Short-range nucleon correlations- looking backward

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Kim Egiyan memorial workshop, Jlab, October 20, 2006

Outline

Introduction - how to describe SRC in high energy processes - deuteron case

Theoretical expectations for SRC related properties of nuclear wave function/spectral function, decay function

Fast backward (FB) nucleon production and SRC

First steps in looking for SRC in high Q^2 electron scattering -
(e,e’) at x> 1, e+A →e+ FB nucleon + X

Key SRC results of last three years:
(e,e’) x>1, pA→ppn +X, eA→epp/epn +X,

Summary and outlook

Old and persistent question: *Why nuclei do not collapse into a system of size of a nucleon/ quark soup?*

Traditional answer: *Short-range repulsion between nucleons - repulsive core*

Strong repulsion at $r < r_c \sim 0.4$ fm !!!

Does it makes sense to speak in this situation about nucleons since

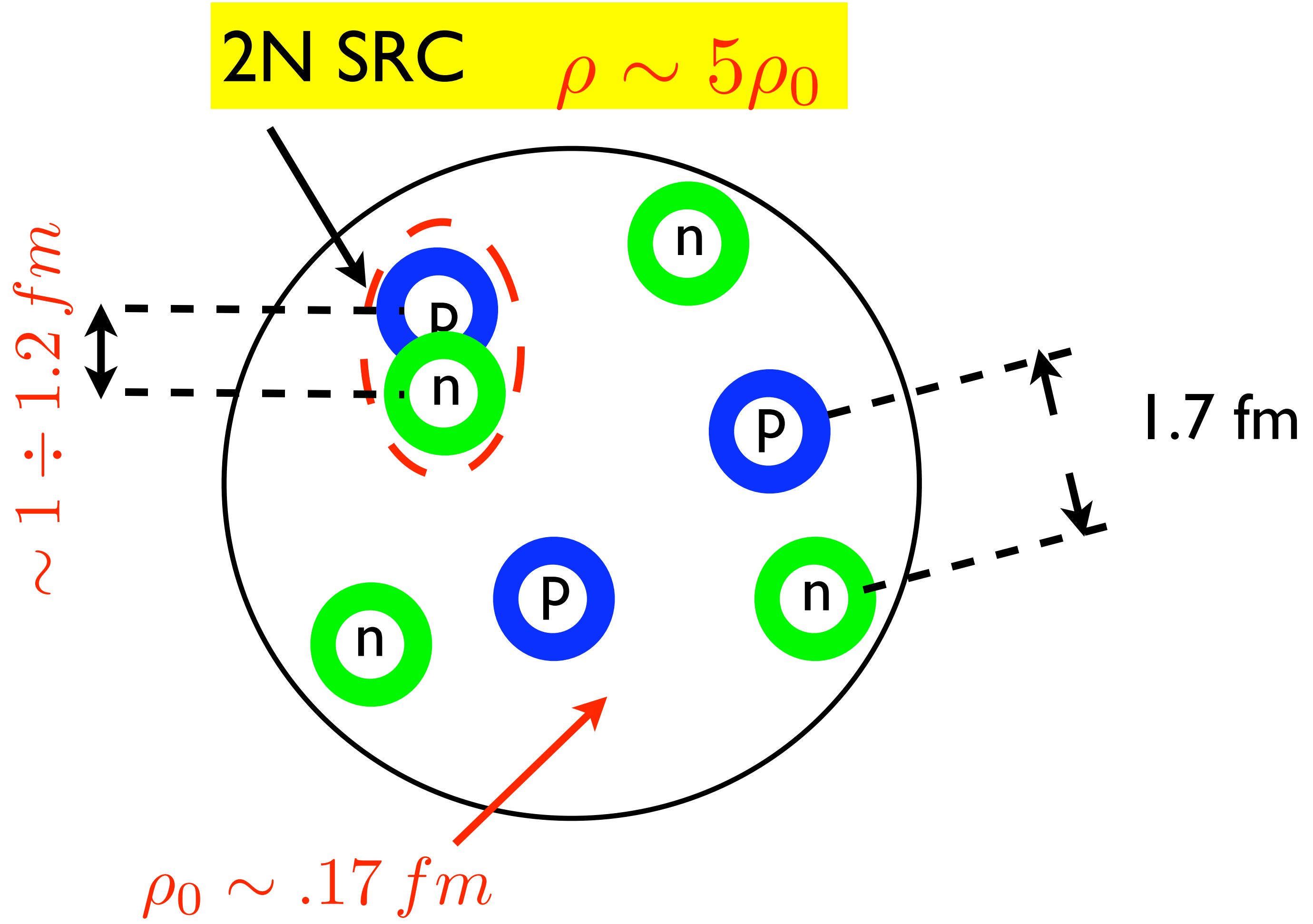
$$r_N = \left\langle r^2_{p_{e.m.}} \right\rangle^{1/2} \approx 0.8\, fm \quad \text{and} \quad r_c \ll 2r_N \ ?$$

Quark distribution in the nucleon is $\rho_N(r) = \exp(-\mu r)$, $\mu = 0.8$ GeV

$2\rho_N(r_c/2) = \rho_N(0) \quad \Rightarrow \quad r_c = .35$ fm

F&S 75

Short-range NN correlations (SRC) have densities comparable to the density in the center of a nucleon - *drops of cold dense nuclear matter*



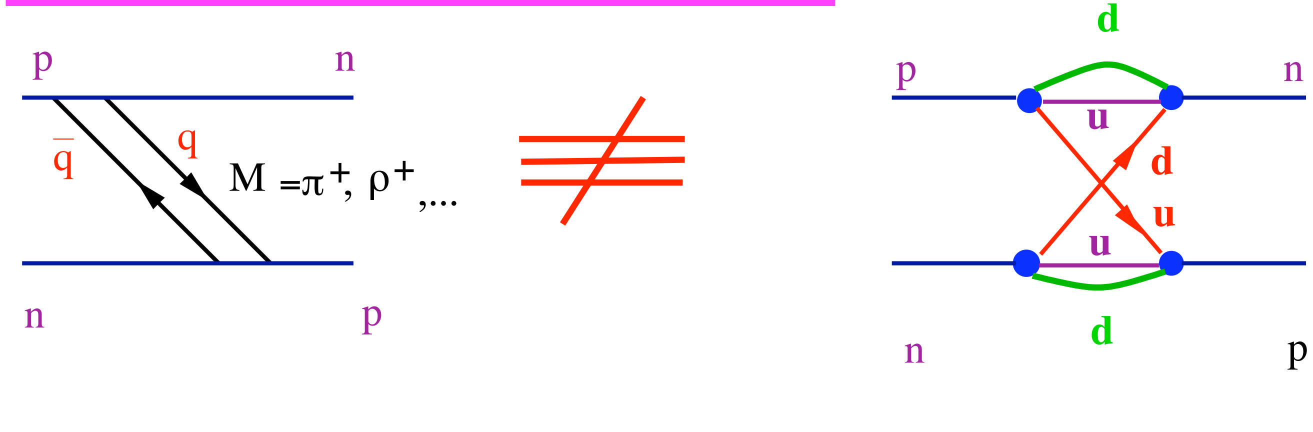
Microscopic
nuclear structure
& study of cold dense nuclear matter - complementary to studies of hot dense matter

Dynamics of neutron star formation and structure

SRC

Quark vs hadronic degrees of freedom in nuclei
Origin of intermediate and short range nucleon-nucleon
forces- quark vs meson exchanges

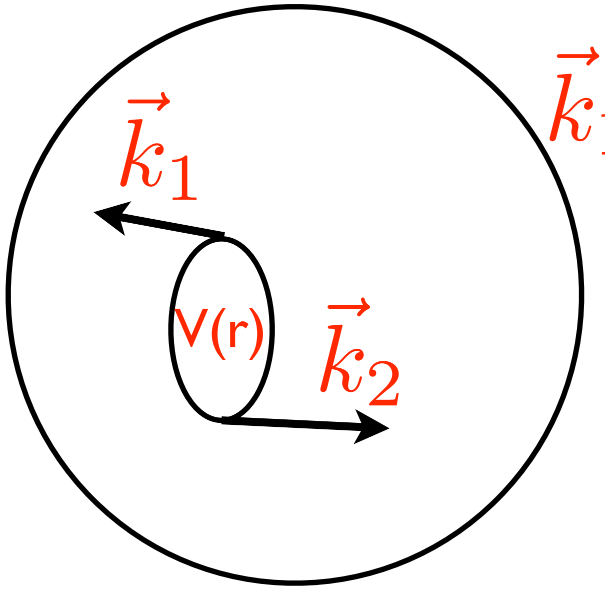
Events generators for heavy ion collisions - fluctuations in central collisions
Baym, Blattel and F &S 93
still not implemented



Meson Exchange

Quark interchange

Short-range correlations in nuclei - for years referred as an elusive though important feature of the nuclear wave structure.



$$\vec{k}_1 + \vec{k}_2 \approx 0$$

Two nucleon short-range correlation.

For our purposes medium range D-wave correlations are included in this definition - *which is a physical/practical one - removal of one nucleon of the correlation leads to a release of the second one.*

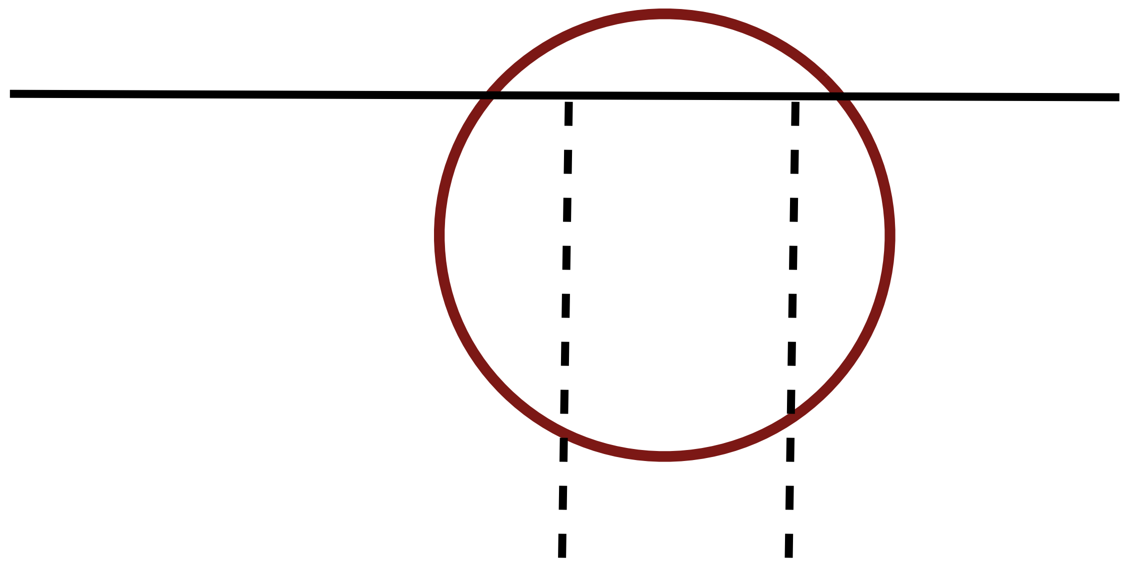
To resolve short-range structure of nuclei *on the level of nucleon/hadronic constituents* one needs processes which transfer to the nucleon constituents of SRC both energy and momentum larger than the scale of the NN short range correlations $q_0 \geq 1GeV, \vec{q} \geq 1\,GeV$

$\Rightarrow$ Need to treat the scattering processes in the relativistic domain. There is a price to pay: relativistic (light-cone) treatment of the nucleus - however in broad kinematic range a smooth connection with nonrelativistic description of nuclei.

Corollary: Properties of nuclei seen by low energy probes described well using notion of quasiparticles - SRC effects are hidden in parameters of these quasiparticle.

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

Relativistic projectile



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

$$t_1 - z_1 = t_2 - z_2$$

Similar to the perturbative QCD the amplitudes of the processes are expressed through the wave functions on the light cone. *Note: in general no benefit for using LC for low energy processes.*

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

Decomposition over hadronic states could be useless if too many states are involved in the Fock representation

$$|D\rangle = |NN\rangle + |NN\pi\rangle + |\Delta\Delta\rangle + |NN\pi\pi\rangle + ...$$

Problem - we cannot use a guiding principle experience of the models of NN interactions based on the meson theory of nuclear forces - *such models have a Landau pole close to mass shell and hence generate a lot of multi meson configurations*. (On phenomenological level - problem with lack of enhancement of antiquarks in nuclei)

Instead, we can use the information on NN interactions at energies below few GeV and the chiral dynamics combined with the following general quantum mechanical principle - *relative magnitude of different components in the wave function should be similar to that in the NN scattering at the energy corresponding to off-shellness of the component.*

Important simplification of the LC description due to the structure of the final states in NN interactions: direct pion production is suppressed for a wide range of energies due to chiral properties of the NN interactions:

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

⇒ Main inelasticity for NN scattering for $T_p \leq 1$ GeV is Δ-isobar production which is forbidden in the deuteron channel.

|Δ Δ> threshold is $k_N = \sqrt{m_\Delta^2 - m_N^2} \approx 800\, MeV$!!!

Small parameter for inelastic effects in the deuteron WF, while relativistic effects are already significant as v/c ~1

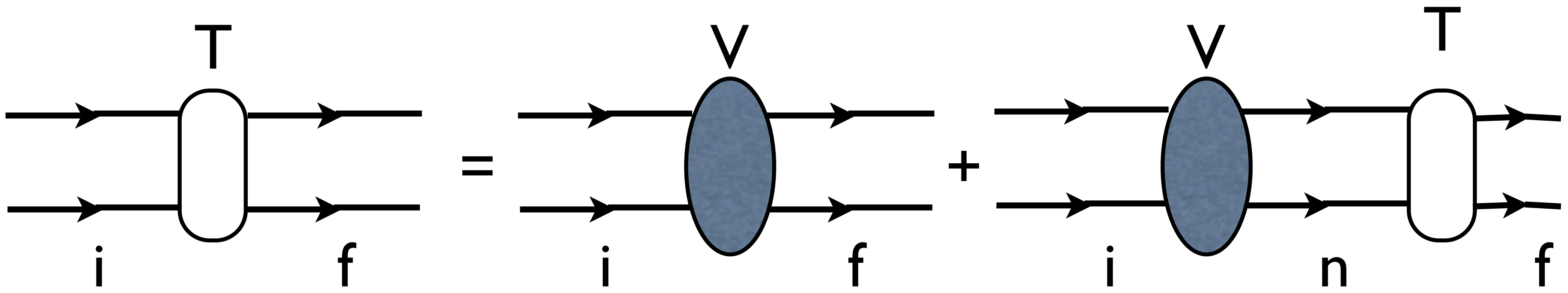
For the nuclei where single Δ can be produced $k_N \approx 550\, MeV$

- Correspondence argument (WF ↔ continuum) is not applicable for the cases when the probe interacts with rare configurations in the bound nucleons due to the presence of an additional scale.

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. FS76

Key point is presence of the unique matching between nonrelativistic and LC wave functions in this approximation. Proof (quite lengthy) is based on Lorentz invariance constrains on the form of interaction which enters in the LC equation for the scattering amplitude:



We found a representation in which equations for the scattering amplitude in NR QM and for LC have very similar structure. So, if a NR potential leads to a good description of phase shifts, the same is true for its LC analog. Hence simple approximate relation for LC and NR two nucleon wave functions

Spin zero case

rescale α light cone fraction (fraction of momentum carried by a nucleon in a fast frame) $\alpha \to 2\alpha$ so that $0<\alpha<2$ with $\alpha=1$ corresponds to a nucleon at rest (more convenient when generalizing to $A>2$)

Relation between LC and NR wf.

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

NR wave function

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

$$\alpha = 1 + \frac{k_3}{\sqrt{m^2+k^2}}$$

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

$$\psi^{\rm D}_\mu \varepsilon^{\rm D}_\mu = \bar{U}(p_1)\{\gamma_\mu \Gamma_1(M^2_{\rm NN}) + (p_1-p_2)_\mu \Gamma_2(M^2_{\rm NN})\}U(-p_2)\varepsilon^D_\mu .$$

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 and LC is in the relation of the wave function and the scattering amplitude

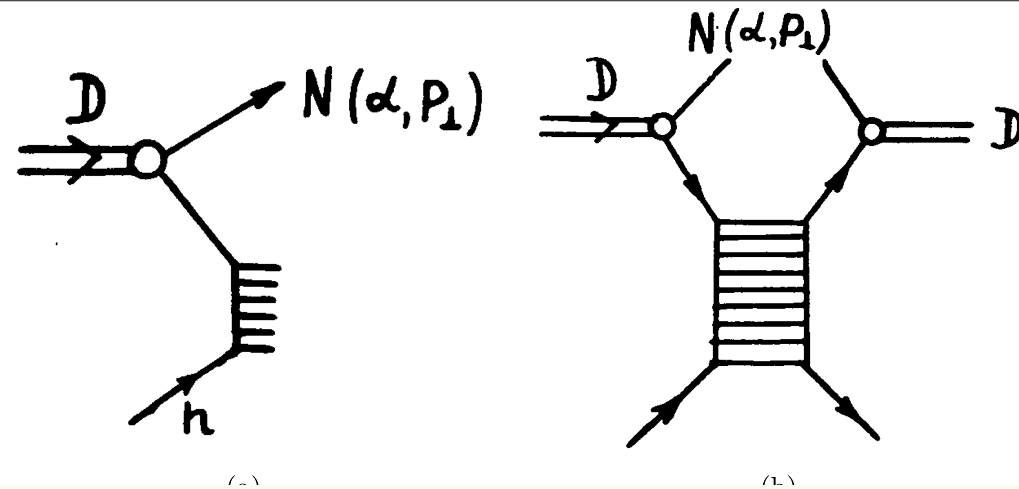
Let us illustrate this for the high energy deuteron break up $h + D \to X + N$ in the impulse approximation with nucleon been in the deuteron fragmentation region - spectator contribution.

For any particle, b, in the final state in the target fragmentation region the light cone fractions are conserved under longitudinal boosts

$$\alpha_{\rm b}/2 = (E_{\rm b} + p_{{\rm b}Z})/(E_{\rm D} + p_{{\rm D}Z})$$

Hence in the rest frame

$$2 > \alpha_{\rm b} \equiv \left(\sqrt{m_{\rm b}^2 + p_{\rm b}^2} - p_{{\rm b}Z}\right)/M_{\rm D}$$



$$\left.\frac{d\sigma^{D+h\to N+\cdots}}{(d\alpha/\alpha)d^2p_\perp}\right|_{\text{LC imp.approx.}} = \sigma^{hN}_{inel.}[(2-\alpha)s_{NN}]\cdot\frac{[U^2(k)+W^2(k)]}{(2-\alpha)}\sqrt{k^2+m^2}$$

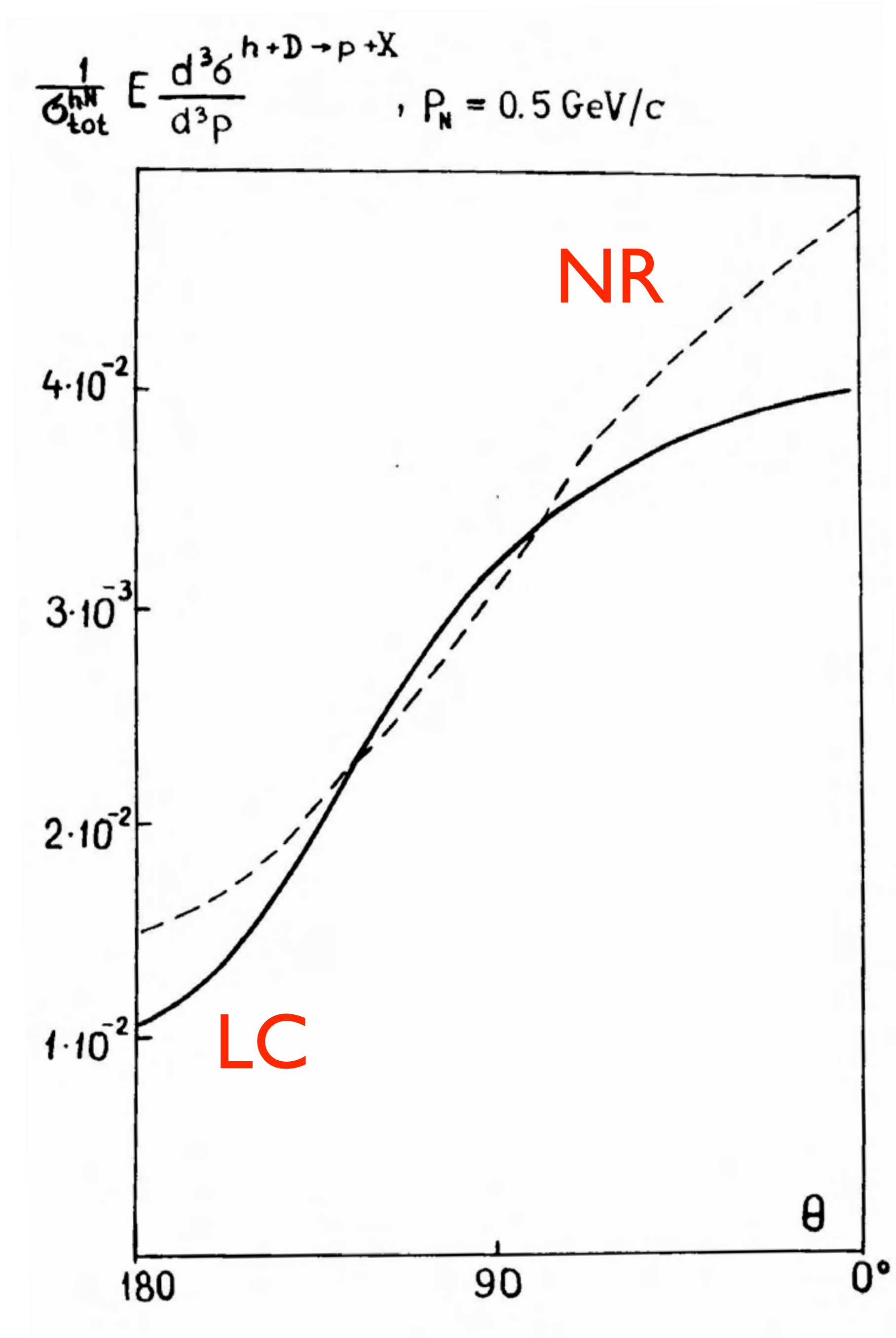
$$\alpha = 1+\frac{k_3}{\sqrt{m^2+k^2}}$$

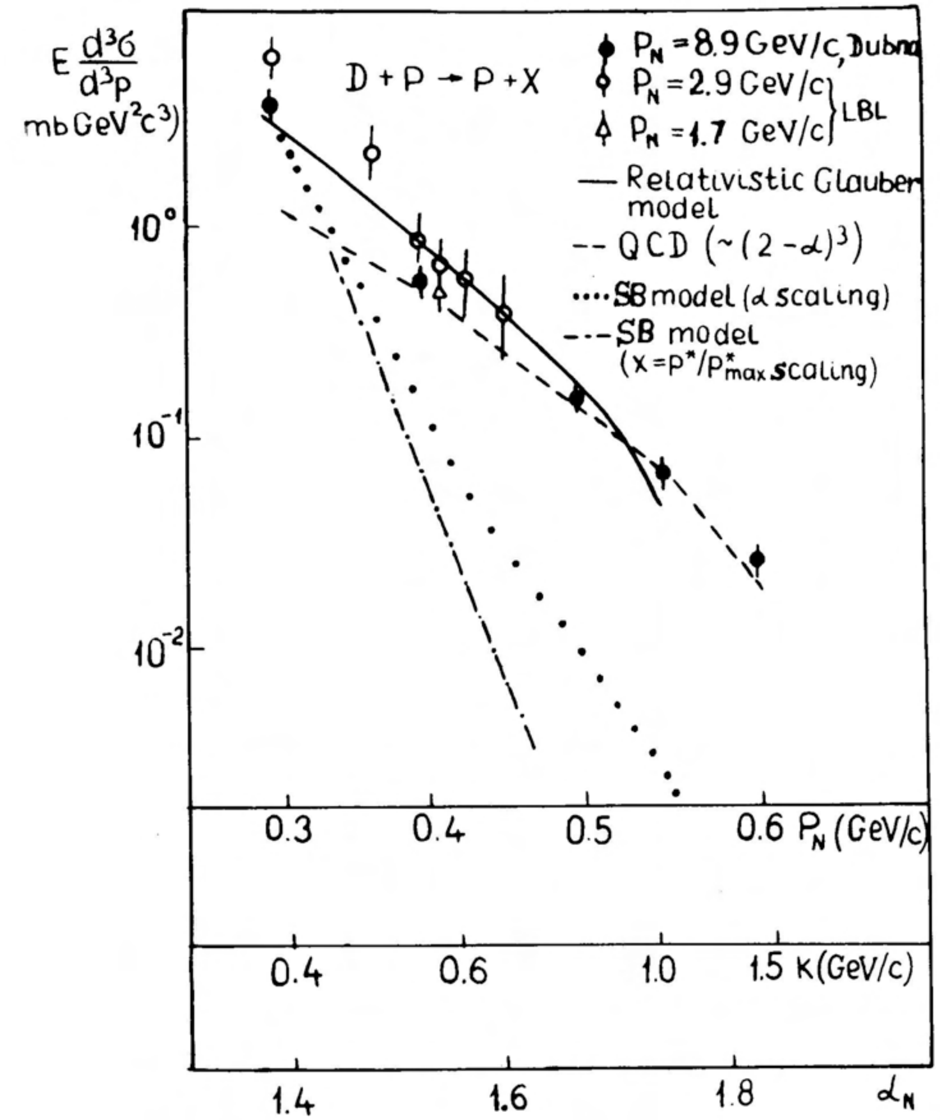
$$\left.\frac{d\sigma^{D+h\to N+\cdots}}{(d\alpha/\alpha)d^2p_\perp}\right|_{\text{NR imp.approx.}} = \sigma^{hN}_{inel.}[(2-\alpha)s_{NN}]\cdot[U^2(p)+W^2(p)](2-\alpha)\sqrt{p^2+m^2}$$

$$\alpha = 2(\sqrt{m^2+p^2}-p_3)/m_D$$

NR/Virtual nucleon: observed momentum is the same as in the WF, asymptotic at $\alpha \to 2, k_t = 0$, is determined by WF at finite momentum 0.75 m, and has the same (2-α) dependence on α.

LC nucleon: nonlinear relation between internal momentum k and observed momentum p. Asymptotic at $\alpha \to 2$, is determined by WF at $k \to \infty$. Similar to particle physics.





Numerical difference between NR and LC for deuteron fragmentation is relatively small up to rather large momenta

Around 1974- measurement of fast backward (cumulative) pion production at high energies at Dubna - turned out to be wrong

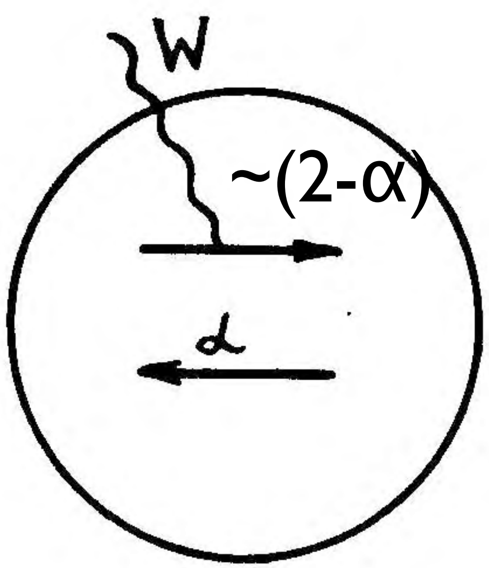
Led to rediscovering of old ITEP (Moscow) data on fast backward nucleon by Leksin group ~ 1975

I first met Kim (May 75?) - heard his discussion with Leksin on merits of measurement of FB proton production in photon -nucleus scattering

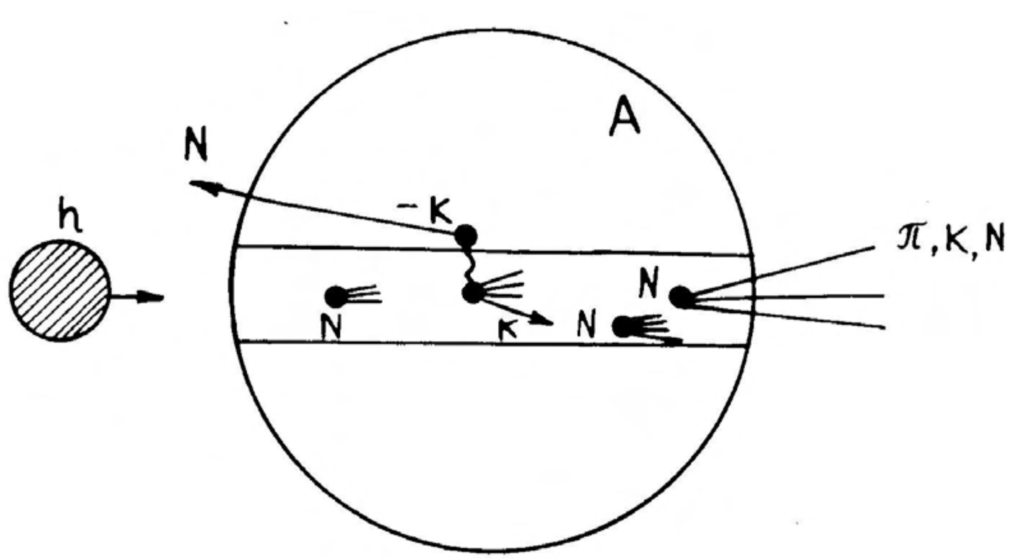
76 - Khovanski from ITEP neutrino group asked me and Leonya Frankfurt whether what we do for the deuteron could be relevant to their observation of production of FB nucleons in $\nu + Ne \to \mu$ + "FB proton" +X reaction (very interesting data - do not have time to discuss it in this talk)

Prompted us to extend studies of structure and ways to probe short range correlations to A>2 nuclei. We suggested that phenomenon of production of fast backward (FB) nucleons and mesons*) is due to the interaction with SRC

*) We wanted to name them backfires (US name for Soviet fighter jets) but gave up because of censorship problems.



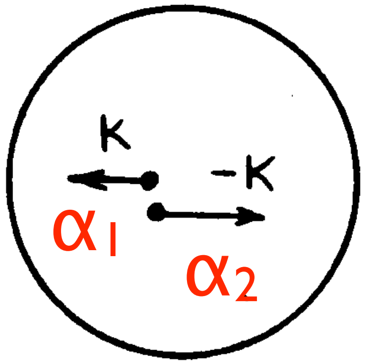
Production of a fast backward nucleon in the W* scattering from 2N SRC spectator mechanism

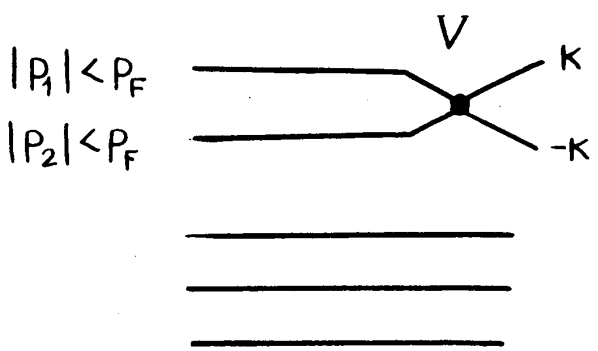


Production of a fast backward nucleon in the hadron - nucleus scattering

Basis of the SRC spectator approximation

(a) asymptotic of the wave function is determined by the singularity of the potential





$\alpha_1+\alpha_2 \sim 2$

For the single nucleon density matrix $n_A(k) = \int d^3k_i \psi_A^2(k_i)\delta(k-k_1)\delta(\sum_1^A k_i)$

$$V(k)\big|_{k\to\infty} \sim k^{-n}, \qquad n_A(k)\big|_{k\to\infty} \sim \frac{V^2(k)}{k^4}.$$

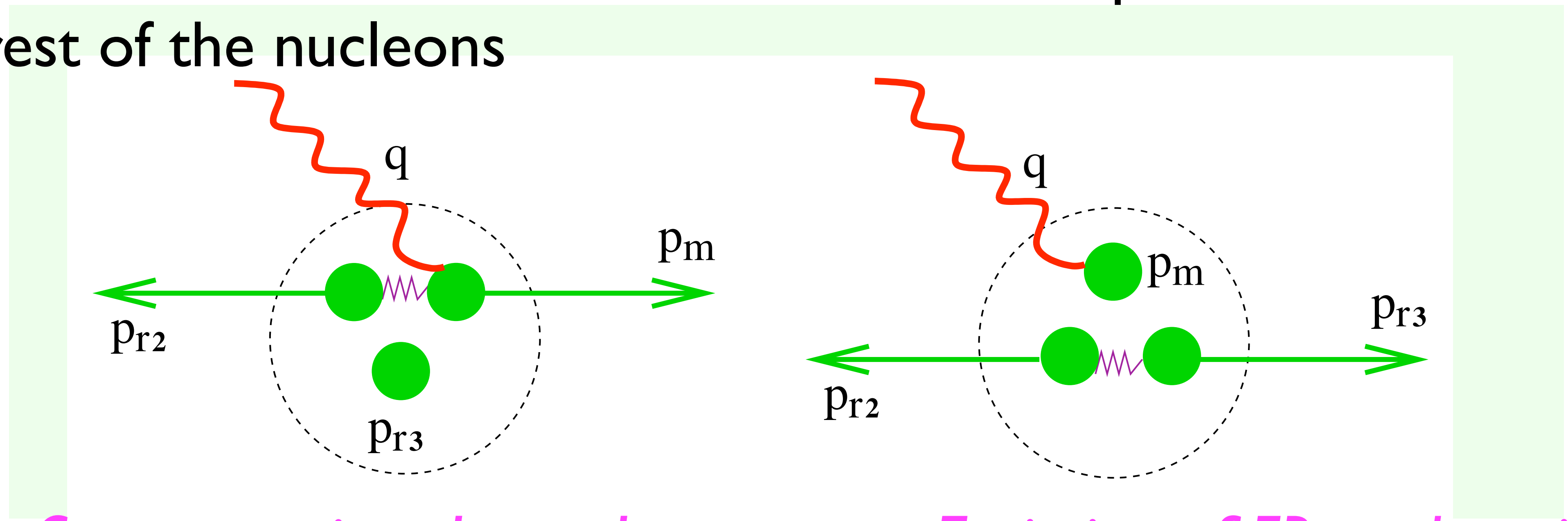
$$n_A(k)_{|k\to\infty} = a_2(A)\psi_D^2(k)$$

$k>k_F$?

In case of LC more complicated but not a bad approximation for

$1.6>\alpha>1.25$

(b) Instantaneous removal of one nucleon of 2N SRC leads to release of the second nucleon of SRC with initial LC fraction and transverse momentum due to a large difference between the scale of local NN potential and interaction with the rest of the nucleons

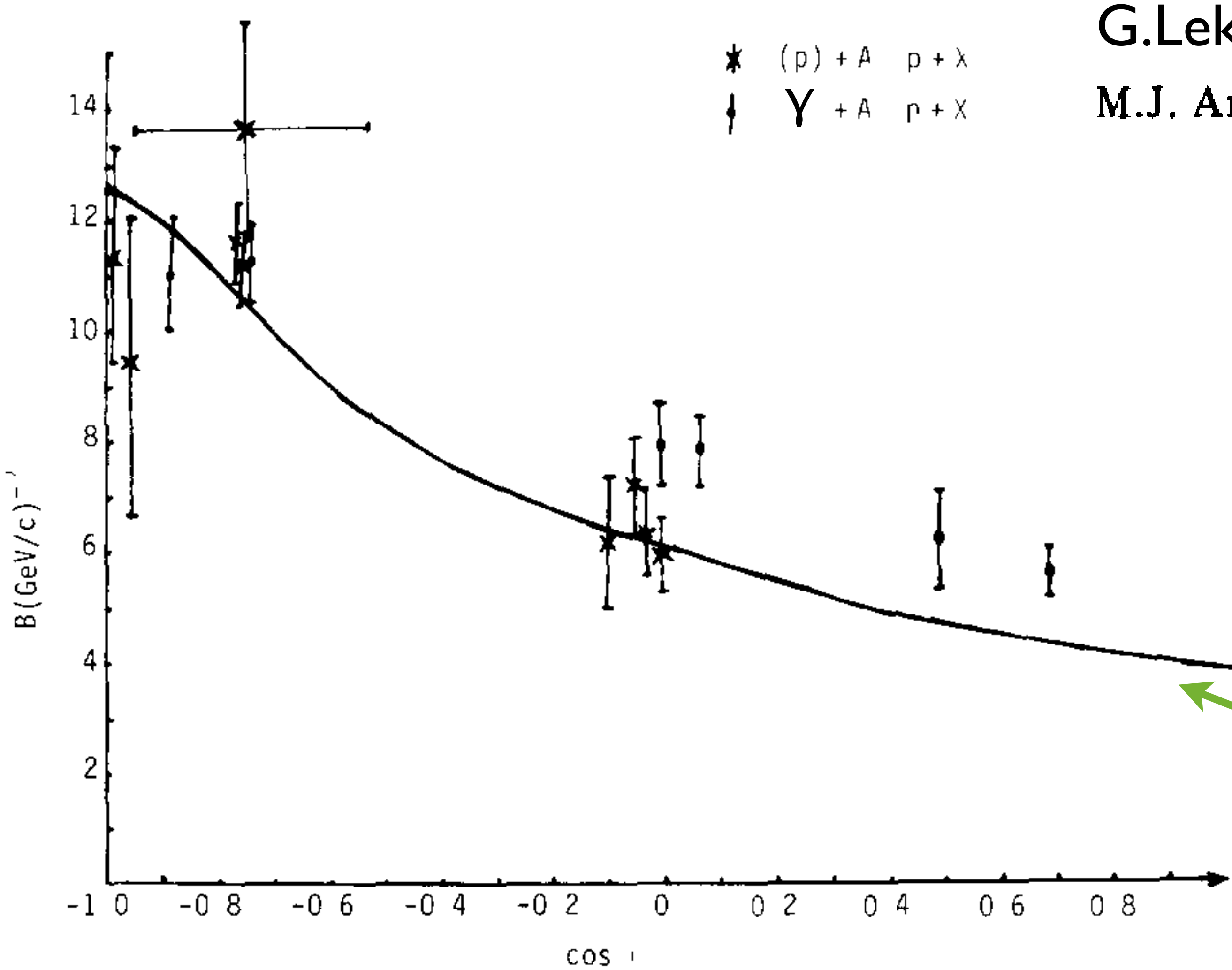


Spectator is released

Emission of FB nucleon is suppressed due to strong FSI

This gives a operational description of a new quantity for probing the structure of SRCs- nuclear decay function (FS 77-88) - probability to emit a nucleon after removal of a fast nucleon (formal operator definition in Phys.Rep.88)

To test the approximation we needed data on FB proton production as a function of the angle and momentum - by chance I found the preprint from Kim's group (just published) with the first angular and momentum spectra - with tables (first tables in these studies !!!)



G.Leksin et al 76

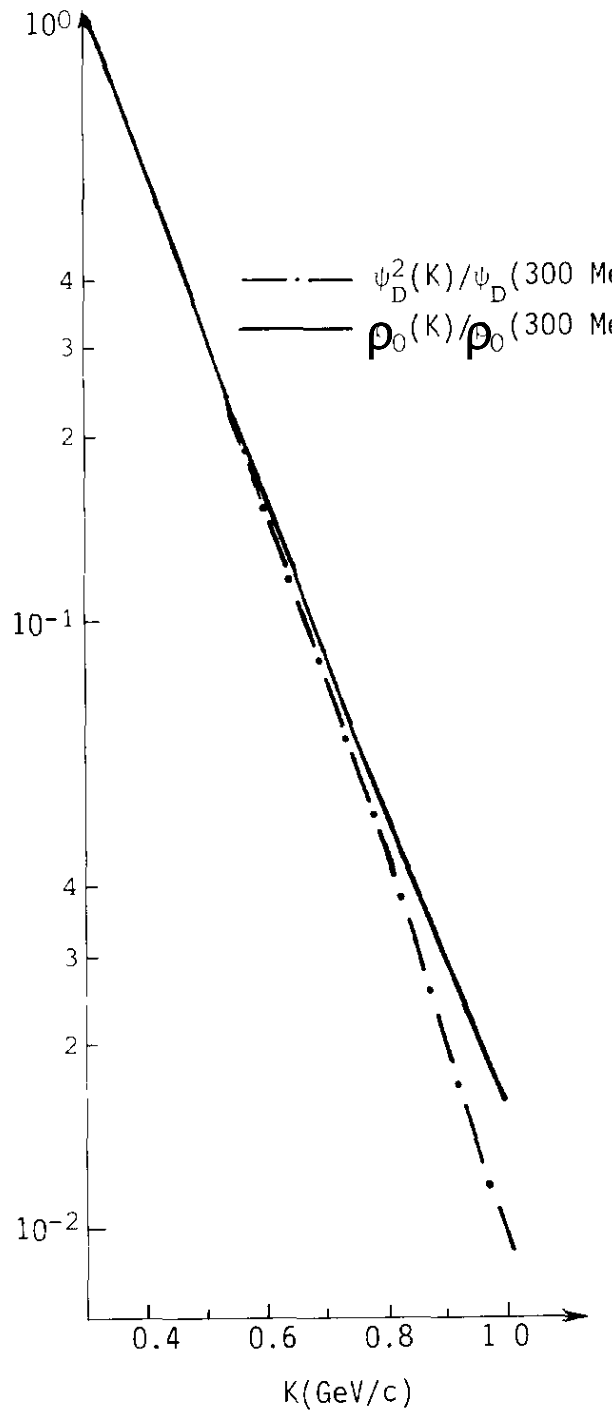
M.J. Amaryan et al., E.P.I. 173/19/-76.

from F&S Phys.Lett. 1977

two nucleon correlation approximation

Angular dependence of the slope of the proton emission spectrum:

$$\frac{d\sigma^{h(\gamma)+A\to p+X}}{d^3p/E} \propto \exp(-B(\theta)p^2)$$



Hamada-Johnston WF

Extracted from the data assuming dominance of 2N SRC

Momentum distribution normalized to its value at 300 MeV/c.

We also estimated from these data $a_2(^{12}C) = 4 \div 5$

We also predicted universal A-dependence of the inclusive spectra for different projectiles

$$\frac{d\sigma^{h+A\to N+X}}{\frac{d\alpha d^2p_t}{\alpha}} = \kappa_h A \sigma_{in}^{hN} \rho_A^N(\alpha, p_t)$$

where factor κ_h accounts for local screening effects

Experimentalists from Moscow claimed that another quantity is univeral - multiplicity of FB nucleon the way to distinguish was to compare proton and photon projectiles (due to very different A-dependence of total inelastic cross sections) - we found that our scaling worked

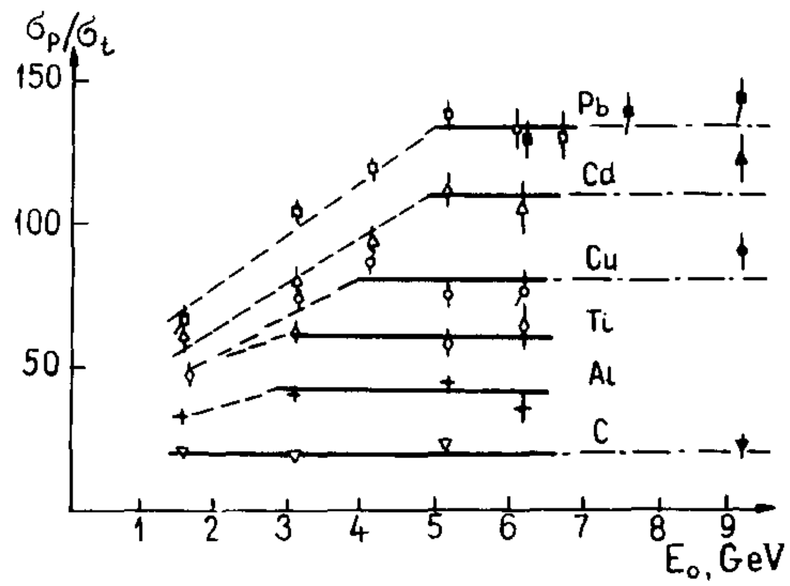


Fig. 8.13. Energy dependence of C/σ_{in}^{hA} for $\theta = 160°$ in π(p)A scattering [15]. Full points correspond to proton scattering. The straight lines represent the fit using eq. (8.13).

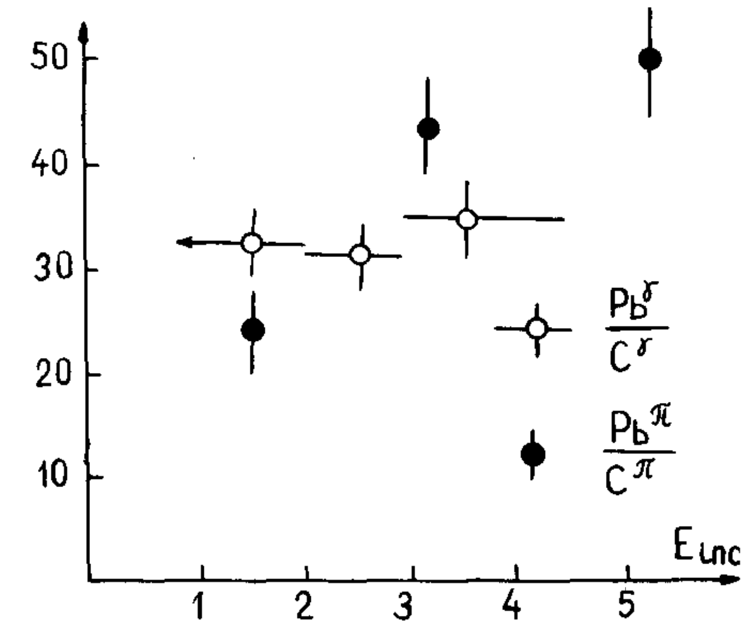


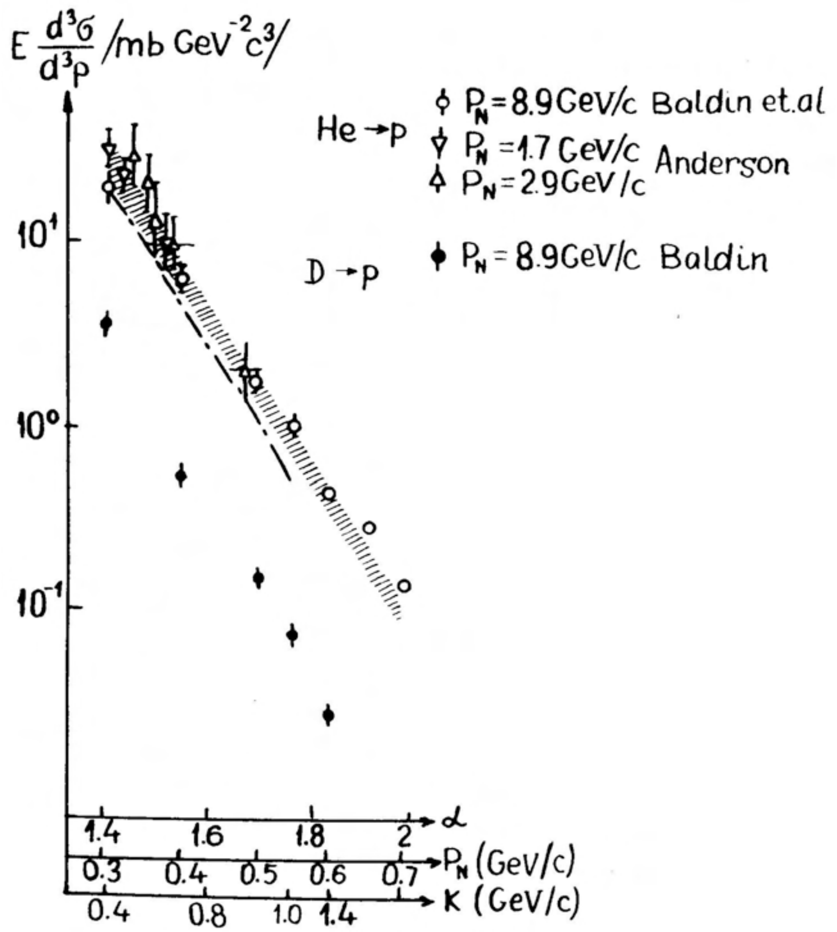
Fig. 8.14. The comparison of the energy dependence of the FB proton yield in pion and photon scattering.

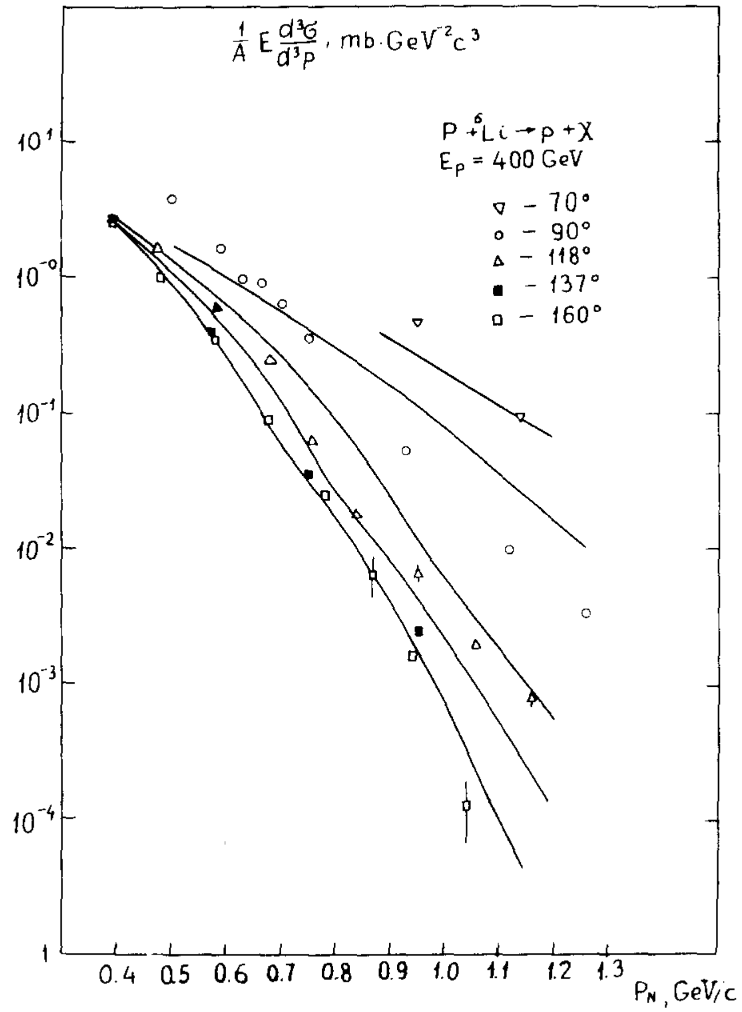
Onset of approximate energy independence of the inclusive spectra is earlier in the γ - A than in pA due to small screening in the γA case

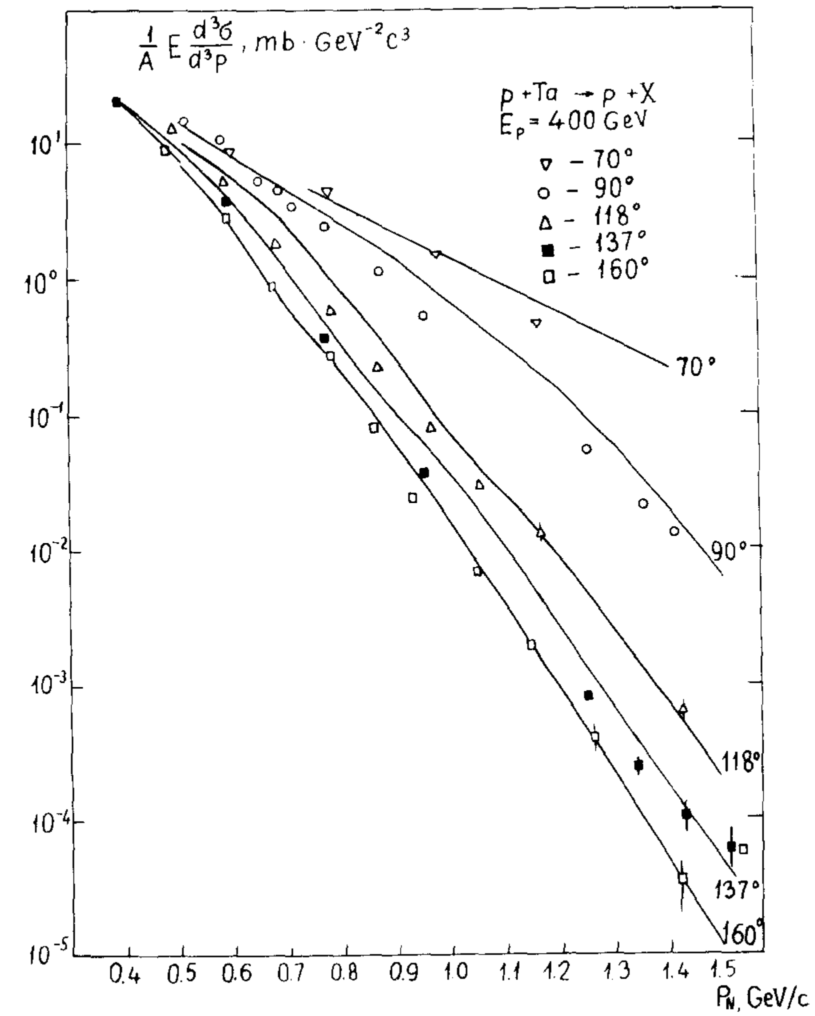
Comparison based on Erevan (γ) and Moscow (p,π) data

Publication of 1977 let to many years of my interactions with Kim and his group, regular visits to Erevan.

For a description of the data at a broad range of momenta we had to introduce and calculate 3-, 4-,... N correlations. Allowed to describe plenty of data on FB nucleon, pion ...production. 3N, 4N dominate at $\alpha > 1.5$







Strength of 2N correlations is similar to the one found in (e,e'),(p,2p)

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

Next step was to look for correlations in large Q eA scattering with FB nucleons - we discussed with Kim in the summer of 83

↓

Suggests that Misak will work with us - to establish interface of theory and experiment

Spring 84 - Misak first comes to Leningrad & we start to write a proposal to do coincidence experiments with electrons at SLAC nuclear facility

August 84 - Kim is due to leave for SLAC - Korean airliner shot down near Sakhalin island - visit is canceled

Forced to focus on the experiment at the Erevan electron machine designed primarily by Yuri Orlov) which previously did not have an extracted beam (because Orlov could not continue his work)

First A(e,e'p) experiment with detection of protons in backward hemisphere was performed by Erevan group in 1986 - previous (e,e'p) experiments measured knocked out protons which are emitted forward along $\vec{q}$.

PhD of M.Amaryan

First results: YERPHI-1351-46-91, Jul 1991

Collapse of USSR ⇗

⇓

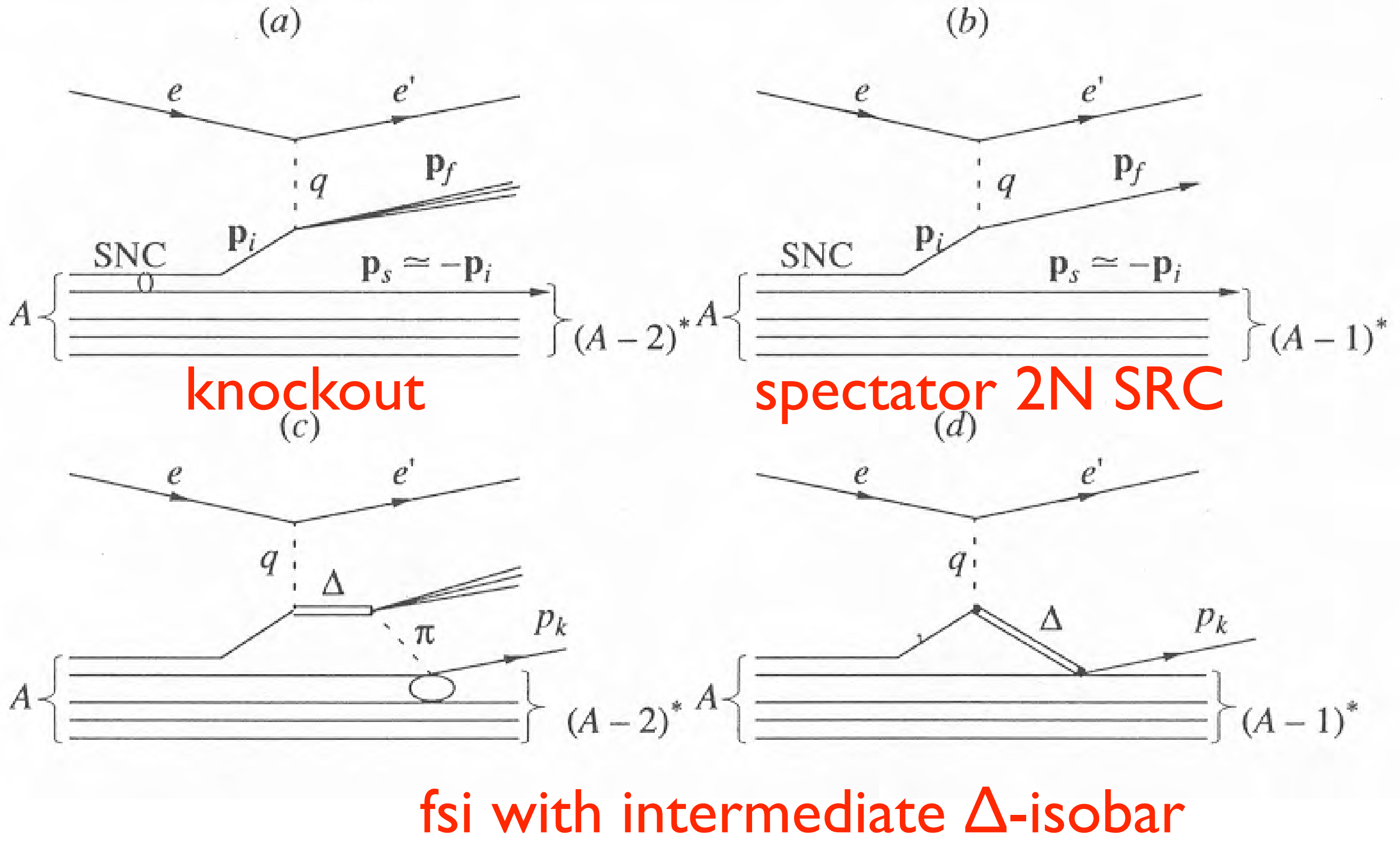
Eli comes in the fall of 91 - no electricity to run upgraded version of experiment

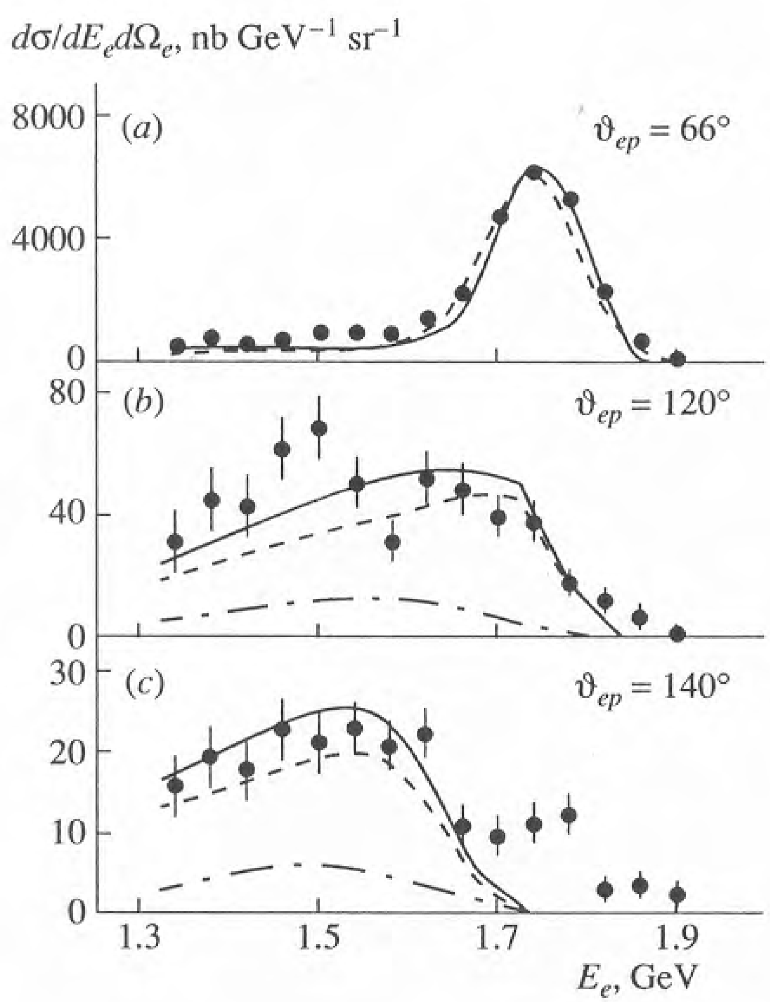
Published: Physics of Atomic Nuclei, Vol. 61, No. 2, 1998, pp. 207–213.

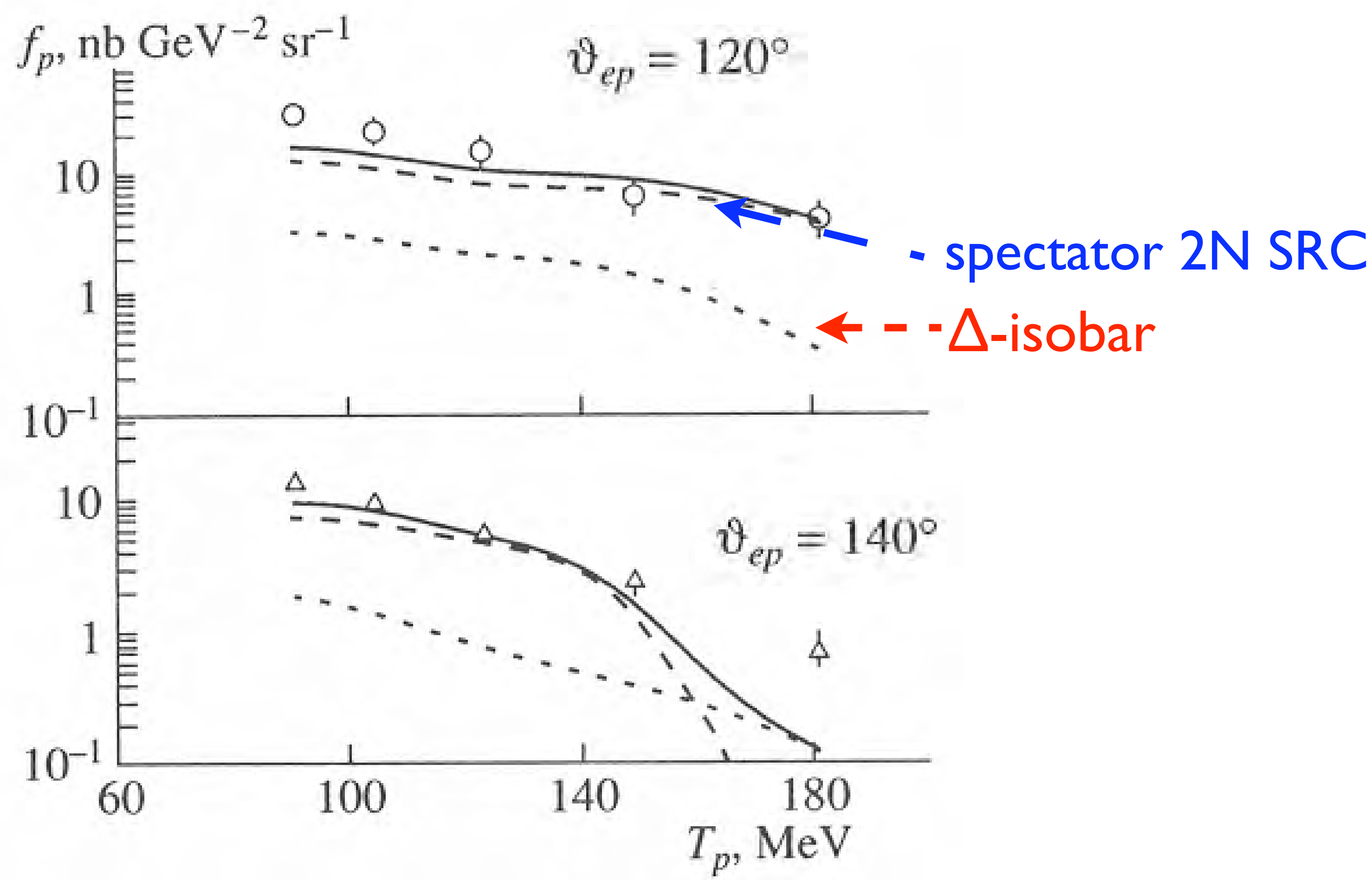
Emission of Cumulative Protons in the Reaction $^{12}C(e, e'p)$

K. V. Alanakyan, M. J. Amaryan, G. A. Asryan, R. A. Demirchyan, K. Sh. Egiyan, M. S. Ohanjanyan, M. M. Sargsyan, S. G. Stepanyan, and Yu. G. Sharabyan

Yerevan Physics Institute, ul. Brat'ev Alikhanian 2, Yerevan, 375036 Armenia


(a)
(b)
(c)
(d)
SNC
knockout
spectator 2N SRC
fsi with intermediate Δ-isobar


dσ/dE_e dΩ_e, nb GeV^-1 sr^-1
ϑ_ep = 66°
ϑ_ep = 120°
ϑ_ep = 140°
E_e, GeV


f_p, nb GeV^-2 sr^-1
ϑ_ep = 120°
ϑ_ep = 140°
T_p, MeV
spectator 2N SRC
Δ-isobar

2EOPreprint YERPHI-1108(71)-88

YEREVAN PHYSICS INSTITUTE

M.J.AMARIAN, G.A.ASRIAN, R.A.DEMIRCHIAN,
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STUDY OF SHORT-RANGE CORRELATIONS IN LIGHT NUCLEI IN PROCESSES OF ELECTRON SCATTERING IN COINCIDENCE WITH BACKWARD NUCLEONS AND Δ-ISOBARS

First nuclear physics proposal for Hall B

It was accepted and led to active participation of the Erevan group in the research of Hall B. *Though most of the ideas of the proposal still not implemented.*

Parallel development

for more details
- D.Day's talk

Study of the simplest reaction to check dominance of 2N, 3N SRC
and to measure absolute probability of SRC: A(e,e') at x>1

Define $x=Q^2/2q_0m_N$

x=1 is **exact** kinematic limit **for all** $\mathbf{Q^2}$ for the scattering off a free nucleon

x=2 (x=3) is **exact** kinematic limit **for all** $\mathbf{Q^2}$ for the scattering off a A=2(A=3) system (up to <1% correction due to nuclear binding

$$W^2 = Q^2 + 2q_0 M_A + M_A^2 \geq M_A^2$$

$$\Longrightarrow \; Q^2 + 2q_0 M_A \geq 0$$

$$\Longrightarrow \; x \leq M_A/m_N$$

Scaling of the ratios of (e,e') cross sections at x>1

Qualitative idea - to absorb a large Q at x>j at least j nucleons should come close together. For each configuration wave function is determined by local properties and hence universal. In the region where scattering of j nucleons is allowed, scattering off j+1 is a small correction.

$$\sigma(A) = \sum_{j=2} A \frac{a_j(A)}{j} \sigma(j) \qquad\qquad a_j(A) \propto \frac{1}{A} \int d^3 r \rho_A^j(r)$$

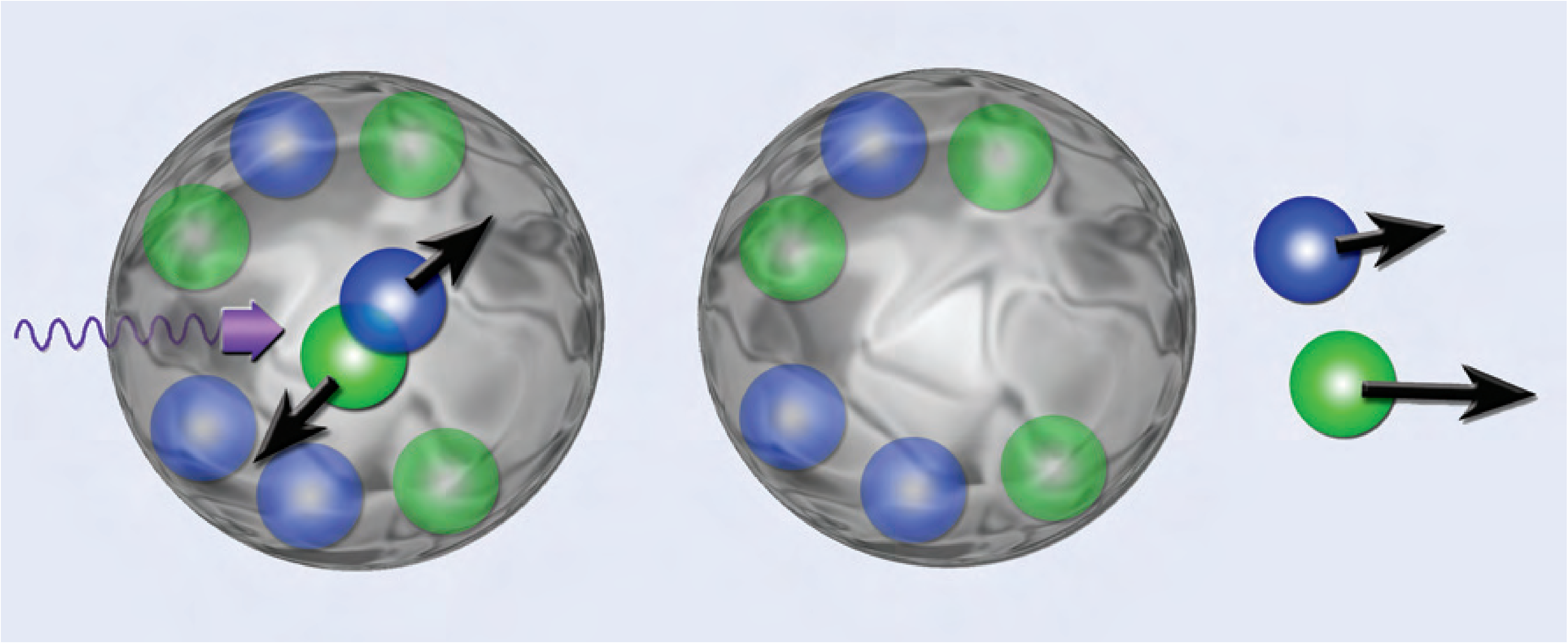
for A> 12

$$a_2 \sim A^{0.15}; \qquad a_3 \sim A^{0.22}; \qquad a_4 \sim A^{0.27}$$

$$\sigma_{eA}(x,Q^2)/\sigma_{eC}(x,Q^2)\Big|_{j-1<x<j} = (A/C) a_j(A)/a_j(C).$$

FSI is present in the interaction with j -nucleons, but not with the rest of the system as they are far away, while j nucleons have a small invariant mass in the final state. However it is also practically universal (fsi NN interaction is practically the same for I=0,1 except very close to the threshold).

Scattering off a two-nucleon correlation, x>1.5

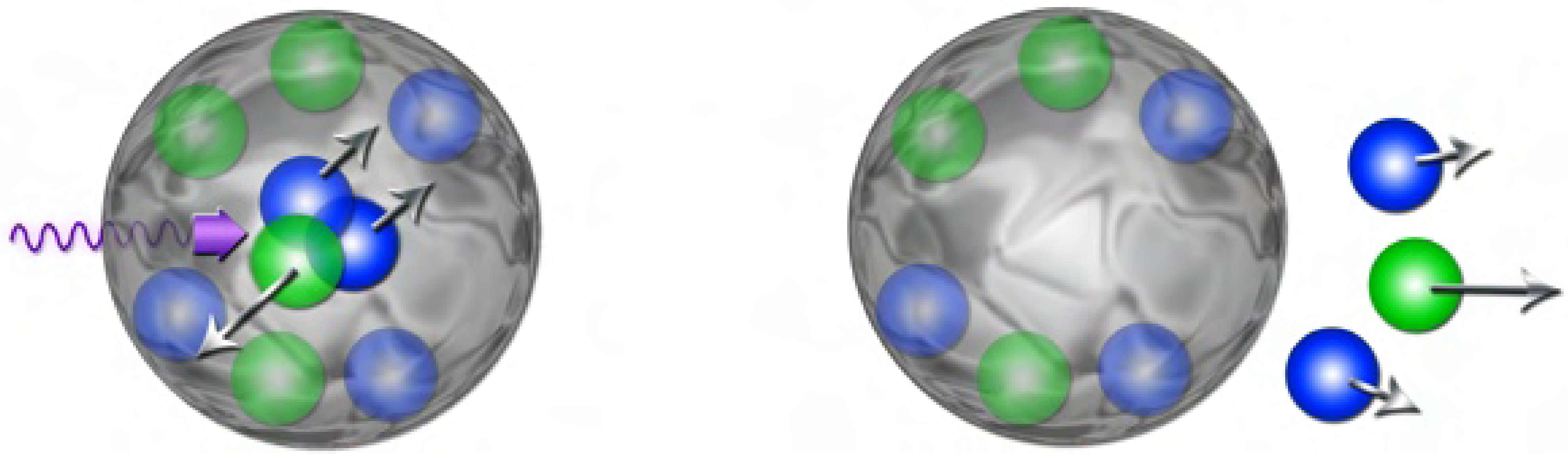


Before absorption of the photon

After absorption

W for γ^* scattering off two nucleon system is well below the threshold for production of Δ-isobar. Hence inelastic processes eN→eX are strongly suppressed. For same reason scattering off 6q configurations (even if they are present in nuclei) does not contribute in this kinematics

Scattering off a three-nucleon correlation, x>2.25



Before absorption of the photon

After absorption

History of study of the scaling ratios.

- Prediction FS 80
- First evidence from 3He/D - FS81
- Al/D - provided by S.Rock , curves by Misak , 88
- Evidence for x> 2 scaling for 4He /3He, 88
- Finally extracted data from SLAC NA3 experiment together with Donal Day and Misak Sargsian 93
- A/^{3}He, 2>x>1, - Jlab 2004
- A/^{3}He, 3>x>2, - Jlab 2005

First direct measurement led by Kim Egiyan

FSI of struck nucleon with slow nucleons at x> 1.3

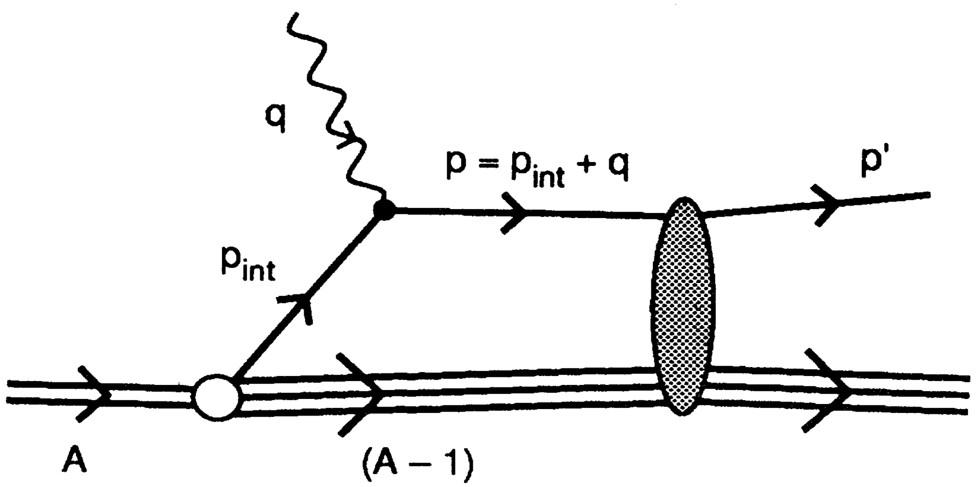


FIG. 8. Reaction diagram for nucleon knockout including final state interactions.

The struck nucleon has virtuality $\Delta M^2 = m_N^2 - p^2$

where $p = p^{int} + q$

If $|p^{int}|$ is small, $\Delta M^2 \approx m_N^2 - Q^2\left(-1 + \frac{1}{x}\right) - (p^{int})^2$

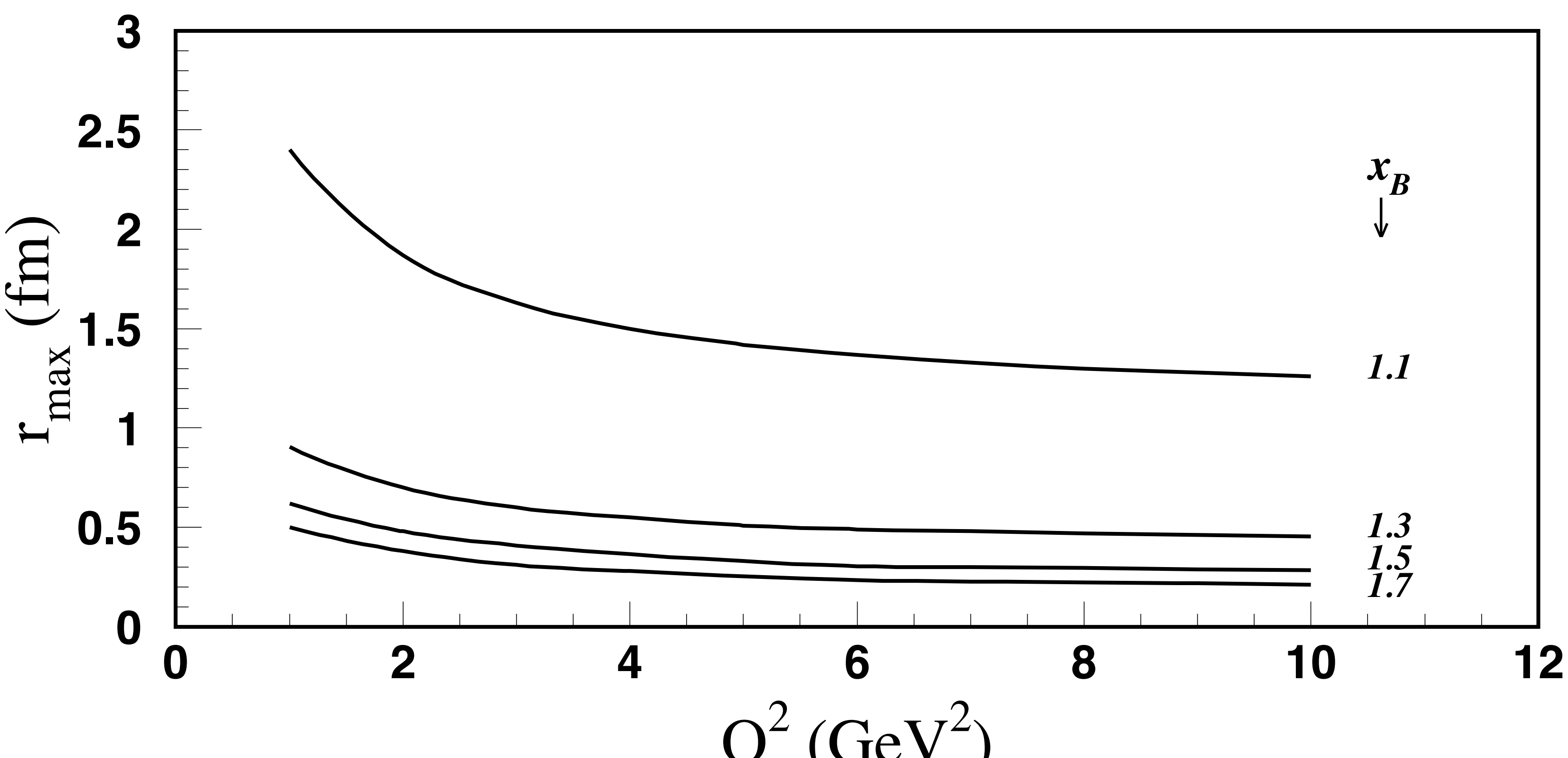
is large. Hence it is not legitimate to apply semiclassical approximation for the calculation of the Green function.

Statements in the literature that FSI with low momentum nucleon is large and strongly enhances the cross section in the discussed limit (Benhar, Fabrocini, Fantoni, Miller, Pandharipande & Sick, 91) are due to neglect of these effects.

Switch to old fashioned non-covariant formalism where energy is not conserved and momentum is conserved to determine what at what distances, r, fsi can contribute

$$r \approx \frac{1}{\Delta E v}$$ where v is the struck nucleon velocity v=p/E,

$$\Delta E = -q_o - M_A + \sqrt{(m^2 + (q + p^{\rm int})^2} + \sqrt{M_{A-1}^{*2} + (p^{\rm int})^2}.$$



Distances for which FSI of a struck nucleon with momentum less than the Fermi momentum can contribute to the inclusive cross section

Only fsi close to mass shell when momentum of the struck nucleon is close to one for the scattering off a correlation. At very large Q - light-cone fraction of the struck nucleon should be close to x (similar to the parton model situation) - only for these nucleons fsi can contribute to the total cross section, though even this fsi is suppressed.

$W - M_D \leq 50\,MeV$

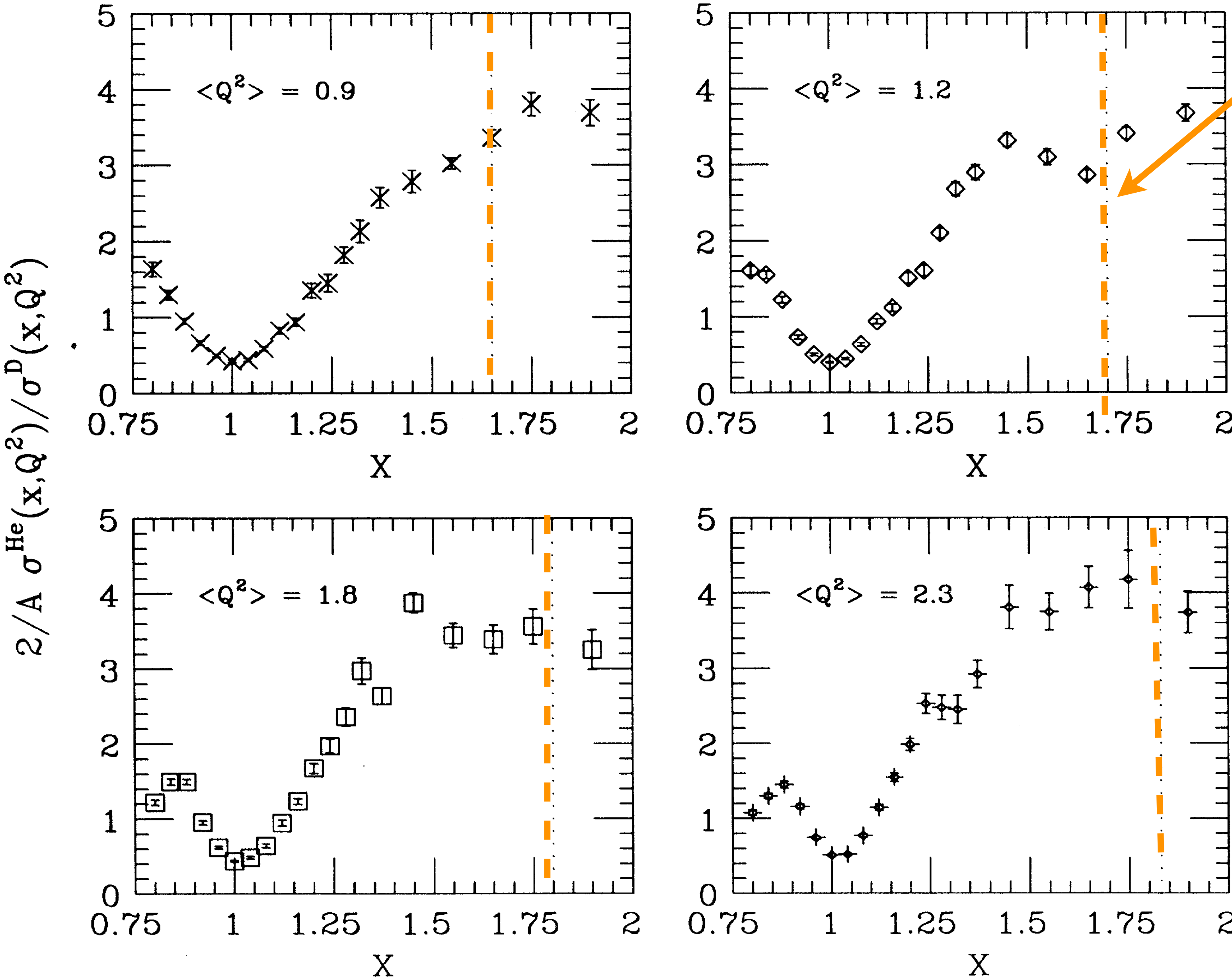


FIG. 1. Ratio $\frac{2}{A}\frac{\sigma_A(x,Q^2)}{\sigma_D(x,Q^2)}$ for ^{4}He at four different Q^2's. The average Q^2 is given for each frame. To the right of the vertical dashed line are those data which correspond to a final state less 50 MeV greater than the deuteron rest mass.

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

Assuming in the spirit of the dominance of the two nucleon correlations in the spectral function that the mean value of excitation energy corresponds to the scattering off the 2N SRC pair at rest we can determine mean value of the light cone fraction at which scattering happens

$$\boxed{\alpha_{tn} = 2 - \frac{q_- + 2m}{2m}\left(1 + \frac{\sqrt{W^2 - 4m^2}}{W}\right)}$$

FS88

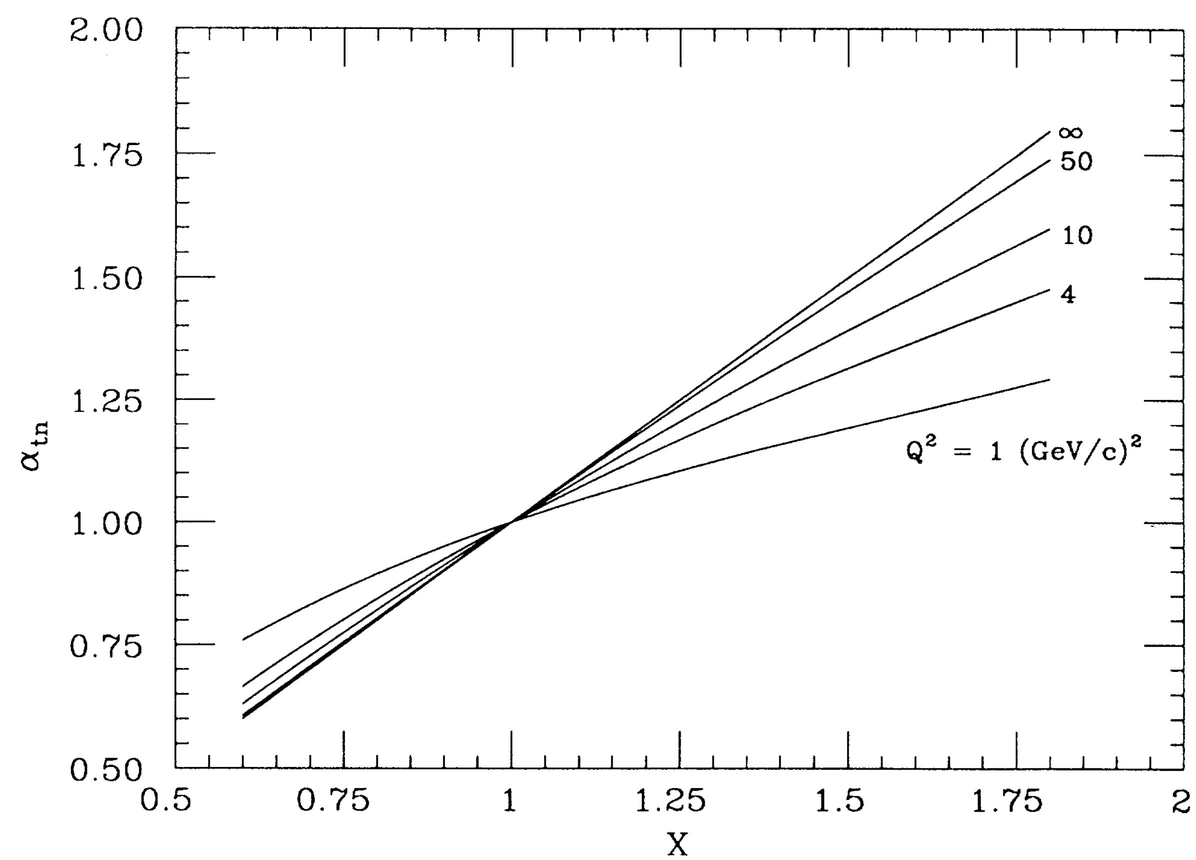


FIG. 5. α_{tn} against x for $Q^2 = 1, 4, 10, 50, \infty$. At $Q^2 = \infty$, $\alpha_{tn} = x$.

$$\frac{\sigma_{A_1}(x,Q^2)}{\sigma_{A_2}(x,Q^2)} = \frac{\int \rho_{A_1}(\alpha_{tn},p_t)d^2p_t}{\int \rho_{A_2}(\alpha_{tn},p_t)d^2p_t}.$$

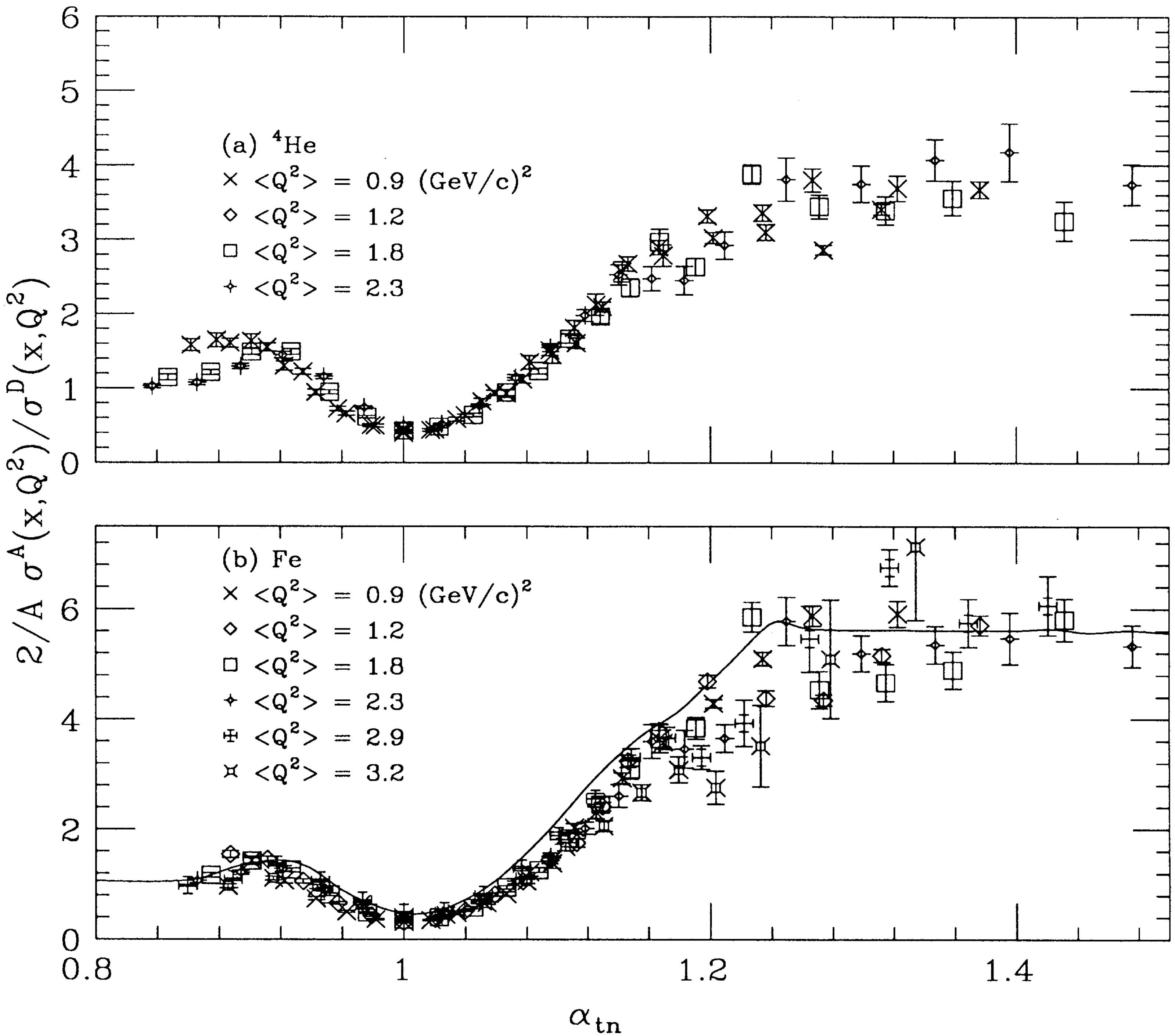
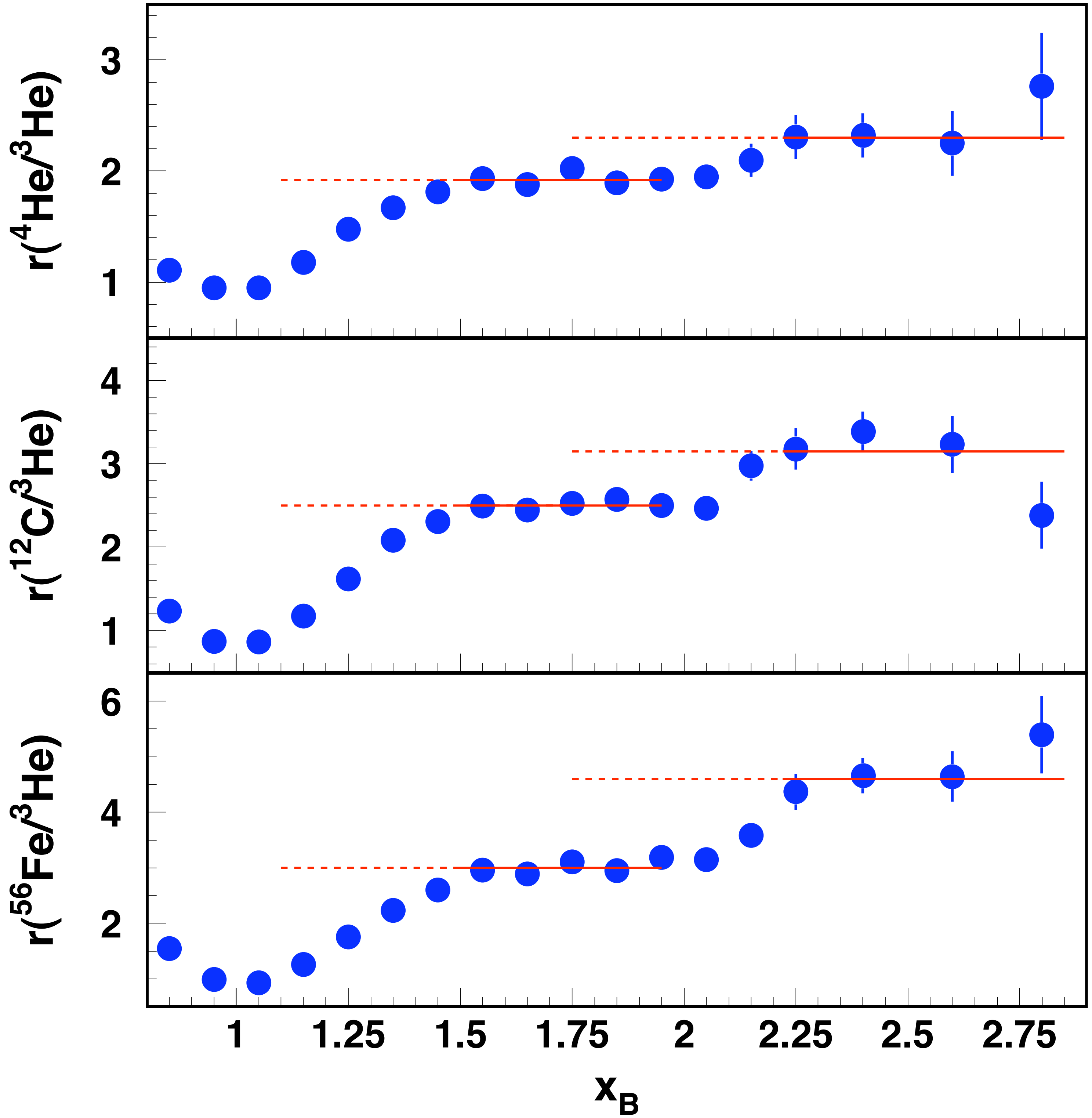


FIG. 6. Ratio $\frac{2}{A}\frac{\sigma_{Fe}(x,Q^2)}{\sigma_D(x,Q^2)}$ for ^{56}Fe for six different Q^2's plotted together against the scaling variable α_{tn}. The solid line is a calculation based on the nuclear spectral function of Ref. [22] (see Sec. VI).



New Jlab data from Hall B.

$Q^2 > 1.5$ GeV^2

Fe/C ratios for x~1.75, x~2.5 agree within experimental errors with our prediction - density based estimate:

$$a_2 = (A_1/A_2)^{0.15}$$
$$a_3 = (A_1/A_2)^{0.22}$$

The best evidence for presence of 3N SRC. One probes here interaction at internucleon distances <1.2 fm corresponding to local matter densities $\geq 5\rho_0$ which is comparable to those in the cores of neutron stars!!!

L.Frankfurt & MS, 88 $a_2(Al) \sim 5\pm1$ from SLAC data

Day, L.Frankfurt, Sargsian, MS, 93

$$a_2(^3\mathrm{He}) = 1.7(0.3)\ ,$$
$$a_2(^4\mathrm{He}) = 3.3(0.5)\ ,$$
$$a_2(^{12}\mathrm{C}) = 5.0(0.5)\ ,$$
$$a_2(^{27}\mathrm{Al}) = 5.3(0.6)\ ,$$
$$a_2(^{56}\mathrm{Fe}) = 5.2(0.9)\ ,$$
$$a_2(^{197}\mathrm{Au}) = 4.8(0.7)\ ,$$

Significant uncertainties in absolute scale

	$a_2(A/^3\mathrm{He})$	$a_{2N}(A)(\%)$	$a_3(A/^3\mathrm{He})$	$a_{3N}(A)(\%)$
$^3\mathrm{He}$	1	8.0±0.0±1.6	1	0.18±0.00±0.06
$^4\mathrm{He}$	1.96±0.01± 0.03	15.6±0.1±3.2	2.33±0.12±0.04	0.42±0.02±0.14
$^{12}\mathrm{C}$	2.51±0.01± 0.15	20.0±0.1±4.4	3.18±0.14±0.19	0.56±0.03±0.21
$^{56}\mathrm{Fe}$	3.00±0.01± 0.18	24.0±0.1±5.3	4.63±0.19±0.27	0.83±0.03±0.27

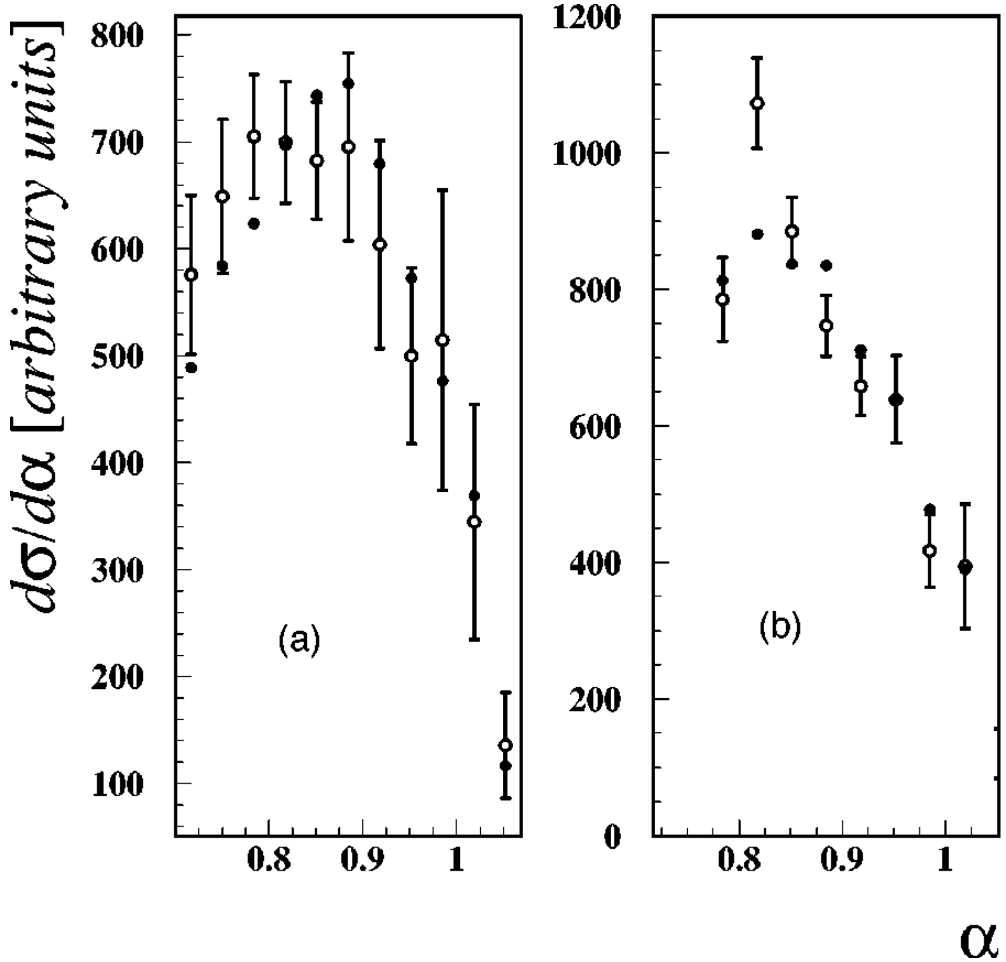
K.Egiyan, et al 2005

Amazingly good agreement between two analyses for $a_2(A)$

Compare also to the analysis of BNL EVA data on large angle C(p,2p) - $a_2(C) \sim 5$

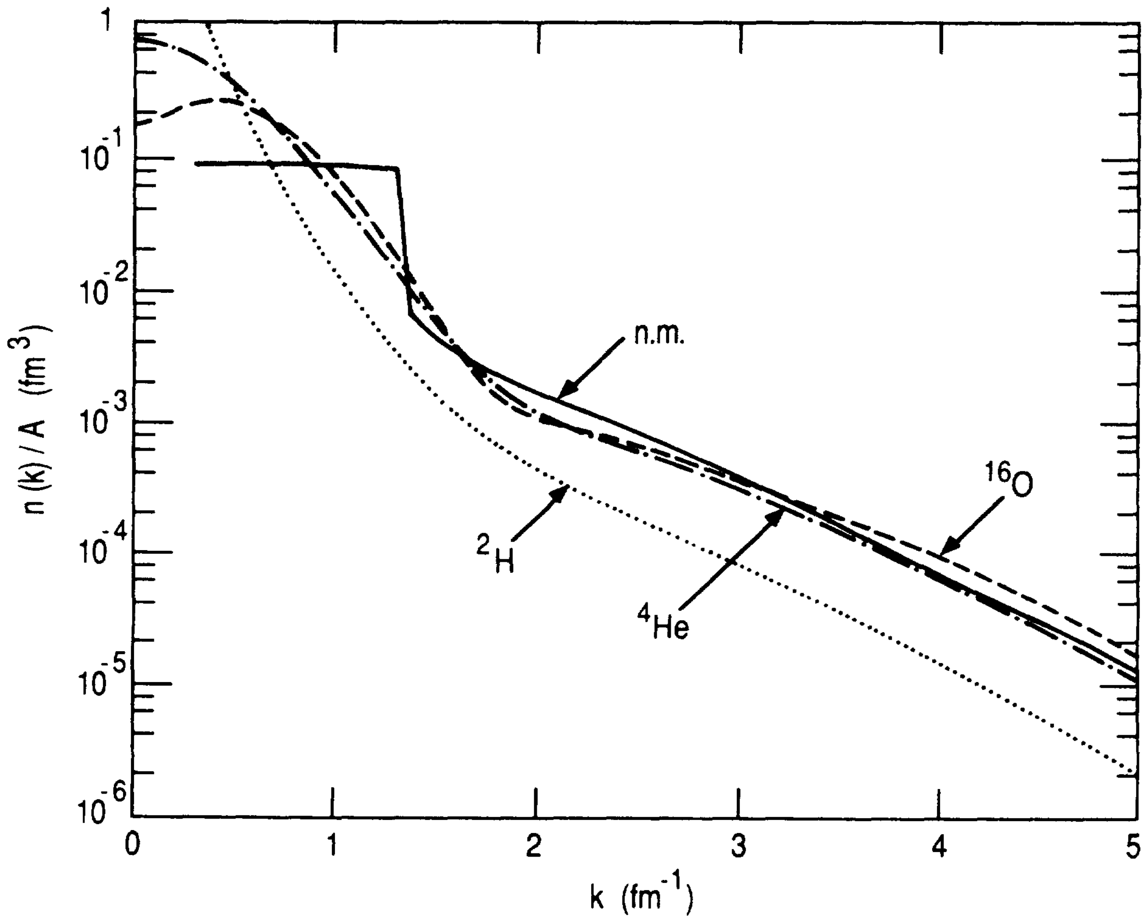
Yaron et al 02

A detailed analysis of the EVA data by I.Yaron, E.Piasetzky, M.Sargsian and F&S 2002 within 2N SRC model including fsi effects, etc allowed to determine light-cone distribution of fast forward moving nucleons



A comparison between calculated α distributions (●) and the experimental data (○) at 5.9 GeV/c (a) and 7.5 GeV/c (b).

Parallel theoretical developments in the nonrel. calculations of high momentum nucleus properties - few glimpses relevant for our discussion



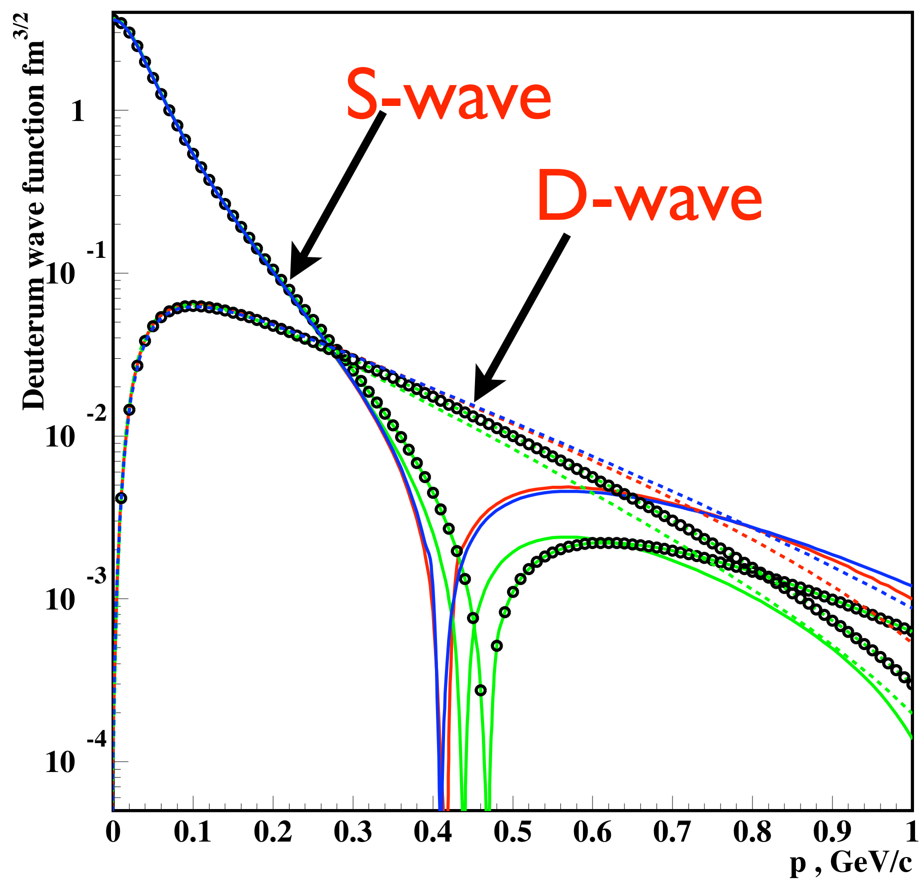
Pieper et al 92

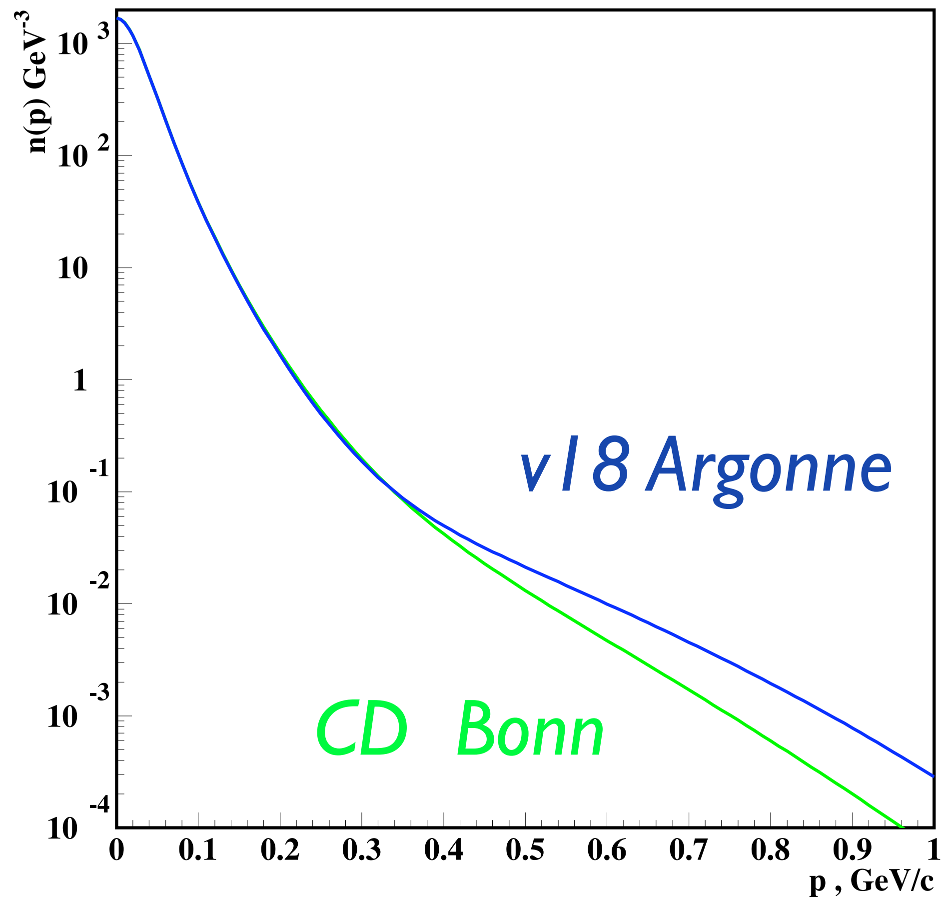
n(k) for ^{2}H, ^{4}He ^{16}O, nuclear matter

Consistent with a fast onset of the asymptotic behavior above the Fermi momentum

a_2(n.m.) ~ 5÷6

Deuteron wave function

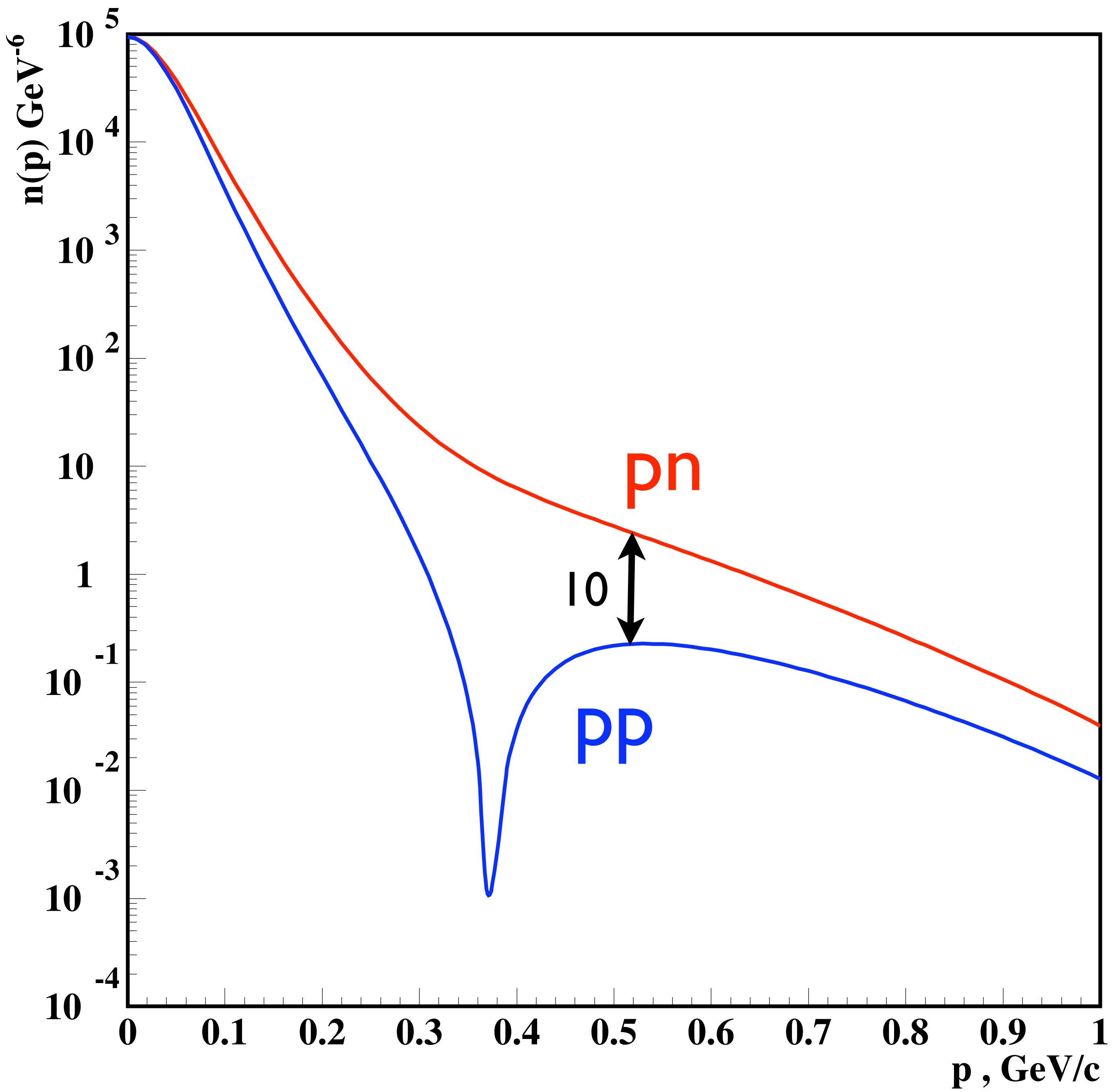


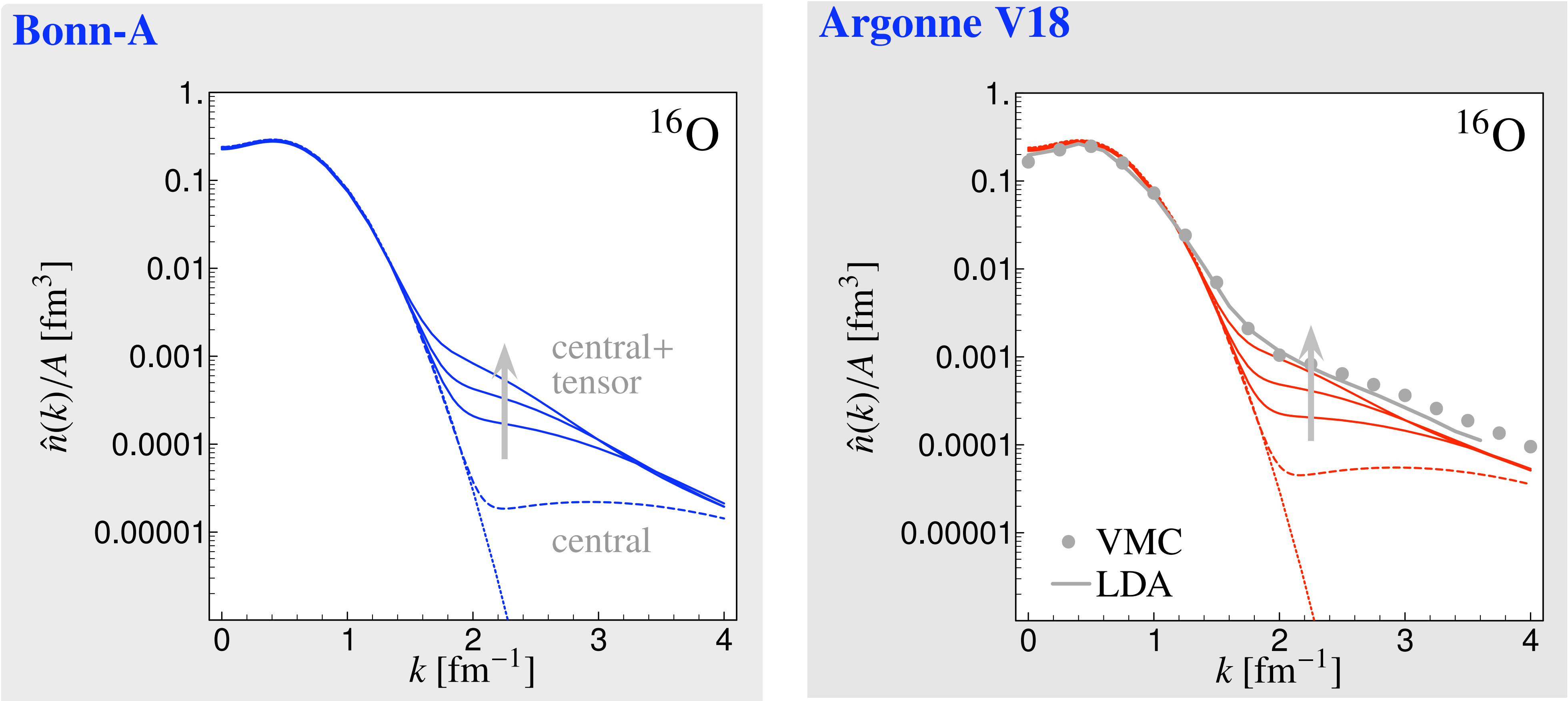


D-wave dominates in a large momentum range above 300 MeV/c. Known at least since 70's

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

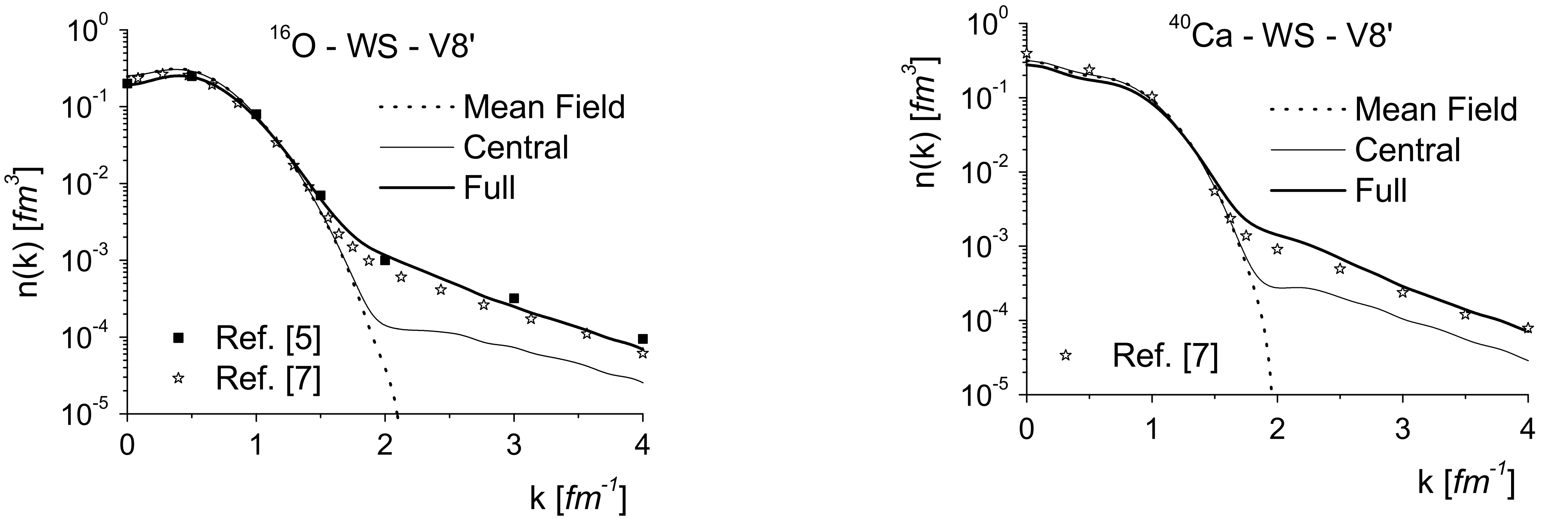
The pp/pn ratio is likely to depend on the momentum of the struck nucleon. For example for ^{3}He for a pn/pp pair with the third nucleon at rest. Fermi motion of the pair smears the momentum dependence of the ratio (M.Sargsian)





Neff et al 03

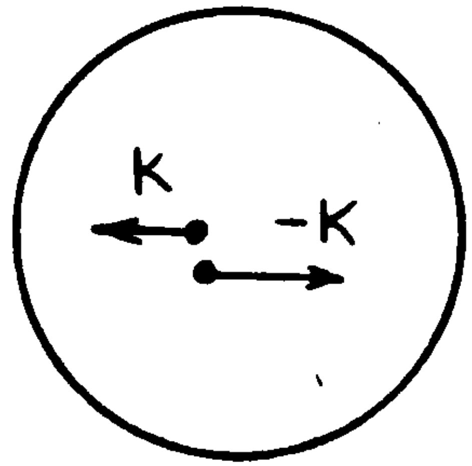
$n_A(k)$ for large k are quite different for different potentials, but a_2 values are rather close

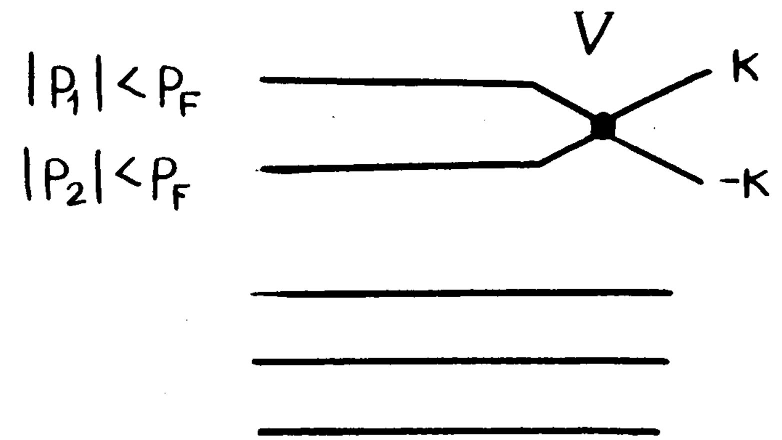


Alvioli et al 05

Calculations confirm dominance of tensor forces, but relative contribution of central forces varies from 10% to 20 %

important number for interpretation of E850 pn rates, will use later





Properties of the spectral function P(k,E) at large nucleon momenta

$$n_A(k) \underset{k\to\infty}{\sim} \psi^2_{2\mathrm{N}}(k) \sim \psi^2_{\mathrm{D}}(k).$$

$$V(k)\big|_{k\to\infty} \sim k^{-n}, \quad n_A(k)\big|_{k\to\infty} \sim \frac{V^2(k)}{k^4}.$$

$$P_A(k,E) = \langle \psi_A | a^+_{\mathrm{N}}(k)\delta(E + E_{\mathrm{R}} - E_{\mathrm{fX}}) a_{\mathrm{N}}(k) | \psi_A \rangle, \; n_A(k) = \int_0^\infty P_A(k,E)\mathrm{d}E.$$

$$E(k) + E_{\mathrm{R}}(k) \sim k^2/2m.$$

Can one check whether indeed the tail is due to SRCs?

Consider distribution over the residual energies, E_R, for A-1 nucleon system after a nucleon with momentum k was instantaneously removed -

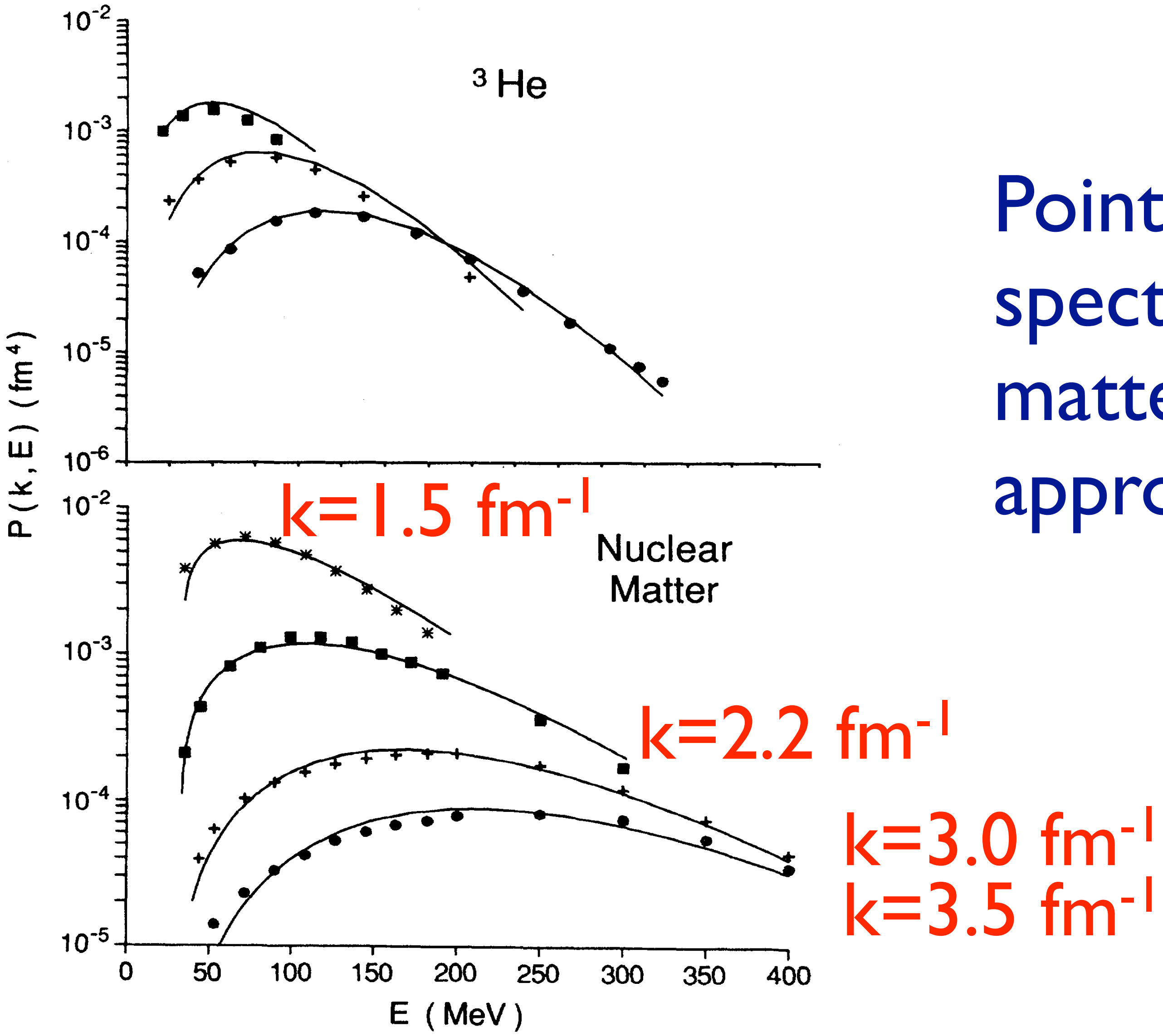
nuclear spectral function

$$P_A(k, E_r), n_A(k) = \int dE_R P_A(k, E_r)$$

for 2N SRC: $\langle E_R(k) \rangle = k^2/2m_N$ FS81-88

Confirmed by numerical calculations

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 pair in a mean field (Ciofi, Simula,Frankfurt, MS - 91). However numerical calculations 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

In addition to 2N correlations higher order correlations

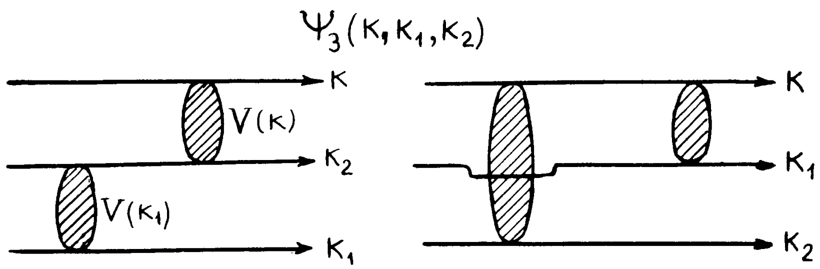
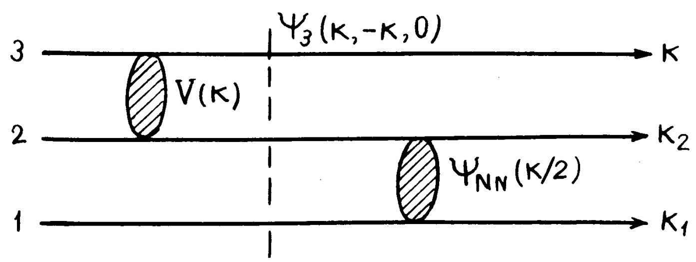


FIG. 8.8:

$$P_A(k,E)\big|_{E<\text{const.},\ k\to\infty} \sim \left(\frac{V(k/2)}{(k/2)^2}\right)^4 \sim n_A^2(k/2).$$



$$P_A(k,E_R(k))_{|k>k_F} = \sum_{j=2}^{A} P_j(k,E_R(k))$$

A new quantity to provide even cleaner test of the structure of SRCs- nuclear decay function (FS 77-88) - probability to emit a nucleon after removal of a fast nucleon. For 2N SRC can model decay function as decay of a NN pair moving in mean field (like for P_A) Piasetzky et al 06

Studies of the spectral and decay function of 3He reveal both two nucleon and three nucleon correlations - Sargsian et al 2004

Kim prompted a new analysis of BNL E850 data

Evidence for the Strong Dominance of Proton-Neutron Correlations in Nuclei PRL Oct.06

E. Piasetzky,[1] M. Sargsian,[2] L. Frankfurt,[1] M. Strikman,[3] and J. W. Watson[4]

n-p Short-Range Correlations from (p,2p + n) Measurements

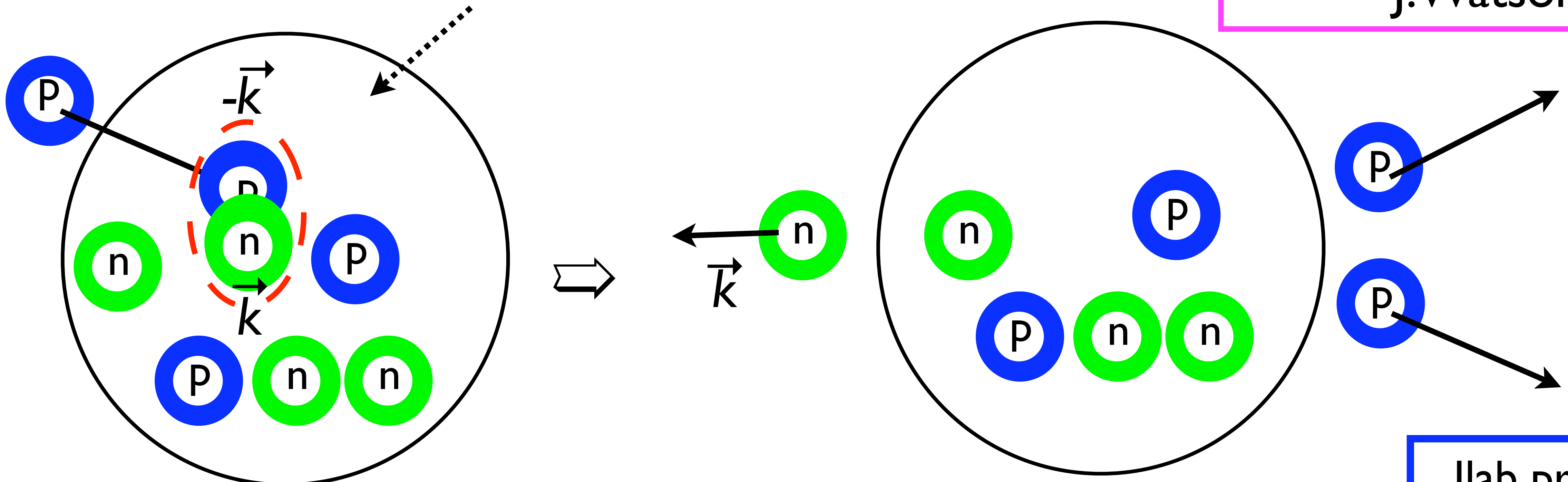
A. Tang[a], J. W. Watson[a], J. Aclander[b], J. Alster[b], G. Asryan[d,c], Y. Averichev[h], D. Barton[d], V. Baturin[f,e], N. Bukhtoyarova[d,e], A. Carroll[d], S. Heppelmann[f], A. Leksanov[f], Y. Makdisi[d], A. Malki[b], E. Minina[f], I. Navon[b], H. Nicholson[g], A. Ogawa[f], Yu. Panebratsev[h], E. Piasetzky[b], A. Schetkovsky[f,e], S. Shimanskiy[h], D. Zhalov[f]

PRL 04

at energy and momentum transfer ≥ 3 GeV

spectator mechanism of backward nucleon production *FS77*

talks of Eli Piasetzki and J.Watson



removal of a proton with momentum > 250 MeV/c

~90% probability of emission of neutron with similar but opposite momentum

+

Jlab preliminary: ~10% probability of proton emission

~100 % correlation! - Confirms our prediction - Farrar et al PRL 89 & indicates a much stronger dominance of pn correlations than according to our initial naive SU(4) symmetry estimate: n/p ~2

What is a naive expectation for $P_{np/X+np}$?

Wigner SU(4) symmetry - probabilities of pp, pn, nn pairs are related as :

$$P_{pp}:P_{pn}:P_{nn}=1:1:4$$

In coincidence rate pp pairs enter with a factor of 2

➠ $P_{np/X+np}=2/3$ → $\boxed{\text{Data indicate Enhancement of pn SRC}}$

However tensor correlations are strongly enhanced according to nonrel. calculations of n(k). Scalar ones contribute fraction λ~ 10-20% to n(k) for discussed momentum range. Assuming that tensor correlations are predominantly pn correlations (likely but not proven), and scalar SRC are isotriplet

$$P_{pp/pp+np}= \frac{2}{3}\frac{\lambda}{1+\lambda} = .06 \div .11$$

Studies of pp/pn yields will allow to discriminate between different models of nuclei/ NN interaction at high nucleon densities.

Consistency between (p,ppn) and (e,e'pN) data is highly nontrivial as in the first case forward moving nucleon is removed and in the second - backward moving.

ΣΣ  E850 provided the first direct observation of 2N SRC in nuclei

 Established strong dominance of pn SRC correlations

 Large pn/pp qualitatively consistent with dominance of tensor forces in the high momentum component

Jlab Preliminary result for $P_{pp/pp+Xp}$= 8±2%

Confirms dominance of pn correlations

Direct measurement of R=σ(e,e’pp)/σ(e,e’ pn) finds R << 1

Proton with momentum 600> p> 300 MeV/c

belongs to a pn correlation with probability $94\% \geq P_{pn} \geq 74\%$

belongs to a pp correlation with probability $8\% \geq P_{pp} \geq 6\%$

5.4%>”# of pp pairs”/”# of pn pairs” >3.2%

Compare to SU(4) expectation of 25%

Future detailed comparisons of (p,2pn) and (e,e’pn) data - important test of universality of the decay function, understanding of interaction mechanism

My last conversation with Kim in July:

From the very beginning when I was doing electron scattering experiments in Kharkov, I tried to find a way to observe short-range correlations in nuclei. I am happy that I finally observed them.

Summary

Recent experiments confirmed expectations of large practically universal SRC in nuclei - 25% probability for two nucleon SRC in heavy enough nuclei with dominant contribution due to pn correlations.

First extensive evidence for presence of 3N short range correlations in nuclei

Dominance of nucleonic degrees of freedom in SRC

Further studies are necessary, preferably using both leptonic and hadronic probes:

Studies of forward - backward correlations for a range of light nuclei $^3He/^4He(e,e')$ pp/pn at Jlab at $Q^2=2 \div 4$ GeV^2. A-dependence of the pp/pn ratio, its dependence on momentum of hit nucleon. Looking for effects of 3N correlations in A(e,e' p +2 backward nucleons). Reminder: for the neutron star dynamics mostly isotriplet nn, nnn,.. SRC are relevant.

Tagged structure functions: $e + {}^2H \rightarrow e +$ "backward nucleon + X

$e+A \rightarrow e$ +forward p + Backward isobars, N*'s +X,...

Use of the hadronic facilities - J-PARC, GSI, FNAL (?)

Calculation of the nuclear LC wave functions, spectral functions and decay functions for A>2

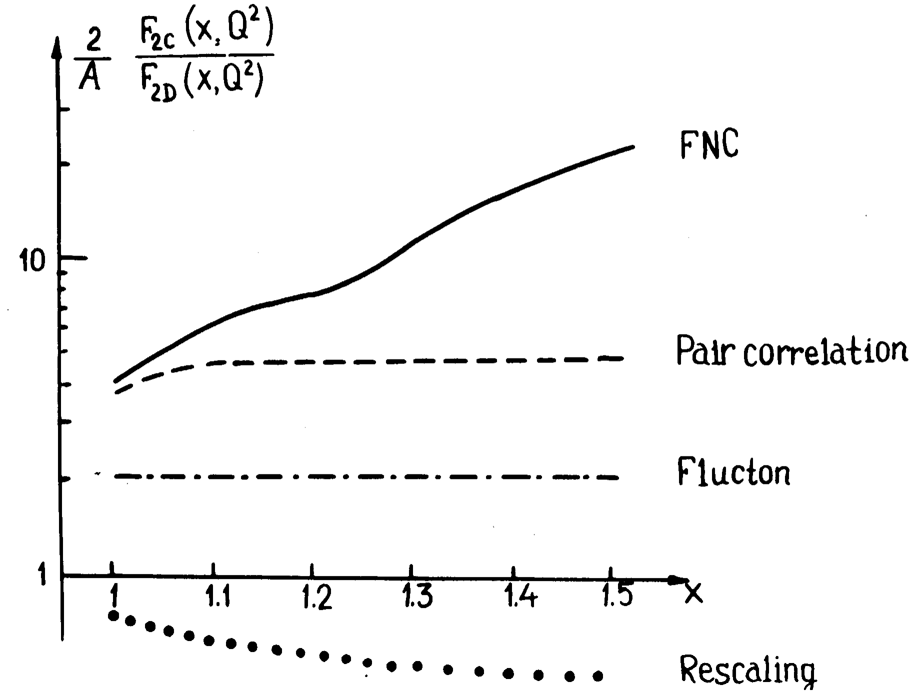
Supplementary pages

$$F_{2A}(x,Q^2) = \sum_{\mathrm{N=p,n}} \int F_{2\mathrm{N}}(x/\alpha, Q^2)\rho_A^{\mathrm{N}}(\alpha, k_{\mathrm{t}})\frac{\mathrm{d}\alpha}{\alpha}\mathrm{d}^2 k_{\mathrm{t}}.$$

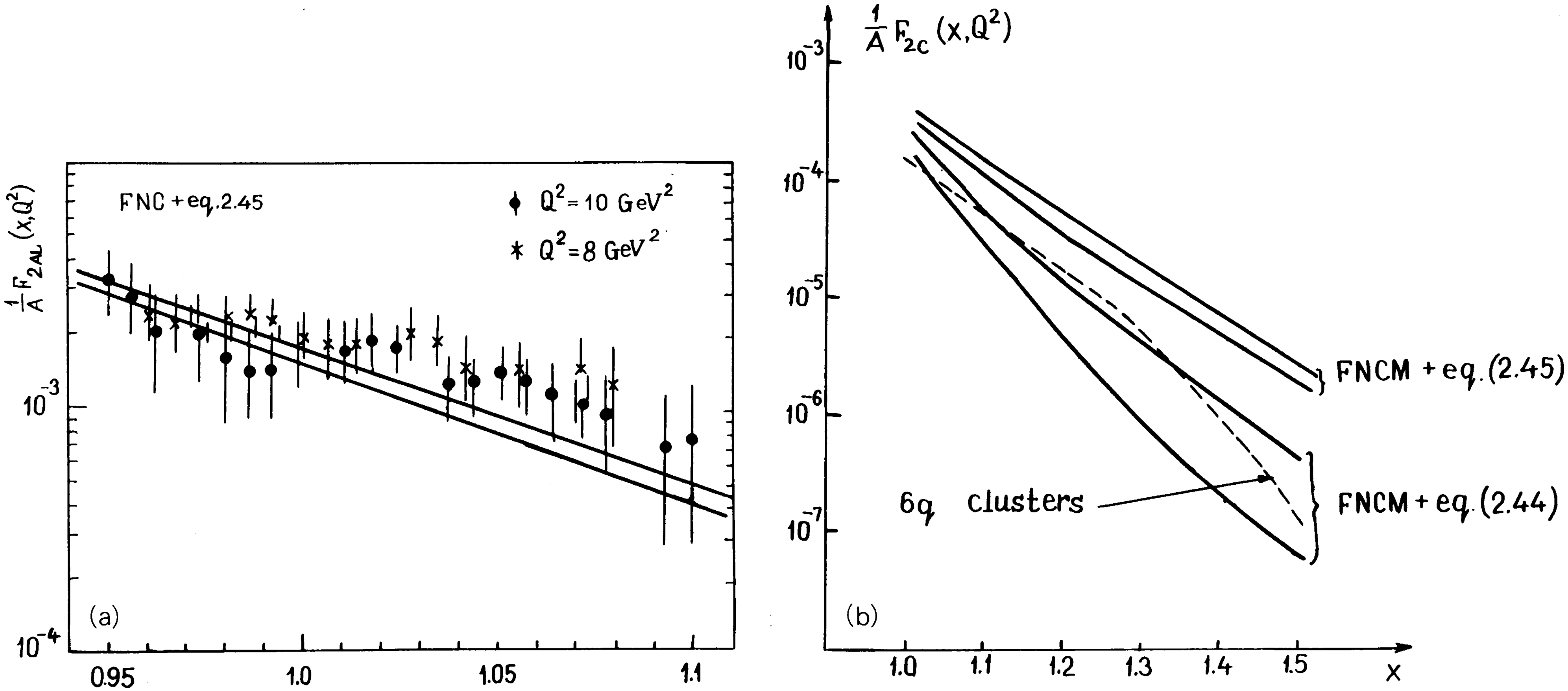
Since $\rho_A^{\mathrm{N}}(\alpha, k_{\mathrm{t}})$ at $\alpha > 1$ rapidly decreases with α ($\sim \exp -7\alpha$), the prediction

$$F_{2A}(x, Q^2 > 10\,GeV^2)_{|\,x>1} \propto \exp(-bx), b \sim 8 \div 9$$

Neutrino DIS CCFR 1999: b = 8.3± 0.7 (stat) ± 0.7 (syst)



Expectations for the A dependence at x>1 in different models



(a) Comparison of the prediction of the FNC model combined with the minidelocalization model of the EMC effect for F_{2Al} (x, Q^2) (solid line) with SLAC data (b) The FNC + minidelocalization model prediction for F_{2C} ($x>1$, $Q^2=100$ GeV^2) and the 6q model predictions neglecting the scaling violation effects.