Introduction: Electron-Nucleus Scattering and Short Range Correlations

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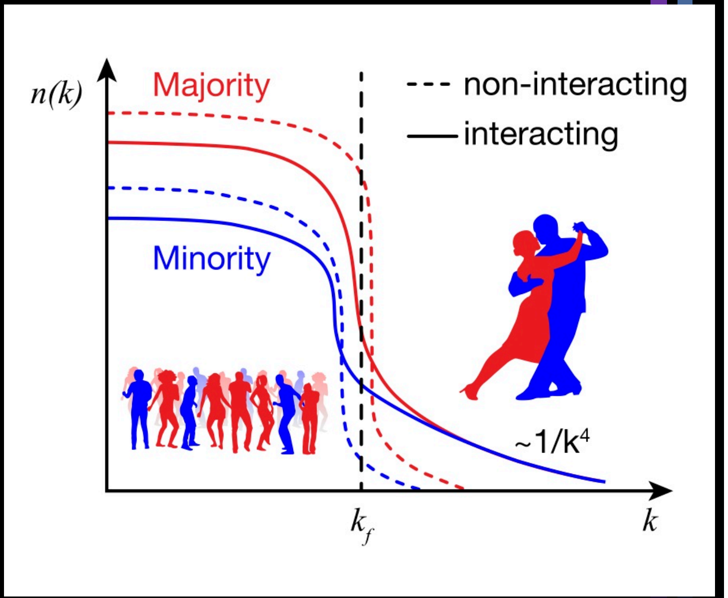
- Comprehensive Theory Overview
- Independent nucleons
- Correlated nucleons (SRC)
- The EMC Effect and SRC
- Studying SRC with (e,e'pN)
- Two-component Fermi systems and Tan's contact
- Summary



Comprehensive Theory Overview

Nuclear Theory, circa 1980

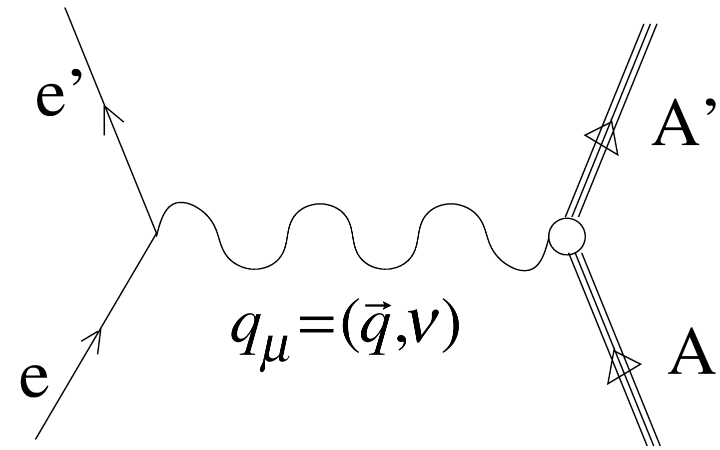
Nuclear Theory - circa 2000

Nuclear Theory - today: 1, 2, 3, … 12, … many

See talks by Ciofi degli Atti, Ryckebusch, Mosel and all the other theorists for more details

Why use electrons?

- Probe structure understood (point particles)
- Electromagnetic interaction understood (QED)
- Interaction is weak ($\alpha = 1/137$)
  - Perturbation theory works!
    - First Born Approx / one photon exchange
  - Probe interacts only once
  - Study the entire nuclear volume



BUT:

- Cross sections are small
- Electrons radiate

Virtual photon:

Momentum q > energy ν (or ω)

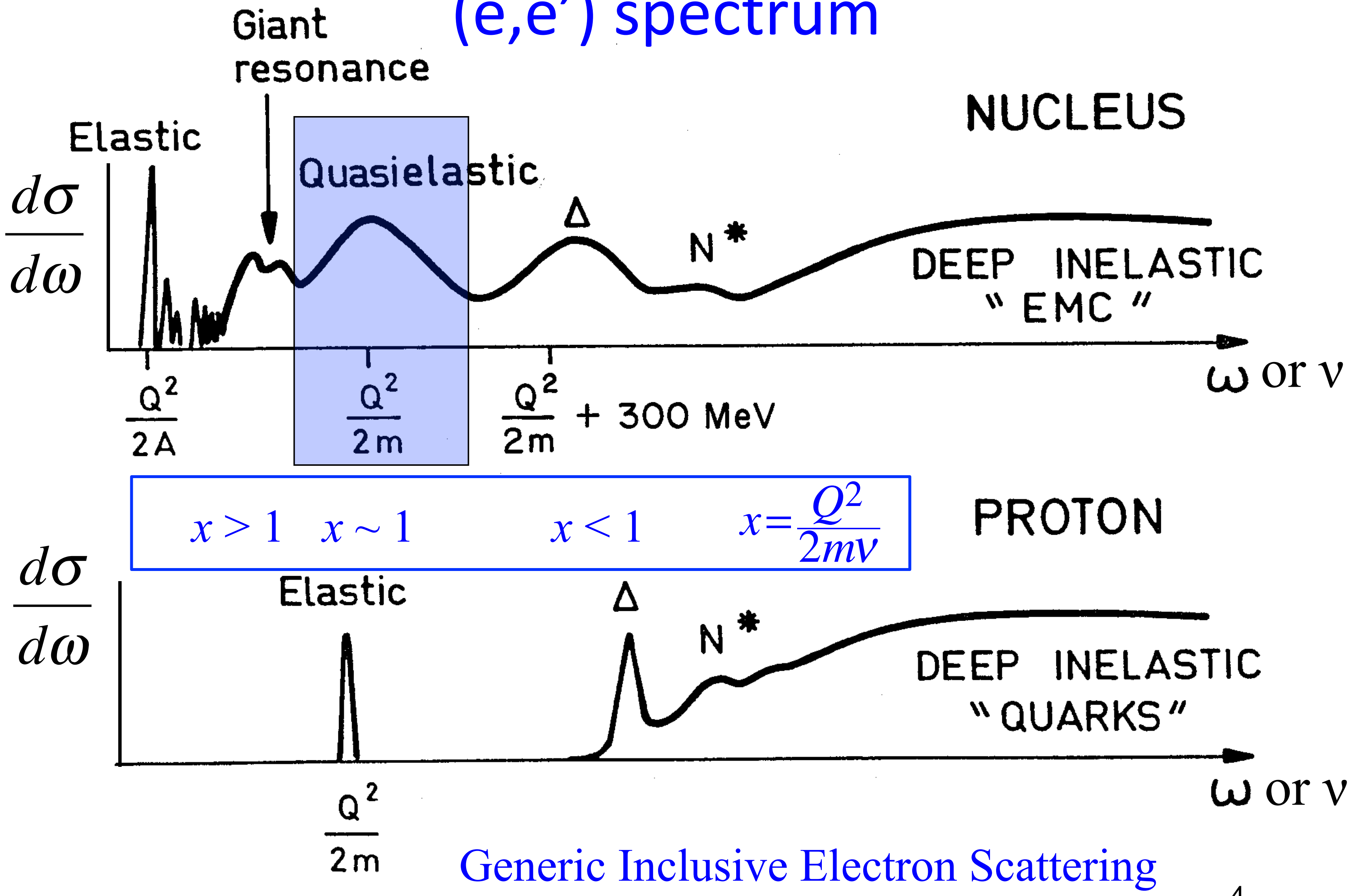
q determines spatial resolution

ν determines excitation energy

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

Virtual photon has mass!

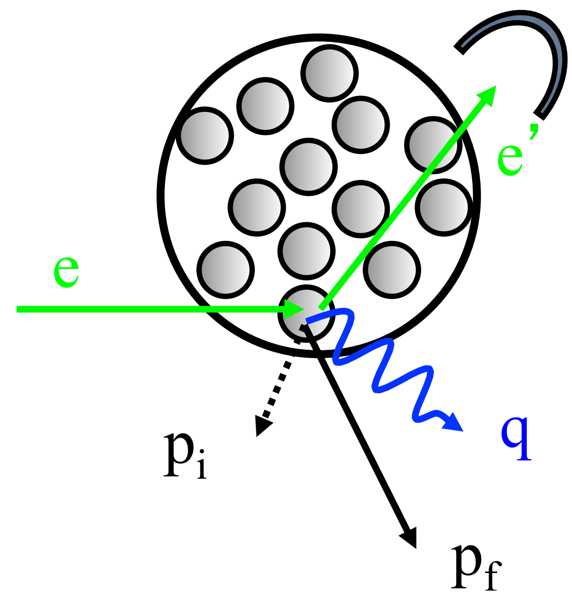
(e,e') spectrum



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

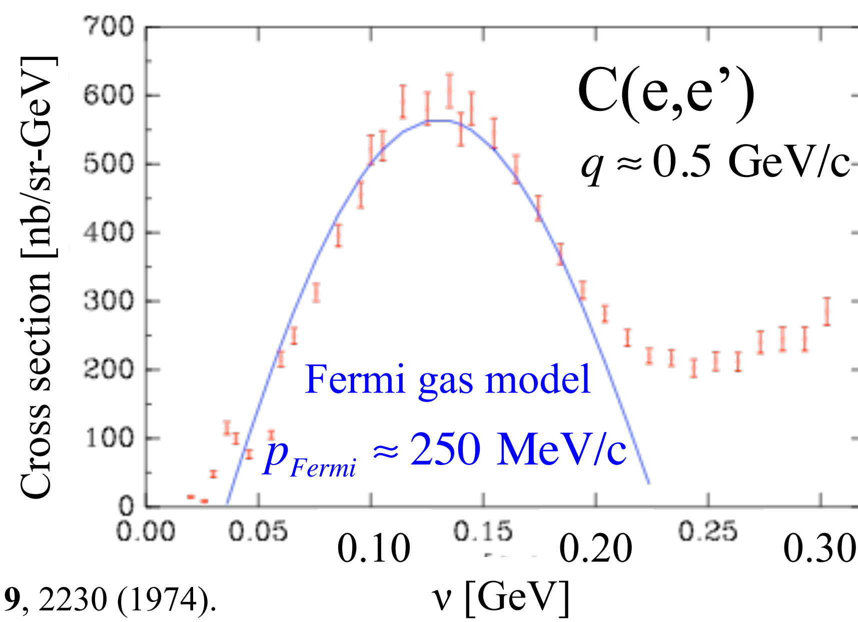
➔ Peak

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

Width: $\Delta\nu = 2qp_{Fermi}/m$

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

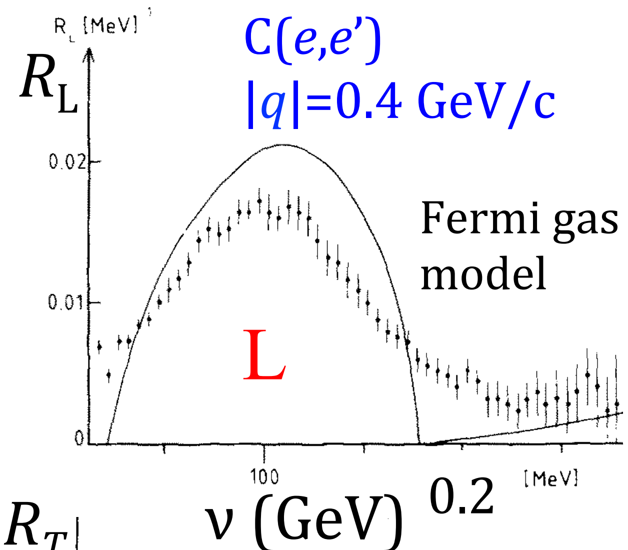
Two parameters: p_{Fermi}, ε (shift)

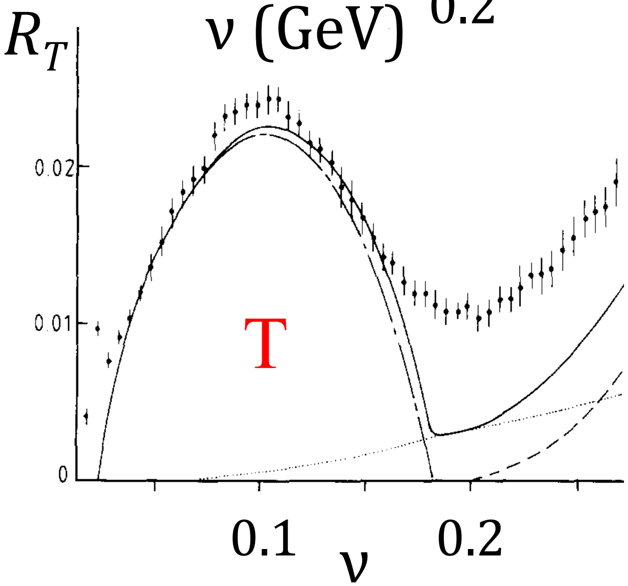


R.R. Whitney et al., PRC **9**, 2230 (1974).

Fermi Gas Model: Too good to be true?

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



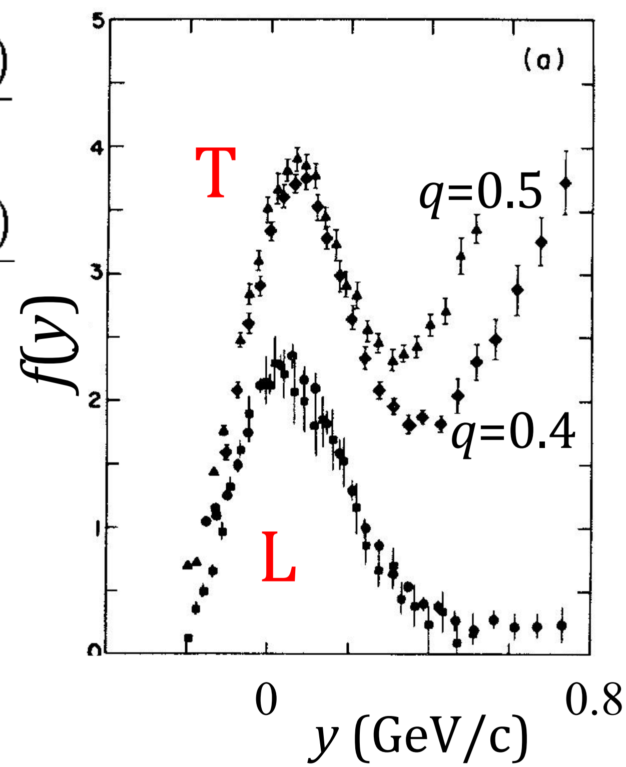


y = minimum initial nucleon momentum
= $m\nu/q - q/2$ (nonrelativistic only!)
f = reduced response function

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

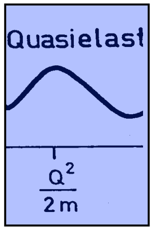
$$f_T(Q^2,\omega) \propto \frac{R_T(Q^2,\omega)}{\tilde{G}_M^2(Q^2)}$$

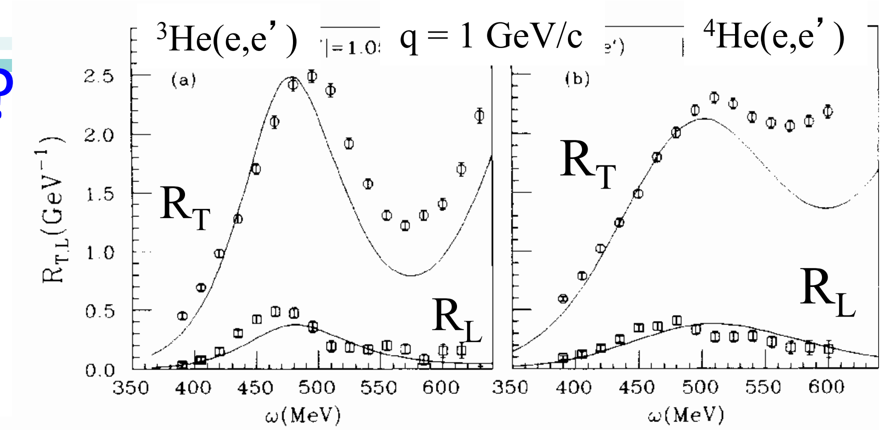
- L scales
- T scales
- T≠L!!

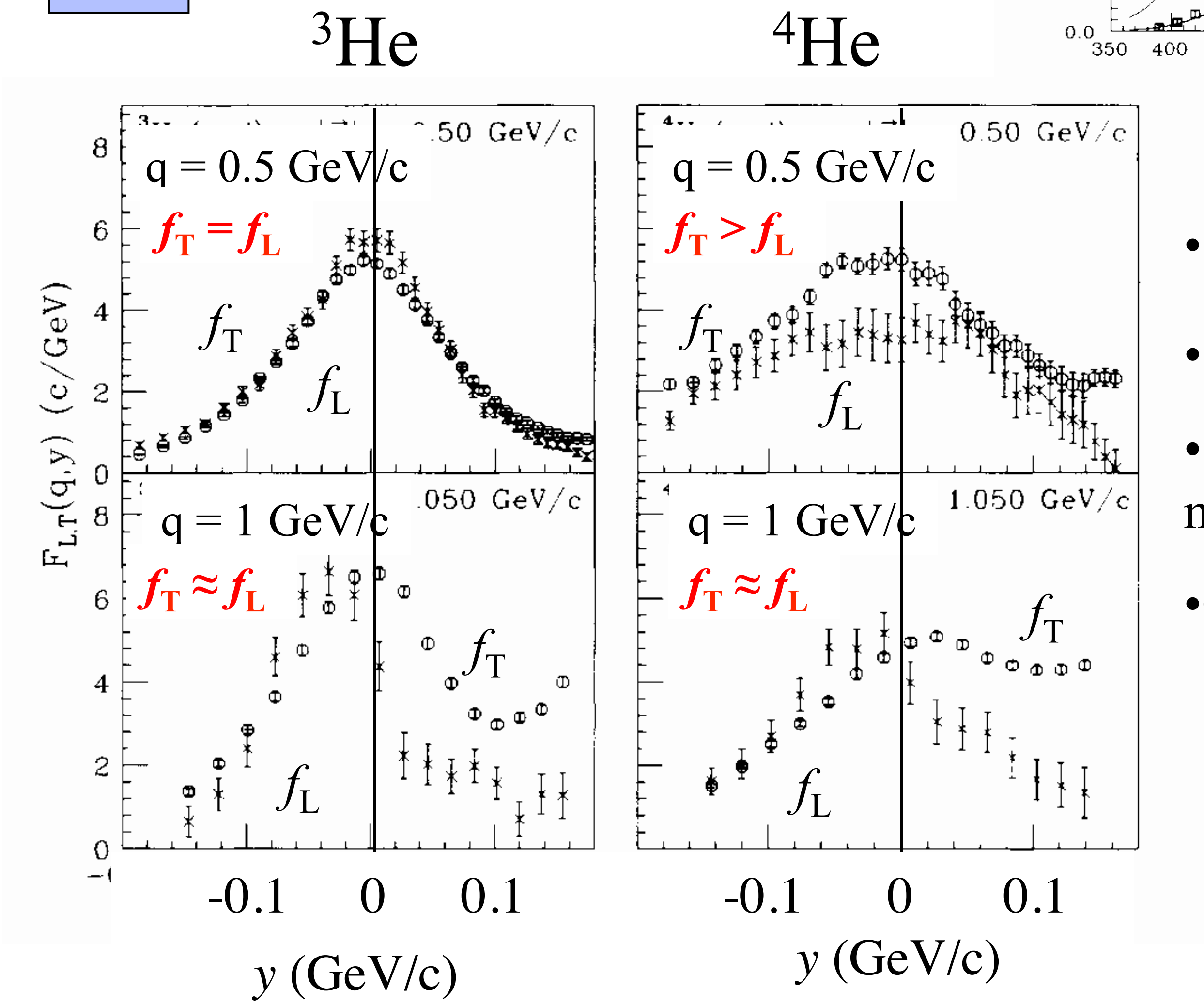


P. Barreau et al, NPA 402, 515 (1983)
Finn et al, PRC 29, 2230 (1984)

What causes the T/L difference?







Meziani et al, PRL 69 41 (1992)

- ^{3}He: $f_T = f_L$ (at $y < 0$)
- ^{4}He and C: $f_T > f_L$
- Extra transverse reaction mechanism in dense nuclei!
- Gets smaller at higher *q*

What is it?
To be continued …

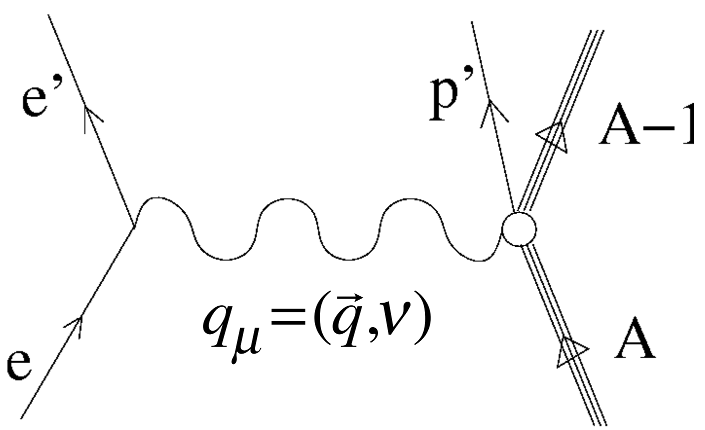
Get more information: detect the proton (e,e'p)

Cross section factorizes (mostly):

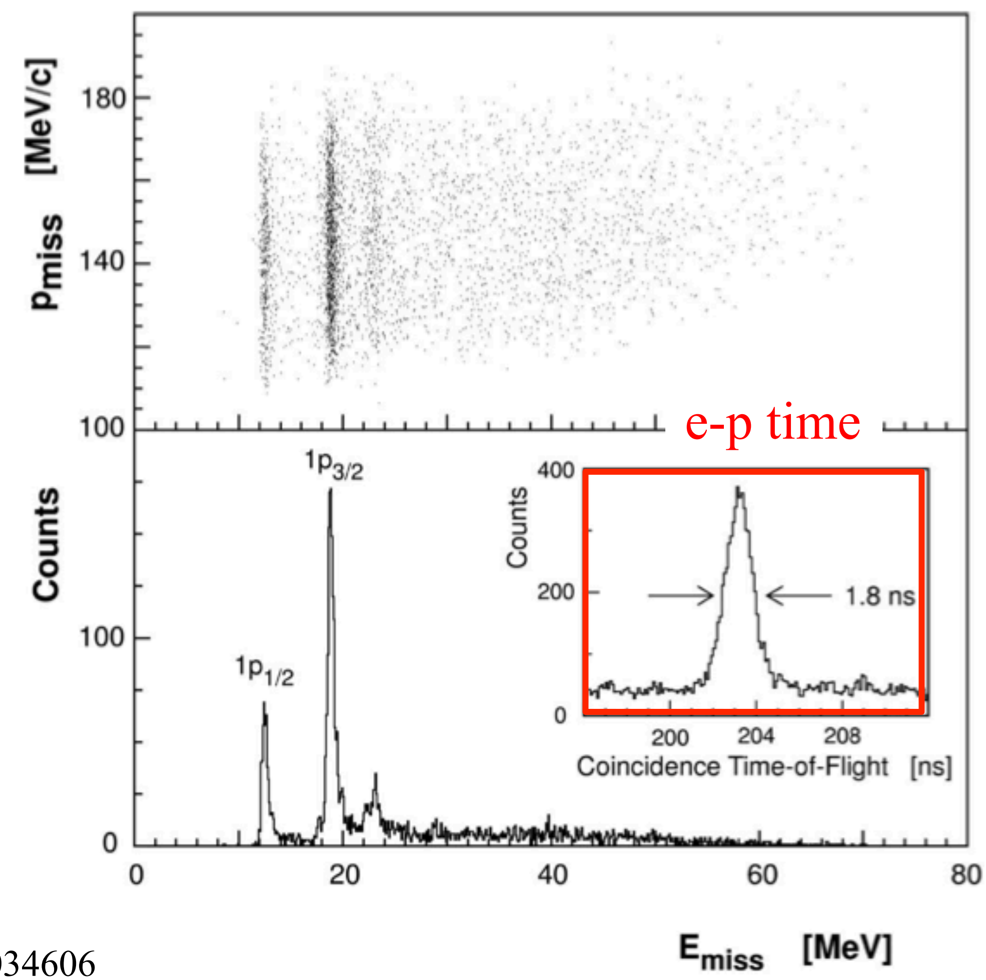
$$\frac{d\sigma}{dE_e d\Omega_e dT_p d\Omega_p} = K S^D(\vec{p}_{miss}, E_{miss}) \frac{d\sigma^{free}}{d\Omega}$$

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

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

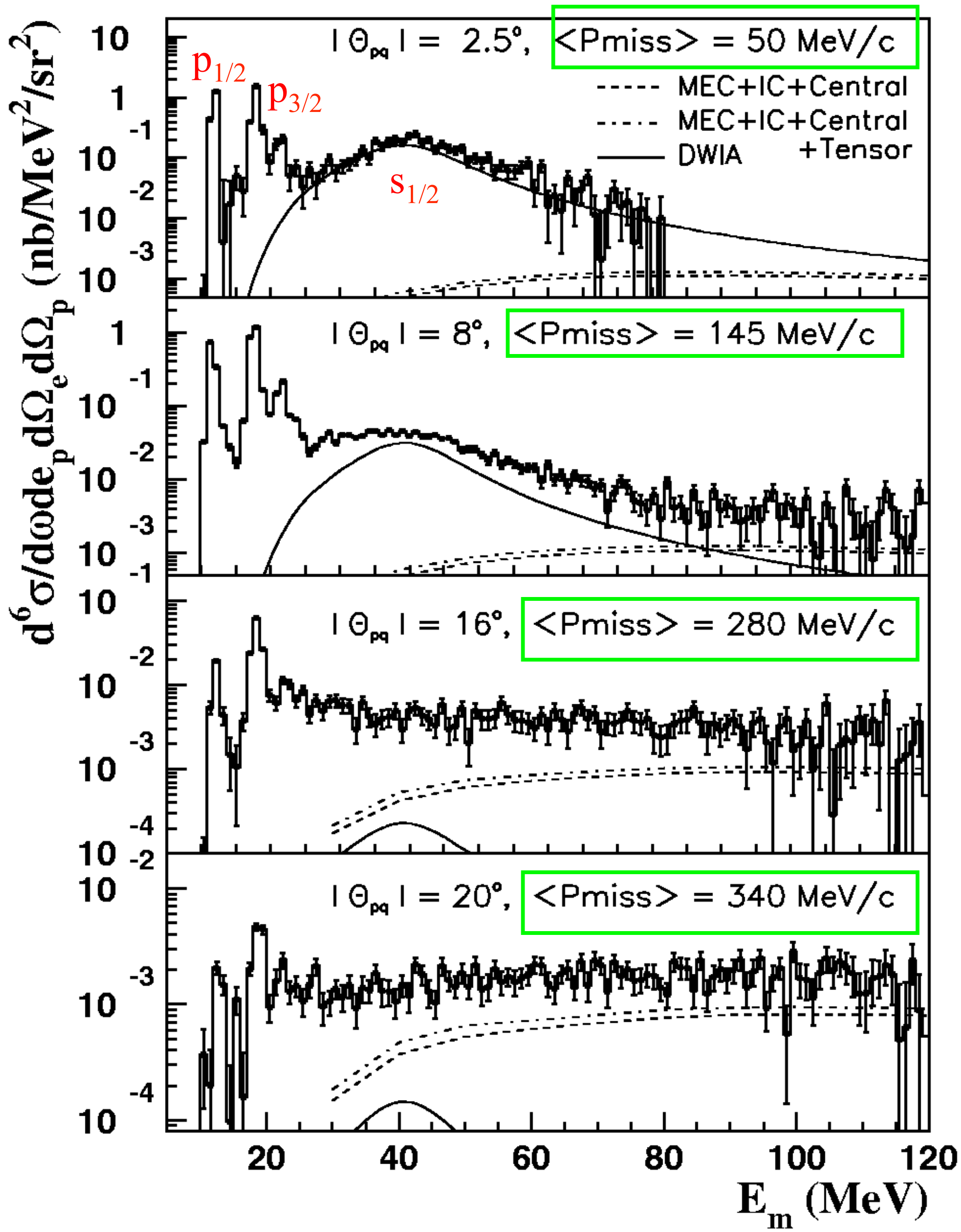


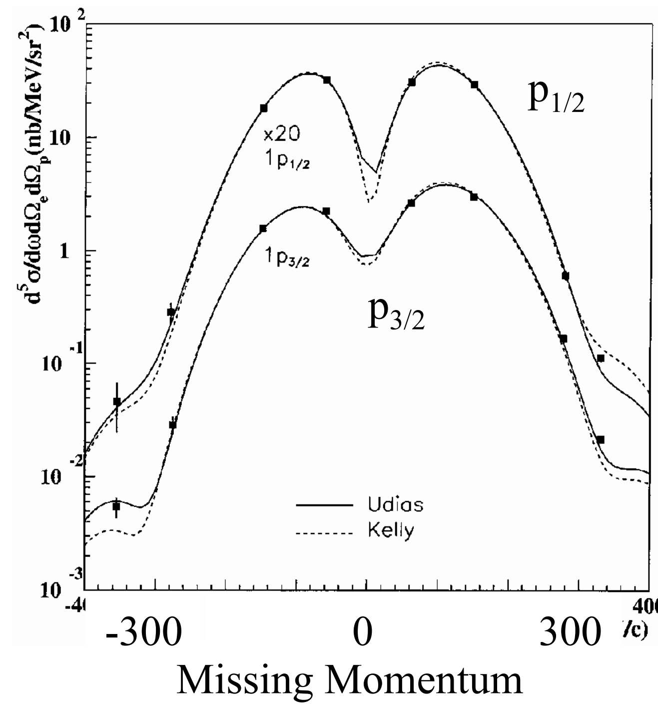
O(e,e'p) JLab Hall A



Fissum, PRC **70** (2004) 034606

O(e,e'p) and shell structure



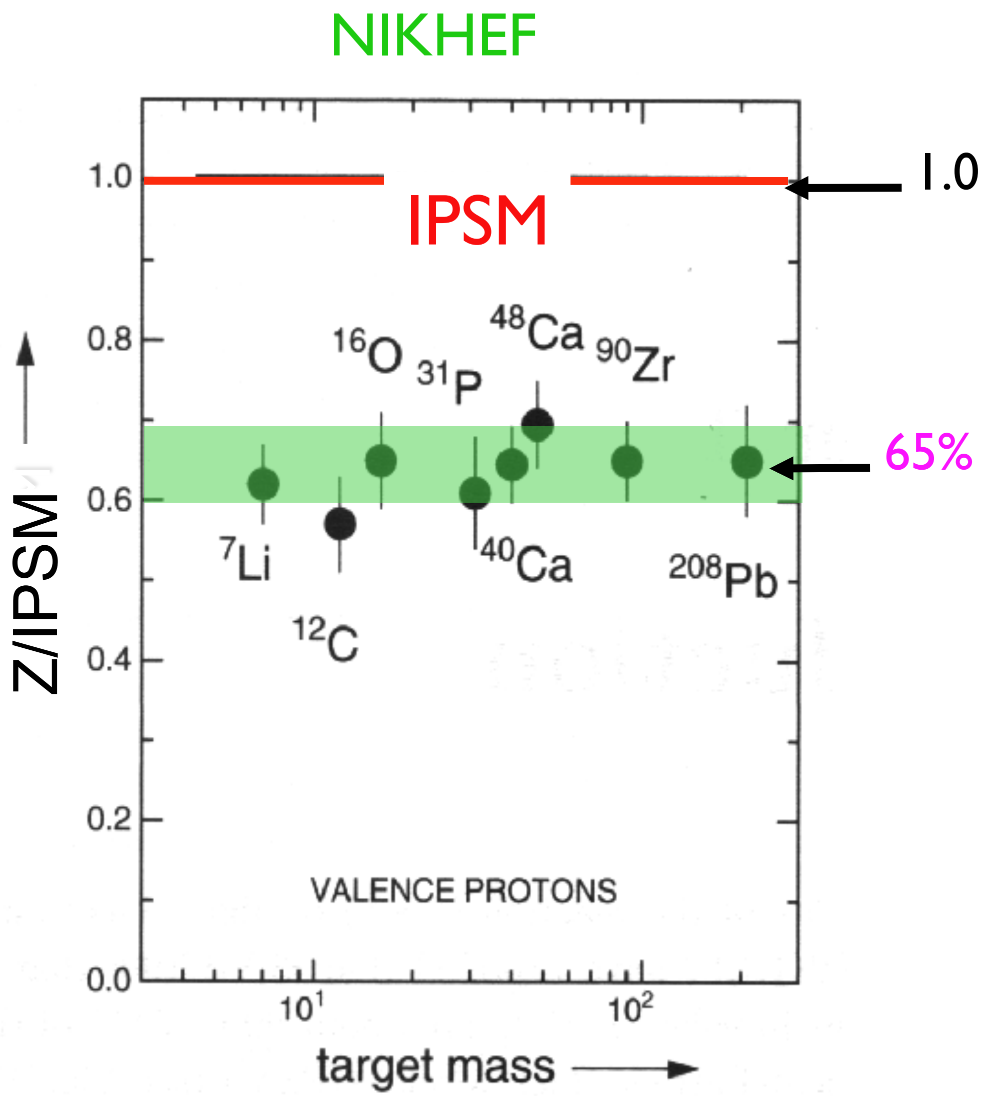


$1p_{1/2}$, $1p_{3/2}$ and $1s_{1/2}$ shells visible

Momentum distribution as expected for $l = 0, 1$

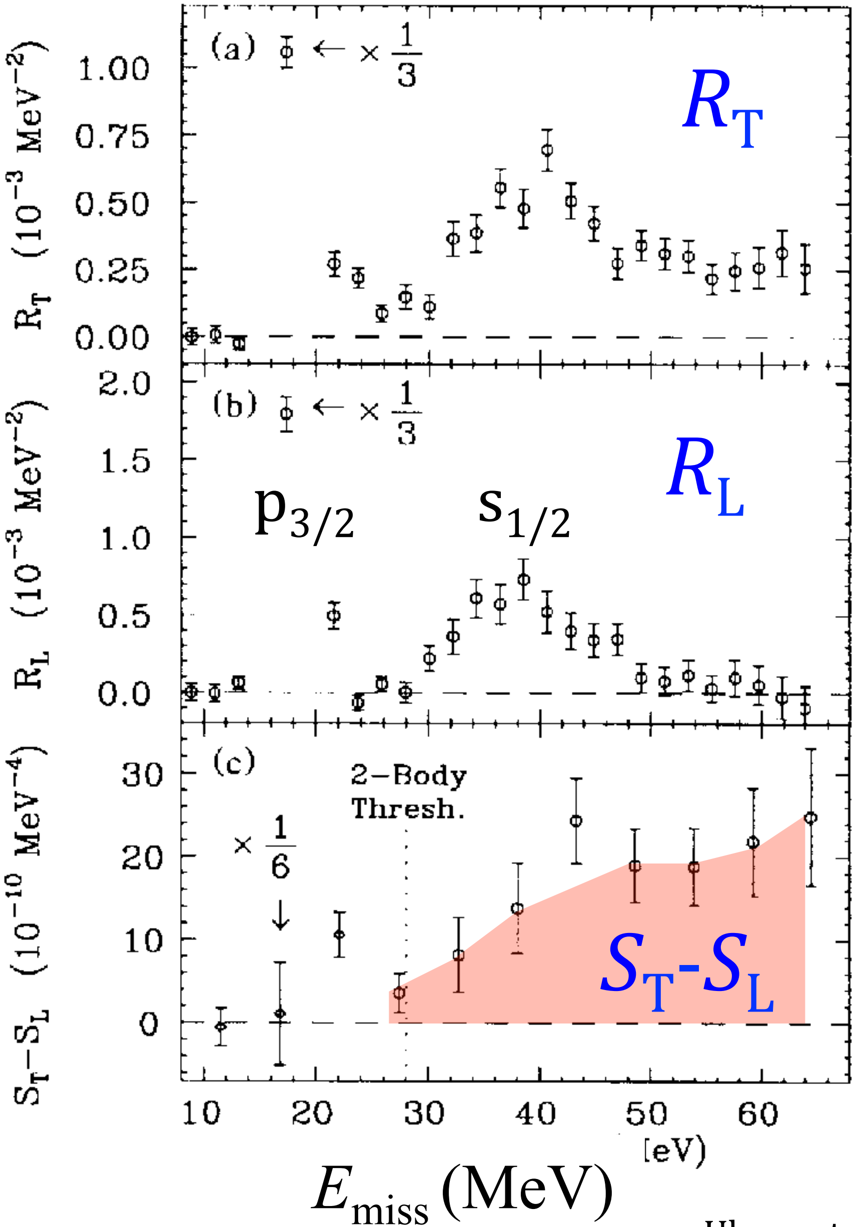
Fissum et al, PRC **70**, 034606 (2003)

But we do not see enough protons!



L. Weinstein, EMMI GSI 2015

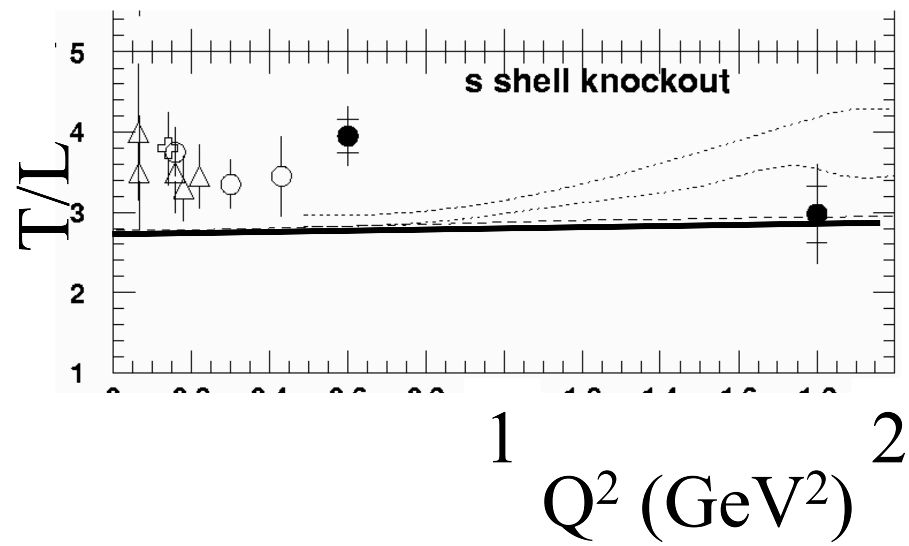
Now separate R_L and R_T



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

q=0.4 GeV and x=1

extra transverse strength starting at the 2N KO threshold



decreases with Q^2

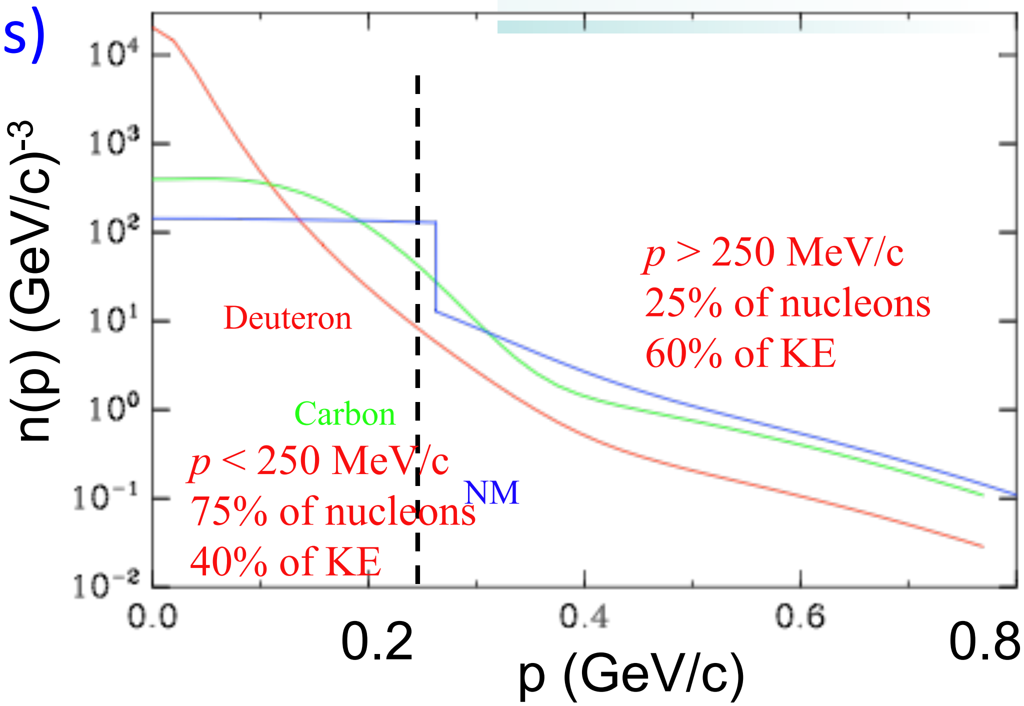
Ulmer et al, PRL 59, 2259 (1987); Dutta et al, PRC 61, 061602 (2000)

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

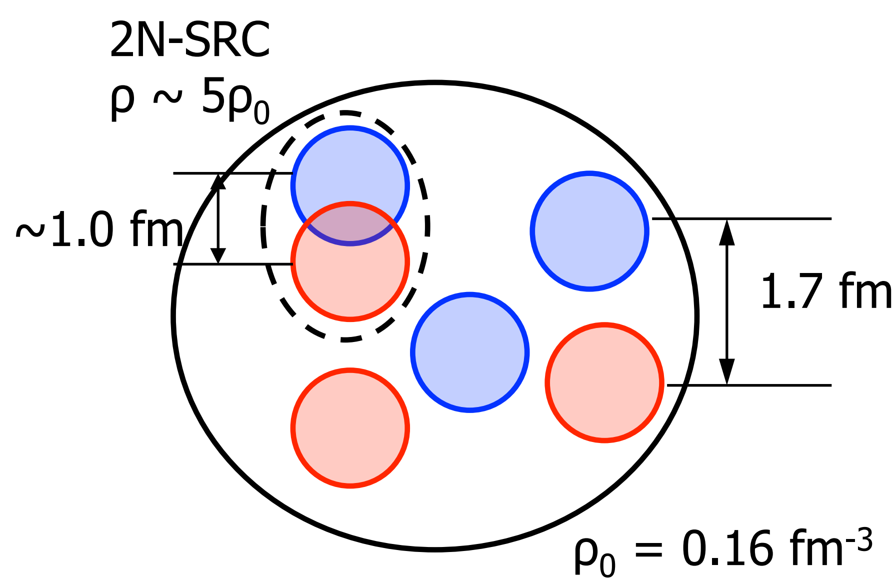
- Measure shell structure directly
- Measure nucleon momentum distributions
- Extra cross section at large missing energy
  - Transverse (mostly)
  - Two nucleon knockout via
    - Meson exchange currents
    - Correlations
- But:
  - Not enough valence nucleons seen!

Short Range Correlations (SRCs)

➔High momentum tails:
$p > p_{Fermi}$
Calculable for $A \leq 12$ nuclei and nuclear matter.
Not well constrained at $p >> p_f$

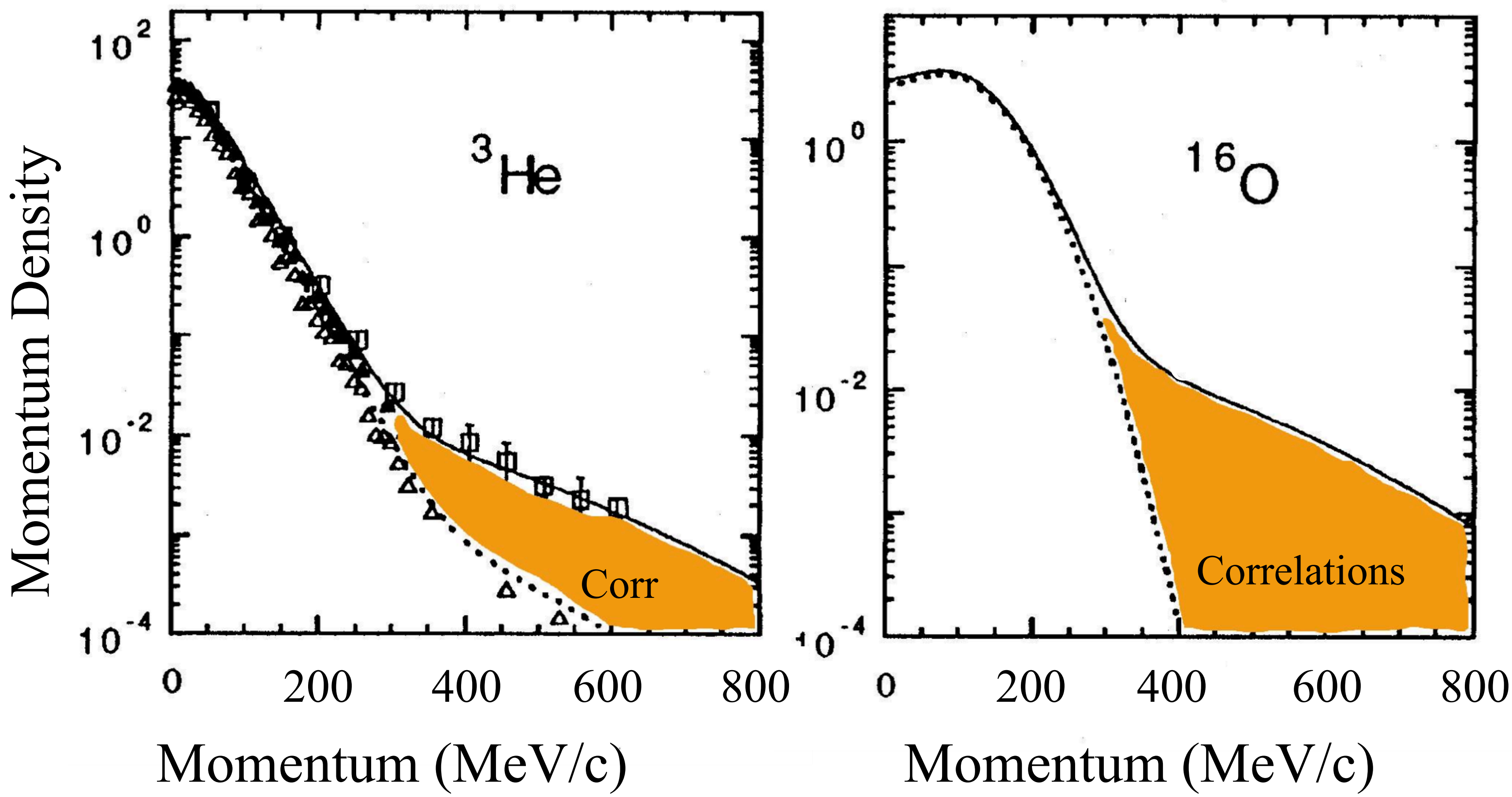


Effects:
- High momentum part of the nuclear wave function
- Short distance behavior of nucleons - modification??
- Cold dense nuclear matter
- Neutron Stars



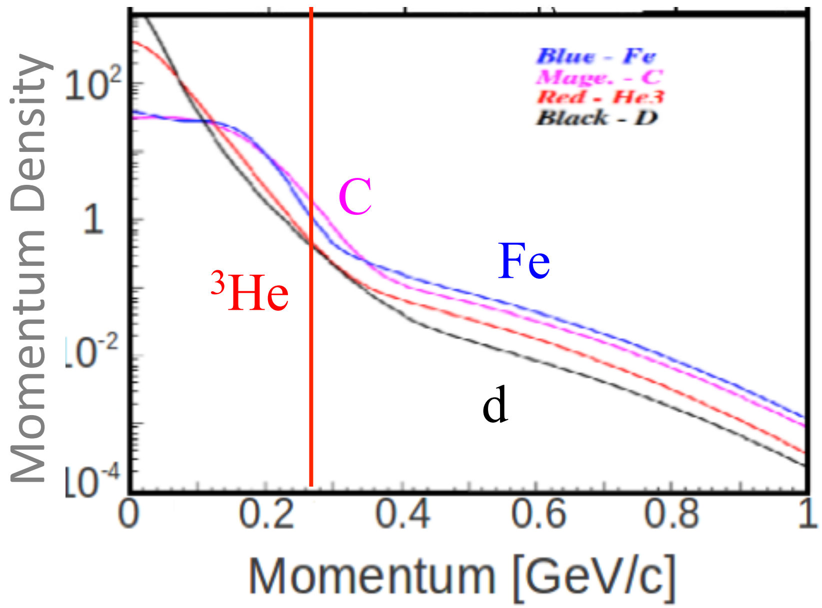
Nucleons are like people …

Correlations and High Momentum



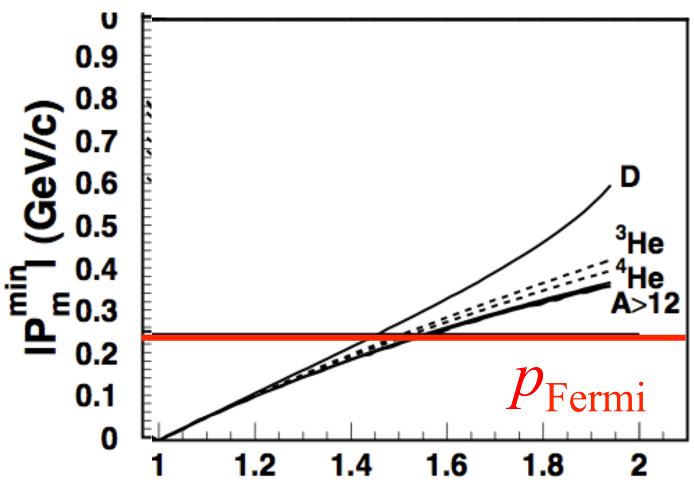
Ciofi degli Atti, PRC 53 (1996) 1689

Correlations should be universal



the high momentum distribution for all nuclei should have the same shape:

$$\frac{n_A(p)}{n_d(p)} = a_2(A) \text{ for } p > p_{Fermi}$$

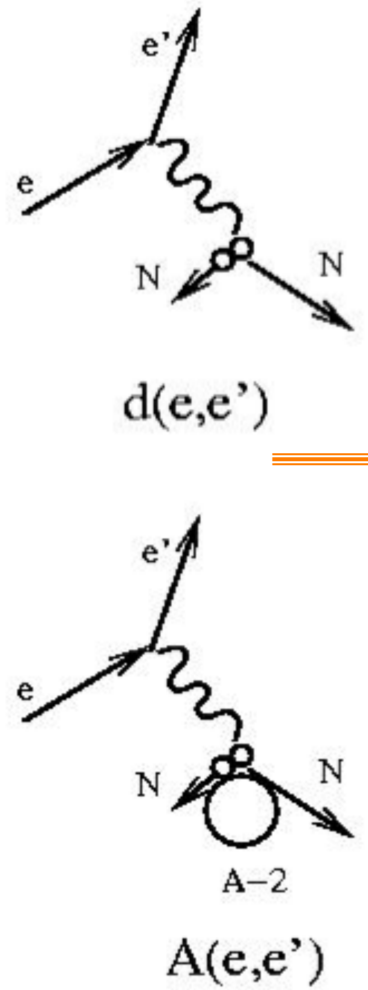


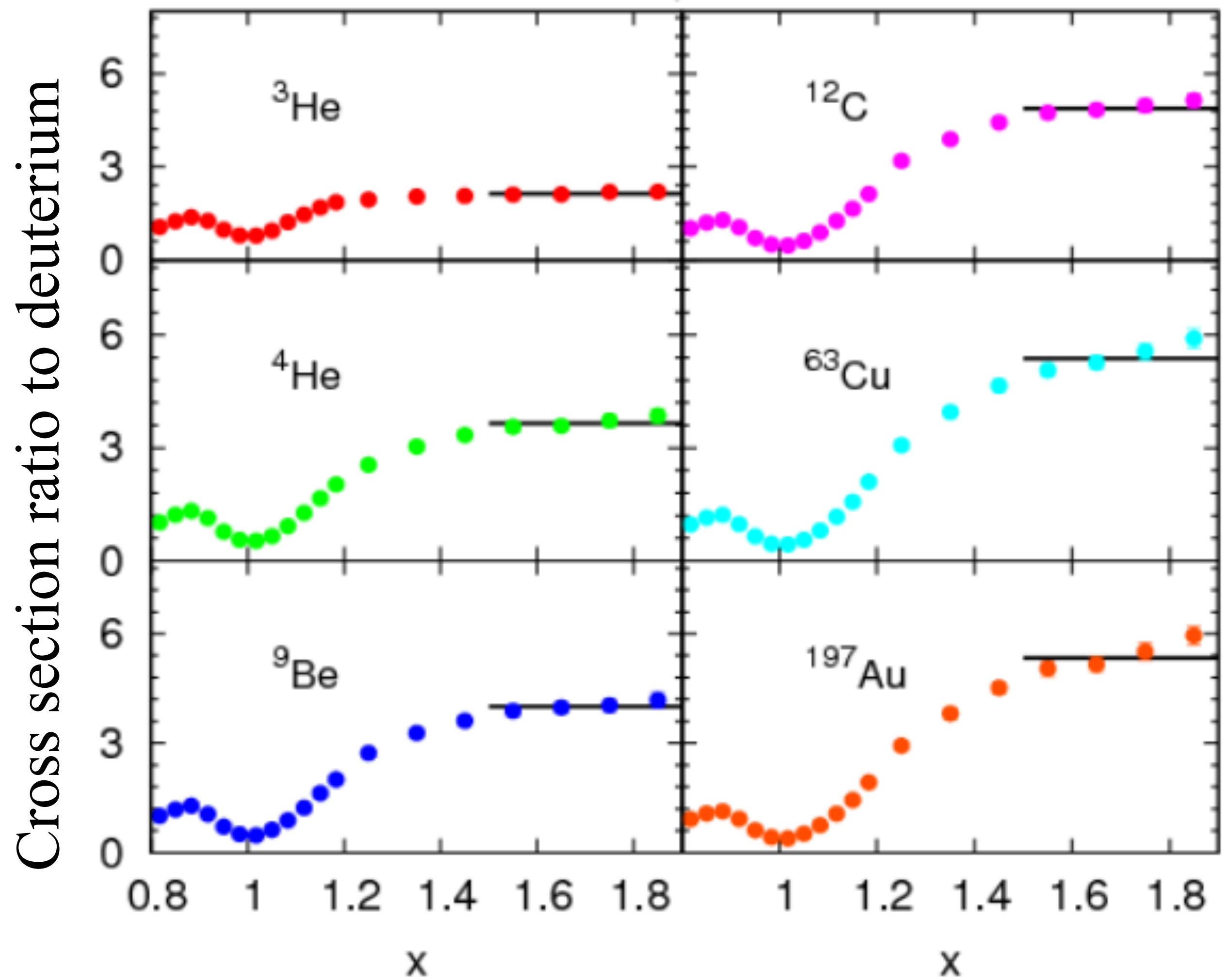
$x = Q^2/2m\nu$

Measure at fixed Q^2.
Choose $x > 1.5$ to select high p

O. Benhar, Phys Lett B **177** (1986) 135
C. Ciofi degli Atti, Phys Rev C **53** (1996) 1689.

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 $n(p)$

$1.5 < x < 2$: dominated by 2N SRC

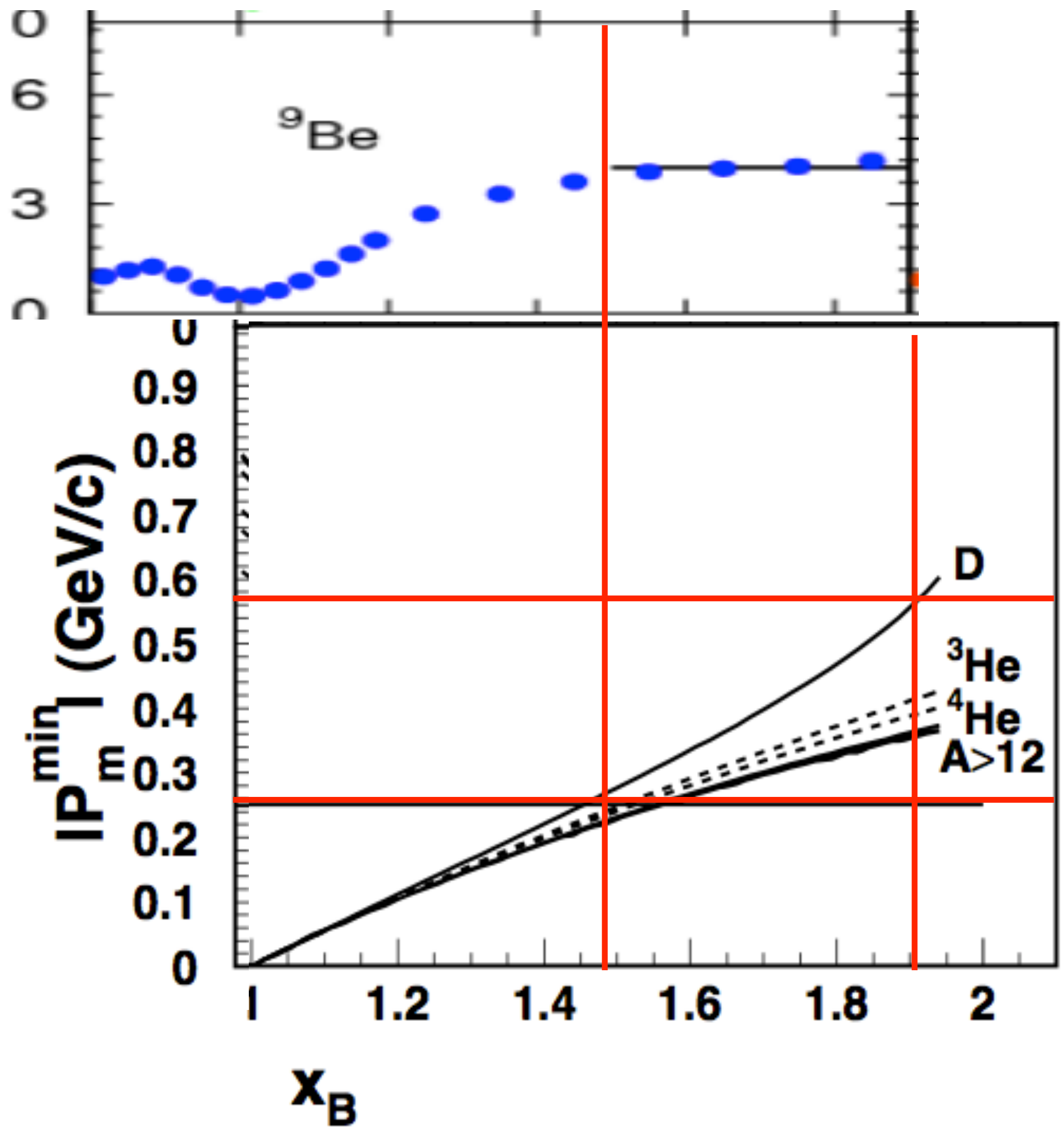
$\alpha_{2N} \approx 20\%$ for $A \geq 12$

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

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

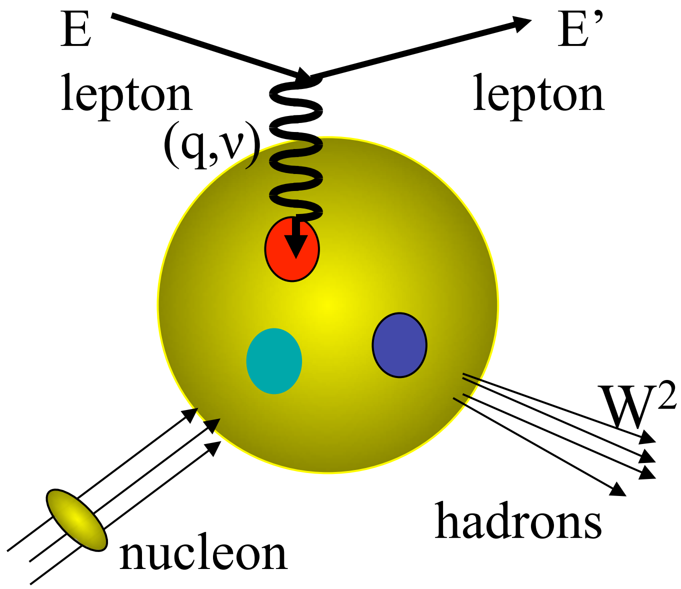
See Fomin talk today

Momentum range of plateau



275 to 600 MeV/c

Deep Inelastic Scattering: the EMC Effect



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

$$\nu = E' - E$$

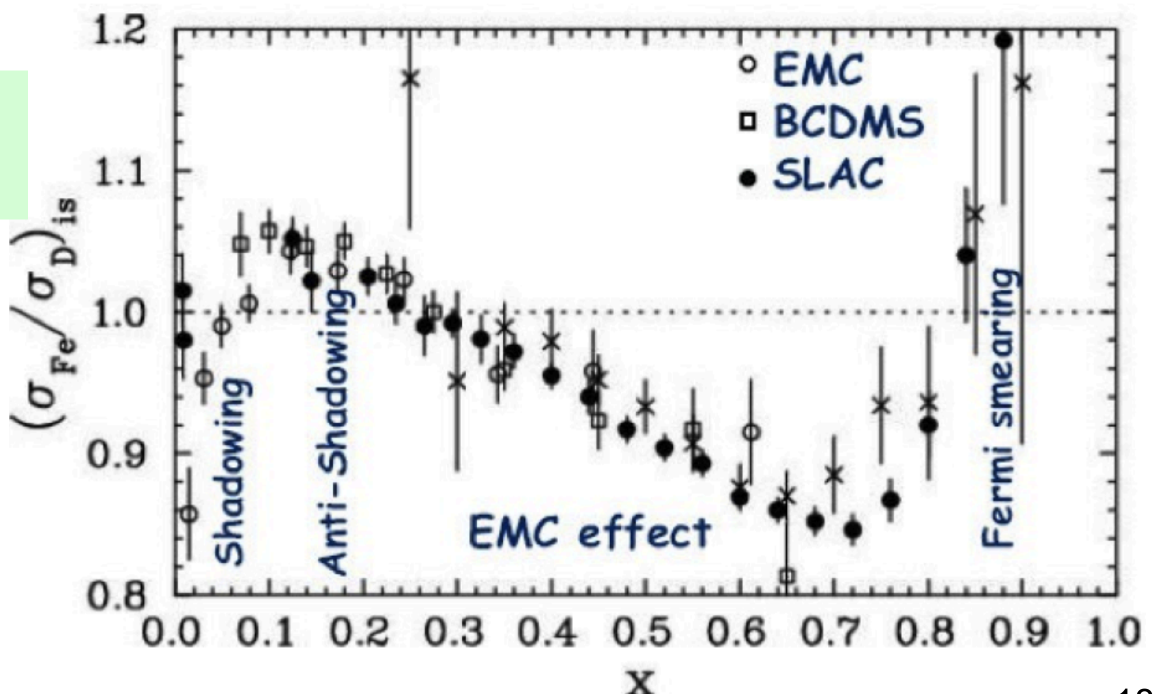
$$0 < x = \frac{Q^2}{2m\nu} < 1$$

- 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

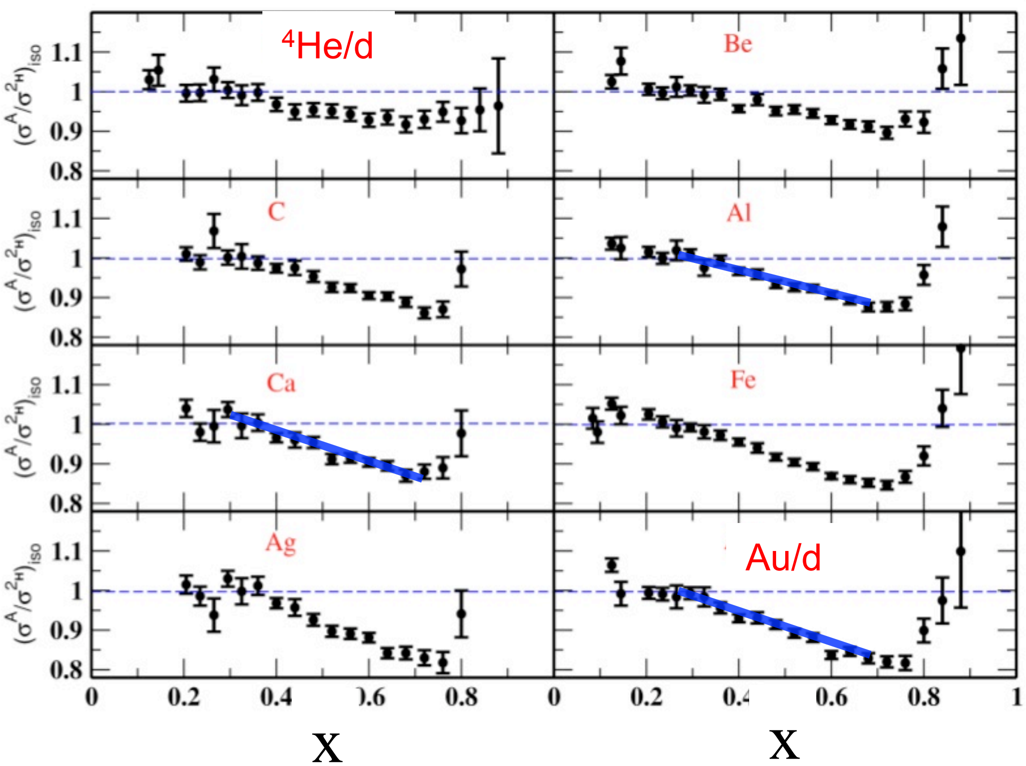
Origin of EMC effect unknown.
Nucleon modification needed.
$\approx 10^3$ publications



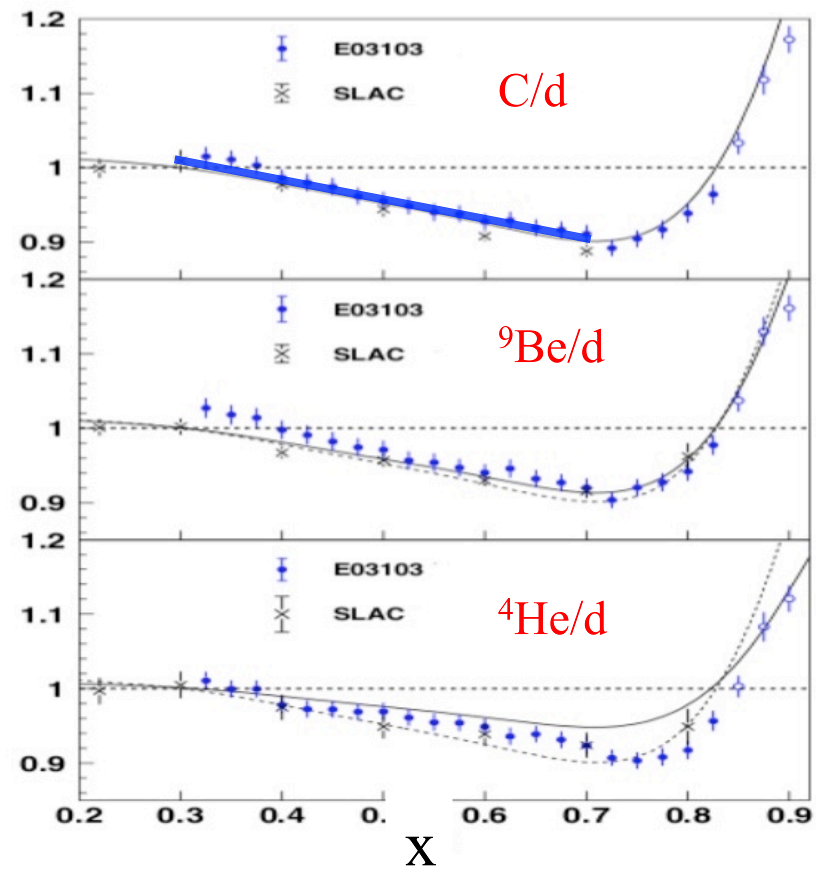
EMC Effect: Universal

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

SLAC



JLab



Very linear for $0.3 < x < 0.7$

(the lines shown are not fits)

J. Seely, PRL 103, 202301 (2009)

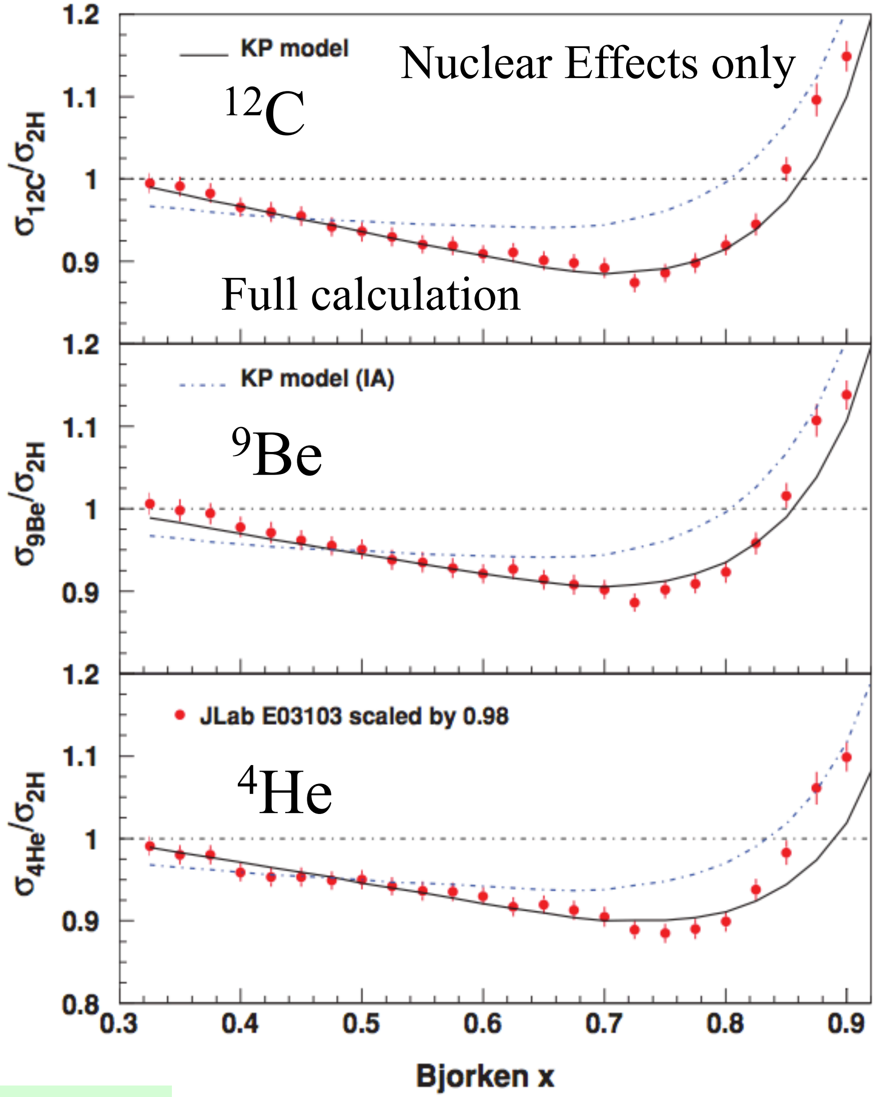
J. Gomez, PRD **49**, 4348 (1994).

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

EMC Effect: Theory

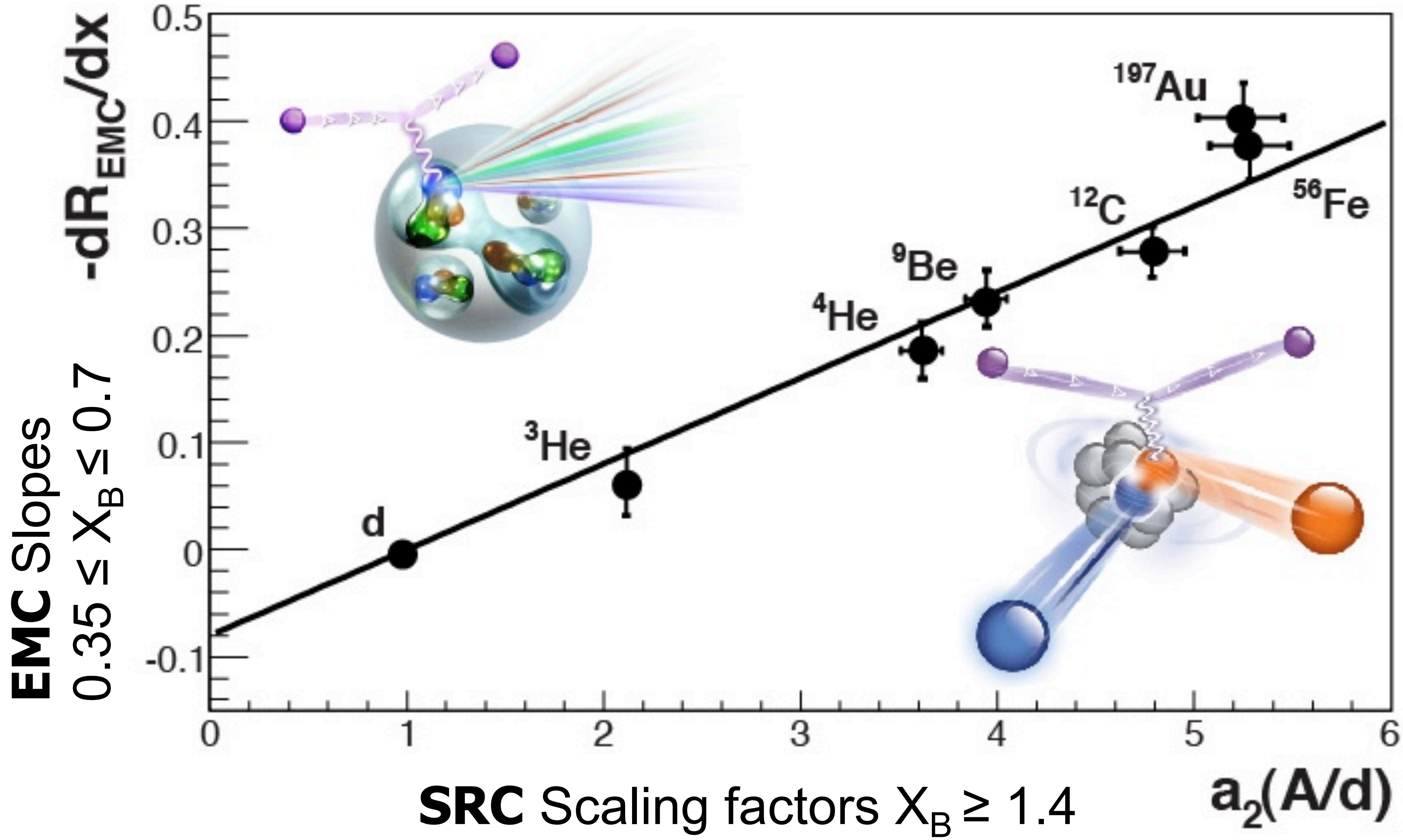
- Nuclear Effects:
  - Fermi motion
  - Binding energy
- Full Calculation
  - Nucleon modification
  - Nuclear pions
  - shadowing

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



Nucleon modification needed to describe data

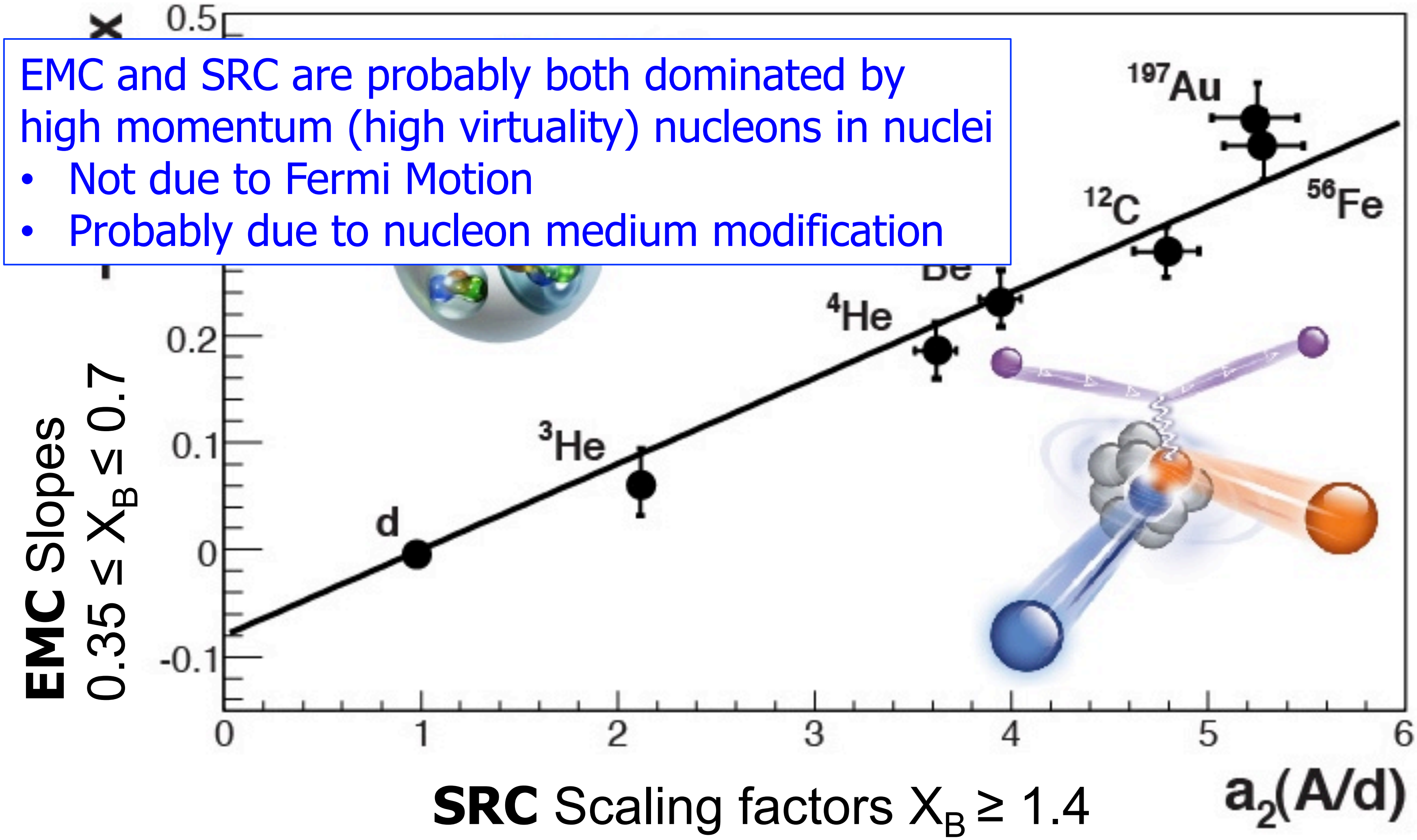
Kulagin and Petty, PRC 82, 054614 (2010)



Weinstein et al, PRL**106**, 052301 (2011)
Hen et al, PRC**85**, 047301 (2012)
SRC data from Fomin et al
EMC data from Gomez et al and Seely et al

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



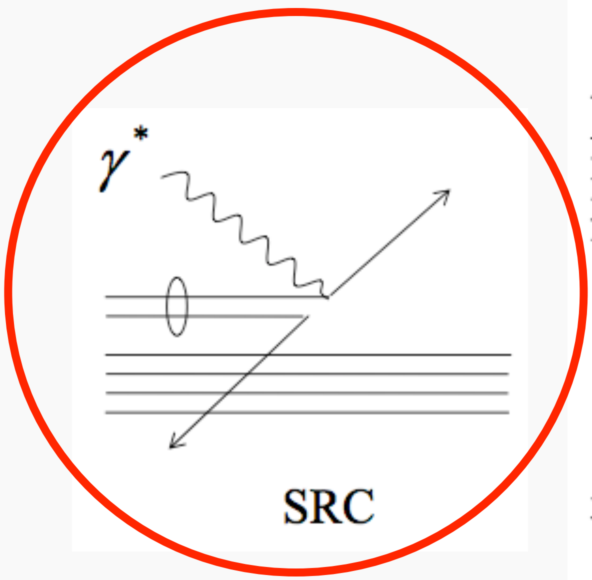
Weinstein et al, PRL**106**, 052301 (2011)
Hen et al, PRC**85**, 047301 (2012)
SRC data from Fomin et al
EMC data from Gomez et al and Seely et al

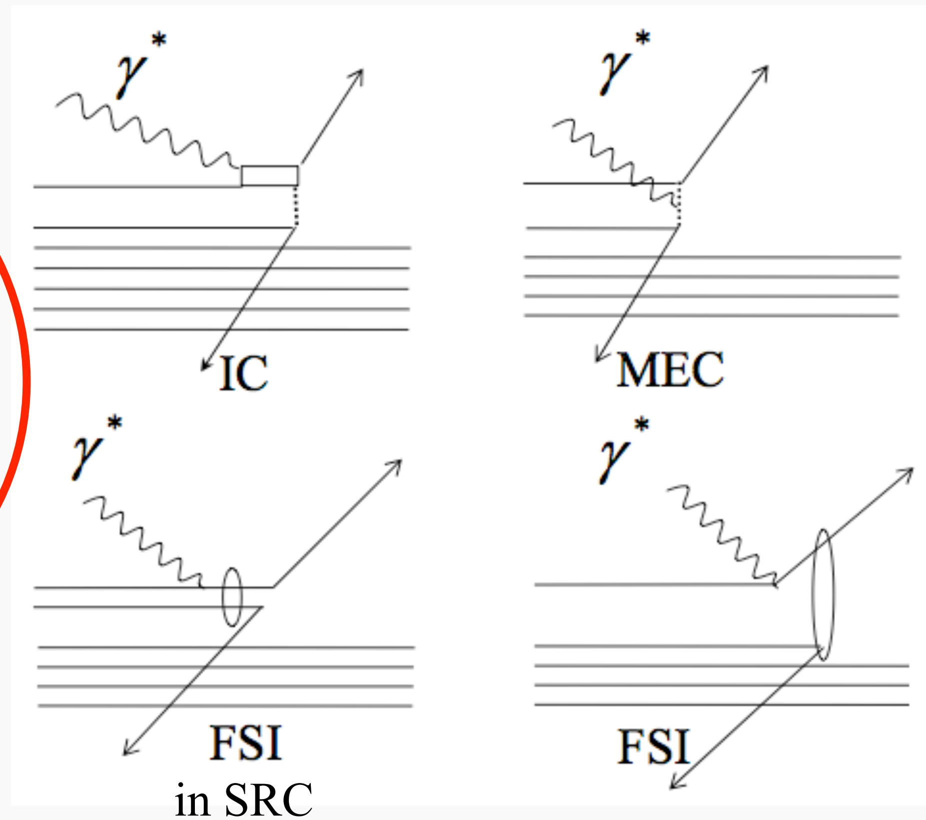
See Arrington, Hen, Keppel and Gilad talks

What are correlations?

Average Two-Nucleon Properties in the Nuclear Ground State

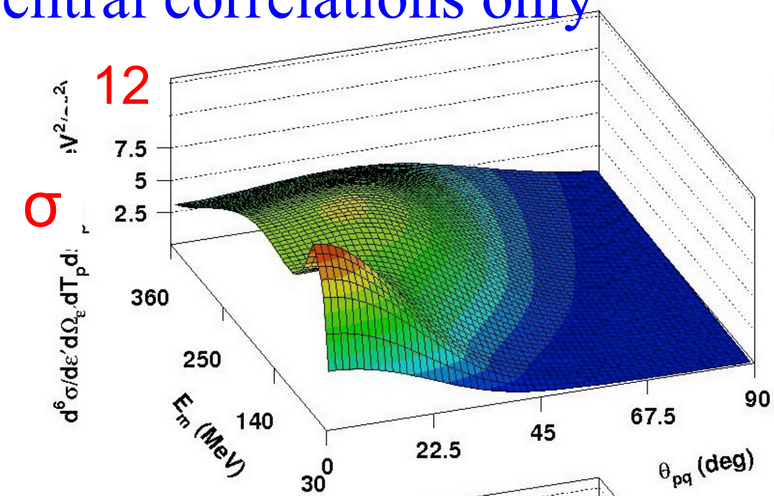
Two-body currents are not Correlations
(but add coherently)



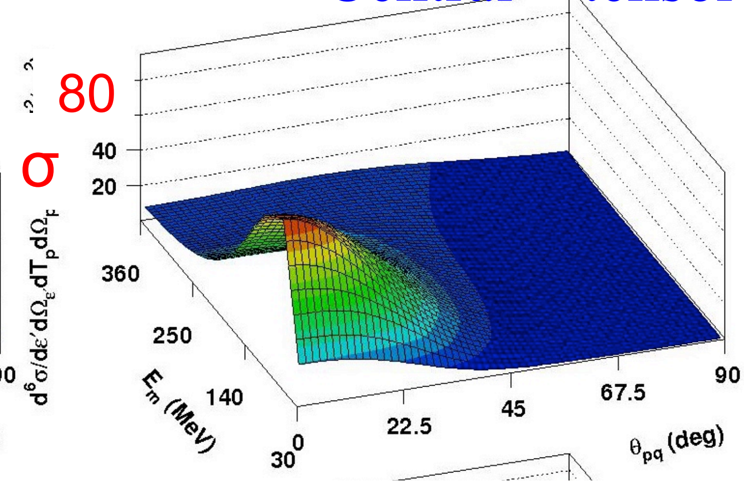


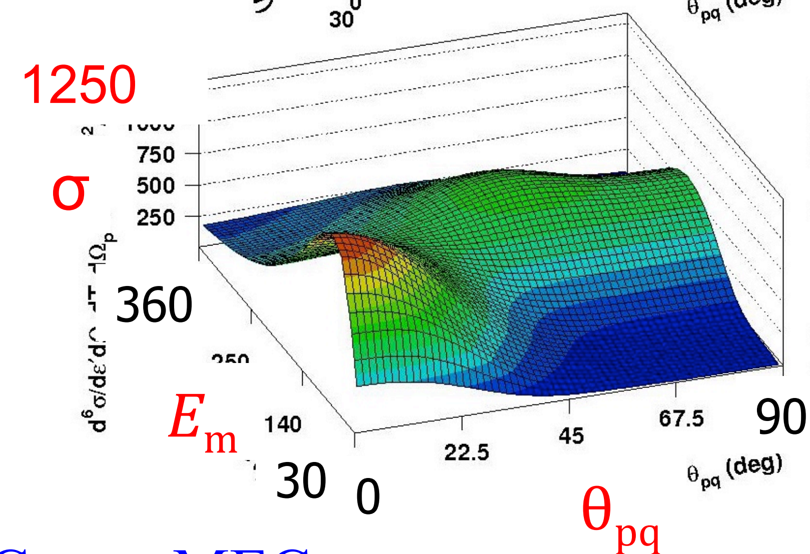
2N currents enhance correlations

Central correlations only



Central + tensor corr





Corr + MEC

O(e,e'p)
$q = 1$ GeV/c
$x \sim 1$

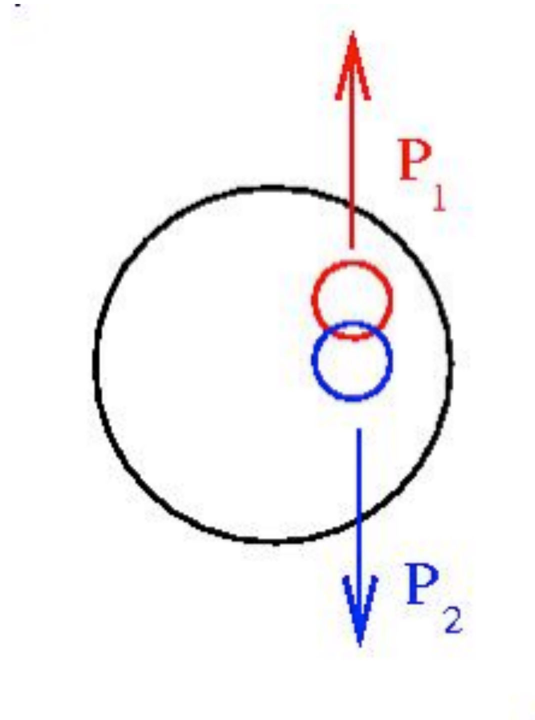
MEC changes the magnitude of the cross section,
not the distribution in E_{miss} vs Theta_{pq}

Janssen, NPA 672 (2000) 285

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



Jefferson Lab Site

Hall C

Hall B
CLAS

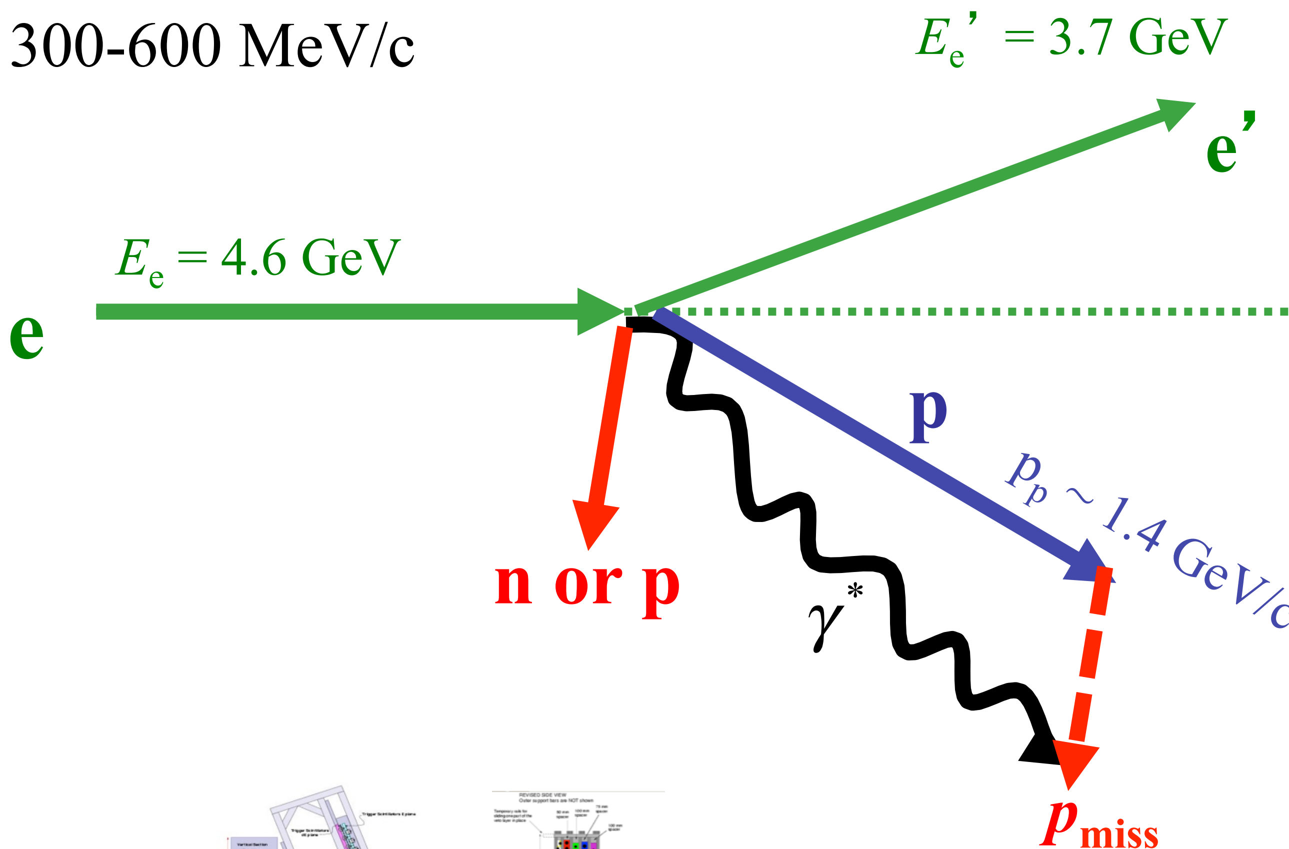
Hall A

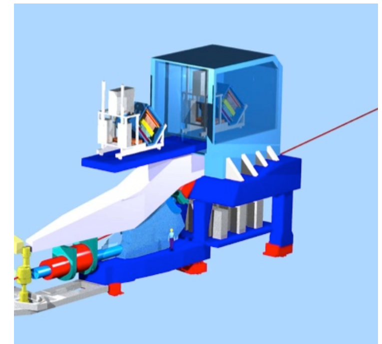
Now detect another nucleon
JLab Hall A C(e,e'pN) - selected kinematics

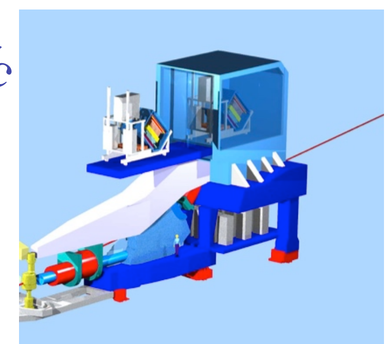
$Q^2 = 2\ \mathrm{GeV}^2$

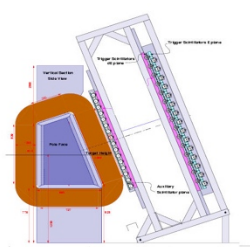
$x = Q^2/2m\nu = 1.2$

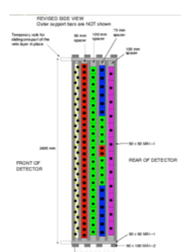
$p_{\mathrm{miss}} = 300\text{-}600\ \mathrm{MeV/c}$











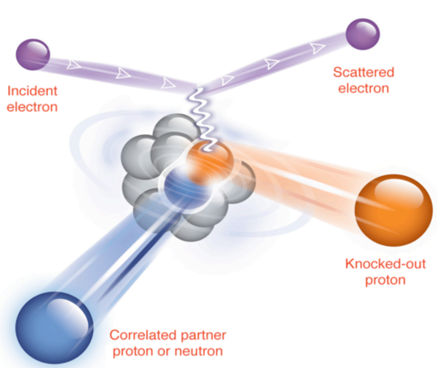
Detect the proton,
look for its partner nucleon

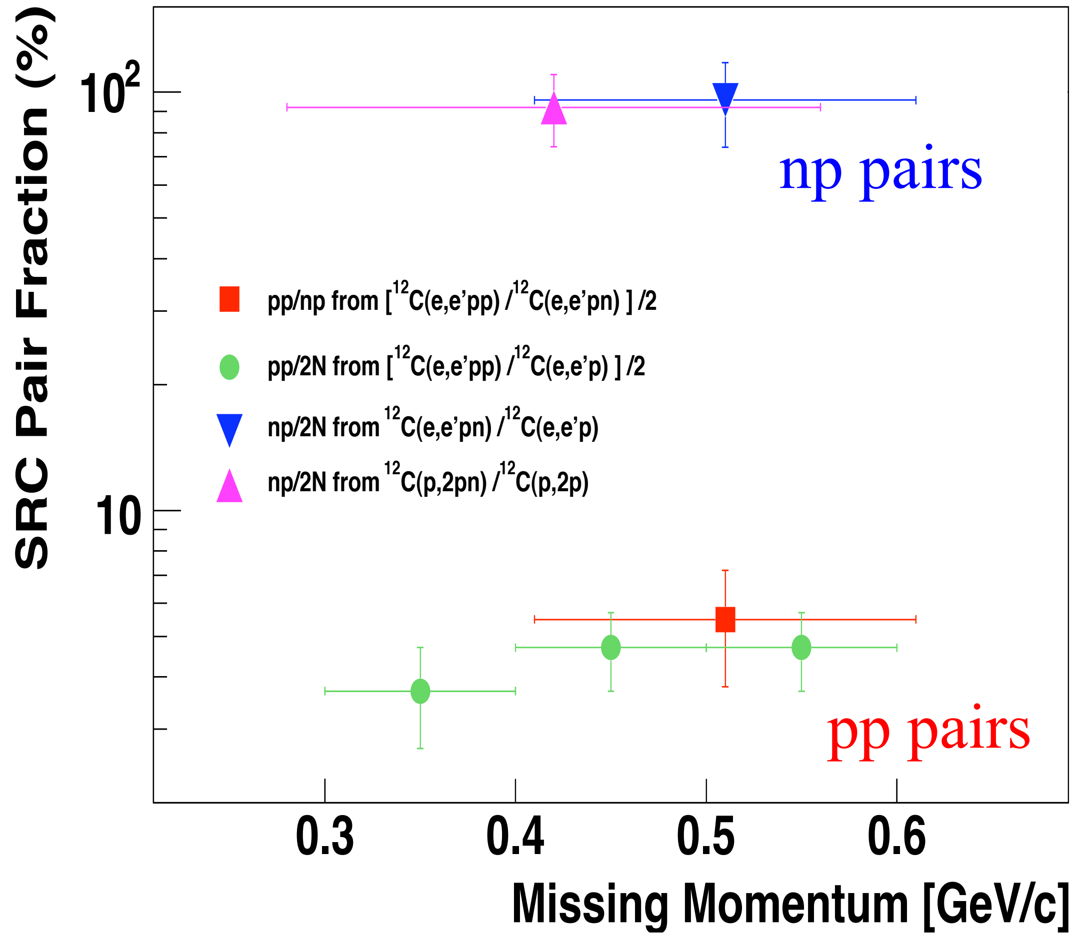
High momentum protons have partners C(*e,e'pN*)

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

➔ np pairs dominate at

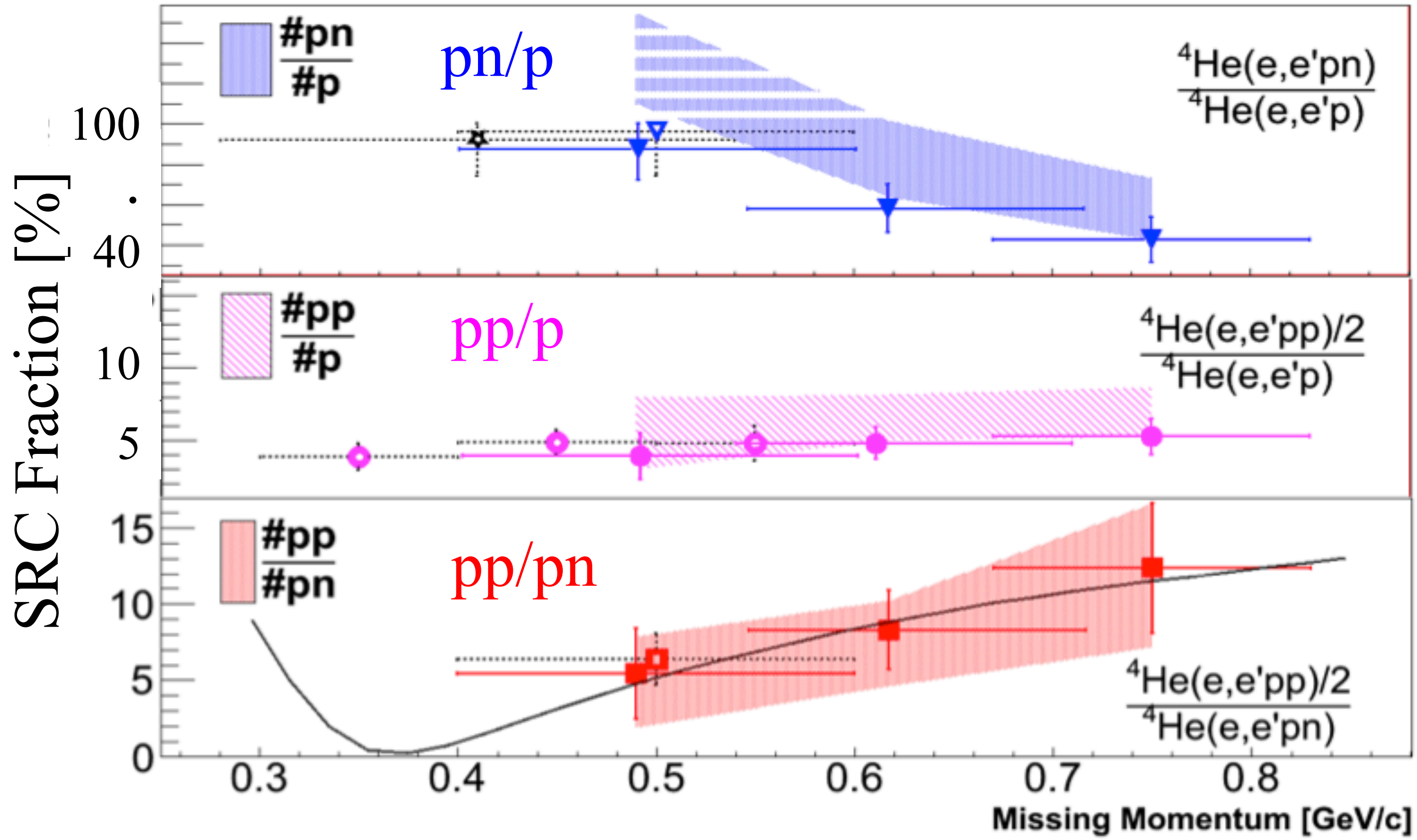
$0.3<p_i<0.6$





R. Subedi et al., Science **320**, 1476 (2008)
R. Shneor et al., PRL **99**, 072501 (2007)

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???

See Korover talk Friday

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

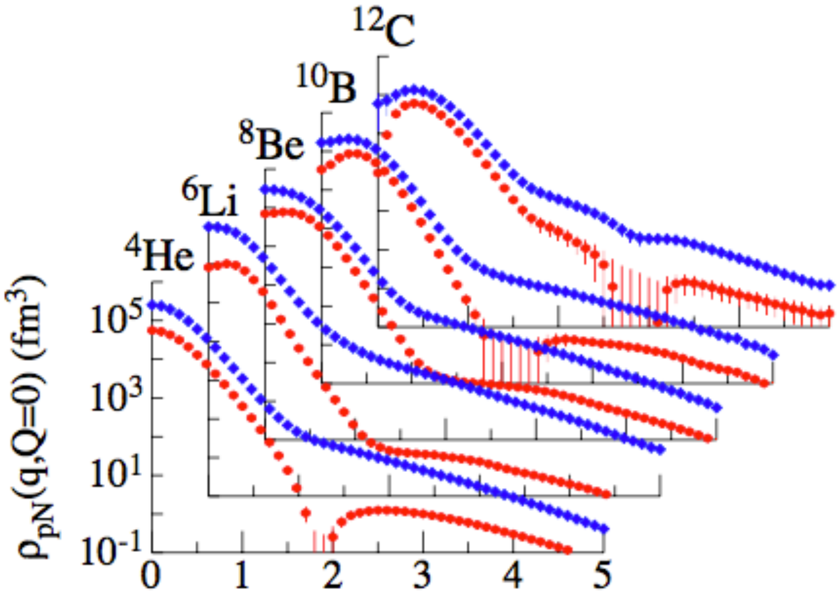
The ratio of pp-SRC / pn-SRC pairs in ^{12}C

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

Why ?

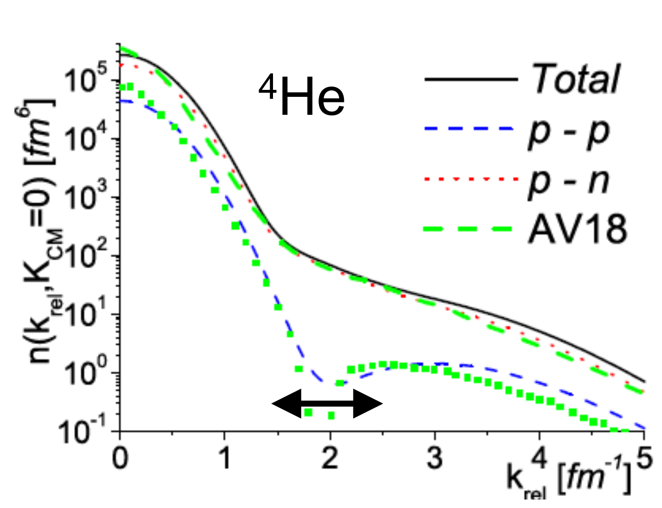
At p_{rel} = 300-500 MeV/c the s-wave momentum distribution has a minimum

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



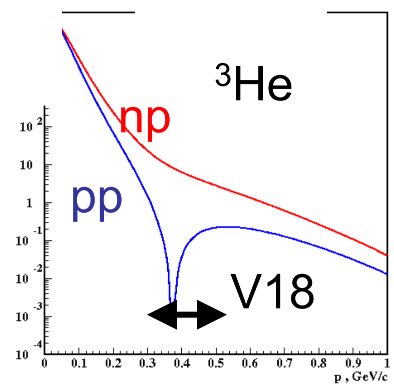
Pair relative momentum (fm-1)

Carlson et al., RMP **87** (2015) 1067



Pair relative momentum

Ciofi degli Atti and Alvioli
Gent workshop, Aug. 2007



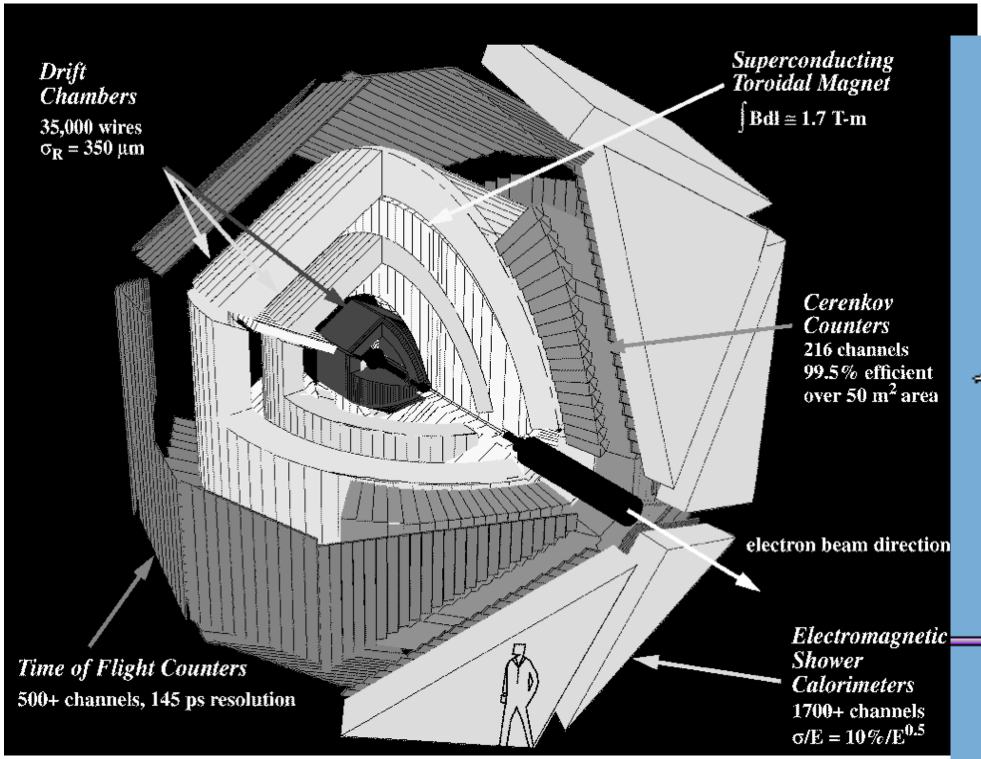
Pair relative momentum

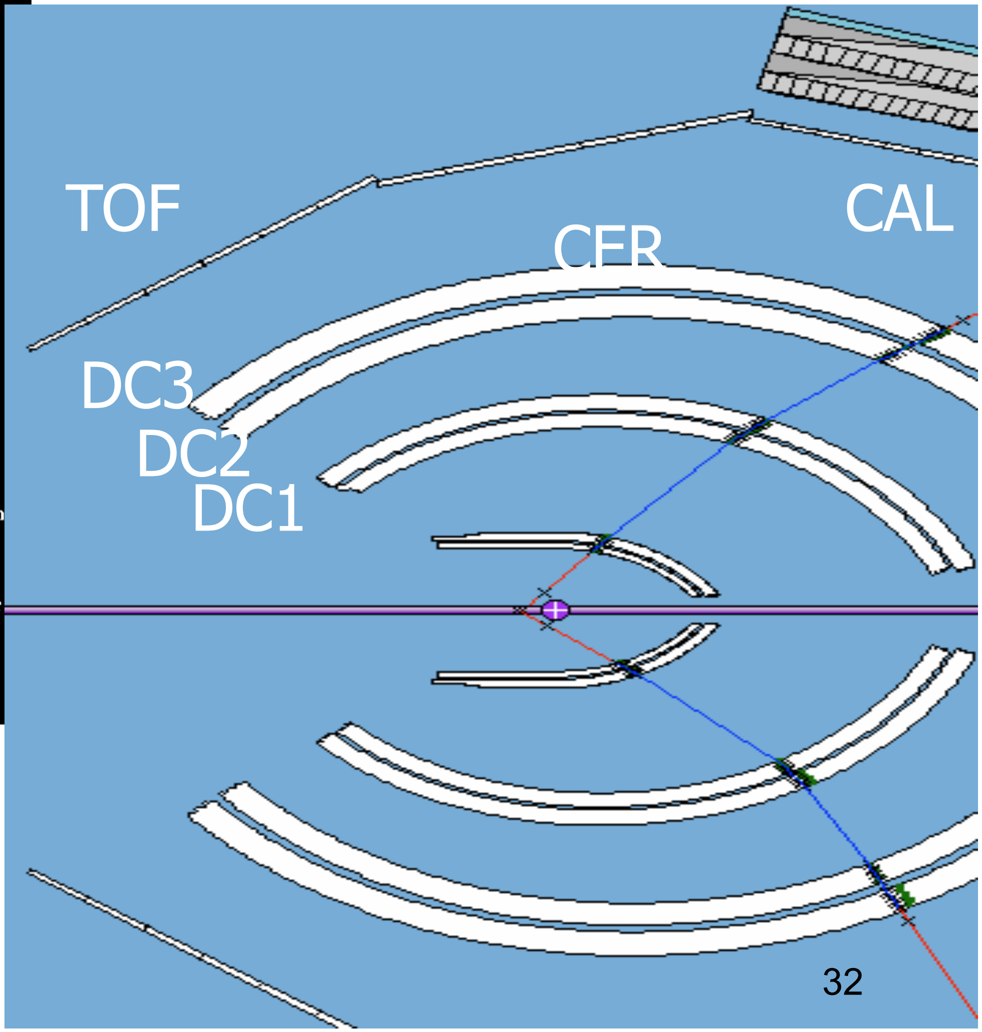
See talk by Ciofi degli Atti next

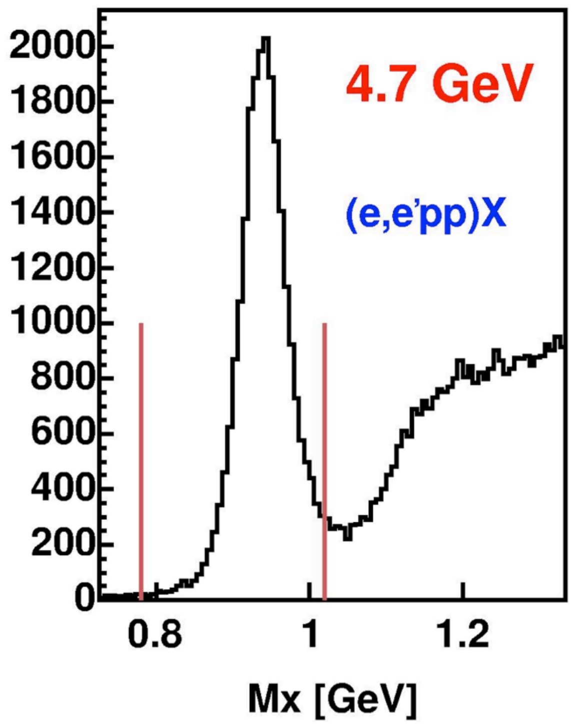
Sargsian, Abrahamyan, Strikman, Frankfurt PRC **71,** 044615 (2005).

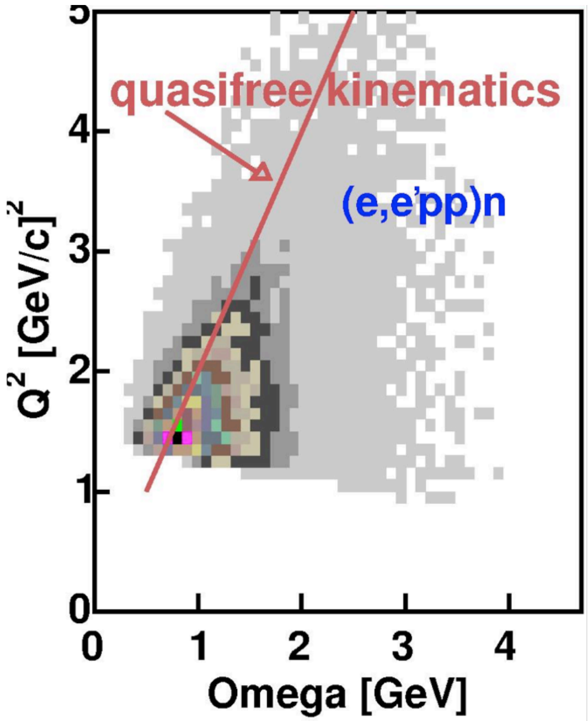
^{3}He(e,epp)n in CLAS

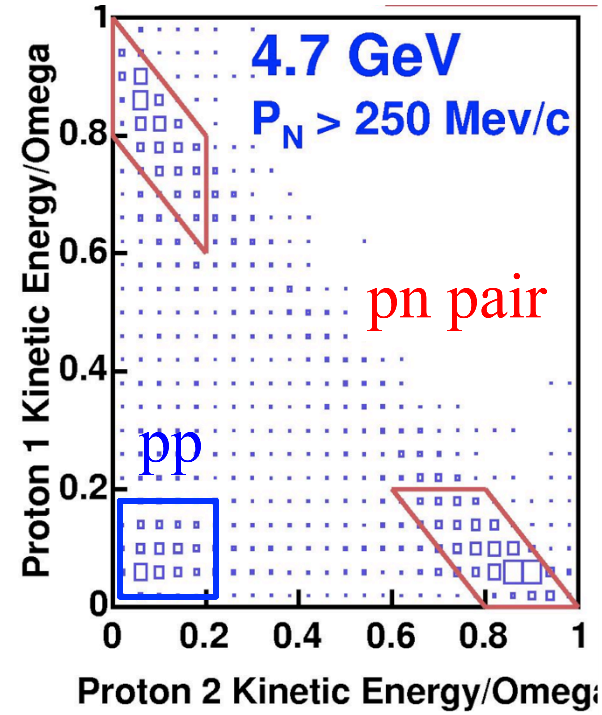
- 2 and 4 GeV electrons
- Inclusive trigger
- Almost 4π detector

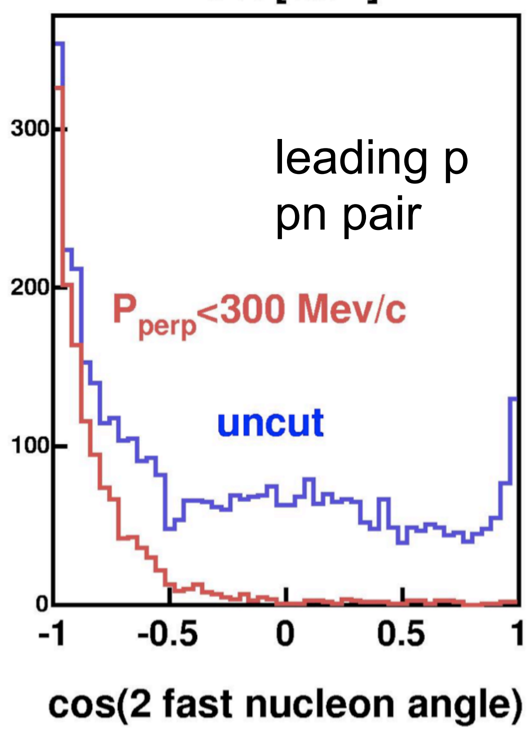




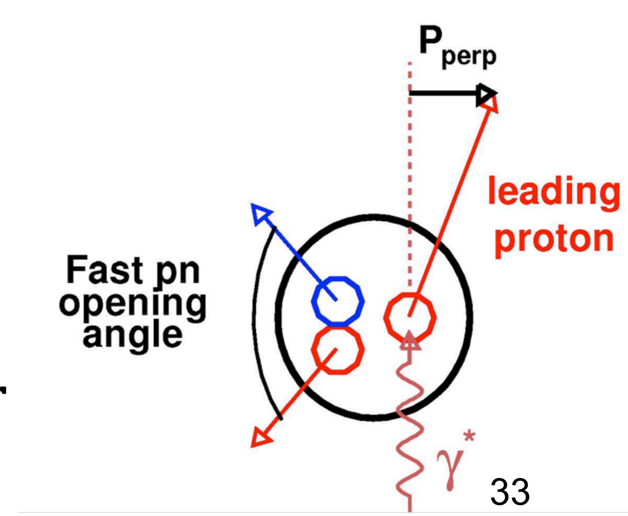




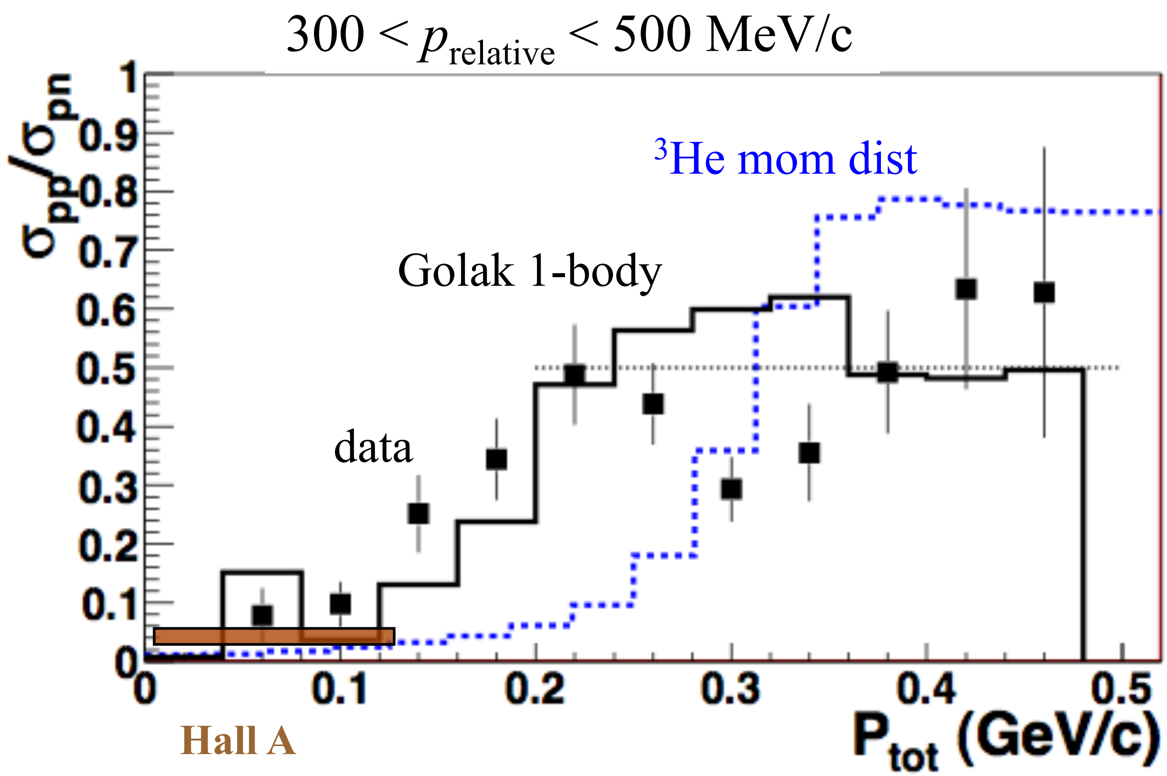




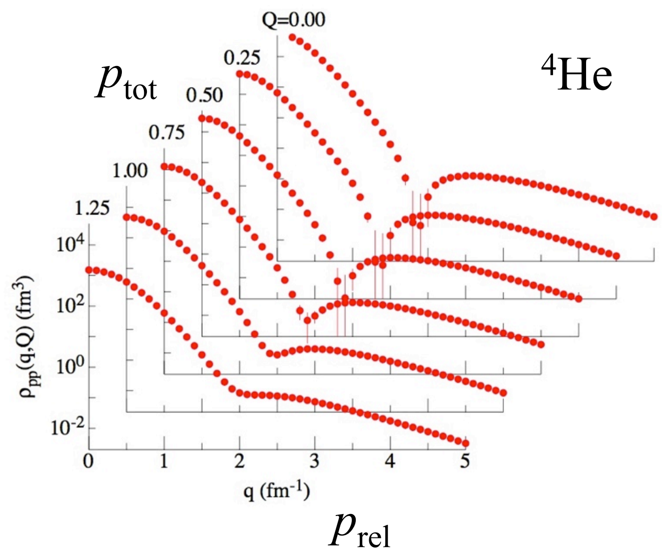
- Detect two protons
- Reconstruct the neutron
- Select peaks in Dalitz plot
- Remaining *NN* pair is back to back



pp/pn ratio and pair total momentum



Wiringa et al, PRC 89 (2014) 024305



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

Baghdasaryan, et al., 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

$x_B > 1.2$

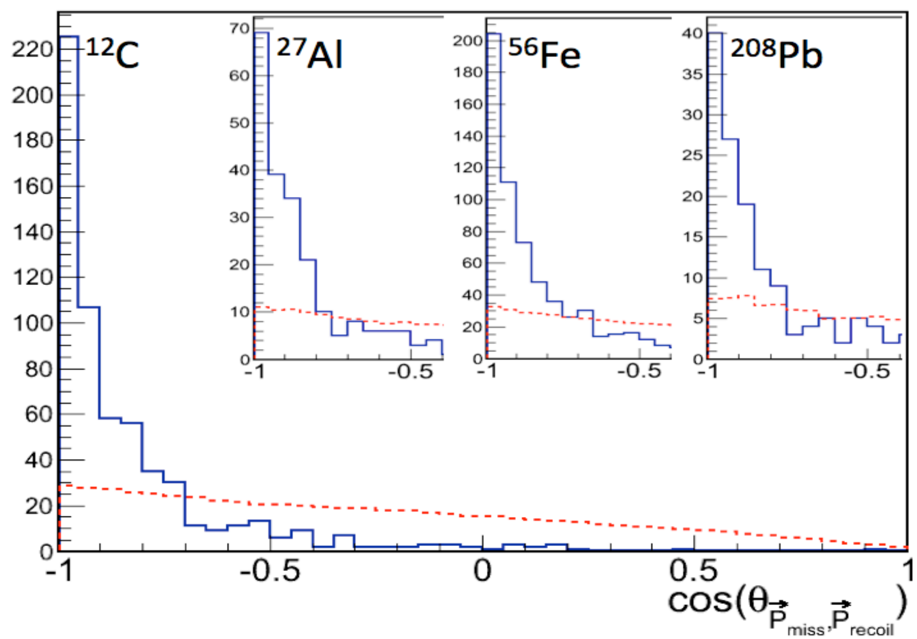
$\rightarrow Q^2 > 1.5$ GeV^2

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

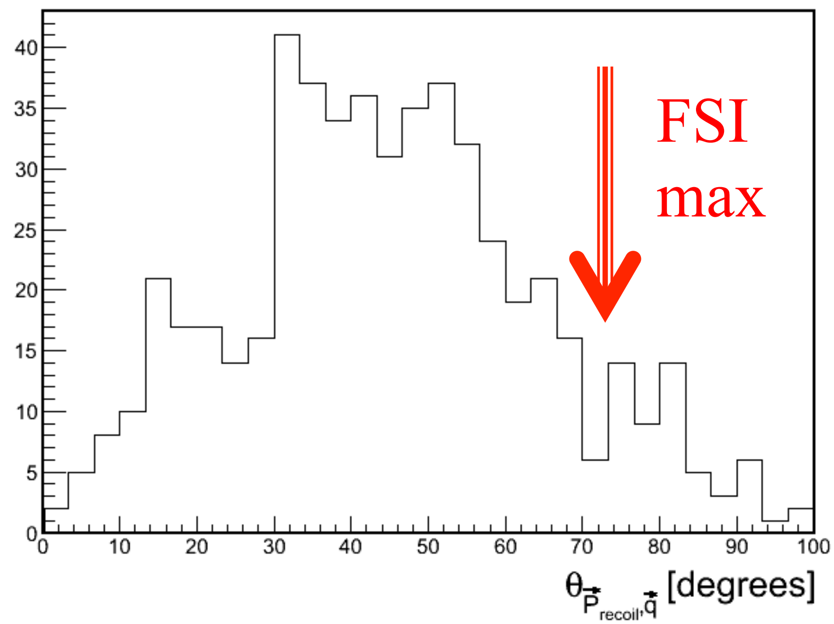
$\theta_{pq} < 25^\circ$

$p_p/q \geq 0.6$

(*e,e'pp*) angular distributions



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

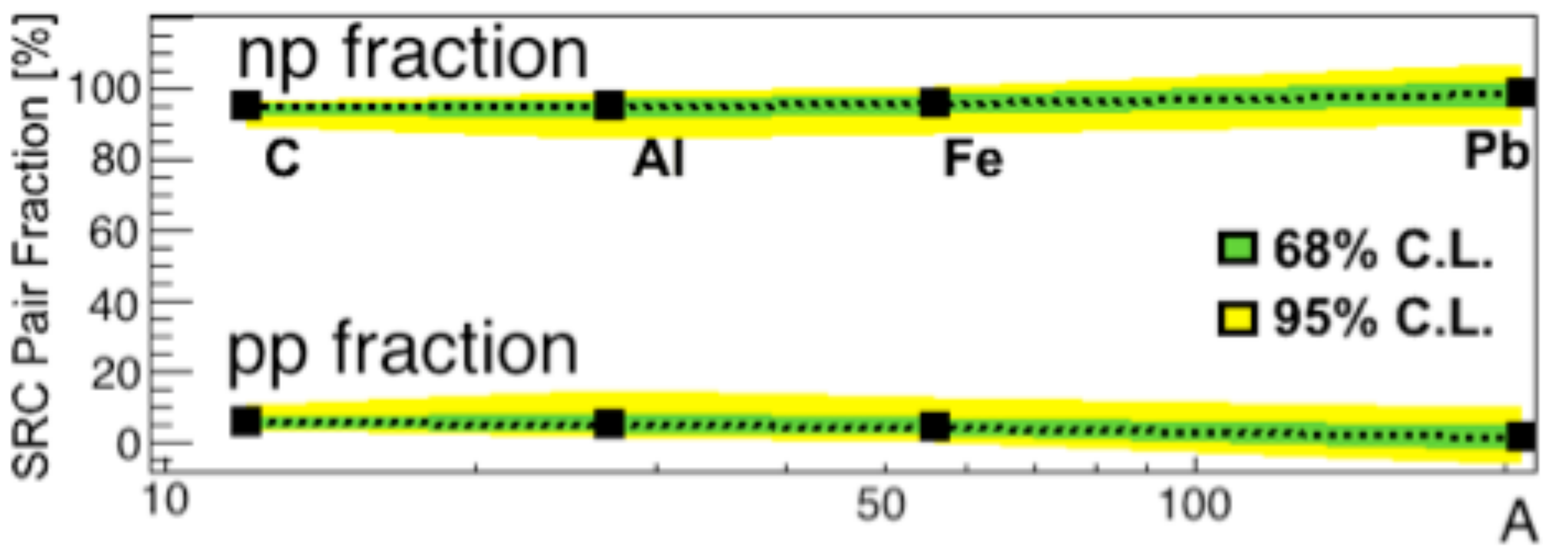


Angle between *q* and the recoil proton momentum

np and *pp* pairs

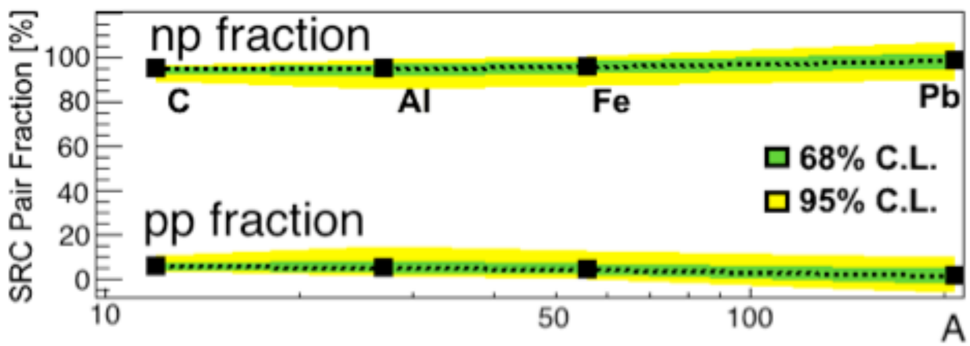
- Correct for proton rescattering via Glauber
- Assume all high-p_{miss} protons have a correlated partner
  - Use double ratio to get pp pair fraction
- ➔ High momentum tail still predominantly *np*

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

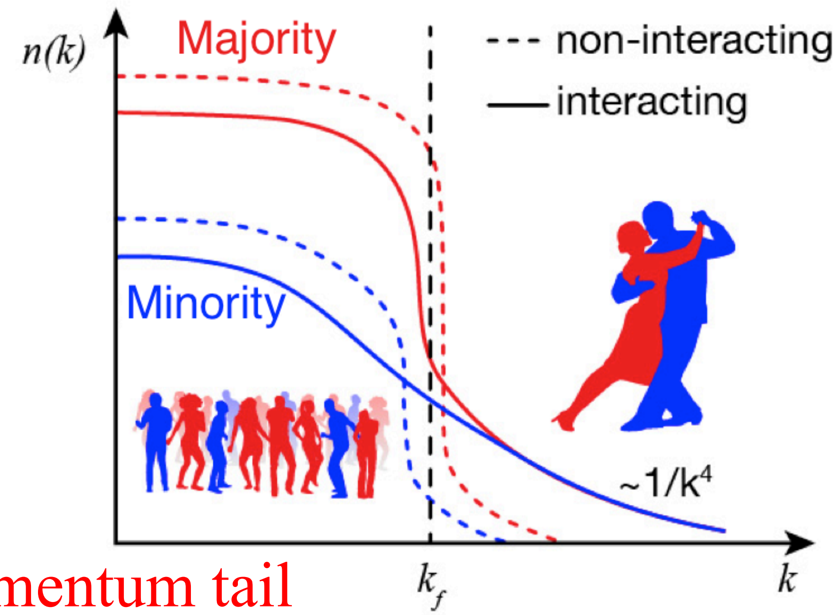


O. Hen *et al*, Science **346** 614 (2014)

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 (see Bao-An Li talk)
- Isospin dependence of the EMC effect
- Understanding neutrino-nucleus scattering
  - Extra energy at the interaction vertex?

Tan's Contact

- Externally-confined interacting Fermi gas with short-range interaction between unlike fermions:

$$a \gg d \gg r_{eff}$$

- Amplitude of the high-*k* tail of the momentum distribution $n(k)$

$$n(k) = Ck^{-4} \;\rightarrow\; C = \lim_{k\rightarrow\infty} k^4 n(k)$$

- Thermodynamics of system described by C
  - Kinetic plus interaction energy
  - Short distance density-density correlator
  - Dependence of energy on the inverse scattering length
  - Virial theorem
  - Pressure and energy density

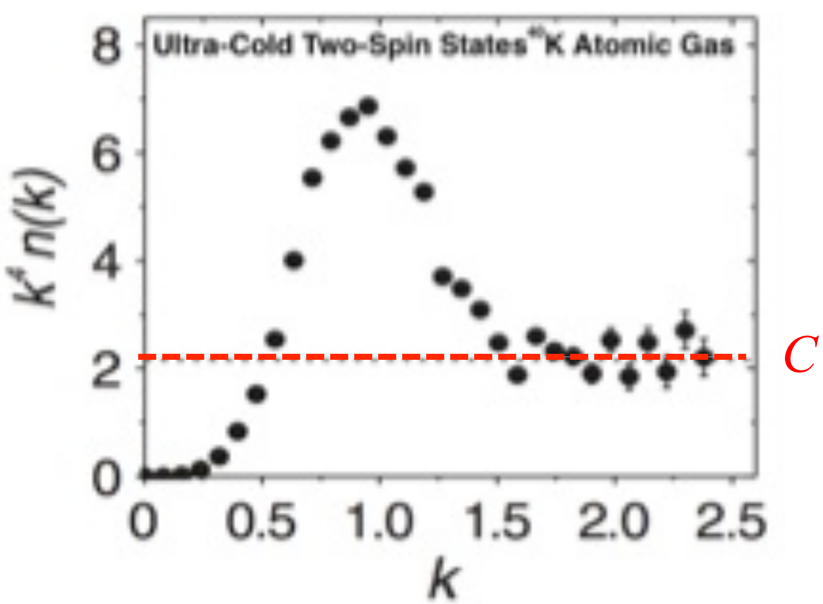
S. Tan, Annals of Physics **323**, 2952 (2008); Ibid., p. 2971; Ibid., p. 2987.
E. Braaten, Lect. Notes Phys. **836**, 193 (2012).

neV Correlations and Tan's Contact

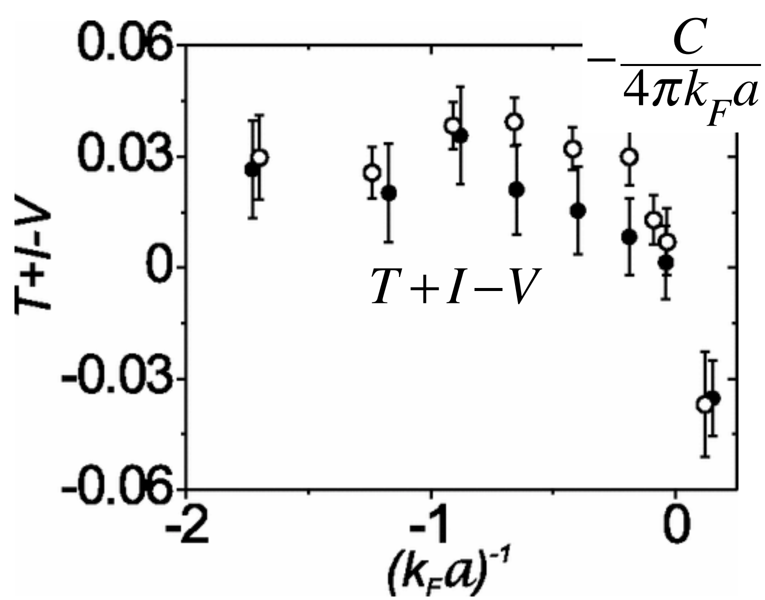
- Trap ultra-cold fermionic ^{40}K atoms
  - Optical dipole trap
  - Two spin states
  - *s*-wave scattering length between unlike spin-states $a = 800a_0$

k_F = 1.6 eV/c
$E_F = k_F^2/2m \approx 30$ peV

Measuring the Contact C



The Virial Theorem



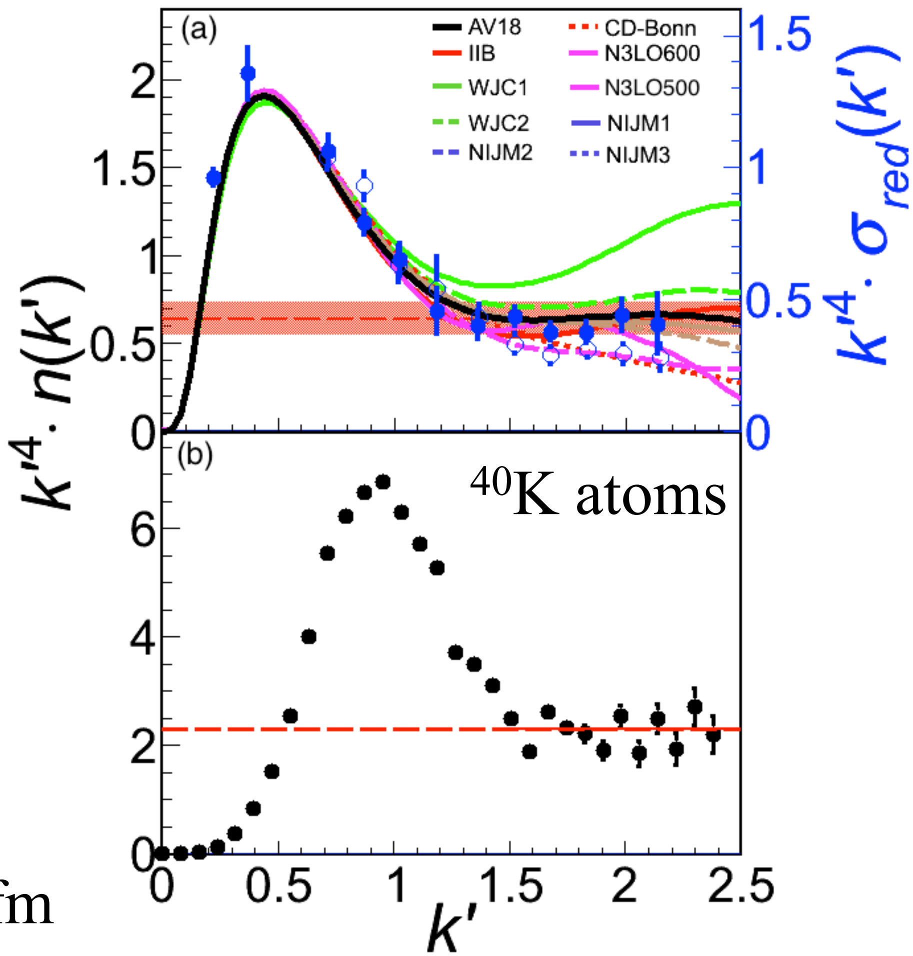
Stewart et al, PRL **104** (2010) 235301

Nuclei and Tan's Contact

- High momentum tail due to unlike-fermion (proton-neutron) pairs
  - $^3S_1$ pairs made into $L = 2$ via tensor interaction
- But *NN* interaction is very complicated
  - Interplay of central and tensor terms
  - Tensor part:

$$a \approx 5.4\ \text{fm} \not\gg d \approx 2\ \text{fm} \not\gg r_{eff} \approx 0.7\ \text{fm}$$

deuteron



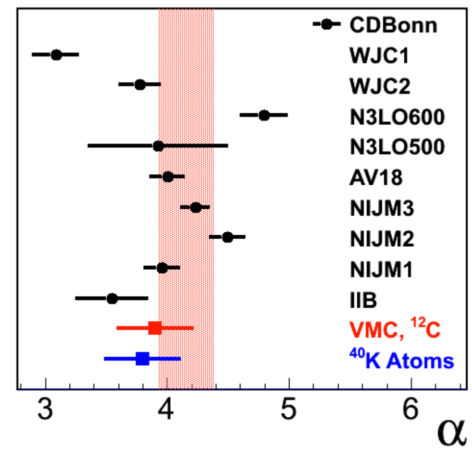
Hen, PRC, in press

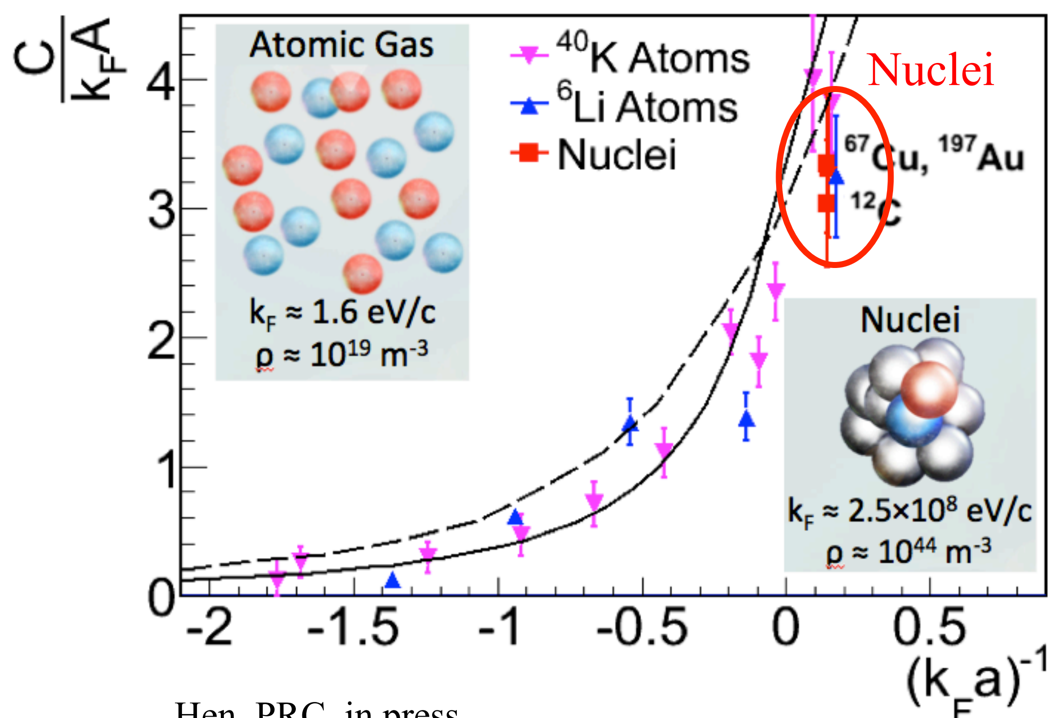
Nuclei and Tan's Contact

- Deuteron $k^4 n(k)$ is flat
  - ➔ contact $C_d = 0.62$
- High momentum tail in nuclei
  - proportional to deuteron
  - Dominated by *np* (unlike fermion) pairs

$$a_2(A) = \frac{2}{A}\frac{\sigma_A(e,e')}{\sigma_d(e,e')}$$

- $C_A = C_d \times a_2(A)$





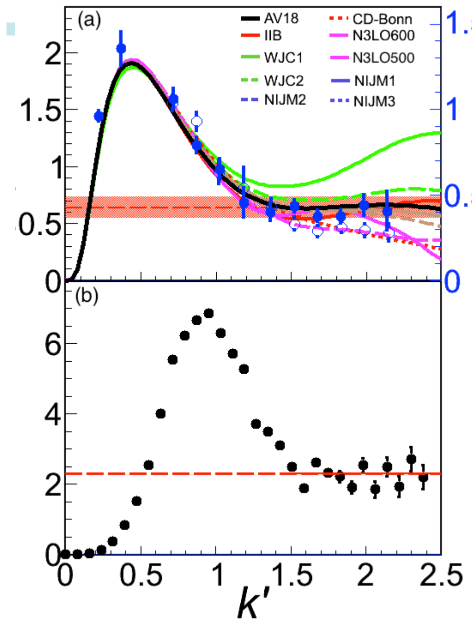
Hen, PRC, in press

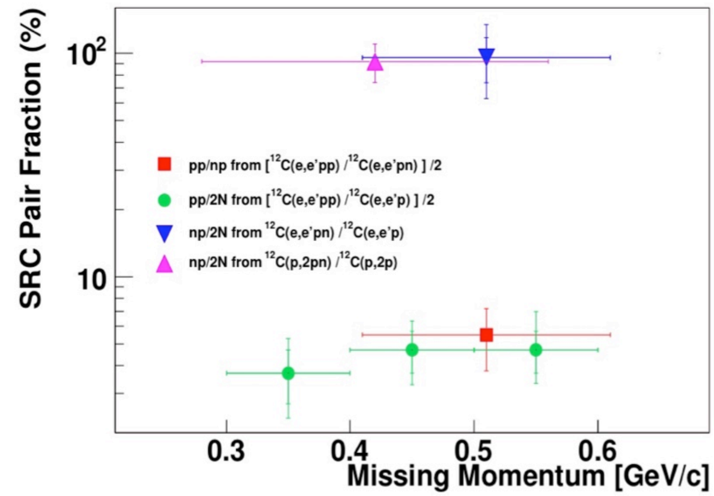
Can we learn anything by applying the Tan Contact to nuclei?

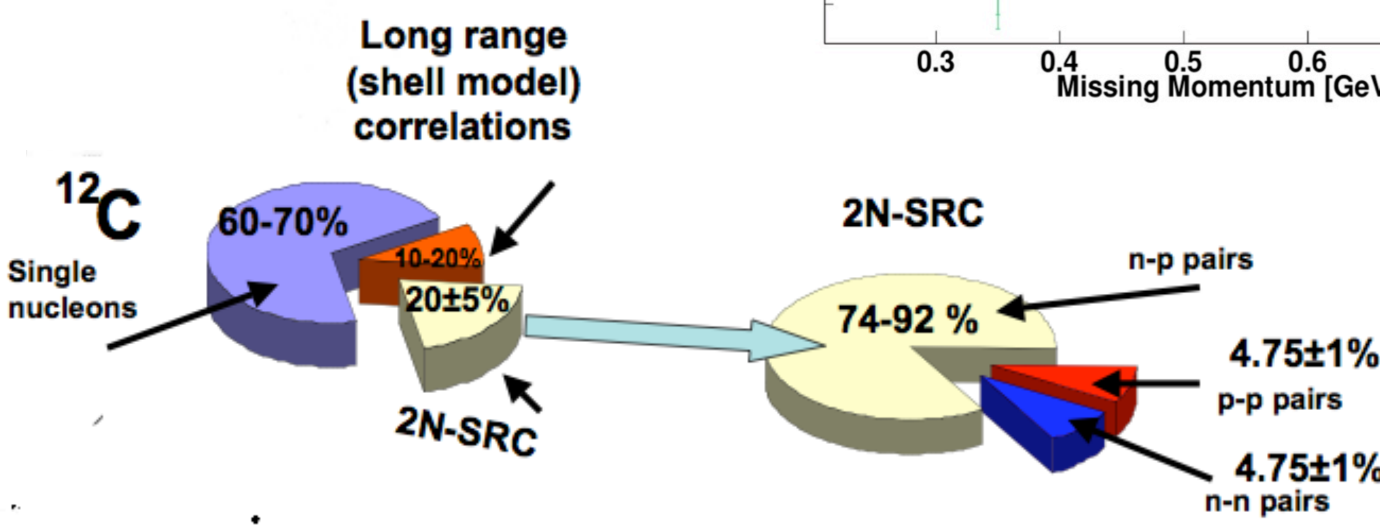
Summary: Correlations in nuclei

- Almost all high momentum nucleons (p > 300 MeV/c) in nuclei belong to an *NN* correlated pair
  - 20% of all nucleons for A ≥ 12
  - Dominated by *pn* pairs, even in heavy asymmetric nuclei
  - Higher probability for minority to be at high p
  - Momentum distributions proportional to deuterium
- Connections to:
  - EMC Effect and nucleon modification in nuclei
  - The nuclear symmetry energy
  - Two component atomic systems

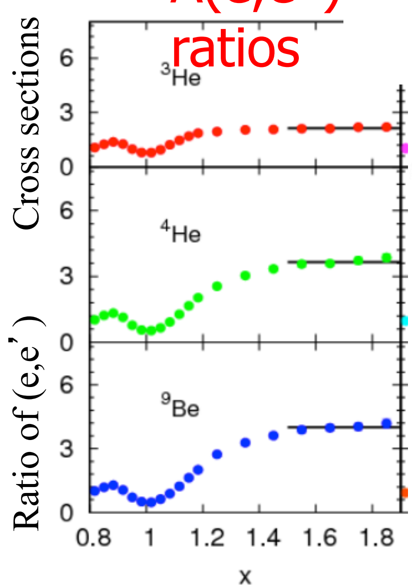
Summary

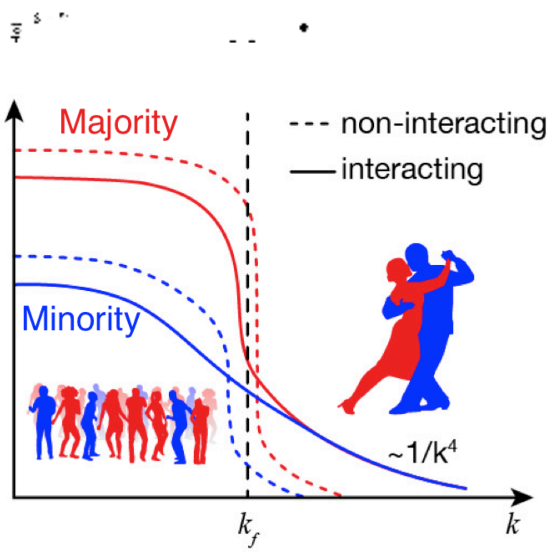


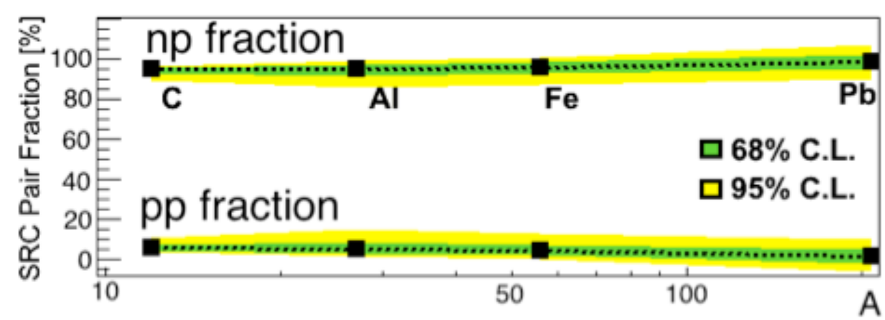




A(e,e') ratios







~20% SRC pairs

- ~90% tensor correlated np pairs