Challenges of studies of the short-range nuclear structure

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Outline

Fundamental questions of microscopic nuclear structure/forces

Why can we do better now - theoretical expectations and the data

Directions for the future studies

Jlab user meeting, June 18, 2007

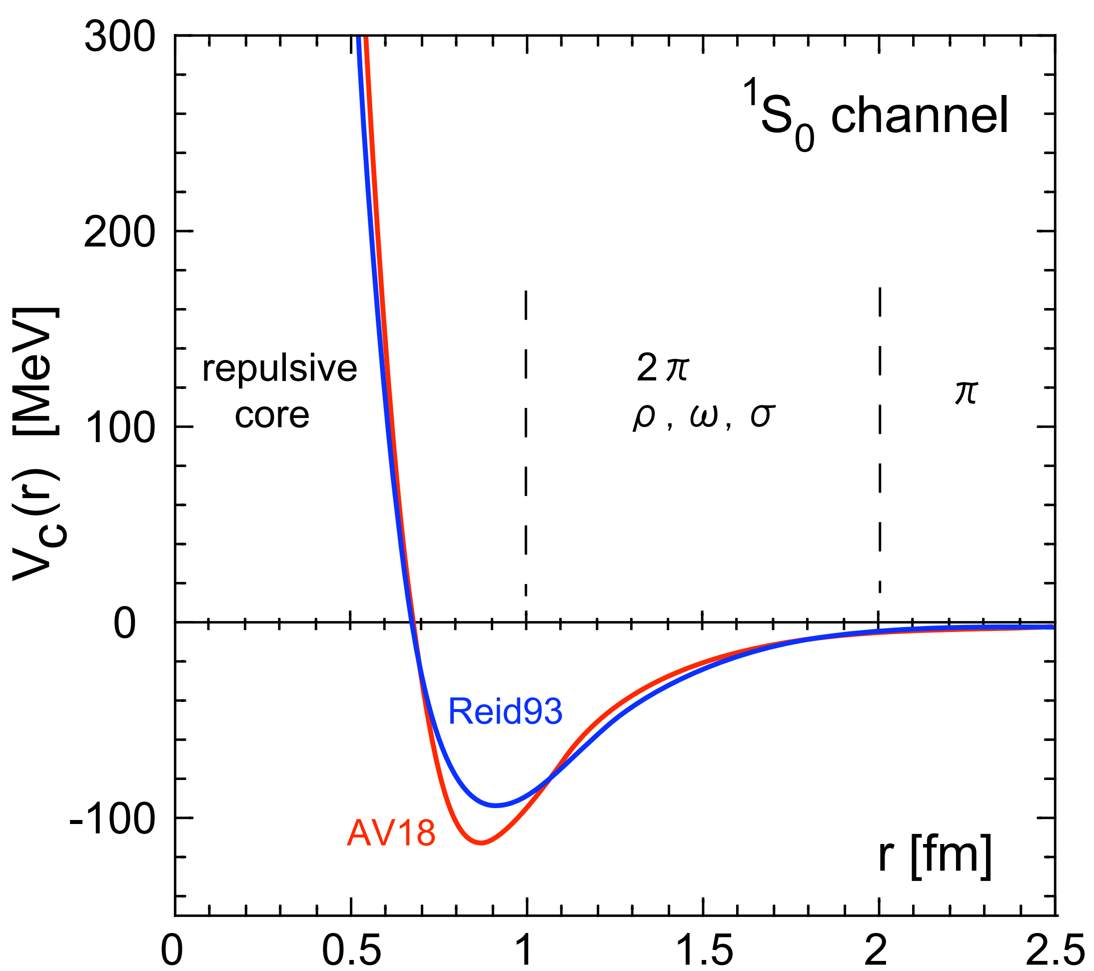
Fundamental questions of microscopic quark-gluon structure of nuclei and nuclear forces

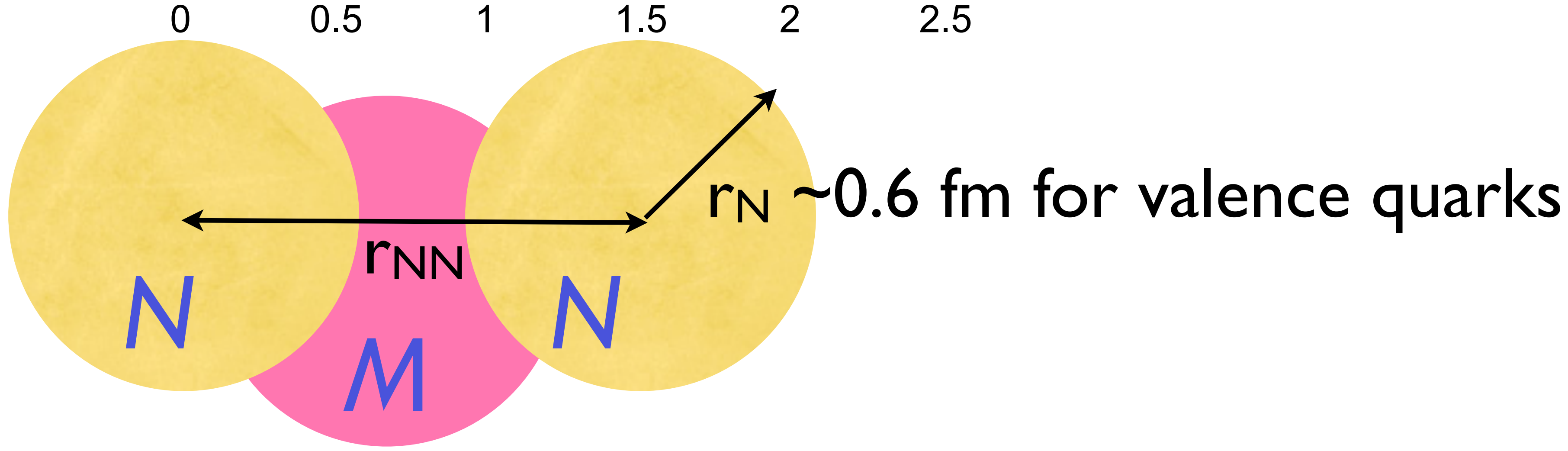
- Microscopic origin of intermediate and short-range nuclear forces

- Are nucleons good nuclear quasiparticles?

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

Origin of intermediate and short-range nuclear forces.
Do nucleons exchange mesons or quarks (gluons) at r< 1.5 fm?





Hard to fit a meson between two nucleons for r_{NN}< 1.5 fm. Can nucleons instead exchange quarks?

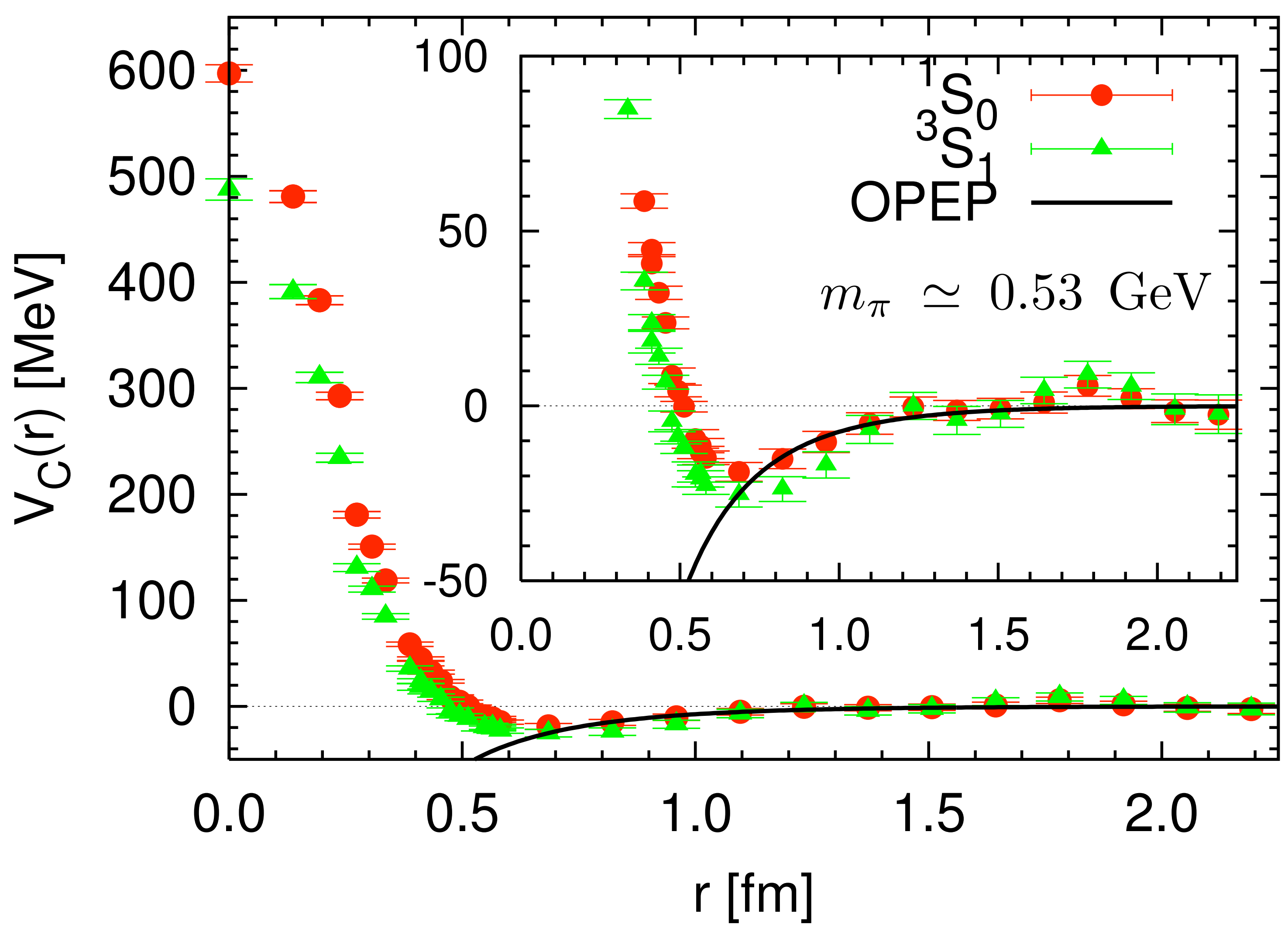
Interesting new development:

The Nuclear Force from Lattice QCD

N. Ishii, S. Aoki, T. Hatsuda, PRL 07

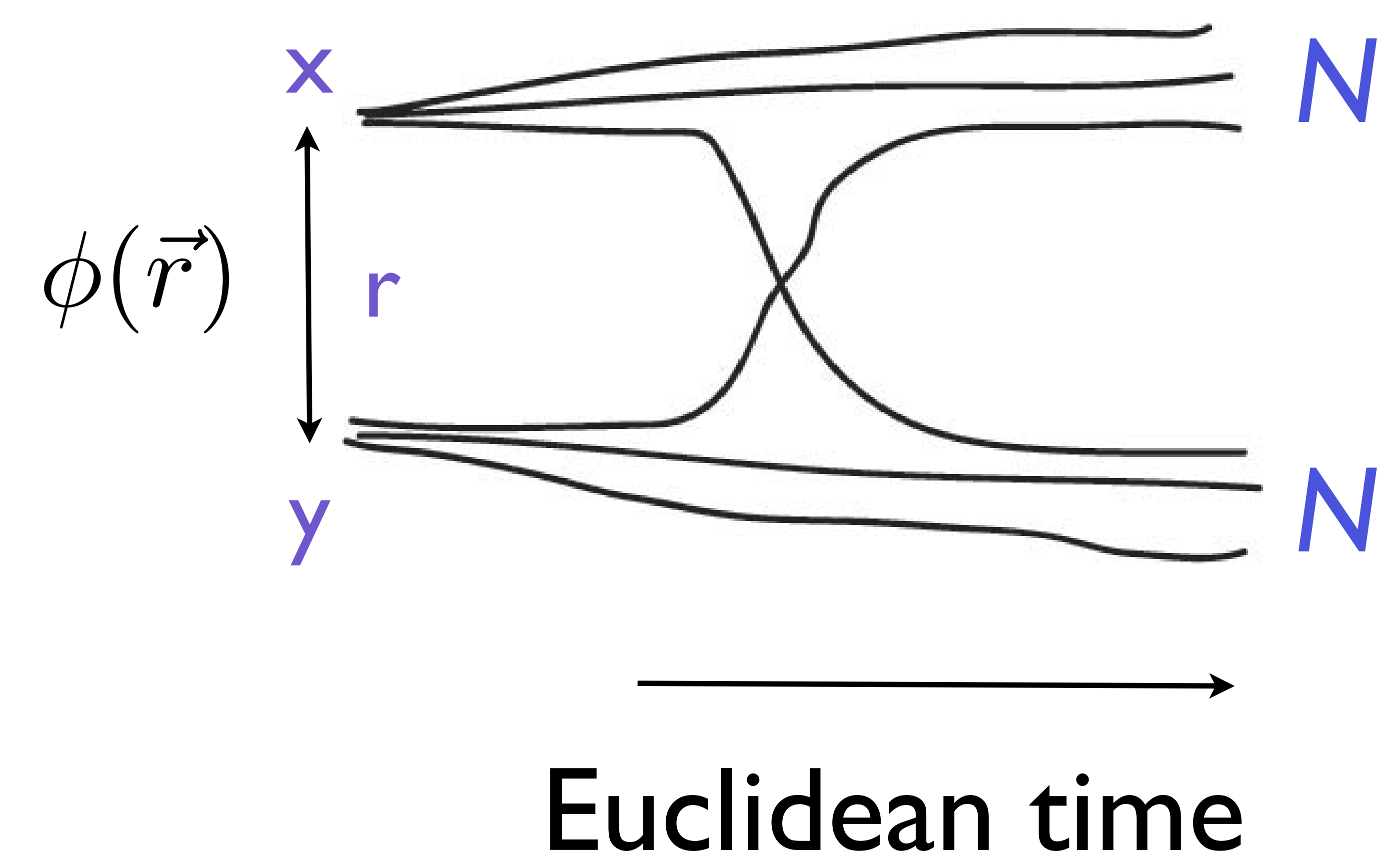
reconstruct potential
from wave function

$$V(\vec{r}) = E + \frac{1}{2\mu}\frac{\vec{\nabla}^2\phi(\vec{r})}{\phi(\vec{r})}.$$



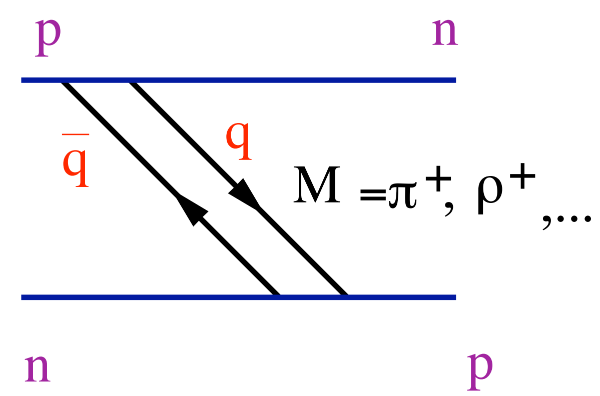
Nuclear core from lattice QCD

Important - quenched approximation
interaction is due to quark exchanges



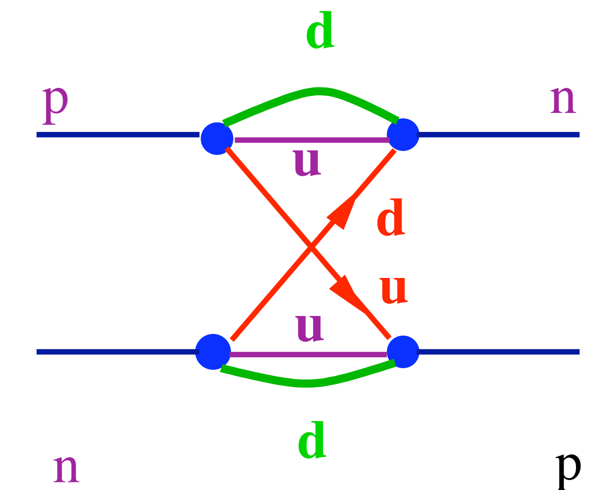
Quark exchanges also lead to transitions to NΔ, ΔΔ - so far neglected in the lattice calculation

Are meson and quark exchanges equivalent -dual? Not necessarily/always



Meson Exchange

$\neq$



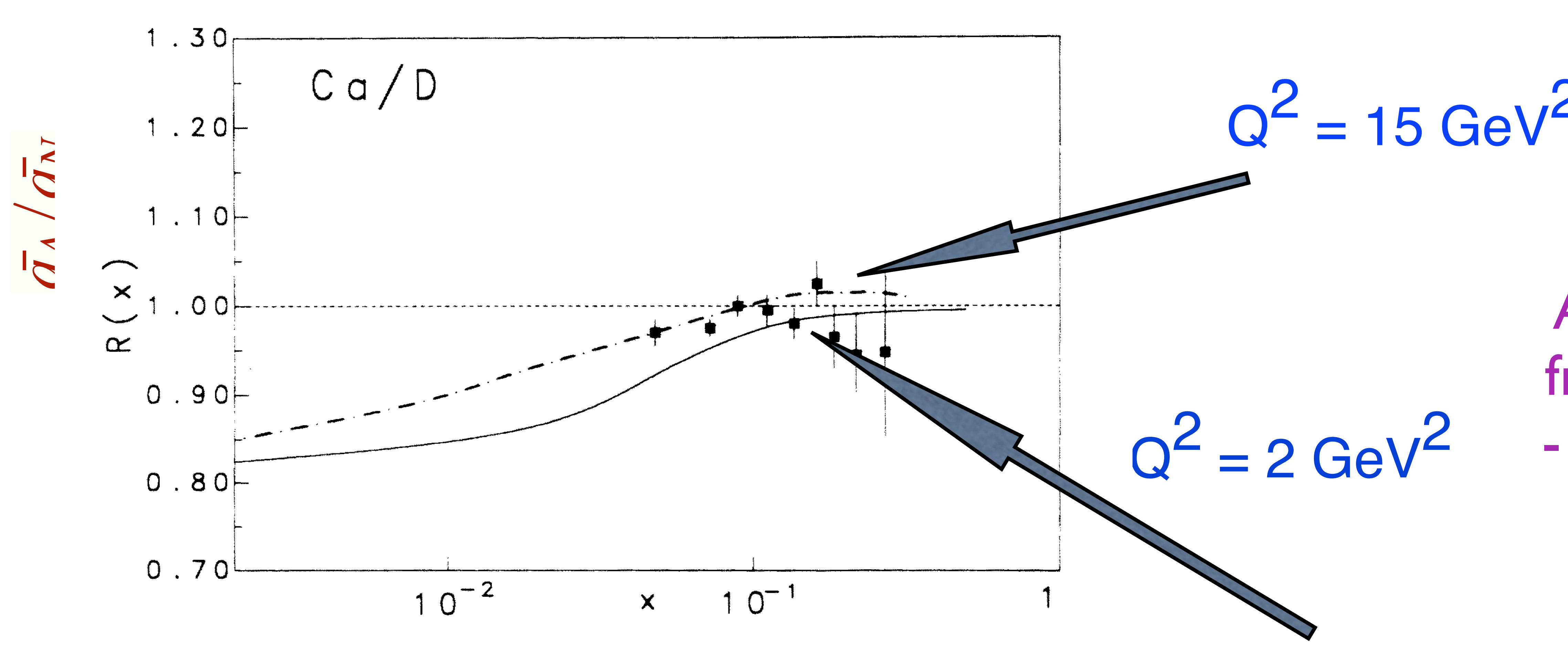
Quark interchange

extra antiquarks in nuclei

no extra antiquarks

$\bar{q}_A/\bar{q}_N \sim 1.1\text{-}1.2$ for $x=0.05$ and $A=40$

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?

Low momentum transfer processes - Fermi liquid theory - effective masses ~0.7 m_N, strong quenching for A(e,e'p) processes Q~0.6

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

Processes with large momentum transfer resolve individual nucleons - legitimate to ask questions about properties of bound nucleon

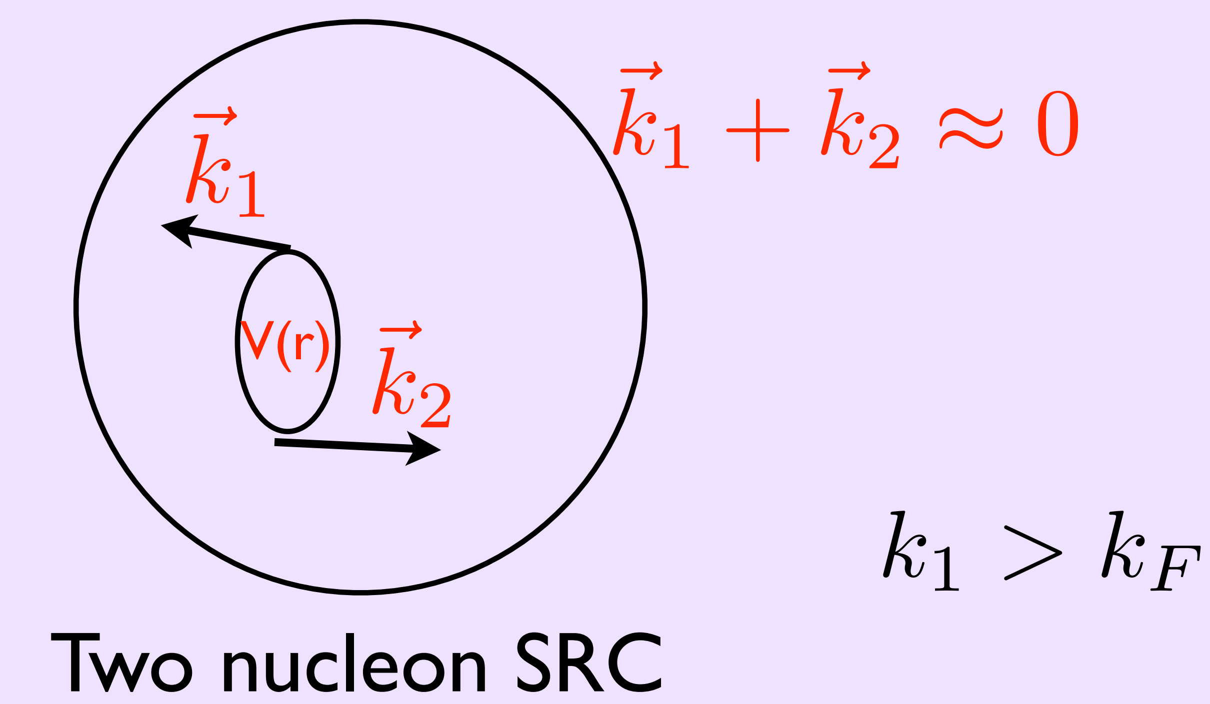
- Form factors (talk of Strauch)
- Structure functions - EMC effect
- Quenching - analyses of the Jlab data at large momentum transfer Q>0.85

Probability and structure of the short-range correlations (SRC) in nuclei

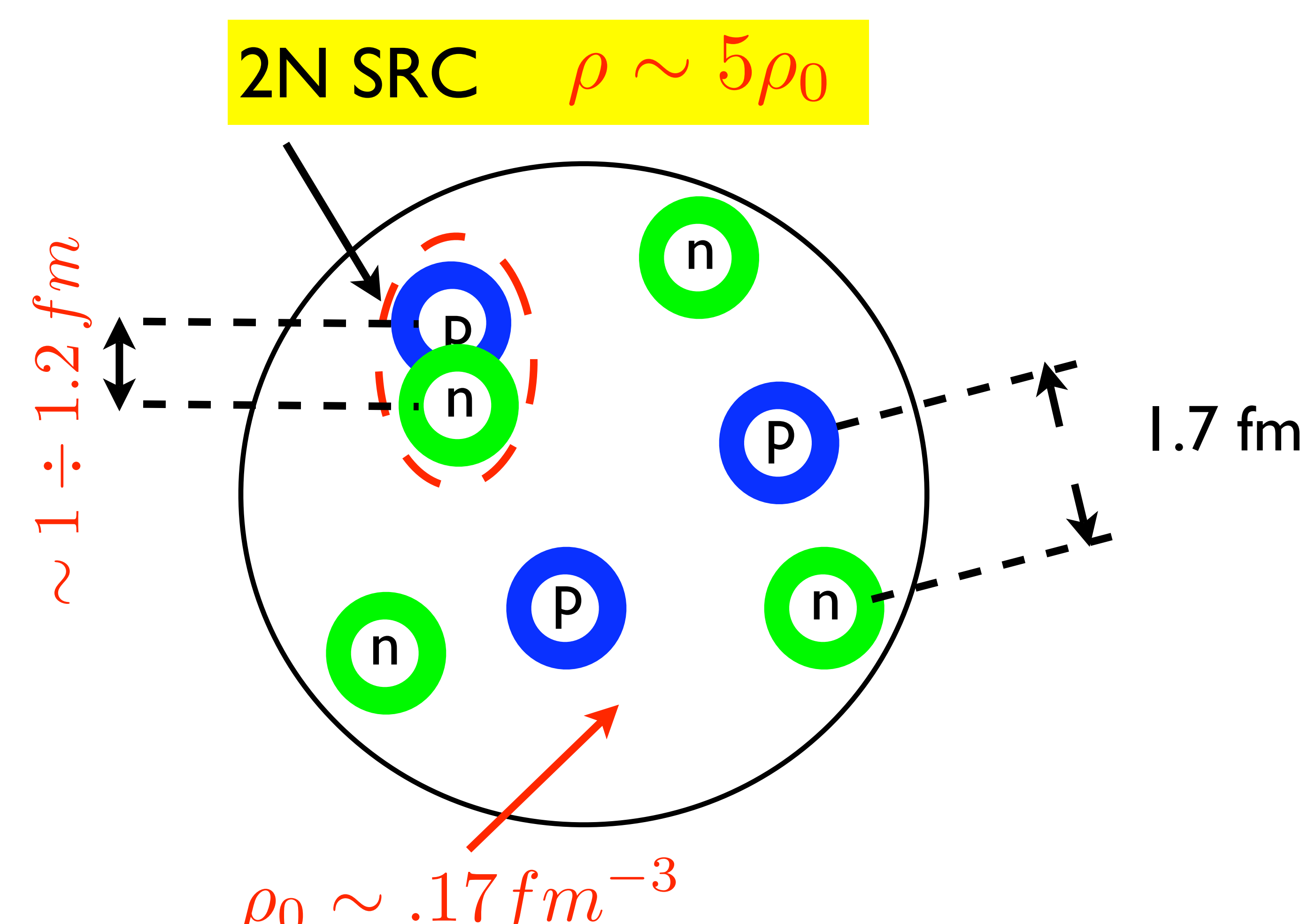
SRC for many years considered to be an elusive feature of nuclear structure

Questions:

- How large is probability of SRC ?
- Isotopic structure
- Non-nucleonic degrees of freedom



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

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

Phys.Lett. rules of 1976 - reject claims to the opposite without review

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 (MEC,...), enhancement of the final state contributions.

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

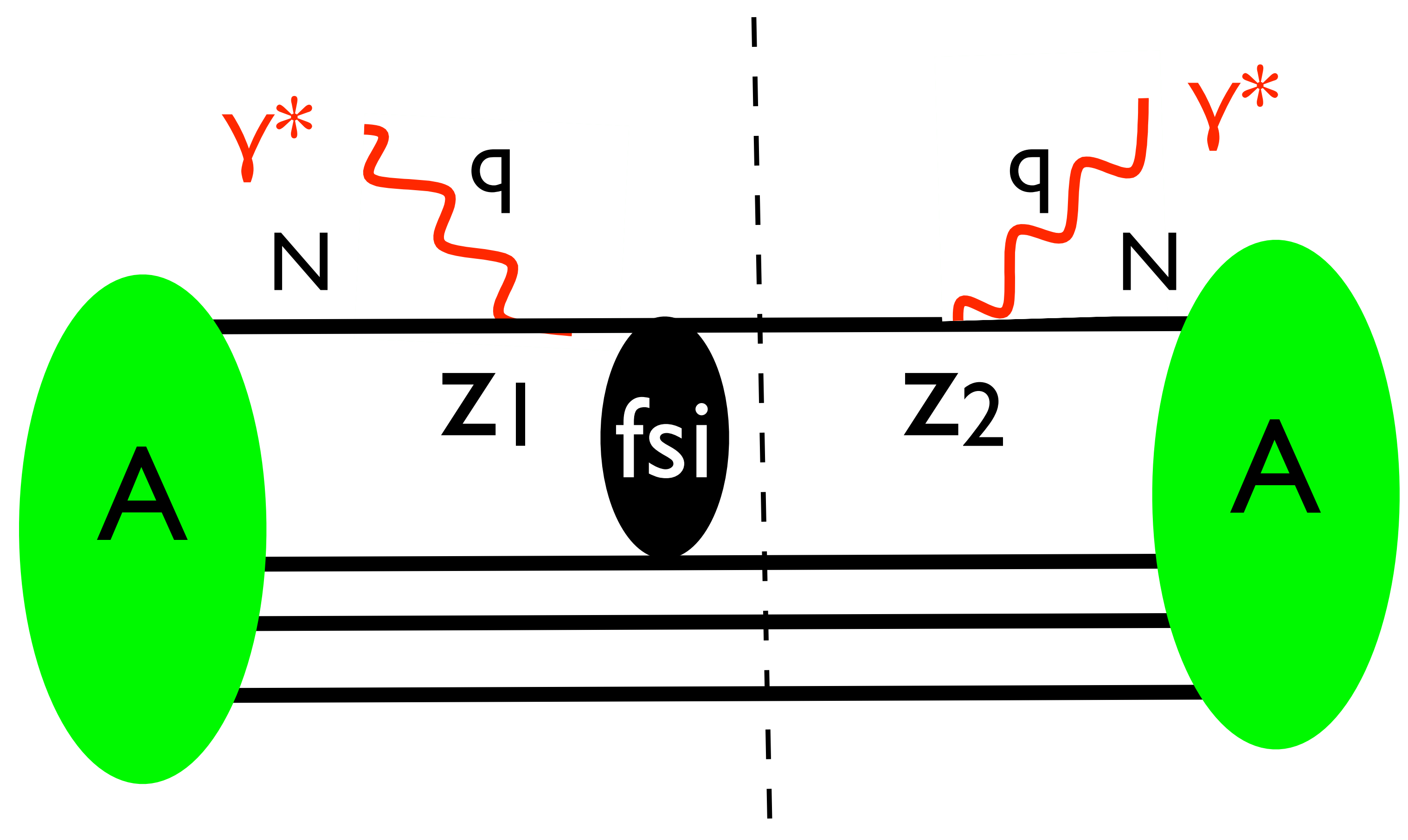
$$q_0 \geq 1GeV \gg |V_{NN}^{SR}|, \vec{q} \geq 1GeV/c \gg 2\ k_F$$

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

$\Rightarrow$ 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. Will briefly mention relativistic effects later.

Progress in the studies of SRC at high momentum due to two concepts

Closure approximation for A(e,e') at $x > 1$, $Q^2 > 1.5$ GeV^2 up to fsi in the SRC



$z_1 - z_1 < 1.2$ fm ➡ only fsi within SRC

In hard exclusive processes where a nucleon of SRC is removed instantaneously

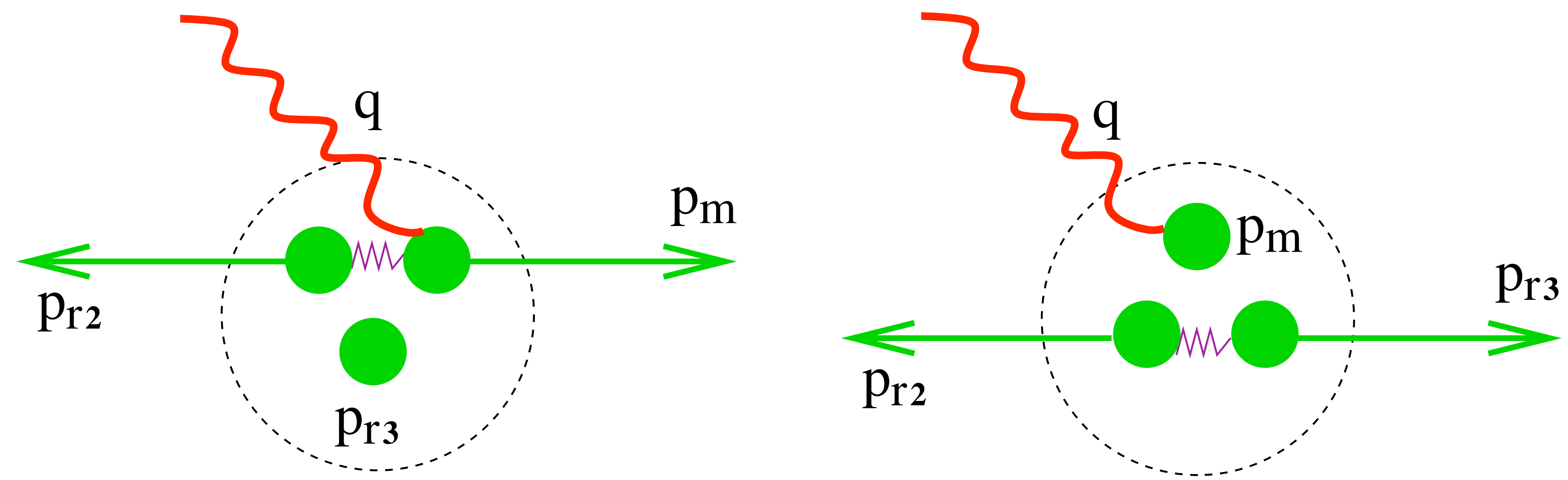
probe another quantity sensitive to SRC - nuclear decay function (FS 77-88) - probability to emit a nucleon with momentum k_2 after removal of a fast nucleon with momentum k_1, leading to a state with excitation energy E_r nonrelativistic definition

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

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.

For 2N SRC can model decay function as decay of a NN pair moving in mean field (like for spectral function) Piasetzky et al 06

Spectator is released



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

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

No simple connection between the decay function and two nucleon momentum distributions in the nuclei.

Last two years a qualitative progress in the study of SRC based on the analysis of the high momentum transfer (e,e') Jlab data, (p,2pn) BNL data and preliminary (e,e'pp) & (e,e'pn) Jlab data. 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

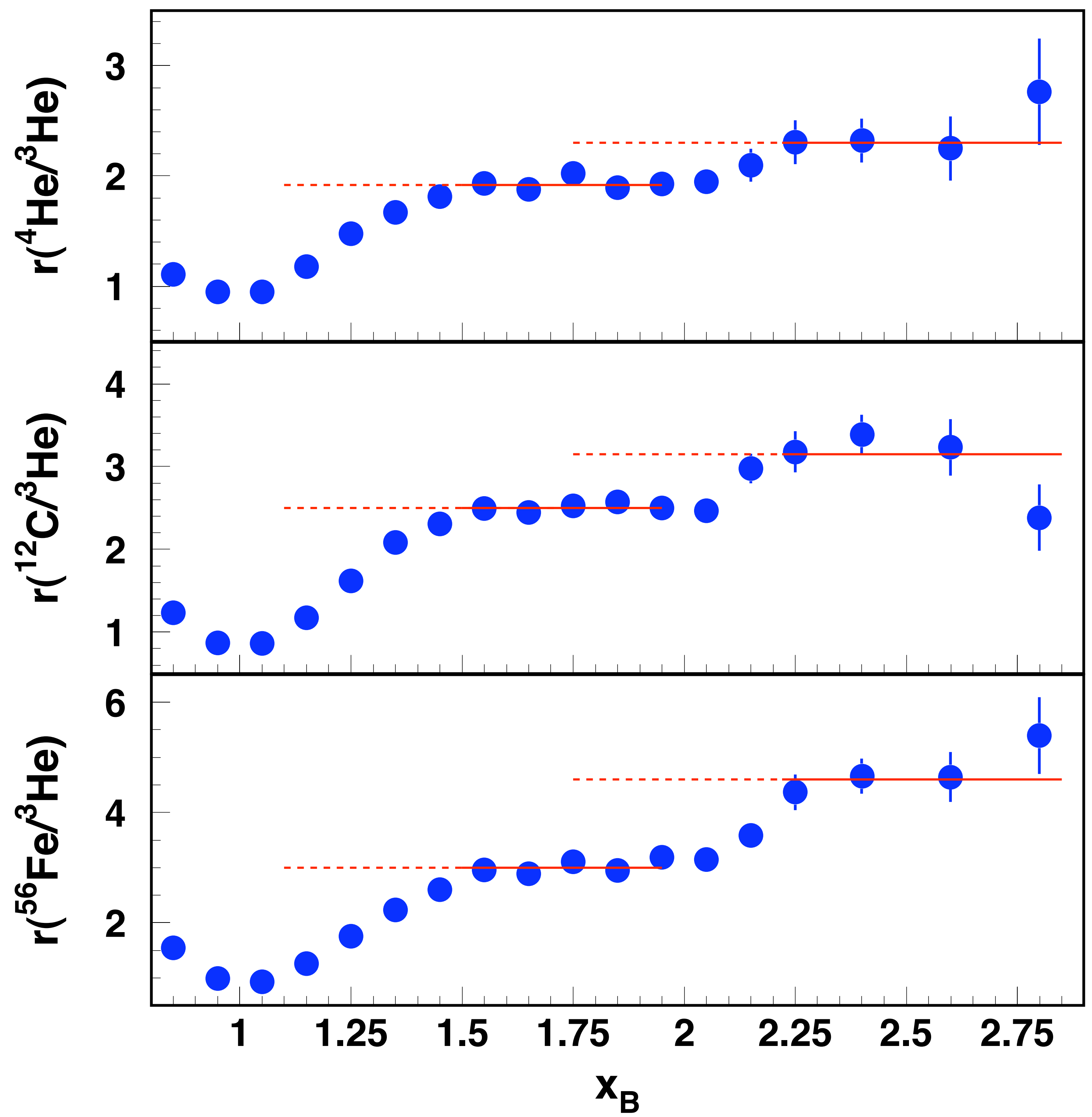
Probability for a given proton with momenta 600> k > 300 MeV/c to belong to pn correlation is ~ 18 times larger than for pp correlation

BNL + Jlab preliminary

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 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. In particular this confirms our interpretation of the fast backward hadron emission observed in the 70's-80's as to due to SRC and allows to use information from these experiments for planning new experiments which would allow unambiguous interpretation.



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

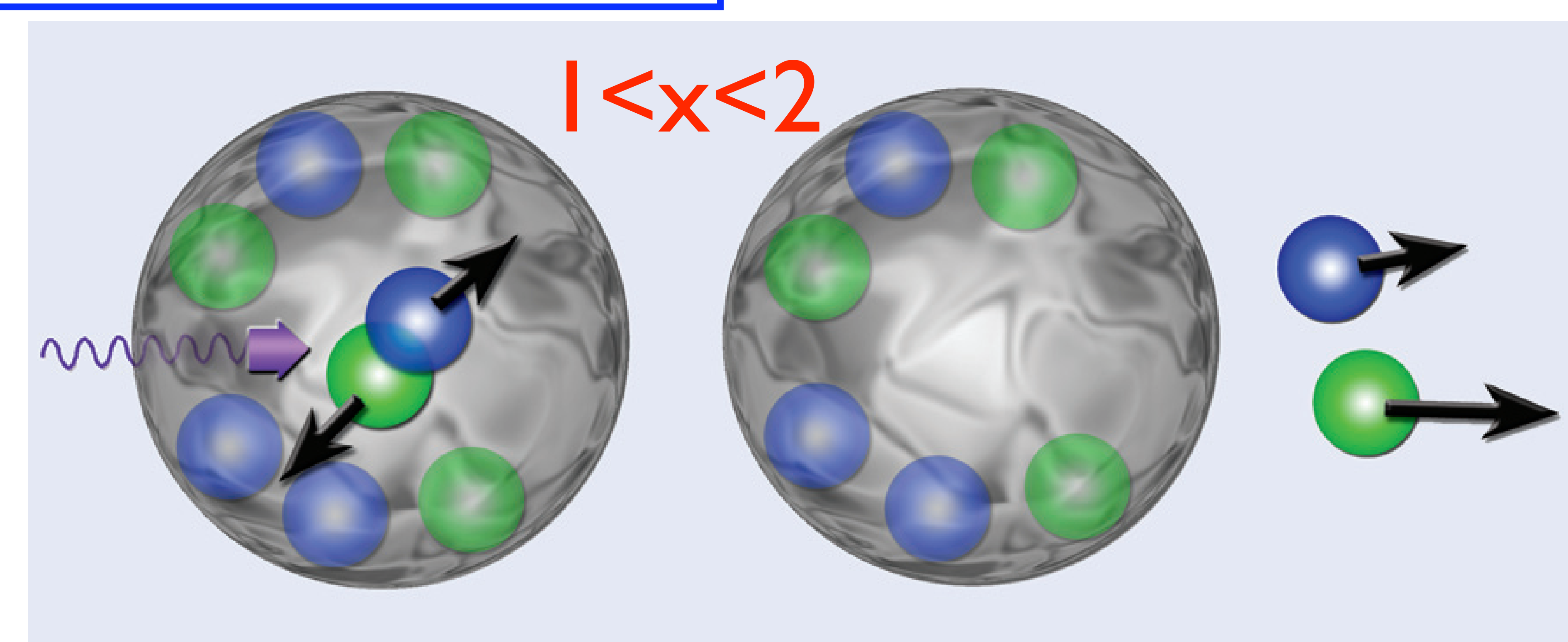
New Jlab data from Hall B.
$Q^2 > 1.5$ GeV^2

confirm our 1980 prediction of scaling 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:

$$r_2 = (A_1/A_2)^{0.15}$$

$$r_3 = (A_1/A_2)^{0.22}$$



Before absorption of the photon

After absorption

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!!!

Analysis of BNL E850 data

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 Oct 06

pn/pp > 16

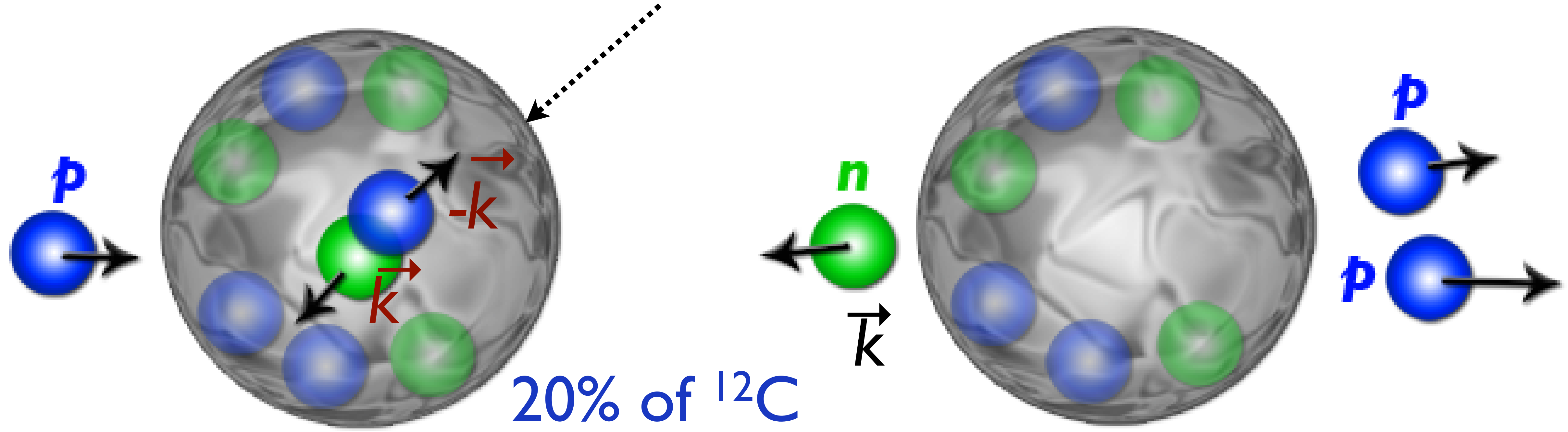
n-p Short-Range Correlations from (p,2p + n) Measurements

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]

at energy and momentum transfer ≥ 3 GeV

PRL 04

spectator mechanism of backward nucleon production *FS77 nucleus decay after instantaneous removal of a nucleon from SRC*



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

20% of ^{12}C wave function

Before collision

removal of a proton with momentum > 250 MeV/c

After collision

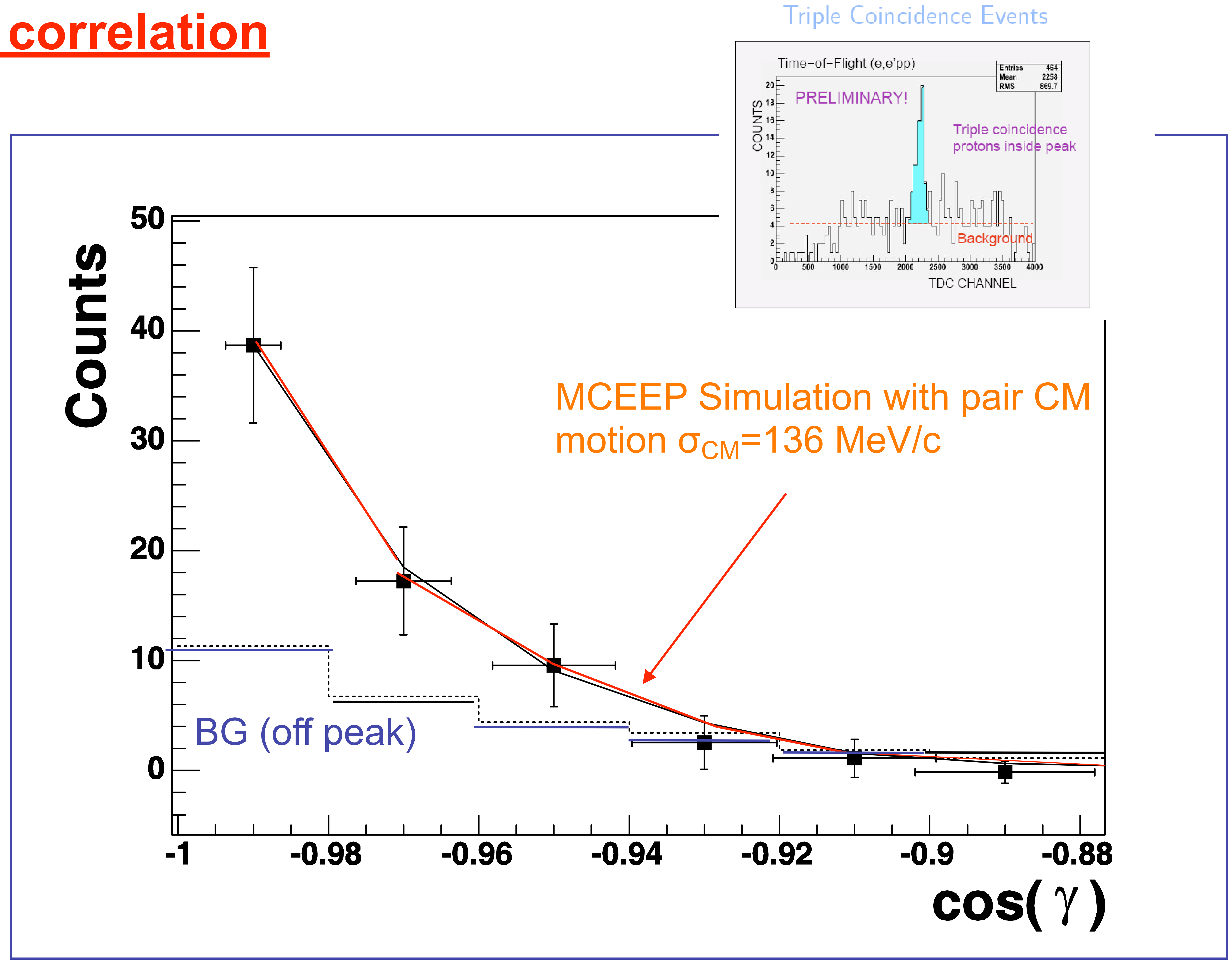
~90% probability of emission of neutron with similar but opposite momentum

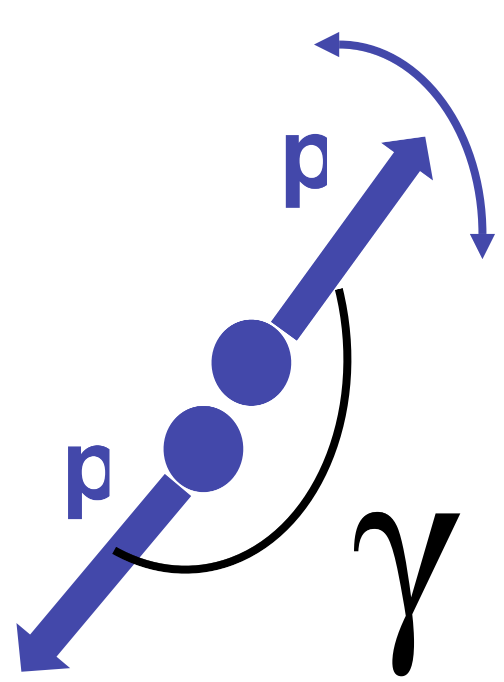
+

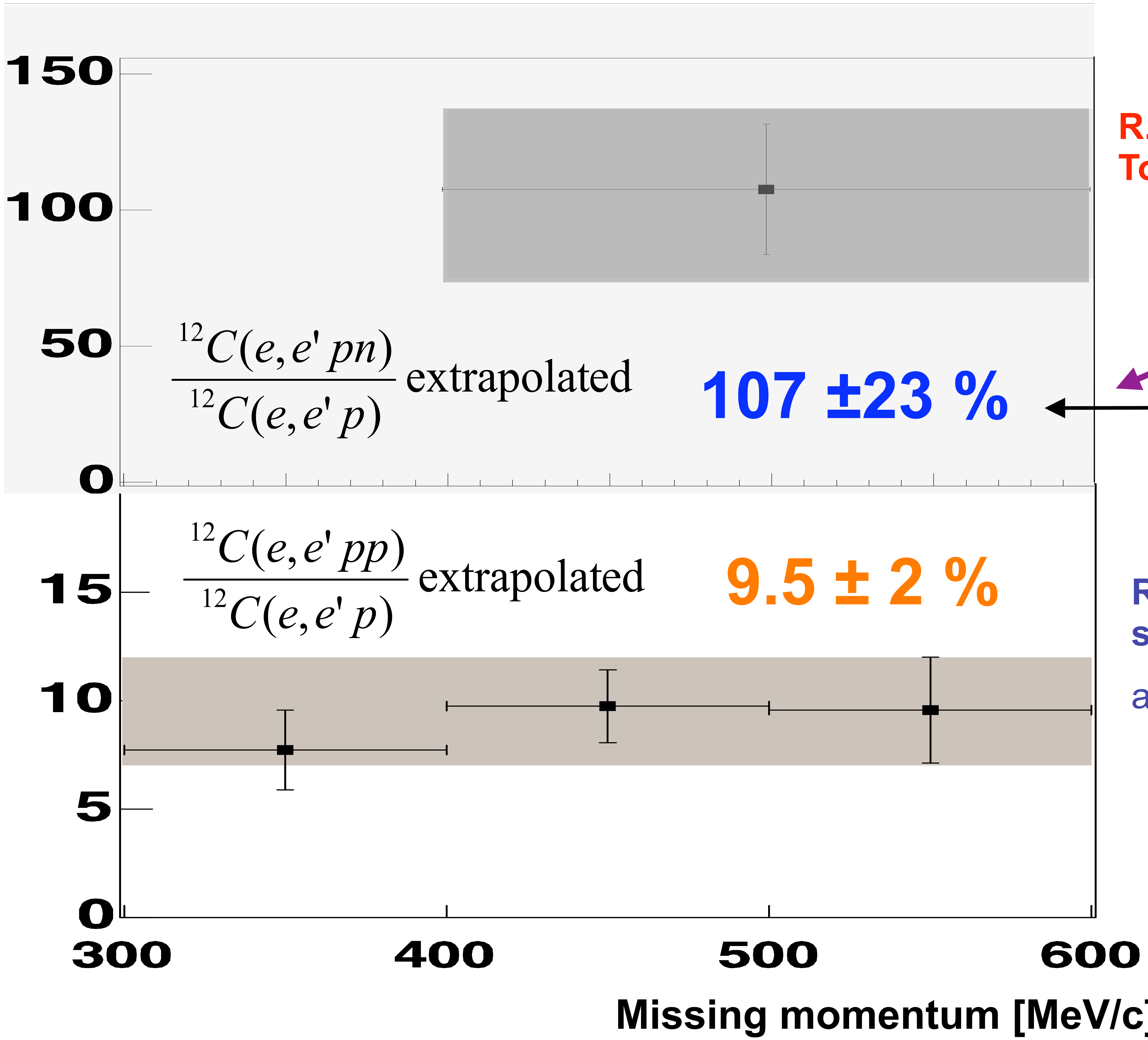
Jlab: from study of (e,e'pp), (e,e'pn)~10% probability of proton emission, strong enhancement of pn vs pp comparable with BNL data

Directional correlation

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







R. Subedi et al.,
To be submitted

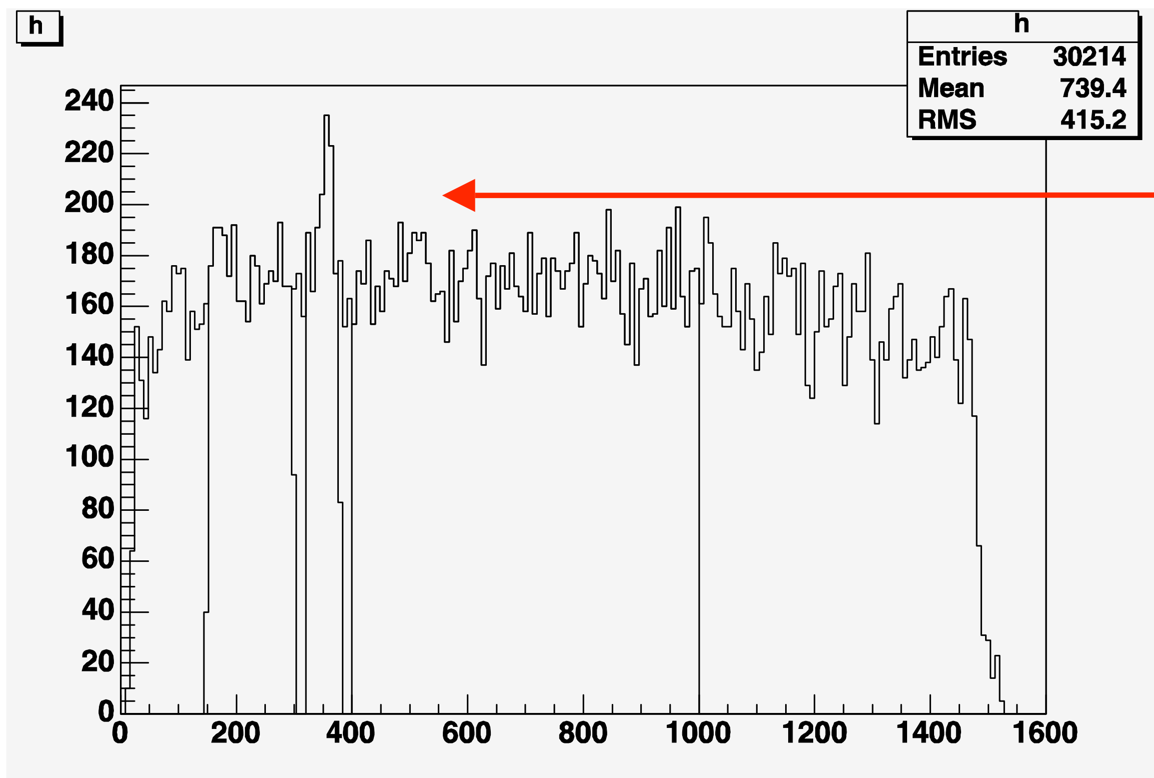
Note - BNL and Jlab studied very different kinematics for break up of 2N SRC - similarity of the numbers is highly non-trivial

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

R. Shneor et al.,
submitted to PRL

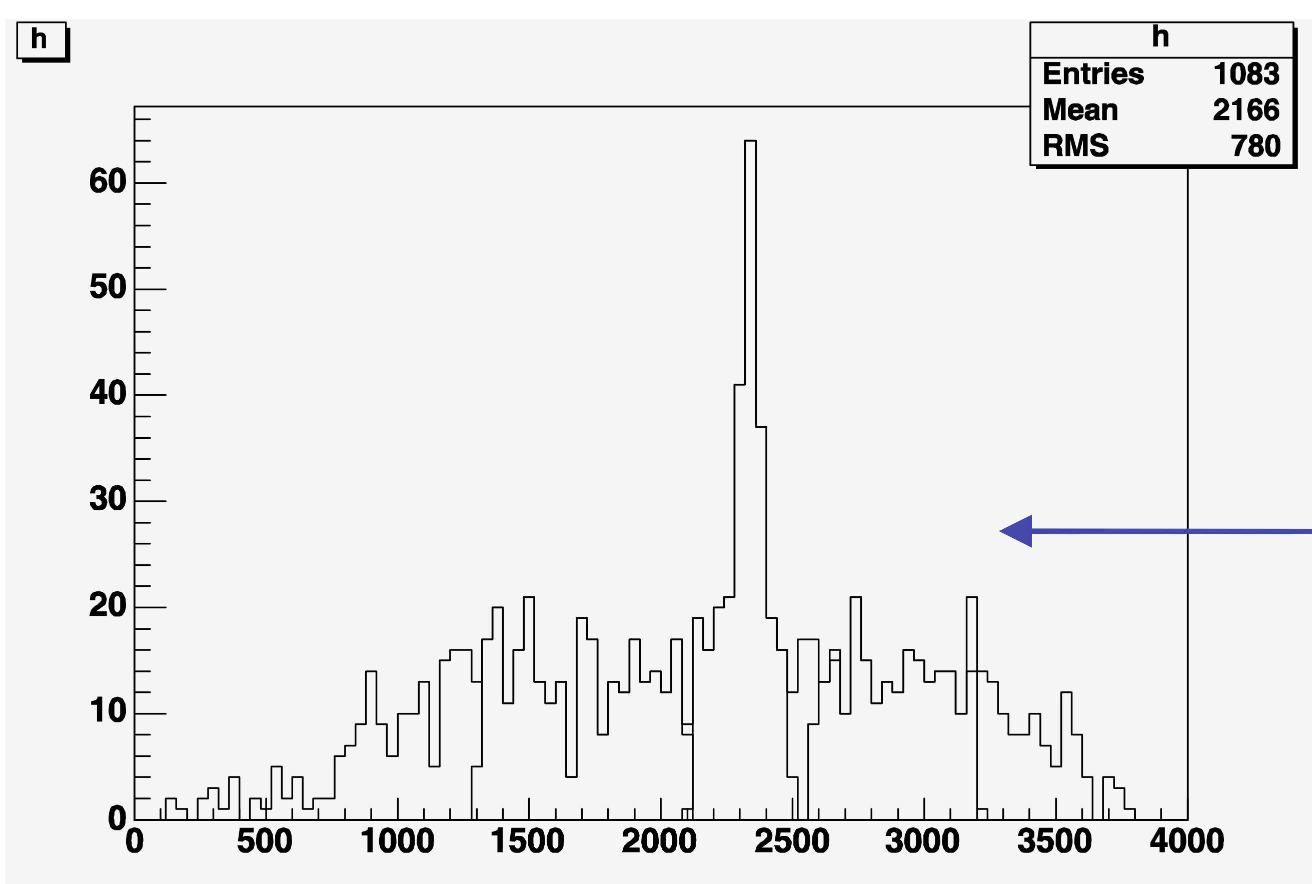
arXiv:nuclex/0703023v2

The (e, e'pn) / (e, e'pp) ratio



TOF for the neutrons [ns]

179 ± 39



TOF for the protons [ch]

116±17

(efficiency corrected)

$$\frac{^{12}C(e,e'\,pn)}{^{12}C(e,e'\,pp)} = 8.2 \pm 2.2$$

X 2

$$\frac{np-SRC}{pp-SRC} = 16.4 \pm 4.4$$

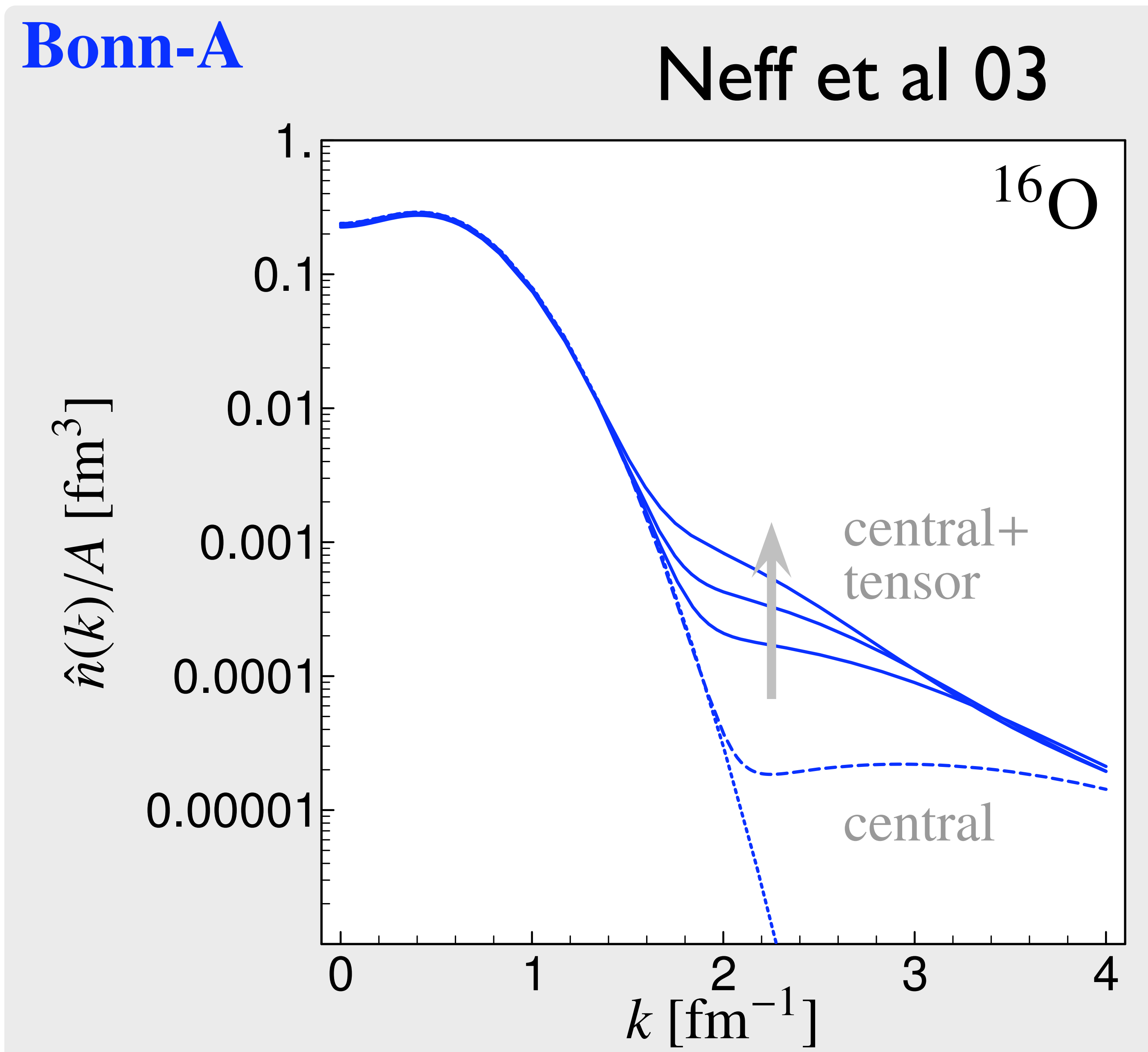
+11

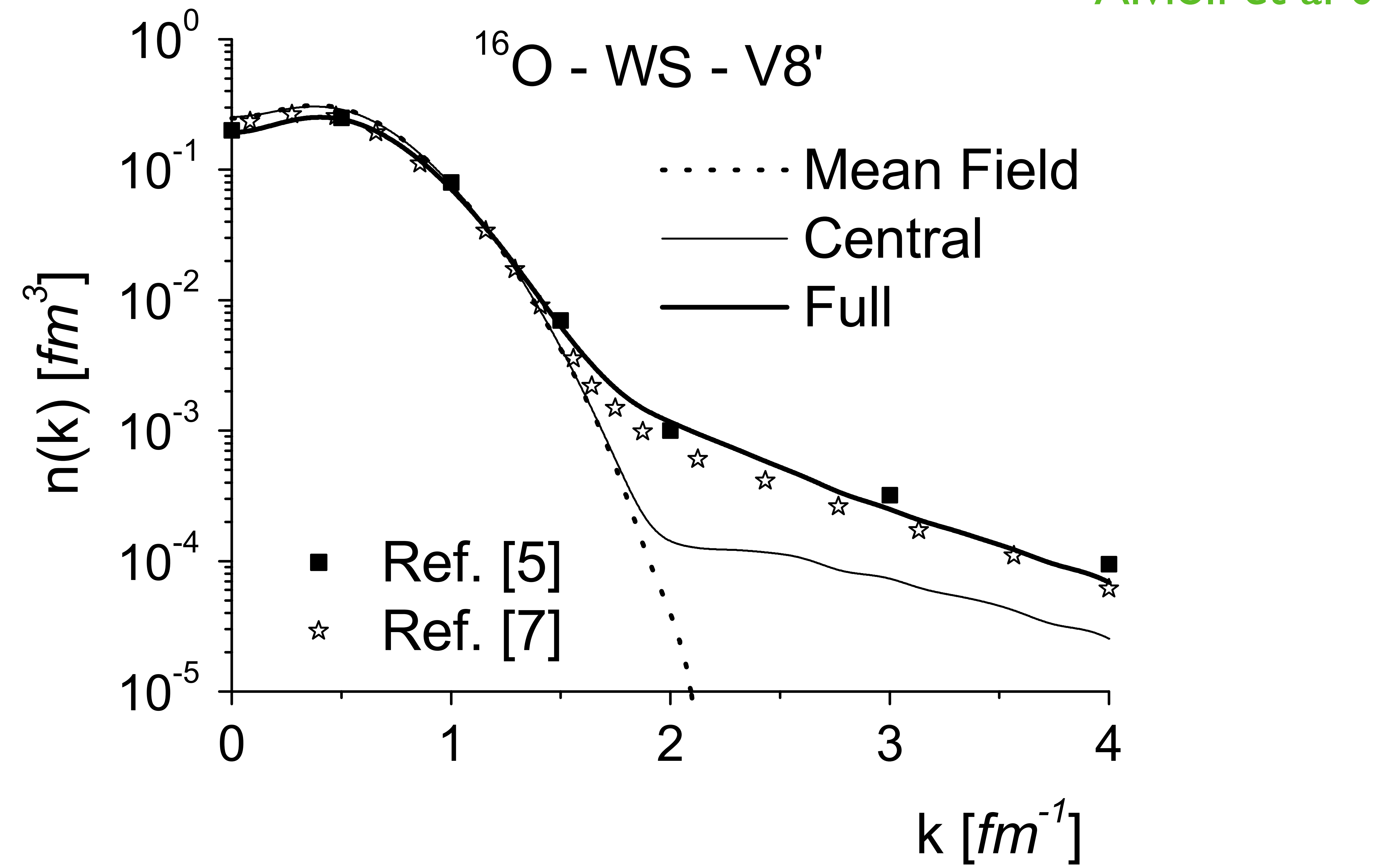
$$\frac{np-SRC}{pp-SRC} = 18.2 \pm 4$$

In 12C

Single Charge Exchange (SCX)

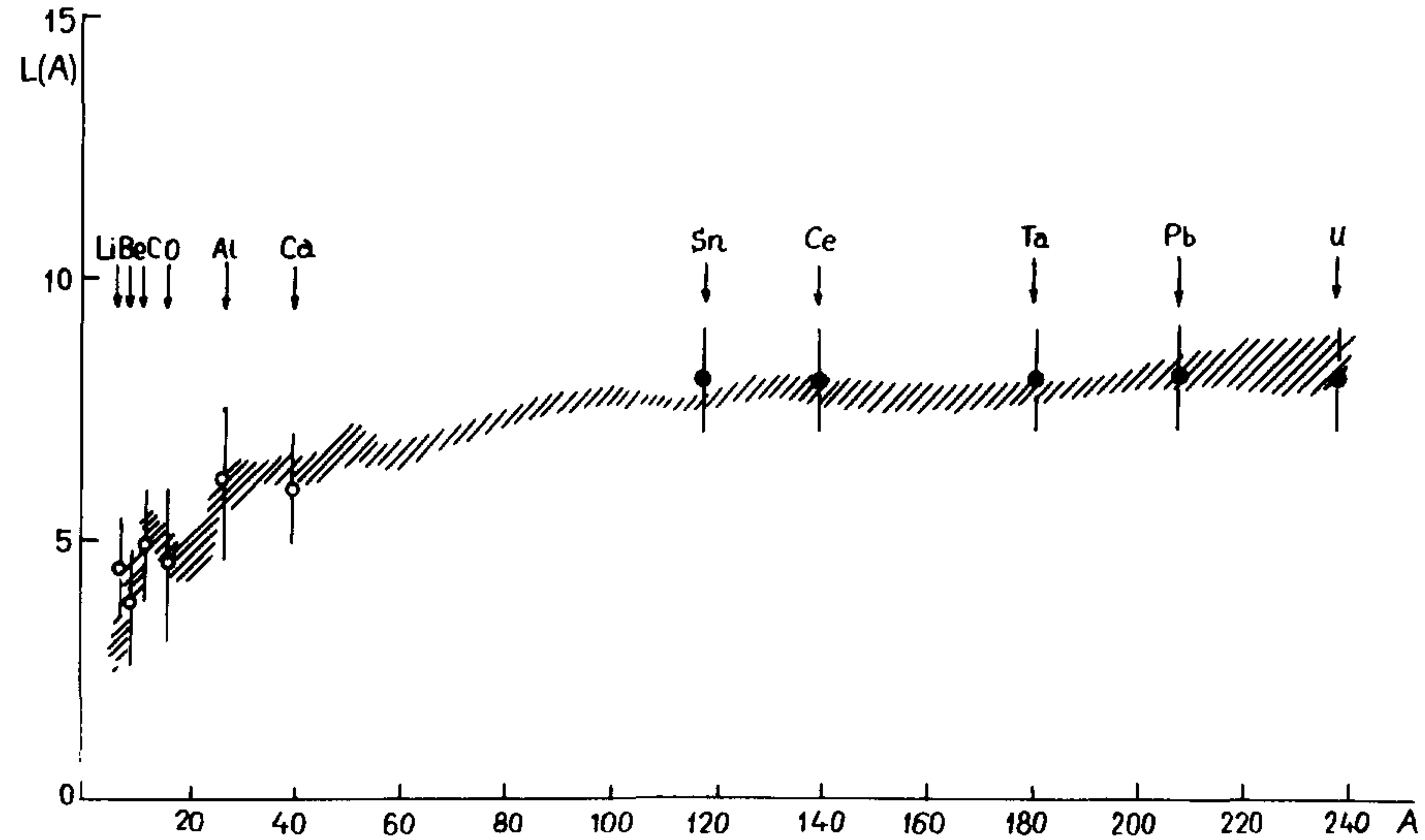
Small pp/pn consistent with dominance of tensor SRC in the high momentum component of the nuclear wave function





Calculations confirm dominance of tensor forces, but relative contribution of central forces varies from 10 to 20 % . However it seems that "pp" correlations are suppressed more experimentally than in the calculations

Side remark - I am often asked - Are these regularities the same as in low energy photo/pion absorption? Answer appears to be **no** *on the quantitative level.*



A-dependence of the Levinger constant - L -

where LNZ/A number of quasideuteron pairs in the nucleus obtained from the analysis of the total photon-nucleus absorption cross sections below the pion threshold

If I=0, S=1 pairs dominate $r_2=L/2$ for N+Z

➡ $r_2(C)= 2.5$ much smaller than the high energy finding of $r_2(C)\approx 5$

Directions for the future

Inclusive (e,e') at x> 1

- Detailed study of onset of scaling at $Q^2 \sim 1$ GeV^2 - sensitive to minimum momentum where SRC dominate.
- Observing a break down of the scaling of ratios at large $Q^2 > 5$ GeV^2 due to onset of the contribution of inelastic processes - ratios A/D should further increase !!!
- *x> 2.2 need much more data*
- Isotopic structure of correlations

pn/pp ^{48}Ca vs ^{40}Ca: $\sigma(e\,^{48}Ca)/\sigma(e\,^{40}Ca) = 28/20$ for x=1.5?

^{3}H vs ^{3}He (Am I asking coooooo much?): $\sigma(e\,^{3}H)/\sigma(e\,^{3}He) = 1$ for x=1.5?

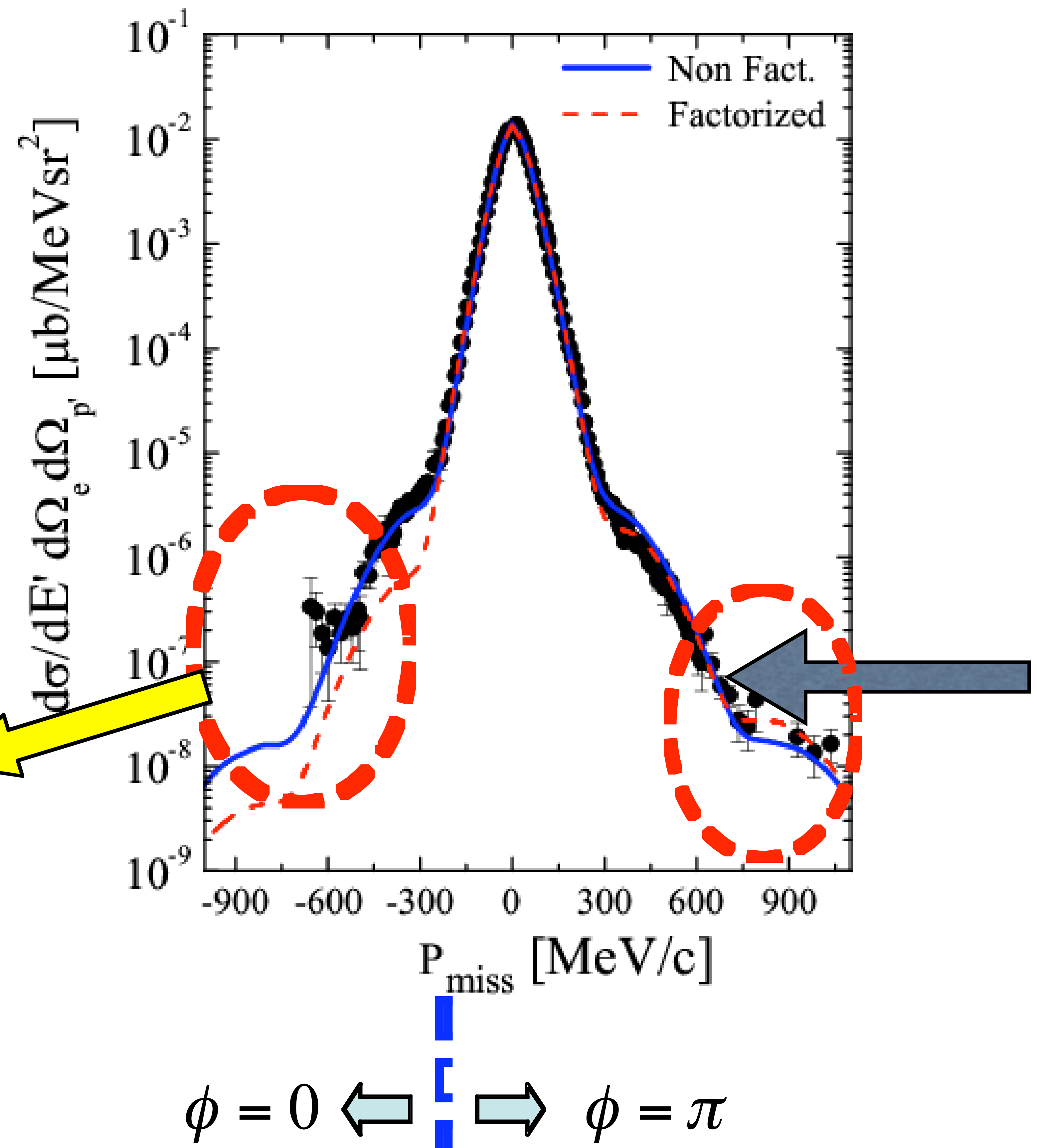
ppn/pnn $\sigma(e\,^{3}H)/\sigma(e\,^{3}He)$= ? at x=2.5 sensitive to 3N forces

(Semi) Exclusive (e,e'pN, pNN) processes

Need processes/kinematics with sufficiently small fsi, which can be taken into account theoretically - GEA - Sabina's talk

Seems to work in the processes where fsi dominates → should be good in the situations where fsi are corrections. Example - recent calculation of Ciofi et al:

Data: JLab E89044 $e +^3 He \to e + p +^2 H$

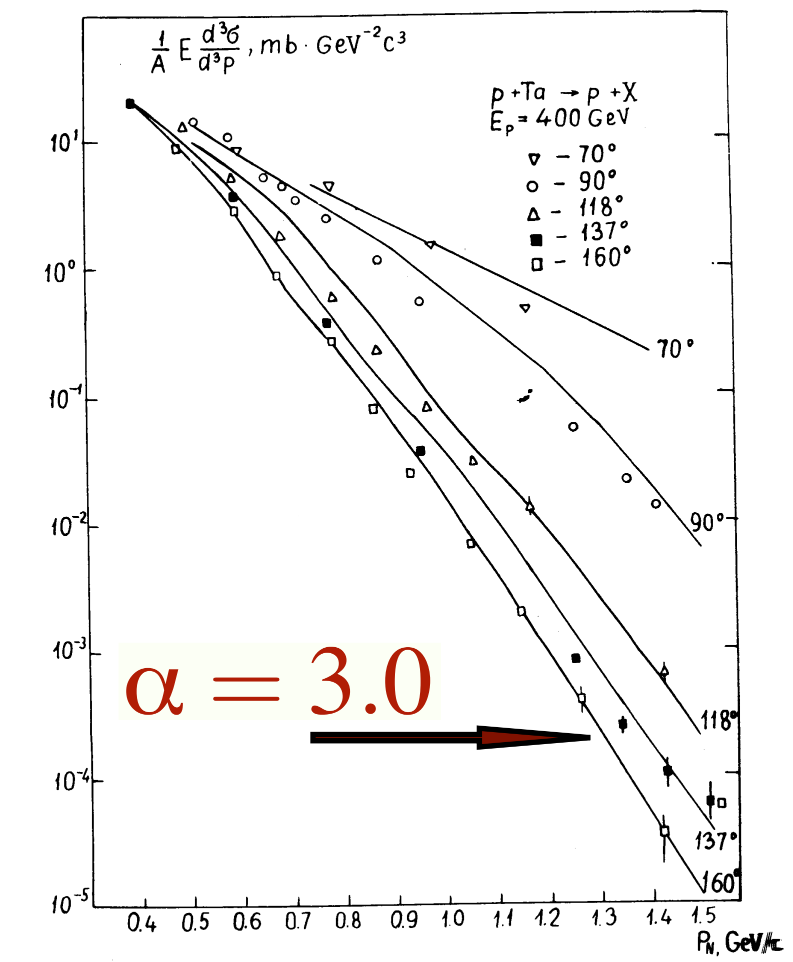


Breaking down of the Fact. App. at large negative $\mathbf{p}_m > 300$(MeV/c). Can be naturally taken care of in GEA

Double rescattering dominates

Factorization tests for 2N SRC - removal of a nucleon at different Q - demonstrate that decay function is universal (like pdf's)

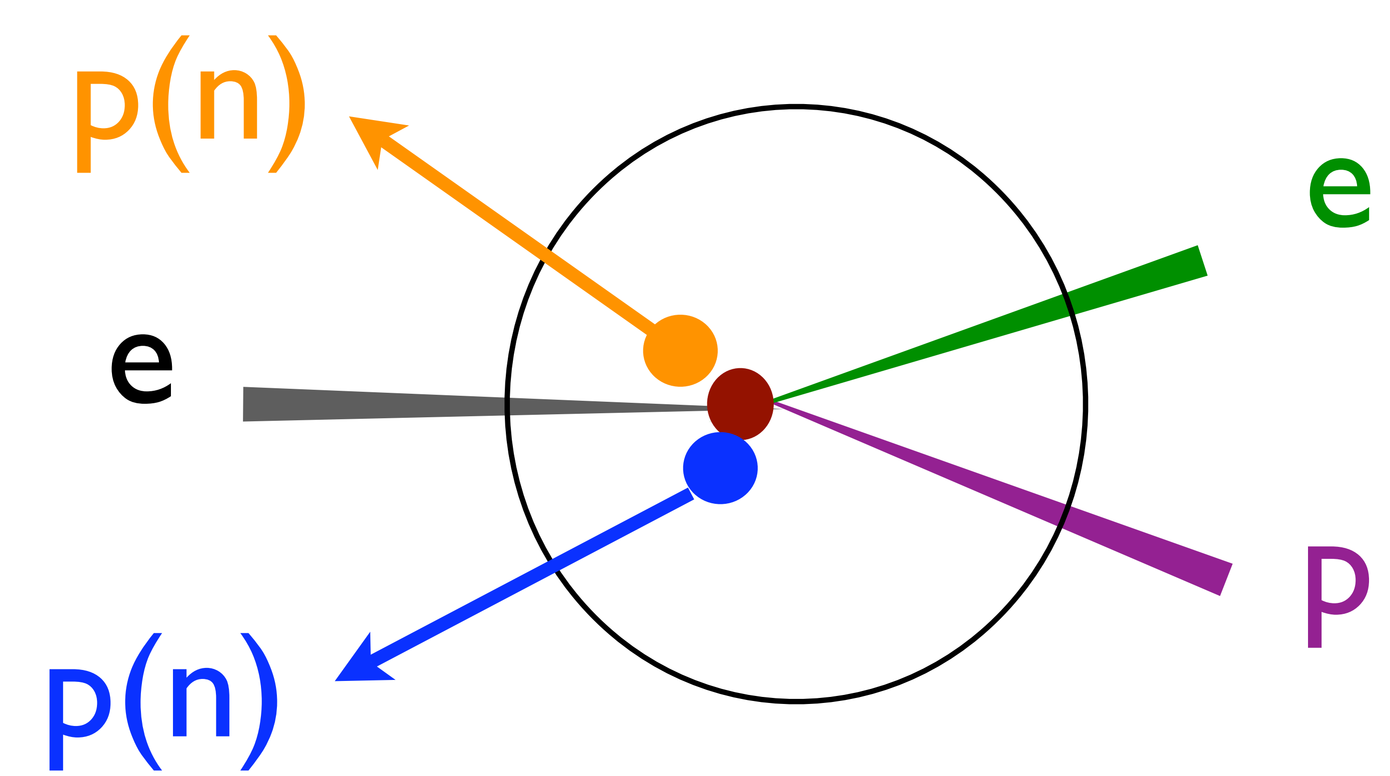
Looking for 3N SRC - should be present at the level 10-20% of 2N SRC - evidence from x> 2 and backward nucleon production (effectively x up to 3.5) - best kinematics - knocked out proton forward - two nucleons backward - requires high energies and appropriate acceptance



pTa→backward p+X

^{3}He is optimal for many of these studies (polarized He target?) - see Misak's talk

Key for neutron stars nnn correlations:
$e^{12}C \rightarrow$ e p (forward) + 2p (backward)



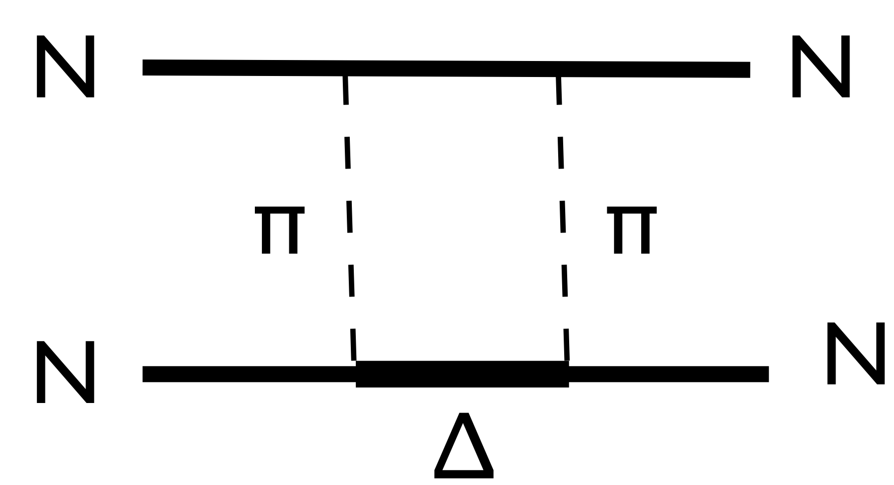
Non-nucleonic degrees of freedom

The reviewed data seem to indicate that 2N correlations dominate for

$600 > k_N > 300$ MeV/c

What about Δ's in nuclei?

Attraction in NN at medium distance (1 fm) is due to two pion exchange



Reminder - quark exchanges also should generate Δ's

Intermediate states with Δ -isobars.

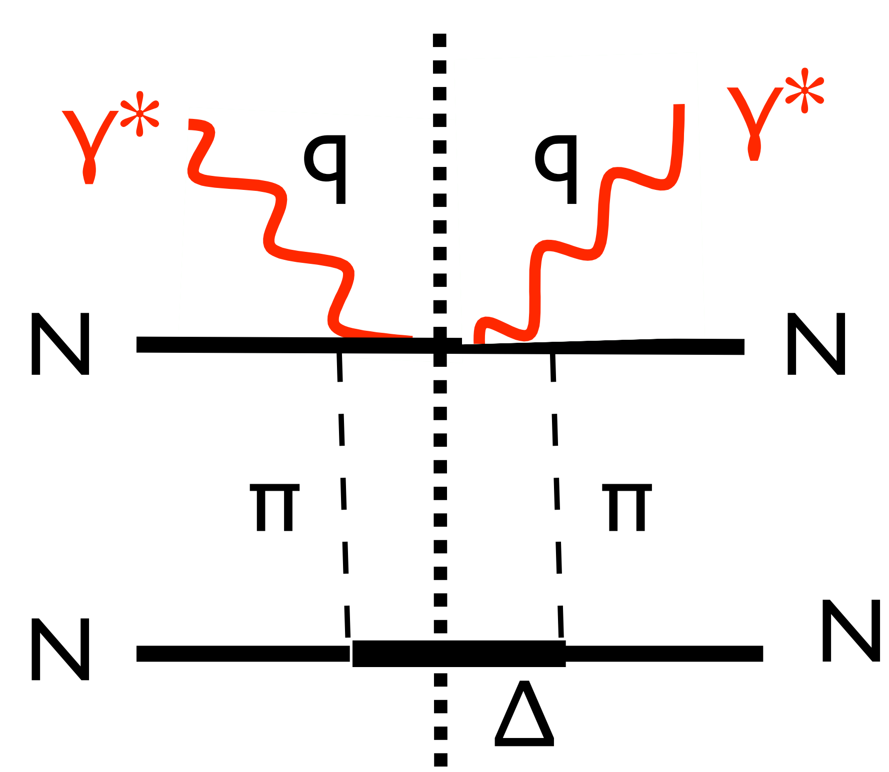
Often hidden in the potential. Probably OK for calculation of the energy binding, energy levels. However wrong for high Q^2 probes.

Explicit calculations of B.Wiringa - ~1/2 high momentum component is due to ΔN correlations, significant also ΔΔ

Large Δ admixture in high momentum component

⇓

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



☞ *Searching/discovering baryonic nonnucleonic degrees of freedom in nuclei*

(a) Knockout of Δ^{++} isobar in $e+{}^2H \rightarrow e+ \ forward\ \Delta^{++} + \ slow\ \Delta^-$

$$e+{}^3He \rightarrow e+ \ forward\ \Delta^{++} + \ slow\ nn$$

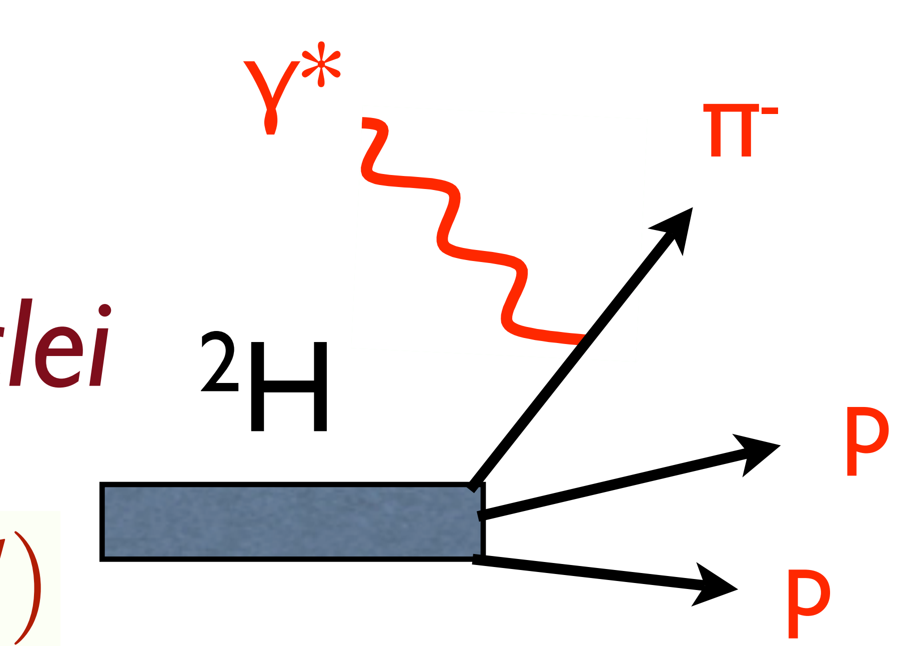
Sufficiently large Q are necessary to suppress two step processes where Δ^{++} isobar is produced via charge exchange. Can regulate by selecting different x - rescatterings are centered at x=1.

(b) Looking for slow (spectator) Δ's in exclusive processes with ^{3}He

Another possibility for 12 GeV, study of x_F ≥0.5 production of Δ− isobars in e+D(A)→e+ Δ +X. For the deuteron one can reach sensitivity better than 0.1 % for ΔΔ (FS 80)

(c) $e+{}^2H \rightarrow e+ \ forward\ N + \ slow\ N^*$

☞ *Searching/discovering mesonic degrees of freedom in nuclei*



$$e+{}^2H \rightarrow e+ \ forward\ \pi^-(along\ \vec{q}) + p(forward)\ + \ p(forward)$$

$$p_N \sim 0.3 - 0.4\ GeV/c$$

FS 77

Origin of the EMC effect.

☛ The EMC effect at $0.7 \geq x \geq 0.4$ is ***unambiguous signature of the presence of nonnucleonic degrees of freedom in nuclei.*** *Claims to the opposite are due to the violation of baryon or energy-momentum conservation or both.*

☛ The lack of the enhancement of antiquarks - *only models which are still viable (not necessarily correct) are those where nucleon wave function is deformed.*

Combined with lack of significant modification of the nucleon form factor in a bound nucleon with small momenta makes appealing idea that deformation grows with momentum of the bound nucleon and enhanced for large x quarks.

Qualitative consideration - consider dependence of deformation for the process $e + A \to e + (A-1)^* + X$ [X=p, inclusive] on virtuality of the interacting nucleon $p_{int}^2 \equiv (p_A - p_{(A-1)^*})^2$. Analytically continue to $p_{int}^2 = m_N^2$ expect no EMC effect.

Natural to have deviations from the free nucleon case to be proportional in the lowest order to

$$(p_A - p_{(A-1)^*})^2 - m_N^2 \approx 2m\left(\frac{A}{A-1}\frac{p^2}{2m_N} + M_{A-1} + m_N - M_A\right)$$

➡ Would be nice to study modification of the nucleon form factors as a function of the nucleon momentum. *If effect is observed at 100 MeV/c - go to 50 MeV/c (150 MeV/c) and see whether the effect will decrease (increase) by a factor of ~1.5.*

Dynamical model - color screening model of the EMC effect (FS 83-85)

Combination of two ideas:

(a) Quark configurations in a nucleon of a size << average size (PLC) should interact weaker than in average and their probability in nucleons is suppressed.

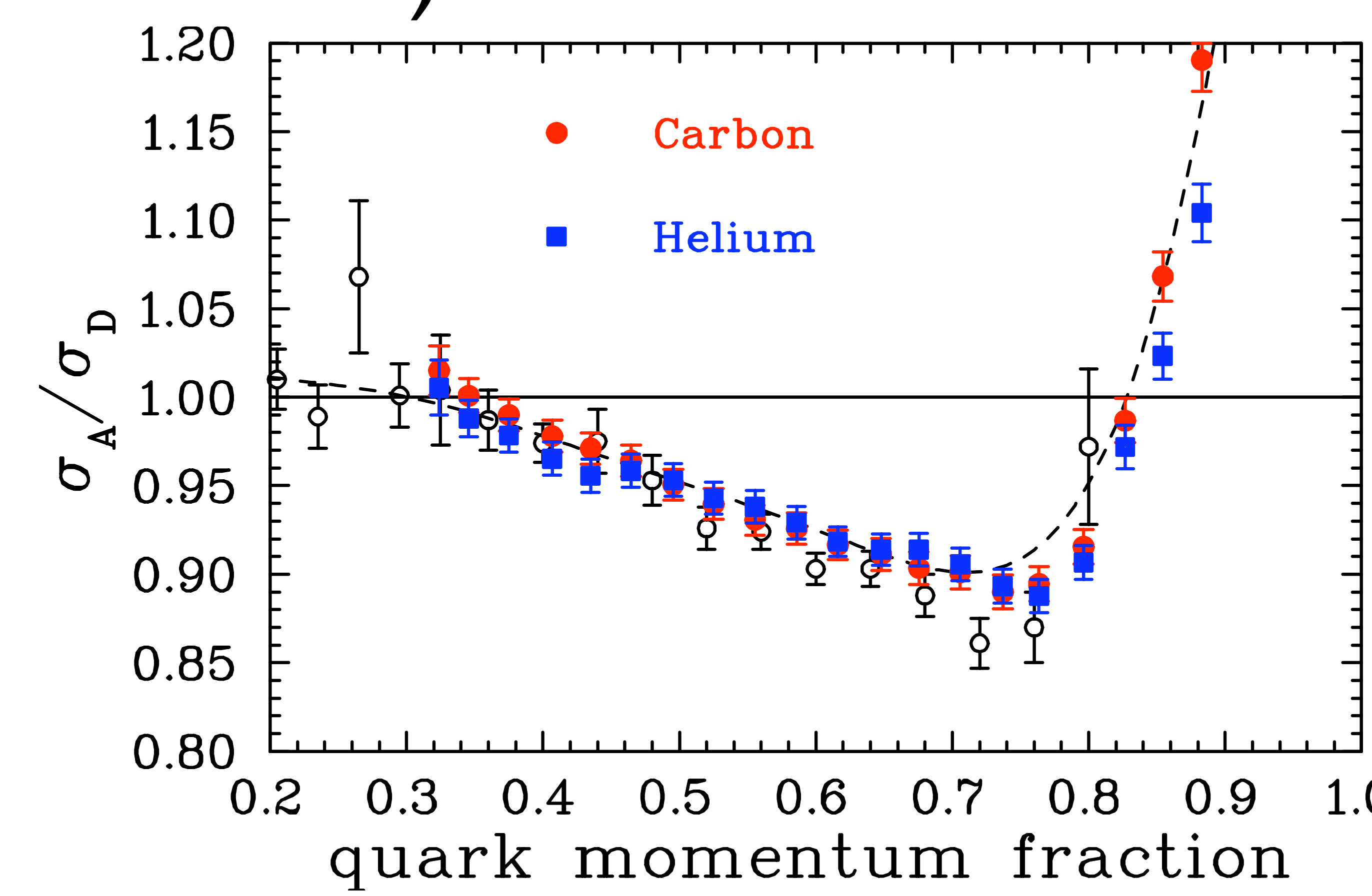
(b) Quarks in nucleon with $x>0.5$ belong to small size configurations (no pion field), large relative quark momenta.

Calculation of deformation in non-relativistic Schrodinger approximation which interaction depending on the size of the system. A posteriori (Melnitchouk, Sargsian, MS (97), Ciofi, Frankfurt, Kaptari MS, 07) it turned out that it satisfies the above mentioned requirement of no effect for $p_{int}^2 = m_N^2$

Leads to factorization of the EMC effect for $R_A(x,Q^2) \equiv \dfrac{2}{A}\dfrac{F_{2A}(x,Q^2)}{F_{2N}(x,Q^2)}$

$R_A(x,Q^2) - 1 = \phi(x,Q^2) f(A)$ consistent with SLAC data

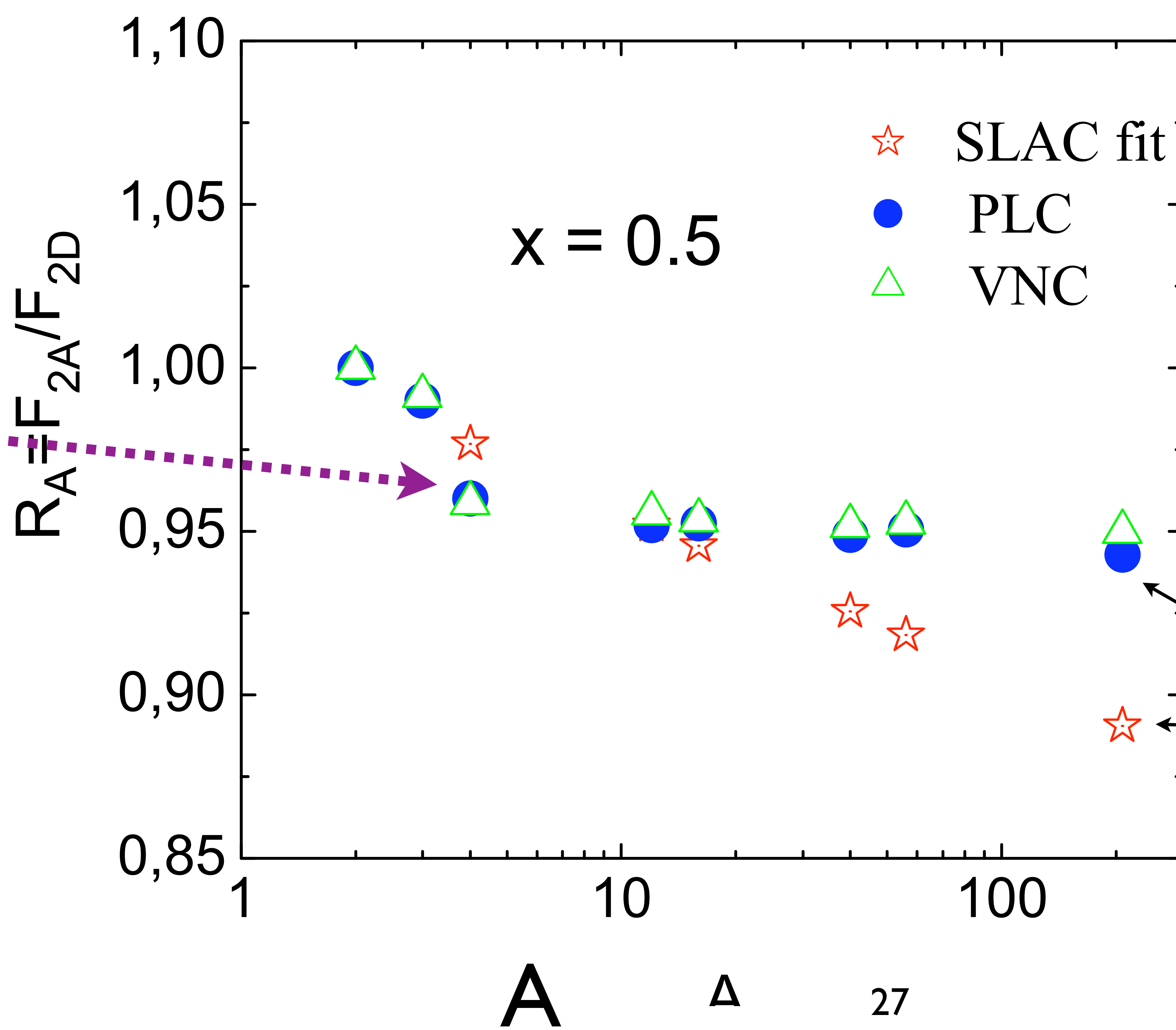
CFKS - detailed analysis of A-dependence using realistic nuclear wave functions with correlations. Used both point-like configuration model and model with EMC effect due to binding (mesons taking a fraction of the nucleus momentum)



we find

$R_{4He} = R_C$

consistent with Jlab recent data



We suggest that significant part of the discrepancy could be due to the coherent Weizecker-Williams photon field of the nucleus

Gaining understanding of the EMC effect (extending current JLab studies)

Studies of the EMC effect will benefit greatly from the Jlab measurement of $F_{2n}(x,Q^2)$ with tagged neutrons - data analysis under way

- ♥ test EMC effect for deuteron
- ♥ more reliable isotopic correction for $Z \neq N$

- Is EMC effect the same for u- and d-quarks? *Use ^{3}He target and pion tagging of knocked out quarks or parity violation with polarized electron beams. Use of ^{3}H (?), Ca isotopes.*

- How EMC effect depends on the virtuality/off-energy-shellness of the nucleon?

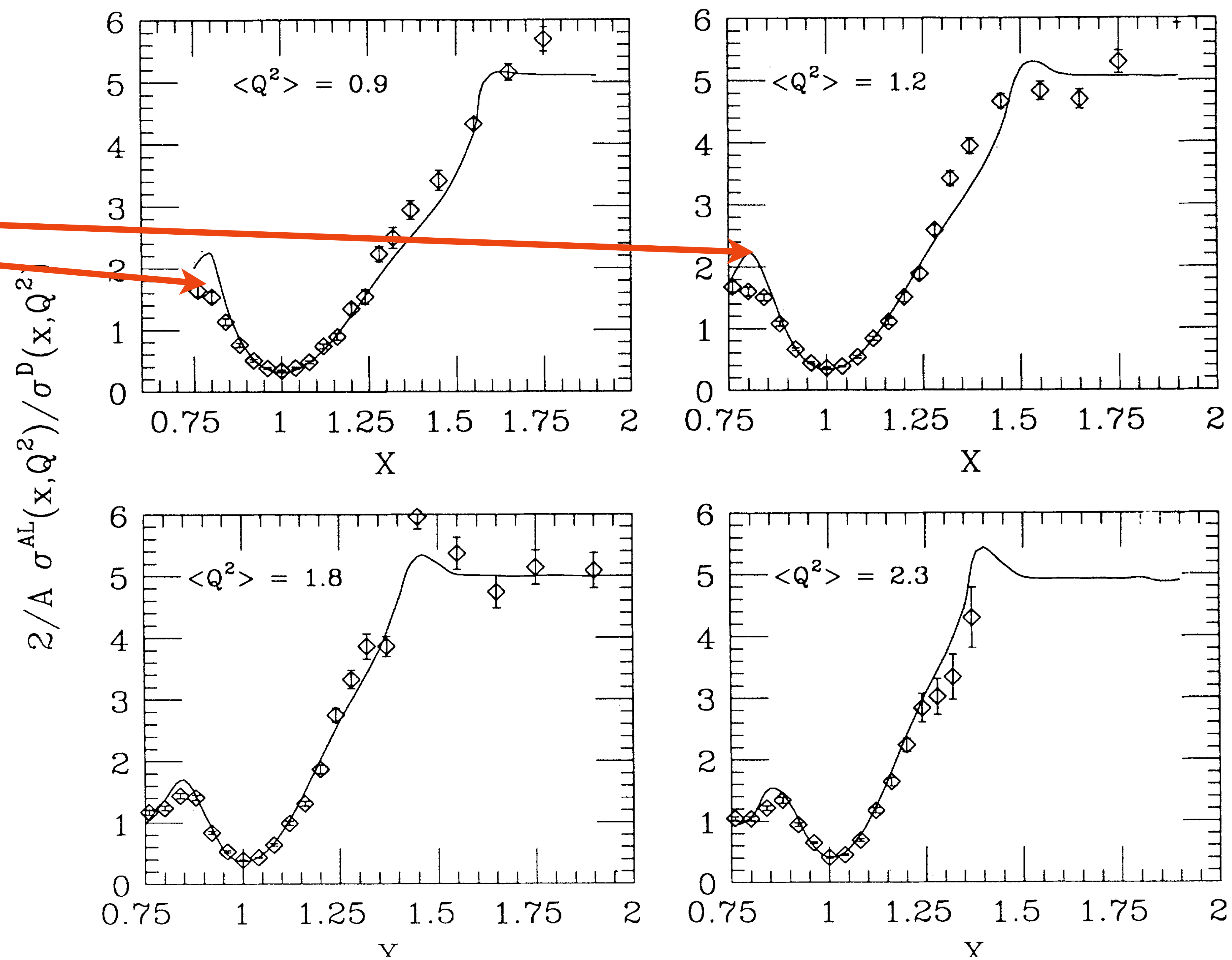
  Is dependence the same for u- and d- quarks?

  Tagging of proton and neutron in $e+D \rightarrow e+N+X$ - Misak's talk

- EMC effect for $g_{1A}(x,Q)$. Best target for the job - $^7\vec{Li}$.

Higher twist contributions in the EMC effect

HT

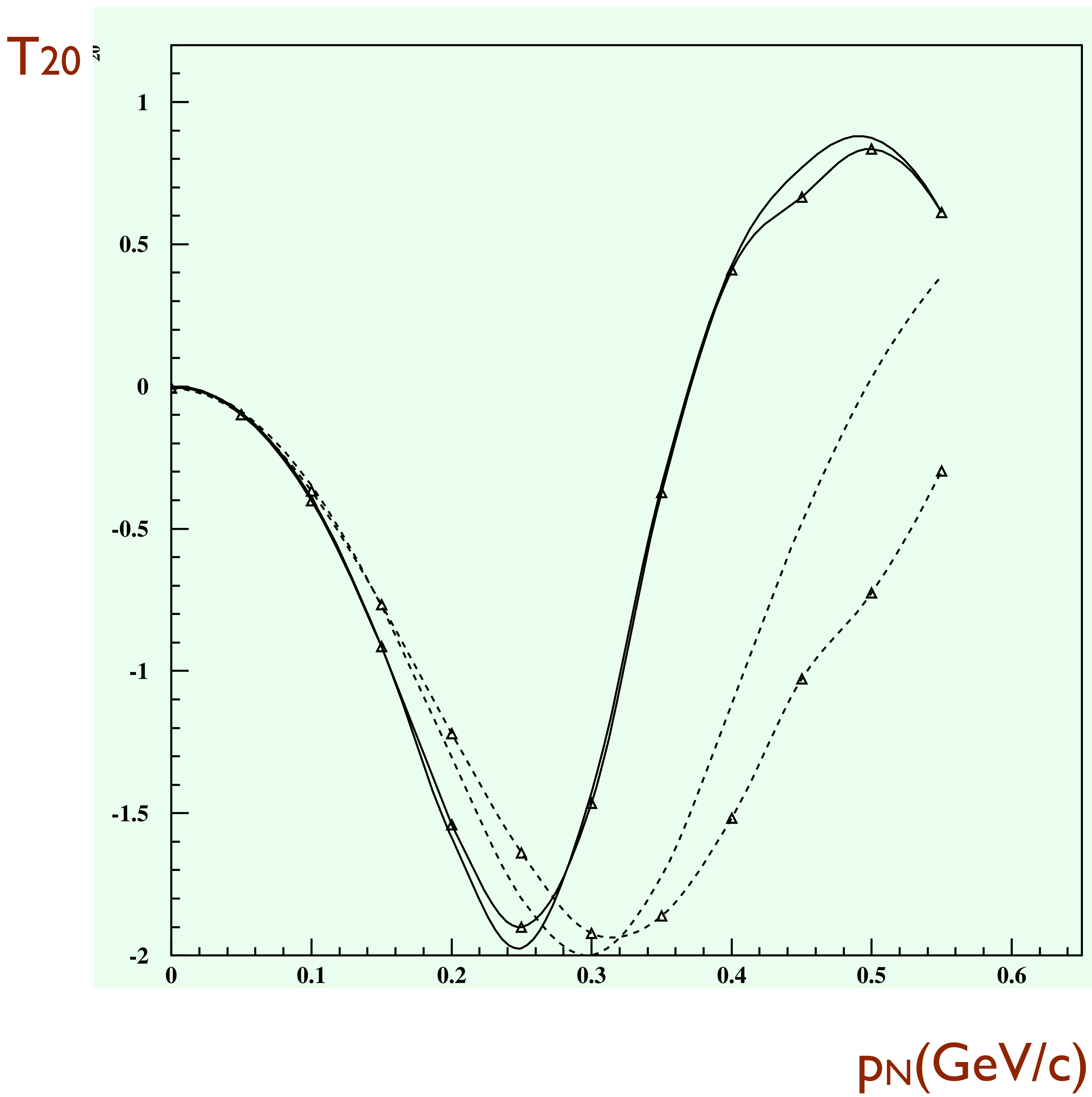


Day, Frankfurt, Sargsian, 93

. Ratio $\frac{2}{A}\frac{\sigma_A(x,Q^2)}{\sigma_D(x,Q^2)}$ for ^{27}Al at four different Q^2's.

Did not have time to discuss relativistic effects

Decisive test to discriminate between Light-Cone and virtual nucleon relativistic models of the deuteron: $e + {}^2\vec{H} \rightarrow e + p + n$



p_s dependence of the (e,e'p) tensor polarization (analog of T_{20} for the elastic form factor) at θ_s=180^0. Solid and dashed lines are PWIA predictions of the LC and VN methods, respective marked curves include FSI.

Conclusions

Impressive experimental progress of the last two years - *discovery of strong short range correlations in nuclei with strong dominance of I=0 SRC* - provides solid basis for further studies. Several experiments are under way/ been planned for 12 GeV

Are detectors optimal for the correlation studies, isobar production? More work is needed in this direction.

Several complementary studies: $x > 1$, correlations, tagged structure functions,... will allow to learn about microscopic nuclear structure in its complexity and probe interactions in nuclei relevant for the structure of the neutron stars.

Three prong approach to the study of short-range correlations

Large Q, x>1
A(e,e') processes:
superfast quarks,
fast nucleons

$Q^2 \geq 2\ GeV^2$
$(e,e'N),(e,e'NN)$
Short-range nucleon cor.
bound N form fact.

Closure: can use all nuclei

Short-range
few nucleon
correlations in nuclei:
quark-gluon &
hadronic
structure

Final state interactions: best to use A=2,3

DIS processes
eA→e+backward N +X
Quark distribution in
bound nucleon