2N and 3N Correlations in Few Body Systems at x > 1

Searching for 3N Correlations at x > 1

Donal Day
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Next generation nuclear physics with JLab12 and EIC

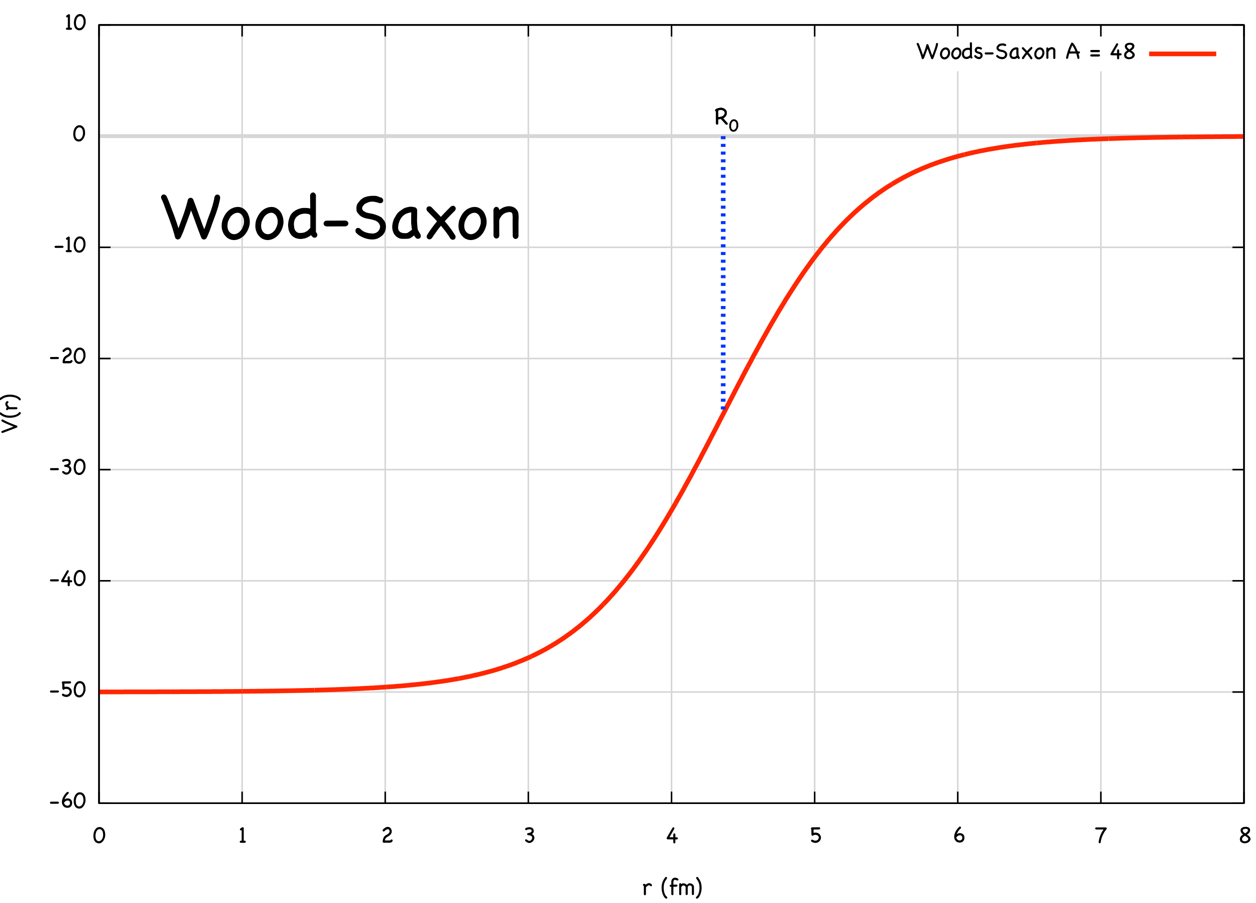
Outline

- Accepted Notions on SRCs
  - NN potential responsible
  - Implications
    - Some examples
- Two nucleon correlations in inclusive data
  - Examples
  - Implications
- Searching for 3N correlations
  - Data in depth
    - 4He/3He
    - 12C/4He etc
- Finish
- Wish List

Mark Strikman, John Arrington, Eli Piasetsky, Or Hen, Erez Cohen, Nadia Fomin, Doug Higinbotham, Patricia Solvignon, Elena Long

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 ξ_α and wave function Φ_α 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).

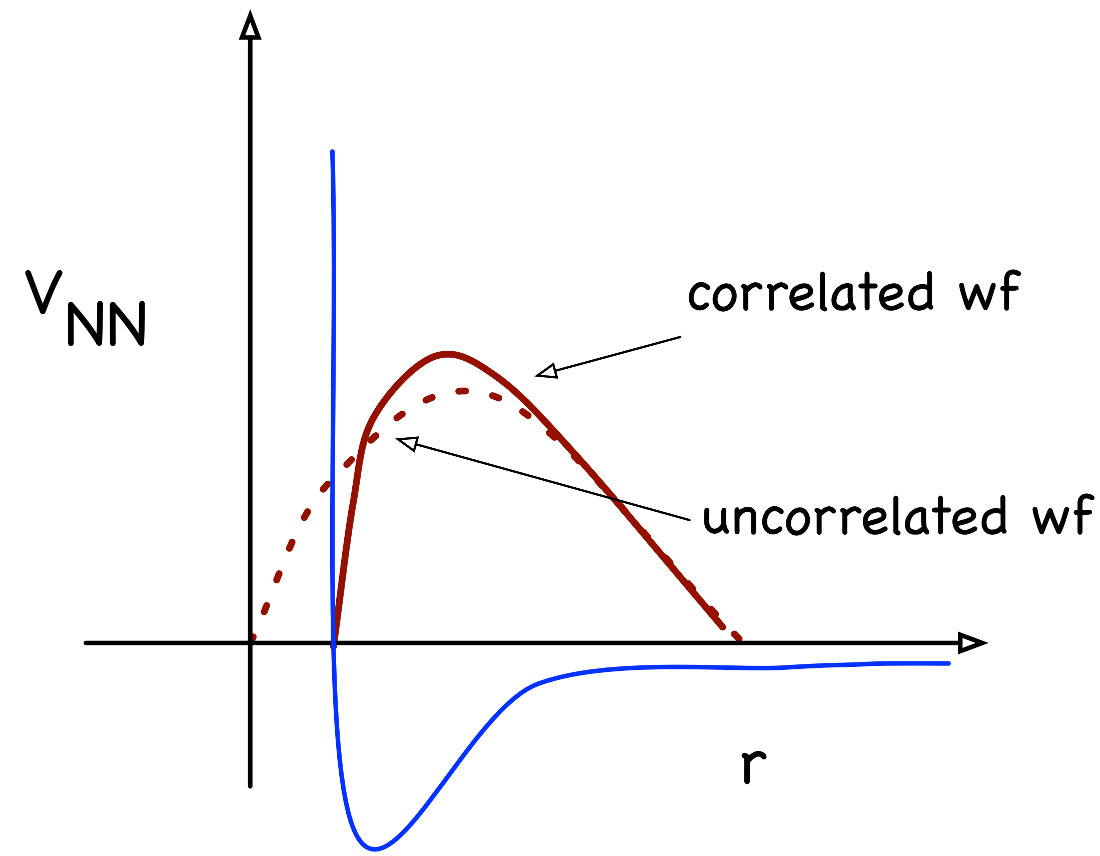
$$S(\vec{p}, E) = \sum_a |\Phi_a(p)|^2 \, \delta(E + \xi_a)$$

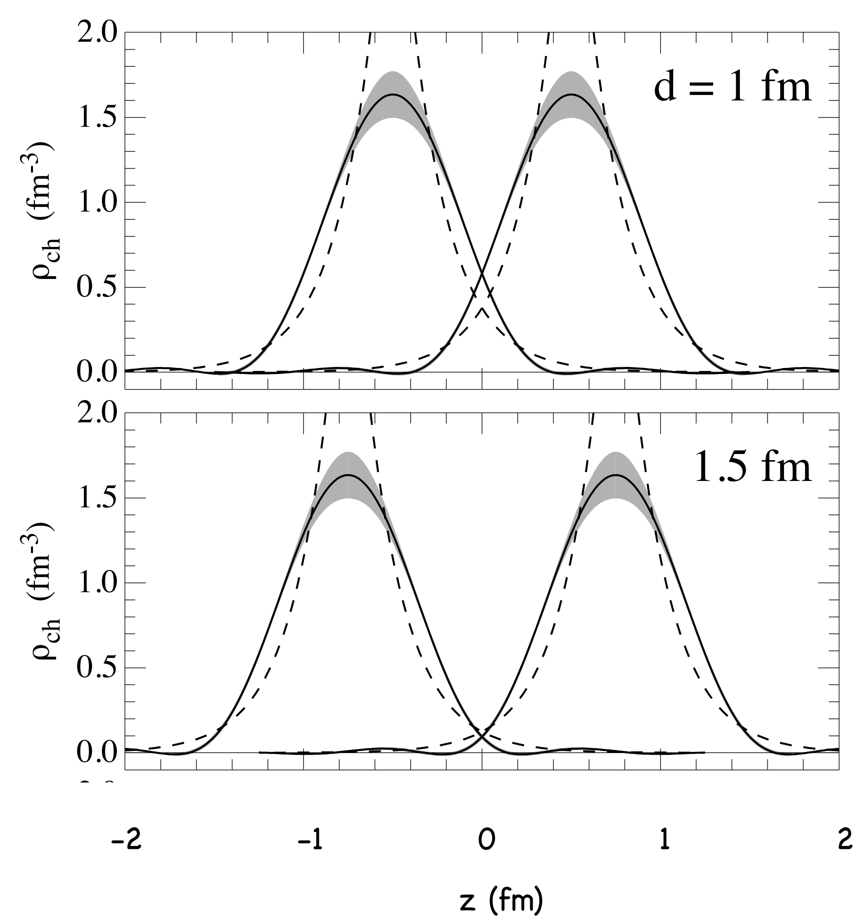
- Enormous strong force acting
- So many nucleons to collide with
- How can nucleons possibly complete whole orbits (10^{21}/s) without interacting?

They do interact and they interact violently

Case for Correlations

- The nucleon-nucleon (NN) interaction is singularly repulsive at short distances
  - Difficult to find two nucleons close to each other.
  - Loss in configuration space components signals an increase of high-momentum components
- Both the correlation hole and the high-k components are absent in IPMs
- Taken together the loss of configuration space and the strengthening of high of momentum components are "correlations".
- The NN tensor force also provides high-momentum components; required to obtain the quadrupole moment of the deuteron and predicts a isospin dependence of SRCs.



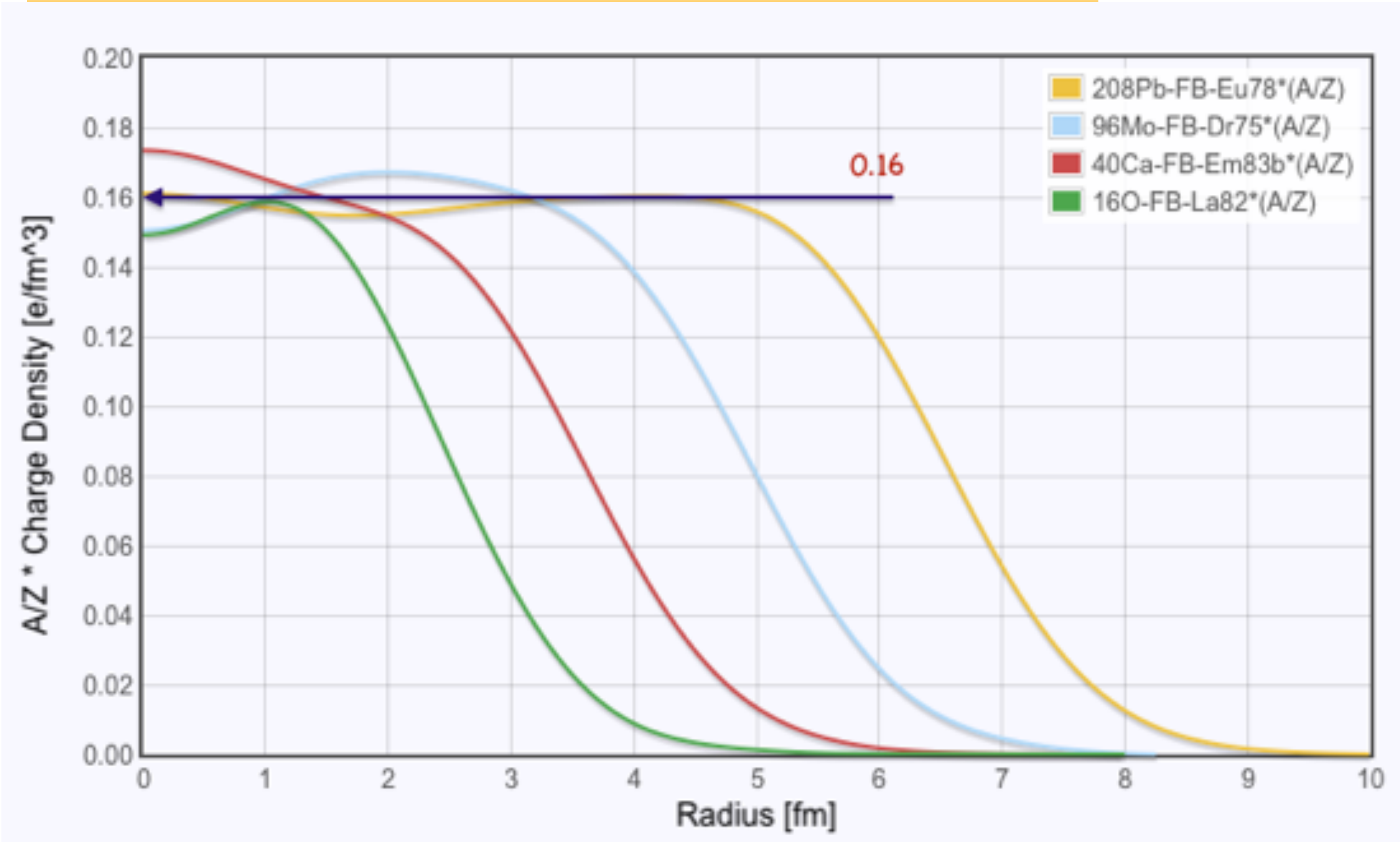


Pandharipande, Pieper and Schiavilla

Densely packed - at small distances multiples of NM

High enough to modify nucleon structure?

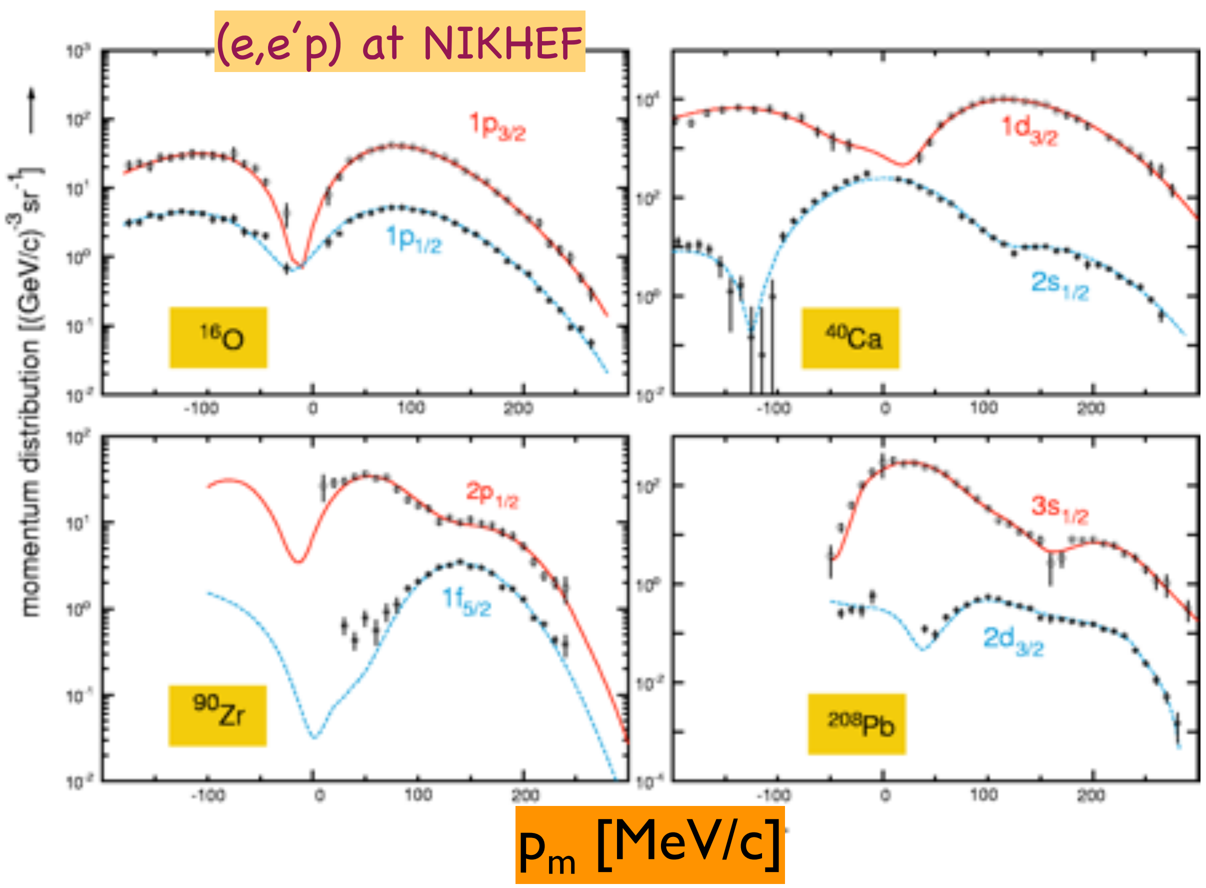
Evidence of SRC

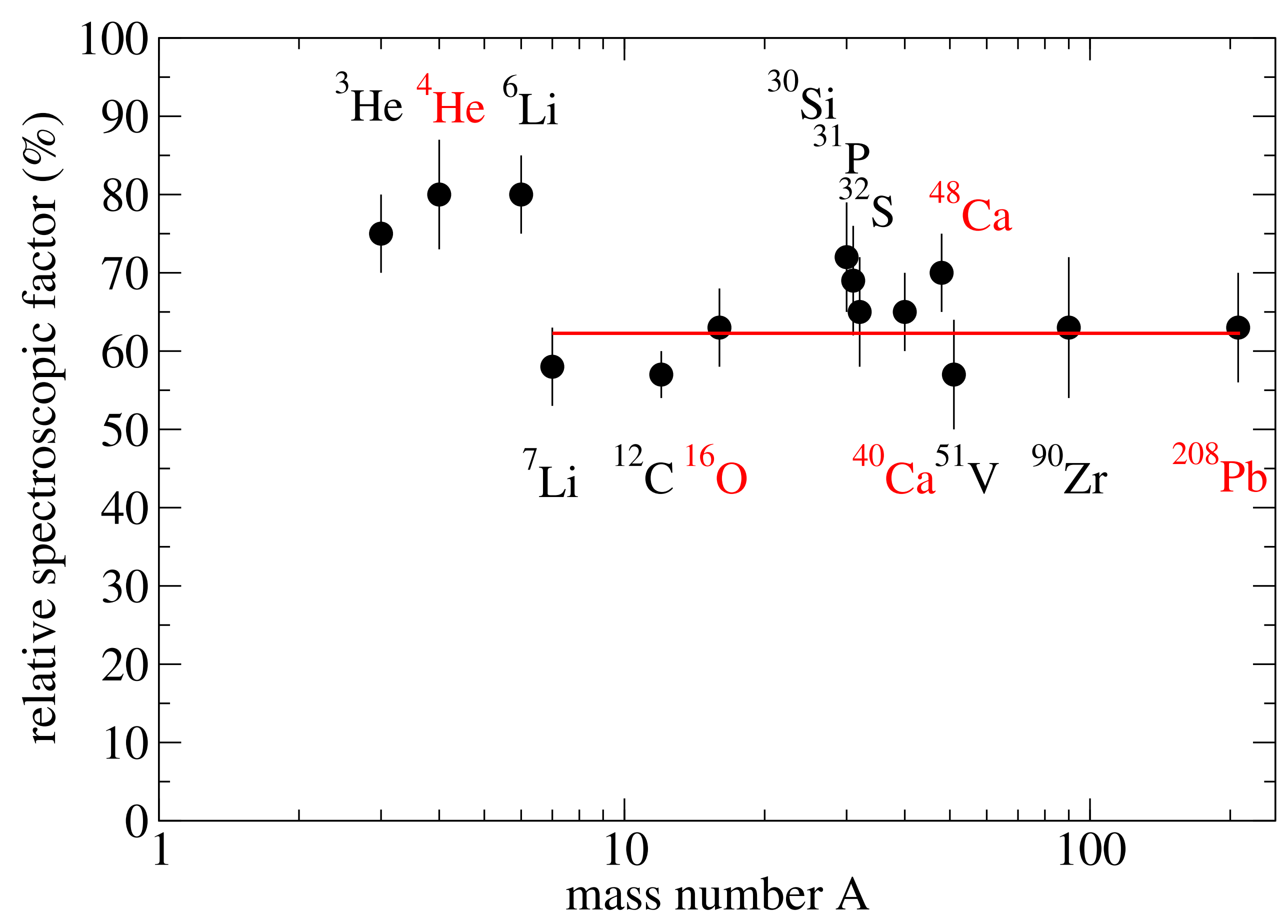


Central density is saturated – nucleons can be packed only so close together:

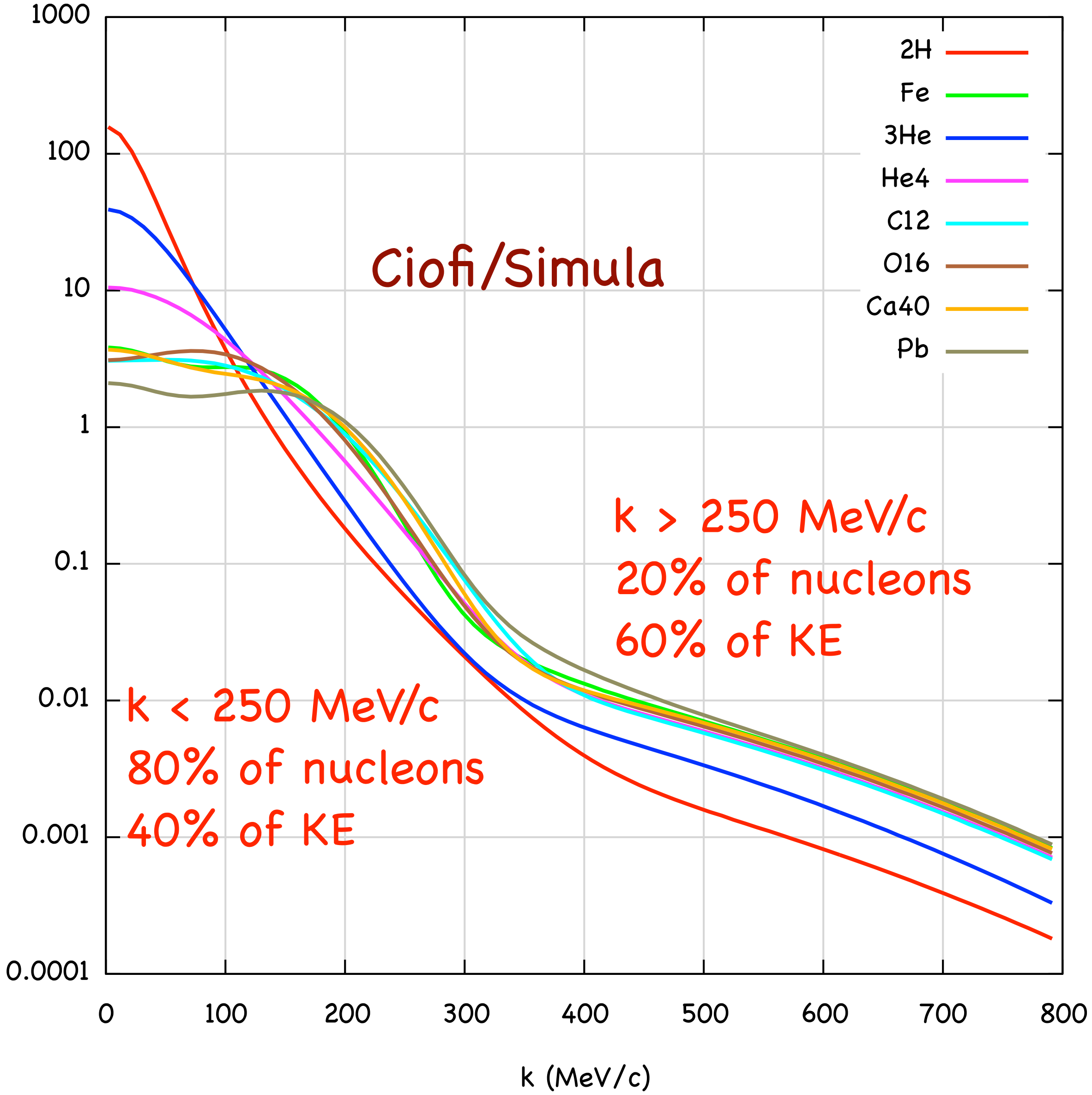
$\rho_{ch} * (A/Z) = \text{constant}$

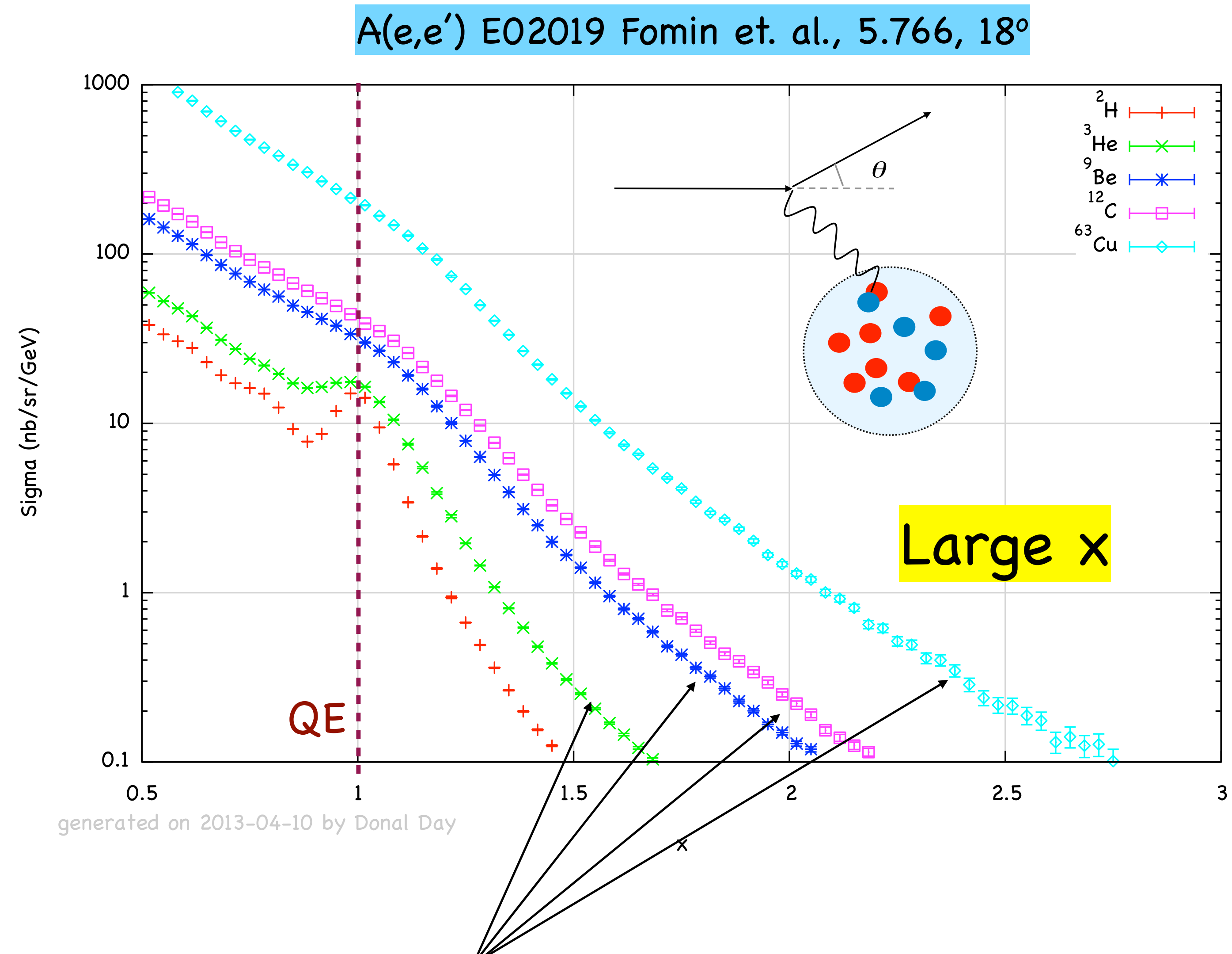
Occupation numbers scaled down by a factor ~0.65.





Momentum distributions and cross sections





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

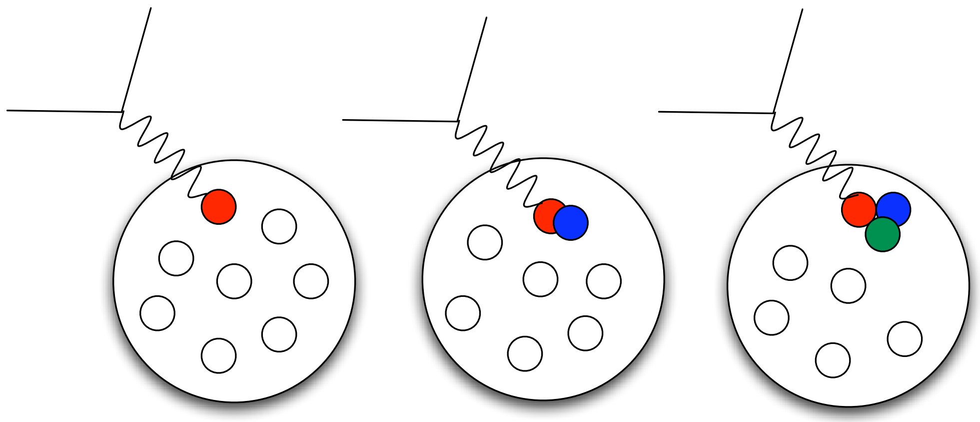
n(k) is A dependent at $k < k_f$ yet has a universal shape at large k, reflecting the details of the NN interaction. The cross sections mirror this universal behavior at x > 1.5.

CS Ratios and SRC

In the region where correlations should dominate, large x,

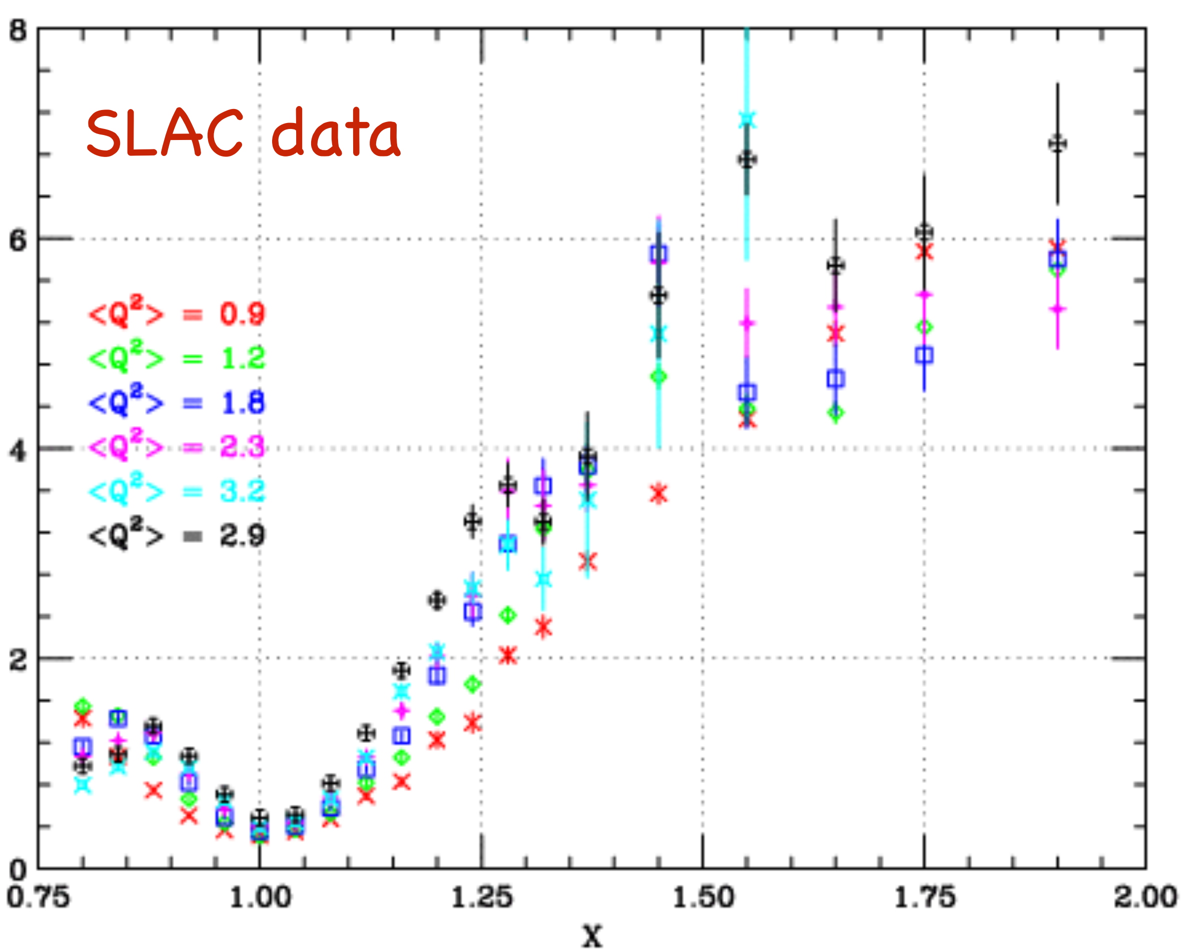
$$\Rightarrow \quad \frac{2}{A}\frac{\sigma_A(x,Q^2)}{\sigma_D(x,Q^2)} = a_2(A)\Big|_{1<x\leq 2}$$

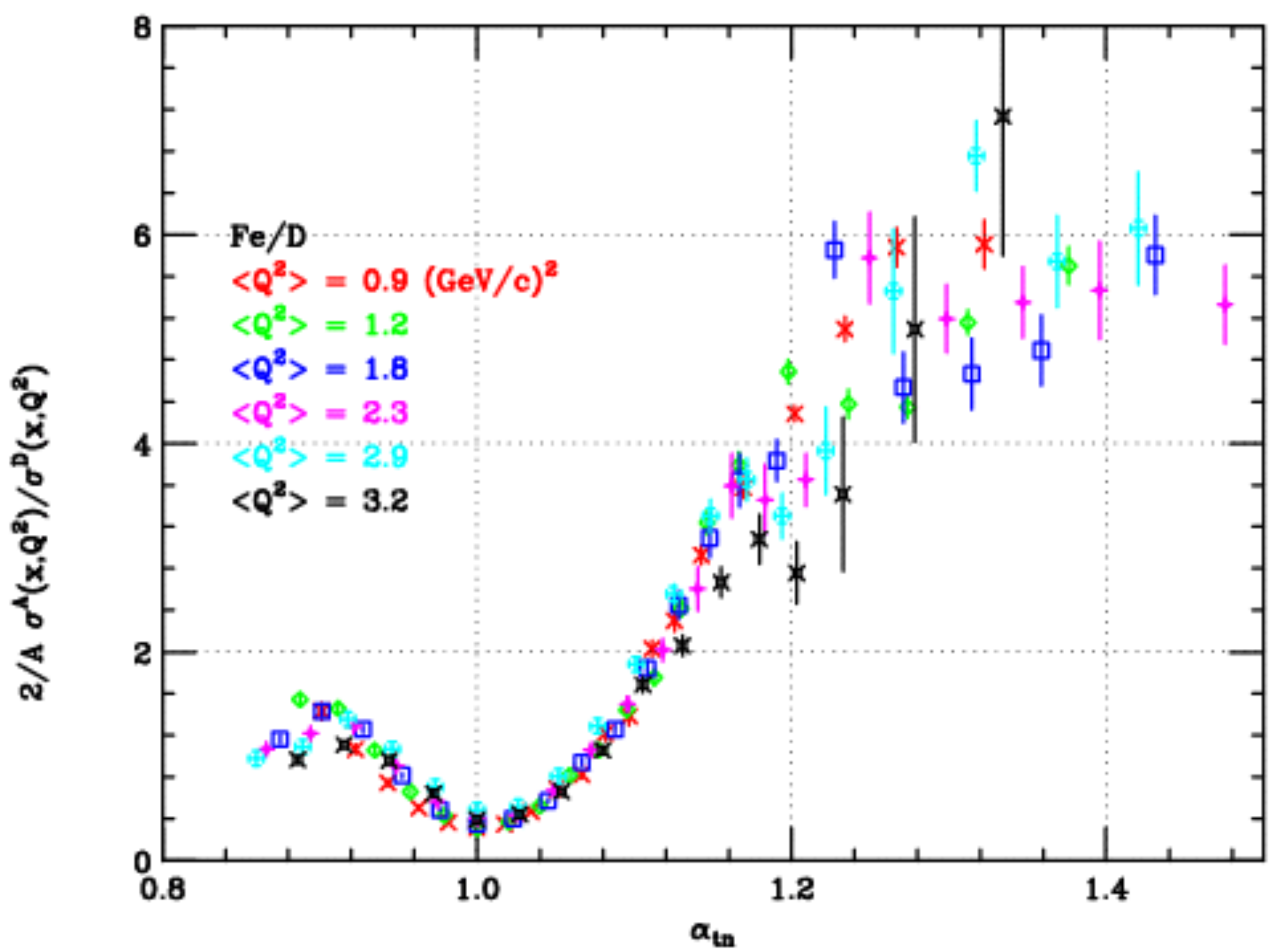
$$\frac{3}{A}\frac{\sigma_A(x,Q^2)}{\sigma_{A=3}(x,Q^2)} = a_3(A)\Big|_{2<x\leq 3}$$



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

$$\alpha_{tn} = 2 - \frac{q_- + 2m}{2m}\left(1 + \frac{\sqrt{W^2 - 4m^2}}{W}\right)$$





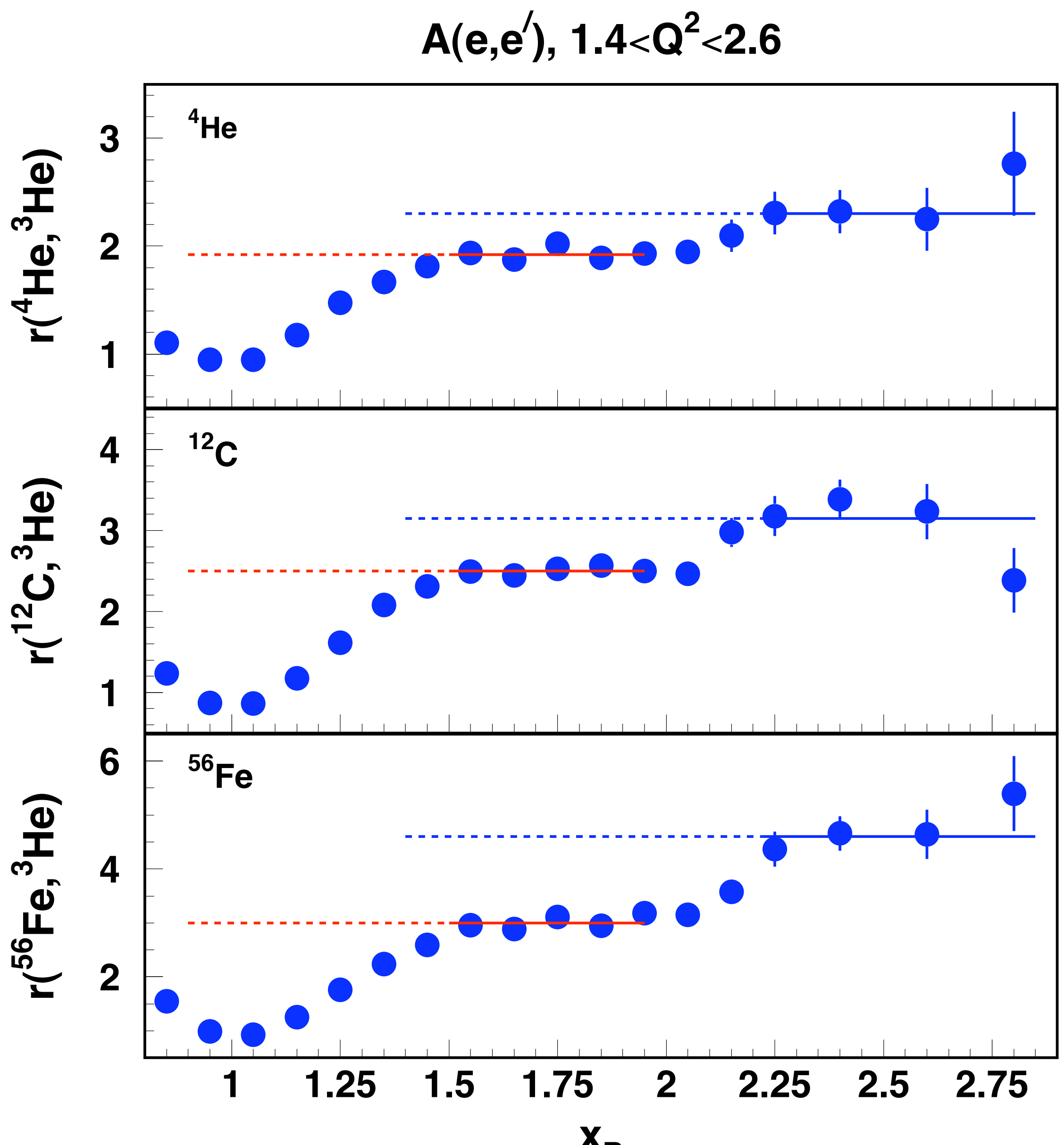
FSDS, Phys.Rev.C48:2451-2461,1993

CS Ratios from Jlab

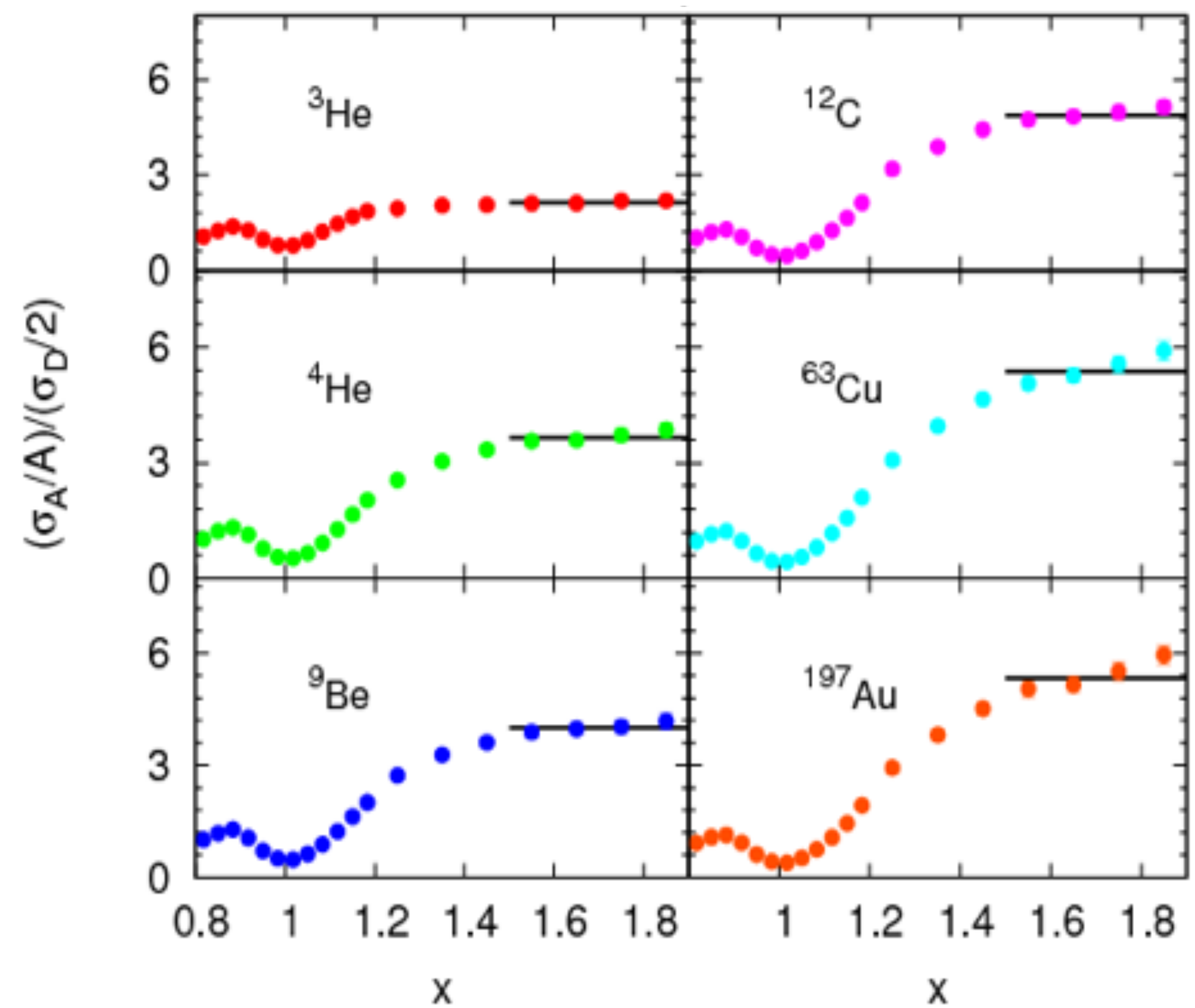
N. Fomin,et al., PRL 108 (2012) 092052

Simple SRC Model:

- 2N, 3N dominate at x ≤ 1, 2
- 2N, 3N configurations "at rest"
- Isospin independent



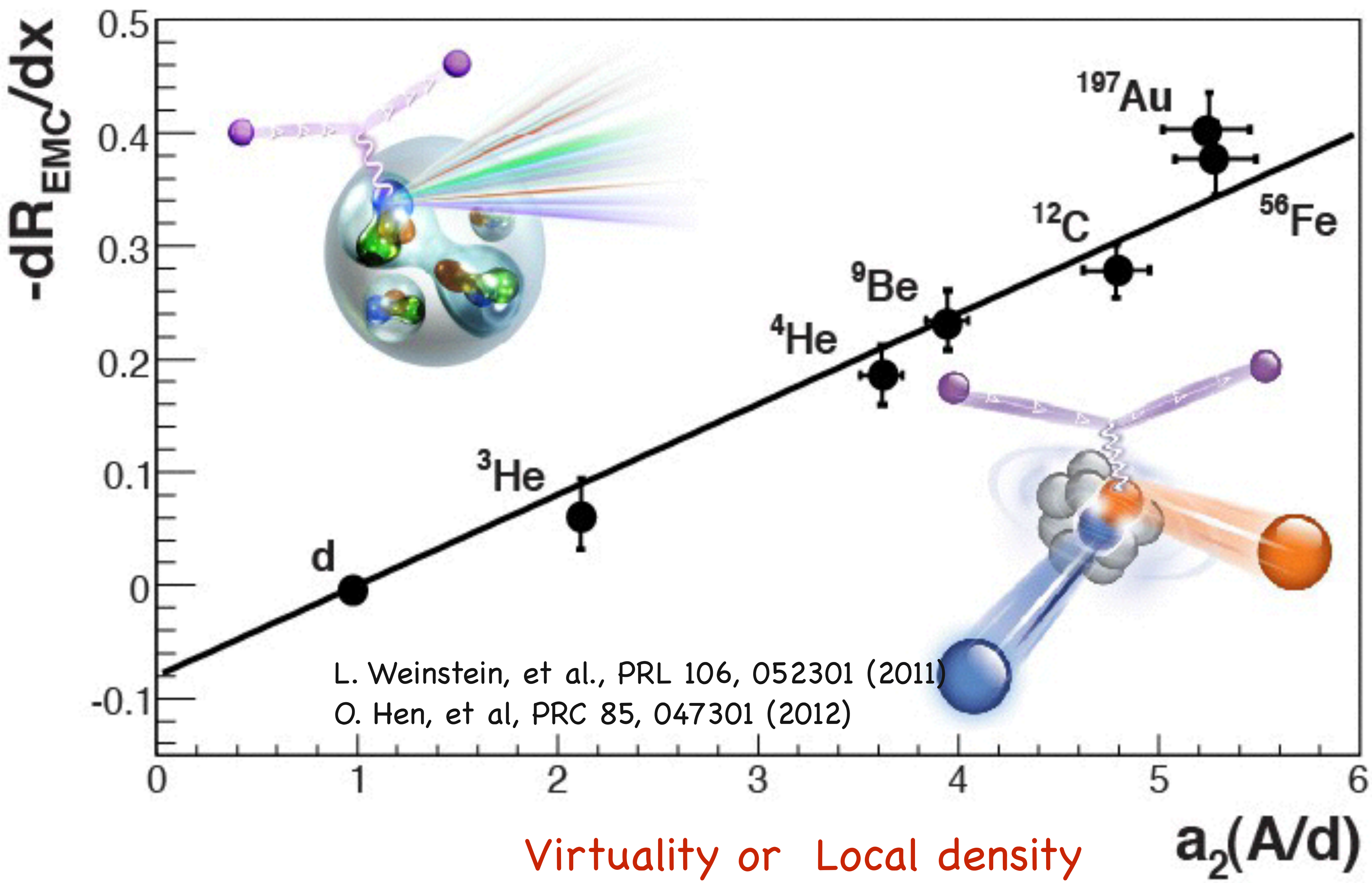
K. Egiyan et al, PRL96, 082501 (2006)



Experimental observations:

- Clear evidence for 2N-SRC at x>1.5
- Suggestion of 3N-SRC plateau(?)
- Isospin dependence ?

Connection between SRCs and EMC effect: Importance of two-body correlations?



Virtuality or Local density

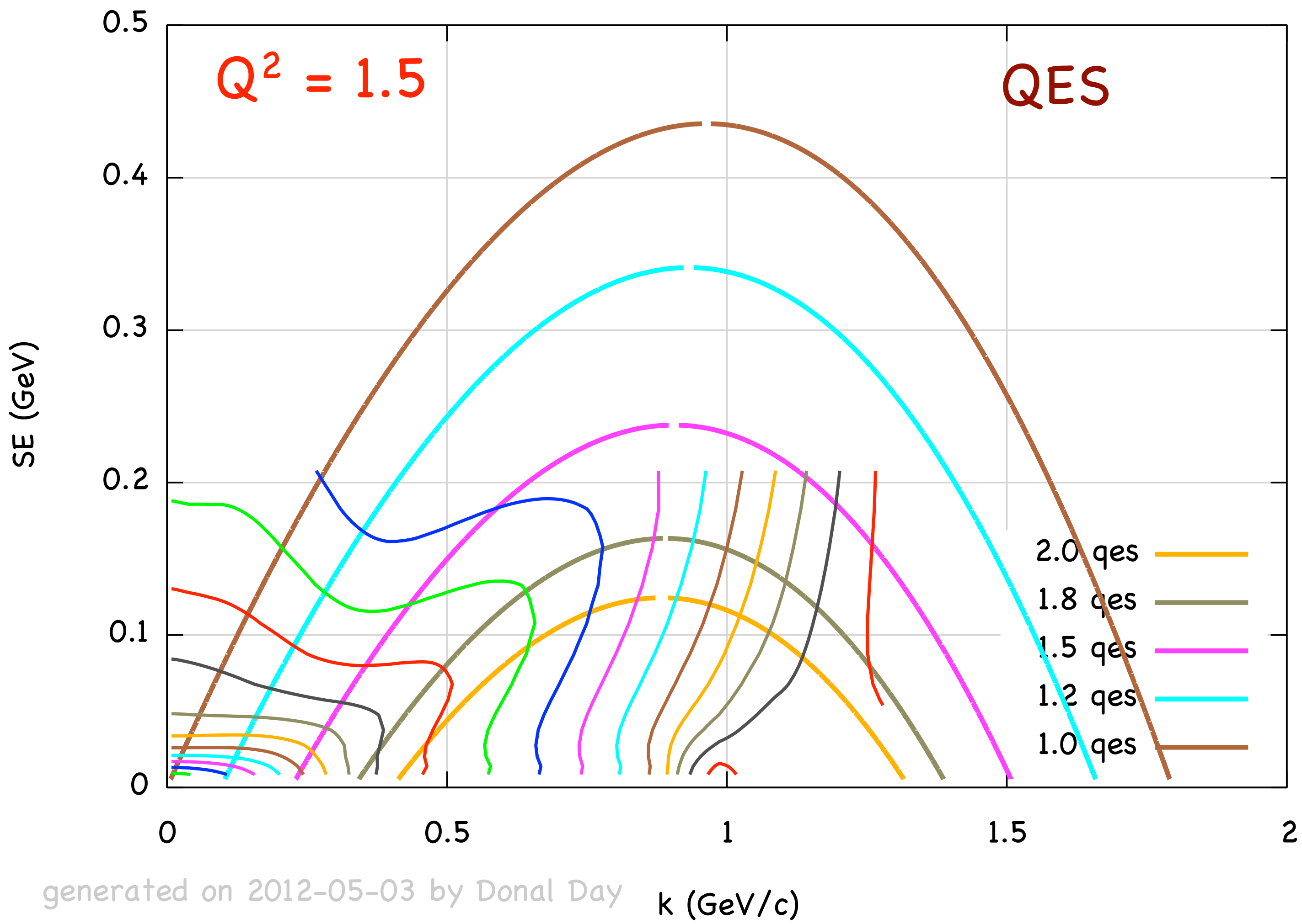
J. Seely, et al., PRL103, 202301 (2009)

N. Fomin, et al., PRL 108, 092052 (2012)

J. Arrington, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86 (2012) 065204

Many body calculations connecting SRC and EMC are lacking

Integration limits over spectral function

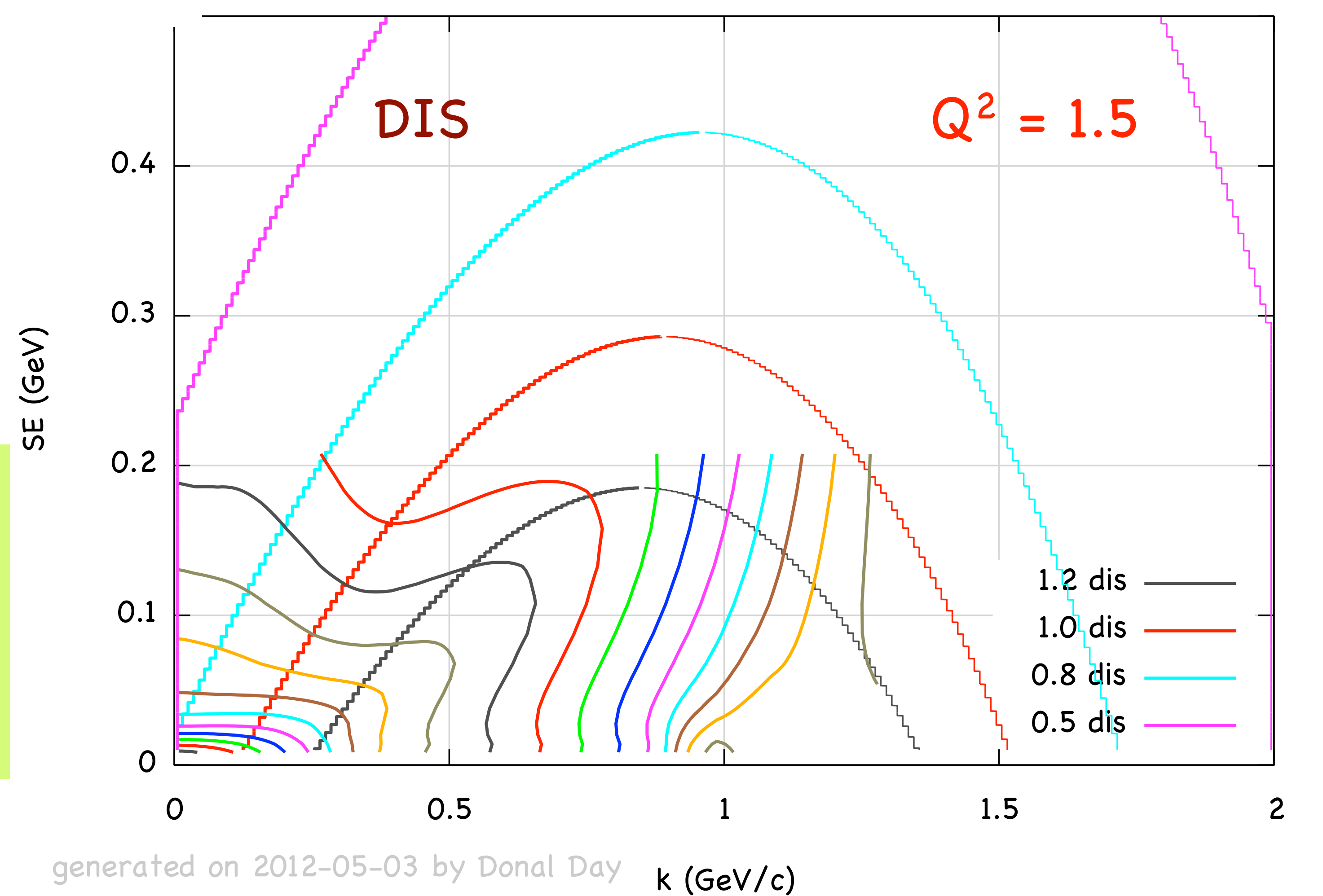


The limits on the integrals are determined by the kinematics. Specific (x, Q^2) select specific pieces of the spectral function.

$$\frac{d^2\sigma}{d\Omega d\nu} \propto \int d\vec{k} \int dE \sigma_{ei} \underbrace{S_i(k,E)}_{\text{Spectral function}} \delta()$$

$$\frac{d^2\sigma}{d\Omega d\nu} \propto \int d\vec{k} \int dE\, W_{1,2}^{(p,n)} \underbrace{S_i(k,E)}_{\text{Spectral function}}$$

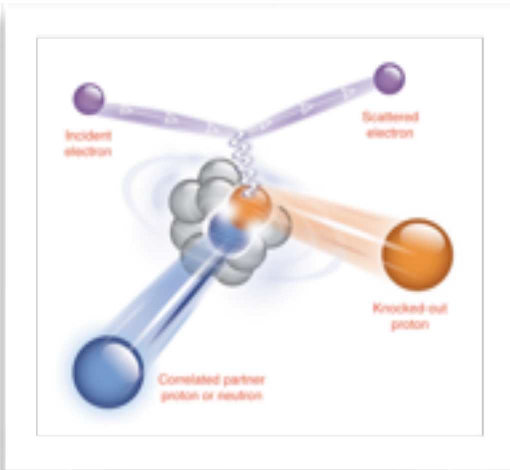
Given the fact that EMC and SRC integrate over very different parts of the spectral function needs close examination

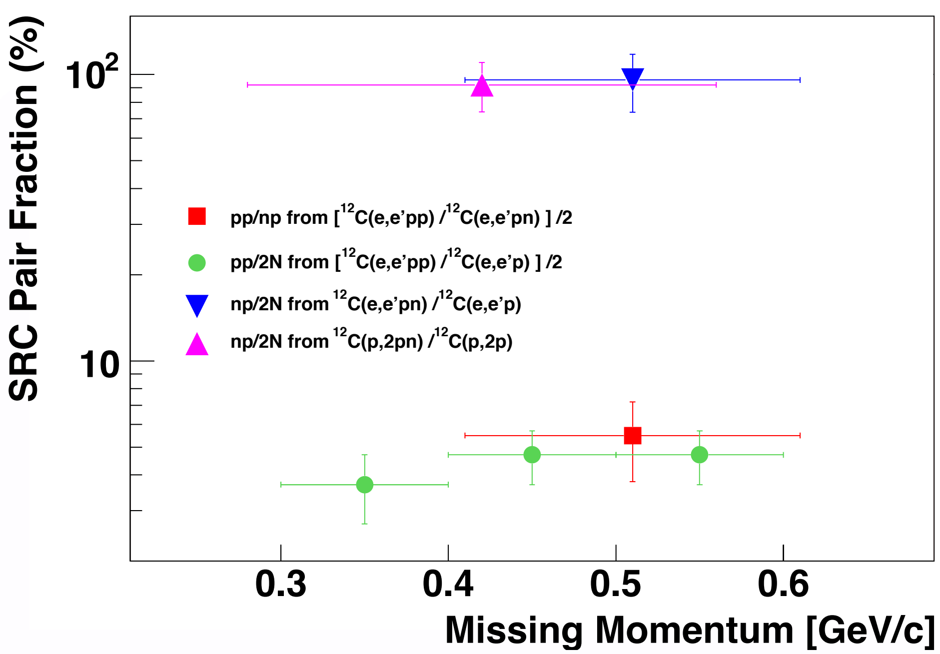


Theory and experiment display isospin dependence

Two-nucleon knock-out experiment

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





PRL 98, 132501 (2007) PHYSICAL REVIEW LETTERS week ending 30 MARCH 2007

Tensor Forces and the Ground-State Structure of Nuclei

R. Schiavilla,[1,2] R. B. Wiringa,[3] Steven C. Pieper,[3] and J. Carlson[4]

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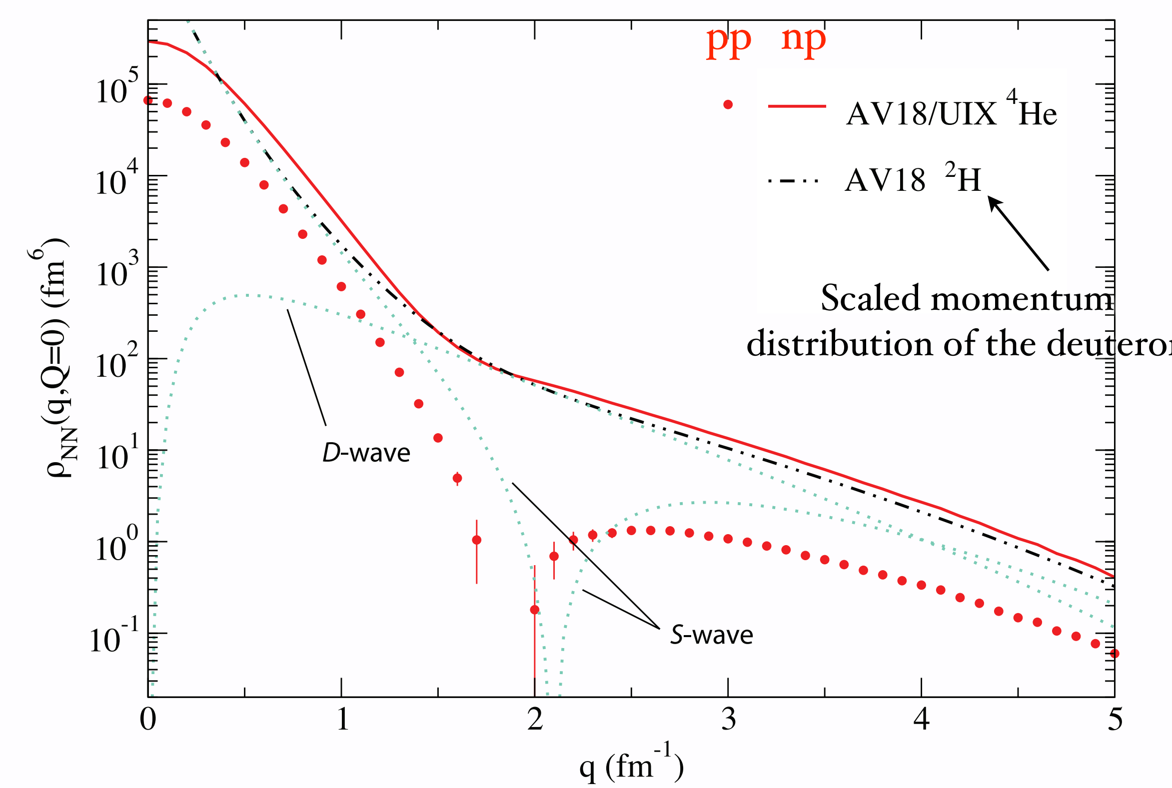
(Received 10 November 2006; published 27 March 2007)



Data show large asymmetry between np, pp pairs:

Qualitative agreement with calculations; effect of tensor force. Huge violation of often assumed isospin symmetry

Isospin structure of 2N-SRCs in inclusive scattering

Patricia Solvignon

E12-11-112: x>1 measurements of correlations

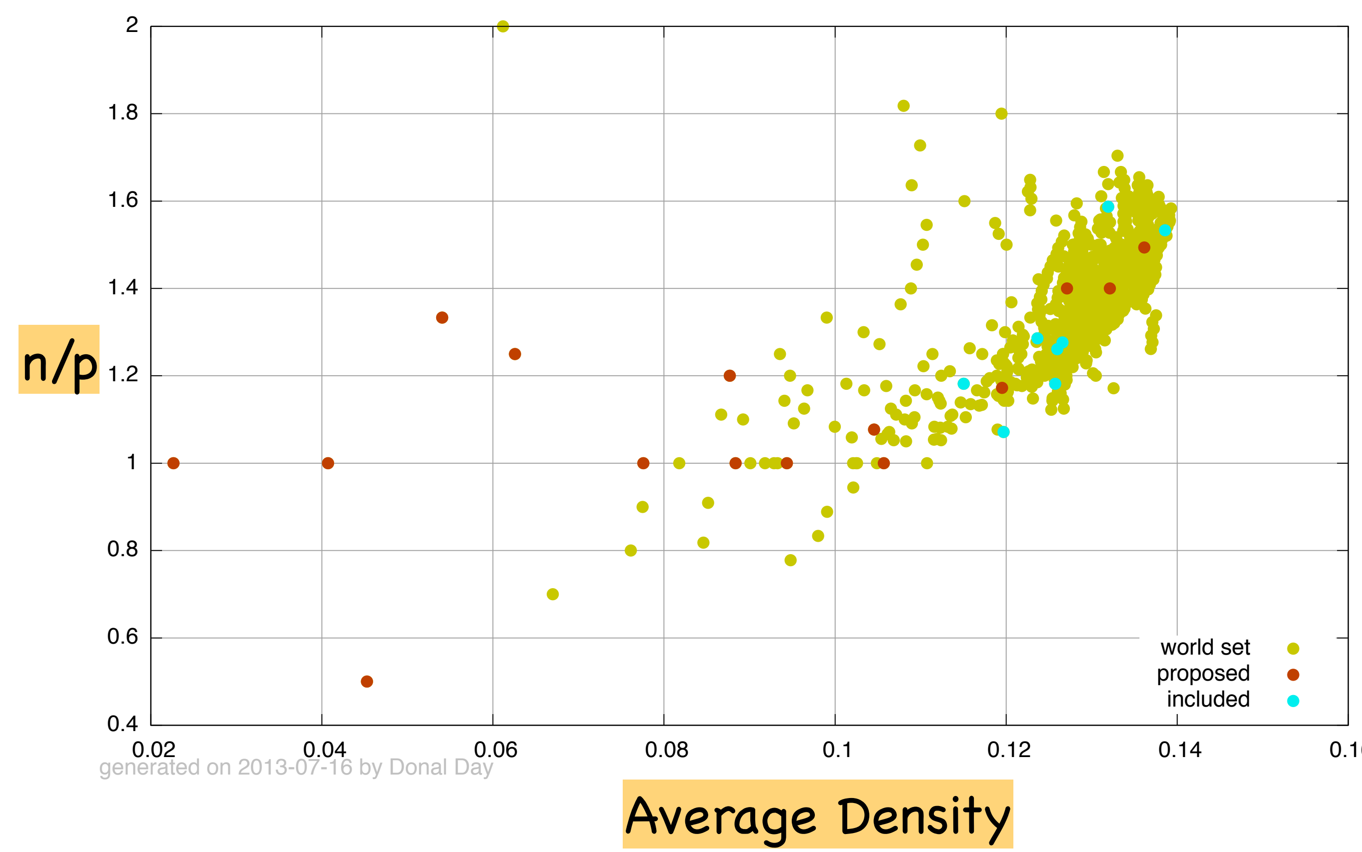
^{3}He/^{3}H is simple/straightforward case:

- 40% difference between full isosinglet dominance and isospin independence in 3He/3H ratio in 2N-SRC region
- Few body calculations [M. Sargisan, Wiringa/Peiper (GFMC)] predict n-p dominance, with sizeable contribution from T=1 pairs
- Goal is to measure ratio 1.5% precision
  - Extract R(T=1/T=0) with uncertainty of 3.8%

To also be addressed in E12-06-105

Other targets

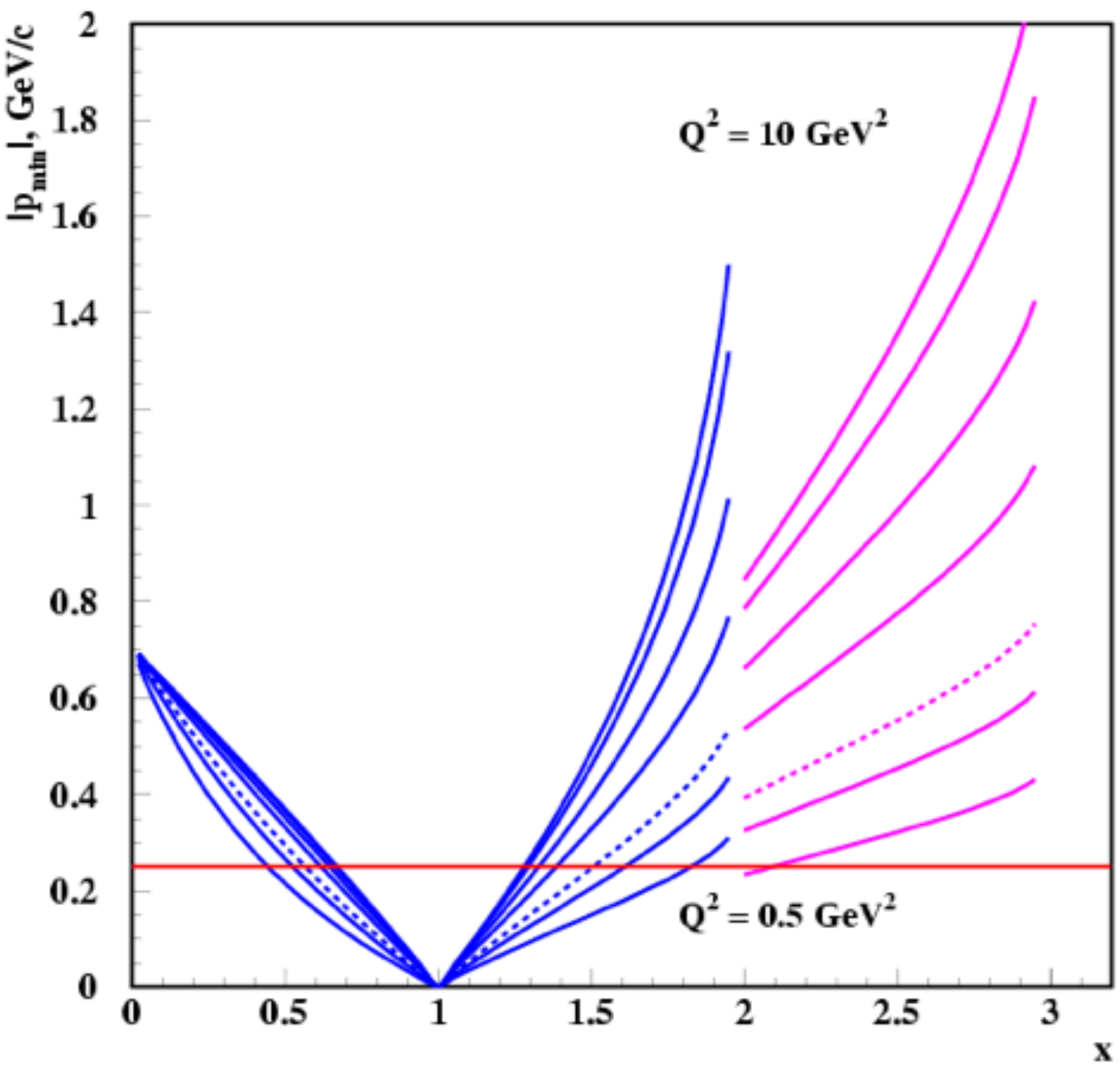
Seek out ranges of n/p ratios for isospin dependence studies



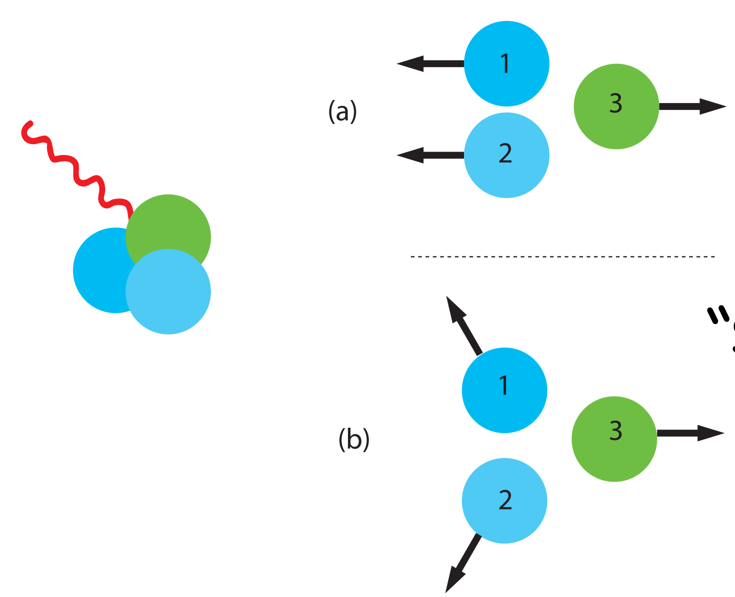
3N Correlations

2N SRC (3N SRC)

- $p >\ k_F$ i.e. its momentum exceeds characteristic nuclear Fermi momentum, ($k_F \gtrsim$ 250 MeV/c)
- balanced by the momentum of a (two) correlated nucleon(s)
- In both cases the center of mass momentum of the SRC, $p_{cm} < k_F$



Onset of scaling for 2<x<3 at which p_{miss} ?



extremely large momentum

$p_3 = p_1 + p_2$

"Star-configuration"

$p_1 = p_2 = p_3$

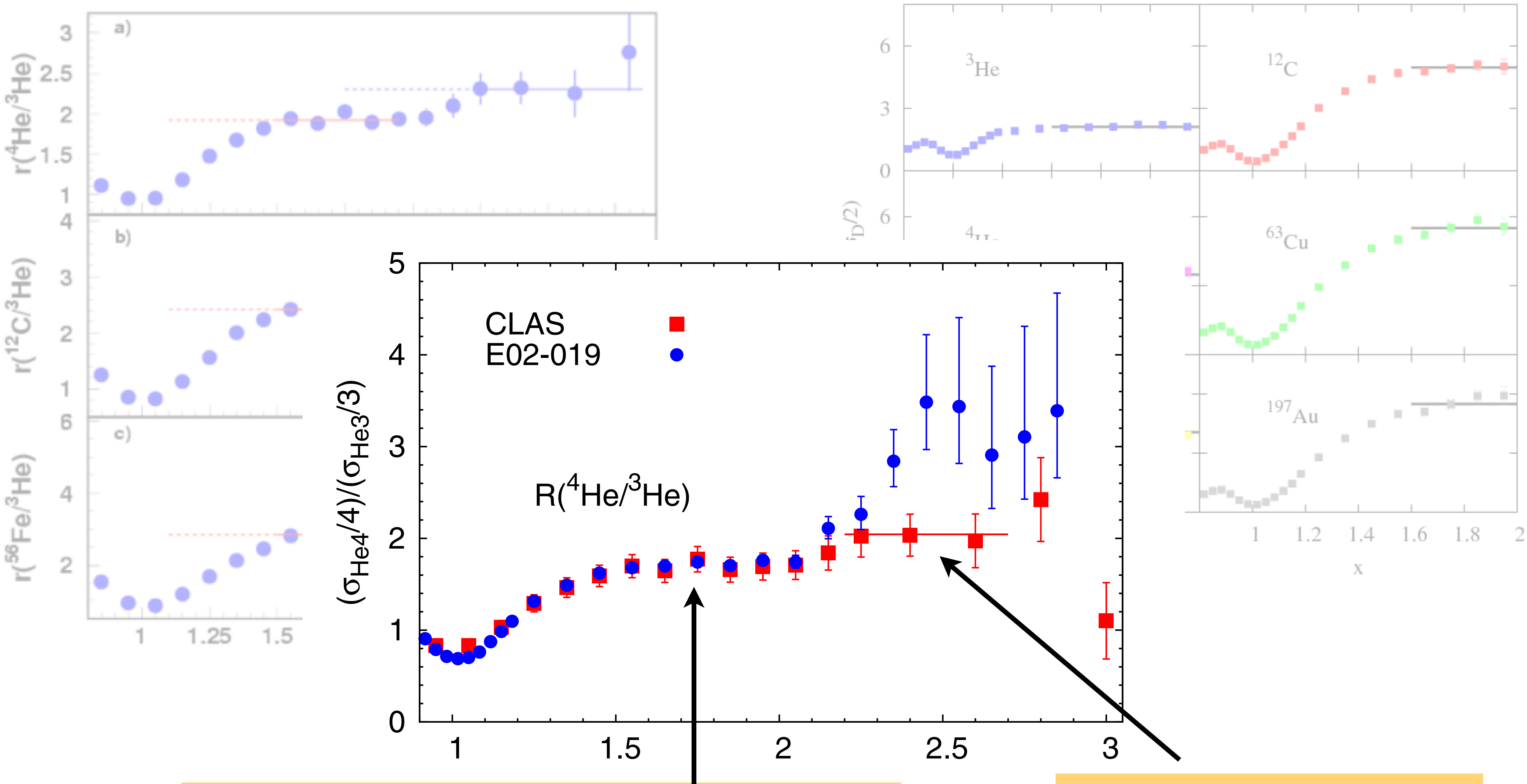
A(e,e’) cross section ratios and SRC

Hall B

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

Hall C

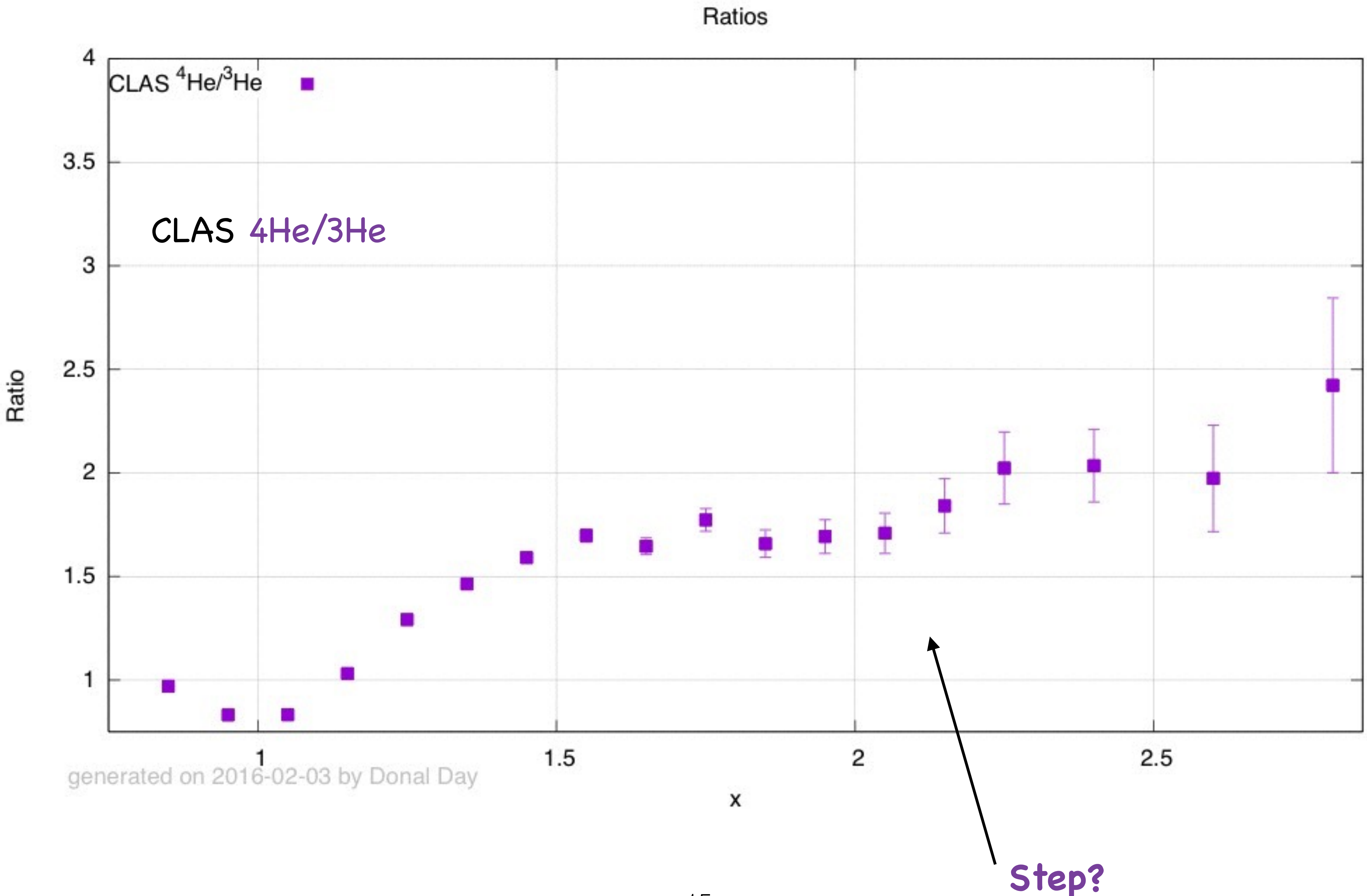
N. Fomin et al., Phys. Rev. Lett. 108, 092502 (2012)



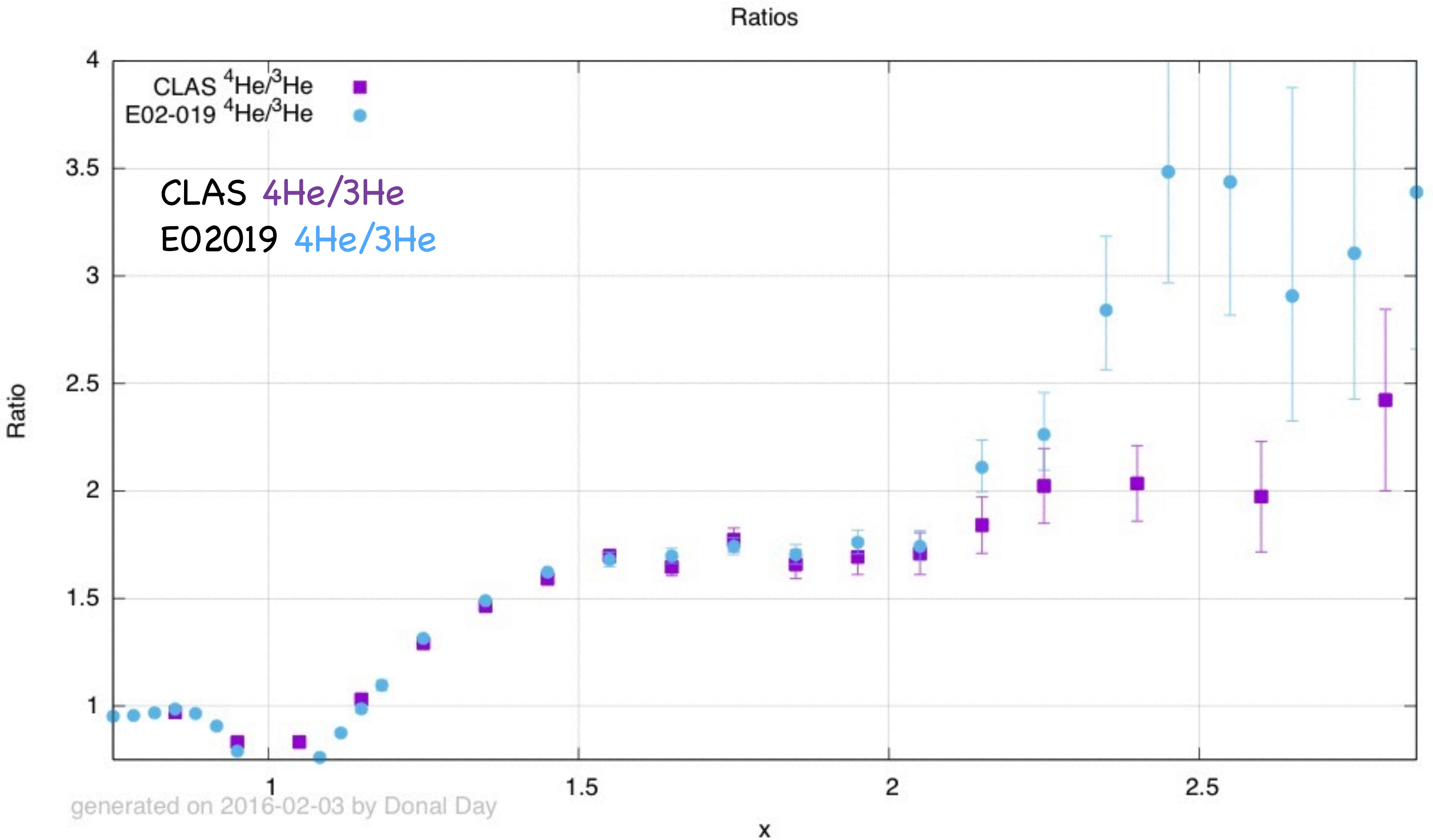
Good agreement in the 2N-SRC region

but potential difference in the 3N-SRC region

A(e,e') cross section ratios and SRC

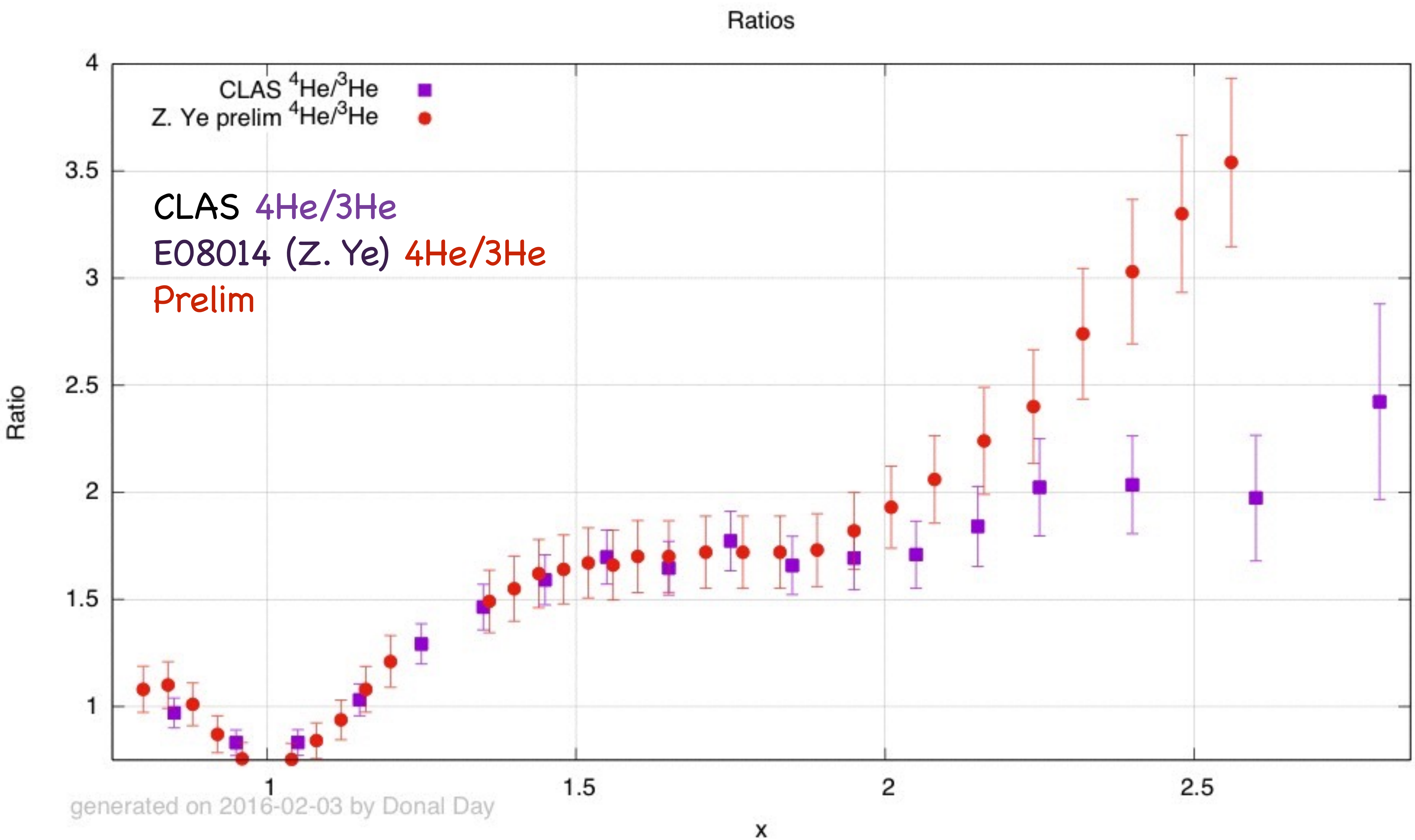


A(e,e') cross section ratios and SRC

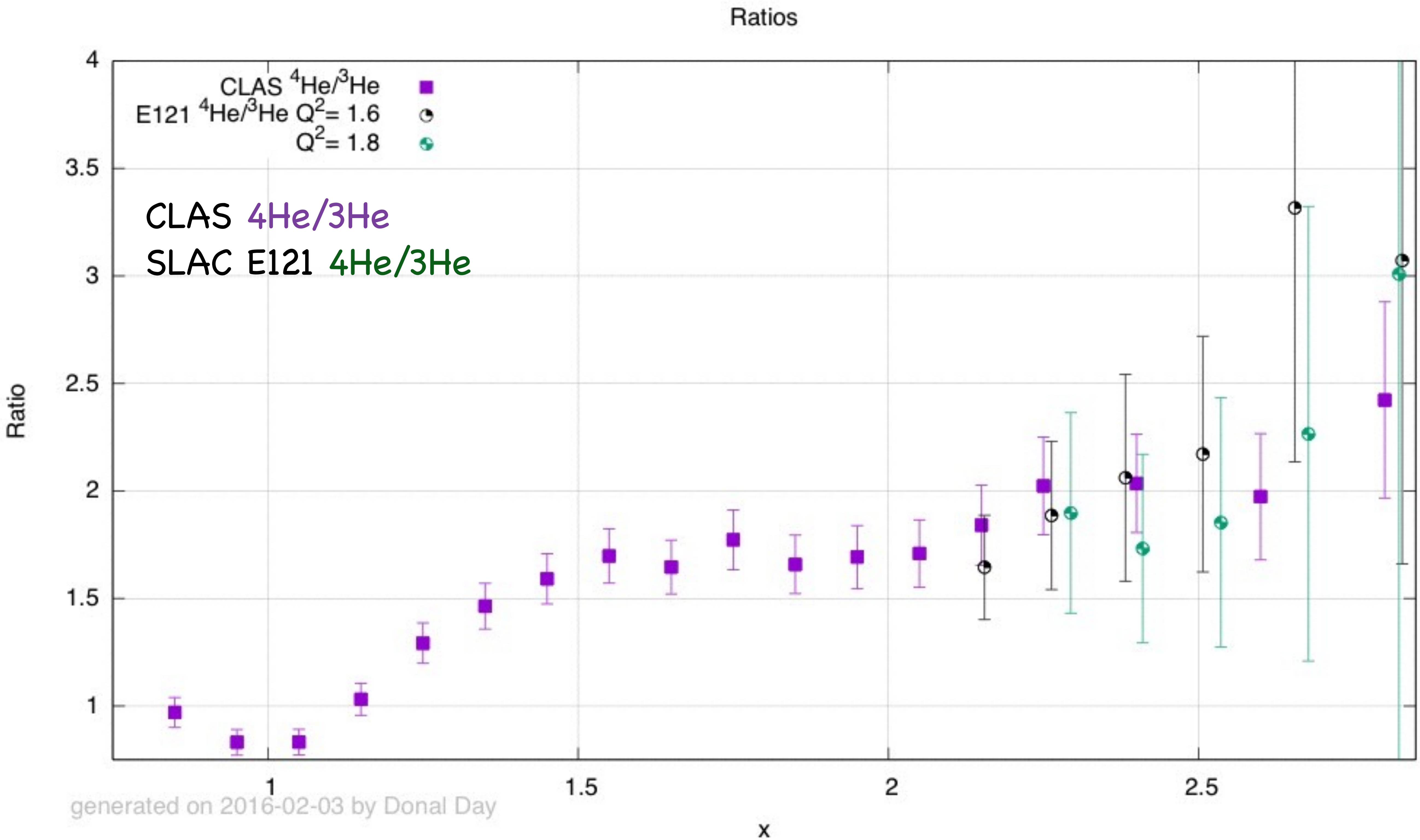


O. Hen and D. Higinbotham, bin drift

A(e,e') cross section ratios and SRC

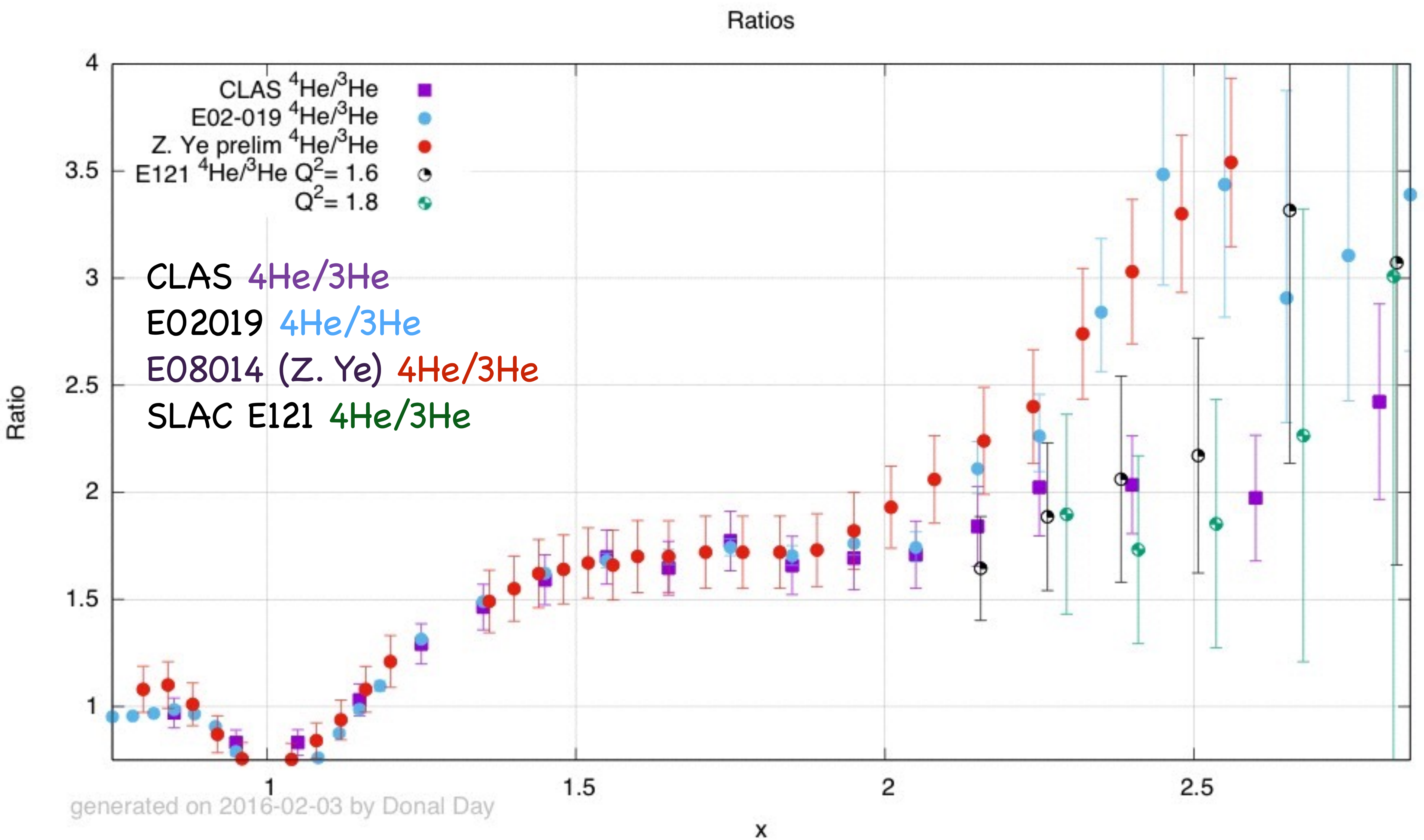


A(e,e') cross section ratios and SRC



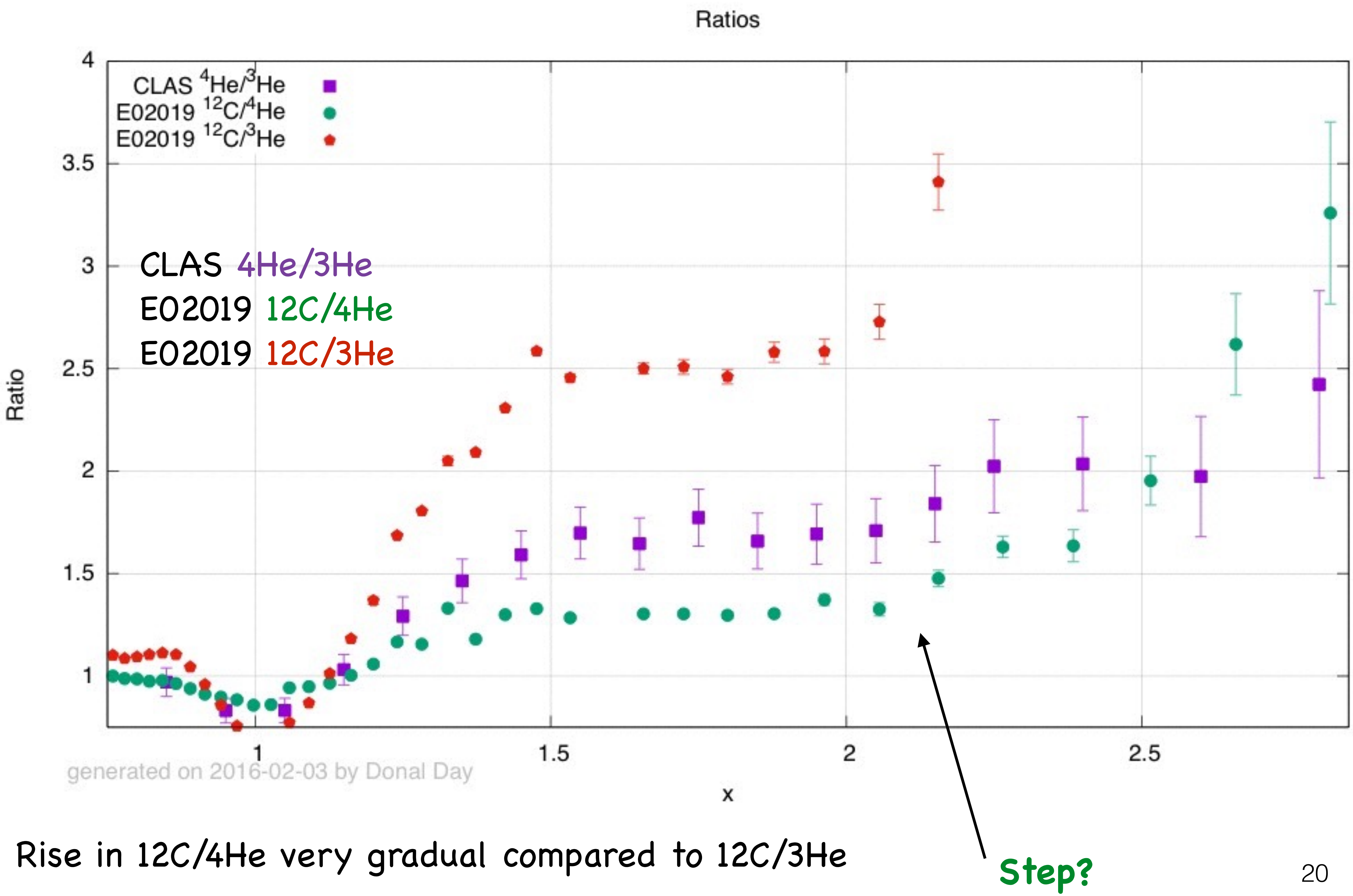
Rock et al, PRC 26, 1593 (1982)

A(e,e') cross section ratios and SRC



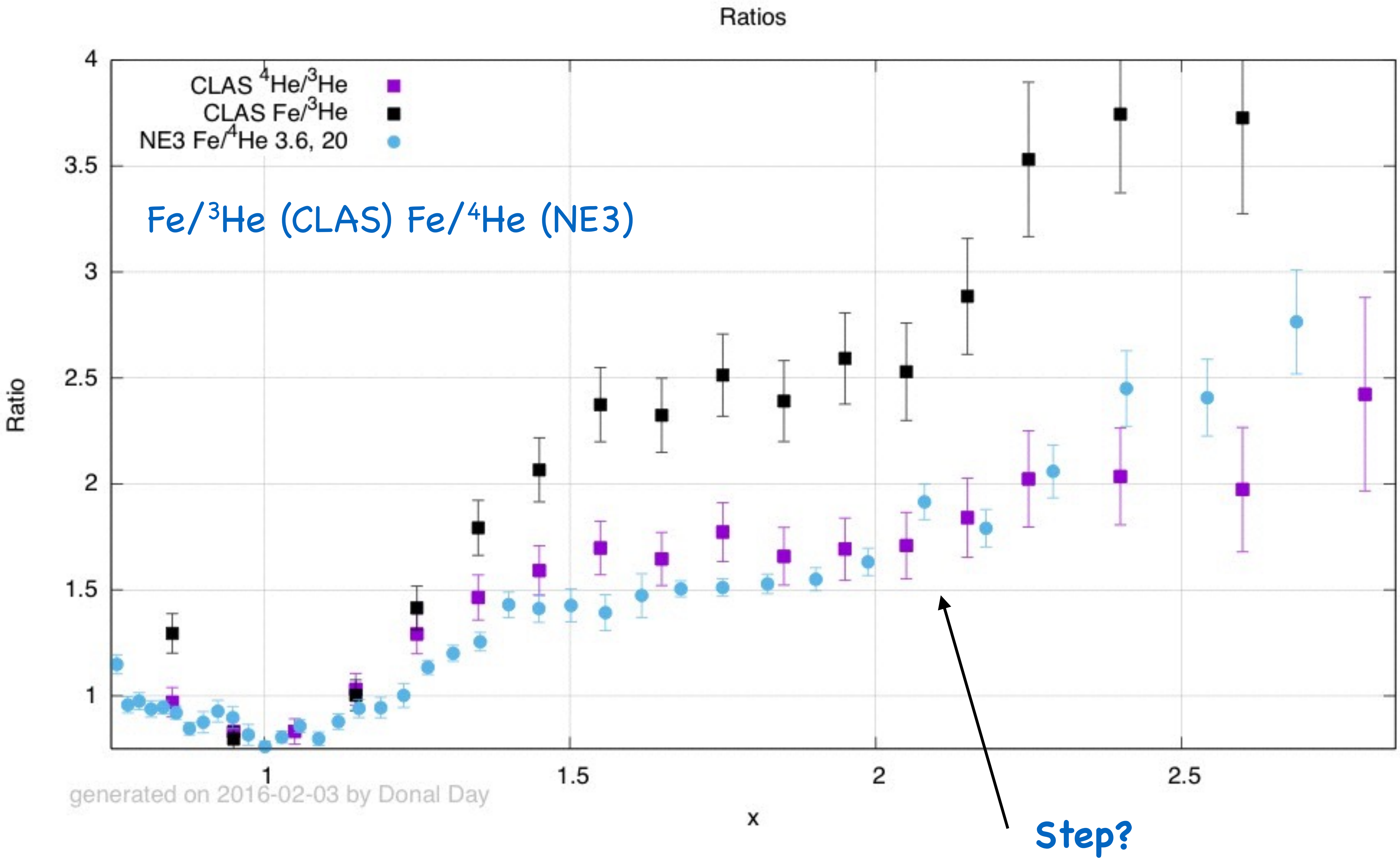
Cross section model shows a rapid falloff of the 3He cross section starting near x approaching 2.5.

A(e,e') cross section ratios and SRC

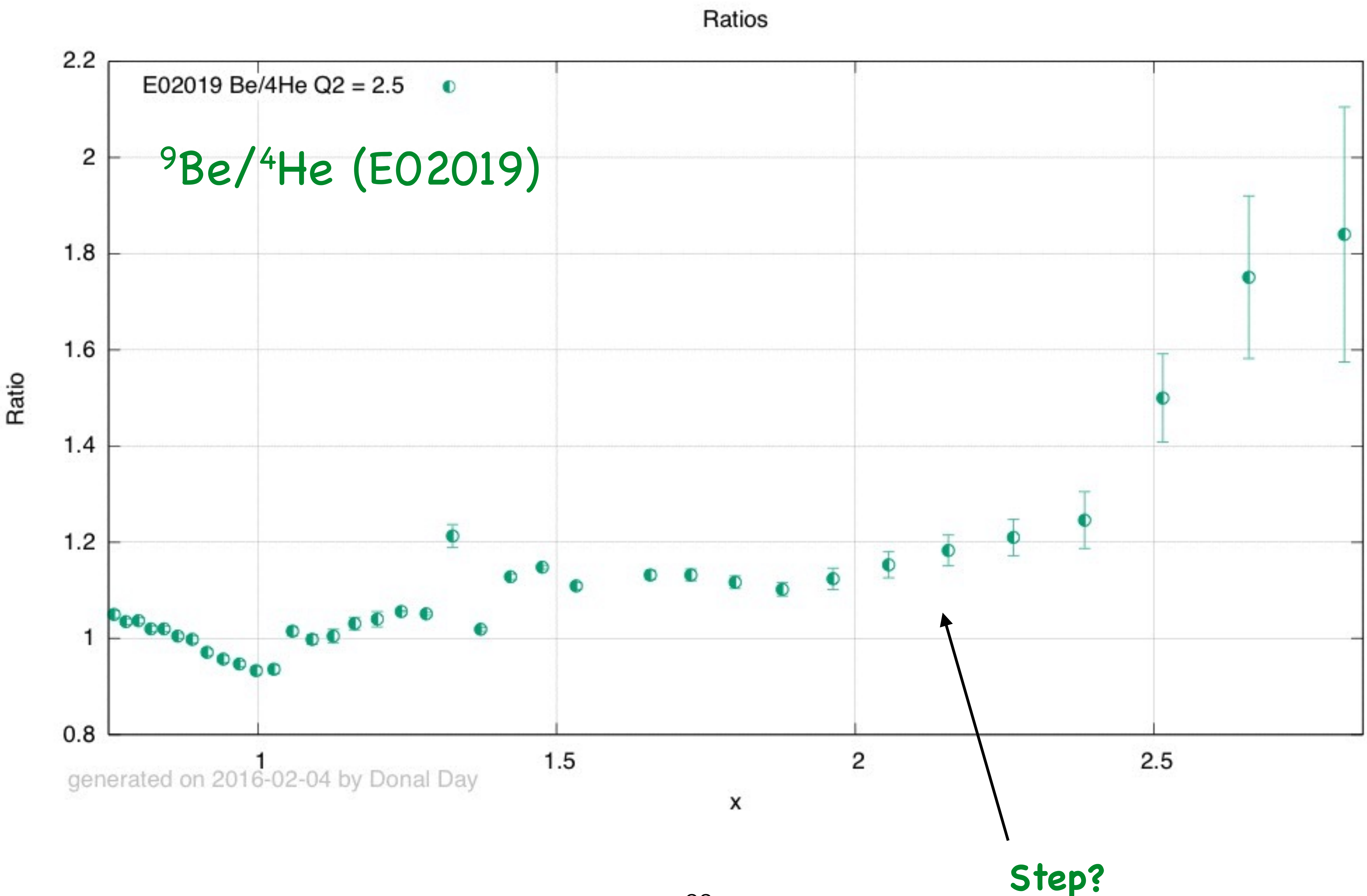


Rise in 12C/4He very gradual compared to 12C/3He

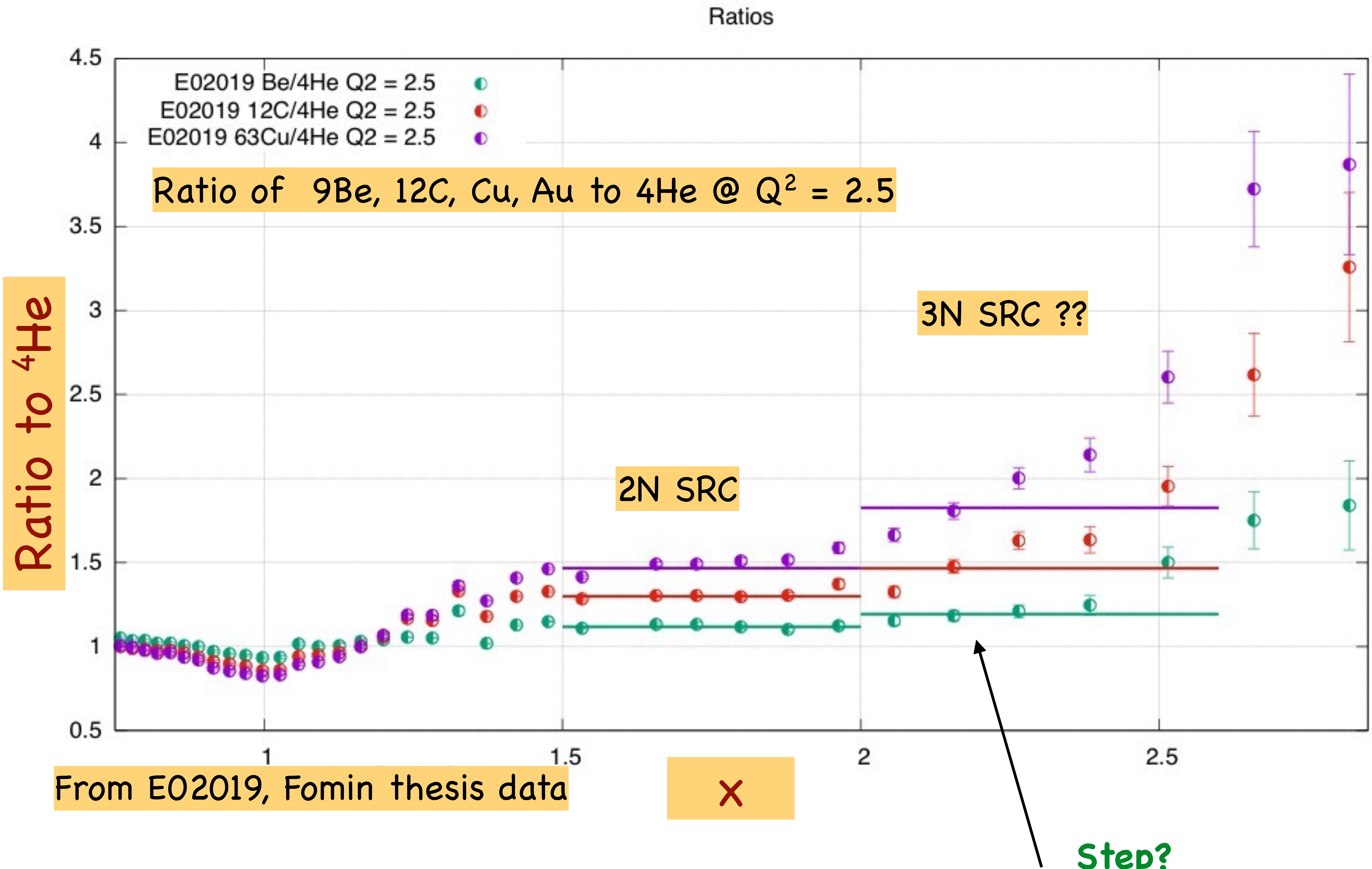
A(e,e′) cross section ratios and SRC



A(e,e′) cross section ratios and SRC

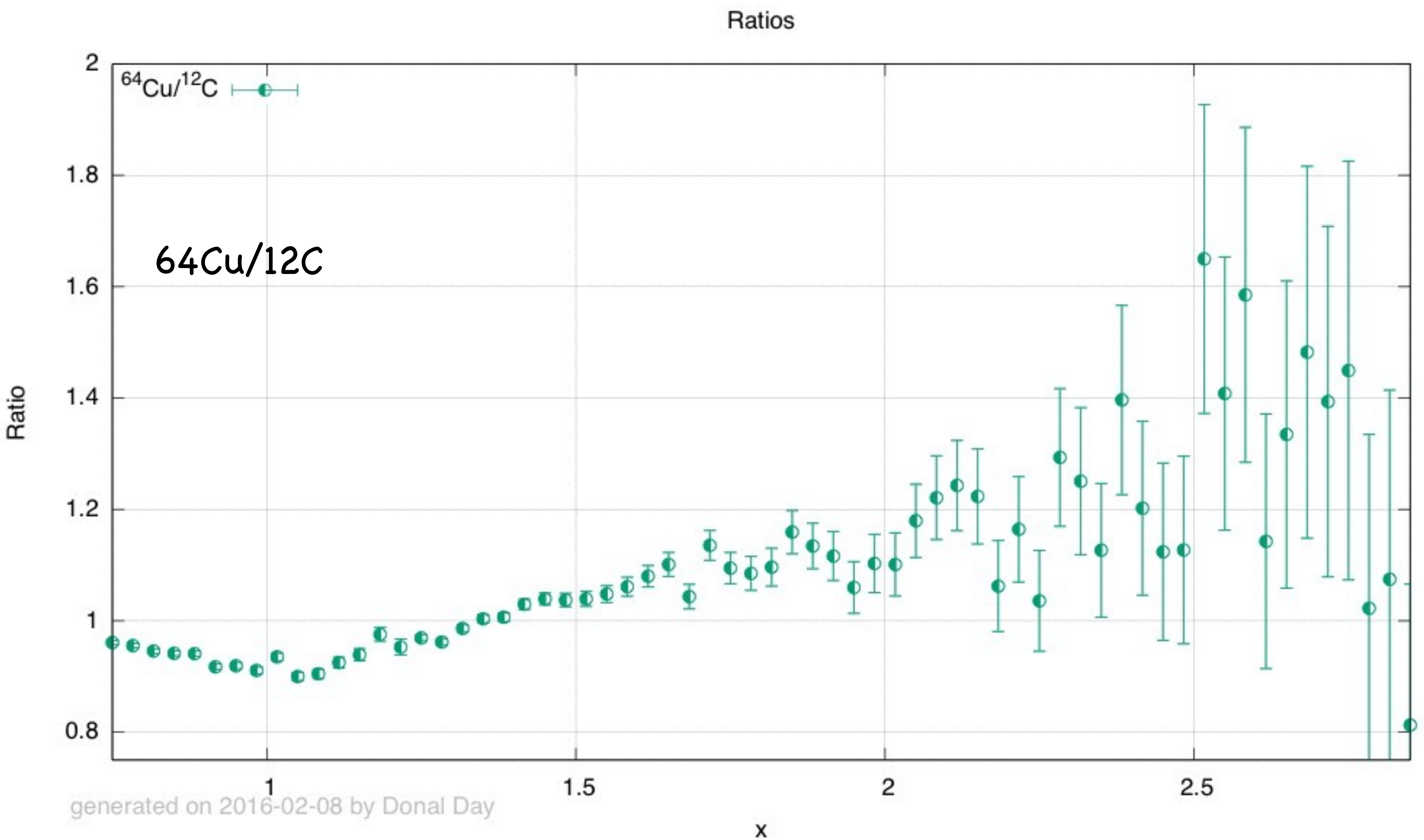


A(e,e') cross section ratios and SRC

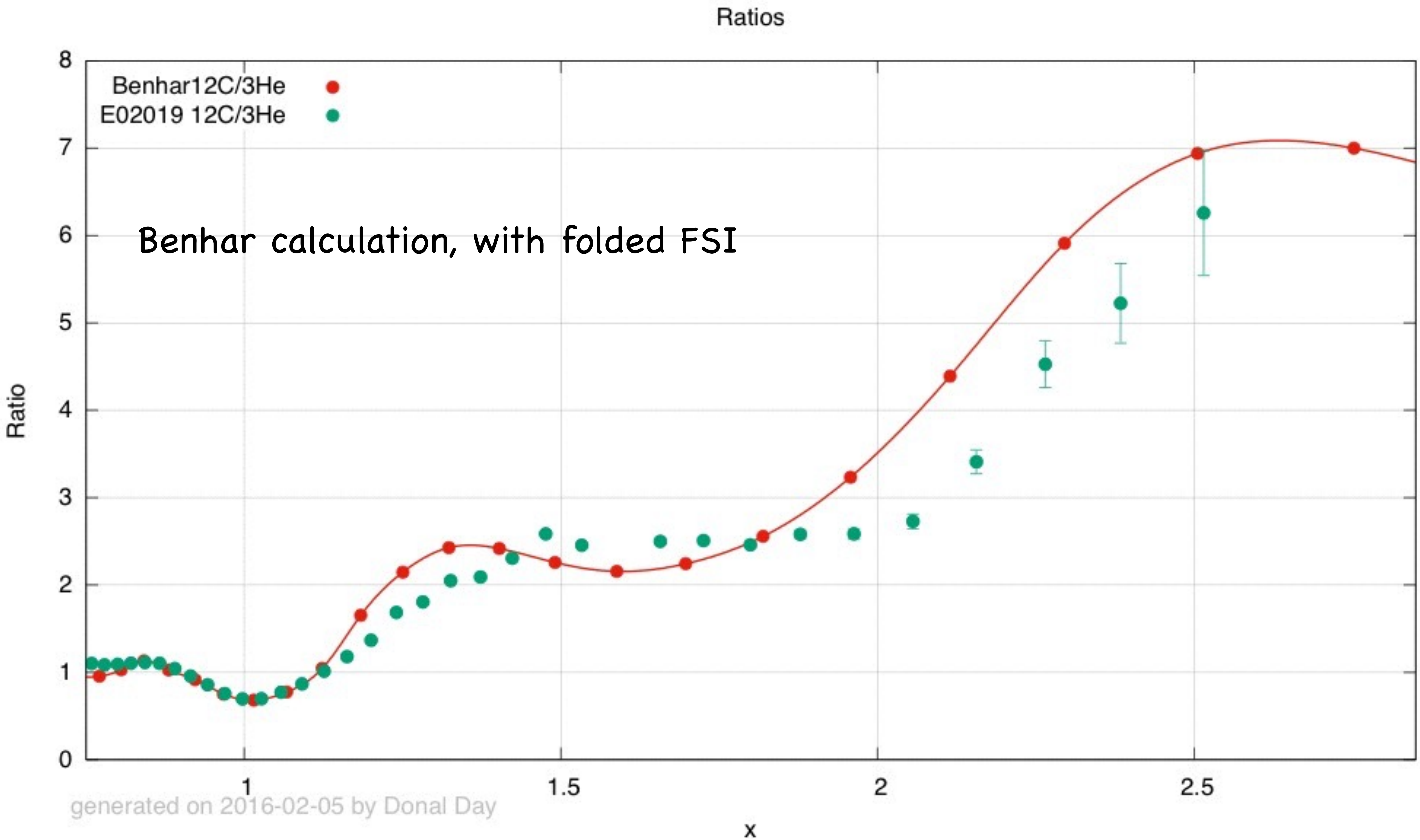


From E02019, Fomin thesis data

A(e,e') cross section ratios and SRC



A(e,e') cross section ratios and SRC



Evidence for 3N correlation in ratios to 3He?

Naive SRC model, where 2N- and 3N-SRCs are at rest, the rise in the ratio as $x \rightarrow 3$ as coming from the difference between stationary 3N-SRC in 3He and moving SRCs in heavier nuclei.

CM motion has to play a role that must be modeled in inclusive

Violation of naive scaling picture, which predicts a plateau

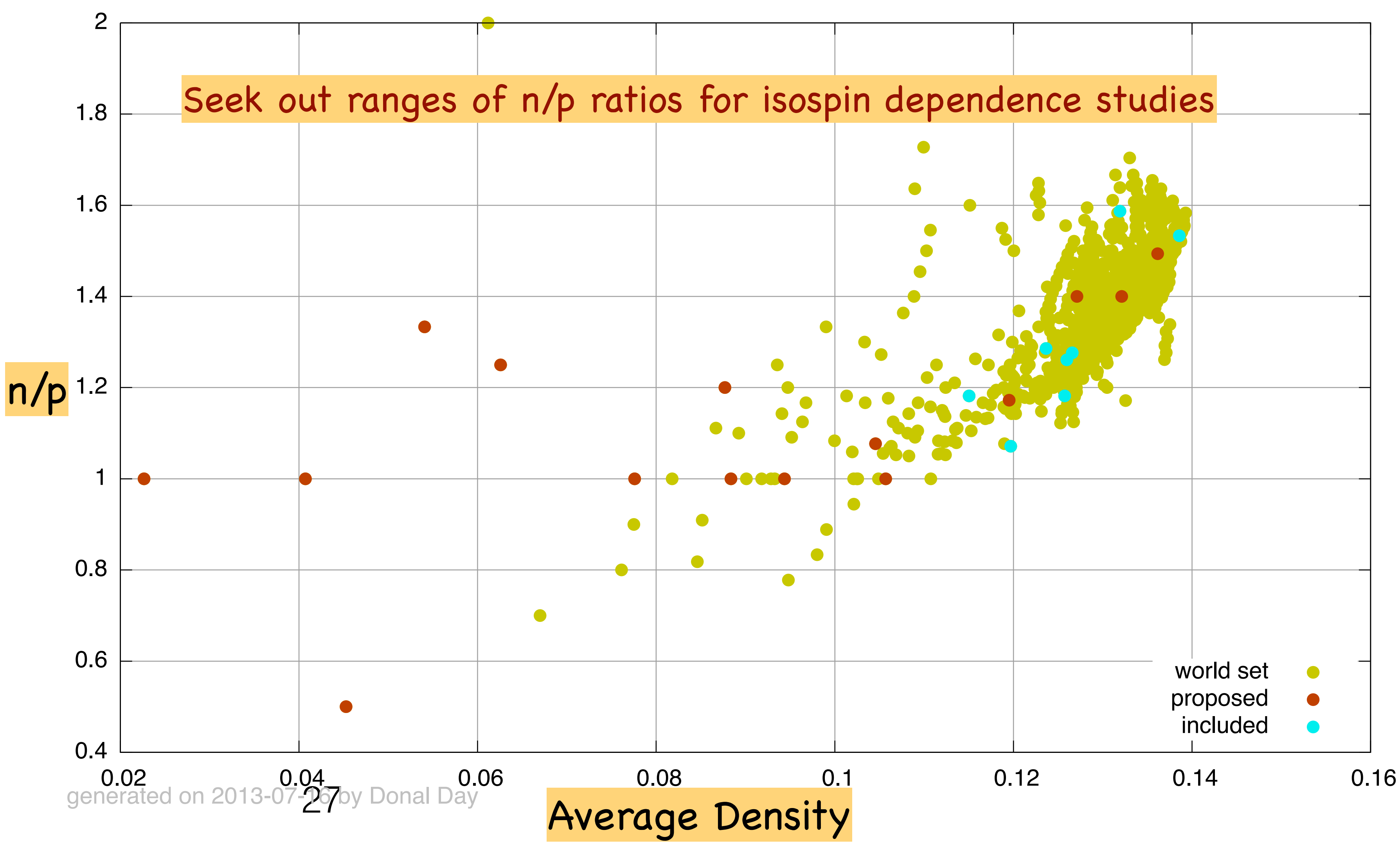
This violation is also seen in ratios to 2H 2N-SRC region.

It different as the motion of the 2N- SRC yields mainly a small enhancement of the plateau, with modest distortion until $x > 1.9$, where the deuteron cross section falls sharply from its exponential falloff with x

For 3N-SRCs, motion of the correlations would yield a sharp rise further from the kinematic limit at $x = 3$ due to the earlier onset of the rapid cross section falloff

Evidence for 3N correlations in ratios to 4He?

Some indication of a step but rise as x grows above is obvious.
What should we expect in magnitude and shape?
CMM is poorly understood and clearly must be
High quality data from medium heavy to light (A = > 4) data



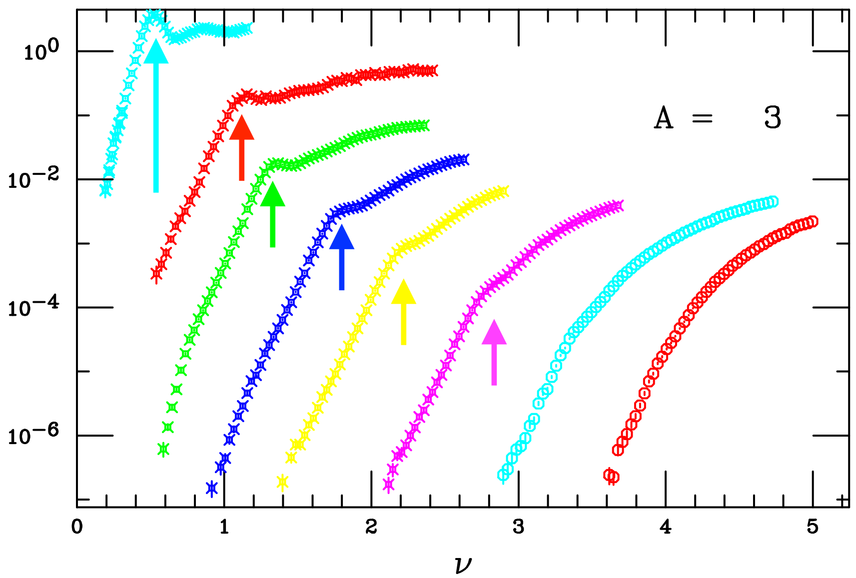
Z	N	Sym	A
26	22	Ti	48
30	28	Ni	58
36	28	Ni	64
52	44	Ru	96
58	46	Pd	104
60	47	Ag	107
146	92	U	238
138	90	Th	228

Beam time is finite,
we have to select
carefully

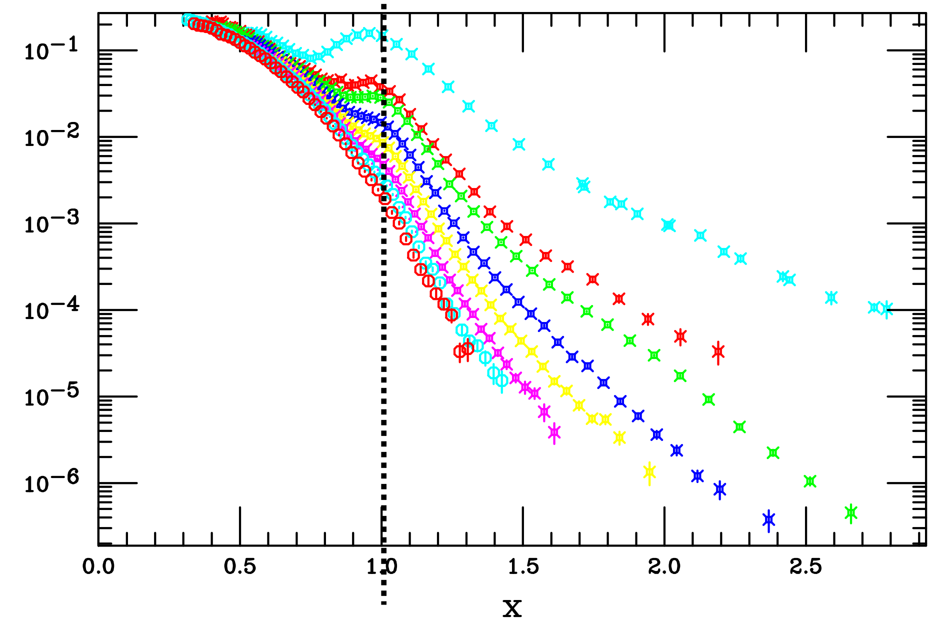
Correlations in DIS at x > 1

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

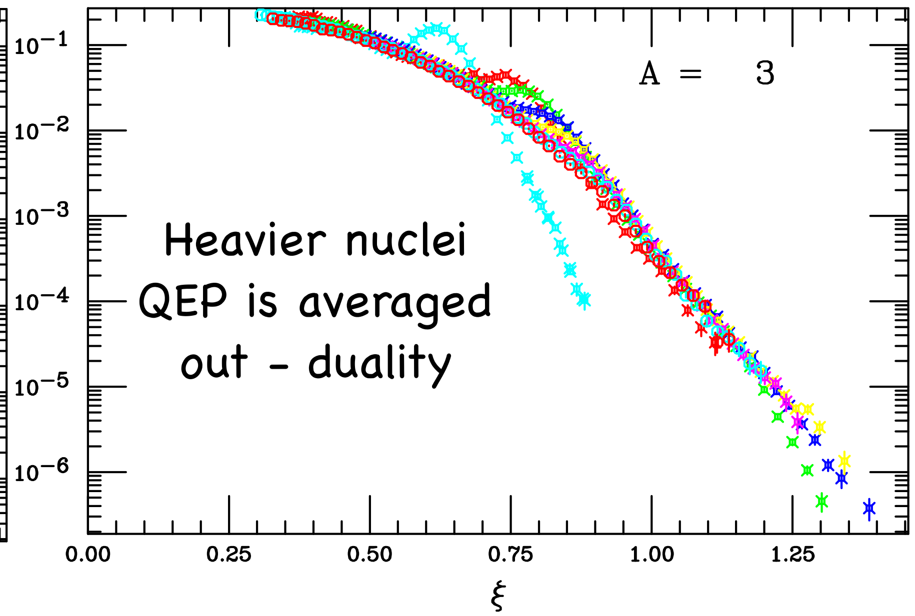
σ vs energy loss



F_2 versus x



F_2 versus ξ



In OPE F_2^0 (not F_2) should be independent Q^2 in absence of QCD evolution and higher twists.

Fomin et. al., Phys.Rev.Lett. 105 (2010) 212502

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

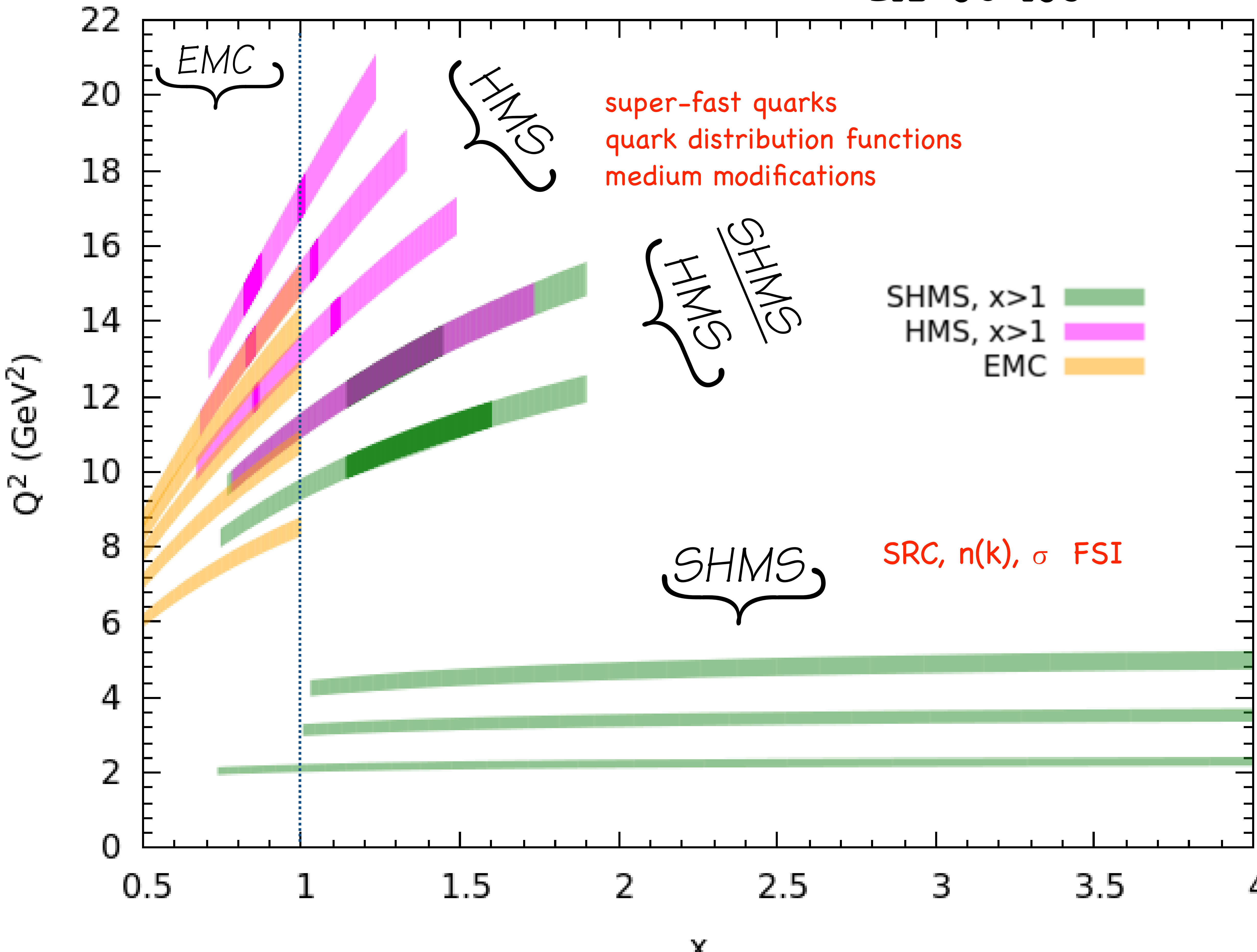
$$+ \quad \frac{6M^2x^3}{Q^2r^4} h_2(\xi,Q^2) + \frac{12M^4x^4}{Q^4r^5} g_2(\xi,Q^2)$$

E12-06-105

SFs 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 SRCs. See slide 10.

Large Q^2, large x additionally sensitive to small admixtures of exotic components - e.g. 5% 6q cluster in D leads to dramatic effect on large x pdfs: Mulders and Thomas

E12-06-105



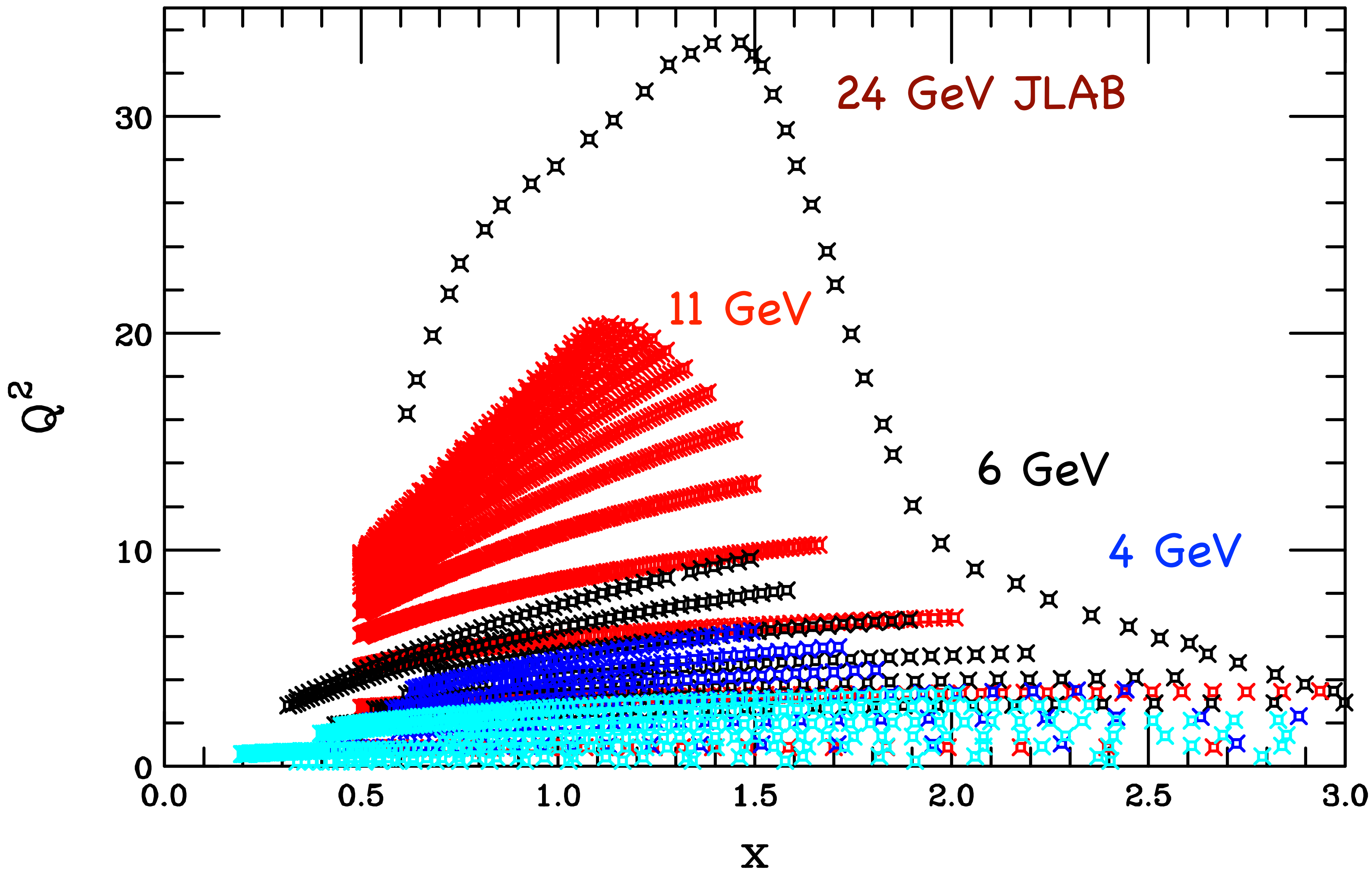
22
20
18
16
14
12
10
8
6
4
2
0
Q^2 (GeV^2)
0.5
1
1.5
2
2.5
3
3.5
4
x
EMC
HMS
HMS SHMS
SHMS
super-fast quarks
quark distribution functions
medium modifications
SHMS, x>1
HMS, x>1
EMC
SRC, n(k), σ FSI

What is possible in the future

CEBAF at 12 and 25 GeV*

Leigh Harwood and Charles Reece
Thomas Jefferson National Accelerator Facility
Newport News, VA, 23606, USA

Replacing the existing cryomodules and revamping the beam transport system could transform the 12 GeV machine into a 25 GeV machine. This might be done when the important research at 12 GeV has been thoroughly mined, perhaps circa 2020. SRF developments in the mean time could potentially boost that capability further.



Summary

- 2N SRC and their isospin dependence (anticipated by our understanding of the NN interaction) is now firmly established in multiple observables, experiments projectiles, final states and nuclei
- Relation of SRC to EMC established - only lacking are calculations that exposes the underlying connection
- Refined theory and calculation are needed incorporating SRC, FSI, and off-shell behavior will advance understanding
- SRC demand high densities (momenta, virtuality) and, if these rare fluctuations can be captured, they should expose, potentially large, medium modifications
- Evidence for 3N SRC are as yet elusive - some sleuthing underway
- Approved experiments across labs with different focuses over next 5-7 years will reveal much
- Next big opportunity in inclusive scattering (in my view) is the transition from QES to DIS at $x > 1$ at very large momenta transfer

SRC Wish List   2N-SRC

1. For the 2N-SRC pair, what is the CM , relative momentum and the correlation between them as a function of all relevant parameters

   a) What are the most important parameters ? momentum, different nuclei.

   b) How to best compare data with theoretical calculations?

2. Can we identify and quantify the amount of 2N-SRC at $X \leq 1$?

3. How to characterize the transition between mean field and 2N-SRC dominant regions ?

4. What is the number and isospin structure of 2N-SRC in very asymmetric nuclei ($N \neq Z$) ?

SRC Wish List 2N-SRC

5. Can we identify and quantify the decay of 2N-SRC to non - 2 nucleon final states?

6. Can we identify and quantify signature for exotica (intermediate hidden color state or non-nucleonic DOF) in the 2N-SRC?

7. How to extrapolate the 2N-SRC (and the EMC) to infinite symmetric nuclear matter?

8. How to extrapolate the 2N-SRC (and the EMC) to high density (n star)?

9. Are 2N-SRC relevant to the neutrino nuclear problems?

SRC Wish List

3N-SRC

1. What is the amount of 3N-SRC as a function of relevant parameters (what are the relevant parameters?: momentum, nuclei….
2. Can we identify the structure of 3N-SRC ? Coplanar, star configuration…?
3. Can we study the isospin structure of 3N-SRC and the relation between it and the geometry of the 3N-SRC ?
4. What determines the transition between 2N-SRC and 3N-SRC dominant regions ?
5. What is the number and isospin structure of 3N-SRC in very asymmetric nuclei ($N \neq Z$).
6. What and how can we learn about 3N forces from 3N-SRC ?