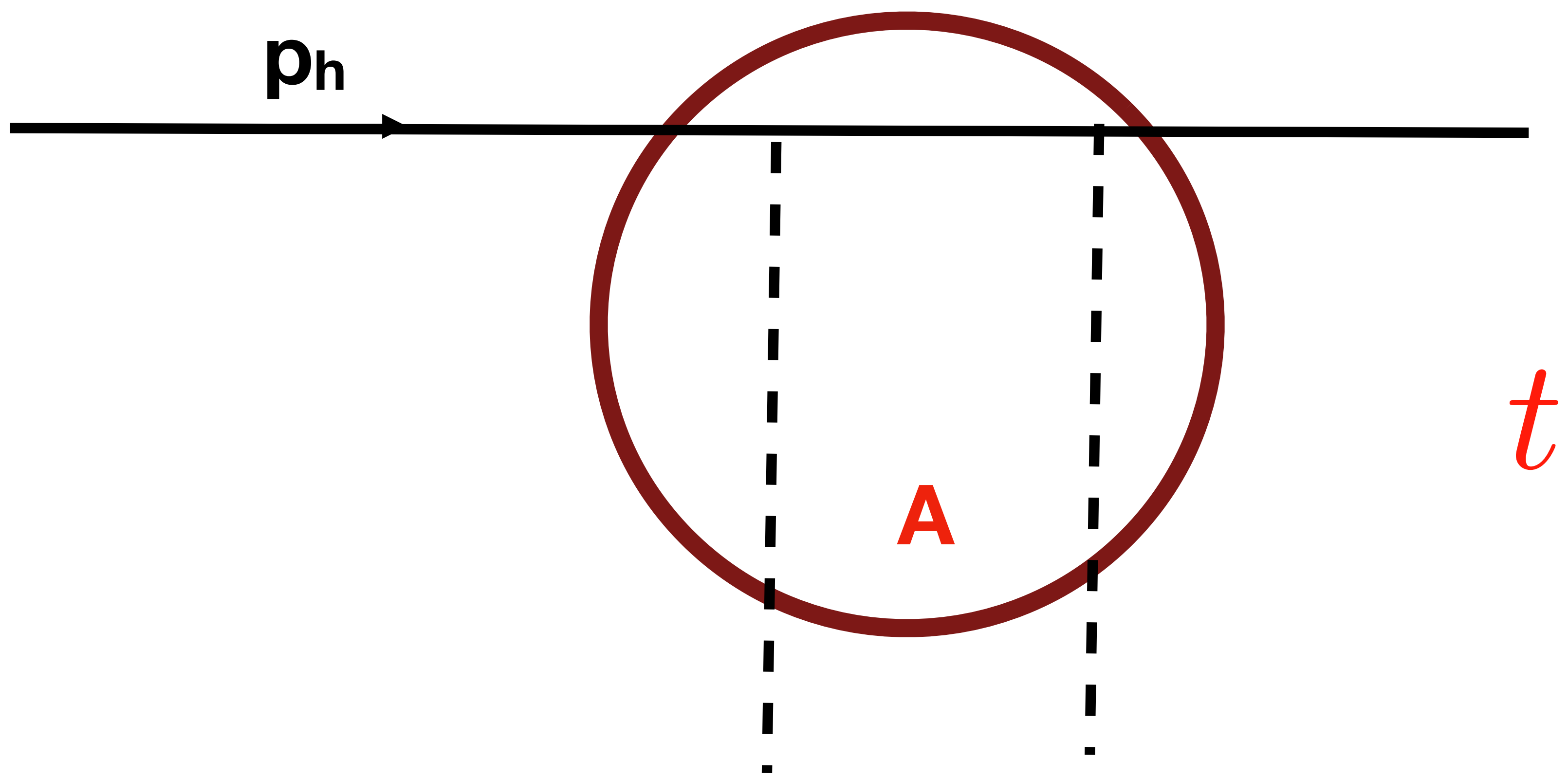
Historical remark: in 70's it was considered hopeless to look for SRC experimentally, hence Phys.Lett. rules (informal) stated to us by the editor were to reject claims to the opposite without peer review

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

⇒ Hence one has to treat the processes in the relativistic domain. The price is a need to treat the nucleus wave function using light-cone quantization - - One cannot use (at least in a simple way) nonrelativistic description of nuclei as well as covariant approaches. (More about this in the second part of the talk (EMC effect…)

$\Rightarrow$ High energy process develops along the light cone.

Relativistic projectile



$$t_1 - z_1 = t_2 - z_2$$

$$t_1,\ z_1 \quad t_2,\ z_2$$

Similar to the perturbative QCD the amplitudes of the processes are expressed through the wave functions on the light cone. In the nucleus rest frame

$$\alpha_N = (E_N - p_{N\,z})/(m_A/A)$$

In the reference frame of collider (LHC,RHIC) $\alpha_N = AE_N/E_A$

Kinematics is much simpler in LC variables. Example: $\gamma + D \to N + X$

$$p_N^{max} = \frac{3}{4} m_N \iff \alpha_N^{max} = 2$$

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

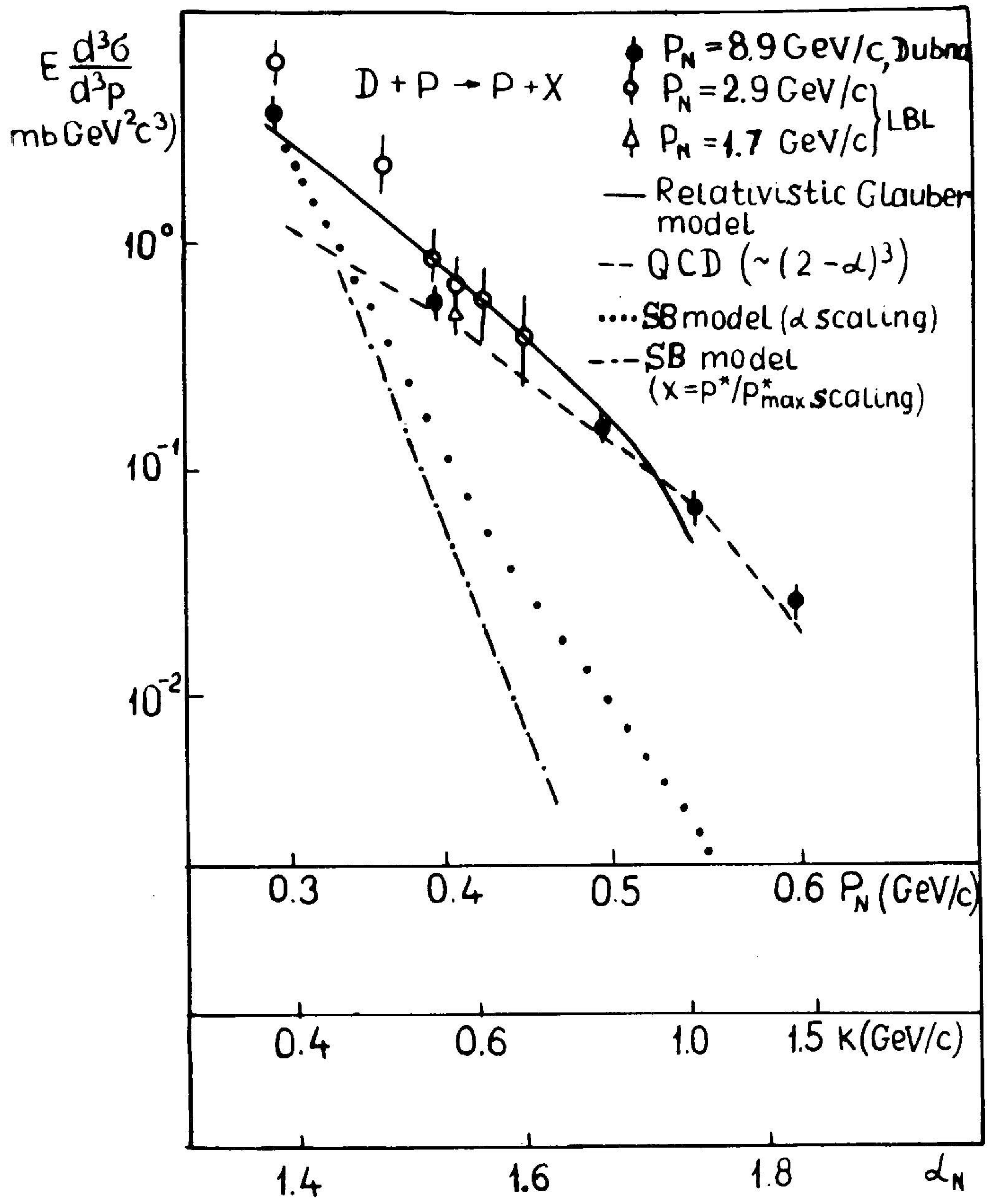
$$\alpha = (\sqrt{p^2+m^2} - p_3)/(m_D/2)$$ where p is rest frame momentum of nucleon spectator in reaction h+ D—> p +X

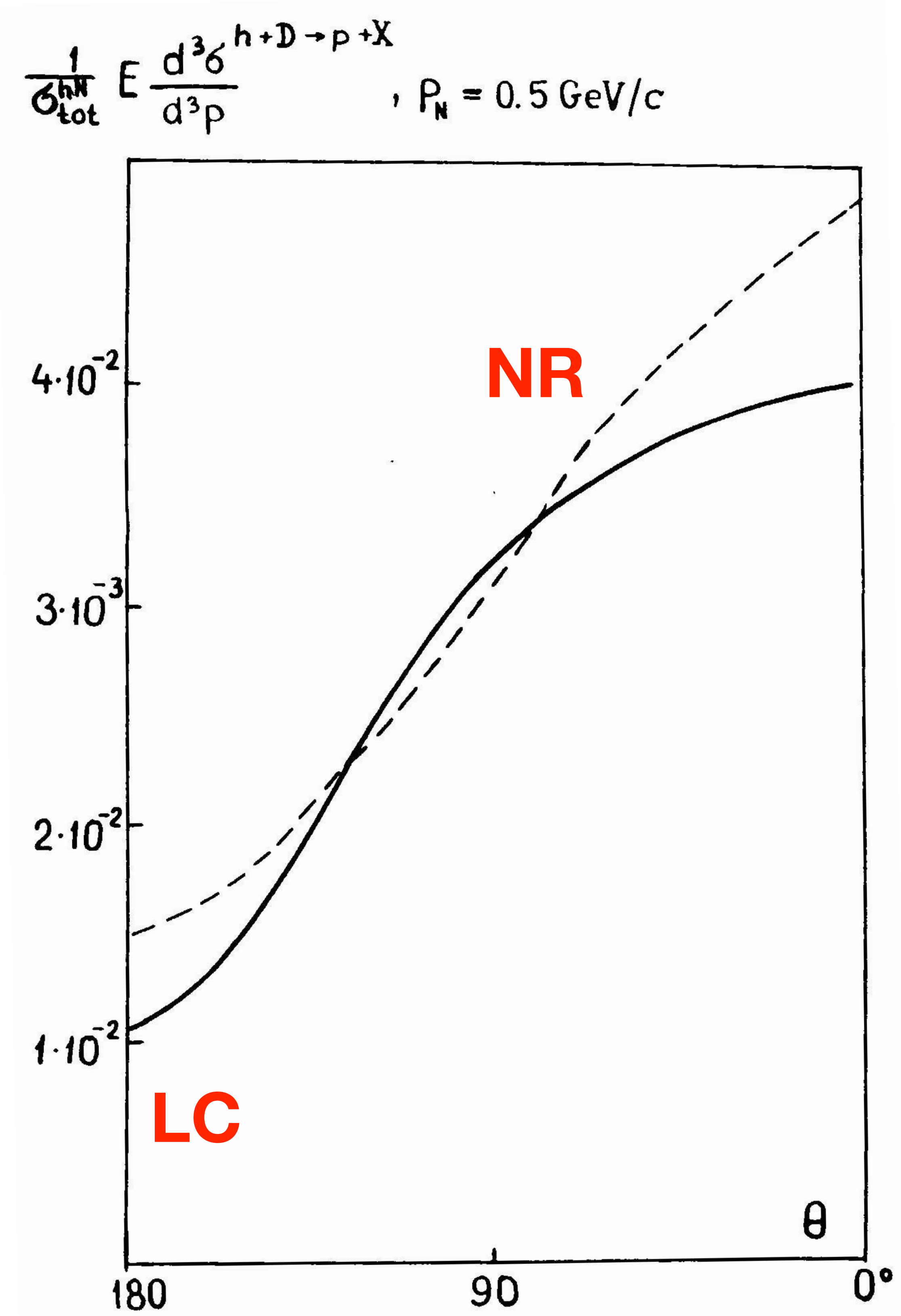
Highly nonlinear relation between momentum k and momentum p: backward p=3m/4 $\Longleftrightarrow k \to \infty$

backward p=0.5 GeV—> k=0.8 GeV

$$\frac{d\sigma(p+D\to p+X)}{d^2k_t d\alpha/\alpha} = \sigma_{NN}^{inel}\psi_D^2(\alpha,k_t)$$

large momentum transfer in NN scattering, spectator mechanism -decay function

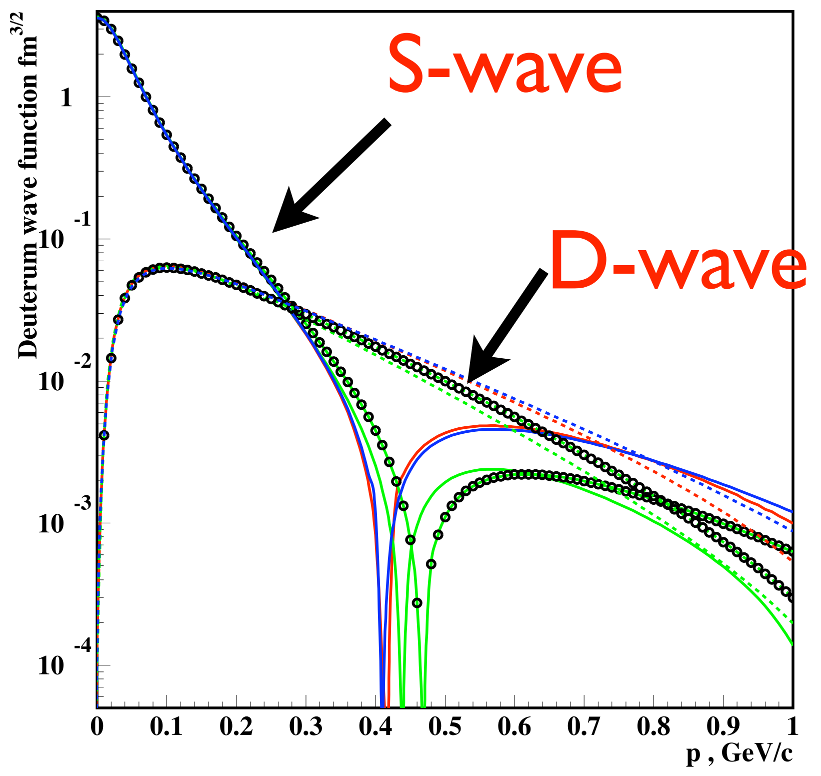




would be highly desirable to have data from Jlab (real photon, moderate x ~.1- .2)

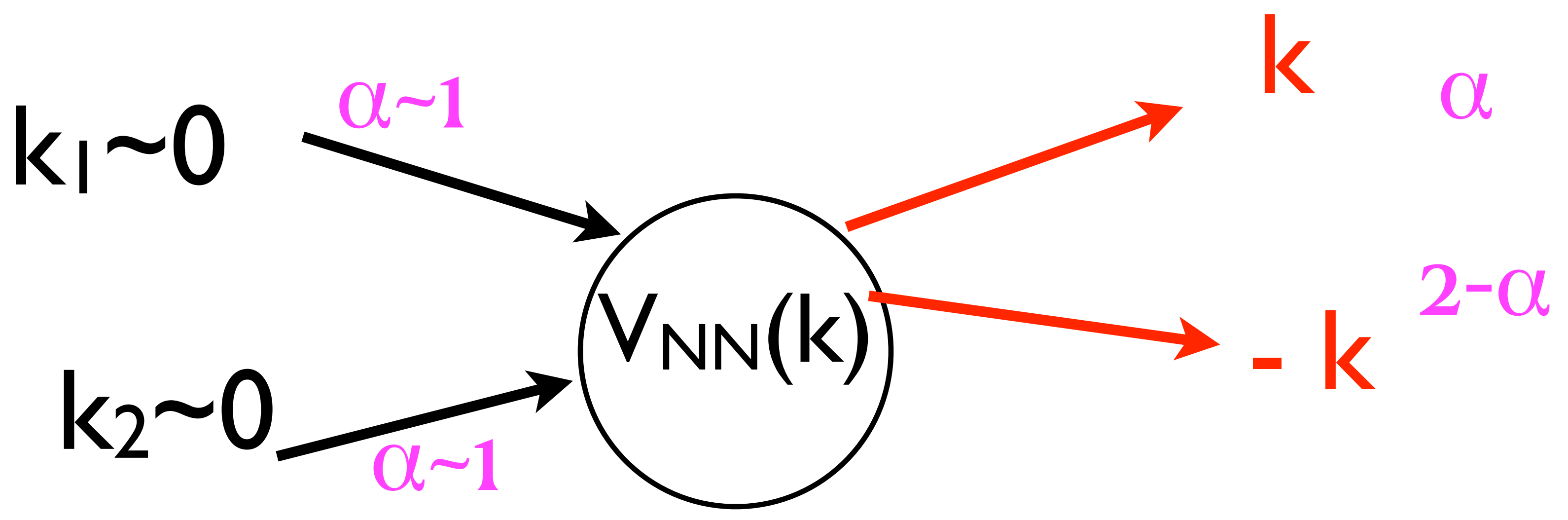
Properties of SRCs

Realistic NN interactions - NN potential slowly (power law) decreases at large momenta
-- nuclear wf high momentum asymptotic determined by singularity of potential:



Deuteron wave function

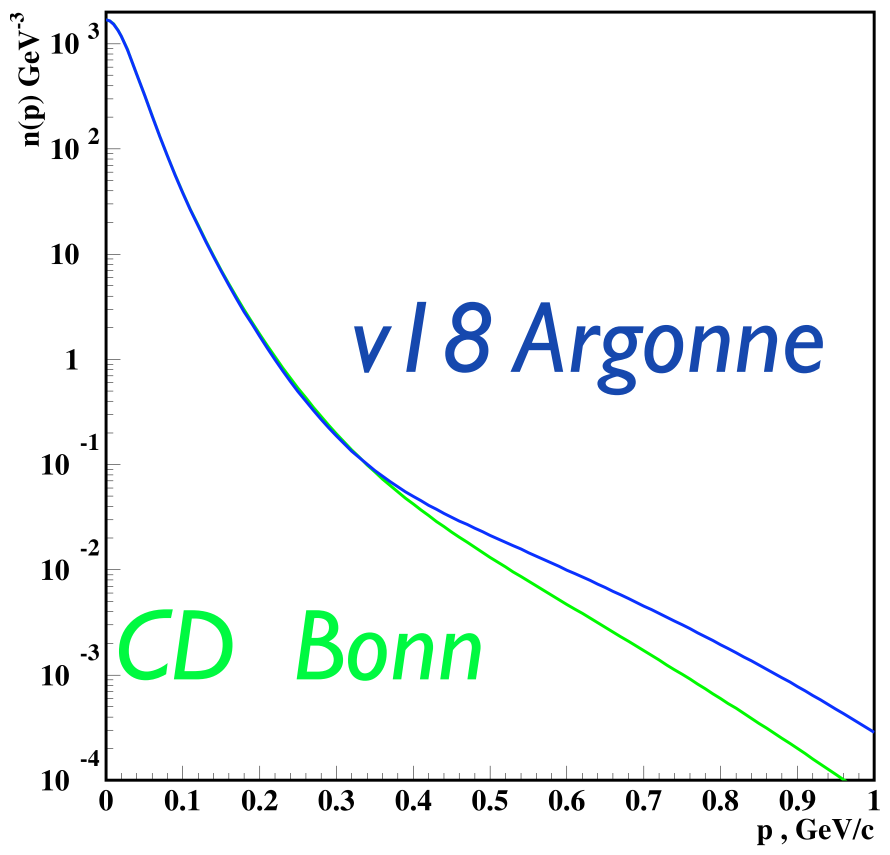
$$\psi_D^2(k)_{|k\to\infty} \propto \frac{V_{NN}^2(k)}{k^4}$$



D-wave dominates in the Deuteron wf for 300 MeV/c < k < 700 MeV/c

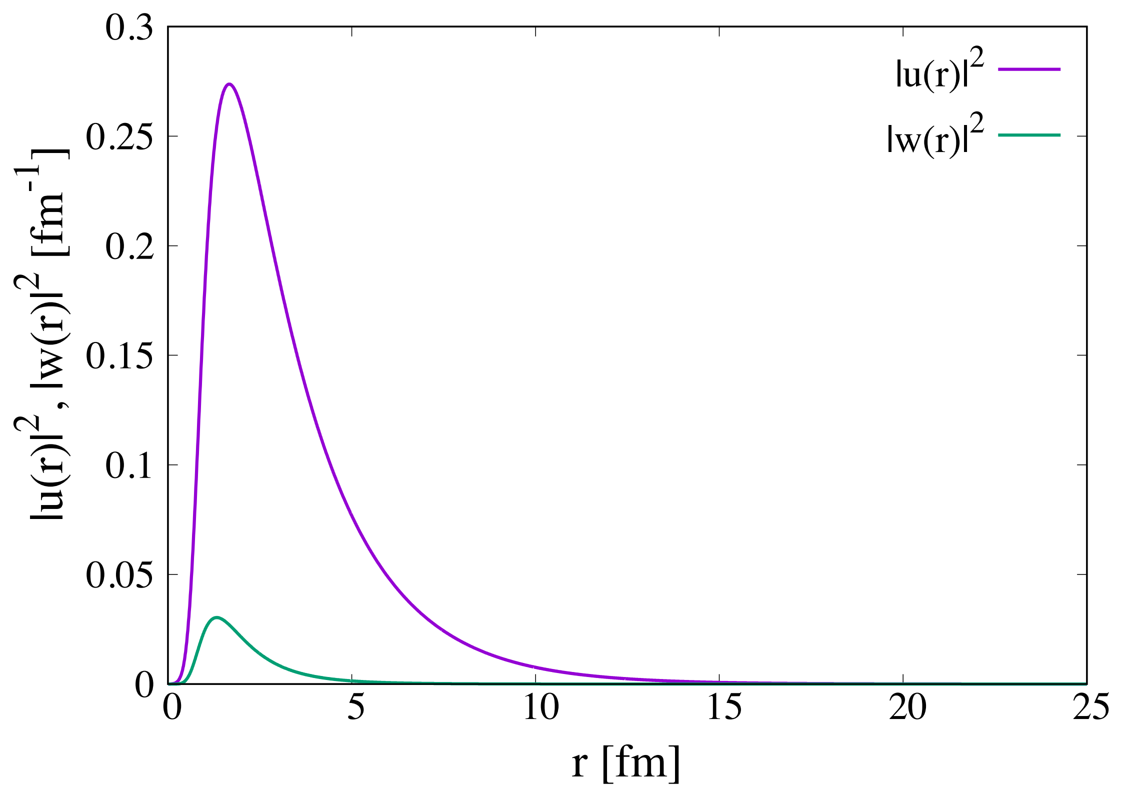
D-wave is due to tensor forces which are much more important for pn than pp

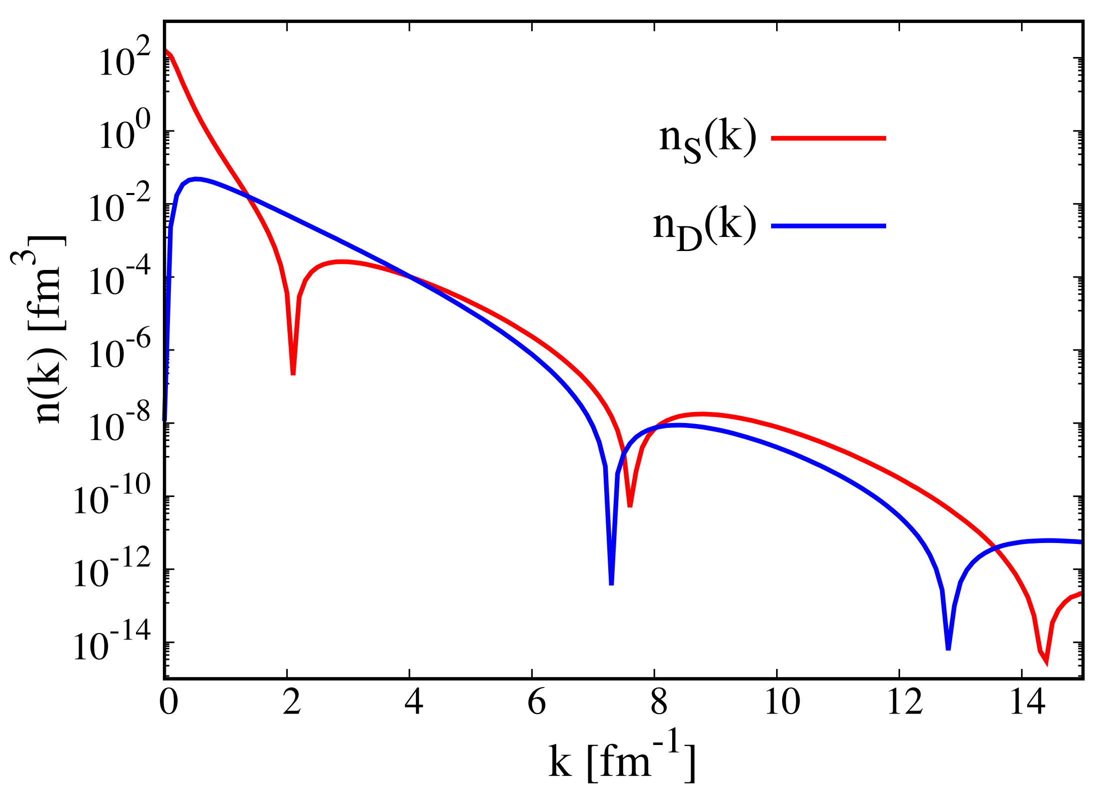
Tensor forces are pretty singular ➟ manifestations very similar to *shorter* range correlations - so we refer to both of them as SRC

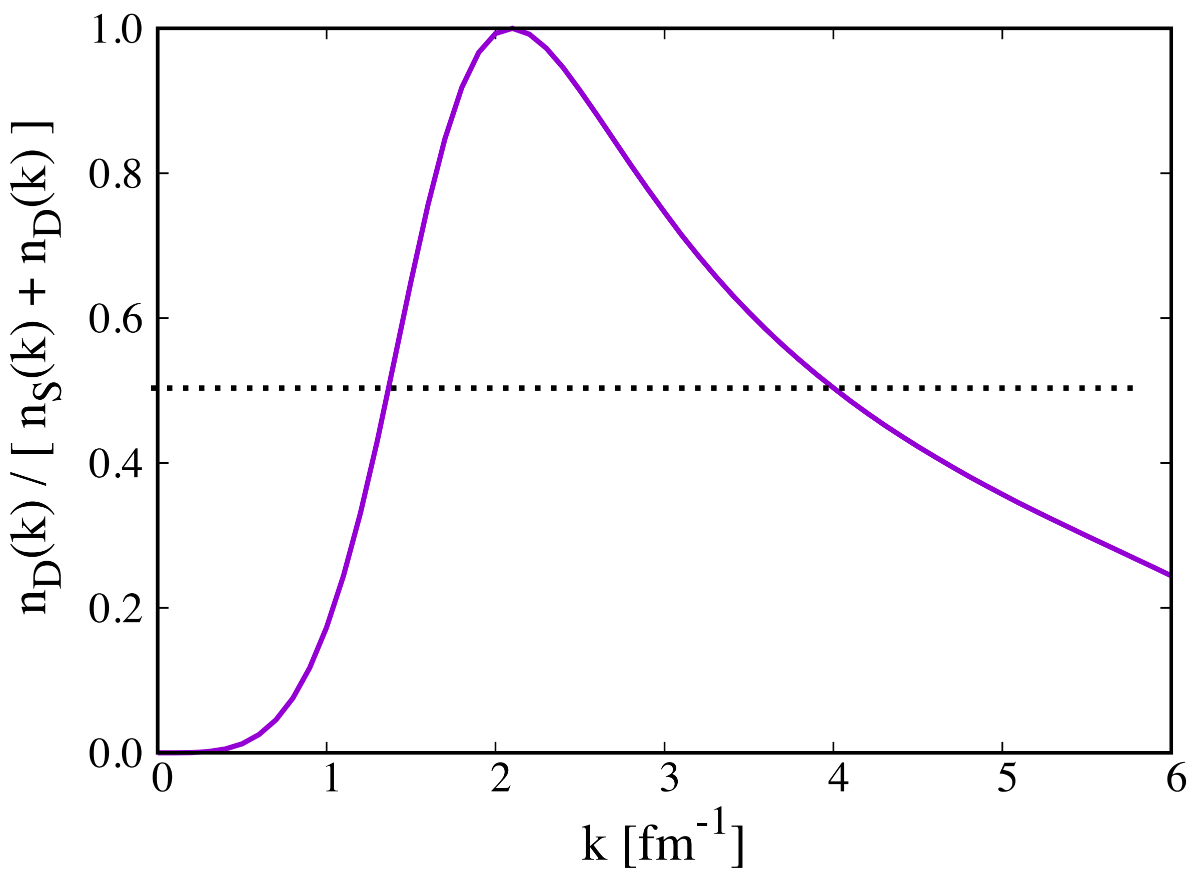


Large differences between in $n_D(p)=\psi^2_D(p)$ for p>0.4 GeV/c - absolute value and relative importance of S and D waves between currently popular models though they fit equally well pn phase shifts. Traditional nuclear physics probes are not adequate to discriminate between these models.

A quick look at coordinate and momentum deuteron wave functions







D-wave dominates in momentum space between 300 and 800 MeV/c in spite of being much smaller than S wave at all distances. High momentum tail in this region is due to Fourier transform of rapidly changing integrand.

No simple relation "high momentum — small distance"

Is w(k) /u(k) universal for k> 300 MeV/c?

No direct calculations so far.

Dynamical quantities (ones which can be directly observe)

Nonrelativistic

Light cone

momentum distribution **n(k)**

not observable directly

LC density matrix $\rho_A(\alpha, k_t)$

calculated for A=3 and nuclear matter → **Spectral function**

modeled in 2N moving in mean field model (next slide)

Decay function

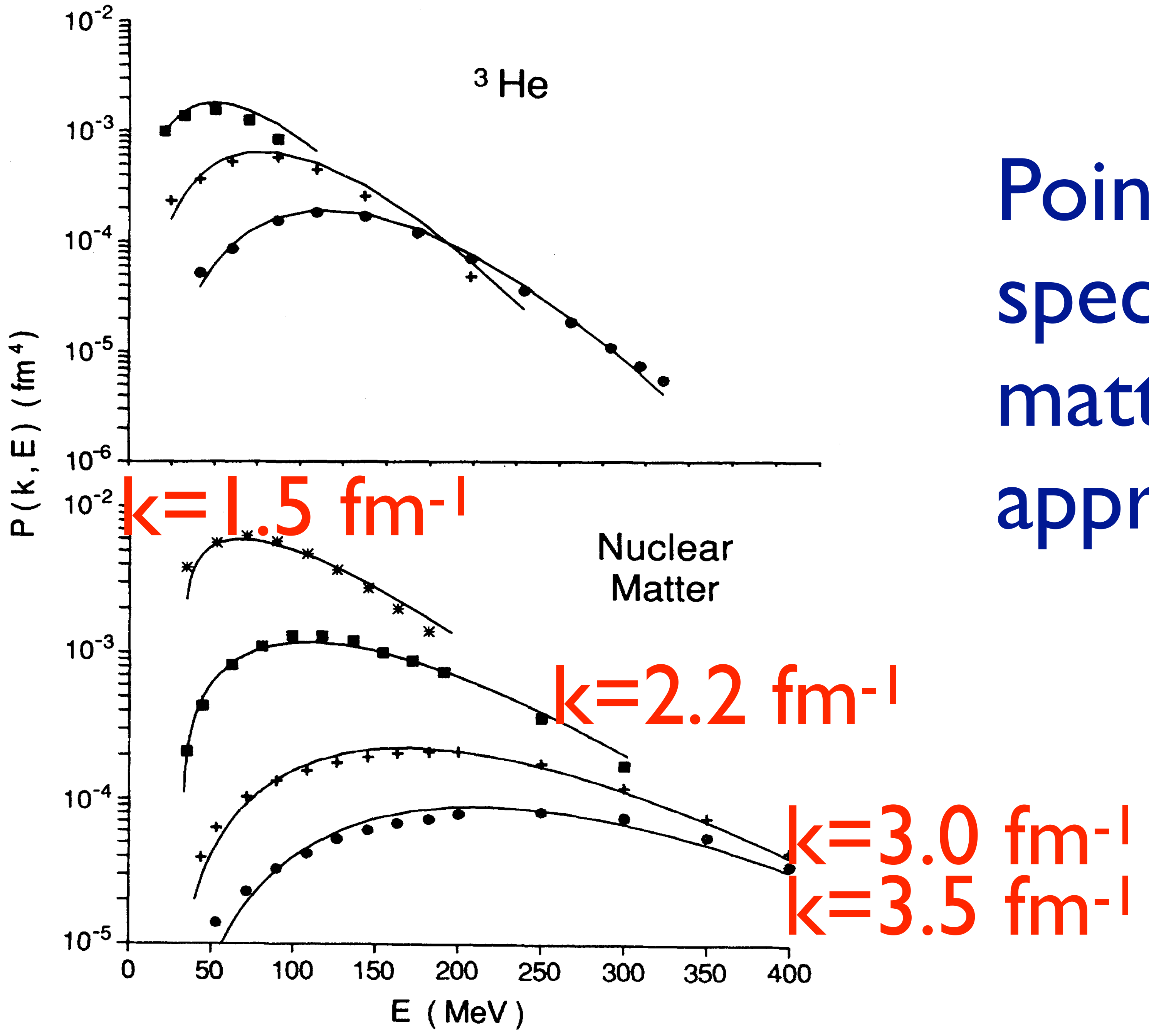
$$D_A(k_2, k_1, E_r) = |\langle \phi_{A-1}(k_2, ...)\,|\delta(H_{A-1} - E_r)a(k_1)|\,\psi_A\rangle|^2$$

FS81 -88

Ab-initio NR calculation of double momentum distribution +
ansatz 2N moving in mean field are used for modeling spectral and decay functions

Numerical calculations in NR quantum mechanics confirm dominance of two nucleon correlations in the spectral functions of nuclei at k> 300 MeV/c - could be fitted by a motion of a NN pair in a mean field (Ciofi, Simula,Frankfurt, MS - 89-91). However numerical calculations for nuclear matter ignored three nucleon correlations - 3p3h excitations.

Relativistic effects maybe important rather early as the recoil modeling does involve k^2/m_N^2 effects.



Points are numerical calculation of the spectral functions of ^{3}He and nuclear matter - curves two nucleon approximation from CSFS 91

For power law potentials expect for momentum distribution: $n_A(k)$: *$n_A(k)/n_D(k)$ —> const for k—>∞*

Agrees with modern calculations. Calculations sum over all partial waves - so no direct confirmation of D-wave dominance

$\alpha \geq 2$ —> 3NSRC. In LC higher order correlations are explicitly seen already on a single particle momentum distribution level - (not the case for n(k)

Proportionality of $\rho_A^N(\alpha, p_t)$ and $\rho_D^N(\alpha, p_t)$ for $1.3 \leq \alpha \leq 1.6$

Standard model first developed in the analysis of the BNL pA -> ppn + X experiment and perfected by the MIT group: SRC described as universal pn, pp, pairs moving in mean field

Additional Ansatz - LC implementation of motion of the pair in the mean field

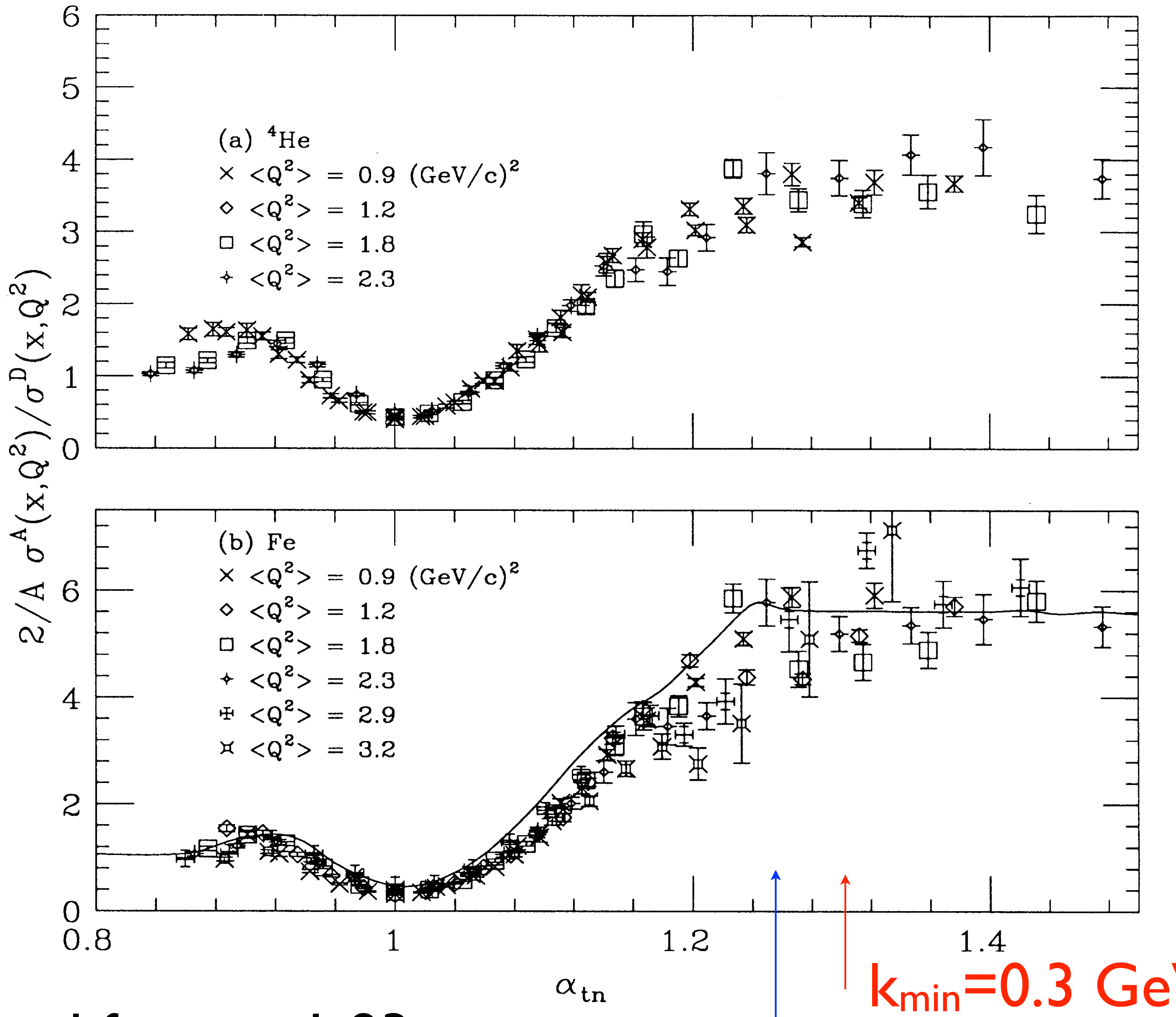
symmetry in LC NN fraction around α_{NN}=2

question/concern: removing one nucleon of SRC does not destroy interactions of second nucleon of SRC with mean field - *should suppress emission from pairs with high momenta of the pair.*

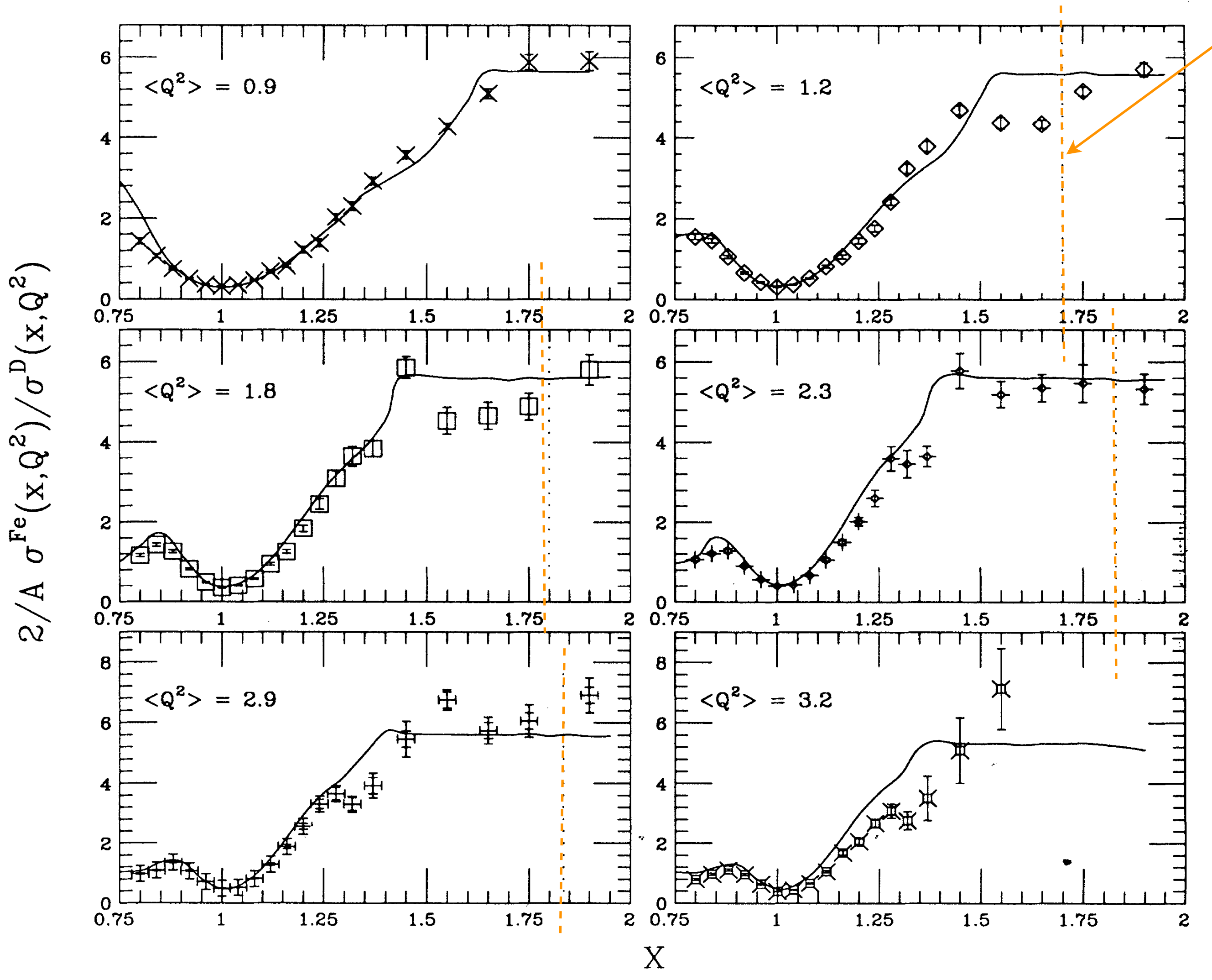
Superscaling of the ratios FS88 α_{tn} is α for scattering off pair at rest

$$\Rightarrow \frac{\sigma_{A_1}(x,Q^2)}{\sigma_{A_2}(x,Q^2)} = \frac{\int \rho_{A_1}(\alpha_{tn},p_t)d^2p_t}{\int \rho_{A_2}(\alpha_{tn},p_t)d^2p_t} = \frac{a_2(A_1)}{a_2(A_2)}\Big|_{1.6>\alpha\geq 1.3}$$

Note - local FSI interaction, up to a factor of 2 for σ(e,e’), cancels in the ratio of σ’s



$W - M_D \leq 50\,MeV$



k_{min}=0.3 GeV

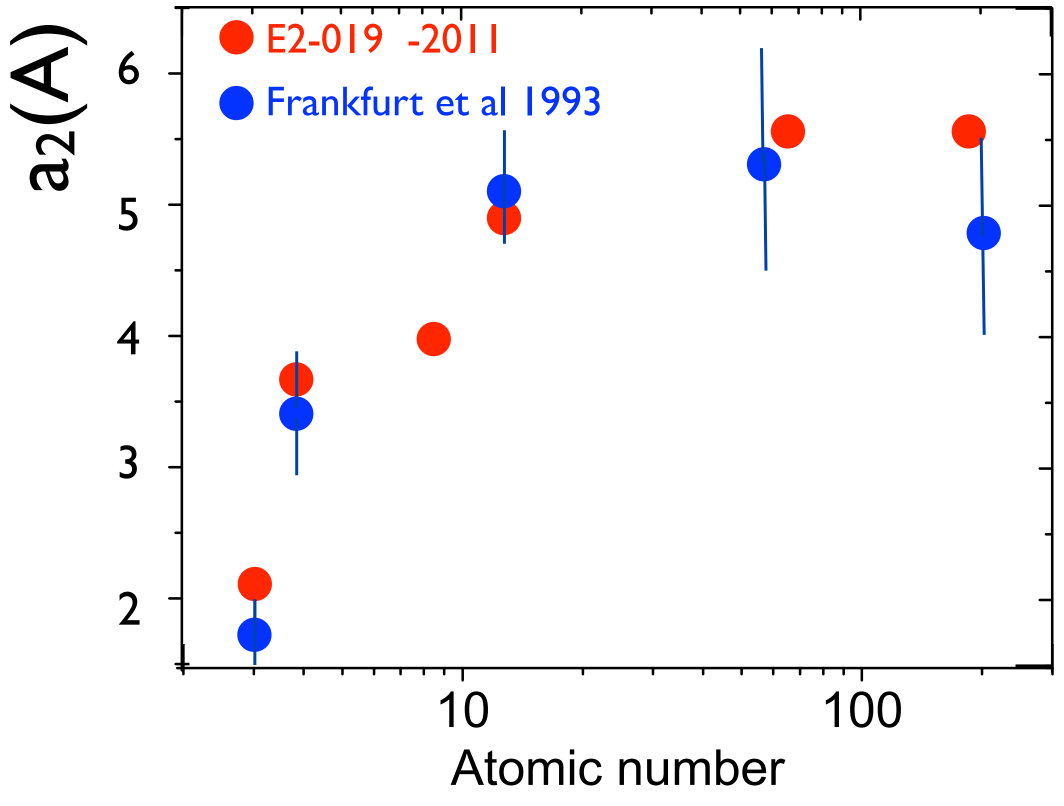
Frankfurt et al, 93

k_{min}=0.25 GeV

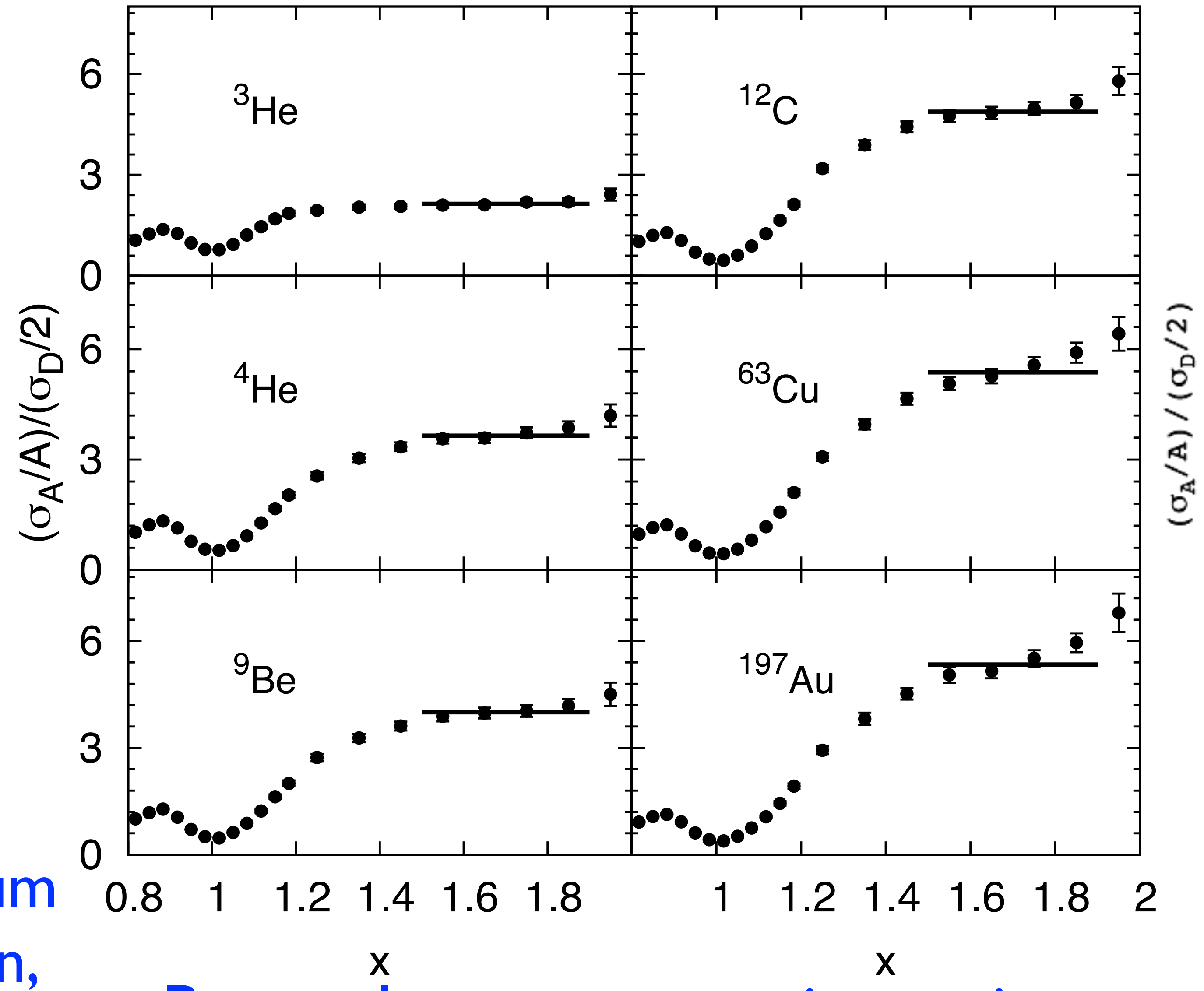
Masses of NN system produced in the process are small - strong suppression of isobar, 6q degrees of freedom.

Right momenta for onset of scaling of ratios !!!

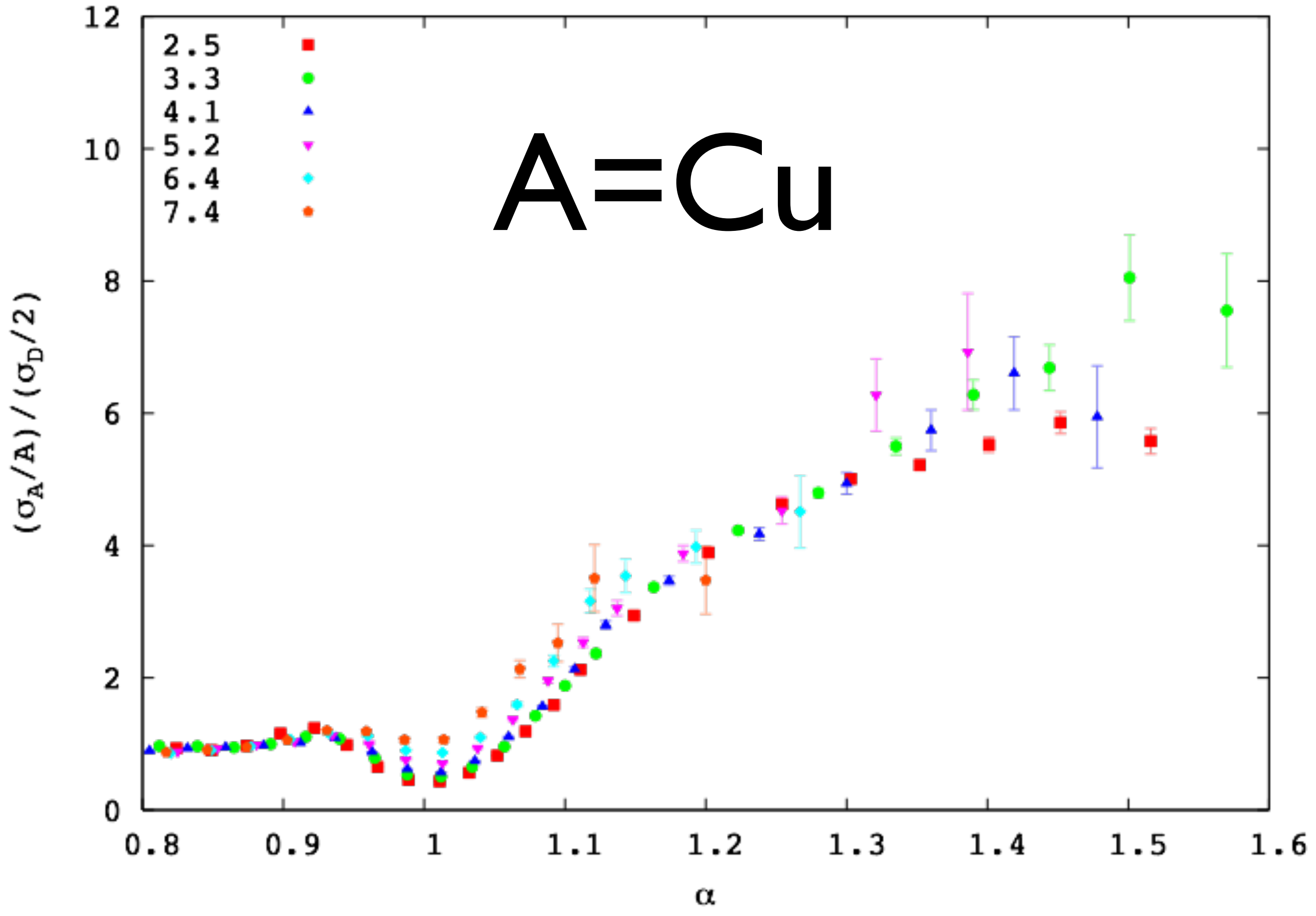
Universality of 2N SRC is confirmed by Jlab experiments



Probability of the high momentum component in nuclei per nucleon, normalized to the deuteron wave function



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



From N.Fomin thesis

E2-019-2011

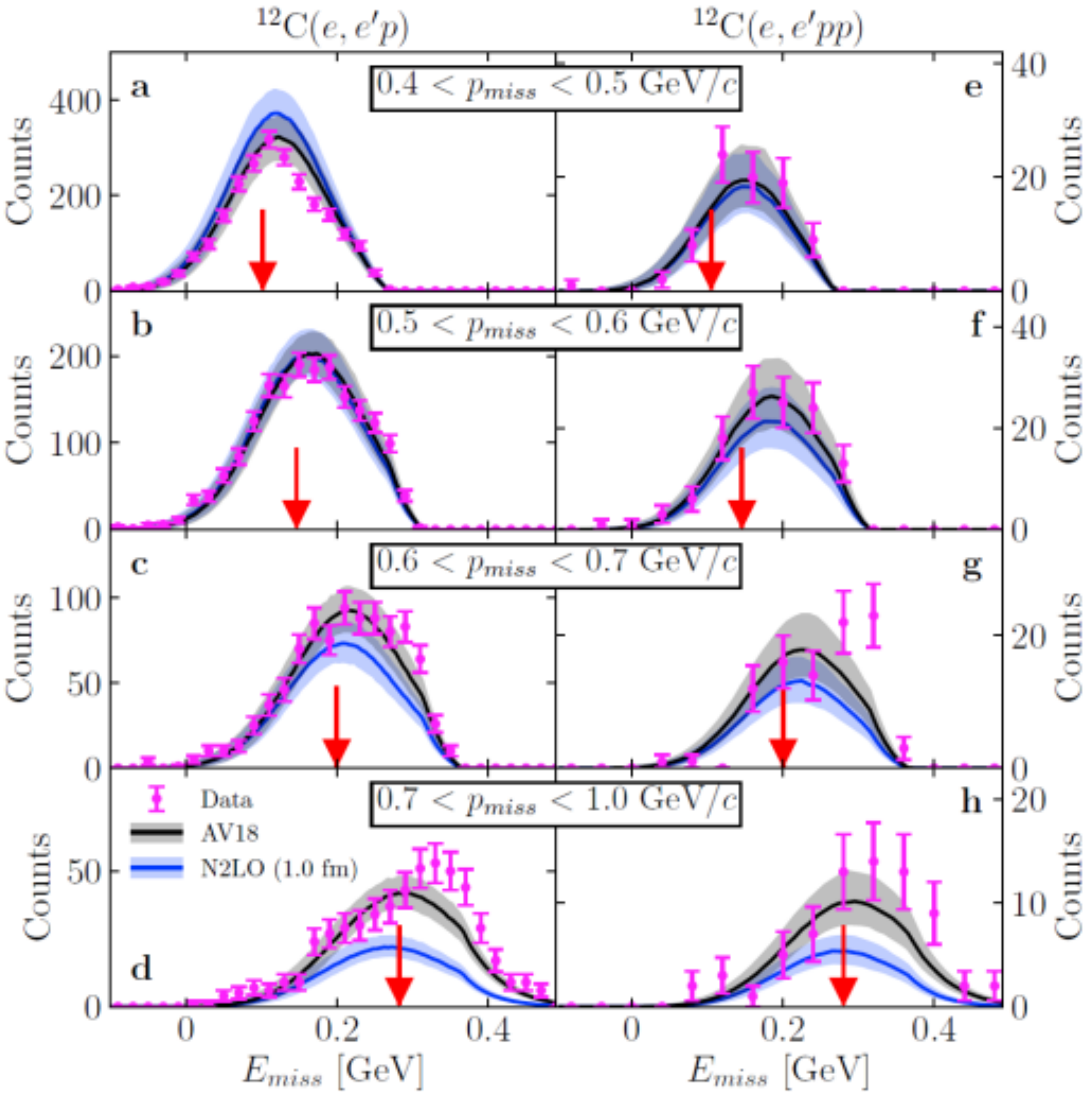
Very good agreement between three (e,e') analyses for $a_2(A)$ as well as recent CLAS data.

So far Jlab experiments marginally reaching 3N correlation region but they are consistent with our prediction of

probability 3N SRC =a_3 , satisfying

$$a_3(A) \propto [a_2(A)]^2$$

Testing spectral function



Nature

Datamining. Group with participation of a few theorists

E_{miss} dependence of the ^{12}C(e,e′p) (left) and ^{12}C(e,e′pp) (right) reactions for different p_{miss} values. The red arrow indicates the expected E_{miss} for a breakup of SRC pair with p_{CM}=0 and a missing-momentum that is equal to the mean value of the data.

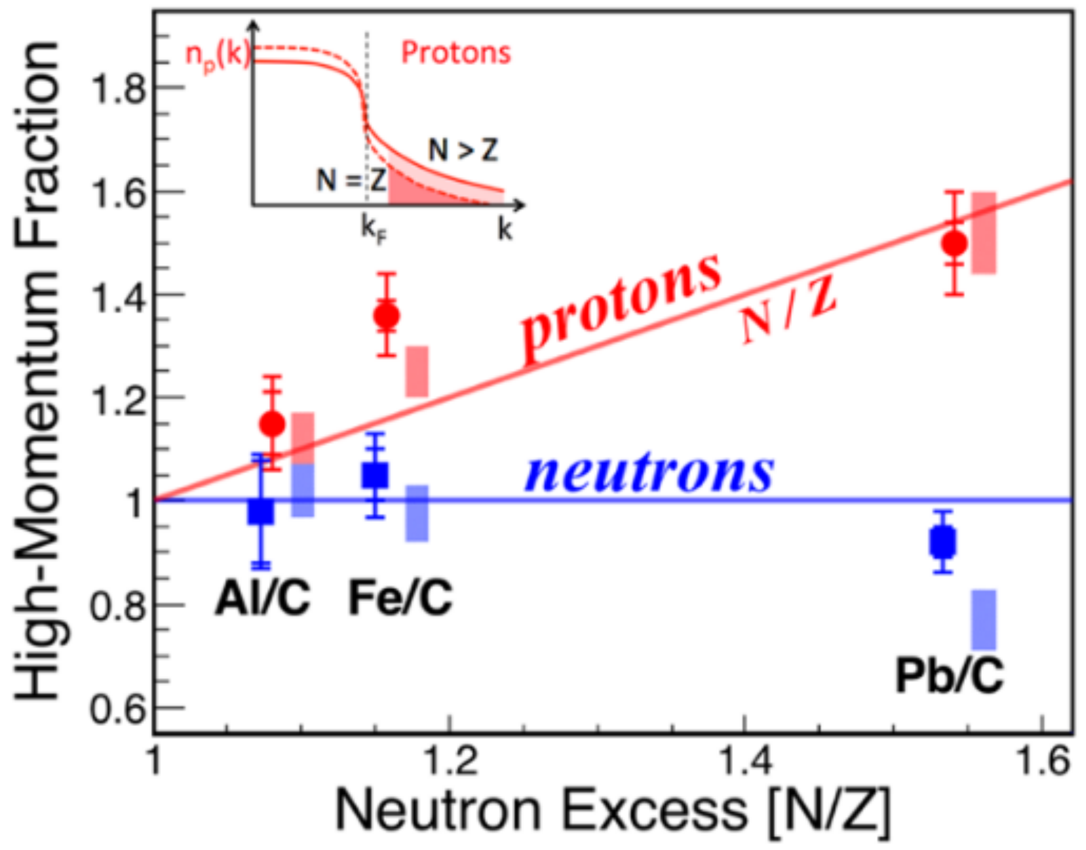
question/concern: removing one nucleon of SRC does not destroy interactions of second nucleon of SRC with mean field - *should suppress emission from pairs with high momenta of the pair. Effects of psi?*

Example: for 12 C absorption for proton knockout is nearly a factor of 2 different for p and s-shells. (Zhalov 90).

Many impressive experimental results in the last few years. Perhaps most impressive

pn dominance is tested in both kinematics when neutron / proton is spectator and proton is knocked out, and in when proton is spectator and neutron is knocked out + restoration of Wigner symmetry at large momenta

if all NN pairs are I=0, # of high momentum protons = # of high momentum neutrons prediction (M.Sargsian)



Extracted fraction of high-momentum ($k>k_F$) protons and neutrons in neutron rich nuclei relative to Carbon. In lead 30% of protons are above Fermi surface, and 20% protons.

In neutron stars for $\rho=2\rho_0$ most of the protons have momenta > $k_F(\rho_0)$

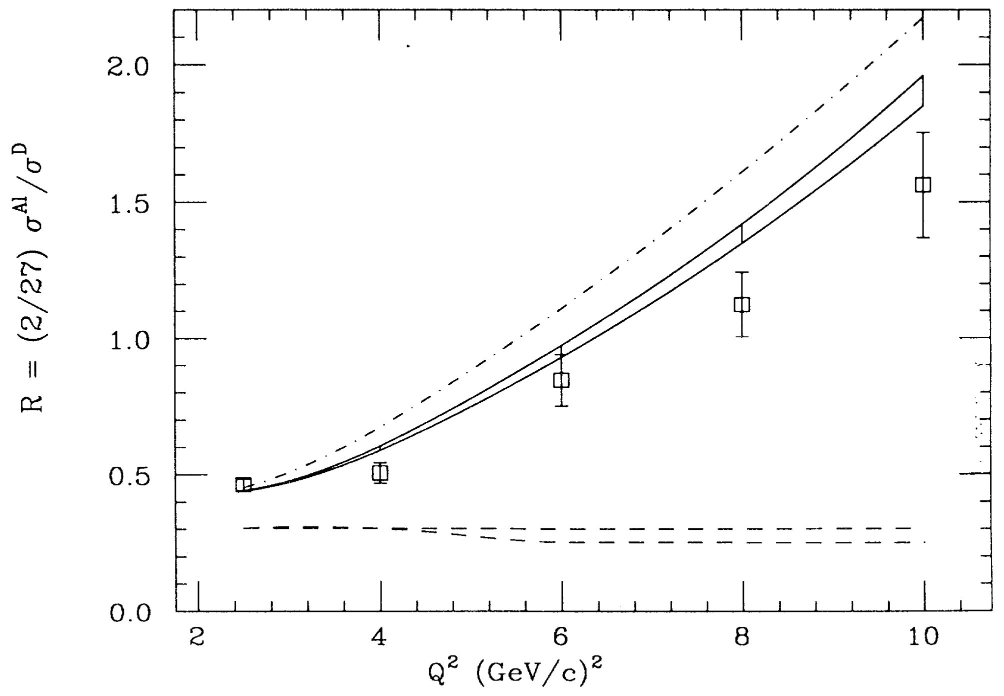
What is established and what should be further studied (cleaning up and discovery):

20% of nucleons belong to SRCs (accuracy ~~20%)

SRC when probed via form factors at Q^2 >1.5 GeV^2 are > 80% nucleonic

- ☞ Measurement of deuteron wave function (in a long run S & D-wave separation)
- ☞ Gross violation of 2N approximation at α >1.6
- ☞ Accuracy of the SRC model - need comparison with wf measured in eD—> epn. Experiment
- ☞ Corrections for fsi & localization of SRC closer to the nucleus center

  Tests of realistic modeling of FSI using nonSRC sample
- ☞ Tests of factorization - independence of the 2N wave function on the hard probe.
- ☞ Extending Q^2 scale at x<2 - best large Q data are still from our analysis of SLAC data; x=1 large Q



Day, Frankfurt, Sargsian MS 1993

Observing 3N SRC in lepton - nucleus scattering.

- ☞ Observing nucleons with α >1.6 (backward with moment >> 600 MeV/c
- ☞ (e,e') at x> 2 and Q^2>3 GeV^2 (current Q^2 are too low)
- ☞ (e,e') at x~0.2 with production of two backward protons

EMC effect and related phenomena

Let us imagine that one would know all features of SRC we know now and would be asked - how large nuclear effects are expected for DIS for deviation of

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

Exotics - one when nucleons are close: SRC P=20% + (P'> 80%) SRC in 2N configuration.

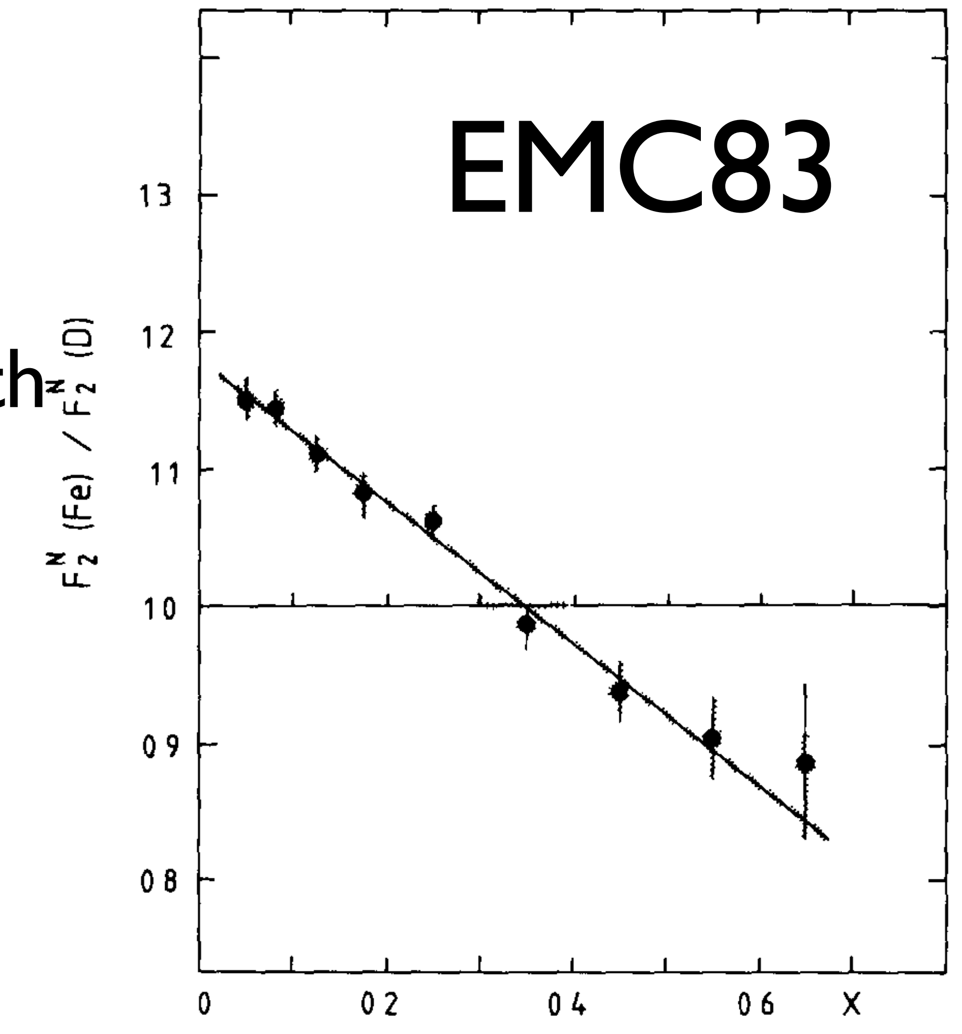
➡ $P \times (1- P') \sim 4$ % effect — and Fermi motion effect is < 2% for x <0.6 (discussion below)

Major discovery (by chance) - the European Muon Collaboration effect - substantial difference of quark Bjorken x distributions at x > 0.25 in A>2 and A=2 nuclei: a large (15%) deviation of the EMC ratio from 1

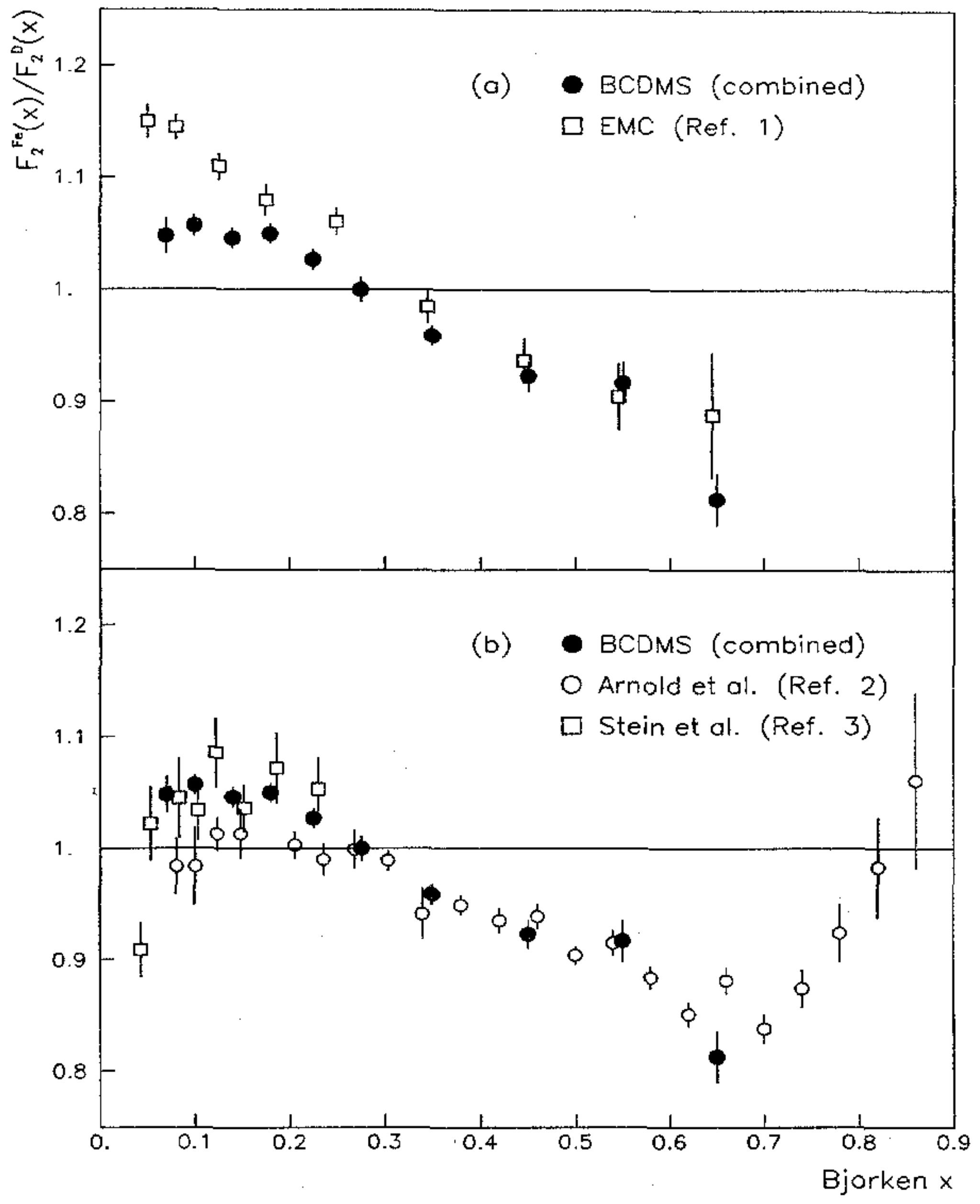
$R_A(x,Q^2) = 2F_{2A}(x,Q^2)/AF_{2D}(x,Q^2)$ from one

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

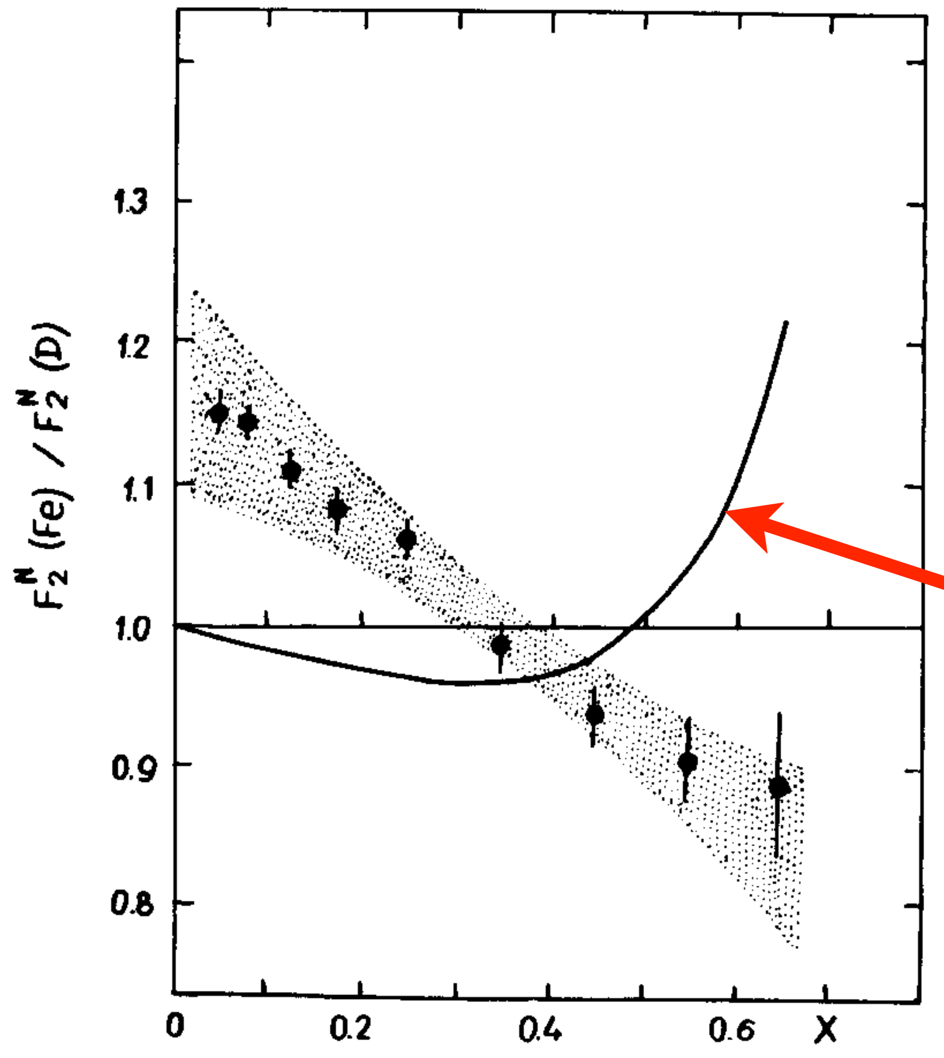
straight line fit - suggested universal mechanism. Fermi motion very small effect with R(x>0.5) >1



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



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



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

Can account of Fermi motion describe the EMC effect?

YES

If one violates exact QCD sum rules of 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 $x = AQ^2/2m_A q_0$

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

Fermi motion

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

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

small negative for x <0.5

> 0 and rapidly growing for x >0.5

Jlab - due to HT effects n~ 2. Crossover x=0.66

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

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

Why one has to use light-cone densities: DIS develops along the LC sampling the LC slice of the wave function

Weinberg has been first (1966) to elucidate the advantages of the infinite momentum frame/ light cone wave functions for the description of bound states. He writes: "The Feynman rules provide a perturbation theory in which the Lorentz invariance of the S matrix is kept visible at every step. However this is accomplished only at the cost of manifest unitarity, by lumping together intermediate states with different numbers of particles and antiparticles. Thus when we try to sum Feynman diagrams to obtain integral equations like the Bethe—Salpeter equation it proves very difficult to justify the omission of any particular diagrams since there is no one-to-one relation between internal lines and intermediate states."

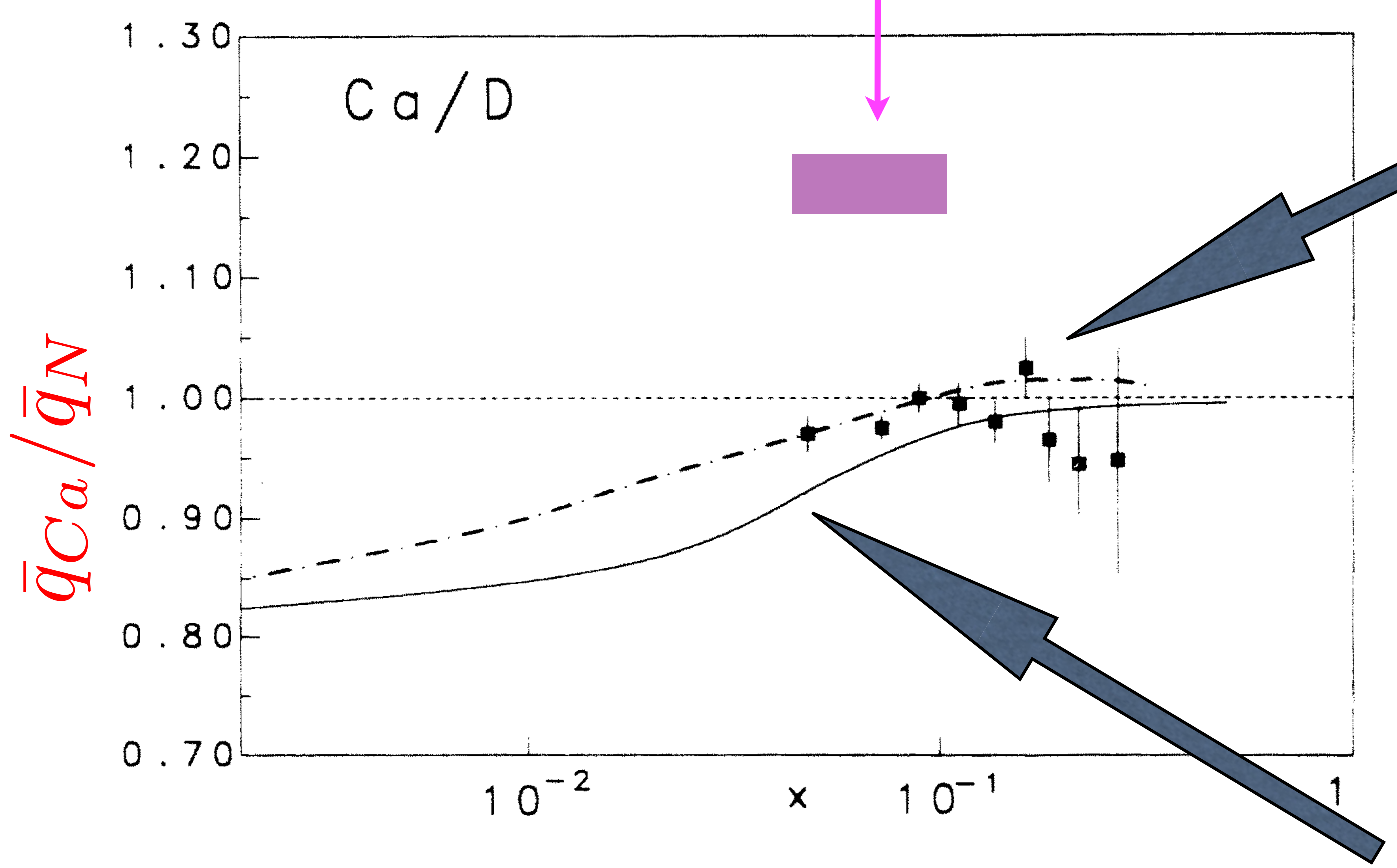
As a result it is very difficult to implement conservation laws using fixed number of degrees of freedom starting from a vertex function, or fixed time (nonrelativistic) description of nuclei

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

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

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

$Q^2 = 15\ \mathrm{GeV}^2$



$Q^2 = 2\ \mathrm{GeV}^2$

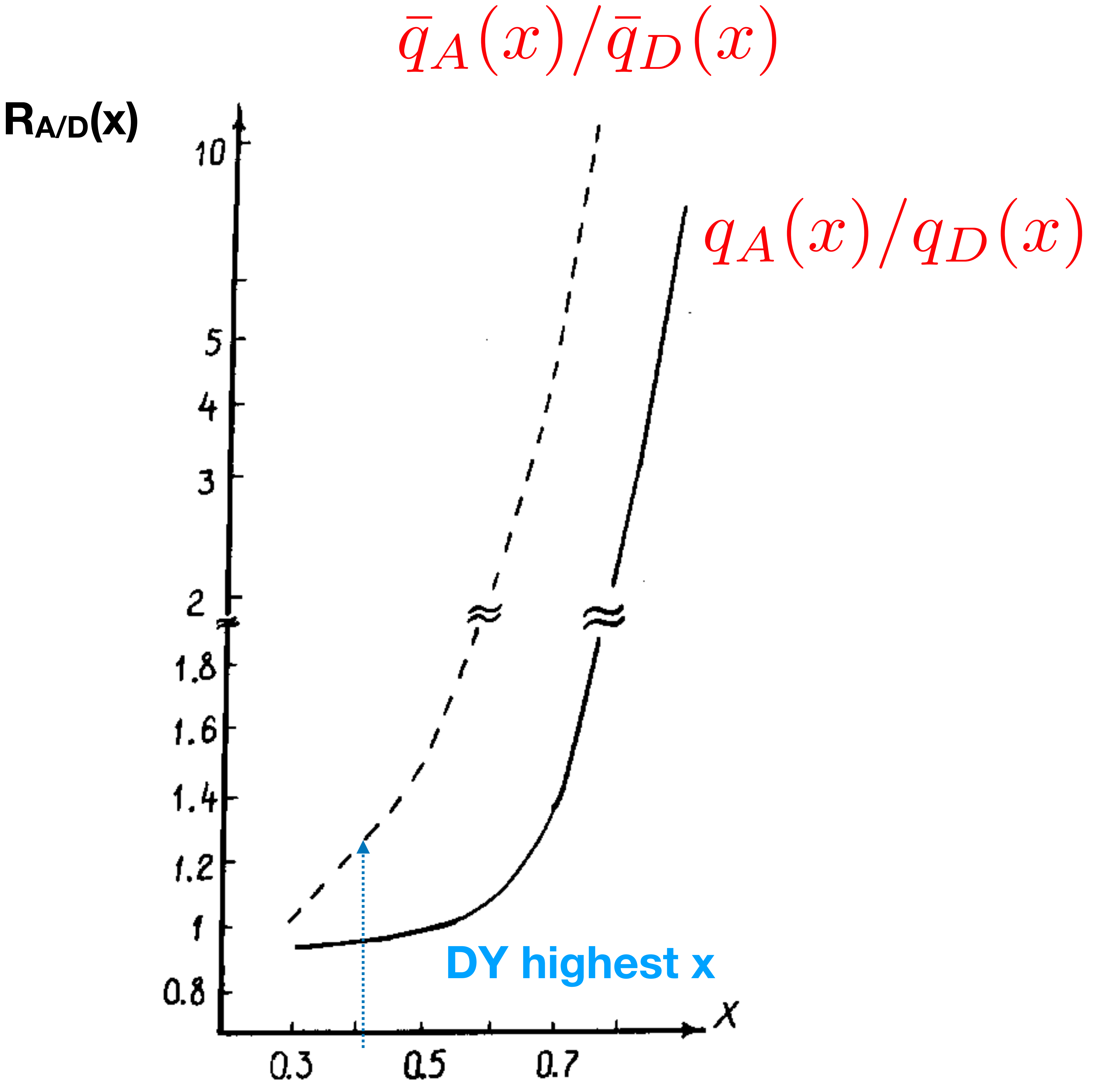
A-dependence of antiquark distribution, data are from FNAL nuclear Drell-Yan experiment, curves - pQCD analysis of Frankfurt, Liuti, MS 90. Similar conclusions Eskola et al 93-07 analyses

Fermi motion expectations - no nonnucleonic degrees of freedom

crossover (R=1) point

$$R_{cr} = 2/(n+1)$$

$$x\bar{q}(x) \propto (1-x)^n, n = 7.$$

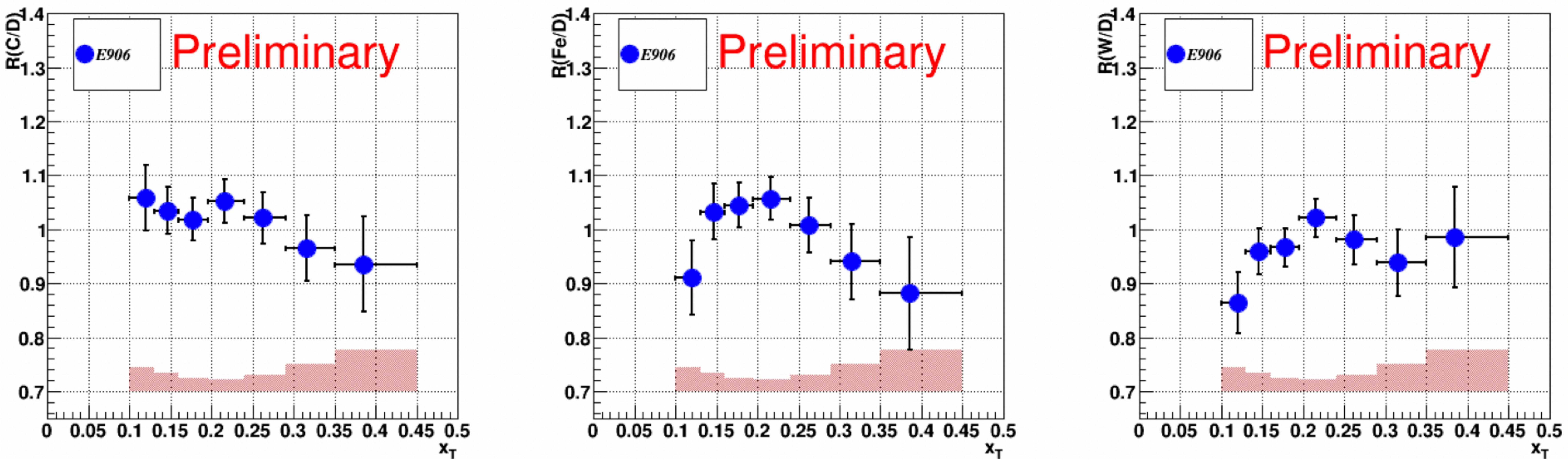


from MS & Leonid Frankfurt, Nucl.Phys. B,1980

For antiquarks no evidence for enhancement for x> 0.25 expected due to Fermi motion

SEAQUEST RESULTS

Present by Arun Tadepalli

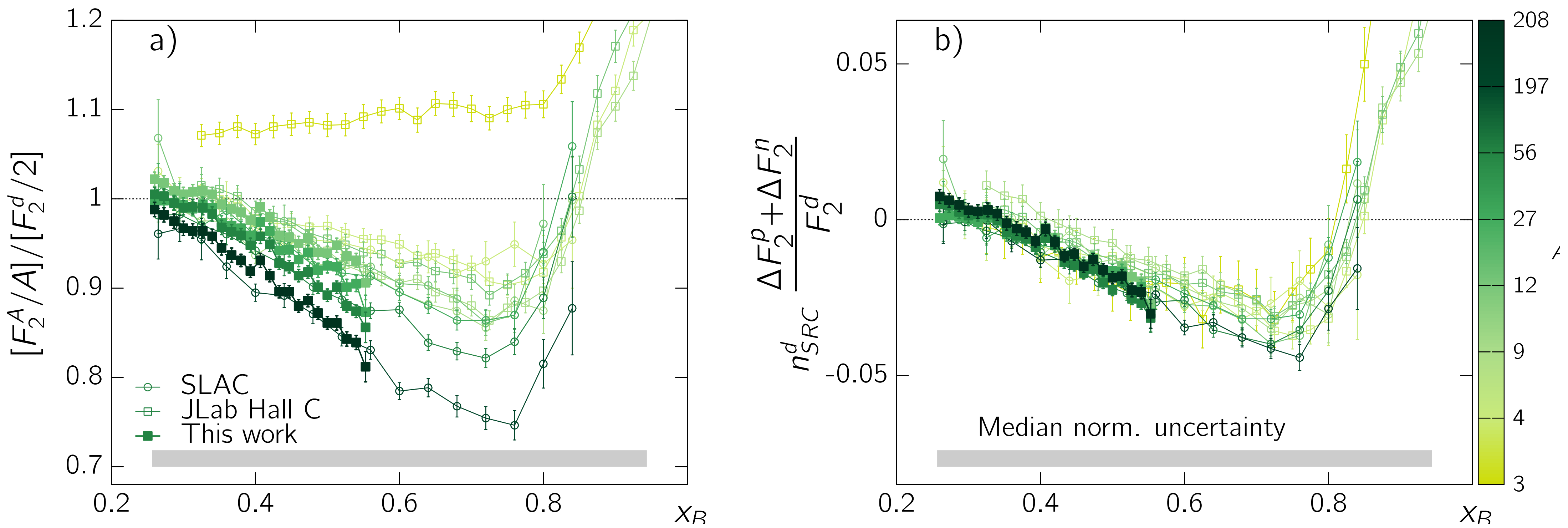


EMC effect like pattern?

Need more theoretical studies and reduced experimental errors to rule out large contribution of the energy losses

Natural expectation: non-nucleonic configurations originate from two nucleons coming close together - the same configurations which generate SRCs. Supported by similar A-dependence of pn SRCs and the EMC effect. Extra neutrons (N-Z) do not contribute to the EMC effect (Data mining analyses)

(Theoretical expectation FS85 (except pn dominance & apresence of contribution of mean field) , observation O.Hen et al 2014 - 2018)



Models have to address the paradox: evidence that EMC effect is predominantly due to SRCs while SRC are at least 90% nucleonic, while the EMC effect for x=0.5 is ≥15%

It appears that essentially one generic scenario survives 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 .

An extreme assumption that EMC effect is present solely for SRC would require huge EMC effect at x=0.5 for EMC (SRC):

EMC inclusive / Prob. SRC ~ 0.15/0.2 ~ 3/4 for all SRC configurations

Current Rules of the game for building models of the EMC effect

- ***Remember baryon conservation law***
- ***Honor momentum conservation law***
- ***Don't introduce a noticeable number dynamic pions into nuclei***
- ***Don't introduce large deformations of low momentum nucleons***

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 $|r_N^{\rm bound}/r_N^{\rm free} - 1| \lesssim 0.04$

two extra rules of the game based on SRC studies

- ***Don't introduce large exotic component in nuclei - 20 % 6q, Δ's***
- ***Honor existence of large predominantly nucleonic short-range correlations***

Problem for the nucleon swelling models of the EMC effect with 20% swelling

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 generic scenario (FS85) survives - strong deformation of rare configurations in bound nucleons increasing with nucleon momentum and with dominant contribution due to the SRCs .

Example: in the color screening model presented below modification of average properties is < 2- 3 %.

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

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 small size configuation 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:

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

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 ∝ virtuality

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

Four vectors

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

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

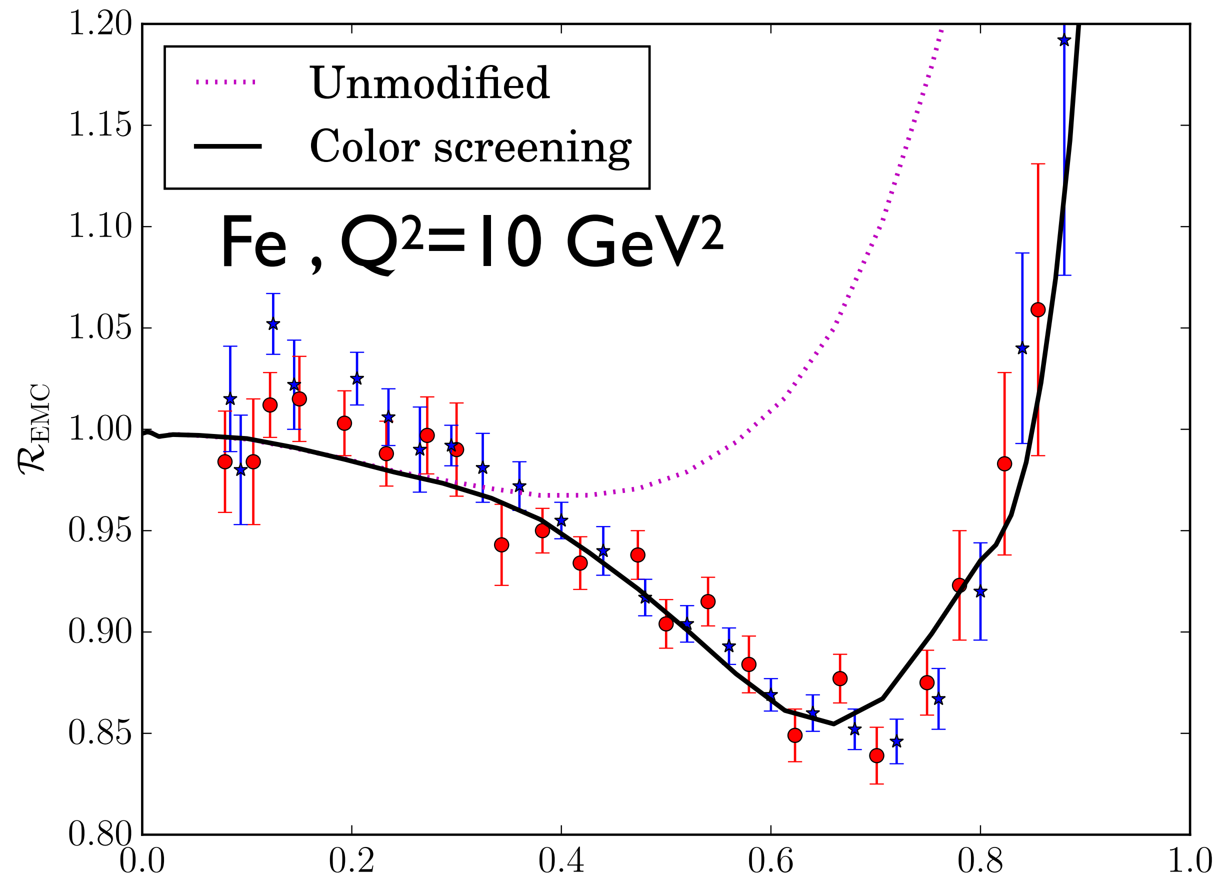
seems to be very general for the modification of the nucleon properties. Indeed, consider analytic continuation of the scattering amplitude to $p^2_{int}-m^2=0$. In this point modification should vanish. Still modification for S- and D- wave maybe different

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%,

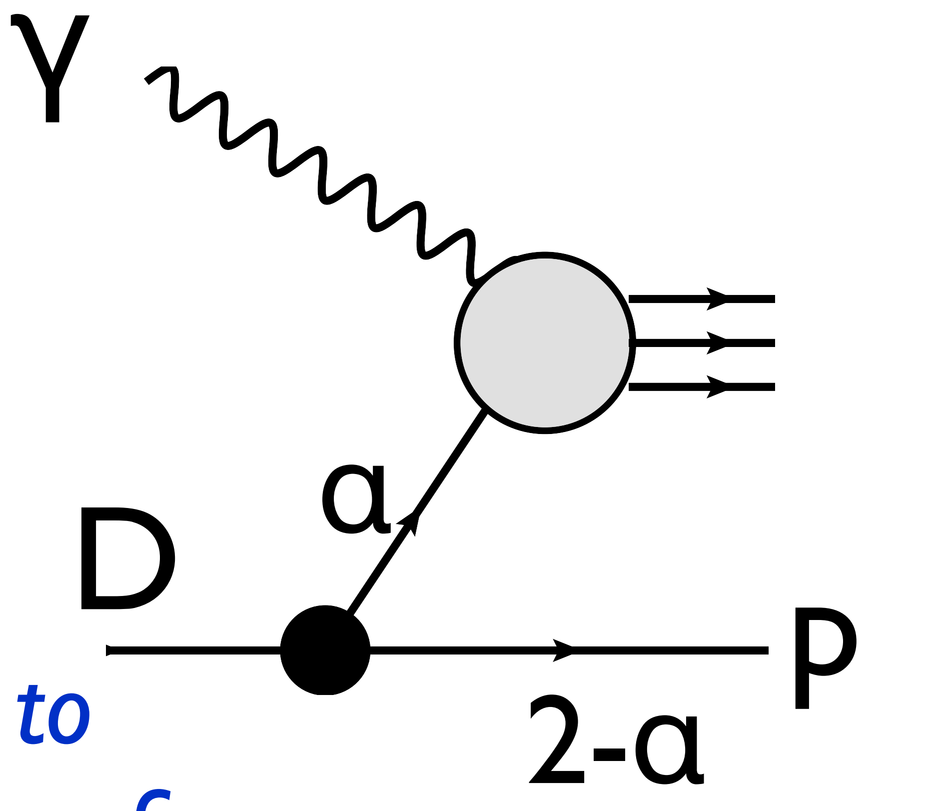
A-dependence of <V> is similar to that of the EMC effect (I.Sick)

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



Freese, Sargsian, MS 14

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.

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.

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

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

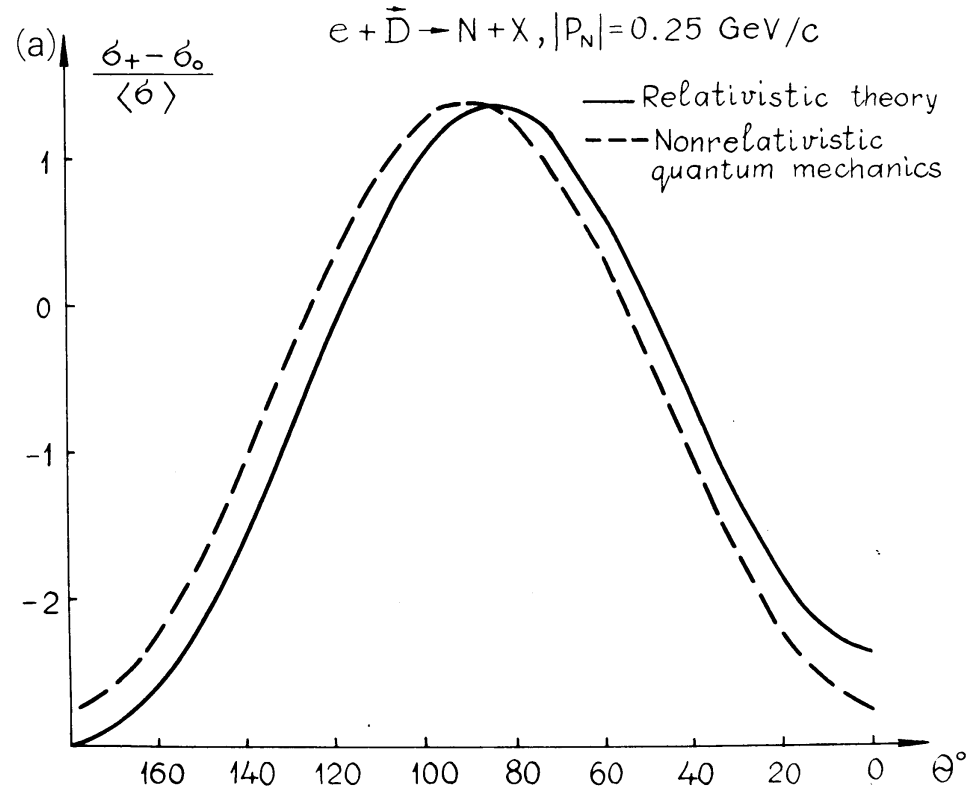
Supplementary slides

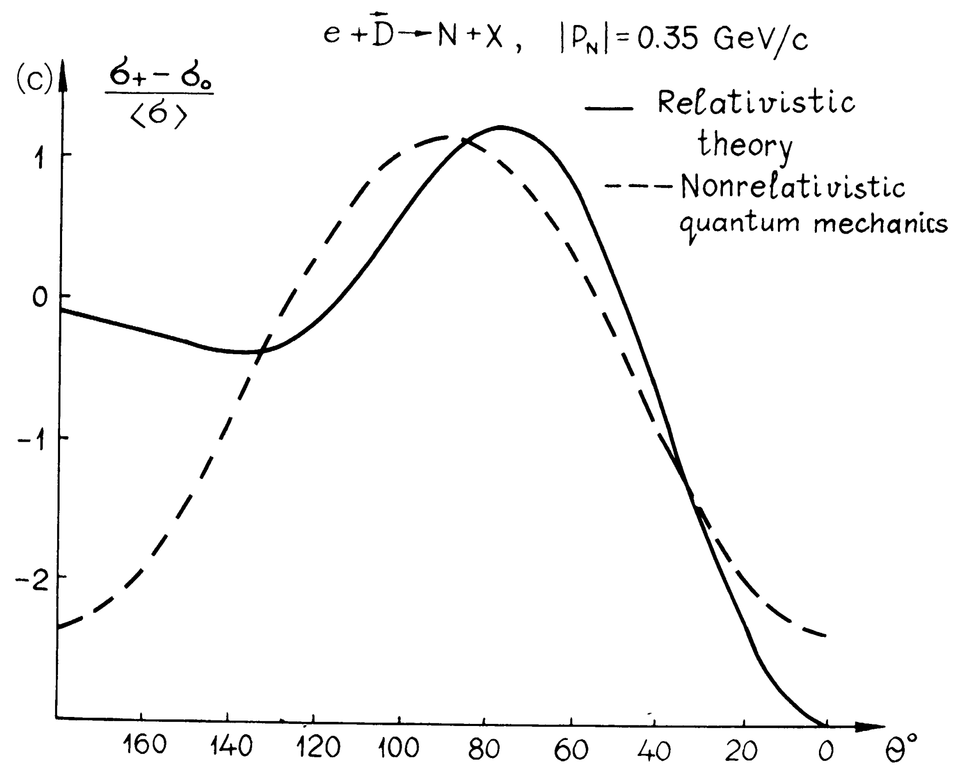
further open questions:

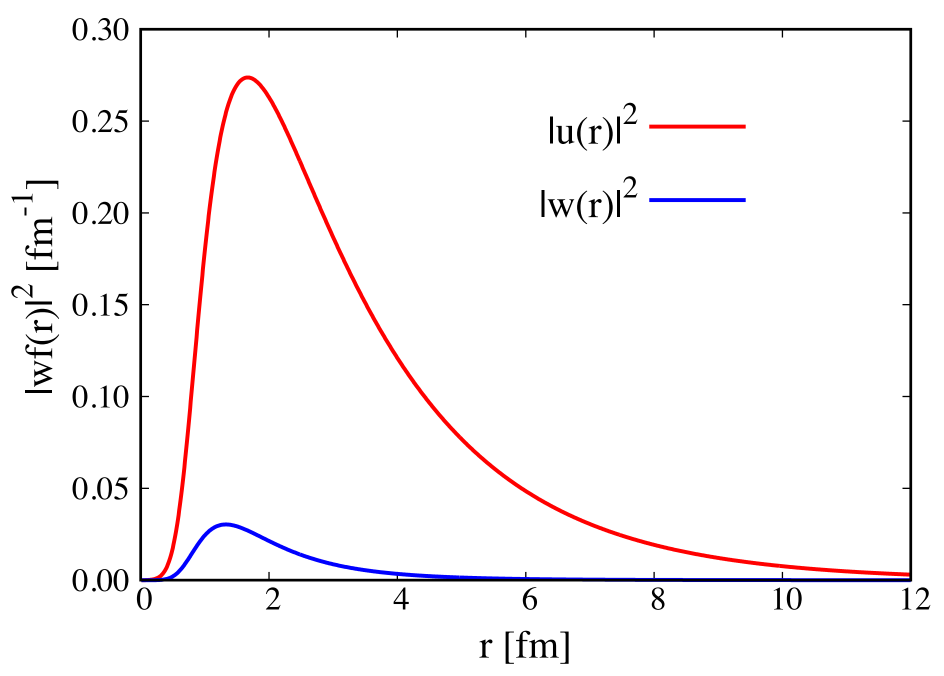
- ✷ with what is accuracy WF of pn pair $\propto$ $\psi^2{}_D(\kappa)$?; **FSIs** Boeglin talk

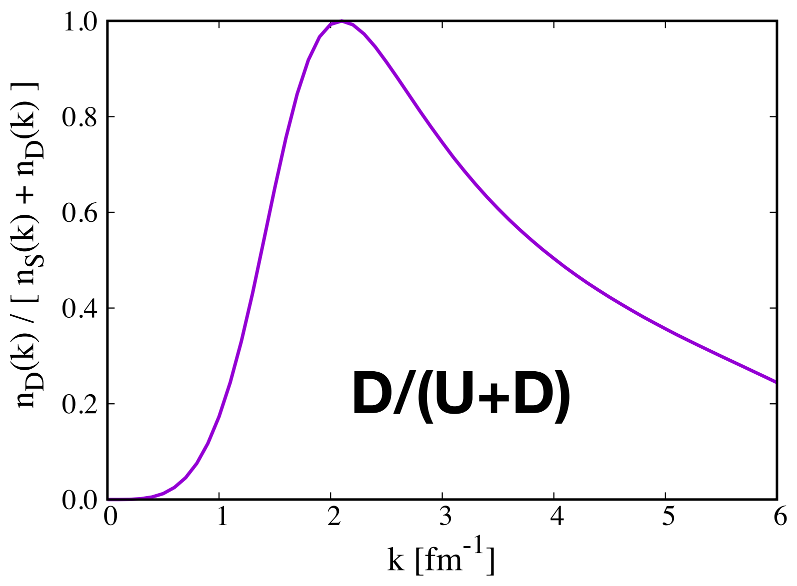
- ✷ Need observables sensitive to LC dynamics

study scattering off polarized deuteron (S/D ratio) or studying variation of scalar/tensor ratio for different angles and same momentum









small component in coordinate space generates dominant contribution in momentum space

- ✷ off shell eN cross section

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

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—What shall I do, my chickens are sick!
—Draw a red circle on the wall of the poultry house.
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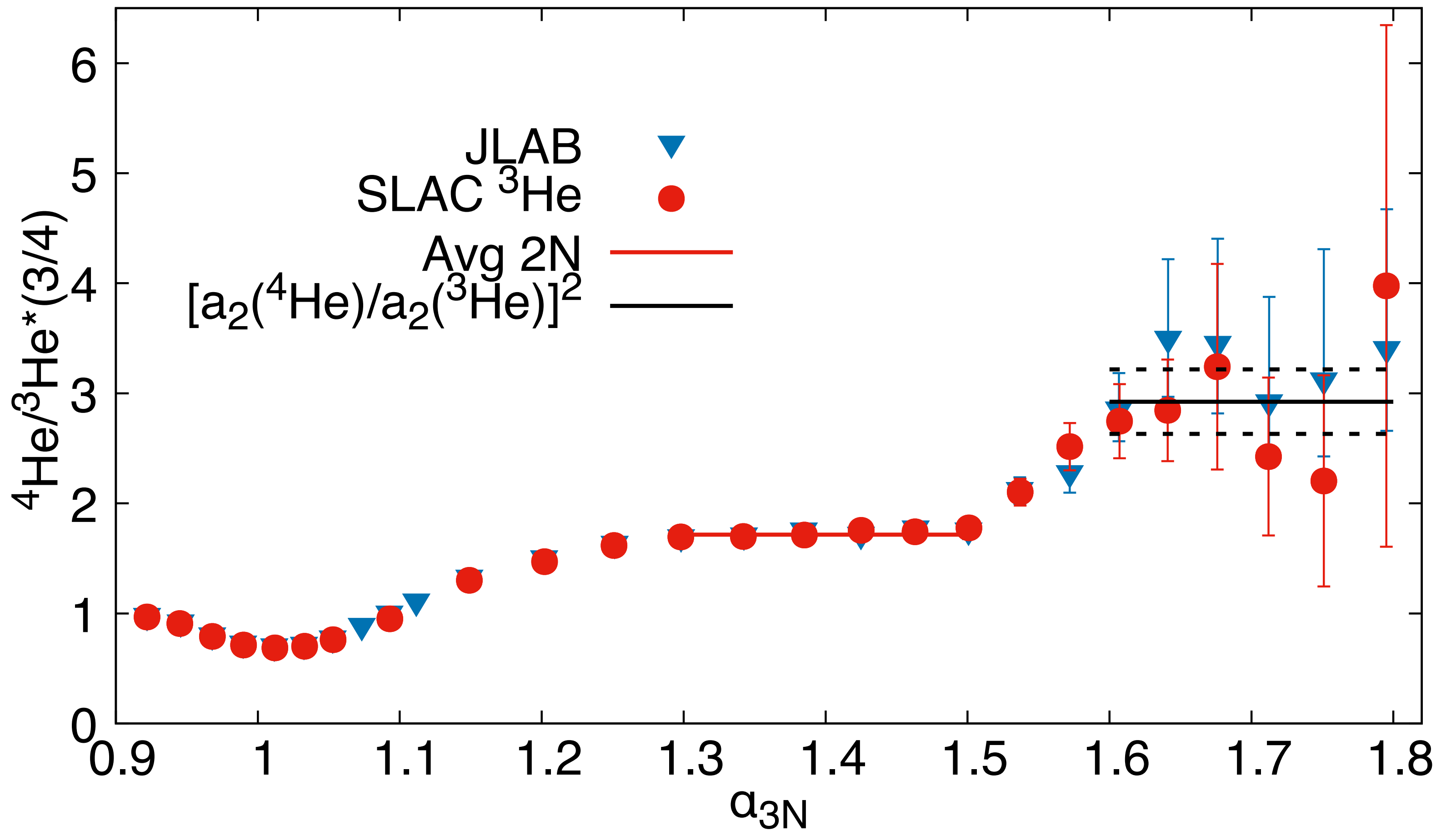
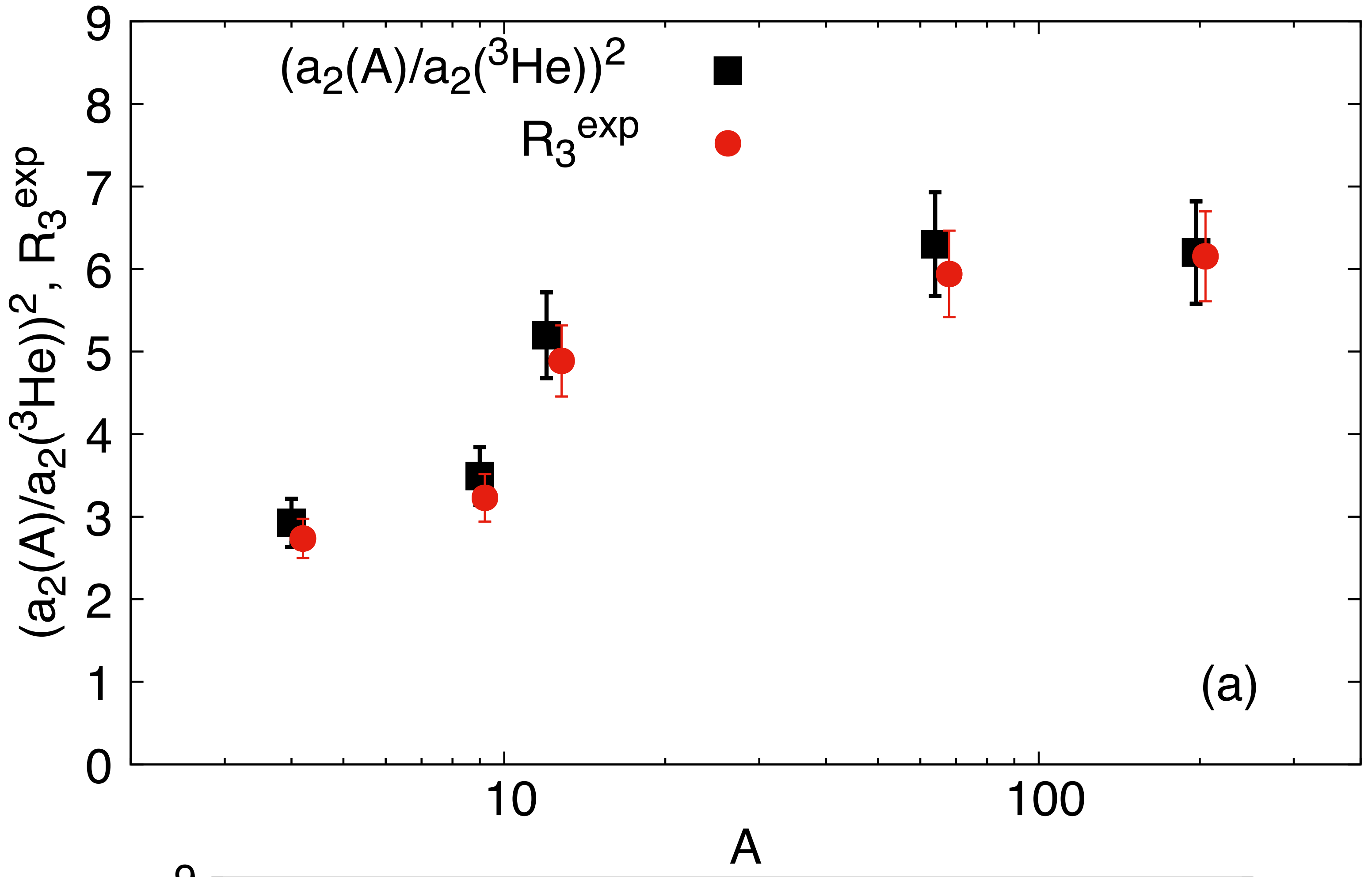
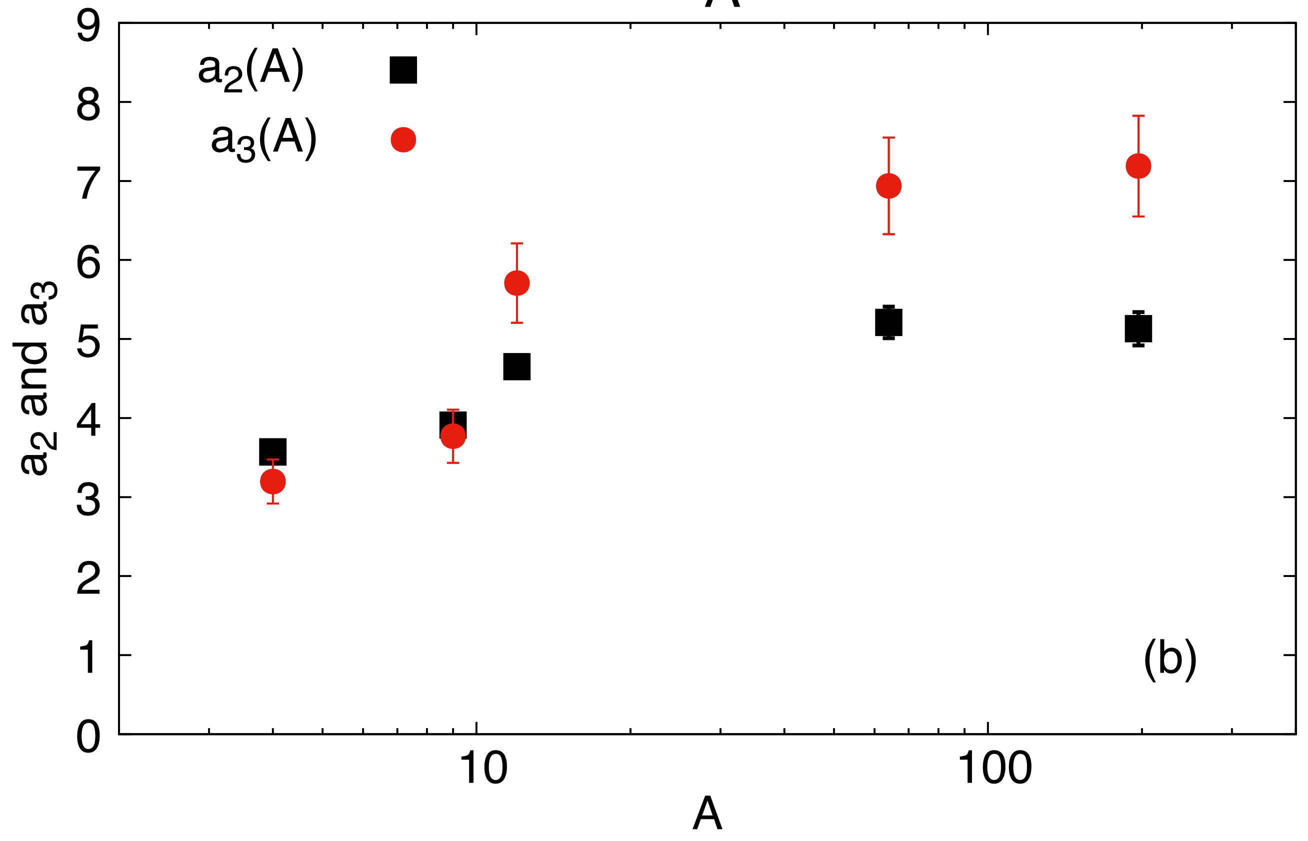
recent analysis of (e,e') x> 2 (Day, Sargsian, LF , MS)

need larger Q^2







Onset of 3N dominance at α~ 1.6

Further studies are necessary of LC scaling of the ratios, etc. Recoil structure more complicated than in 2N case

Three nucleon SRCs = three nearby nucleons with large relative momenta

Since NN interaction is sufficiently singular for large momenta

$\rho_A^N(\alpha, p_t)$ can be expanded over contributions of j-nucleon correlations $\rho_j(\alpha, p_t)$

$$\rho_A^N(\alpha > 1.3, p_t) = \sum_{j=2}^{A} a_j(A)\rho_j(\alpha, p_t)$$

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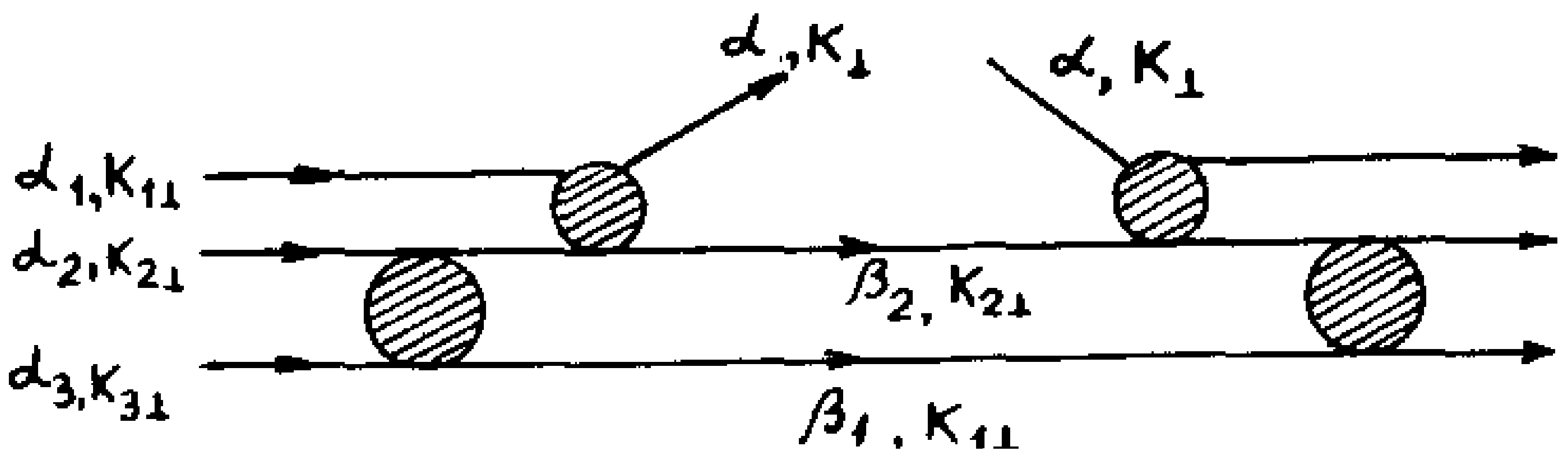
iterations of NN interactions (Plus 3N from 3N forces possible)

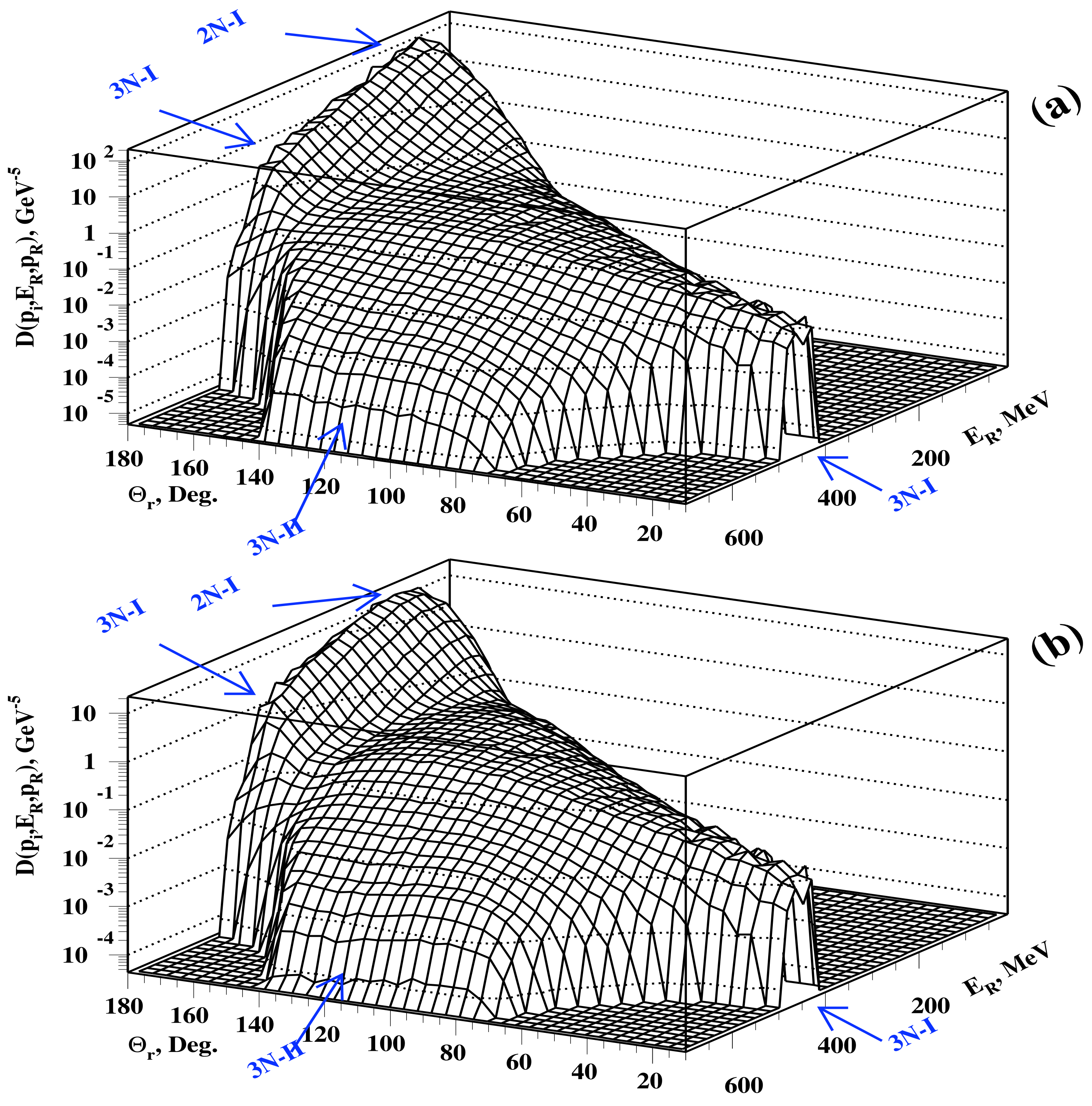


$$\rho_j(\alpha, p_t)(j-\alpha)^{n(j-1)+j-2}, \; where \, \rho_j(\alpha, 0) \propto (2-\alpha)^n$$

α up to 2 (3) are allowed for 2N (3N) SRC (plus small mean field corrections)

NR case large k = 2N SRC, qualitative difference relativistic and nonrelativistic dynamics

Evidence from NR calculations? *3N SRC can be seen in the structure of decay of ^3He* (Sarsgian et al).



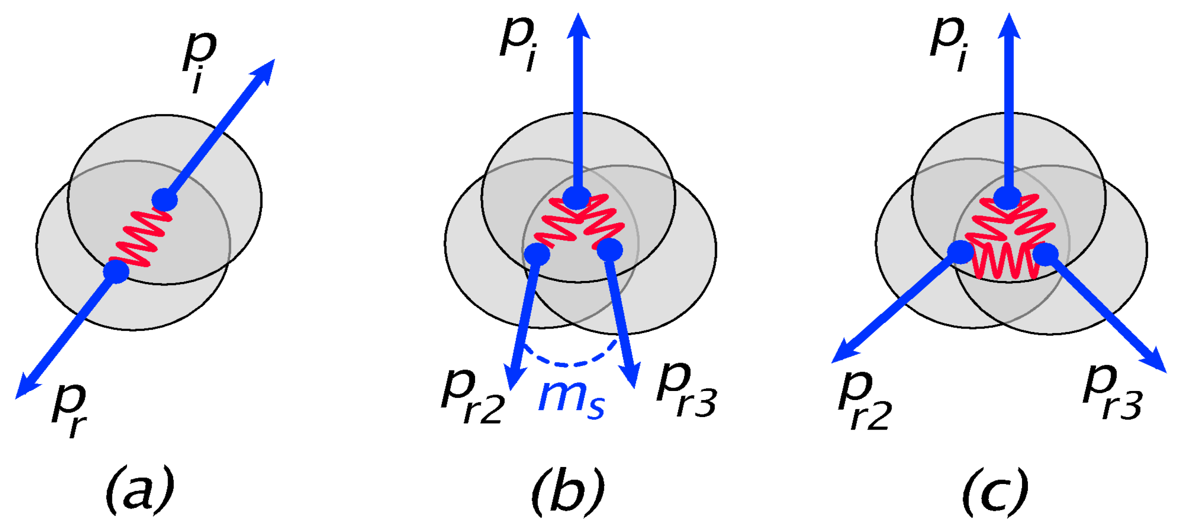
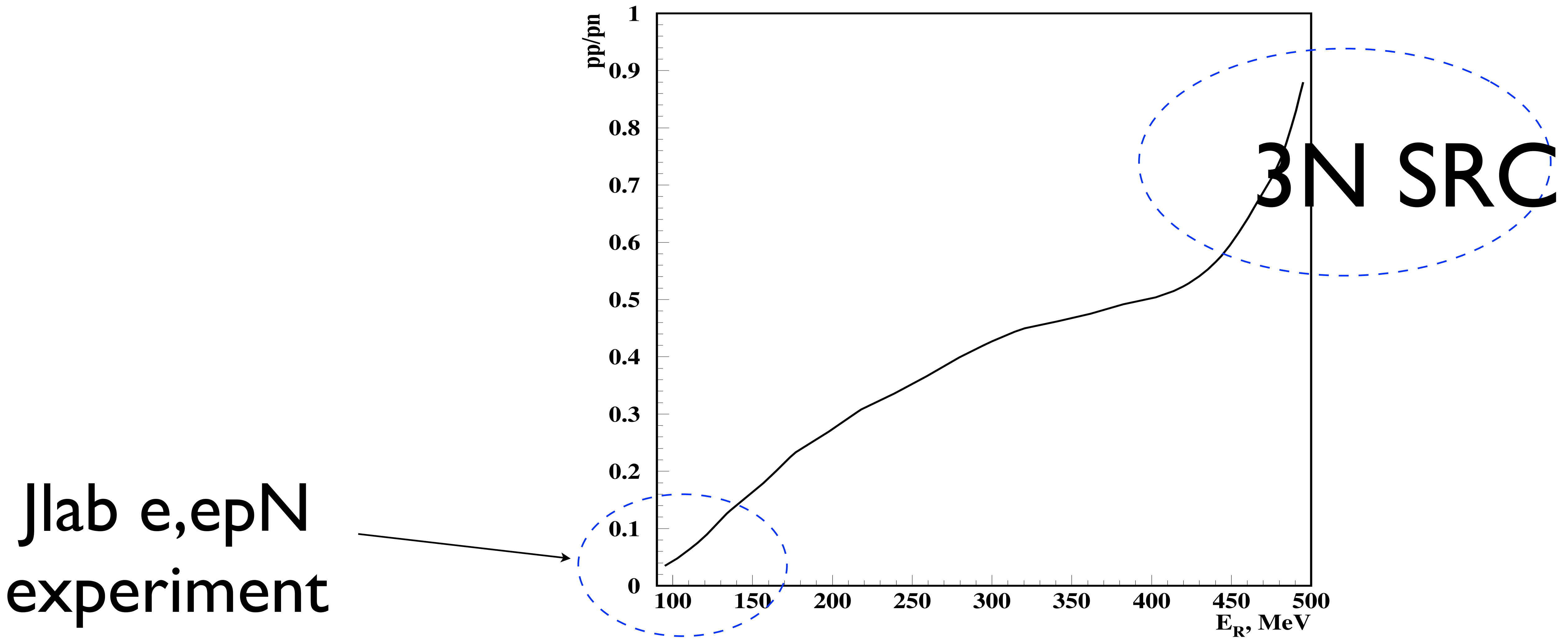


Figure 8: Dependence of the decay function on the residual nuclei energy and relative angle of struck proton and recoil nucleon. Figure (a) neutron is recoiling against proton, (b) proton is recoiling against proton. Inital momentum of the struck nucleon as well as recoil nucleom momenta is restricted to $p_{in}, p_r \geq 400$ MeV/c.

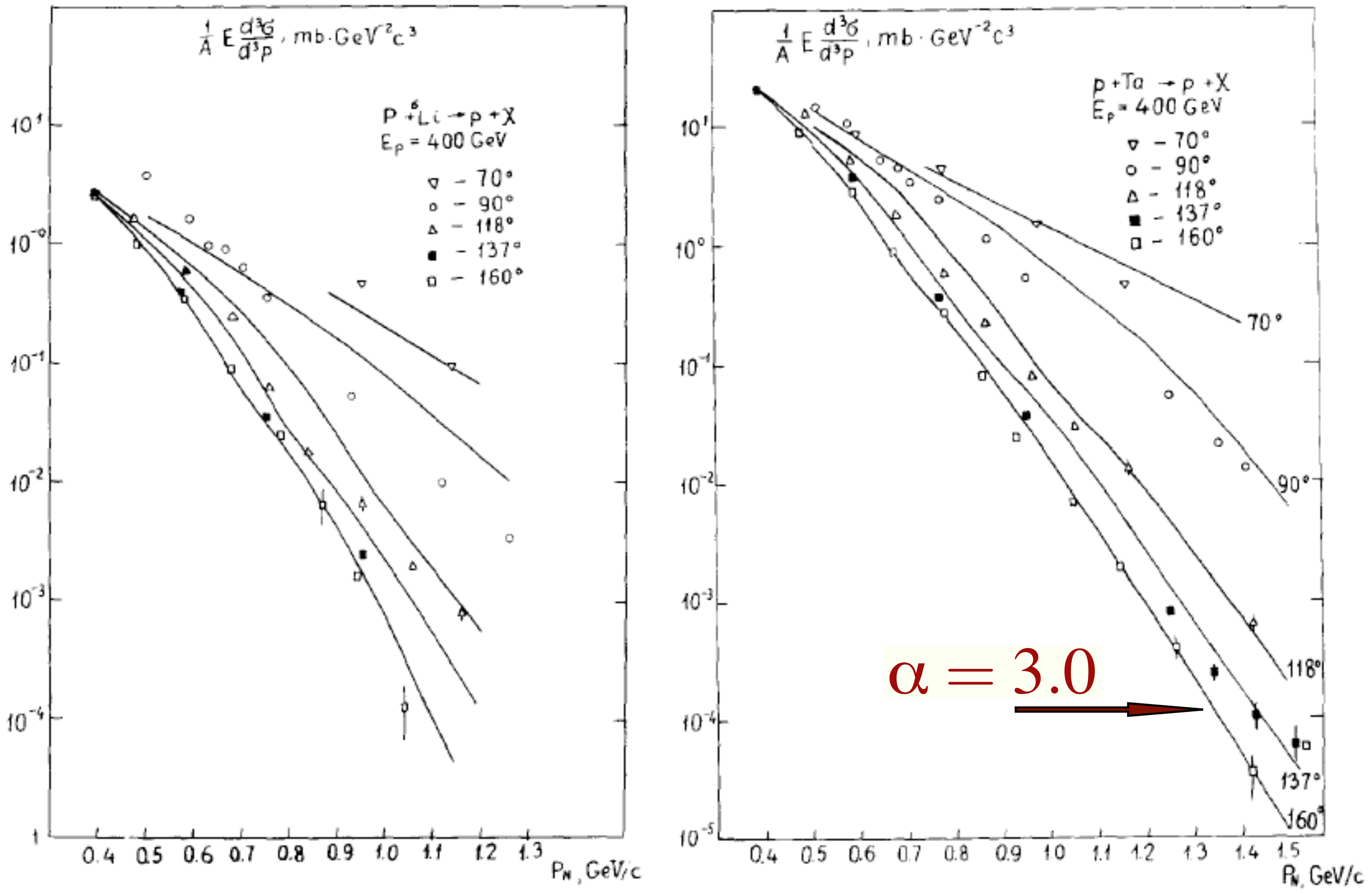


Recoil energy dependence of the ratio of decay function calculated for the case of struck and recoil nucleons - p_s & p_r for struck proton and recoil proton and neutron for p_s & p_r > 400MeV/c & $180^\circ > \theta(p_s\ \ p_r) > 170^\circ$

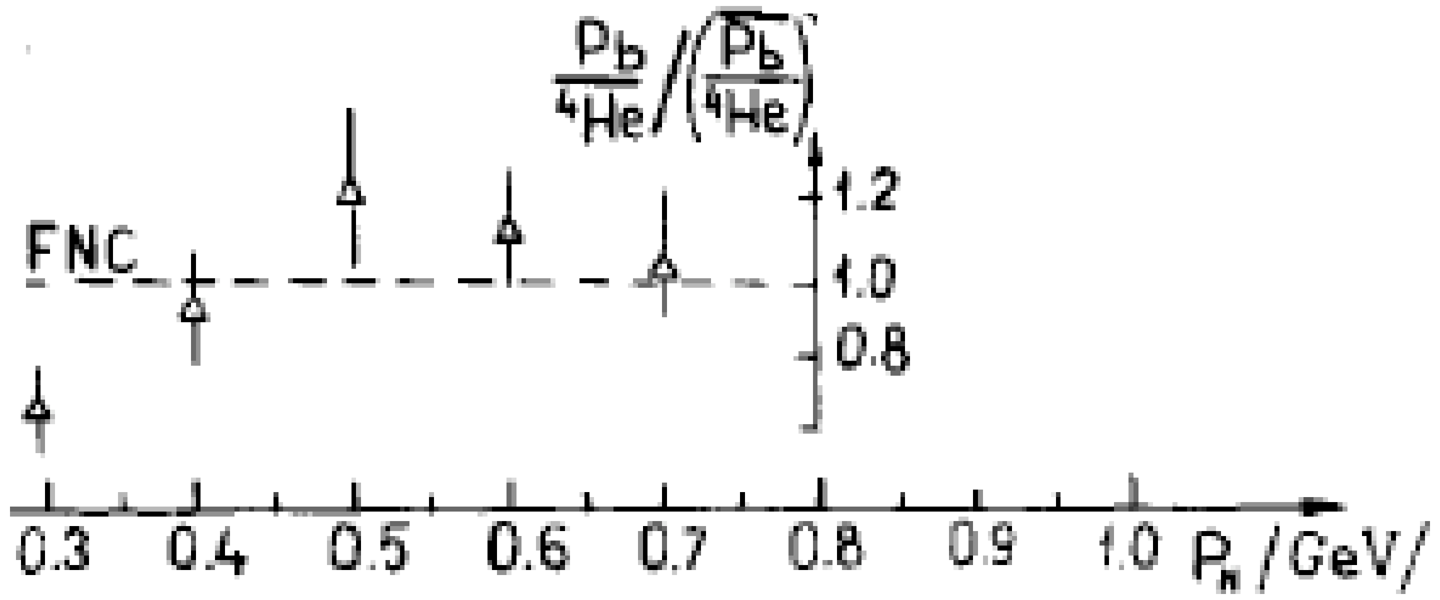
Some of experimental evidence in historic order

Plenty of data were described using few nucleon SRC approximation with 3N, 4N correlations dominating in certain kinematic ranges. Strength of 2N correlations is similar to the one found in (e,e'), (p,2p)

$p^6Li \to$ backward $p+X$ $pTa \to$ backward $p+X$



Comparison of few nucleon SRC approximation with pA data at E_p^{inc}=400 GeV

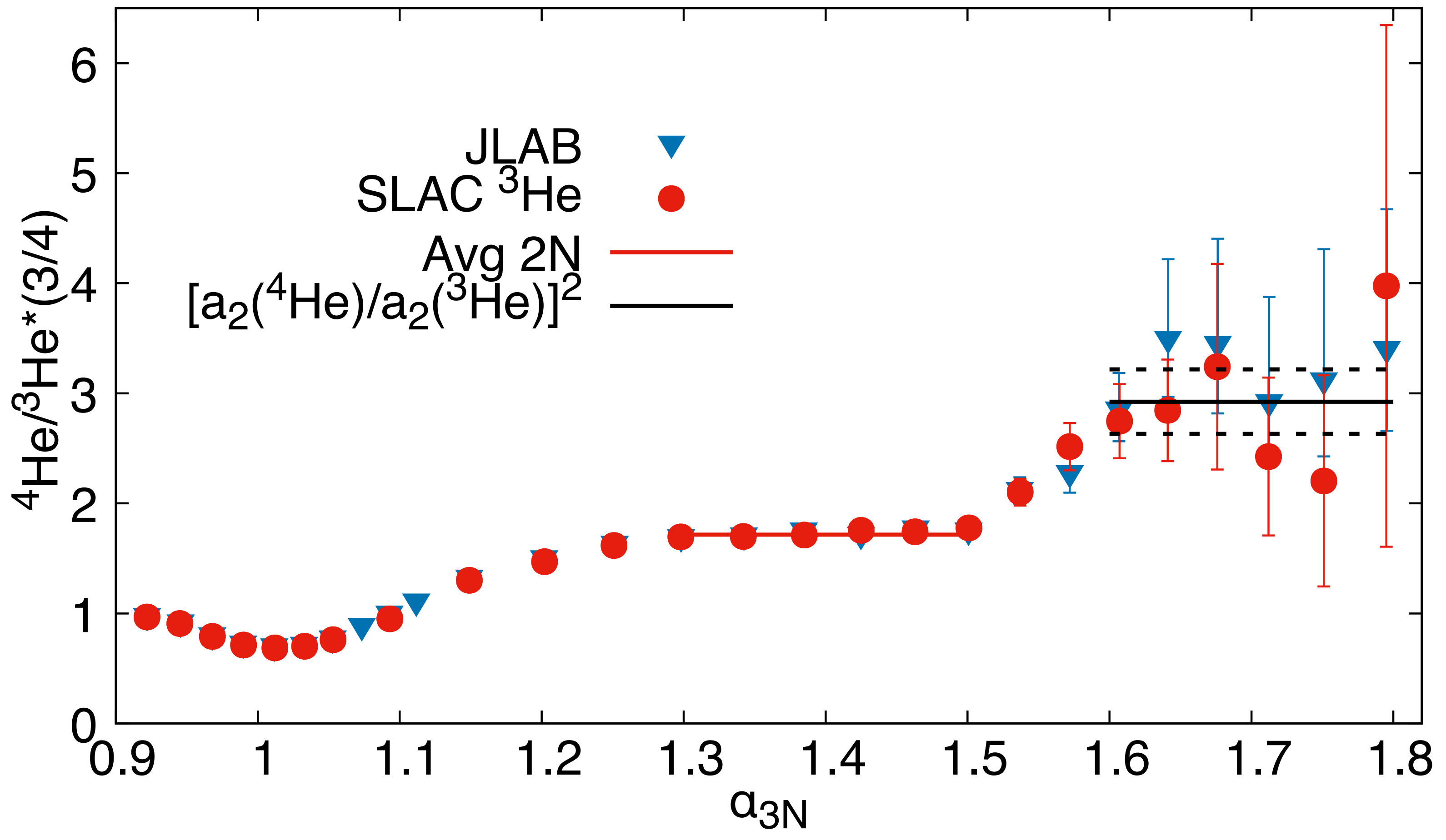


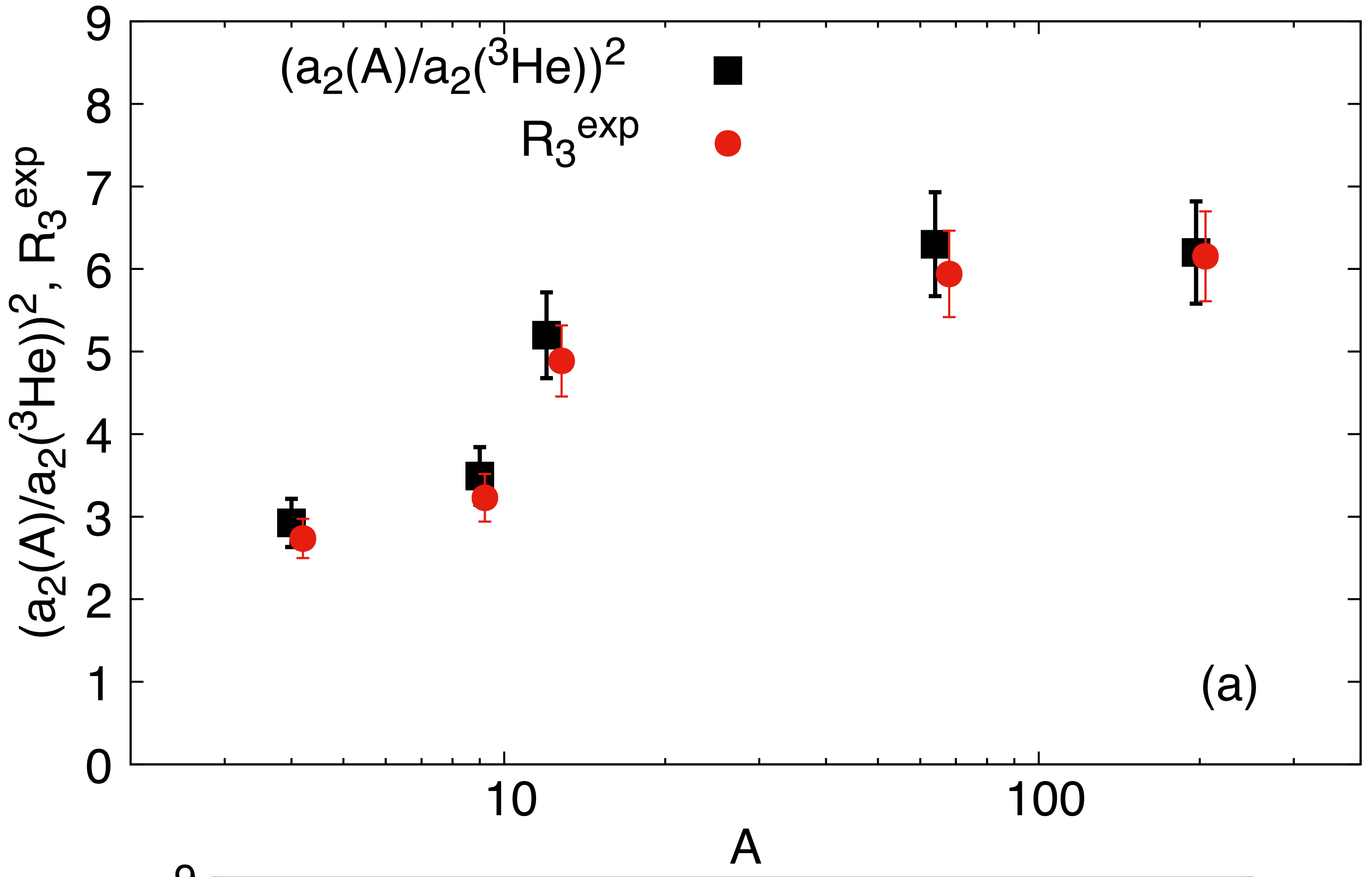
Test of universality for $pA \to p+X$ spectra for backward emission at Ep= 9 GeV

Observations of (p,2pn) &(e,e') at x>1 confirm the origin of SRC as the dominant source of the fast backward nucleons

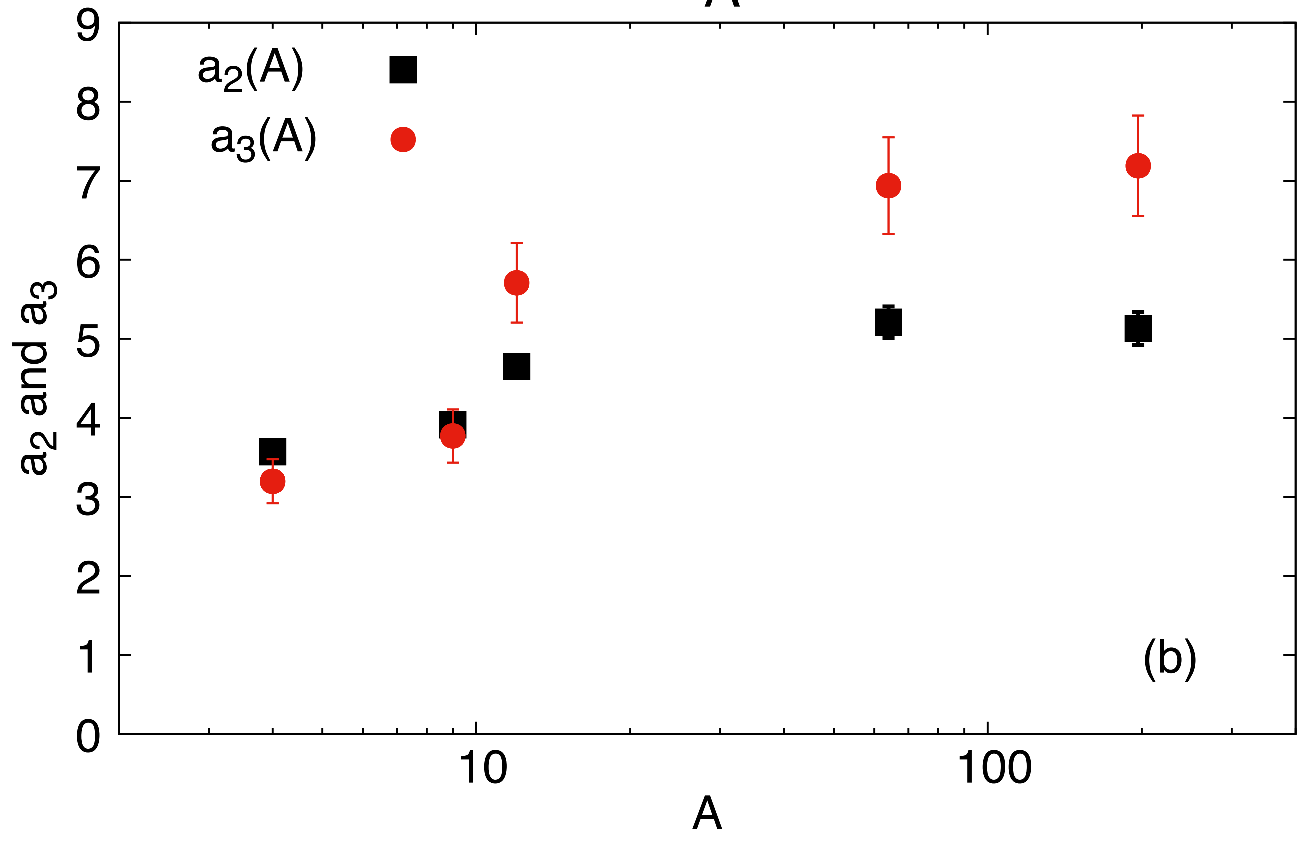
recent analysis of (e,e') x> 2 (Day, Sargsian, LF , MS)

need larger Q^2





Onset of 3N dominance at α~ 1.6



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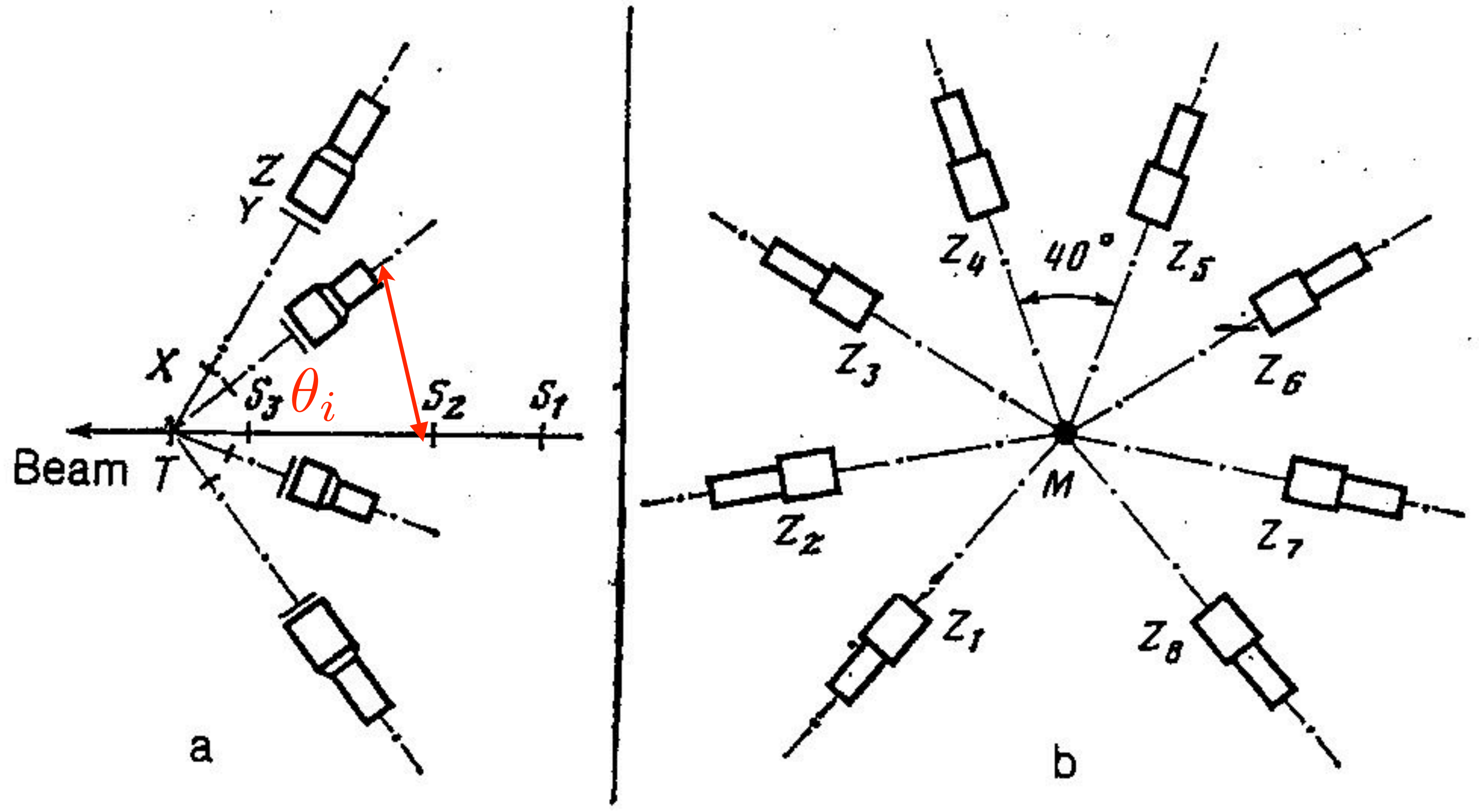
Correlations in p A→ p (backward) + p (backward) +X

measurements of Bayukov et al 86

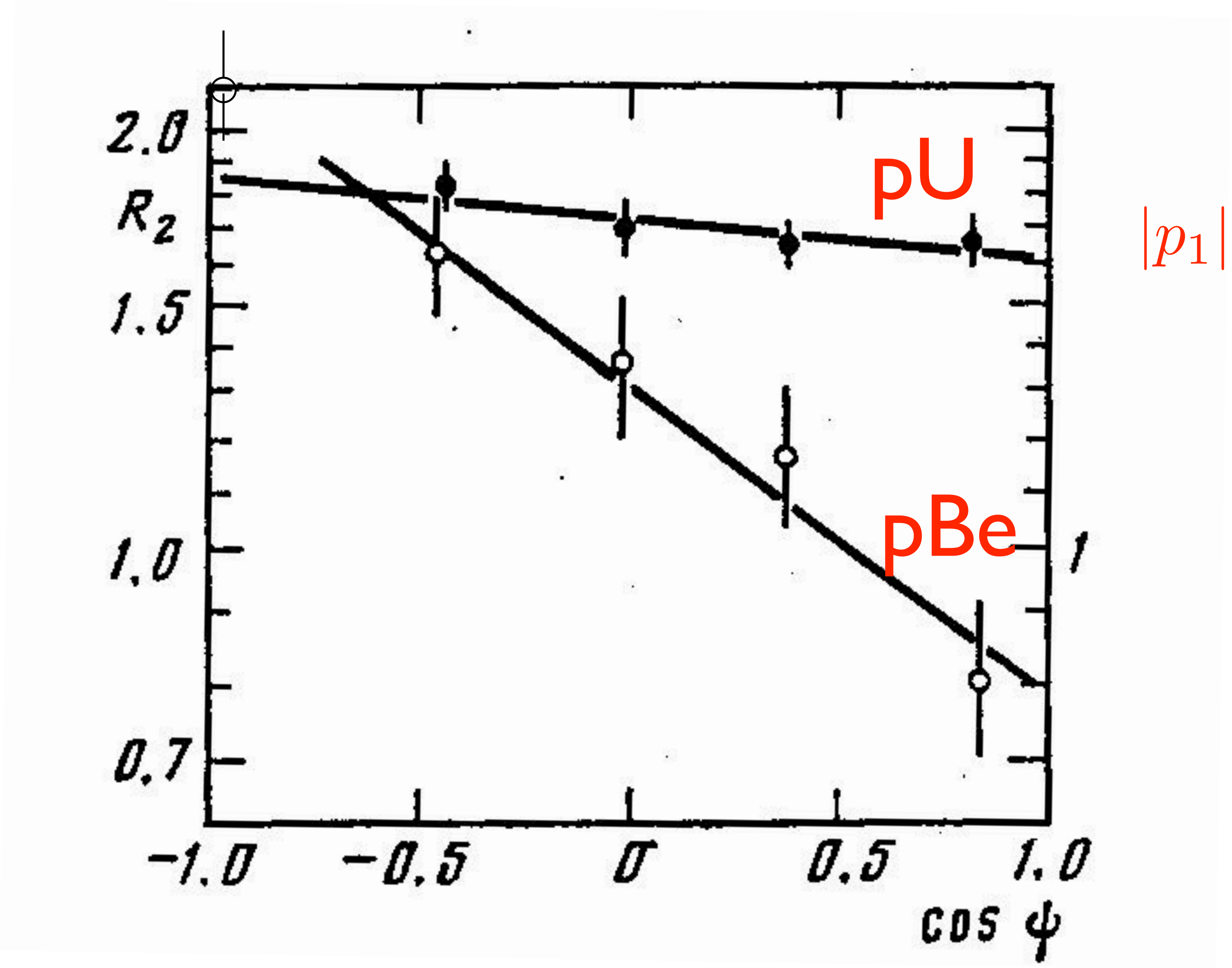


$\theta_i = 120^o$

FIG. 1. Diagram of apparatus. (a)—Side view, (b)—view along the beam direction. Only the Z counters are shown.

$$p_i \approx 0.5\, GeV, \alpha \approx 1.4, p_t \approx .25\, GeV$$

$$R_2 = \frac{1}{\sigma_{pA}^{in}} \frac{d\sigma(p+A \to pp+X)/d^3p_1 d^3p_2}{d\sigma(p+A \to p+X)/d^3p_1 d\sigma(p+A \to p+X)/d^3p_2}$$



$|p_1| = |p_2| \approx 500 MeV/c$

Curves is experimental fit.

the pattern of ψ dependence of R_2 can be reproduced