Short-Range Correlation Studies at the AGS and JLab

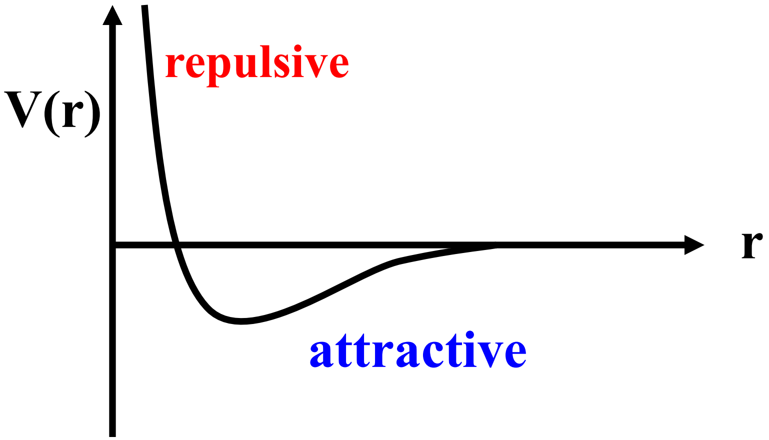
John Watson: Kent State University

“The structure of correlated many-body systems, particularly at distance scales small compared to the radius of the constituent nucleons, presents a formidable challenge to both experiment and theory”

(Nuclear Science: A Long Range Plan, The DOE/NSF Nuclear Science Advisory Committee, Feb. 1996 [1].)

The N-N Interaction and the Shell Model

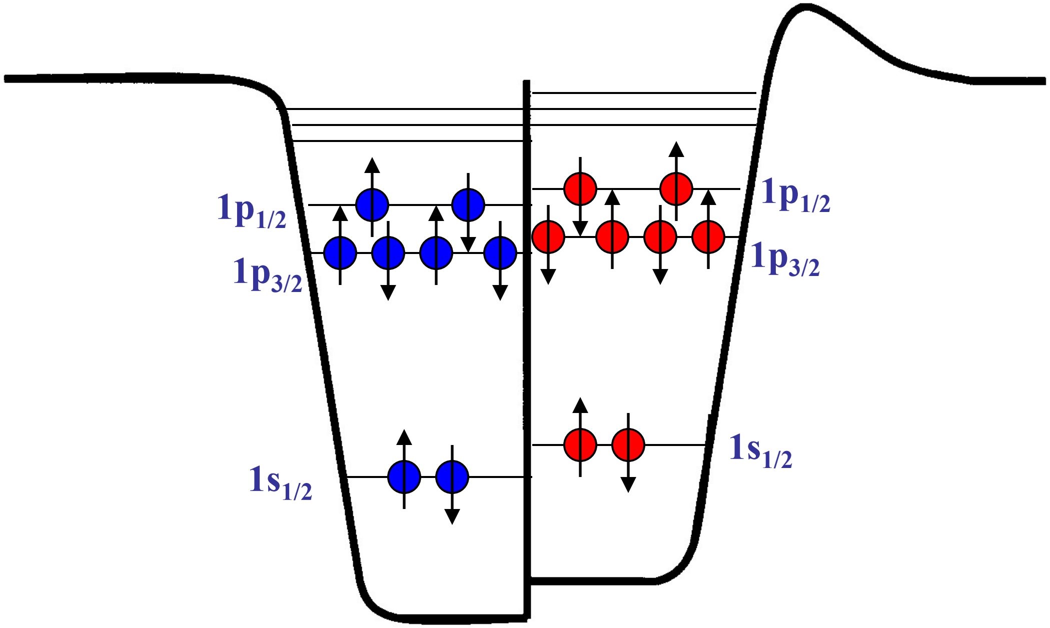
The N-N interaction is attractive at a typical distance of 2 fm, but highly repulsive at distances < 0.5 fm.



The attractive part of this interaction between all of the pairs of nucleons in a nucleus, in combination with the Pauli principle, produces a mean field in which the neutrons and protons move like independent particles in well-defined quantum states.

Maria Mayer and J.H.D. Jensen received the Nobel Prize in 1963 for developing the shell model.

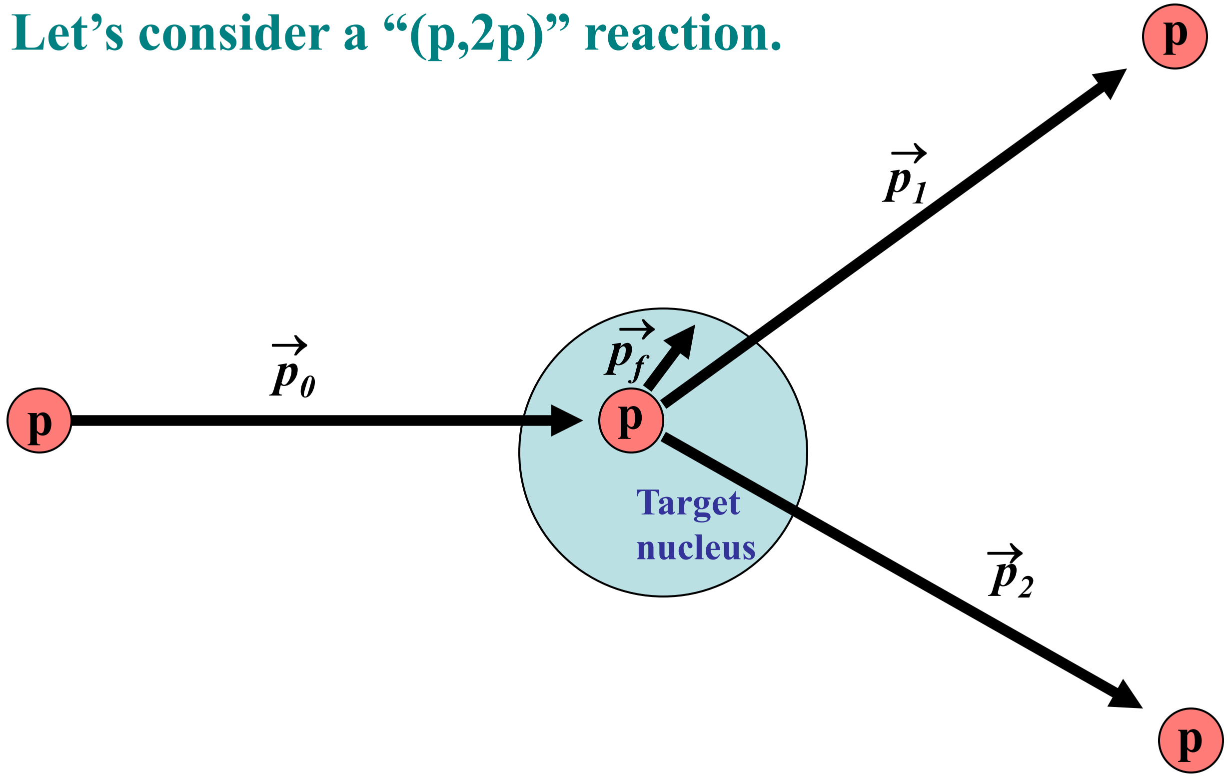
Simple, schematic, shell-model picture of ^{16}O (8n,8p)



n p

One of the best ways to study the shell model is with “knockout” reactions (also called “quasi-elastic scattering”)..

Let’s consider a “(p,2p)” reaction.



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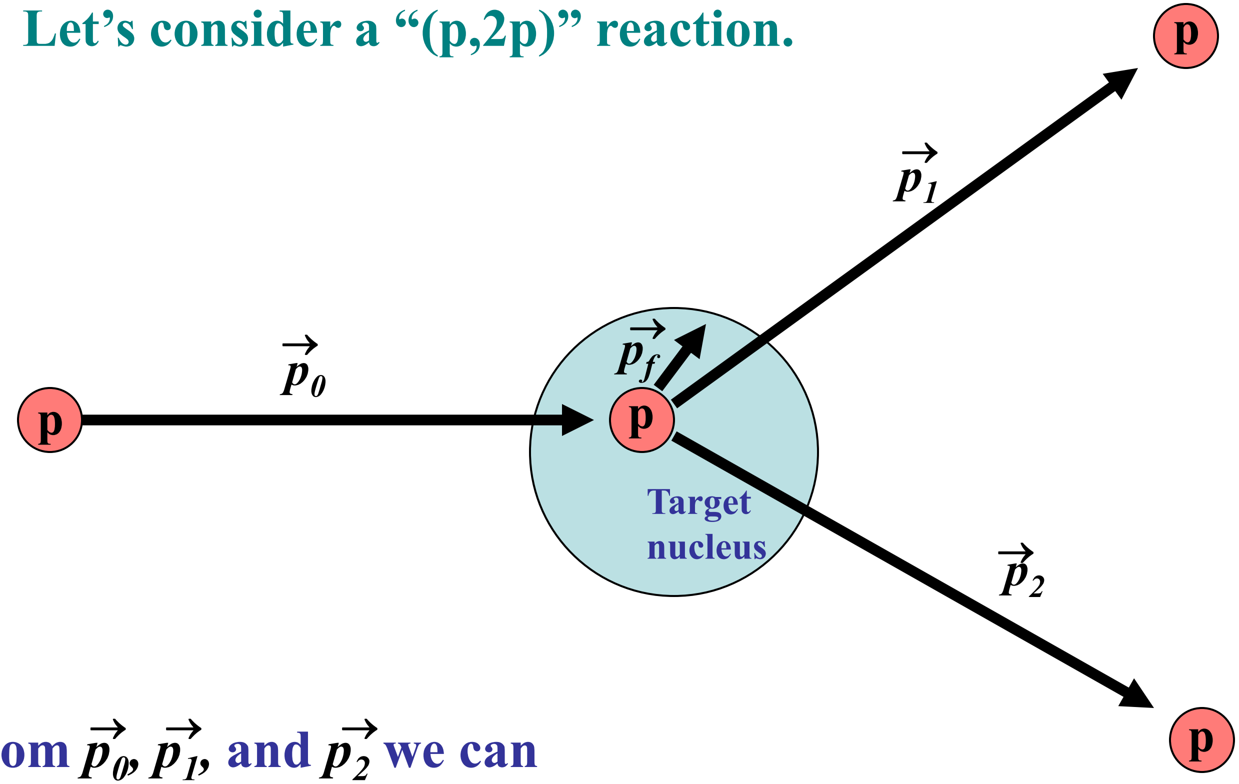
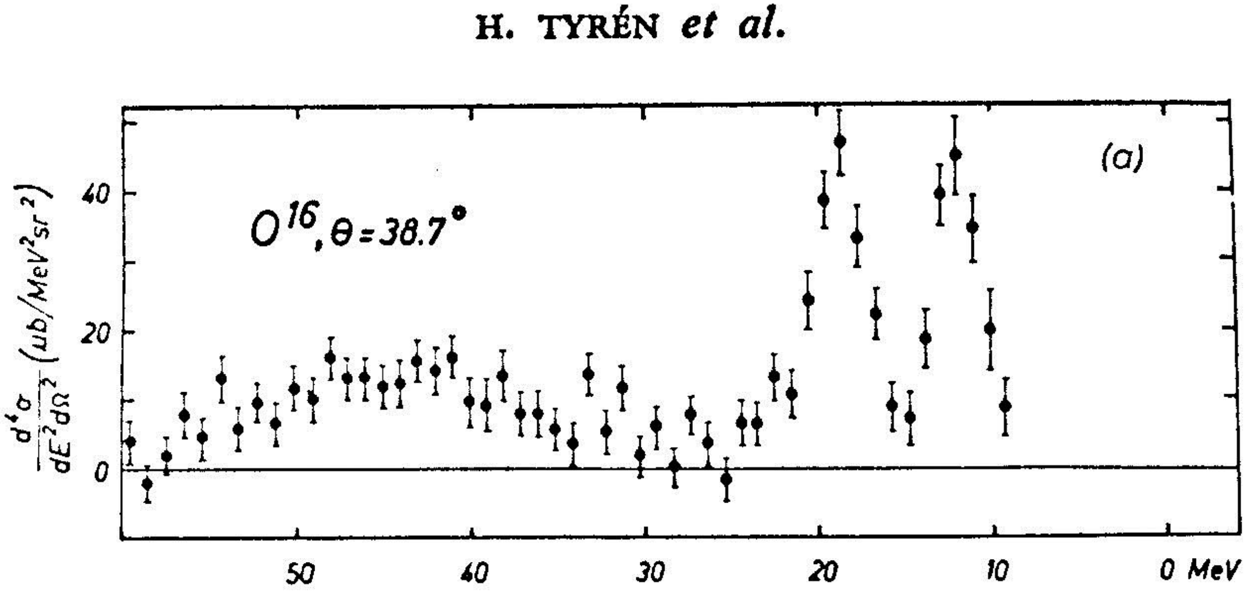


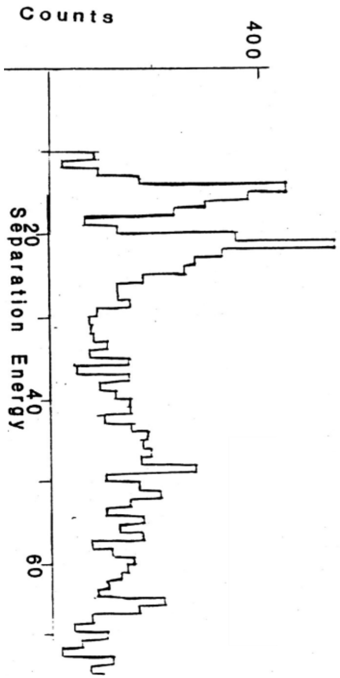
From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event, what $\vec{p}_f$ and the *separation energy* of each knocked-out proton is.

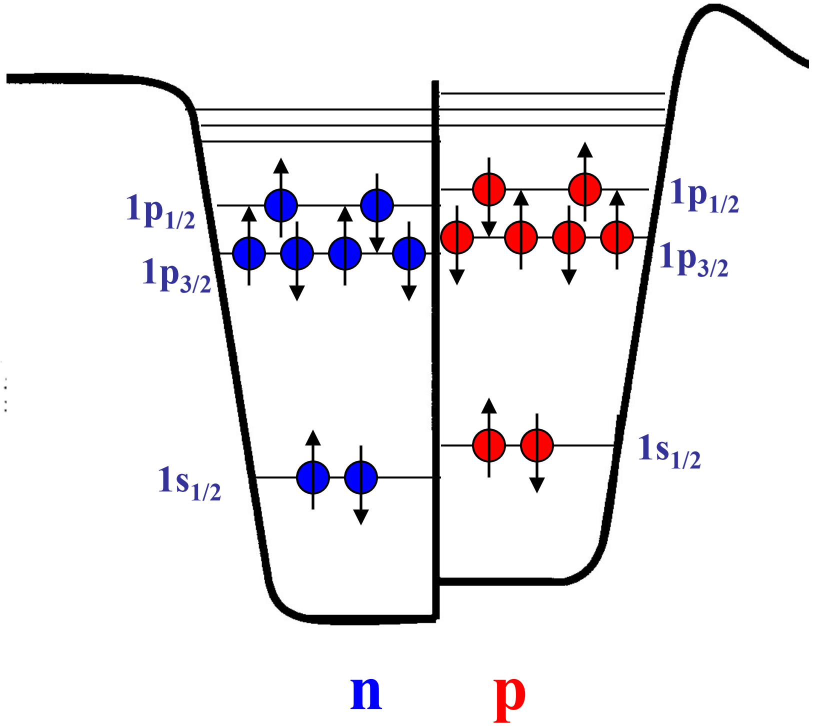
^{16}O(p,2p) at 460 MeV from the Enrico Fermi Institute University of Chicago: Nucl. Phys. **79,** 321 (1966).

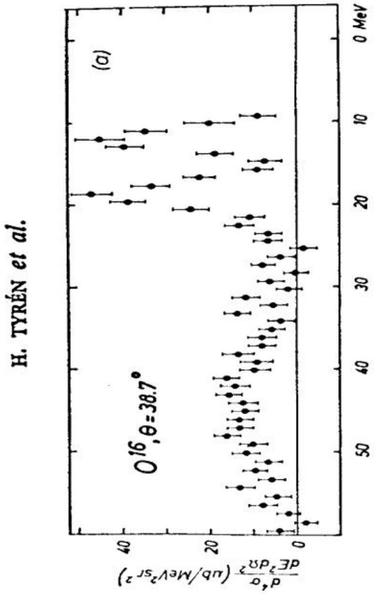


Separtion Energy (MeV)

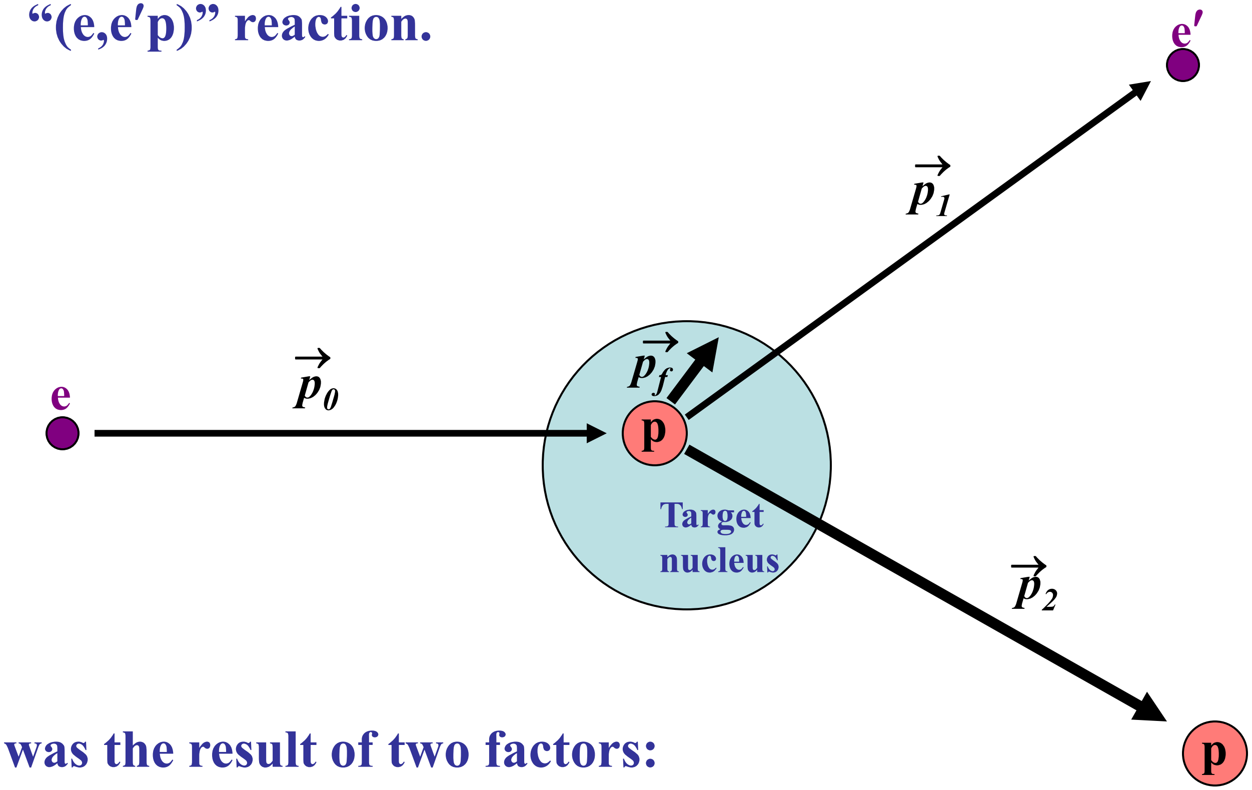
Simple, schematic, shell-model picture of ^{16}O (8n,8p)







During the ‘80s and ‘90s the premier tool for knockout-reaction spectroscopy became the “(e,e′p)” reaction.

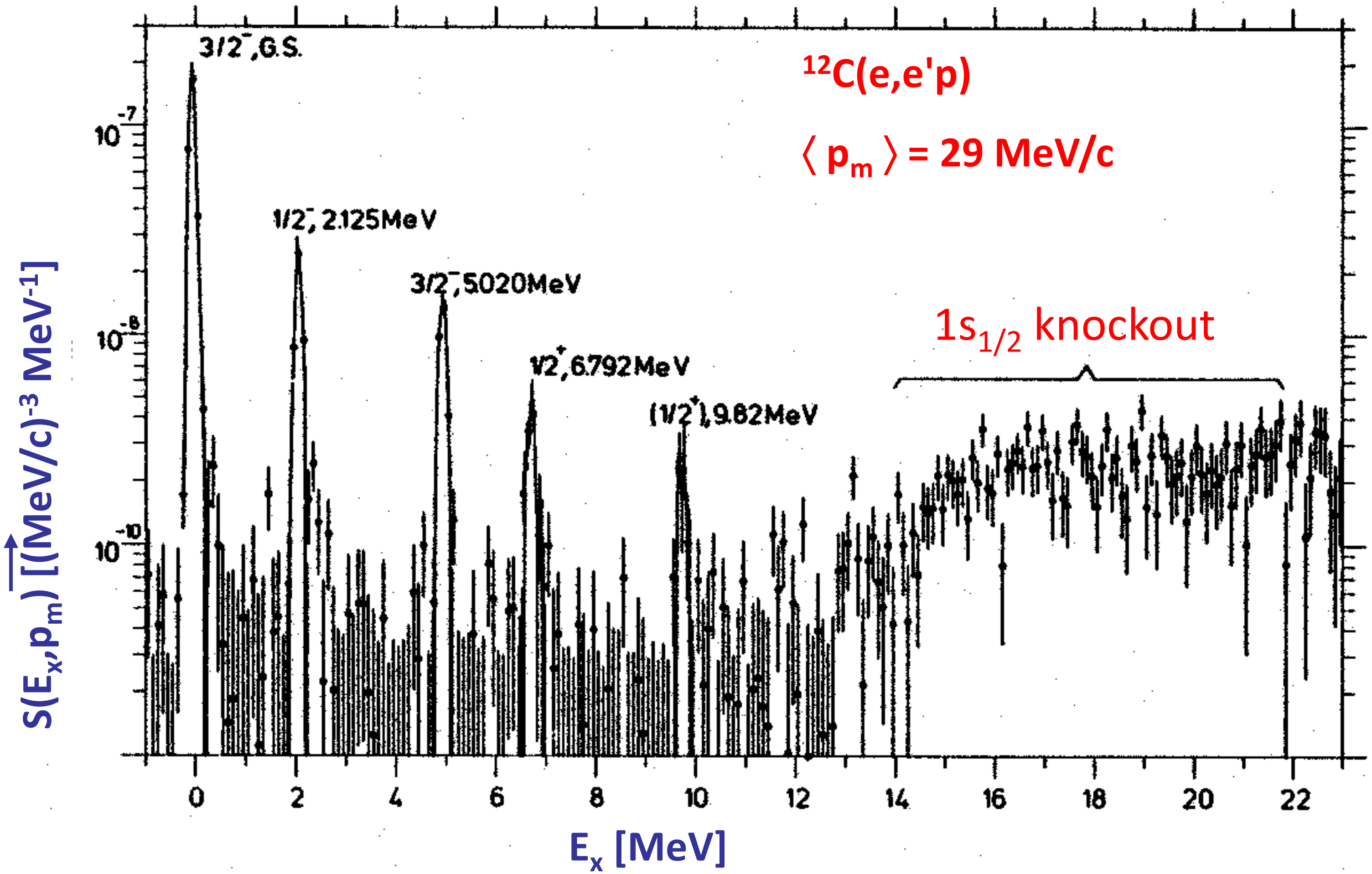


This was the result of two factors:

1) Improvements in electron accelerators.

2) The ability to do “exact” reaction calculations because the e-p interaction is electromagnetic.

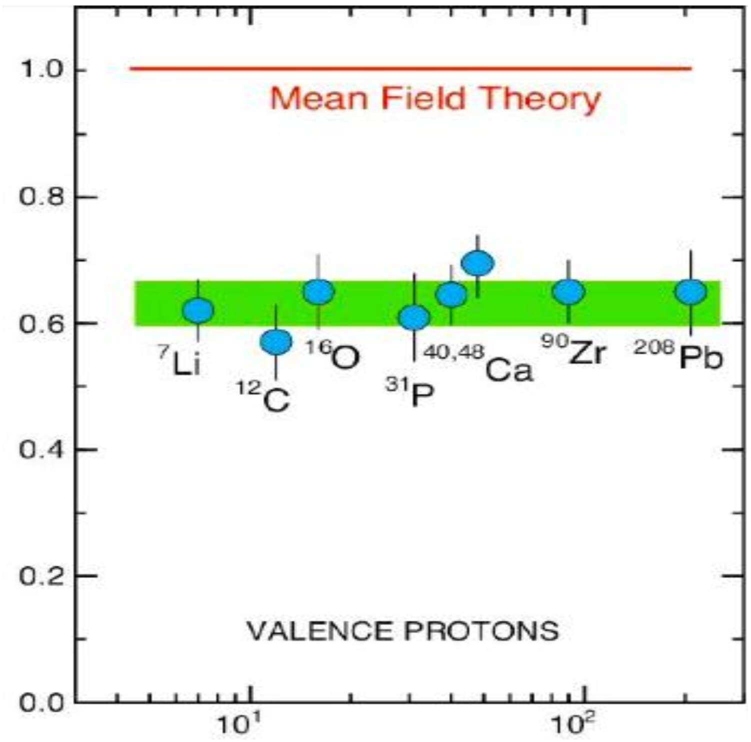
1988: NIKHEF



G. van der Steenhoven *et al.,* Nucl. Phys. **A484**, 445 (1988).

Something is *MISSING!*

Spectroscopic factors for (e,e'p) reactions show only 60-70% of the expected single-particle strength.

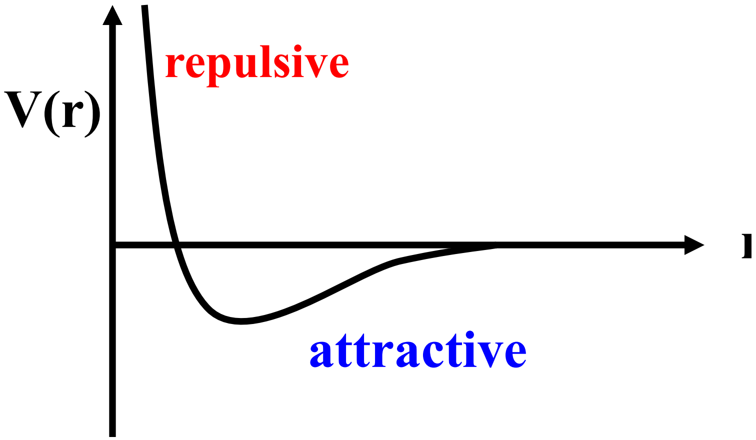


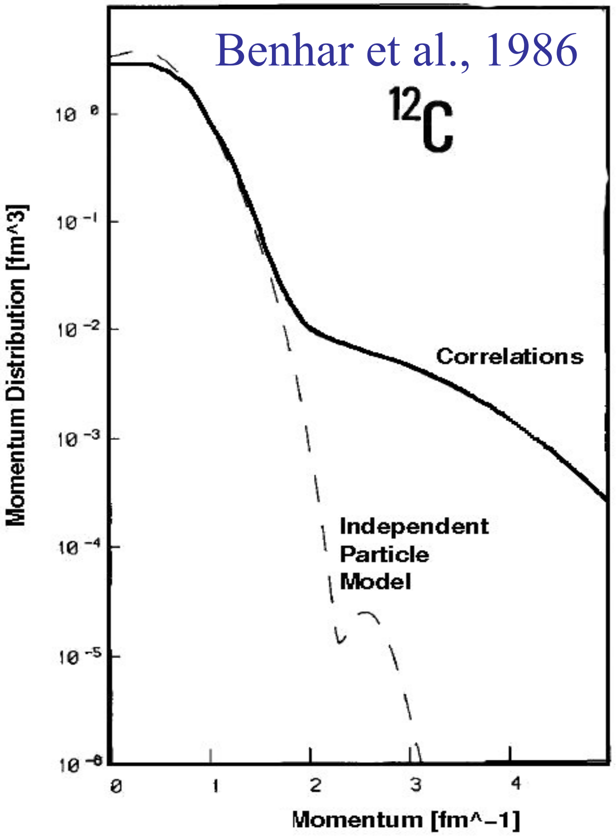
L. Lapikas, Nucl. Phys. A553, 297c (1993)

There must be more!

The N-N Interaction and Correl

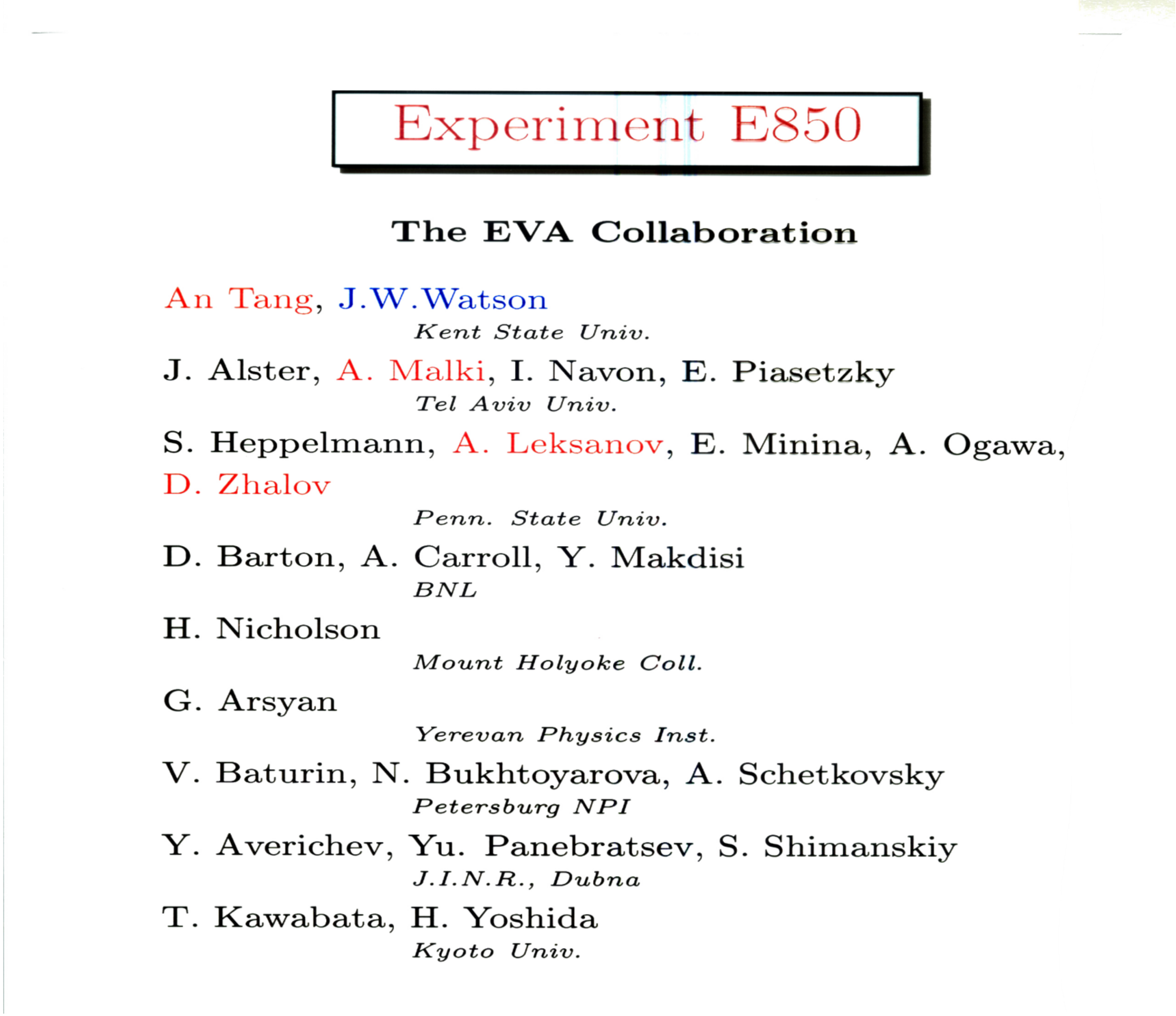
The N-N interaction is attractive at a typical c
but highly repulsive at distances < 0.5 fm.





Benhar et al., 1986

The **short-range repulsion** leads to phenomena such as the saturation of central nuclear densities. But it also must manifest itself in the wave functions of the nucleons in the nucleus. Because it is **short range**, high-momentum components should be affected. Typically we might expect **N-N interactions at short range** to produce pairs of nucleons with large, roughly equal, and opposite momenta.



Experiment E850

The EVA Collaboration

An Tang, J.W.Watson

Kent State Univ.

J. Alster, A. Malki, I. Navon, E. Piasetzky

Tel Aviv Univ.

S. Heppelmann, A. Leksanov, E. Minina, A. Ogawa, D. Zhalov

Penn. State Univ.

D. Barton, A. Carroll, Y. Makdisi

BNL

H. Nicholson

Mount Holyoke Coll.

G. Arsyan

Yerevan Physics Inst.

V. Baturin, N. Bukhtoyarova, A. Schetkovsky

Petersburg NPI

Y. Averichev, Yu. Panebratsev, S. Shimanskiy

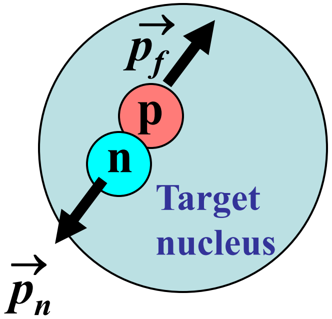
J.I.N.R., Dubna

T. Kawabata, H. Yoshida

Kyoto Univ.

Instead of considering a single proton in a nucleus, let’s consider a short-range correlated neutron-proton pair.

Let’s start with a (p,2p) reaction.



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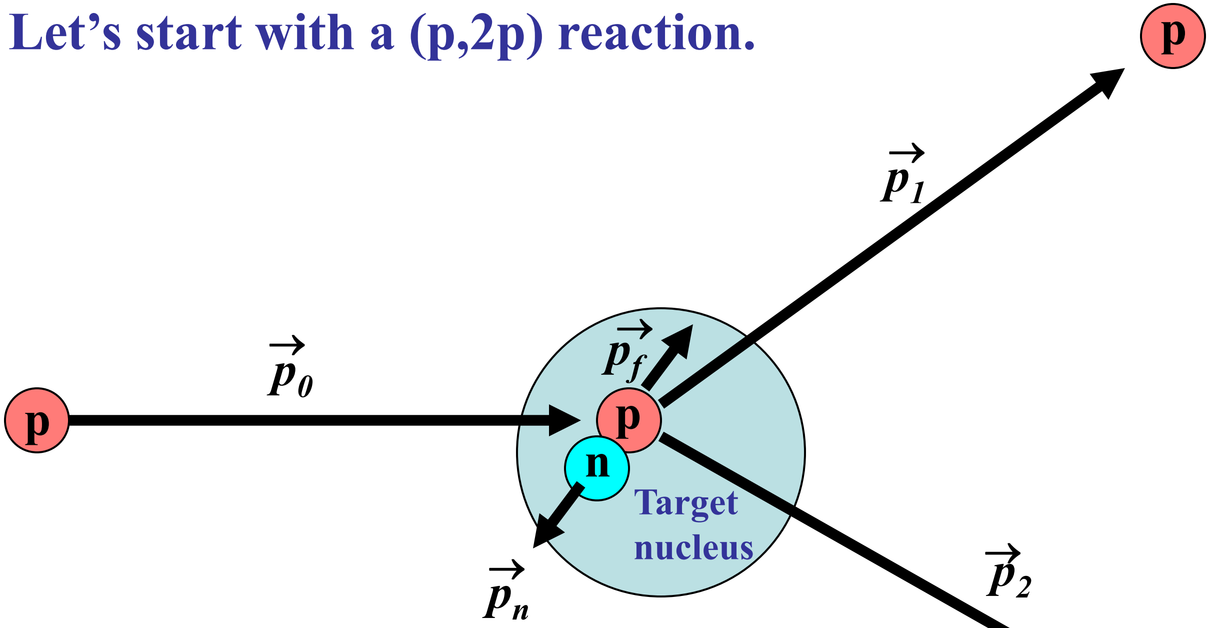

From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event what $\vec{p}_f$ and the binding energy of each knocked-out proton is.

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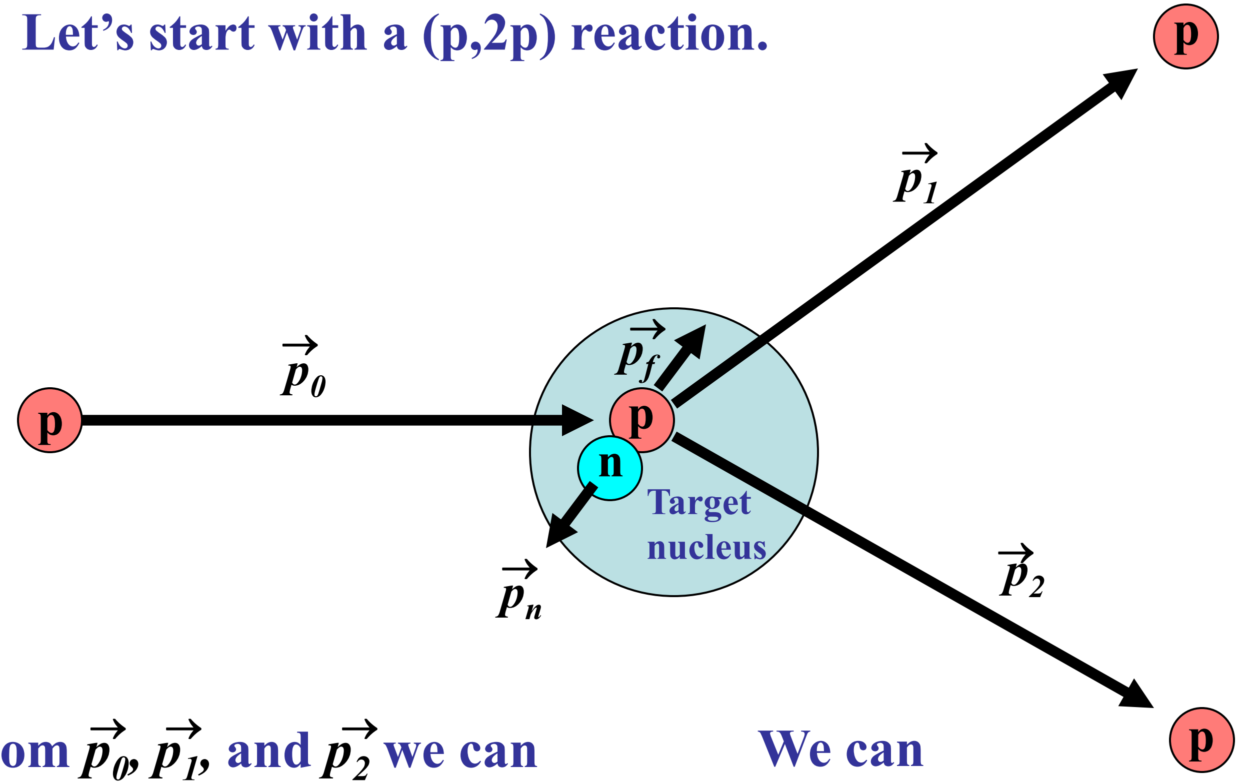


From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event what $\vec{p}_f$ and the binding energy of each knocked-out proton is.

We can then compare $\vec{p}_n$ with $\vec{p}_f$ and see if they are roughly "back to back."

VOLUME 26, NUMBER 8 PHYSICAL REVIEW LETTERS 22 FEBRUARY 1971

Nuclear Fermi Momenta from Quasielastic Electron Scattering

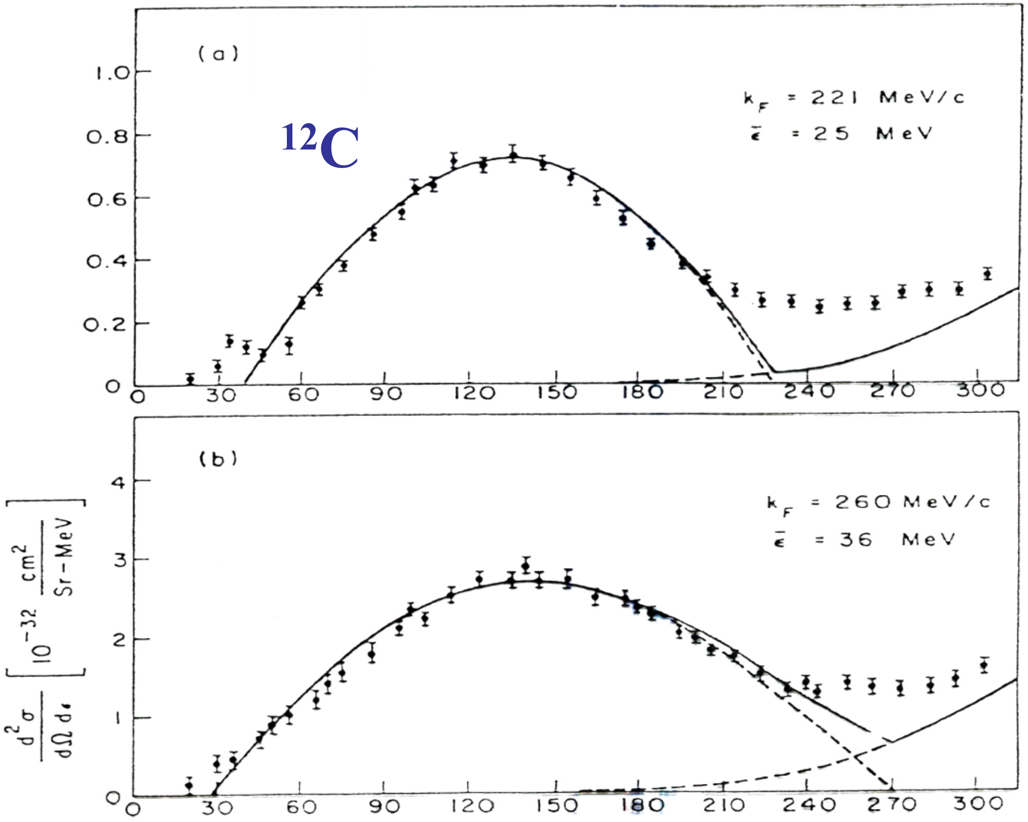
E. J. Moniz
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305*

and

I. Sick† and R. R. Whitney
High Energy Physics Laboratory and Department of Physics, Stanford University,‡ Stanford, California 94305

and

J. R. Ficenec, R. D. Kephart, and W. P. Trower
Physics Department, Virginia Polytechnic Institute and State University,§ Blacksburg, Virginia 24061
(Received 12 January 1971)



***k_F* = 221 MeV/c**

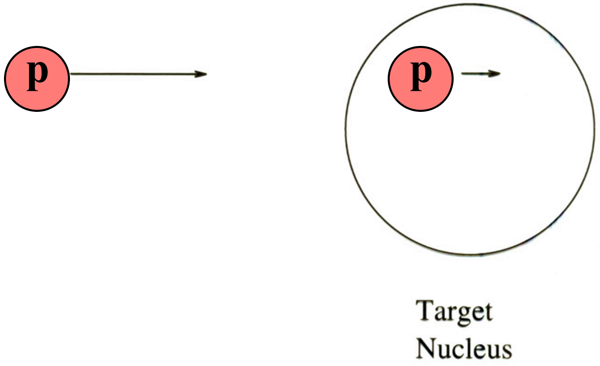
For energies of several GeV and up,
For p-p elastic scattering near 90° c.m.,

$$\frac{d\sigma}{dt} \sim s^{-(n_1+n_2+n_3+n_4-2)}$$

$$\sim s^{-10}$$

where the Mandelstam variable $s = (P_0 + P_F)^2$ is the square of the total c.m. energy.

So for quasi-elastic p-p scattering near 90° c.m., we have a very strong preference for reacting with nuclear protons with their Fermi motion in the beam direction.



Forward going, high-momentum protons are preferentially selected, because this minimizes s.

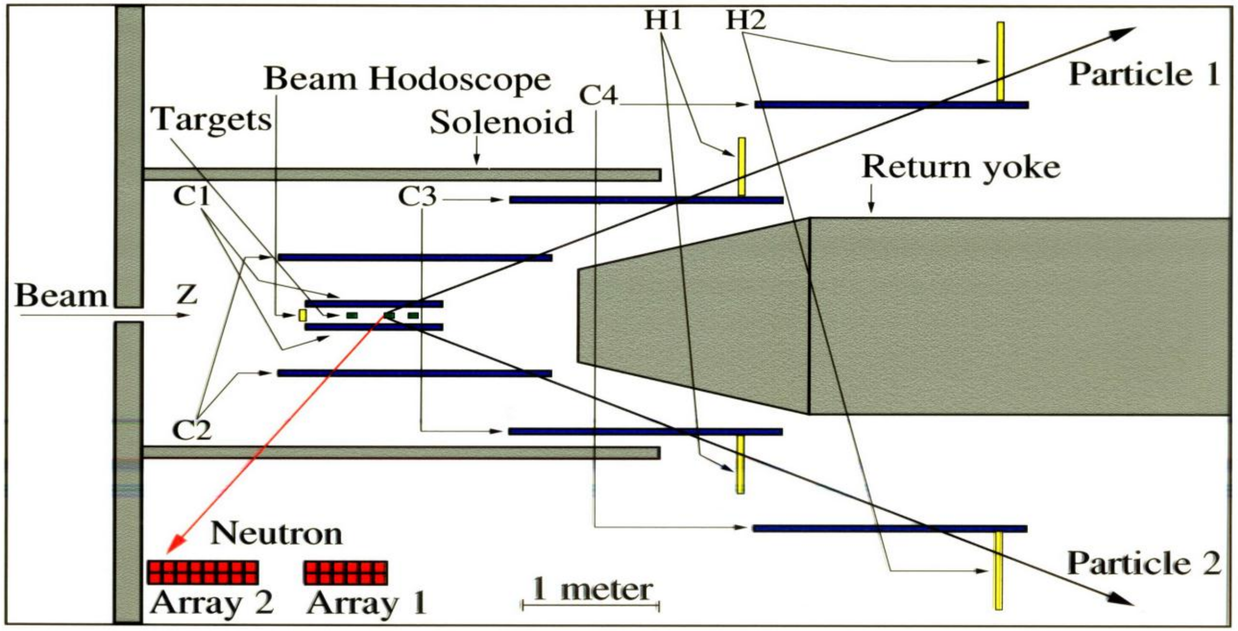
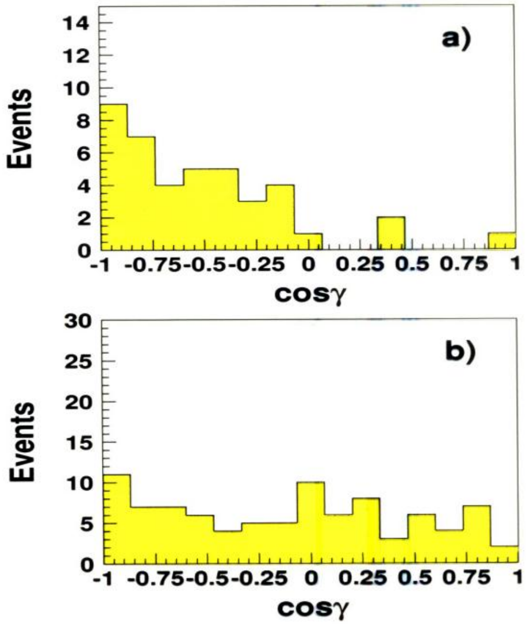


Figure 1: A schematic side view of the EVA spectrometer.

Full Correlations:

We then construct the directional correlation between $\vec{p}_f$ and $\vec{p}_n$ as

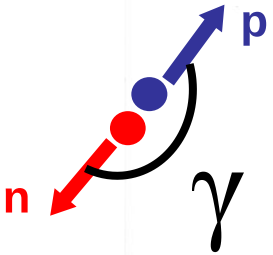
$$cos\gamma = \frac{\vec{p}_f \cdot \vec{p}_n}{\mid \vec{p}_f \mid\mid \vec{p}_n \mid}$$



$p_n > k_F$

$p_n < k_F$

Figure 21: Plots of cosγ, where γ is the angle between $\vec{p}_n$ and $\vec{p}_f$. Panel (a) is for events with $p_n > 0.22$ GeV/c, and panel (b) is for events with $p_n < 0.22$ GeV/c; 0.22 GeV/c = k_F, the Fermi momentum for ^{12}C.



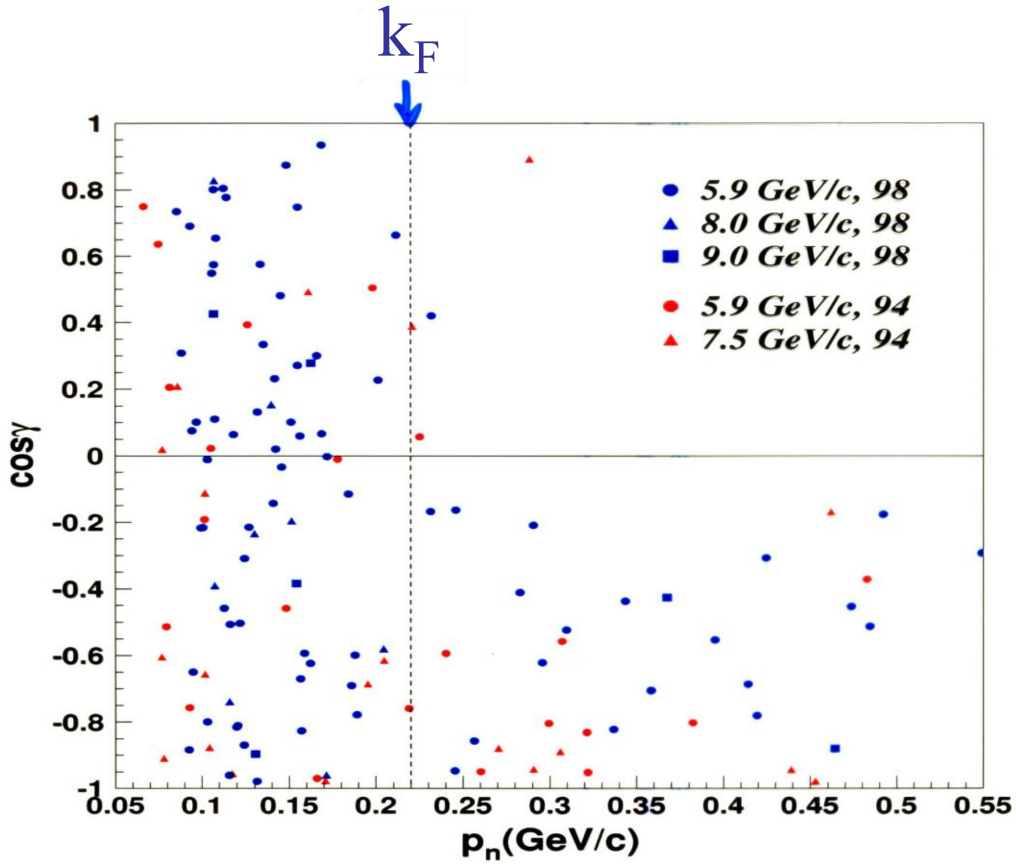


Figure 22: cosγ vs. p_n for ^{12}C(p,2p+n) events. The vertical line at 0.22 GeV/c corresponds to k_F, the Fermi momentum for ^{12}C.

So why did this work so well when our count rate was only ⊠ ⊠ 1 per week ?

1. The s^{-10} dependence of p-p elastic scattering, which preferentially selects high momentum nuclear protons.

2. The improved resolution from using light cone variables.

3. The small deBroglie wavelength of the incident protons:

$$\lambda = h/p = hc/pc = 2\pi \bullet 0.197 \text{ GeV-fm}/(6 \text{ Gev})$$

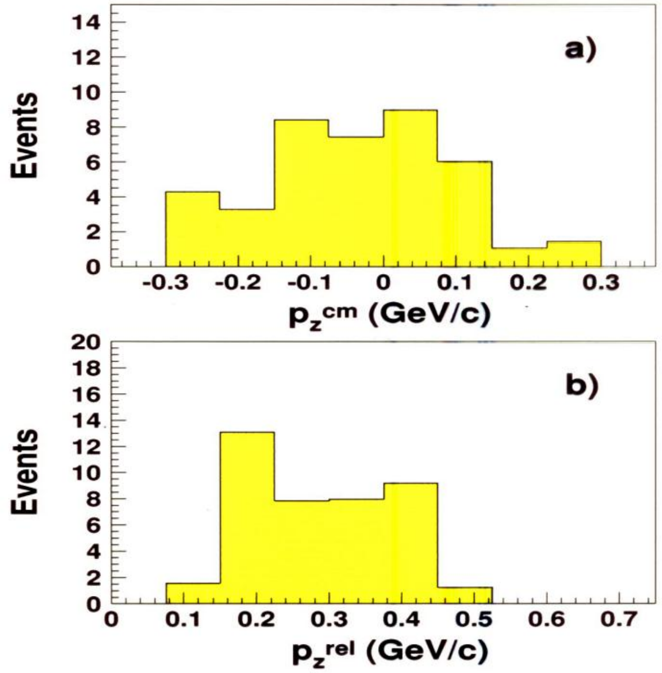
$$\approx 0.2 \text{ fm.}$$

This meant that our probe could interact with a single member of a correlated pair!

The Relative and c.m. Motion of Correlated n-p Pairs:

$$p_z^{cm} = 2m\left(1 - \frac{\alpha_p + \alpha_n}{2}\right),$$

$$p_z^{rel} = m|\alpha_p - \alpha_n|.$$

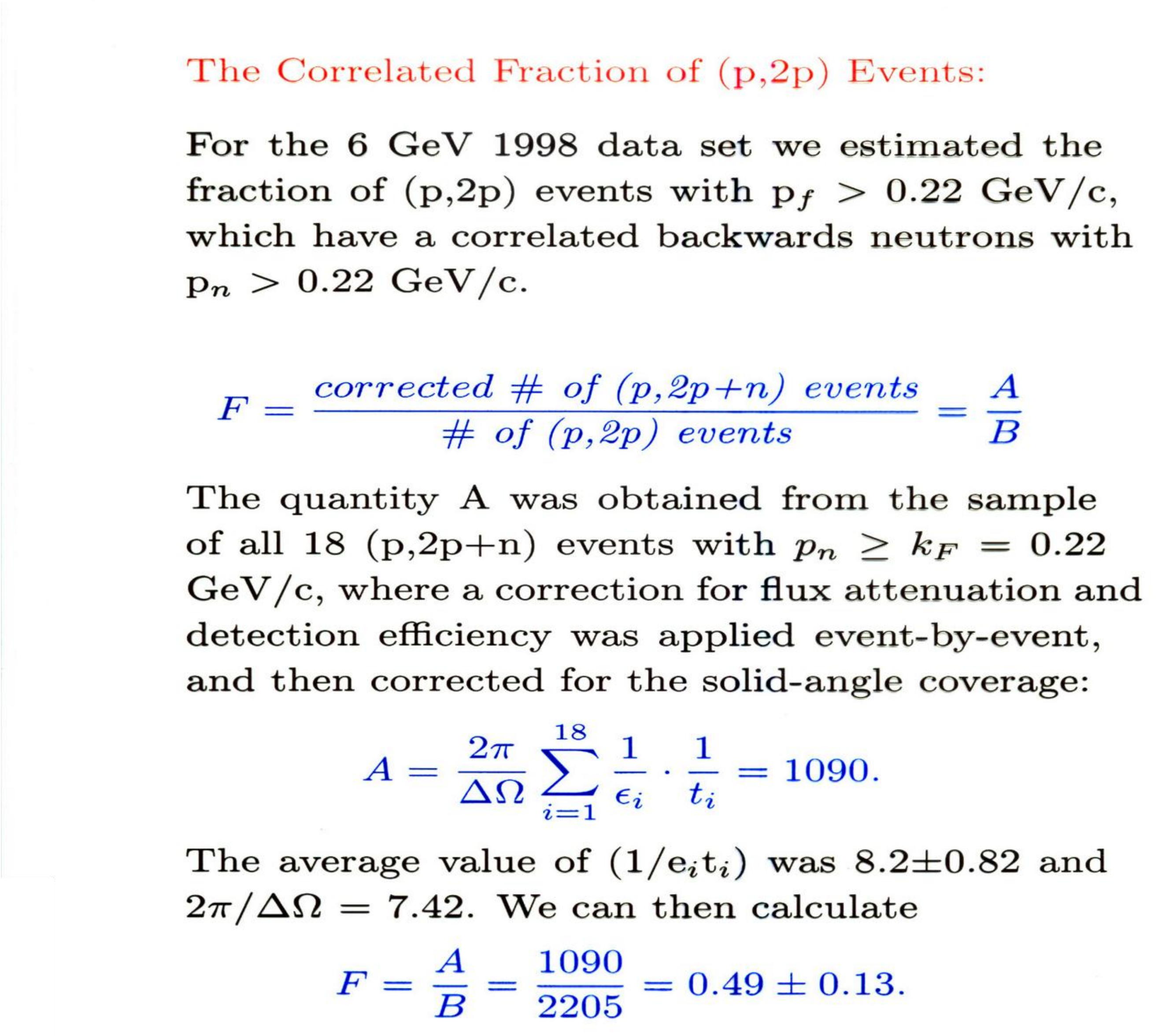


Centroid = -0.013 ± 0.027 GeV/c
σ = 0.143 ± 0.017 GeV/c

Remember this one

Centroid = 0.289 ± 0.017 GeV/c
σ = 0.097 ± 0.007 GeV/c

Figure 23: Plots of (a) p_z^{cm} and (b) p_z^{rel} for correlated n-p pairs in ^{12}C, for ^{12}C(p,2p+n) events. Each event has been "*s*-weighted".



The Correlated Fraction of (p,2p) Events:

For the 6 GeV 1998 data set we estimated the fraction of (p,2p) events with $p_f > 0.22$ GeV/c, which have a correlated backwards neutrons with $p_n > 0.22$ GeV/c.

$$F = \frac{\textit{corrected \# of (p,2p+n) events}}{\textit{\# of (p,2p) events}} = \frac{A}{B}$$

The quantity A was obtained from the sample of all 18 (p,2p+n) events with $p_n \geq k_F = 0.22$ GeV/c, where a correction for flux attenuation and detection efficiency was applied event-by-event, and then corrected for the solid-angle coverage:

$$A = \frac{2\pi}{\Delta\Omega} \sum_{i=1}^{18} \frac{1}{\epsilon_i} \cdot \frac{1}{t_i} = 1090.$$

The average value of $(1/e_i t_i)$ was 8.2 ± 0.82 and $2\pi/\Delta\Omega = 7.42$. We can then calculate

$$F = \frac{A}{B} = \frac{1090}{2205} = 0.49 \pm 0.13.$$

Subsequent Development

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

by

E. Piasetzky, M Sargsian, L. Frankfurt, M Strikman
and J. W. Watson

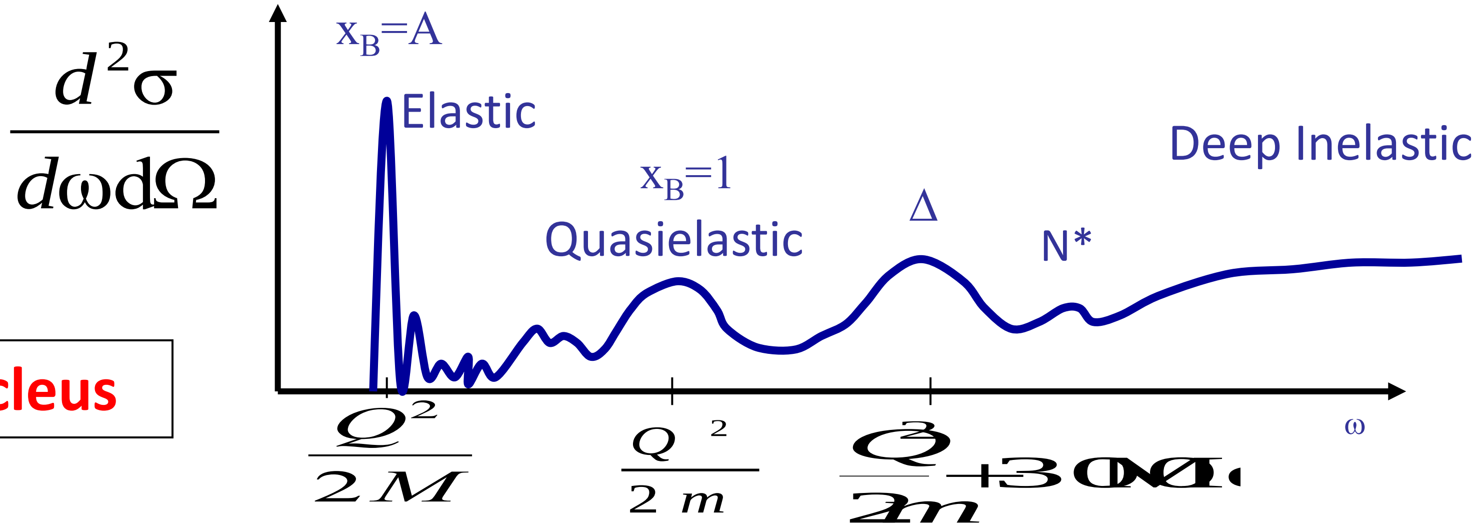
Phys. Rev. Lett., 20 October 2006

- Further Analysis of the EVA Data
- Assumes 100% SRC above 275 MeV/c
- Includes the motion of the pair
- Includes absorption of entering and exiting nucleons in the nuclear medium

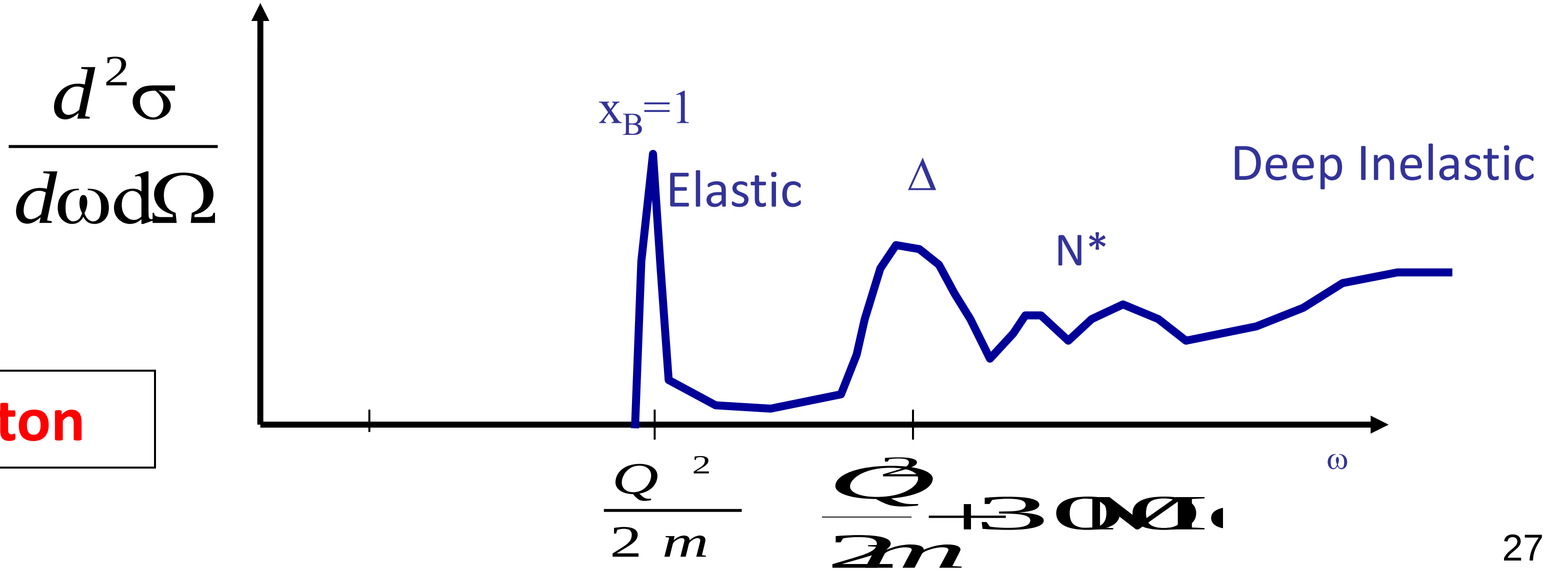
Conclusion: 92 ± 18% of high-momentum protons have correlated neutrons.

A. A. Tang et al.,
Phys. Rev. Lett. <u>90</u>, 042301 (2003)

Electron Scattering at Fixed Q^2



Nucleus



Proton

CLAS A(e,e') Data

K. Sh. Egiyan *et al.*, Phys. Rev. C **68** (2003) 014313.

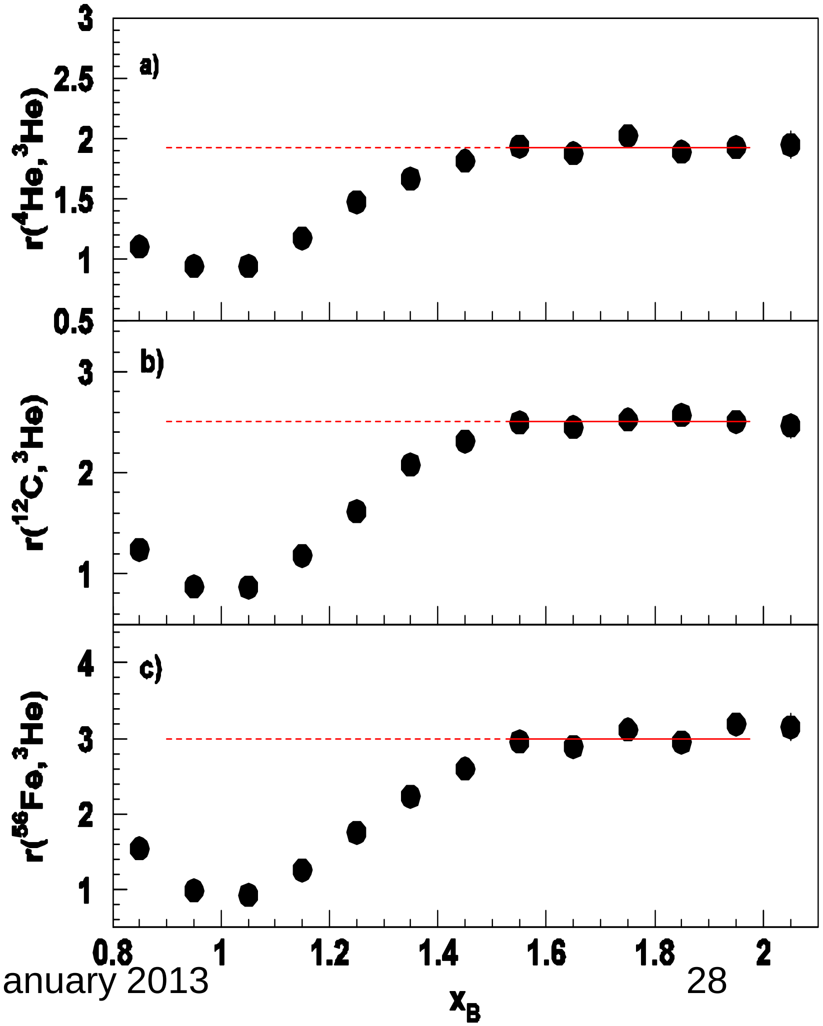
Originally done with SLAC data by D.B. Day *et al.*, Phys. Rev. Lett. 59 (1987) 427.

$x = \frac{Q^2}{2M\omega} > 1.5$ and $Q^2 > 1.4\ [\mathrm{GeV/c}]^2$

then

r(A,3He) = a2n(A)/a2n(3He)

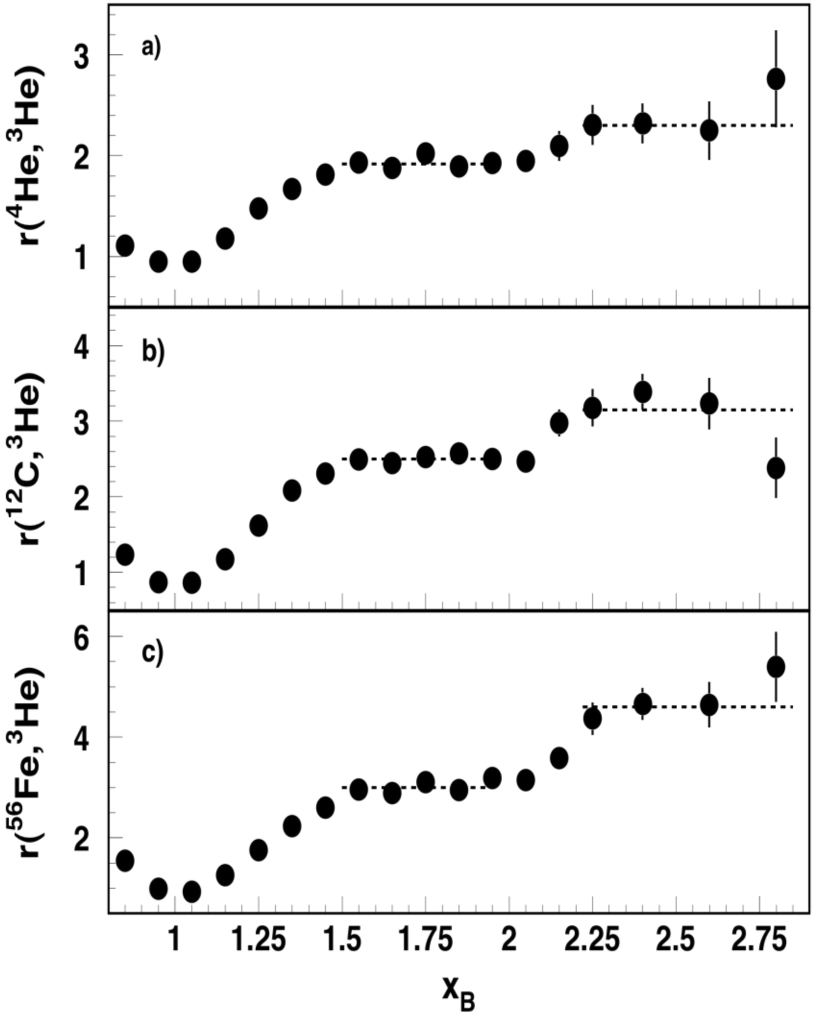
The observed *scaling* means that the electrons probe the high-momentum nucleons in the 2N-SRC phase, and the scaling factors determine the per-nucleon probability of the 2N-SRC phase in nuclei with A>3 relative to 3He



Estimate of ^{12}C Two and Three Nucleon SRC

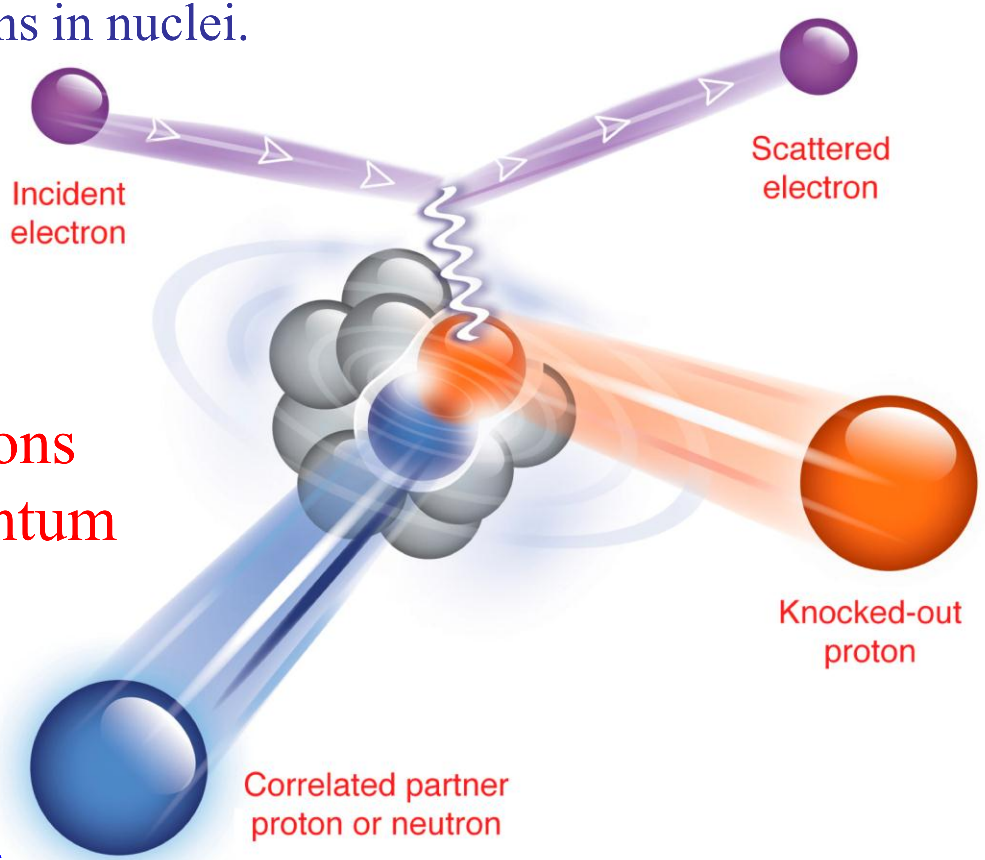
K. Sh. Egiyan *et al.*, Phys. Rev. Lett. **96** (2006) 082501.

- K. Egiyan *et al*. related the known correlations in deuterium and previous r(^{3}He,D) results to find:
- ^{12}C 20% two nucleon SRC
- ^{12}C <1% three nucleon SRC



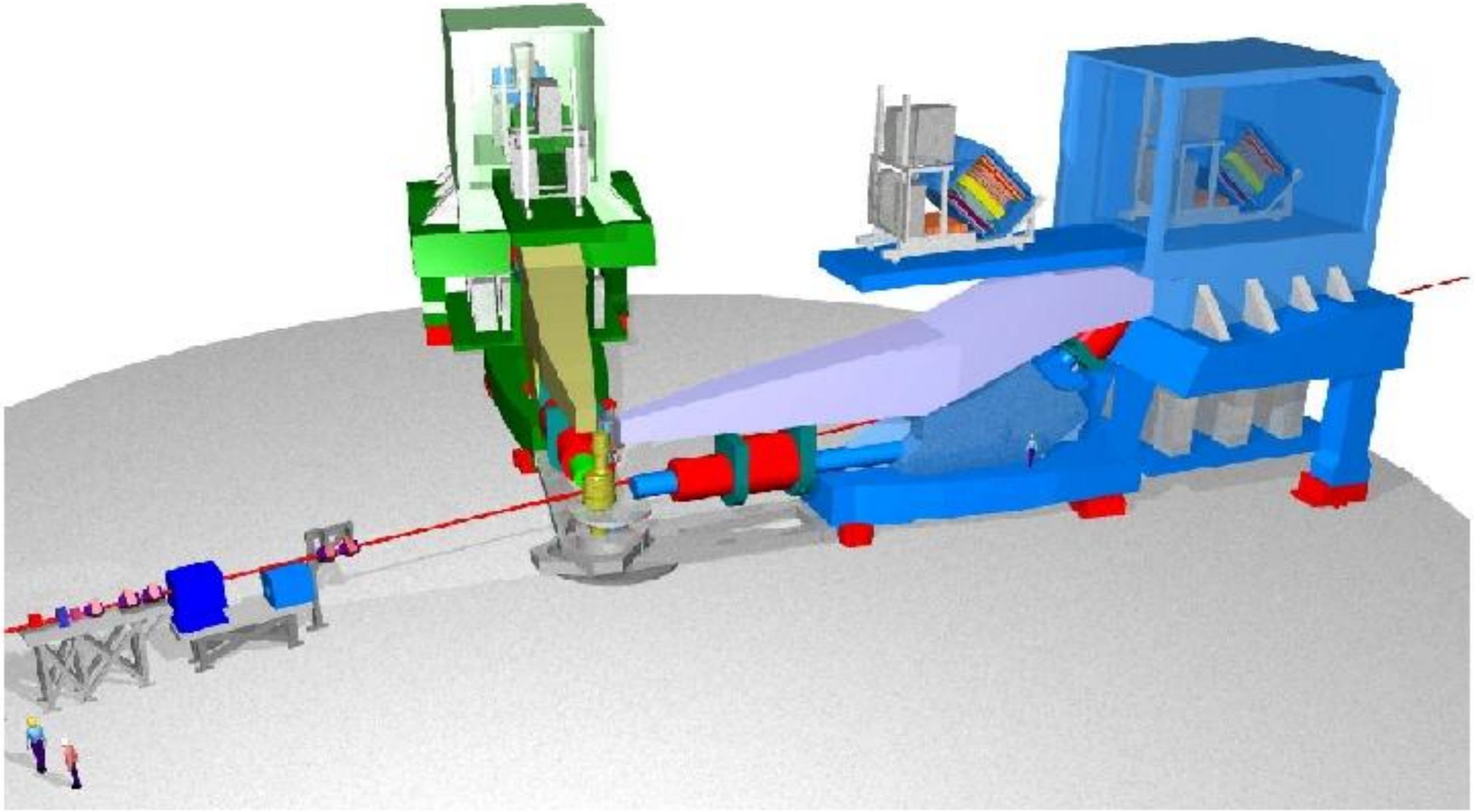
E01-105: A customized (e,e'pN) Measurement

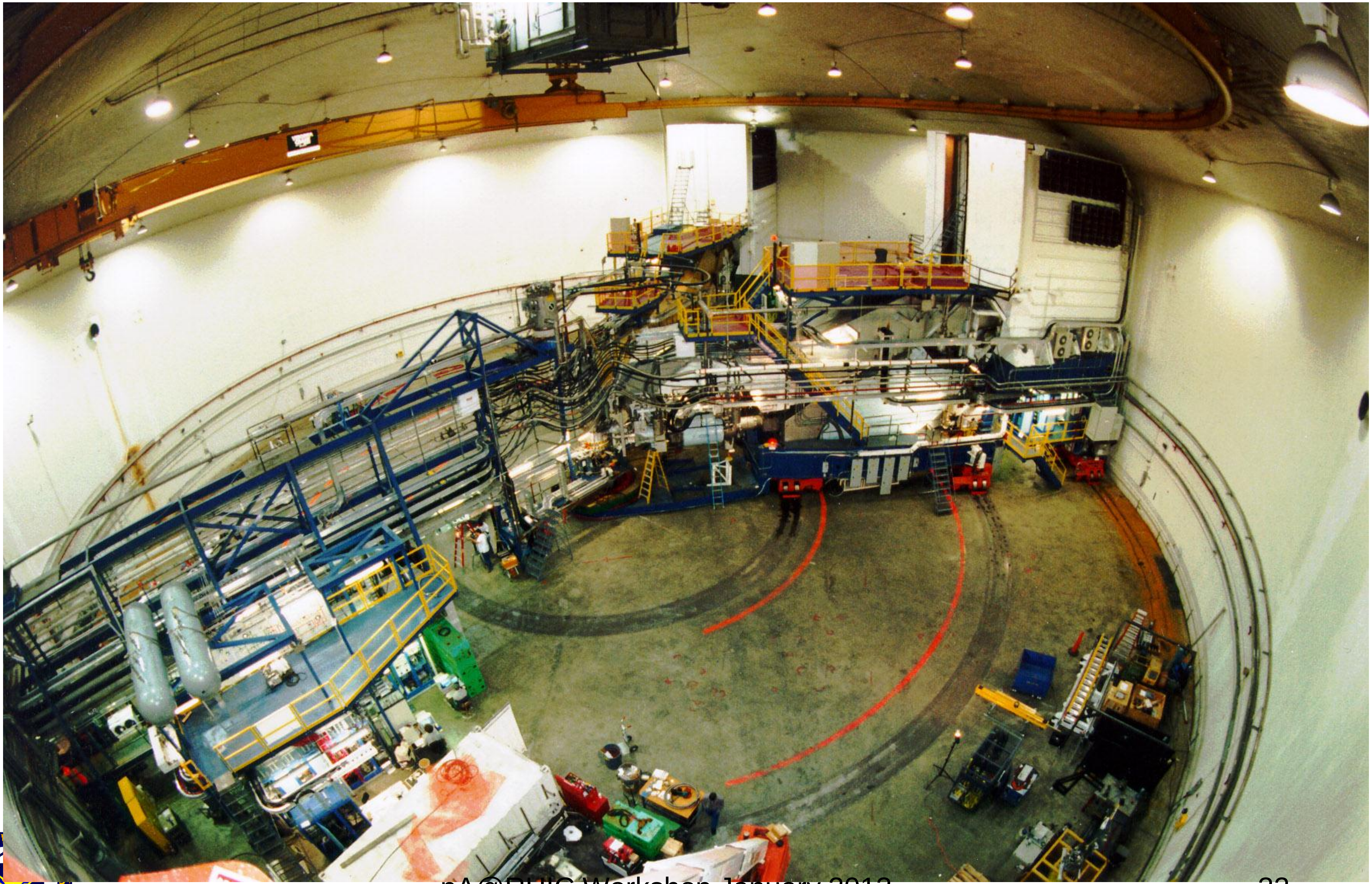
To study nucleon pairs at close proximity and their contributions to the large momentum tail of nucleons in nuclei.



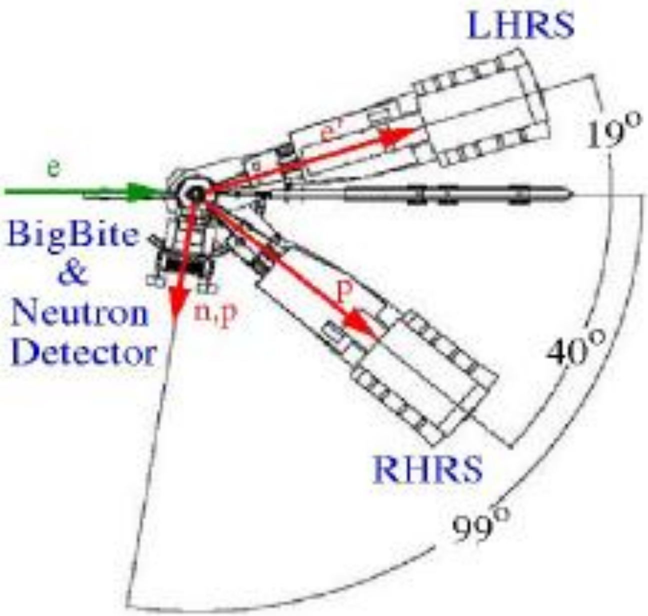
A pair with "large" relative momentum between the nucleons and small center of mass momentum

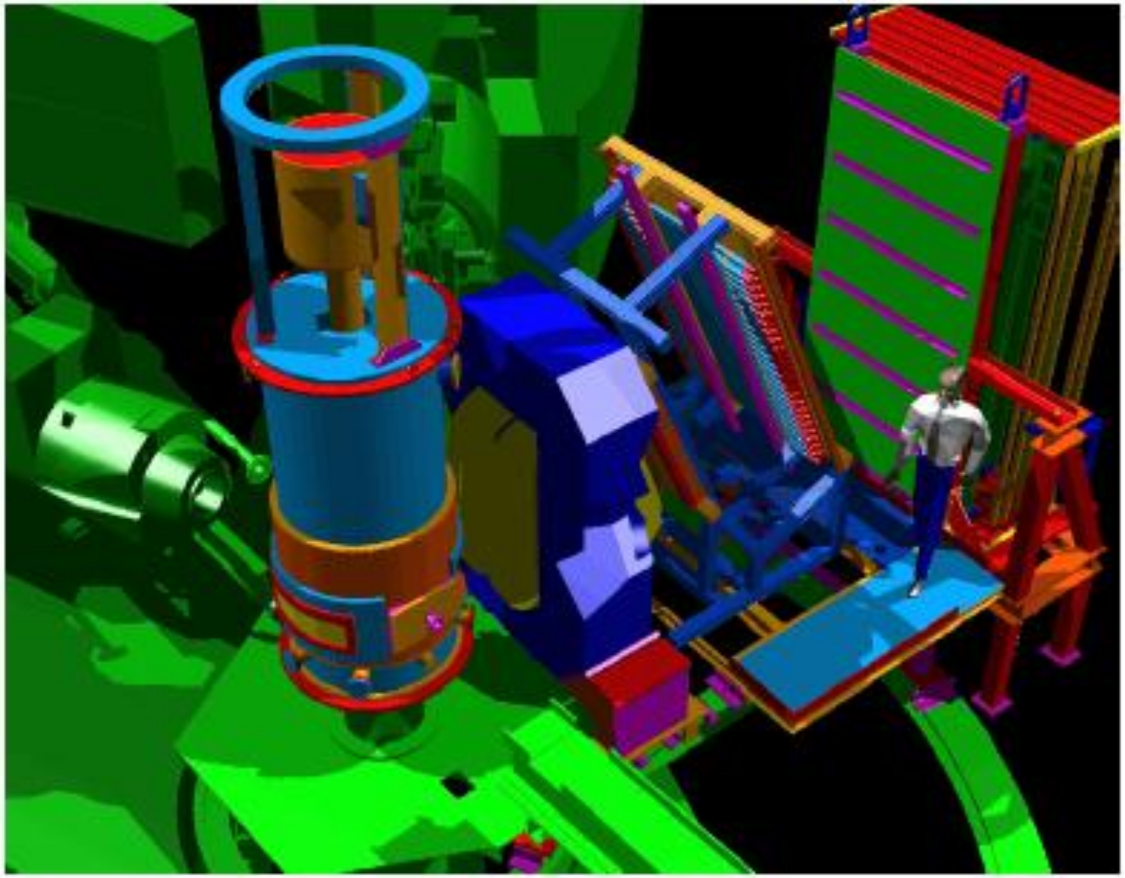
- high Q2 to minimize MEC
- x>1 to suppress isobar contributions
- anti-parallel kinematics to suppress FSI





New Equipment for the Experimental Setup

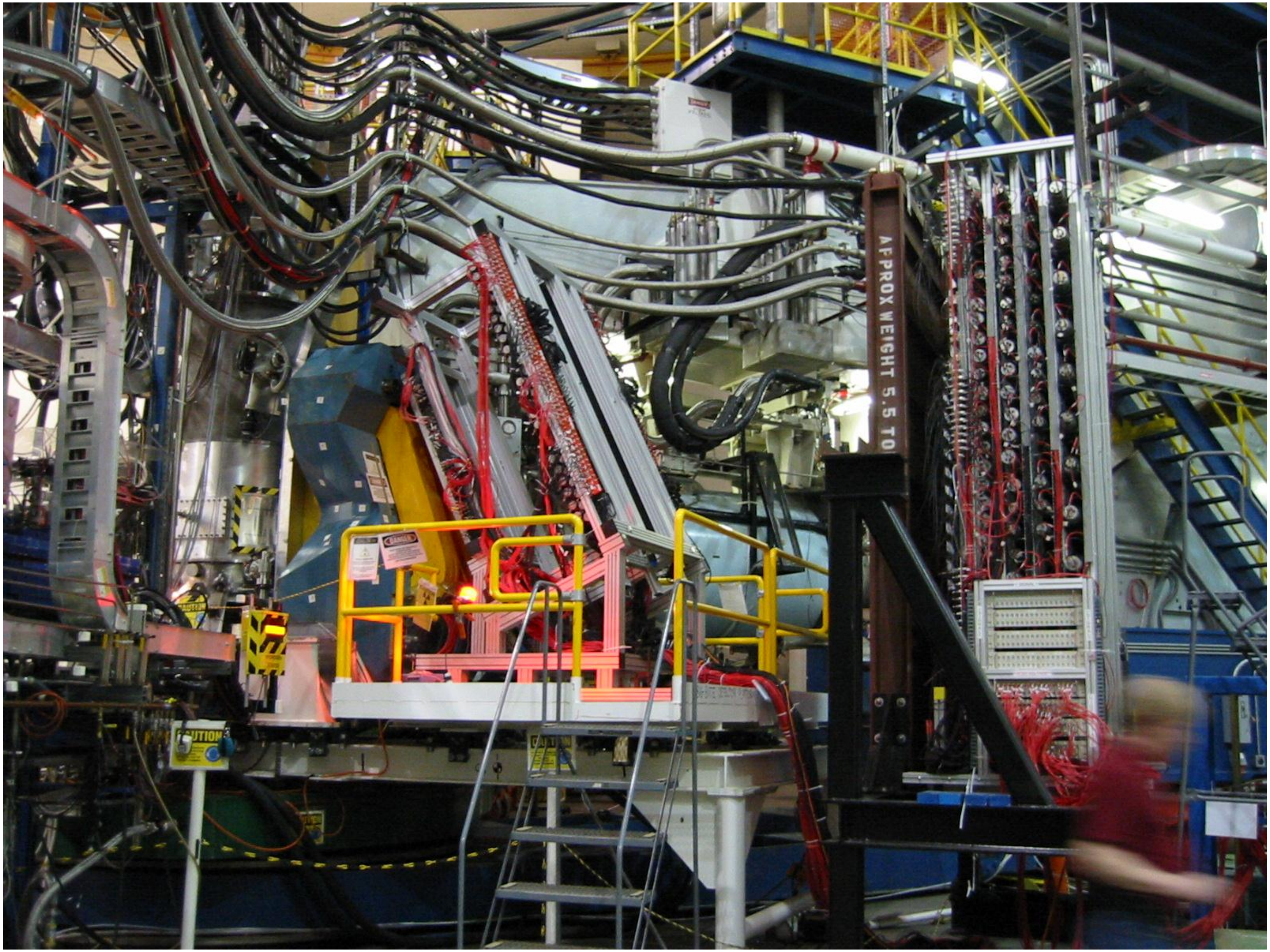




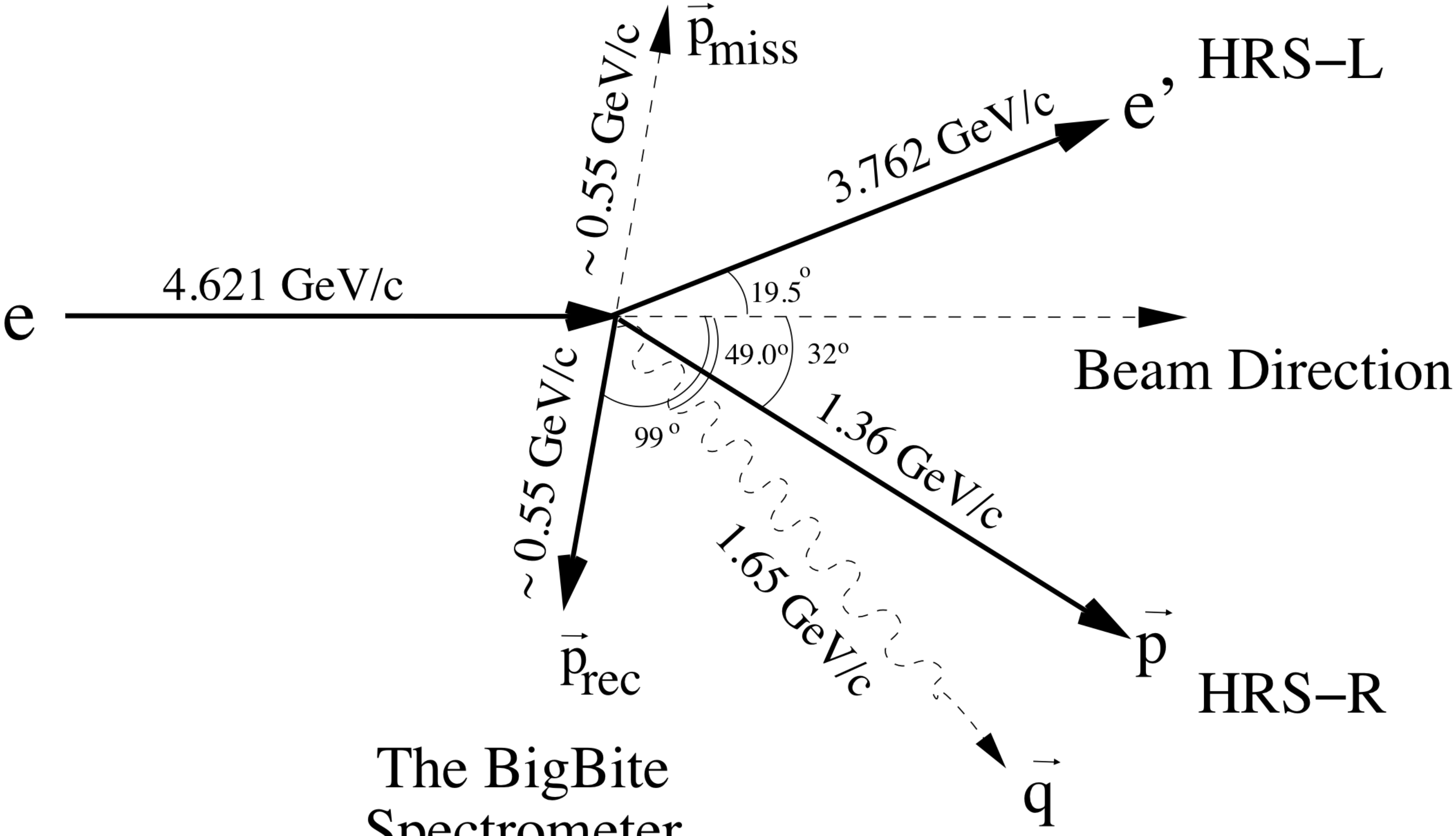
- New Scattering Chamber
- New BigBite Hadron Spectrometer (100 msr)
- New Low Energy Neutron Detector

The neutron detector array consisted of 88 bars of plastic scintillator, with a PMT on each end of each bar, for “mean timing.”

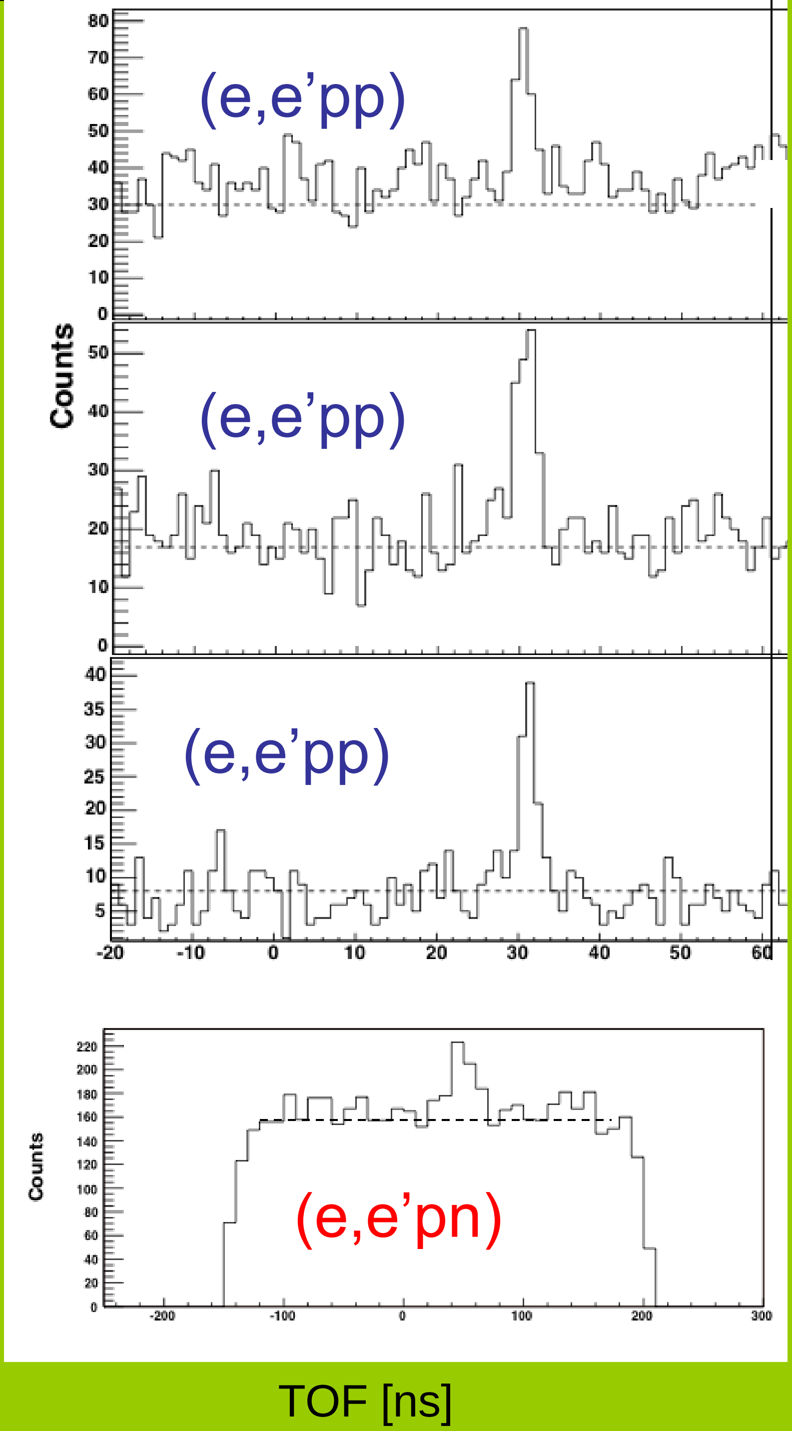
These were gathered from around the world.


APPROX WEIGHT 5.5 TO
CAUTION
DANGER

Kinematics



The BigBite
Spectrometer
and
Neutron Detector



P_{mis}="300" MeV/c

(Signal : BG= 1.5:1)

P_{mis}="400" MeV/c

(Signal : BG= 2.3:1)

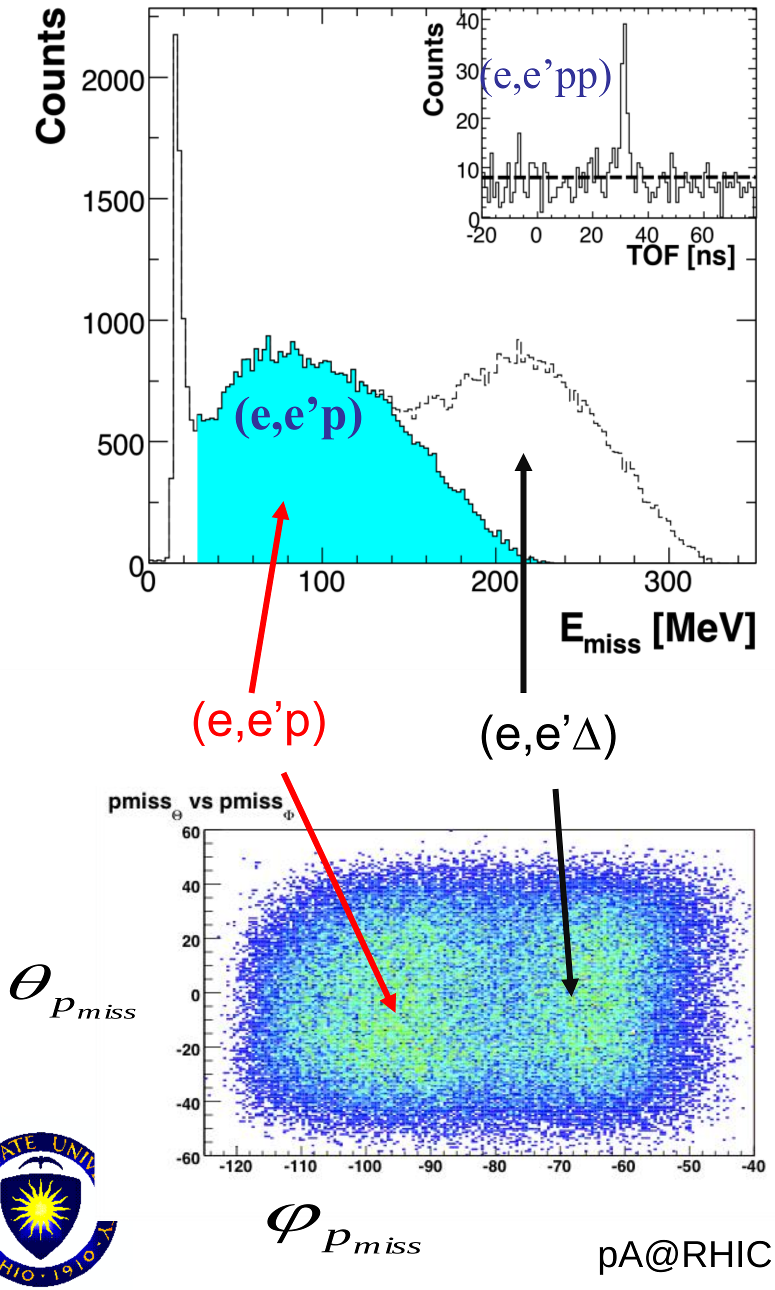
P_{mis}="500" MeV/c

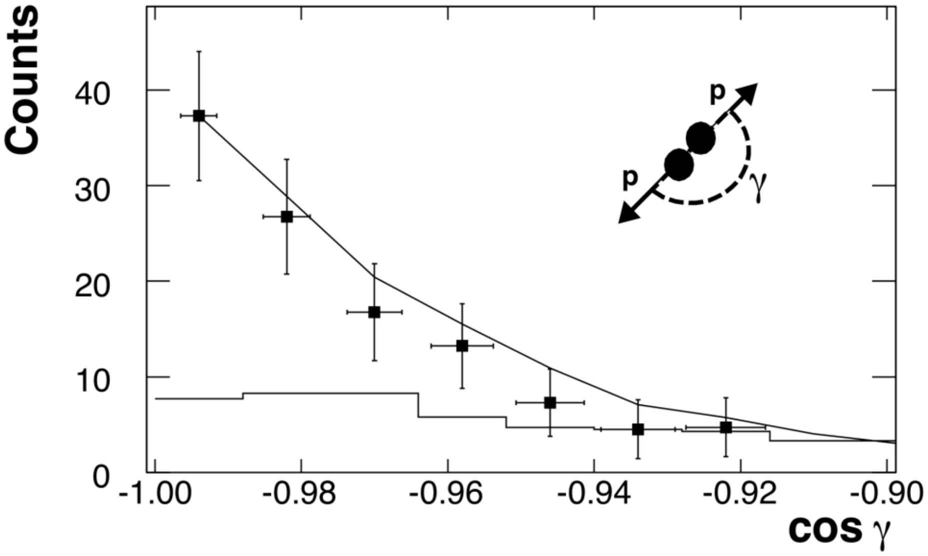
(Signal : BG= 4:1)

P_{mis}="500" MeV/c

(Signal : BG= 1:7)

(e,e'p) & (e,e'pp) Data



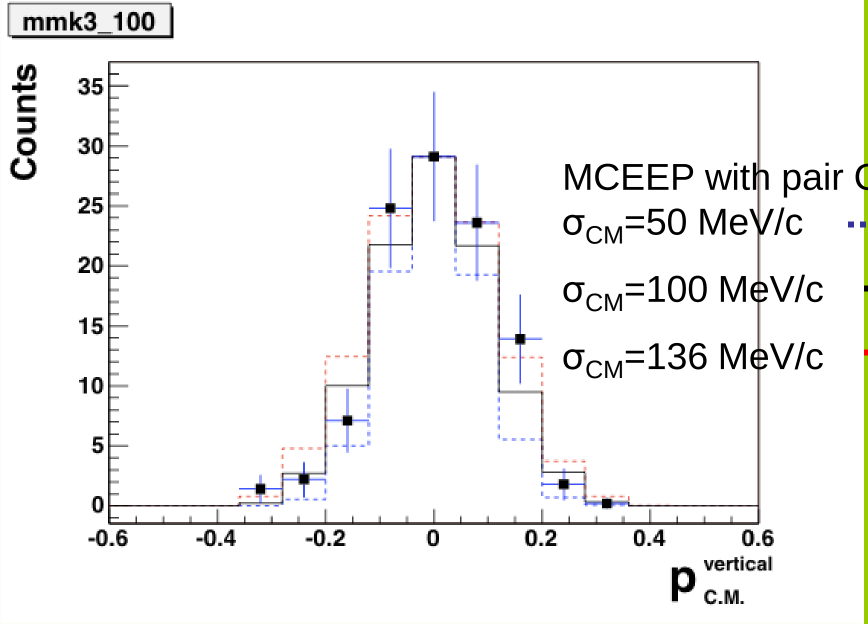


Strong back-to-back correlation!

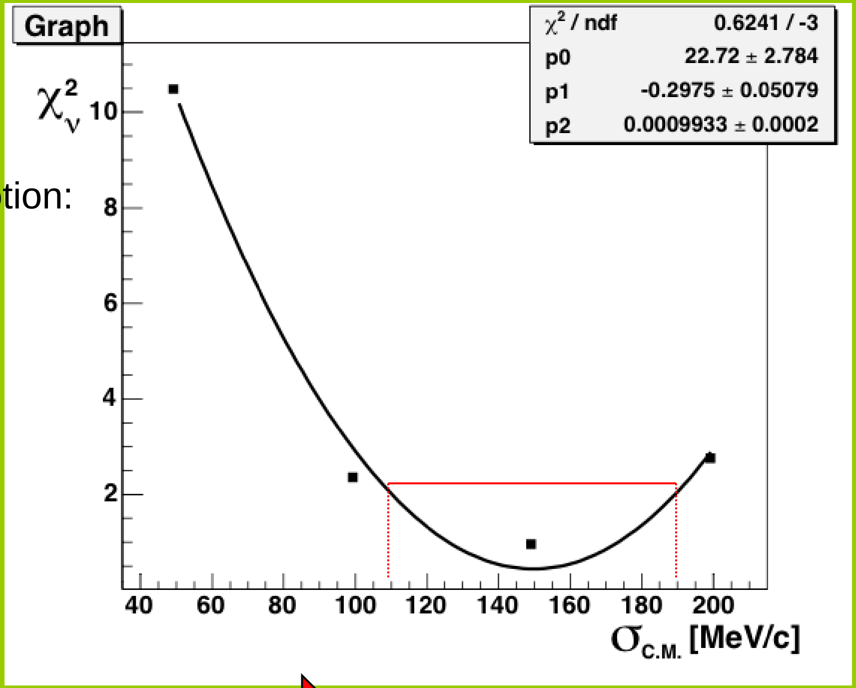
R. Shneor *et al.*,
Phys. Rev. Lett. 99 (2007) 072501.

CM motion of the pair:

$P_{c.m}^{vertical}$, “500 MeV/c “ setup



MCEEP with pair CM motion:
σ_{CM}=50 MeV/c ··········
σ_{CM}=100 MeV/c ——
σ_{CM}=136 MeV/c ··········



2 components of $\vec{p}_{c.m}$ and 3 kinematical setups

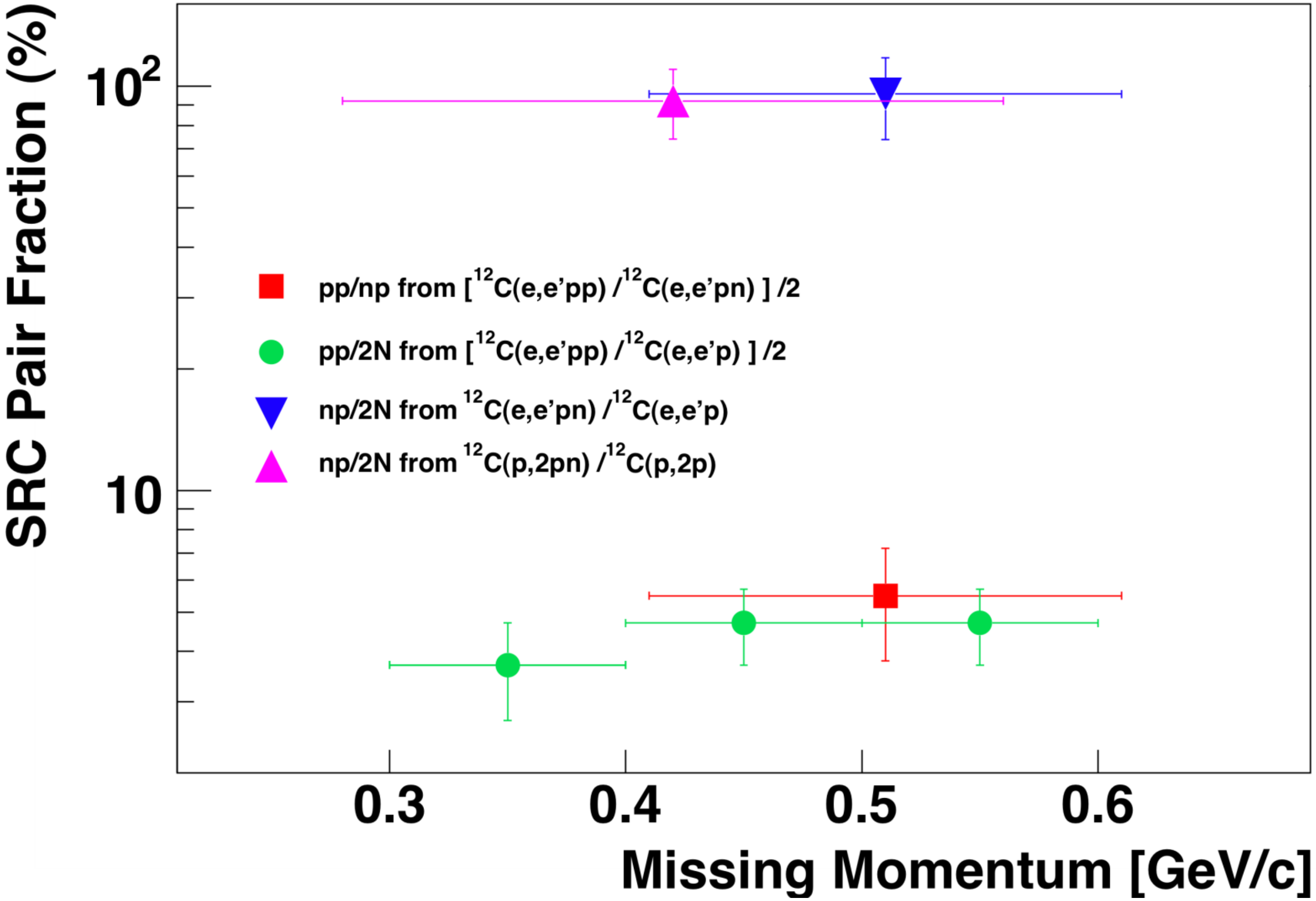
This experiment : σ_{CM}=0.136 ± 0.020 GeV/c

(p,2pn) experiment at BNL : σ_{CM}=0.143±0.017 GeV/c

Theoretical prediction (Ciofi and Simula) : σ_{CM}=0.139 GeV/c

Short-Range Correlation Pair Factions

R. Subedi *et al.*, Science **320** (2008) 1476).



The Results from E01-015 can be found in:

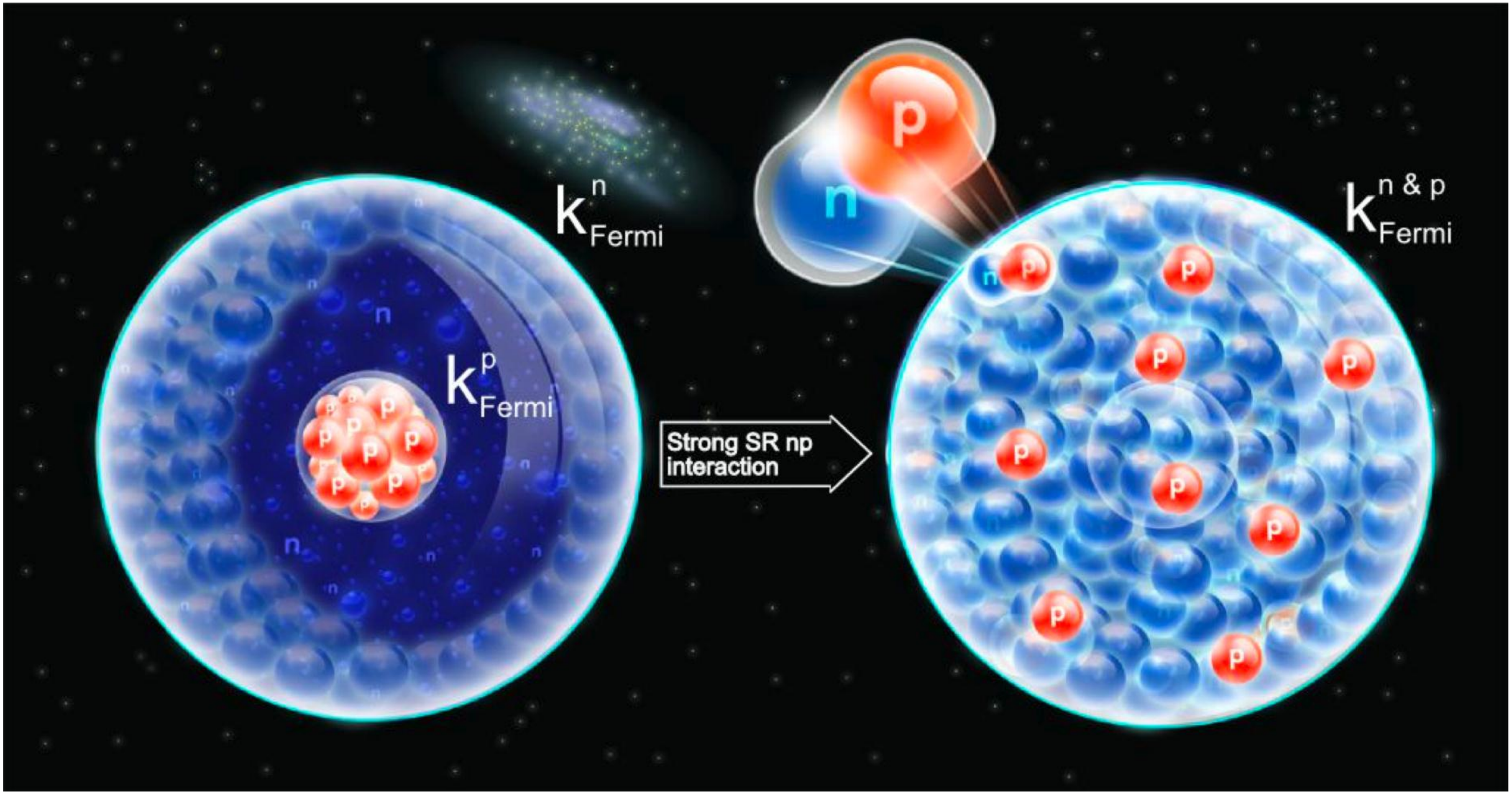
1) R. Shneor, et al., Phys. Rev. Lett. **99**, 072501 (2007).

2) R. Subedi, et al., **SCIENCE 320**, 1476 (2008).

The results of the BNL (p,2p+n) experiment are fully consistent with the results of the JLab (e,e'p+N) experiment:

☒ Different Laboratories
☒ Different probes
☒ Different Graduate Students
☒ Different millenia
☒ **Same Results!**
☒ **We are observing nuclear structure**

Implications for Neutron Stars

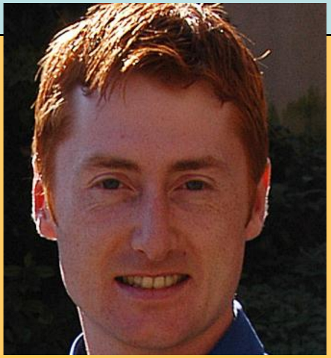


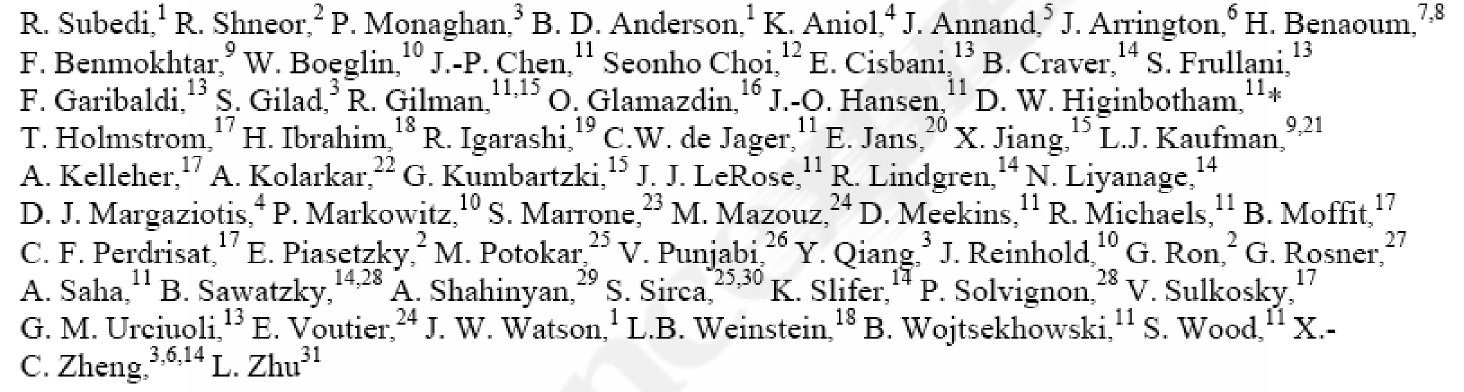
Acknowledgment

Exp 01 – 015 collaboration **Hall A /JLab**

E. Piasetzky, S. Gilad, S. Wood, J. Watson, W. Bertozzi

D. Higinbotham, R. Subedi, R. Shneor, P. Monaghan





R. Subedi,[1] R. Shneor,[2] P. Monaghan,[3] B. D. Anderson,[1] K. Aniol,[4] J. Annand,[5] J. Arrington,[6] H. Benaoum,[7,8] F. Benmokhtar,[9] W. Boeglin,[10] J.-P. Chen,[11] Seonho Choi,[12] E. Cisbani,[13] B. Craver,[14] S. Frullani,[13] F. Garibaldi,[13] S. Gilad,[3] R. Gilman,[11,15] O. Glamazdin,[16] J.-O. Hansen,[11] D. W. Higinbotham,[11]* T. Holmstrom,[17] H. Ibrahim,[18] R. Igarashi,[19] C.W. de Jager,[11] E. Jans,[20] X. Jiang,[15] L.J. Kaufman,[9,21] A. Kelleher,[17] A. Kolarkar,[22] G. Kumbartzki,[15] J. J. LeRose,[11] R. Lindgren,[14] N. Liyanage,[14] D. J. Margaziotis,[4] P. Markowitz,[10] S. Marrone,[23] M. Mazouz,[24] D. Meekins,[11] R. Michaels,[11] B. Moffit,[17] C. F. Perdrisat,[17] E. Piasetzky,[2] M. Potokar,[25] V. Punjabi,[26] Y. Qiang,[3] J. Reinhold,[10] G. Ron,[2] G. Rosner,[27] A. Saha,[11] B. Sawatzky,[14,28] A. Shahinyan,[29] S. Sirca,[25,30] K. Slifer,[14] P. Solvignon,[28] V. Sulkosky,[17] G. M. Urciuoli,[13] E. Voutier,[24] J. W. Watson,[1] L.B. Weinstein,[18] B. Wojtsekhowski,[11] S. Wood,[11] X.-C. Zheng,[3,6,14] L. Zhu[31]

PRL 99, 072501 (2007)

Science 320,1476 (2008)

From the 2007 NSAC Long-Range Plan:

“. . .the direct observation of correlated two-nucleon and three-nucleon effects in the nuclear medium has been evasive. The powerful combination of the multi-GeV electron beam and a large-acceptance detector at JLAB has permitted the direct observation of two- and three-nucleon correlations in nuclei”

Two New Directions

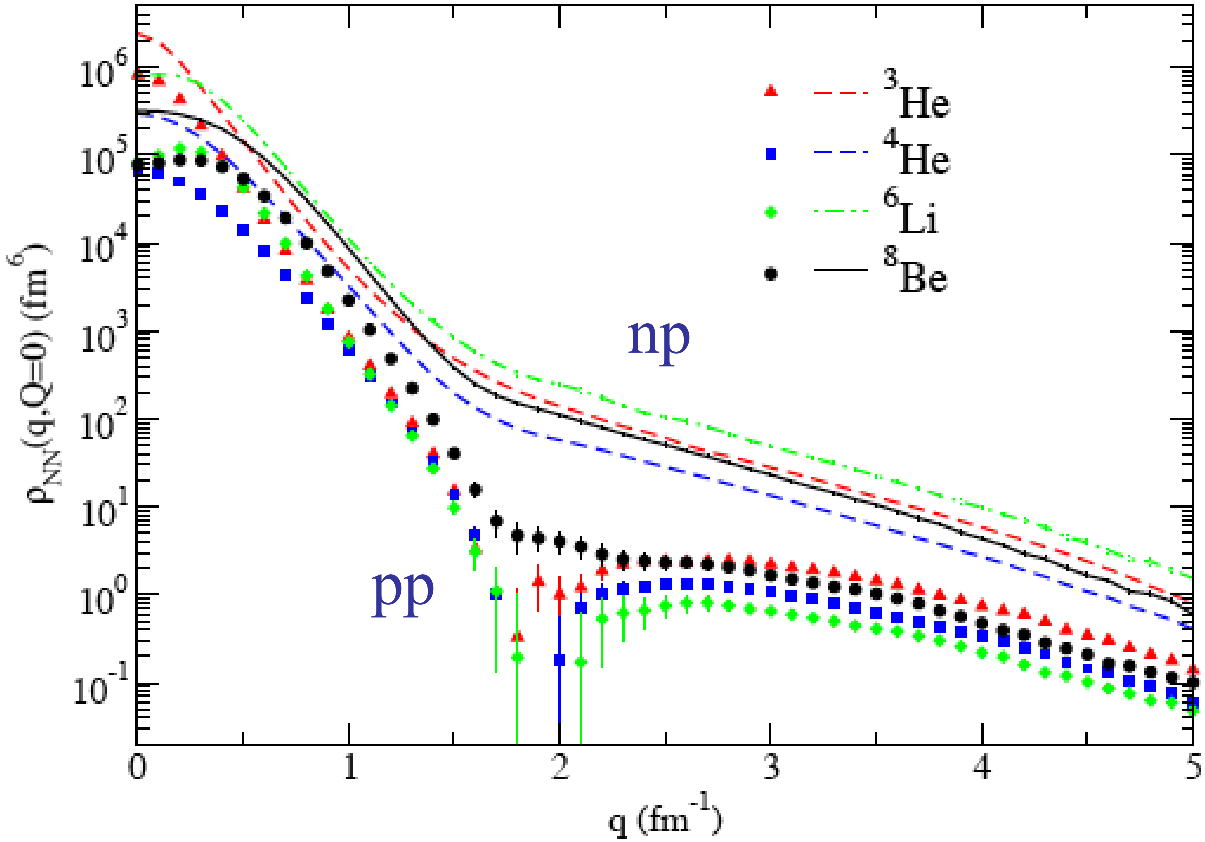
1.) Why is the np:pp ratio 20:1?

➔➔ JLab Experiment E07-006 on ^{4}He

2.) Is there a connection to the EMC effect?

➔➔ JLab Experiment E12-11-107

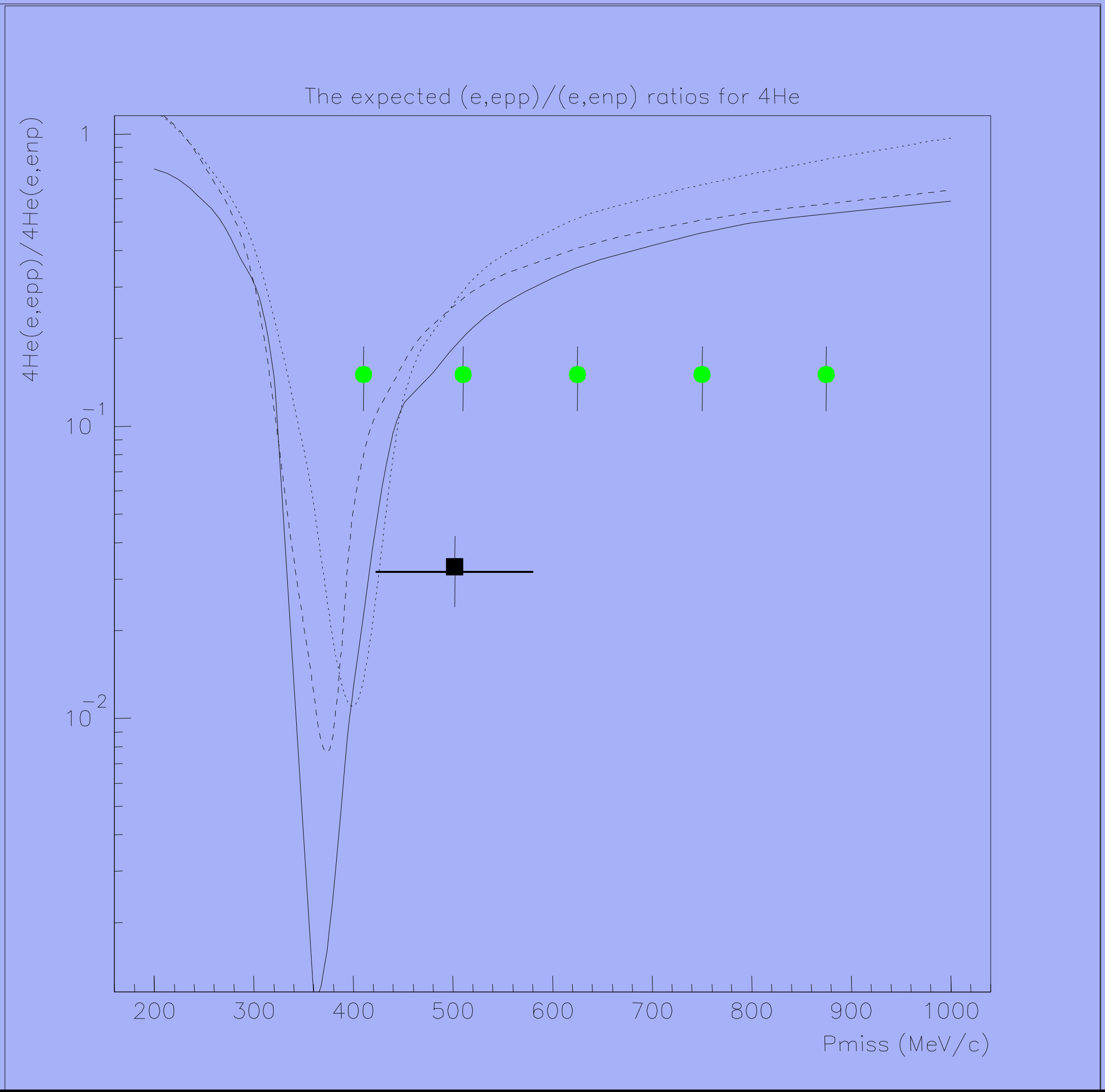
Importance of Tensor Correlations

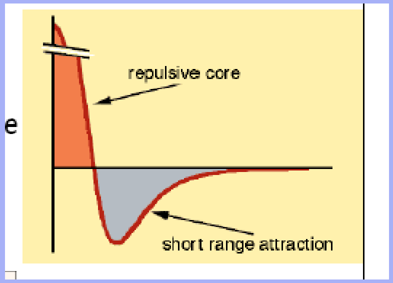


- M. Sargsian et al., Phys. Rev. C (2005) 044615.
- R. Schiavilla et al., Phys. Rev. Lett. 98 (2007) 132501. [shown above]
- M. Alvioli, C. Ciofi degli Atti, and H. Morita, Phys. Rev. Lett. 100 (2008) 162503.

A new approved experiment at Jlab E07-006

Measurement of the ^{4}He(e,e'pp) and ^{4}He(e,e'pn) reactions over the ^{4}He(e,e'p) missing momentum range from 400 to 875 MeV/c.





■ E01-105 ^{12}C (scaled to ^{4}He)

● This proposal - ^{4}He

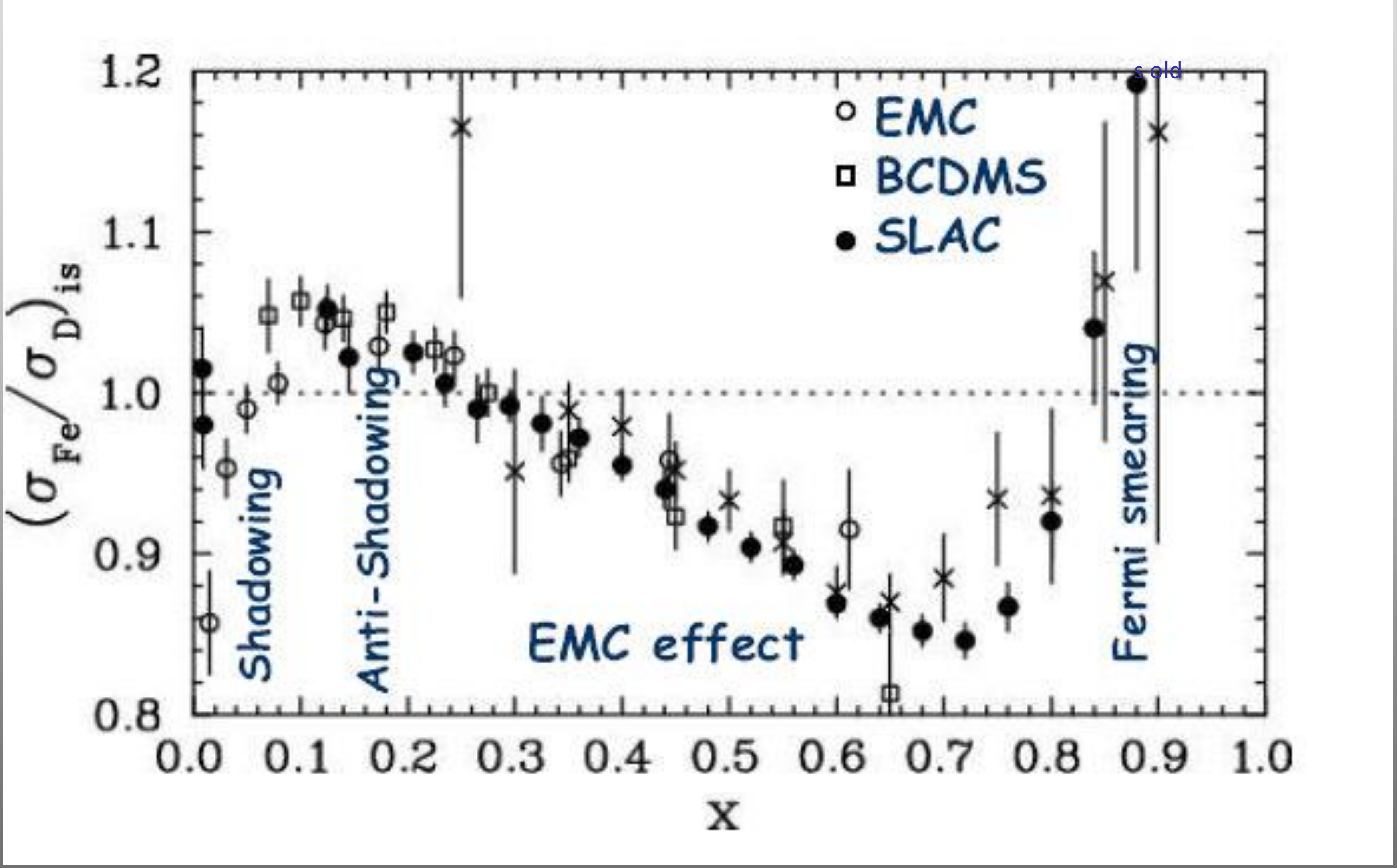
Density distributions:

Sargsian et al.

Schiavilla et al.

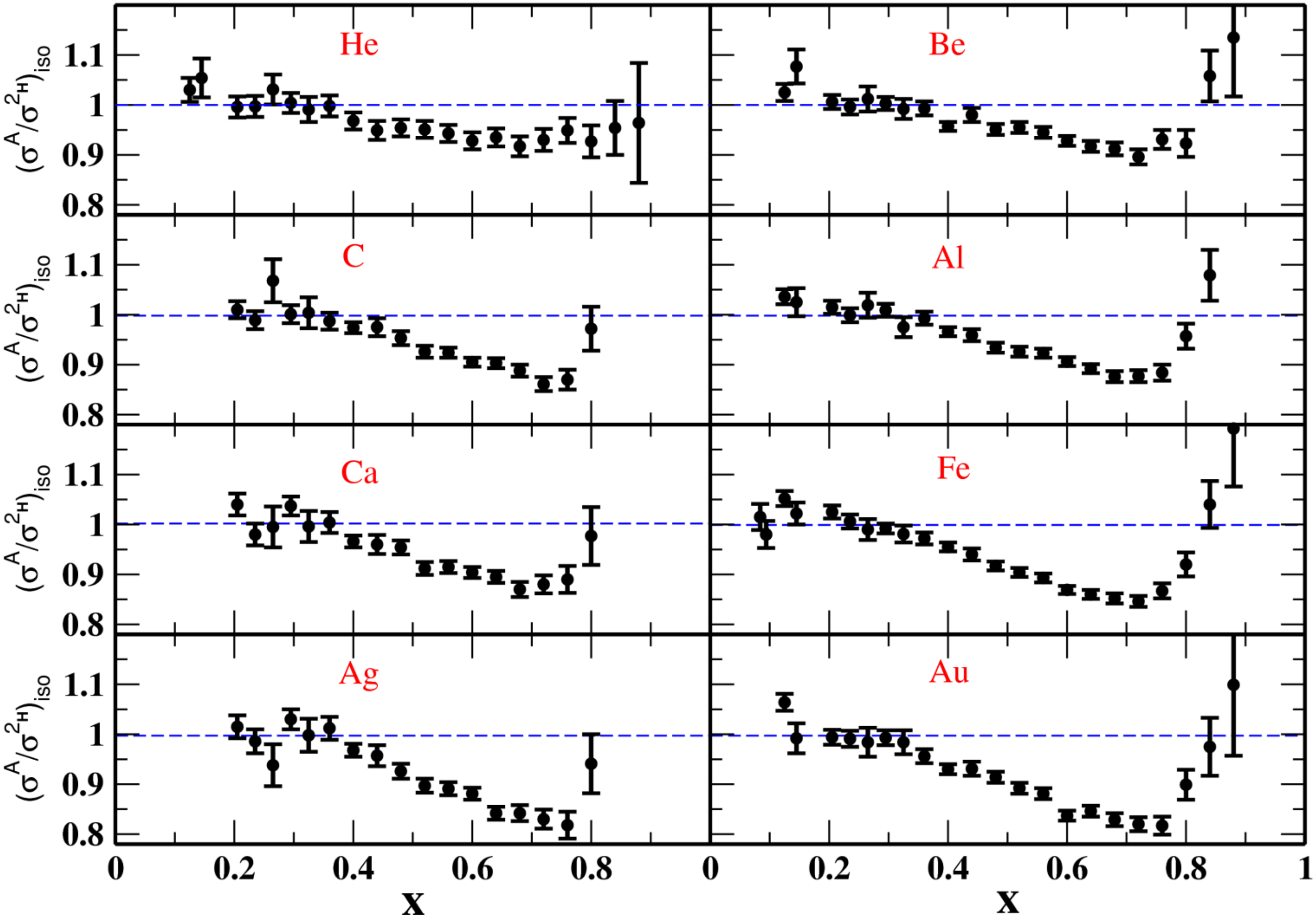
(e,e'pN) calculations are needed

The European Muon Collaboration (EMC) effect



σ^{DIS} per nucleon in nuclei $\neq$ σ^{DIS} per nucleon in deuteron

SLAC E139



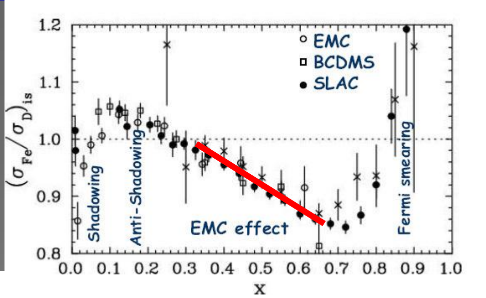
Data from CERN SLAC JLab 1983- 2009

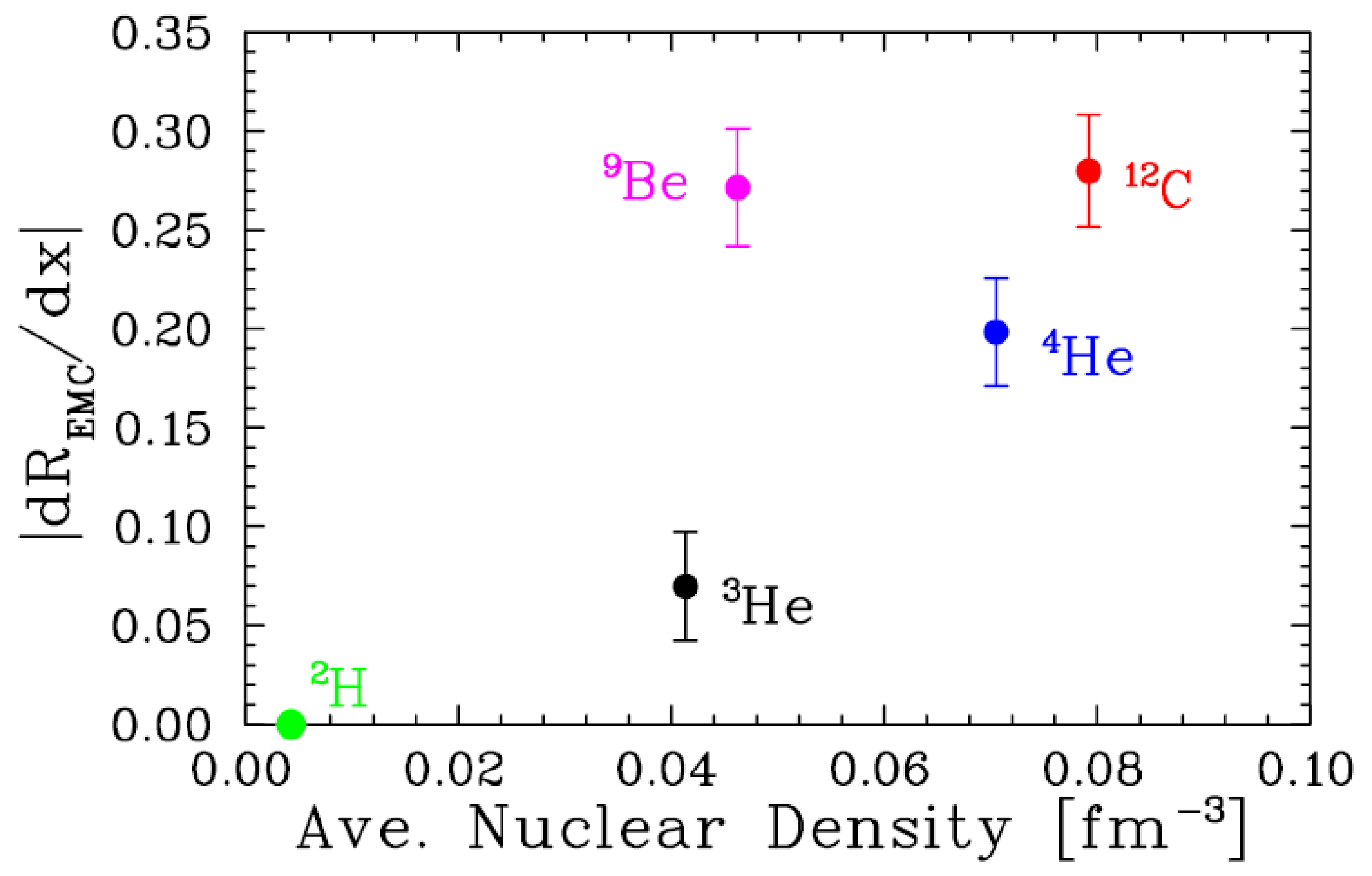
EMC collaboration, Aubert et al. PL B 123,275 (1983)

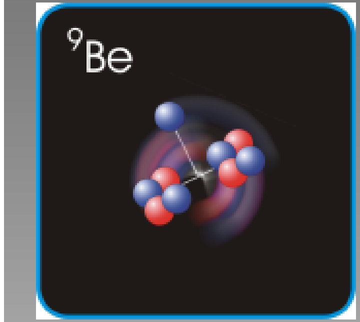
SLAC Gomez et al., Phys Rev. D49,4348 (1994)

A review of data collected during first decade, Arneodo, Phys. Rep. 240,301(1994)

EMC is a not a bulk property of nuclear medium







JLab / Hall C

Seely et al. PRL 103, 202301 (2009)

Scaled nuclear density = $(A-1)/A \langle\rho\rangle$
→ remove contribution from struck nucleon

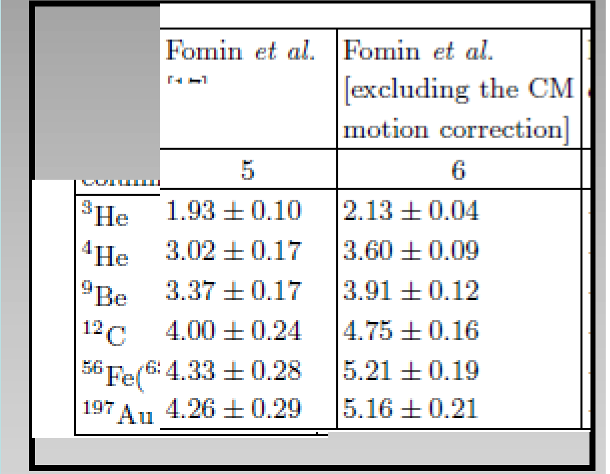
$\langle\rho\rangle$ from ab initio few-body calculations

→ *[**S.C. Pieper and R.B. Wiringa,** Ann. Rev. Nucl. Part. Sci 51, 53 (2001)]*

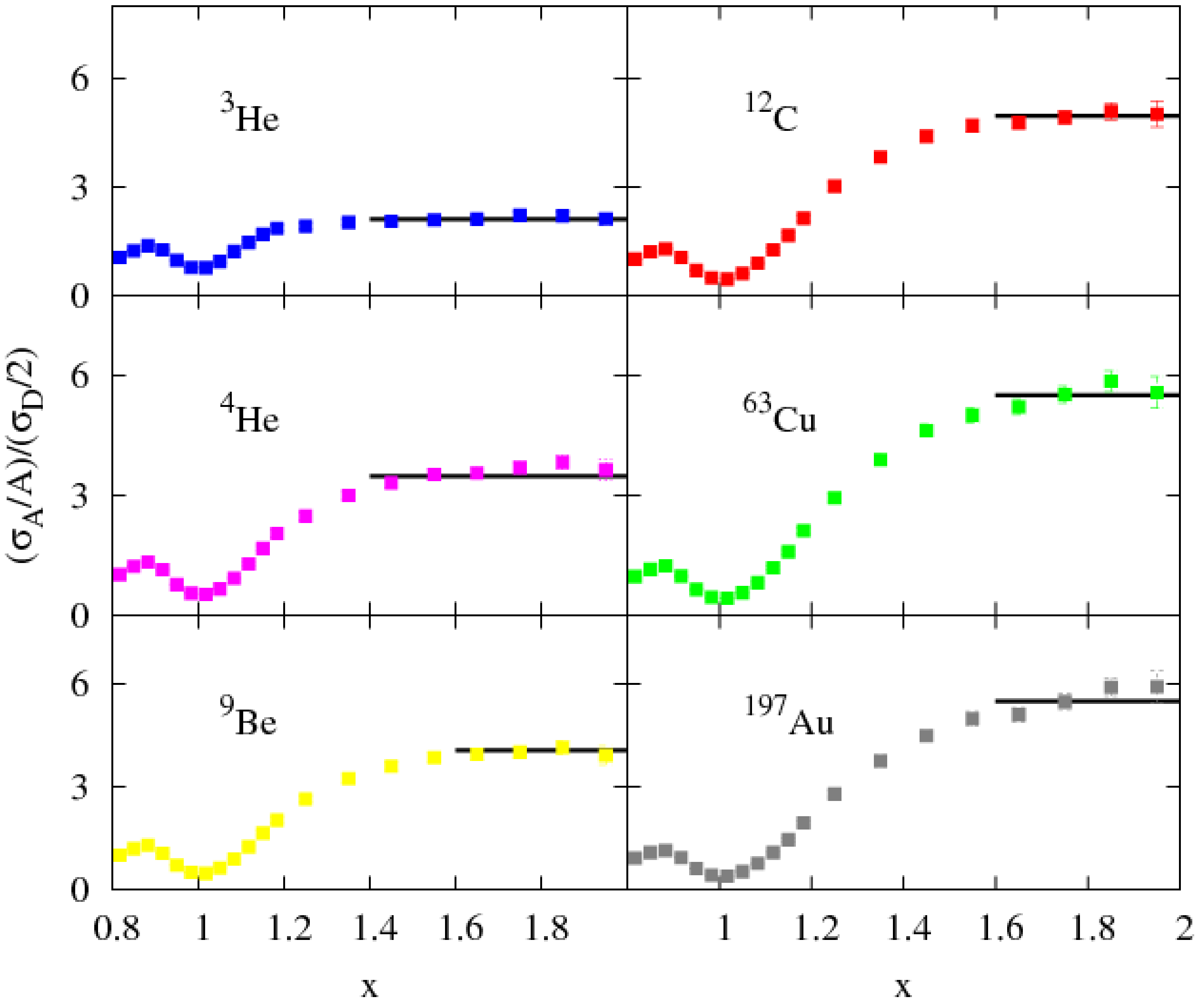
New Results from JLab Hall C (E02-019)

Q2=2.5GeV2

$a_{2N}(A/d)$

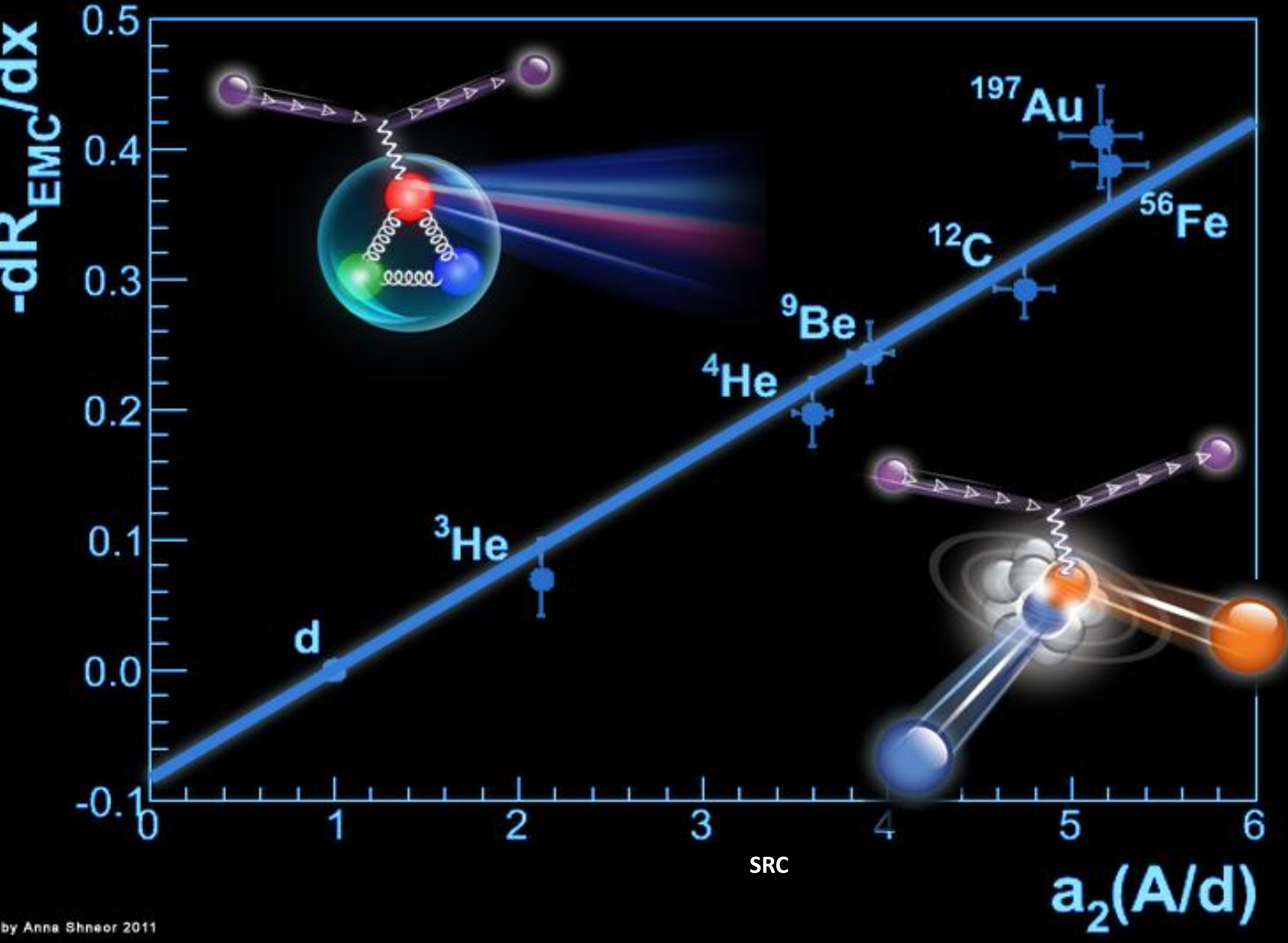


	Fomin *et al.*	Fomin *et al.* [excluding the CM motion correction]
	5	6
^{3}He	1.93 ± 0.10	2.13 ± 0.04
^{4}He	3.02 ± 0.17	3.60 ± 0.09
^{9}Be	3.37 ± 0.17	3.91 ± 0.12
^{12}C	4.00 ± 0.24	4.75 ± 0.16
^{56}Fe(6	4.33 ± 0.28	5.21 ± 0.19
^{197}Au	4.26 ± 0.29	5.16 ± 0.21



N. Fomin et al. Phys. Rev. Lett. 108:092502, 2012.

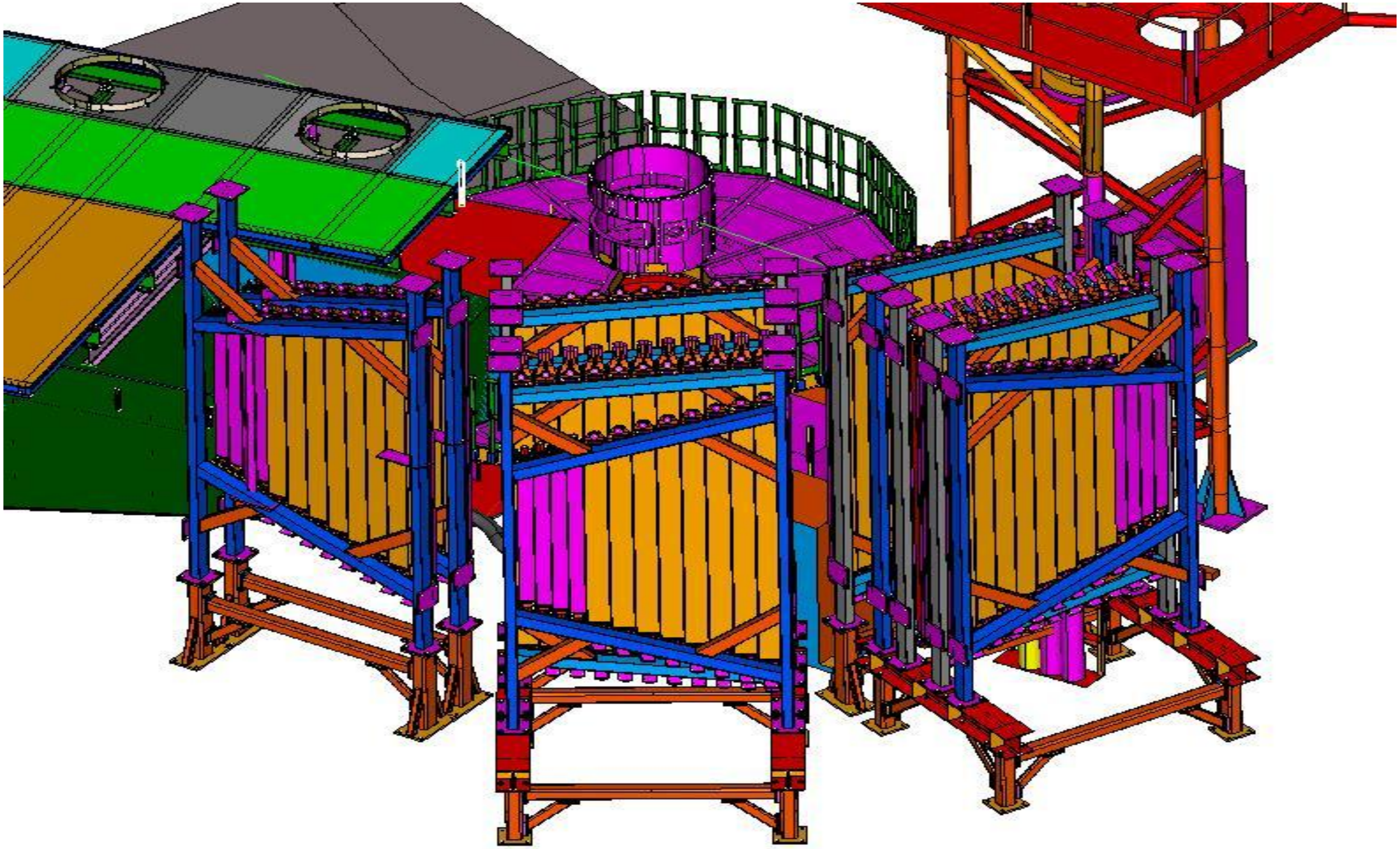
PRL 106, 052301 (2011), also PRC 85 047301 (2012)



EMC

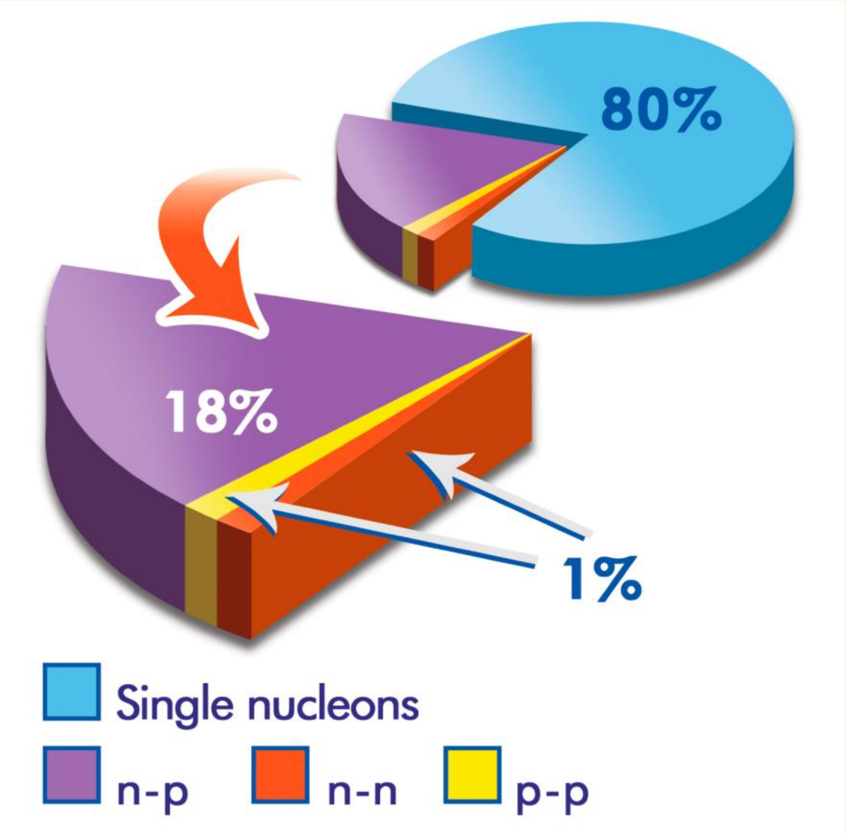
SRC

New Idea: Large Acceptance Device



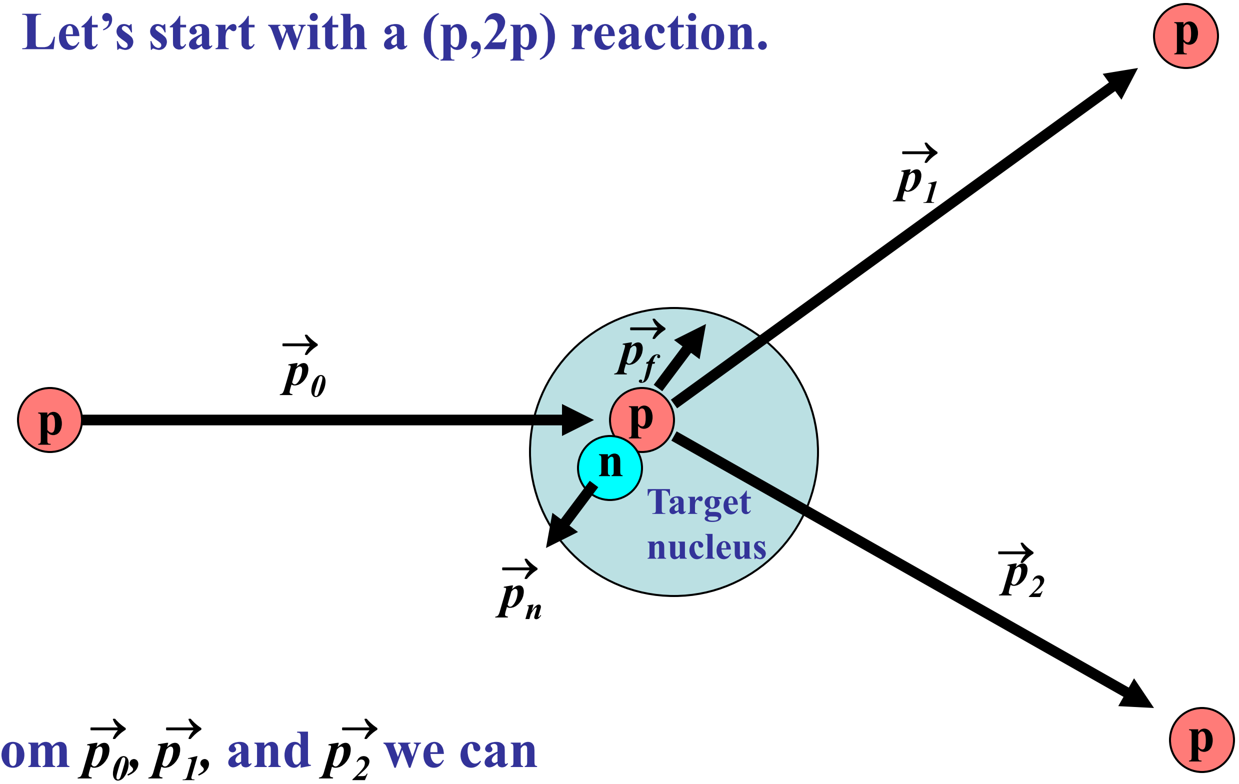
Summary of Results

- Almost all nucleons above the Fermi sea are part of 2N-SRCs.
- These SRC pairs move inside the nucleus with c.m. motion of σ~140 MeV/c.
- The 2N-SRC consists of –
  n-p pairs (90%)
  p-p pairs(5%)
  n-n pairs(5%).
- A new experiment on ^{4}He has been completed at JLab—analysis is underway.
- An experiment to explore the relationship between SRCs and the EMC effect has been approved.



Instead of considering a single proton in a nucleus, let's consider a short-range correlated neutron-proton pair.

Let's start with a (p,2p) reaction.



From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event what $\vec{p}_f$ and the binding energy of each knocked-out proton is.