# High Momentum Components Scaling, and Short Range Correlations

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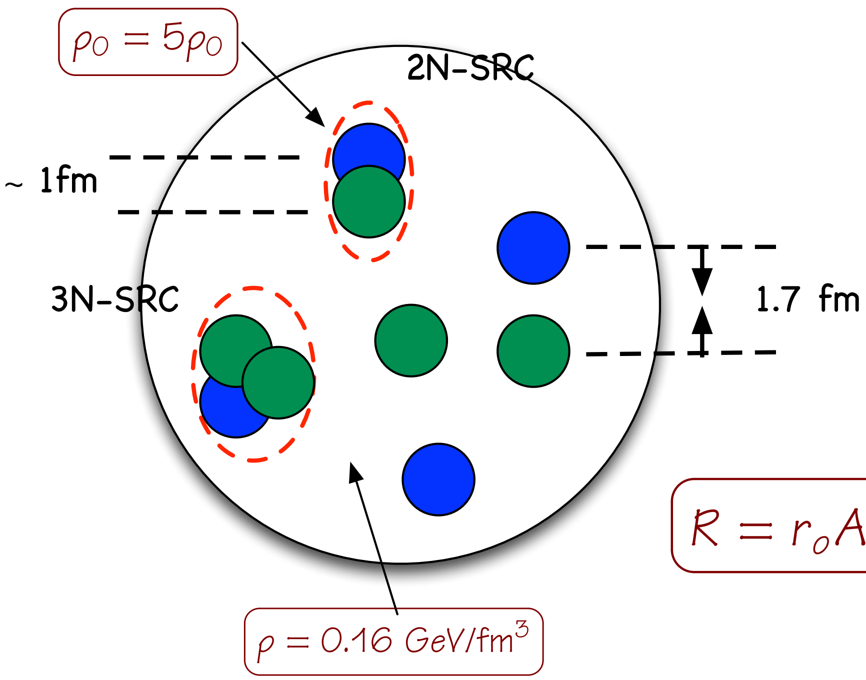
# Outline

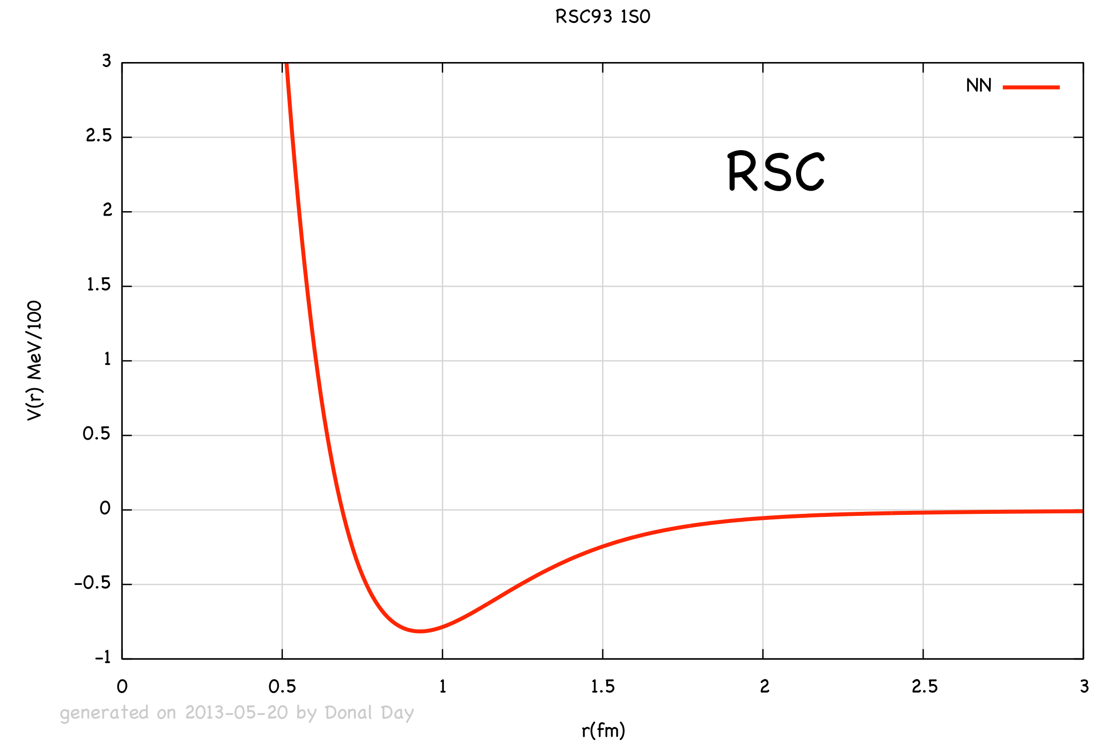
- IPSM
  - ‘Corrections’ to IPSM
- Correlations and high-k components in ground state
  - Universality
  - Inclusive A(e,e’)
    - y-scaling
    - Ratios
    - EMC and SRC
  - Exclusive A(e,e’p)
  - Triple Coincidence
    - Exclusive A(p,2pn), A(e,e’2N)
  - NN Potential
  - DIS at x > 1
- Summary

# Structure of the nucleus




$R = r_o A^{1/3}$

Nucleon separation is limited by the short range repulsive core



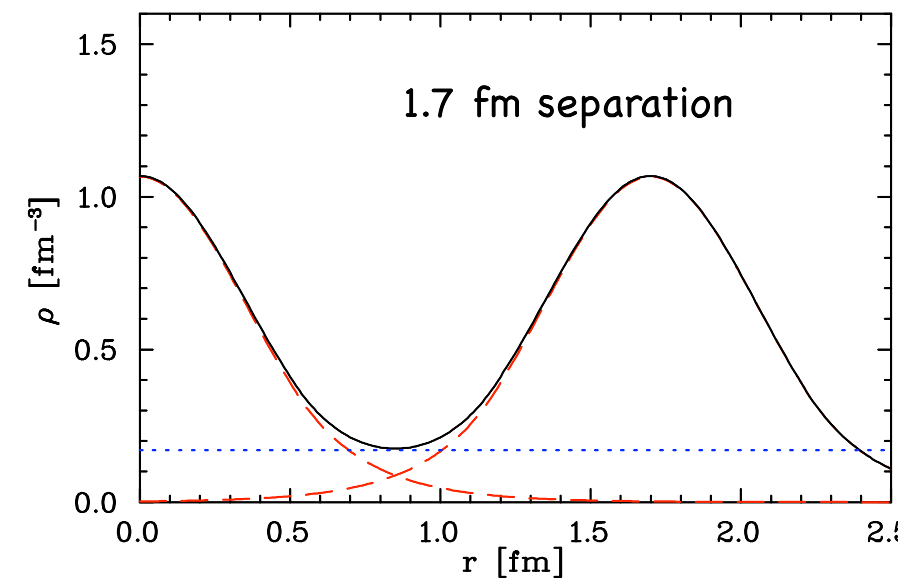

## Determined by N-N potential

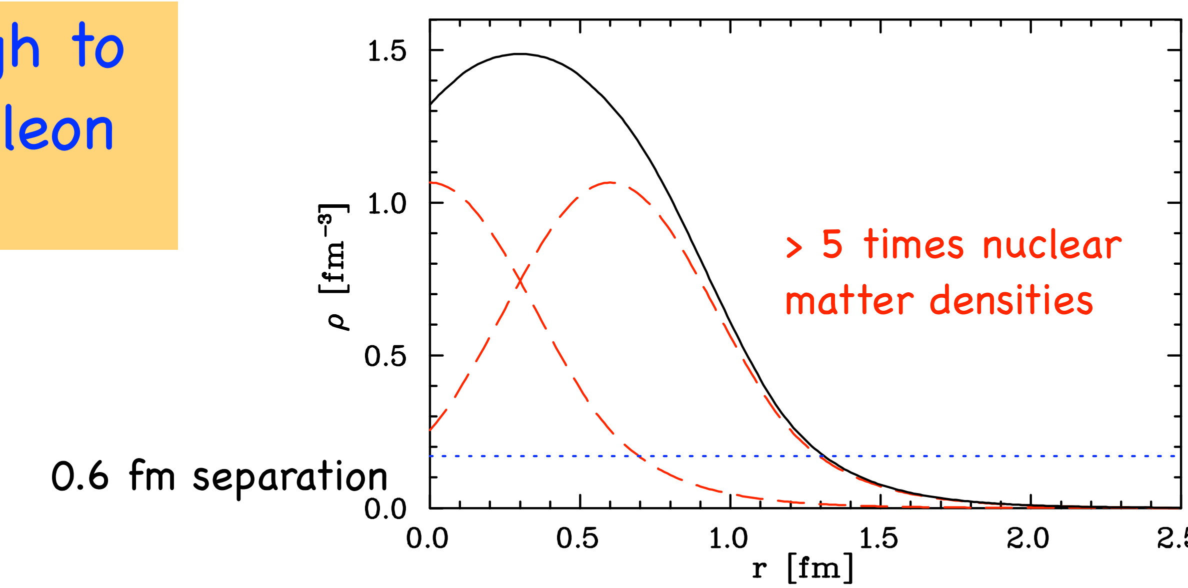
Densely packed - at small distances multiples of NM

- nucleons are bound
  - energy (E) distribution
  - shell structure
- nucleons are not static
  - momentum (k) distribution

High enough to modify nucleon structure?

Correlations - when 2N are at small $r_{12}$. How is this manifested?

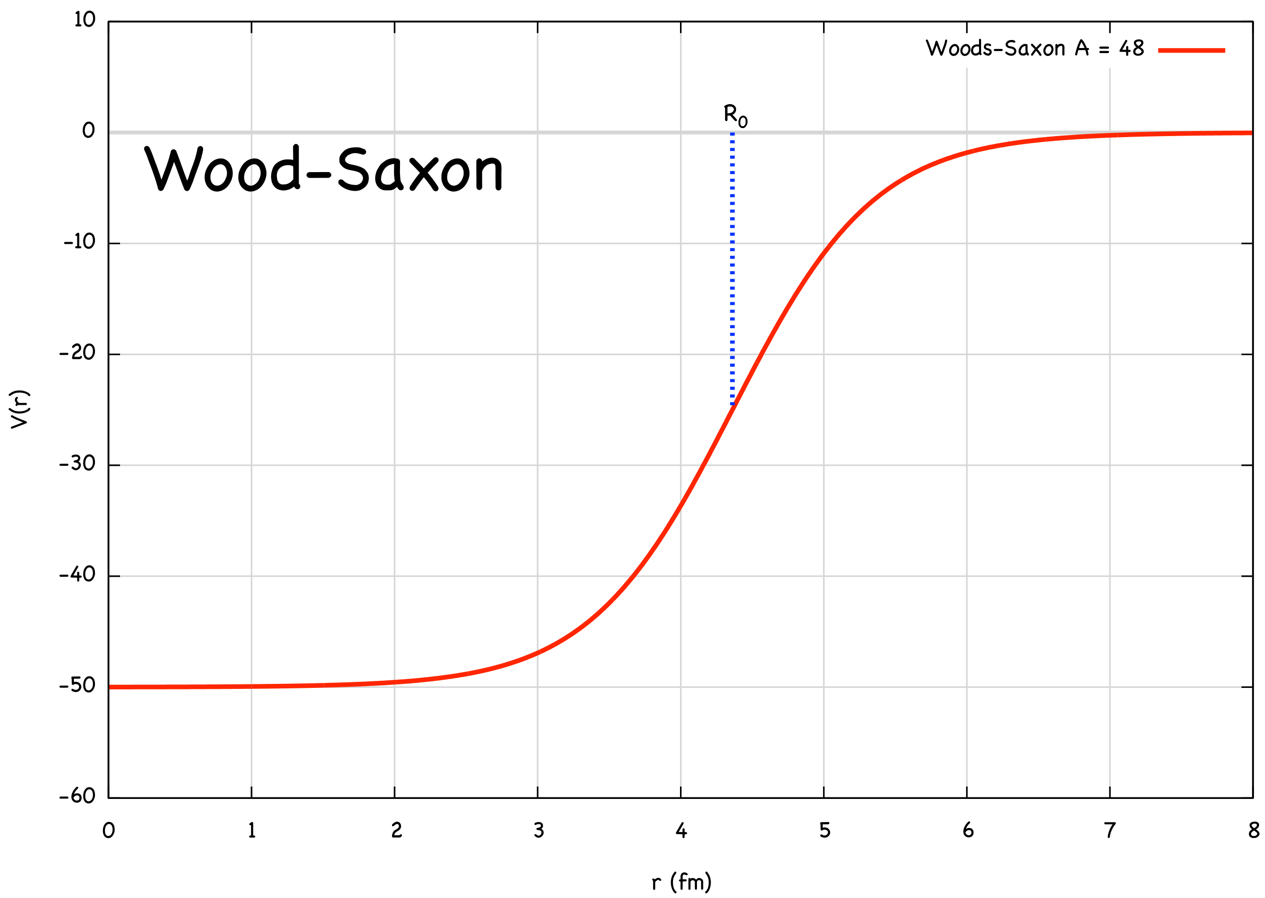



J. Arrington

# Independent Particle Shell Model

- Independent particle states of a uniform potential - a mean field.




- Long mean free paths
- No two-body interactions
- Absence of correlations in ground-state wave function.

- The single-particle energies $\xi_\alpha$ and wave function $\Phi_\alpha$ are the basic quantities - can be accessed in knockout reactions
- The spectral function should exhibit a structure at fixed energies with momentum distributions characteristic of the shell (orbit).

$$S(\vec{p},E) = \sum_a |\,\Phi_a(p)\,|^2\,\delta(E+\xi_a)$$

- Enormous strong force acting
- So many nucleons to collide with
- How can nucleons possibly complete whole orbits ($10^{21}$/s) without interacting?

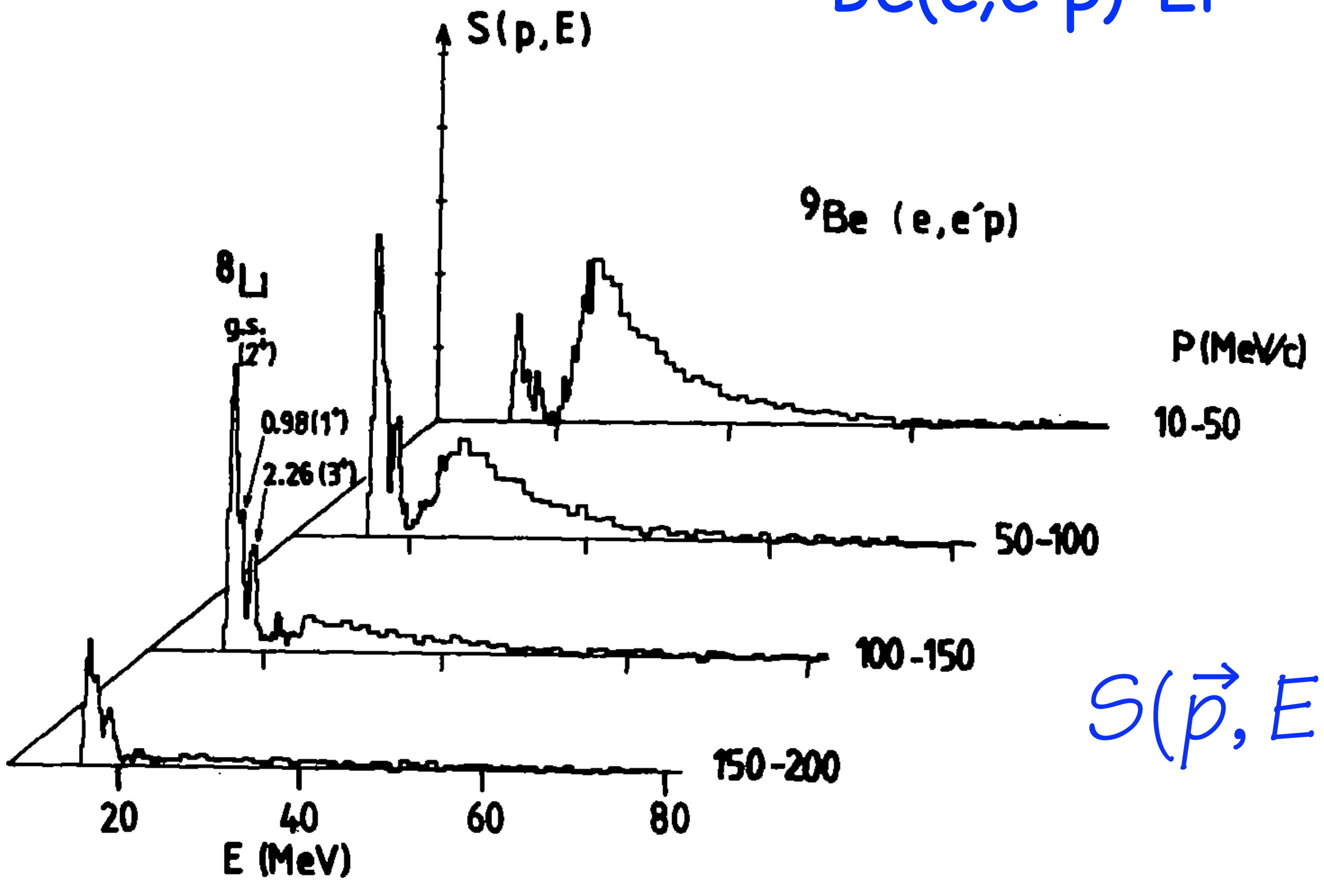
Hard core is small part of the nuclear volume

$$\frac{V_c}{V_{total}} = \left(\frac{c}{2r_o}\right)^3 \approx 1/100$$

# Spectral Function in IPSM

Saclay

$^{9}Be(e,e'p)^{8}Li$



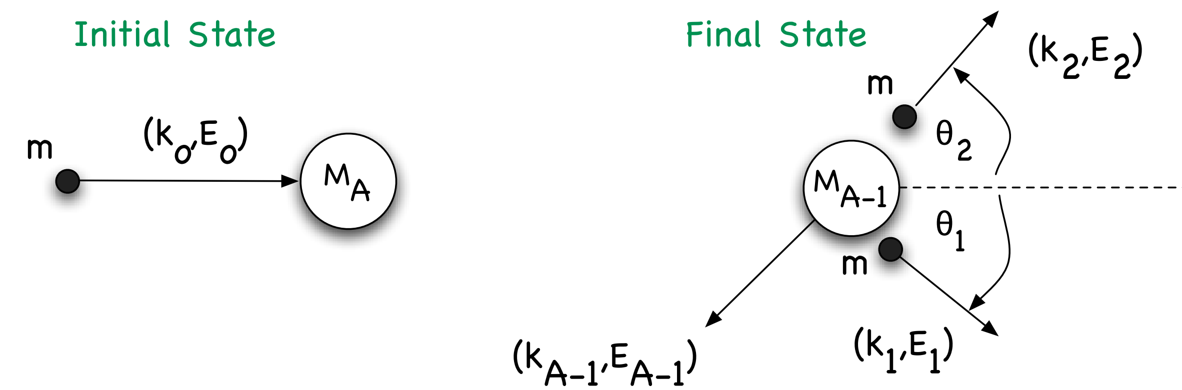




*Fig. 10. Proton separation energy spectra for the $^{9}Be(e,e'p)$ reaction, within different recoil momentum bins. The energy resolution of ∼ 0.9 MeV renders visible some different excited states of $^{8}Li$ at low separation energy. Data have been corrected for radiative effects, but the overall absolute scale is arbitrary.*

$$S(\vec{p}, E) = \sum_i |\, \Phi_a(p) \,|^2 \, \delta(E + \epsilon_a)$$

Characteristic momentum behavior of the s and p shells can be clearly seen. J. Mougey ``The (e.e'p) reaction” Nuclear Physics A Volume 335, (1980) 35-53

PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

# High-Energy Reactions and the Evidence for Correlations in the Nuclear Ground-State Wave Function*

K. A. BRUECKNER, R. J. EDEN,† AND N. C. FRANCIS
*Indiana University, Bloomington, Indiana*

(Received January 13, 1955)

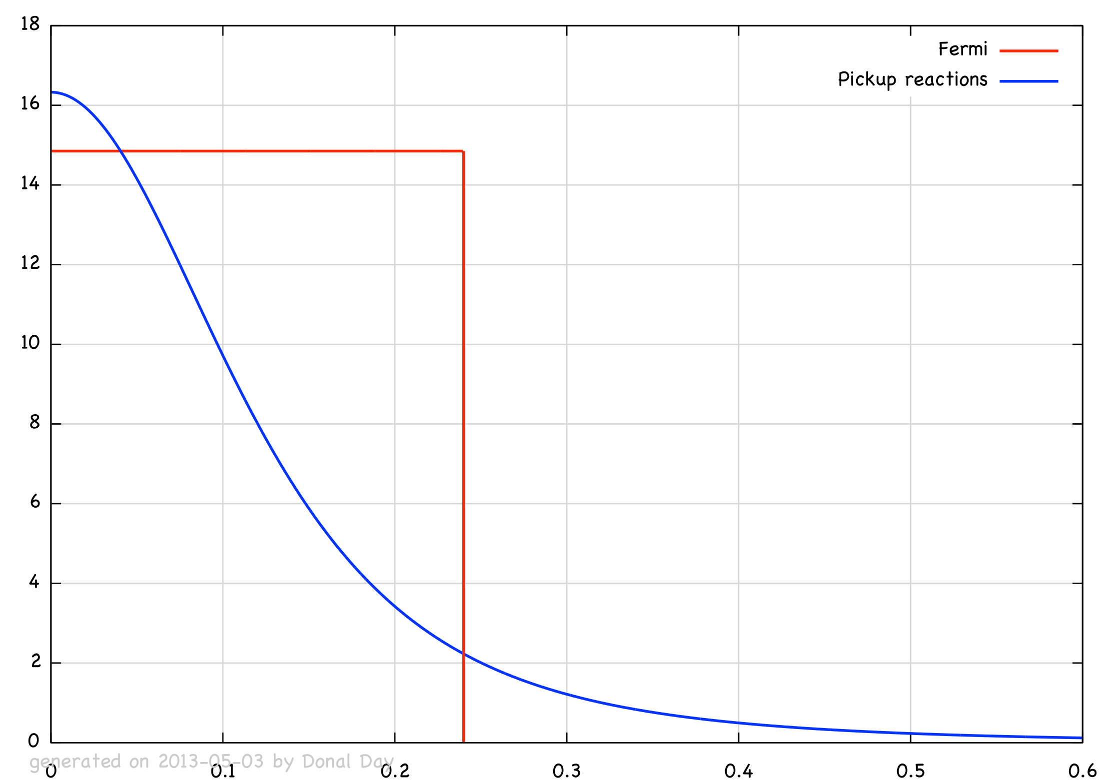
High-energy nuclear reactions which depend strongly on nucleon position correlations .. give evidence for marked correlations effects ... This momentum distribution differs substantially from that for the shell model ..... strong evidence for correlations in the nuclear ground state wave function.

## fast neutrons + nucleus ⇒ deuteron

Fast neutron p encounters a proton with such a momentum that the relative momentum of the neutron and proton can be accommodated in the deuteron wave function.

Forces acting between nucleons in nuclei are very nearly the same as those acting between free nucleons -- very strong and short ranged.

Marked correlation effects - the momentum distribution!!



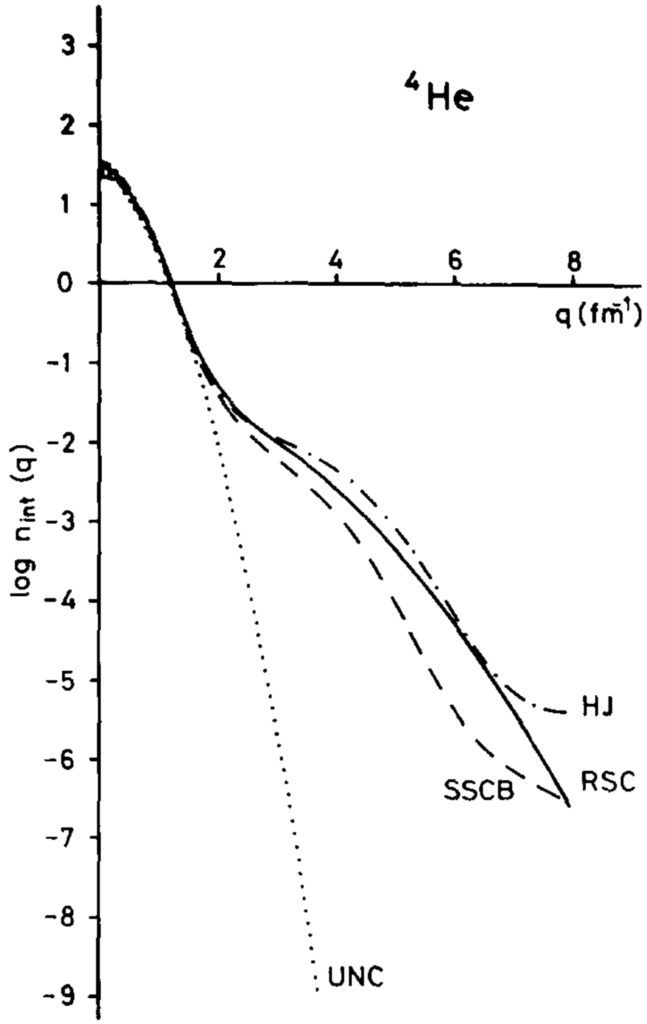



Fig. 2. Momentum distributions for $^4$He, HJ: Hamada–Johnston potential, RSC: Reid soft core potential, SSCB: de Tourreil–Sprung super soft core potential B, UNC: uncorrelated, for the RSC potential. The other uncorrelated distributions do not differ appreciably for $q > 2$ fm$^{-1}$.

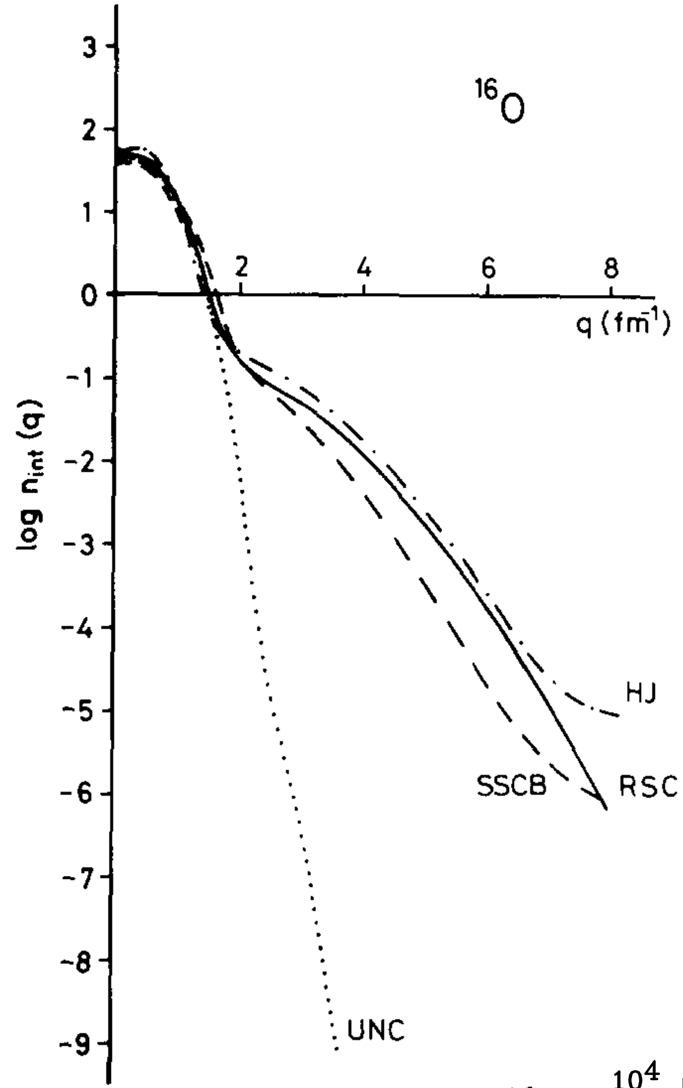
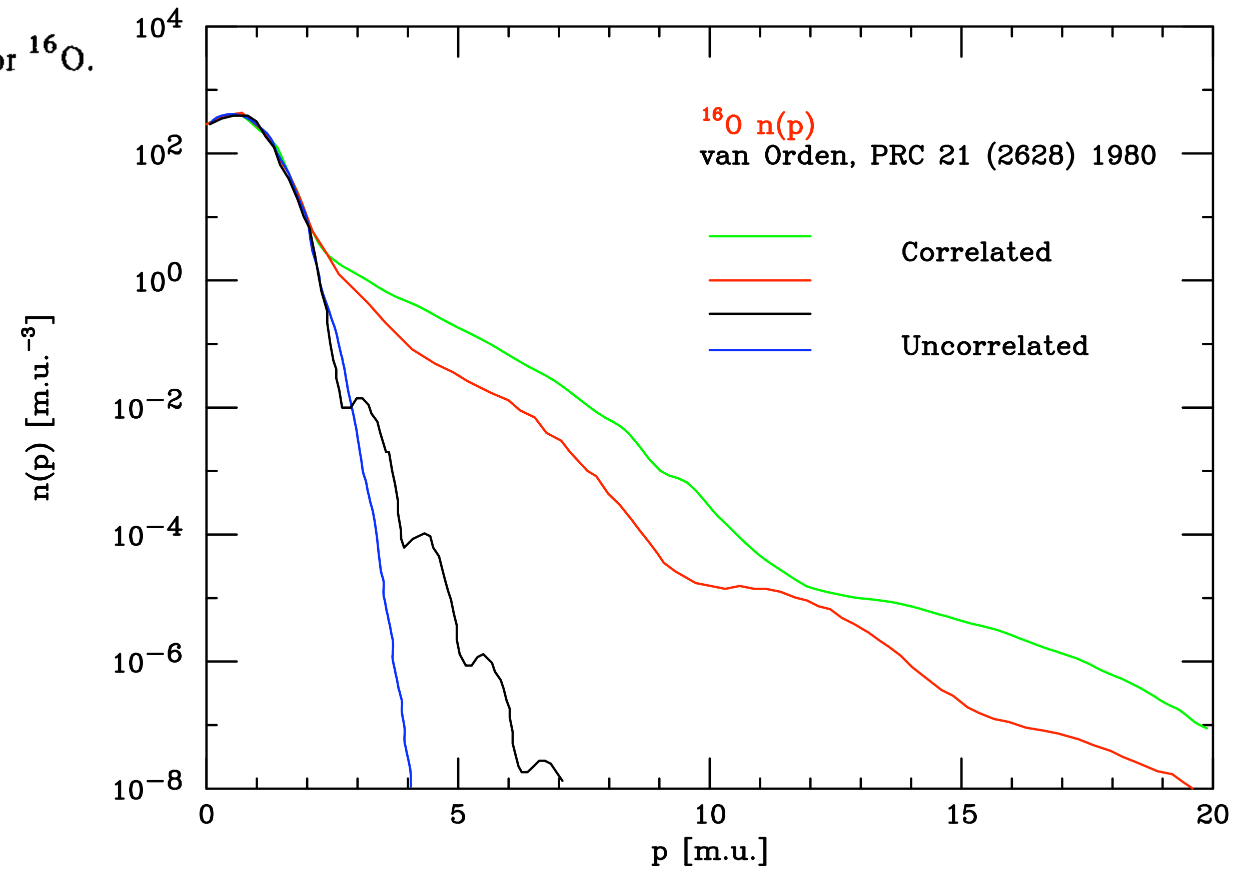



Fig. 3. Same as fig. 2, for $^{16}$O.

# Calculations of SRC

## Show up at large momentum

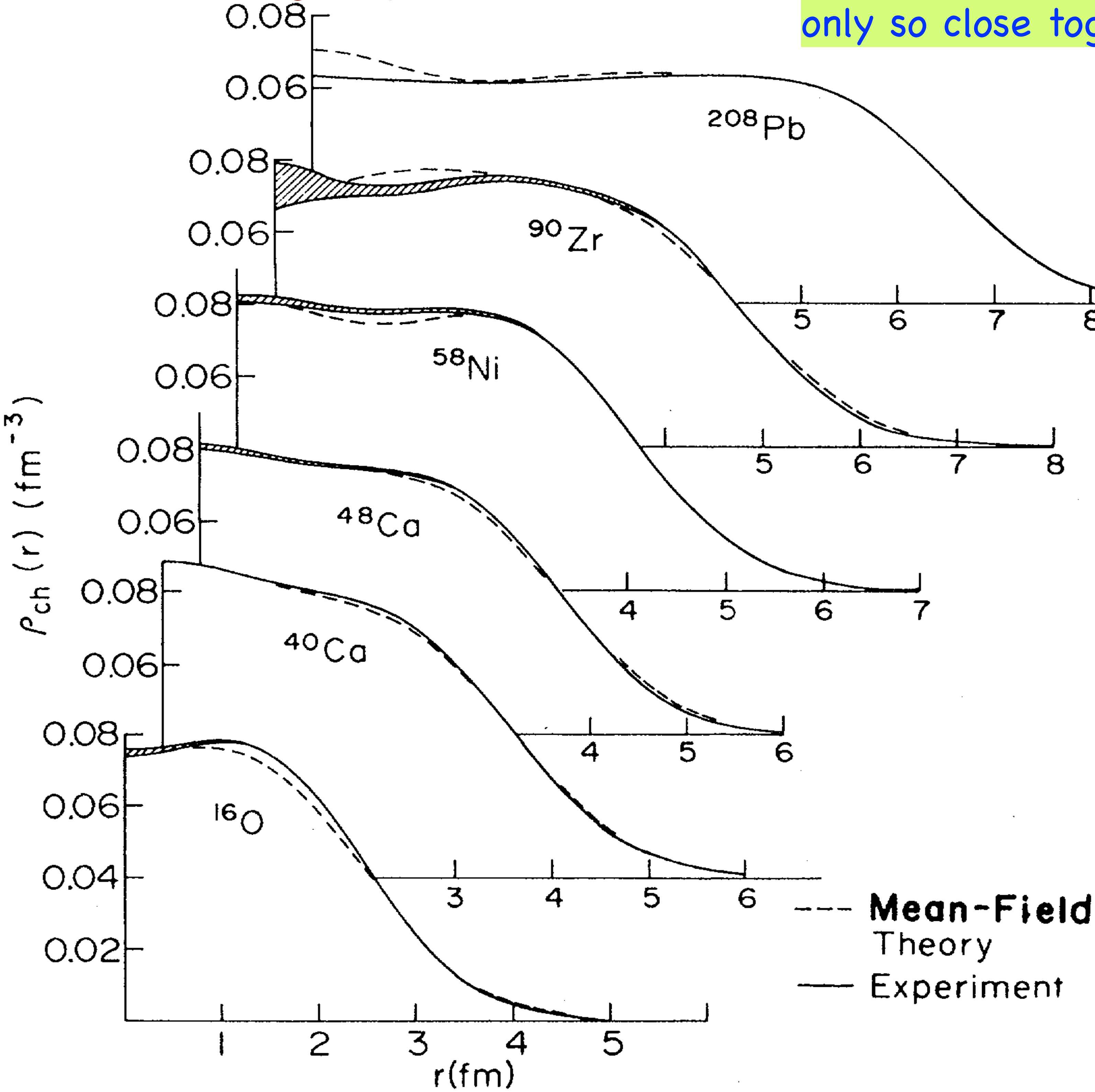


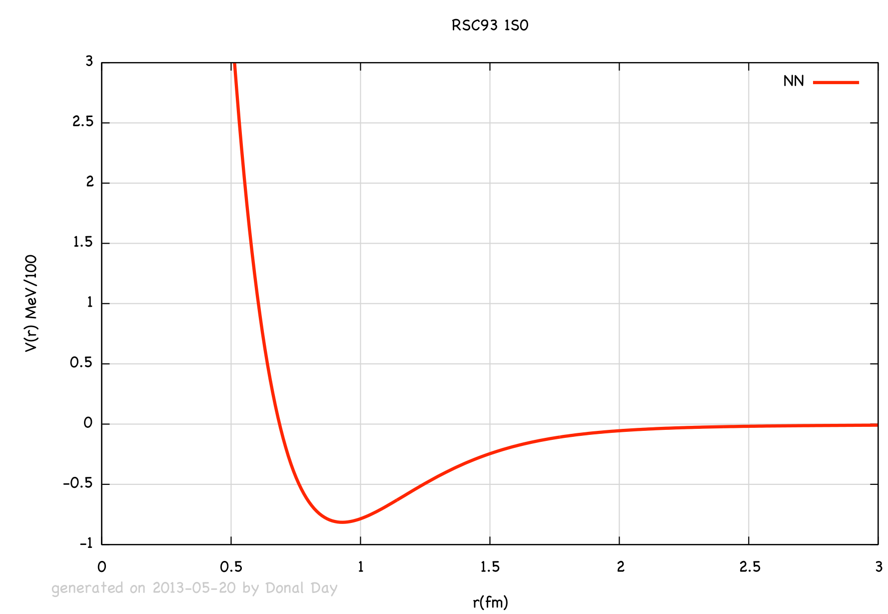

Zabolitzky and Ey, PLB 76, 527 (1974)

Van Orden et al., PRC 21, 2628 (1980)

# Evidence of SRC

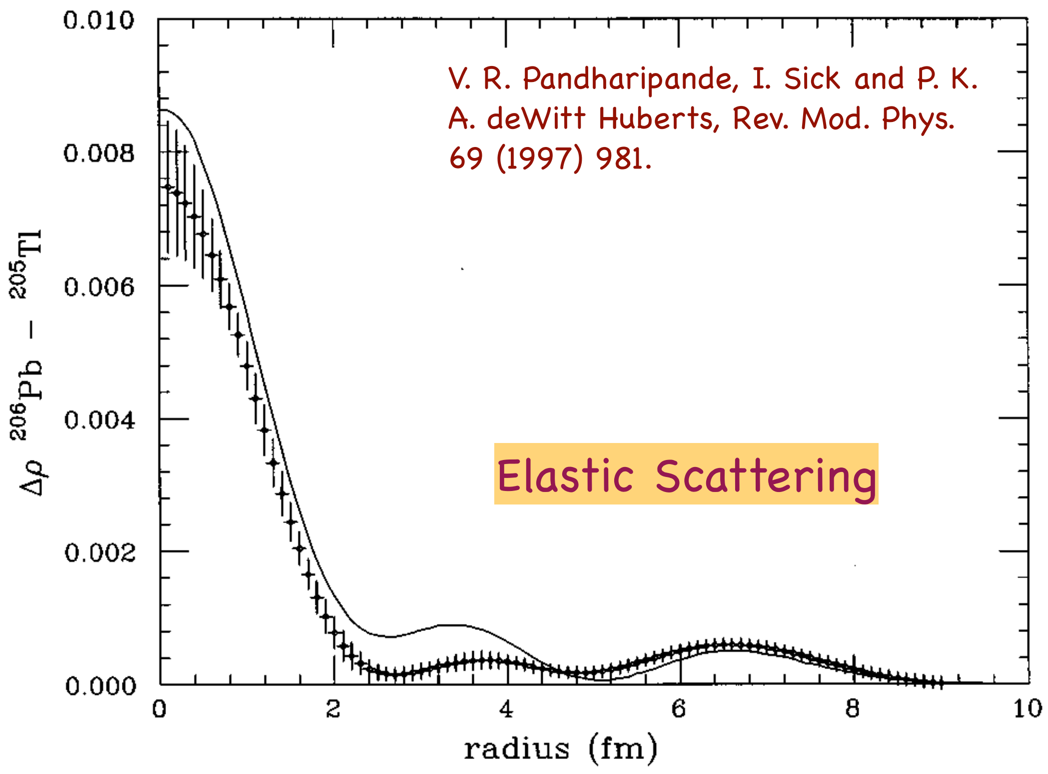
Central density is saturated – nucleons can be packed only so close together: $\rho_{ch} * (A/Z) = \text{constant}$




J.W. Negele RMP 54 (913) 1982

# What else? Occupation Numbers

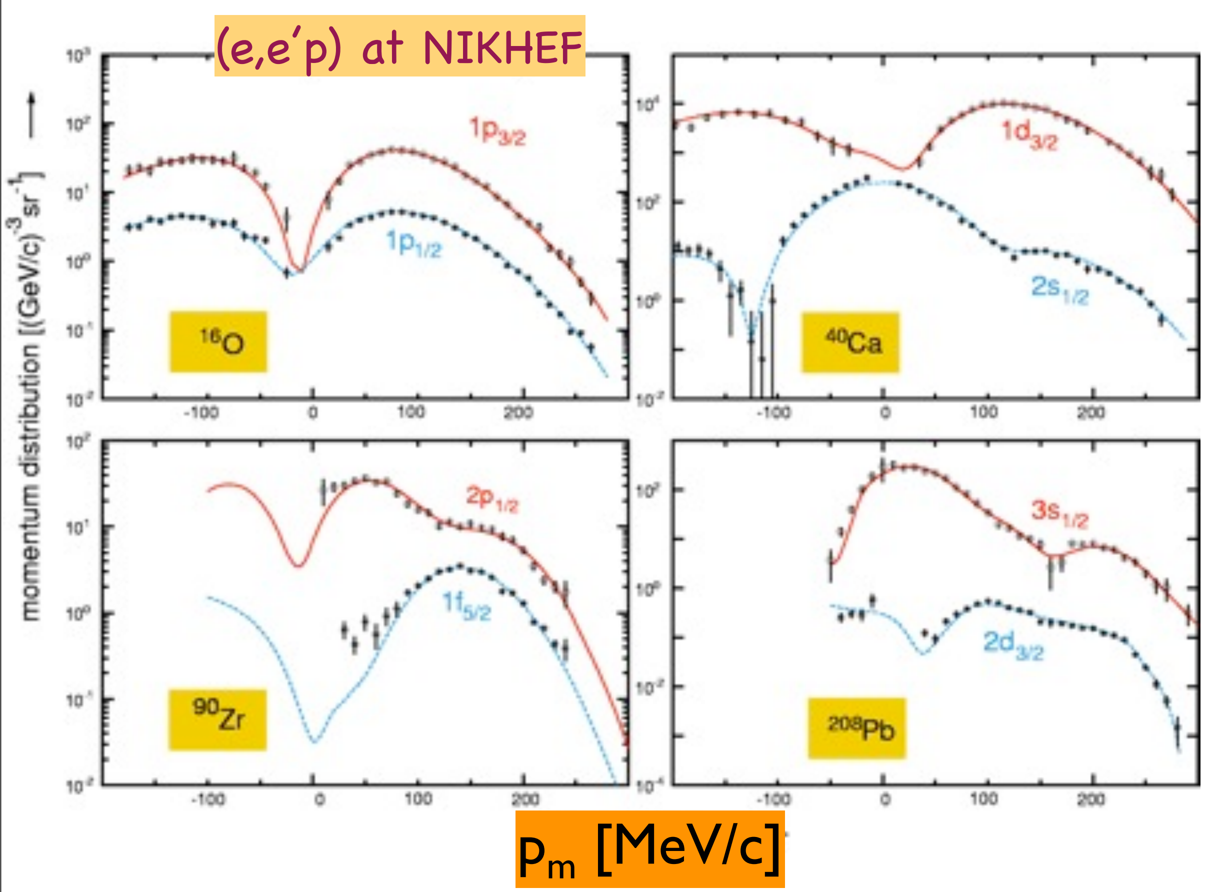


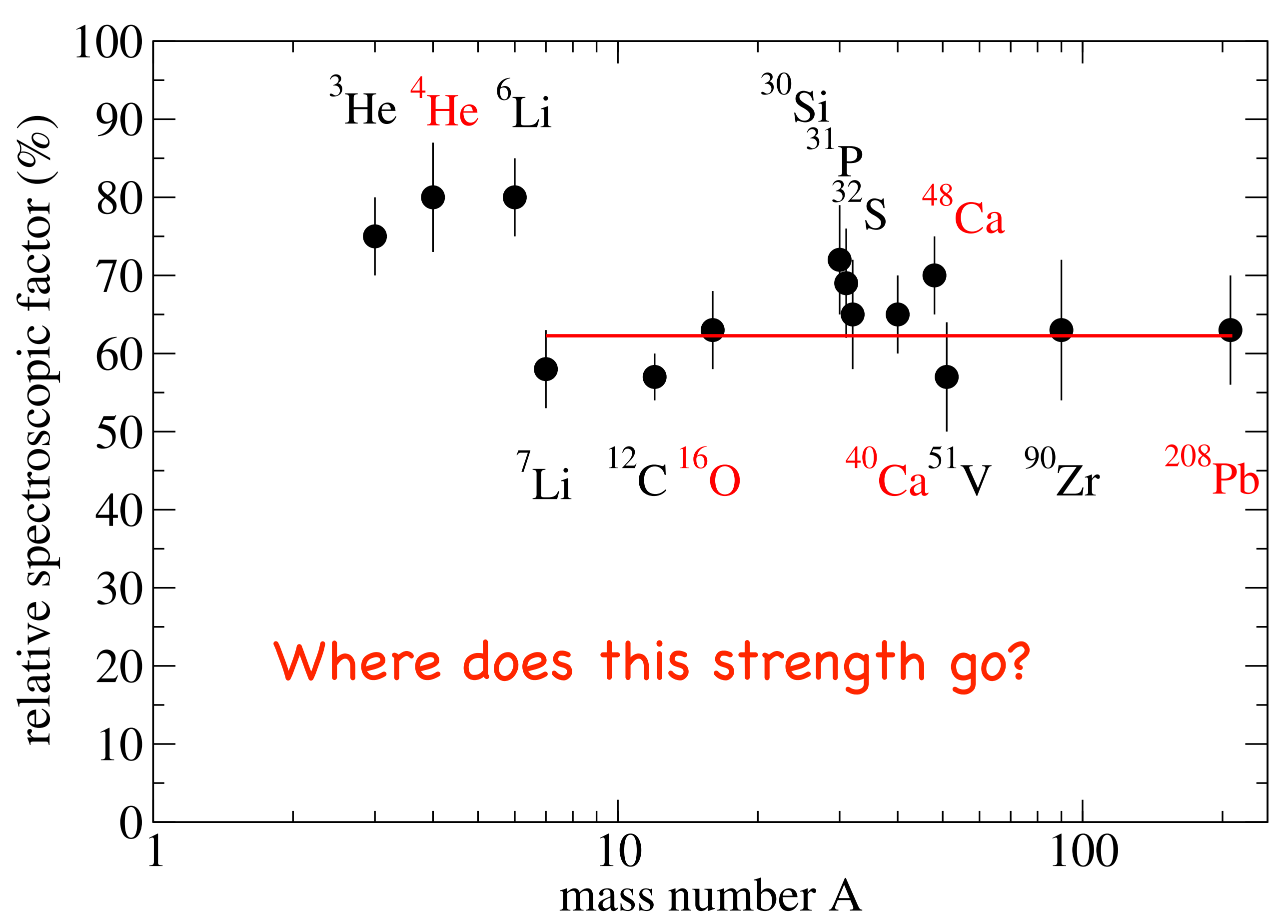

Density difference between $^{206}$Pb and $^{205}$Tl.: differ by a single $3s^{1/2}$ proton

Experiment - Cavedon et al (1982)
Theory: Hartree-Fock orbitals with adjusted occupation numbers is given by the curve.

The shape of the $3s^{1/2}$ orbit is very well given by the mean field calculation.

**Occupation numbers scaled down by a factor ~0.65.**

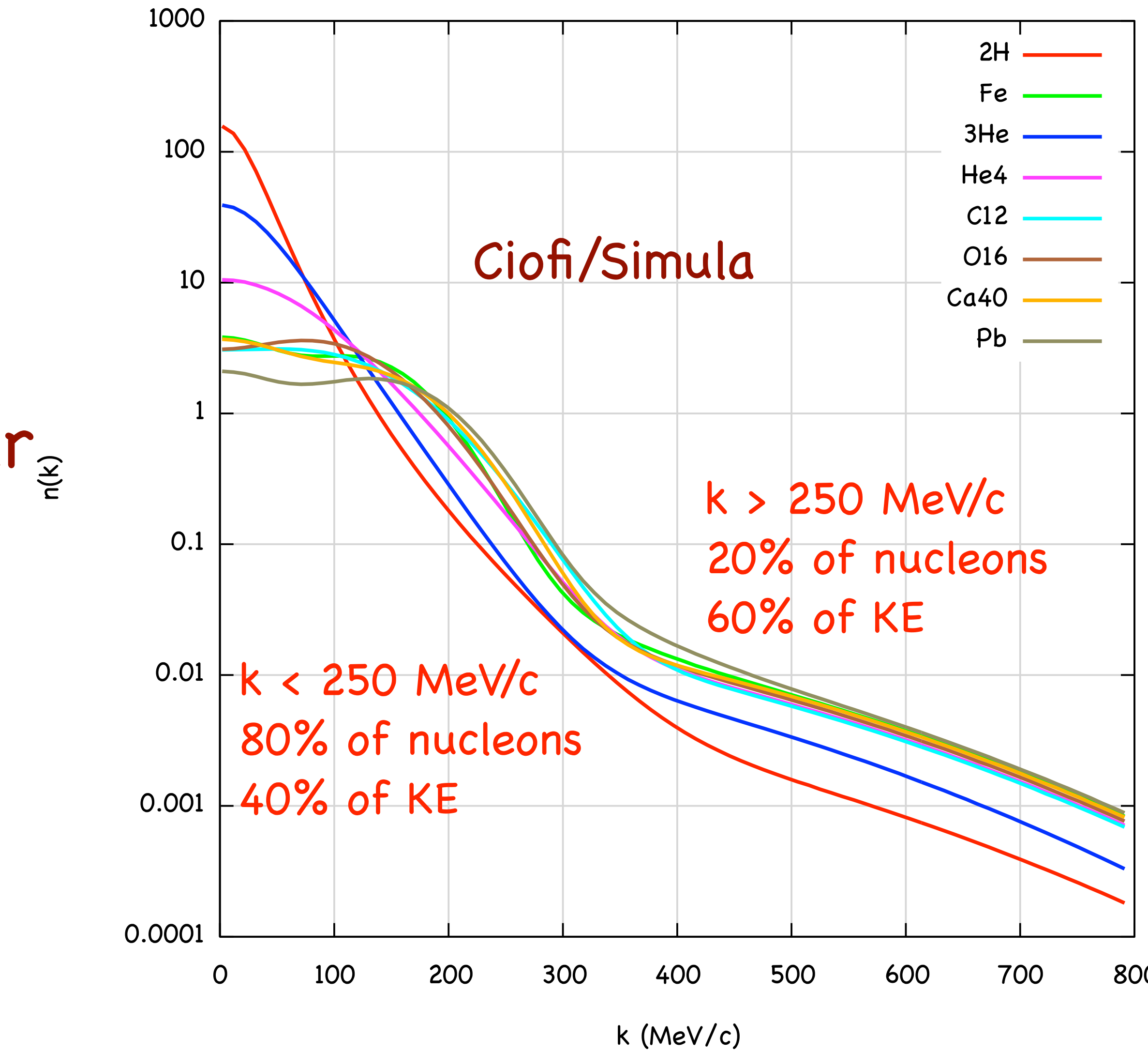


# Theory suggests a common feature for all nuclei

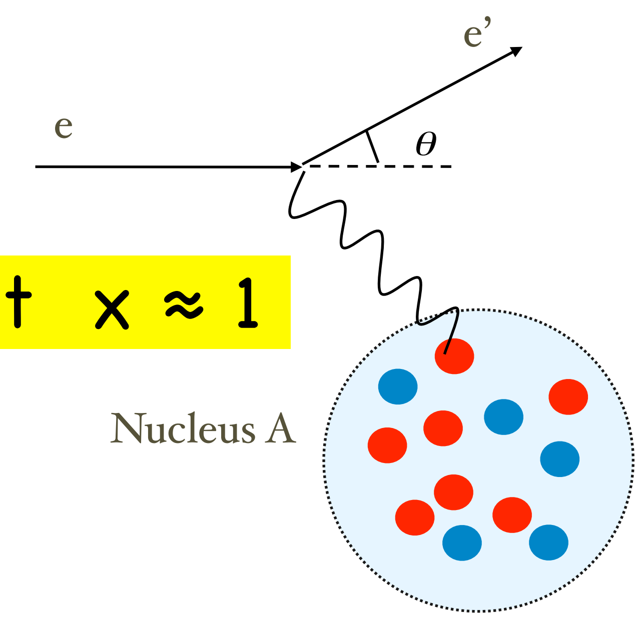
What many calculations indicate is that the tail of n(k) for different nuclei has a similar shape - reflecting that the NN interaction, common to all nuclei, is the source of these dynamical correlations.

Suggests isospin dependence - similar to deuteron




Isolate short range interactions (and SRC's) by probing at high $p_m$: (e,e'p) and (e,e')

# Inclusive scattering at large x

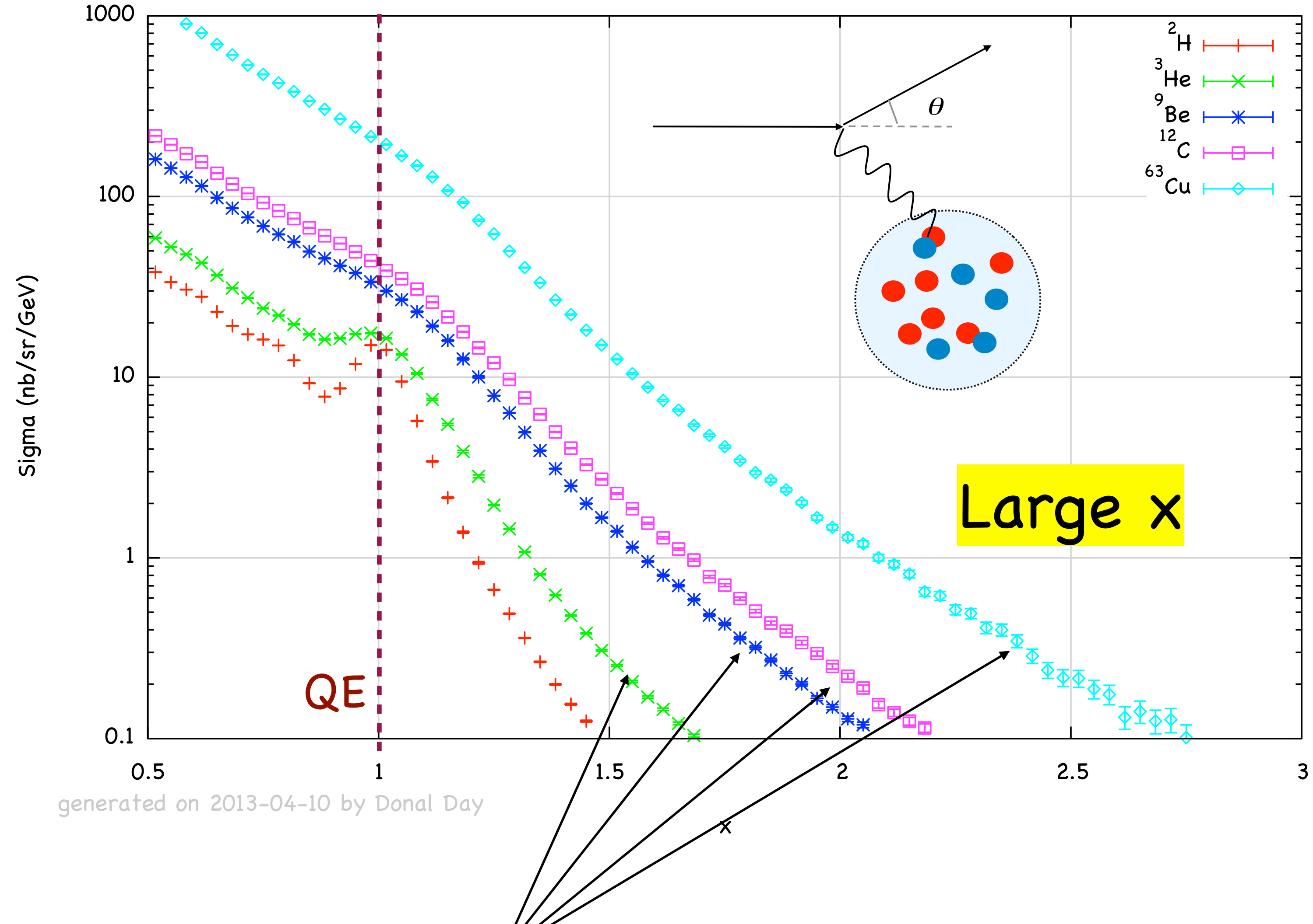


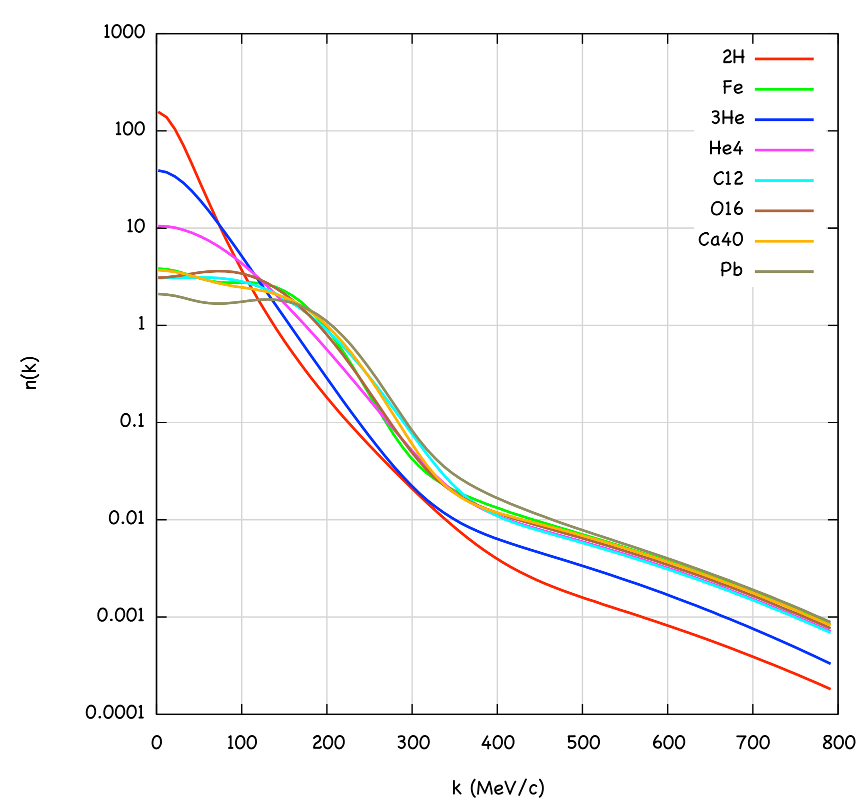

**At  $x \approx 1$**

➡ Motion of nucleon in the nucleus broadens the peak.

➡ little strength from QE above $x \approx 1.3$.

A(e,e') E02019 Fomin et. al., 5.766, 18°

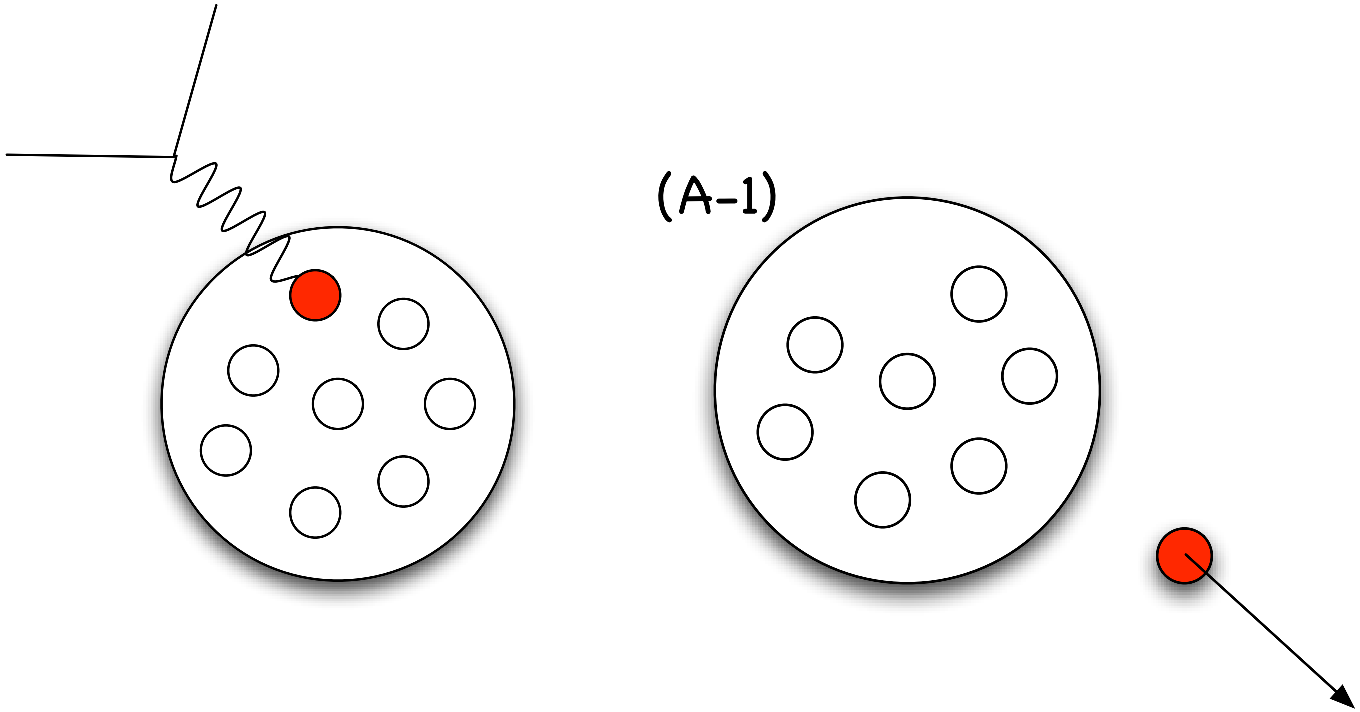



High momentum tails accessible AND should yield constant ratio if seeing SRC

# Access n(k) through y-scaling ($\nu$, q ⇒ y)

Single nucleon knock-out, $E = E_{min}$, A-1 system unexcited




- No FSI
- No internal excitation of (A-1)
- Full strength of S(p,E) is integrated over at finite q
- No inelastic processes
- No medium modifications

$$\nu + M_A = \sqrt{M^2 + (p+q)^2} + \sqrt{M_{A-1}^2 + p^2}$$

$$y \simeq \sqrt{\nu(2m_n + \nu)} - q$$

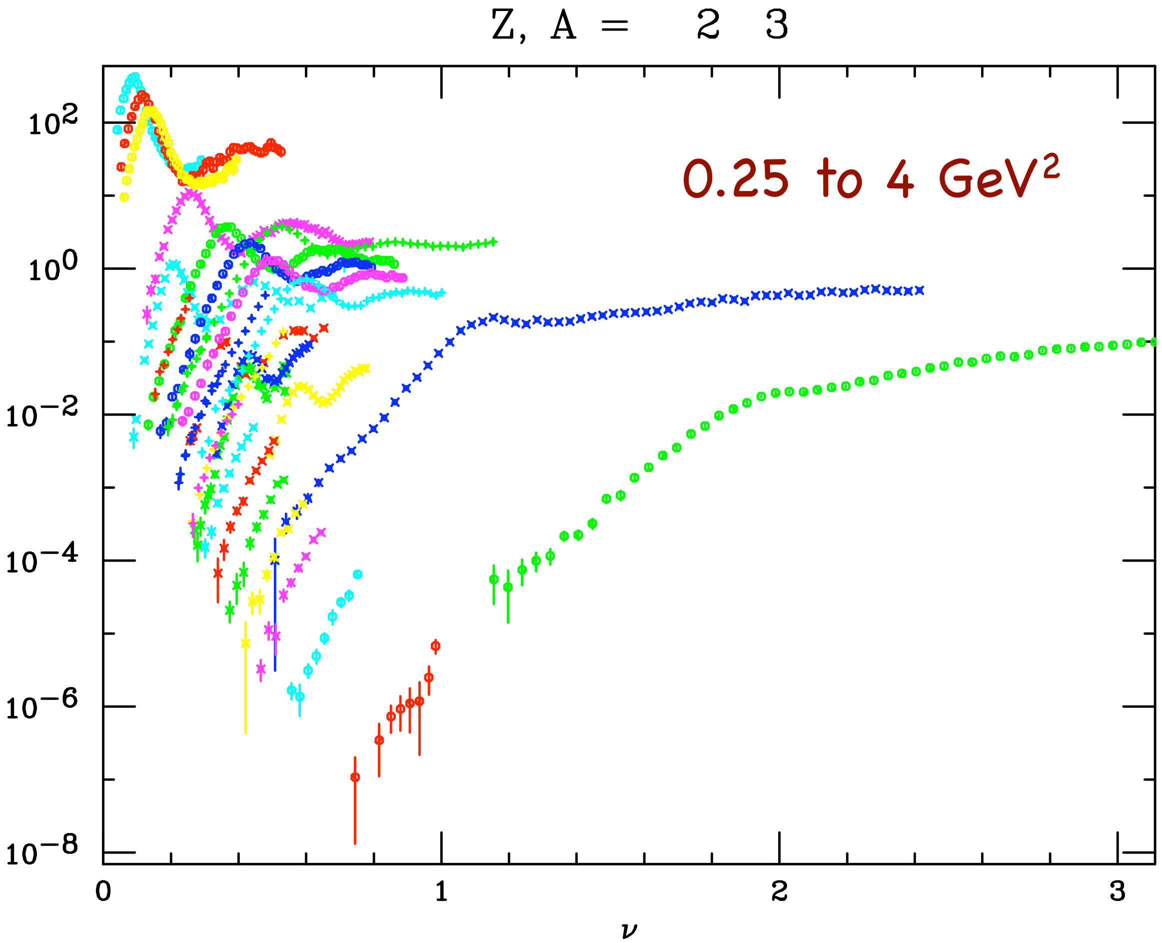
y: Momentum of knocked-out nucleon parallel to q

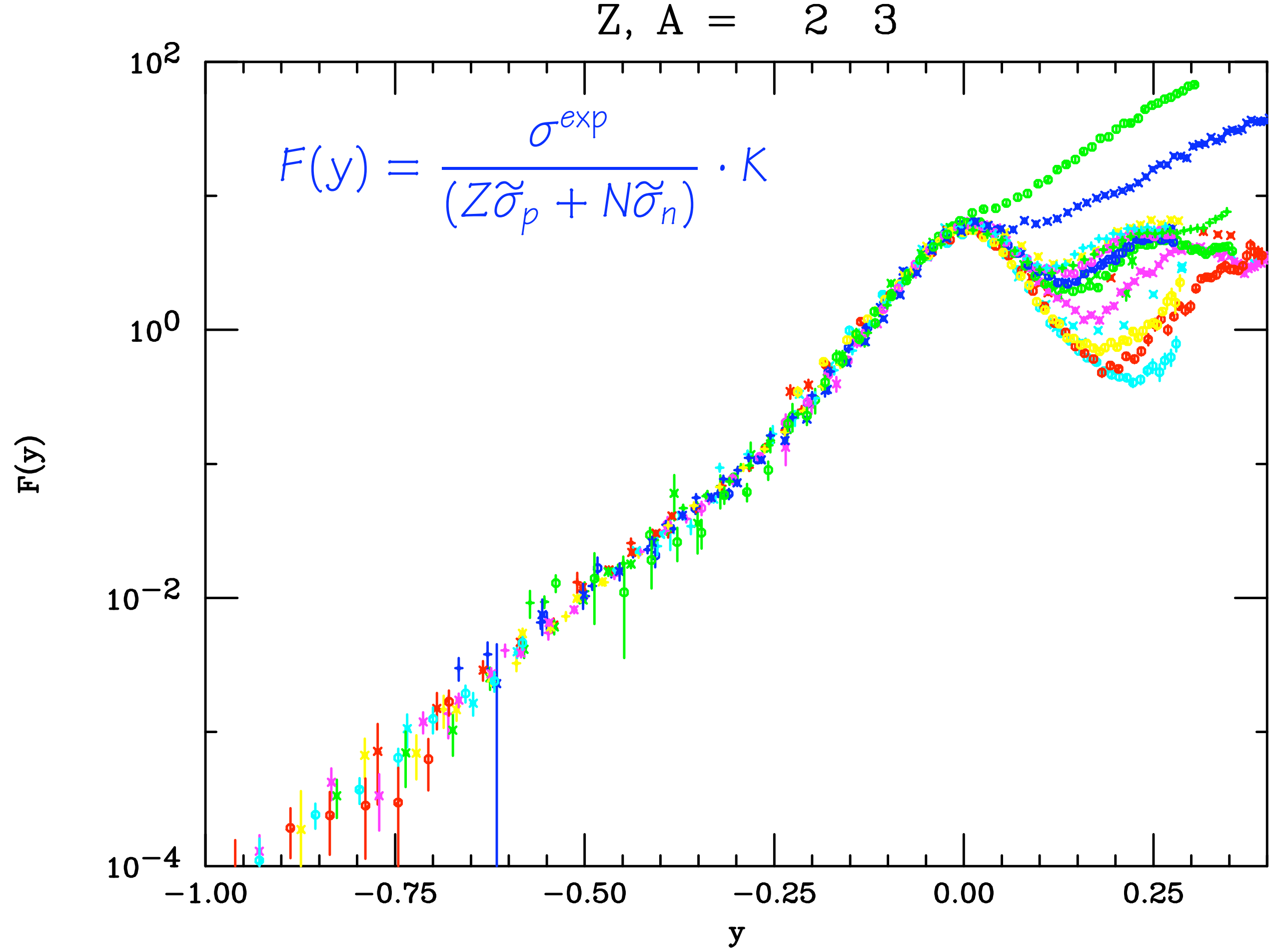
$$F(y) = \frac{\sigma^{exp}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K$$

$$n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

G. West Phys.Rept. 18 (1975) 263-323

# First observed in $^3$He at SLAC (1980)



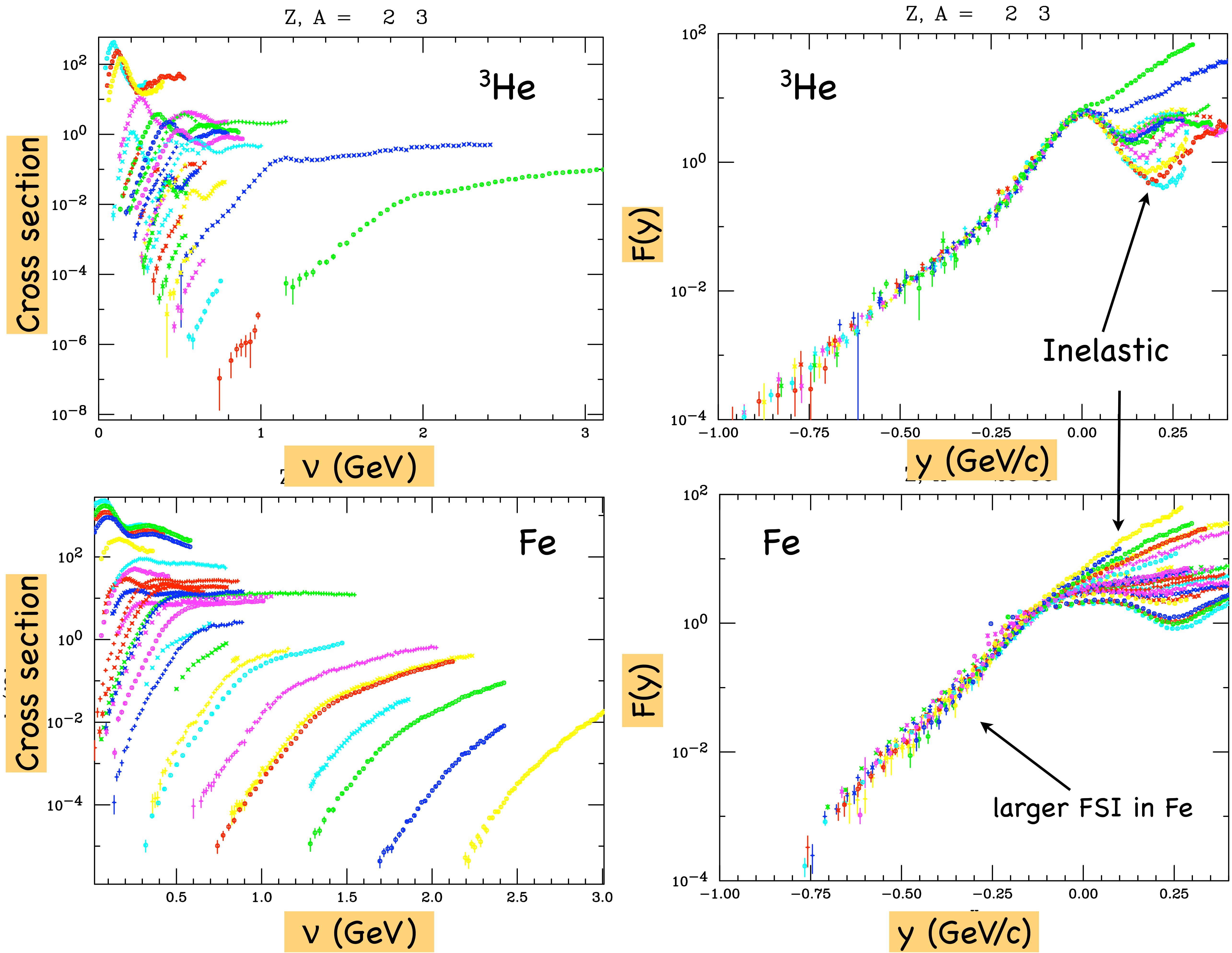

Looks great but ... a problem: Full integral over S(k,E) impossible

PWIA: convergence from below

Data: Scales at lower $Q^2$ than expected and convergences from above.

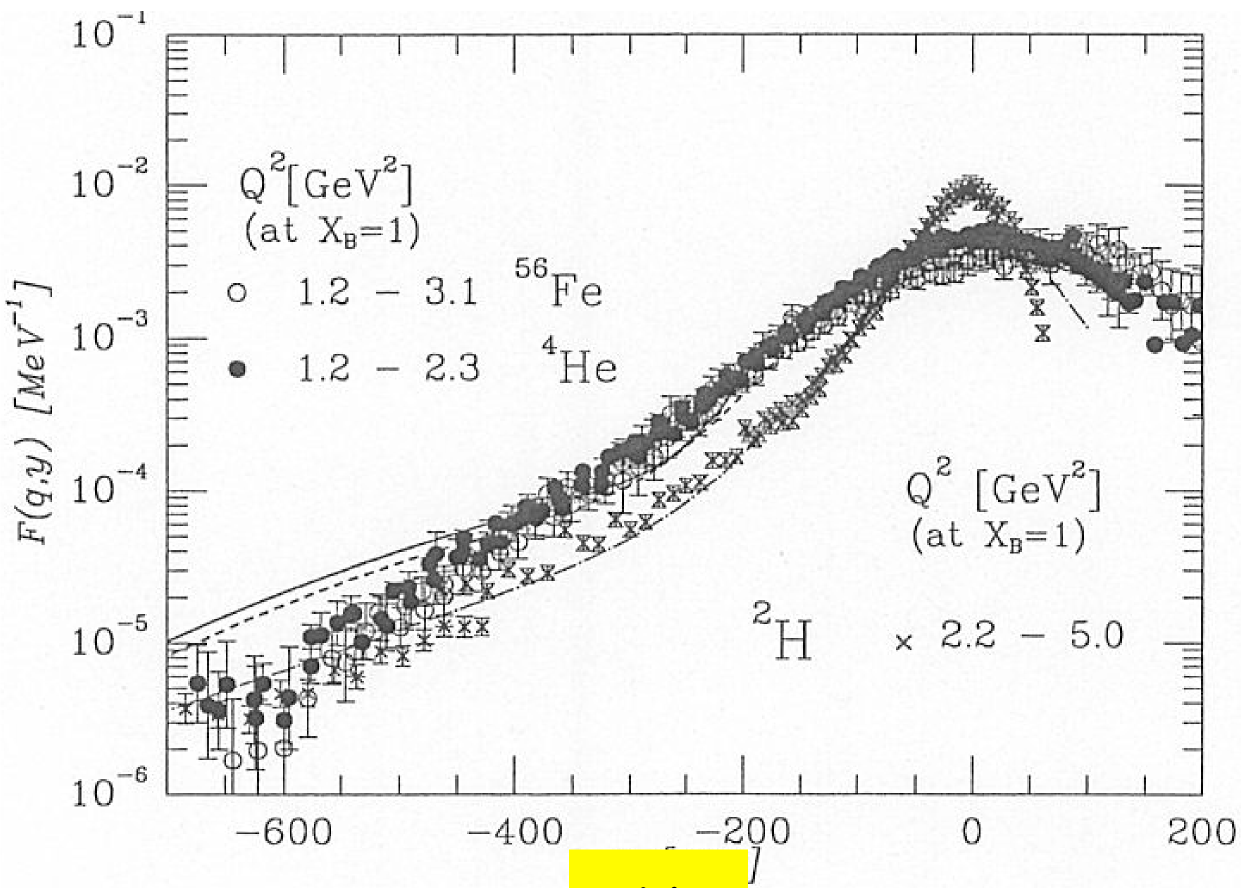
FSIs involved - diminish with $Q^2$

$$n(k) \neq -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

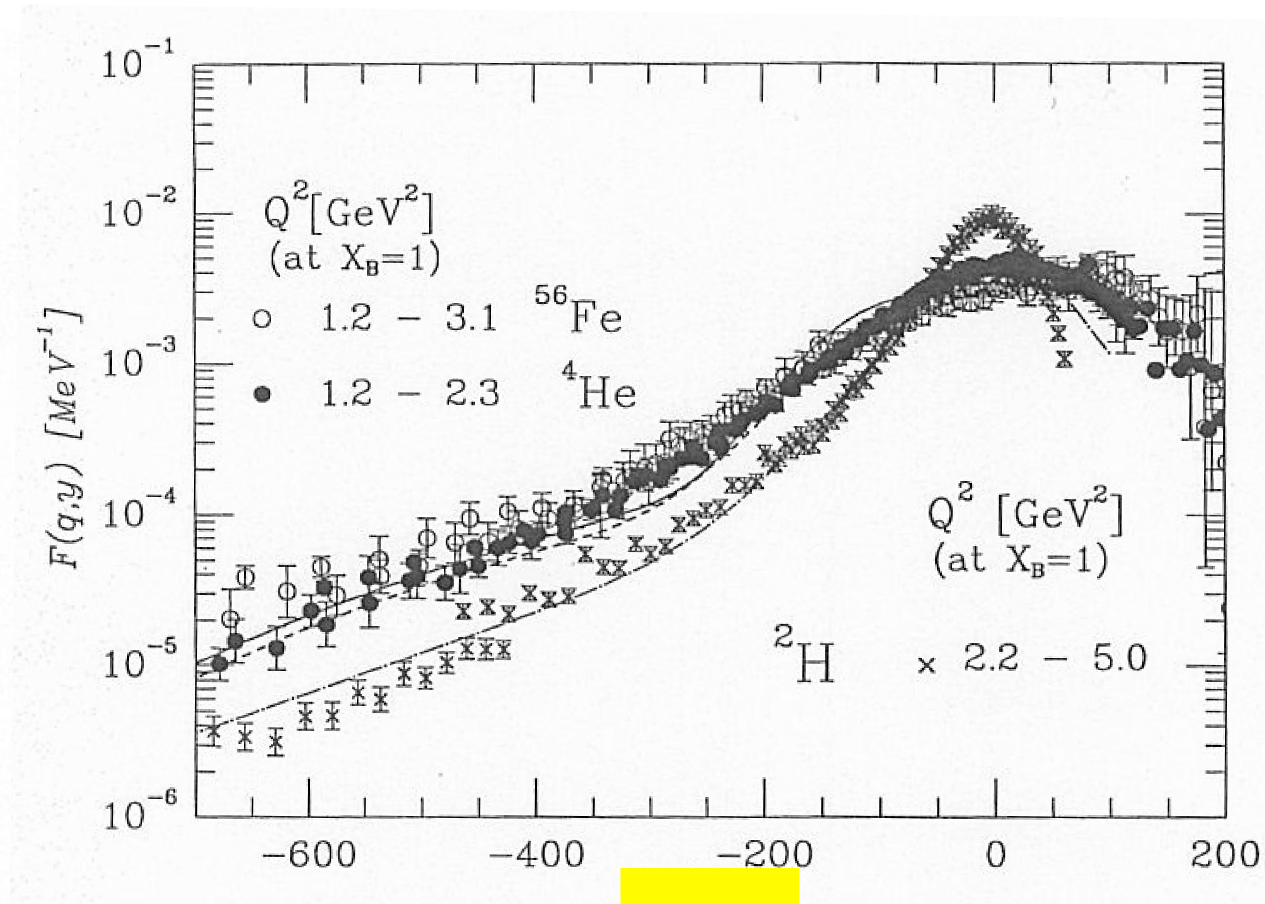


Z, A = 2 3
$^3$He
Cross section
ν (GeV)
Z, A = 2 3
$^3$He
F(y)
y (GeV/c)
Inelastic
Fe
Cross section
ν (GeV)
Fe
F(y)
y (GeV/c)
larger FSI in Fe

# Global scaling variable to account for energy balance when scattering from correlations, CM motion - model dependent




y



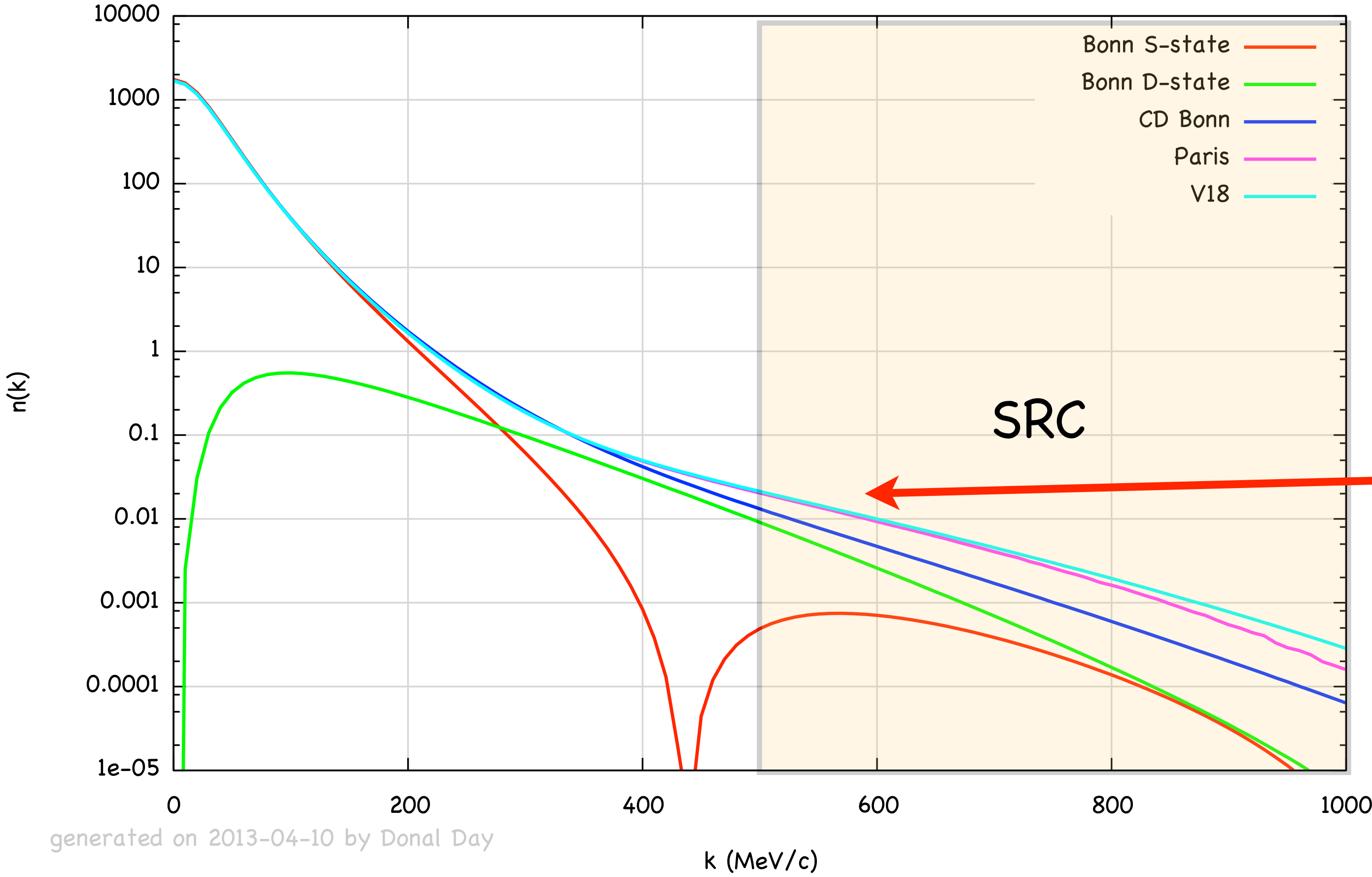

$y_{CW}$

degli Atti and West PLB 458 (19990 447-453

Many body calculations at high momenta indicate that nuclear momentum distributions are rescaled versions of the deuteron

$$n_A(p) \approx C_A n_D(p)$$
$$F_A(q, y_{CW}) \approx C_A F_D(q, y_{CW})$$

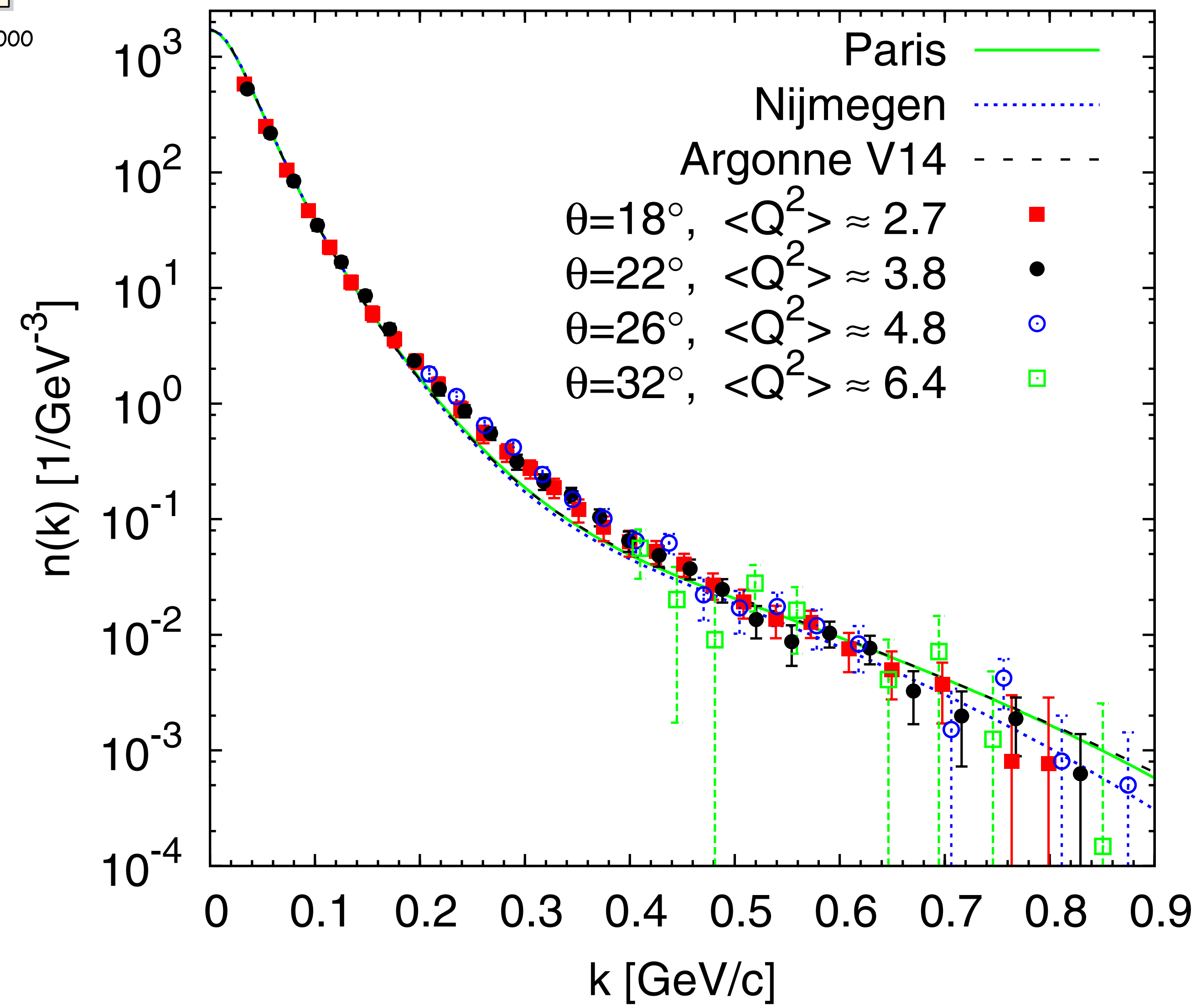
# Deuteron momentum distribution




Virtually no experimental d(e,ep)n data exist for $p_m$ > 0.5 GeV/c without large contributions of FSI, MEC and IC

large k dominated by D-state

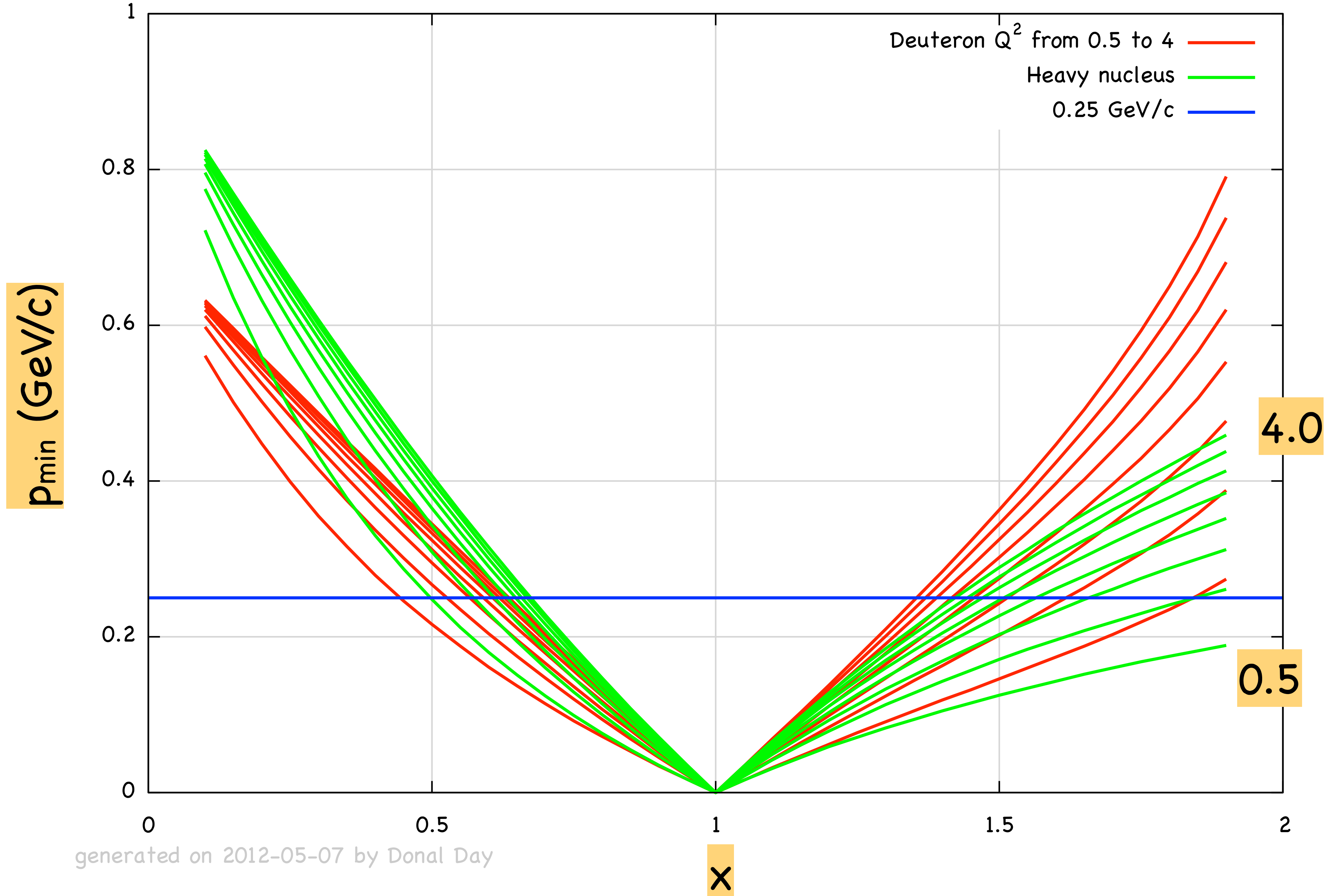
E02019: Fomin et al. PRL 108, 092502 (2012)




Inclusive D(e,e’) via y-scaling provides n(k) well into the SRC region

$$n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

# Where to look for SRC's




Appearance of plateaus is A dependent.

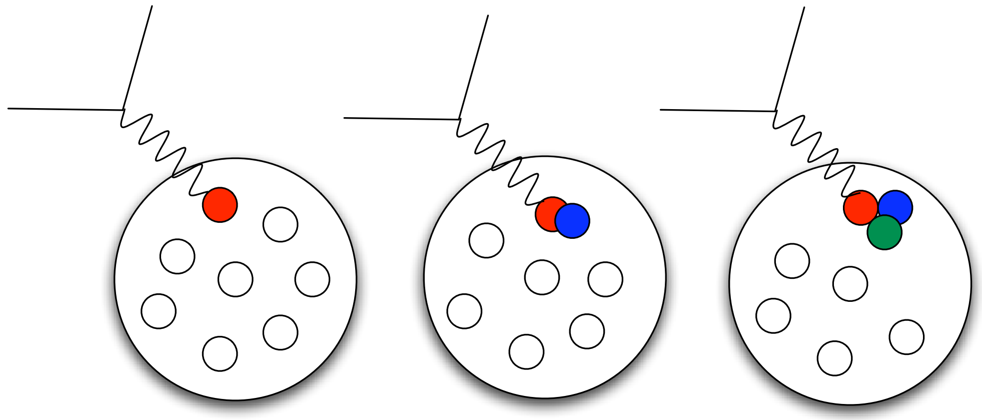
Kinematics: heavier recoil systems do not require as much energy to balance momentum of struck nucleon - hence $p_{min}$ for a given x and $Q^2$ is smaller.

Dynamics: mean field part in heavy nuclei persist in x to larger values

Have to go to higher x or $Q^2$ to insure scattering is not from mean-field nucleon

# A(e,e') CS Ratios and SRC

In the region where correlations should dominate, large x,



$$\sigma(x,Q^2) = \sum_{j=2}^{A} A\frac{1}{j}a_j(A)\sigma_j(x,Q^2)$$
$$= \frac{A}{2}a_2(A)\sigma_2(x,Q^2) + \frac{A}{3}a_3(A)\sigma_3(x,Q^2) + \vdots$$

$a_j(A)$ are proportional to finding a nucleon in a j-nucleon correlation.

$$\sigma_2(x,Q^2) = \sigma_{eD}(x,Q^2) \text{ and } \sigma_j(x,Q^2) = 0 \text{ for } x > j.$$

$$\Rightarrow \quad \frac{2}{A}\frac{\sigma_A(x,Q^2)}{\sigma_D(x,Q^2)} = a_2(A)\Big|_{1<x\leq 2}$$

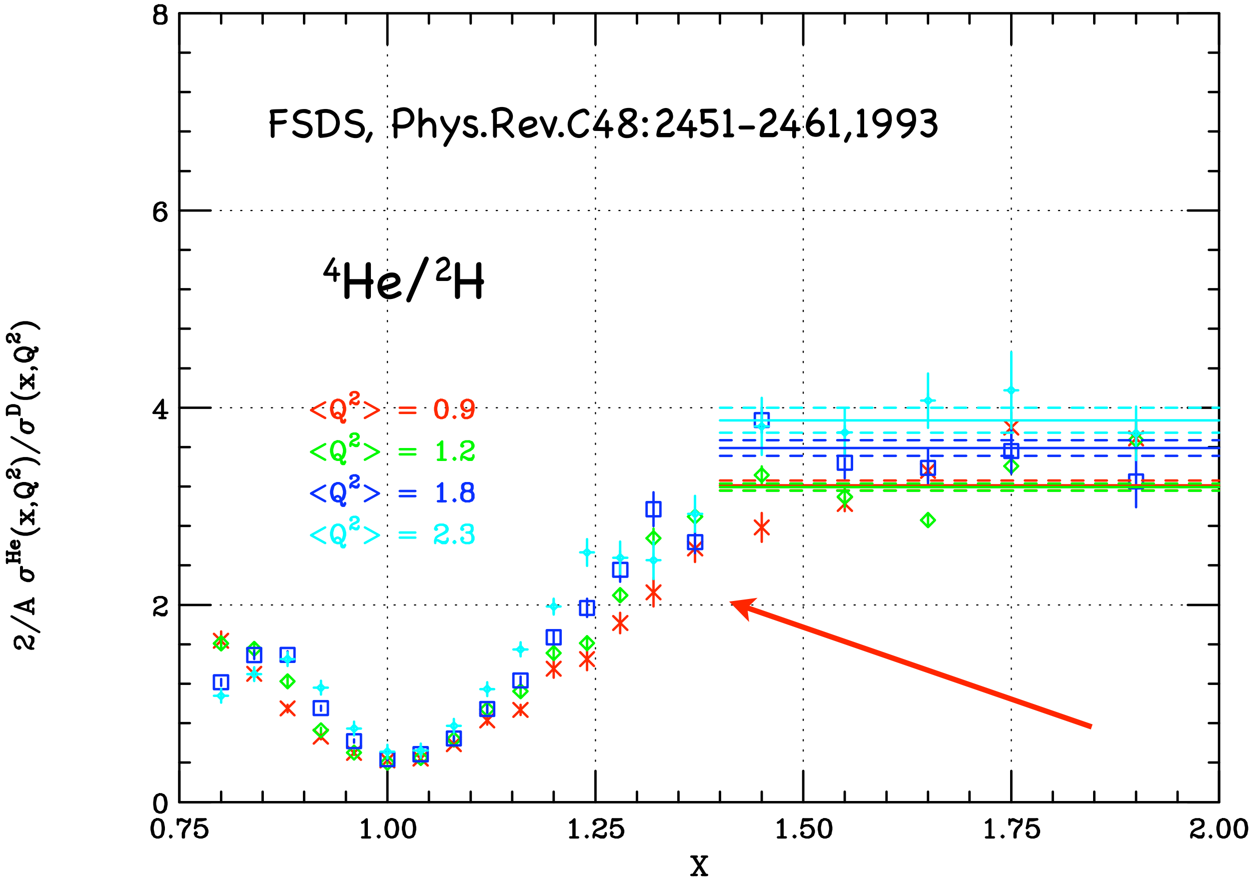
$$\frac{3}{A}\frac{\sigma_A(x,Q^2)}{\sigma_{A=3}(x,Q^2)} = a_3(A)\Big|_{2<x\leq 3}$$

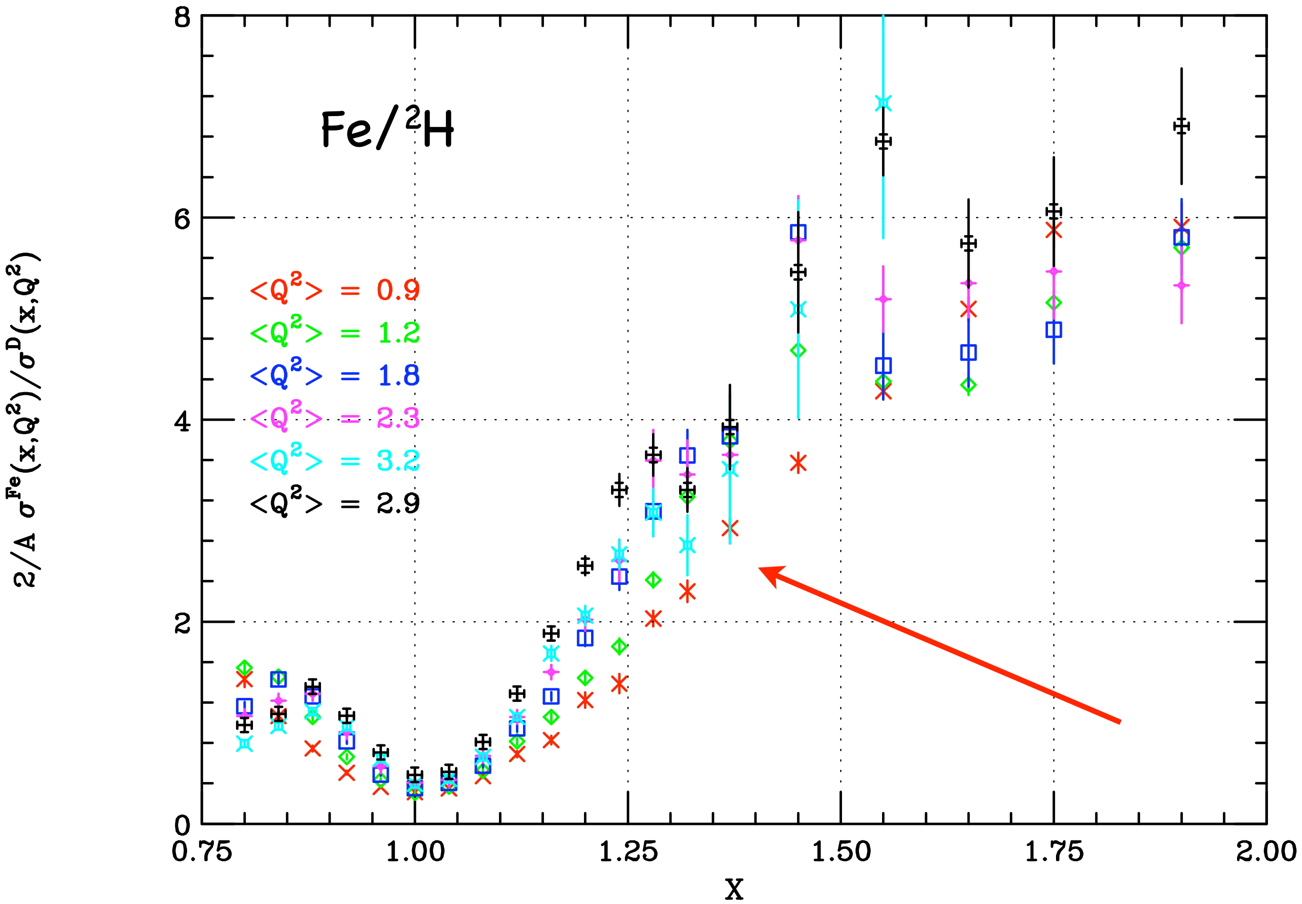
Assumption is that in the ratios, off-shell effects and FSI largely cancel.

$a_j(A)$ is proportional to probability of finding a $j$-nucleon correlation

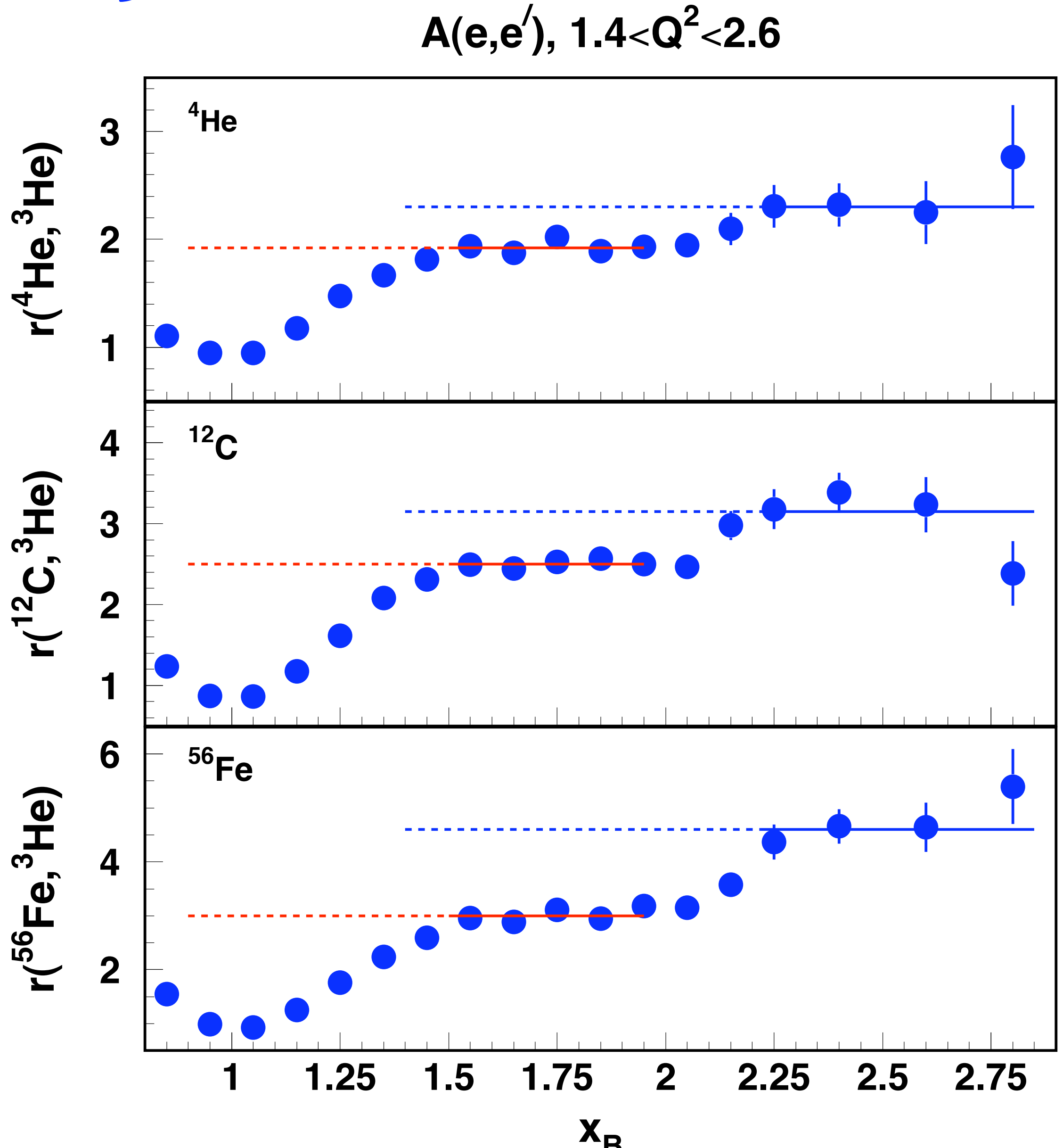
F&S

# Ratios, SRC's and $Q^2$ scaling




$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A);\ (1.4 < x < 2.0)$$



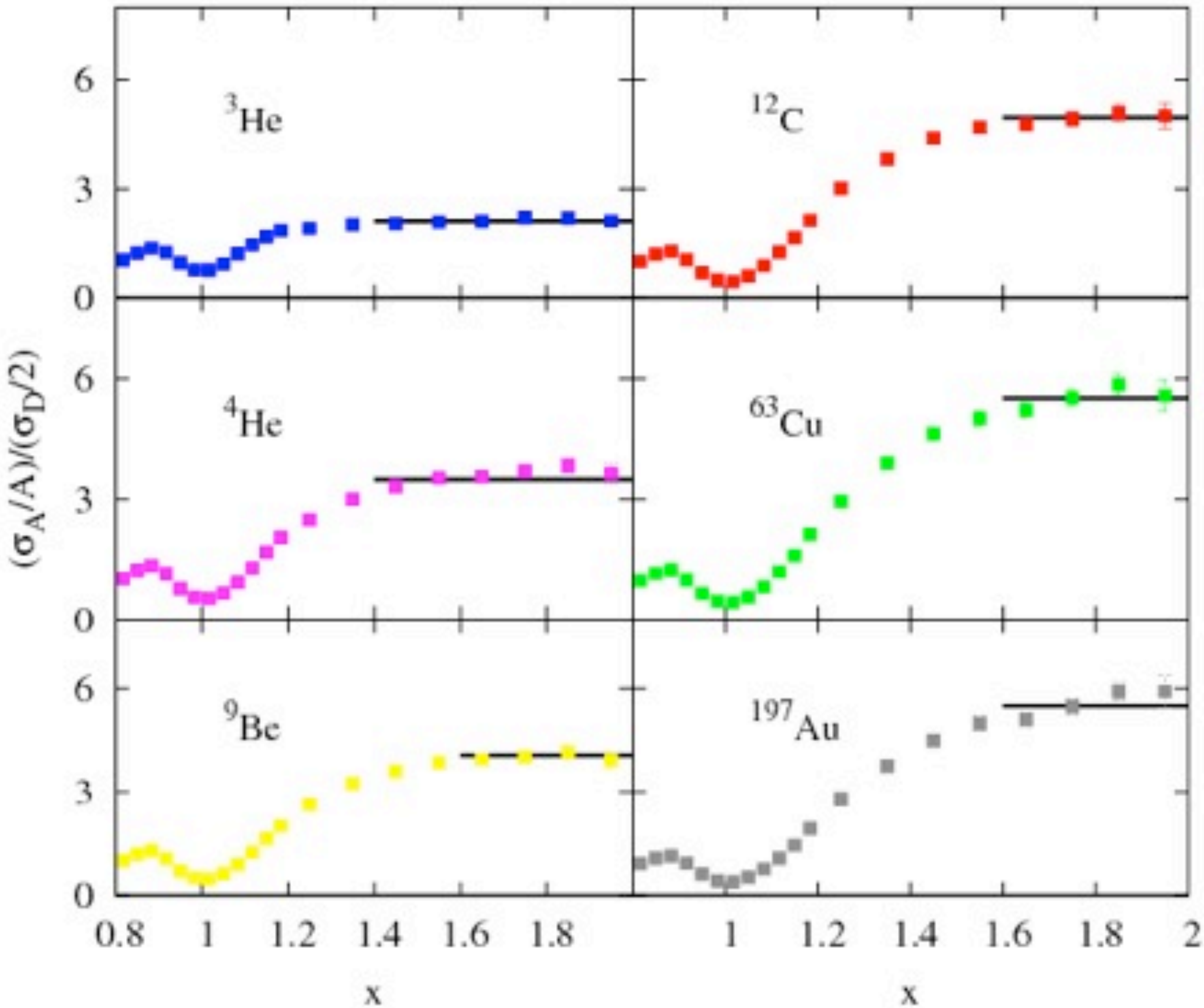

$\alpha_{2N} \approx 20\%$
$\alpha_{3N} \approx 1\%$

CLAS data
Egiyan et al., PRL 96, 082501, 2006

$a_j(A)$ is probability of finding a j-nucleon correlation

# SRC evidence at JLAB

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



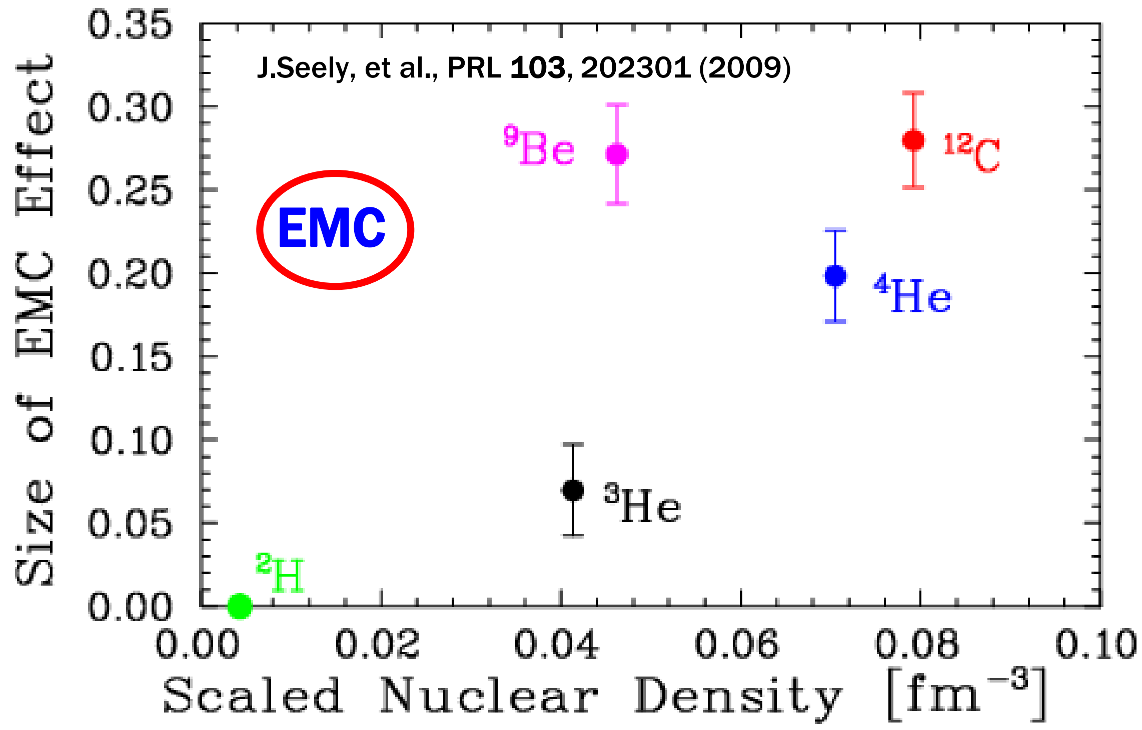
Dominance of np pairs in SRC region leads us to drop the isocalar correction. We correct for COM motion of pair

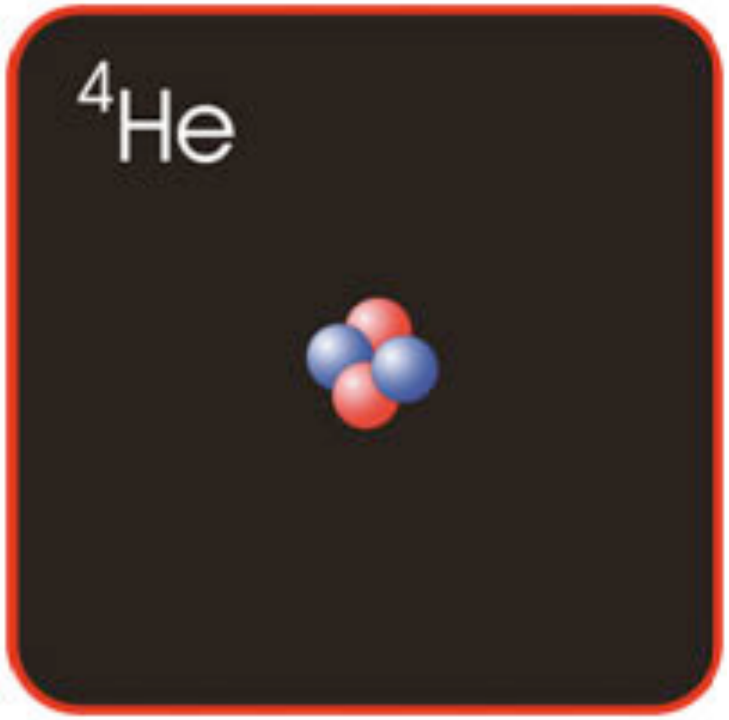
$R_{2n}$: number of (np) pairs, relative to the deuteron

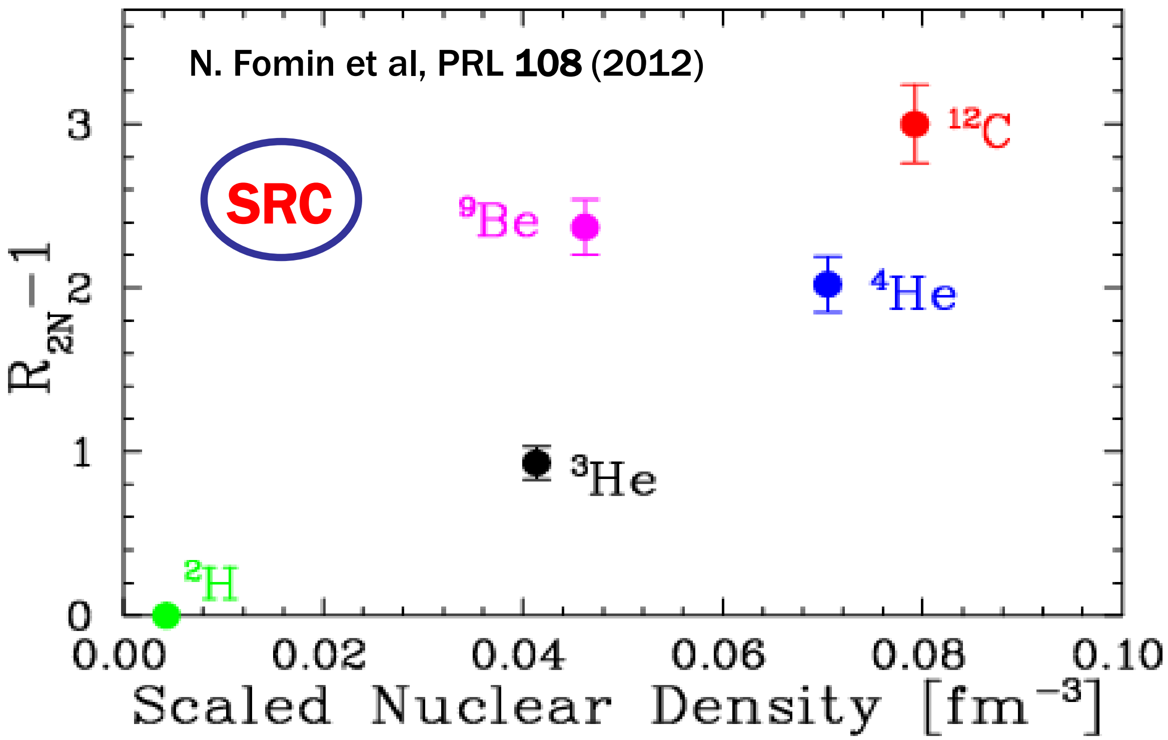
| A | $R_{2N}$ (E02-019) | SLAC | CLAS | $F_{CM}$ | | Ciofi/Simula |
|---|---|---|---|---|---|---|
| $^3$He | 1.93 ± 0.10 | 1.8 ± 0.3 | ⋯ | 1.10 ± 0.05 | | 1.9 |
| $^4$He | 3.02 ± 0.17 | 2.8 ± 0.4 | 2.80 ± 0.28 | 1.19 ± 0.06 | | 3.8 |
| Be | 3.37 ± 0.17 | ⋯ | ⋯ | 1.16 ± 0.05 | | |
| C | 4.00 ± 0.24 | 4.2 ± 0.5 | 3.50 ± 0.35 | 1.19 ± 0.06 | | 4.0 |
| Cu(Fe) | 4.33 ± 0.28 | (4.3 ± 0.8) | (3.90 ± 0.37) | 1.20 ± 0.06 | * | 4.5 |
| Au | 4.26 ± 0.29 | 4.0 ± 0.6 | ⋯ | 1.21 ± 0.06 | | 4.8 ($^{208}$Pb) |
| $\langle Q^2 \rangle$ | ~2.7 GeV$^2$ | ~1.2 GeV$^2$ | ~2 GeV$^2$ | | | |
| $x_{\min}$ | 1.5 | ⋯ | 1.5 | | | |
| $\alpha_{\min}$ | 1.275 | 1.25 | 1.22–1.26 | | | |

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

# SRC, EMC and density dependence



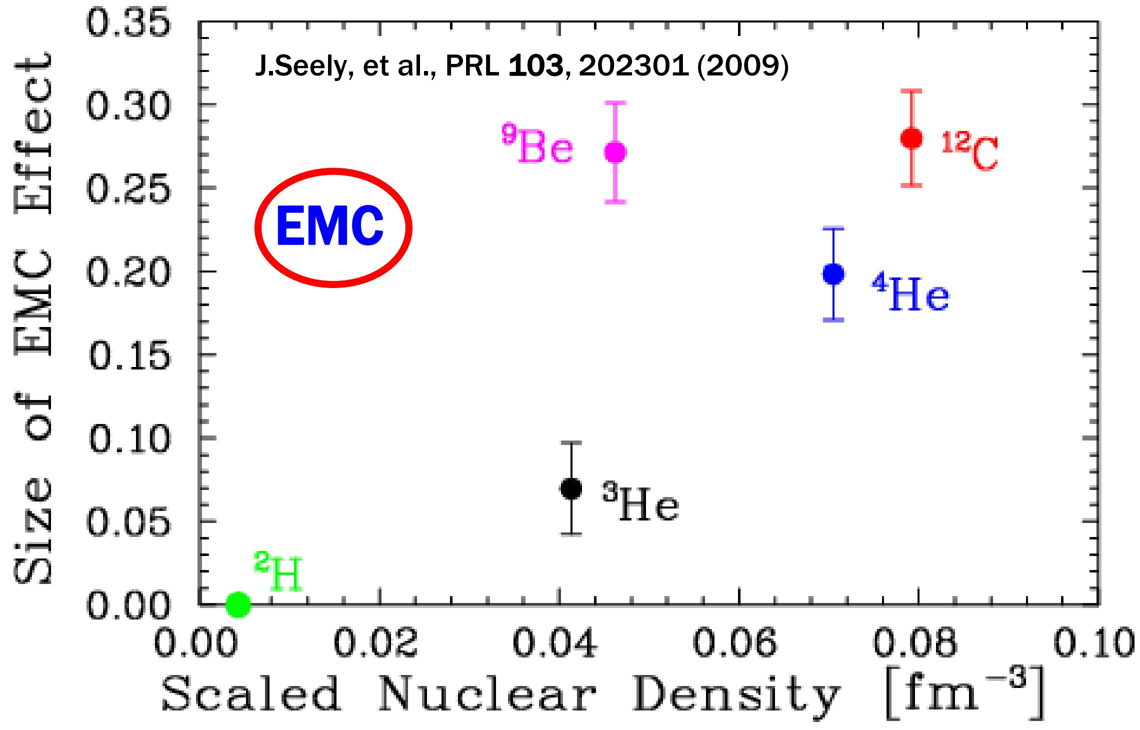



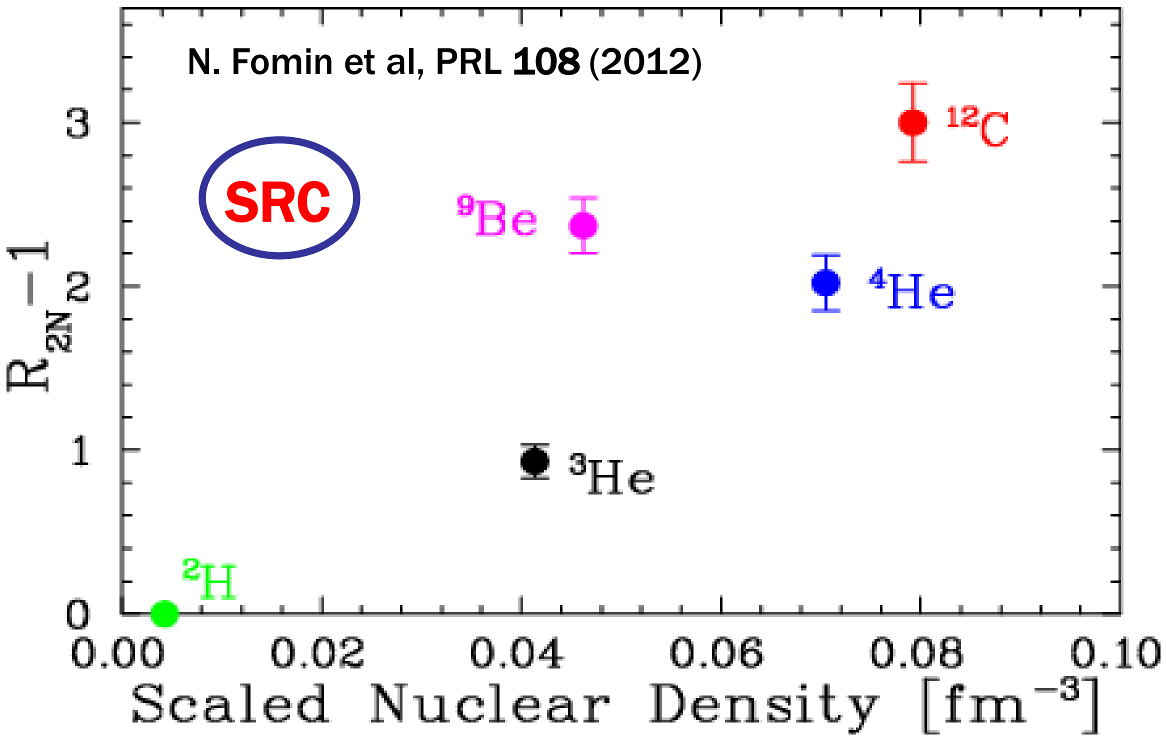



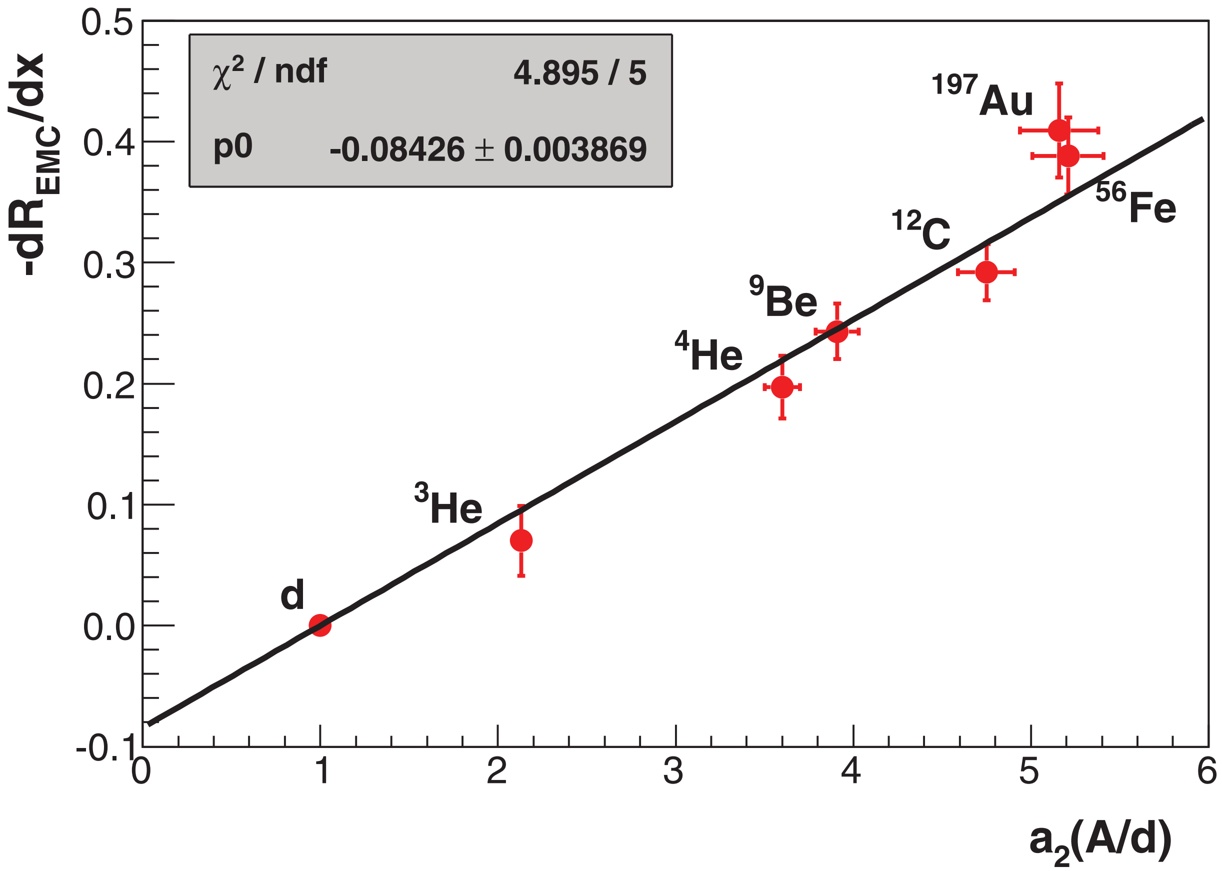


main bulk properties: $\rho(r)$ and $n(k)$

# SRC, EMC and density dependence




L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, and R. Shneor Phys. Rev. Lett. 106, 052301 (2011)

O. Hen, E. Piasetzky, and L. B. Weinstein, Phys. Rev. C 85, 047301 (2012)

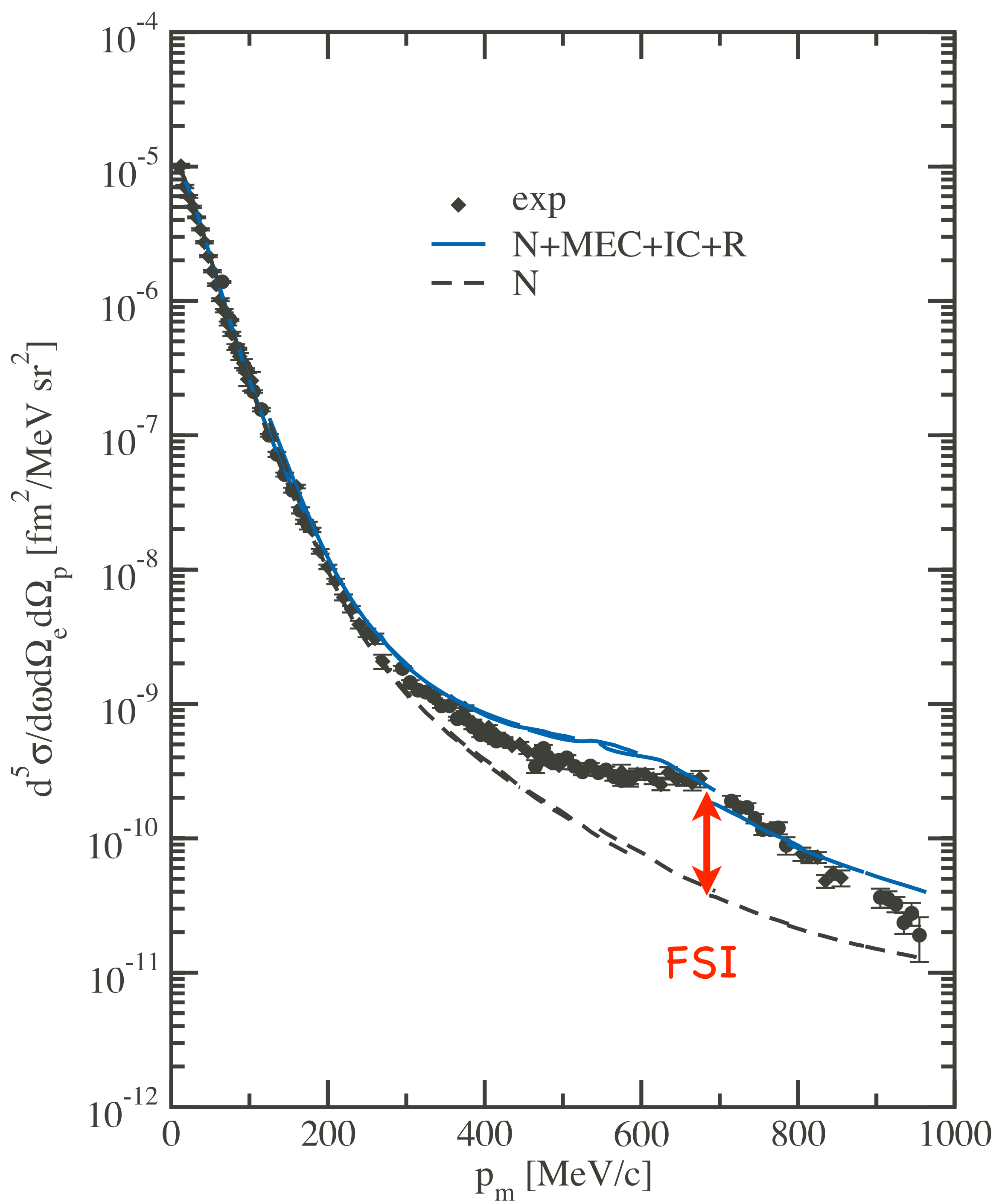
J.Arrington, A. Daniel, DD, N. Fomin, D. Gaskell, P. Solvignon, Phys. Rev. C 86, 065204 (2012)

Density dependence!

FSIs do not connect the EMC effect to the SRC!

# Exclusive A(e,e'p)

Deuteron




High momentum(!!) strength in proton knockout in (e,e'p)

## $^2$H(ee'p)n Mainz

Boeglin et al, Phys. Rev. C 78, 054001 (2008)

Blomqvist et al, Phys Lett B, (1998), 33-38

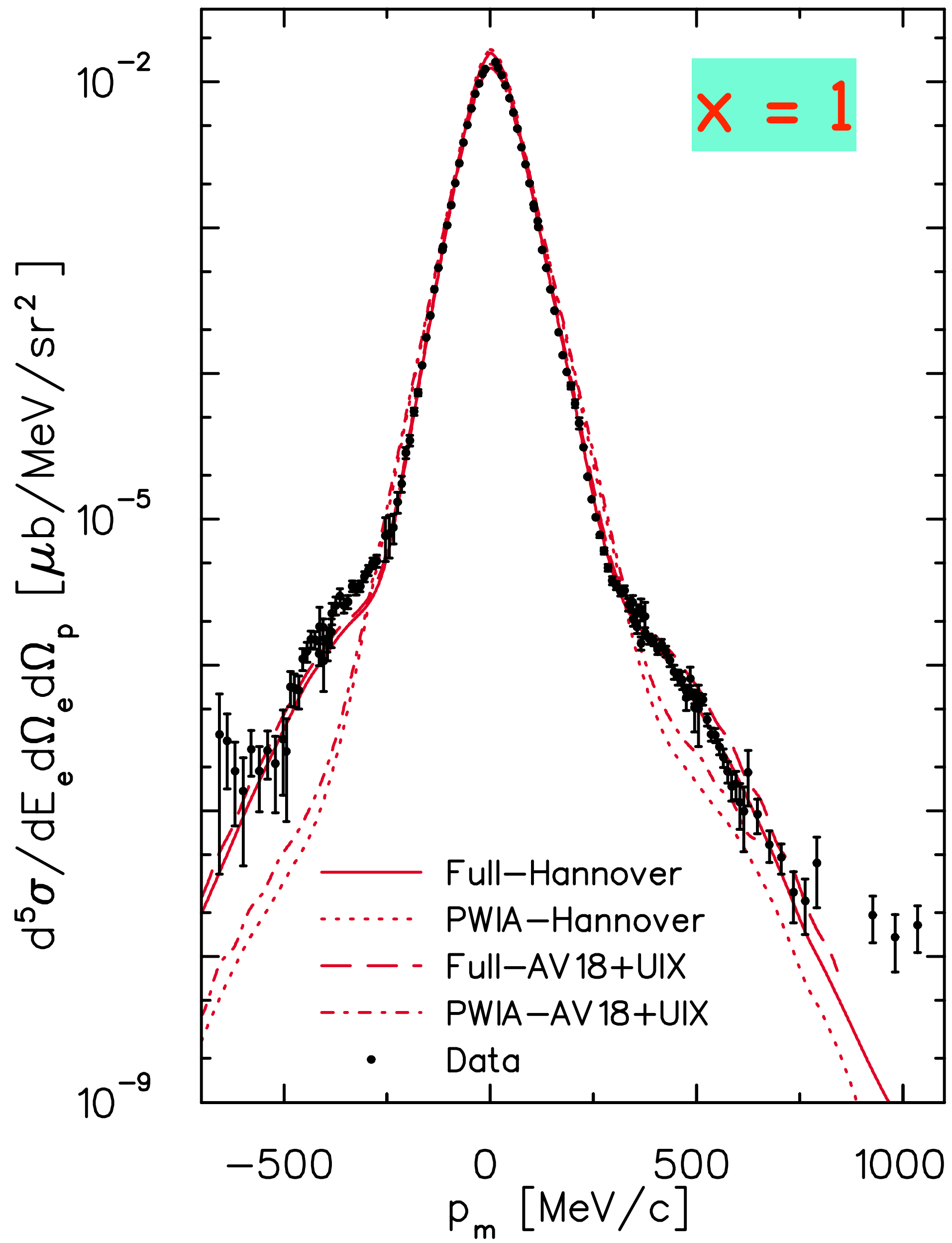
E = .855
θ = 45
E' = .657
$Q^2$ = 0.33
x = .88

Not the best place to look for SRCs - Δs, MECs FSI dominate

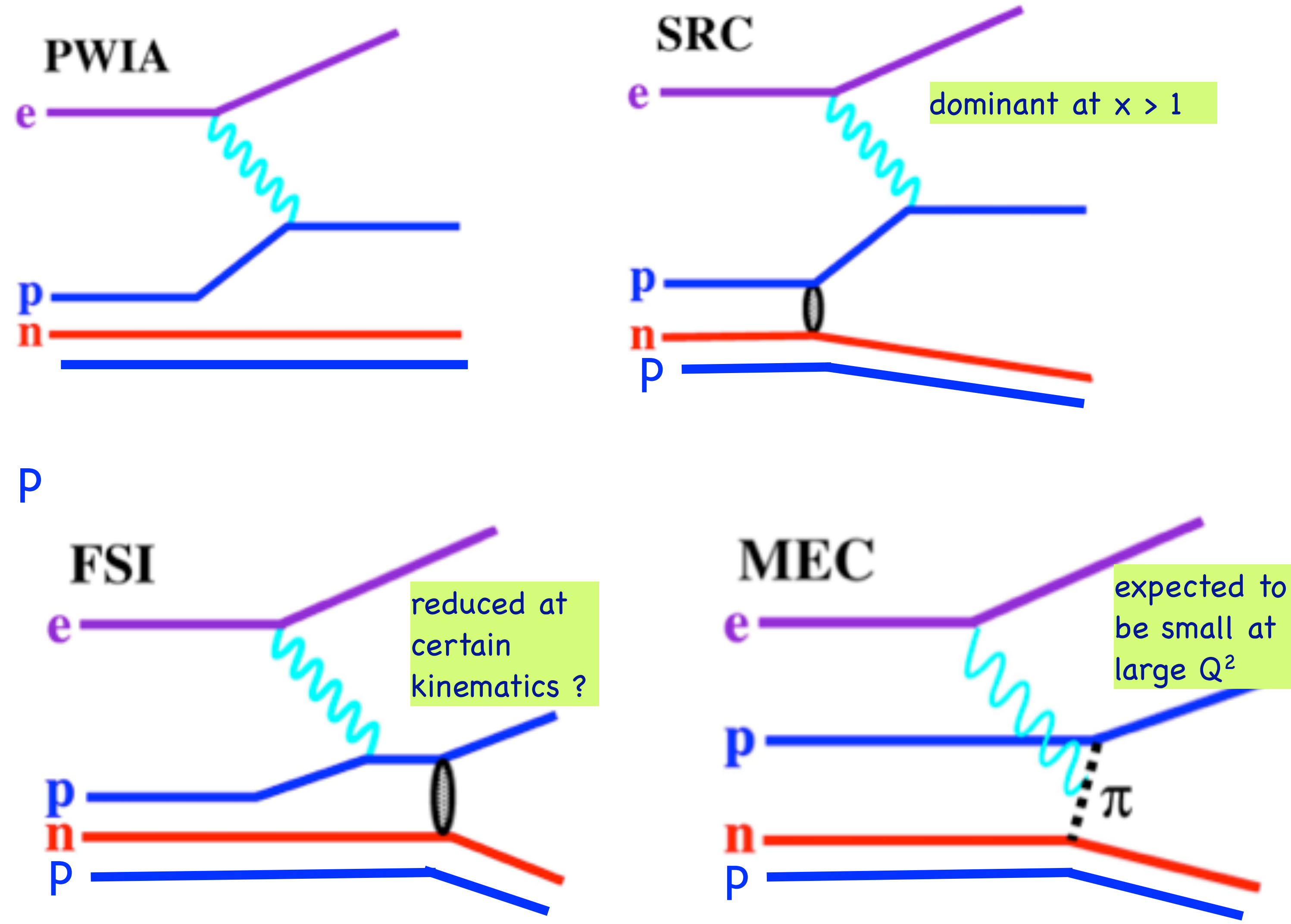
large IC+MEC

# Exclusive A(e,e'p)

## $^{3}$He(e,e'p)d E89-044, Hall A




M. M. Rvachev et al.
PRL 94, 192302 (2005)

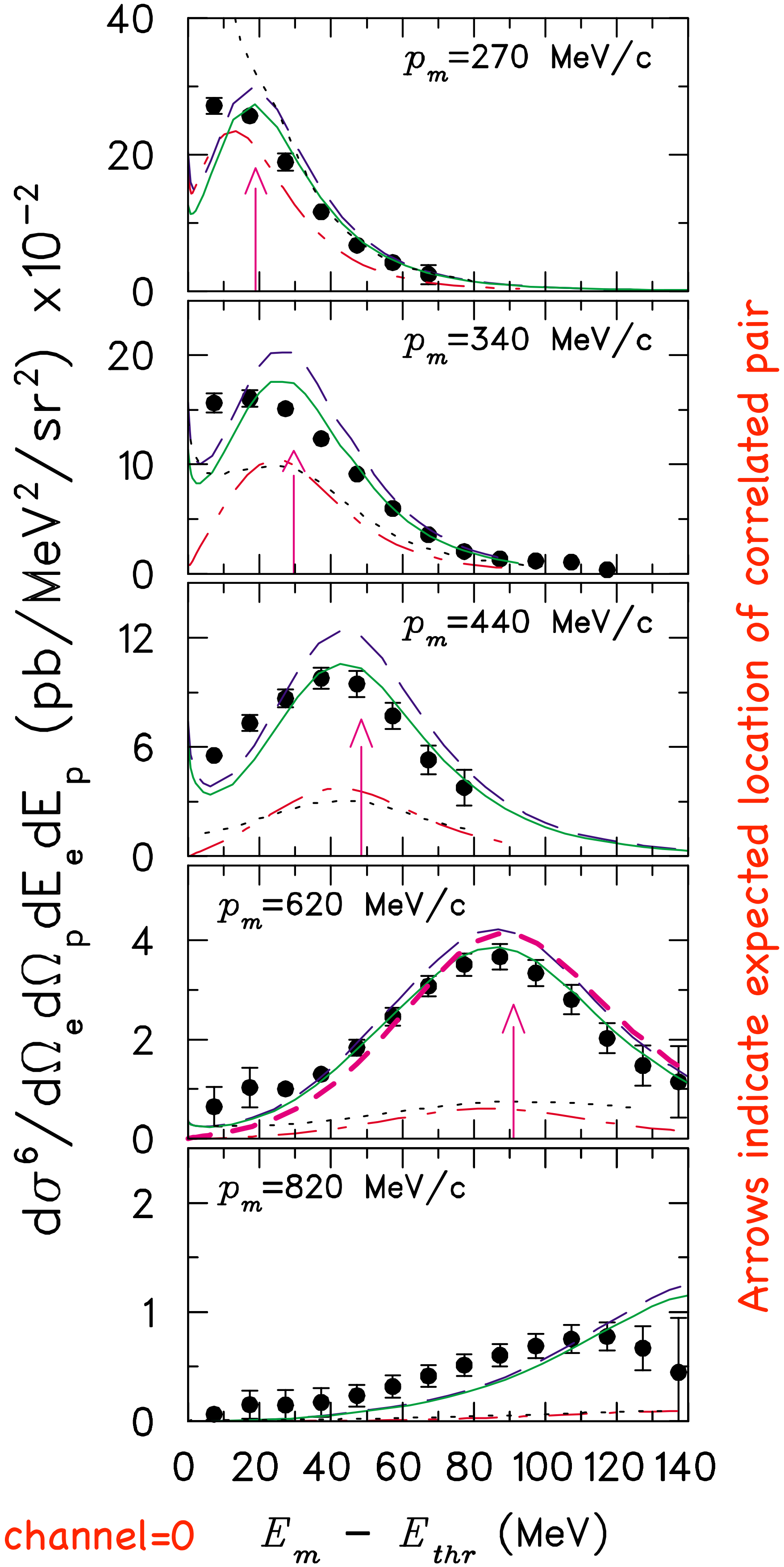



Measured far into high momentum tail
Cross section is ~5-10x expectation
High momentum pair can come from SRC (initial state)
OR
Final State Interactions (FSI) and Meson Exchange Contributions (MEC), Δ's

# Exclusive A(e,e′p)

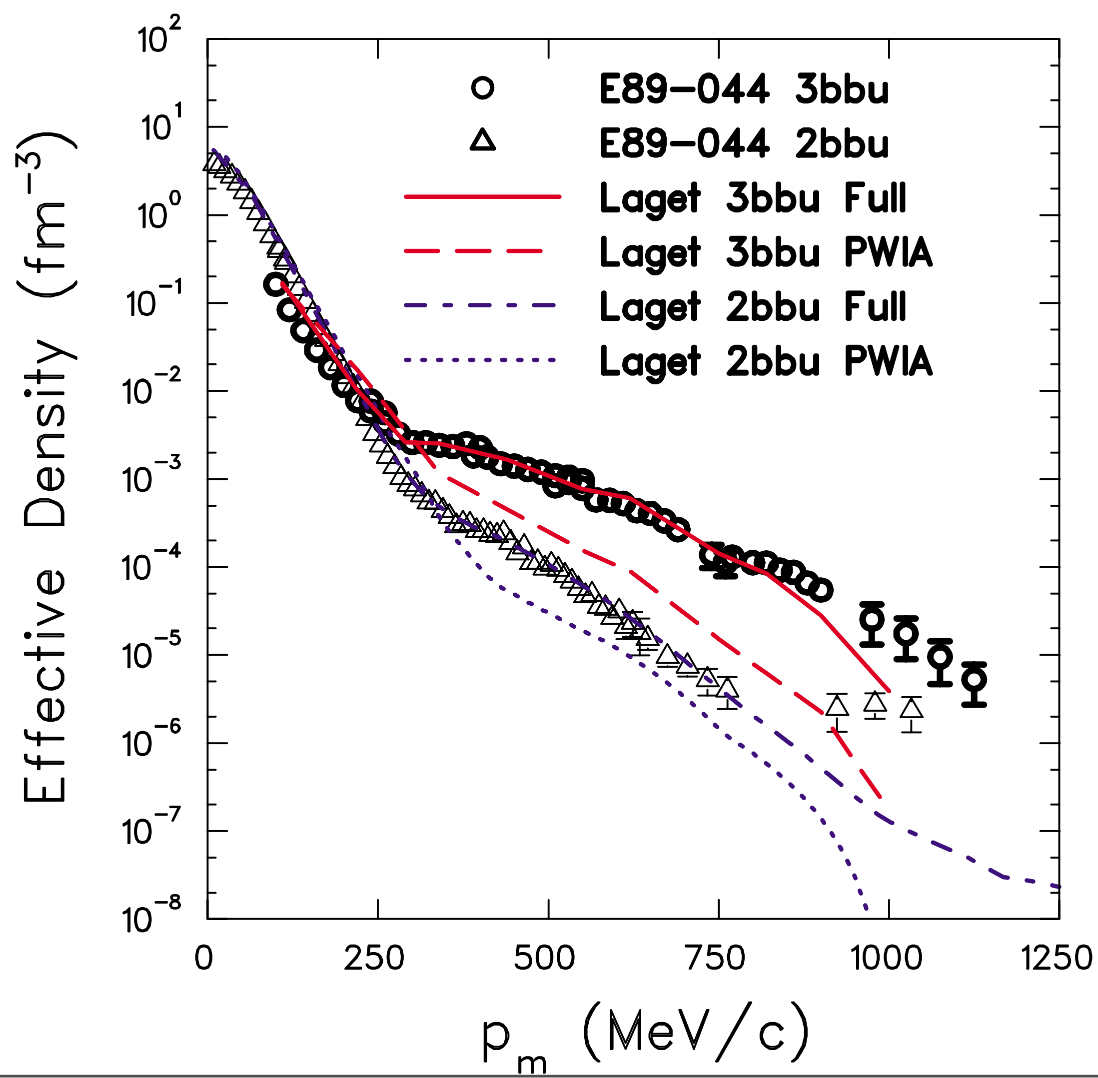
## $^3$He(e,e′p)pn E89-044, Hall A

$^3$He(e,e′p)np F. Benmokhtar et al. , PRL 94, 082305 (2005)




3bbu channel=0

- dotted line PWIA
- dash-dot: Laget (PWIA)
- FSI (long dashed line) to full calculation (solid line), including meson-exchange current and final-state interactions: Laget
- In the 620 MeV/c panel
  - short dashed curve is a calculation with PWIA + FSI only within the correlated pair.

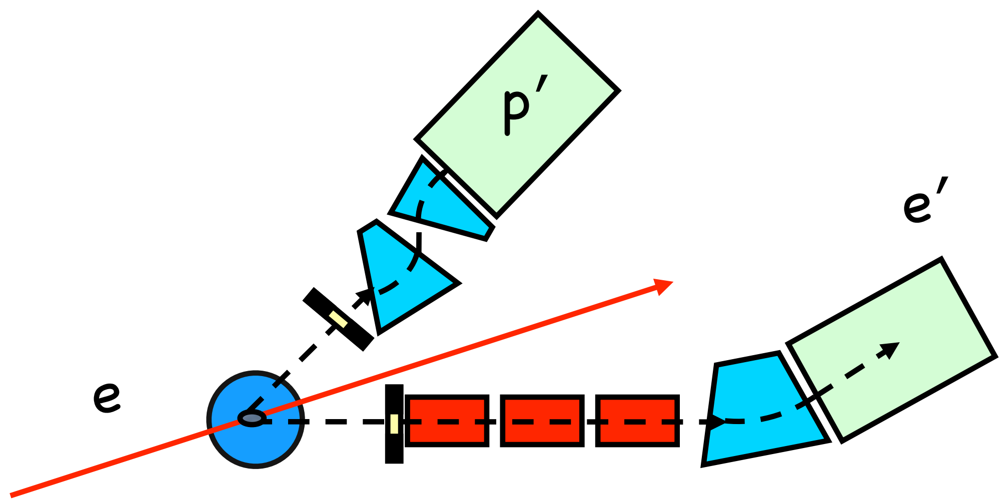



x = 1

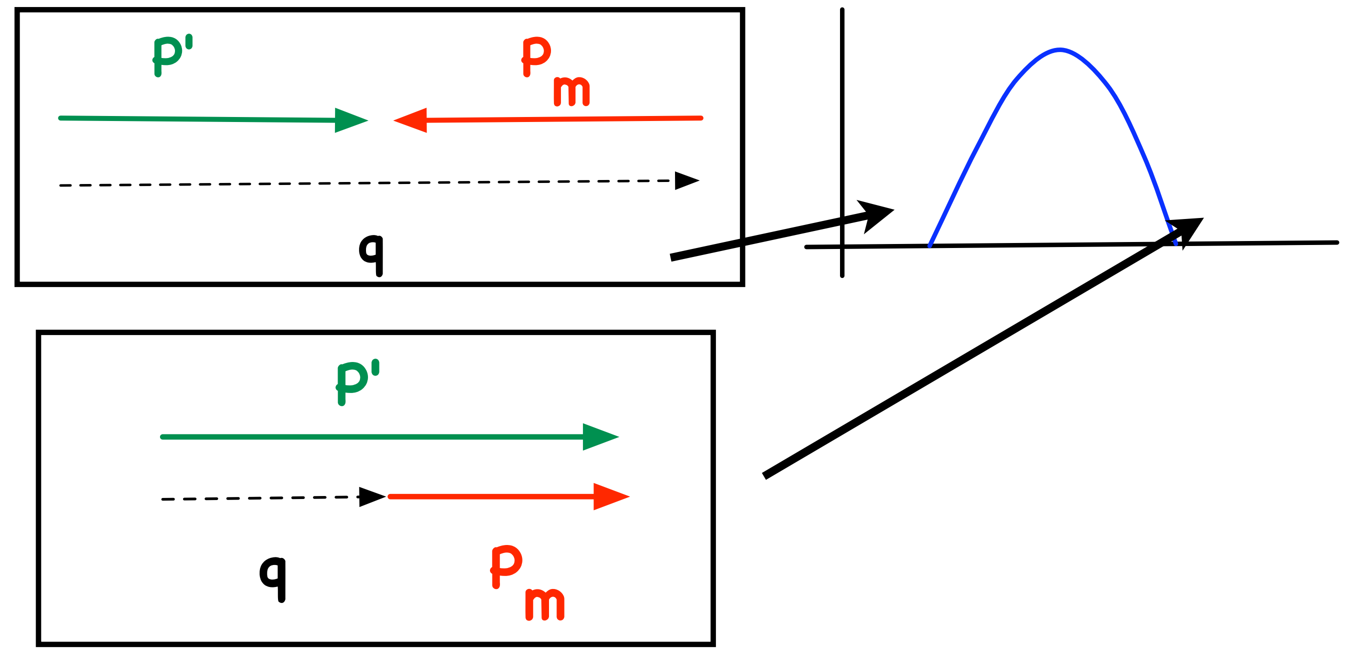
# E97-006 Correlated Spectral Function and (e,e'p) Reaction Mechanism

Data at high $p_m$, $E_m$ measured in Hall C at Jlab:

- targets: C, Al, Fe, Au
- kinematics: 3 parallel $p \parallel q$



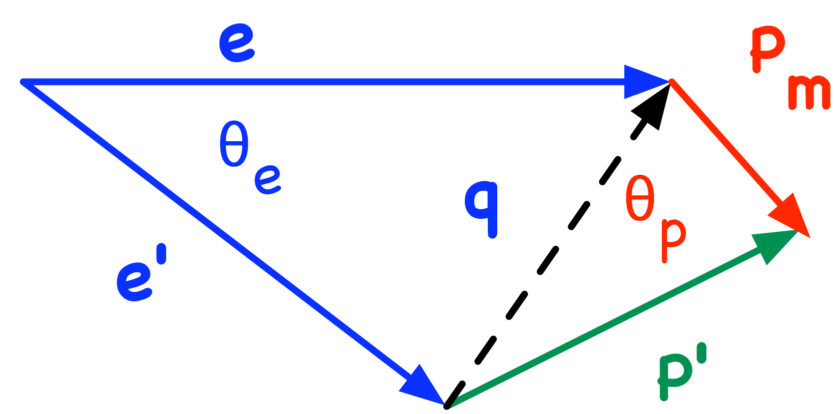

SOS and HMS in Hall C




To map out $S(E_m,p_m)$ vary **q** keeping $p'$ $(T_p)$ constant so that FSI are constant

- kinematics: 2 perpendicular $p_m \perp q$

- Fix e, $\theta_e$, p′
- Vary $E_m$ thru e′
- Vary $p_m$ with proton angle $\theta_p$




D. Rohe, et al. Phys. Rev Lett. 93 182501

Daniela Rohe Habilitation

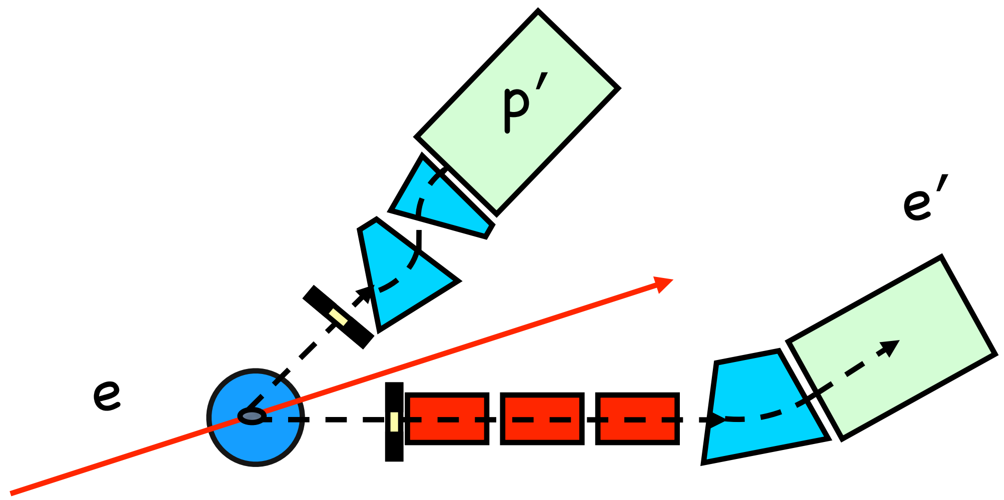
Study reaction mechanism

# E97-006 Correlated Spectral Function and (e,e'p) Reaction Mechanism

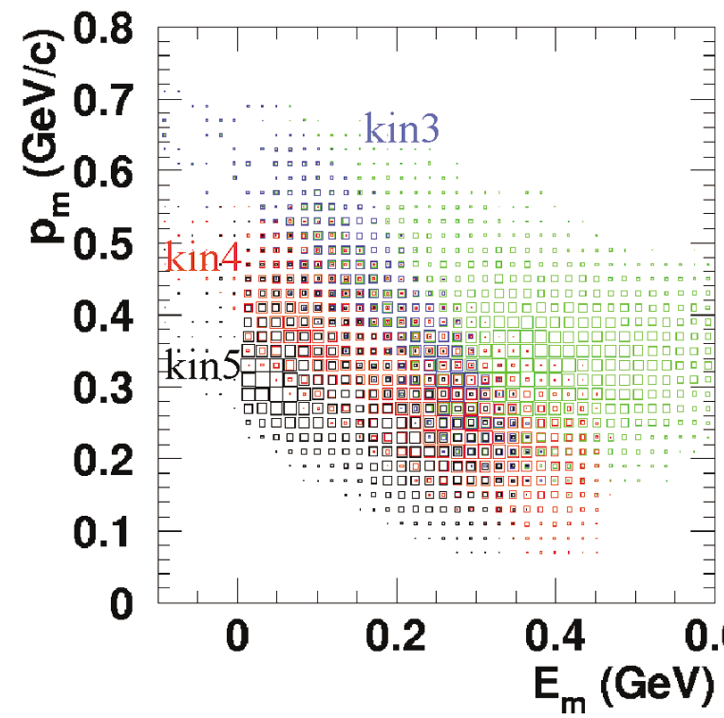
D. Rohe, et al. Phys. Rev Lett. 93 182501

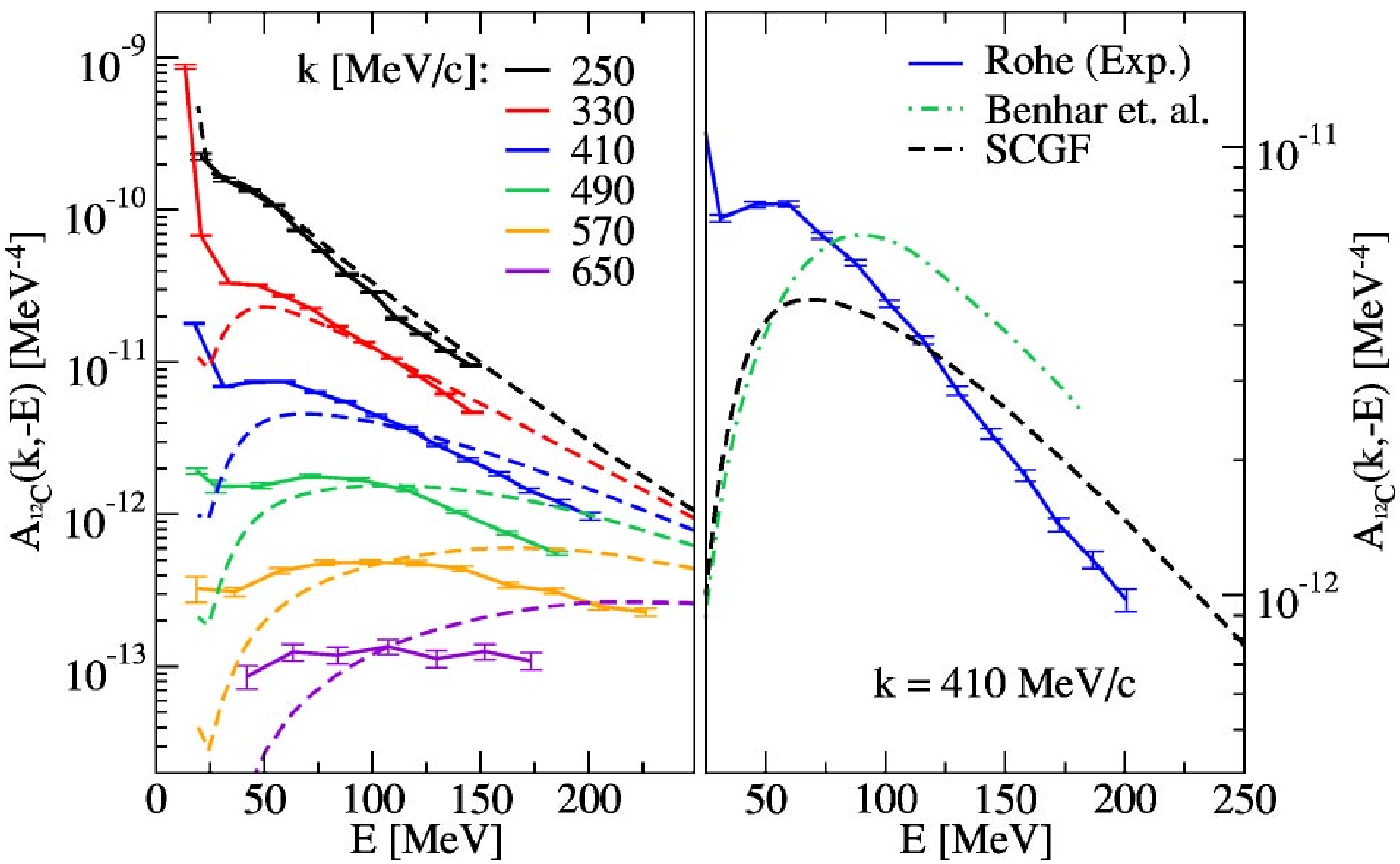
Parallel kinematics selected to minimize FSI

C. Barbieri et al, PLB 608, (2005), 47-52




SOS and HMS in Hall C




Data suggests more SRC strength at smaller E than theory - COM?

Frick et al. PRC 70, 024309 (2004)

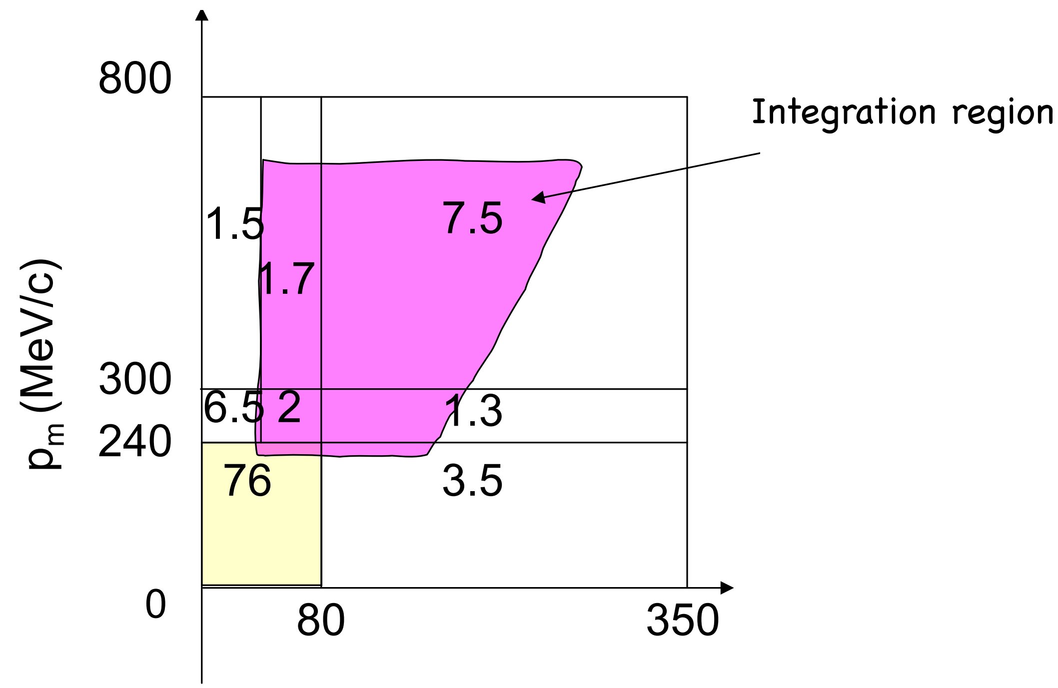
Self consistent Green's Function (SCGF)

## Integrated strength in the covered $E_m$-$p_m$ region:

Rohe et al.,
Phys. Rev. Lett. 93, 182501 (2004)

$$Z_c = 4\pi \int_{130}^{670} dp\, p_m^2 \int dE_m S(E_m, p_m)$$

"correlated strength" in the chosen $E_m$-$p_m$ region:




In terms of # of protons in $^{12}C$

| $^{12}C$ | exp. | CBF theory | G.F. 2.order | self-consistent G.F. |
|---|---|---|---|---|
| experimental area | 0.61 | 0.64 ≈ 10 % | 0.46 | 0.61 |
| in total (correlated part) | | 22 % | 12% | ≈20% |

contribution from FSI: -4 %

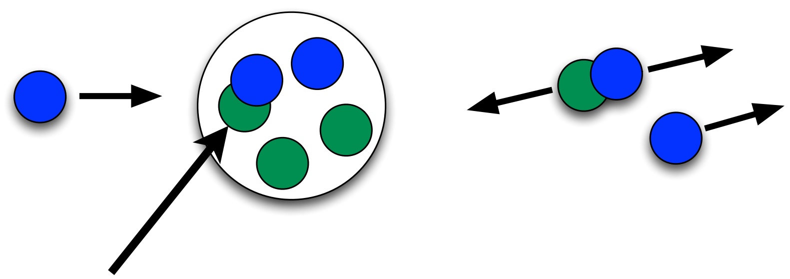
comparing to theory leads to conclusion that

**≈ 20% of the protons in Carbon are beyond the IPSM region**

# Triple Coincidence SRC Measurements - BNL

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

A. Tang, J. W. Watson et al. Phys. Rev. Lett. 90, 042301 (2003)



Correlated pair have equal and opposite momenta

"That neutrons emitted into the backward hemisphere with $p_n > k_F$ come from n-p SRC, since SRC is a natural mechanism to explain such momentum-correlated pairs"

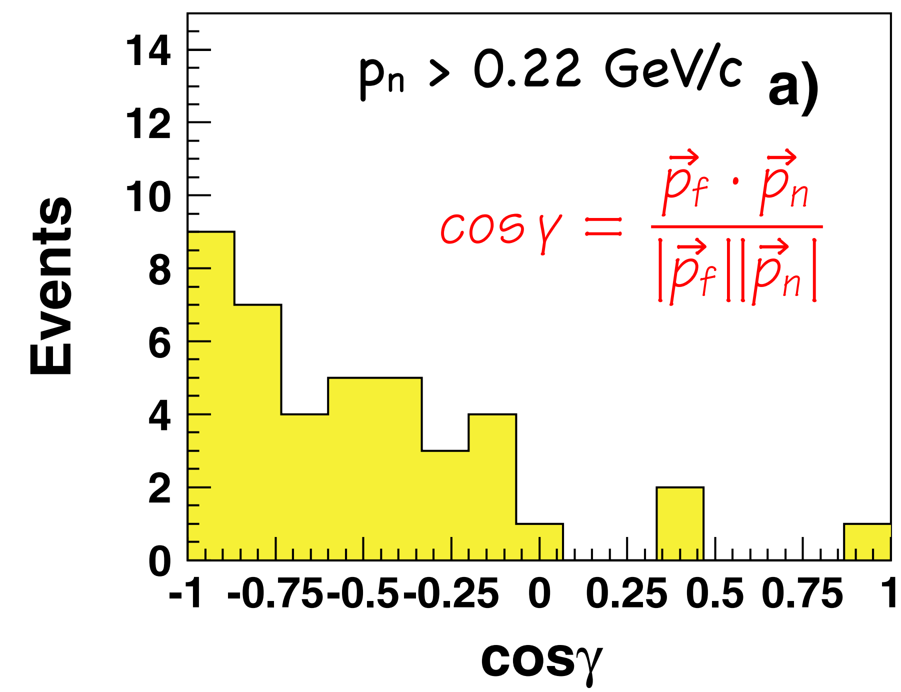
49 ± 13% of events with $|p_f| > k_F$ had directionally correlated neutrons with $|p_n| > k_F$

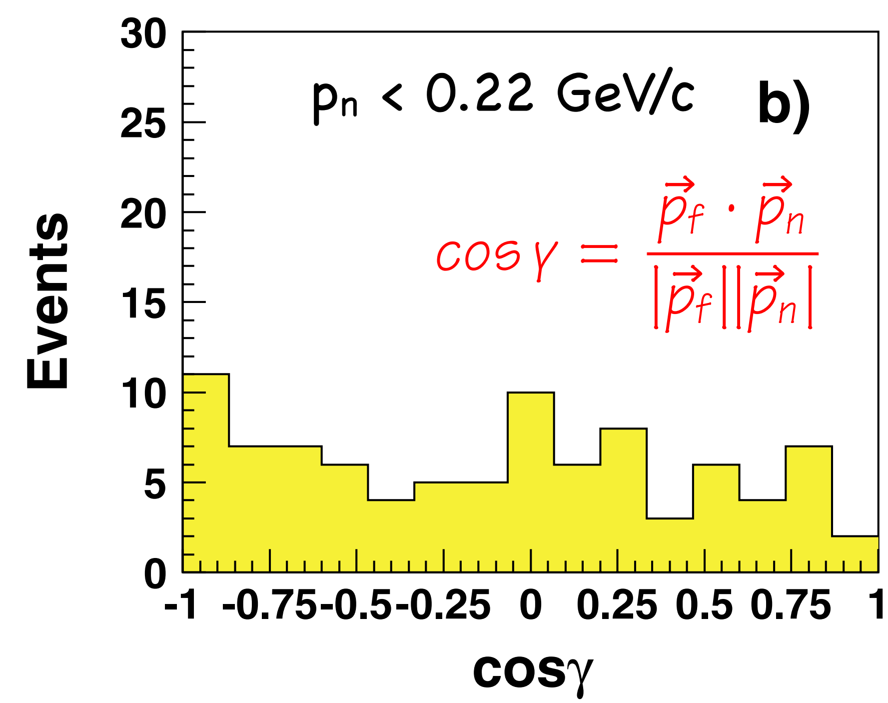
Isospin dependence unstated but SRCs must be the source of high-k

Reconstruct the struck proton before scattering

$$\vec{p}_f = \vec{p}_1 + \vec{p}_2 - \vec{p}_o$$

Detect 2 protons along with emerging neutron



## Neutron absorption as it moves through the (A-2) system?

Significant possibility that the neutron momentum falls below $k_f$

**Analysis** E. Piasetzky, M. Sargsian, L. Frankfurt, M. Strikman, and J. W. Watson, Phys. Rev. Lett. 97, 162504 (2006)

- Modeling of the spectral and decay functions of the reaction in light cone approximation
  - Extraction of the quantity $P_{pn/px}$
  - $P_{pn/px}$: the probability of finding a pn correlation in the "pX" configuration that is defined by the presence of at least one proton with $p > k_{Fermi}$.
  - Results: removal of a proton with initial 275 < p > 550 MeV/c is associated by the emission of a correlated neutron with equal and opposite momentum of the proton 92 (+8/-18)% of the time.
- Proton recoils (eg A(p,pp)n) were not detected but an estimate could be made
- Probabilities of pp or nn SRCs in the nucleus are at least a factor of 6 smaller than that of pn SRCs.

**Isospin dependence of SRC**

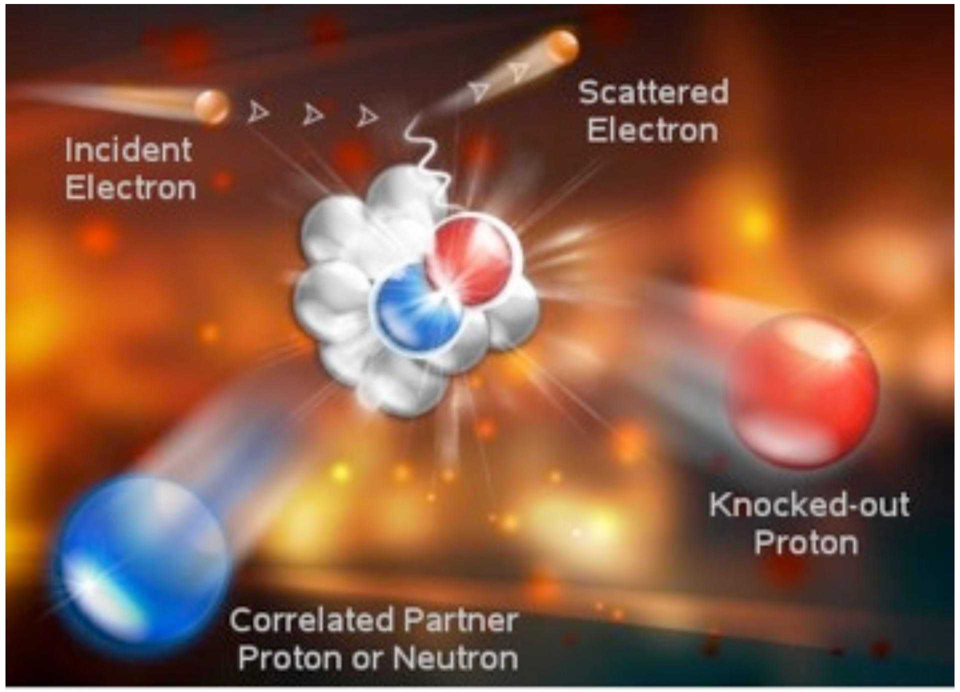
# JLAB Experiment E01-015

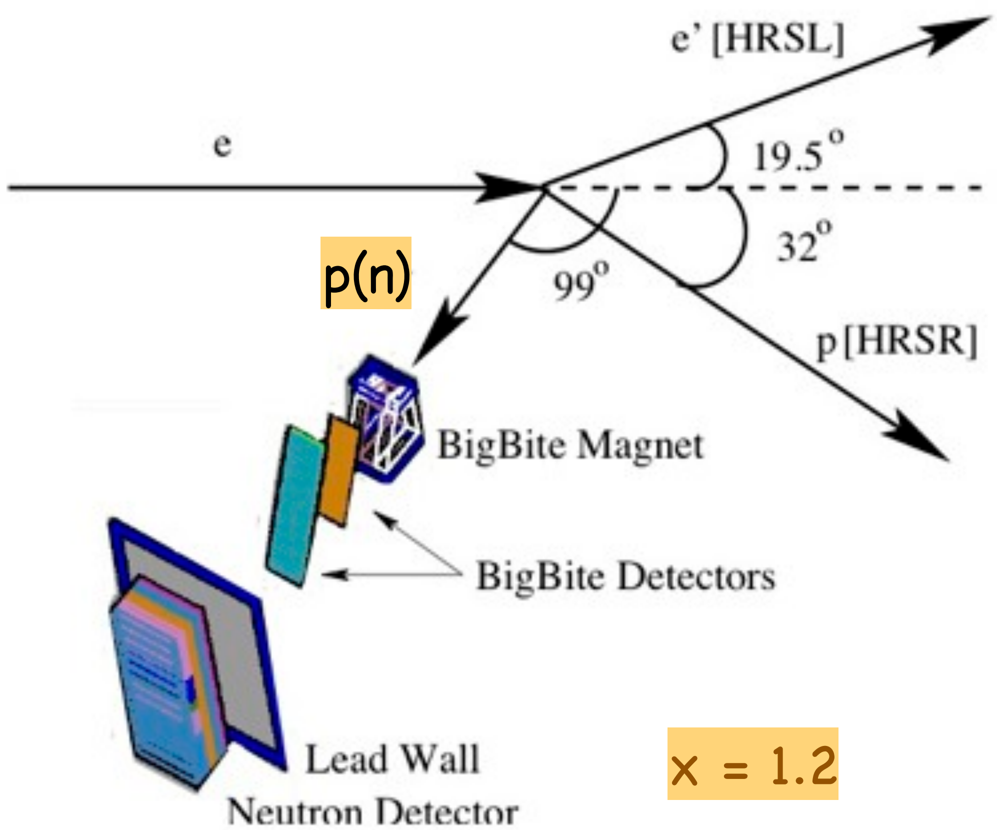
Simultaneous measurements of the (e,e′p), (e,e′pp), and (e,e′pn) reactions

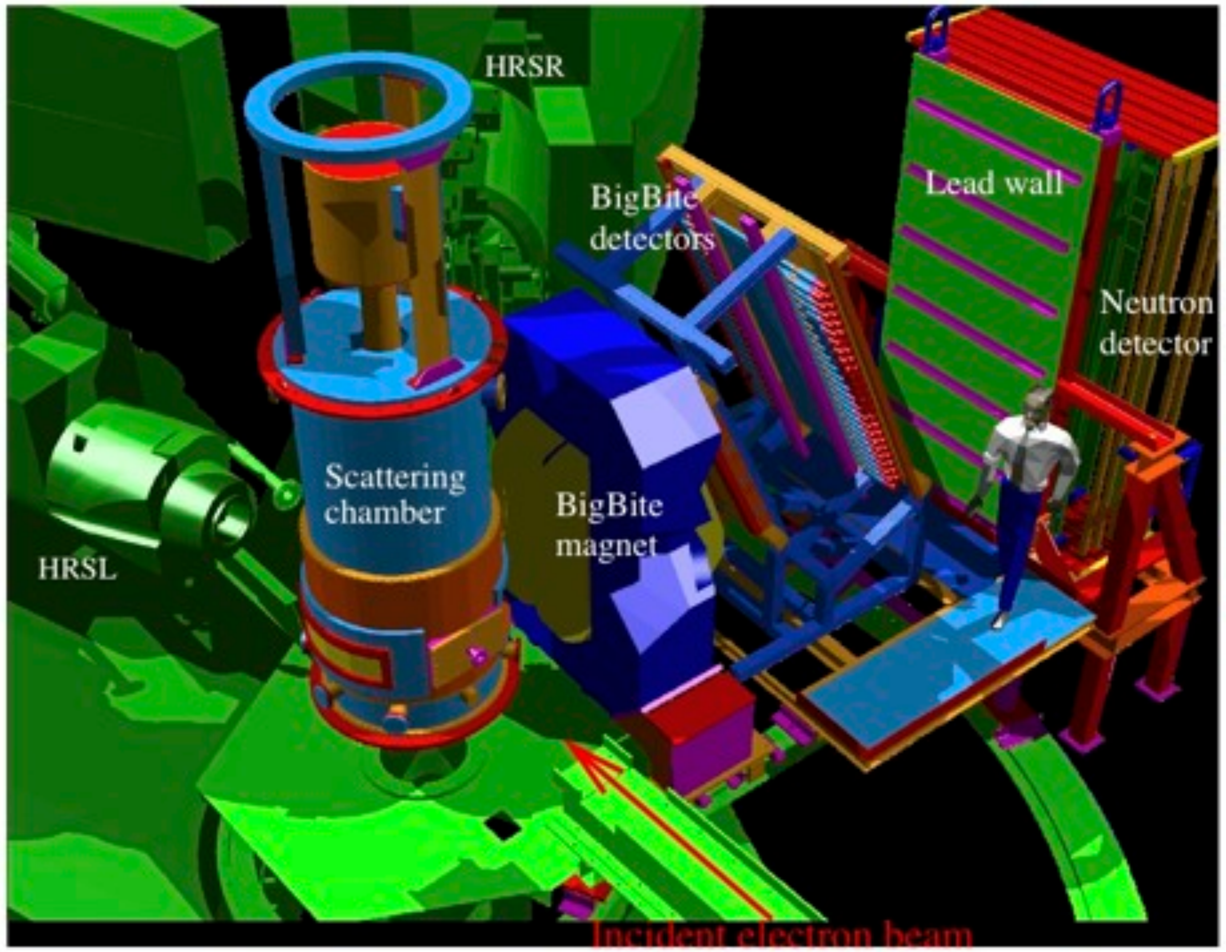
Use $^{12}C(e,e'p)$ as a tag to measure $^{12}C(e,e'pN)/^{12}C(e,e'p)$

Optimized kinematics:

$Q^2 \approx 2.0$ $x_B \approx 1.2$ "Semi anti-parallel" kinematics



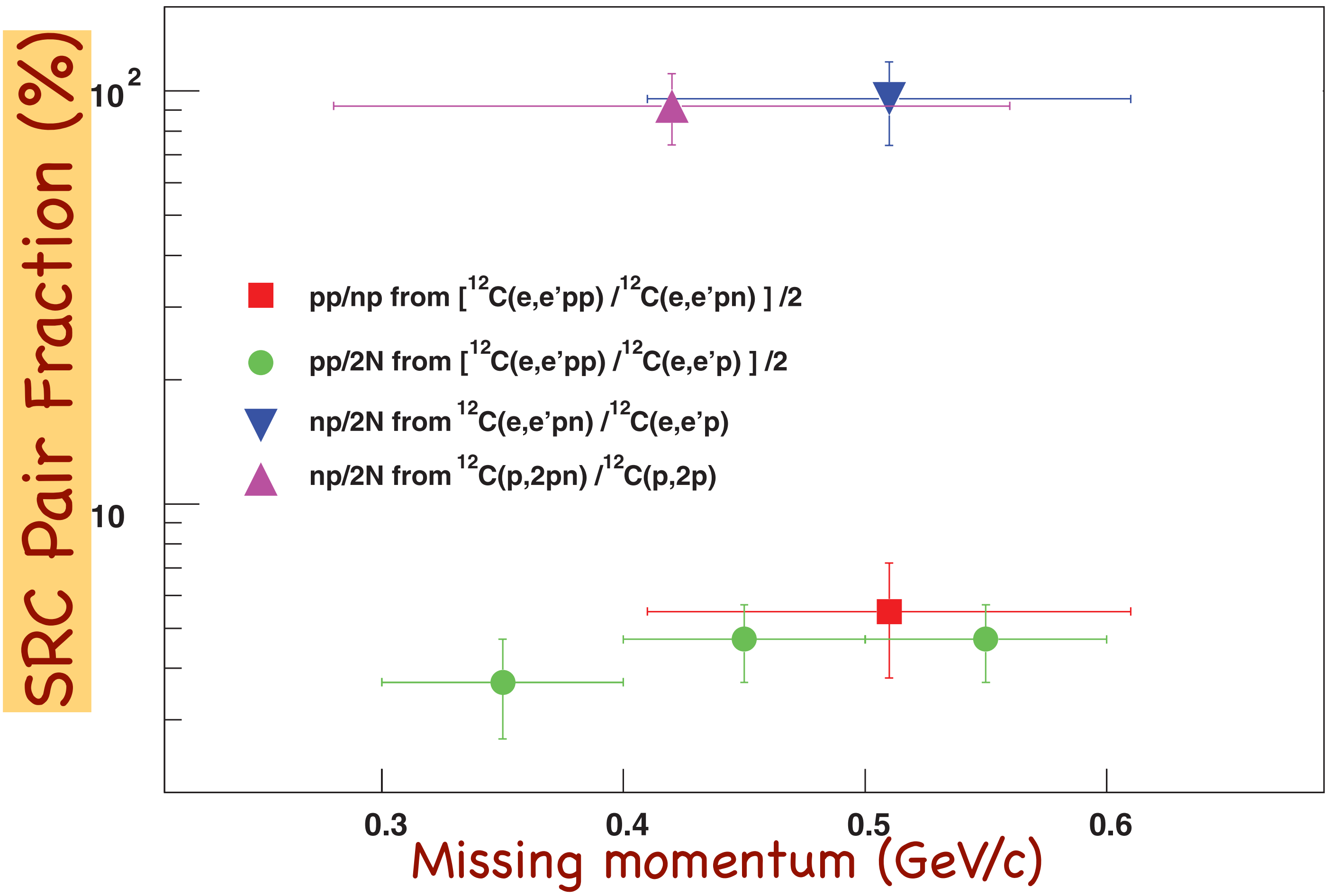



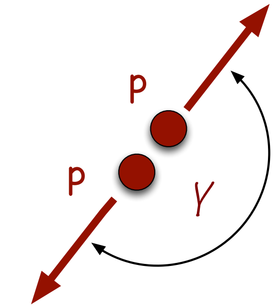

R. Shneor, et al., Phys. Rev. Lett. 99 (2007) 072501.

R. Subedi, et al., Science 320 (2008) 1476-1478.

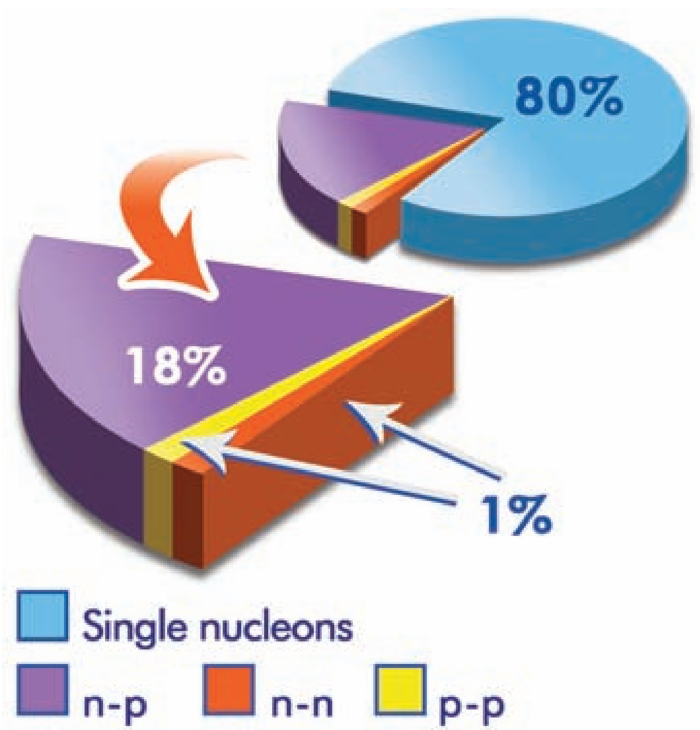
# JLAB Experiment E01-015




# Findings




- Almost all protons with $p_i > k_F$ in $^{12}$C(e,e′p) have a paired proton or neutron with similar momentum in opposite direction!
- CM momentum of pair $\sigma_{CM}$= 136±20 MeV/c
  - (BNL)=143±17
  - (Ciofi degli Atti&Simula)=139 MeV/c




Data show large asymmetry between np, pp pairs.
Qualitative agreement with calculations; effect of tensor force

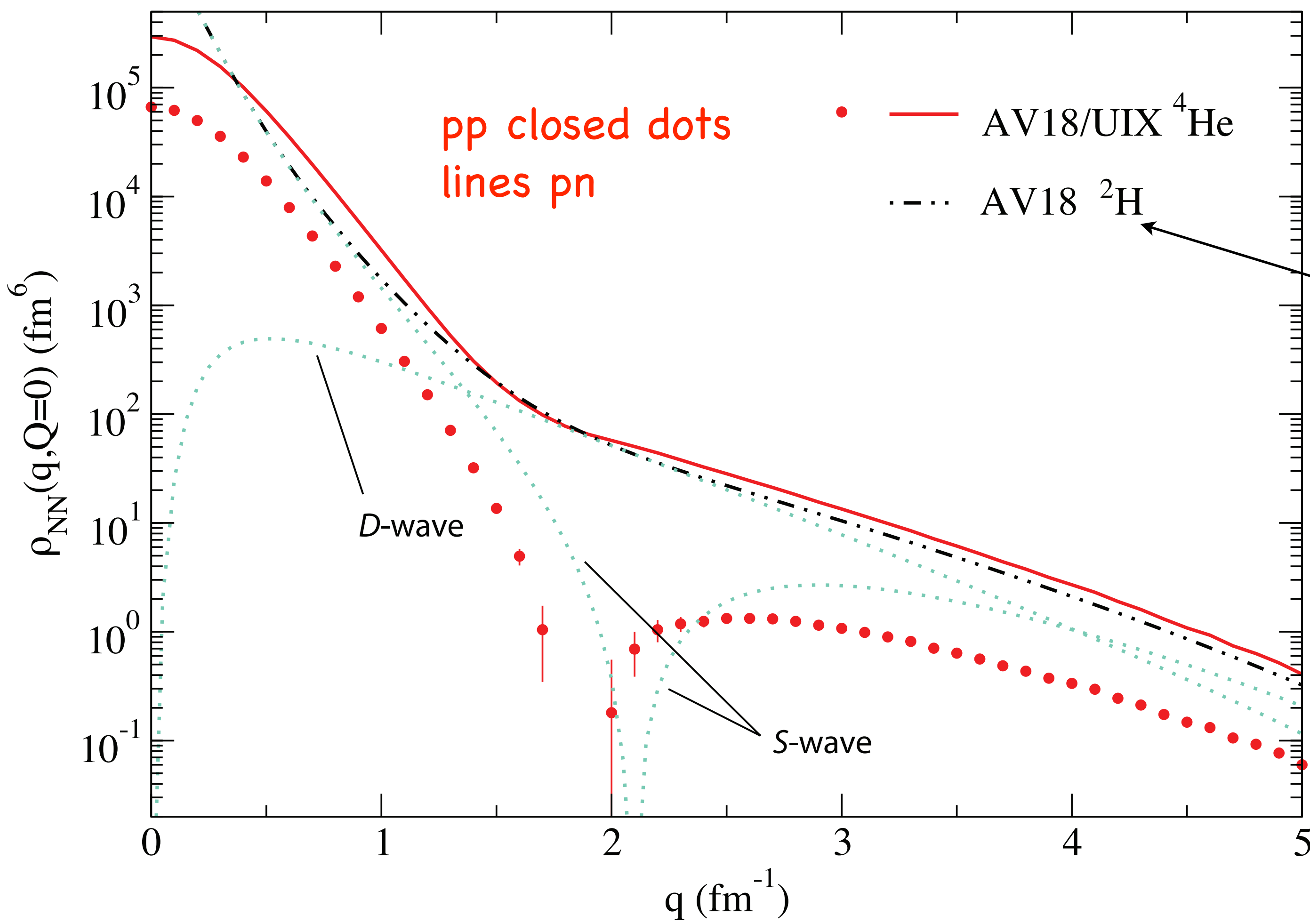
$$\frac{^{12}C(e,e'pp)}{^{12}C(e,e'p)} = 9.5 \pm 2\%$$

$$\frac{^{12}C(e,e'pn)}{^{12}C(e,e'p)} = 96^{+4}_{-23}\%$$

$$\frac{^{12}C(e,e'pn)}{^{12}C(e,e'pp)} = 9.0 \pm 2.5\%$$

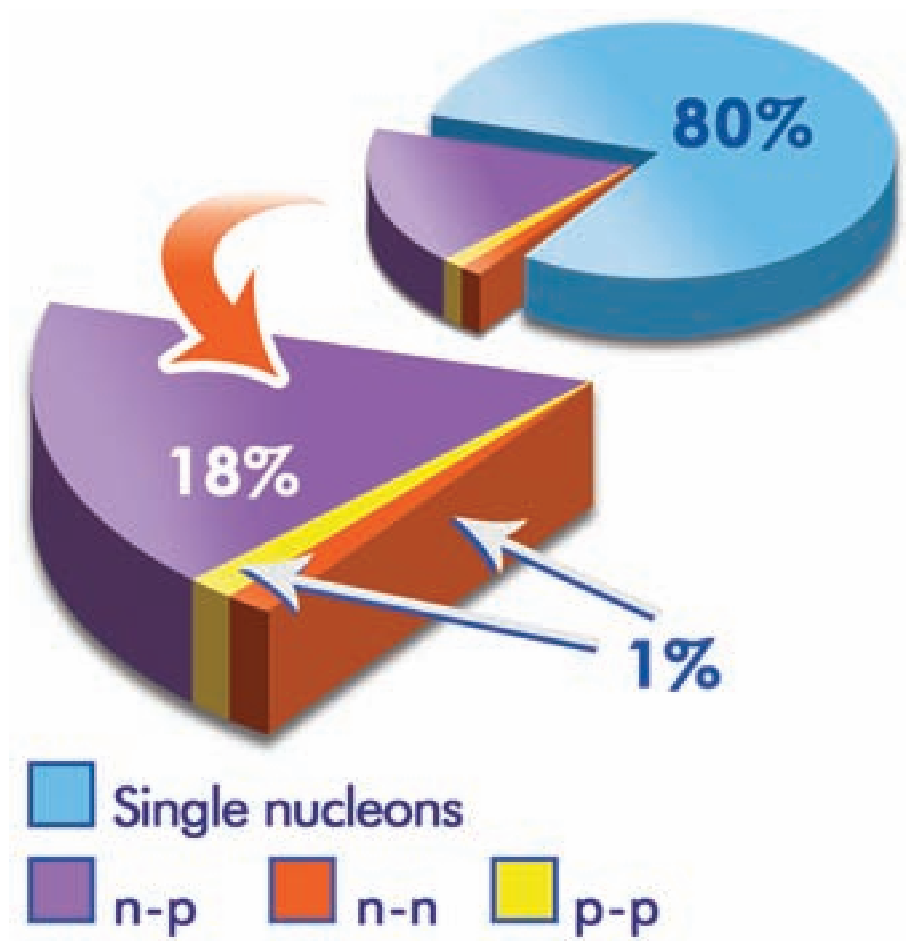
**Isospin dependence of SRC**

# Tensor force responsible for dominant part of SRC and correlations are largely of pn pairs

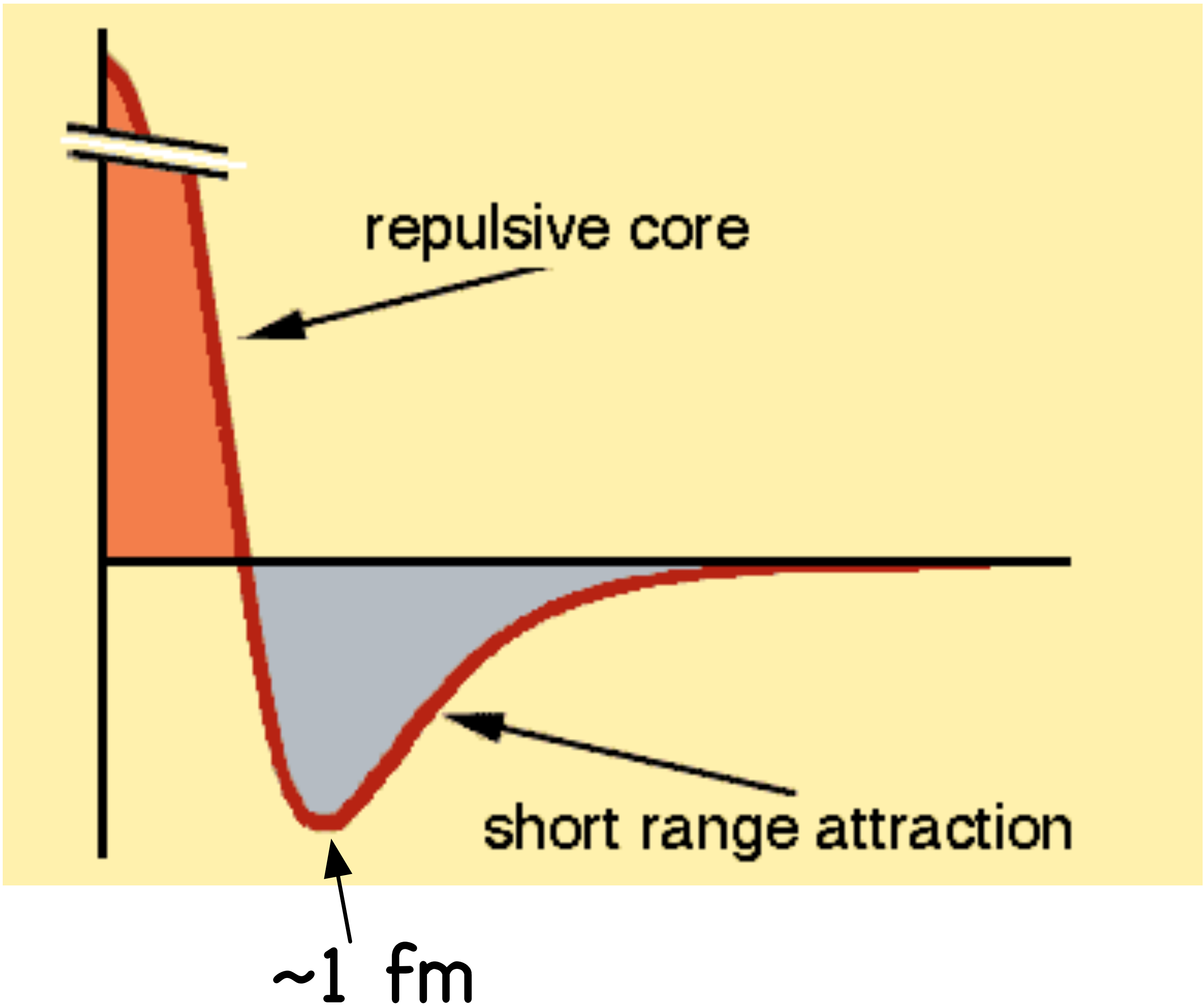



Schiavilla et al. PRL 98, 132501 (2007), VMC and AV18/UIX

Scaled momentum distribution of the deuteron



# Nucleon-Nucleon Potential




We can surmise that a SRC is a virtual NN pair formed and due to the repulsive core at short distances both nucleons are scattered to high momenta

# How can two nucleons combine?

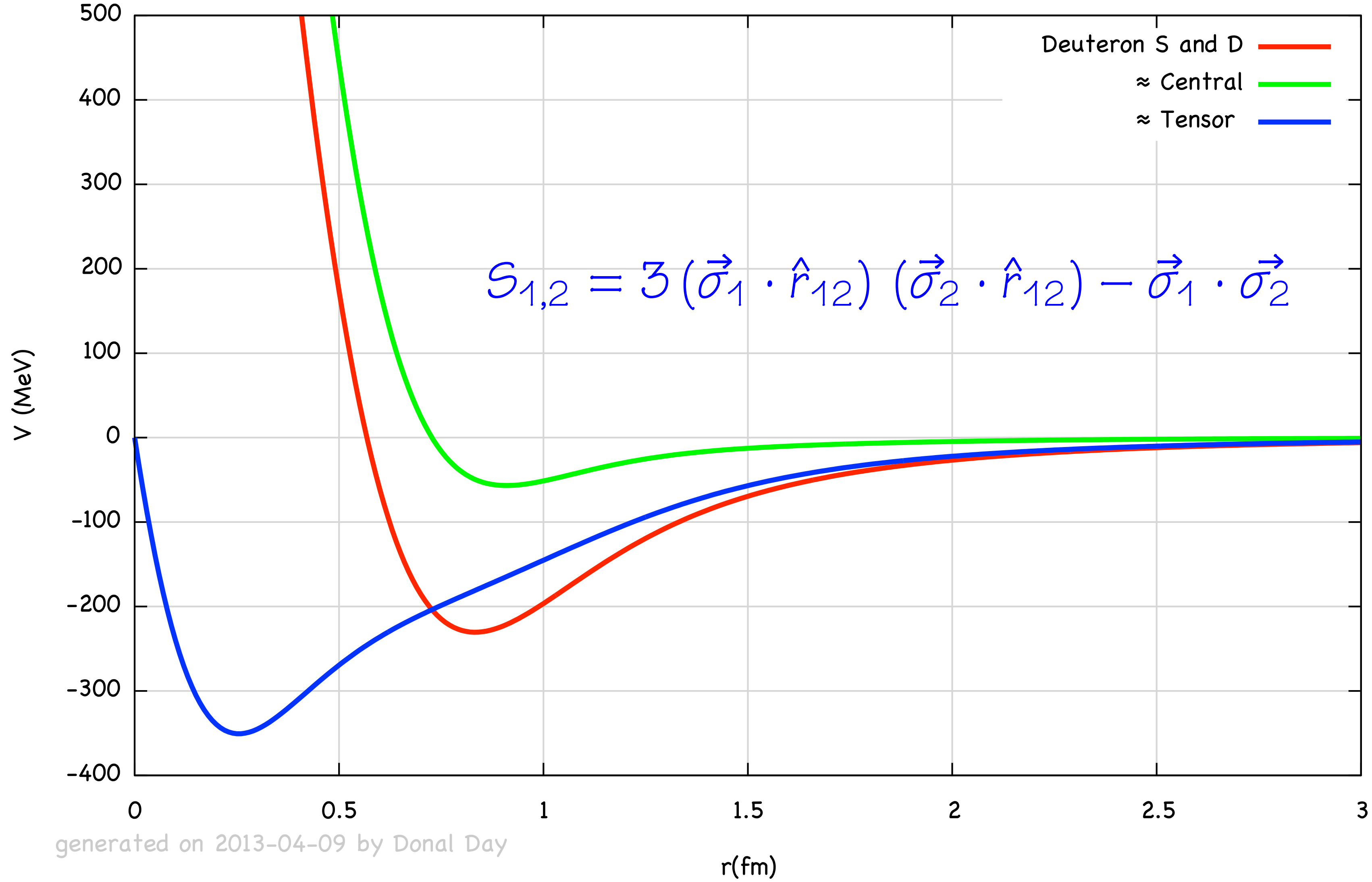
| L | S | J | $\pi = -1^L$ | T(L+S+T odd) | $^{2S+1}L_J$ |
|---|---|---|---|---|---|
| 0 | 0 | 0 | + | 1 | $^1S_0$ |
| 0 | 1 | 1 | + | 0 | $^3S_1$ |
| 1 | 0 | 1 | - | 0 | $^1P_1$ |
| 1 | 1 | 0 | - | 1 | $^3P_0$ |
| 1 | 1 | 1 | - | 1 | $^3P_1$ |
| 1 | 1 | 2 | - | 1 | $^3P_2$ |
| 2 | 0 | 2 | + | 1 | $^1D_2$ |
| 2 | 1 | 1 | + | 0 | $^3D_1$ |
| 2 | 1 | 2 | + | 0 | $^3D_2$ |
| 2 | 1 | 3 | + | 0 | $^3D_3$ |

Two-nucleon states

The Pauli principle requires that two-nucleon states be antisymmetric wrt to exchange of the nucleons' space, spin, and isospin coordinates

Without the tensor contribution the deuteron would not be bound

And it only contributes to T=0 2N states



# Possible Two Nucleon states

| L | S | J | $\pi = -1^L$ | T(L+S+T odd) | $^{2S+1}L_J$ |
|---|---|---|---|---|---|
| 0 | 0 | 0 | + | 1 | $^1S_0$ |
| 0 | 1 | 1 | + | 0 | $^3S_1$ |
| 1 | 0 | 1 | - | 0 | $^1P_1$ |
| 1 | 1 | 0 | - | 1 | $^3P_0$ |
| 1 | 1 | 1 | - | 1 | $^3P_1$ |
| 1 | 1 | 2 | - | 1 | $^3P_2$ |
| 2 | 0 | 2 | + | 1 | $^1D_2$ |
| 2 | 1 | 1 | + | 0 | $^3D_1$ |
| 2 | 1 | 2 | + | 0 | $^3D_2$ |
| 2 | 1 | 3 | + | 0 | $^3D_3$ |

Two-nucleon states

## not all pn pairs are in T = 0

Symmetric triplet $T = 1$

$^3(T)_1 = |p_1\rangle\,|p_2\rangle$ proton-proton state

$^3(T)_{-1} = |n_1\rangle\,|n_2\rangle$ neutron-neutron state

$^3(T)_0 = \frac{1}{\sqrt{2}}(|p_1\rangle\,|n_2\rangle + |p_2\rangle\,|n_1\rangle)$ neutron-proton state

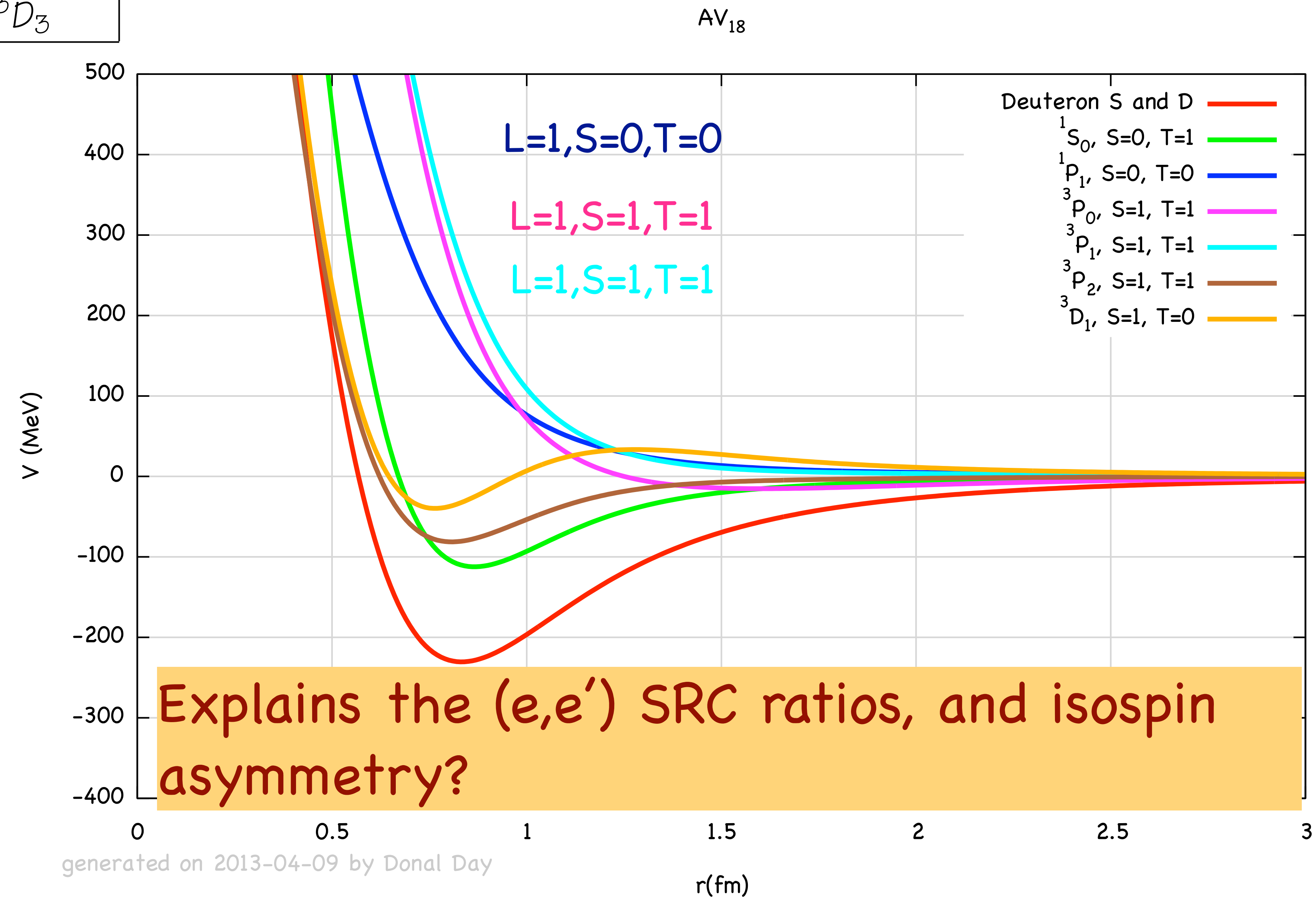
Antisymmetric singlet $T = 0$

$^1(T)_0 = \frac{1}{\sqrt{2}}(|p_1\rangle\,|n_2\rangle - |p_2\rangle\,|n_1\rangle)$ neutron-proton state

The SR NN attraction dominated by tensor interaction, which yields high-momentum isosinglet (np) pairs.

Absent in the isotriplet channel (pp, nn, np).

2-body distribution in nucleus should be identical to the deuteron and ratio of scattering cross sections between a heavy nucleus A and the deuteron to yield $a_2$ (A, Z )




Explains the (e,e') SRC ratios, and isospin asymmetry?

# Coming up

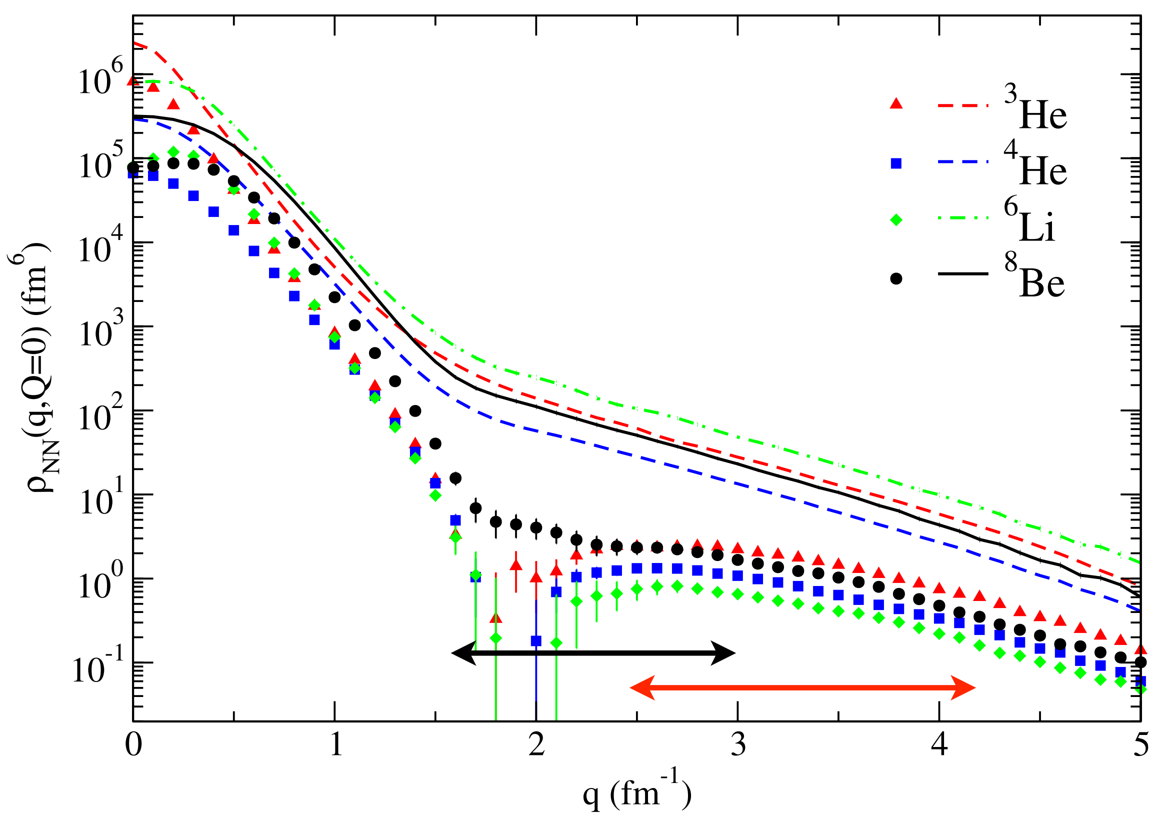
## 6 GeV (completed in Spring 2011)

[Hall A], Z. Ye (UVa)

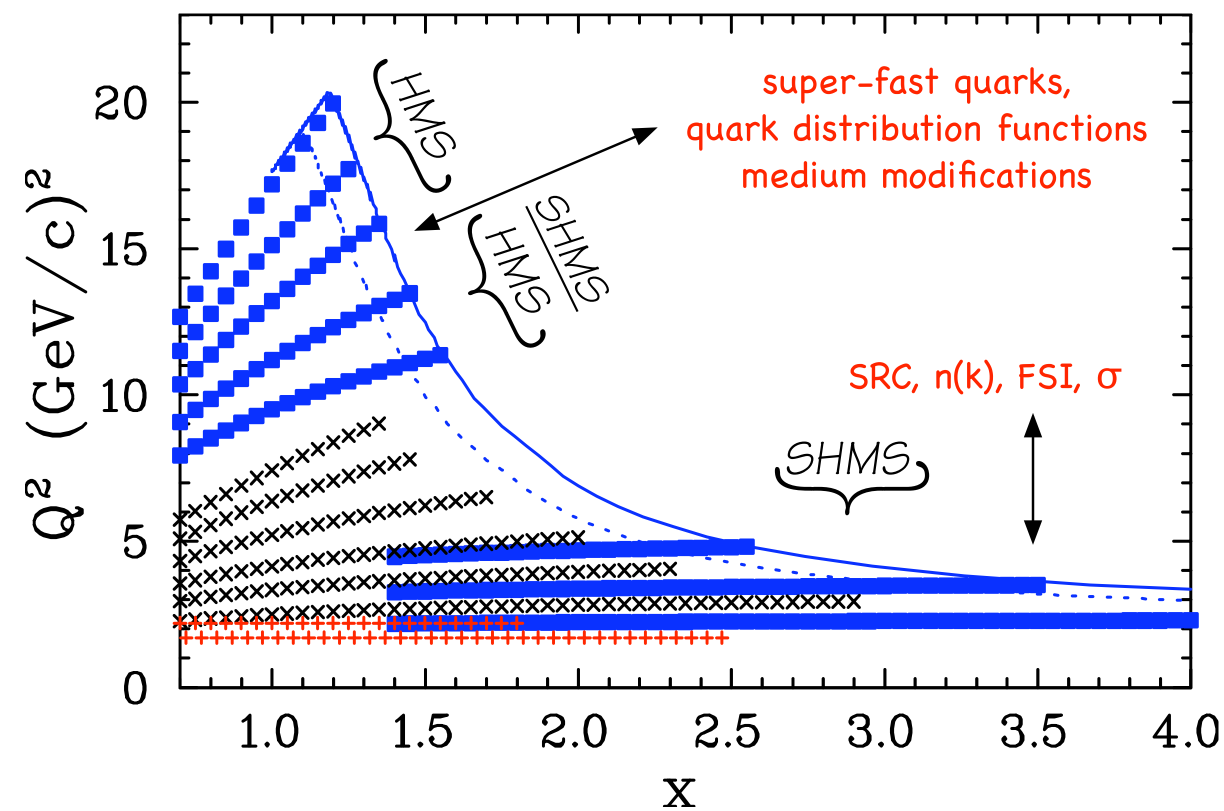
- E08-014: Three-nucleon short range correlations studies in inclusive scattering for 0.8 < 2.8 $(GeV/c)^2$

$^2H$, $^3He$, $^4He$, $^{12}C$, $^{40}Ca$, $^{48}Ca$, isospin dependence

- E07-006: Exclusive X-sctions $^4He(e,e'p)$, $^4He(e,e'pp)$, $^4He(e,e'pn)$, $^4He(e,e'p_{recoil})$
  - Does pp/pn ratio change?! Are there signs of repulsive core? Can the reactions be calculated?




- E12-06-105: Inclusive Scattering from Nuclei at x > 1 in the quasielastic and deeply inelastic regimes [Hall C], $^1H$, $^2H$, $^3He$, $^4He$, $^{6,7}Li$, $^9Be$, $^{10,11}B$, $^{12}C$, $^{40}Ca$, $^{48}Ca$, Cu, Au




Arrington, DD, Fomin, Solvignon

## E12-11-112 Precision measurement of the isospin dependence in the 2N and 3N short range correlation region [Hall A], $^3H$, $^3He$ 2015?

# Physics goals

### Isospin-dependence

- ✓ Improved precision: extract R(T=1/T=0) to 3.8%
- ✓ FSI much smaller (inclusive) and expected to cancel in ratio

### Improved A-dependence in light and heavy nuclei

- ✓ Average of $^3H$, $^3He$ --> A=3 "isoscalar" nucleus
- ✓Determine isospin dependence --> improved correction for N>Z nuclei, extrapolation to nuclear matter

### Absolute cross sections (and ratios) for $^2H$, $^3H$, $^3He$

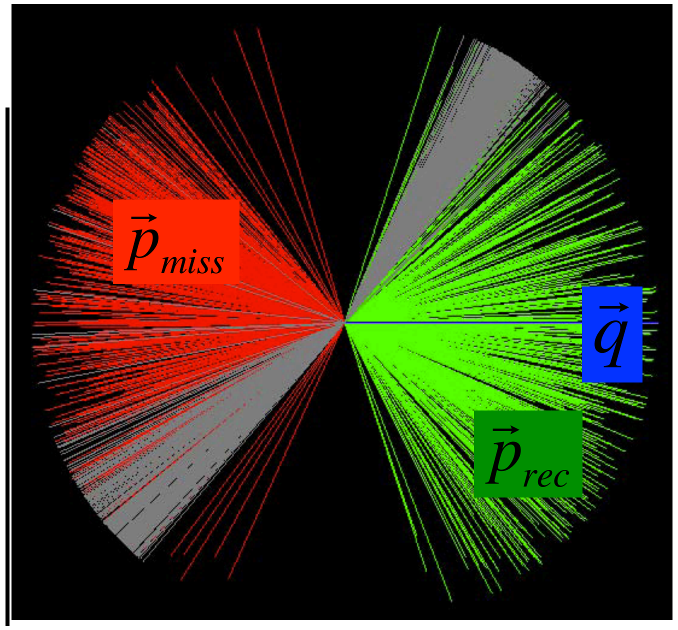
test calculations of FSI for simple, well-understood nuclei

P. Solvignon, J.Arrington, DD, D. Higinbotham

# Data Mining from CLAS E2

Analysis Goals

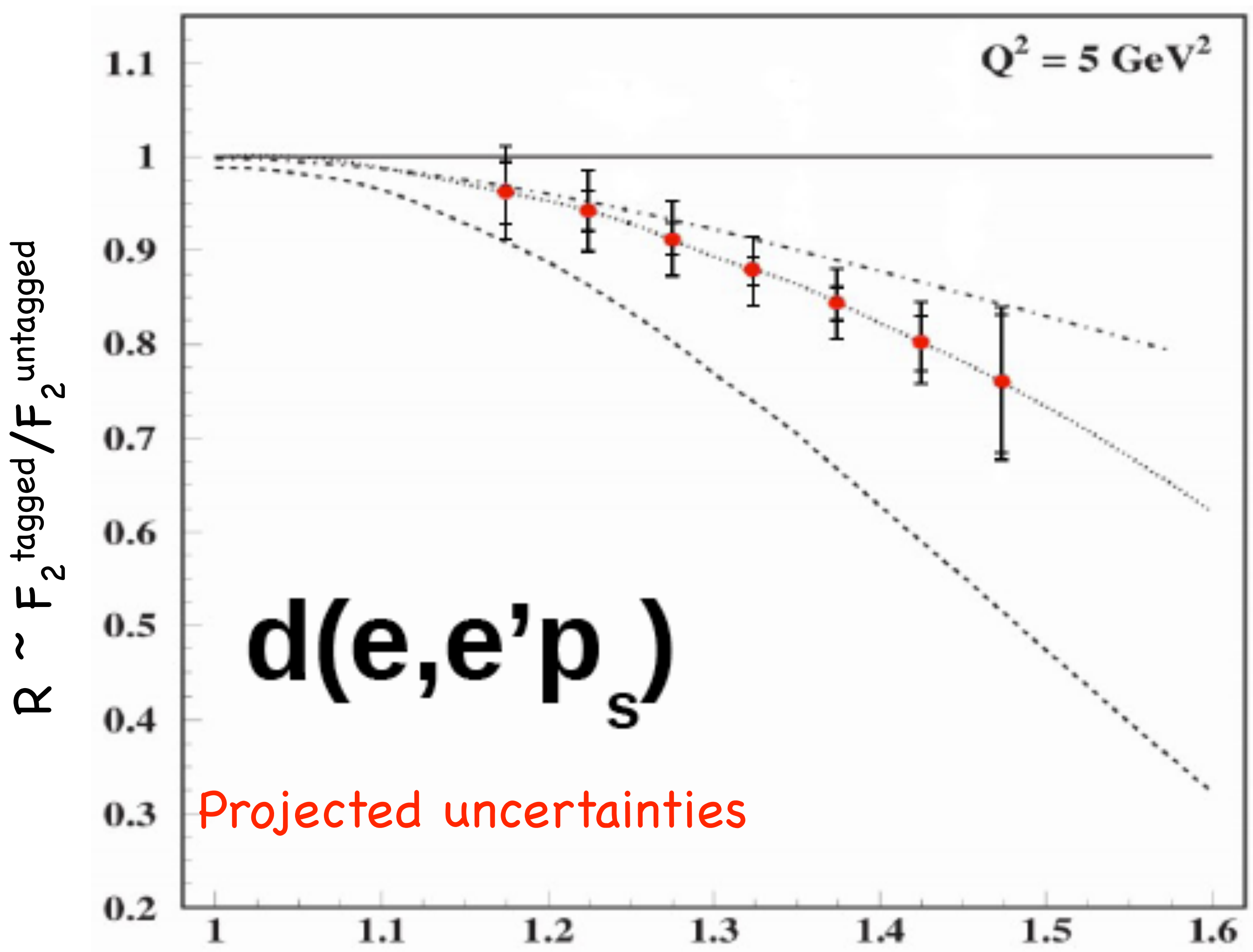
1. pp-SRC universality in large A nuclei
   1. Existence
   2. Characteristics (cm and rel. momentum distributions)
   3. Probabilities
2. Extend $|P_{miss}|$ coverage - transition to scalar force
3. Nuclear transparency - FSI in SRC kinematics
   a. O, Hen et al. Measurement of transparency ratios for protons from short-range correlated pairs, arXiv:1212.5343
4. and more....



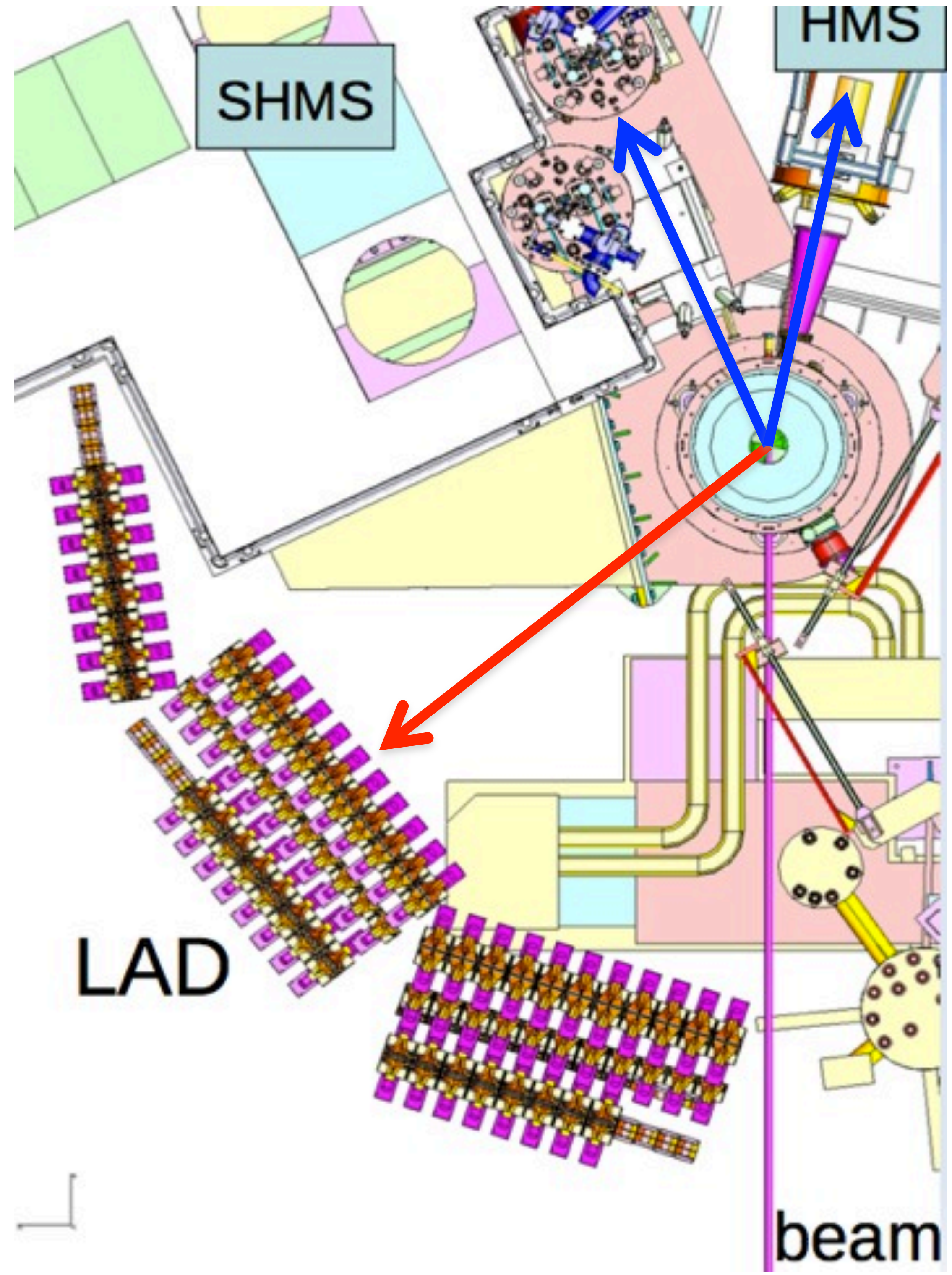
# In-Medium Nucleon Structure Functions

E11-107: O. Hen, L.B. Weinstein, S. Gilad, S.A. Wood

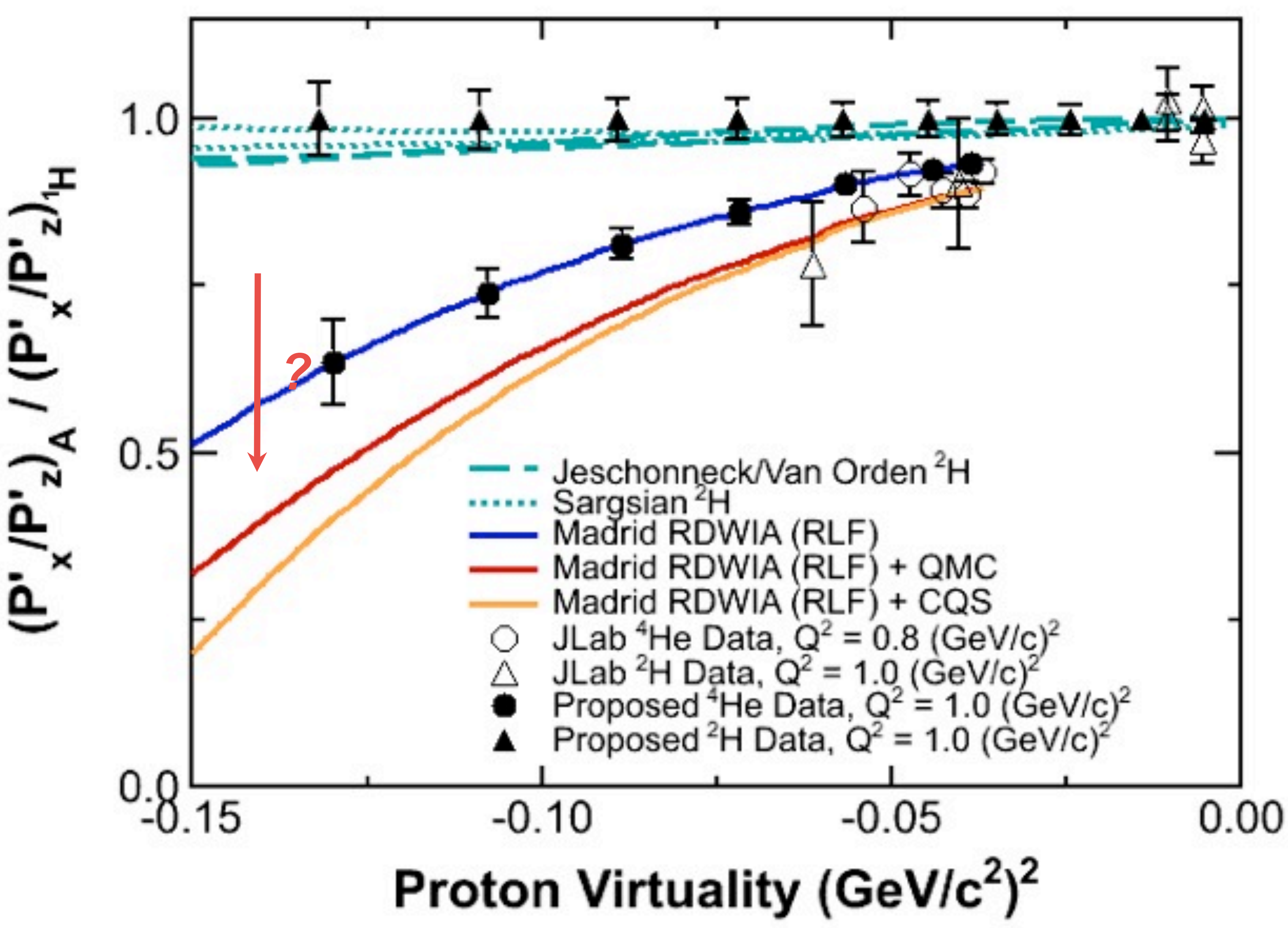
- DIS scattering from nucleon in deuterium
- Tag high-momentum struck nucleons by detecting backward "spectator" nucleon in Large-Angle Detector
- $\alpha_s$ related to initial nucleon momentum




$\alpha_S = (E_S - p_S^Z) / m_S$



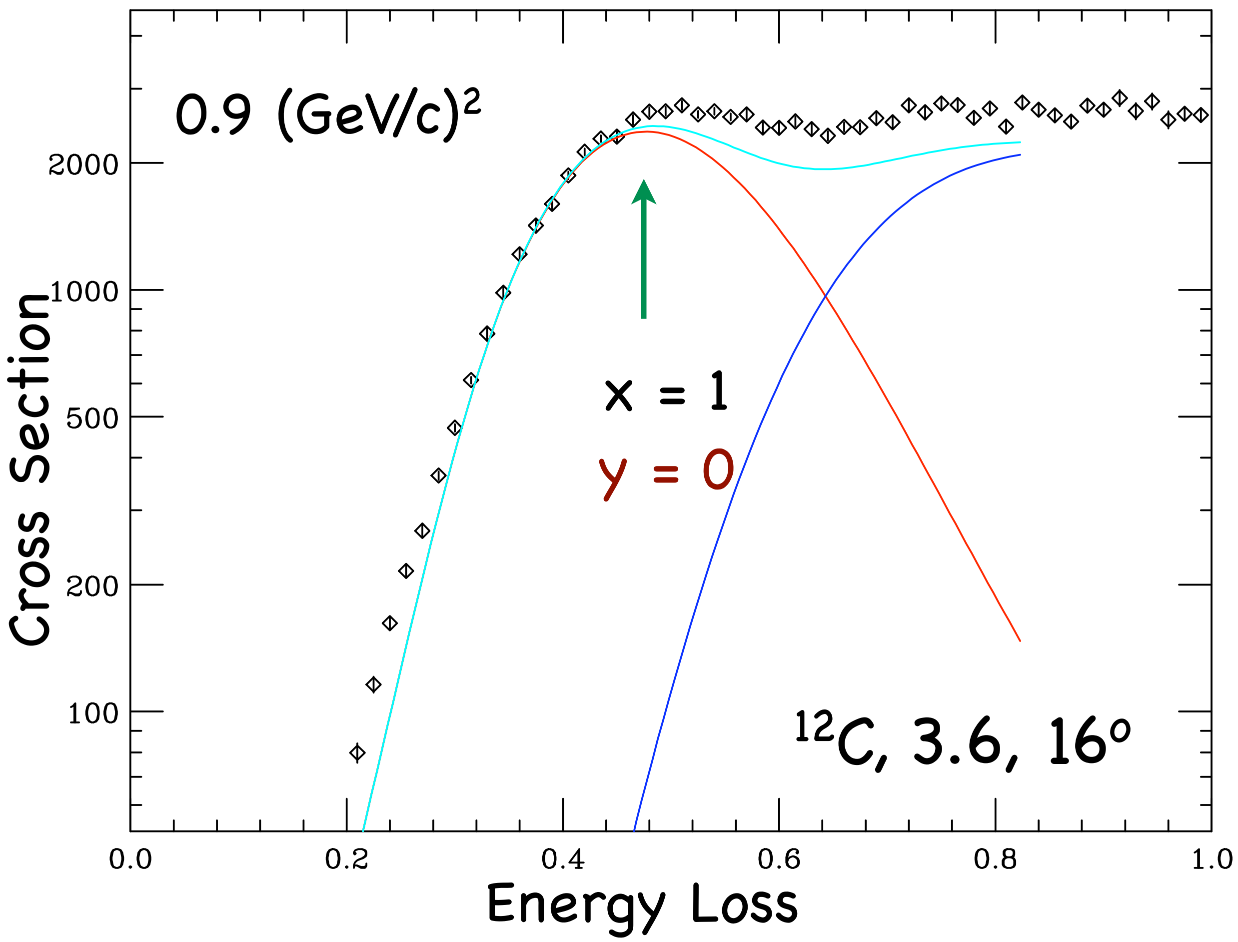
# In-Medium Nucleon Form Factors
## E11-002: E. Brash, G. M. Huber, R. Ransom, S. Strauch

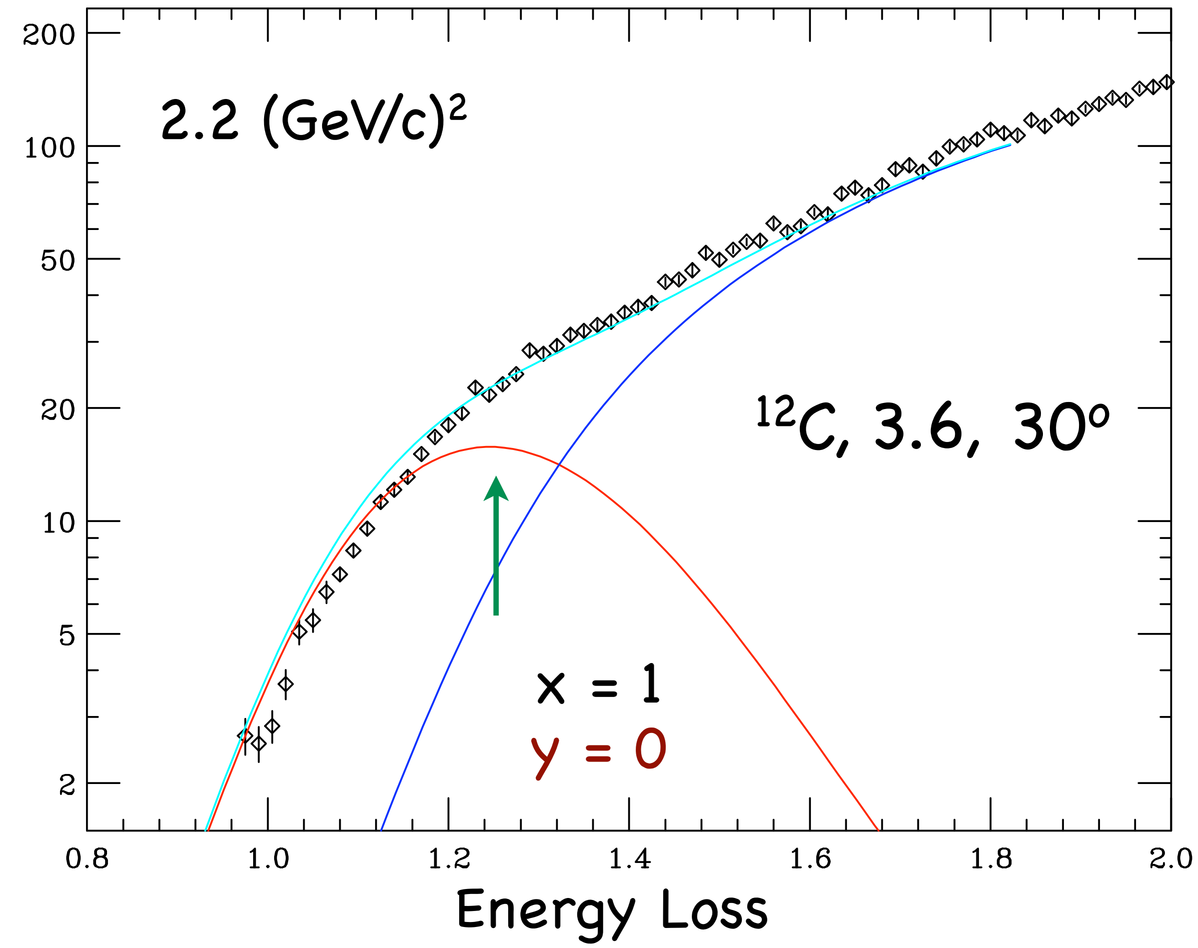



- Compare proton knock-out from dense and thin nuclei: $^4$He(e,e′p)$^3$H and $^2$H(e,e′p)n
- Modern, rigorous $^2$H(e,e′p)n calculations show reaction-dynamics effects and FSI will change the ratio at most 8%
- QMC model predicts 30% deviation from free nucleon at large virtuality

S. Jeschonnek and J.W. Van Orden, Phys. Rev. C 81, 014008 (2010) and Phys. Rev. C 78, 014007 (2008); M.M. Sargsian, Phys. Rev. C82, 014612 (2010)

# Return to A(e,e′) Inelastic contribution increases with $Q^2$

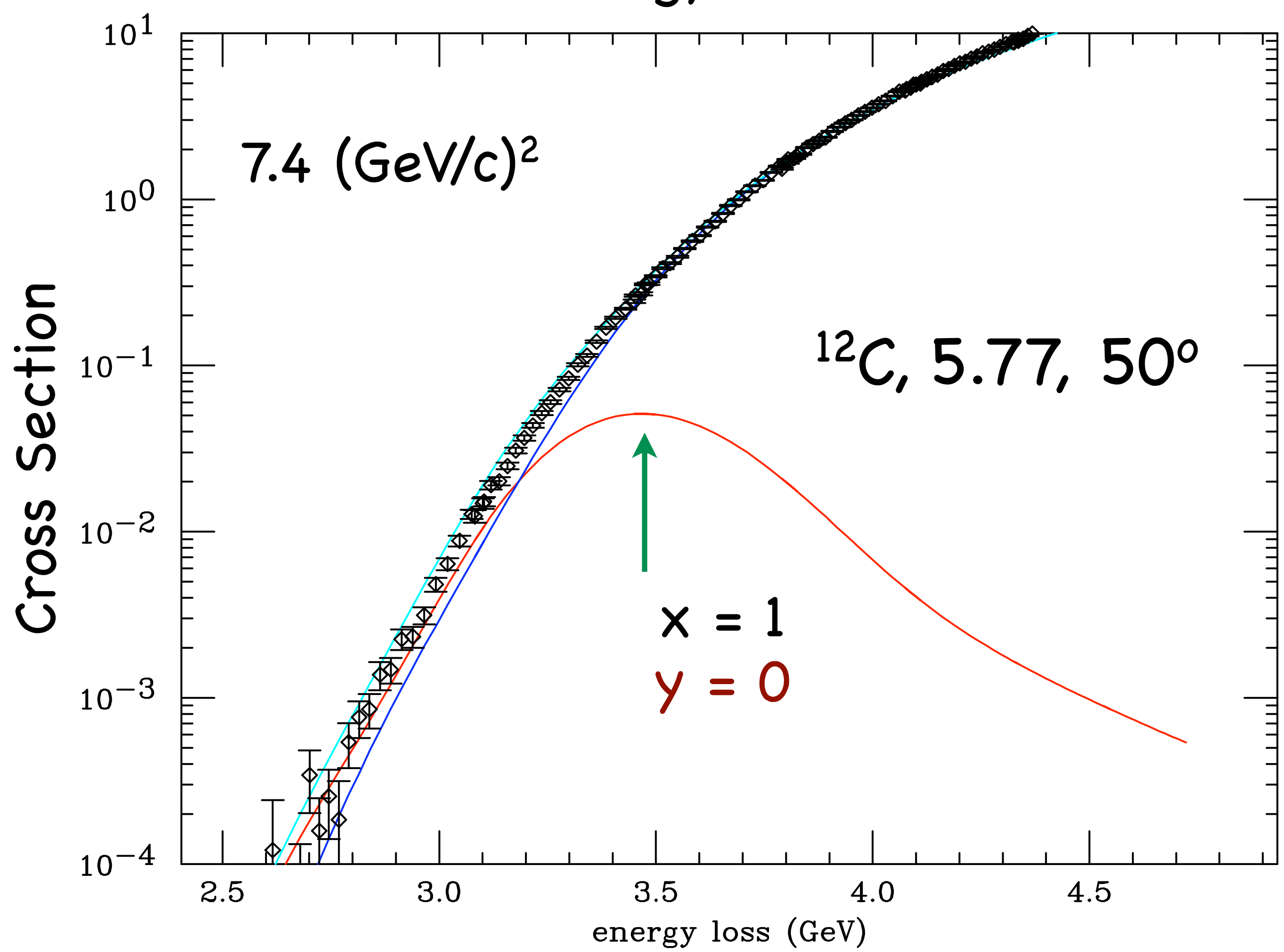



DIS begins to contribute at x > 1

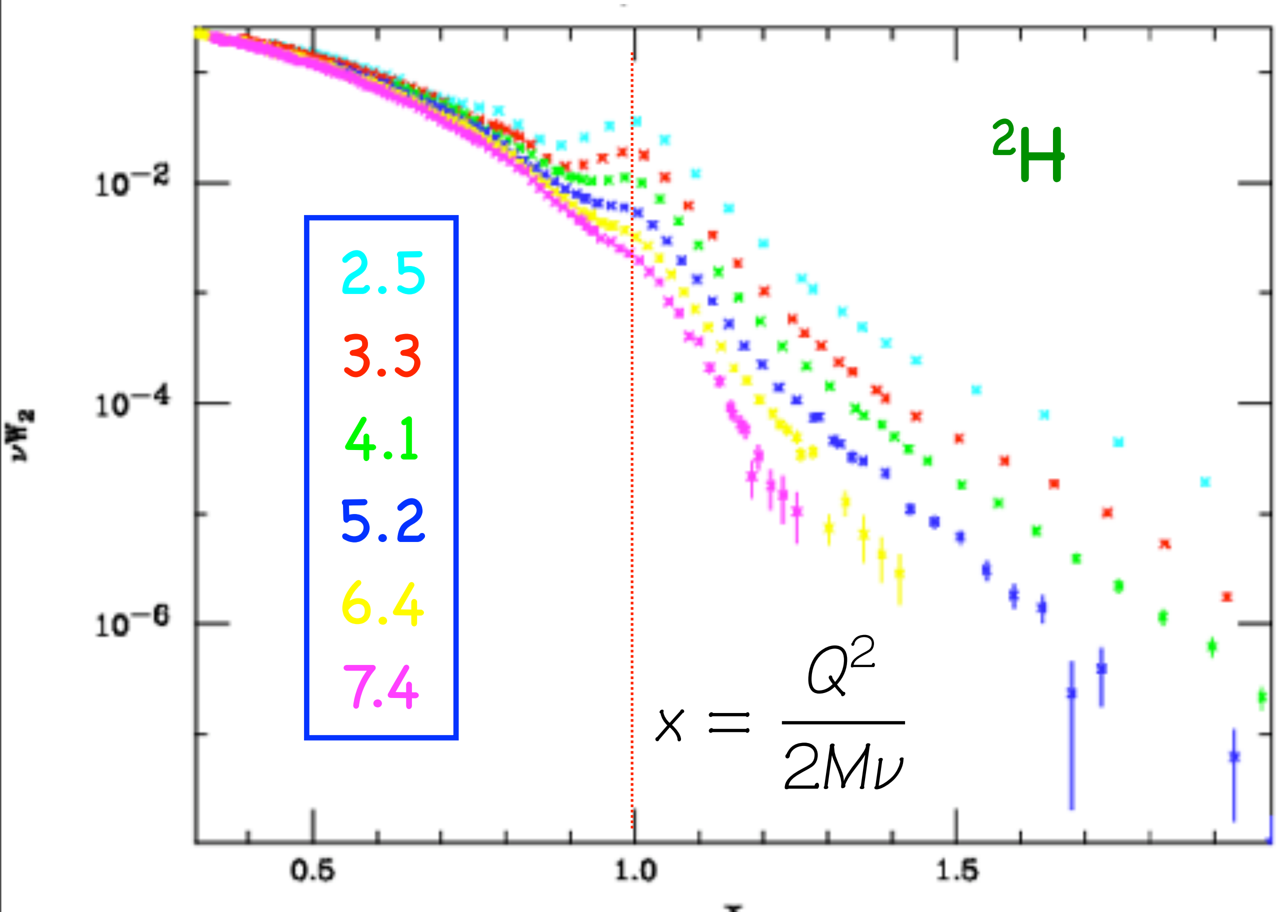
Convolution model

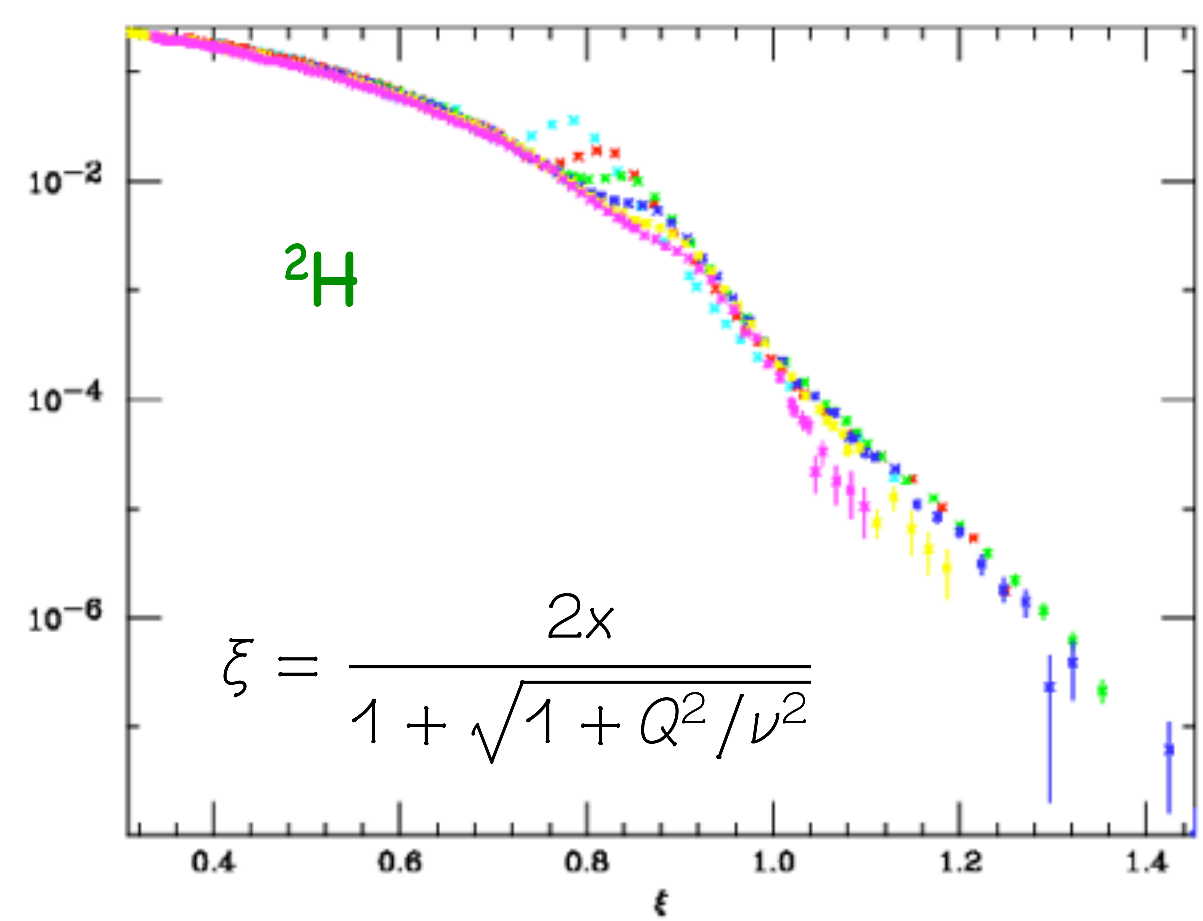
We expect that as $Q^2$ increases to see evidence (x-scaling) that we are scattering from a quark at x > 1



# x and $\xi$ scaling

Remarkably when the data  is presented is presented in terms of the nuclear inelastic structure functions evidence of scaling emerges.

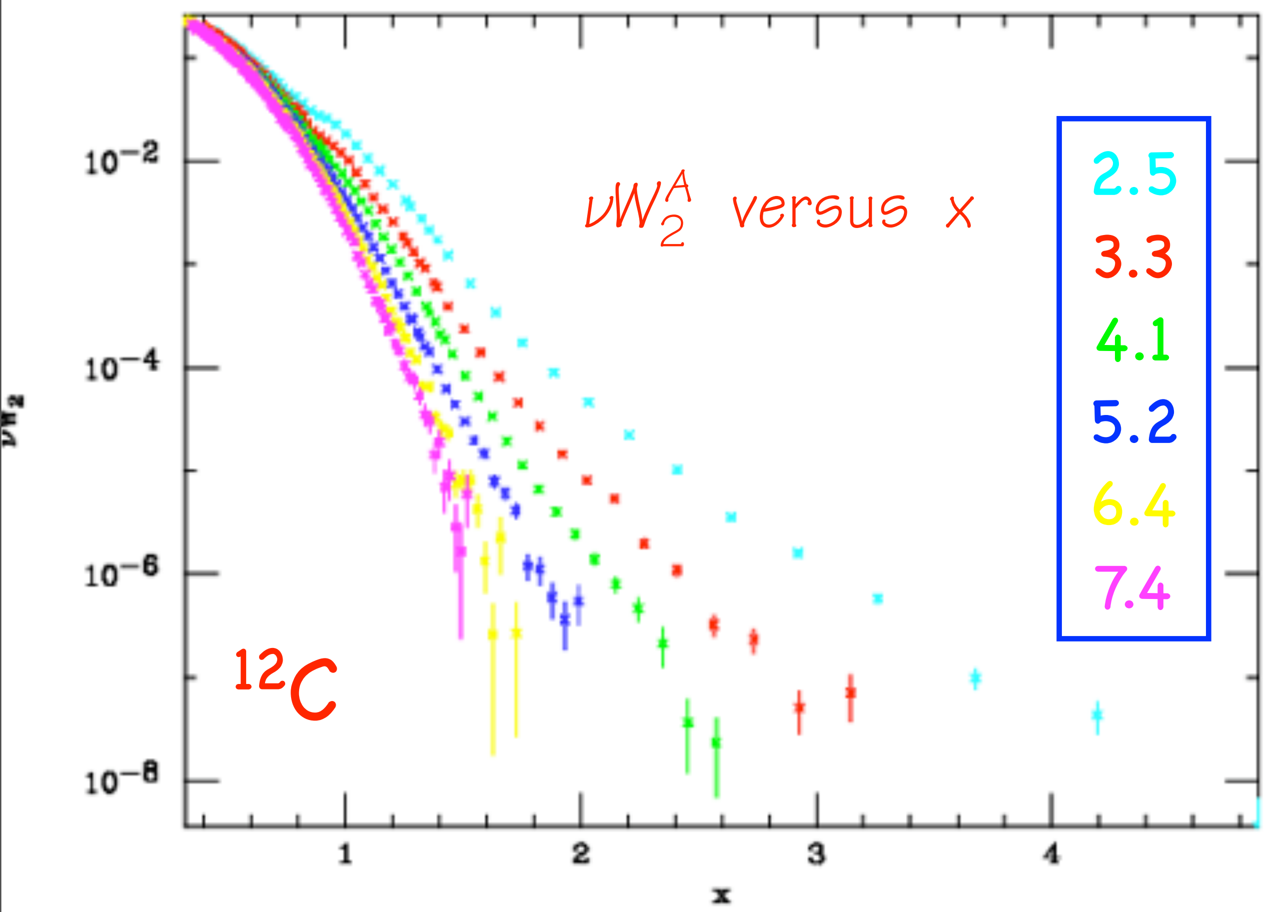


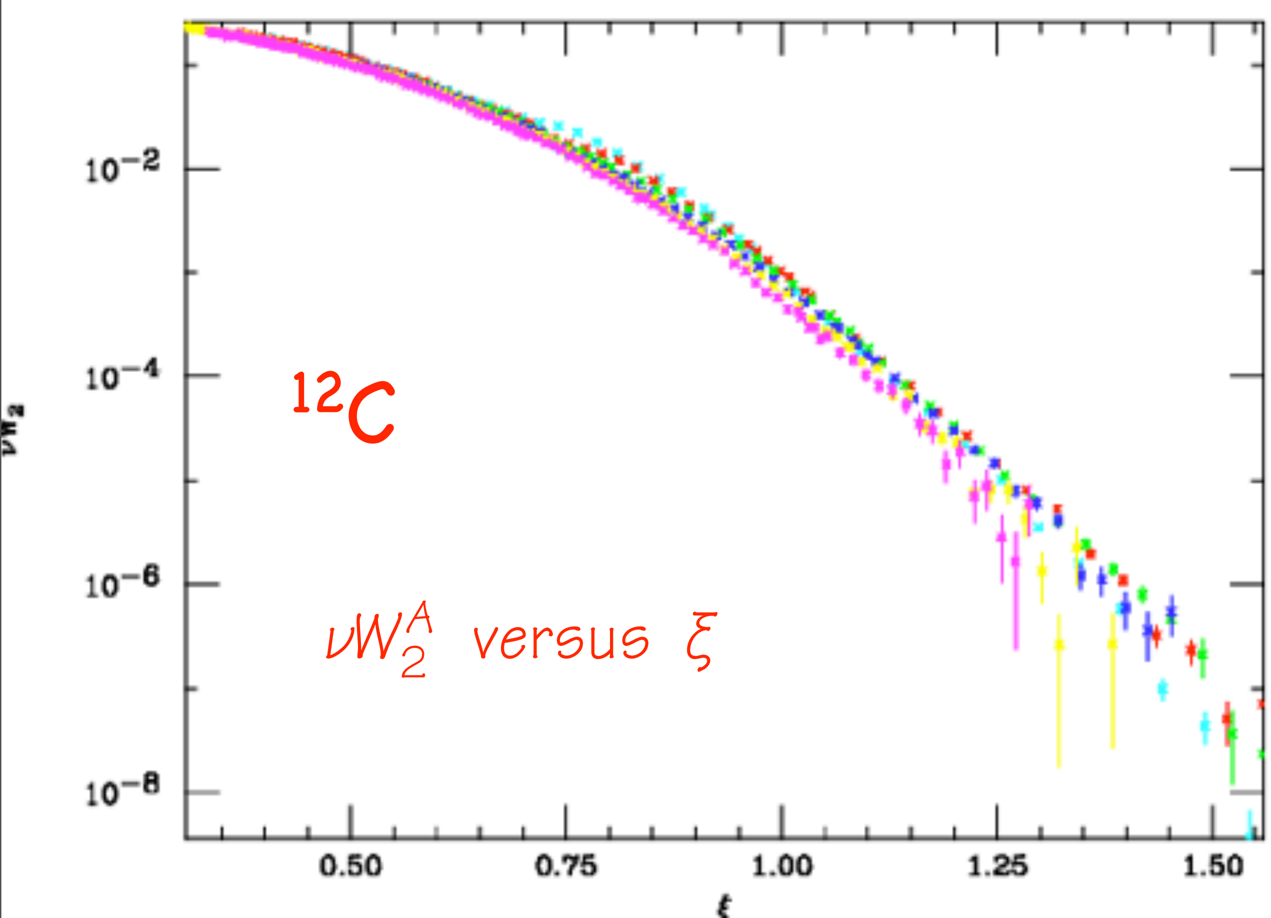




$\nu W_2^A$ versus $x$ $\qquad$ $\nu W_2^A$ versus $\xi$

---

$$\nu W_2^A = \nu \cdot \frac{\sigma^{exp}}{\sigma_M}\left[1 + 2\tan^2(\theta/2)\cdot\left(\frac{1+\nu^2/Q^2}{1+R}\right)\right]^{-1}$$



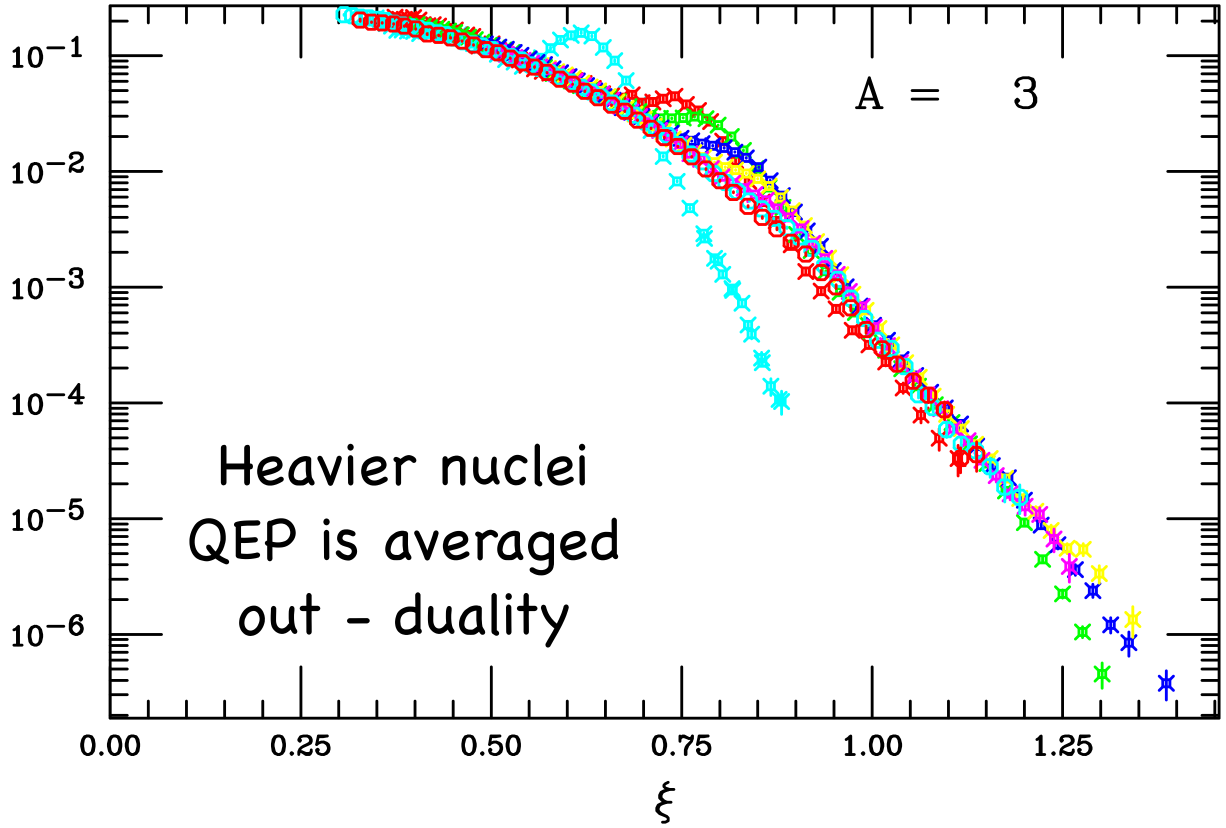

## Especially for the heavier nuclei

$\xi$ (fraction of nucleon light cone momentum $p^+$) is proper variable in which logarithmic violations of scaling in DIS should be studied.

Local duality (averaging over finite range in x) should also be valid for elastic peak at x = 1 if analyzed in $\xi$

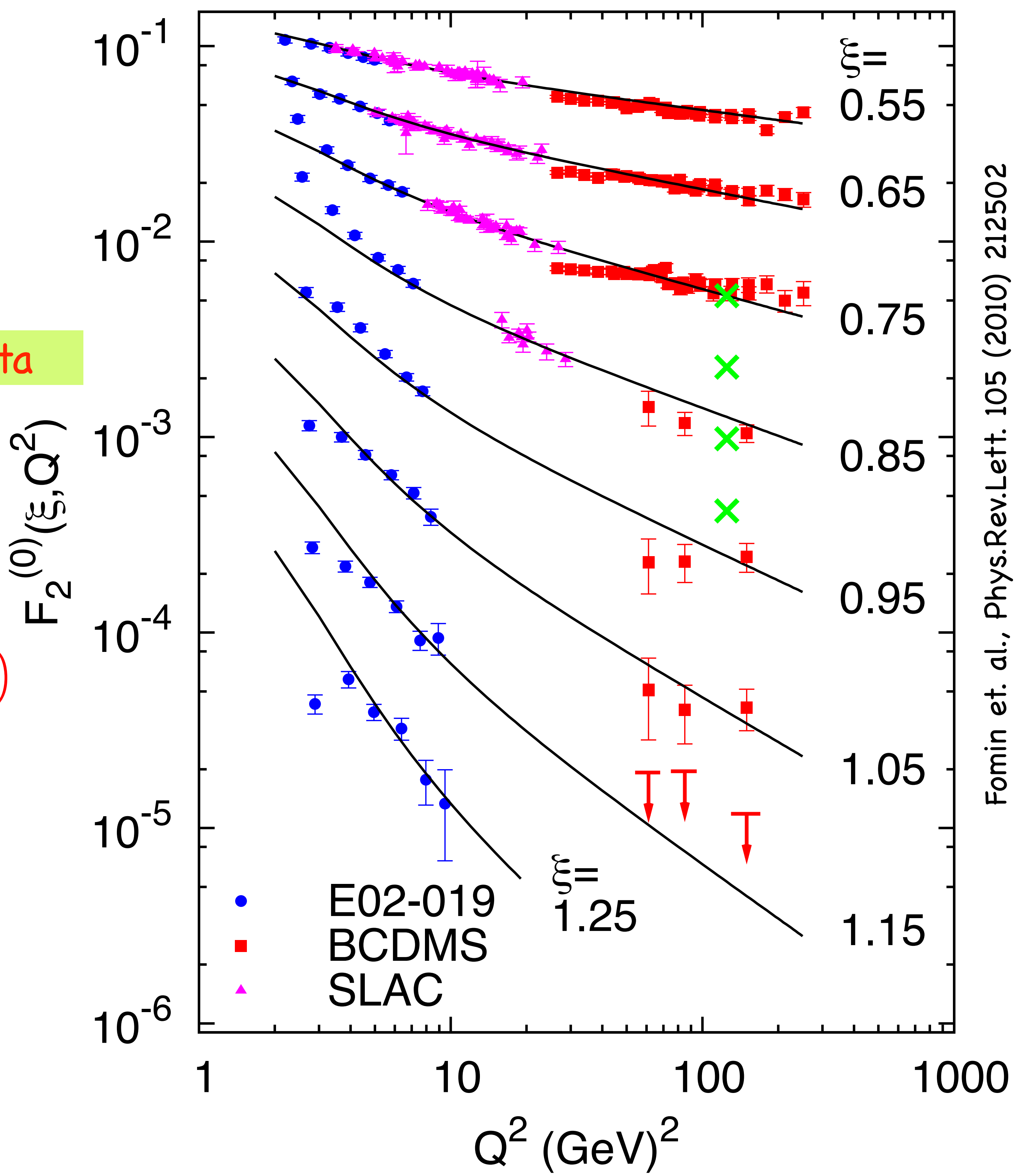
$$F_2^A(\xi) = \underbrace{\int_\xi^A dz F(z) F_2^n(\xi/z)}_{\text{averaging}}$$

Evidently the inelastic and quasielastic contributions cooperate to produce $\xi$ scaling.
Is this local duality?




Nachtmann scaling variable accounts for some of the $Q^2$ dependence "Target Mass Corrections"

$$\xi = 2x/(1+\sqrt{1+4M^2x^2/Q^2})$$




Full corrections have been done to E02-019 data

$$F_2(x,Q^2) = \frac{x^2}{\xi^2 r^3} F_2^0(\xi,Q^2)$$

$$+ \quad \frac{6M^2x^3}{Q^2r^4} h_2(\xi,Q^2) + \frac{12M^4x^4}{Q^4r^5} g_2(\xi,Q^2)$$

PDFs at x > 1 sensitive to SRC. The bulk of the strength for x ≥ 1.1–1.2 come from the high momentum nucleons generated by short range correlations in nuclei.

# Summary

- Evidence for high momentum components and SRC seen in inclusive and exclusive reactions
- Isospin asymmetry established experimentally -> probably should not be a surprise
- New experiments under analysis and approved that should illuminate both the gross and fine features
- SRC demand high densities (momenta) and, if these rare fluctuations can be captured, they should expose, potentially large, medium modifications