The Nucleons Go Two By Two: Correlations in Nuclei

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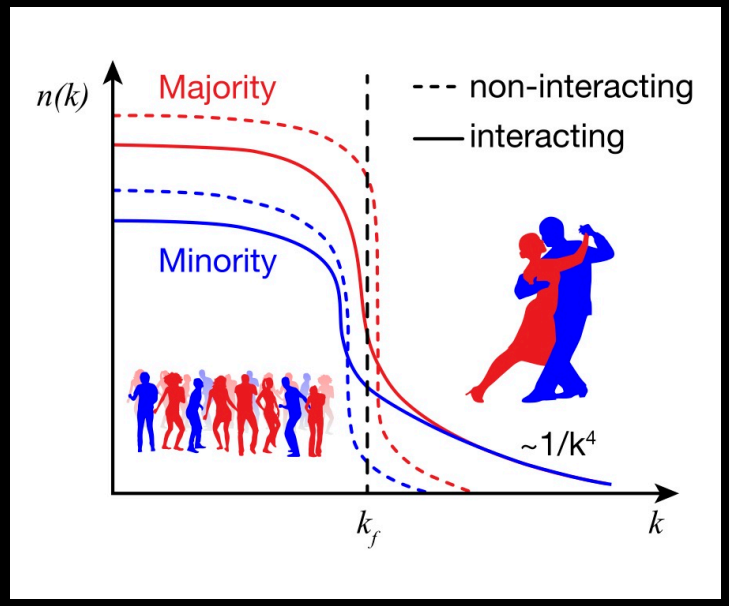
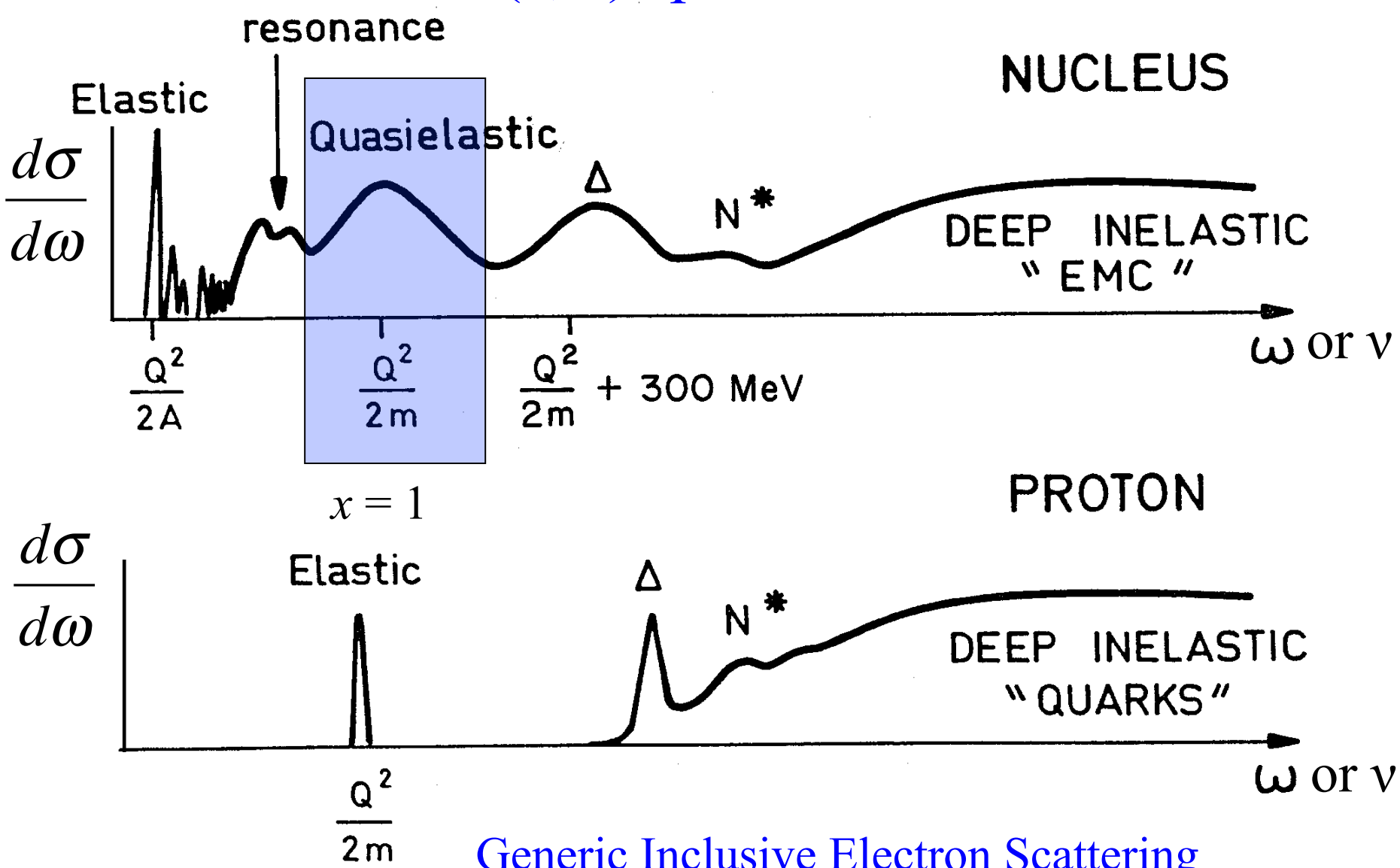
Old Dominion University

- Nucleons One by One
- Nucleons Two by Two
  - What are Correlations?
  - How big are they?
  - Who are they?
- NN pairs and neutrinos
  - Correlations
  - Not correlations
- Summary



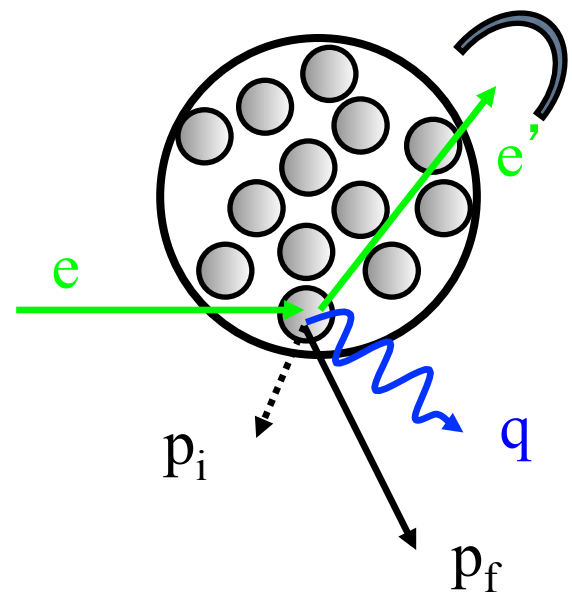
(e,e') spectrum



Generic Inclusive Electron Scattering
at fixed momentum transfer

Fermi gas model:

how simple a model can you make ?



Virtual photon:

Momentum q, energy ν

$$Q^2 = q_\mu q^\mu = |\vec{q}|^2 - \nu^2 > 0$$

Initial nucleon energy: $KE_i = p_i^2/2m$

Final nucleon energy: $KE_f = (\vec{q} + \vec{p}_i)^2/2m$

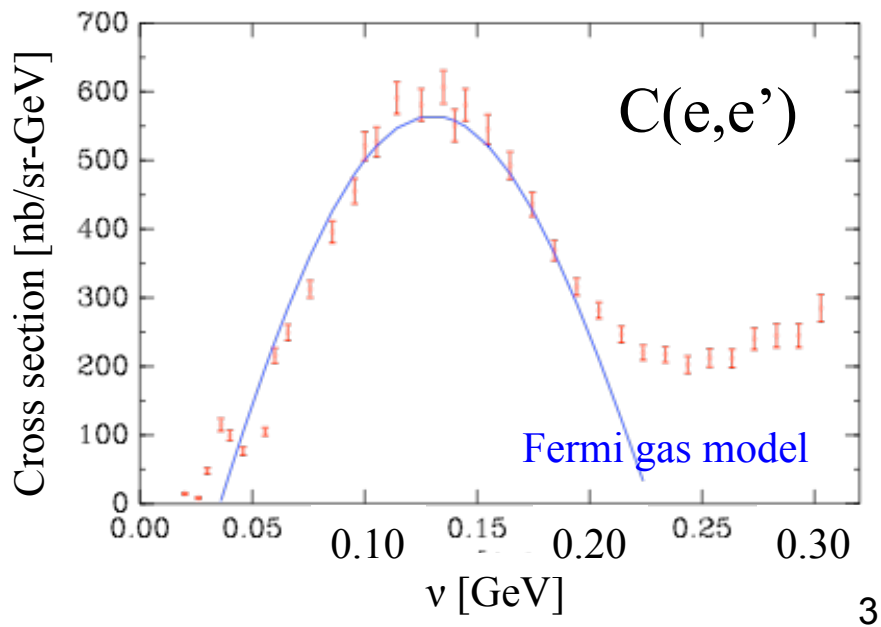
Energy transfer: $\nu = KE_f - KE_i = q^2/2m + (\vec{q}\cdot\vec{p}_i)/m$

➔Peak

Centroid: $\bar{\nu} = \vec{q}^2/2m$

Width: $\Delta\nu = (\vec{q}\cdot\vec{p}_i)/m$

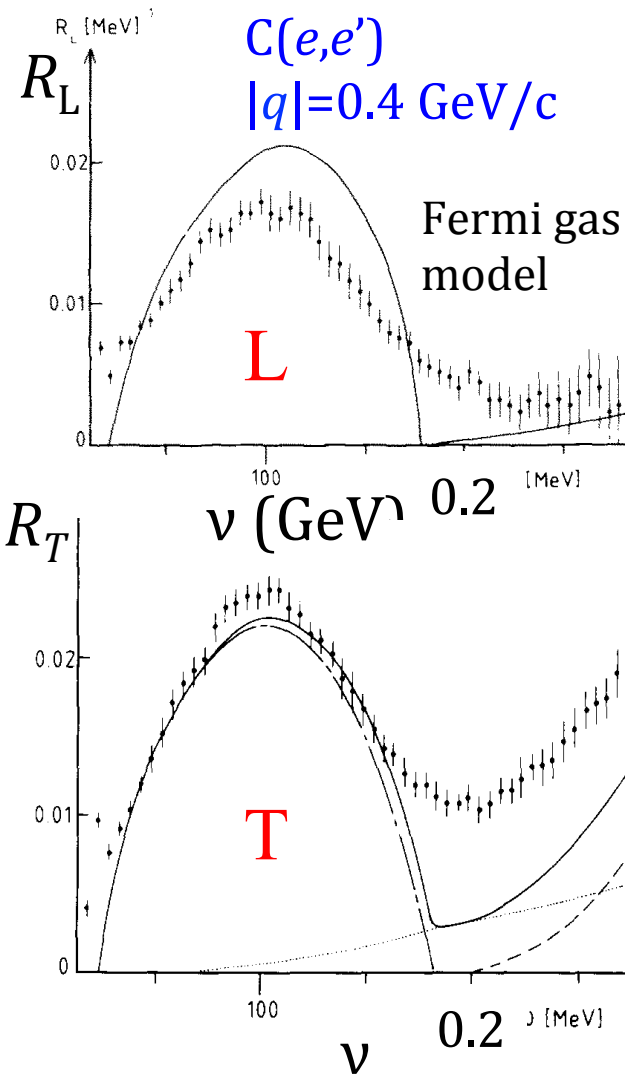
Cross section: $\sigma_{total} = Z\sigma_{ep} + N\sigma_{en}$



R.R. Whitney et al., PRC 9, 2230 (1974).

Fermi Gas Model: Too good to be true?

$$\frac{d\sigma}{d\Omega d\nu} = \sigma_M \frac{E'}{E}\left[\frac{Q^4}{\vec{q}^4} R_L(Q^2,\nu) + \left(\frac{Q^2}{2\vec{q}^2} + \tan^2\frac{\theta}{2}\right) R_T(Q^2,\nu)\right]$$

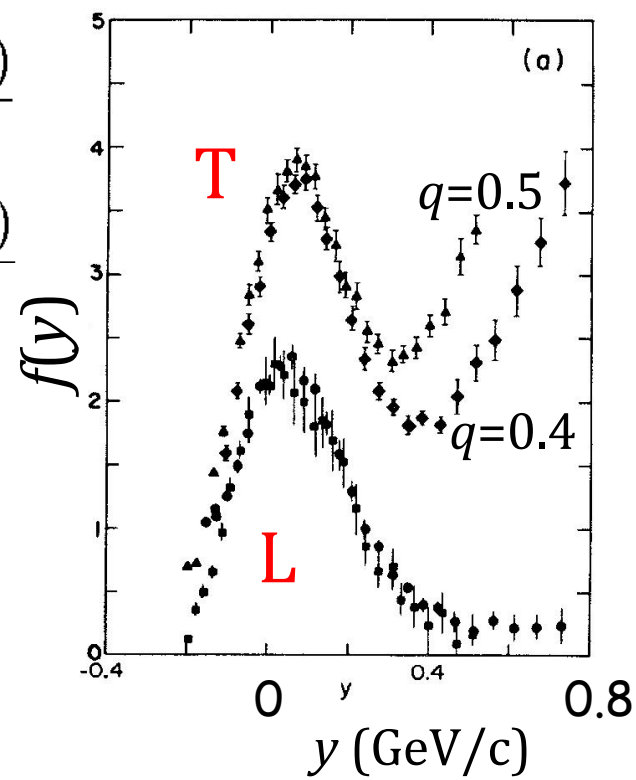


y = minimum initial nucleon momentum
= $m\nu/q - q/2$ (nonrelativistic only!)
f = reduced response function

$$f_L(Q^2,\omega) \propto \frac{R_L(Q^2,\omega)}{\tilde{G}_E^2(Q^2)}$$

$$f_T(Q^2,\omega) \propto \frac{R_T(Q^2,\omega)}{\tilde{G}_M^2(Q^2)}$$

- L scales
- T scales
- T≠L!!



P. Barreau et al, NPA 402, 515 (1983)
Finn et al, PRC 29, 2230 (1984)

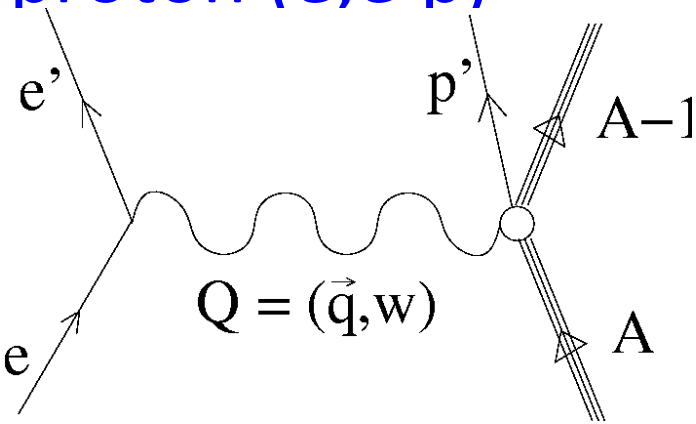
Get more information: detect the proton (e,e'p)

Cross section factorizes:

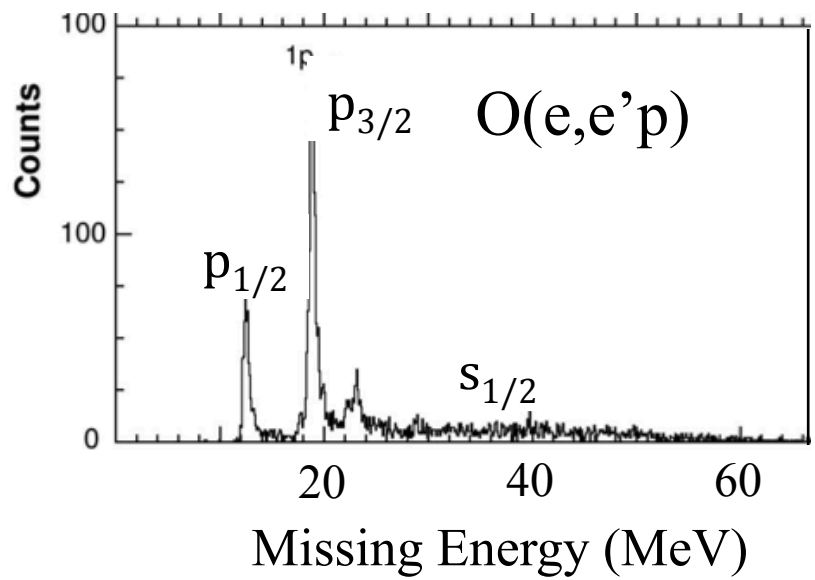
$$\frac{d\sigma}{dE_e d\Omega_e dT_p d\Omega_p} = KS(\vec{p}_{miss}, E_{miss}) \frac{d\sigma^{free}}{d\Omega}$$

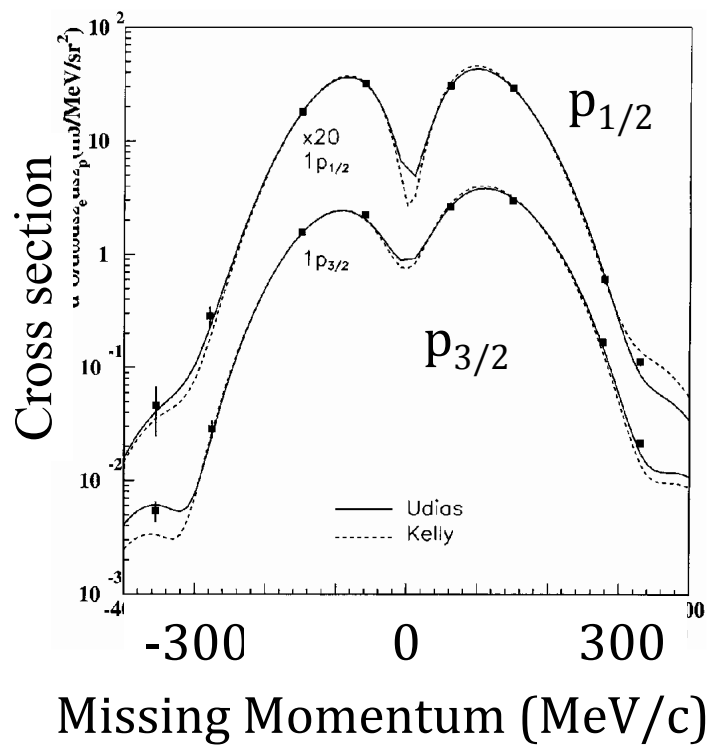
$$E_{miss} = \nu - T_p - T_{A-1}$$

$$\vec{p}_{miss} = \vec{q} - \vec{p}_p$$

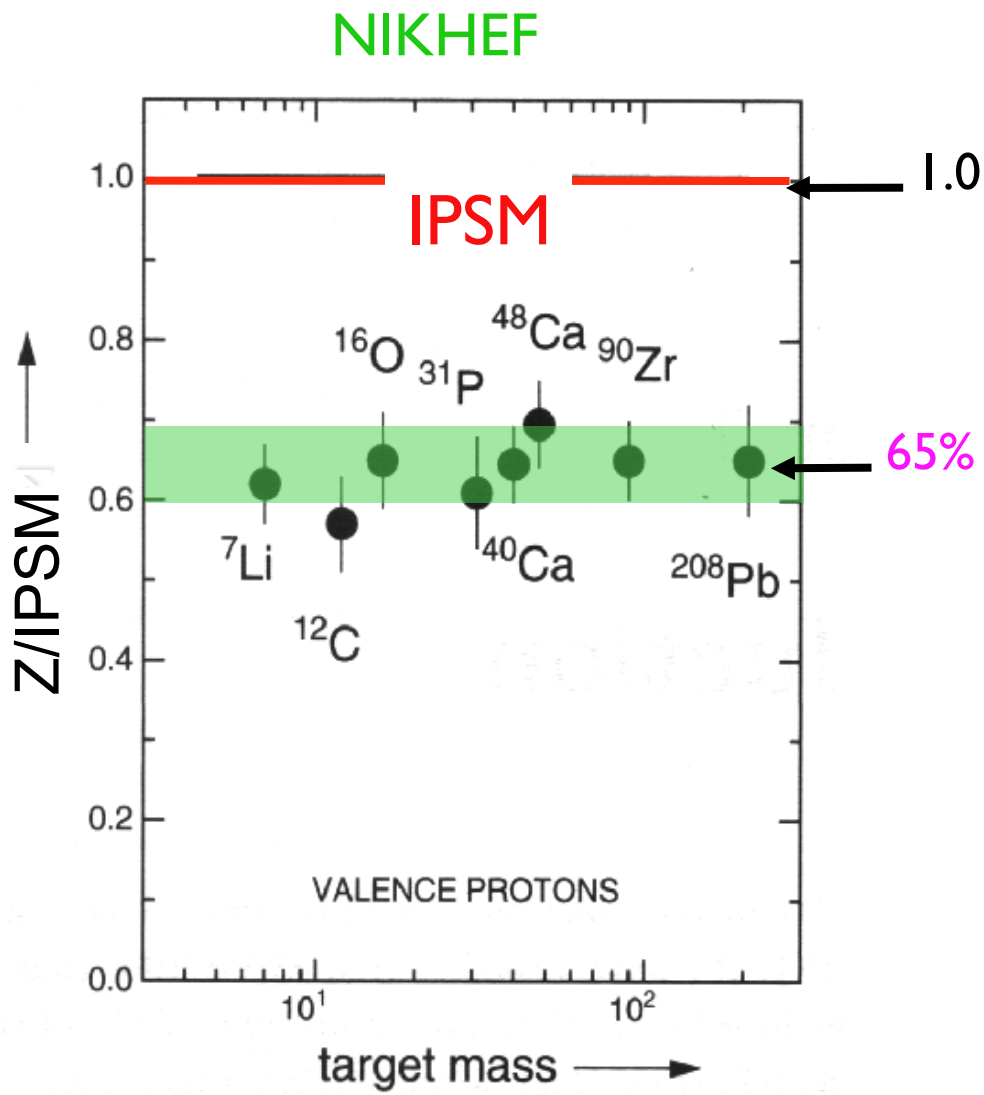


O(e,e'p)

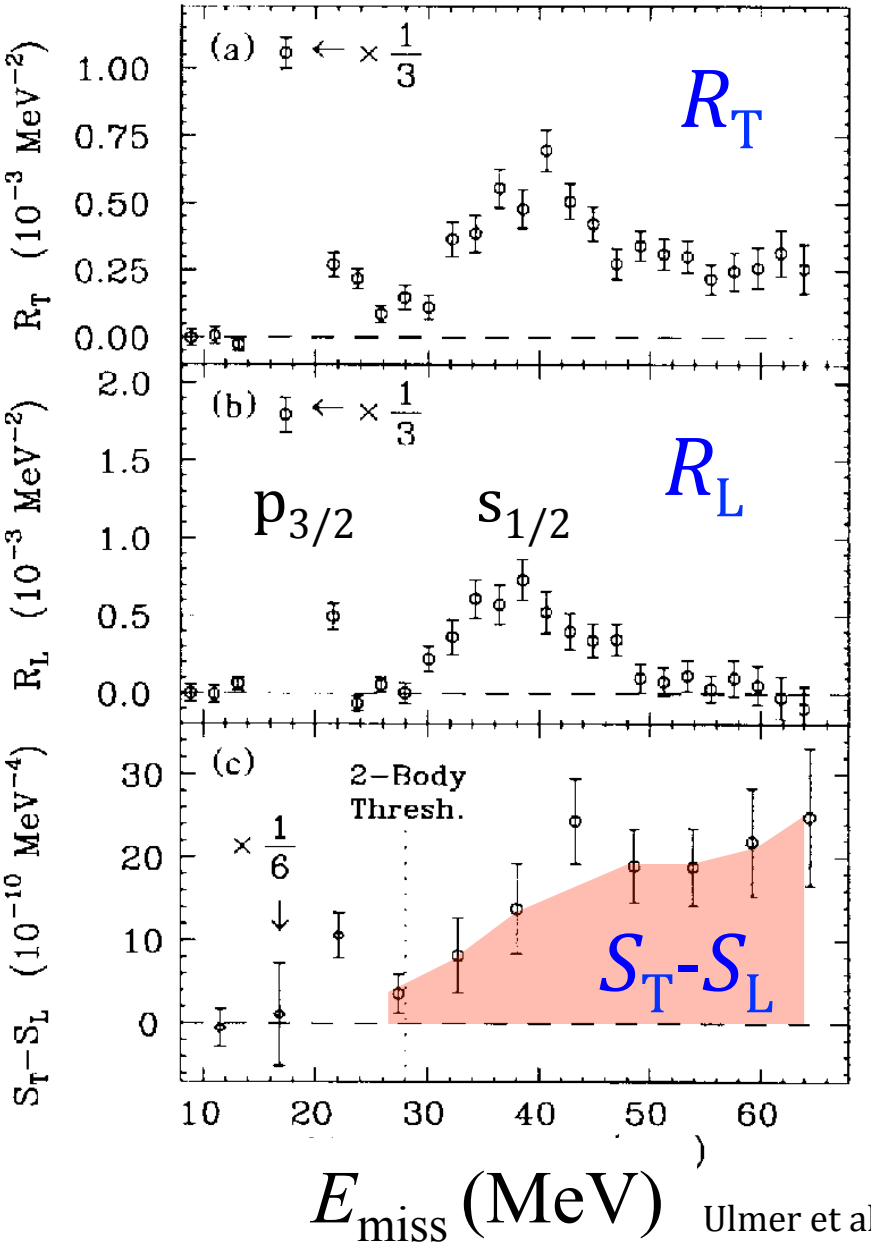




But we do not see enough protons!



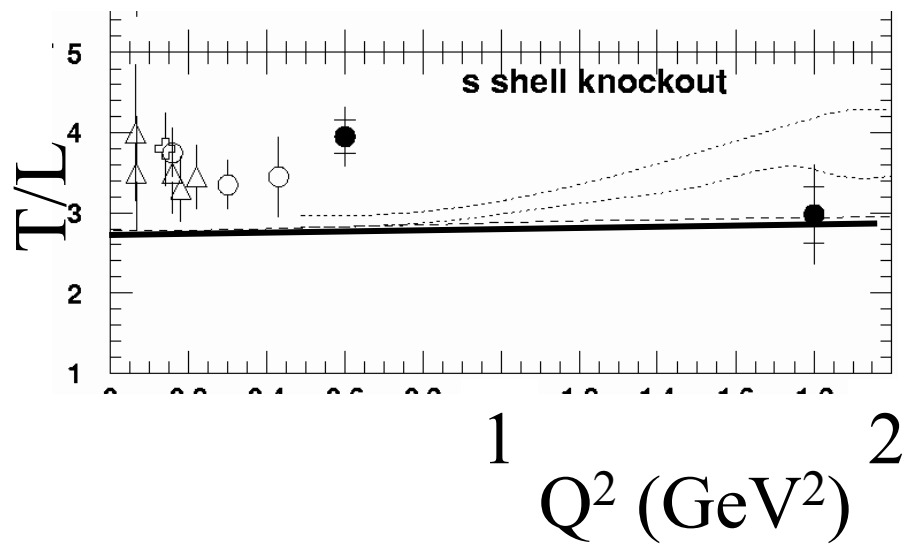
Now separate R_L and R_T



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

q=0.4 GeV and x=1

extra transverse strength starting at the 2N KO threshold



decreases with Q^2

Ulmer et al, PRL 59, 2259 (1987); Dutta et al, PRC 61, 061602 (2000)

(*e*,*e*'*p*) summary

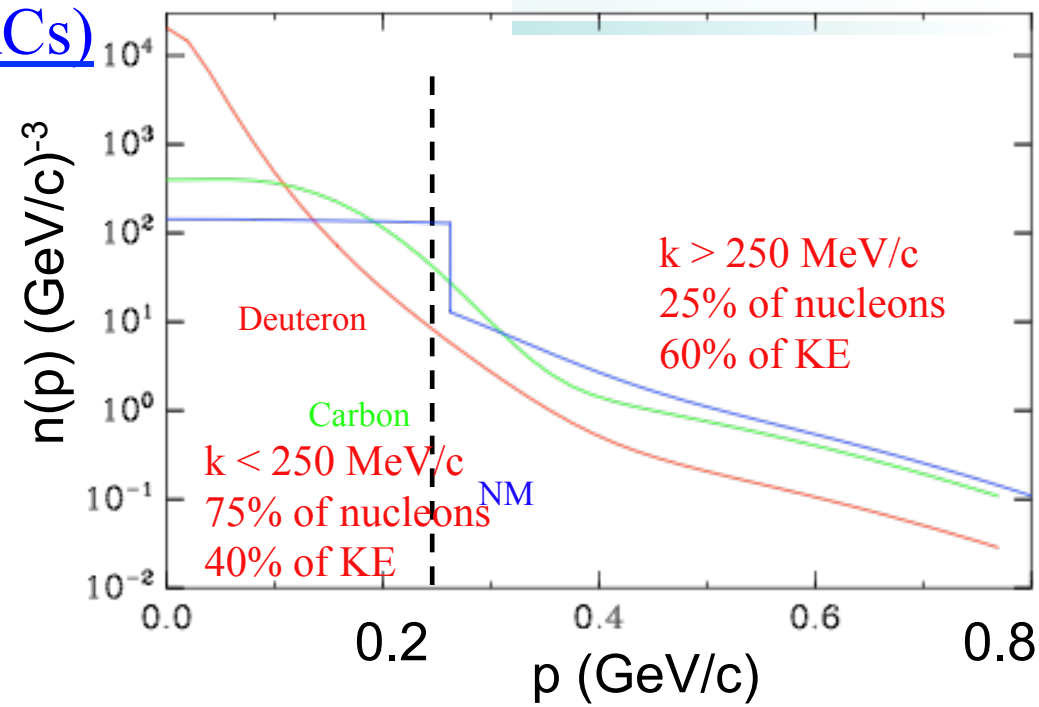
- Measure shell structure directly
- Measure nucleon momentum distributions
- Extra cross section at large missing energy
  - Transverse (mostly)
  - Two nucleon knockout via
    - Meson exchange currents
    - Correlations
- But:
  - Not enough valence nucleons seen!

Short Range Correlations (SRCs)

➔High momentum tails:
$k > k_F$

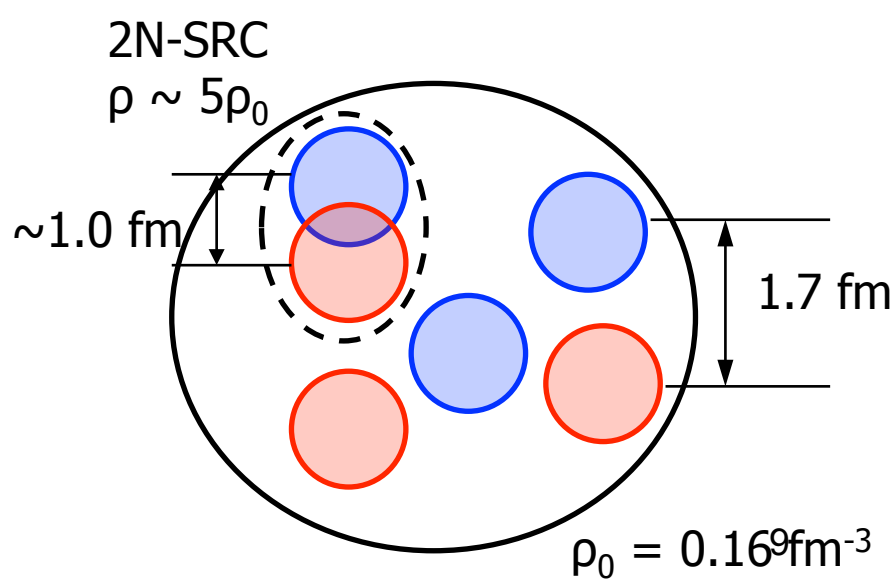
Calculable for $A \leq 12$ nuclei and nuclear matter.

Not well constrained at $k >> k_f$



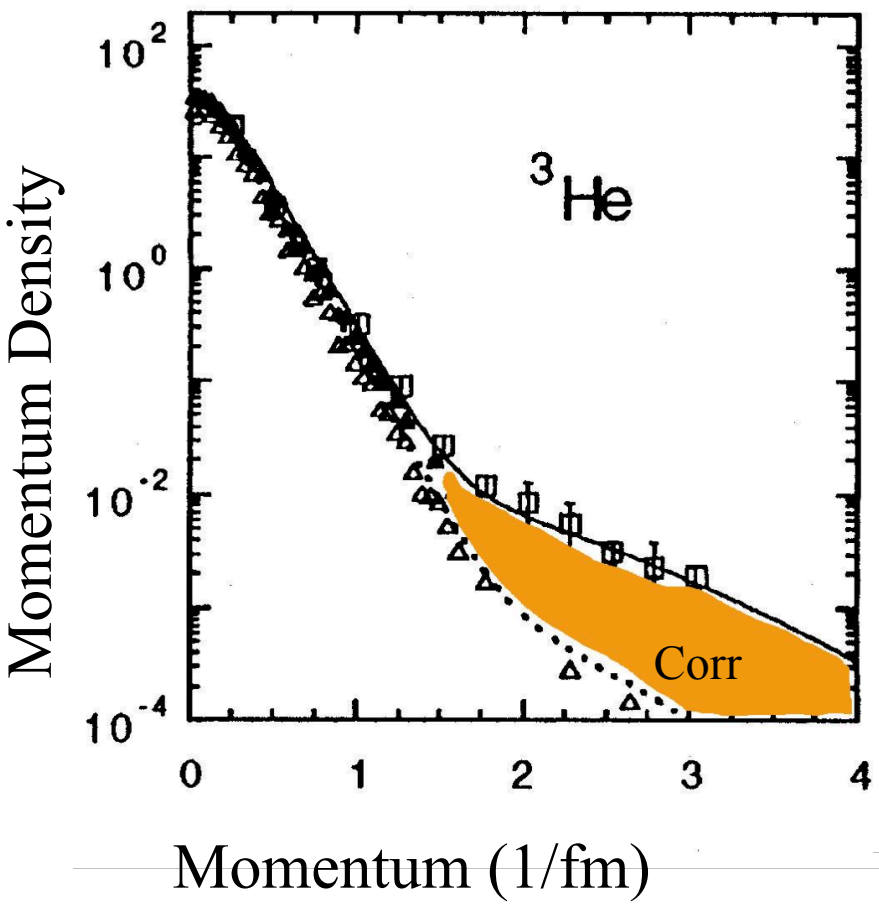
Effects:

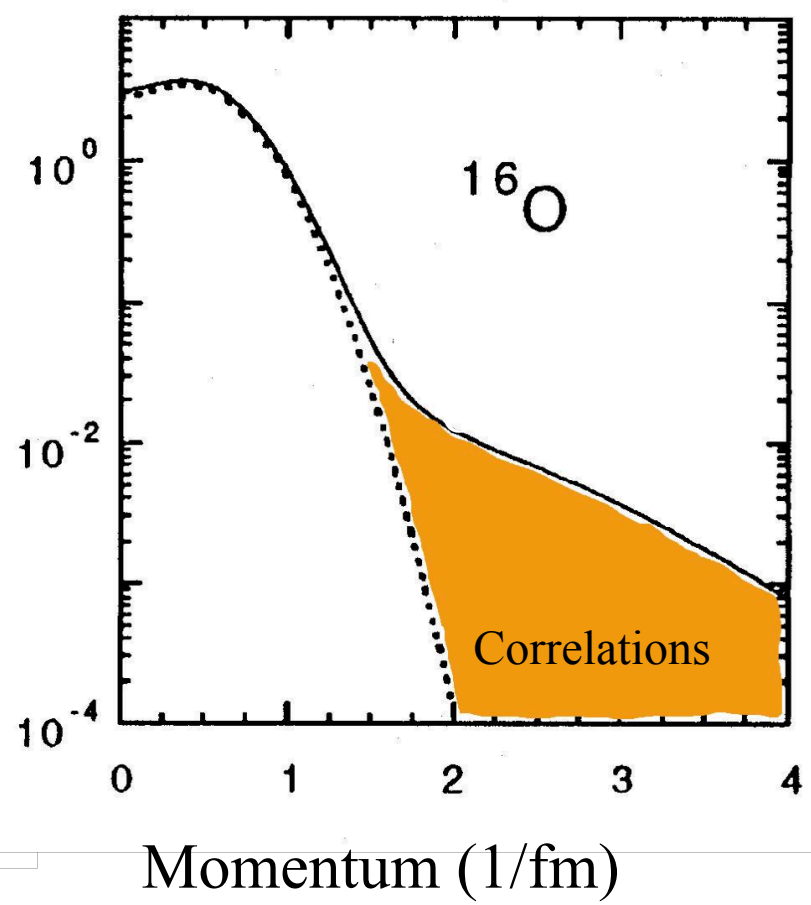
- High momentum part of the nuclear wave function
- Short distance behavior of nucleons - modification??
- Cold dense nuclear matter
- Neutron Stars



Nucleons are like people …

Correlations and High Momentum





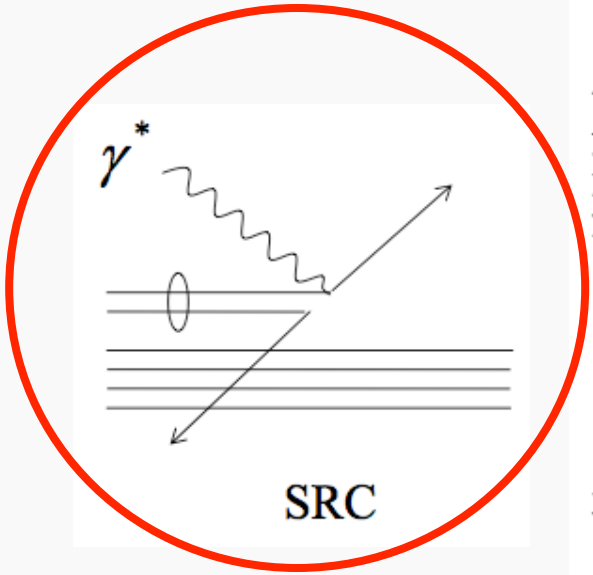
Ciofi degli Atti, PRC 53 (1996) 1689

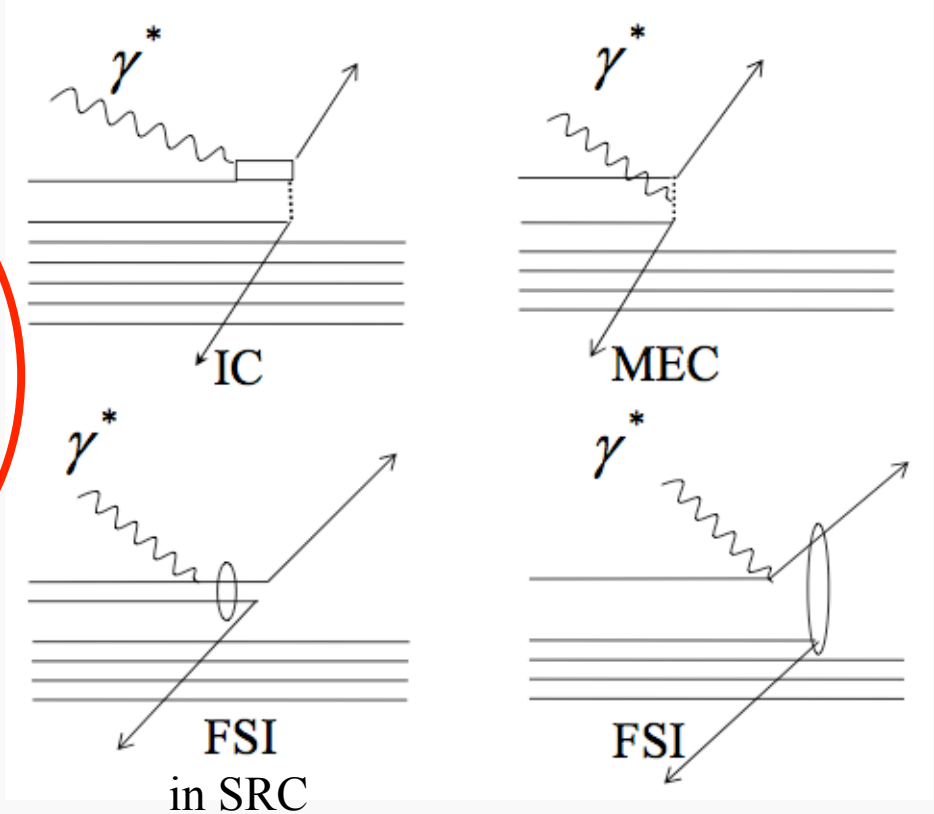
What are correlations?

Average Two-Nucleon Properties in the Nuclear Ground State

Responsible for the high momentum part of the Nucleon Wf

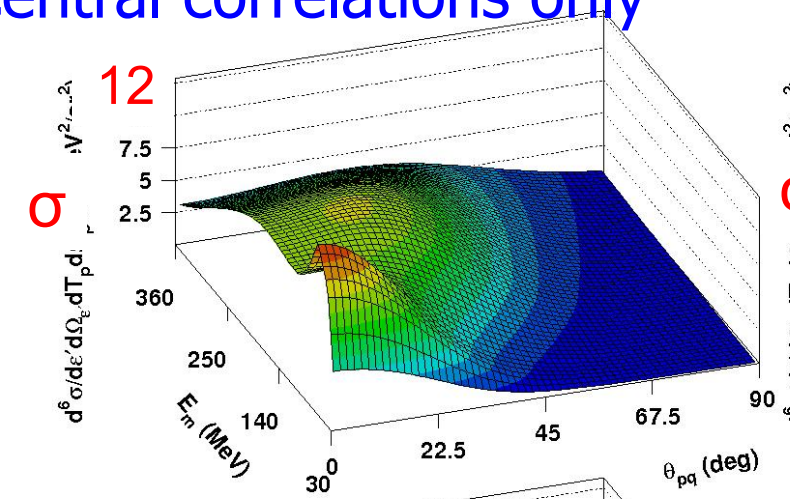
Two-body currents are not Correlations
(but add coherently)



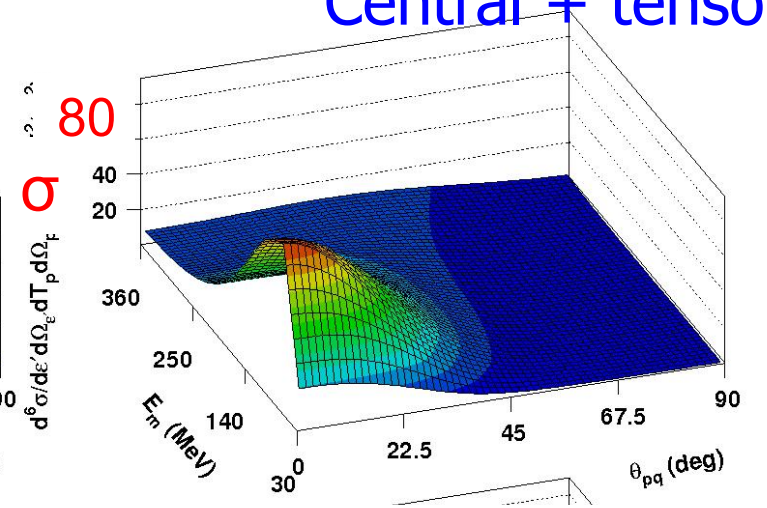


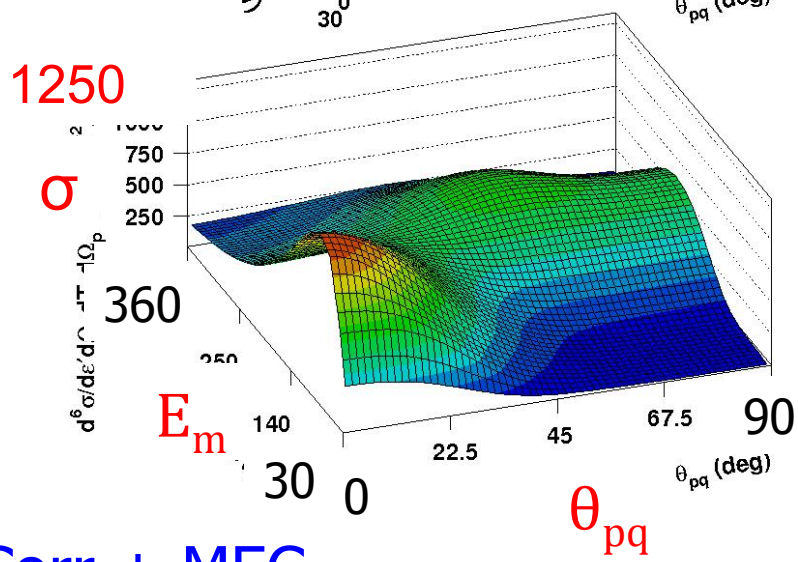
2N currents enhance correlations

Central correlations only



Central + tensor corr





Corr + MEC

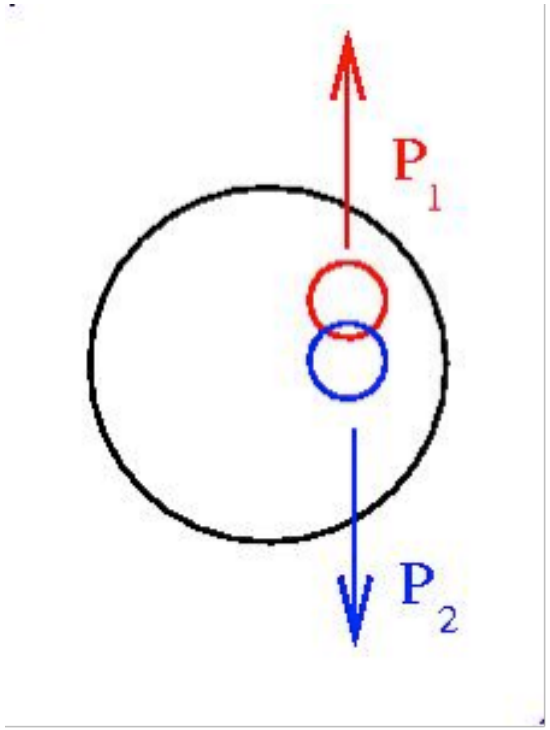
MEC changes the magnitude of the cross section,
not the distribution in E_{miss} vs $Theta_{pq}$

O(e,e'p) Ryckebusch

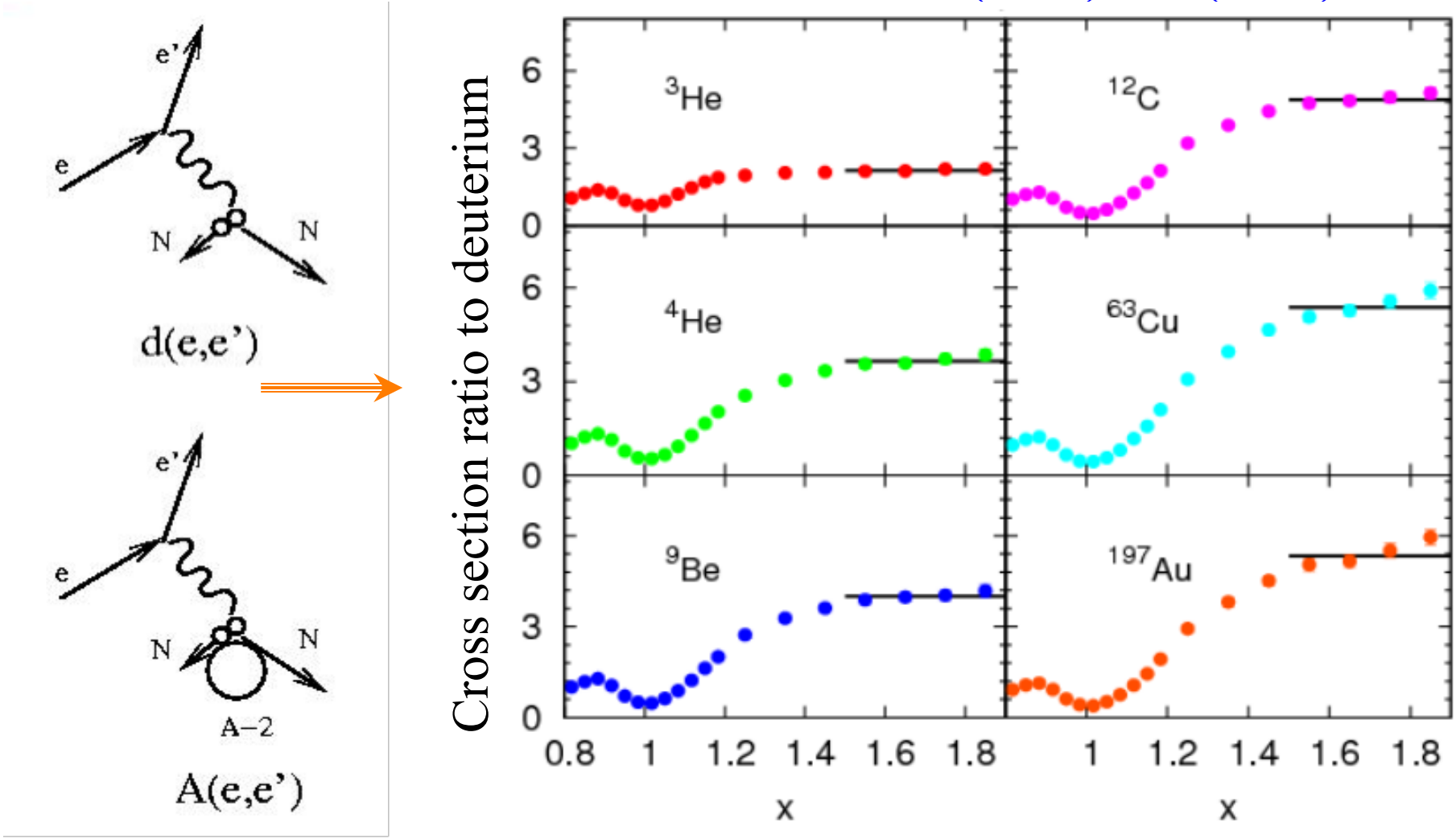
Signatures for Correlations

An Experimentalist's Definition:

- A high momentum nucleon whose momentum is balanced by **one** other nucleon
  - NN Pair with
    - Large Relative Momentum
    - Small Total Momentum



Correlations are Universal: A(e,e') / d(e,e')



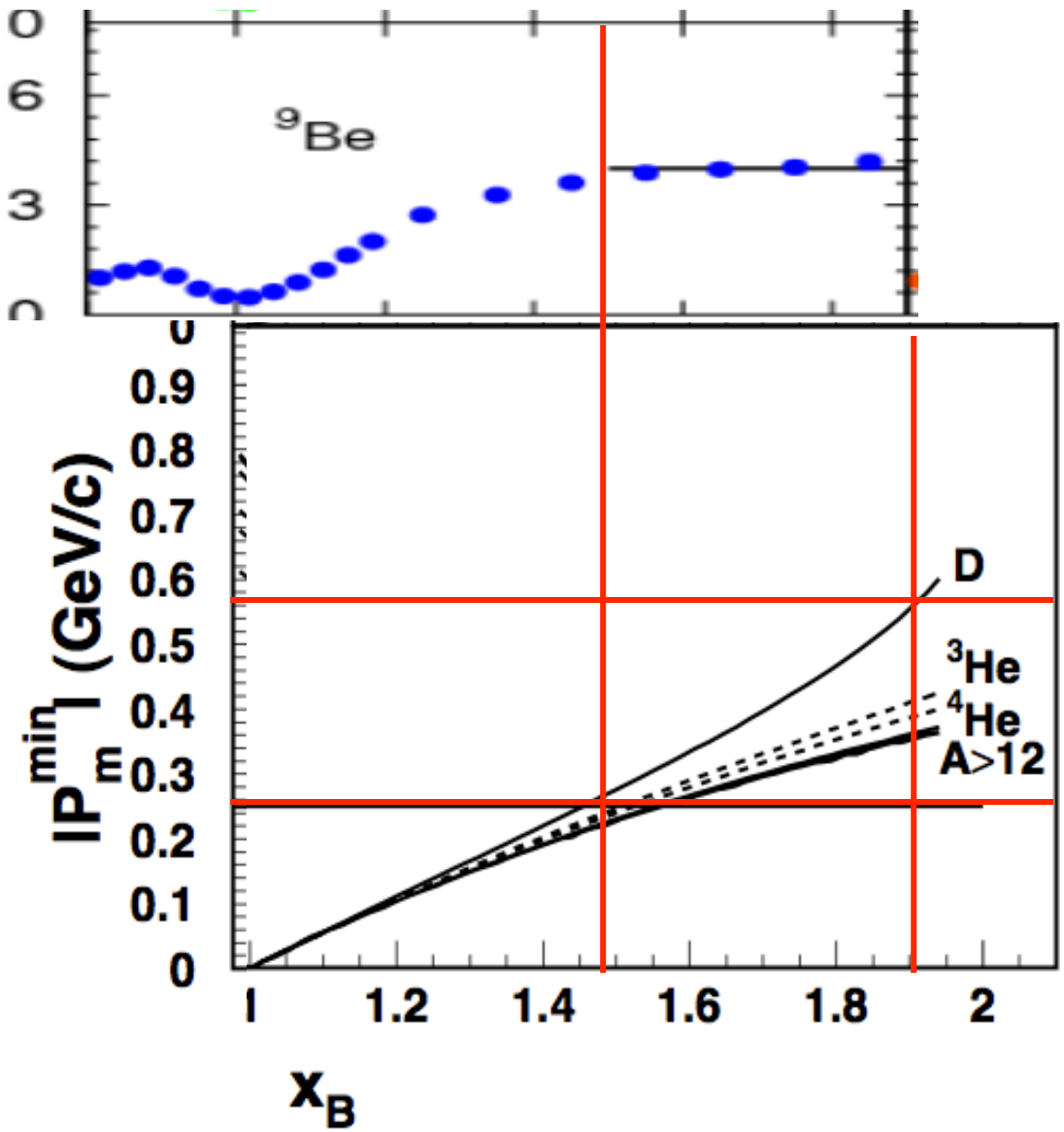
Scaling (flat ratios) indicates a common momentum distribution.
1 < x < 1.5: dominated by different mean field n(k)
1.5 < x < 2: dominated by 2N SRC

$$x = Q^2 / 2m\nu$$

$\alpha_{2N} \approx 20\%$

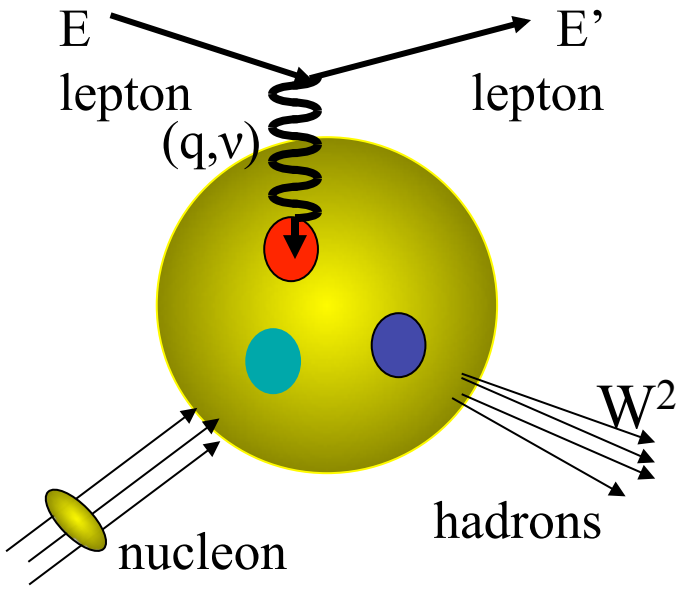
N. Fomin et al, PRL 108, 092502 (2012)

Momentum range of plateau



275 to 600 MeV/c

Deep Inelastic Scattering: the EMC Effect



$$Q^2 = -q_\mu q^\mu = q^2 - \nu^2$$

$$\nu = E' - E$$

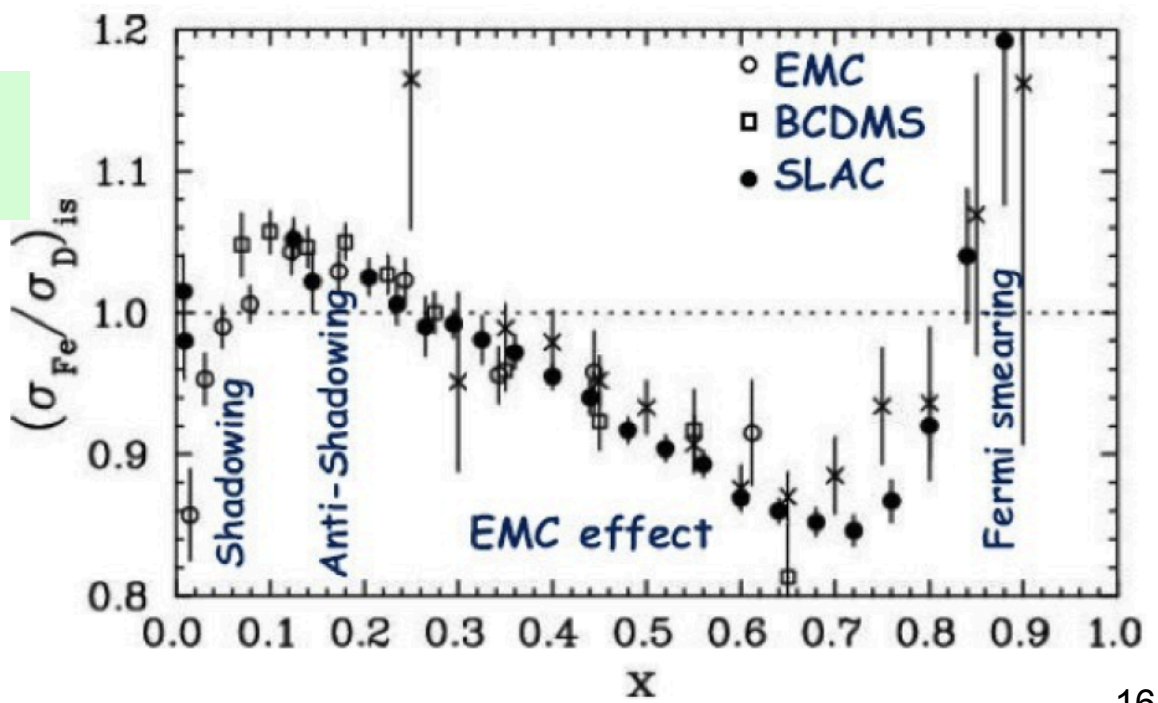
$$0 < x_B = \frac{Q^2}{2m_N \nu} < 1$$

- EMC Scale: several GeV
- Nuclear binding energy scale: several MeV

Expectation: DIS off bound nucleons equals DIS of a free nucleons

Reality: Bound nucleon DIS **does not equal** free DIS

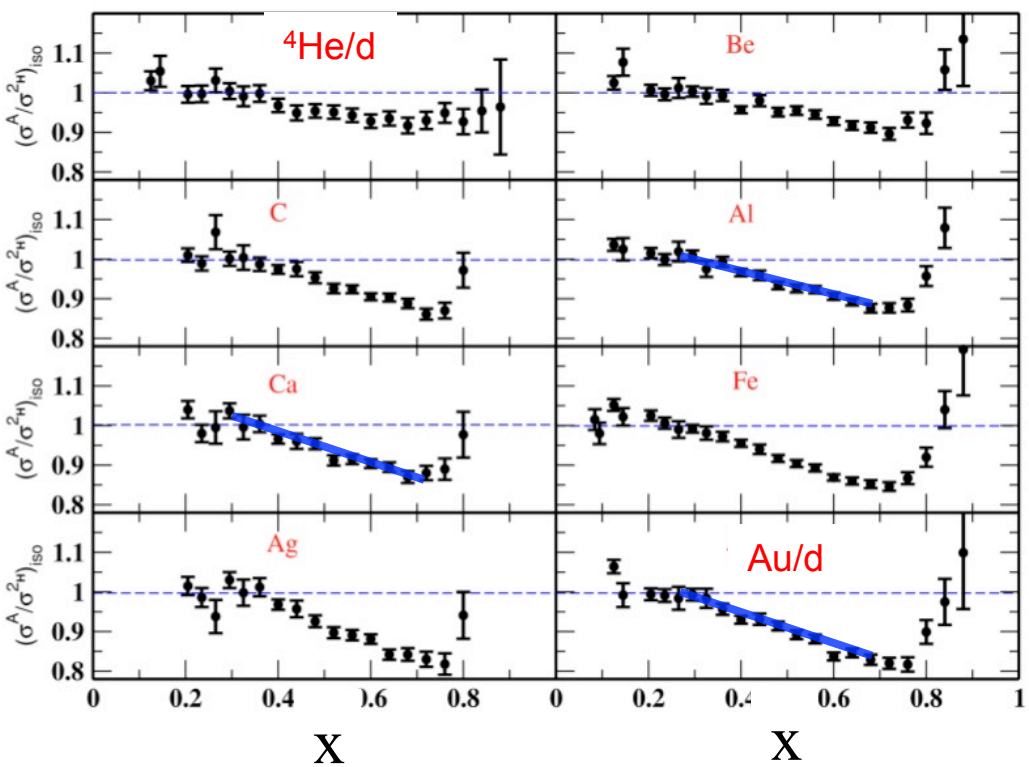
Origin of EMC effect unknown.
Nucleon modification needed.
$\approx 10^3$ publications



EMC Effect: Universal

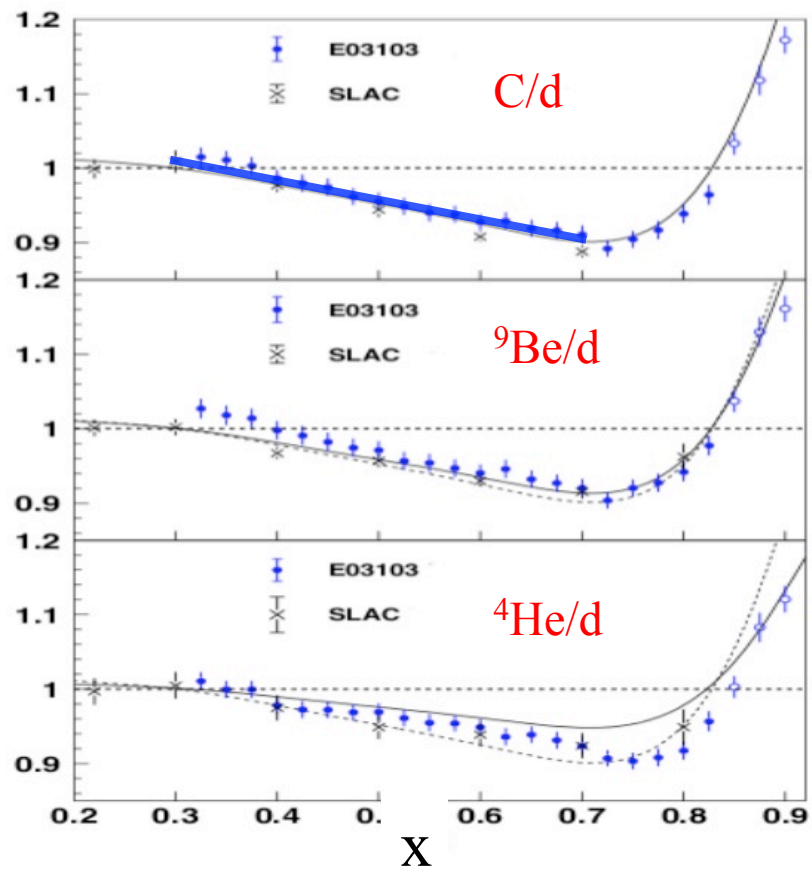
$$\frac{2}{A} \cdot \frac{\sigma^A}{\sigma^d}$$

SLAC



Very linear for $0.3 < x_B < 0.7$
(the lines shown are not fits)

JLab



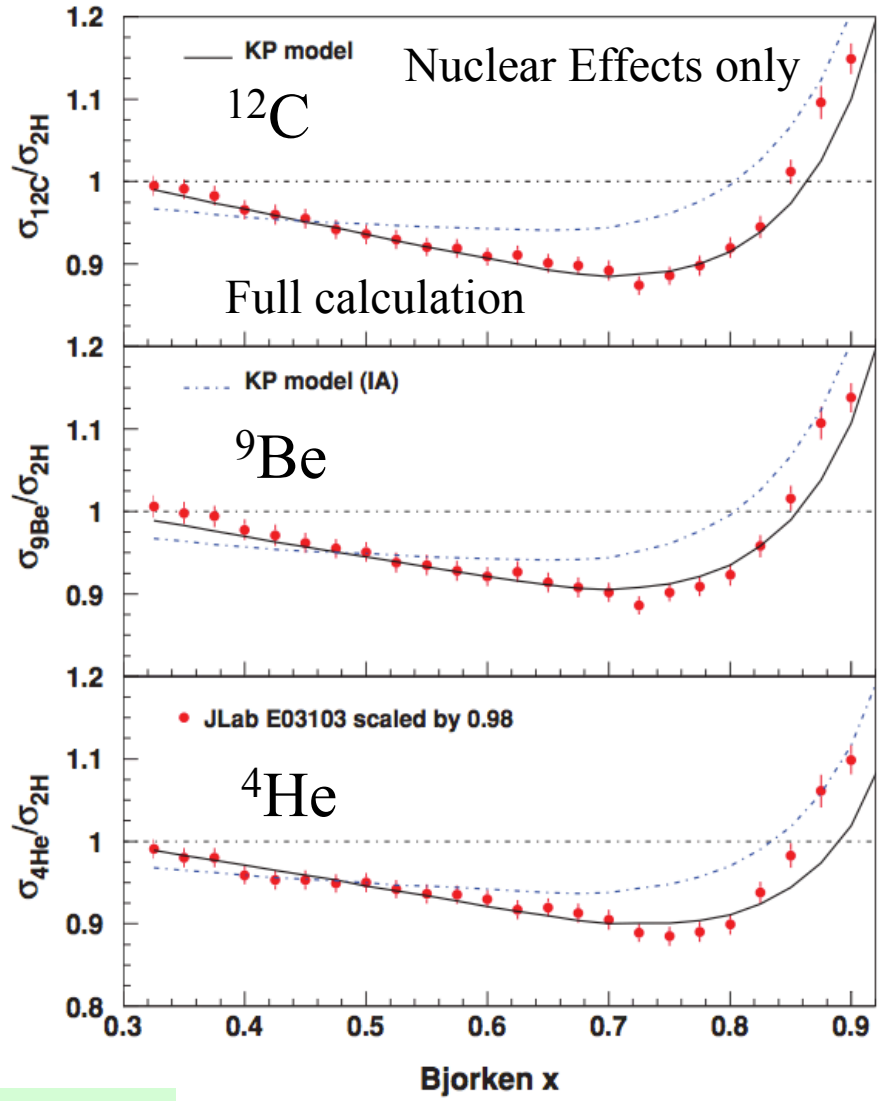
J. Seely, PRL 103, 202301 (2009)
J. Gomez, PRD **49**, 4348 (1994).

Size of effect ("depth" or slope) grows with *A*

EMC Effect: Theory

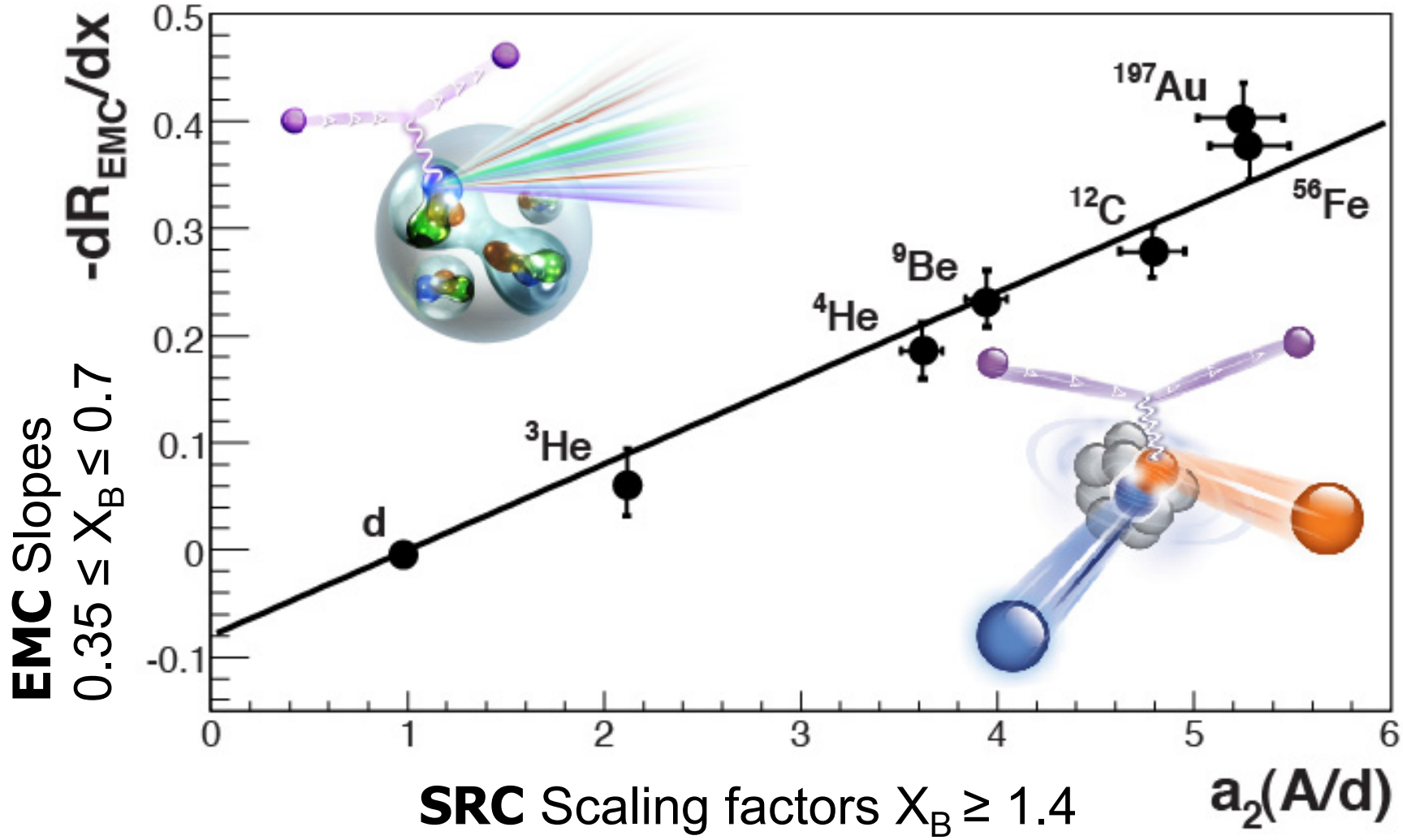
- Nuclear Effects:
  - Fermi motion
  - Binding energy
- Full Calculation
  - Nucleon modification
  - Nuclear pions
  - shadowing

Nucleon modification:
Phenomenological change to bound nucleon structure functions, change proportional to virtuality
$\nu = (p^2 - M^2)/M^2$



Nucleon modification needed to describe data

Kulagin and Petty, PRC 82, 054614 (2010)

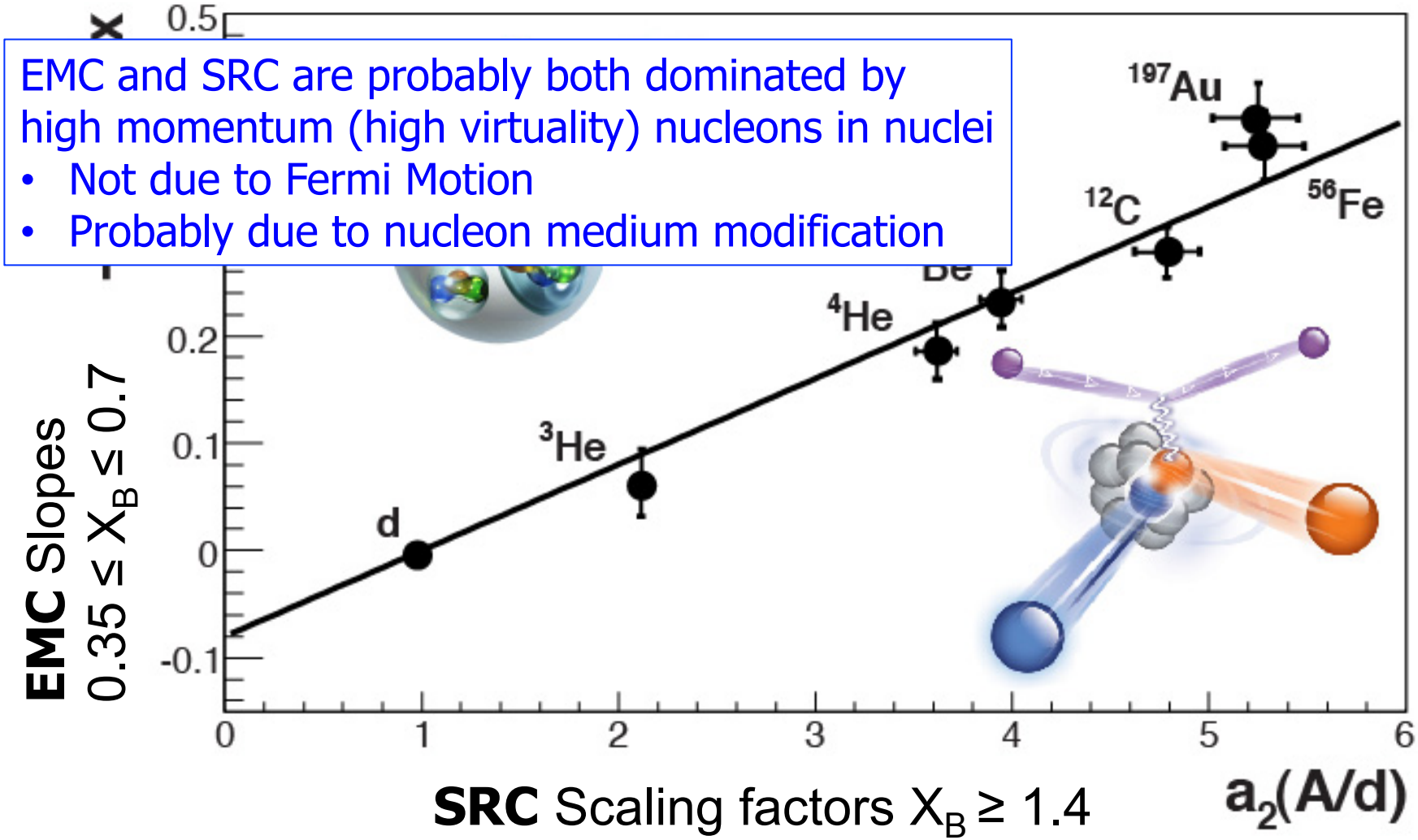


SRC data from Fomin et al
EMC data from Gomez et al and Seely et al

Weinstein et al, PRL**106**, 052301 (2011)
Hen et al, PRC**85**, 047301 (2012)

EMC and SRC are probably both dominated by high momentum (high virtuality) nucleons in nuclei

- Not due to Fermi Motion
- Probably due to nucleon medium modification



SRC data from Fomin et al
EMC data from Gomez et al and Seely et al

Weinstein et al, PRL**106**, 052301 (2011)
Hen et al, PRC**85**, 047301 (2012)

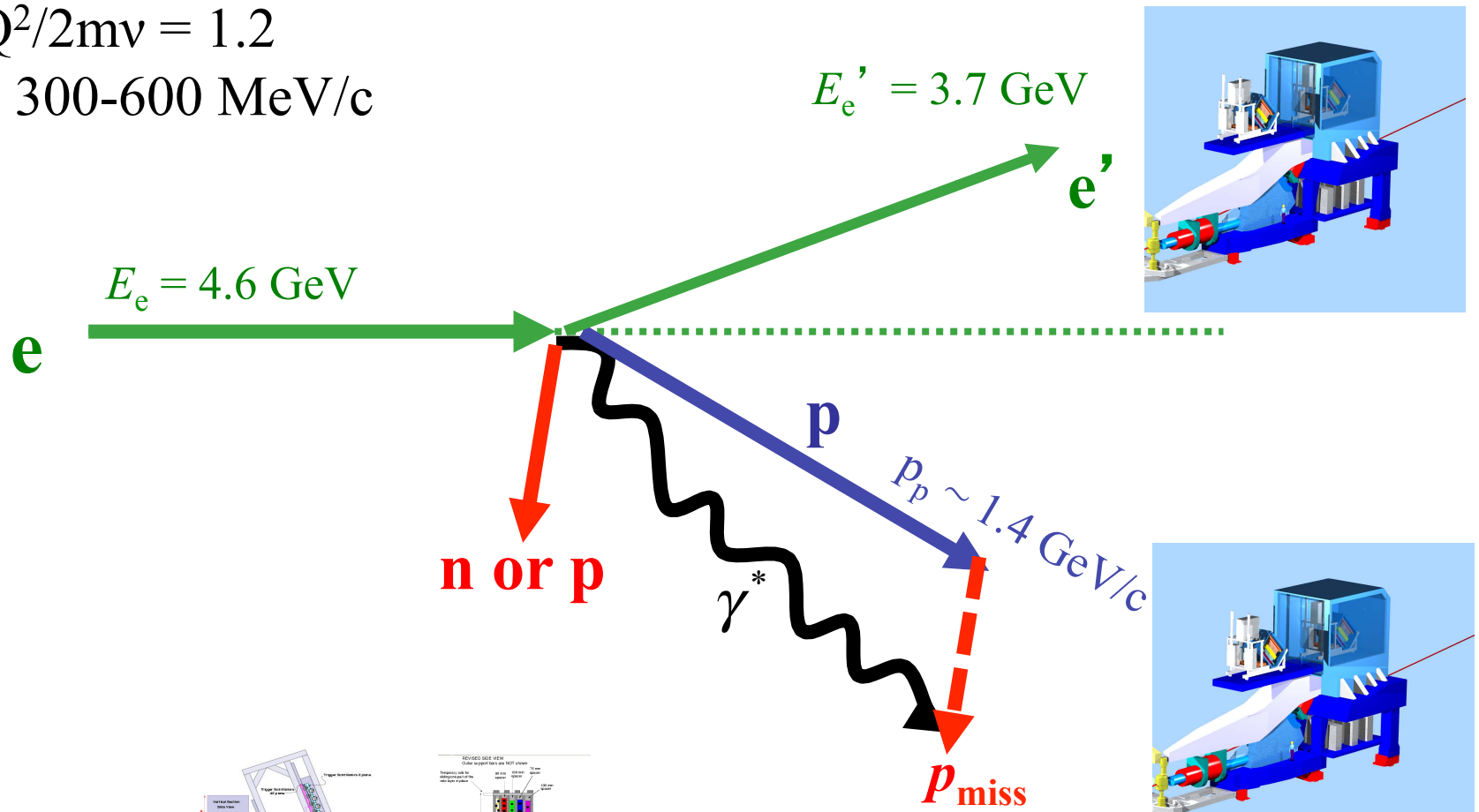
Jefferson Lab Site

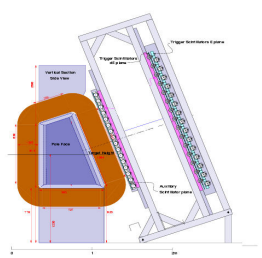
Now detect yet another nucleon
JLab Hall A C(e,e'pN) - selected kinematics

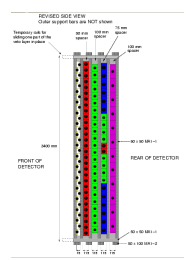
$Q^2 = 2\ \mathrm{GeV}^2$

$x_B = Q^2/2m\nu = 1.2$

$P_{miss} = 300\text{-}600\ \mathrm{MeV/c}$





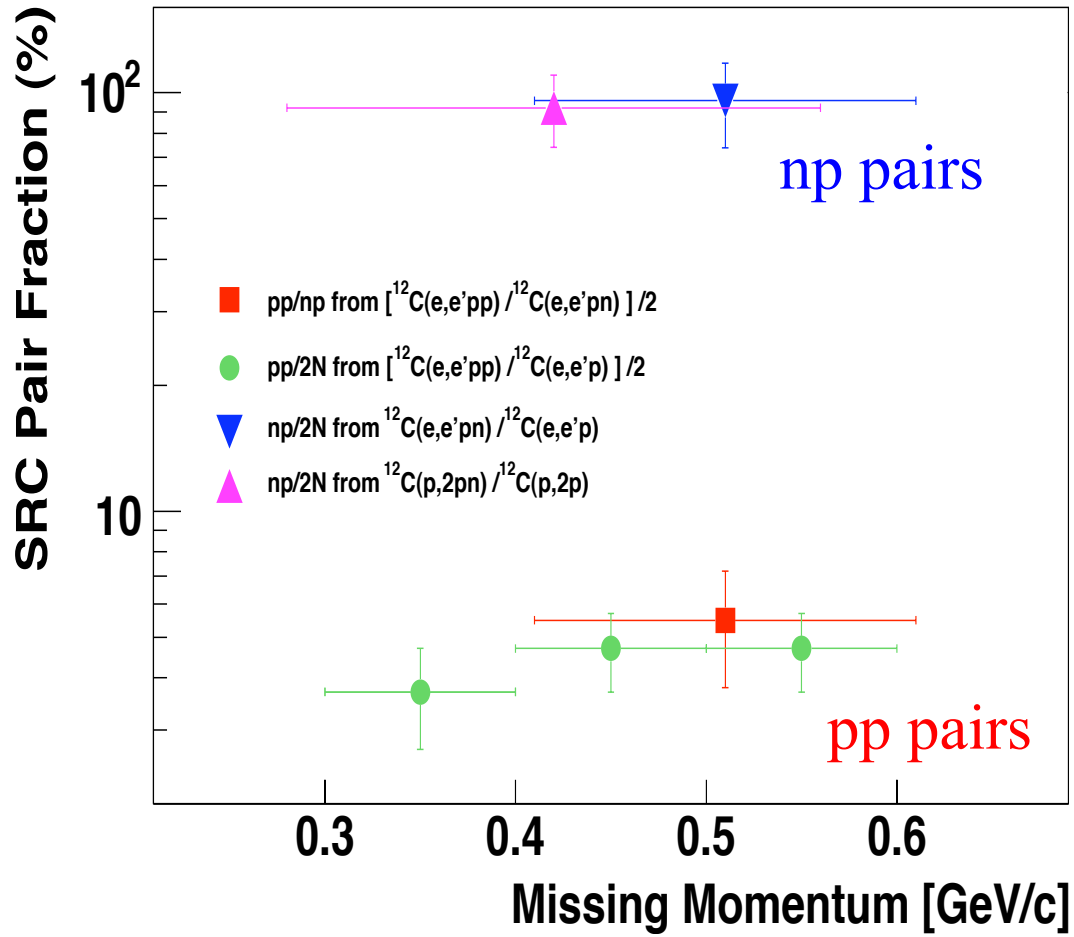


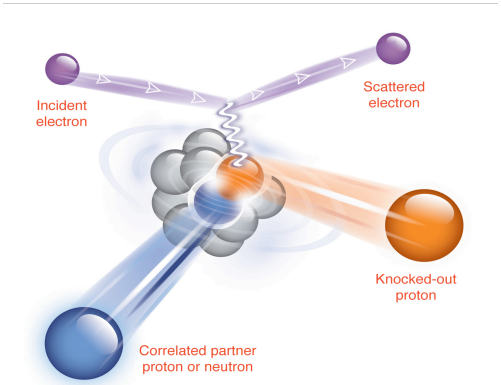
Detect the proton,
look for its partner nucleon

High momentum protons have partners
C(*e,e'pN*)

- Detect the knocked-out proton
- Look for its partner nucleon
- All high momentum protons have partners

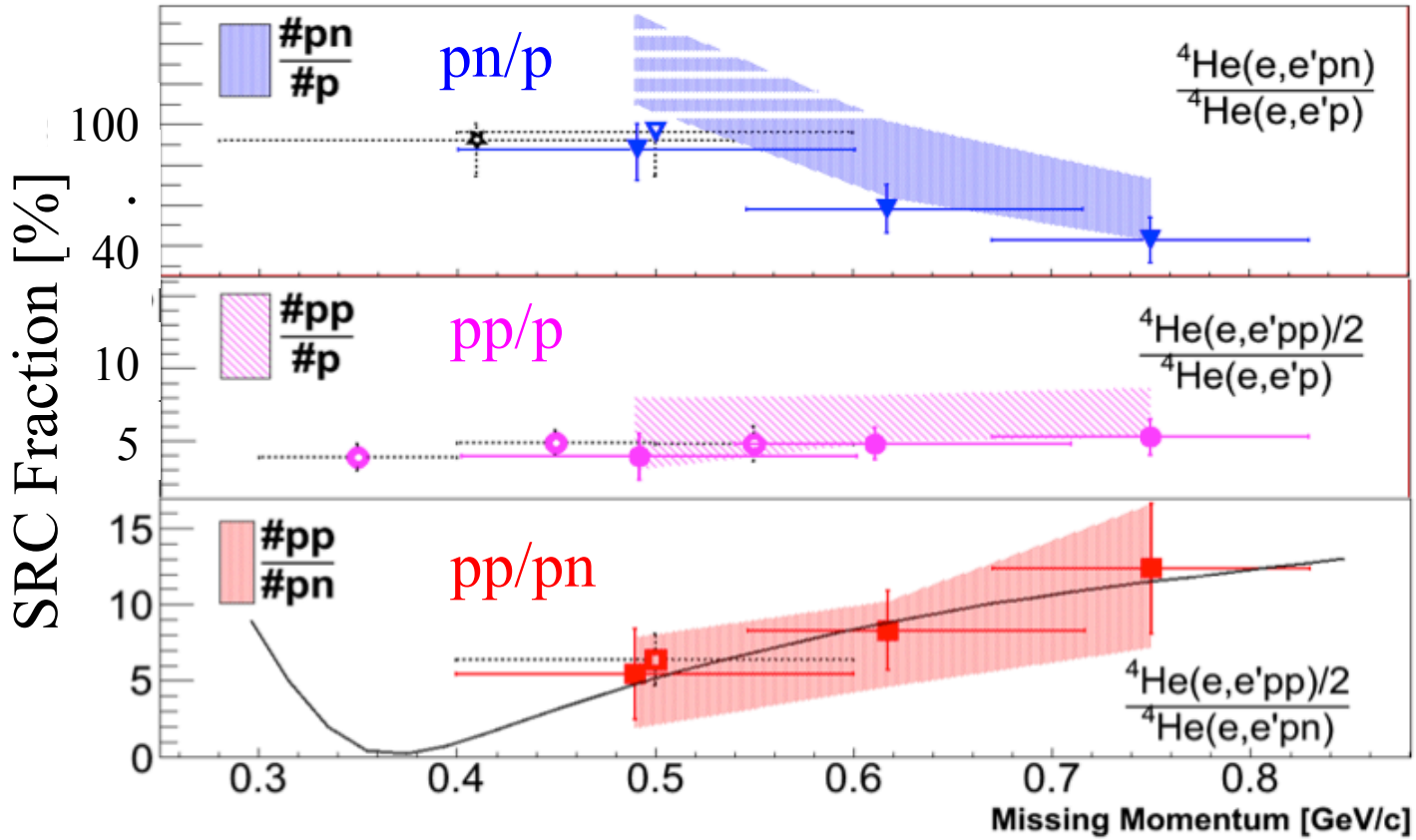
➔ np pairs dominate at $0.3<p_i<0.6$





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

Higher momentum protons?
^{4}He(e,e'pN)



- pp pairs still only 5% of high momentum protons
- np pairs decrease with missing momentum
- Three nucleon correlations???

I. Korover et al., PRL 113, 022501 (2014)

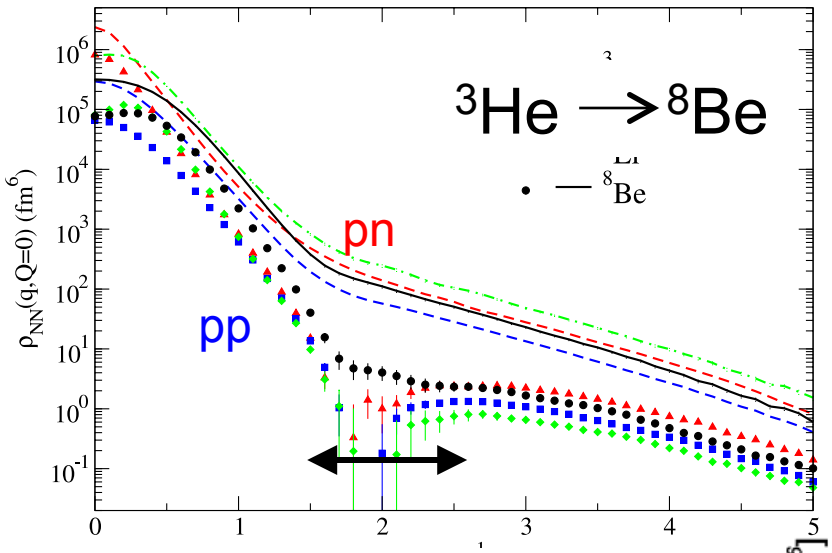
The ratio of pp-SRC / pn-SRC pairs in ^{12}C

There are 18 ± 2 times more np-SRC than pp-SRC pairs in ^{12}C.

Why ?

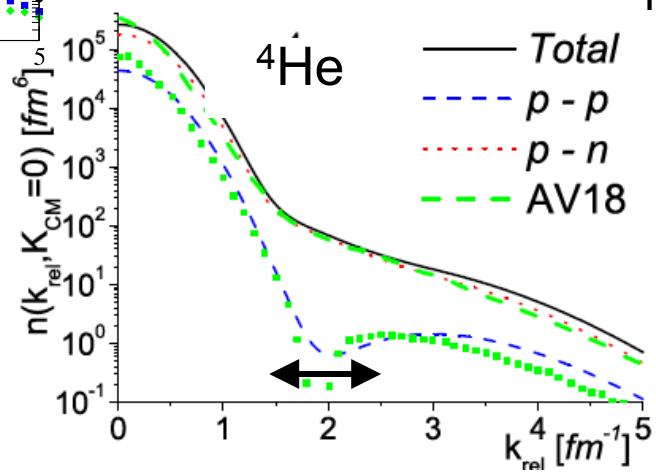
At p_{rel} = 300-500 MeV/c the s-wave momentum distribution has a minimum

The *np* minimum is filled in by strong tensor correlations



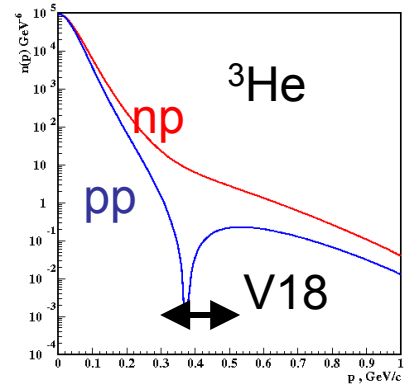
Pair relative momentum

Schiavilla, Wiringa, Pieper, Carlson, PRL **98**, 132501 (2007).



Pair relative momentum

Ciofi and Alvioli
Gent workshop, Aug. 2007

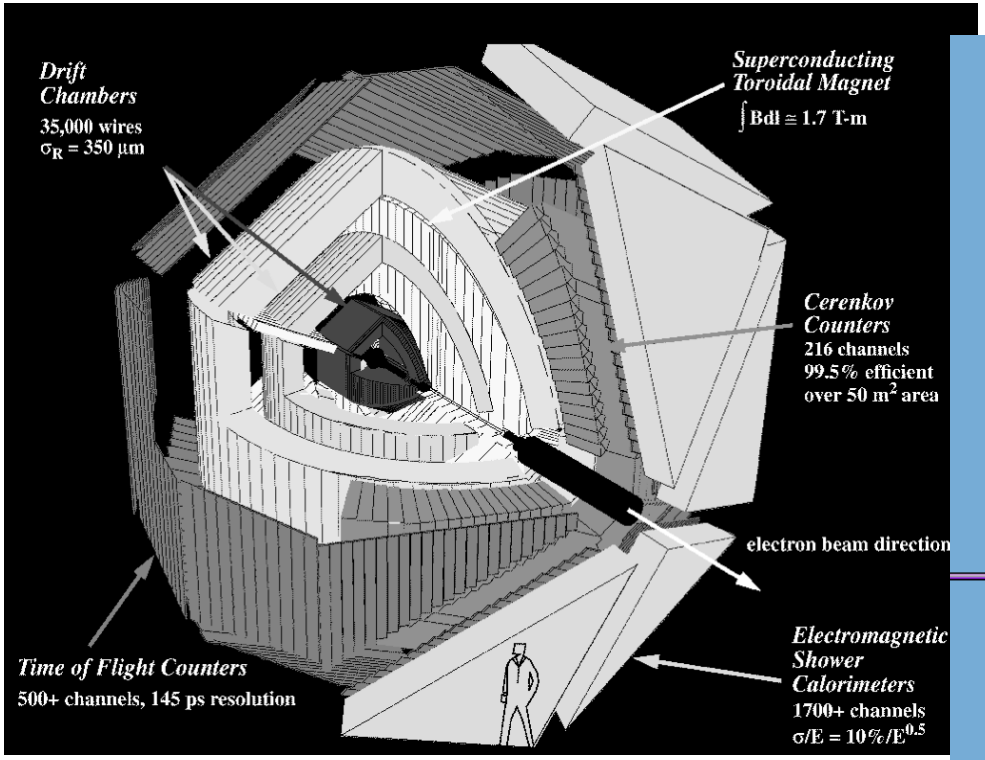


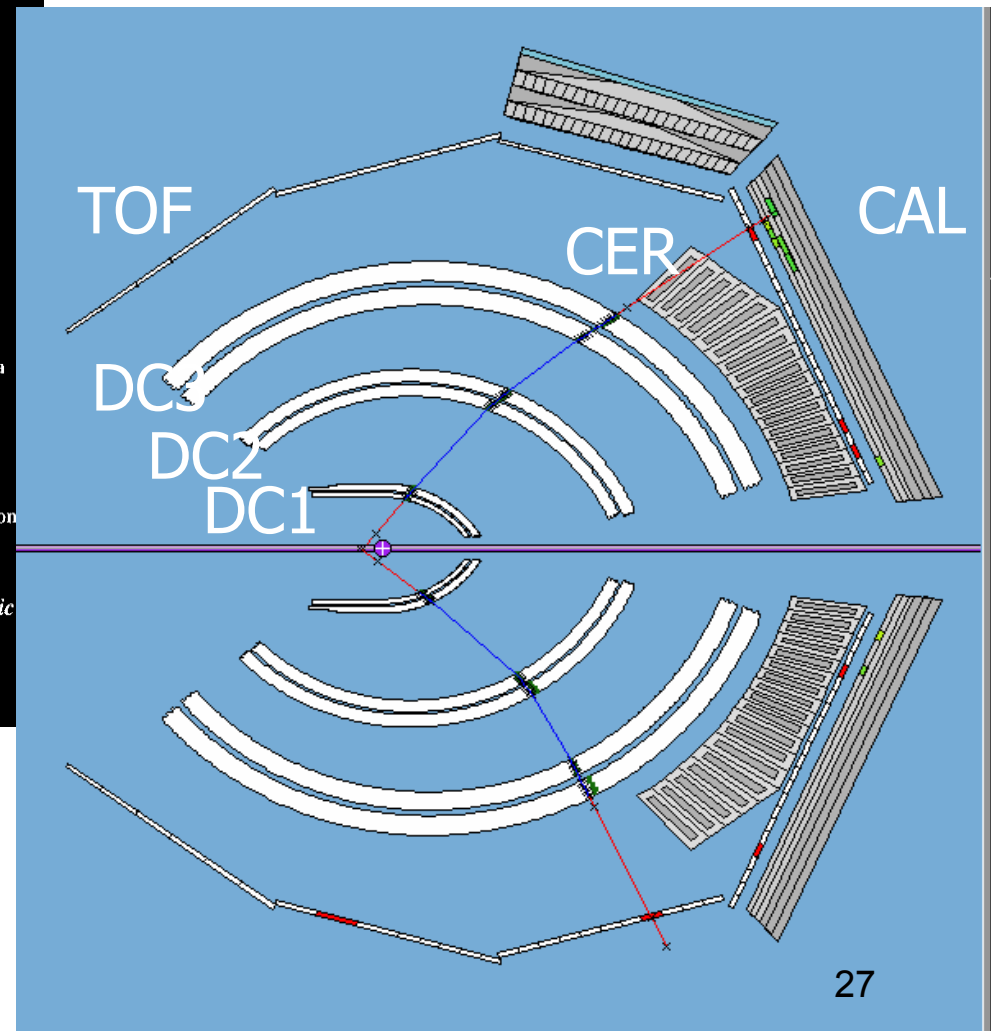
Pair relative momentum

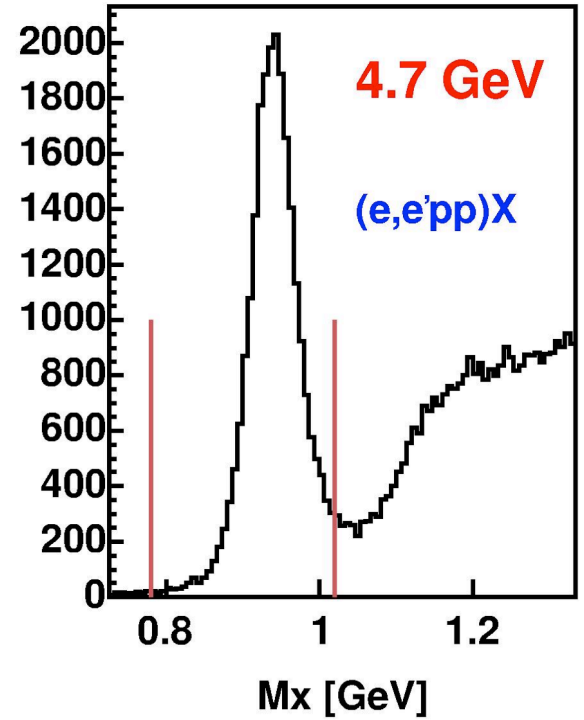
Sargsian, Abrahamyan, Strikman, Frankfurt
PRC **71,** 044615 (2005).

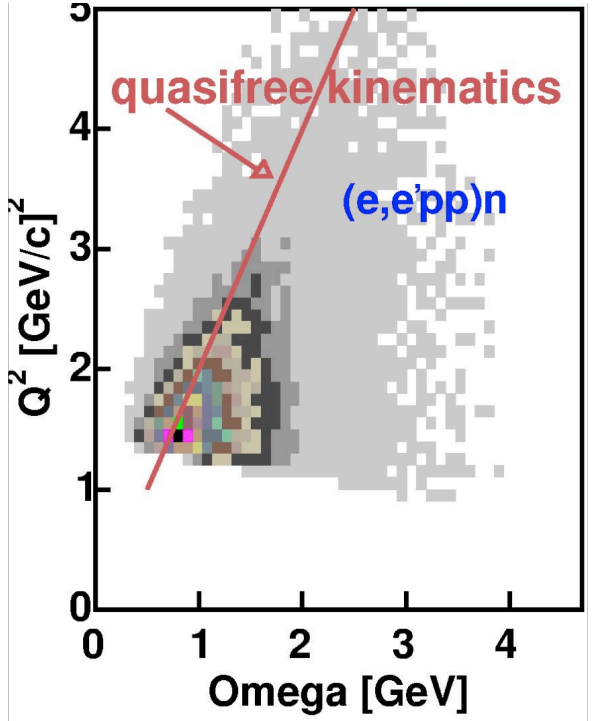
^{3}He(e,epp)n in CLAS

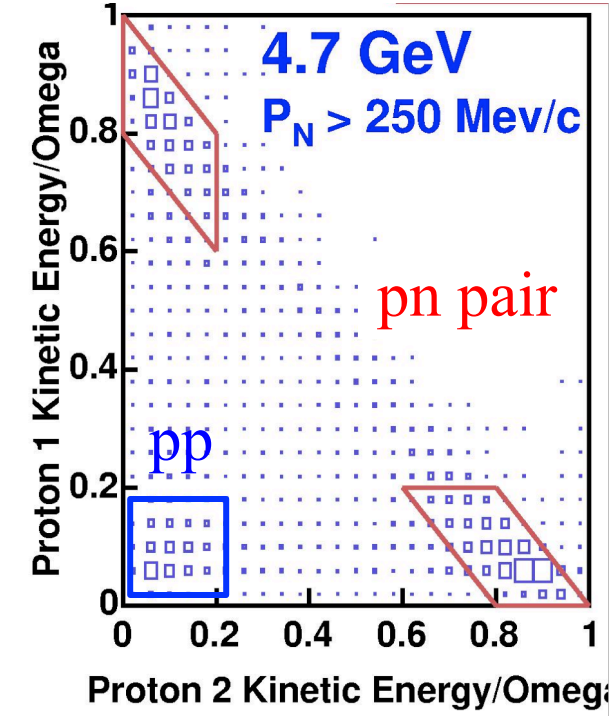
- 2 and 4 GeV electrons
- Inclusive trigger
- Almost 4π detector

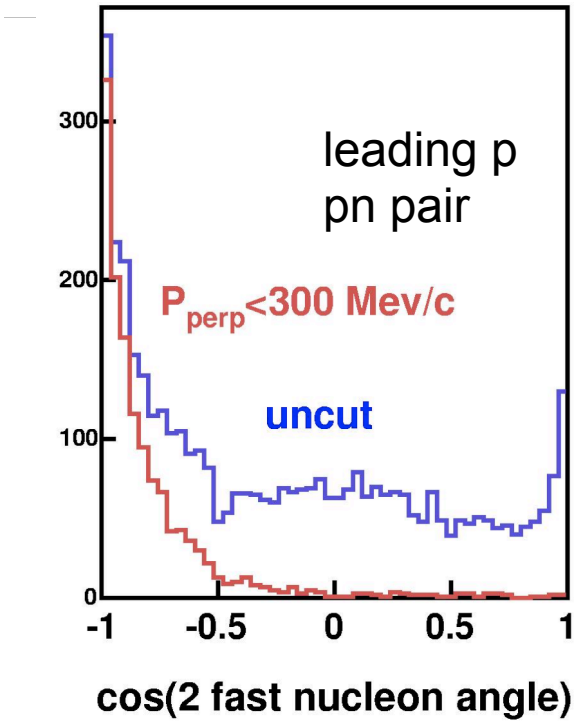




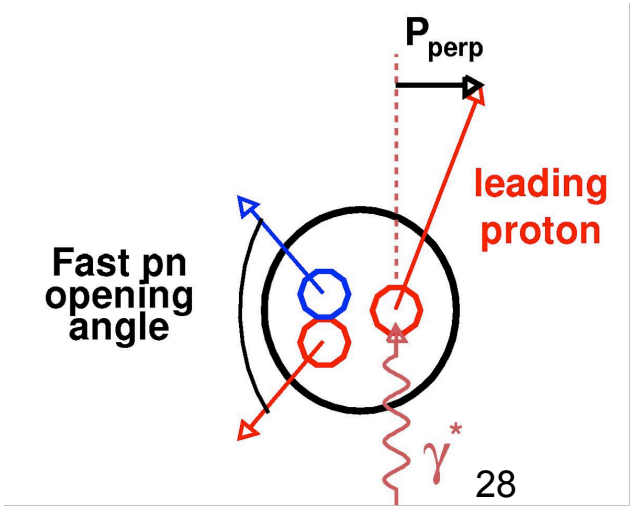






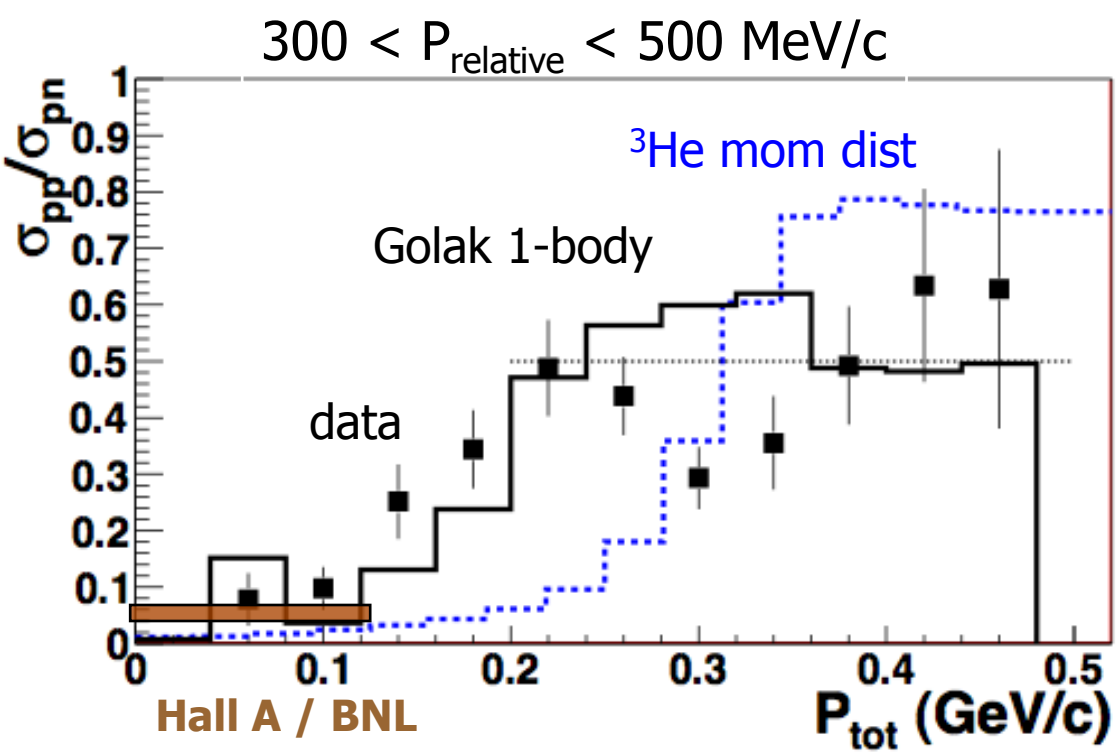


- Detect two protons
- Reconstruct the neutron
- Select peaks in Dalitz plot
- Remaining *NN* pair is back to back

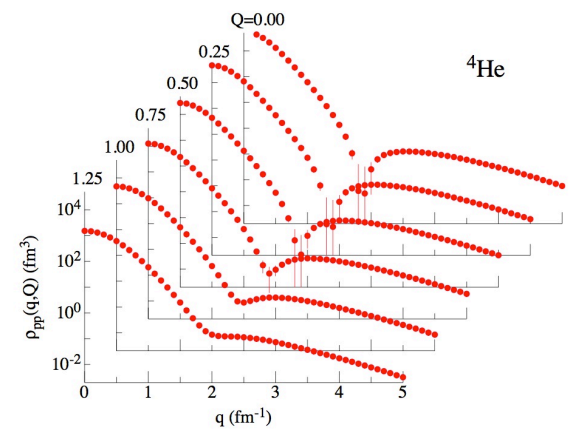


L. Weinstein, FermiLab 2015

pp/*pn* ratio and pair total momentum



Wiringa, UG meeting 2014



Increasing P_{tot} fills in *pp* minimum

Small P_{tot} ➔ *pp* pair in s-wave (no tensor)
➔ wave fn minimum at $P_{relative}$=400 MeV/c

Increase in *pp*/*pn* ratio with P_{tot} ➔tensor correlations

PRL 105, 222501 (2010)

$A(e,e'p)$ and $(e,e'pp)$ in heavy nuclei

(a data mining analysis)

- 5 GeV CLAS data
- C, Al, Fe, Pb targets
- Select leading (knocked-out) proton
- How many high p_{miss} leading protons have a correlated proton partner?

$E_{beam} = 5$ GeV

$x_B > 1.2$

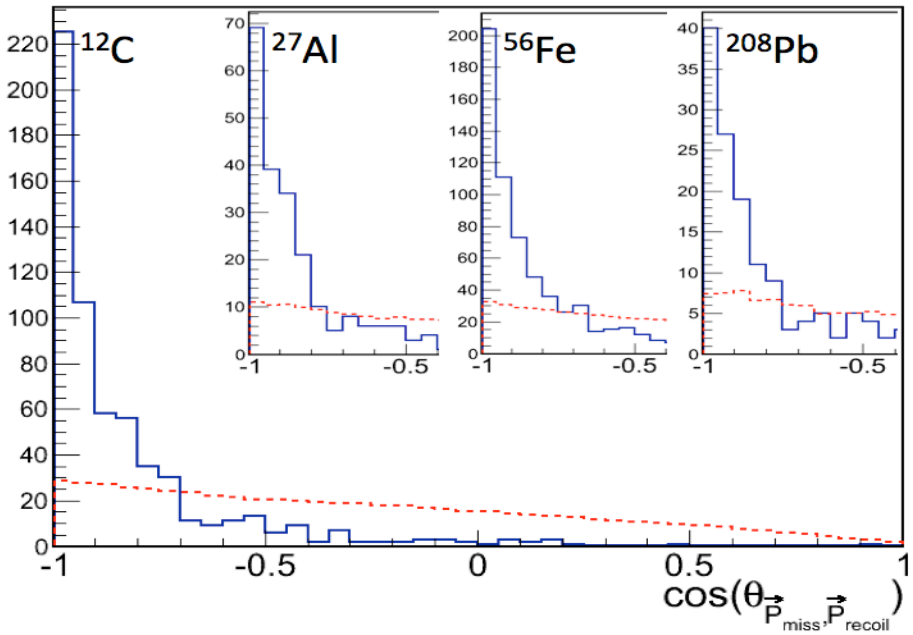
$\rightarrow Q^2 > 1.5$ GeV^2

$300 < p_{miss} < 600$ MeV/c

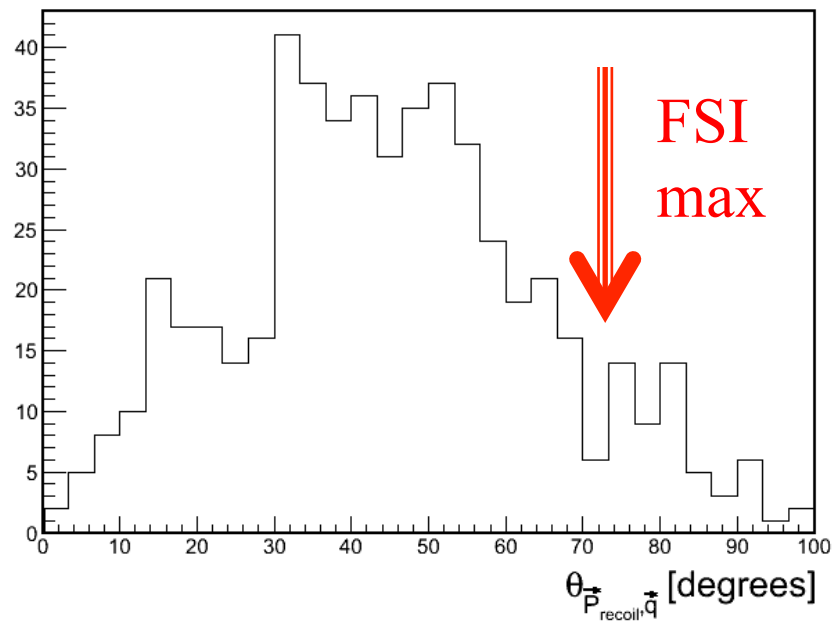
$\theta_{pq} < 25^\circ$

$p_p/q \geq 0.6$

(*e*,*e'pp*) angular distributions



Angle between the (e,e'p) missing momentum and the recoil proton momentum

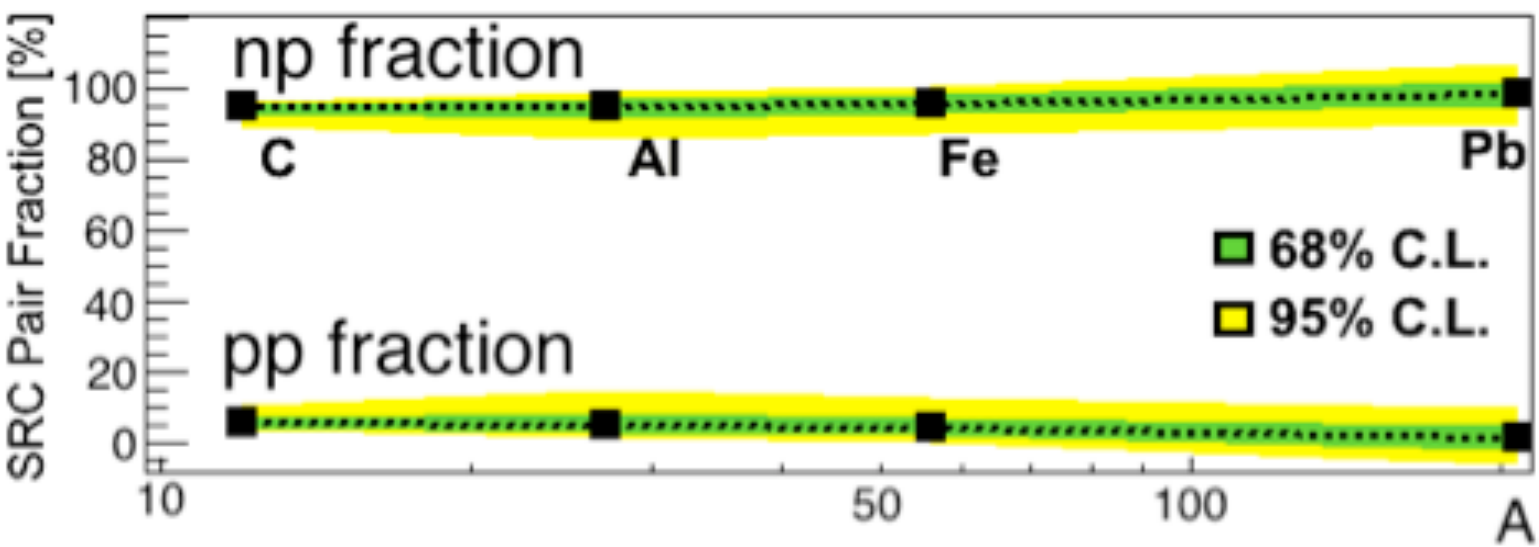


Angle between *q* and the recoil proton momentum

np and *pp* pairs

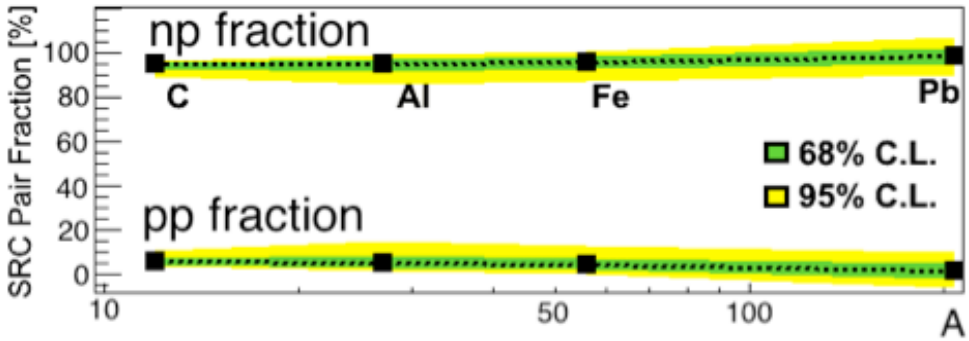
- Correct for proton rescattering via Glauber
- Assume all high-p_{miss} protons have a correlated partner
  - Use double ratio to get pp pair fraction
- ➔ High momentum tail still predominantly *np*

$$R = \frac{\dfrac{\sigma_A(e,e'pp)}{\sigma_A(e,e'p)}}{\dfrac{\sigma_C(e,e'pp)}{\sigma_C(e,e'p)}}$$

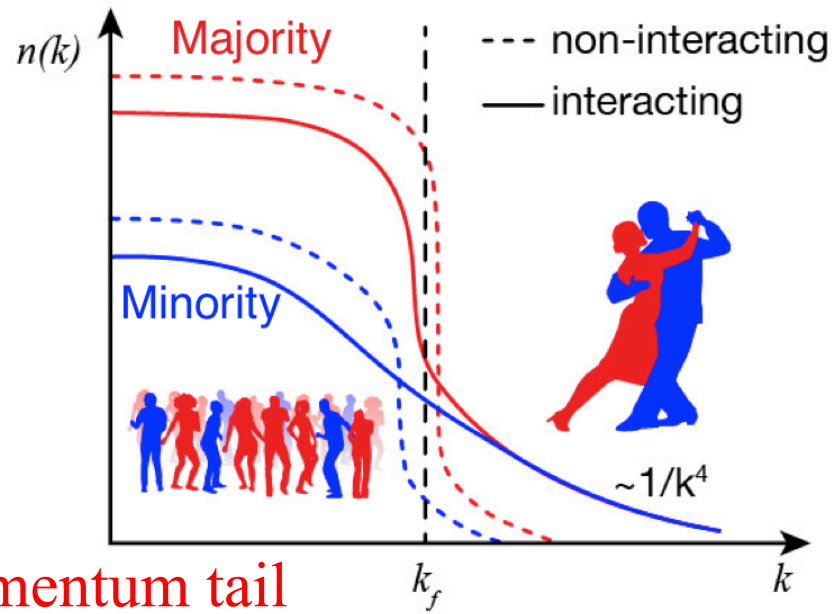


O. Hen *et al*, Science **346** 614 (2014)

Momentum inversion?



O. Hen *et al*, Science **346** 614 (2014)



Asymmetric nuclei:

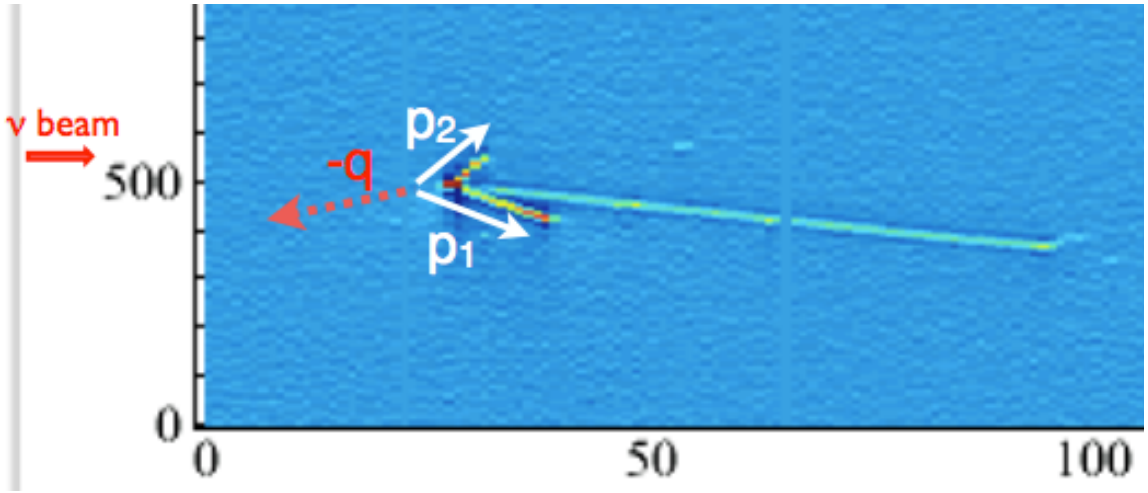
np pairs still dominate the high momentum tail

➔higher probability for each proton to be in tail

Important for:

- Nuclear symmetry energy
- Isospin dependence of the EMC effect
- Understanding neutrino-nucleus scattering
  - Extra energy at the interaction vertex?

ArgoNeut SRC Event



Event from O. Palamara, NuInt14 talk

Reconstructed initial proton 1 momentum back-to-back to p_2

$$\vec{p}_n^i = \vec{p}_{p1} - \vec{q} \approx -\vec{p}_{p2}$$

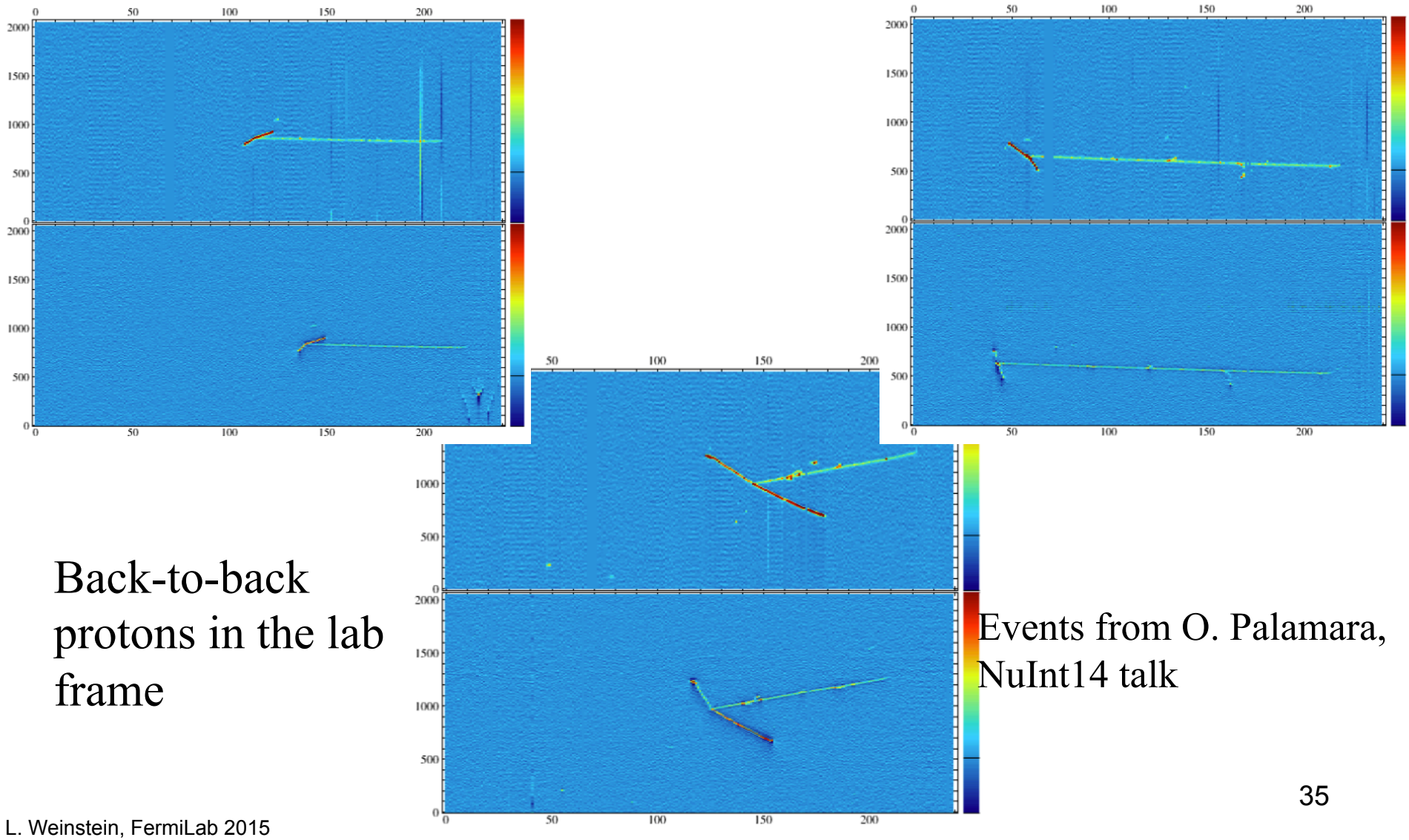
Same method as JLab (*e,e'pN*) measurements

$$\vec{p}_{miss} = \vec{q} - \vec{p}_{p1}$$

$$\vec{p}_{rel} = (\vec{p}_{miss} - \vec{p}_{p2})/2$$

$$\vec{p}_{tot} = (\vec{p}_{miss} + \vec{p}_{p2}) \approx 0$$

NN Pairs and neutrinos
ArgoNeut Hammer Events: Not SRC



Back-to-back protons in the lab frame

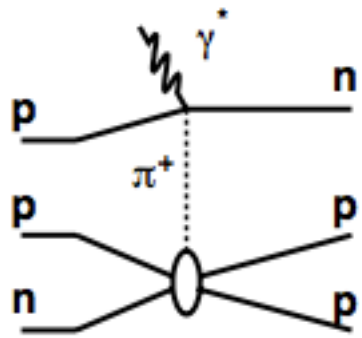
Events from O. Palamara, NuInt14 talk

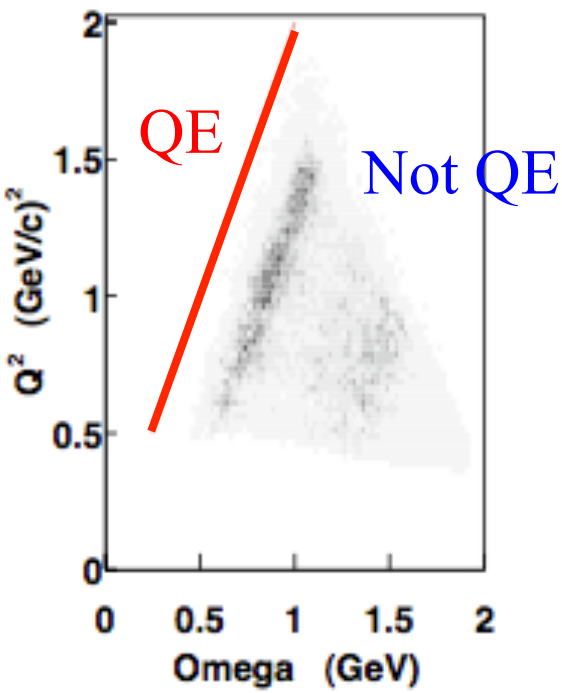
Pion production and reabsorption

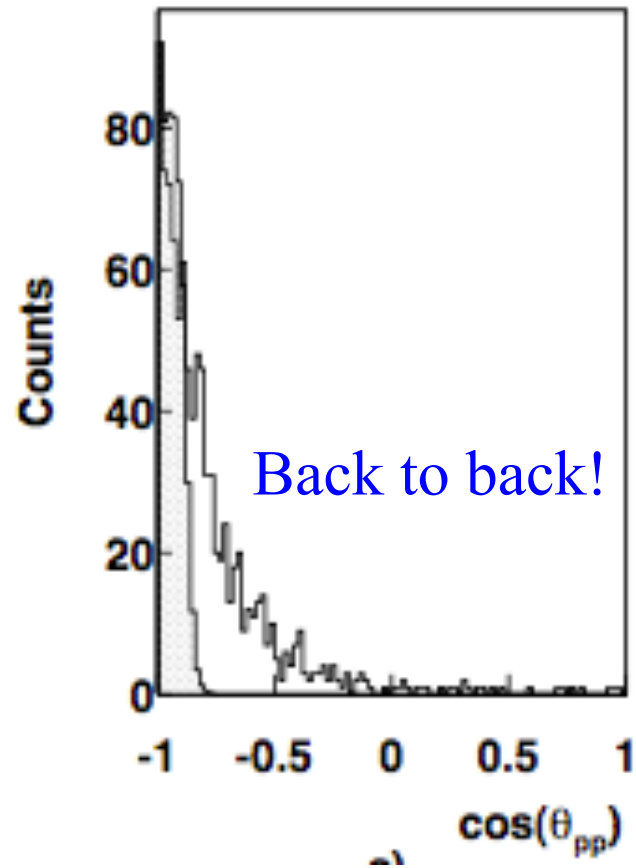
^{3}He($e,e'pp$)n simulation

Knock out pion from nucleon 1, absorb on nucleons 2 and 3.

1. Measured ^{3}He momentum distributions
2. Pion production from MAID-2000
3. Pion absorption from SAID-1998



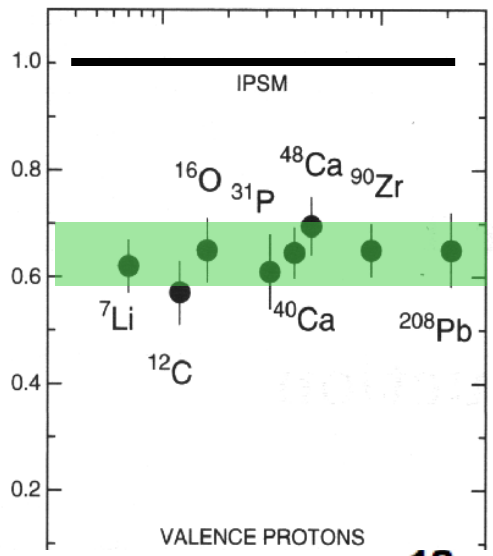




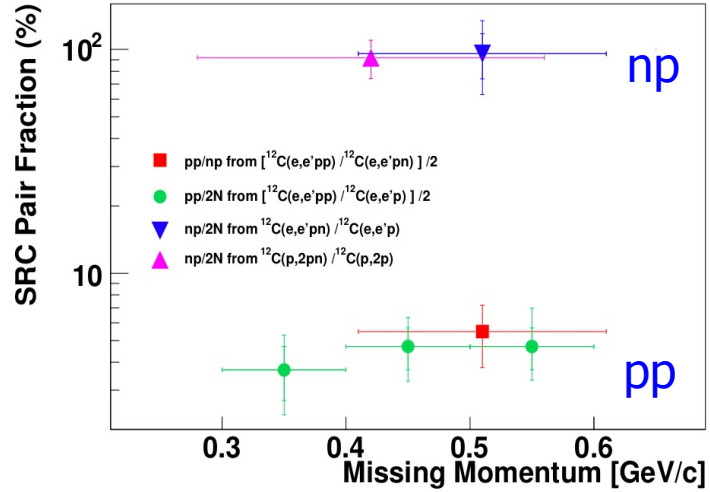
Summary: Correlations in nuclei

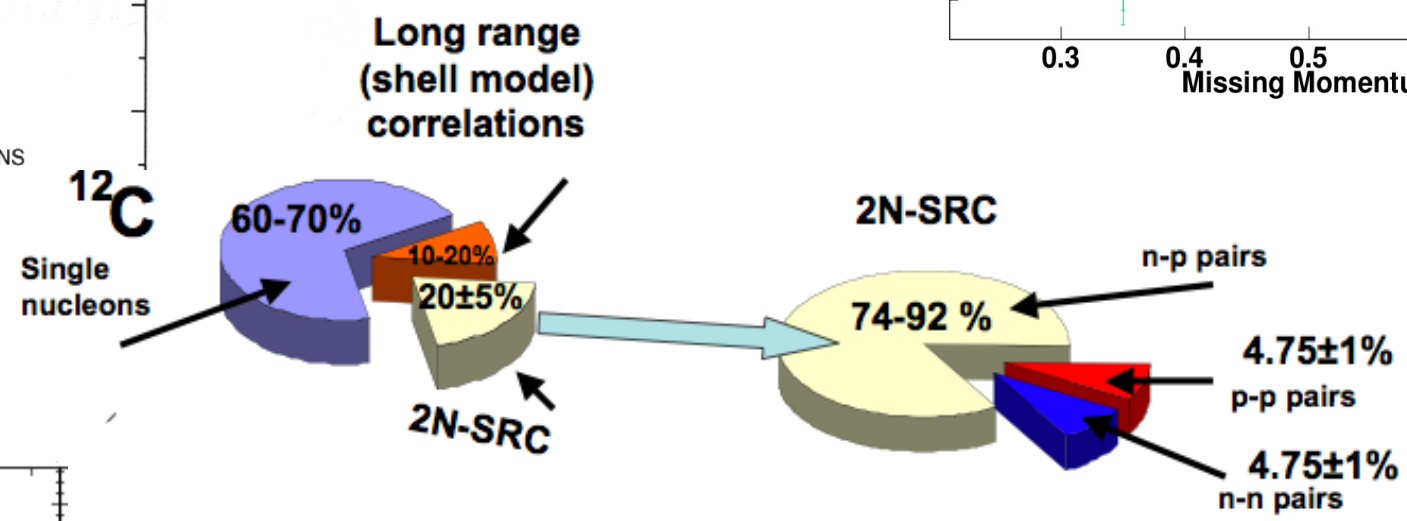
- Almost all high momentum nucleons ($k > 300$ MeV/c) in nuclei belong to an *NN* correlated pair
- 20% of all nucleons for $A \geq 12$
- Dominated by *pn* pairs, even in heavy asymmetric nuclei
- Momentum distributions proportional to deuterium

Summary

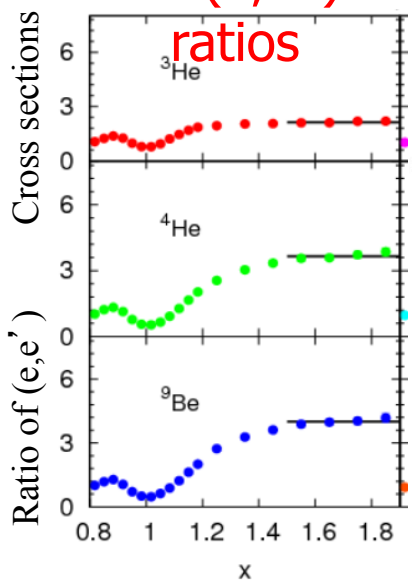


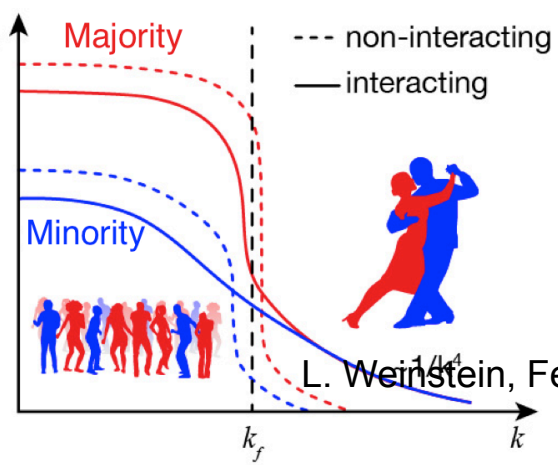
(e,e' p) Shell occ

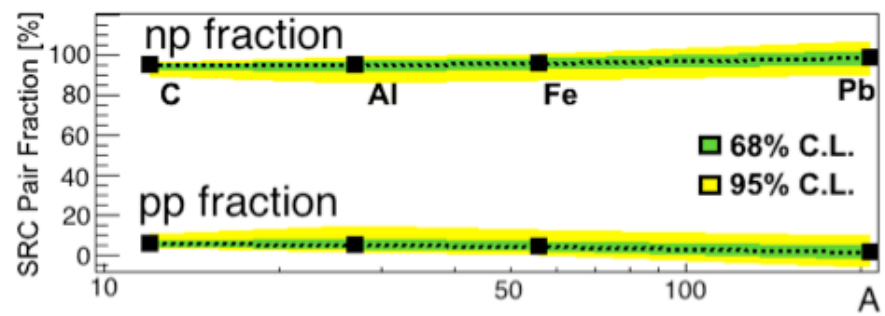




A(e,e') ratios







~25% SRC pairs

- ~90% tensor correlated np pairs