Short-range nucleon correlations in nuclei: direct observation and applications

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Outline

Open questions of microscopic nuclear structure

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

Structure of short-range NN correlations in nuclei and concept of the decay function

Direct observations of short-range correlations using high energy probes

Strategies for further studies: Jlab and FAIR (PANDA, CBM,...) potential.

Examples of Implications: neutron stars & heavy ion collisions

Bumpy history of short-correlation studies

Bethe-Bruckner-Goldstone *theory developed in 60's - short-range correlations between nucleons play a very important role - however* numerically challenging.

Mean field models explain many regularities of nuclear structure with no need to invoke short - range correlations

Experimental searches for SRC in photon and pion absorption -- processes definitely involve at least two nucleons but not clear whether process occurs due to initial state or final state ?

General sentiment of late seventies is well expressed in the letter we received from the editor of Phys.Lett.. in 1977: For many years the claims were made repeatedly that it is possible to observe experimentally short-range correlations in the nucleus wave function. All of them turned out to be false. Hence I made a decision to reject manuscripts with such claims without review.

Four energy scales in structure (interactions with) nuclei

Low momentum nucleons ($< k_F$ - a naive estimate of the highest momenta in nuclei for non-interacting gas)

High momentum nucleons - due to local NN interactions - slowly decreasing with k

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

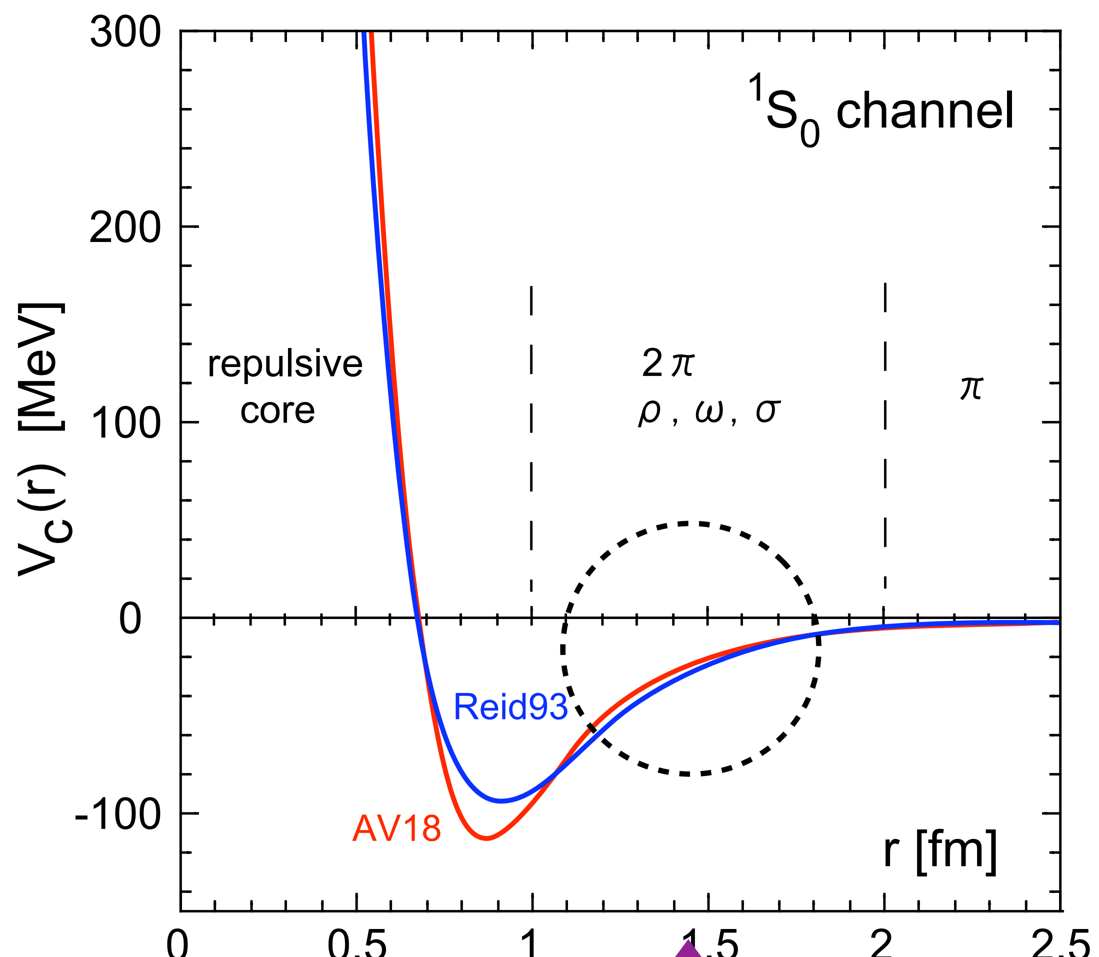
② Nuclear observables at intermediate energy scale: energy transfer < 1 GeV and momentum transfer q < 1 GeV. Transition from quasiparticles to bare nucleons - very difficult region - observation of the momentum dependence of quenching (suppression) factor for A(e,e'p) (Lapikas, MS, LF, Van Steenhoven,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

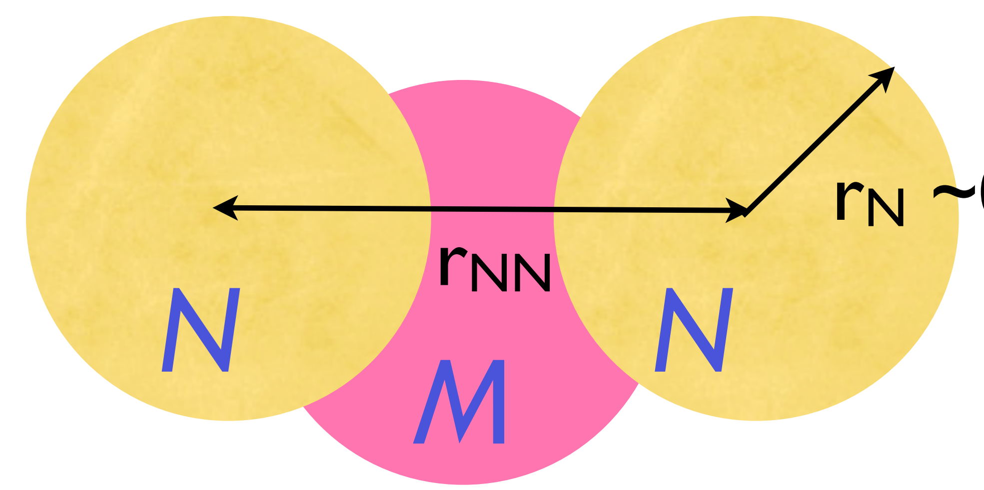
③ Hard nuclear reactions I: energy transfer > 1 GeV and momentum transfer q > 1 GeV. Resolve SRCs = direct observation of SRCs but not sensitive to quark-gluon structure of the bound states

④ Hard nuclear reactions I: 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

Why short-range structure of nuclei is interesting from QCD angle

Before QCD - paradox - strength of meson nucleon interaction increases with virtuality in the meson-nucleon field theoretical models: *zero charge (Landau) pole is present at rather small virtualities. No trace of this effect in NN and πN interactions. Even without the zero charge pole - interaction is very strong - why nucleus is build of nucleons and does not looks as a meson soup?*



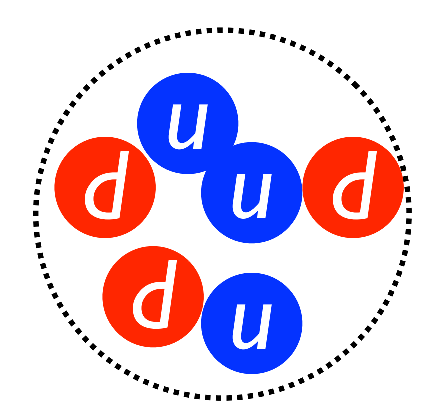


For r_{NN}< 1.5 fm difficult to exchange a meson; valence quarks of two nucleons start to overlap

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

Could nucleus be a quark soup?

quark kneading (FS75)



became popular under name six quark bags

quark interchanges?

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

high sensitivity to microscopic dynamics of SRC

Why studying SRC is important

- Best chance to observe new physics beyond many nucleon approximation - Δ's, quark - gluon degrees of freedom, etc

- Properties of drops of very dense nuclear matter ➜ Eq. of state for cores of neutron stars

  Very different strength of pp and pn SRC, practical disappearance of the Fermi step for protons for ρ(neutron star) >ρ (nuclear matter)

- ~80% of kinetic energy of heavy nuclei is due to SRCs = powerhouse of nuclei

- Microscopic origin of intermediate and short-range nuclear forces

- Numerous applications

Modeling of νA quasielastic scattering

Neutron production in AA collisions at RHIC, LHC

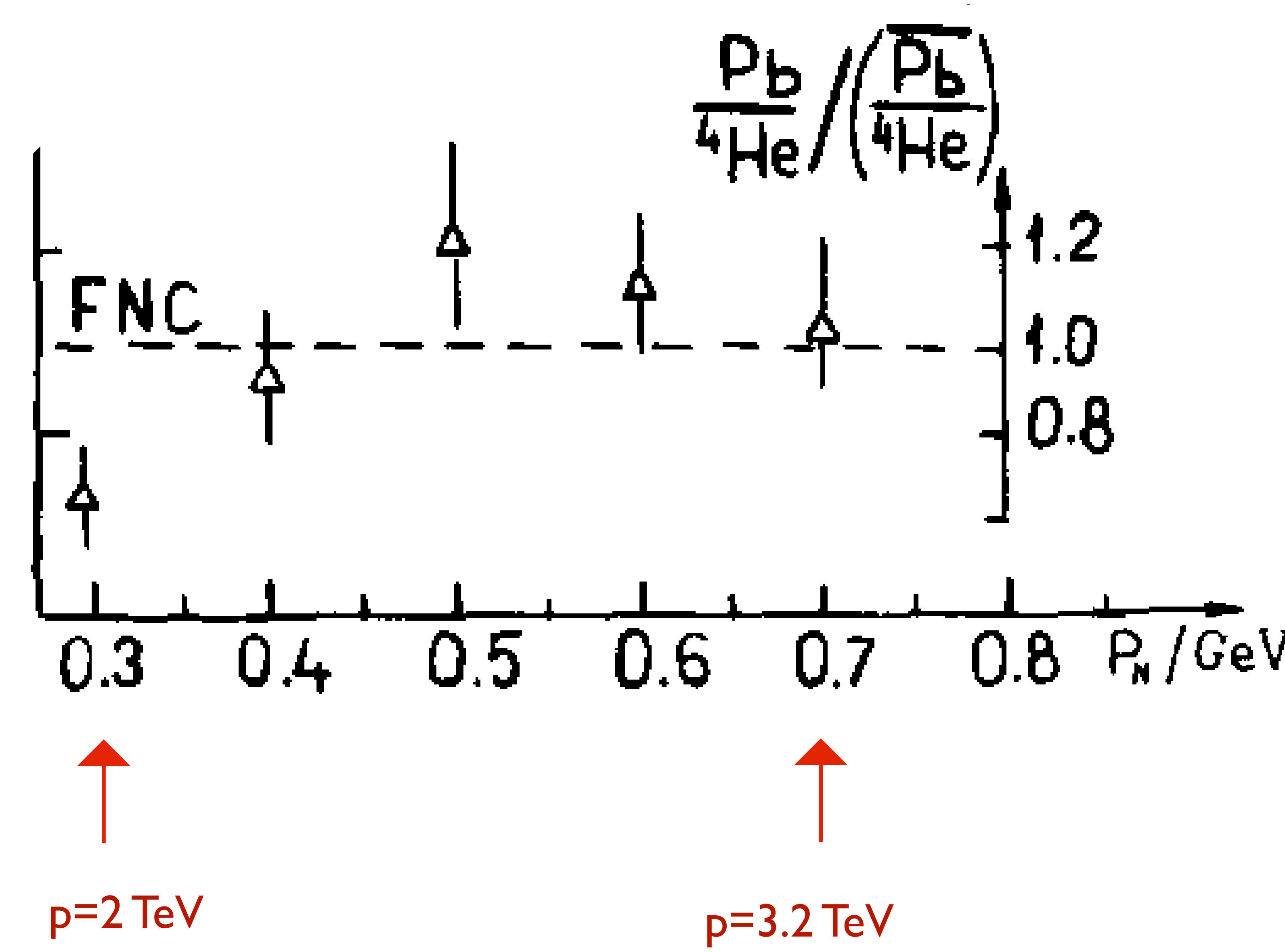
Together with Leonid Frankfurt we started our studies of the microscopic nulcear structure in 1974. Our prime motivation was: quarks were seen in DIS - large momentum transfer processes - can one perform similar program in nuclei and see constituents of the nucleus?

On experimental side: no lepton induced data - first data on large Q^2 momentum transfer reactions with deuteron emerged only a year later. However there was a puzzle in (lepton)hadron - nucleus interactions.

Formulation using collider kinematics *(actual measurements at fixed targets with proton, photon, pion and nuclear beams):*

Consider collision of nuclei A_1 and A_2 at a collider - LHC with E_A/A= 1.6 TeV

- *nucleons E_N up to 4.8 TeV are observed*
- *shapes of the spectra from A=^{4}He and A=Pb are practically same between 2 TeV and 3.2 TeV while each cross section drops by a factor of 100.*



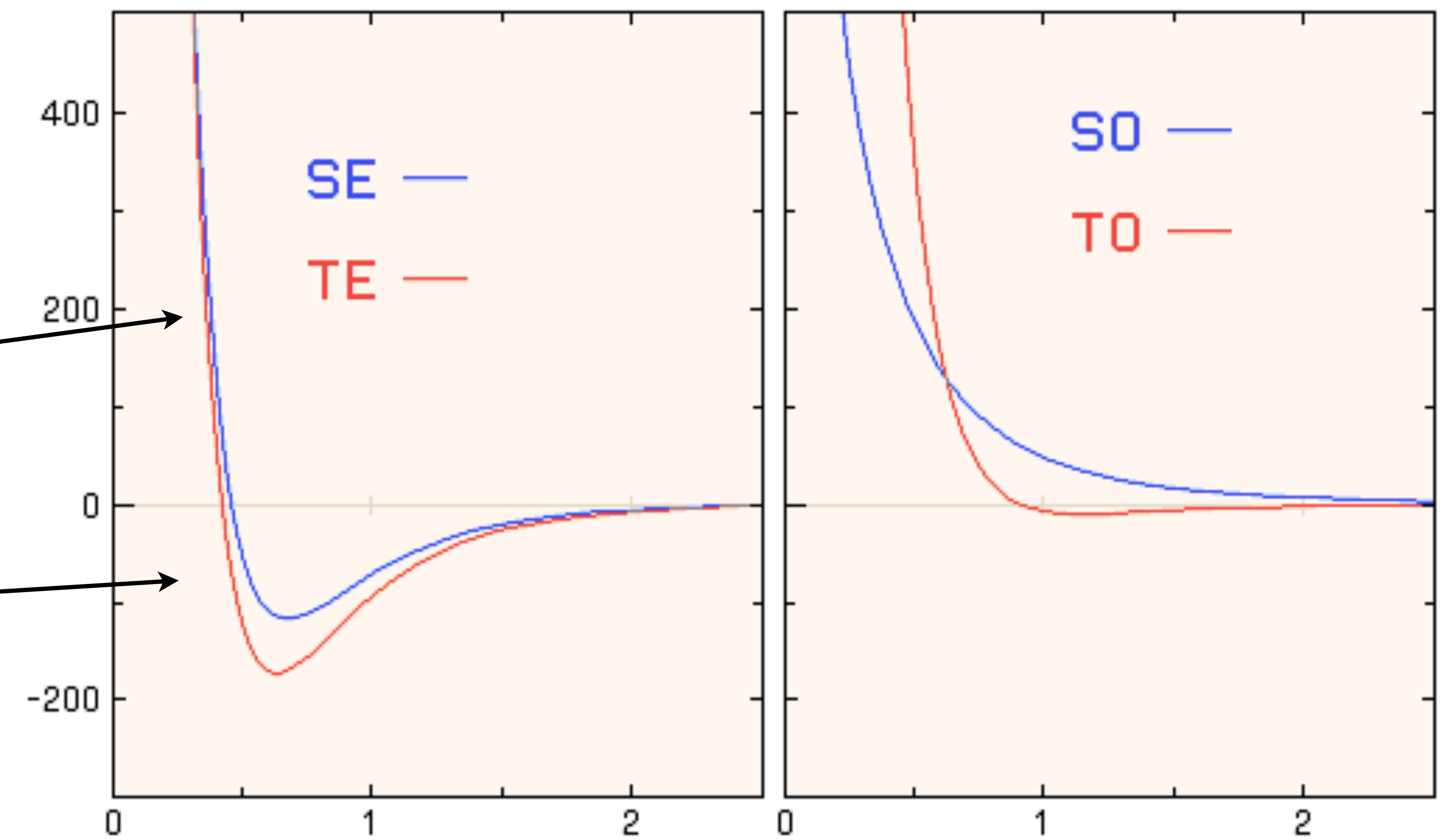
Properties of SRC in nonrelativistic QM

I=0 and I=1 pn interactions differ (but for most cases the difference is small

$V_{NN}(r)$ [MeV]

strong repulsion

strong attraction



S= singlet - spin 0, T=triplet - spin 1

E (O)= even (odd) --- wave function on NN system

TE curve corresponds to the deuteron - no such state for channel pp and nn due to Pauli principle.
SE exists for pp, nn, np - attraction is a bit smaller ➡ no bound states - only resonances.

Use hard nuclear phenomena to answer fundamental questions of microscopic quark-gluon structure of nuclei and nuclear forces

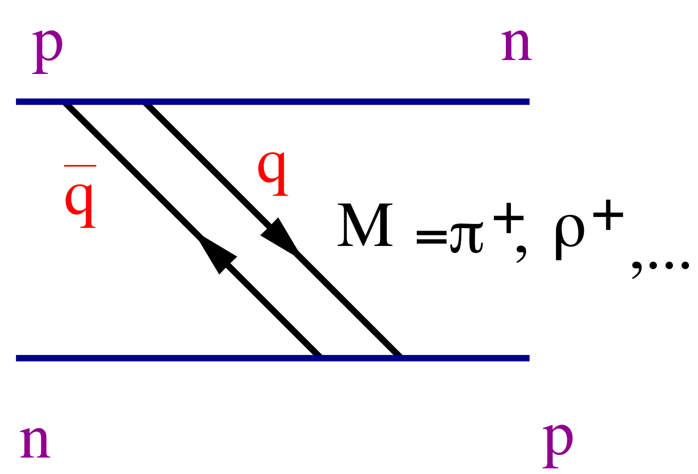
- Are nucleons good nuclear quasiparticles?

- Microscopic origin of intermediate and short-range nuclear forces

- Probability and structure of the short-range correlations in nuclei

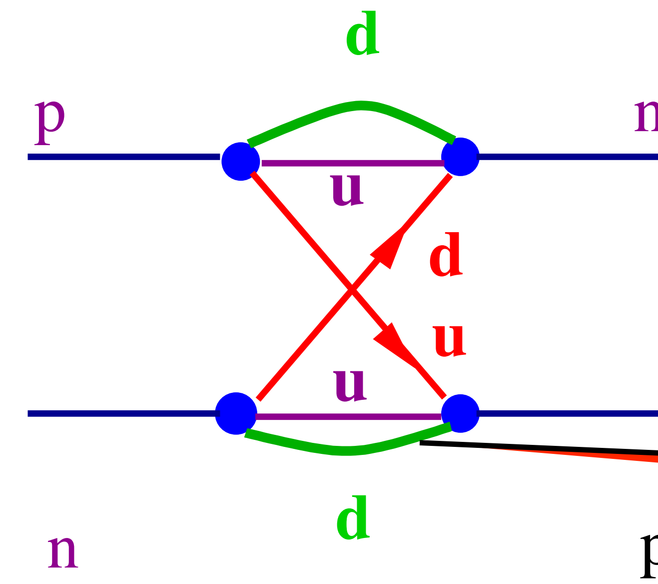
- What are the most important non-nucleonic degrees of freedom in nuclei?

- Microscopic origin of intermediate and short-range nuclear forces
  - do nucleons exchange mesons or quarks/gluons? Duality?



Meson Exchange

extra antiquarks in nuclei



Intermediate state may not be = pn

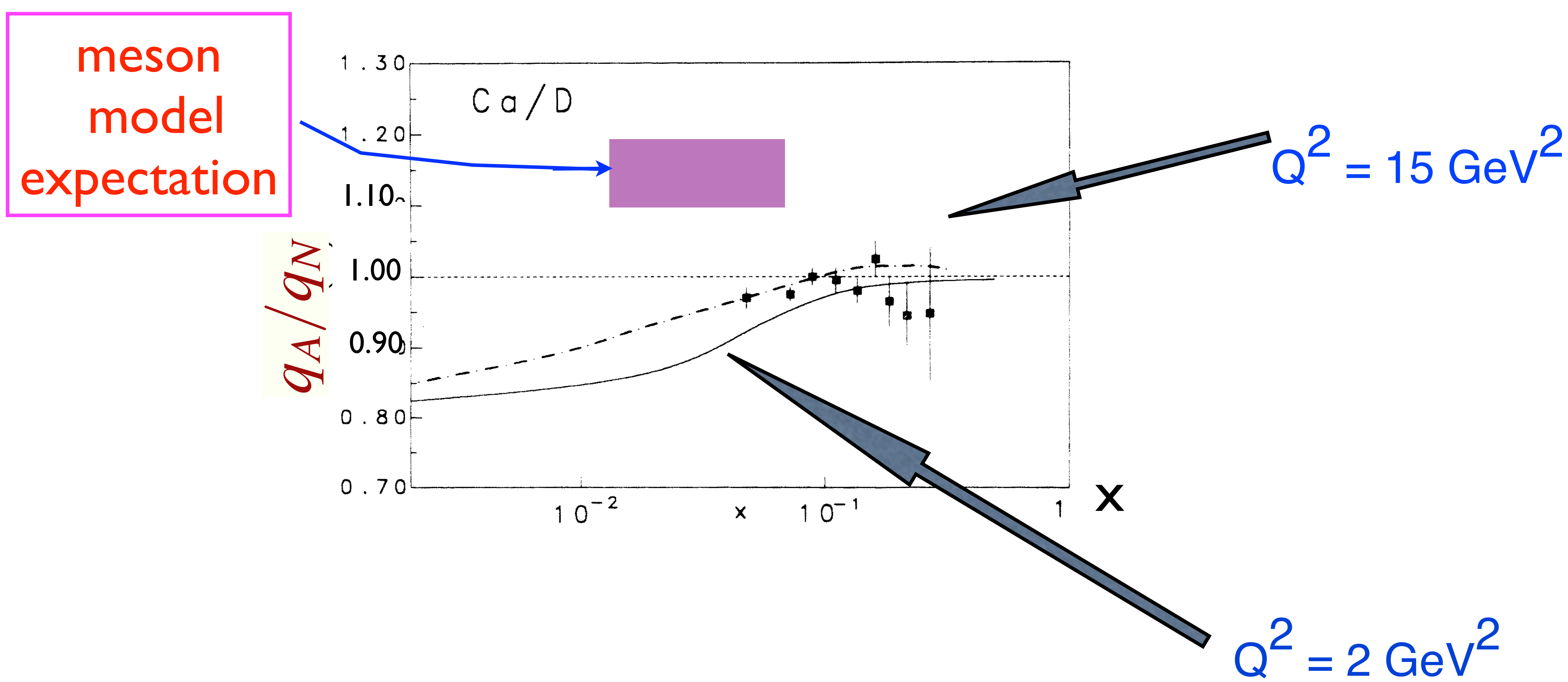
Quark interchange

no extra antiquarks

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

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

Drell-Yan experiments: $\bar{q}_A/\bar{q}_N \sim 0.97$



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

- Are nucleons good nuclear quasiparticles?

Successes of nuclear physics build on description of nucleus as a multinucleon system - "explanation" of 70's - treat nucleus as a Landau-Migdal Fermi liquid theory with nucleons as quasiparticles (close connection to mean field approaches) - should work for processes with energy transfer ~ E_F and momentum transfer $q \sim k_F$. 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 (Lapikas, MS, LF, Van Steenhoven, Zhalov 2000)

Short range correlation (SRC) effects are hidden in parameters of the quasiparticles

A.B. Migdal & V. Khodel told us - SRC could be 10% or 50% does not matter

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

Geometric reasoning questions all this picture. We argued that it is misleading and that 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 production which is forbidden in the deuteron channel.

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

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

Not surprisingly for high energy physicists - there is a price to pay for using high energy processes - taking into account relativistic dynamics of high energy interaction - high energy processes develop along the light cone: t-z=const

☝ - *Correspondence argument 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.*

Logic of quantum mechanics does not map easily to the language of virtual particles - transformational vacuum pairs. At the same time language of QM does not match space-time development of high energy processes which are usually light-cone dominated.

⇒ Relativistic (light-cone) treatment of the nucleus (FS76) - price of switching from nonrelativistic to light-cone quantum mechanics is not very high: in broad kinematic range a smooth connection with nonrelativistic description of nuclei (more complicated structure of the scattering amplitude). Will use relativistic approach when absolutely necessary.

Best chance to find new physics is to focus on the studies of configuration in nuclei where nucleons nucleons are close together and have large momenta - short-range correlations (SRC)

Popular perceptions about SRC:

- SRC is elusive feature of nuclei - cannot be observed

✔ Wrong - problem was due to use of low energy probes

- SRC small correction to any characteristic of nuclei - exotic feature - of no importance

✔ Wrong - >60% of kinetic energy of nucleons for A≥50 is due to SRC, strong influence on the nucleus excitation spectrum (more examples in the end of the talk)

- Can predict properties of the core of neutron stars based on studies of nuclei using mean field

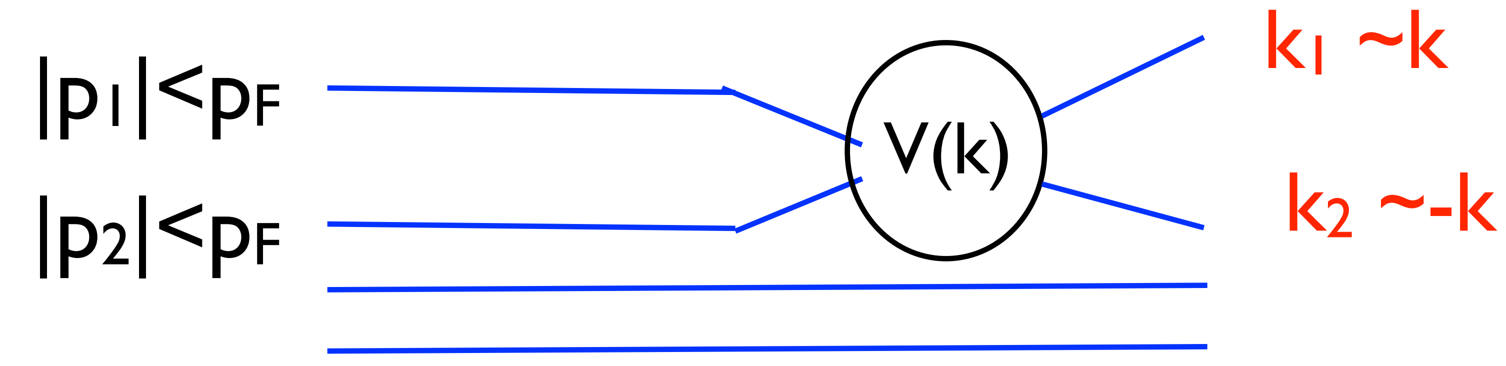
✔ Wrong - Very different strength of pp and pn SRC, practical disappearance of the Fermi step for protons for ρ(neutron star) >ρ (nuclear matter)

Probability and structure of SRC in nuclei

Questions:

- Probability of SRC?
- Isotopic structure
- Non-nucleonic components

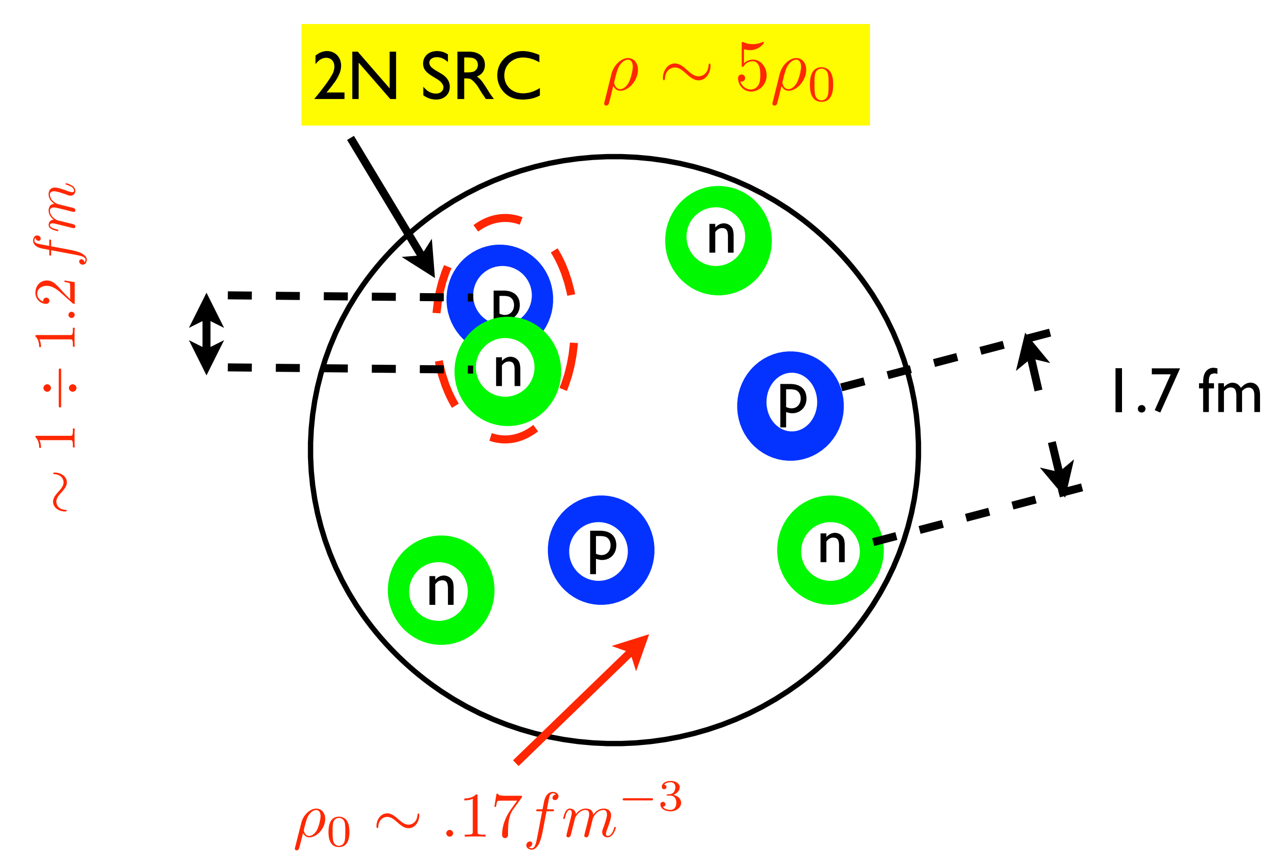
Dominant contribution for large k; 2N SRC:
universal (A-independent up to isospin effects)
momentum dependence



Two nucleon SRC

$k_2 \sim - k_2 > k_F$

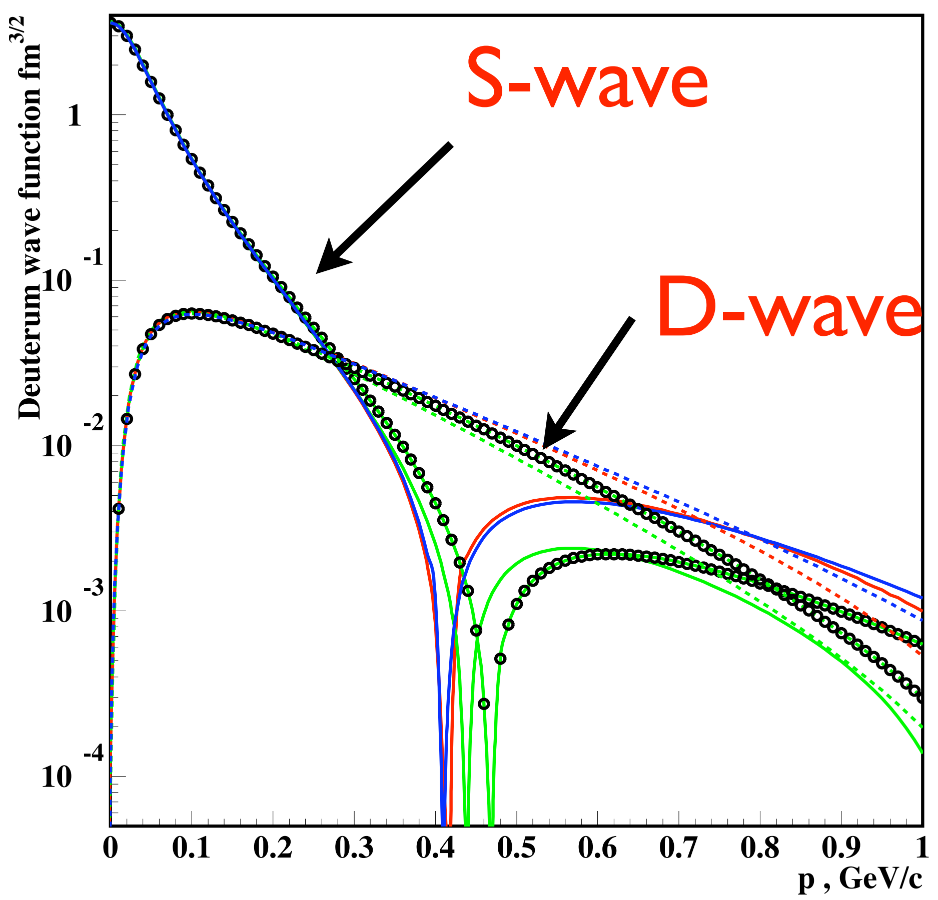
Short-range NN correlations (SRC) have densities comparable to the density in the center of a nucleon - *drops of cold dense nuclear matter*



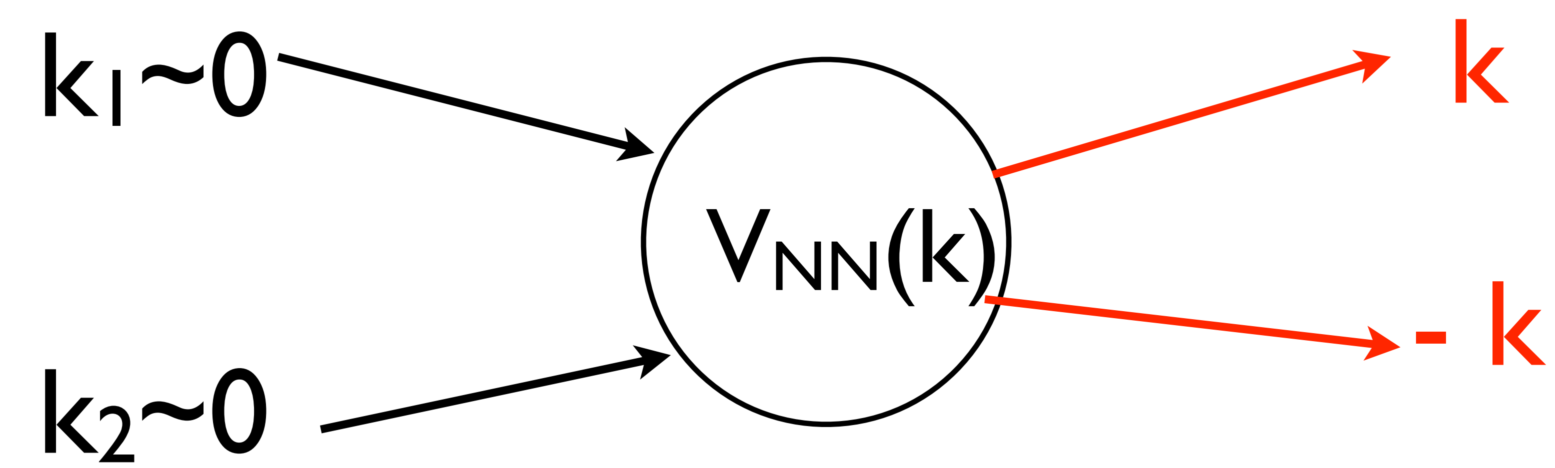
Connections to neutron stars:
a) I=1 nn correlations,
b) admixture of protons in neutron stars → I=0 sensitivity
c) multi-nucleon correlations

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:



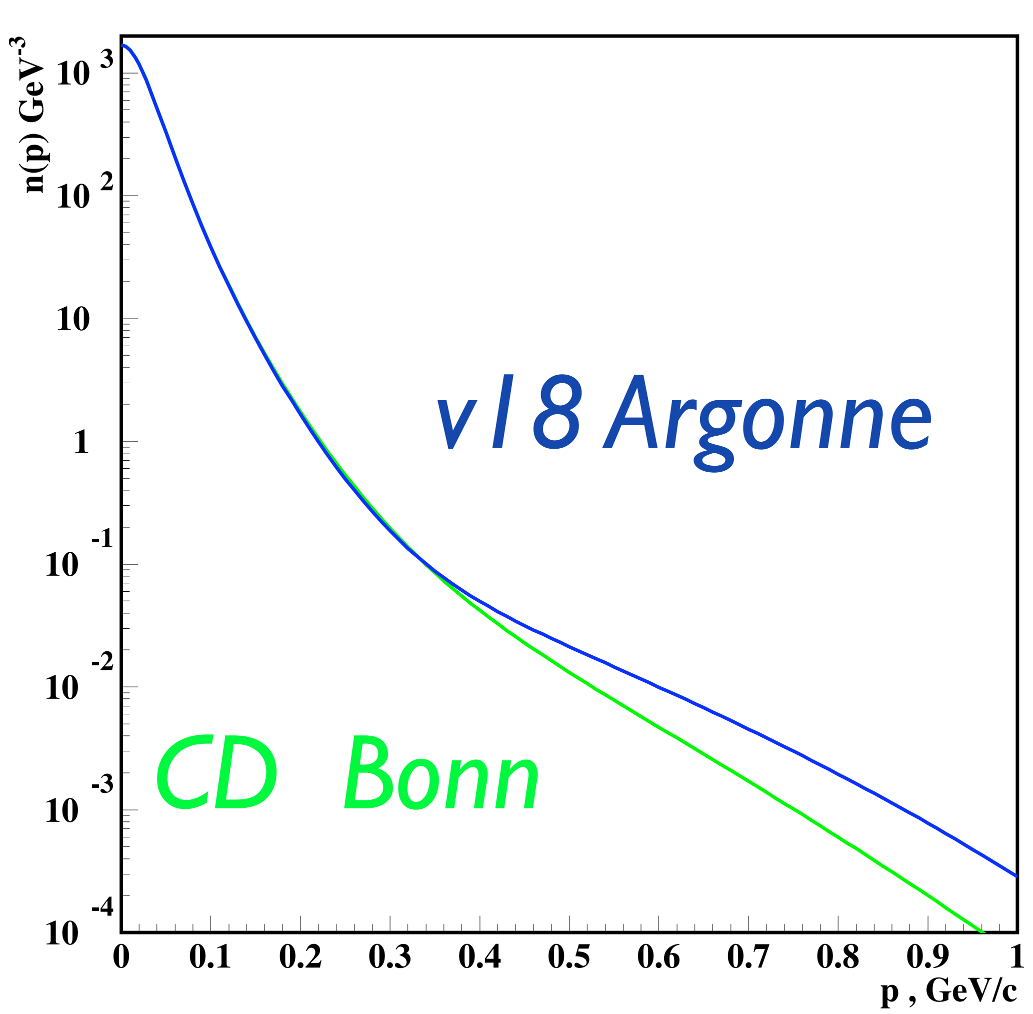
$$\psi_D^2(k)_{|k\to\infty} \propto \frac{V_{NN}^2(k)}{k^4}$$



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

Deuteron wave function



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

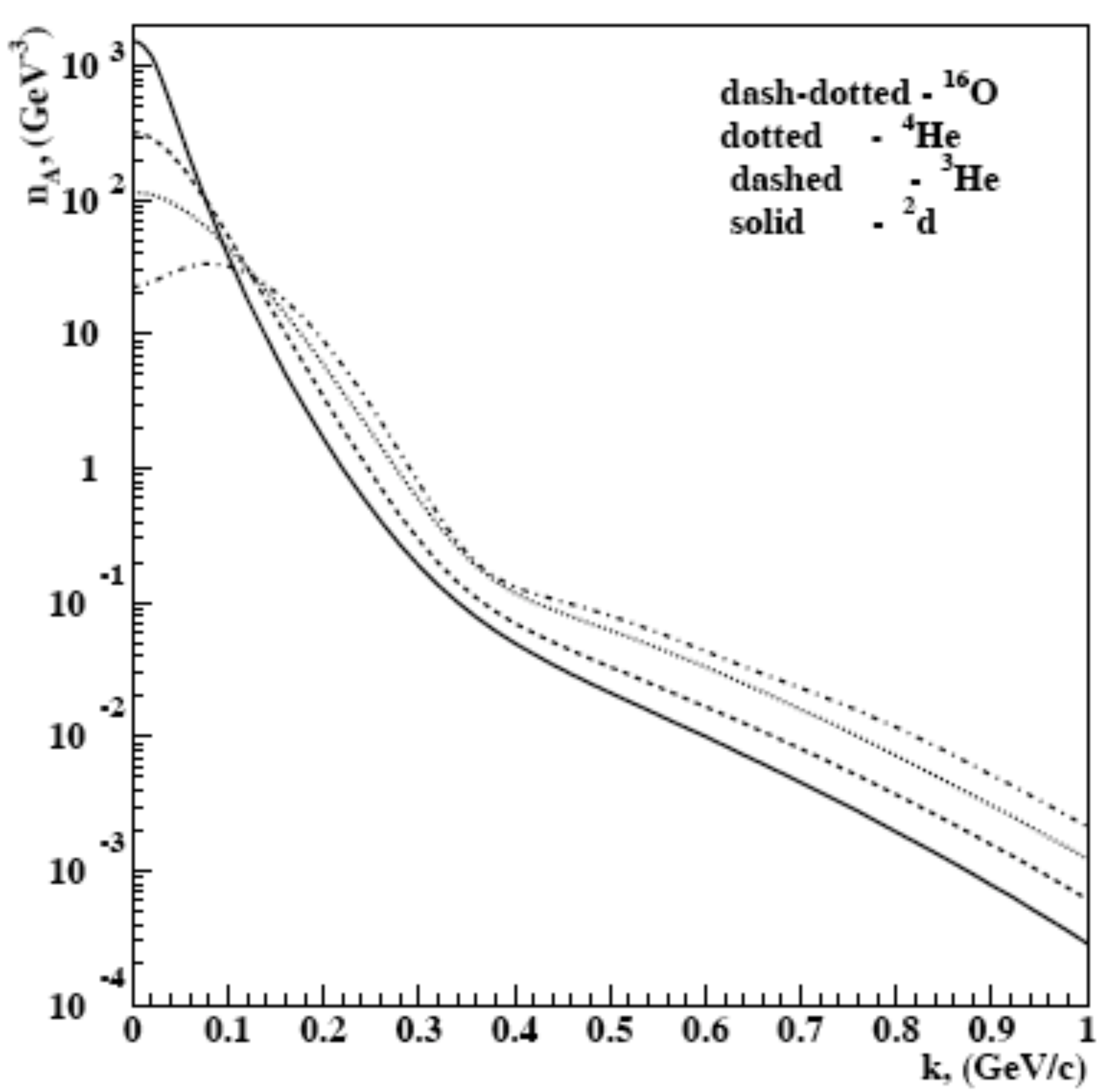
Large differences between in $n_D(p)=\psi^2{}_D(p)$ for p>0.4 GeV/c - absolute value and relative importance of S and D waves between currently popular models though they fit equally well pn phase shifts. Traditional nuclear physics probes are not adequate to discriminate between these models.

Similarly for $n_A(k) = \int \prod_{i=1}^{i=A} d^3k_i \psi_A^2(k_i)\delta^3(k - k_1)$

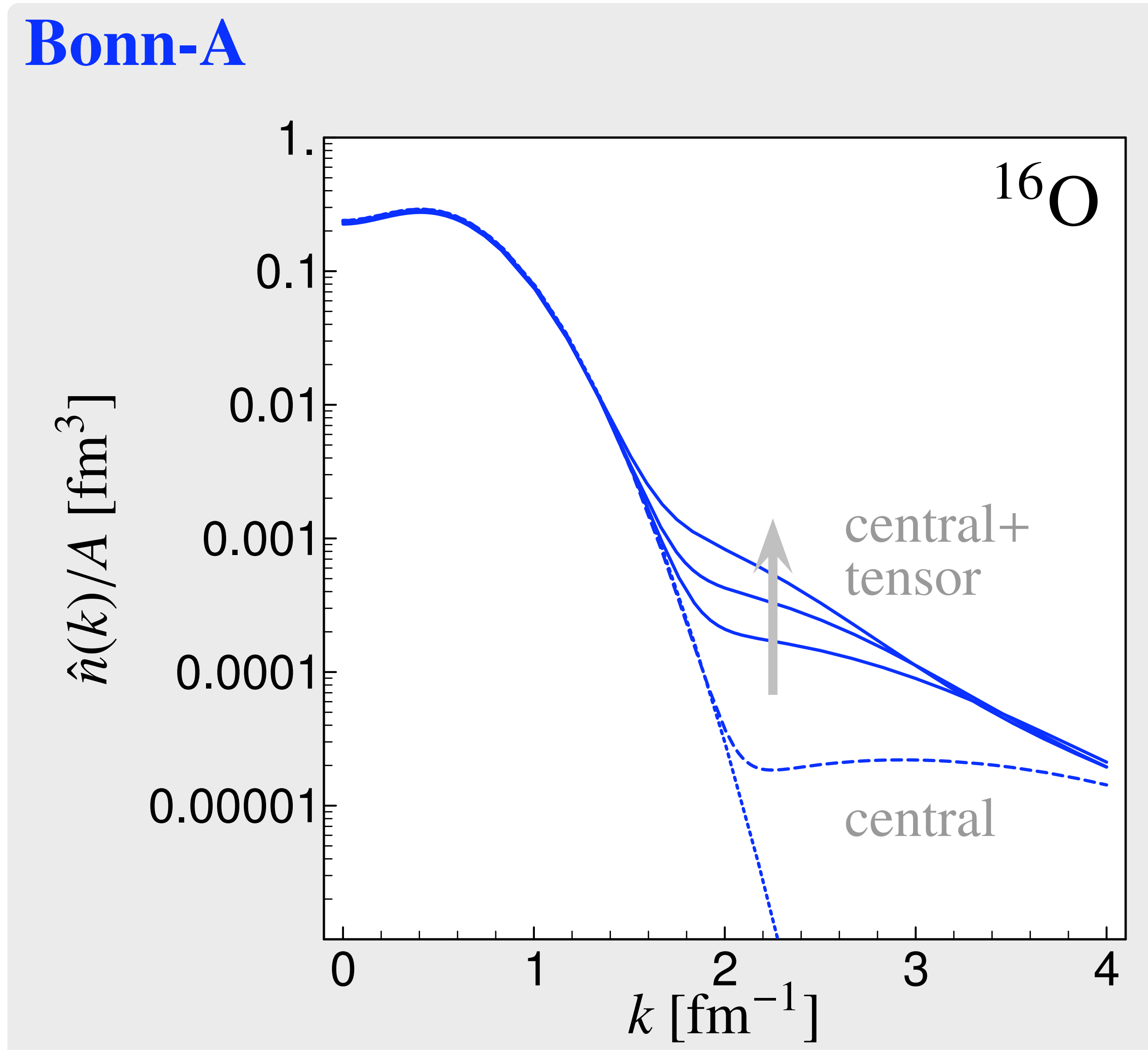
$$n_A(k)_{|k\to\infty} \propto \frac{V_{NN}^2(k)}{k^4}$$

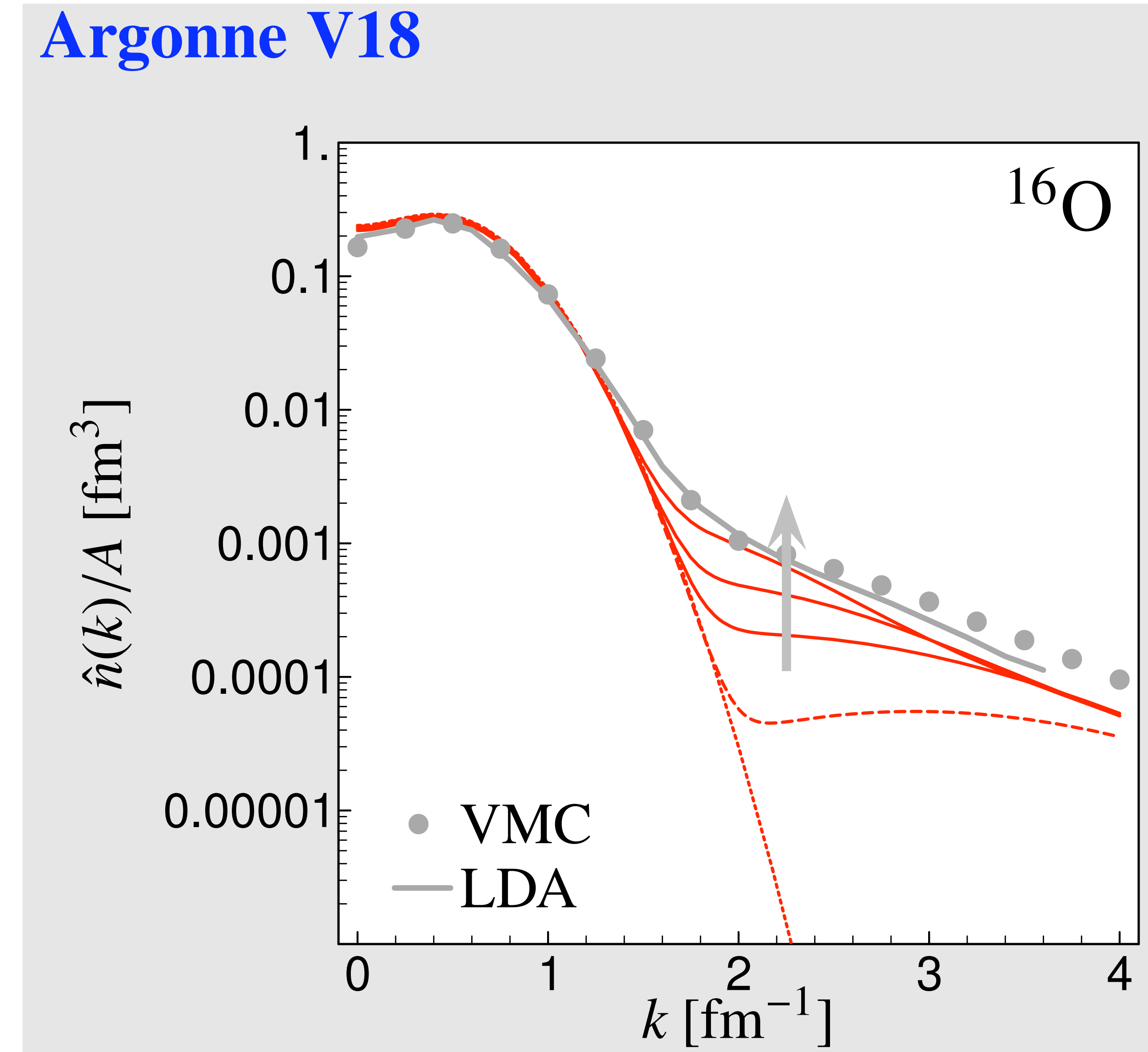
$$\Longrightarrow n_A(k) \approx a_2(A)\psi_D^2(k)_{|k\to\infty}$$

confirmed by numerical calculations starting ~ 1980



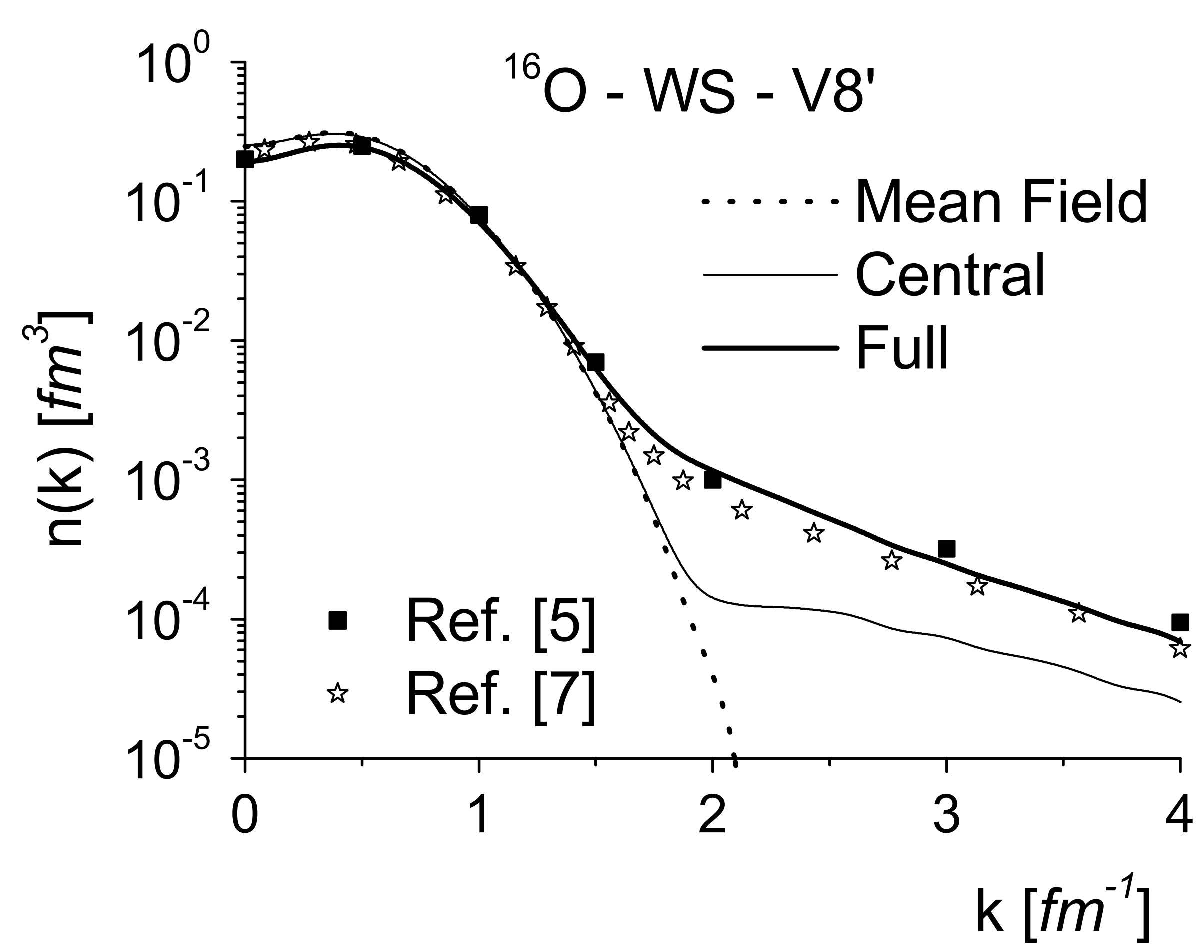
Pieper et al 92

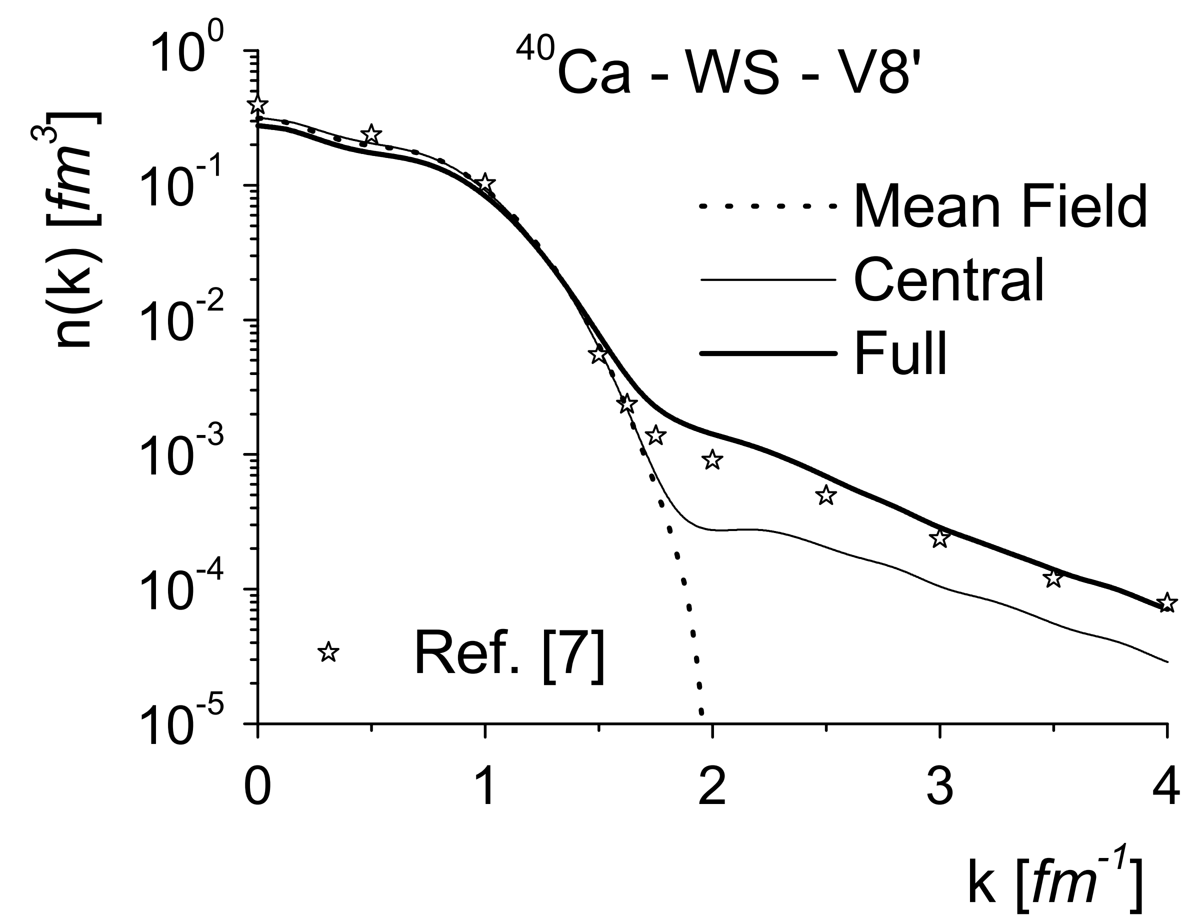




Neff et al 03

$n_A(k)$ 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 %

The trend is qualitatively consistent with observed large pn/pp ratios in hard processes

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 -

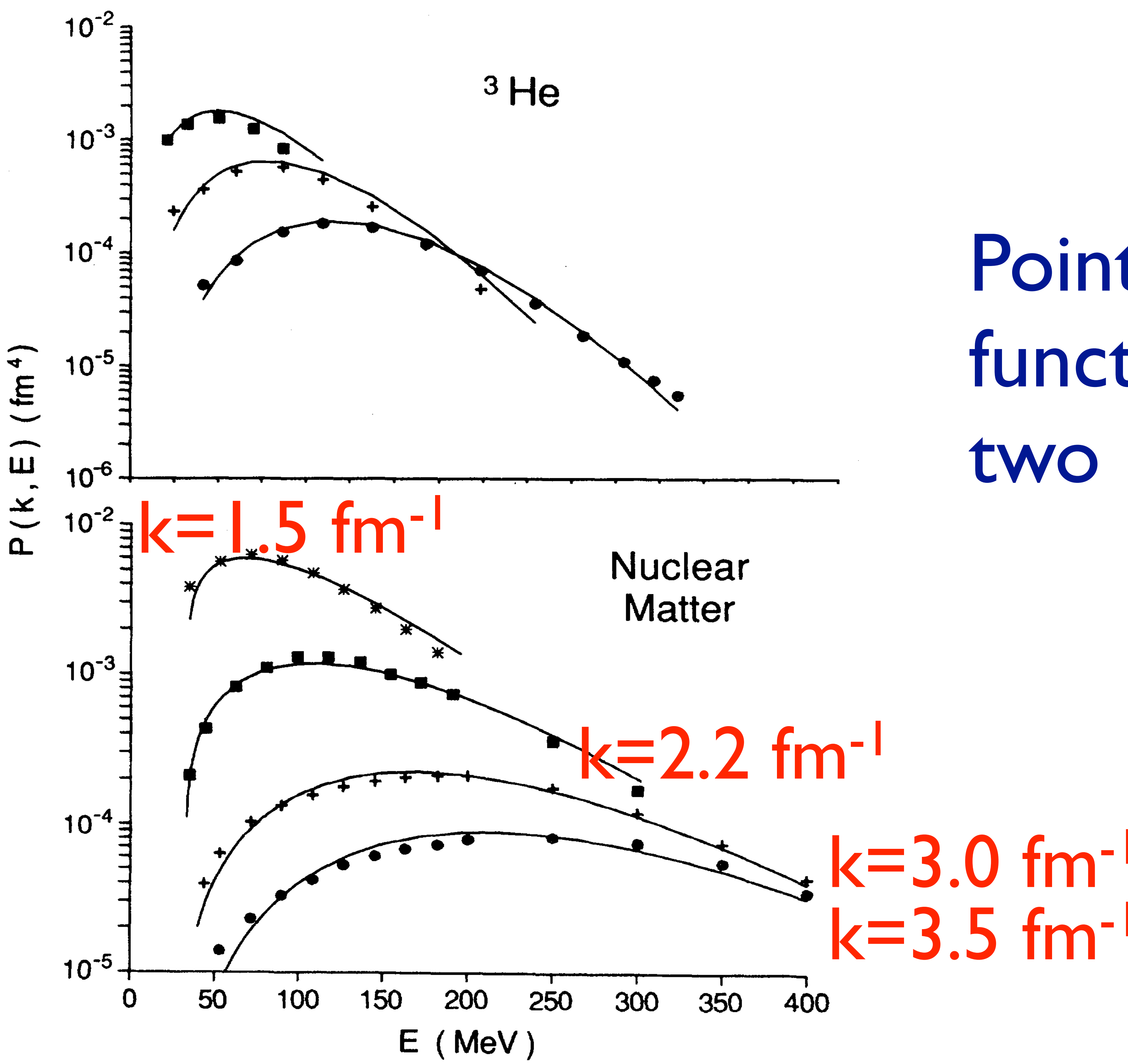
nuclear spectral function

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

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

Consensus of the 70's: it is hopeless to look for SRC experimentally

NO GO theorem: high momentum component of the nuclear wave function is not observable (Amado 78)

Theoretical analysis of F&S (75) : results from the medium energy studies of short-range correlations are inconclusive due to insufficient energy/momentum transfer leading to complicated structure of interaction (so called meson exchange currents,...), enhancement of the final state contributions.

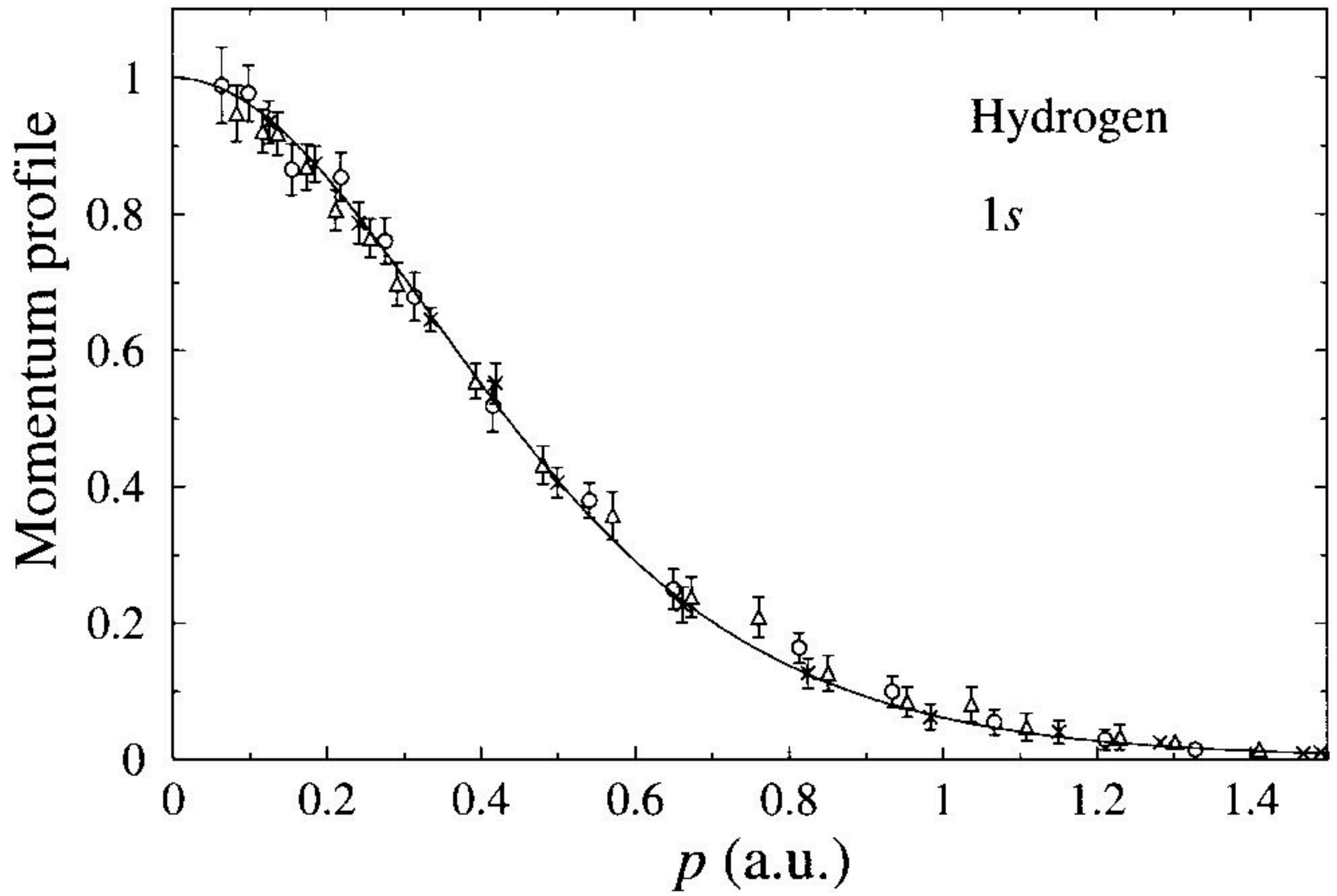
Way out - use processes with large energy and momentum transfer:

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

Adjusting resolution scale as a function of the probed nucleon momentum allows to avoid Amado theorem. Standard trick in QCD

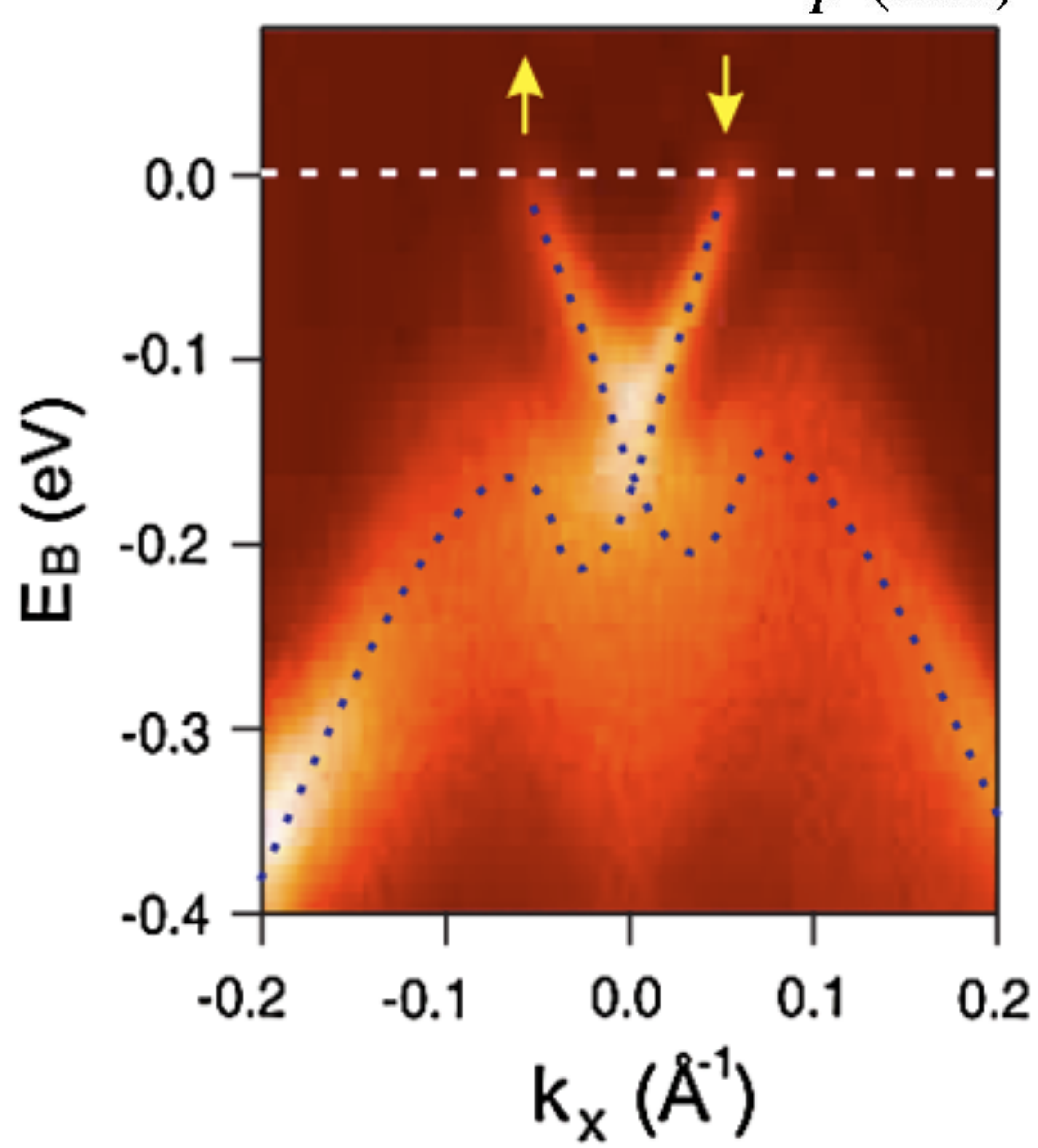
Hence for probing momenta < 400 MeV/c lower energy & momentum transfer should be sufficient than those used at BNL.

Actually it is now a standard trick in atomic (10 eV vs 1000 eV) and solid state physics (0.2 eV vs 30 eV) scales.



Atomic physics:

Comparison of the normalized (e,2e) cross section (momentum profile) for hydrogen with the square of the 1s wave function in the momentum space (Lohmann and Weigrod (1981)]. The solid line represents $(1+p^2)^{-4}$. The measurements were performed at 1200 eV (crosses), 800 eV(circles), and 400 eV (triangles).



Solid state physics:

Angle resolved photo emission spectroscopy (ARPES) ($\gamma\ e^* \rightarrow e$) using monochromatic photon beams from synchrotron light source allows to measure distribution over energy binding and momentum of electrons - spectral function in nuclear physics)

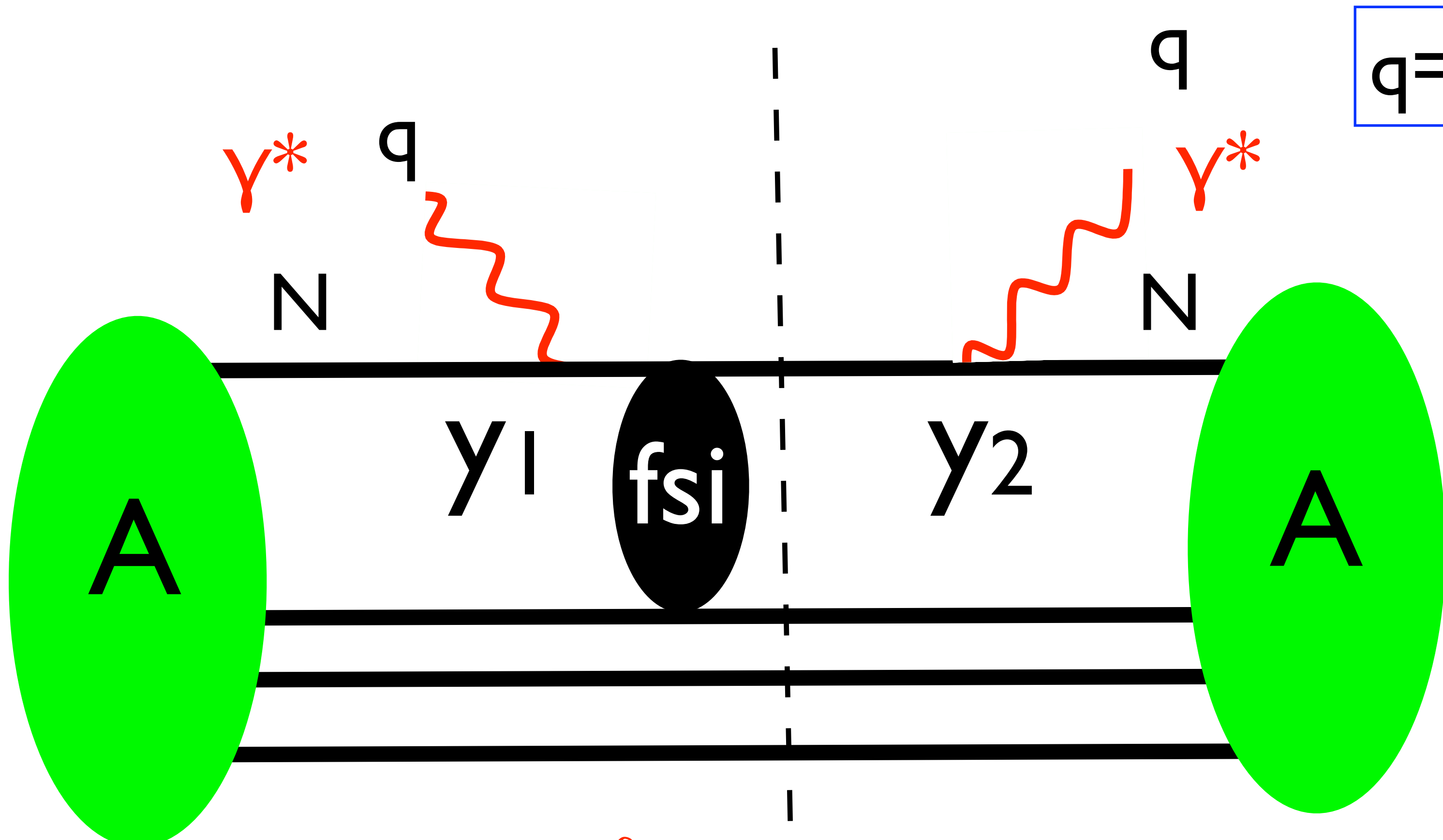
Intensity map of the gapless surface state bands $Bi_{2-x}Mn_xTe_3$, D.Hsieh et al, 09

Progress in the study of SRCs of the last several years is due to analysis of two classes of hard processes we suggested in the 80's: inclusive scattering in the kinematics forbidden for scattering off free nucleon & nucleus decay after removal of fast nucleus.

One group of processes which led to the progress in the studies of SRC at high momentum is A(e,e') at $x > 1$, $Q^2 > 1.5$ GeV^2

Closure approximation for A(e,e') at $x = AQ^2/2q_0m_A > 1$, $Q^2 > 1.5$ GeV^2 up to final state interaction (fsi) between constituents of the SRC

$q = p_e - p_{e'}$ is four momentum of virtual photon, $Q^2 = -q^2$



In lab frame $q = (q_0, q_z)$,

$q_- = q_0 - q_z << q_+ = q_0 + q_z$

DIS like kinematics for nucleons= partons

$$2m_A q_3 \sigma^{(r)} = \int e^{iqy} \langle A \left| [J_\mu(y), J_\lambda(0)] \right| A \rangle \epsilon_\mu^{(r)} \epsilon_\lambda^{(r)} d^4 y$$

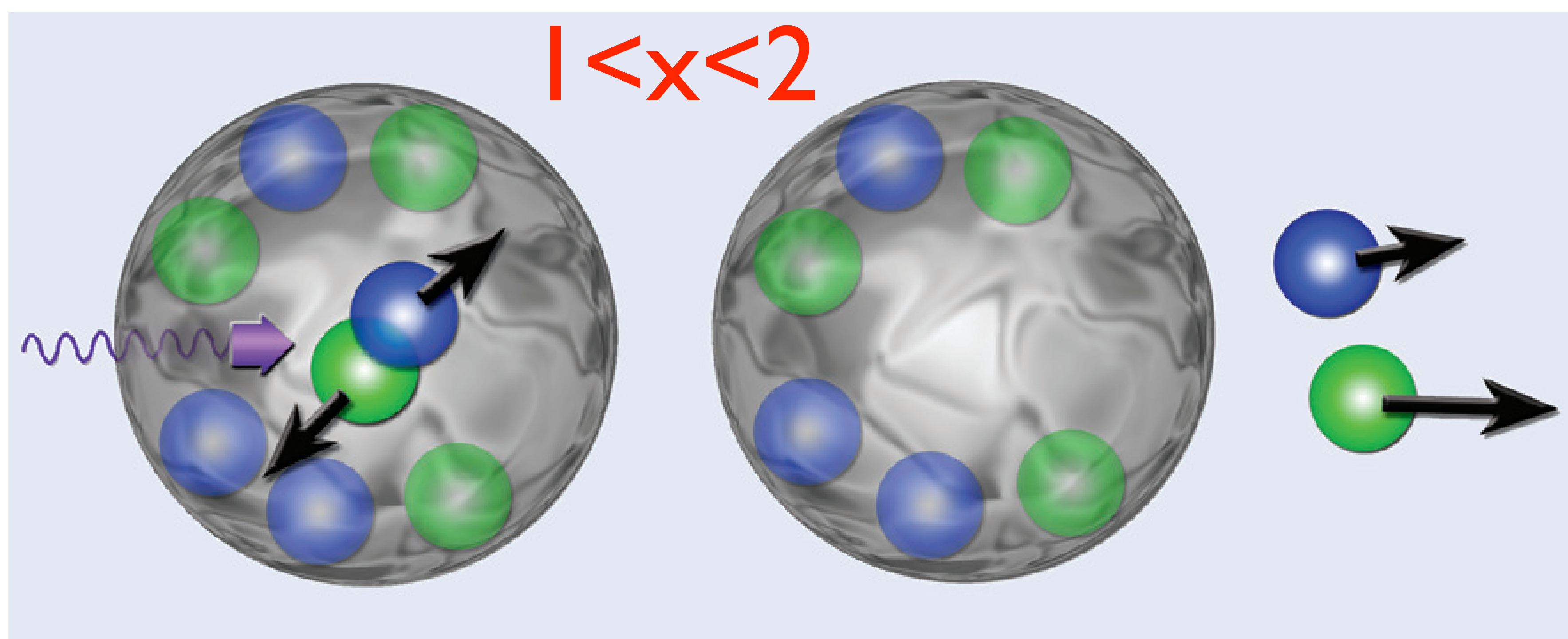
analog of Ioffe time in DIS $y_1^{(z)} - y_2^{\,z)} < 1.2$ fm

fsi **only** within SRC - may be large for some kinematics - but **universal**

Corrections could be calculated for large Q using generalized eikonal approximation. For interactions of knocked out nucleon with slow nucleons they are less than few % - LF & Misak Sargsian & MS (08)

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

$x=AQ^2/2q_0m_A=1$ is **exact** kinematic limit **for all Q^2** for the scattering off a free nucleon; $x=2$ ($x=3$) is **exact** kinematic limit **for all Q^2** for the scattering off a A=2(A=3) system (up to <1% correction due to nuclear binding)



Before absorption of the photon

After absorption

two nucleons of SRC are fast

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. Since the local structure of WFs is universal - these *local fsi should be also universal.*

Scaling of the ratios of (e,e') cross sections

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 nucleons is a small correction.

$$\sigma_{eA}(x,Q^2)_{x>1} = \sum_{j=2} A\frac{a_j(A)}{j}\sigma_j(x,Q^2) \qquad \sigma_j(x>j,Q^2)=0$$

$$a_j(A) \propto \frac{1}{A}\int d^3r\rho_A^j(r) \qquad a_2\sim A^{0.15}; \qquad a_3\sim A^{0.22}; \qquad a_4\sim A^{0.27}$$

for A> 12

$$\sigma_{A_1}(j-1<x<j,Q^2)/\sigma_{A_1}(j-1<x<j,Q^2) = (A_1/A_2)a_j(A_1)/a_j(A_2)$$

Scaling of the ratios FS80

Superscaling of the ratios FS88

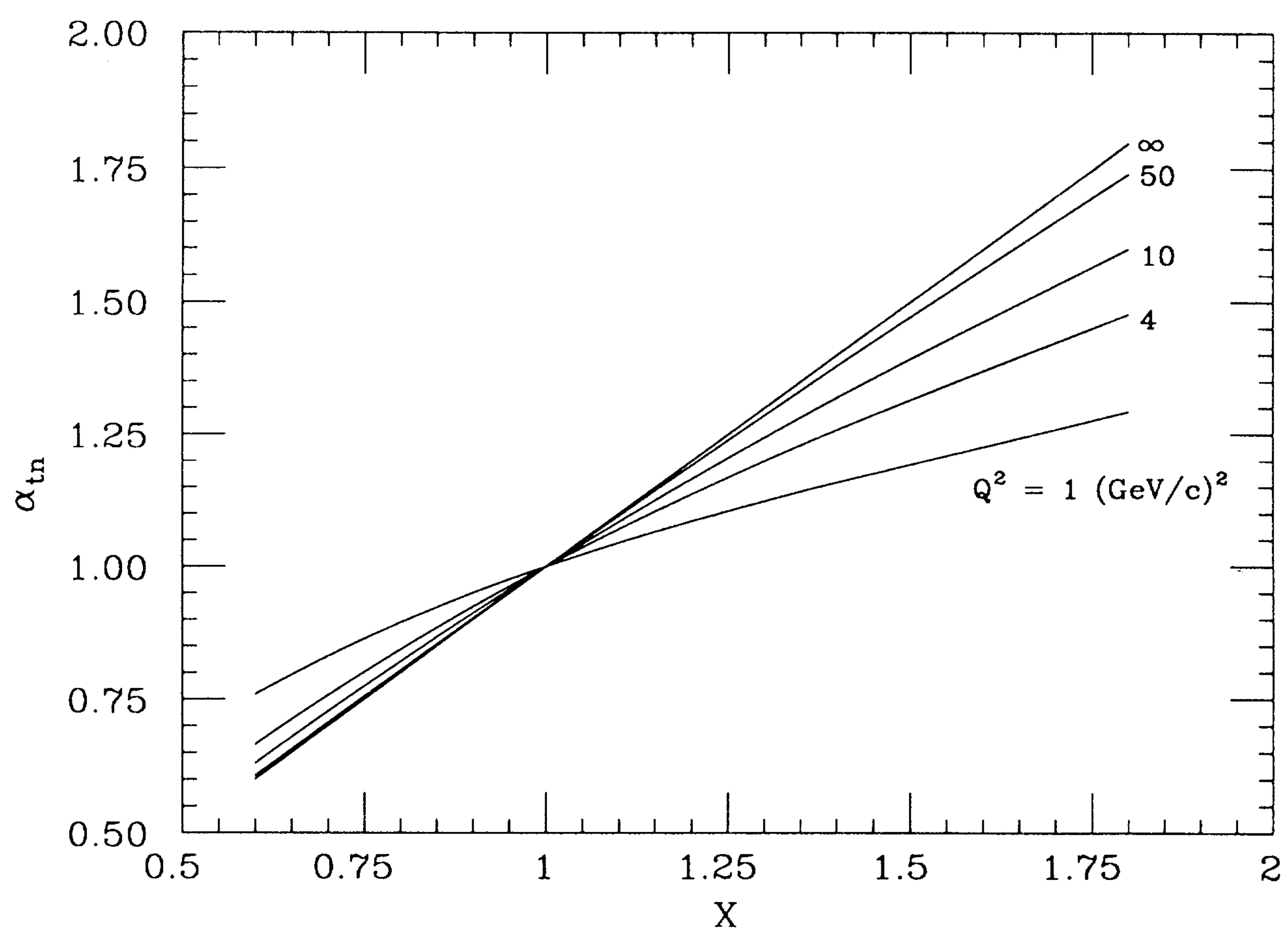
Compare the ratios for different Q^2 at x corresponding to the same momentum of nucleon in nuclei (including effect of excitation of the residual system - best done in the light-cone formalism)

Main dependence is on "+" component (α) of p_N^{int}, allows to take "-" component in average point given by two nucleon SRC approximation

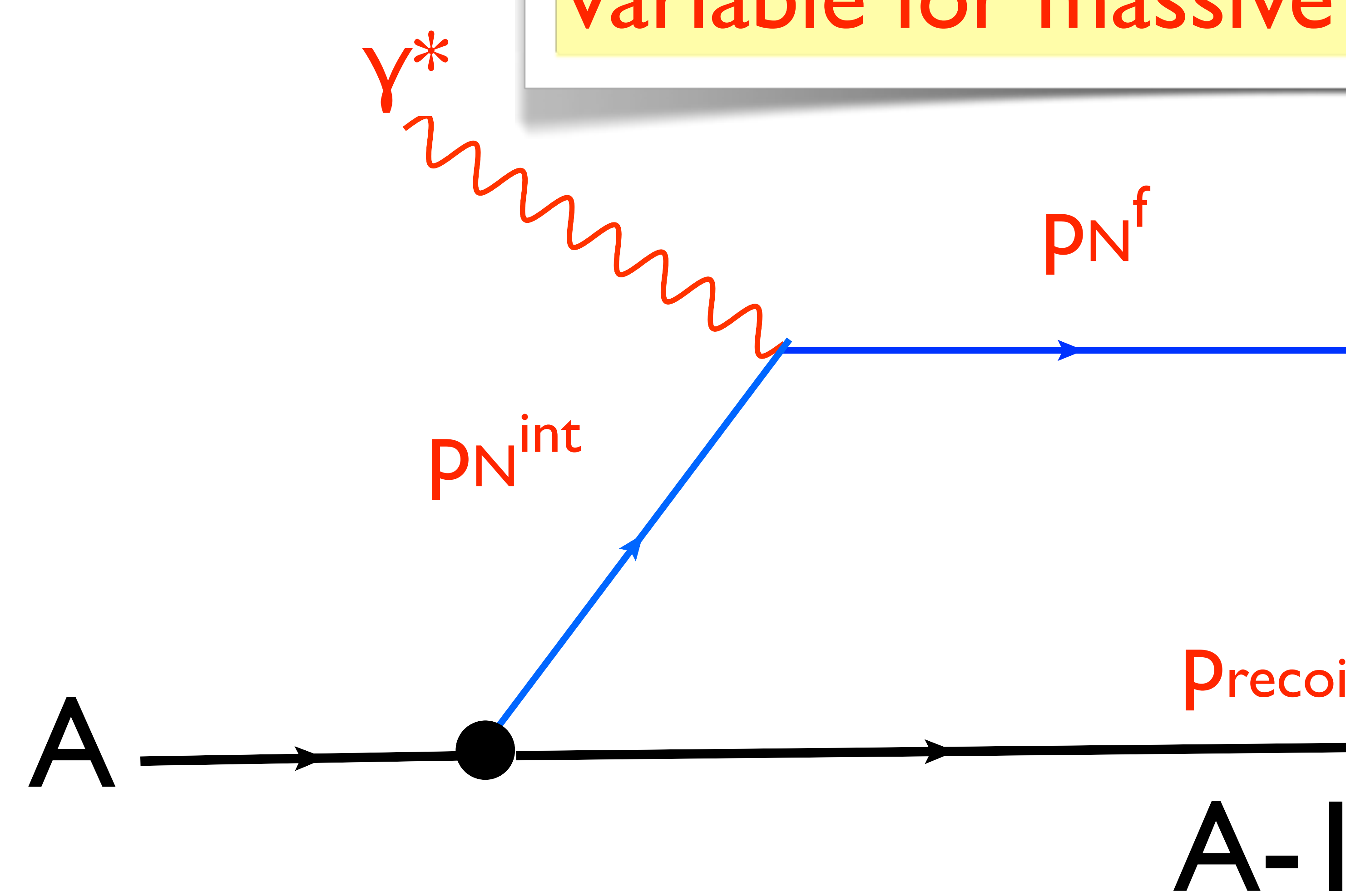
$$\alpha_{tn} = 2 - \frac{q_- + 2m_N}{2m_N}\left(1 + \frac{\sqrt{W^2 - 4m_N^2}}{W}\right)$$

$$where\ q_- = q_0 - q_3,\ W^2 = 4m_N^2 + 4q_0 m_N - Q^2$$

Remark for people with a QCD background: α_{tn} is rather close to Nachtmann variable for massive quarks



α_{tn} vs x for Q^2=1, 4, 10, 50, ∞.

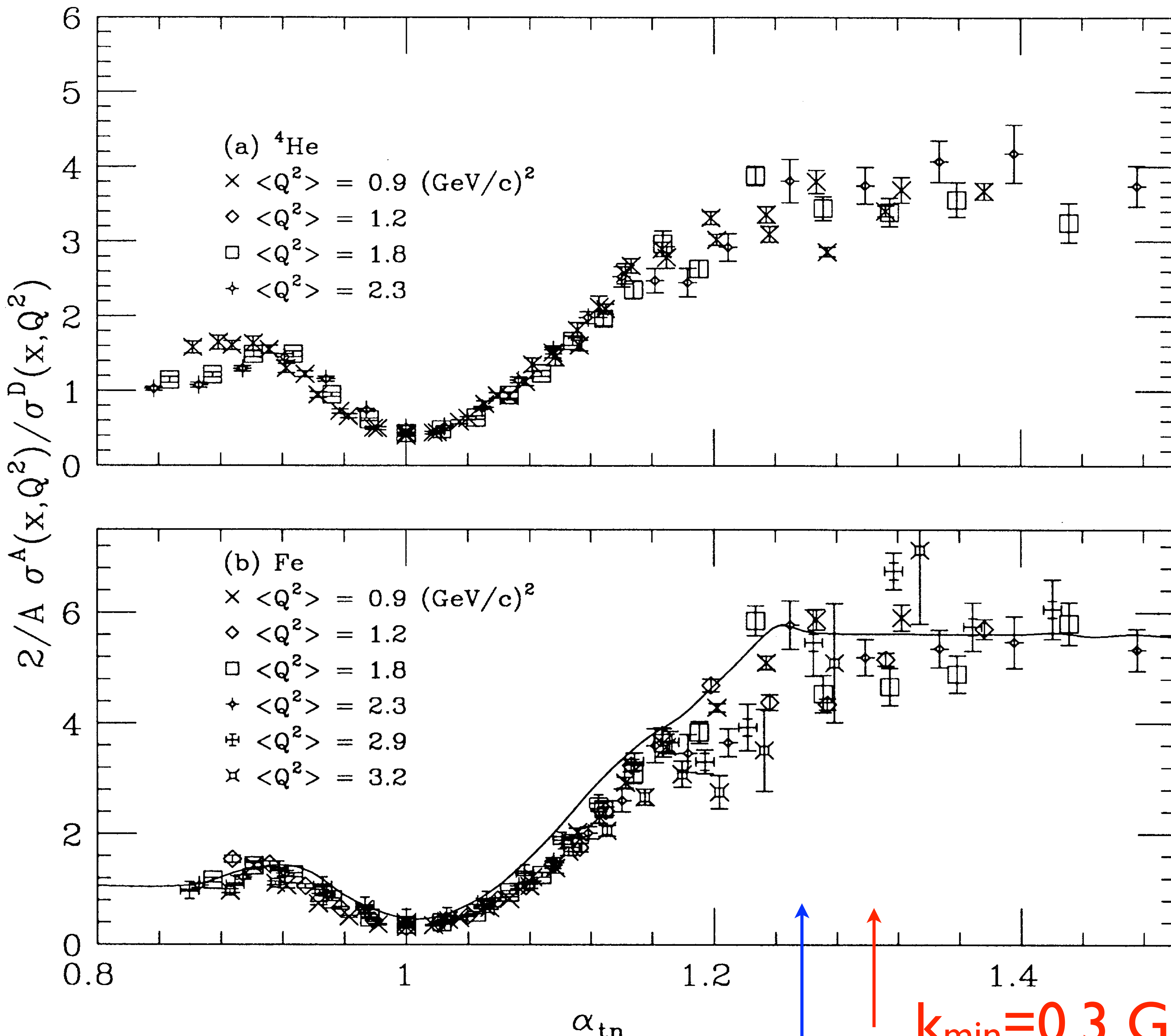


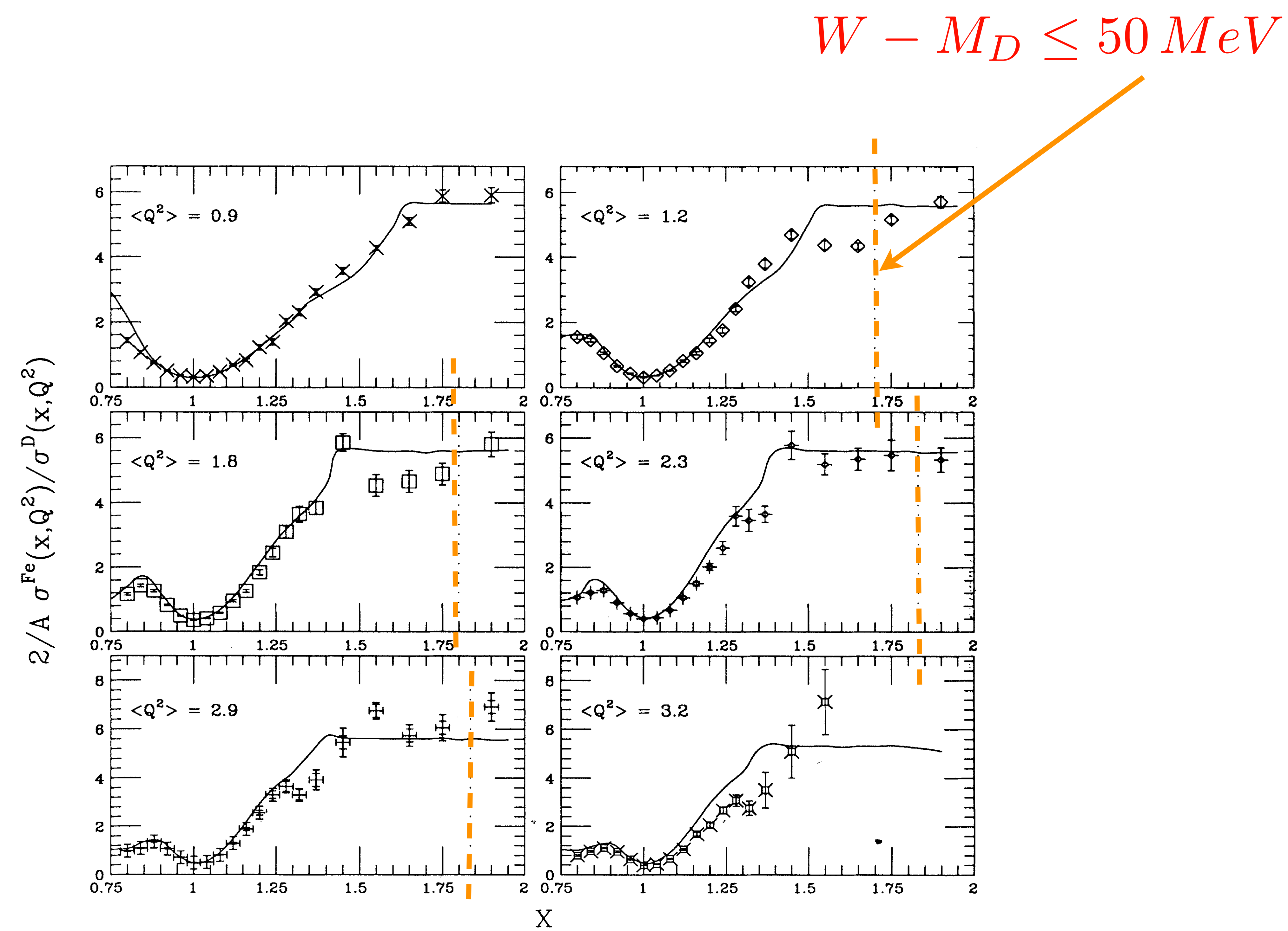
At $Q^2 \to \infty$, $\alpha_{tn} = x$

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

ρ- Light-cone density

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





k_{min}=0.3 GeV

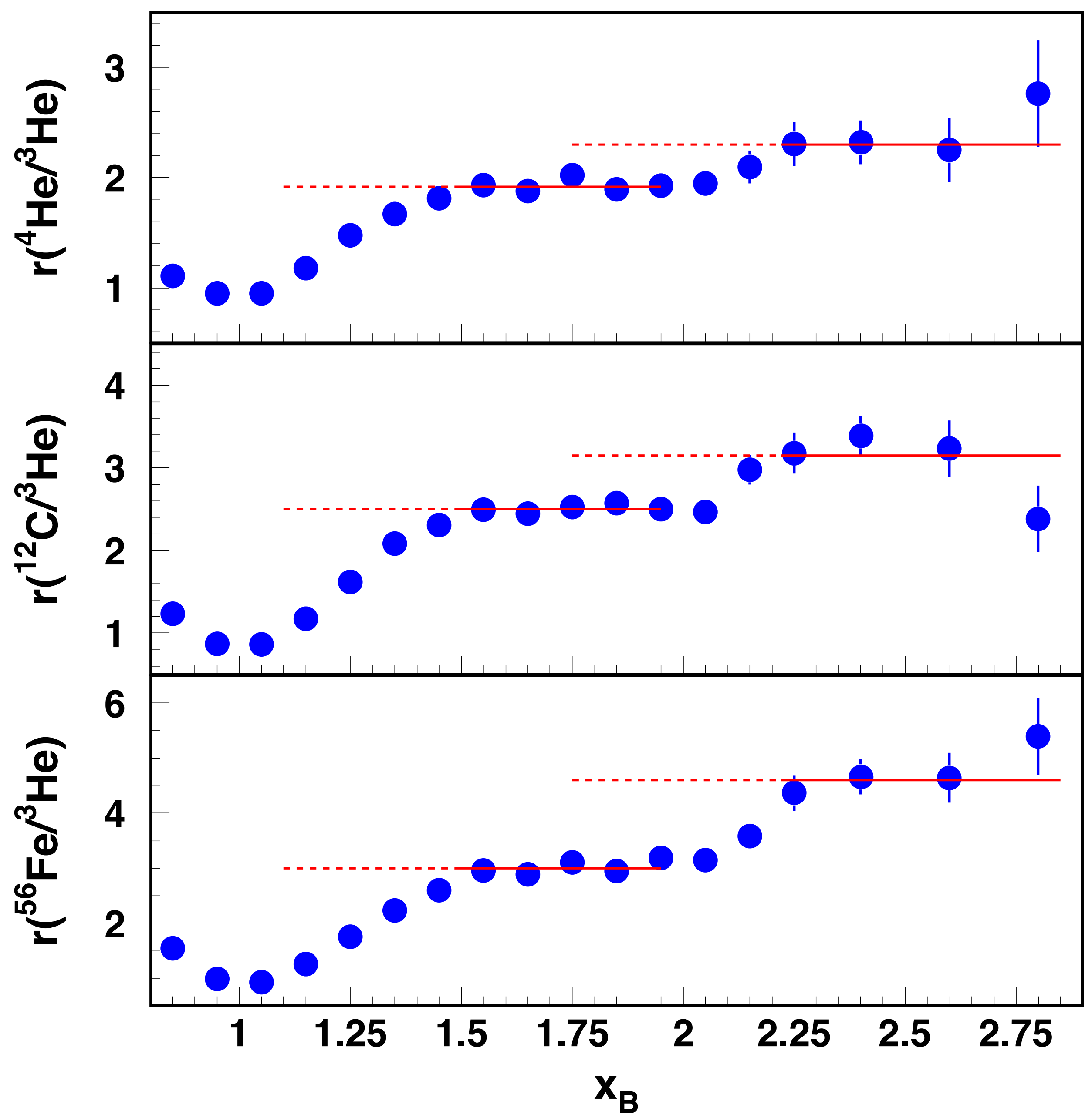
k_{min}=0.25 GeV

Frankfurt et al, 93

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 !!!

Hall B (Kim Egiyan)
$Q^2 > 1.5$ GeV^2



Ratio of the cross sections of (e,e')scattering off a ^{56}Fe(^{12}C,^{4}He) and ^{3}He per nucleon

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!!!

Note - fsi in the studied Q range and x> 2 is probably very large but it is still local - within SRC

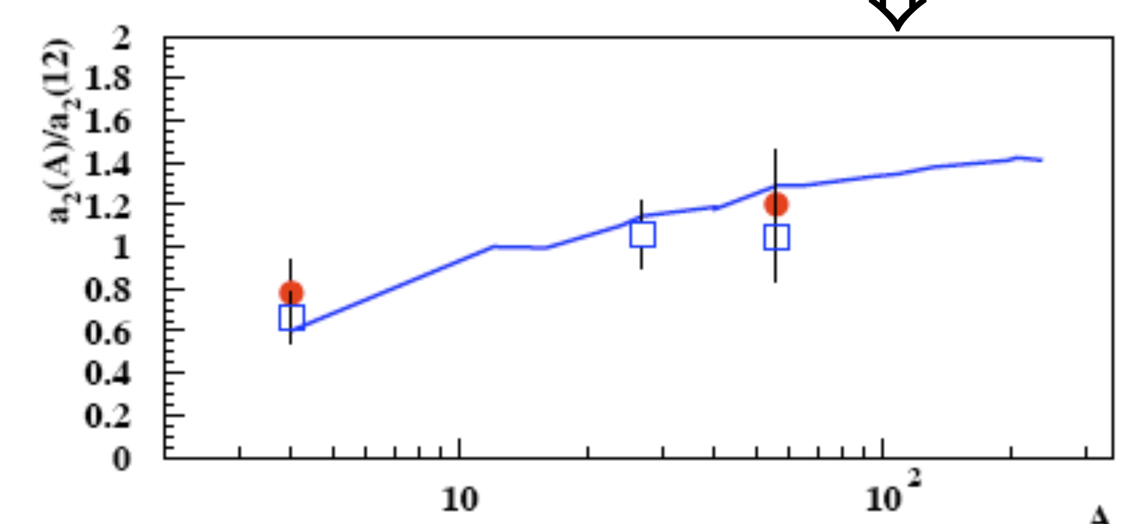
confirm our 1980 prediction of scaling and A -dependence for the ratios due to SRC

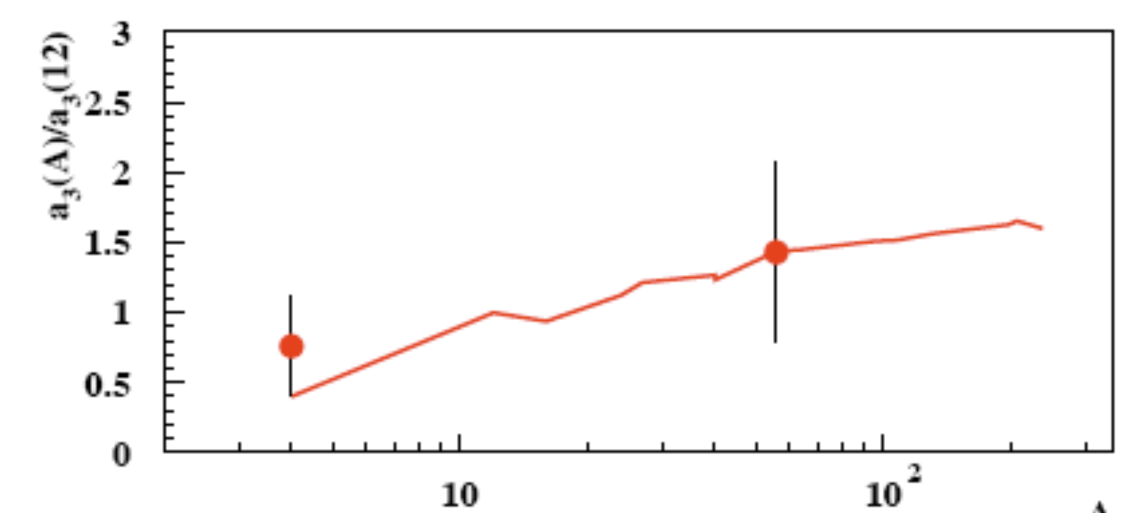
Fe/C ratios for x~1.75, x~2.5 agree within experimental errors with our prediction - density based estimate:

$$a_2 \propto \int \rho_A^2(r) d^3r, r_2 = (A_1/A_2)^{0.15}$$

$$a_3 \propto \int \rho_A^3(r) d^3r, r_3 = (A_1/A_2)^{0.22}$$

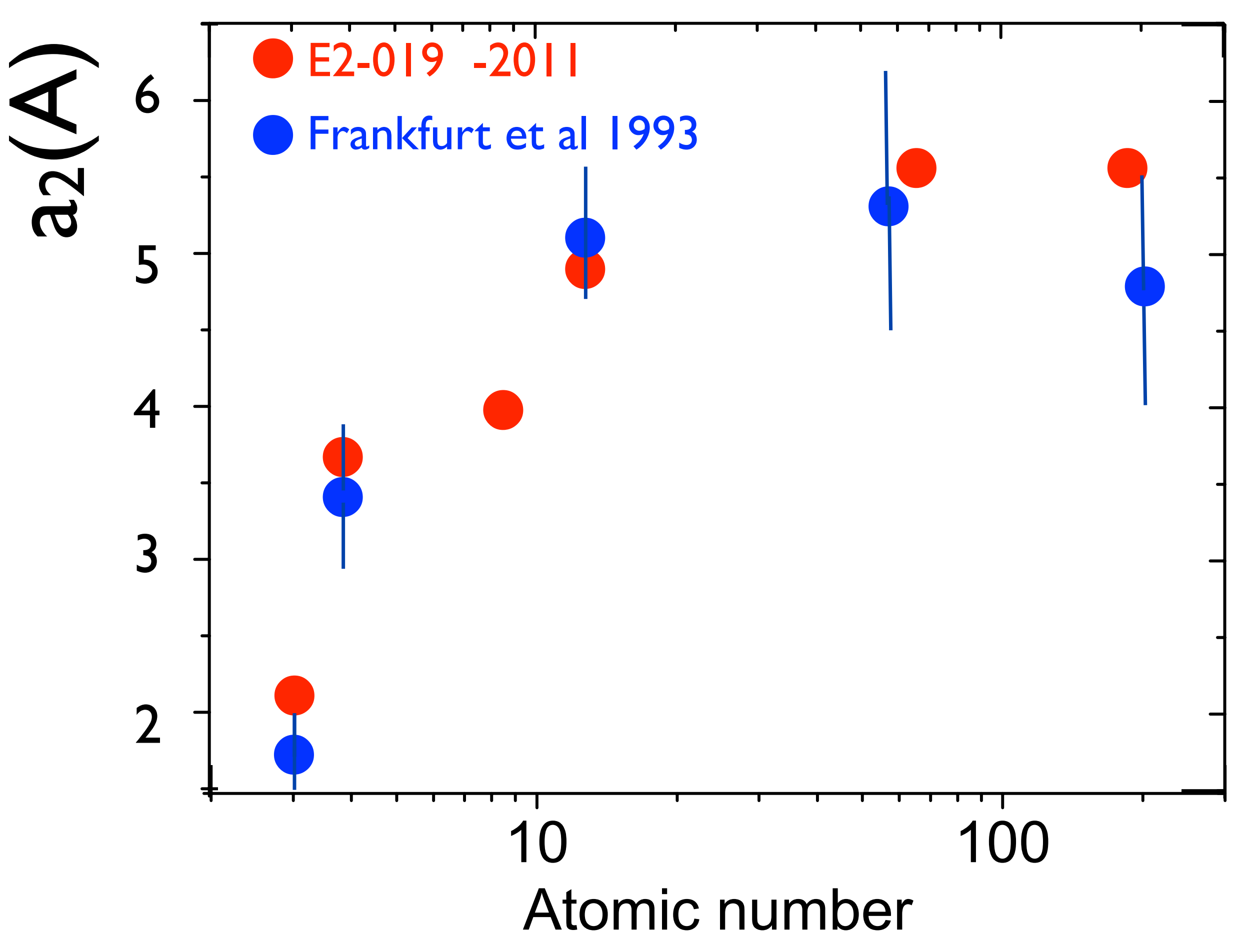
⇓



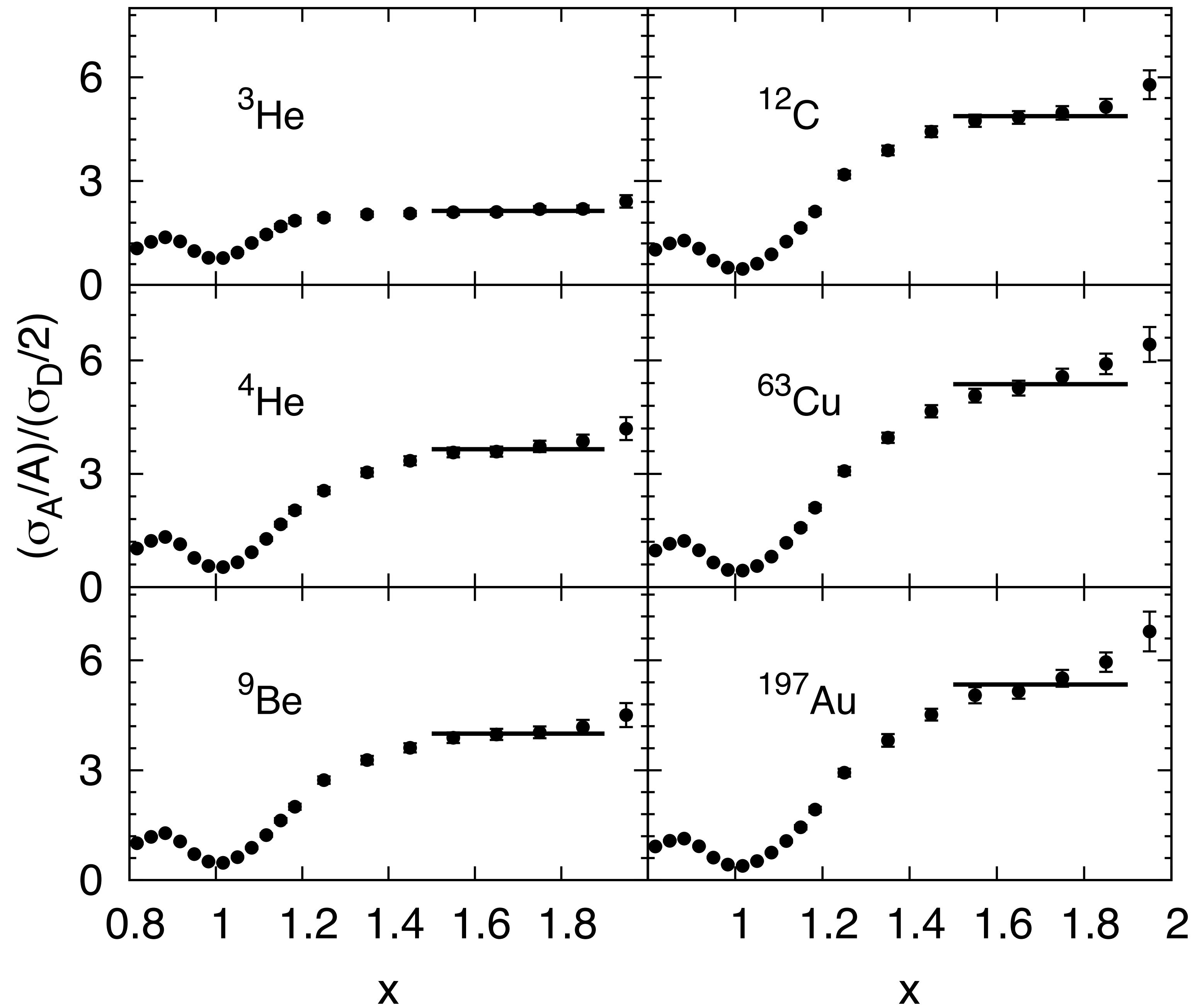


Currently the ratios are the best way to determine absolute probability of SRC - main uncertainty ~20% - deuteron wave function

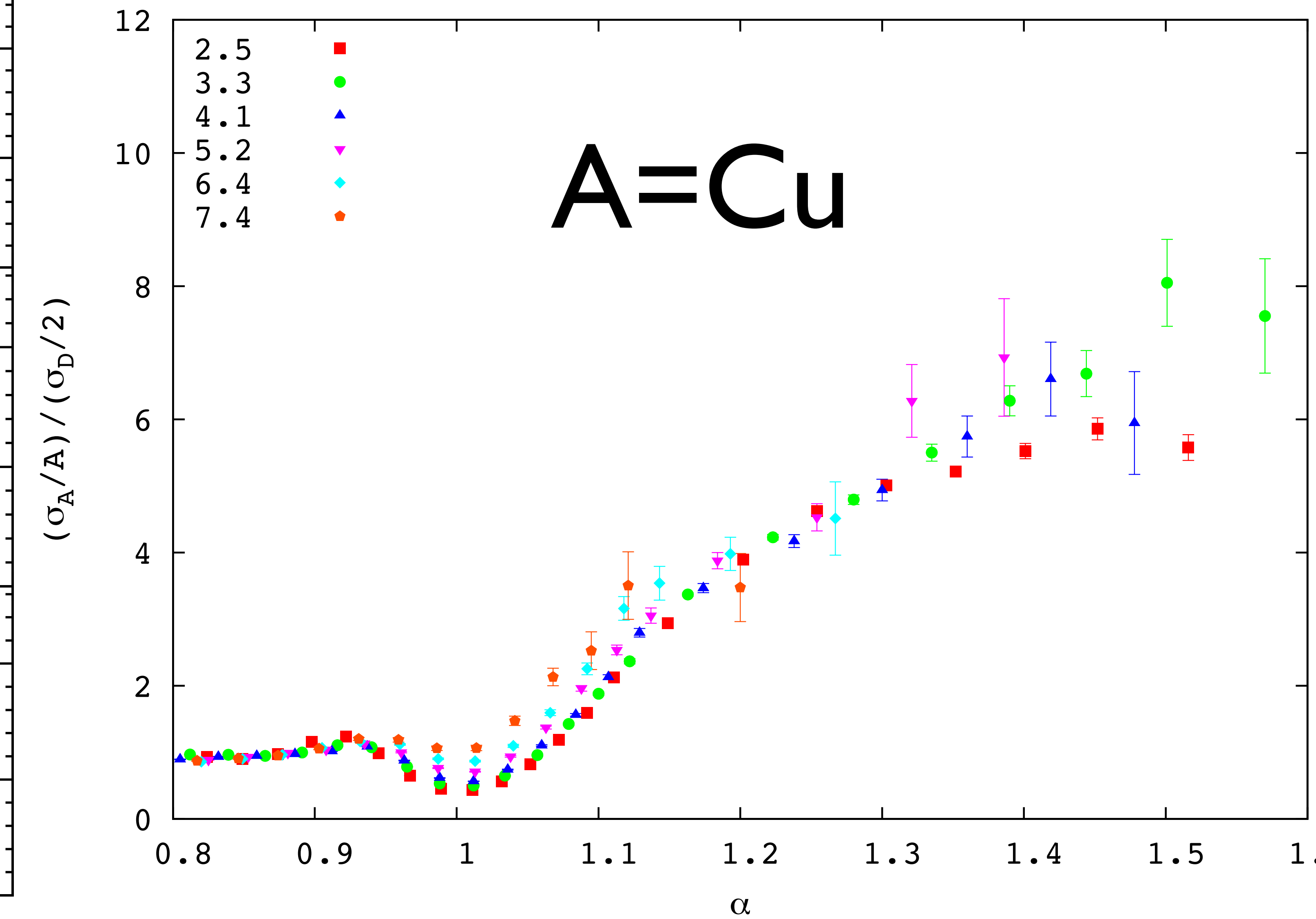
Universality of 2N SRC is confirmed by Jlab experiments



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)

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.

Nuclear Decay Function

What happens if a nucleon with momentum k belonging to SRC is instantaneously removed from the nucleus (hard process)? Our guess is that associated nucleon from SRC with momentum ~ -k should be produced.

Formal definition of a new object - 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)

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

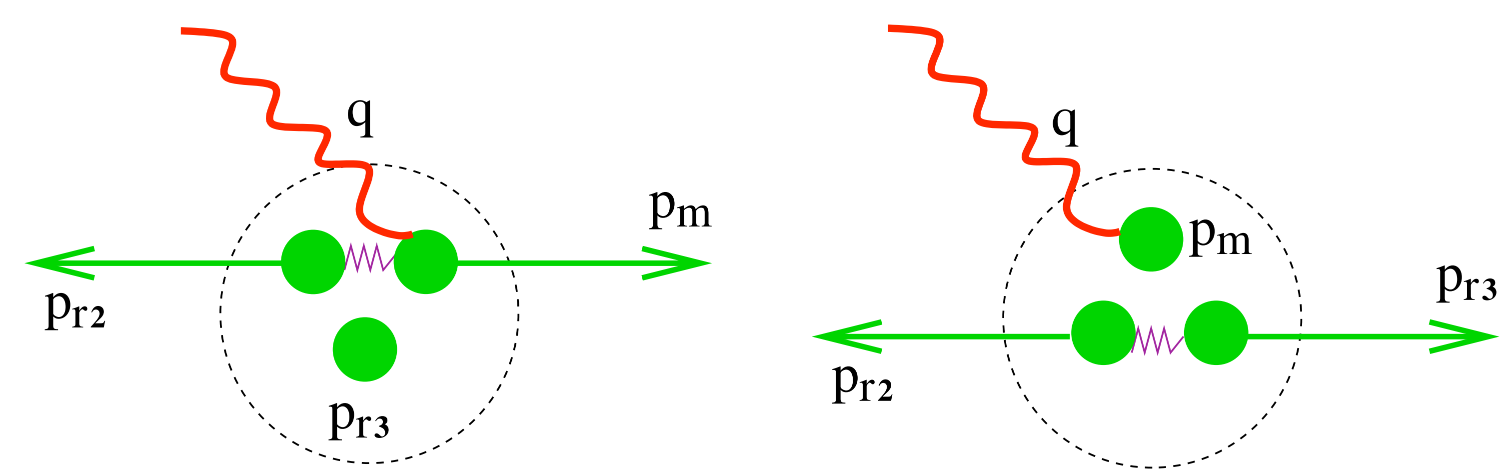
General principle (FS77): to release a nucleon of a SRC - necessary to remove nucleons from the same correlation - perform a work against potential $V_{12}(r)$

If we would consider the decay in the collider kinematics: nucleus with momentum Ap scatters off a proton at rest - removal of a nucleon with momentum αp leads to removal of a nucleon with momentum $(2-\alpha)p$

Operational definition of the SRC: nucleon belongs to SRC if its instantaneous removal from the nucleus leads to emission of one or two nucleons which balance its momentum: includes not only repulsive core but also tensor force interactions. Prediction of back - to - back correlation.

For 2N SRC we can model decay function as decay of a NN pair moving in mean field (like for spectral function in the model of Ciofi, Simula and Frankfurt and MS91), Piasetzky et al 06

Spectator is released



Emission of fast nucleons "2" and "3" is strongly suppressed due to FSI

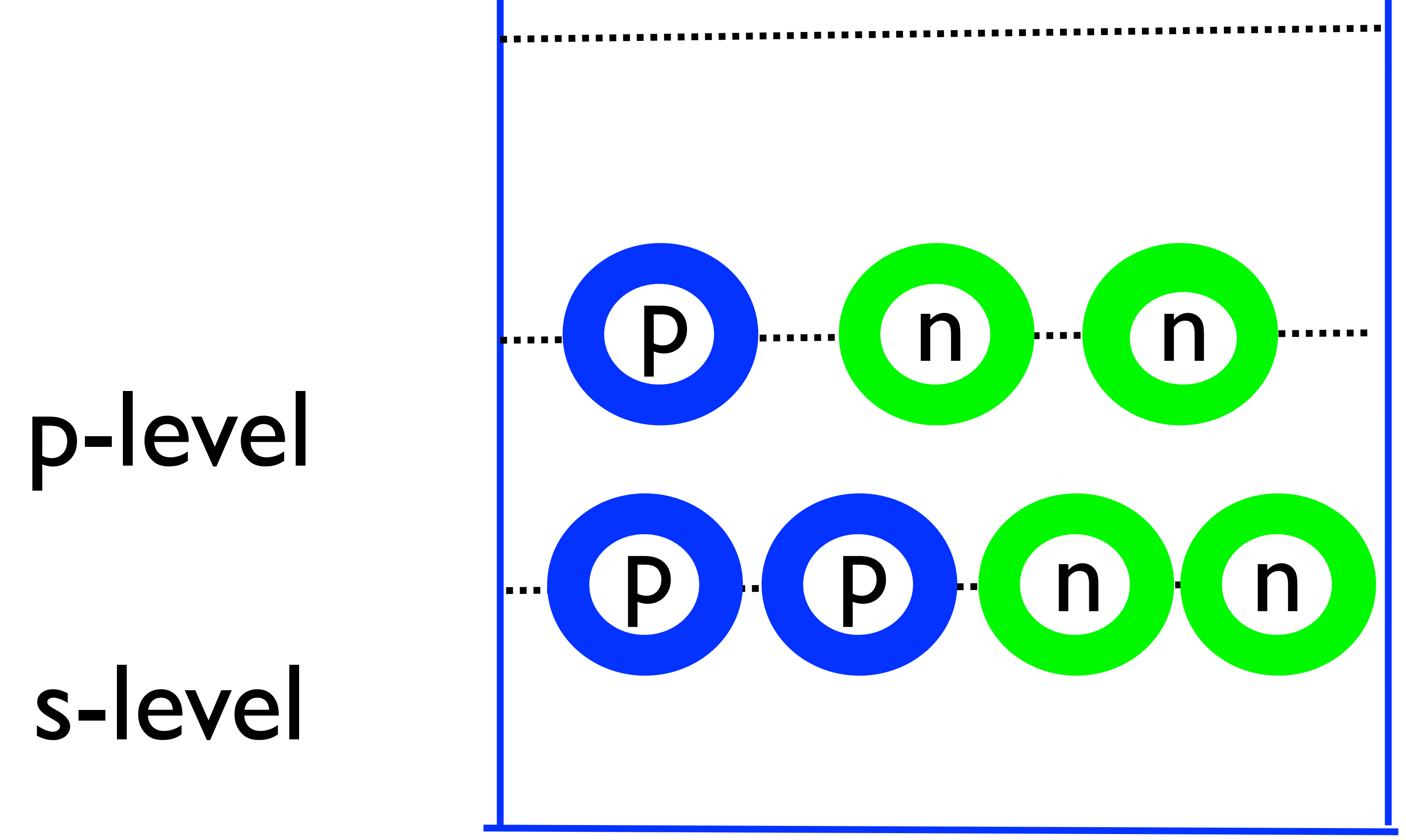
resembles 2N momentum distribution

does not resemble 2N momentum distribution -

Studies of the spectral and decay function of ^{3}He reveal both two nucleon and three nucleon correlations

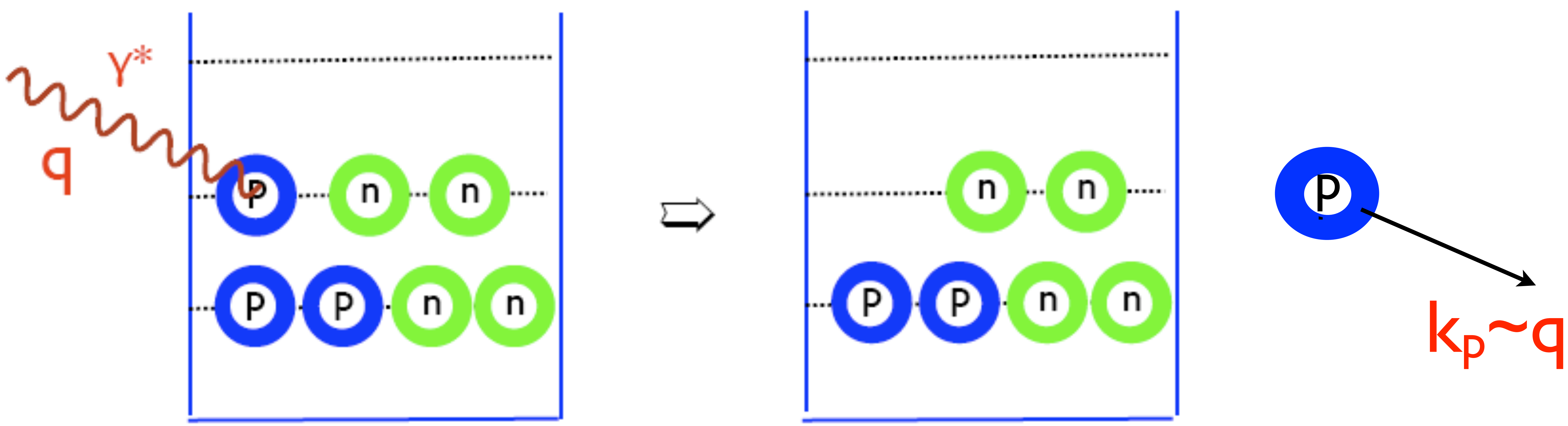
Sargsian et al 2004

The prediction of back - to - back correlation differs from the expectations based on the textbook picture of nuclei:



Nucleons occupy the lowest levels given by the shell model

What happens if a nucleon is removed from the nucleus?

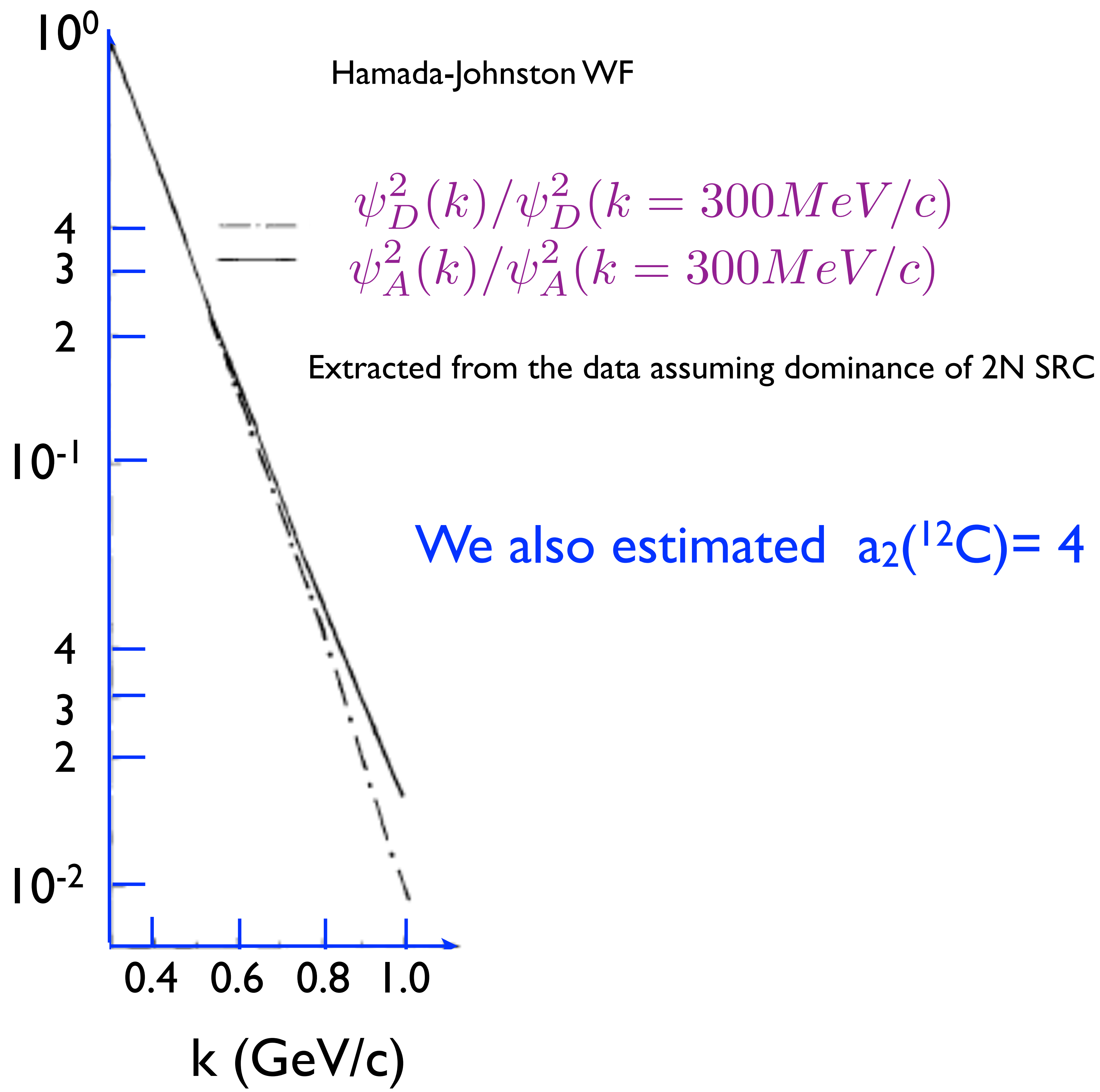


removal of a nucleon

Residual nucleus in ground or excited state of the shell model Hamiltonian - decay product practically do not remember direction of momentum of struck proton. RIKEN studies such decays including complicated ones where several nucleons were emitted.

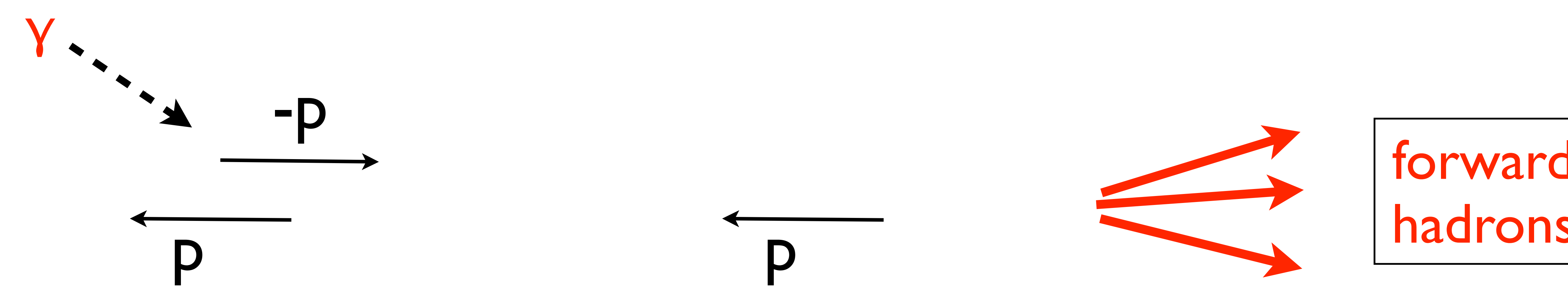
First application of the logic of decay function - spectator mechanism of production of fast backward nucleons - observed in high energy proton, pion , photon - nucleus interactions with a number of simple regularities. We suggested - spectator mechanism - breaking of 2N, 3N SRCs. We extracted (Phys.Lett 1977) two nucleon correlation function from analysis of $\gamma(p)\ ^{12}C \rightarrow$ backward p+X processes [no backward nucleons are produced in the scattering off free protons!!!]

Spectator production of the backward proton from 2N SRC



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

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



Before collision

After collision collision

In the collider frame where nucleus has momentum Ap: SRC is two nucleons with momenta αp and $(2-\alpha)p$

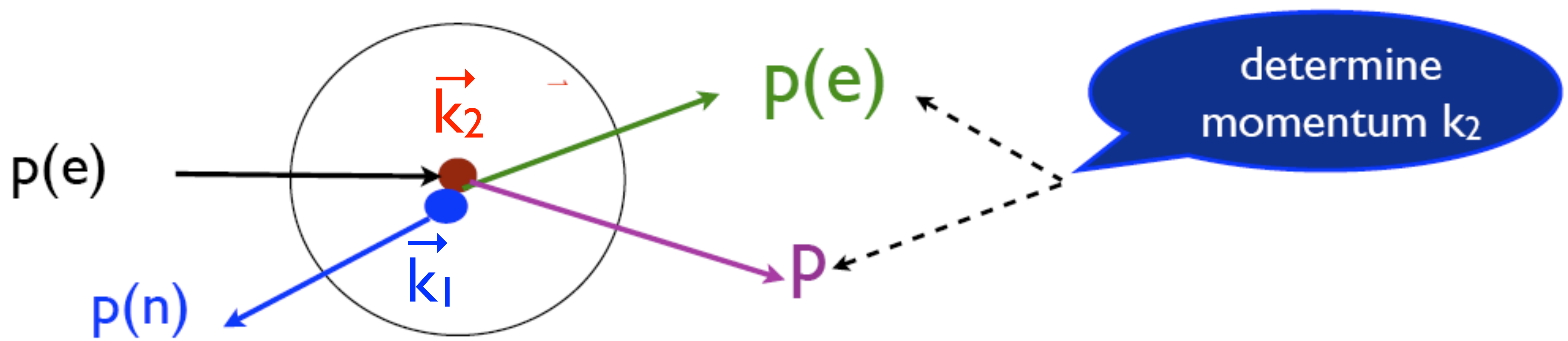
Backward direction is very good for looking for decay of SRCs

We were prompted by G. Farrar in 86 to discuss large angle pp scattering off the bound nucleon: p + A → pp (A-1)* - prime topic was color transparency. Next we realized that this process selects scattering off the fast forward moving protons since elastic pp cross section

$$\frac{d\sigma}{d\theta_{c.m.}} = \frac{1}{s^{10}} f(\theta_{c.m.})$$

Hence in a large fraction of the events there should be fast neutrons flying backward. We heard of plans of a new experiment - EVA. So without much hope that somebody would notice we wrote that it would be nice to have a backward neutron detector added to EVA. Eli Piazetski did notice!!! He probably did not know that it is impossible to measure SRCs !!!

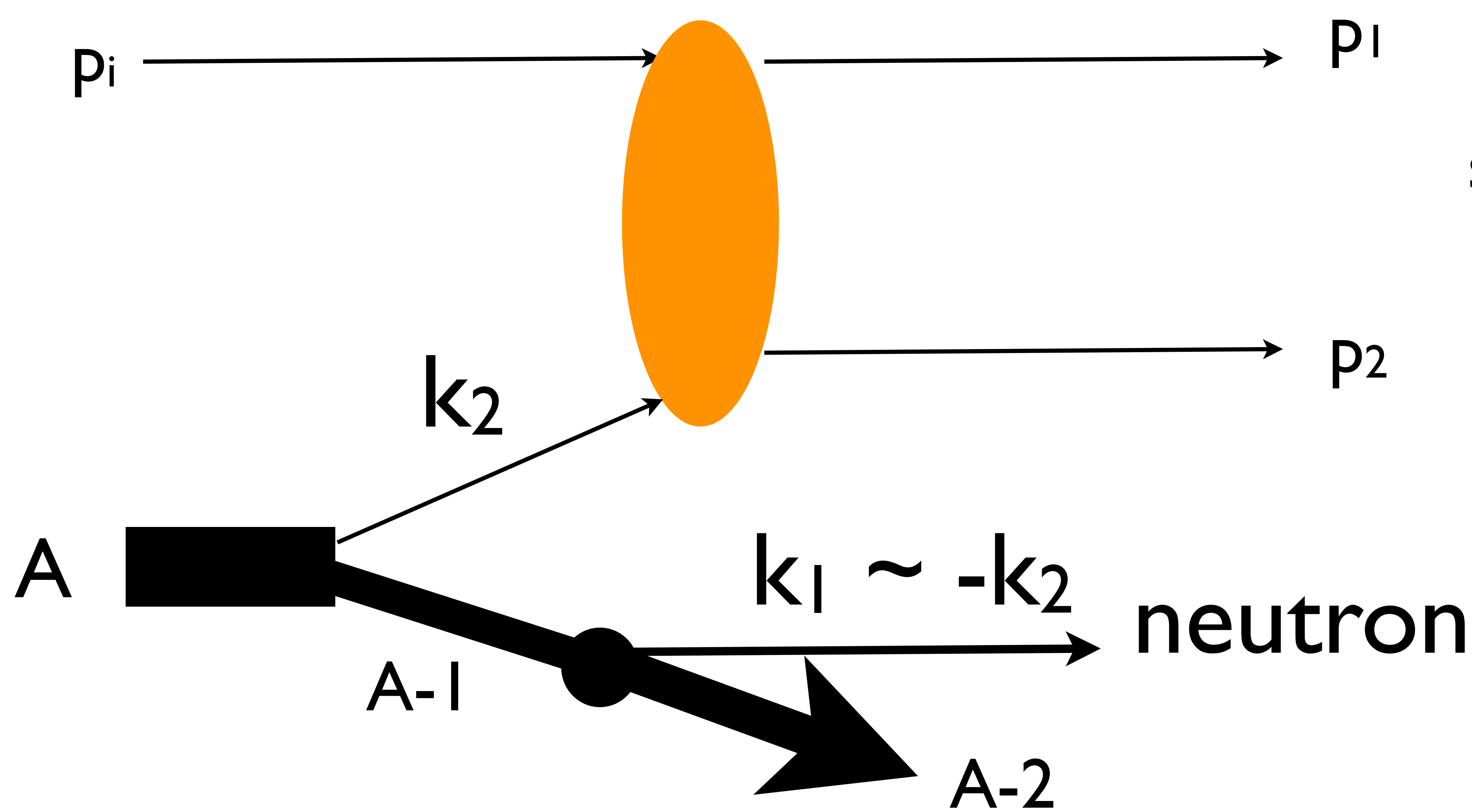
To observe SRC directly it is far better to consider semi-exclusive processes
e(p) +A → e(p) + p + " nucleon from decay" +(A-2) since it measures
both momentum of struck nucleon and decay of the nucleus



Two novel experiments reported results in the last 5 years

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



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

$t = (p_1 - p_p)^2$

$k_2 = p_1 + p_2 - p_i$

Collider frame

$s' = \alpha s_{NN}$, $\alpha < 1$

neutron momentum $(2-\alpha)p$

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

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

Test of Factorization: $\sigma / d\,\sigma^{pp \rightarrow pp}/dt(s',t)$ independent of s', t

Analysis of BNL E850 data

pC→ppn +(A-2)*

at energy and momentum transfer ≥ 3 GeV

Evidence for the Strong Dominance of Proton-Neutron Correlations in Nuclei

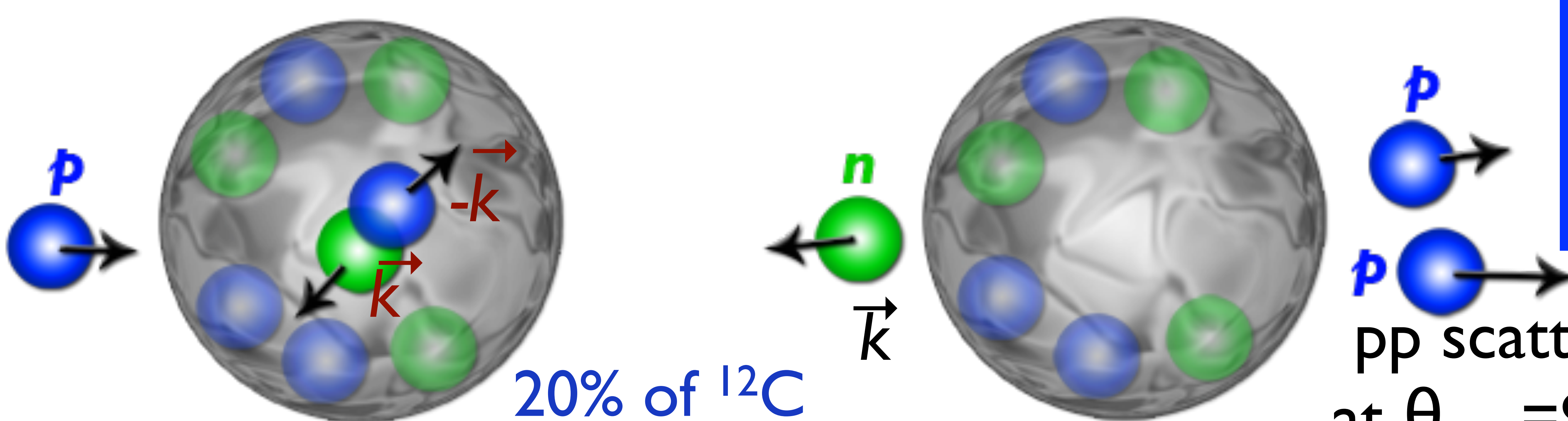
E. Piasetzky,[1] M. Sargsian,[2] L. Frankfurt,[1] M. Strikman,[3] and J. W. Watson[4]

PRL 06

spectator mechanism of backward nucleon production *FS77*

Analysis using decay function modeled using 2N correlation model (including relativistic effects) - the same approximation as for spectral function in CSFS 91

Probability to emit neutron is amazingly high ~90% after we accounted for the motion of the pair (measured/calculated independently) and detector acceptance



20% of ^{12}C wave function

pp scatter at $\theta_{c.m.}=90^o$

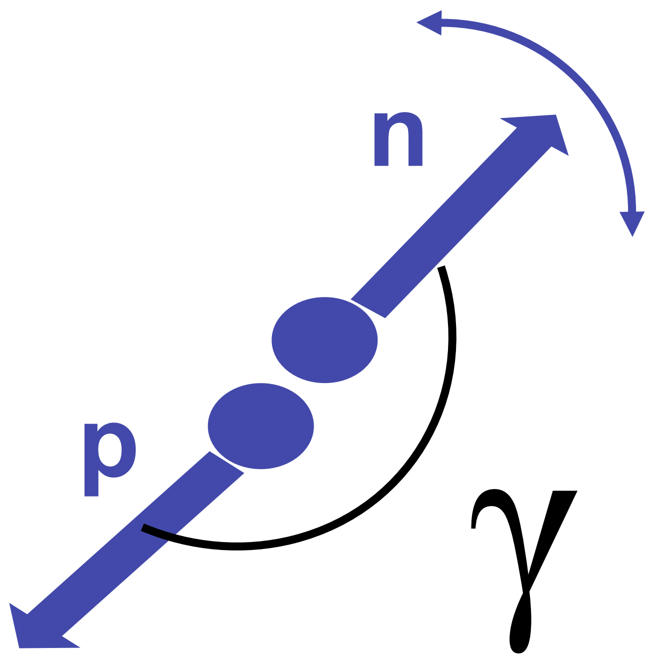
pn/pp > 16; I=0 dominance - qualitatively consistent with current calculations of nuclear wave functions

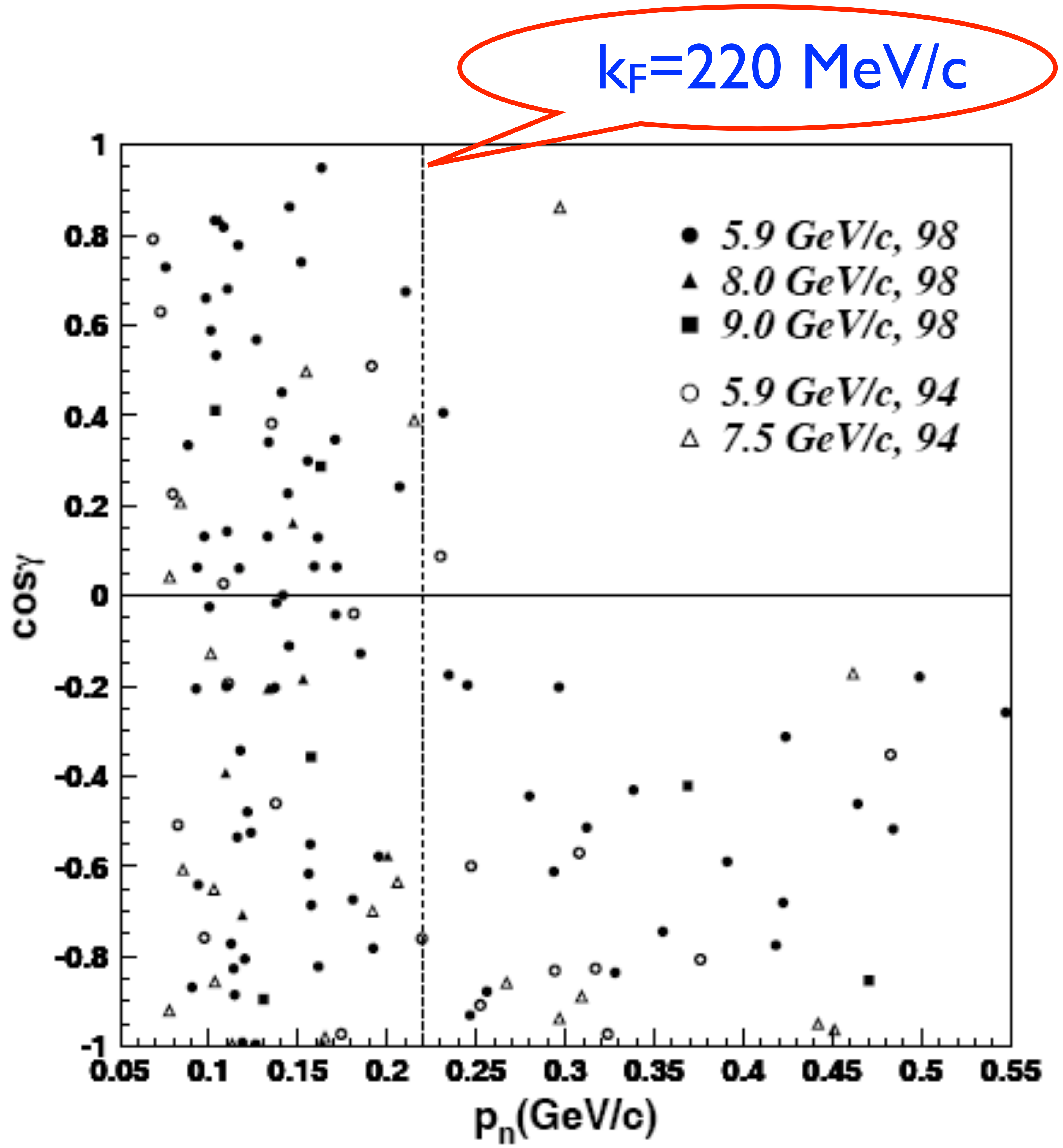
Before collision

removal of a proton with momentum > 250 MeV/c

After collision

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

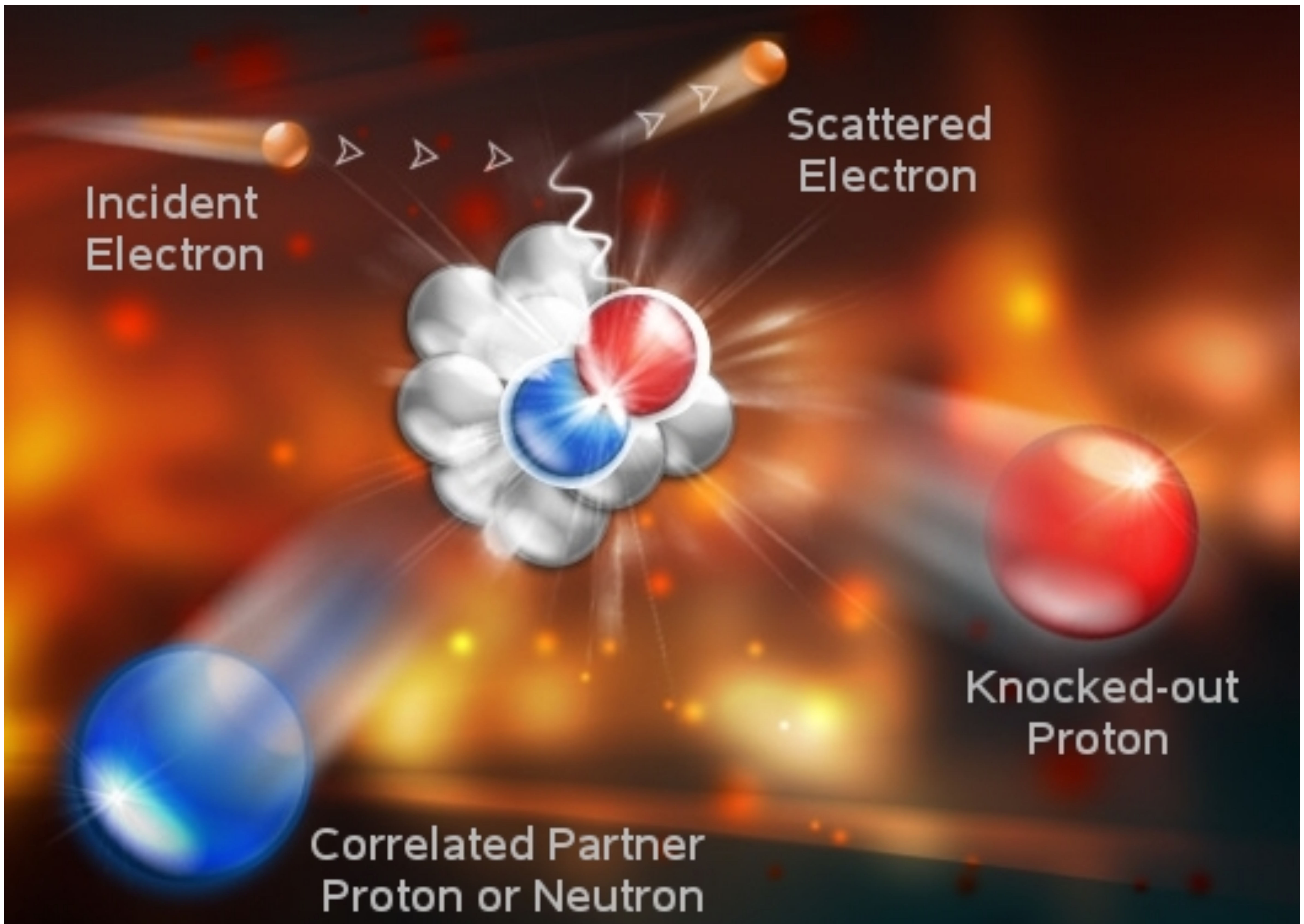




BNL Carbon data of 94-98. The correlation between p_n and its direction γ relative to p_i. The momenta on the labels are the beam momenta. The dotted vertical line corresponds to k_F=220 MeV/c.

SRC appear to dominate at momenta k> 250 MeV/c - very close to k_F. *A bit of surprise* - we expected dominance for k> 300 - 350 MeV/c. Naive inspection of the realistic model predictions for $n_A(k)$ clearly shows dominance only for k > 350 MeV/c. Important to check a.s.p. - Can be done at lower momentum transfer than at $k>>k_F$

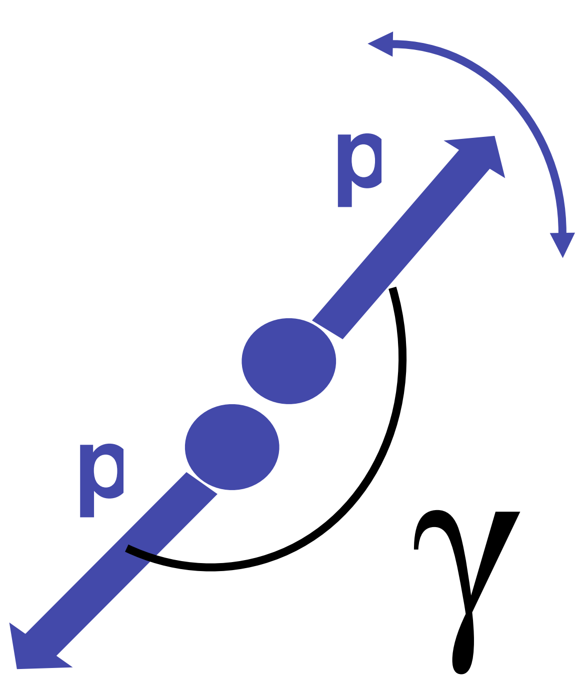
Jlab: from study of (e,e'pp), (e,e'pn)~10% probability of proton emission, strong enhancement of pn vs pp. The rate of pn coincidences is similar to the one inferred from the BNL data

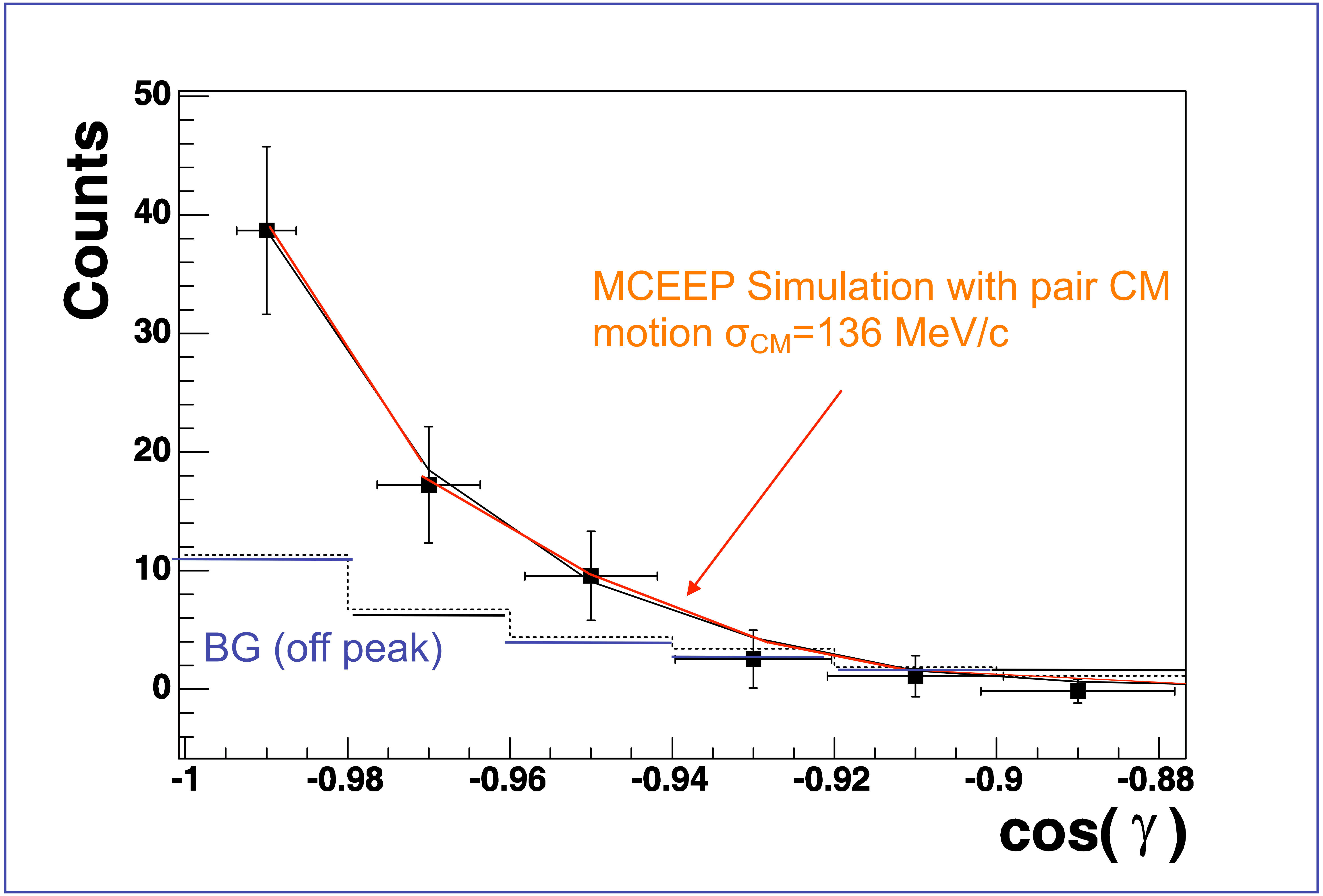


T-shirt of Jlab 09

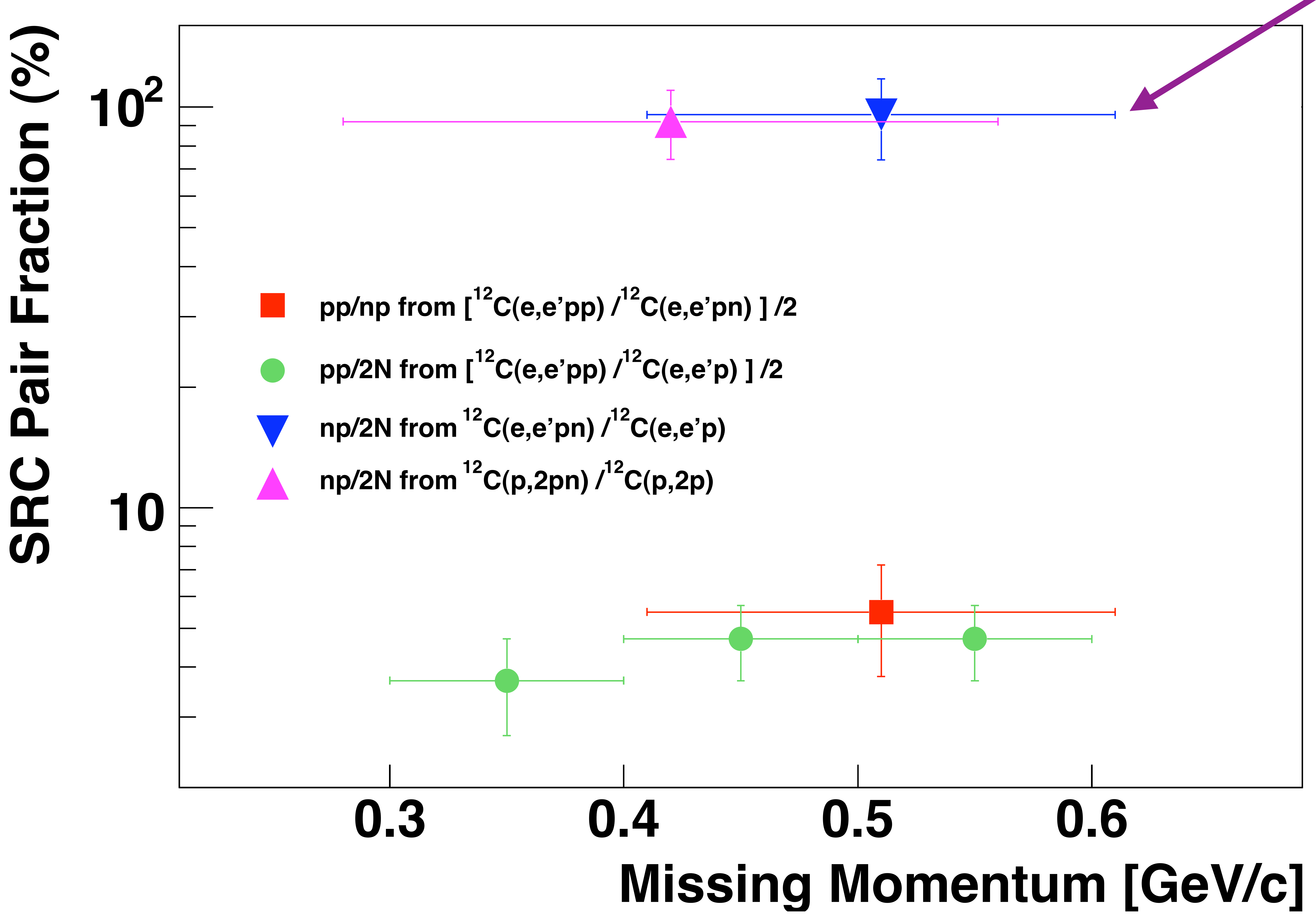
Directional correlation

$^{12}C(e,e'pp)$





Note - BNL and Jlab studied very different kinematics for breakup of 2N SRC - similarity of the numbers is highly non-trivial



Our analysis of BNL Experiment measurement was 92^{+8}_{-18} %

accounting for charge exchange

$$\frac{np-SRC}{pp-SRC} = 18 \pm 5$$

In Carbon 12

The analysis of the absolute rates of EVA for (p,2p) - $a_2(C) \sim 5$ ← with a significant uncertainties in absolute scale

Yaron et al 02

Our first result of 77 from backward proton production $a_2(C) \sim 4 \div 5$

→ *Puzzle of fast nucleon production is solved!!!*

Due to the findings of the last fewr years at Jlab and BNL SRC are not anymore an elusive property of nuclei !!

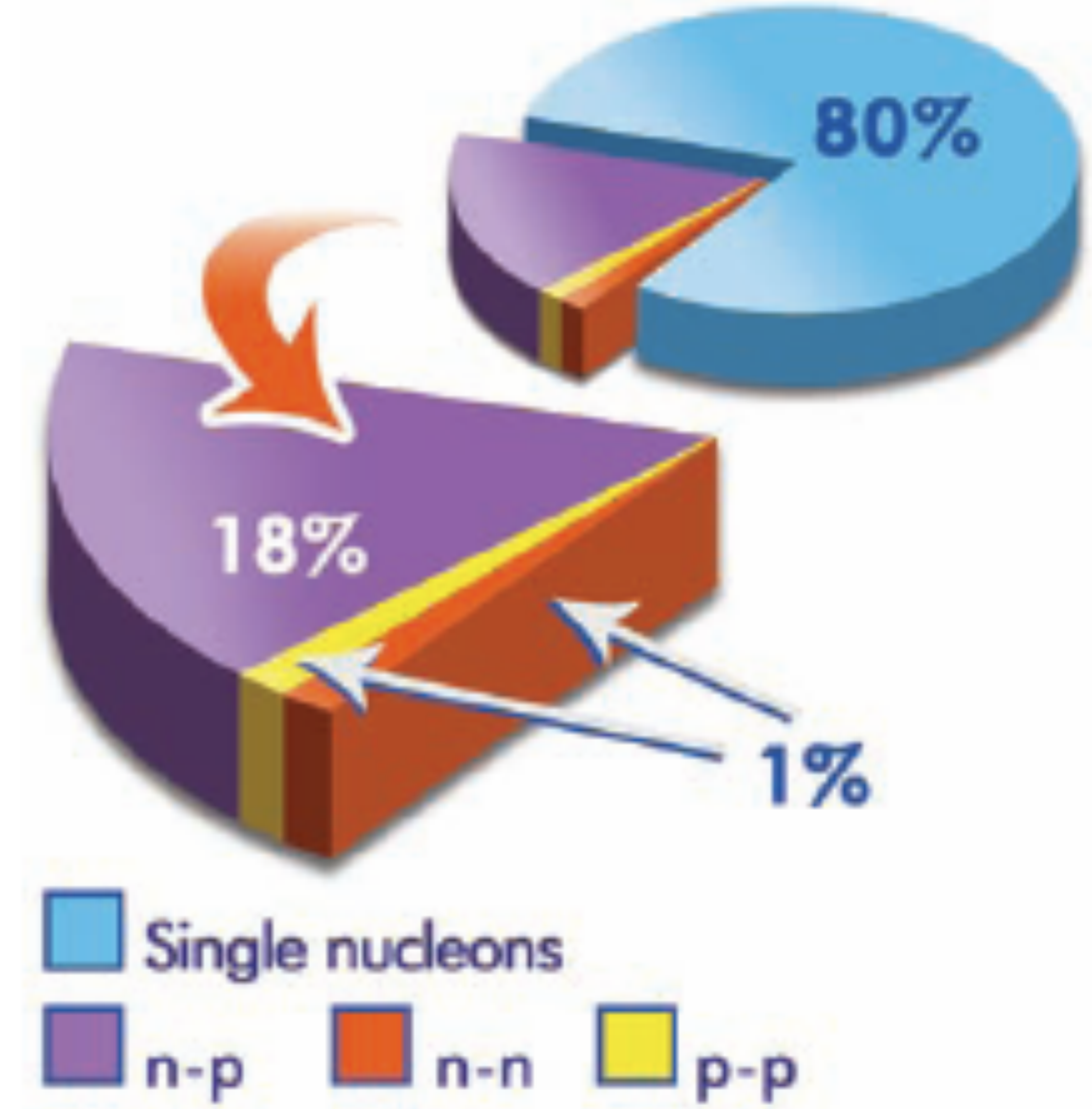
Summary of the findings

- Practically all nucleons with momenta k≥300 MeV belong to two nucleon SRC correlations BNL + Jlab +SLAC

- Probability for a given proton with momenta 600> k > 300 MeV/c to belong to pn correlation is ~ 18 times larger than for pp correlation BNL + Jlab

- Probability for a nucleon to have momentum > 300 MeV/c in medium nuclei is ~25% BNL + Jlab 04 +SLAC 93

- Three nucleon SRC are present in nuclei with a significant probability Jlab 05



The average fraction of nucleons in the various initial-state configurations of ^{12}C.

The findings confirm our predictions based on the study of the structure of SRC in nuclei (77-93), add new information about isotopic structure of SRC.

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?"

These observations match recent finding of a heavy neutron star $M \approx 2\ M_\odot$ - models where nonnucleonic degrees of freedom are easily excited cannot reach this mass range.

$\langle V_{pn} \rangle$ due to SRCs is dominant > 80% contribution to $\langle V_{NN} \rangle$

Extrapolation from properties of nuclei with Z ~ N to Z<<N - neutron starts is very dangerous.

Future directions

- Theory of e.m. hard processes sensitive to SRCs. Discriminating between different ways to account for relativistic effects (light cone vs virtual nucleon) -one aims at studying WF for k up to 1 GeV/c!!!
  - special focus reactions with polarized deuteron: $\vec{e} + \overrightarrow{^2H} \to e + \vec{p} + n$ S/D wave ratio.

- In many processes final state interactions complicate treatment - one needs large energy large momentum transfer and proper kinematics to minimize these effects. If energies are large (3 - 20 GeV range) - picture simplifies and one can use generalized eikonal approximation to account for for rescatterings

Critical to have sets of complementary measurements - like BNL - Jlab for first measurements

New possible set: eA Jlab, γA Jlab - for example large angle reaction

$\gamma\,^2H \to \pi^- p$ + *backward proton*

+ new player PANDA (storage ring at FAIR Germany) can collect ~10^3 more events than BNL experiment in several channels

- Looking for non-nucleonic degrees of freedom (Δ, N*) on 1% level using exclusive hard processes with electron & hadron beams like

$$\bar{p} +^2 H \to \pi^- \pi^- + \Delta^{++}$$

large c.m. angle

- Going to 4th resolution scale - which select special configurations in nucleons

  → Large angle scattering in the region of color transparency

  → Tagged EMC effects - looks tough effect is pretty small - but perhaps angular dependence is strong and averages out in inclusive case

- Theoretical and experimental studies of transition between mean field and SRC with 2 GeV protons

  Lanzhou, China?

- Data mining at Jlab

Data mining at Jlab: First results

Similar strength of pp correlations in (e,e'p) in heavy and light nuclei

Dominance of pn SRC at high momenta in heavy nuclei = equal number of protons and neutrons above Fermi surface= larger fraction of protons -- 30% protons and 20 % neutrons

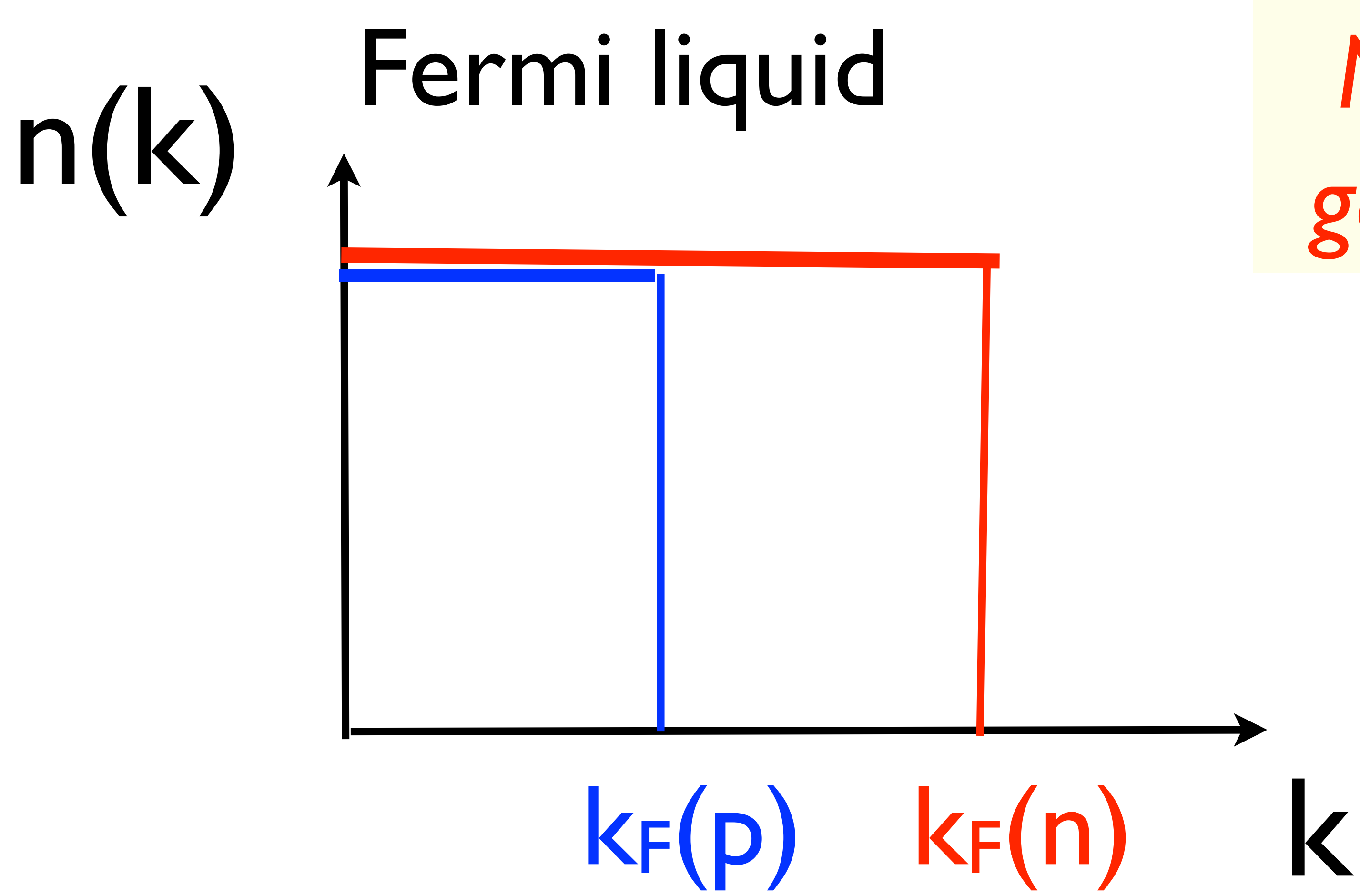
Future studies of short-range nuclear structure

Expect discoveries of several new phenomena in the next 5 --10 years

- *Direct observation of 3N SRC*
- *Direct observation of non-nucleonic degrees of freedom in nuclei in reactions like (e,e'ΔN)*

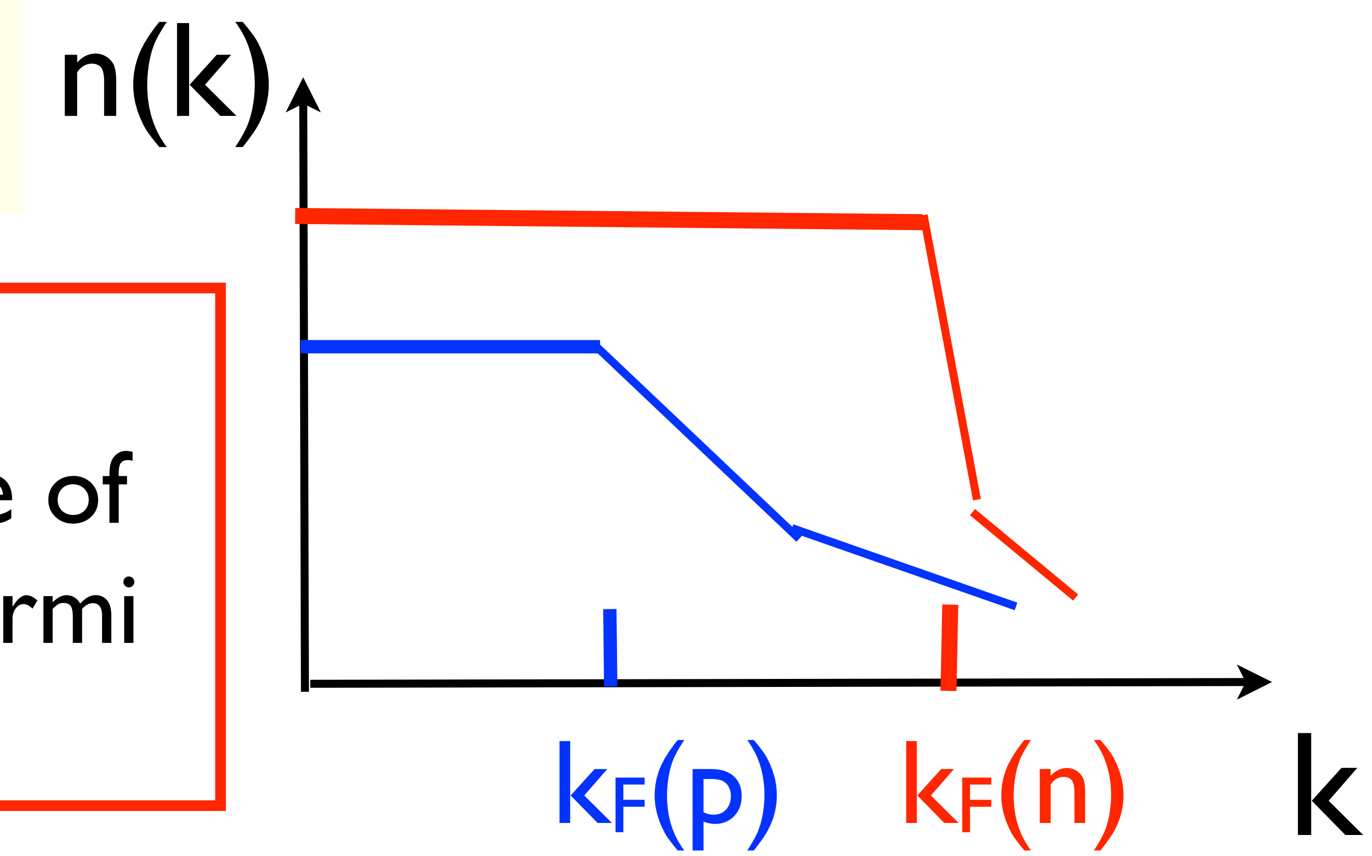
Some implications for neutron stars

- Our focus is on the outer core where nucleon density is close to nuclear one:
  $\rho \sim (2 \div 3)\ \rho_0$; $\rho_0 \approx 0.16$ nucleon/fm^3 and p/n ~ 1/10



Neutron gas heats proton gas due to large pn SRC

⇒ practical disappearance of the proton Fermi surface



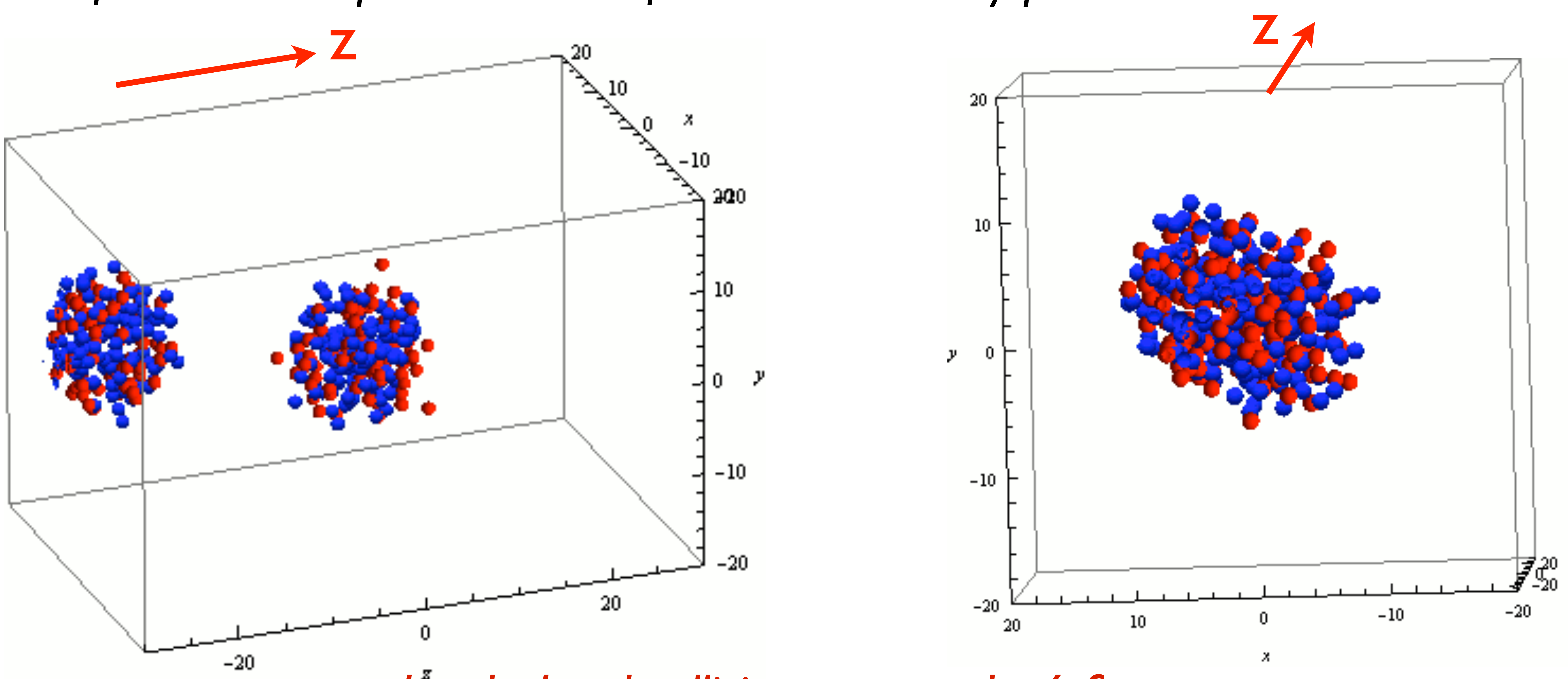
Large enhancement of neutrino cooling of the neutron stars at finite temperatures FS08

Suppression of the proton Fermi surface leads to the suppression of proton superconductivity, etc

Relativistic heavy ion collisions

What happens when a piece of the nucleus is chopped off? How does the residual system decay?

We developed nucleon configuration generator with SRC. Combing it with Glauber model we developed first microscopic treatment of the nucleus decay process. Alvioli and MS



Lead - Lead collision event at b=6 fm

- protons
- neutrons
- spectator nucleons which were near wounded nucleons

Average energy of emitted neutrons is consistent with the data. Many predictions can be checked at RHIC and LHC

Conclusions

Impressive experimental progress of the last few years - discovery of strong short range correlations in nuclei with strong dominance of I=0 SRC - has proven validity of general strategy of using hard nuclear reactions. It provides solid basis for further studies.

Top aims for the further studies:

i) Direct observation of 3N SRCs

ii) SRC near Fermi surface and at very large momenta

iii) Nonnucleonic degrees of freedom in nuclei

Would be highly beneficial to have parallel programs of studies with electron beams (Jlab 6 including data mining) and hadron beams in the next few years. Experiments at 12 GeV Jlab will further expand the scope of the studies of SRC. Additional studies are likely to be performed at FAIR (PANDA,...). Experiment at Lanzhou maybe the first experiment to study onset of the SRC regime with a high statistics and a number of cross checks.

A number of theoretical challenges including a) calculation of the decay functions for A >3, b) isotopic effects for SRC, c) including Δ-isobars, d) relativistic effects, e) studies of FSI dynamics - optimizing for signal of SRC, understanding the role of color transparency effects.