PROBING THE ISOSPIN STRUCTURE OF SHORT RANGE CORRELATIONS IN INCLUSIVE QUASIELASTIC SCATTERING

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Advisor: Patricia Solvignon

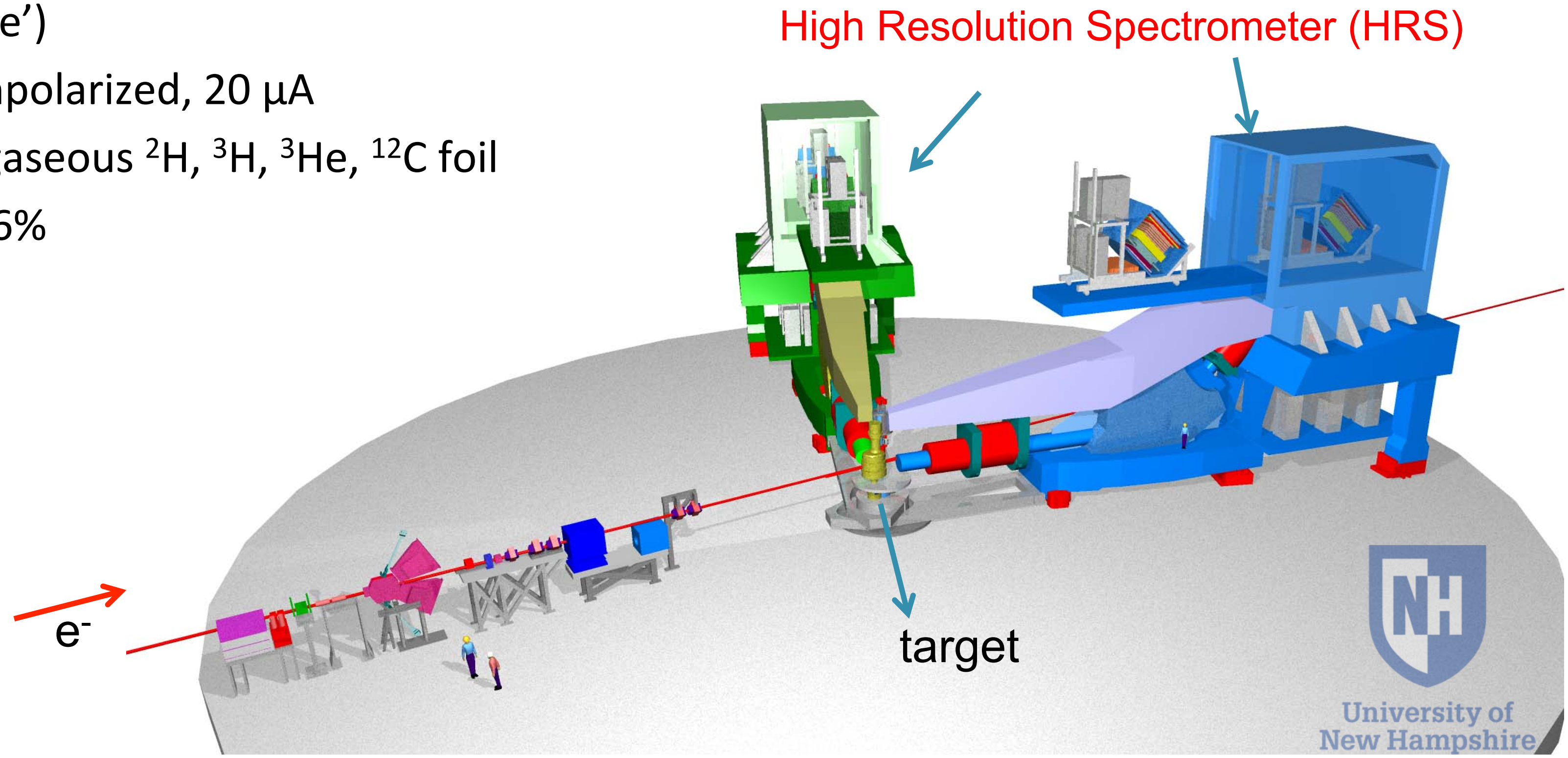
Jefferson Lab

University of New Hampshire

Thesis Experiment: JLAB E12-11-112

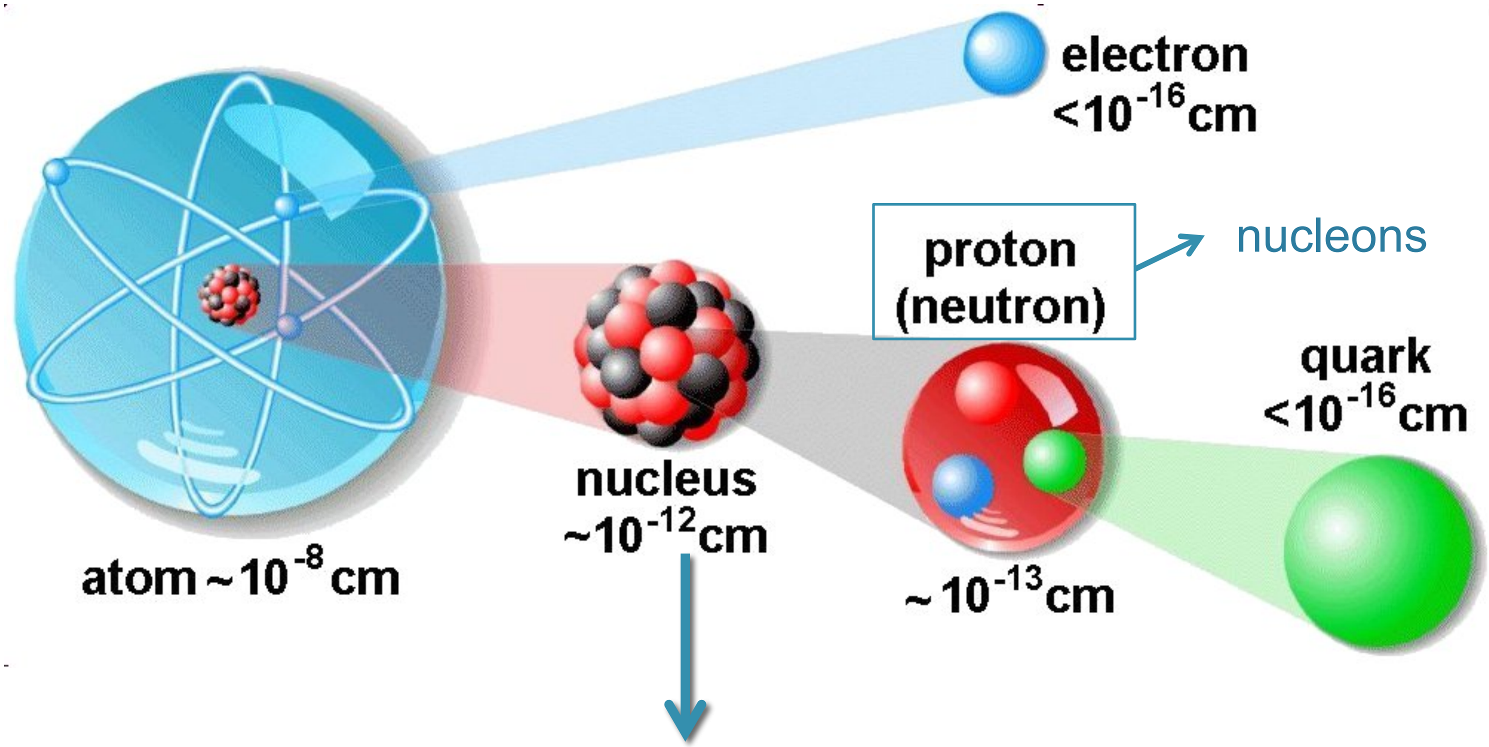
- *Precision measurement of the isospin dependence in the 2N and 3N SRC region*

- Spokesperson P. Solvignon, , J. Arrington, D. B. Day, D. Higinbotham
- Schedule 2016 fall @ Hall A, Jefferson Lab, VA
- Kinematics E=2.2 and 4.4 GeV, $Q^2 \sim 1.5\ (GeV)^2$, $1< x <3$
- Type (e, e')
- Beam unpolarized, 20 μA
- Target gaseous ^2H, ^3H, ^3He, ^{12}C foil
- Error 4.6%



Nuclear Structure

http://www.ehs.utoronto.ca/services/radiation/radtraining/module1.htm



Schrödinger Equations

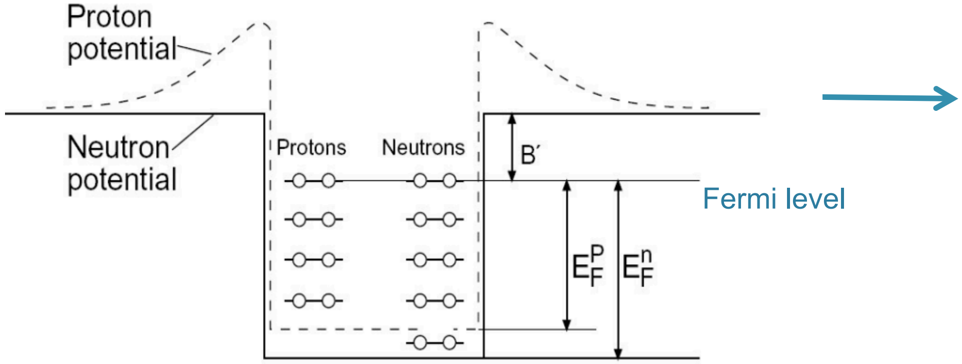
Independent Particle Shell Model(IPSM)

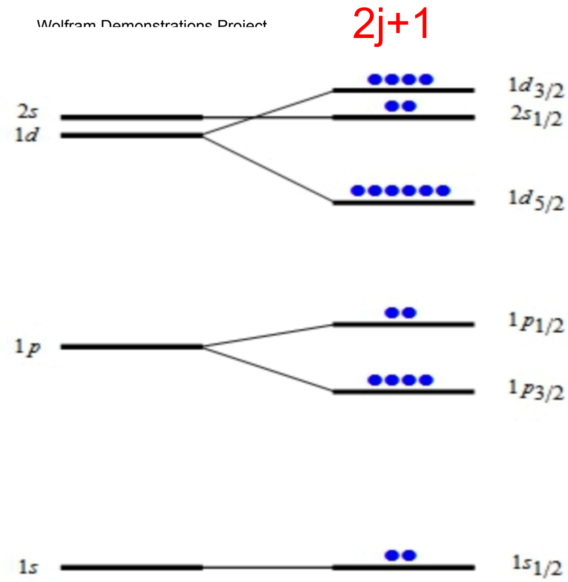
- Low energy, non-relativistic:

$$[\sum_i -\frac{\hbar^2}{2m_N}\nabla_i^2 + \sum_{i<j} v_2(\boldsymbol{x}_i, \boldsymbol{x}_j) + \sum_{i<j<k} v_3(\boldsymbol{x}_i, \boldsymbol{x}_j, \boldsymbol{x}_k) + ...]\Psi_A = E_A\Psi_A$$

- Nucleons move independently in an averaged potential induced by the rest of the nucleus system:

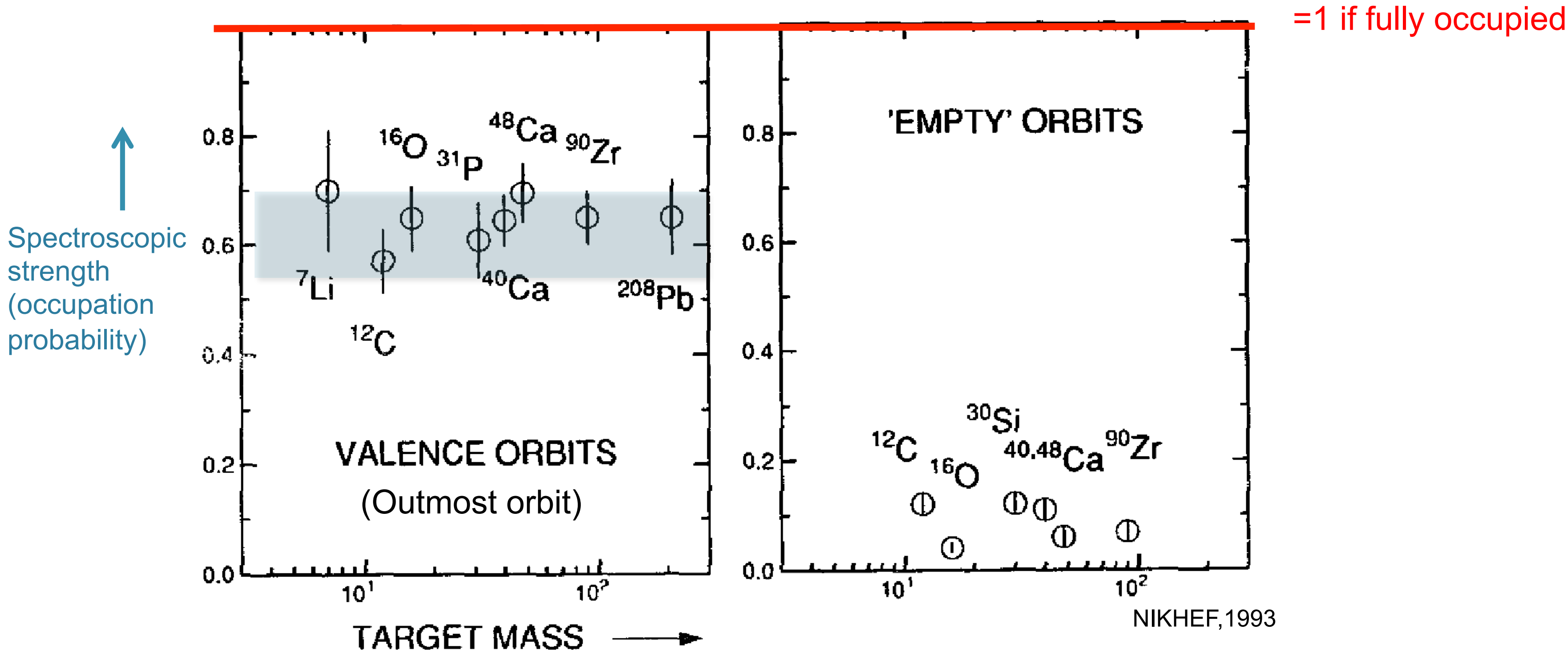
$$[-\frac{\hbar^2}{2m_N}\nabla_i^2 + U(\boldsymbol{x})]\phi_\alpha(\boldsymbol{x}_i) = \epsilon_\alpha\phi_\alpha(\boldsymbol{x}_i),$$





proton (neutron)

Missing Strength



- The closed orbits are NOT fully occupied, ~30% of strength is missing.
- Nucleons can live in orbits above Fermi level ($k > k_F$)

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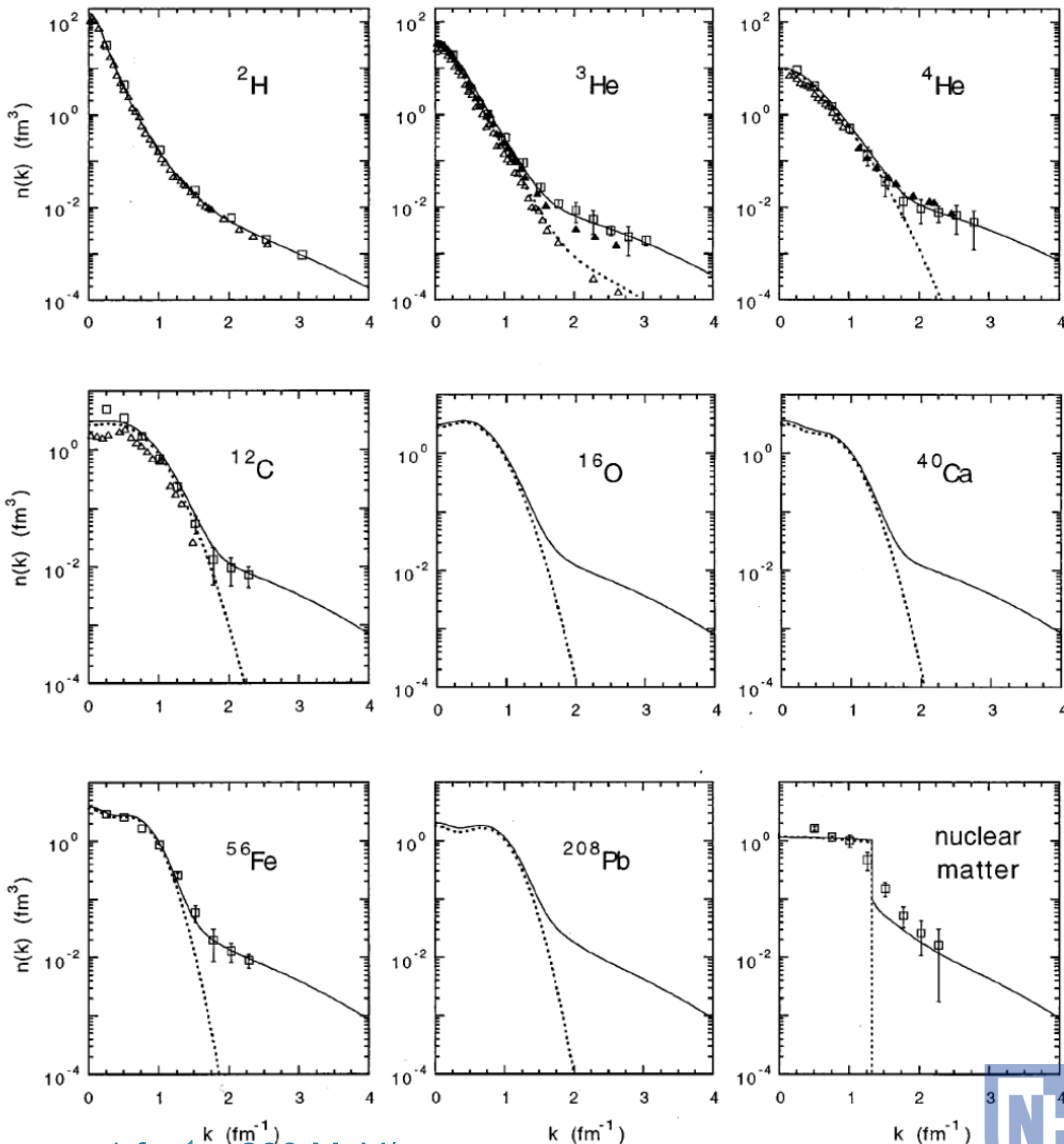
Nucleon momentum distribution

Distribution function n(k)

$$\int_0^\infty dk\ k^2 n(k) = 1$$

Atti and Simula, 1995



1 fm^{-1} ~ 200 MeV/c

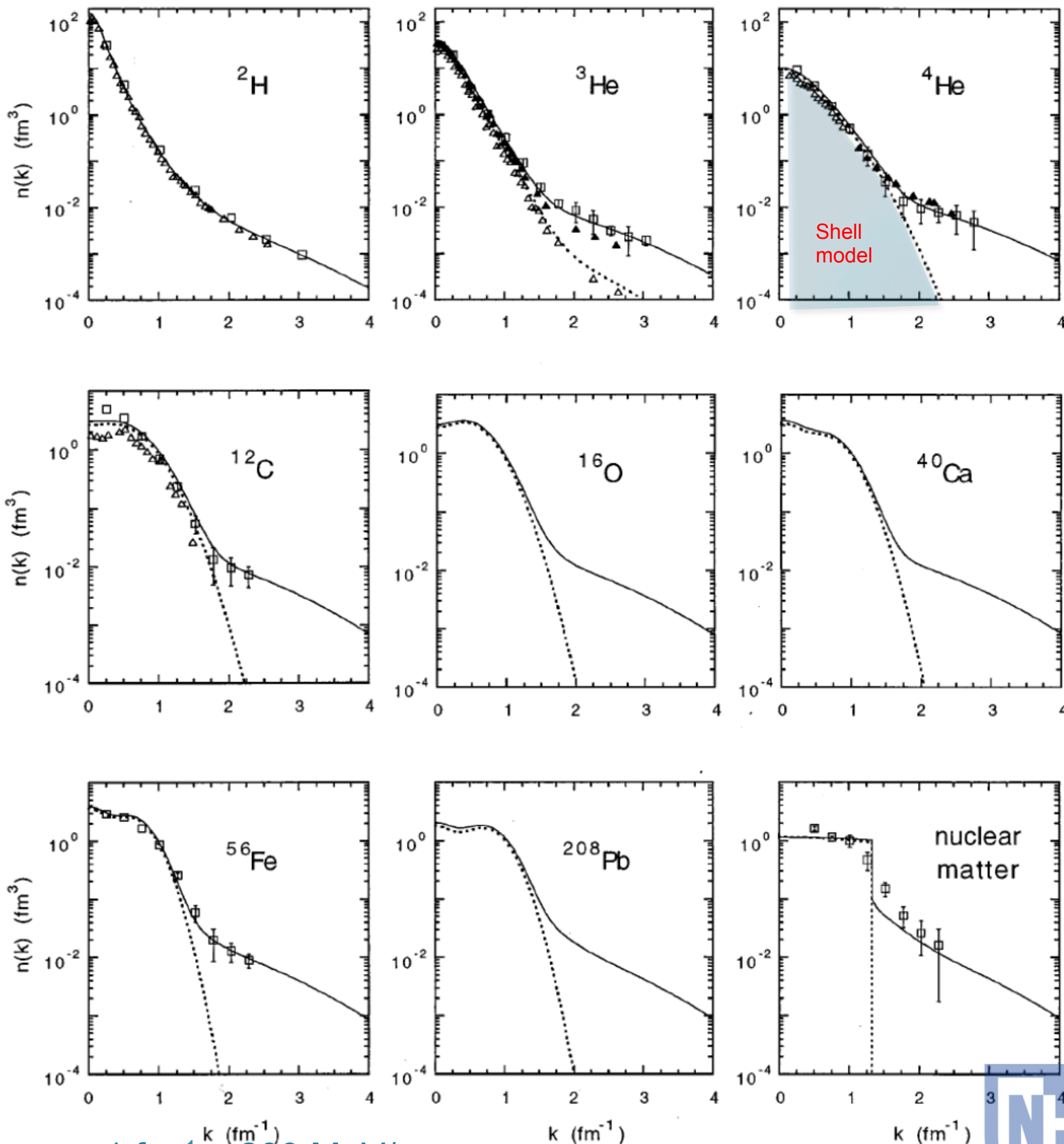
Momentum k

High momentum tails

Distribution function n(k)

$$\int_0^\infty dk\ k^2 n(k) = 1$$

Atti and Simula, 1995



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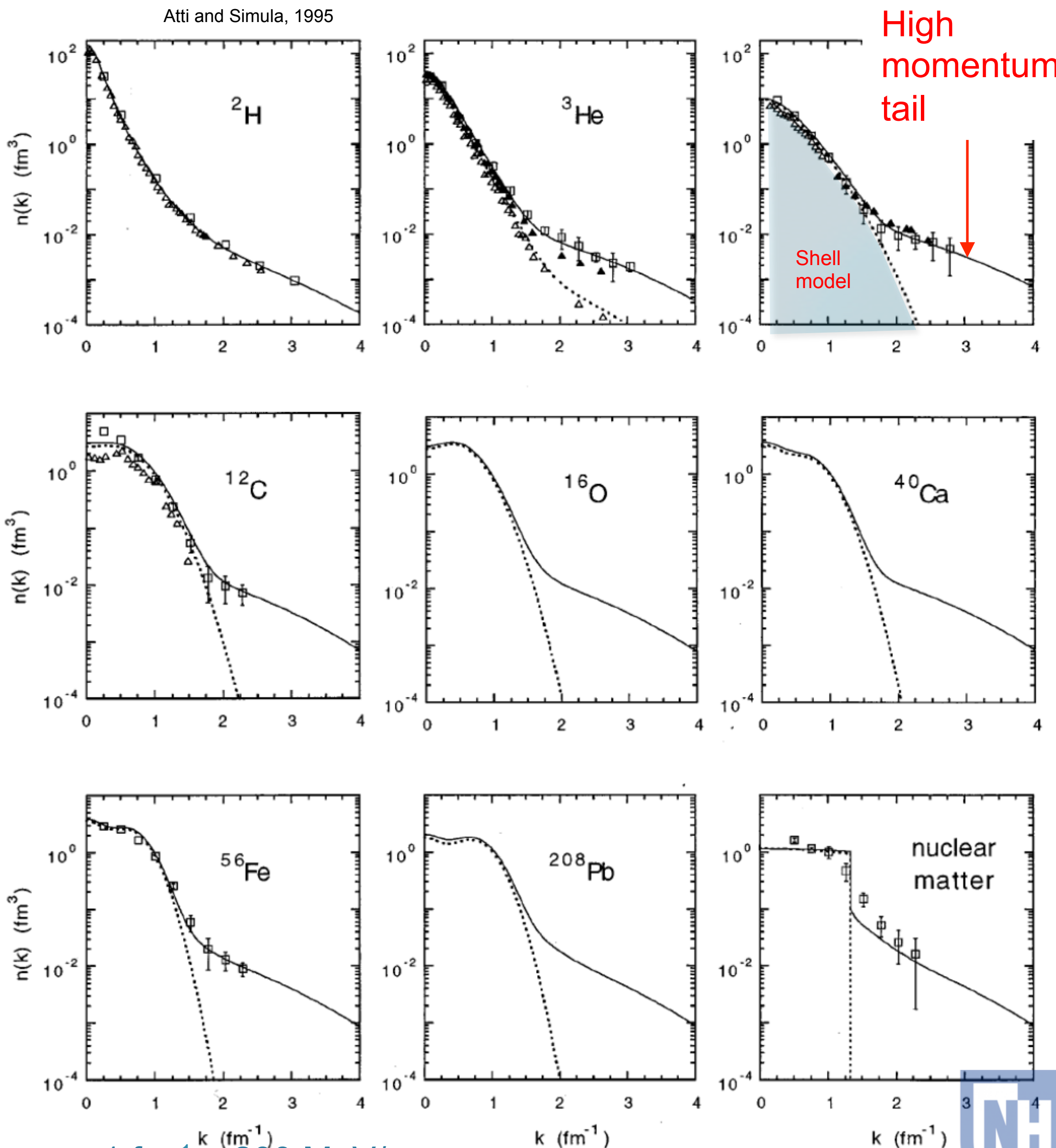

1 fm^{-1} ~ 200 MeV/c

Momentum k

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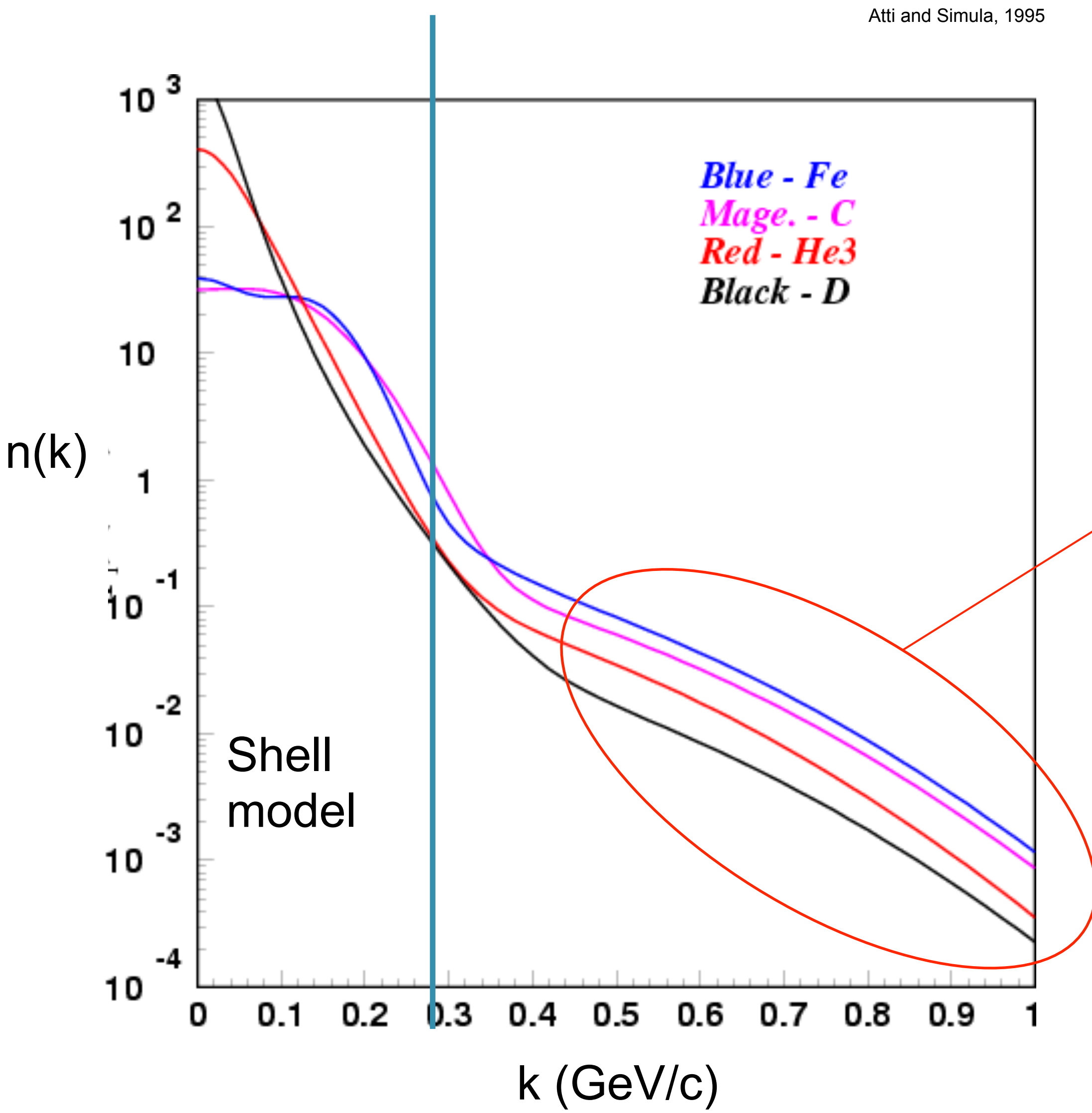
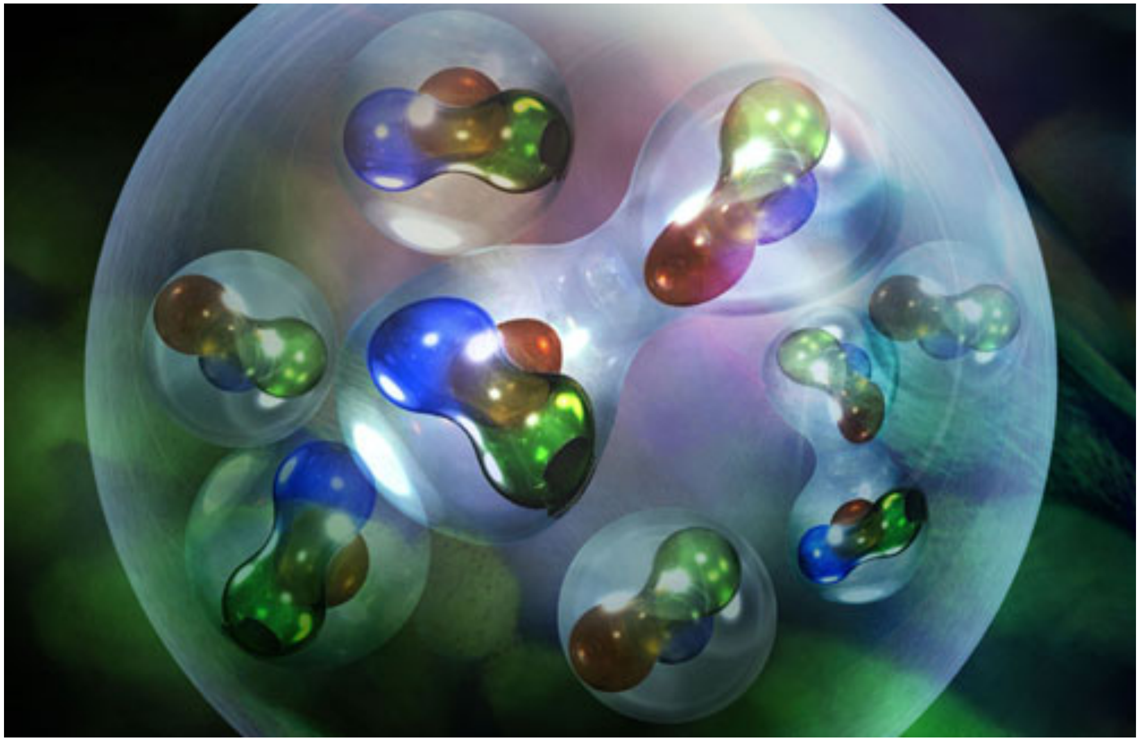
High momentum tails



- 20% of Nucleons have momentum above Fermi level
- There is a universal shape of the high momentum tails

SRC explanation?

Short Range Correlation(SRC) of Nucleons



Proton radius ~ 0.84 fm

Inter-nucleon separation in nuclear matter (A->inf): 1.6 fm??

In short distance

-Largely overlapped wave functions

-In-medium quarks/gluons interactions

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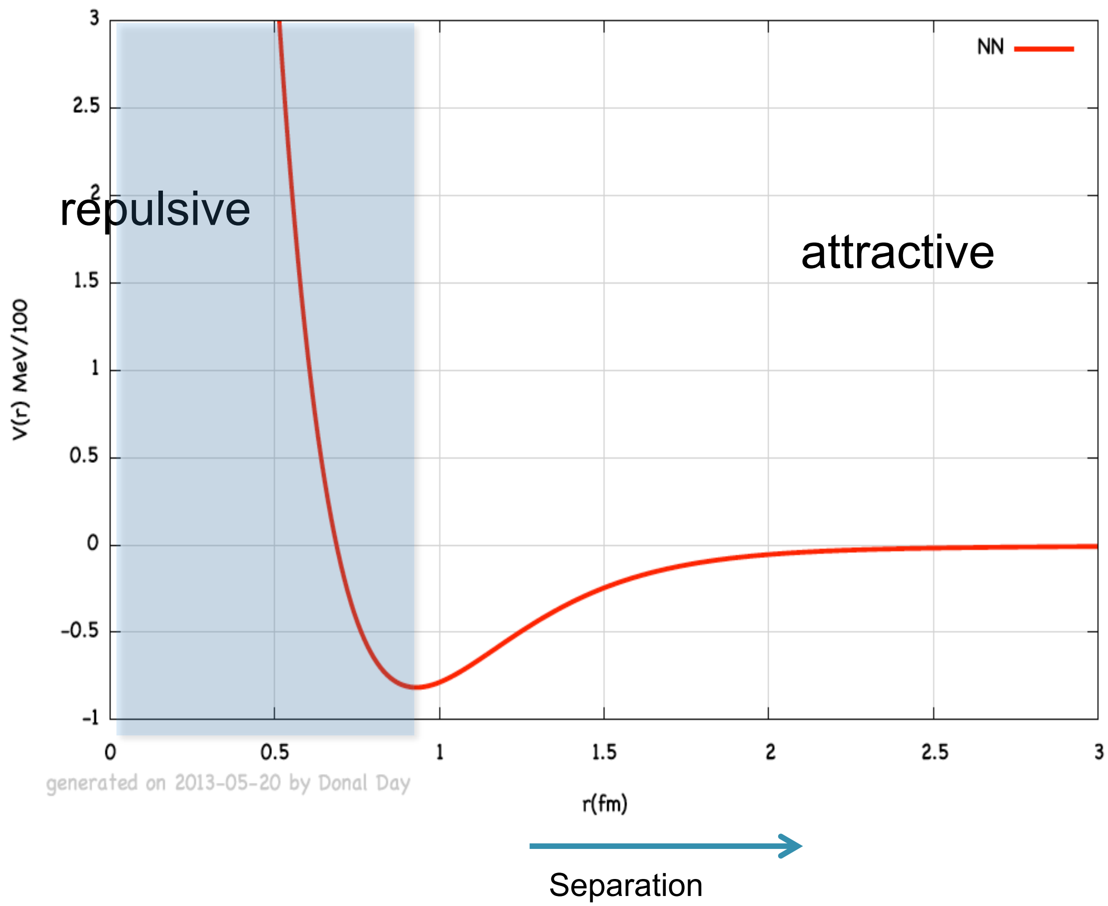
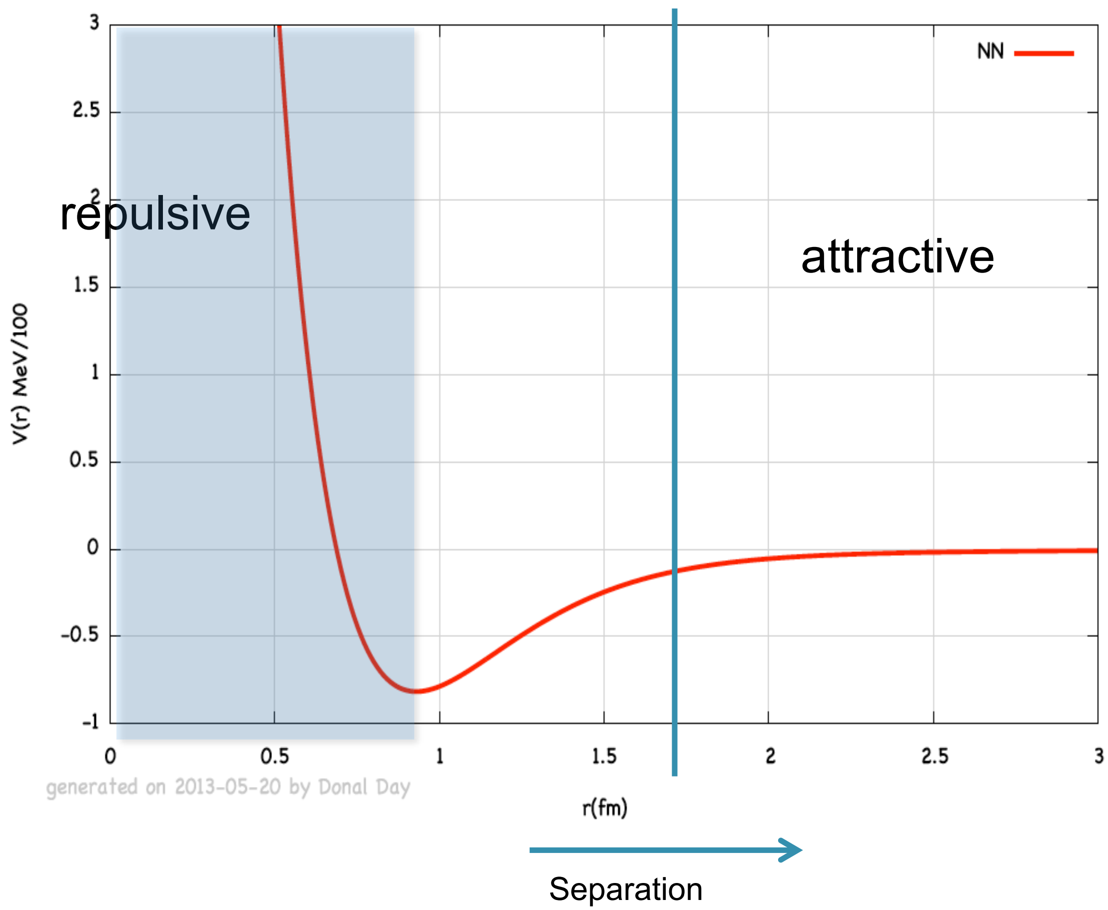
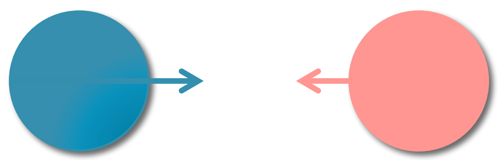
Deuteron (np) potential

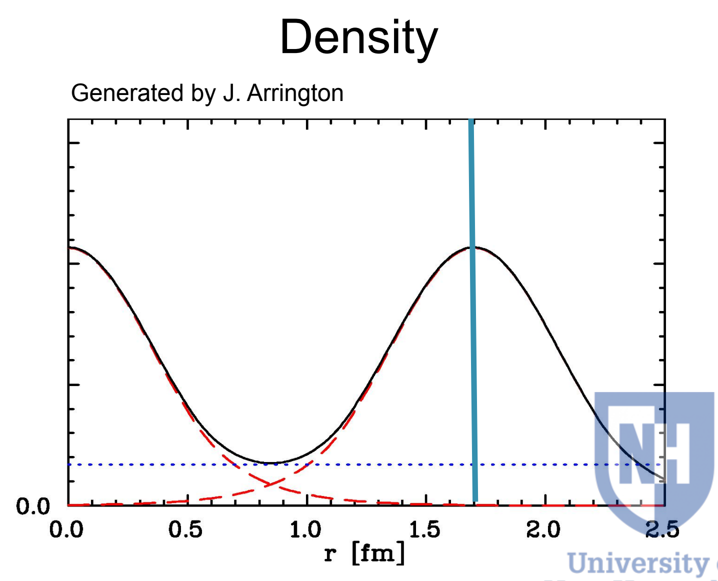


R = 1.7 fm (typical inter-nucleon distance in heavy nuclei)

Deuteron (np) potential







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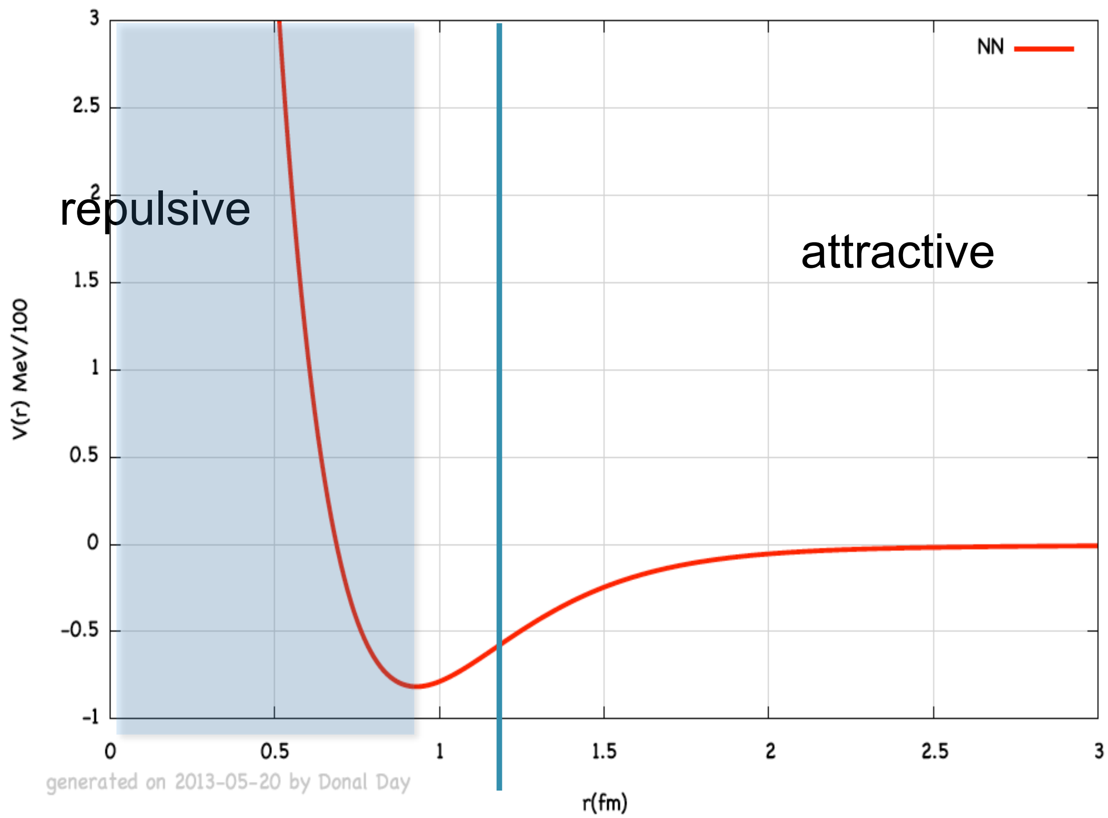
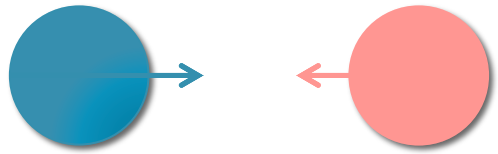
R = 1.2 fm

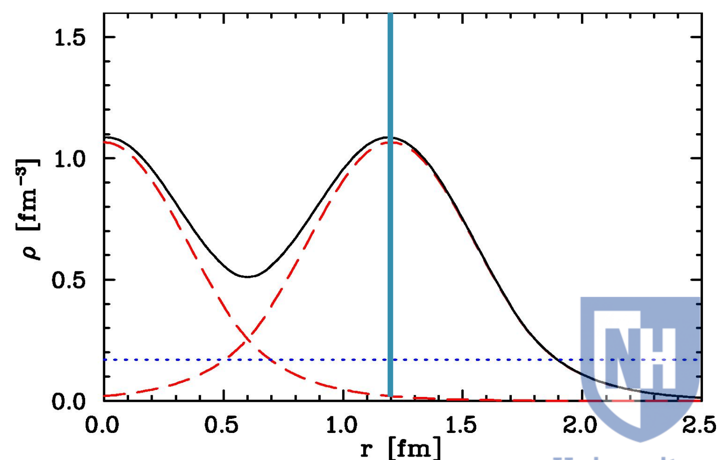
Deuteron (np) potential



Separation



Density



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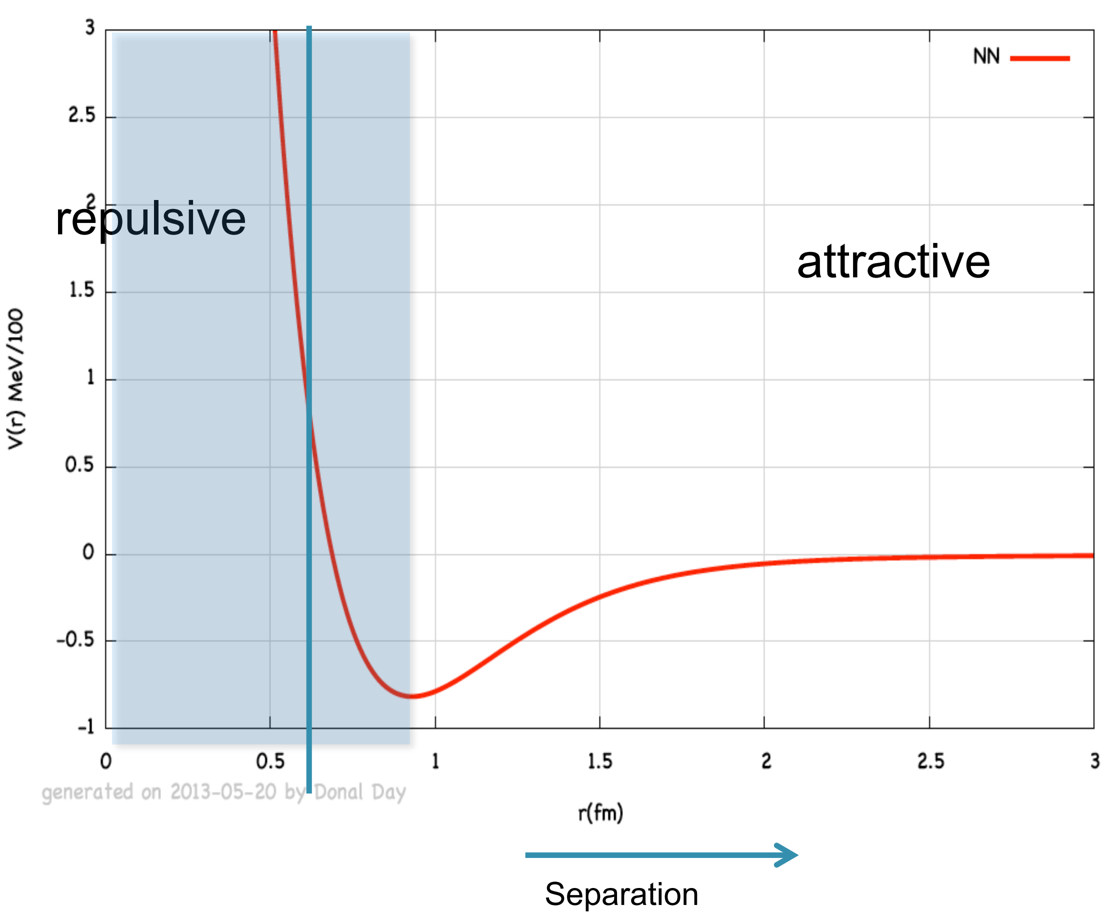
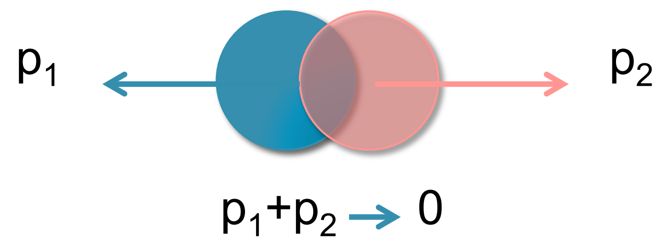
R = 0.6 fm

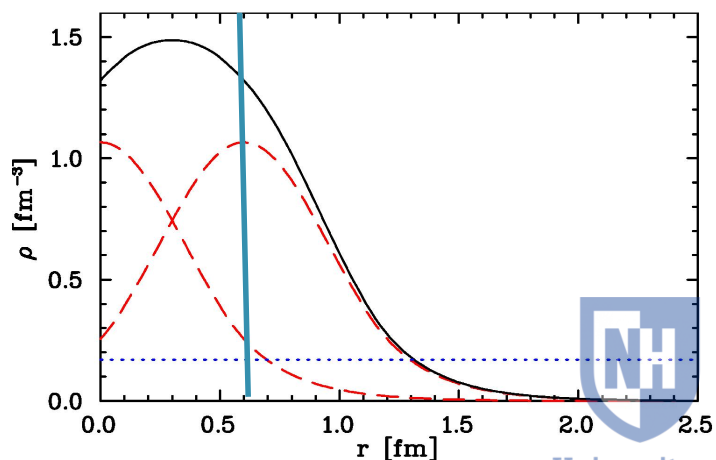
Deuteron (np) potential



Large back-to-back momentum (>k_F)



Density



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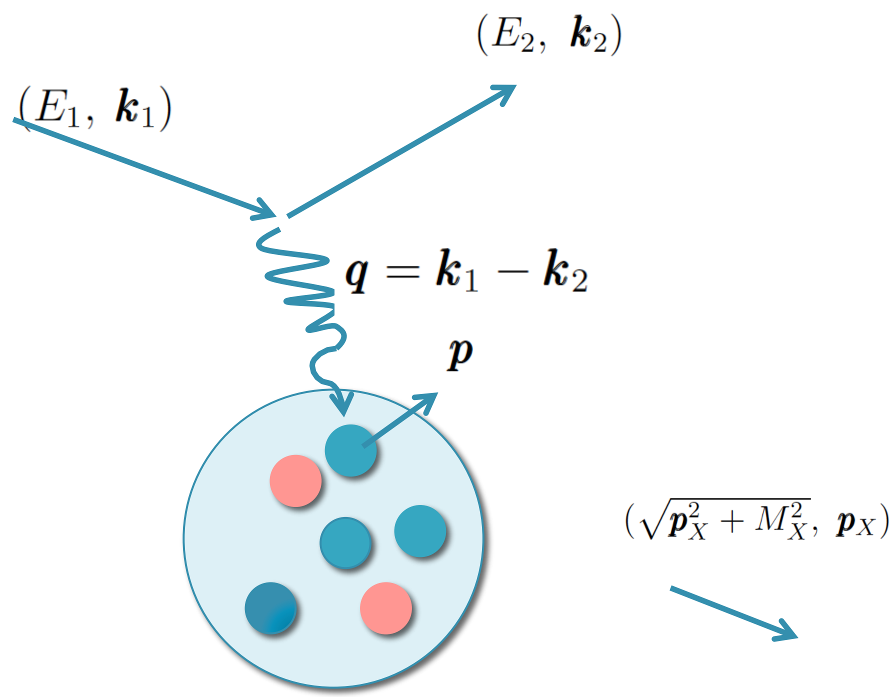
Quasi-elastic Electron Scattering

- Momentum transfer $\boldsymbol{q} = \boldsymbol{k}_1 - \boldsymbol{k}_2$
- Energy transfer $\nu = E_1 - E_2$
- Initial momentum $\boldsymbol{p} = \boldsymbol{p}_X - \boldsymbol{q}$



$$Q^2 = -\boldsymbol{q}^2$$

$$x = \frac{Q^2}{2 m_N \nu}$$

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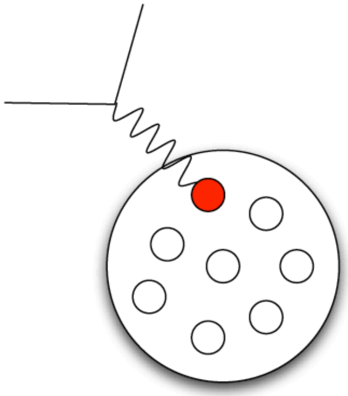
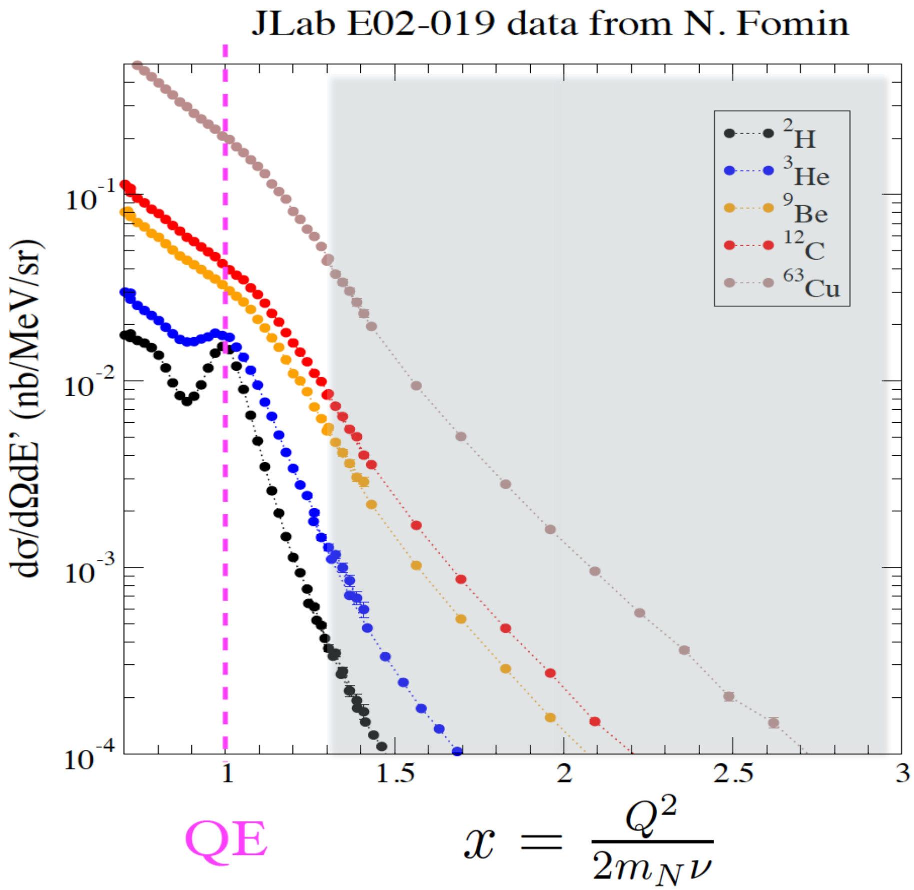
Inclusive Quasi-elastic Scattering



- QE cross section



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SRC in Exclusive Quasi-elastic Scattering

Isospin structure:

T = 1: np, pp, nn
T = 0: np Deuteron-like

np:pp?

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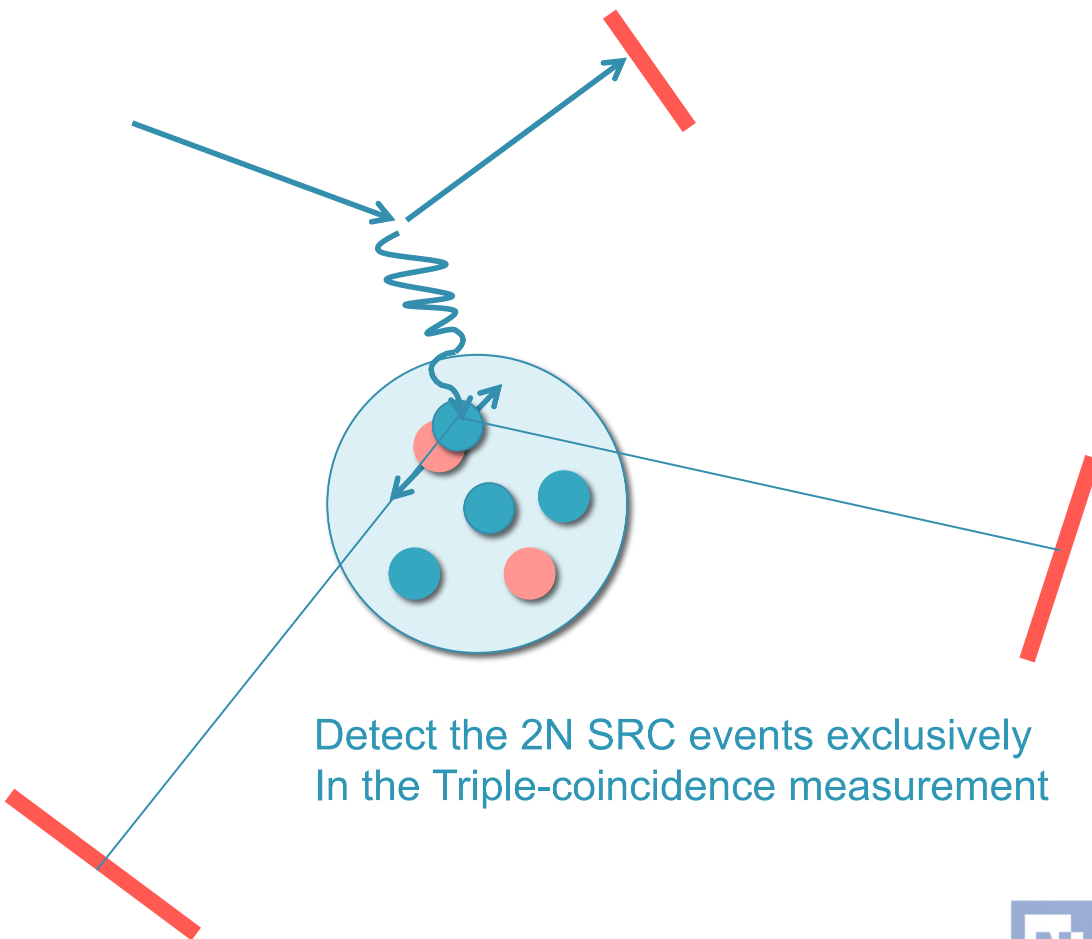
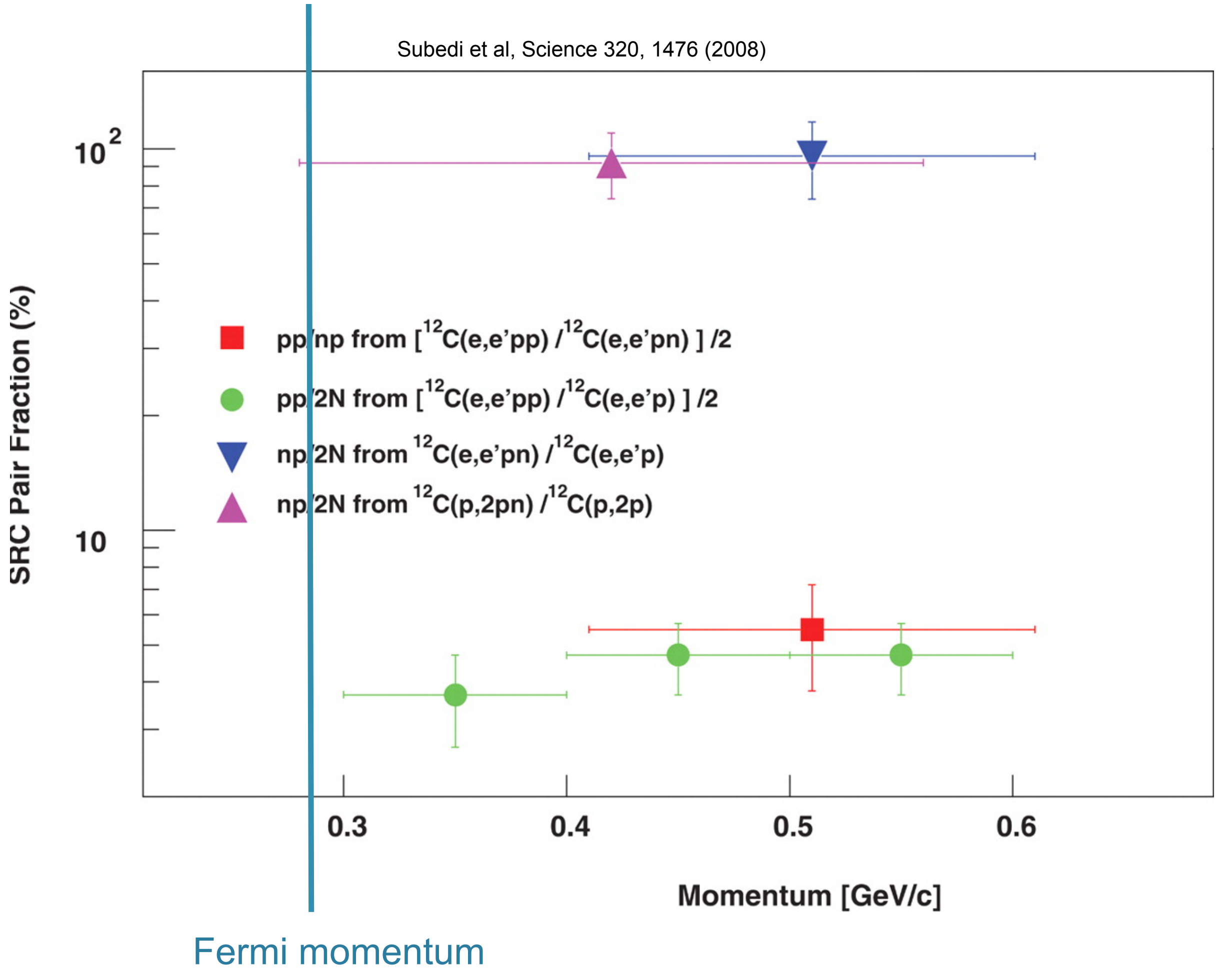
SRC in Exclusive Quasi-elastic Scattering

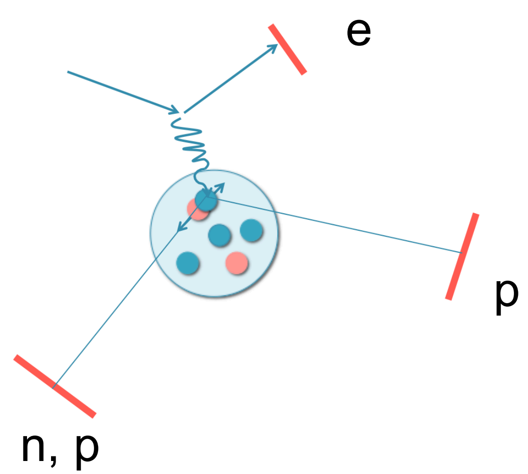
JLAB E01-015



Detect the 2N SRC events exclusively
In the Triple-coincidence measurement

SRC in Exclusive Quasi-elastic Scattering





- 20% of events with high momentum pairs
- ~90% of high momentum pairs detected in ^{12}C are Deuteron-like np pairs !

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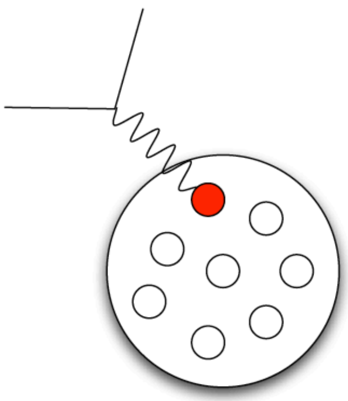
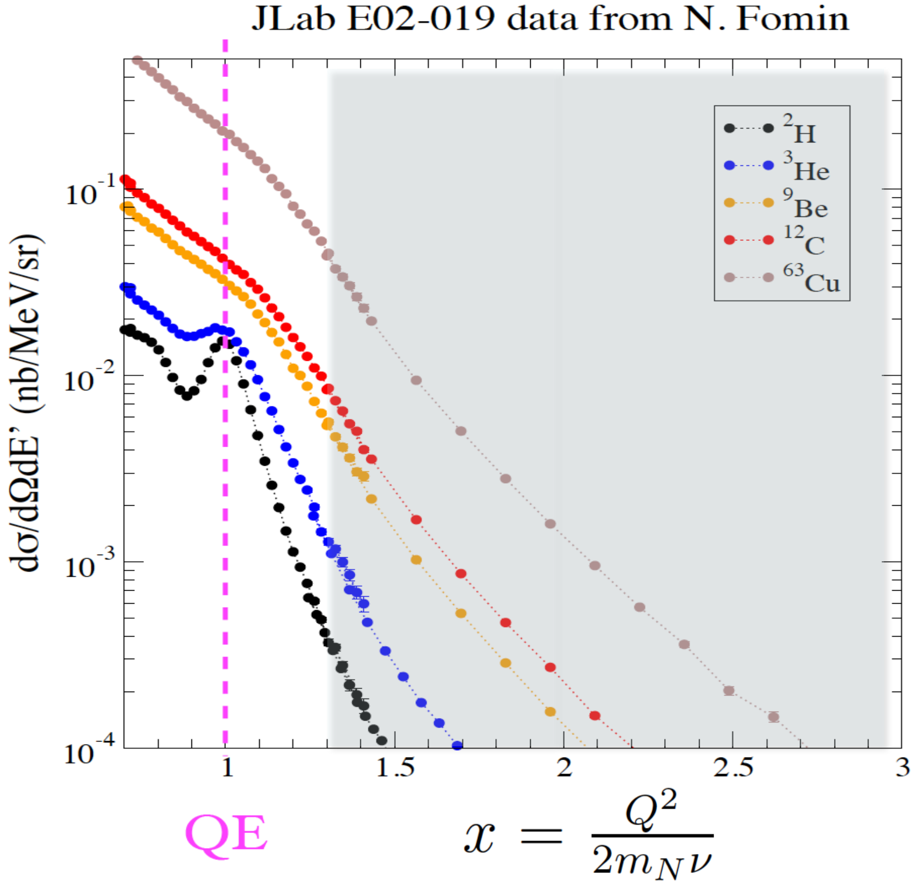
Inclusive Quasi-elastic Scattering



- QE cross section



SRC in Inclusive Quasi-elastic Scattering

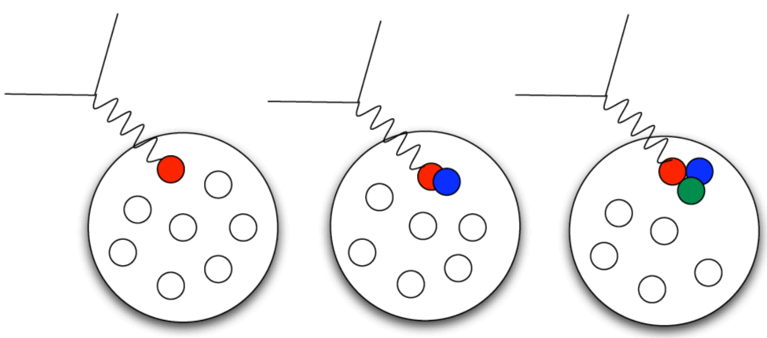
Cross section:

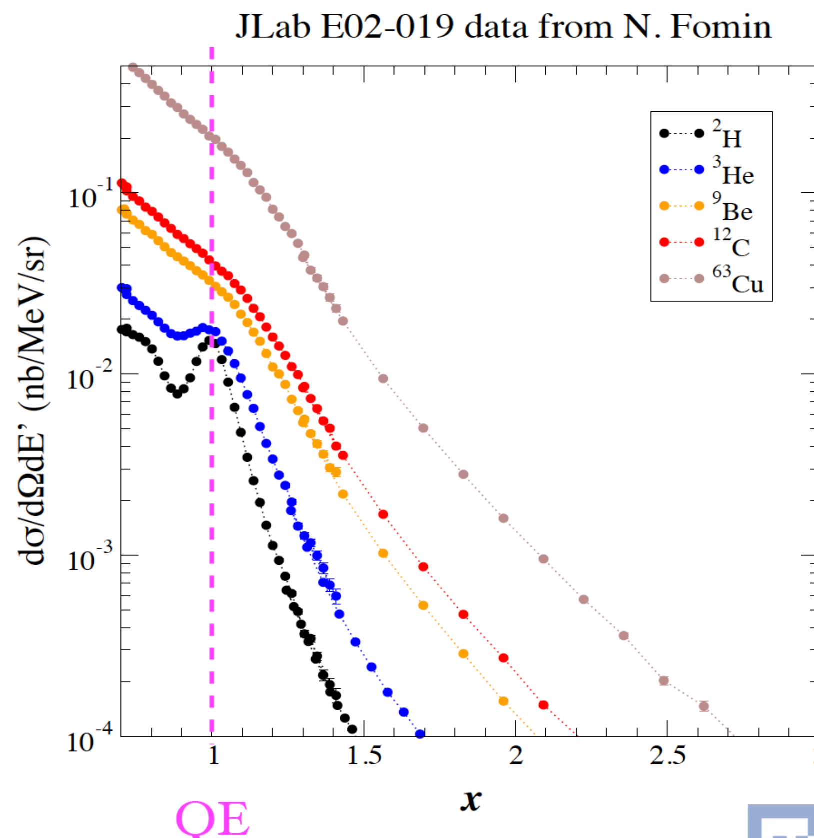
Nucleus A

Probability to find 2N SRC in nucleus A

$$\sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \ldots$$

Cross section from 2N SRC





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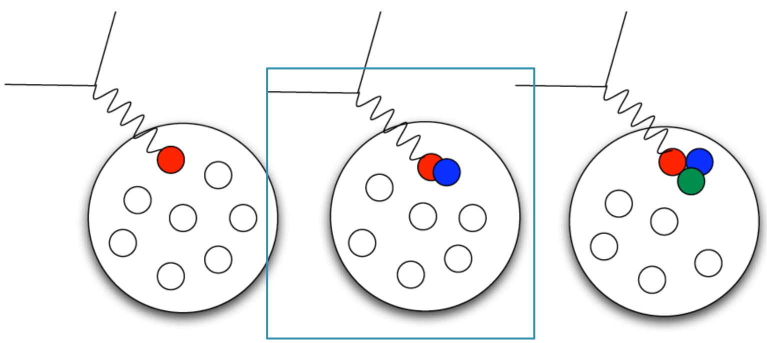
SRC in Inclusive Quasi-elastic Scattering

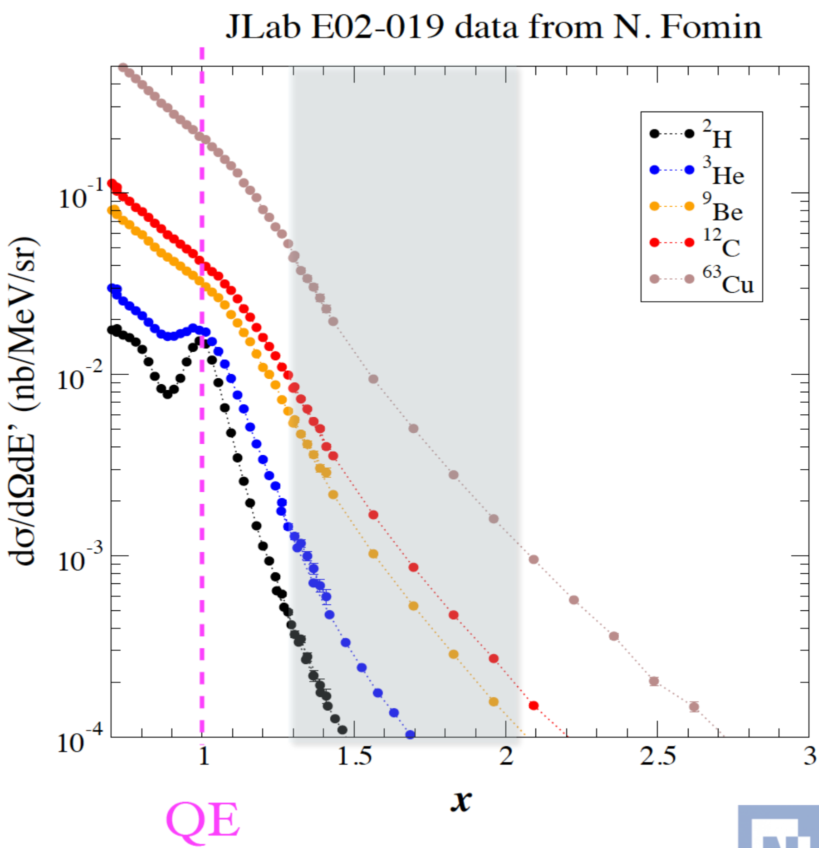
1.3<x<2:

$$\sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \ldots$$

$$\sigma_A \approx a_2(A) \cdot \sigma_{^2H}$$

$$\frac{\sigma_A}{\sigma_{^2H}} \approx \frac{a_2(A)}{a_2(^2H)} = const$$





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SRC in Inclusive Quasi-elastic Scattering

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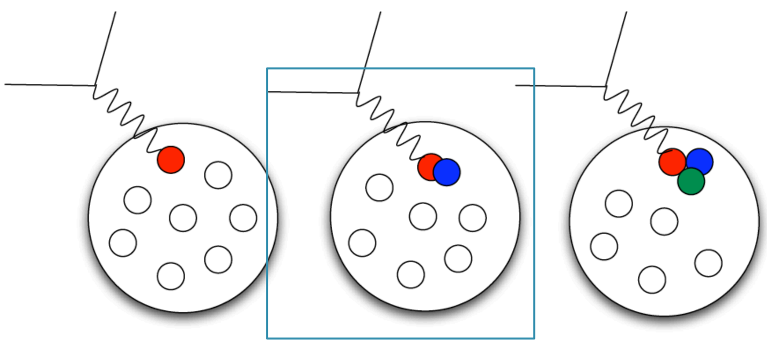
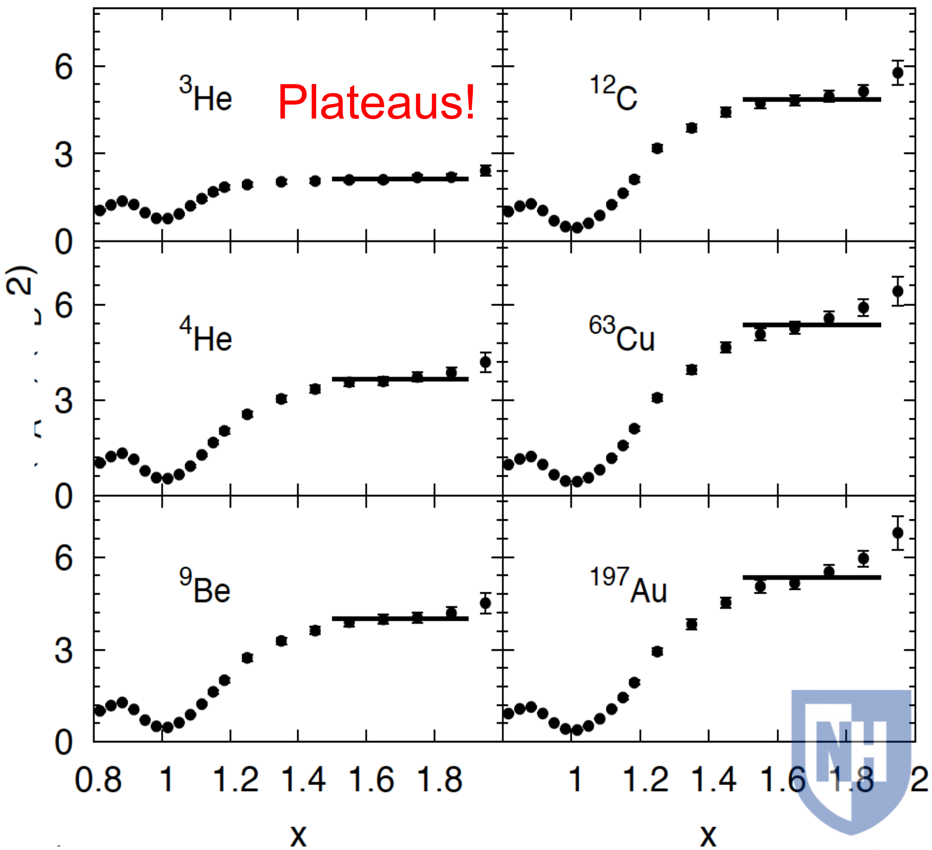


N. Fomin et al., Phys. Rev. Lett. **108** (2012) 092502.



SRC in Inclusive Quasi-elastic Scattering

1.3<x<2:

$$\sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \dots$$

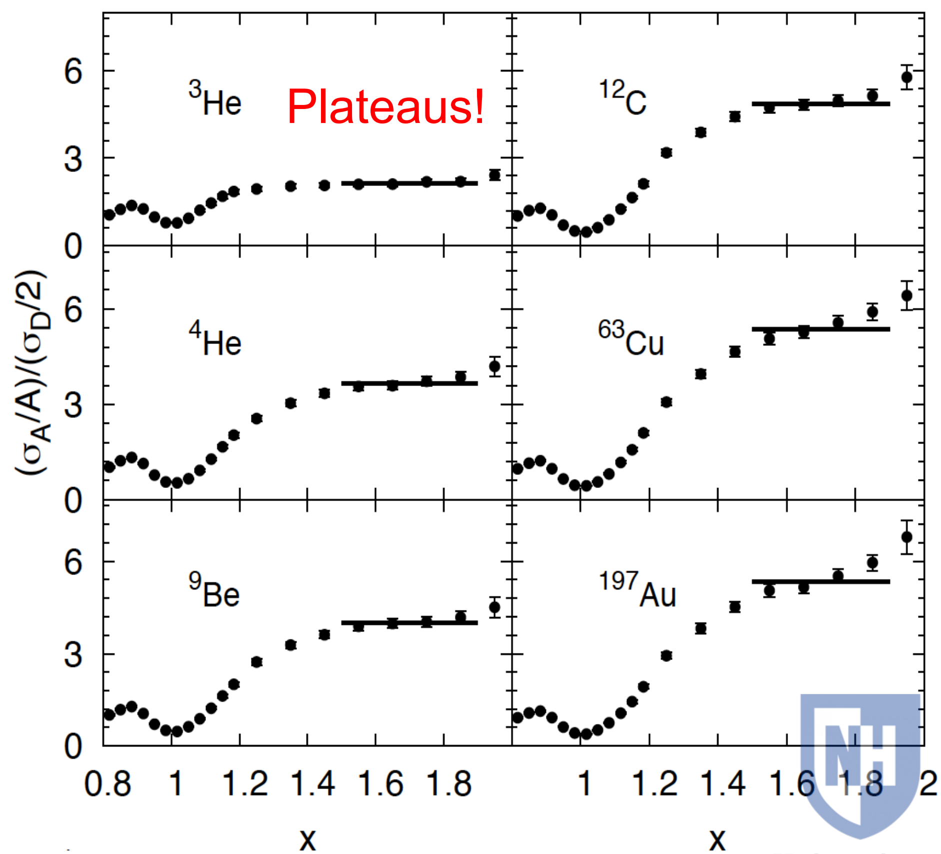
$$\sigma_A \approx a_2(A) \cdot \sigma_{^2H}$$

$$\frac{\sigma_A}{\sigma_{^2H}} \approx \frac{a_2(A)}{a_2(^2H)} = const$$

=0.04

$$a_2(^{12}C) \approx 0.04 \times 5 = 0.2$$

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



SRC in Inclusive Quasi-elastic Scattering

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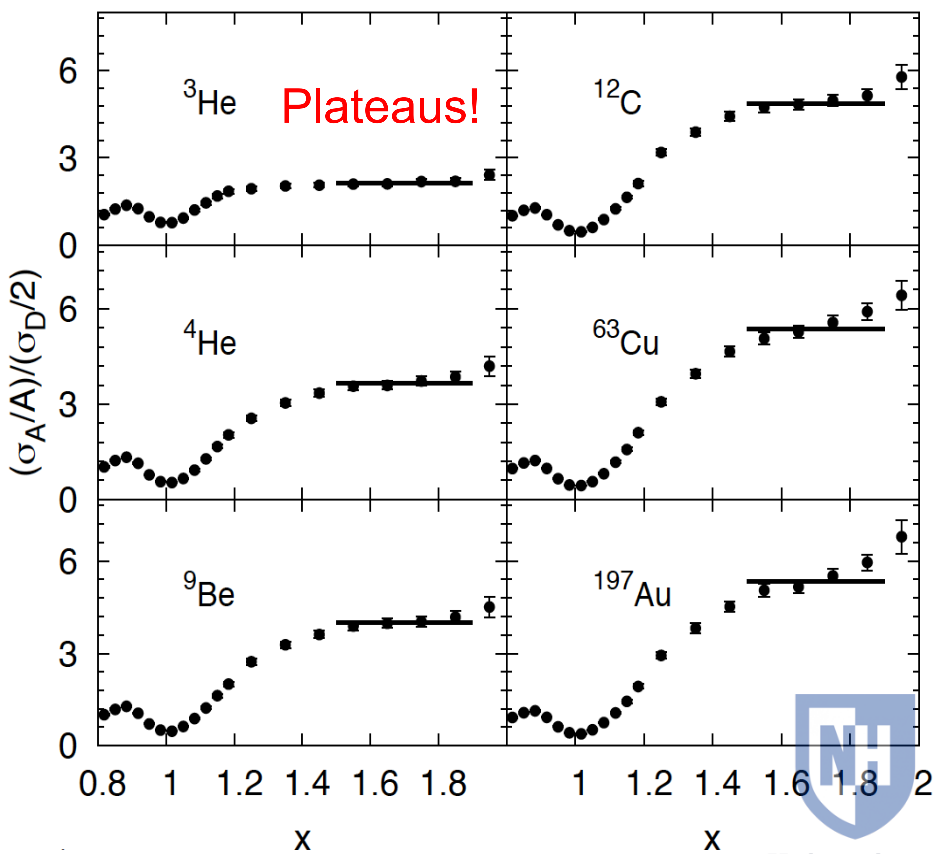
$$\sigma_A \approx a_2(A) \cdot \sigma_{^2H}$$

$$\frac{\sigma_A}{\sigma_{^2H}} \approx \frac{a_2(A)}{a_2(^2H)} = const$$

Final state interaction and systematic errors are cancelled

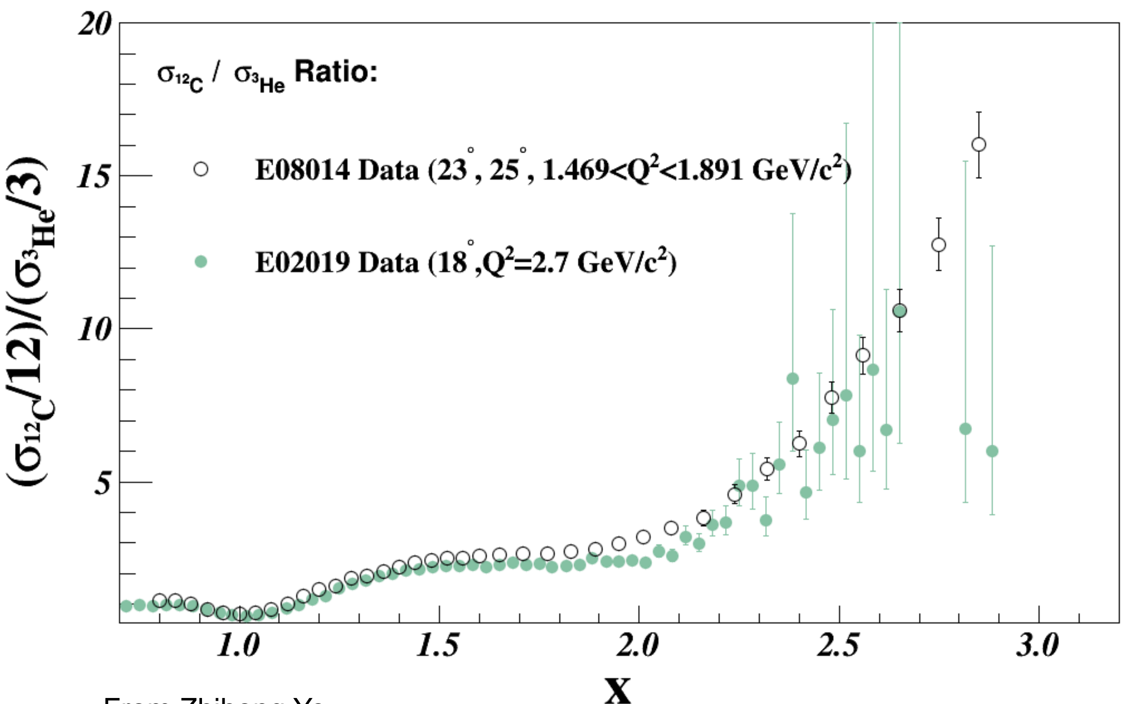
N. Fomin et al., Phys. Rev. Lett. **108** (2012) 092502.



SRC in Inclusive Quasi-elastic Scattering

x>2:

$$\sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \ldots$$



From Zhihong Ye

- ^{3}H? ^{3}He?
- Q^2 too low?
- 3N SRC dominant?

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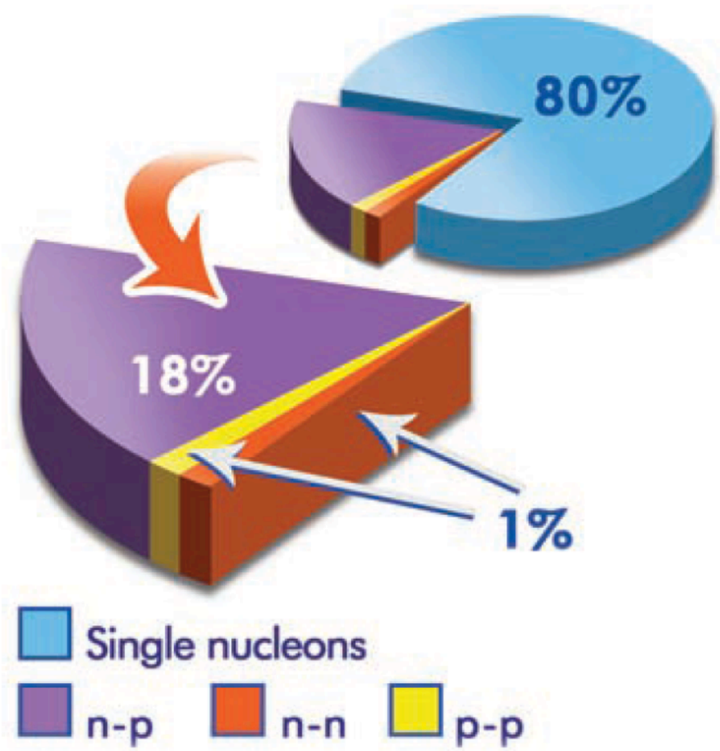
SRC in Quasi-elastic Scattering

- Nucleons in ^{12}C:

Subedi et al, Science 320, 1476 (2008)



- Isospin dependence in 2N SRC
- Possible 3N SRC at x>2

Thesis experiment:

- ^{3}H, ^{3}He, (^{3}H+^{3}He)/2
- Precision ~4.6%

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Thesis Experiment: JLAB E12-11-112

- *Precision measurement of the isospin dependence in the 2N and 3N SRC region*

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- Schedule 2016 fall @ Hall A, Jefferson Lab, VA
- Kinematics E=2.2 and 4.4 GeV, $Q^2 \sim 1.5\ (\mathrm{GeV})^2$, $1< x <3$
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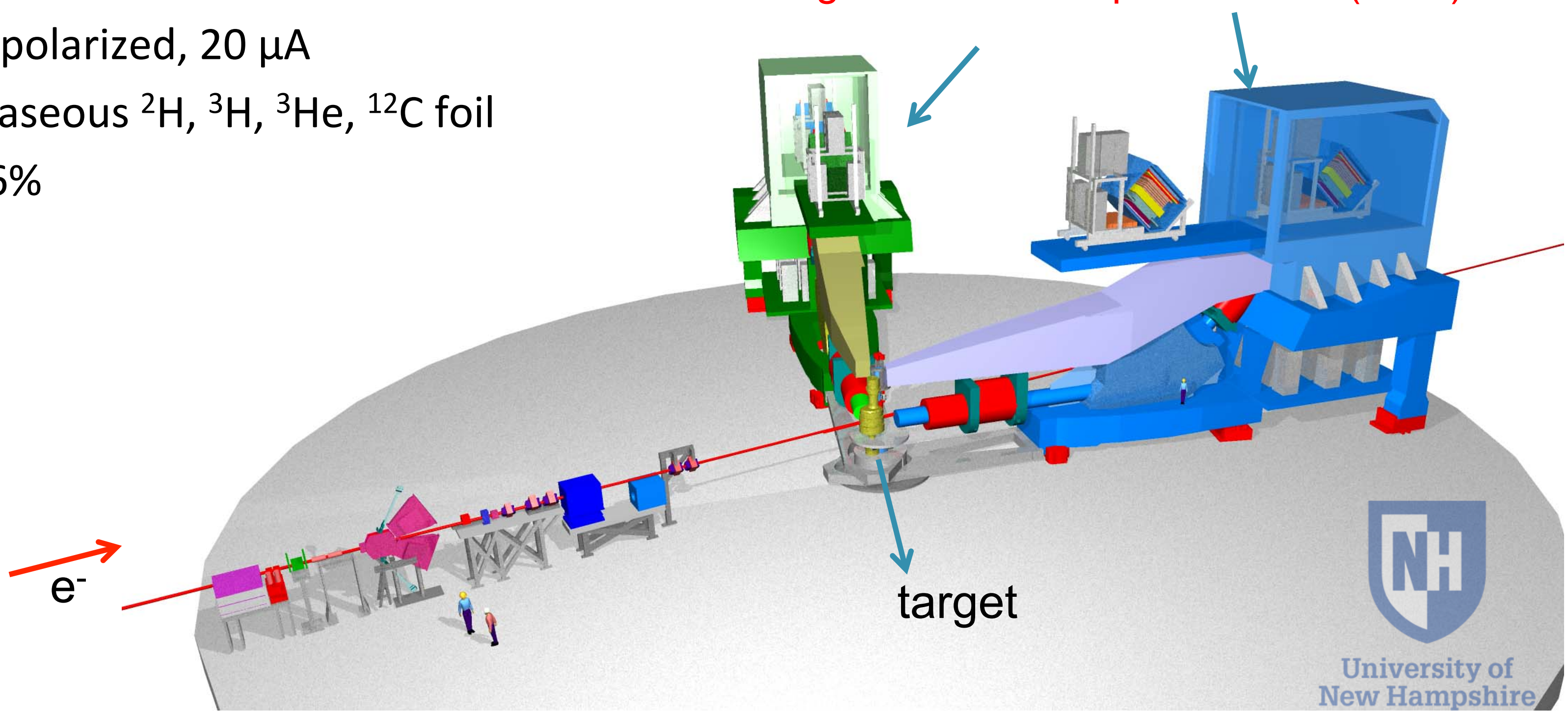
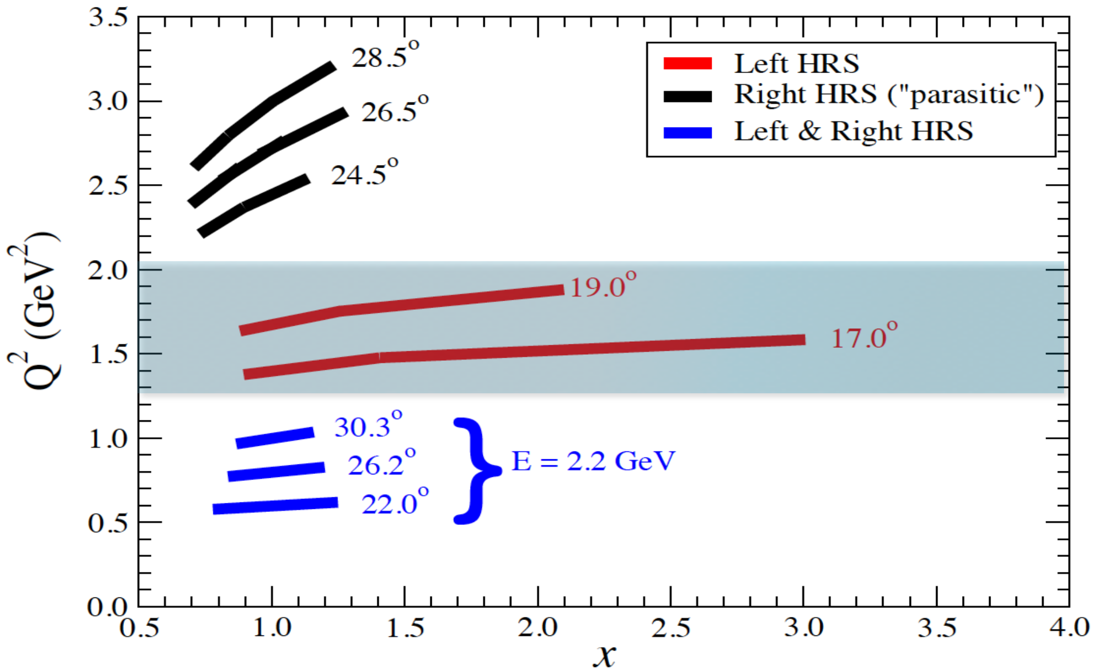
- Target gaseous ^2H, ^3H, ^3He, ^{12}C foil
- Error 4.6%



Thesis Experiment: JLAB E12-11-112

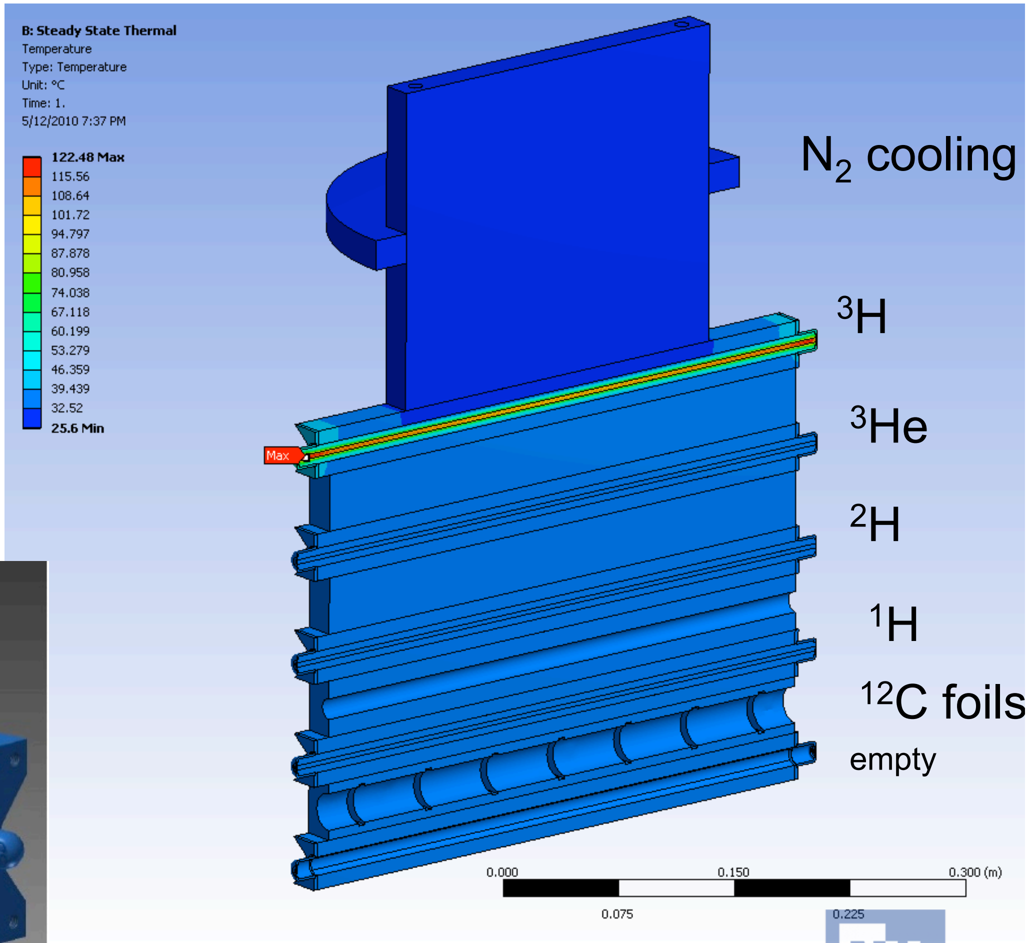
- Kinematics

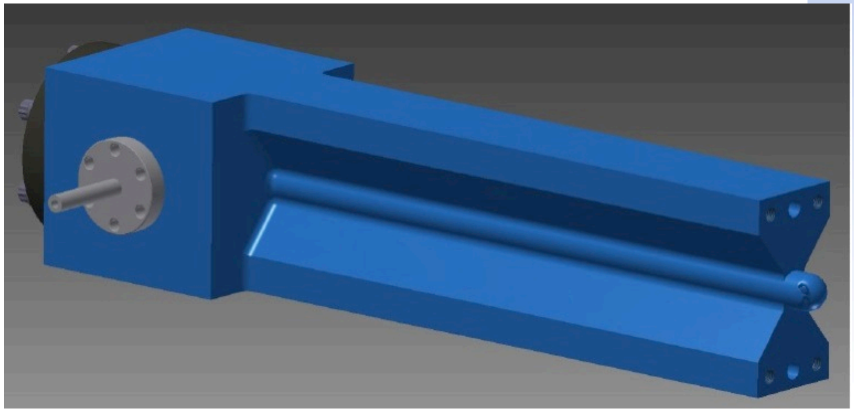


- High Q^2: suppress final state interaction
- Low energy transfer: suppress meson exchange current

Thesis Experiment: JLAB E12-11-112

- Target:
  - 25 cm x 1.25 cm Al cell
  - room temperature
  - hold 1000 Ci ^3H, ^2H or ^3He





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Thesis Experiment: JLAB E12-11-112

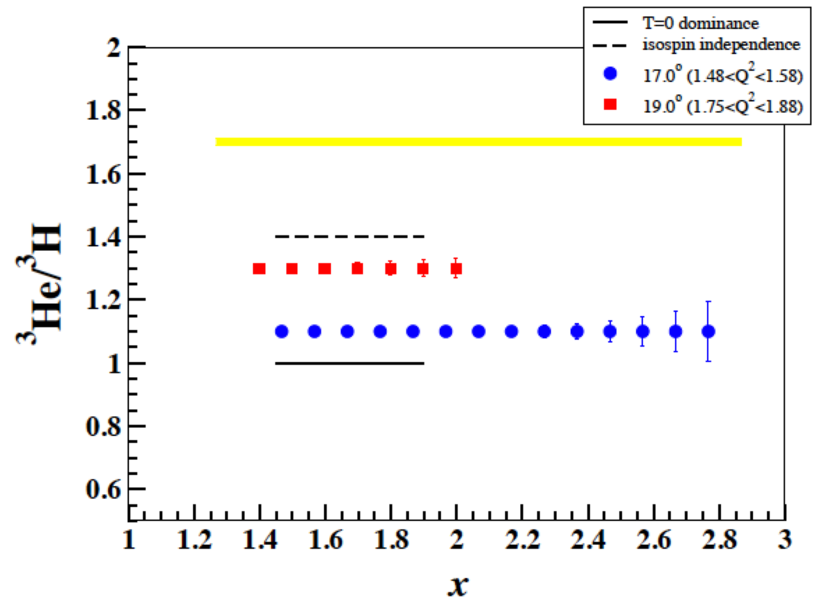
- Goal 1: Check the isospin dependence in 2N SRC at 1<x<2

- np pair dominant:

$$\frac{\sigma_{^3He}}{\sigma_{^3H}} = \frac{\sigma_{np} + \sigma_p}{\sigma_{np} + \sigma_n} \approx \frac{\sigma_{np}}{\sigma_{np}} = 1$$

- No isospin preference:

$$\frac{\sigma_{^3He}}{\sigma_{^3H}} = \frac{\sigma_n + 2\sigma_p}{2\sigma_n + \sigma_p} \xrightarrow{\sigma_p \approx 3\sigma_n} 1.4$$



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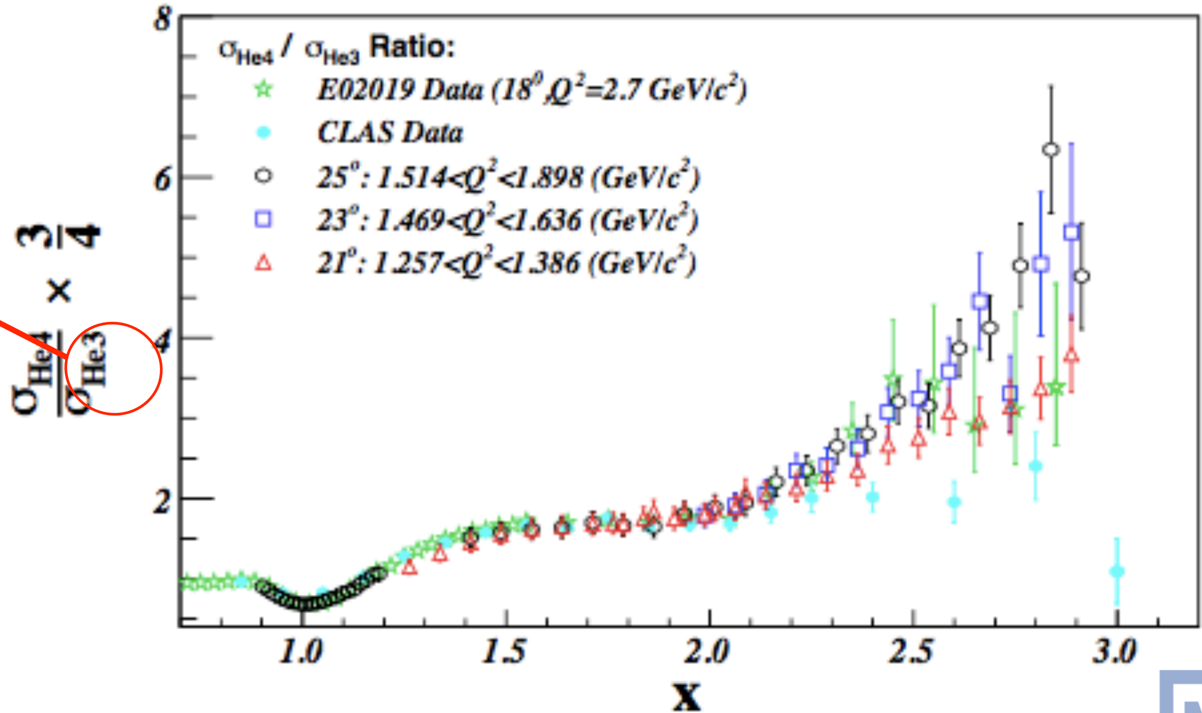
Thesis Experiment: JLAB E12-11-112

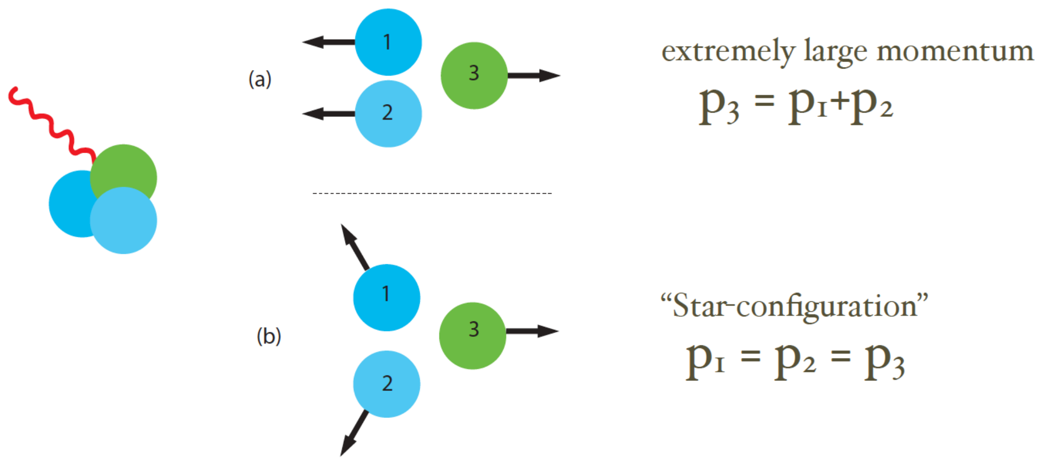
- Goal 2 Probing the possible 3N SRC at 2<x<3
  - 3N plateaus:

3He-like?
3H-like?
average?



Thesis Experiment: JLAB E12-11-112

- Goal 2 Probing the possible 3N SRC at 2<x<3
  - Isospin structure



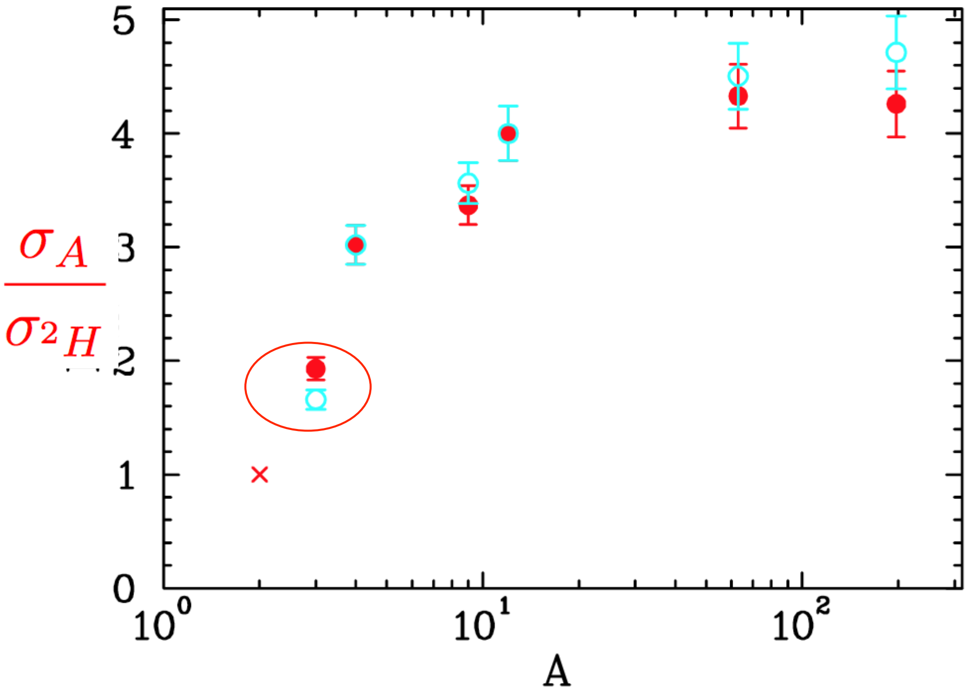
Isospin independent:

$$\frac{\sigma_{^3He}}{\sigma_{^3H}} = \frac{\sigma_n + 2\sigma_p}{2\sigma_n + \sigma_p} \xrightarrow{\sigma_p \approx 3\sigma_n} 1.4$$

Thesis Experiment: JLAB E12-11-112

- Goal 3: Check the A dependence in 2N SRC at 1<x<2

S. Egiyan et al.,PRL 96, 082501 (2006)



($^3He+^3H$)/2

Isoscalared nuclei

Cross section ratio with isoscalar correction (blue hollow) and without it (red dot)

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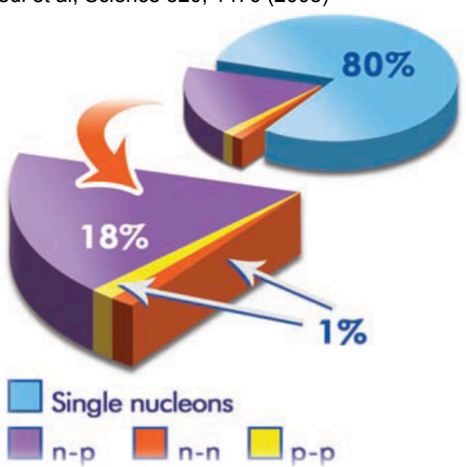
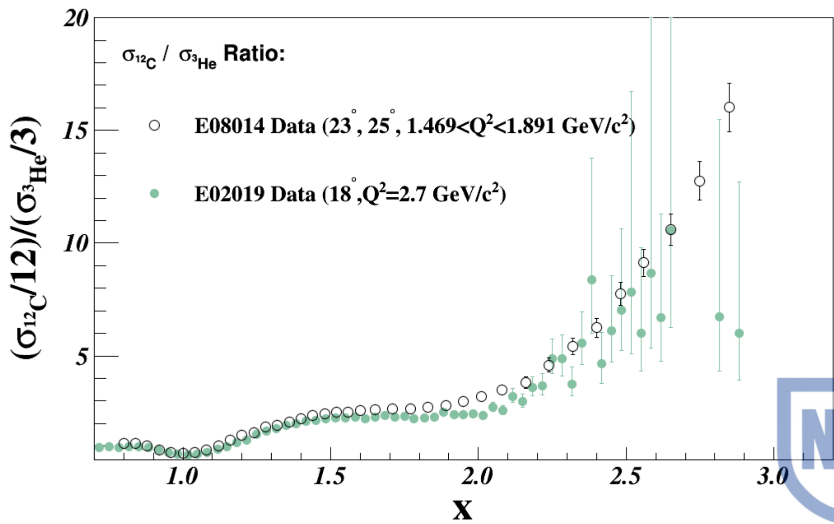
Why SRC is interesting to you?

- Nuclear physics:
  - Go beyond mean field theory to explain high momentum nucleons in nuclear systems
  - Understand the repulsive core in 2N potential
  - Study the local-density-related properties of nuclei, e.g. EMC effect
- QCD:
  - In-medium modification of PDFs

Subedi et al, Science 320, 1476 (2008)





Thank you!

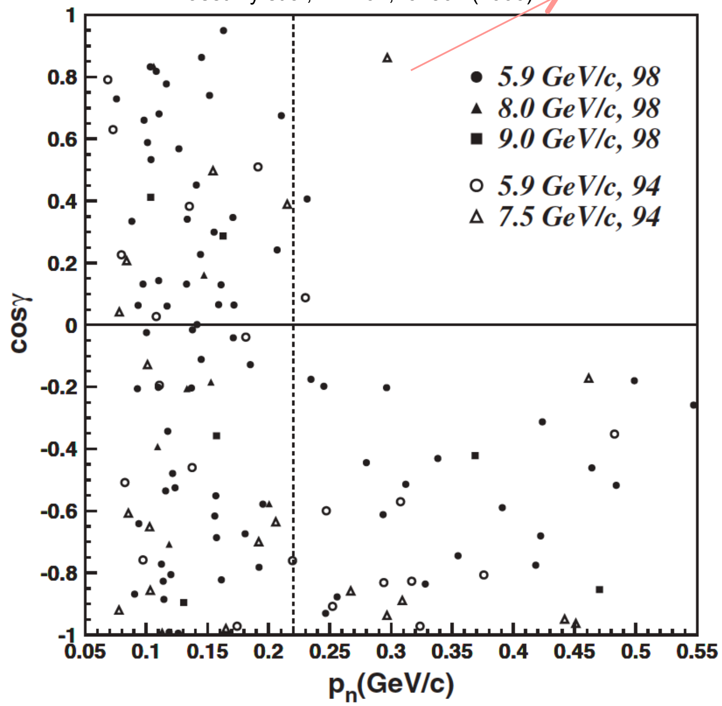
BACKUP

SRC in Quasi-elastic Scattering

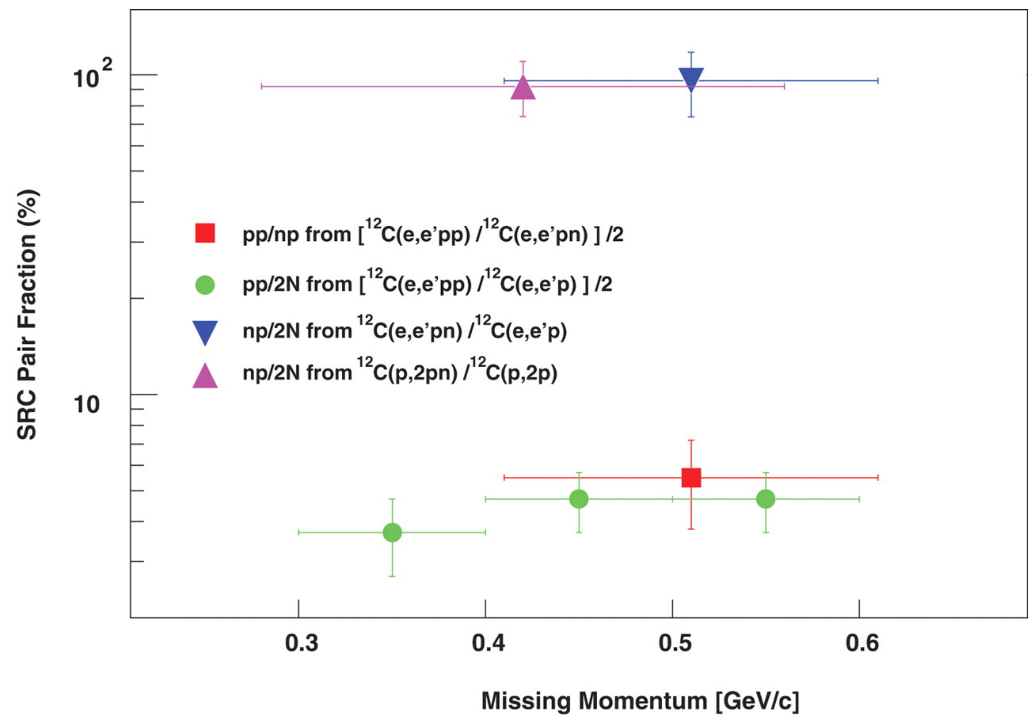
exclusive
inclusive

$k_F \approx 220$ MeV/c

Piasetzky et al, PRL 97,162504 (2006)



Subedi et al, Science 320, 1476 (2008)



Directional correlation between recoiled neutron momentum and the angle γ in A(p, p'pn).

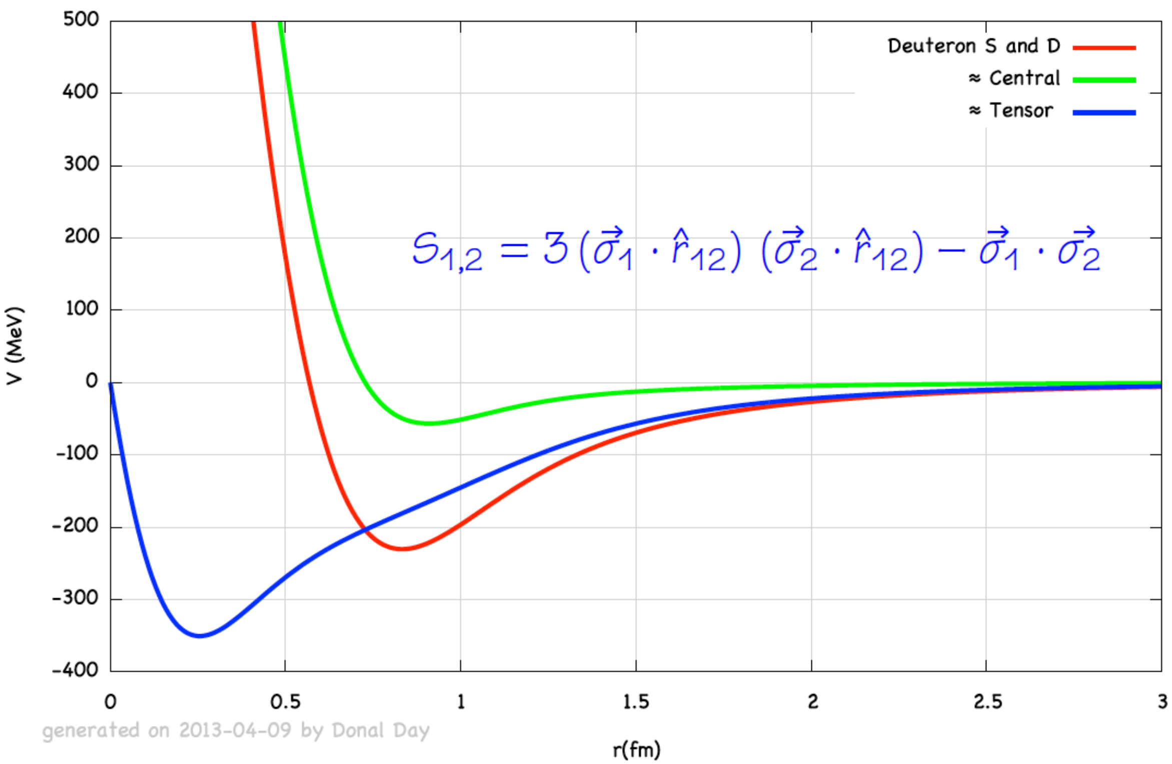
~90% of SRC pairs are np pairs.
The ratio of np to pp pairs are 18:1 in 12C

np Pair Dominance at Short Inter-nucleon Distance

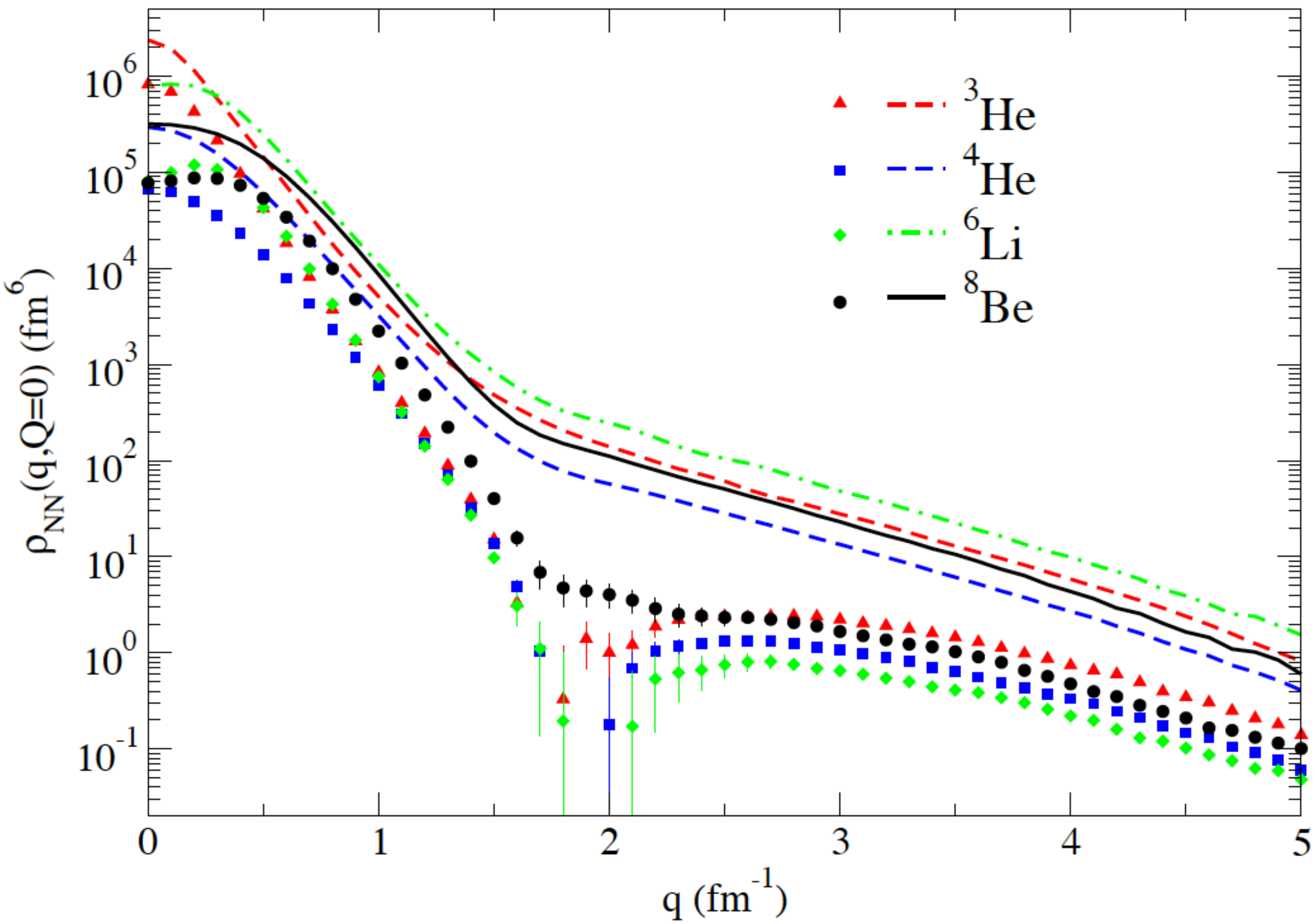
- Free nucleon-nucleon potential = Repulsive core + attractive tensor force
  - Tensor operator

$$S_{12} = 2\left[3\frac{(\vec{S}\cdot\vec{r})^2}{r^2} - \vec{S}^2\right]$$

- T = 1, S = 0 :np, pp, nn pairs. S_{12} = 0, no attractive tensor force
- T = 0, S = 1: Deuteron-like np pair.



Lines: np pair. Symbols: pp pair



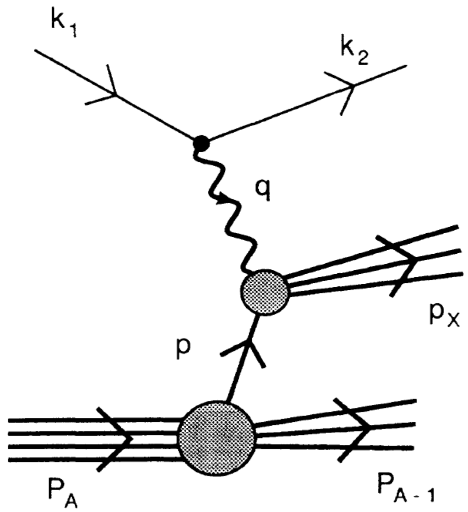
Tests of Shell Model

Occupation number Momentum Distribution

Experiment: Quasi-elastic (QE) electron scattering provides a clean picture on single nucleon wave function.

- QE cross section:

$$\frac{d^6\sigma}{d\boldsymbol{p}_X dE'} = K\sigma_{ep} S(\boldsymbol{p}, E_m)$$



Spectral function: probability of knocking off a nucleon with initial momentum p and removal energy E_m

$$\int S(\boldsymbol{k}, E_m = \epsilon_\alpha) d\boldsymbol{k} = 2j + 1$$?

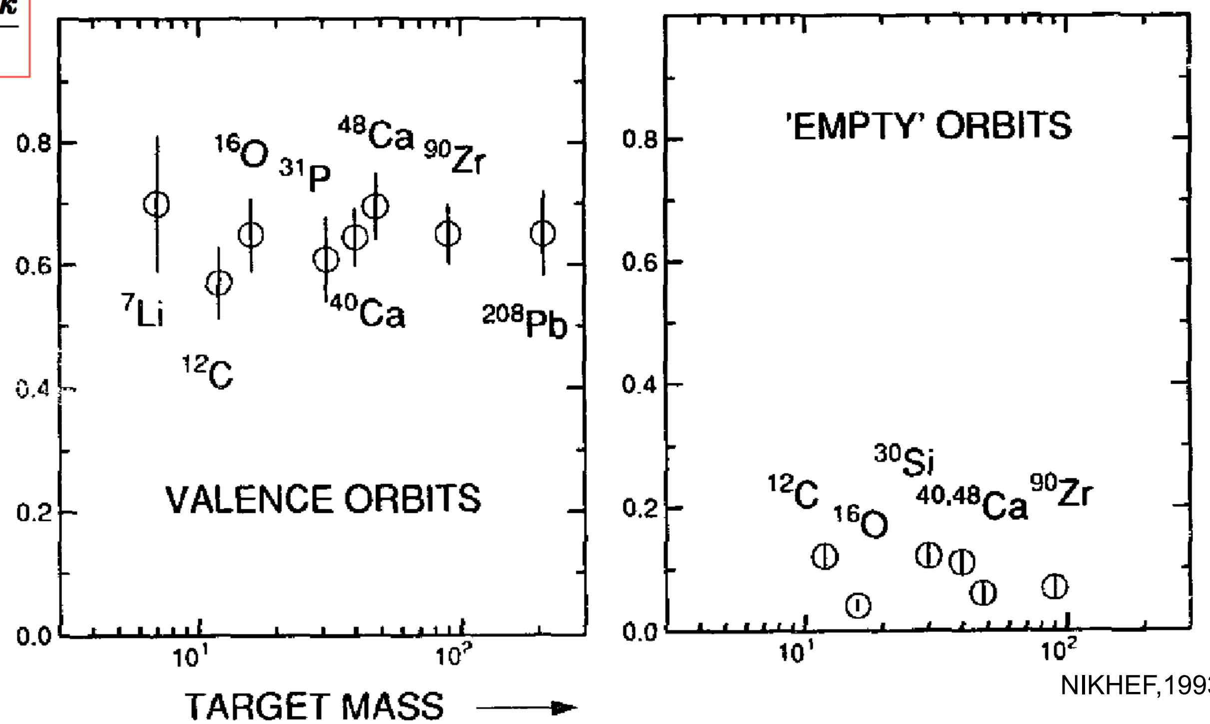
probability of knocking off a nucleon in orbit α

Tests of Shell Model

Occupation number Momentum Distribution

$$\frac{\int S(\boldsymbol{k},\epsilon_\alpha)d\boldsymbol{k}}{2j+1}$$

Spectroscopic strength

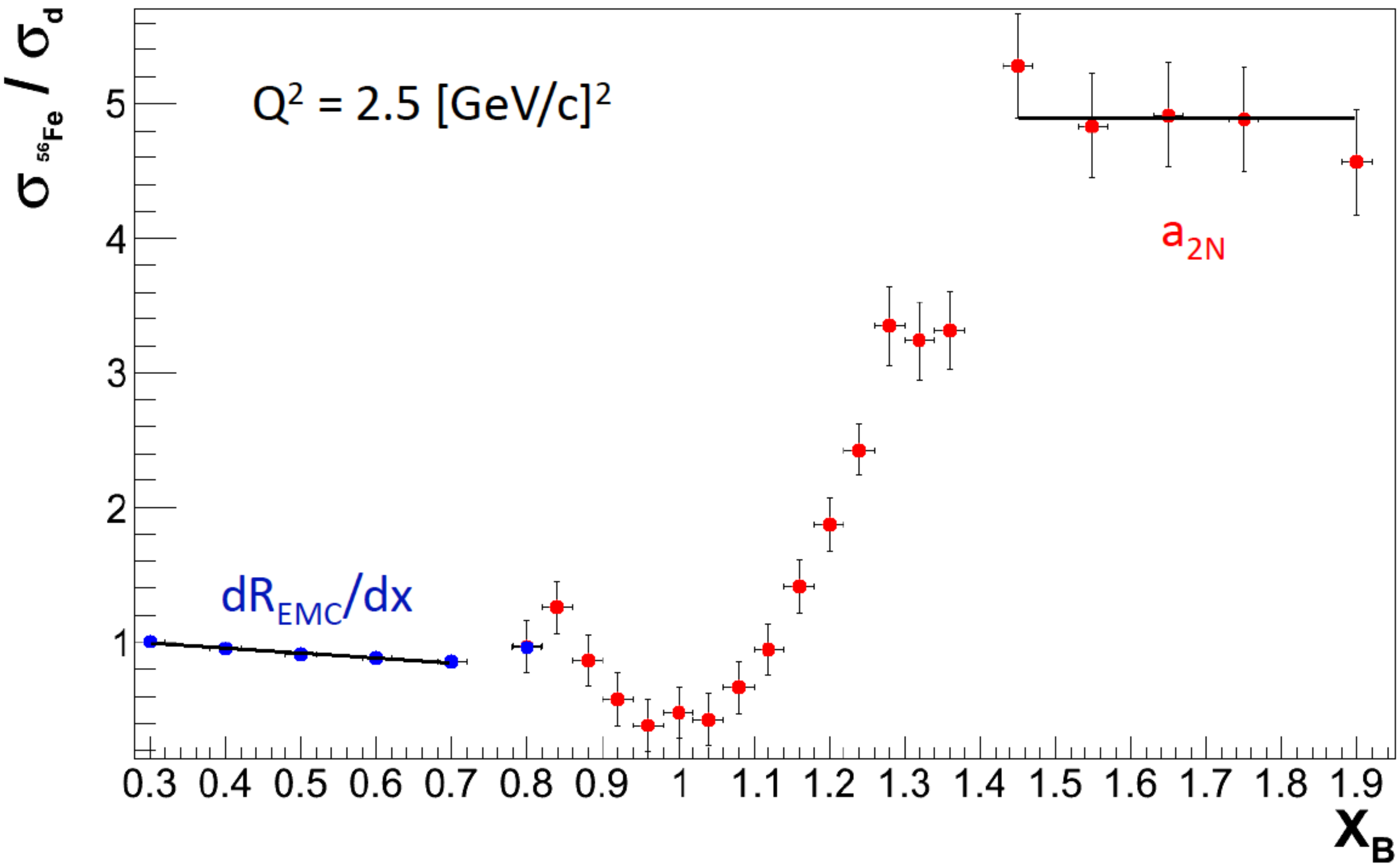


NIKHEF,1993

- The closed orbits are NOT fully occupied.
- Nucleons can live in orbits above Fermi level

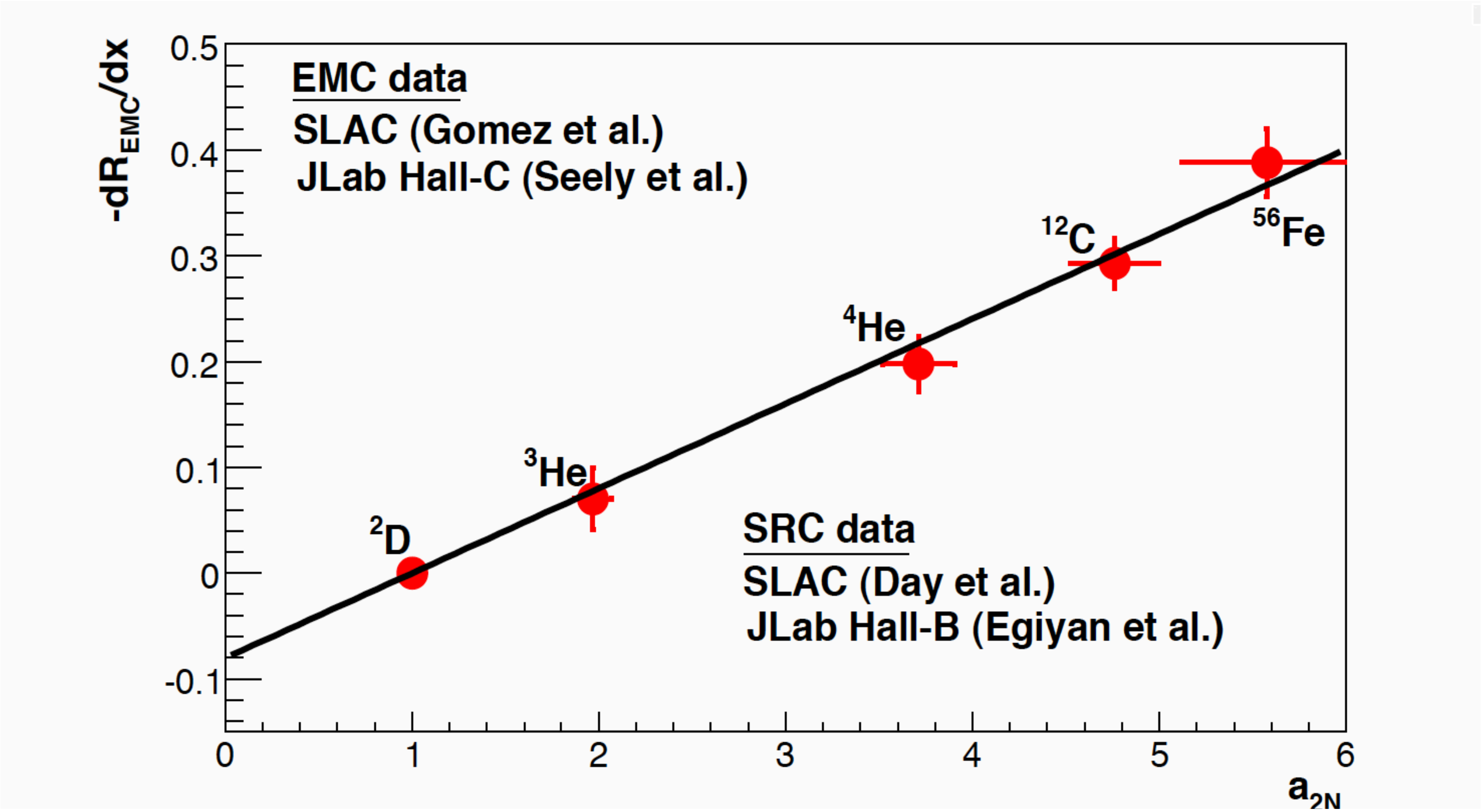
EMC and SRC

Higinbotham *et al.*, arXiv:1003.4497.

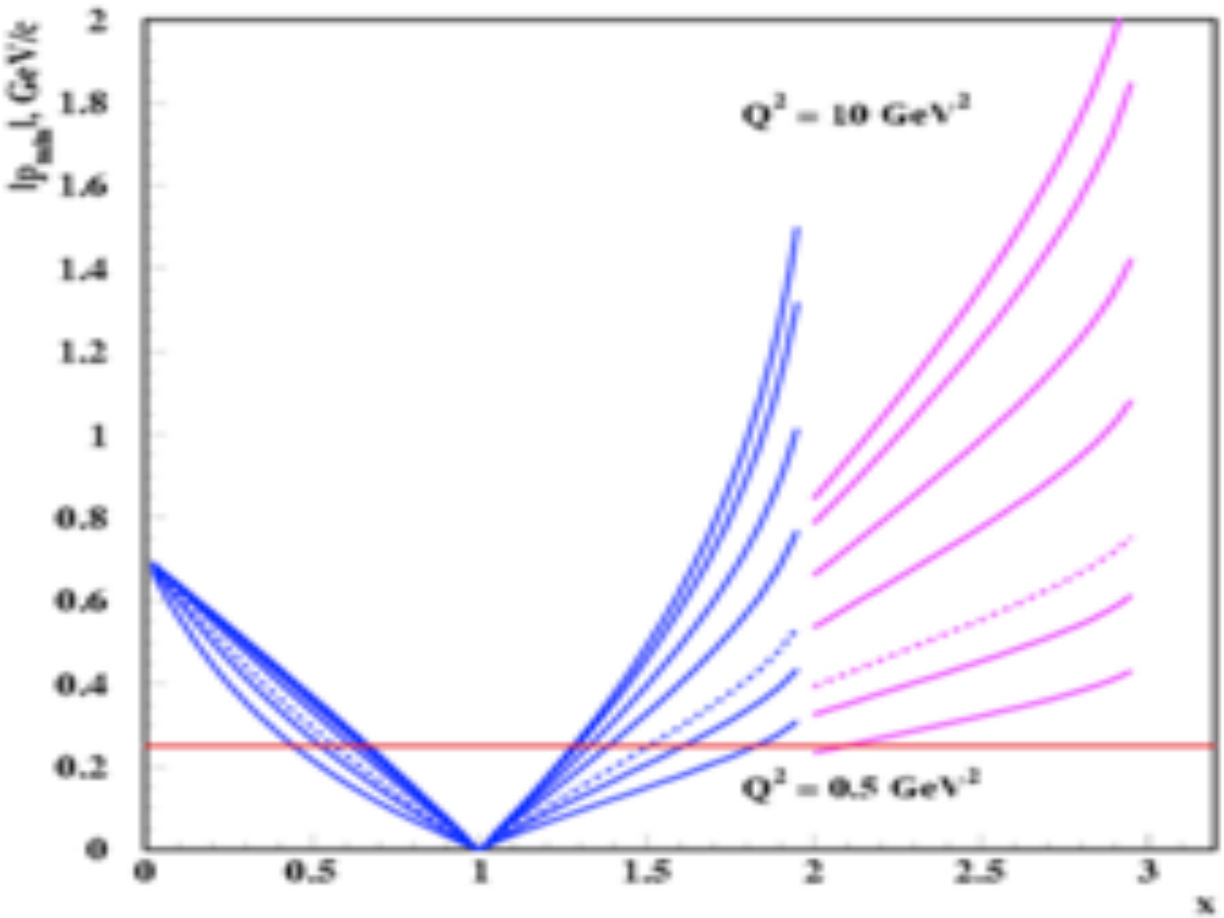


SRC and EMC Correlation

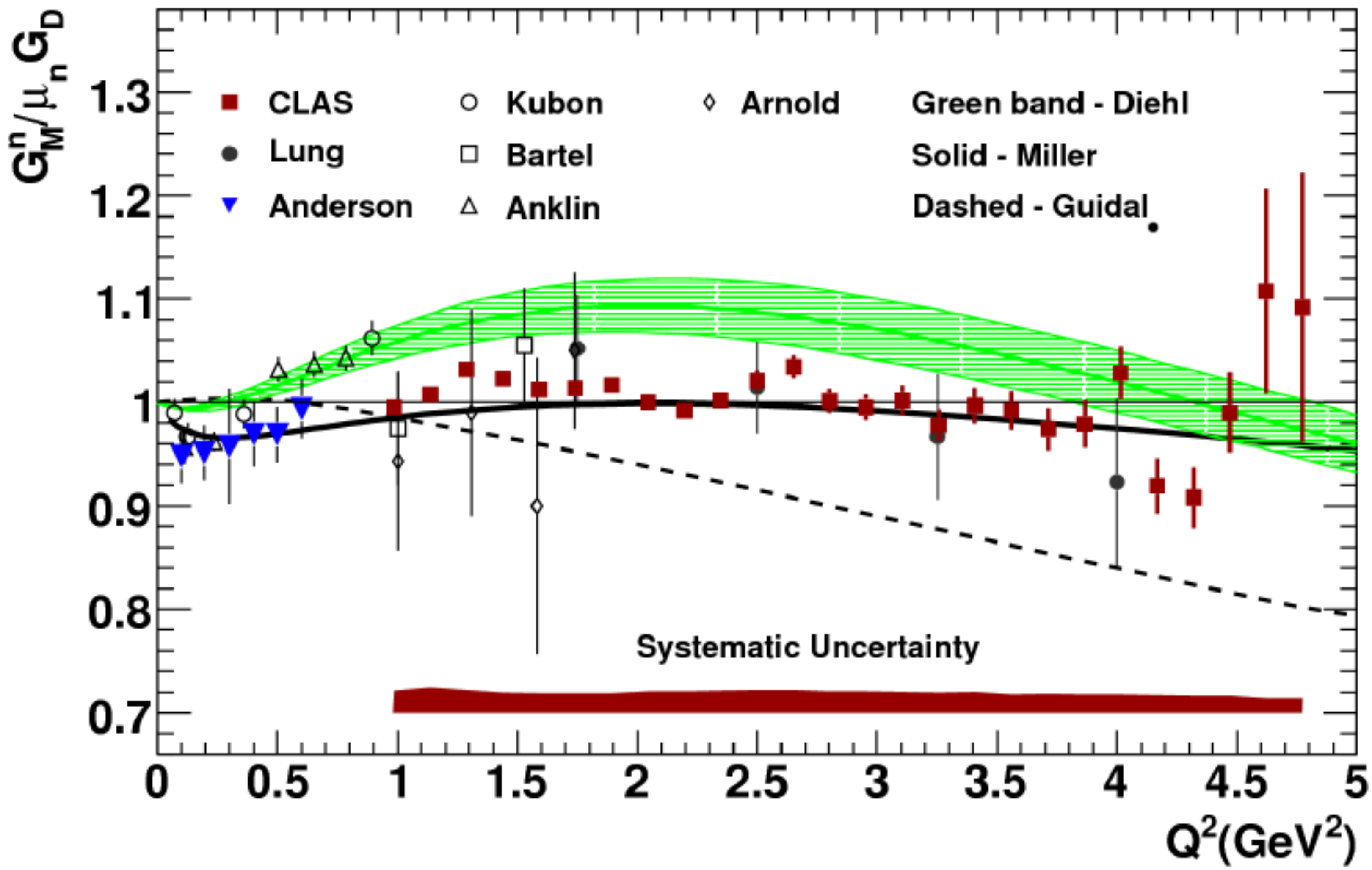
L. Weinstein *et al.*, Phys. Rev. Lett. **106** (2011) 052301.



X scaling onset



Neutron magnetic form factor



SRC in Inclusive Quasi-elastic Scattering

1.3<x<2:

$$\sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \ldots$$

$$\sigma_A \approx a_2(A) \cdot \sigma_{^2H}$$

$$\frac{\sigma_A}{\sigma_{^2H}} \approx \frac{a_2(A)}{a_2(^2H)} = const$$

=0.04

$$a_2(^{12}C) \approx 0.04 \times 5 = 0.2$$