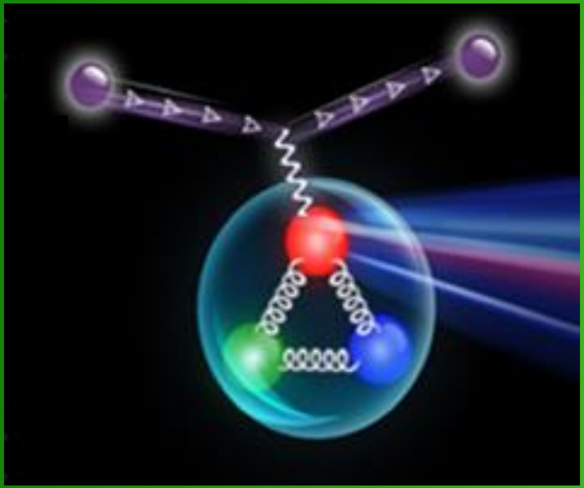
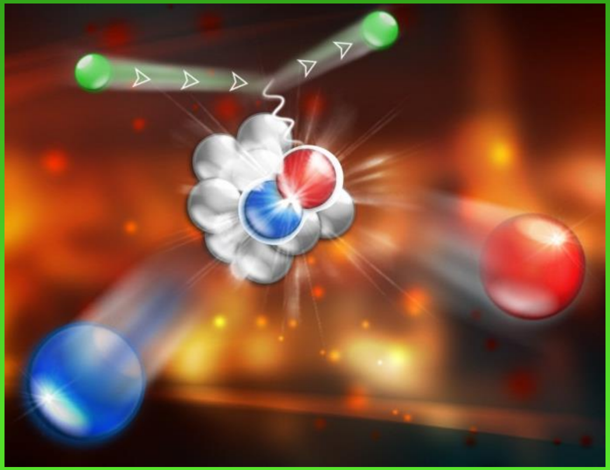
Unlocking what underlies the common nuclear dependence of EMC effect and Short Range Correlations





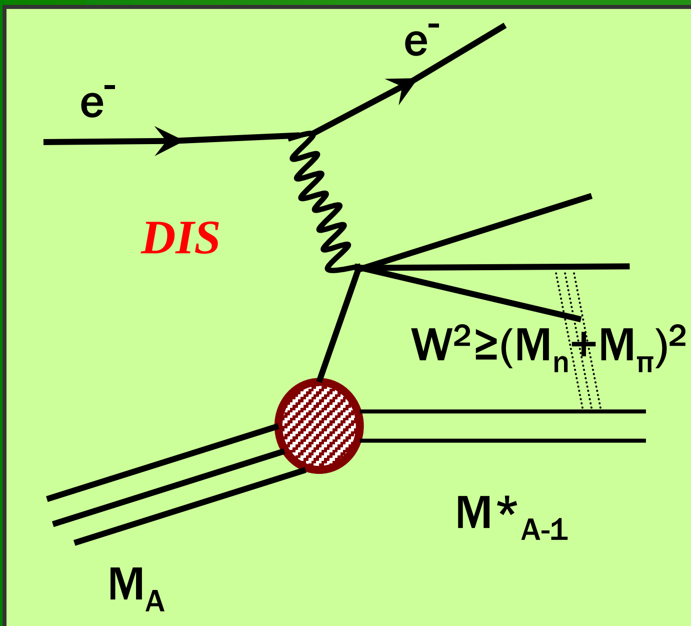
Nadia Fomin

Los Alamos National Laboratory

INT workshop on nuclear structure and dynamics

February 11th, 2013

The inclusive reaction



Same initial state

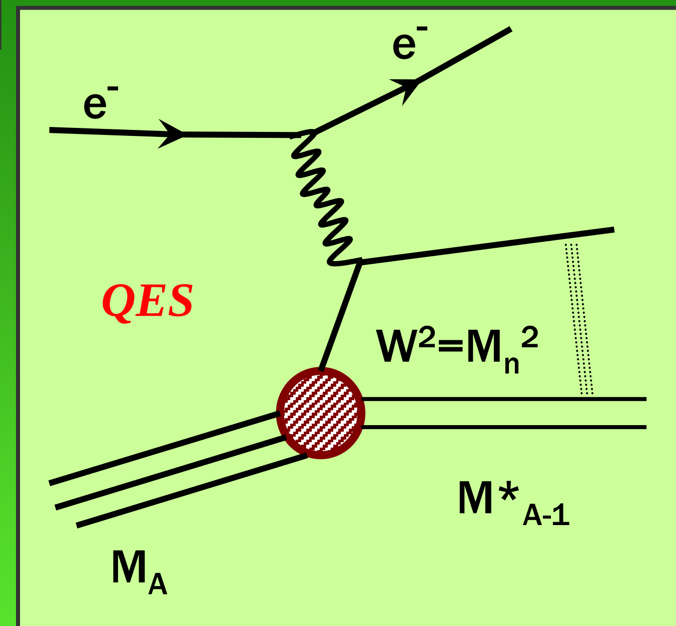
Different Q^2 behavior

$$\nu = E - E'$$

$$Q^2 = -q^2 = \vec{q}^{\,2} - \nu^2$$

$$W^2 = 2M\nu + M^2 - Q^2$$

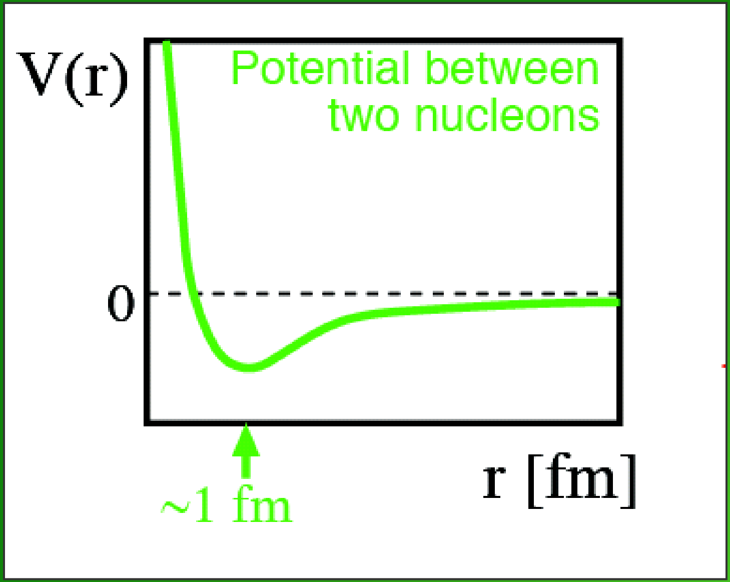
$$x = \frac{Q^2}{2M\nu}$$

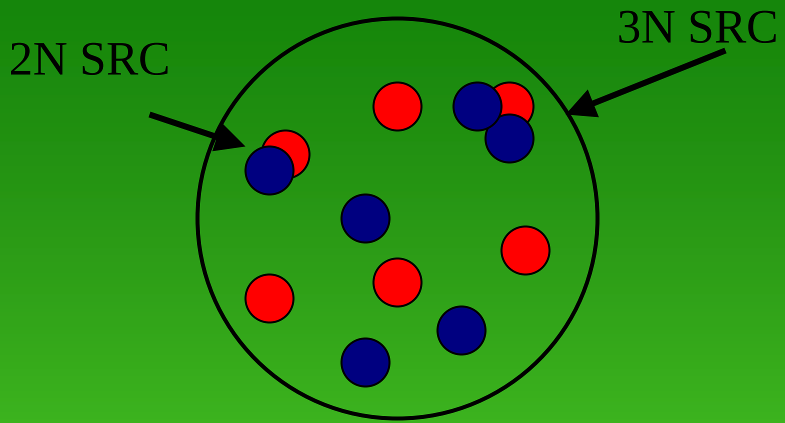


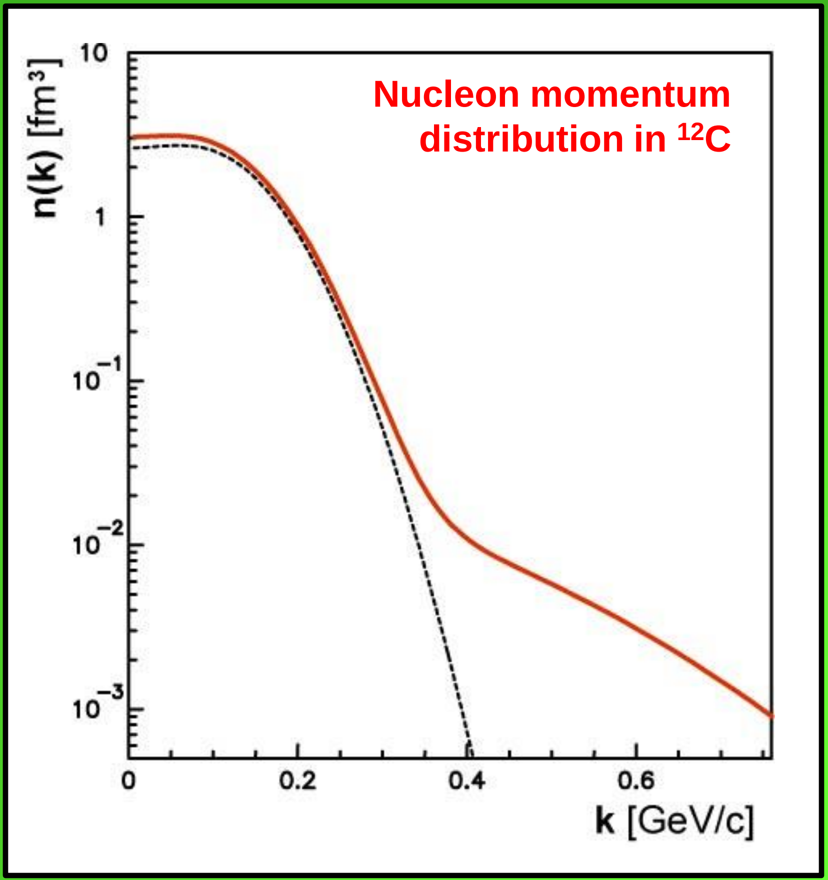
$$\frac{d\sigma}{d\Omega dE} \propto \int d\vec{k} \int dE W_{1,2}^{p,n} S(k,E)$$

$$\frac{d\sigma}{d\Omega dE} \propto \int d\vec{k} \int dE \sigma_{eN} S(k,E) \delta()$$

High momentum nucleons - Short Range Correlations

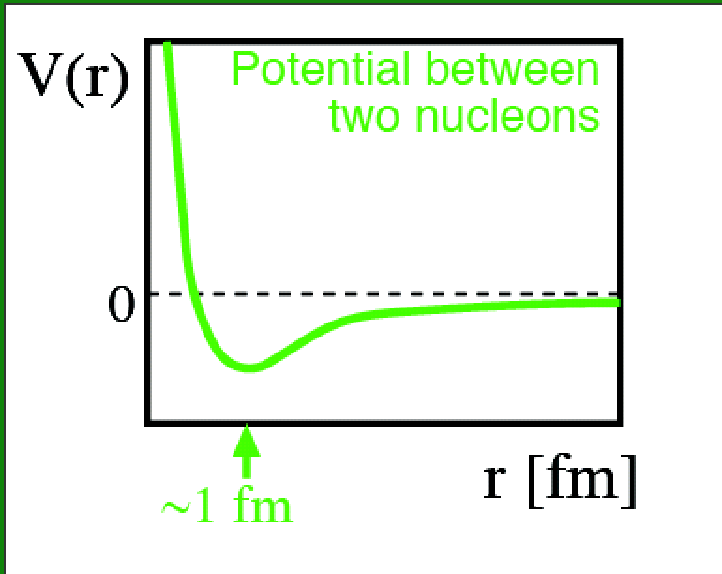


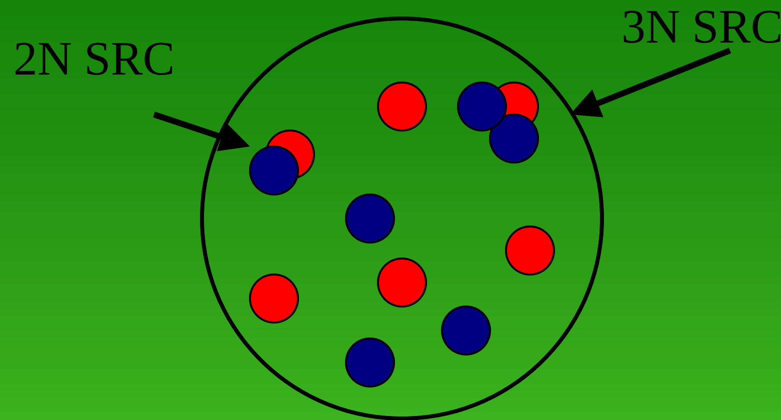




Cannot extract momentum distributions directly from inclusive data for A>2

High momentum nucleons - Short Range Correlations





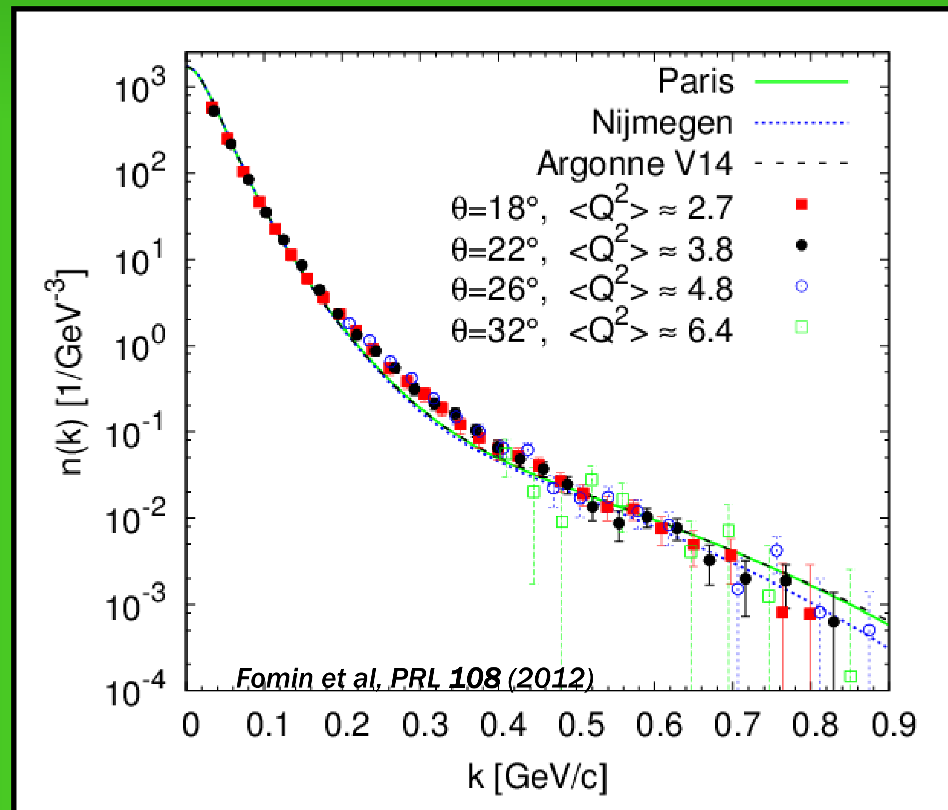
$$\frac{d\sigma^{QE}}{d\Omega dE'} \propto \int d\vec{k} \int dE \sigma_{ei} S_i(k,E) \delta(Arg)$$

$$Arg = \nu + M_A - \sqrt{M^2 + p^2 - \sqrt{M_{A-1}^{*2} + k^2}}$$

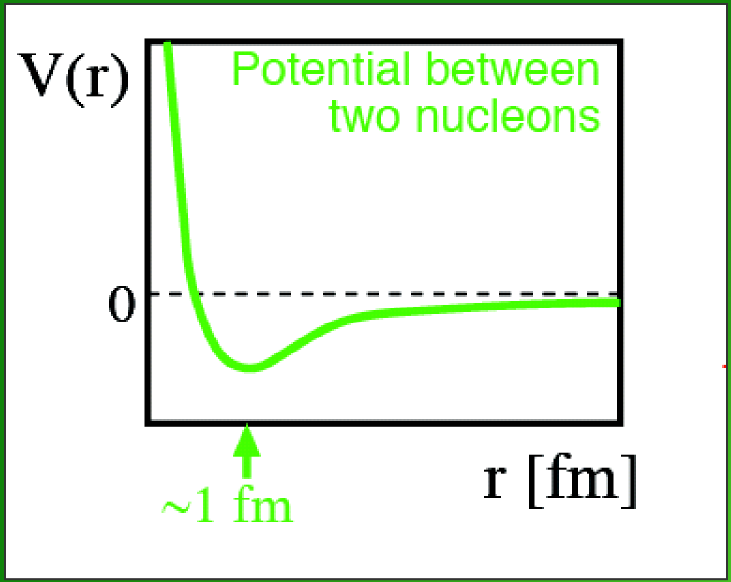
$$F(y,\mathbf{q}) = \frac{d^2\sigma}{d\Omega d\upsilon} \frac{1}{(Z\bar{\sigma}_p + N\bar{\sigma}_n)} \frac{\mathbf{q}}{\sqrt{M^2 + (y+q)^2}}$$

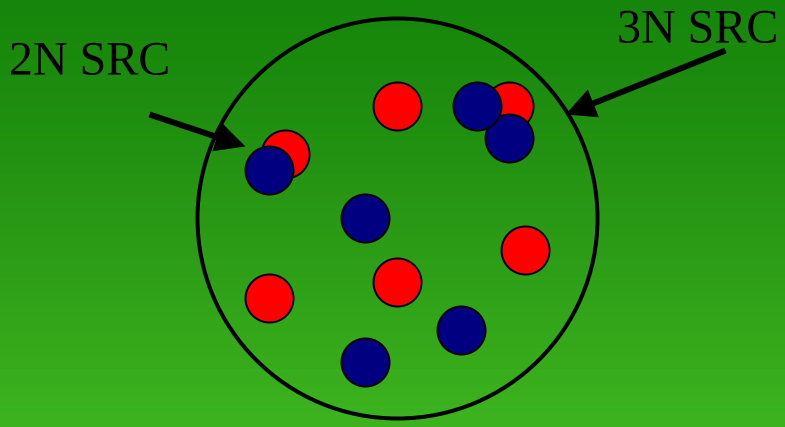
$$= 2\pi \int_{|y|}^{\infty} n(k) k dk$$

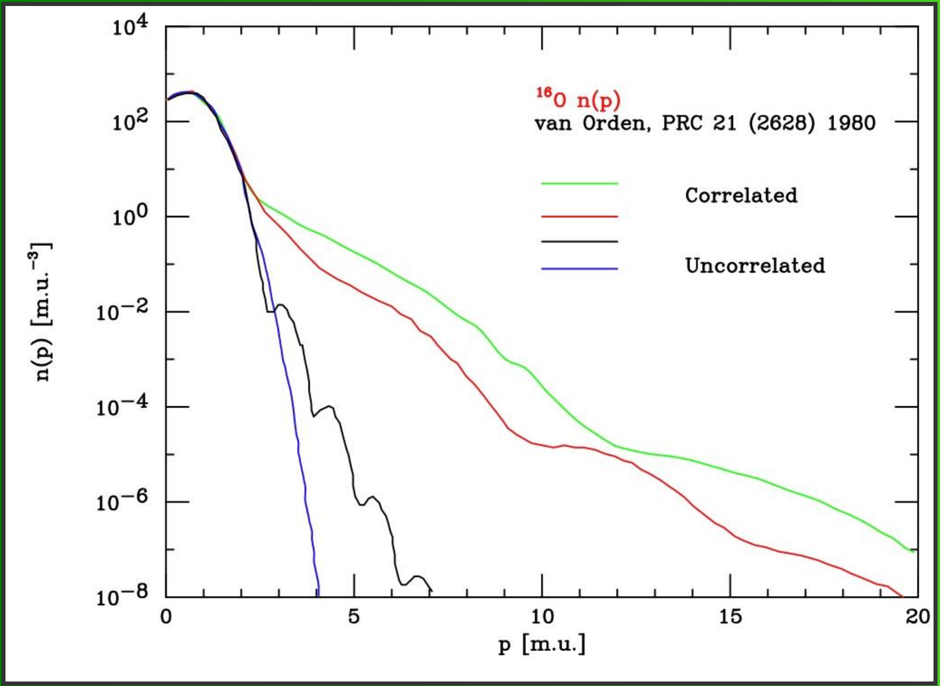
Ok for A=2

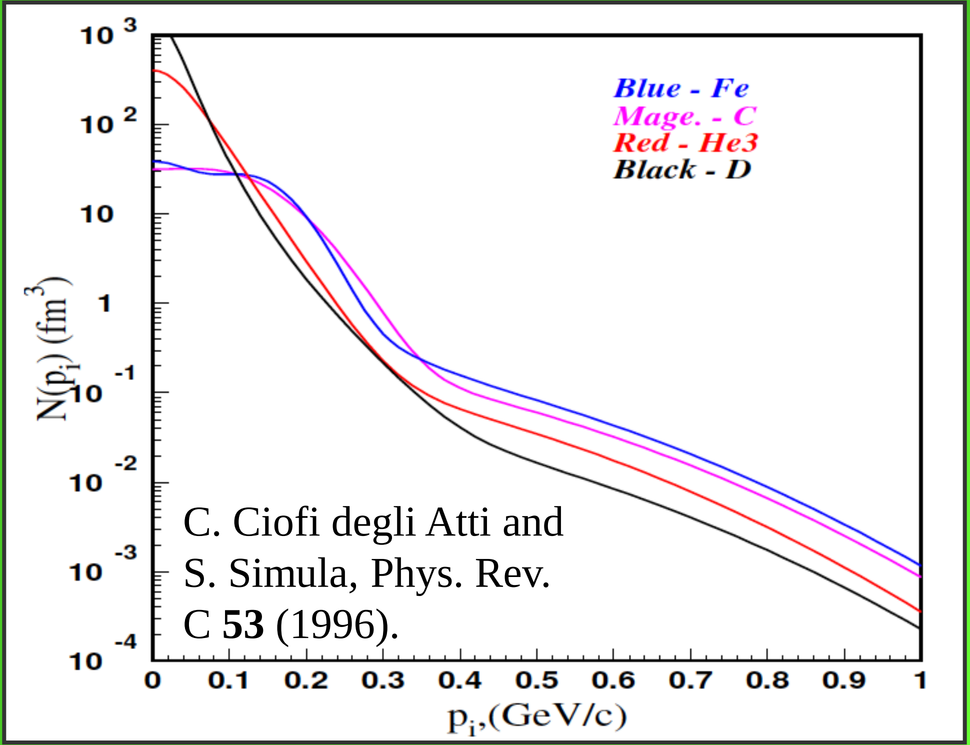


High momentum nucleons - Short Range Correlations









Short Range Correlations

- To experimentally probe SRCs, must be in the high-momentum region (x>1)

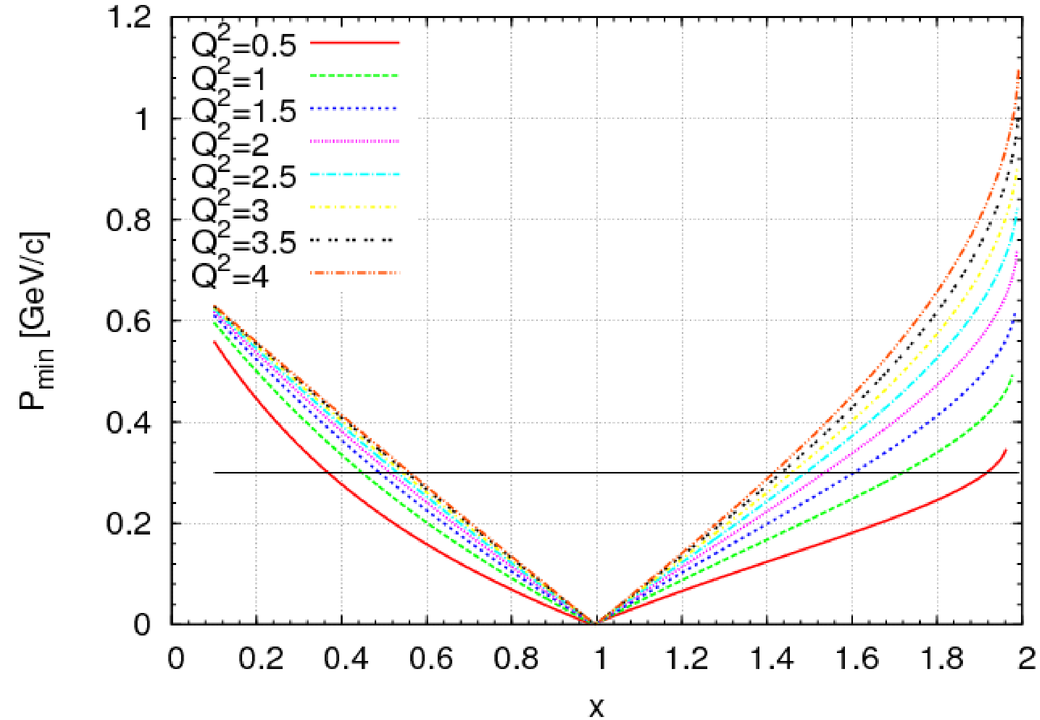
- To measure the relative probability of finding a correlation, ratios of heavy to light nuclei are taken

- In the high momentum region, FSIs are thought to be confined to the SRCs and therefore, cancel in the cross section ratios

1.4<x<2 => 2 nucleon correlation

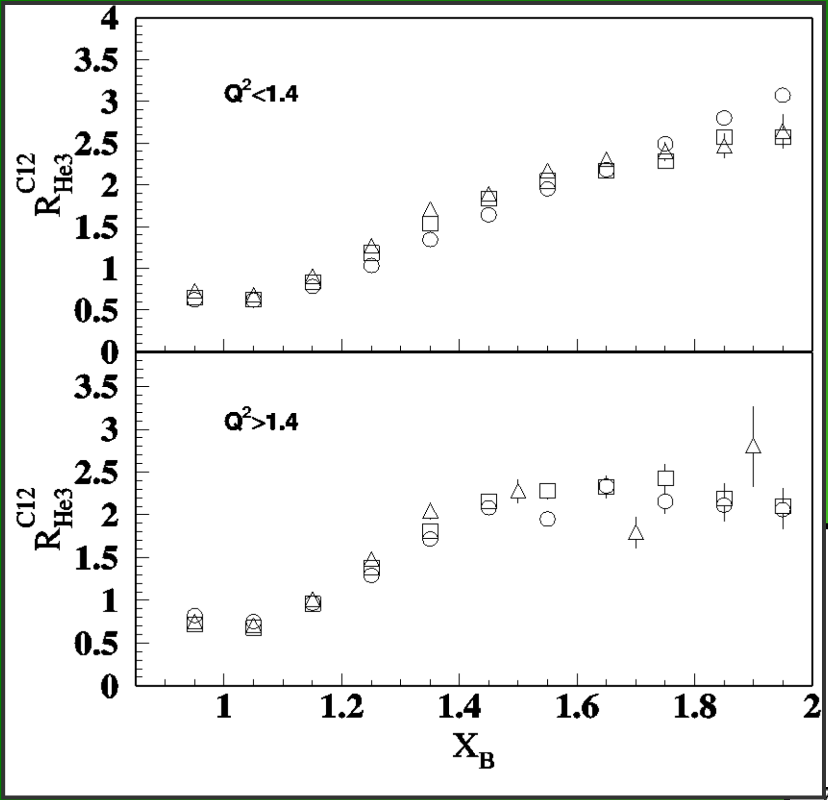
2.4<x<3 => 3 nucleon correlation

- *L. L. Frankfurt and M. I. Strikman, Phys. Rept. 76, 215(1981).*
- *J. Arrington, D. Higinbotham, G. Rosner, and M. Sargsian (2011), arXiv:1104.1196*
- *L. L. Frankfurt, M. I. Strikman, D. B. Day, and M. Sargsian, Phys. Rev. C 48, 2451 (1993).*
- *L. L. Frankfurt and M. I. Strikman, Phys. Rept. 160, 235 (1988).*
- *C. C. degli Atti and S. Simula, Phys. Lett. B 325, 276 (1994).*
- *C. C. degli Atti and S. Simula, Phys. Rev. C 53, 1689 (1996).*



$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A)$$

Previous measurements

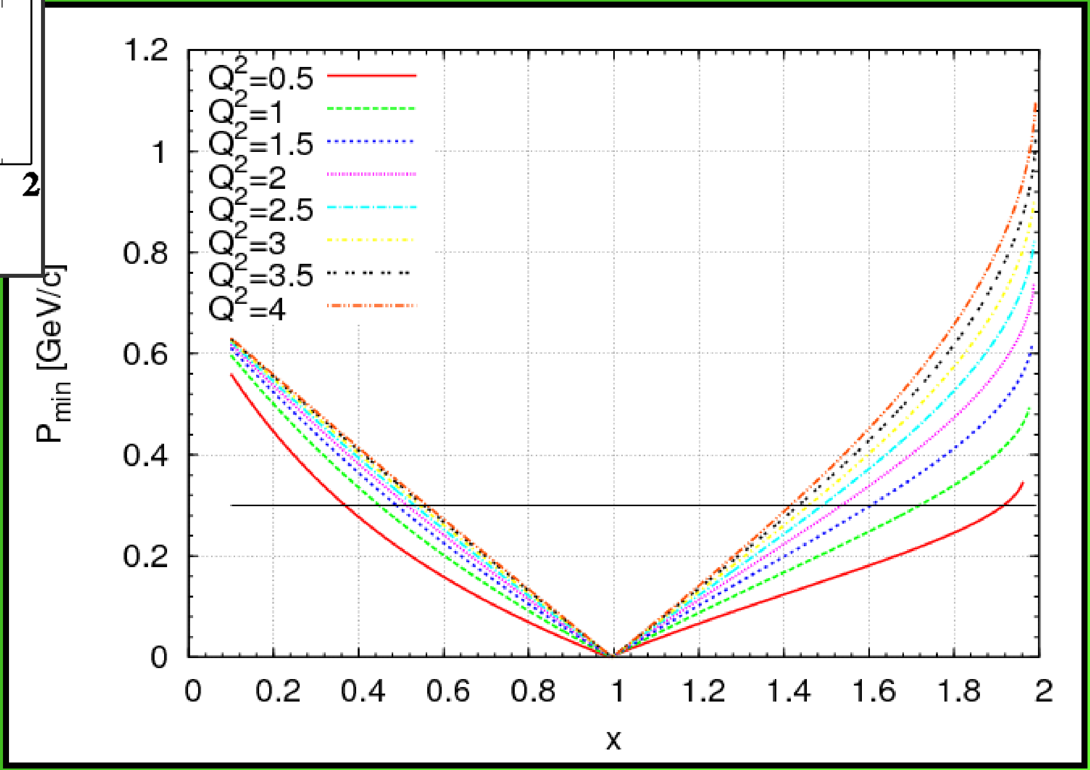


1.4<x<2 => 2 nucleon correlation

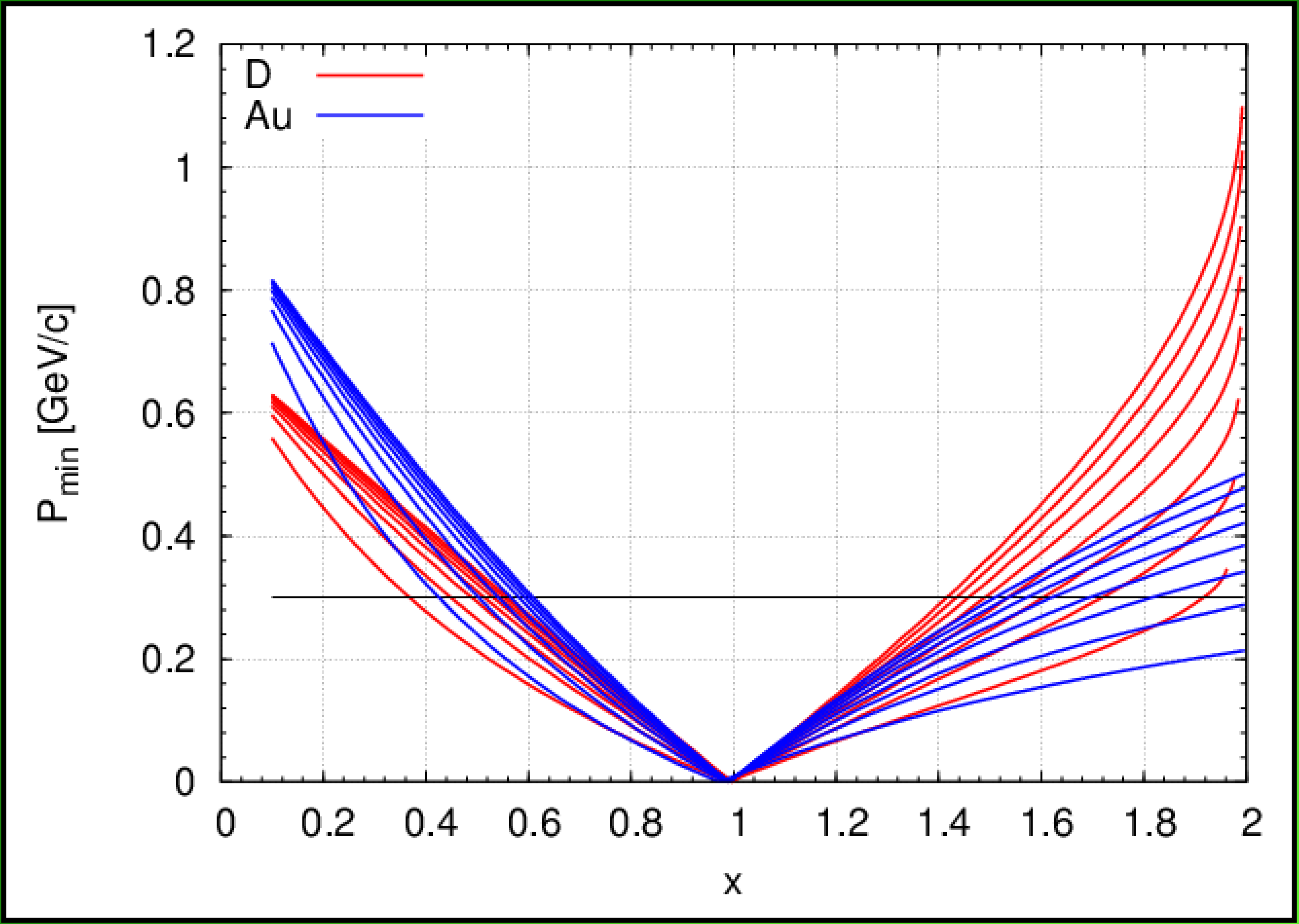
2.4<x<3 => 3 nucleon correlation

Egiyan et al, Phys.Rev.C68, 2003

No observation of scaling for $Q^2<1.4$ GeV^2

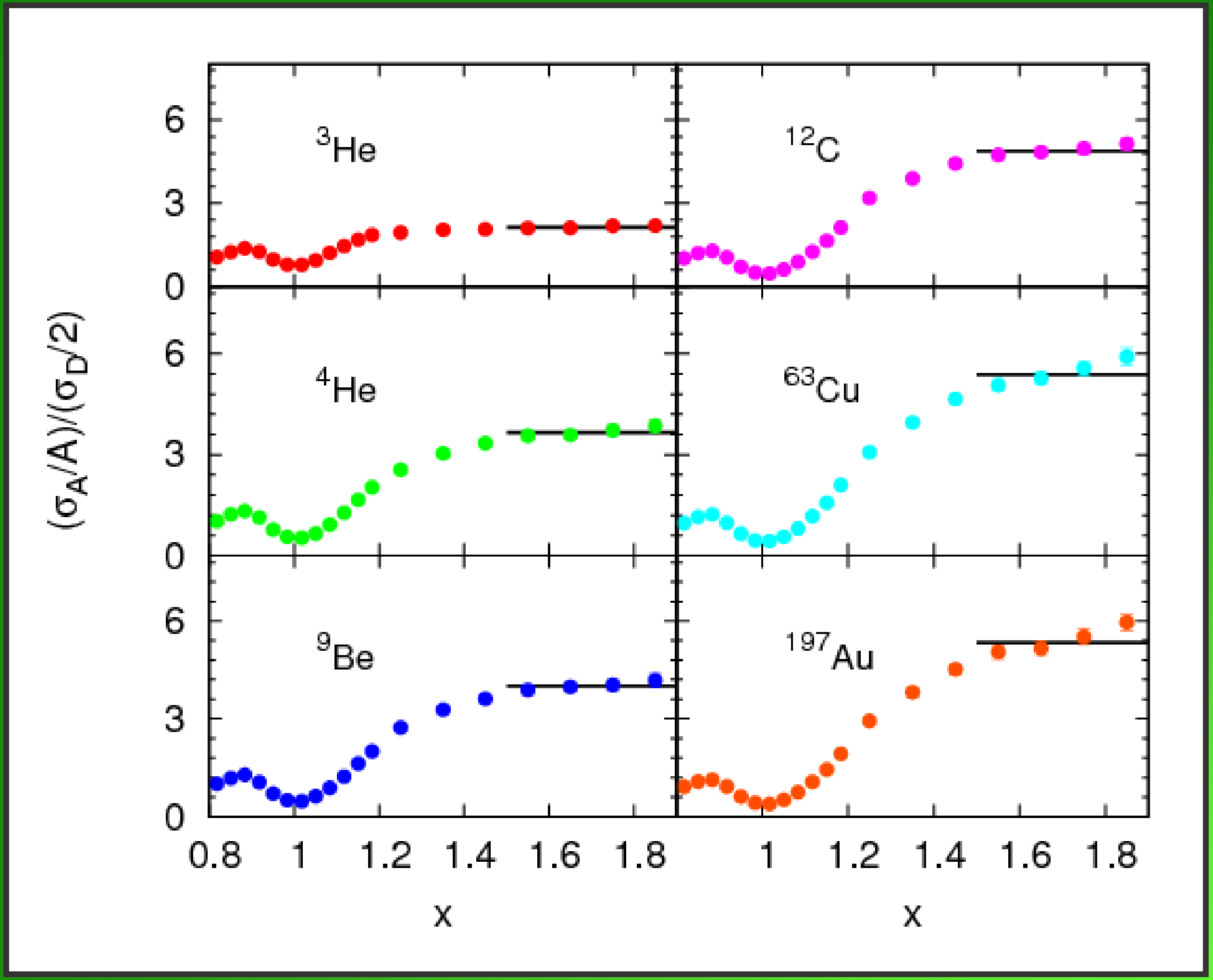


Kinematic cutoff is A-dependent



- For heavy nuclei, the minimum momentum changes → heavier recoil system requires less kinetic energy to balance the momentum of the struck nucleon
- Larger fermi momenta for A>2 → MF contribution persists for longer

E02-019: 2N correlations in A/D ratios



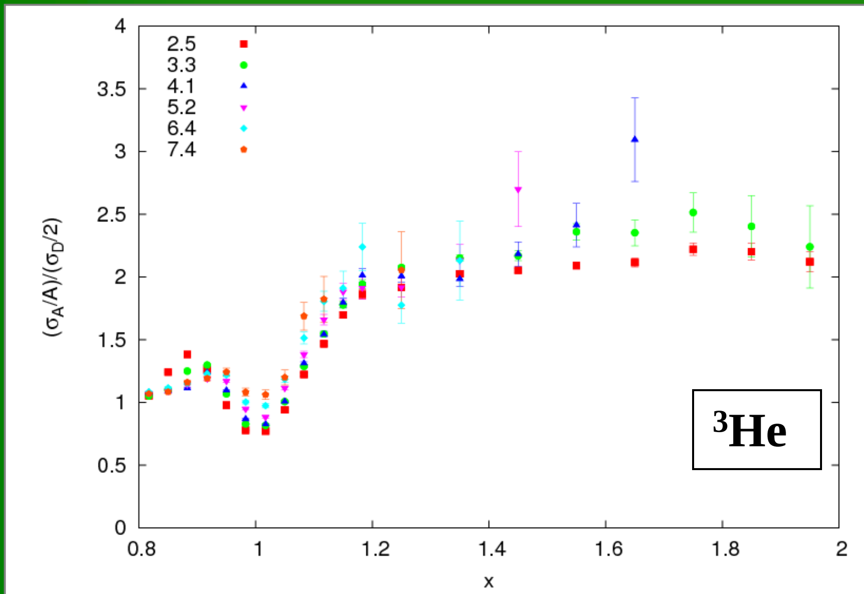
*Fomin et al, PRL **108** (2012)*

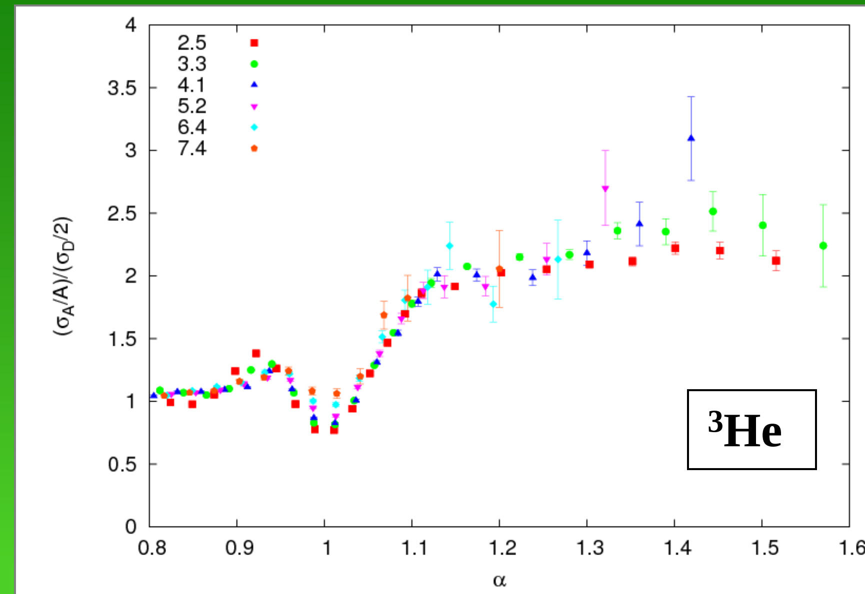
Jlab E02-019

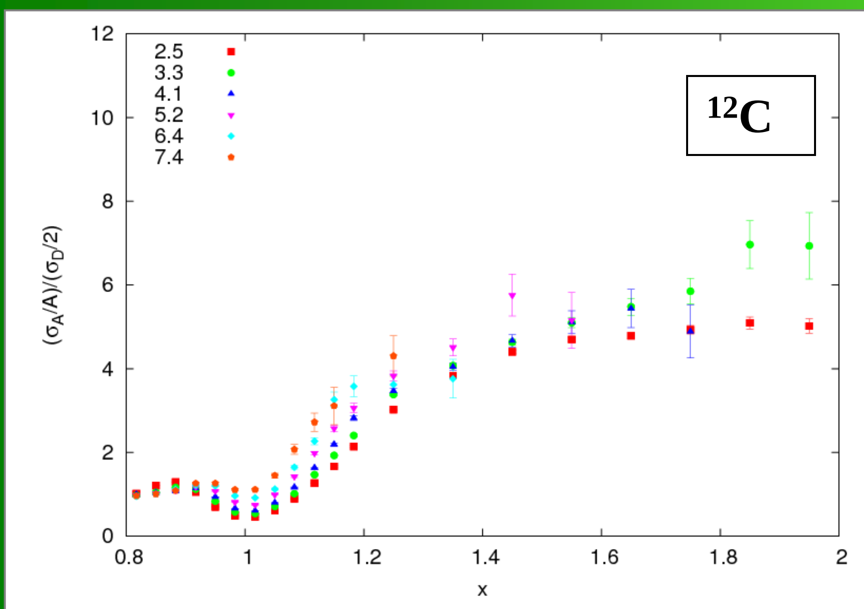
$\langle Q^2 \rangle = 2.7\ GeV^2$

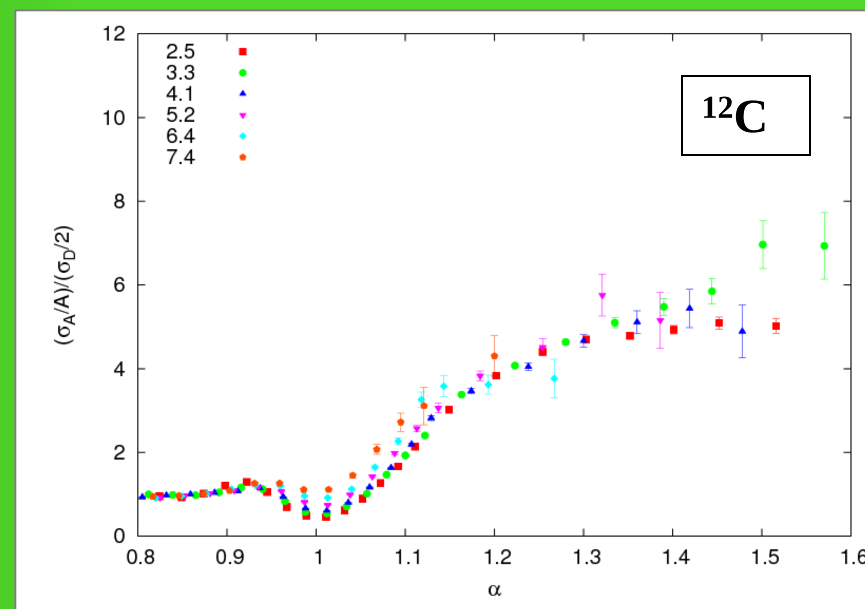
Q^2 dependence features

$$\alpha = 2 - \frac{q^- + 2M}{2M}\left(1 + \frac{\sqrt{W^2 - 4M^2}}{W}\right)$$

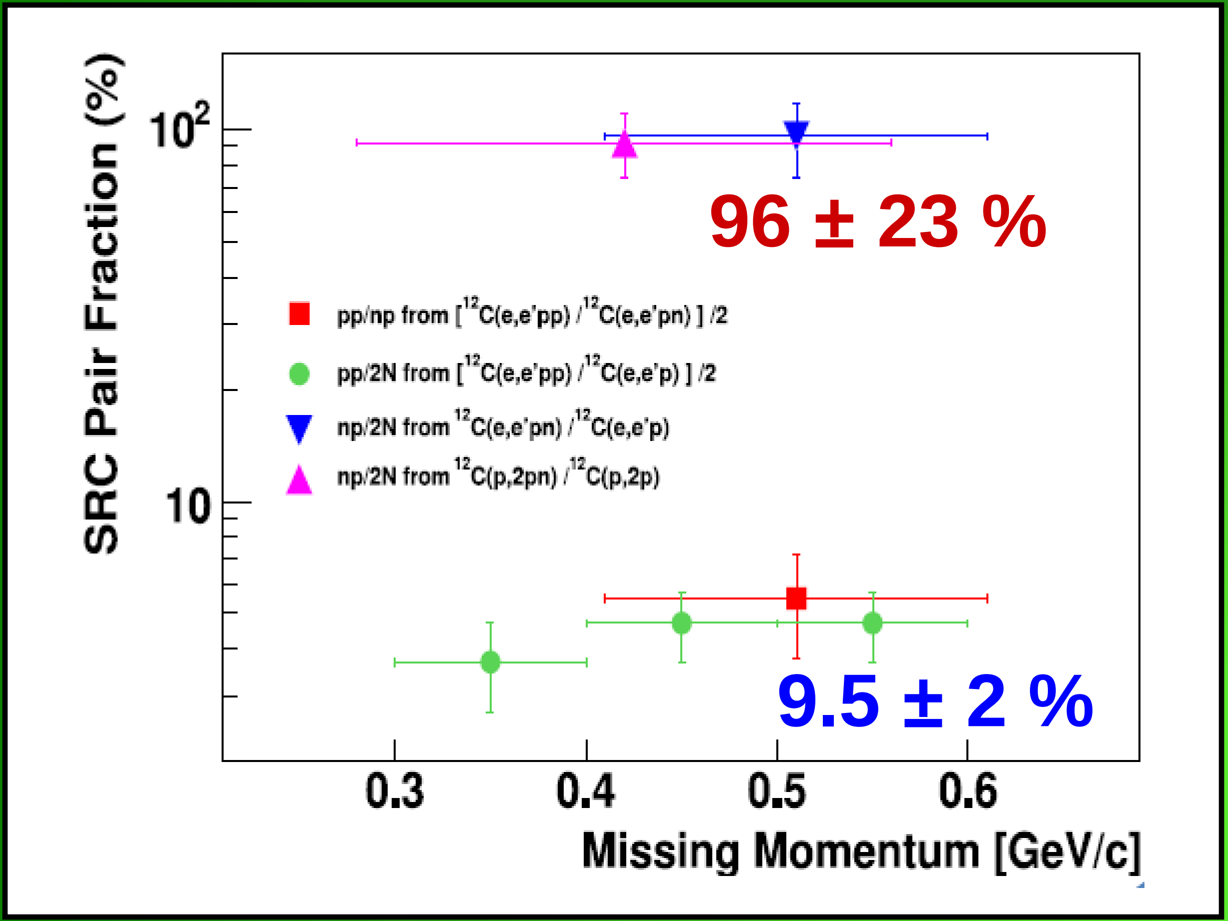








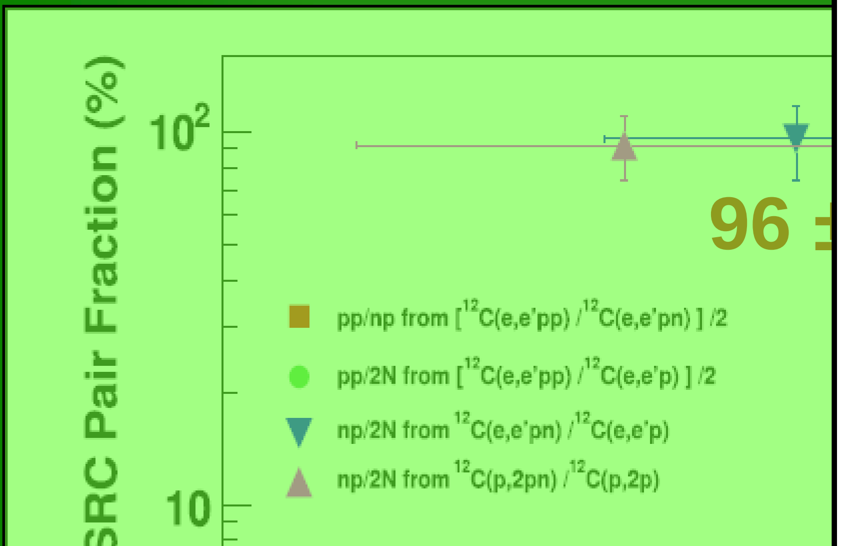
NP dominance

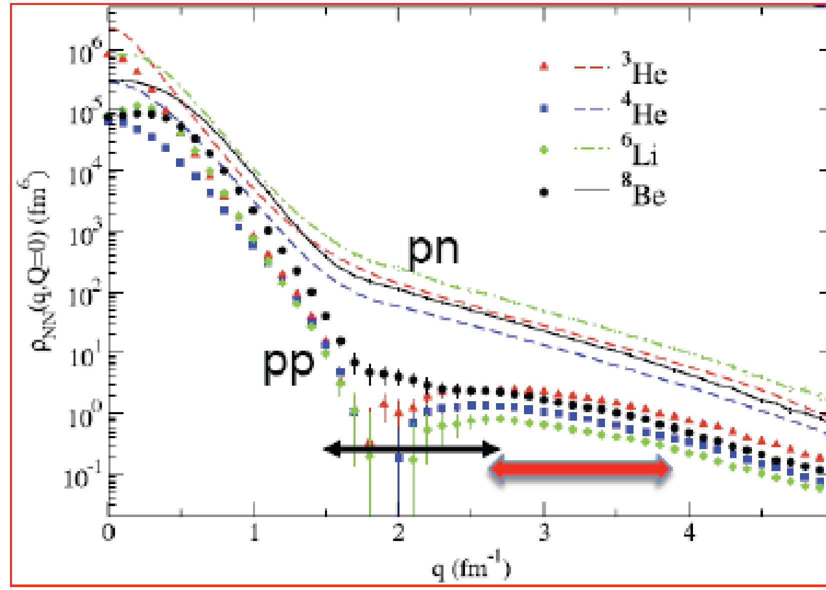


R. Subedi et al., Science 320, 1476 (2008)

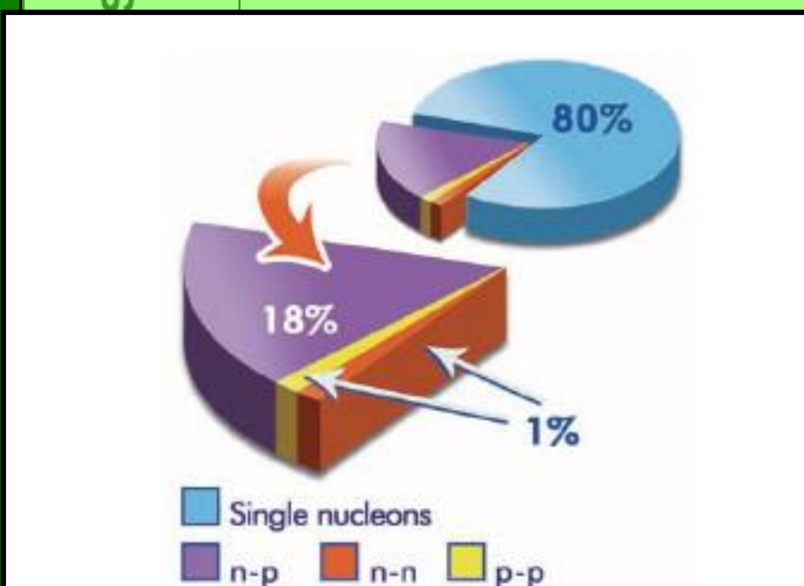
R. Shneor et al., PRL 99, 072501 (2007)

NP dominance





R. Schiavilla, R. B. Wiringa, S. C. Pieper, J. Carlson, Phys. Rev. Lett. **98** (2007) 132501

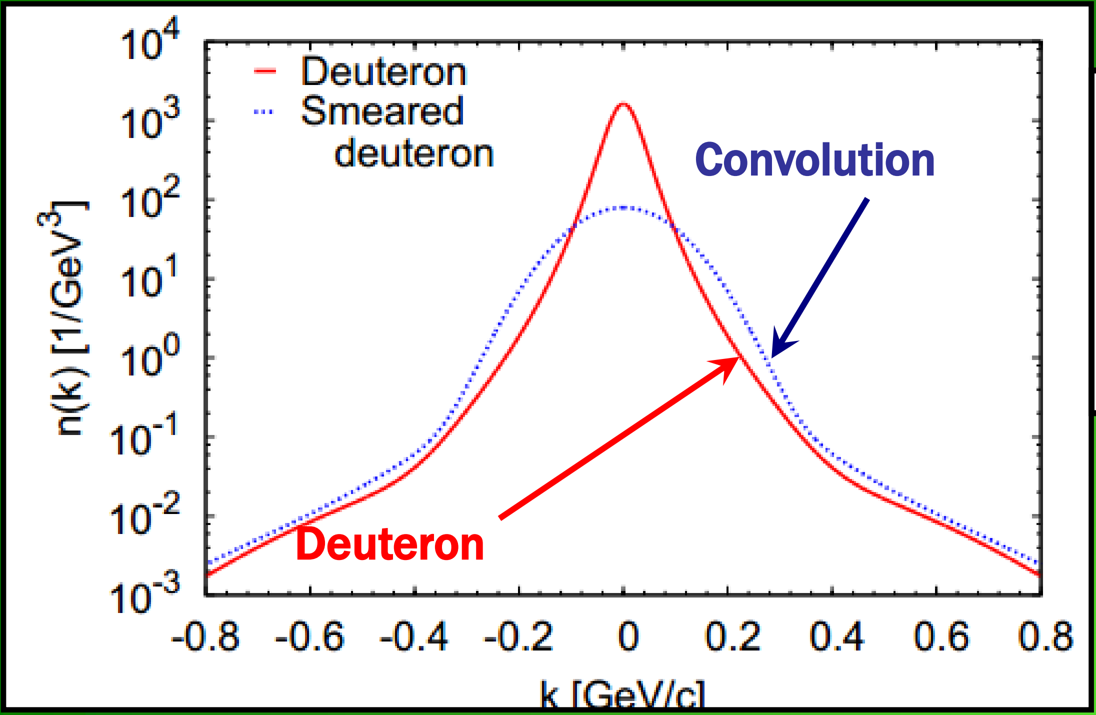


also

→ Ciofi and Alvioli PRL 100, 162503 (2008)

→Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005)

$(a_2=\sigma_A/\sigma_D)$!= Relative #of SRCs



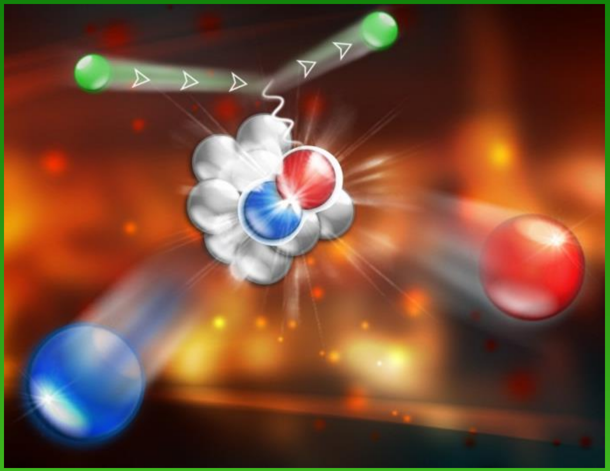
$n_D^{CONV}(k)$ is the convolution of $n_D(k)$ with the CM motion of correlated pairs in iron

Following prescription from C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53 (1996)

	E02-019	SLAC	CLAS	R_{2N}-ALL	a_2-ALL
^{3}He	1.93±0.10	1.8±0.3	–	1.92±0.09	2.13±0.04
^{4}He	3.02±0.17	2.8±0.4	2.80±0.28	2.94±0.14	3.57±0.09
Be	3.37±0.17	–	–	3.37±0.17	3.91±0.12
C	4.00±0.24	4.2±0.5	3.50±0.35	3.89±0.18	4.65±0.14
Al	–	4.4±0.6	–	4.40±0.60	5.30±0.60
Fe	–	4.3±0.8	3.90±0.37	3.97±0.34	4.75±0.29
Cu	4.33±0.28	–	–	4.33±0.28	5.21±0.20
Au	4.26±0.29	4.0±0.6	–	4.21±0.26	5.13±0.21

$a_2=\sigma_A/\sigma_D$ → *relative measure of high momentum nucleons*

R_{2n} → *relative measure of correlated pairs*

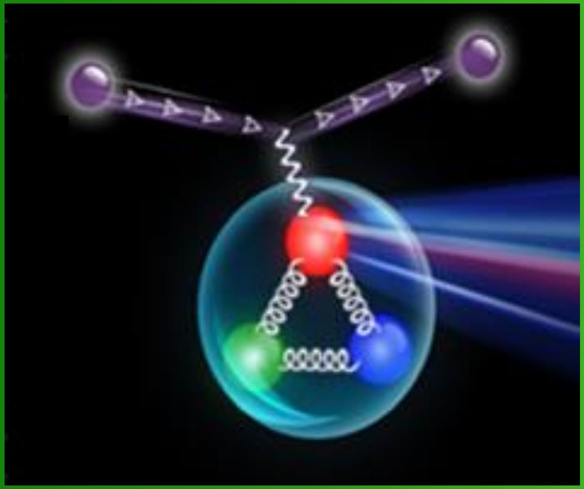


FROM

Quasielastic Scattering at x>1

to

DIS at x<1



Where an unexpected connection is made

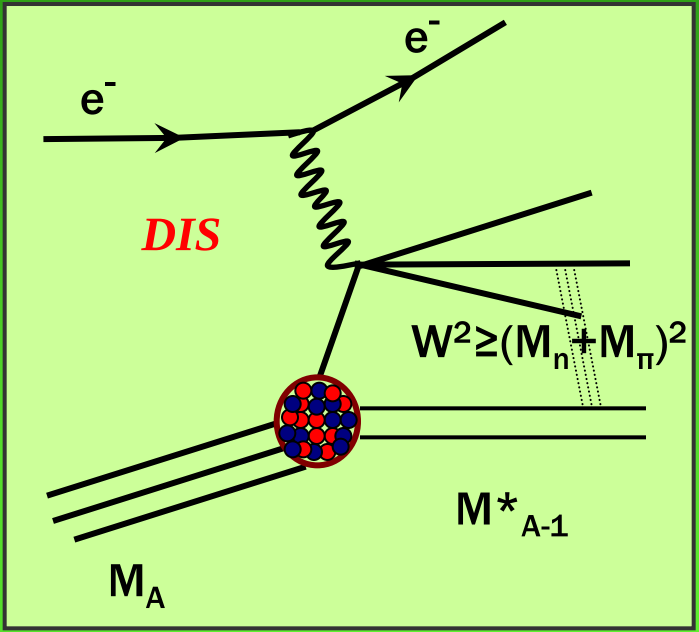
Discovery of the EMC effect

- Goal was a measurement of the lepton-nucleon cross section at high Q^2
  - To achieve statistical precision in a reasonable amount of time, an iron target was used, on the assumption that

$$\frac{\sigma_A / A}{\sigma_D / 2} \approx 1$$

meaning

$$F_2^A(x) = ZF_2^p(x) + NF_2^n(x)$$

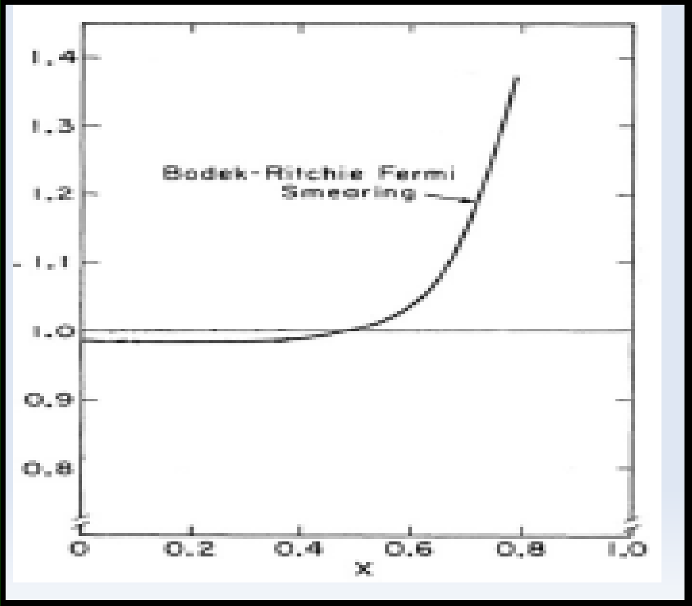


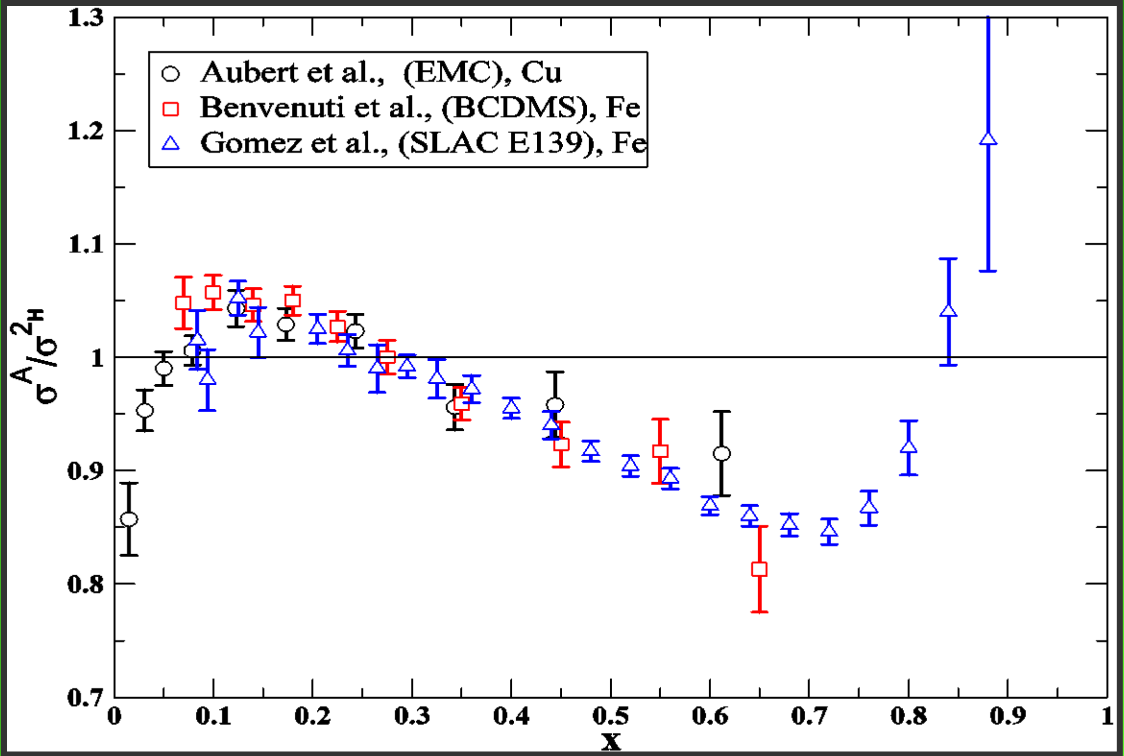
The EMC effect

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

Nuclear dependence of the structure functions discovered 30 years ago by the European Muon Collaboration (EMC effect)

Nucleon structure functions are modified by the nuclear medium





Shadowing

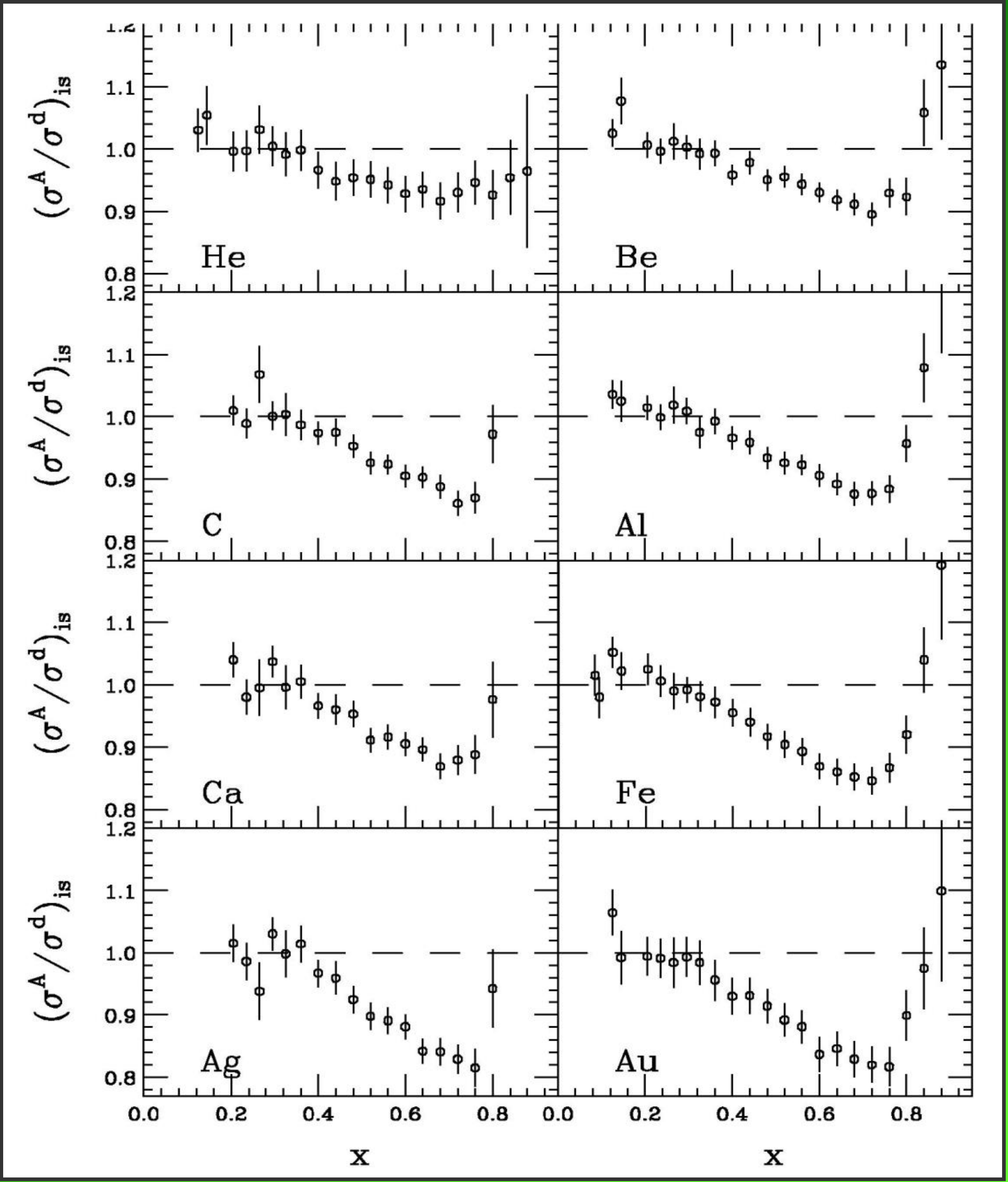
Anti-Shadowing (pion excess)

EMC region

Fermi motion effects

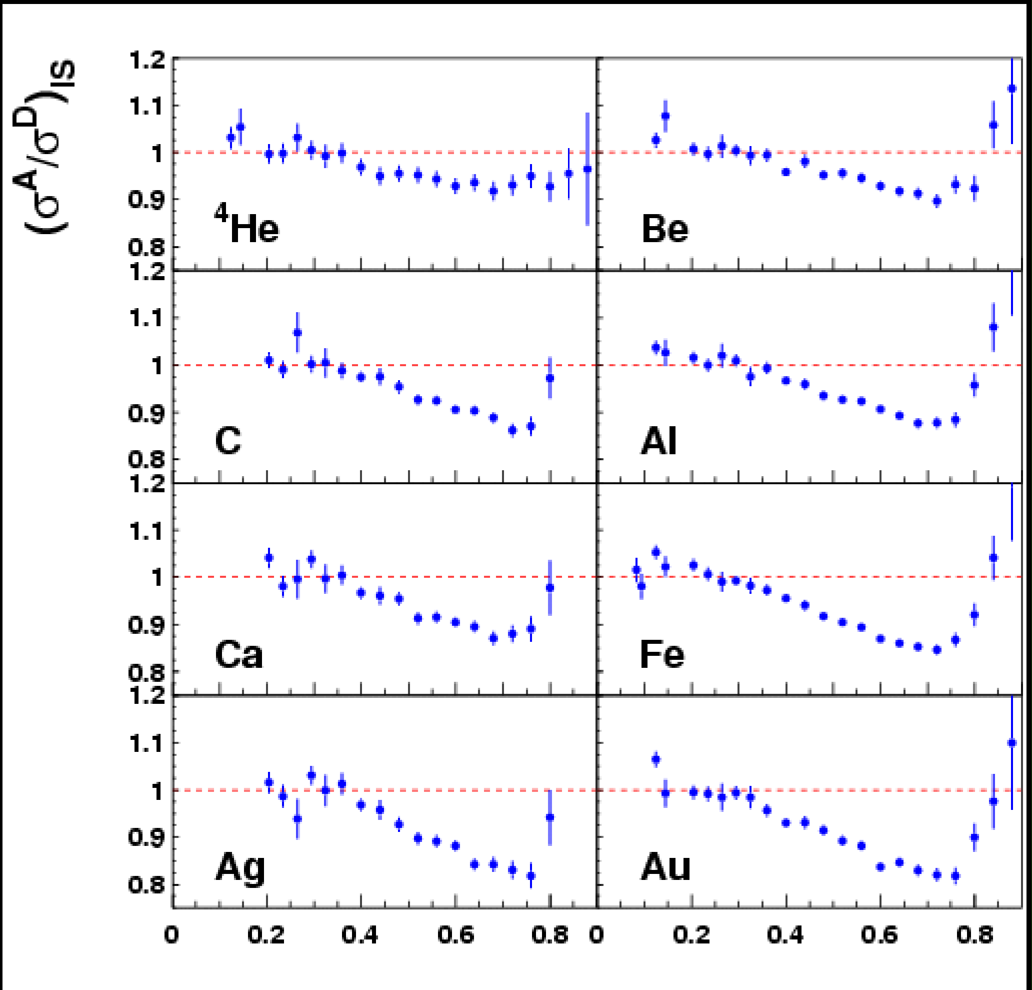
Measurements before 2004

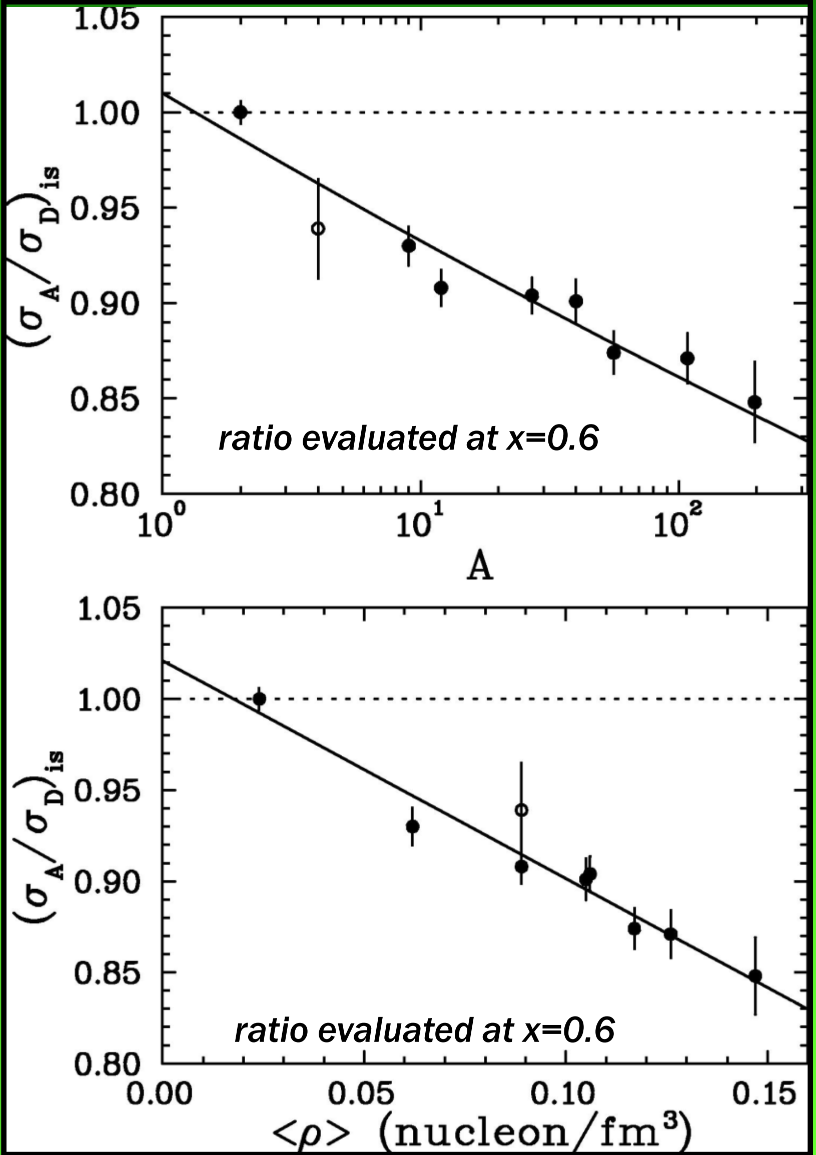
- ***NMC*** – extraction of F_2^n/F_2^p
- ***BCDMS*** – 50 < Q^2 < 200 (GeV^2)
- ***HERMES*** – first measurement on ^3He
- ***SLAC E139*** – most precise large x data
  - Q^2 independent
  - Universal shape
  - Magnitude approximately scales with density



Nuclear Dependence of the EMC effect

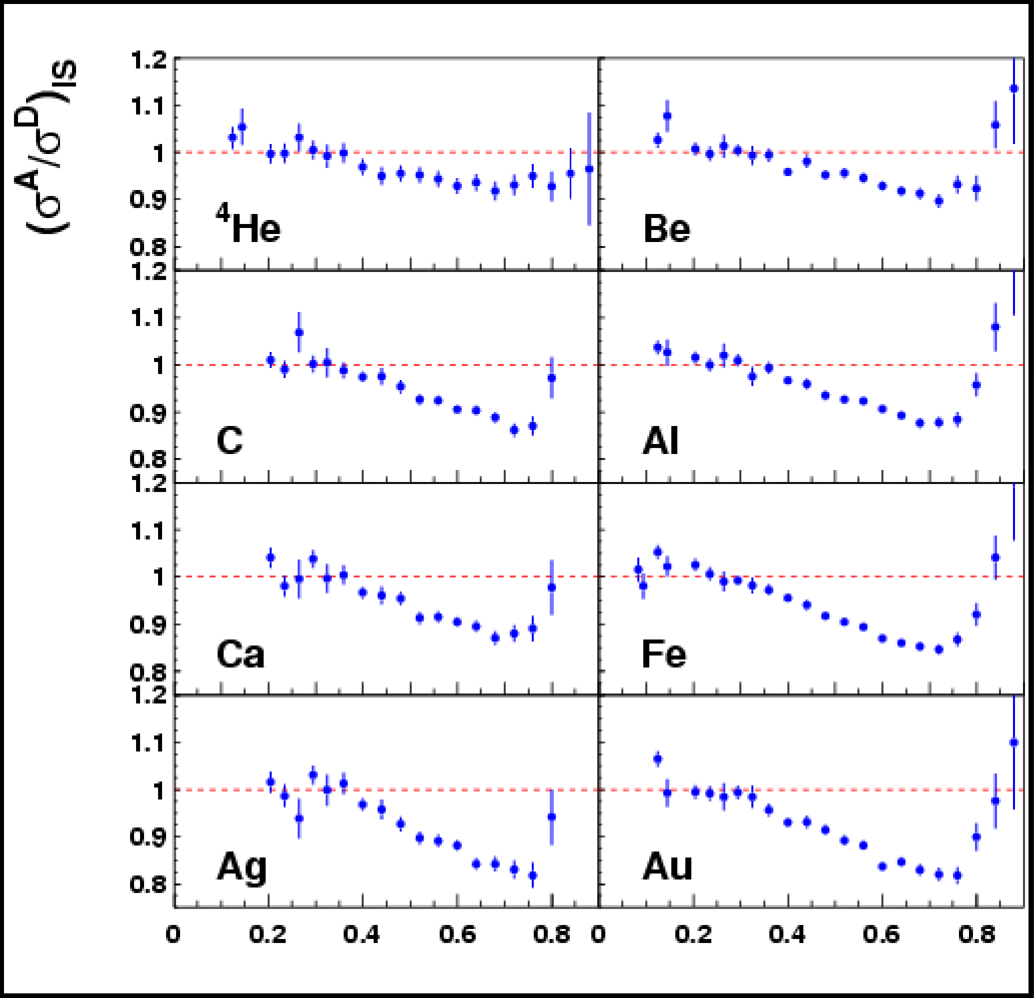
- → *Quark distributions are modified in nuclei*
- → *Modification scales with A*

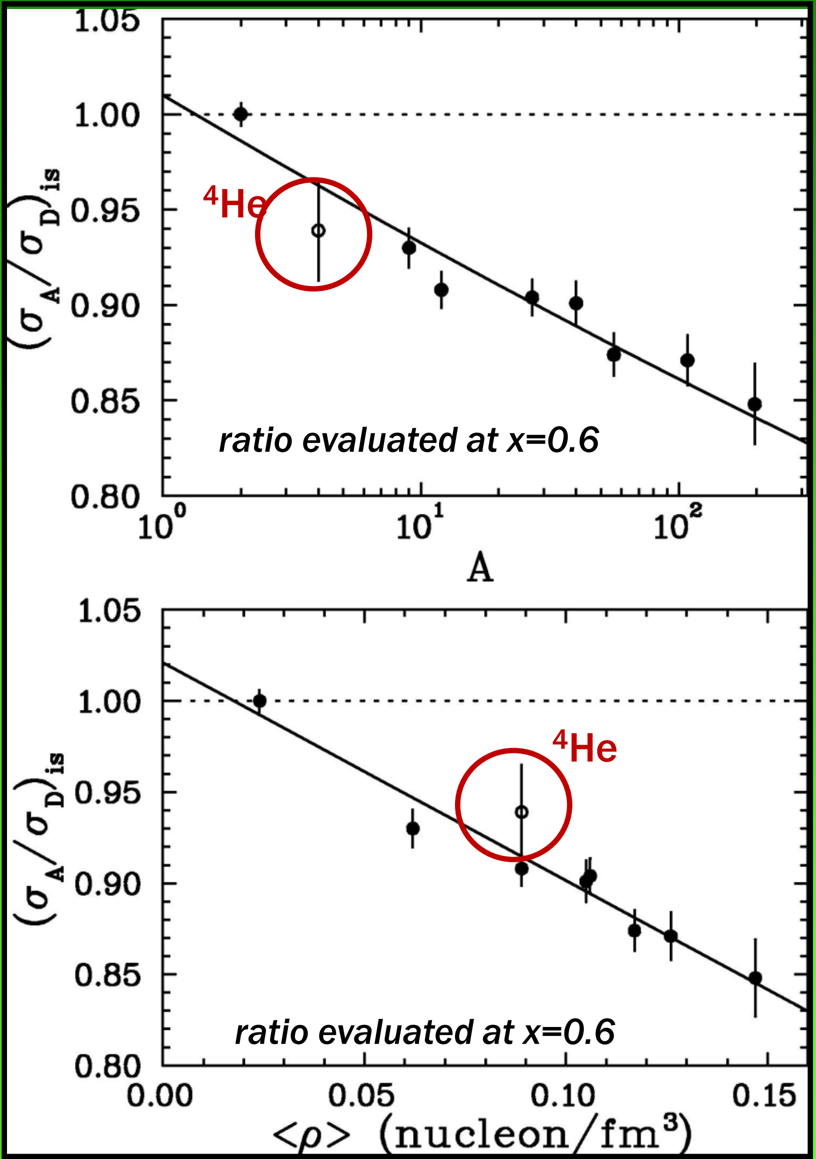




Nuclear Dependence of the EMC effect

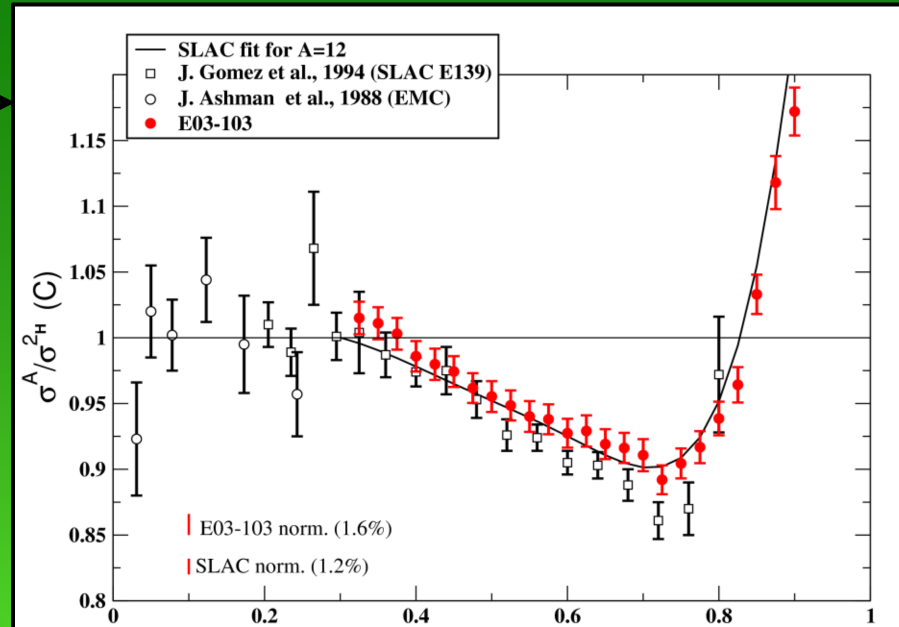
- → *Quark distributions are modified in nuclei*
- → *Modification scales with A*



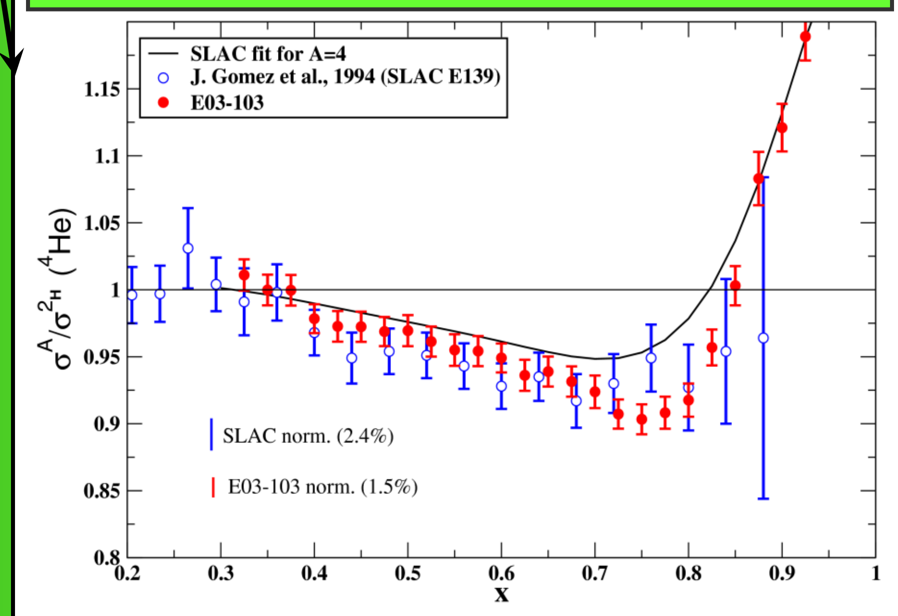


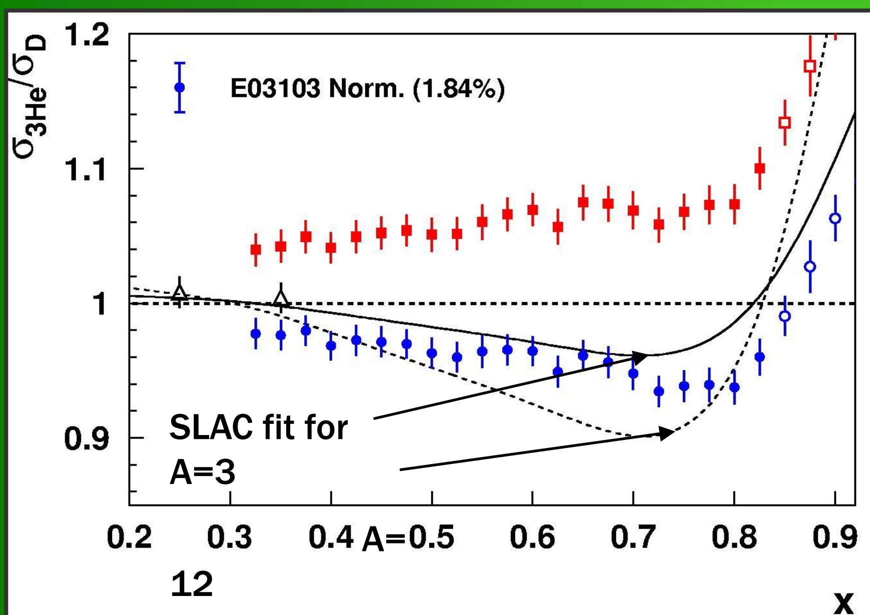
Precision results on light nuclei from JLab E03-103

- *C/D* and ^{4}*He/D* ratios – no isoscalar correction necessary
- Consistent with SLAC results, but much higher precision at high x



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

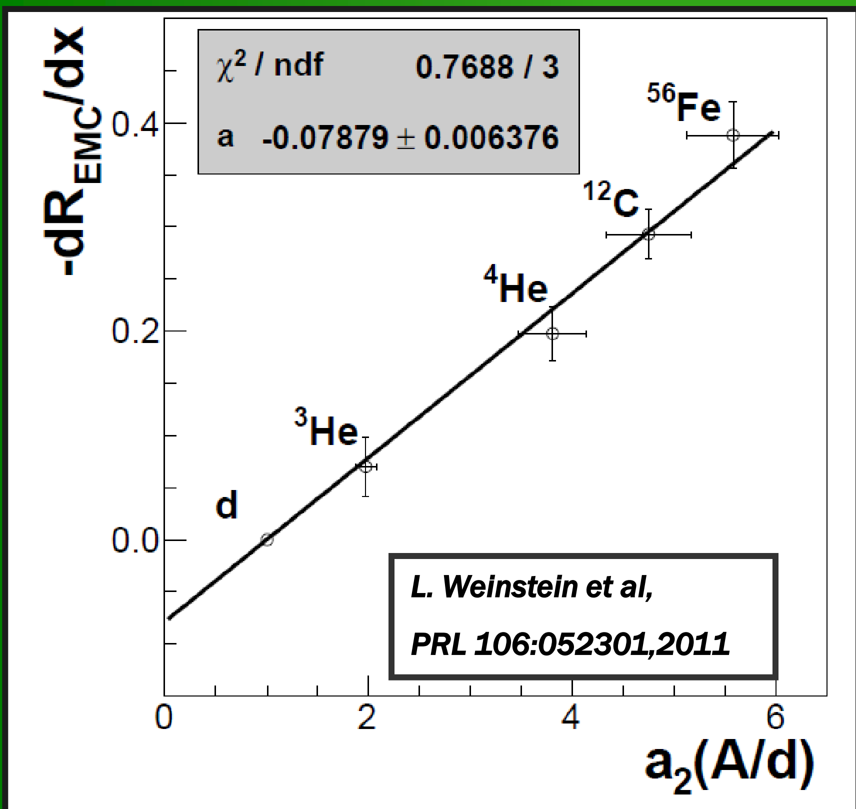


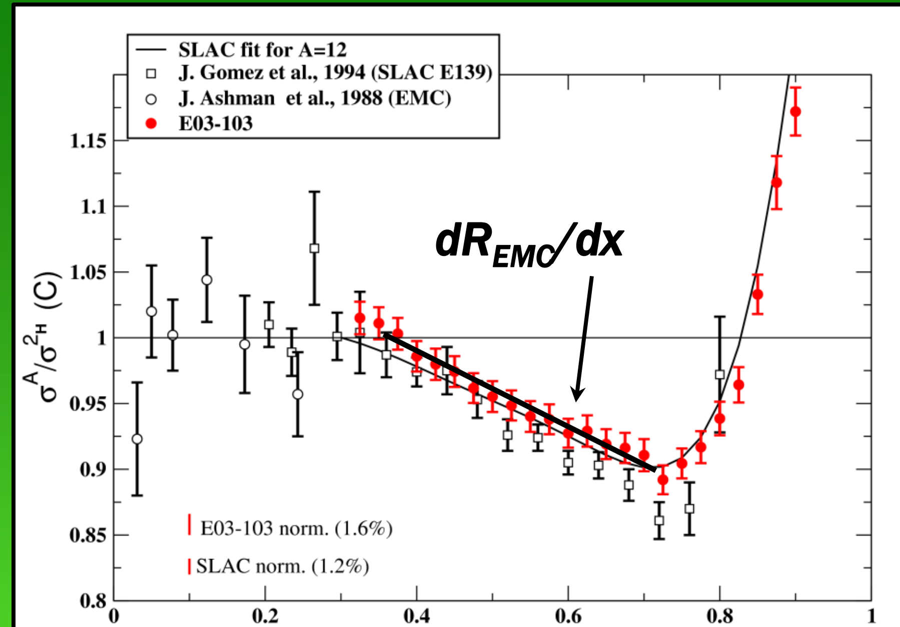


PhD theses: J. Seely, A. Daniel

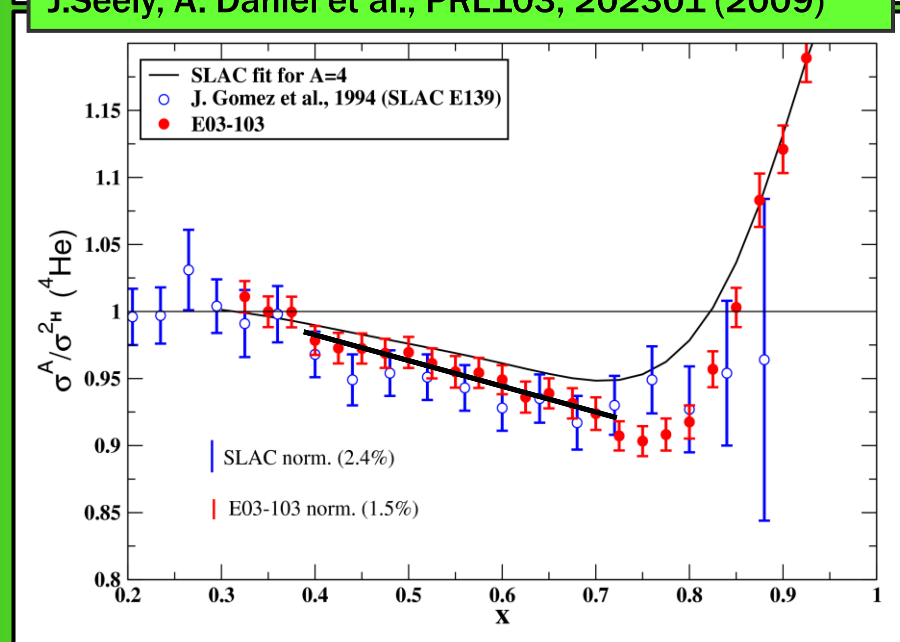
SRCs and EMC effect share the same nuclear dependence.

a_2 – relative measure of SRCs
dR_{EMC}/dx – slope of the A/D cross section ratio in the 0.35<x<0.7 region

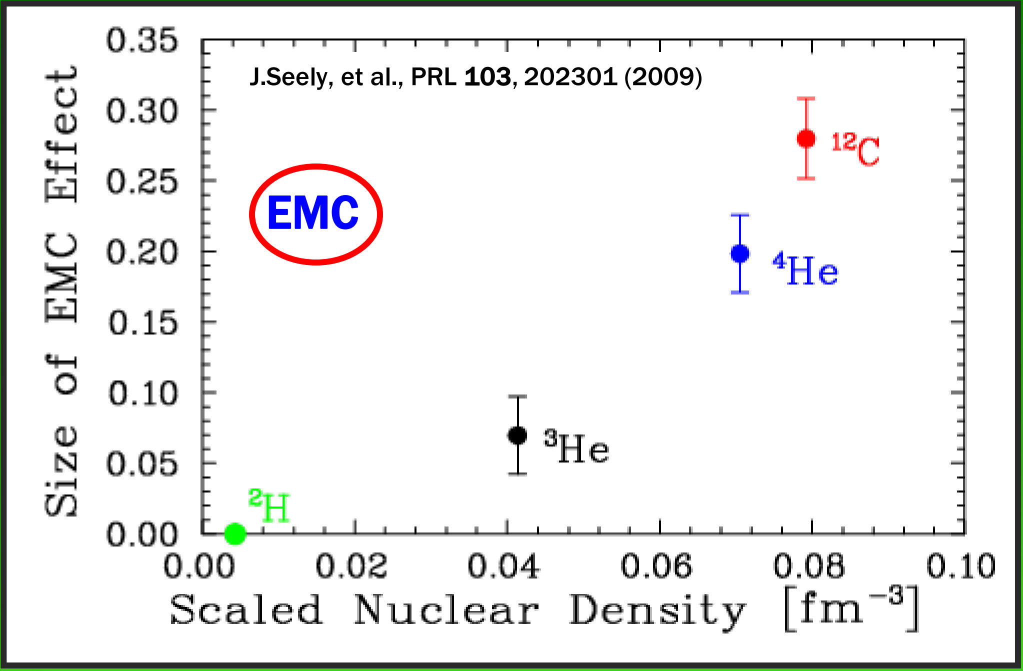


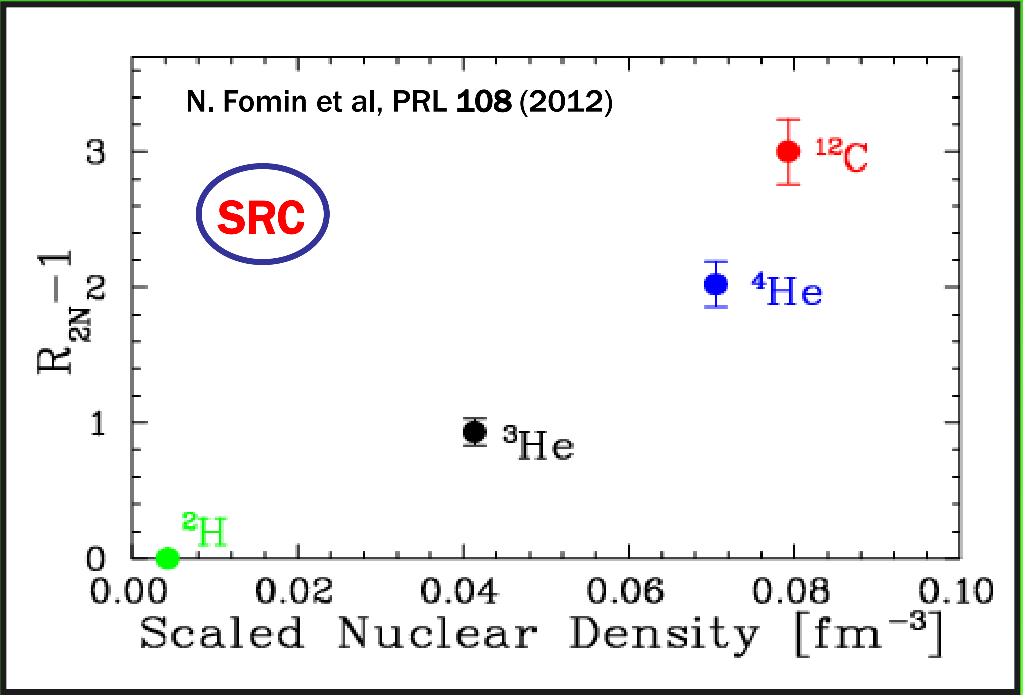


J.Seely, A. Daniel et al., PRL103, 202301 (2009)

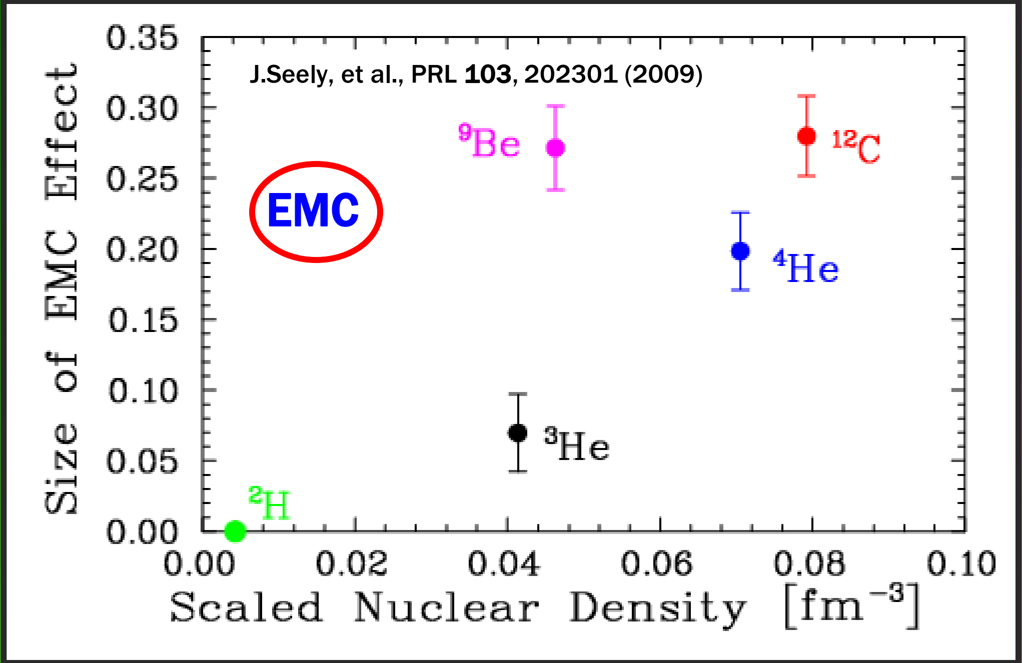


Common Density (or A) dependence → linear correlation makes sense

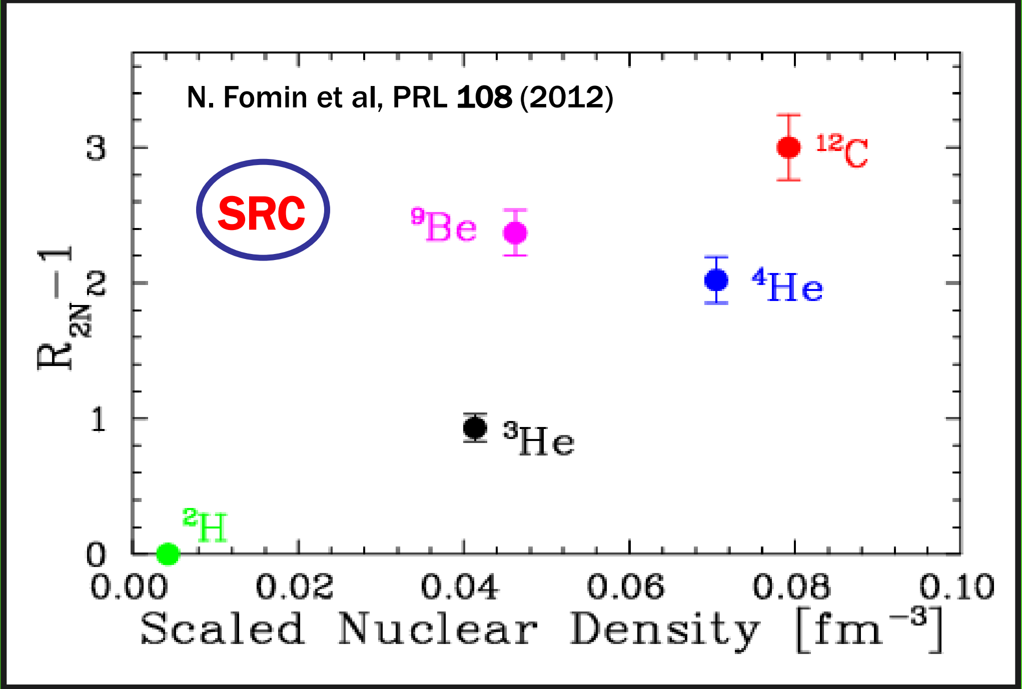




Enter ^{9}Be

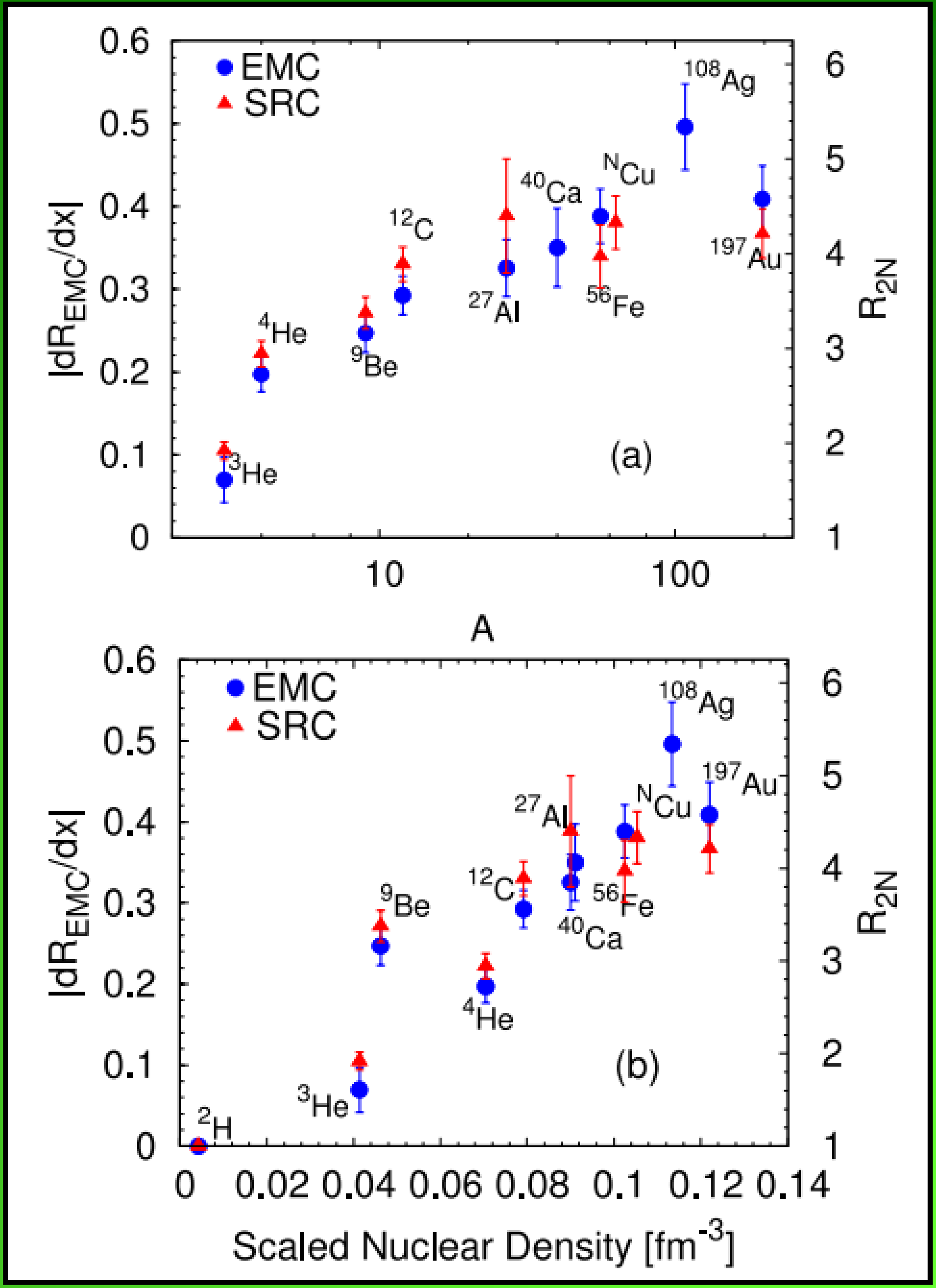


J.Seely, et al., PRL 103, 202301 (2009)
EMC
Size of EMC Effect
Scaled Nuclear Density [fm^{-3}]
^{9}Be
^{12}C
^{4}He
^{3}He
^{2}H
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.00
0.02
0.04
0.06
0.08
0.10

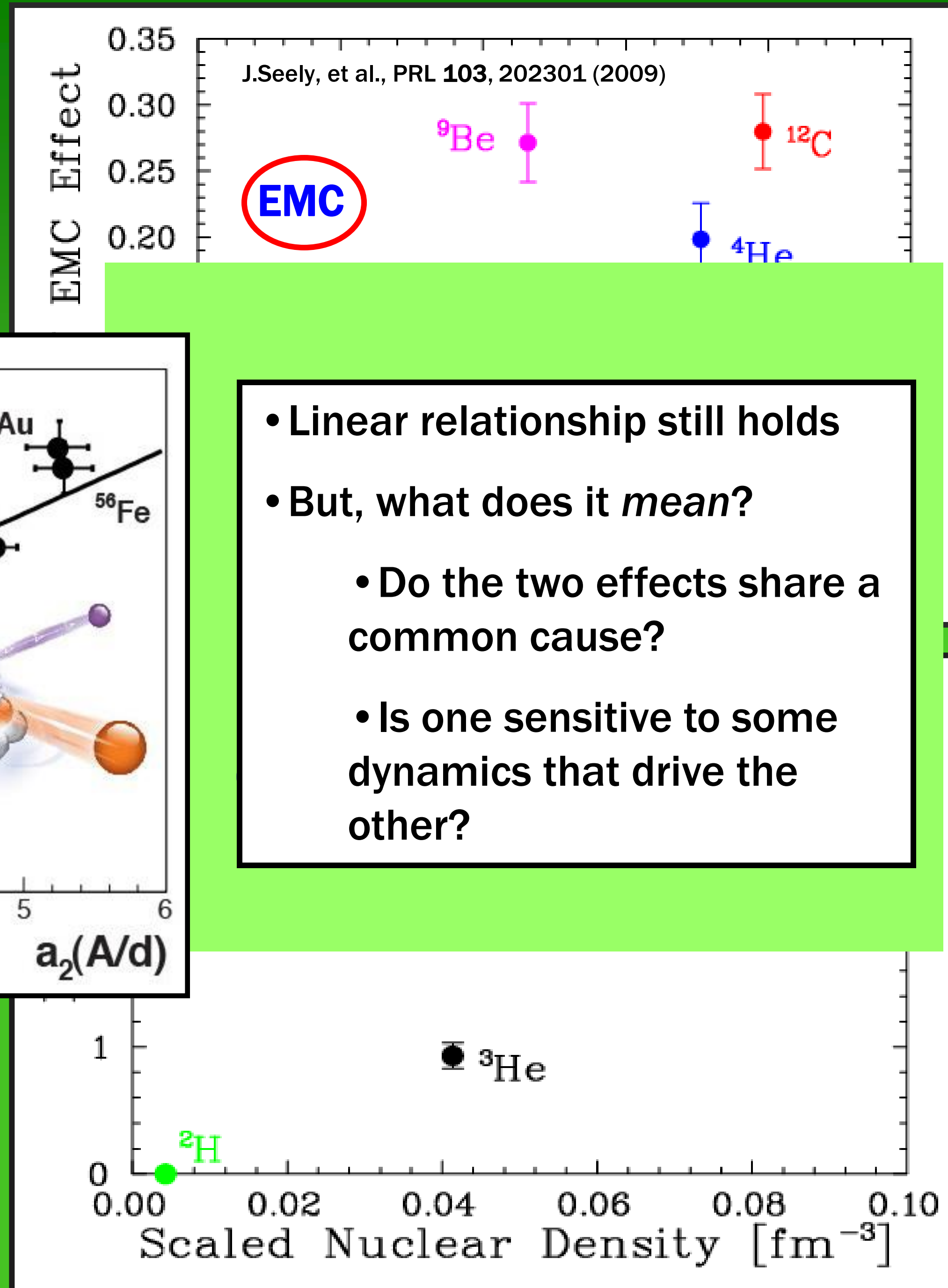


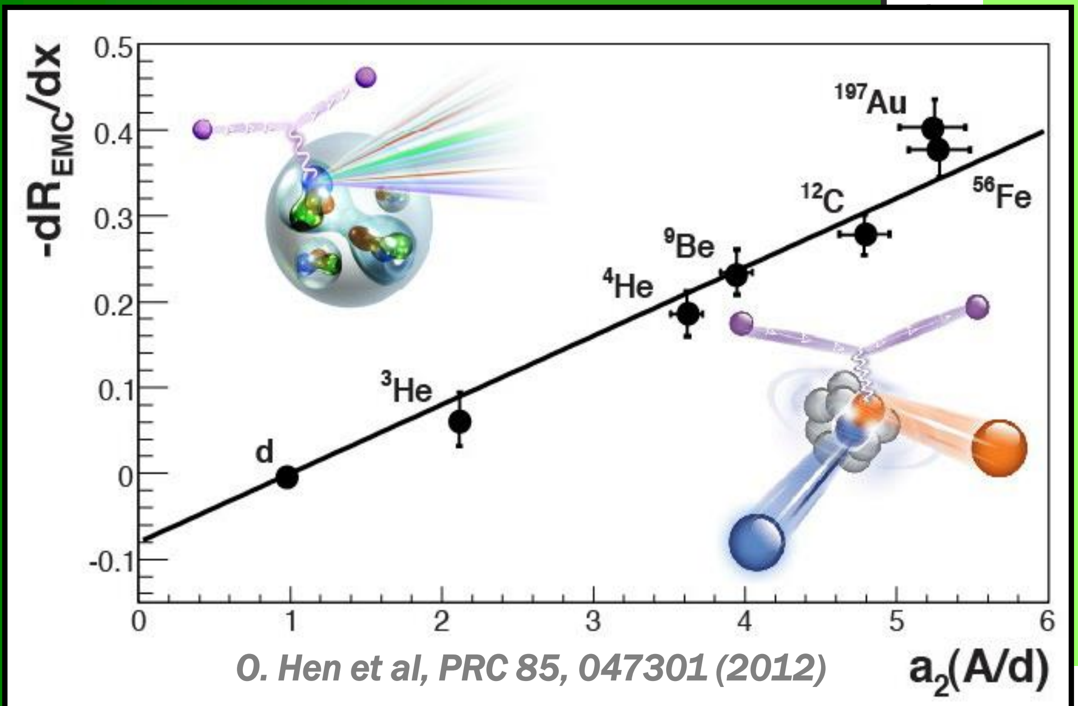
N. Fomin et al, PRL 108 (2012)
SRC
$R_{2N}-1$
Scaled Nuclear Density [fm^{-3}]
^{9}Be
^{12}C
^{4}He
^{3}He
^{2}H
3
2
1
0
0.00
0.02
0.04
0.06
0.08
0.10

- Correlation between EMC effect and SRC data can no longer be explained by common density- or A-scaling
- However, the trends for both sets of data mirror each other as a function of A, or density



Enter ^{9}Be



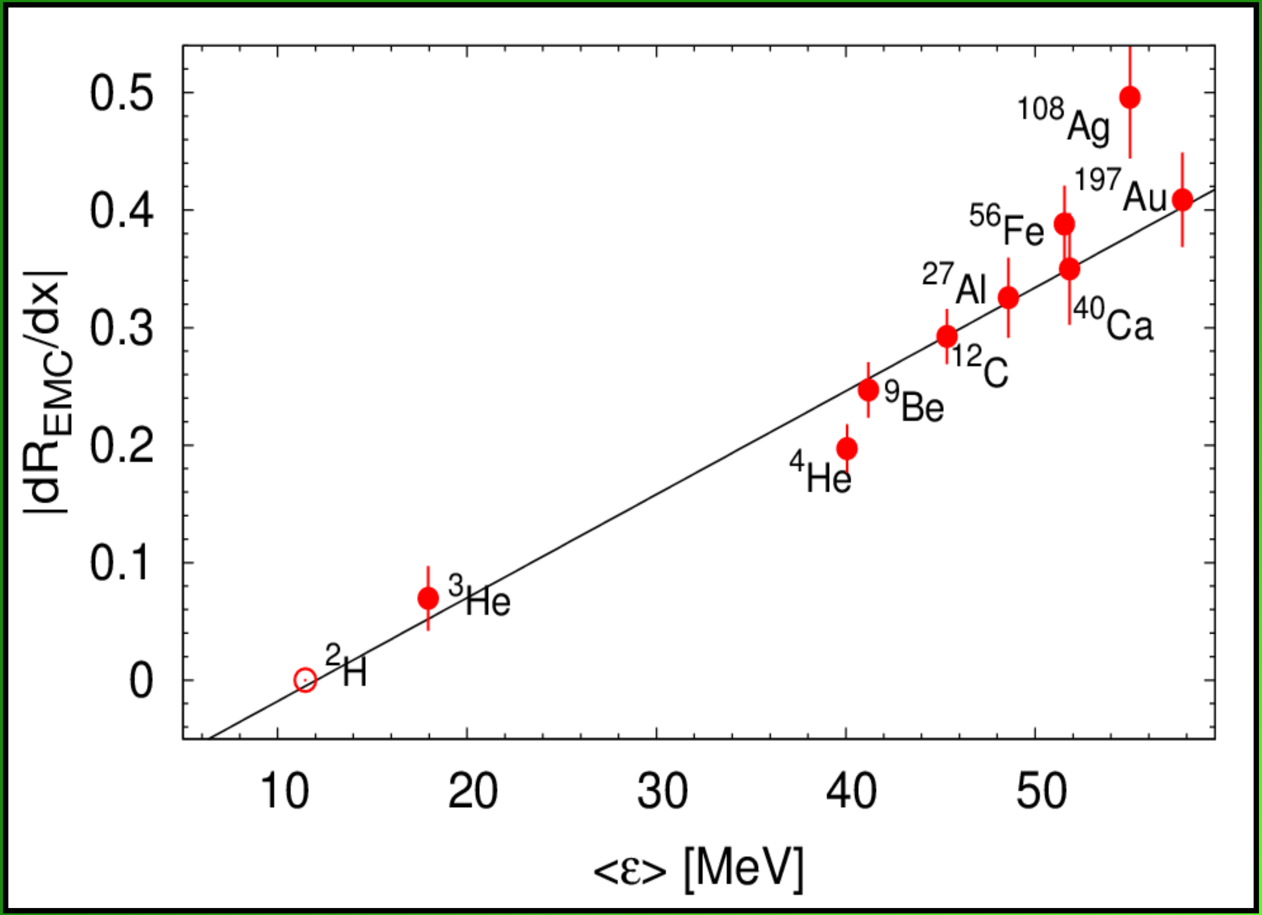


O. Hen et al, PRC 85, 047301 (2012)

- Linear relationship still holds
- But, what does it *mean*?
  - Do the two effects share a common cause?
  - Is one sensitive to some dynamics that drive the other?

Both driven by a similar underlying cause?

Separation Energy

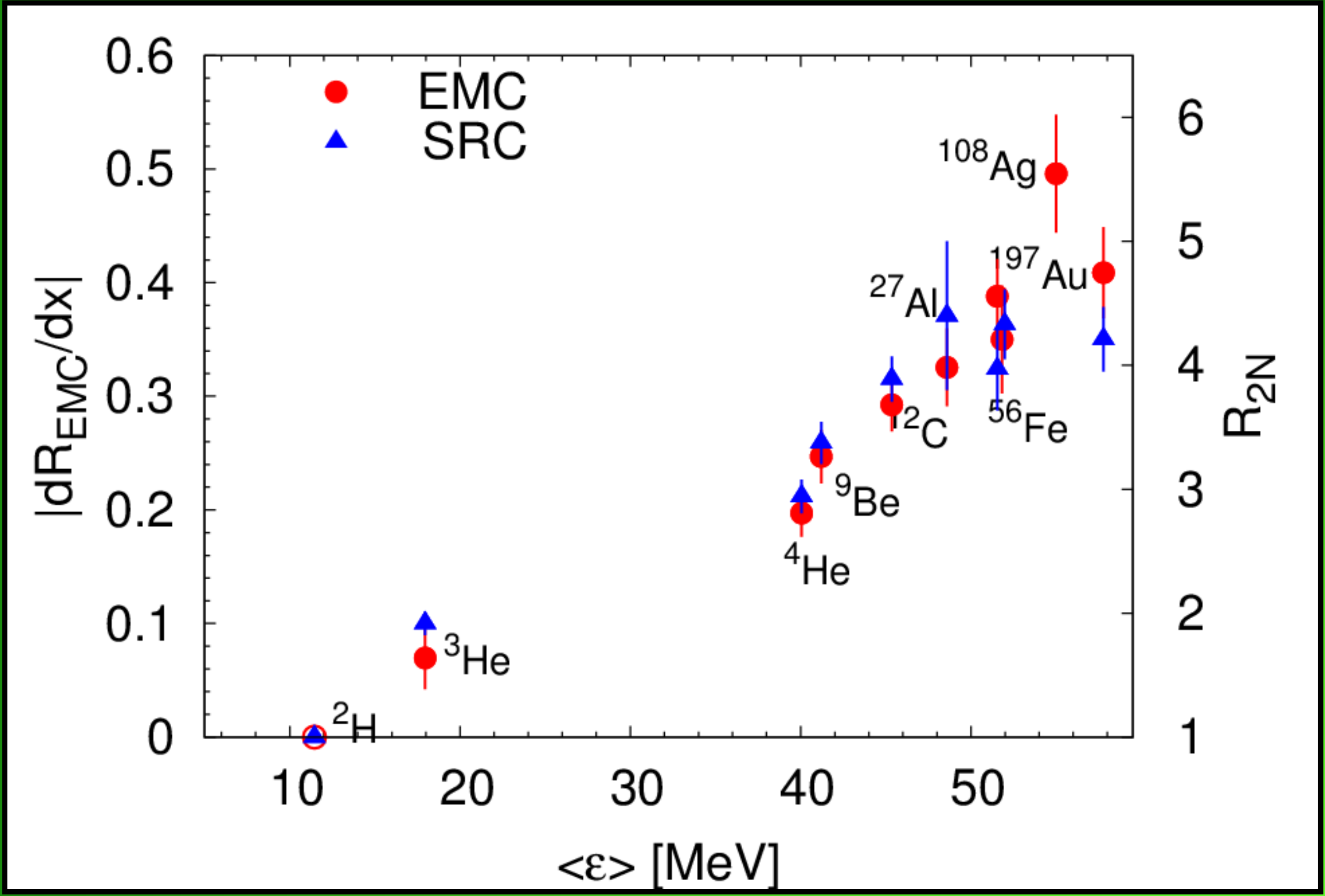


Separation energies were calculated from spectral functions, including MF and correlations

S.A. Kulagin and R. Petti, Nucl. Phys. A 176, 126 (2006)

Both driven by a similar underlying cause?

Separation Energy

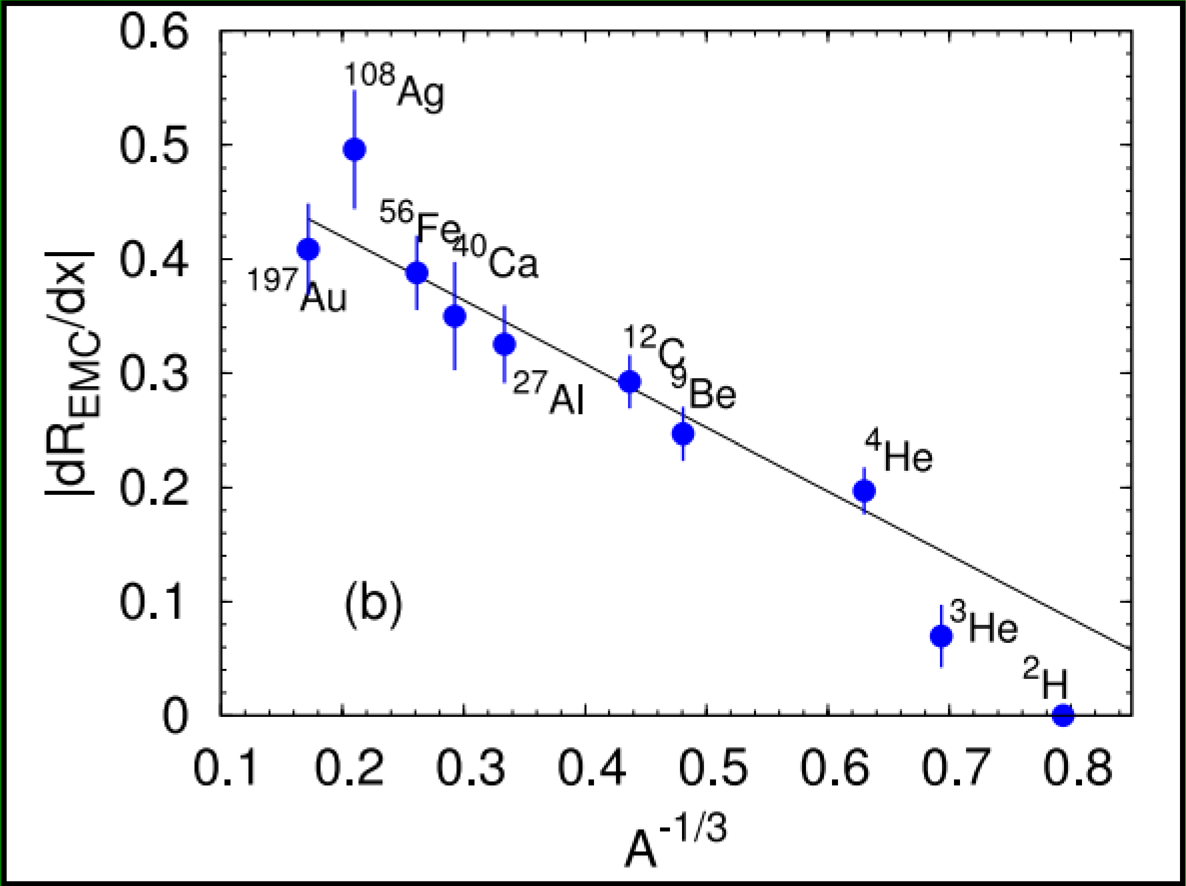


For SRCs, a linear relationship with <ε> is less suggestive

S.A. Kulagin and R. Petti, Nucl. Phys. A 176, 126 (2006)

Both driven by a similar underlying cause?

A $^{-1/3}$



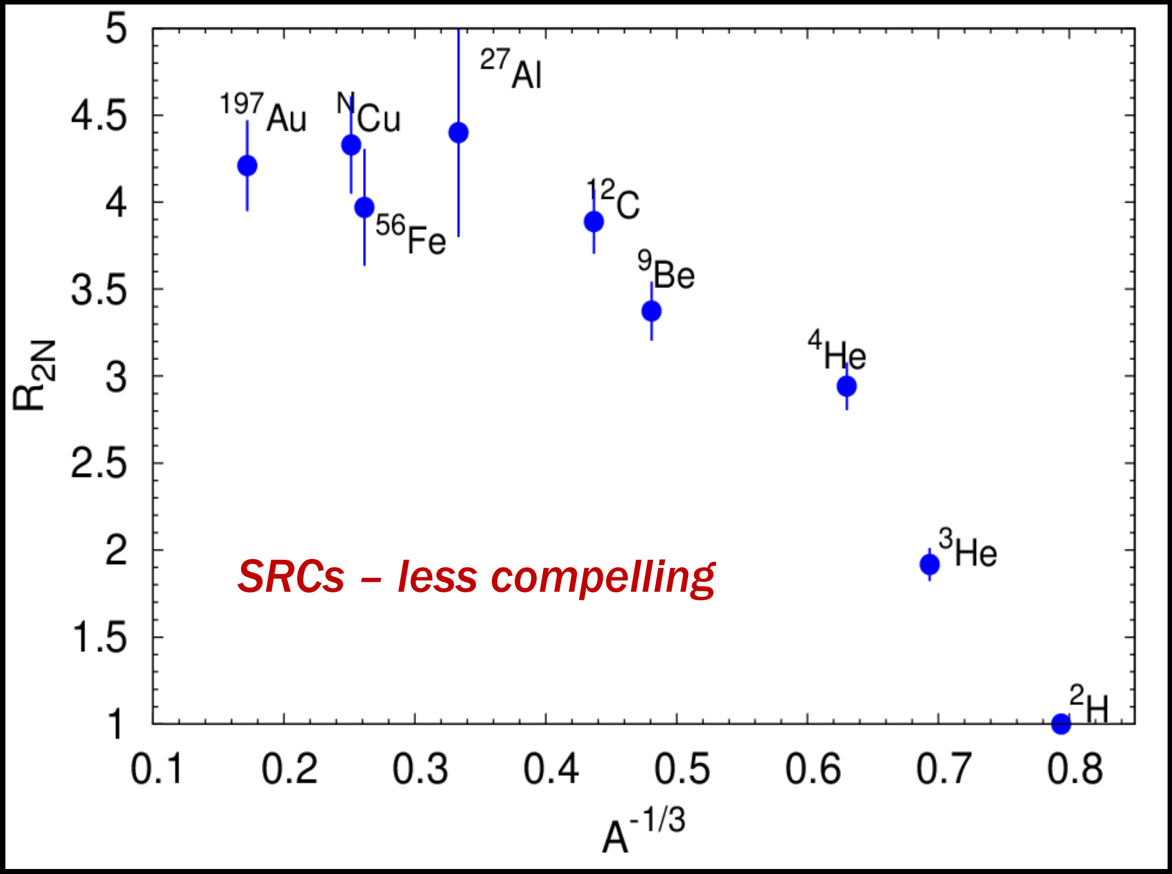
Apply exact NM calculations to finite nuclei via LDA

- *(A. Antonov and I. Petkov, Nuovo Cimento A 94, 68 (1986))*
- *(I. Sick and D. Day, Phys. Lett B 274, 16 (1992))*

- **For A>12, the nuclear density distribution has a common shape; constant in the nuclear interior (bulk)**
  → ***Scale with A***
- **Nuclear surface contributions grow *as* $A^{2/3}$ (R^2)**
- **σ per nucleon would be constant with small deviations that go with $A^{-1/3}$**

Both driven by a similar underlying cause?

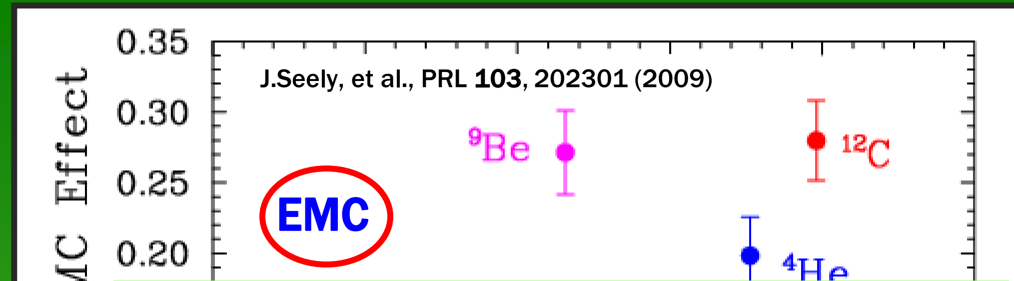
$A^{-1/3}$

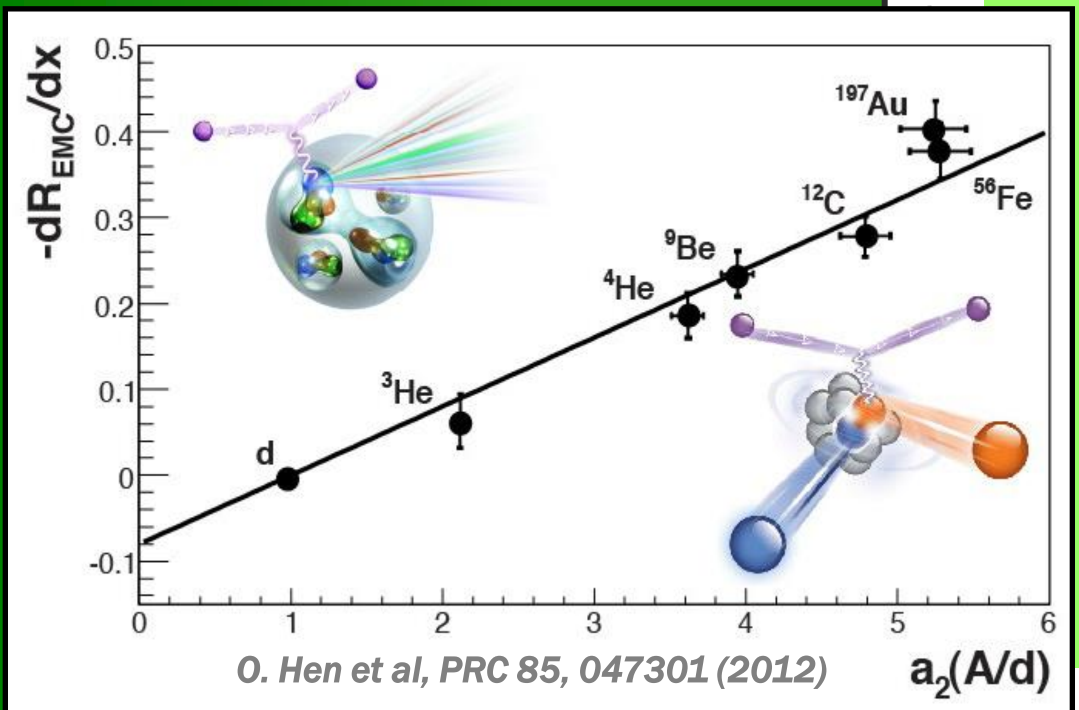


Apply exact NM calculations to finite nuclei via LDA

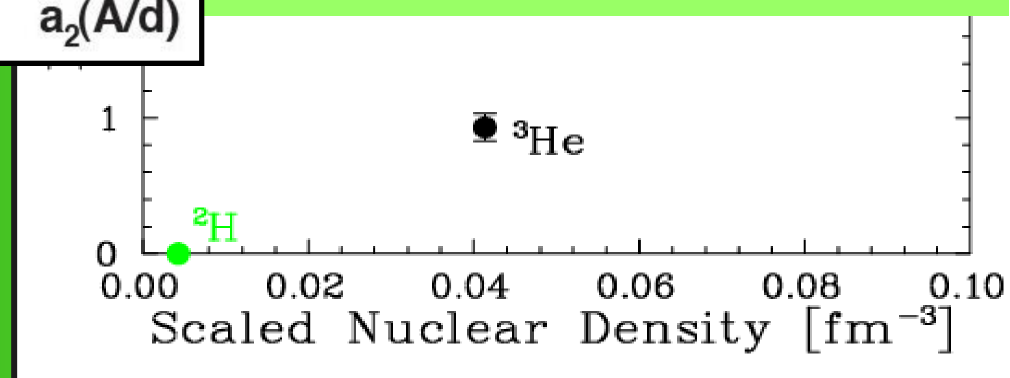
- *(A. Antonov and I. Petkov, Nuovo Cimento A 94, 68 (1986)*
- *(I. Sick and D. Day, Phys. Lett B 274, 16 (1992))*

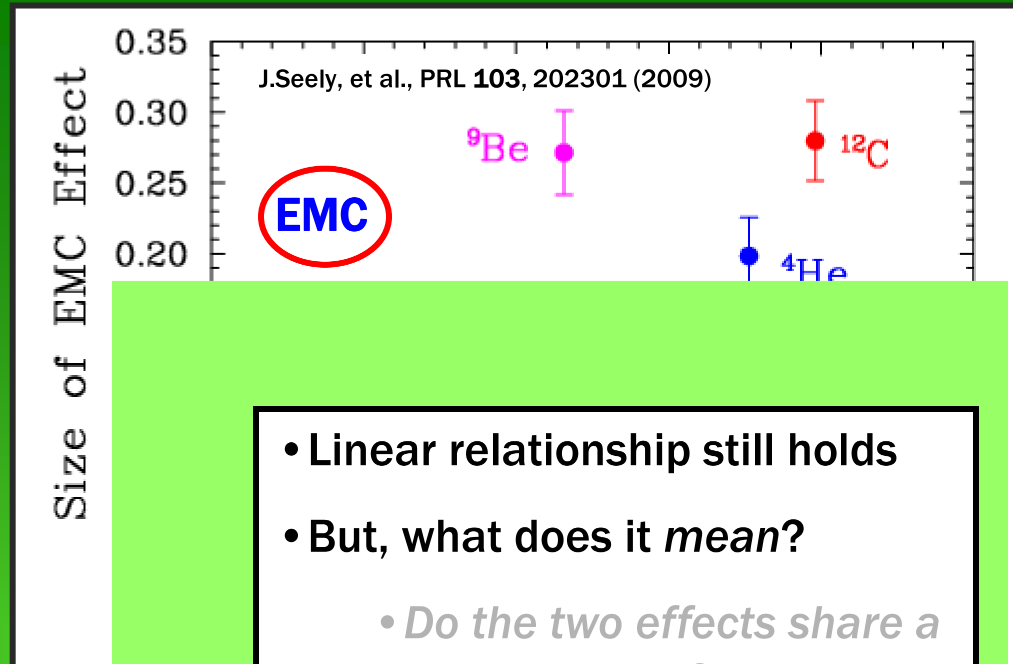
- For A>12, the nuclear density distribution has a common shape; constant in the nuclear interior (bulk)
  → ***Scale with A***
- Nuclear surface contributions grow ***as*** $A^{2/3}$ (R^2)
- σ per nucleon would be constant with small deviations that go with $A^{-1/3}$





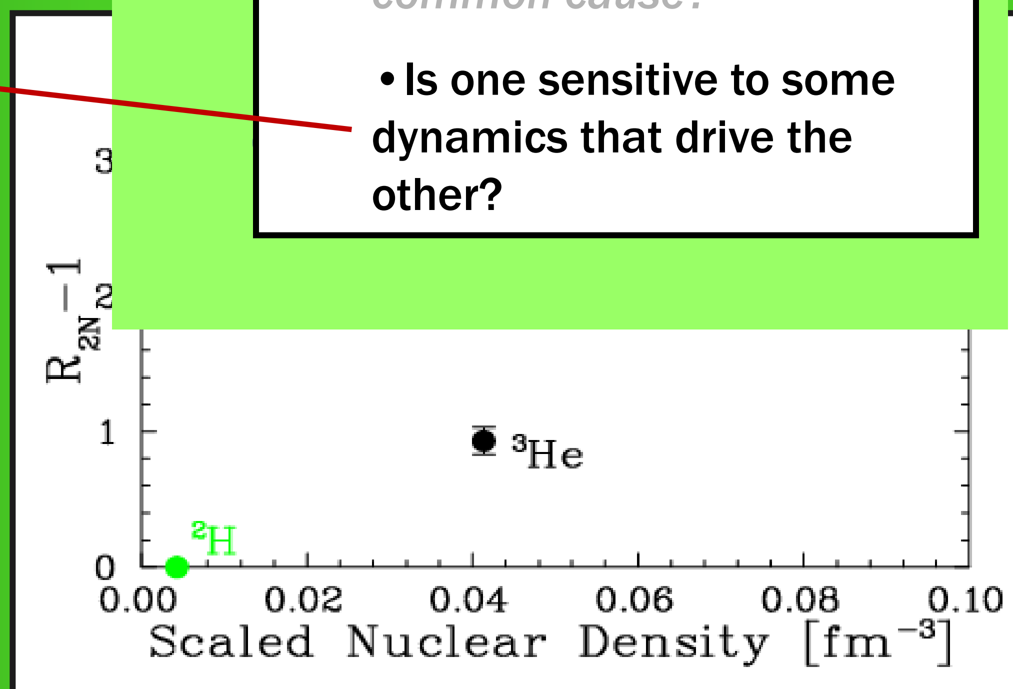
- Linear relationship still holds
- But, what does it *mean*?
  - Do the two effects share a common cause?
  - Is one sensitive to some dynamics that drive the other?





- All the usual (historical) suspects don't adequately describe the trends seen in both sets of data
- Perhaps, SRCs are an indirect (or not so indirect) measure of what drives medium modification

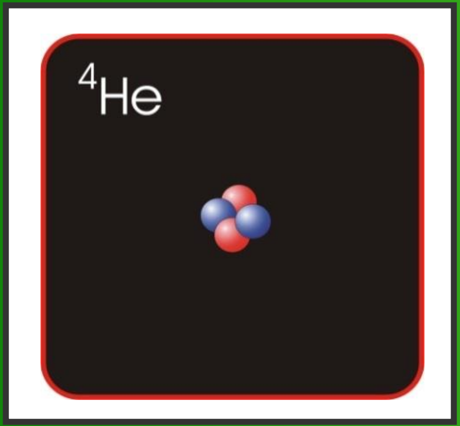
- Linear relationship still holds
- But, what does it *mean*?
  - *Do the two effects share a common cause?*
  - Is one sensitive to some dynamics that drive the other?



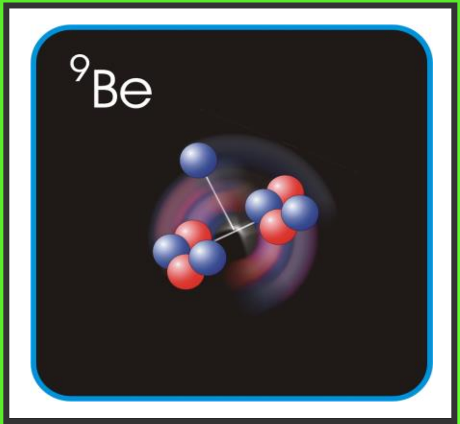
Two Hypotheses

1. Both quantities reflect ***virtuality*** of the nucleons (*L. Weinstein et al, PRL 106:052301,2011*)
   - ***a_2*** measures the relative high momentum tail – good for testing virtuality
   - dR_{EMC}/dx – relevant quantity

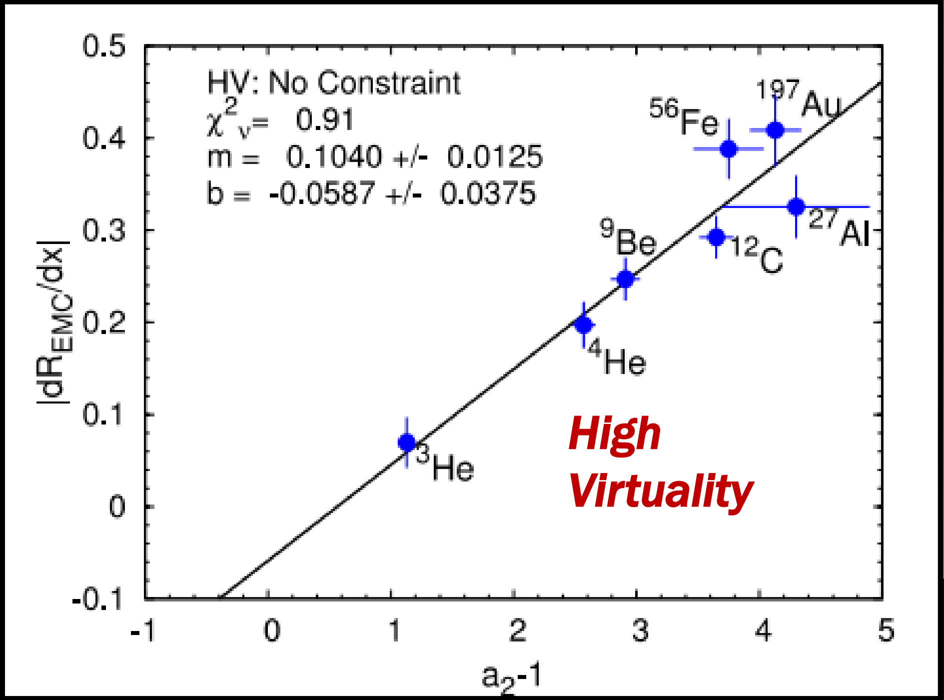
2. EMC effect is driven by ***"local density"***
   - SRCs are sensitive to high density configurations, but MUST remove the center of mass motion smearing to get ***R_{2N}***
     – measure of correlated pairs relative to the deuteron
   - EMC effect samples ***all*** the nucleons, whereas ***R_{2N}*** is only sensitive to *np* pairs, a subset of all possible NN configurations
     - If we're going to use SRCs as a measure of local density, must scale ***R_{2N}*** by N_{total}/N_{iso}.



Now that we have the relevant quantities, we can test the two hypotheses



Two hypotheses



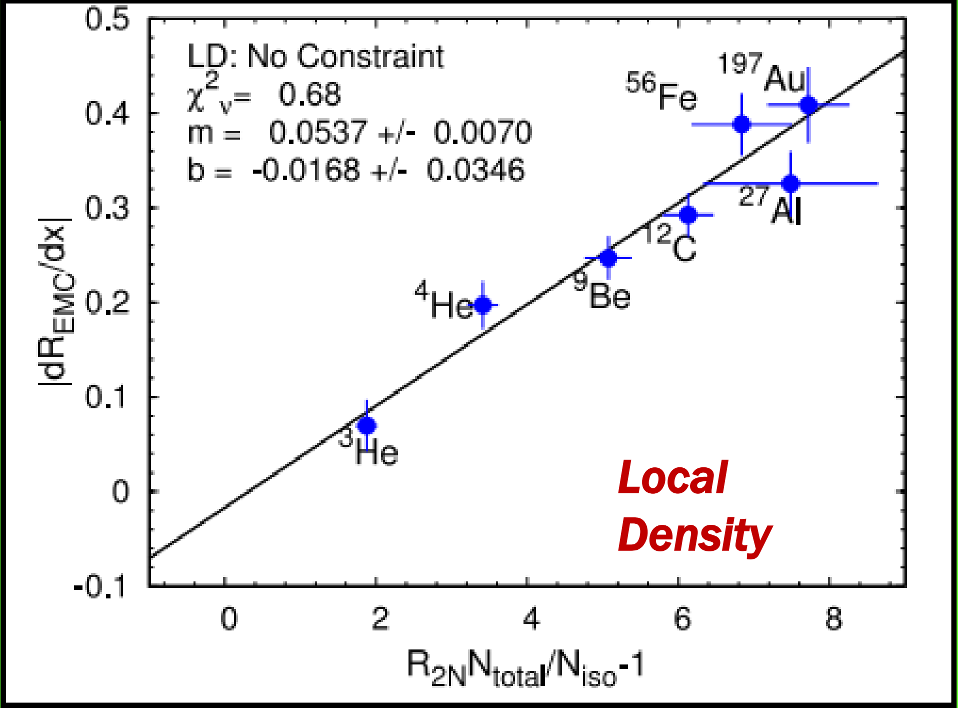
1. Both quantities reflect ***virtuality*** of the nucleons (*L. Weinstein et al, PRL 106:052301,2011*)
   - ***a_2 is a measure of high momentum nucleons relative to the deuteron***

2. A measure of "***local density***"

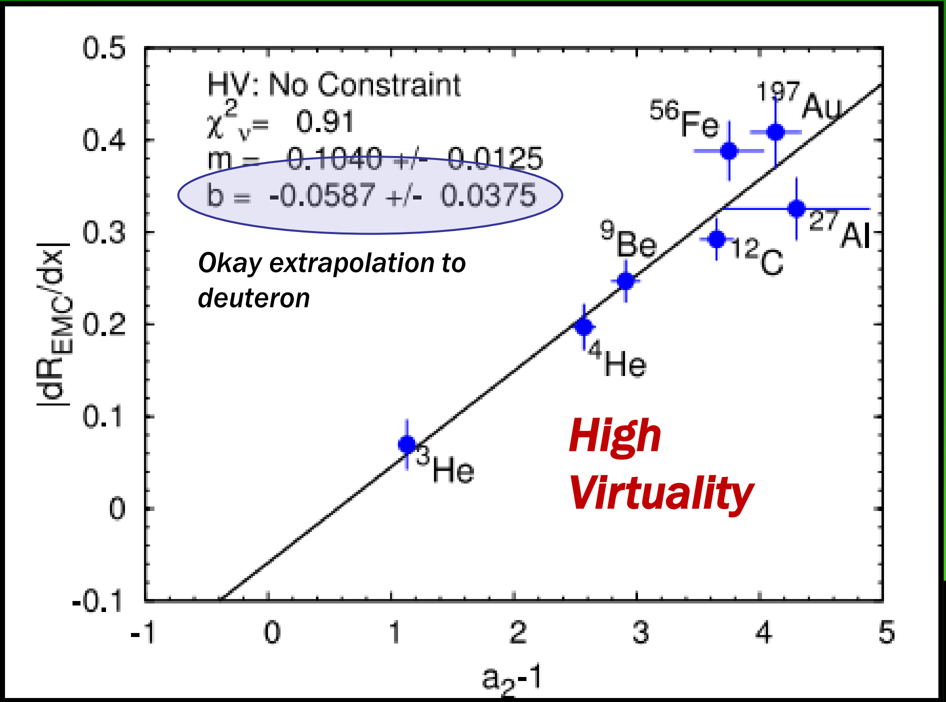
   R_{2N}

   – *measure of correlated pairs relative to the deuteron*

   - *Only sensitive to **np** pairs, scale by N_{total}/N_{iso}.*

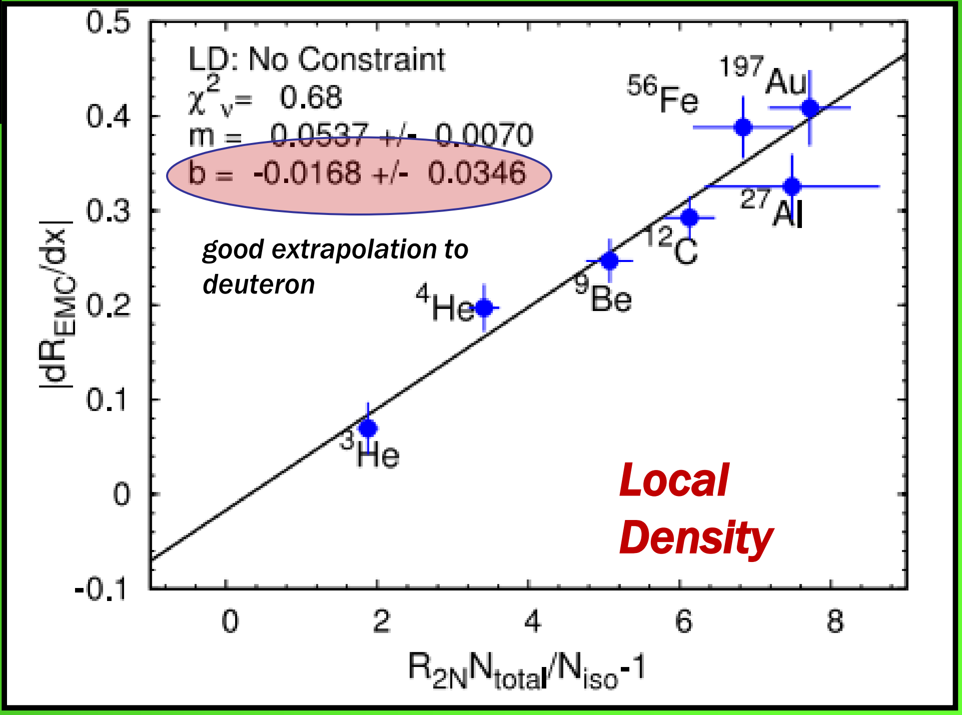


Two hypotheses



1. Both quantities reflect ***virtuality*** of the nucleons (*L. Weinstein et al, PRL 106:052301,2011*)
   - ***a_2 is a measure of high momentum nucleons relative to the deuteron***

2. A measure of "***local density***"
   R_{2N}
   – measure of correlated pairs relative to the deuteron
   *- Only sensitive to **np** pairs, scale by N_{total}/N_{iso}.*



Hypothesis	Fit type	χ^2_ν	EMC(D)	IMC(D)
High Virtuality	2-param No constraints	0.91	-0.0587±0.037	0.1040±0.012
High Virtuality	1-param	1.17	–	0.0856±0.004
High Virtuality	2-param D-constraint	1.14	-0.0041±0.010	0.0869±0.005
Local Density	2-param No constraints	0.68 (0.83)	-0.0168±0.035	0.0537±0.007
Local Density	1-param	0.61 (0.73)	–	0.0505±0.003
Local Density	2-param D-constraint	0.61 (0.73)	-0.0013 ±0.010	0.0508±0.003

Each hypothesis is tested with 3 types of fits:

1) 2-parameter linear fit, no deuteron constraint
2) 1-parameter fit, strict deuteron constraint
3) 2–parameter fit, deuteron constraint, partial accounting for correlated errors within a given experiment

Hypothesis	Fit type	χ^2_ν	EMC(D)	IMC(D)
High Virtuality	2-param No constraints	0.91	-0.0587±0.037	0.1040±0.012
High Virtuality	1-param	1.17	–	0.0856±0.004
High Virtuality	2-param D-constraint	1.14	-0.0041±0.010	0.0869±0.005
Local Density	2-param No constraints	0.68 (0.83)	-0.0168±0.035	0.0537±0.007
Local Density	1-param	0.61 (0.73)	–	0.0505±0.003
Local Density	2-param D-constraint	0.61 (0.73)	-0.0013 ±0.010	0.0508±0.003

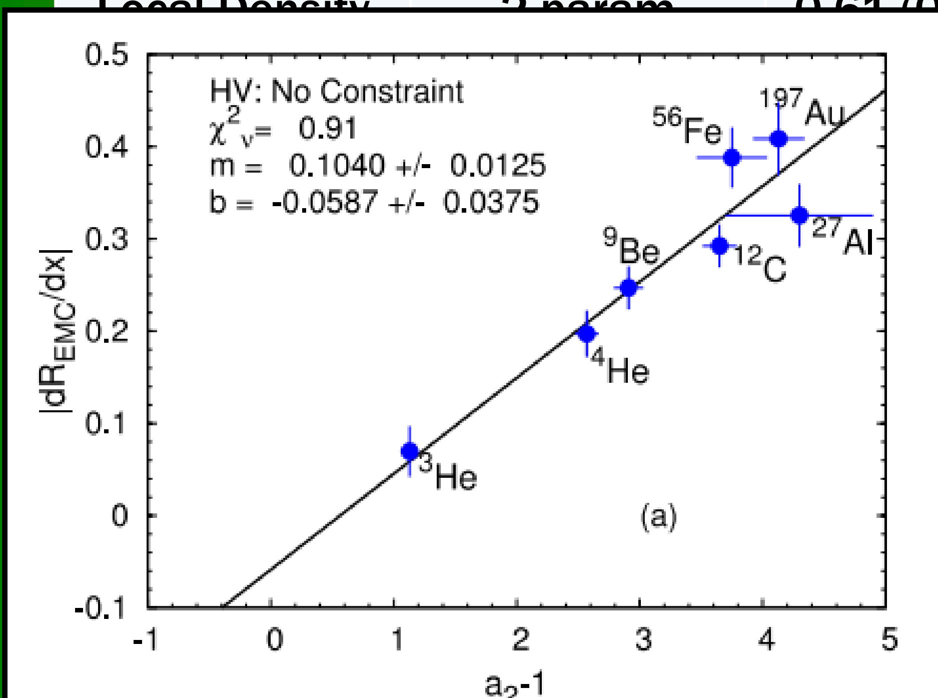
Hypothesis	Fit type	χ^2_ν	EMC(D)	IMC(D)
High Virtuality	2-param No constraints	0.91	-0.0587±0.037	0.1040±0.012
High Virtuality	1-param	1.17	–	0.0856±0.004
High Virtuality	2-param D-constraint	1.14	-0.0041±0.010	0.0869±0.005
Local Density	2-param No constraints	0.68 (0.88)	-0.0168±0.031	0.0537±0.007
Local Density	1-param	0.61 (0.73)	–	0.0505±0.003
Local Density	2-param D-constraint	0.61 (0.73)	-0.0013 ±0.010	0.0508±0.003

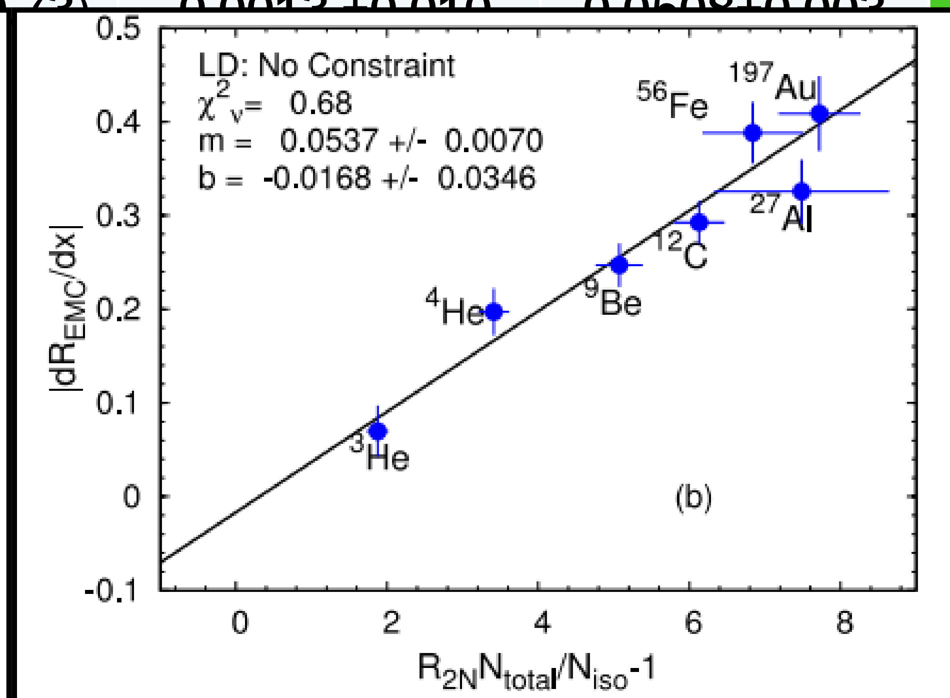
$$\left.\frac{dR_{IMC}}{dx}\right|_D = \left.\frac{dR_{EMC}}{dx}\right|_{a_2 = 0} - \left|\frac{dR_{EMC}}{dx}\right|_D$$

IMC effect → in-medium correction effect, the ratio of the DIS cross section per nucleon bound in a nucleus relative to the free (unbound) pn pair cross section

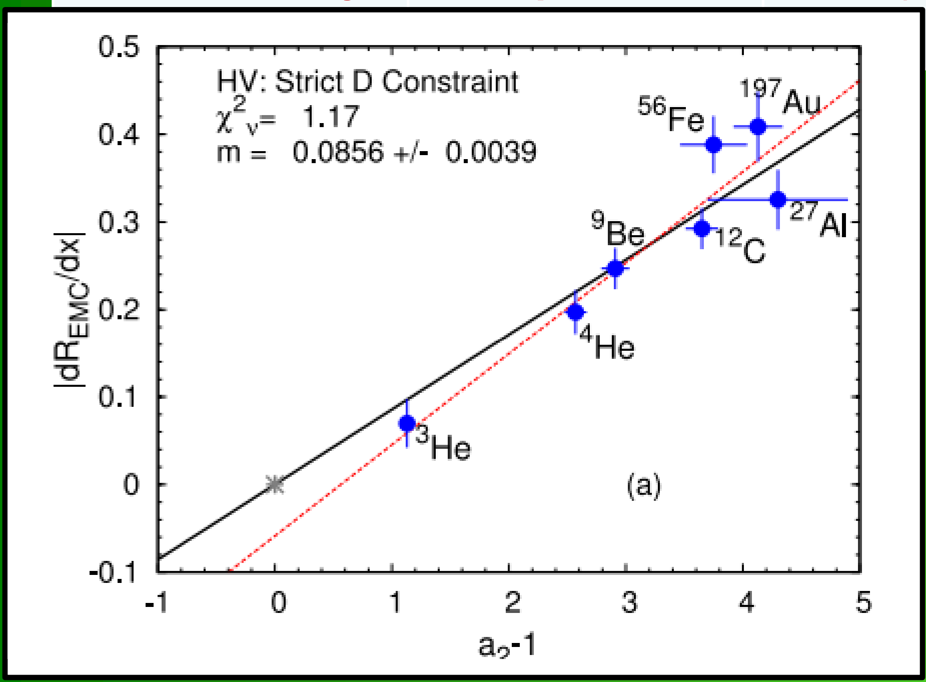
L. Weinstein et al, PRL 106:052301,2011

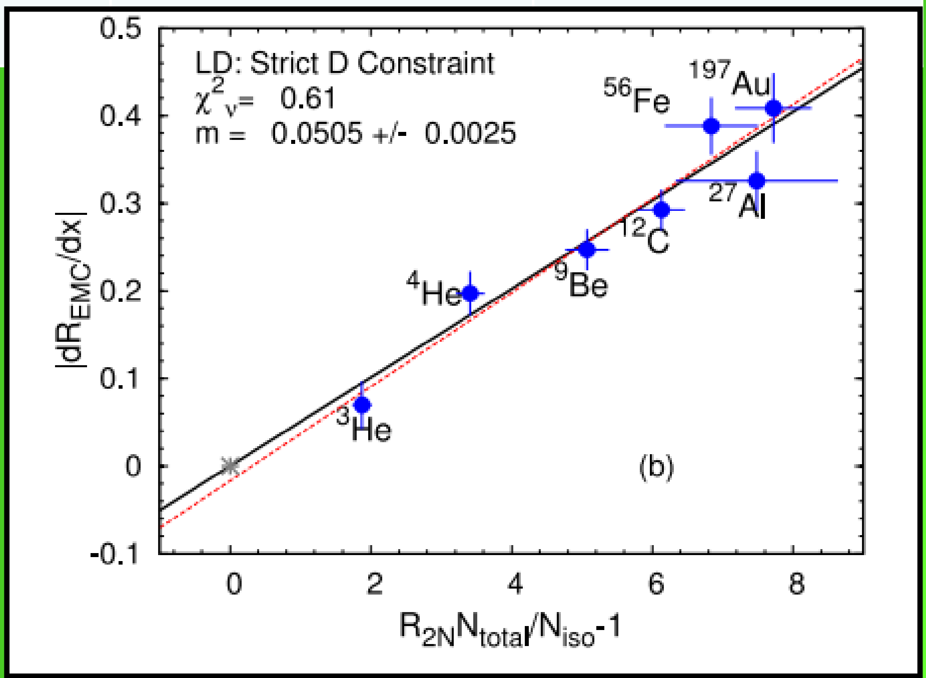
Hypothesis	Fit type	χ^2_ν	EMC(D)	IMC(D)
High Virtuality	***2-param No constraints***	***0.91***	***-0.0587±0.037***	***0.1040±0.012***
High Virtuality	1-param	1.17	–	0.0856±0.004
High Virtuality	2-param D-constraint	1.14	-0.0041±0.010	0.0869±0.005
Local Density	***2-param No constraints***	***0.68 (0.83)***	***-0.0168±0.035***	***0.0537±0.007***
Local Density	1-param	0.61 (0.73)	–	0.0505±0.003
Local Density	2-param	0.61 (0.73)	0.0013±0.010	0.0508±0.003



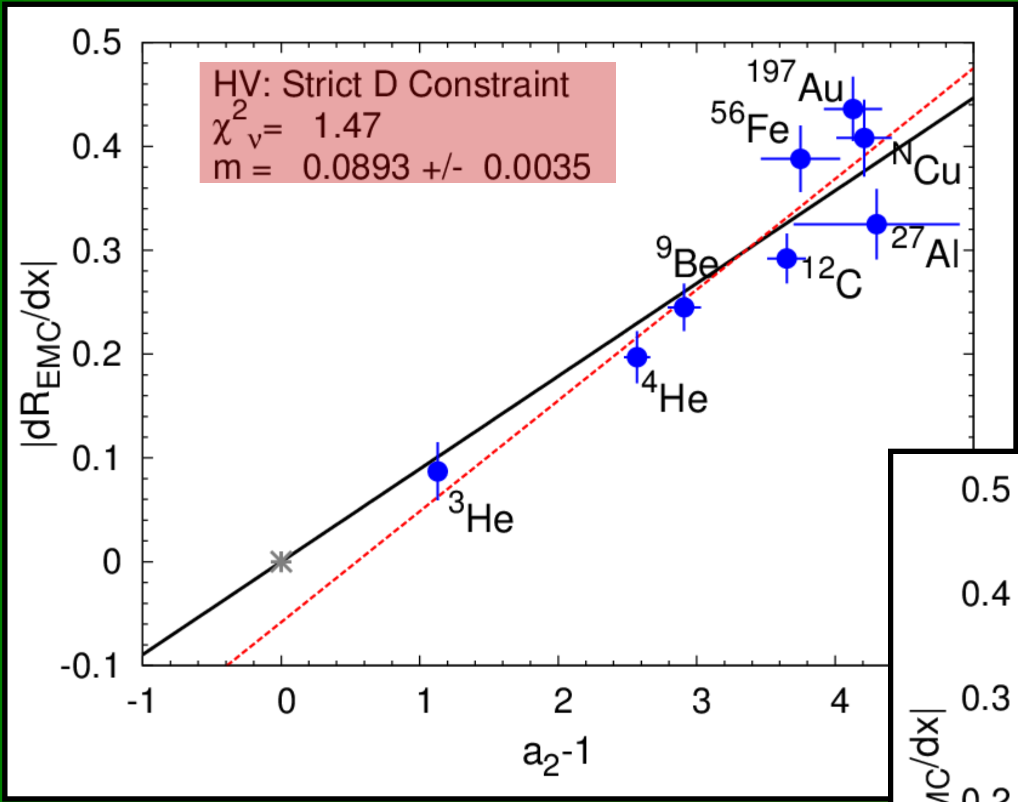


Hypothesis	Fit type	χ^2_ν	EMC(D)	IMC(D)
High Virtuality	2-param No constraints	0.91	-0.0587±0.037	0.1040±0.012
High Virtuality	***1-param***	***1.17***	***–***	***0.0856±0.004***
High Virtuality	***2-param D-constraint***	***1.14***	***-0.0041±0.010***	***0.0869±0.005***
Local Density	2-param No constraints	0.68 (0.83)	-0.0168±0.035	0.0537±0.007
Local Density	***1-param***	***0.61 (0.73)***	***–***	***0.0505±0.003***
Local Density	***2-param***	***0.61 (0.73)***	***-0.0013 ±0.010***	***0.0508±0.003***

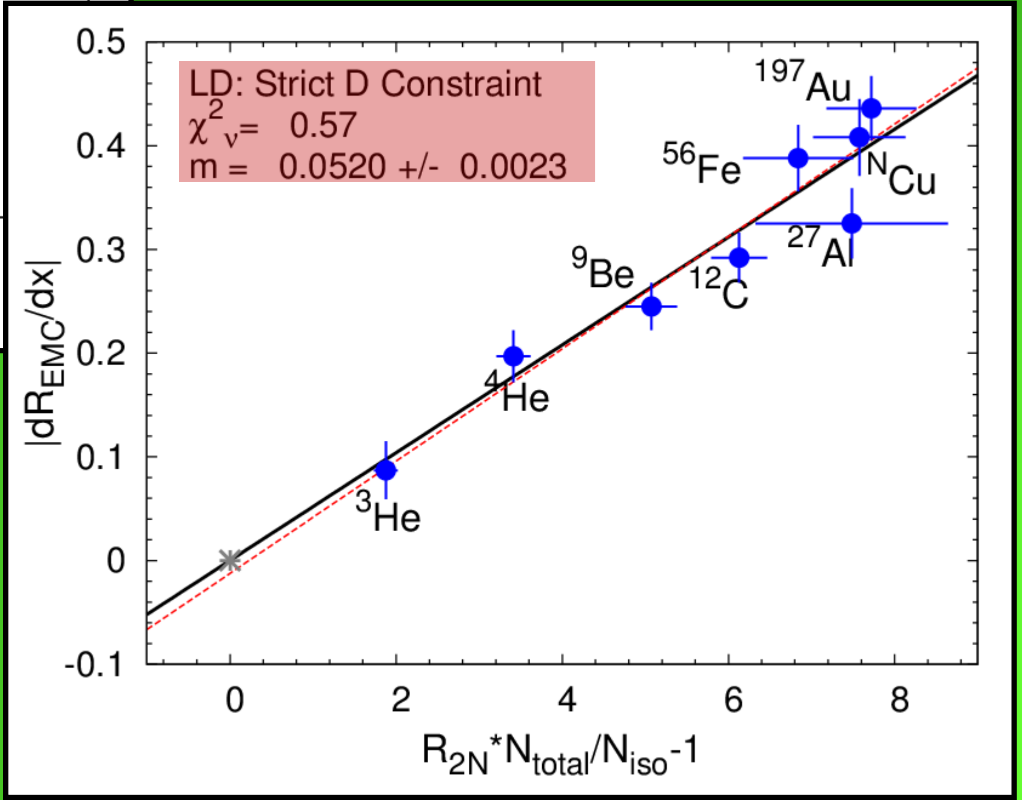




New Data are helping and more data will help even further

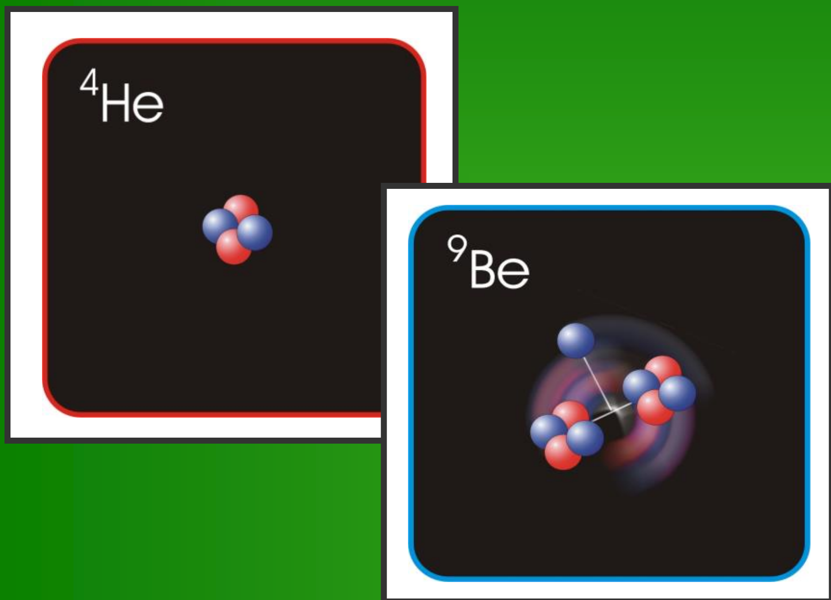


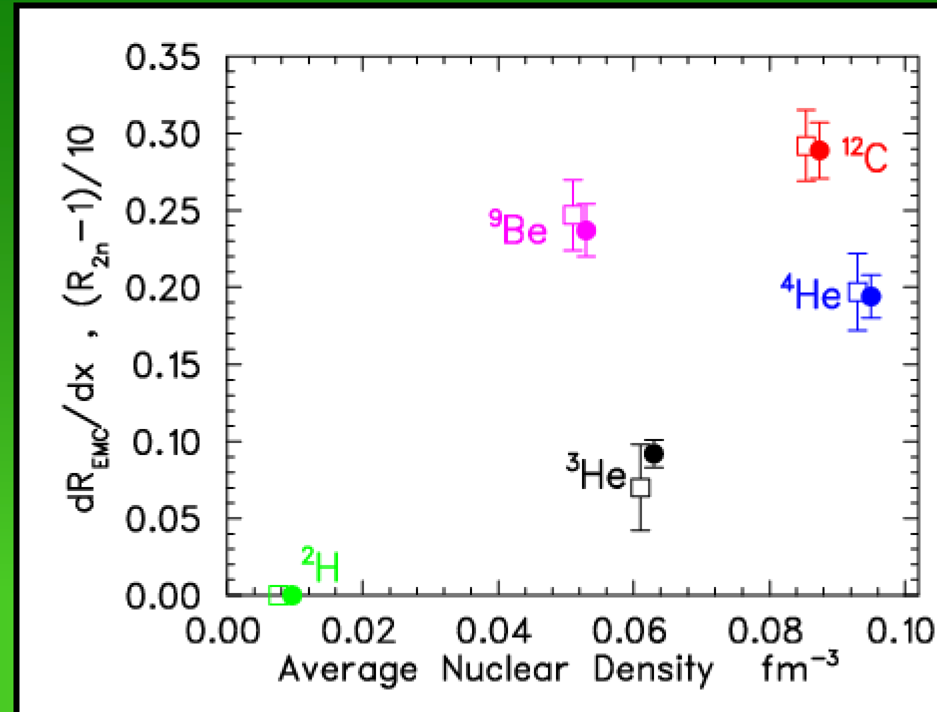
Heavy target data from Jlab E03-103 (Cu, Au)



Compare χ^2 of **1.47 and 0.57** to χ^2 of **1.14 and 0.61**, respectively

Why local density?





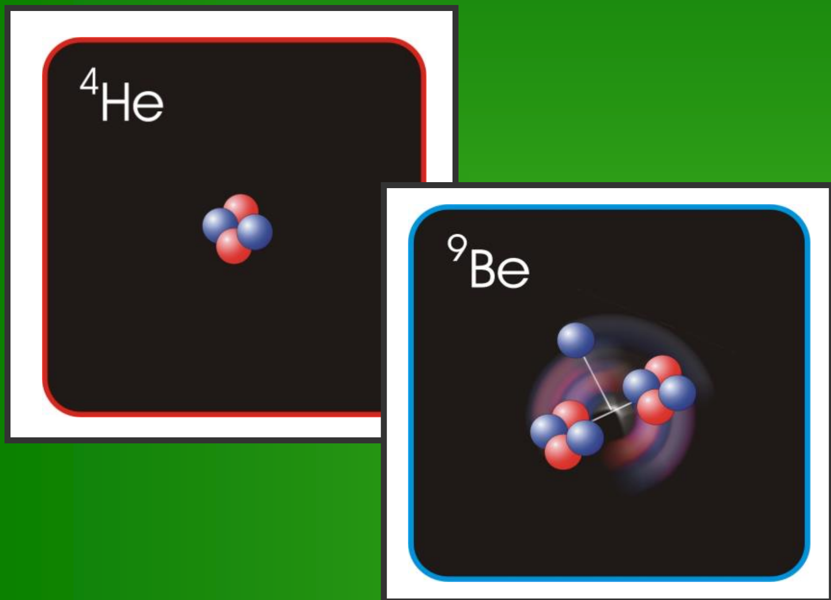
- SRCs mirror same behavior

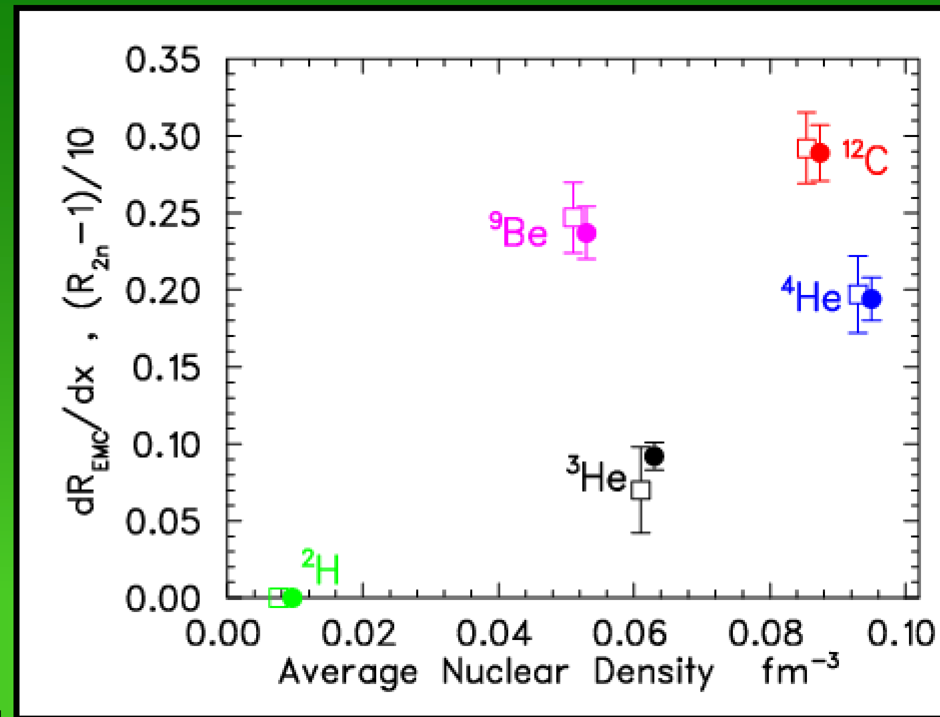
Nucleons can have significant overlap before feeling the repulsive force

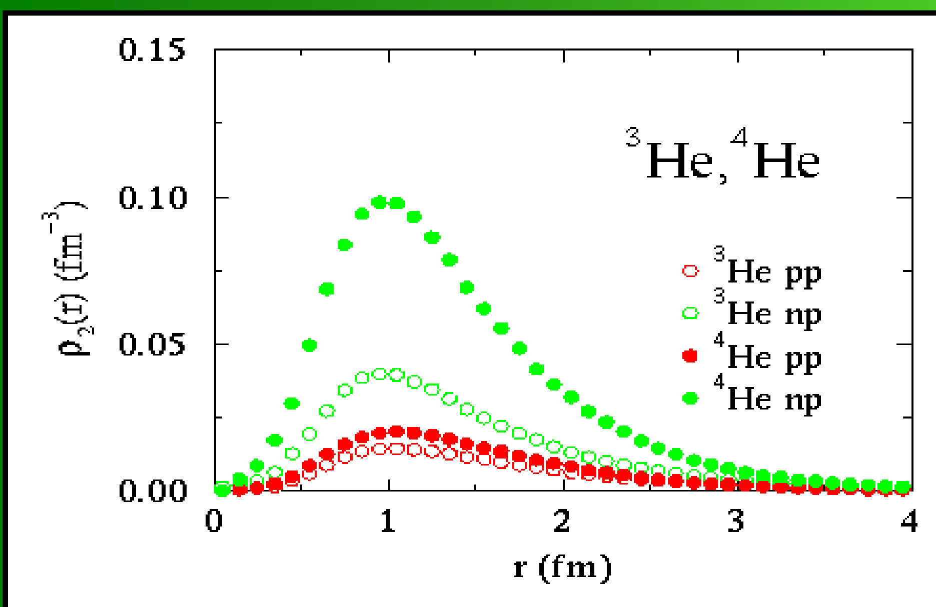
We can calculate this overlap using 2-body density distributions via

$$\int_0^\infty W(r)\rho_2^{NN}(r)d^3r$$

Why local density?





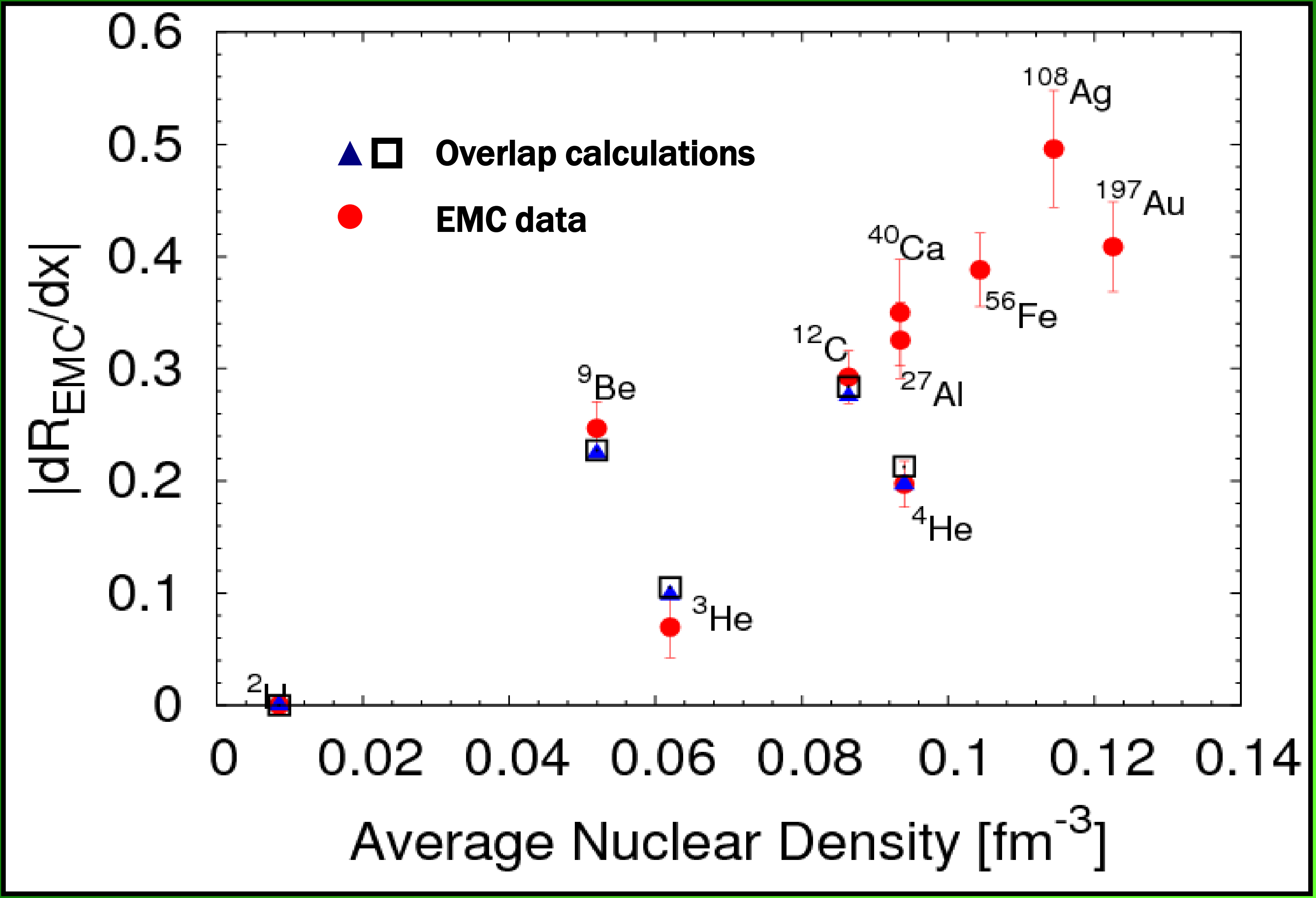


Nucleons can have significant overlap before feeling the repulsive force

We can calculate this overlap using 2-body density distributions via

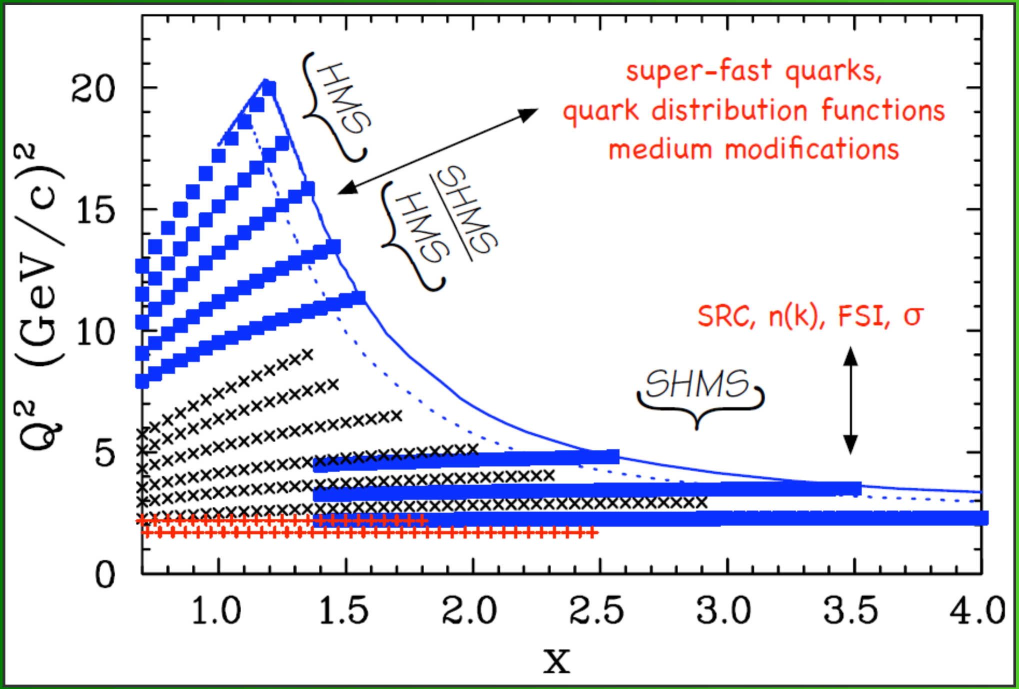
$$\int_0^\infty W(r)\rho_2^{NN}(r)d^3r$$

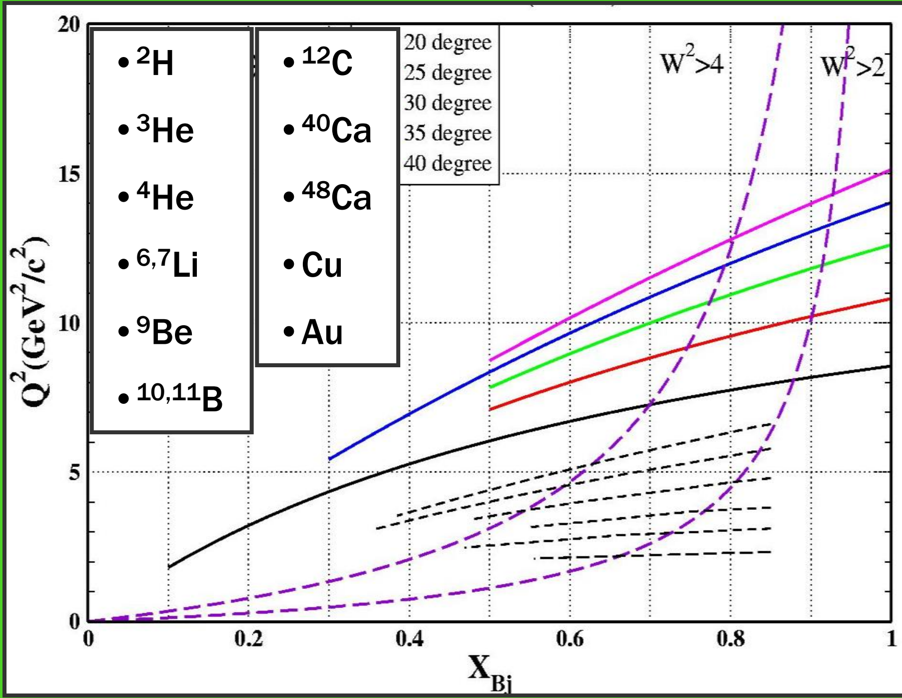
NN Overlap exhibits same density dependence

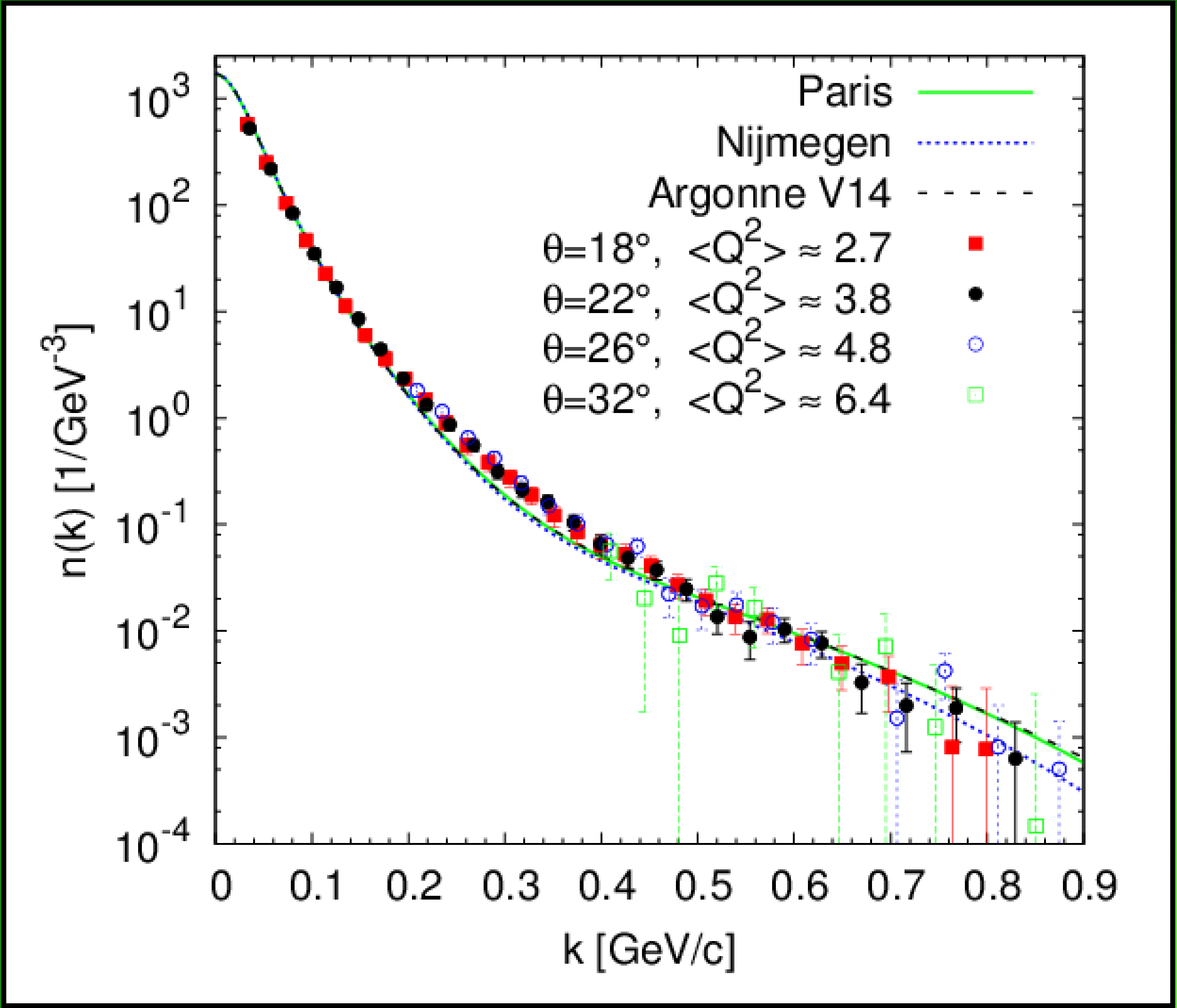


Summary

- New results suggest a local density dependence of the EMC effect as well as SRCs
- These hints and suggestions need to be further investigated with new experiments, focusing on light targets
  - E12-06-105 (x>1) approved at Jlab
  - E12-10-008 (EMC effect) approved at Jlab

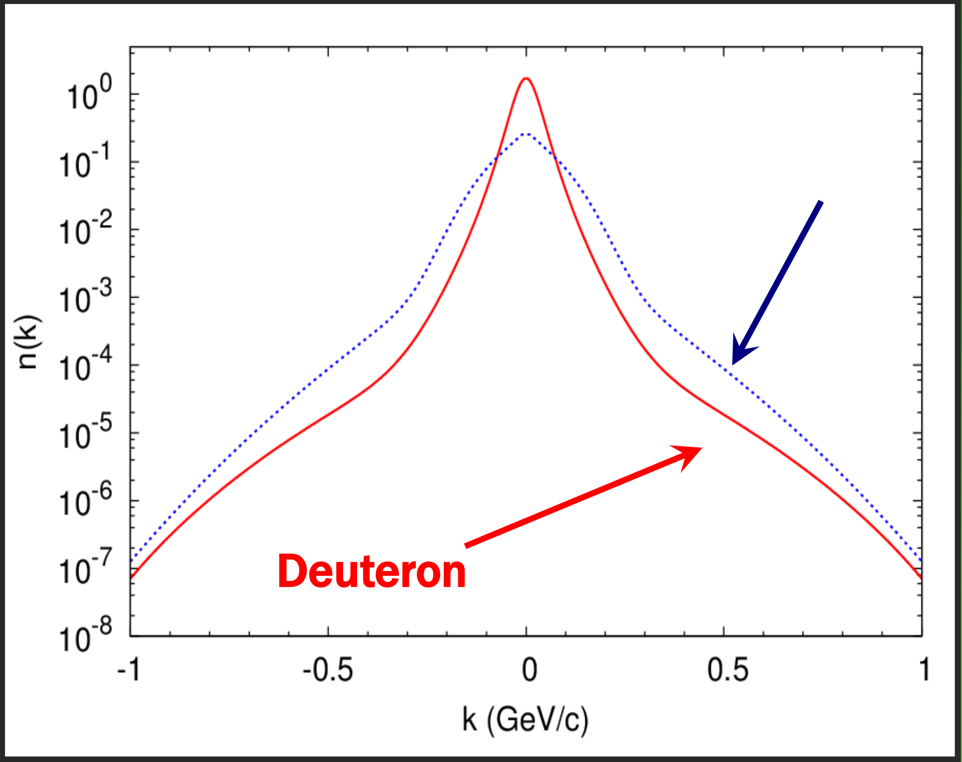




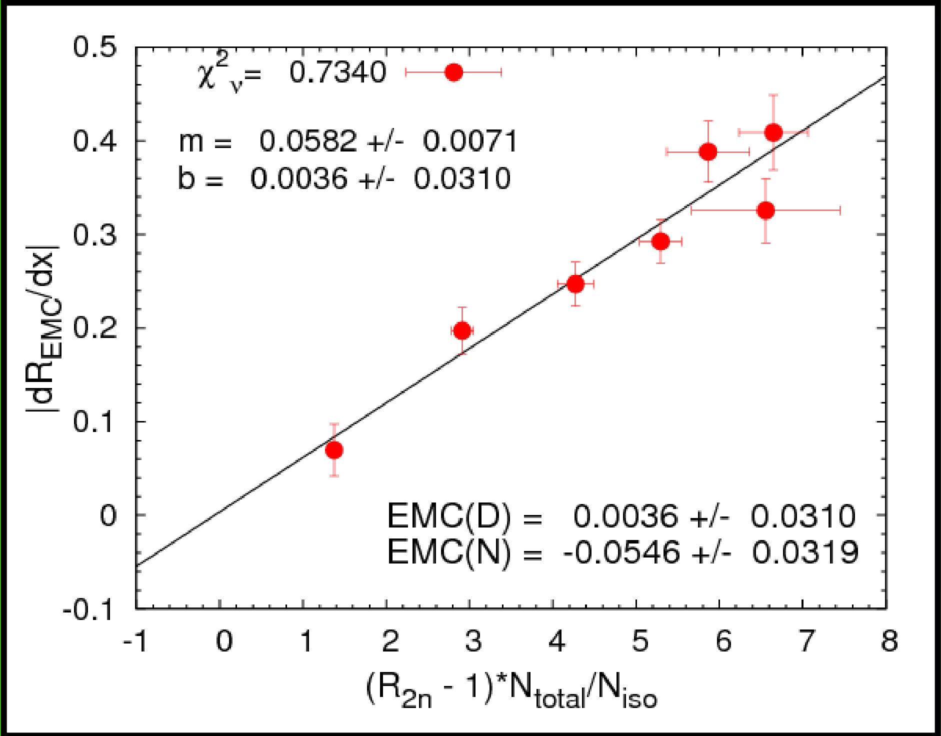


Paris
Nijmegen
Argonne V14
θ=18°, <Q^2> ≈ 2.7
θ=22°, <Q^2> ≈ 3.8
θ=26°, <Q^2> ≈ 4.8
θ=32°, <Q^2> ≈ 6.4
n(k) [1/GeV^-3]
k [GeV/c]
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Two hypotheses

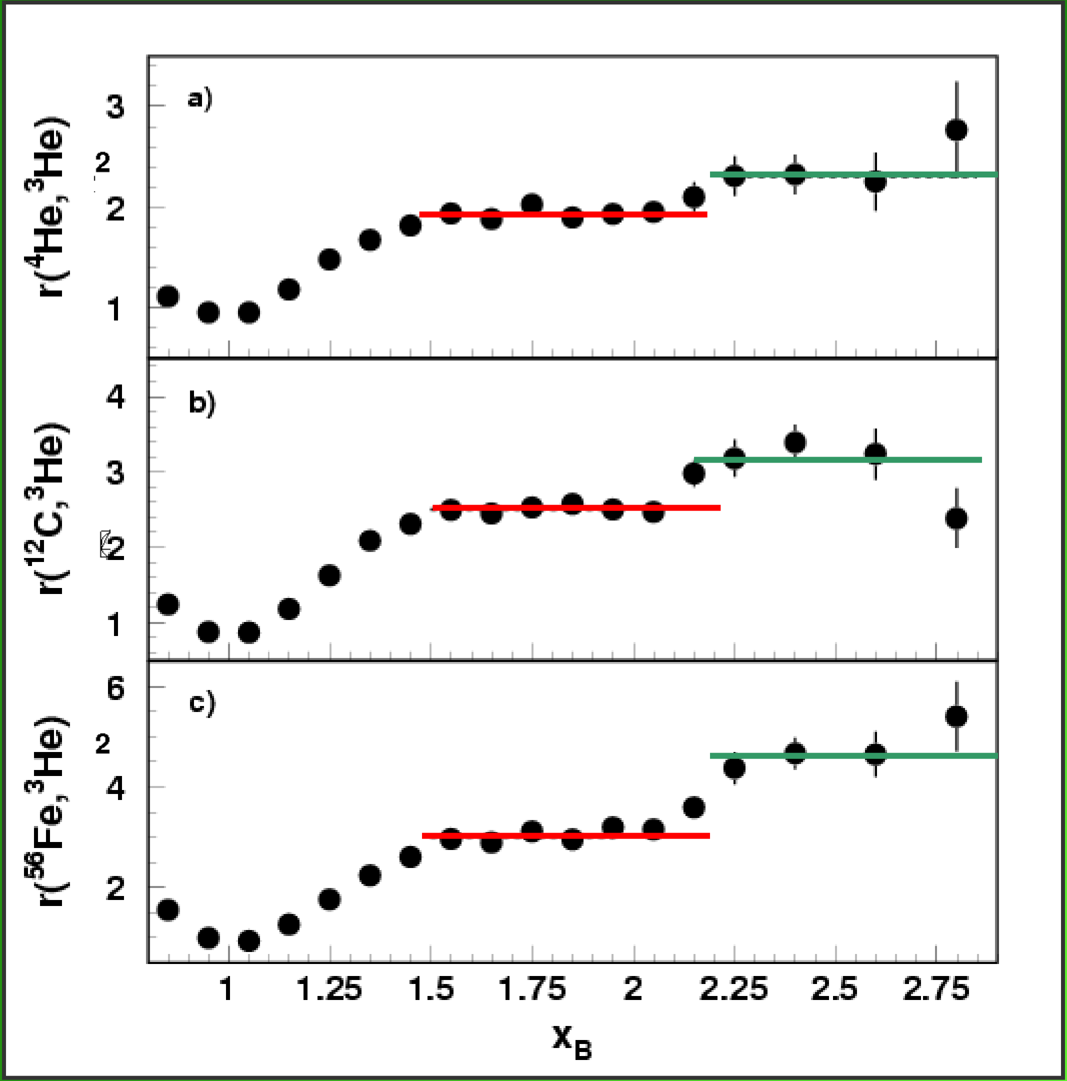


$$R_{2N} = a_2 / \frac{n_D^{CONV}(k)}{n_D(k)}$$



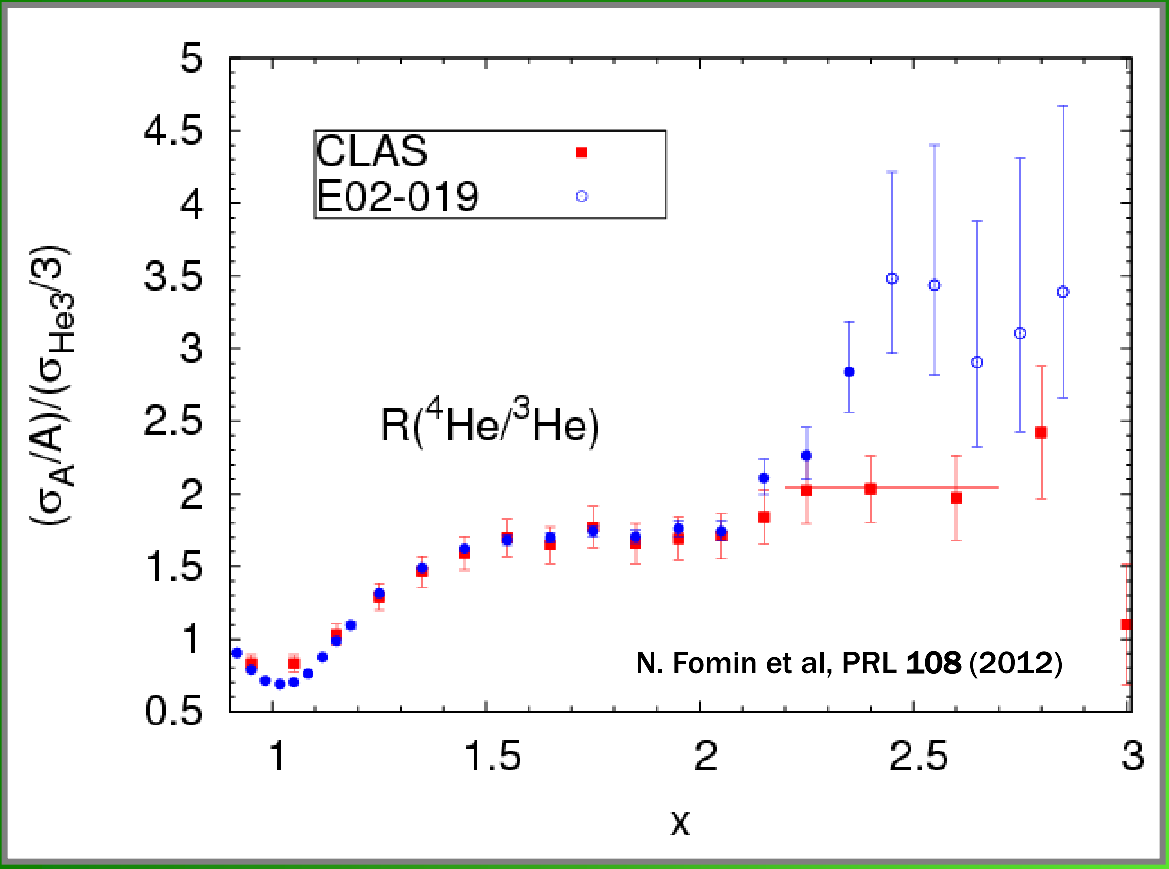
2. A measure of "local density"
   R_{2n}
   – measure of correlated pairs relative to the deuteron
   *- Only sensitive to **np** pairs, scale by N_{total}/N_{iso}.*

Short Range Correlations – 3N



Egiyan et al, PRL 96, 2006

E02-019 Ratios

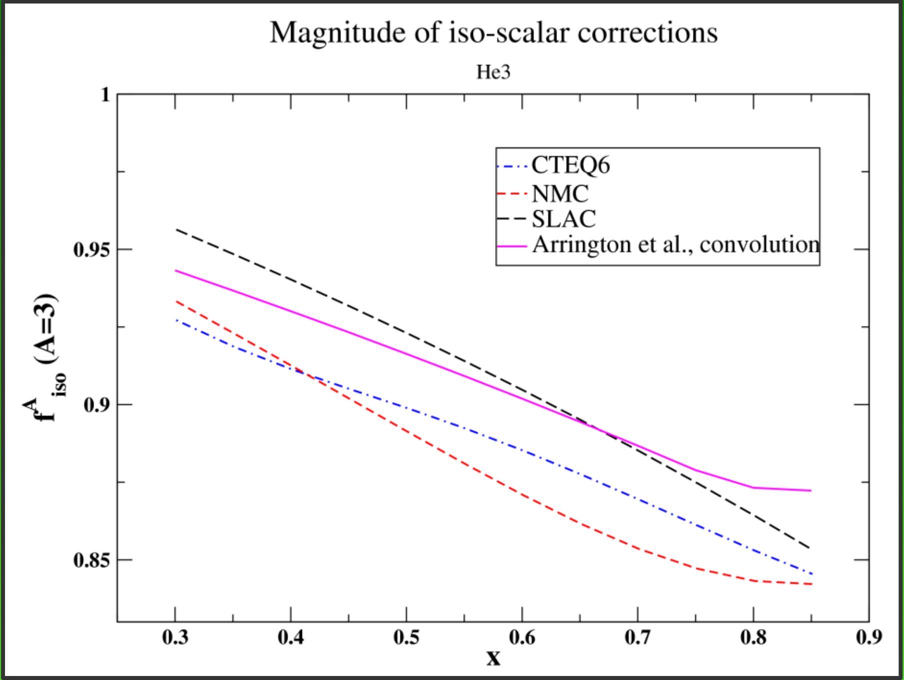


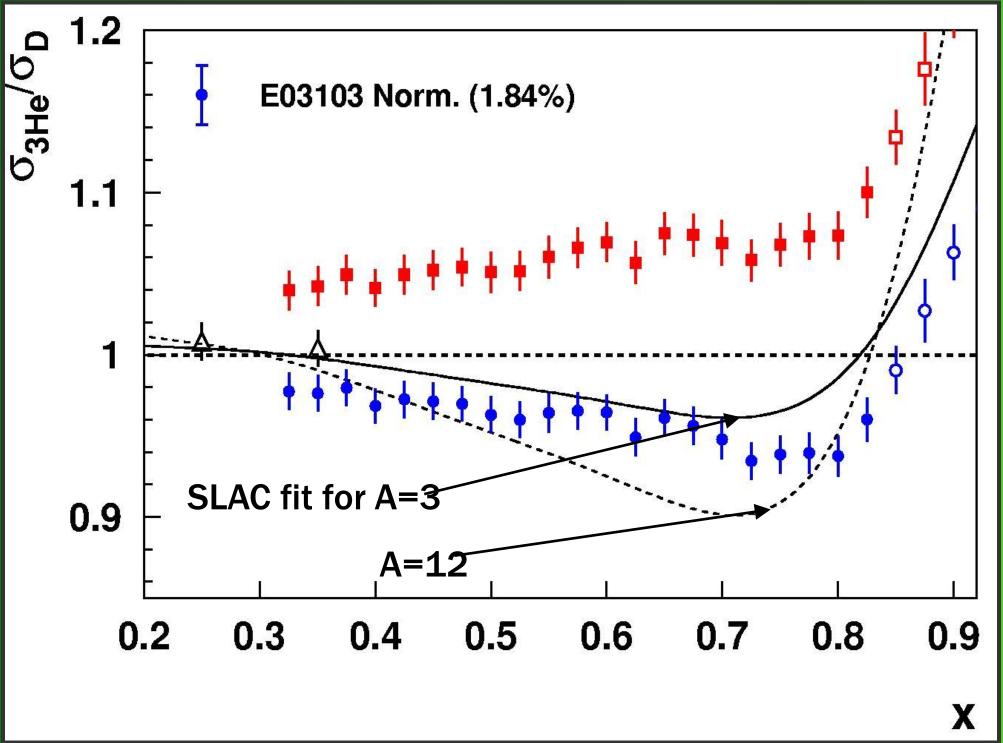
<Q^2> (GeV^2)
CLAS: 1.6
E02-019: 2.7

- Excellent agreement for x≤2
- Very different approaches to 3N plateau, later onset of scaling for E02-019
- Very similar behavior for heavier targets

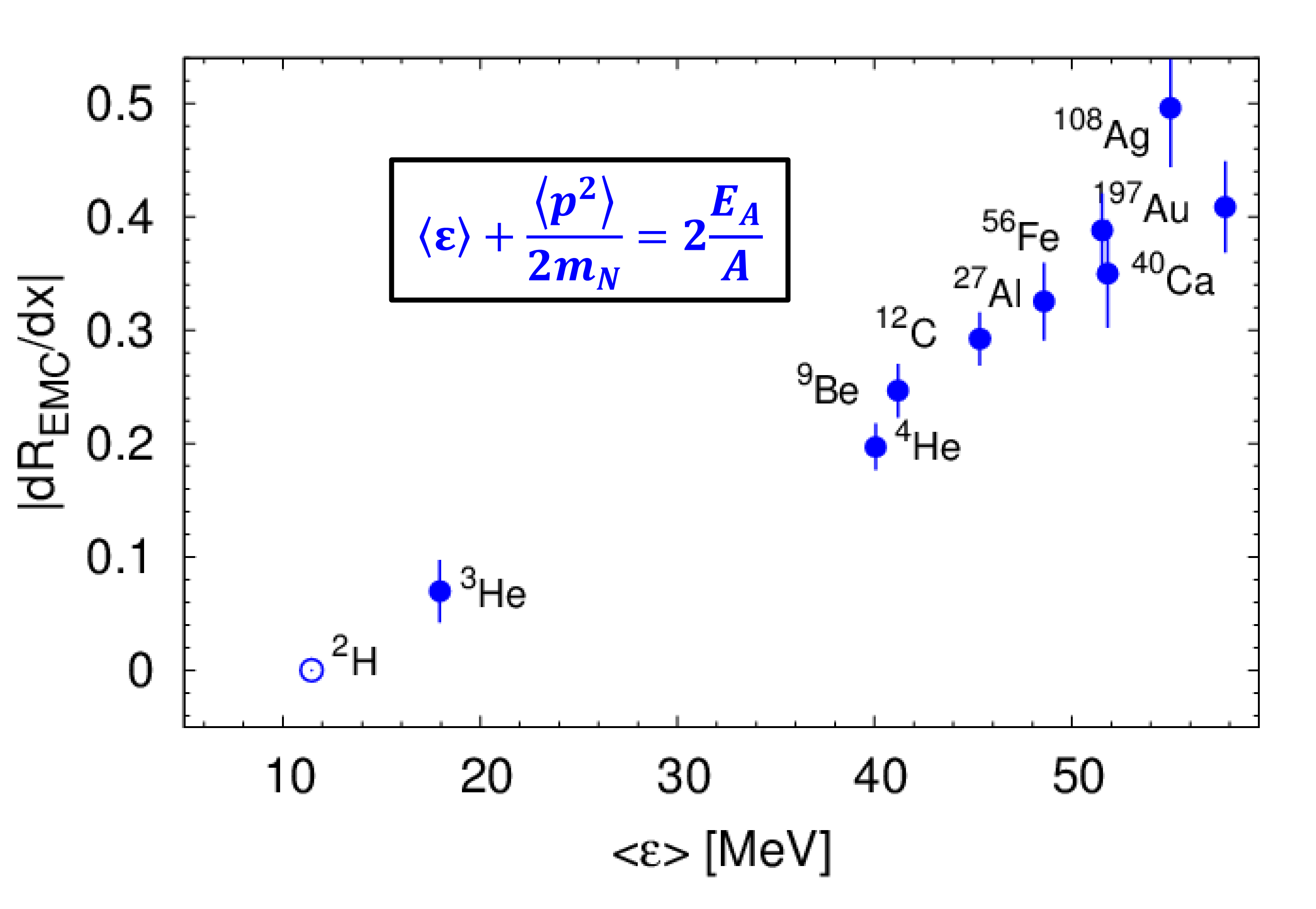
Isoscalar Correction if Z≠P

$$Cor_{iso} = \frac{(Z\sigma_p + N\sigma_n)/A}{(\sigma_p + \sigma_n)/2}$$

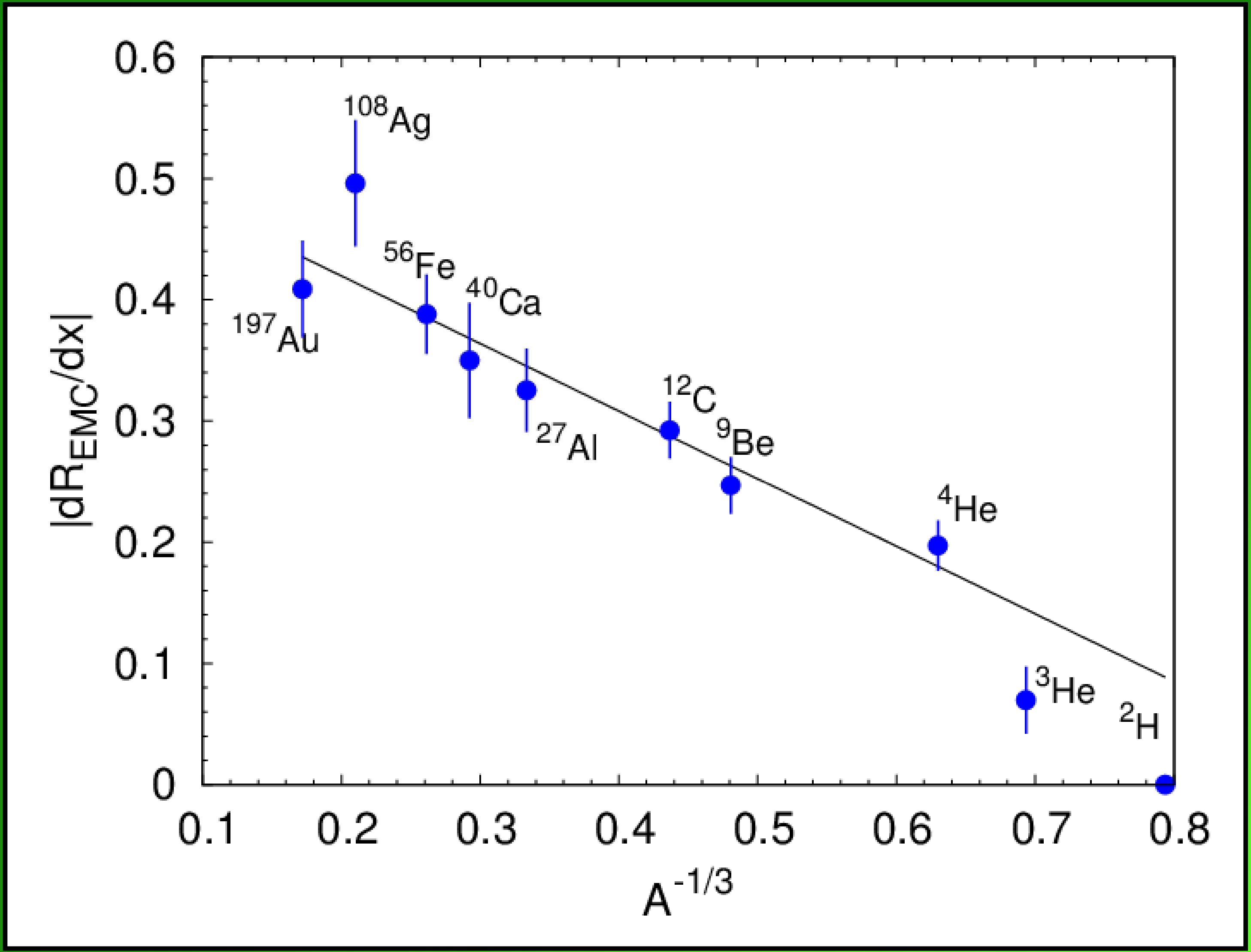




- No free neutron target → extraction of F_2^n/F_2^p is model-dependent
- For E03-103, F_2^n/F_2^p for bound nucleons was used



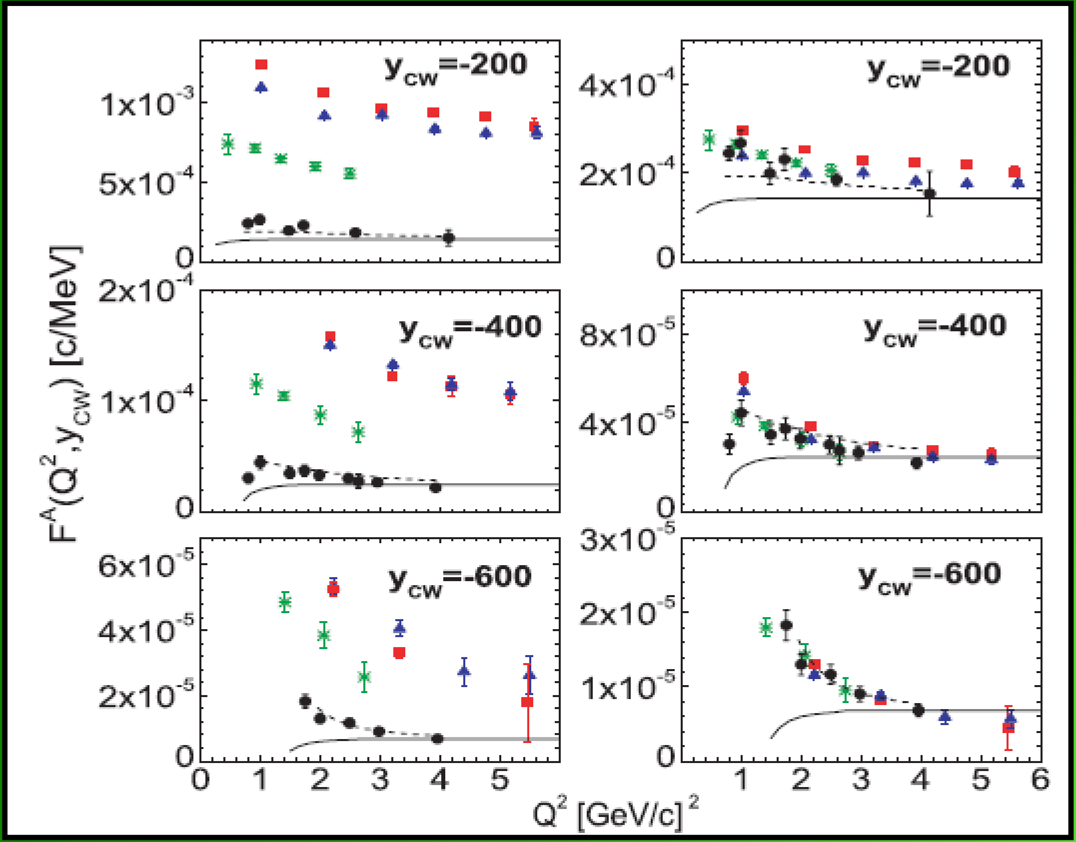
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
|dR_EMC/dx|
<ε> [MeV]
$\langle \varepsilon \rangle + \frac{\langle p^2 \rangle}{2m_N} = 2\frac{E_A}{A}$
108Ag
197Au
56Fe
40Ca
27Al
12C
9Be
4He
3He
2H



0.6
0.5
0.4
0.3
0.2
0.1
0
|dR_EMC/dx|
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
A^-1/3
108Ag
56Fe
40Ca
197Au
27Al
12C
9Be
4He
3He
2H

Rescaling of the Deuteron

$F_A(y)=C_nF_D(y)$



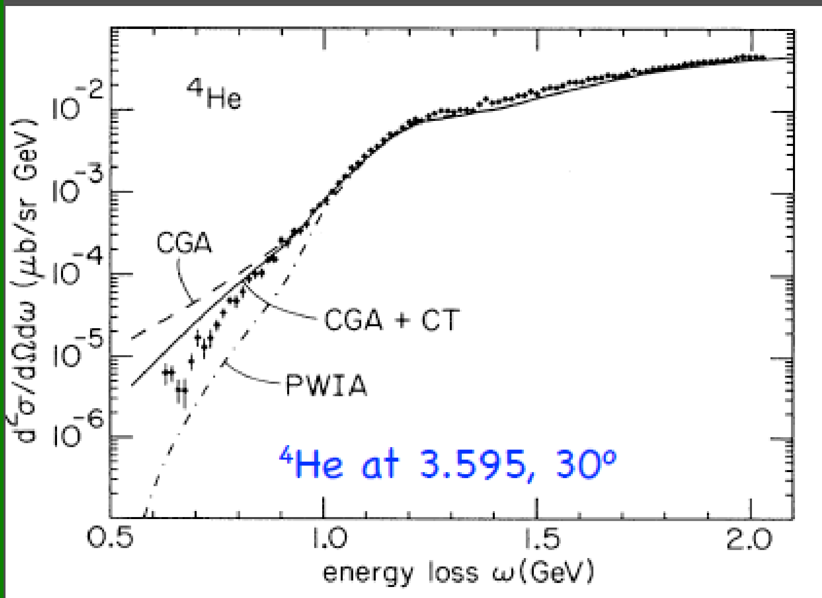
$F_A(y)$

$F_A(y)/C_n$

FSI in A>2 are identical to those in the deuteron, and match calculations

Ciofi degli Atti, Mezzetti, PRC79

Overestimate of cross sections



Benhar et al. PRC 44, 2328

Benhar, Pandharipande, PRC 47, 2218

Benhar et al. PLB 3443, 47