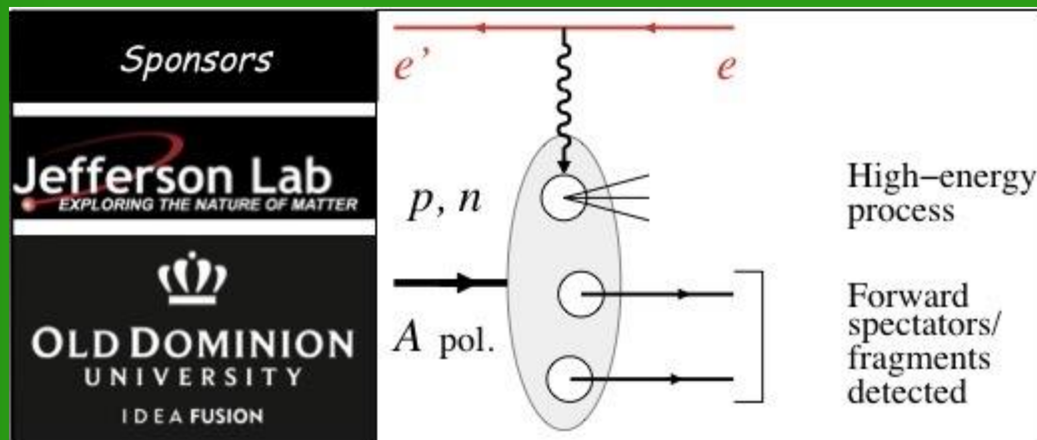
High Momentum Nucleons:
where have we been and where are we going



Nadia Fomin

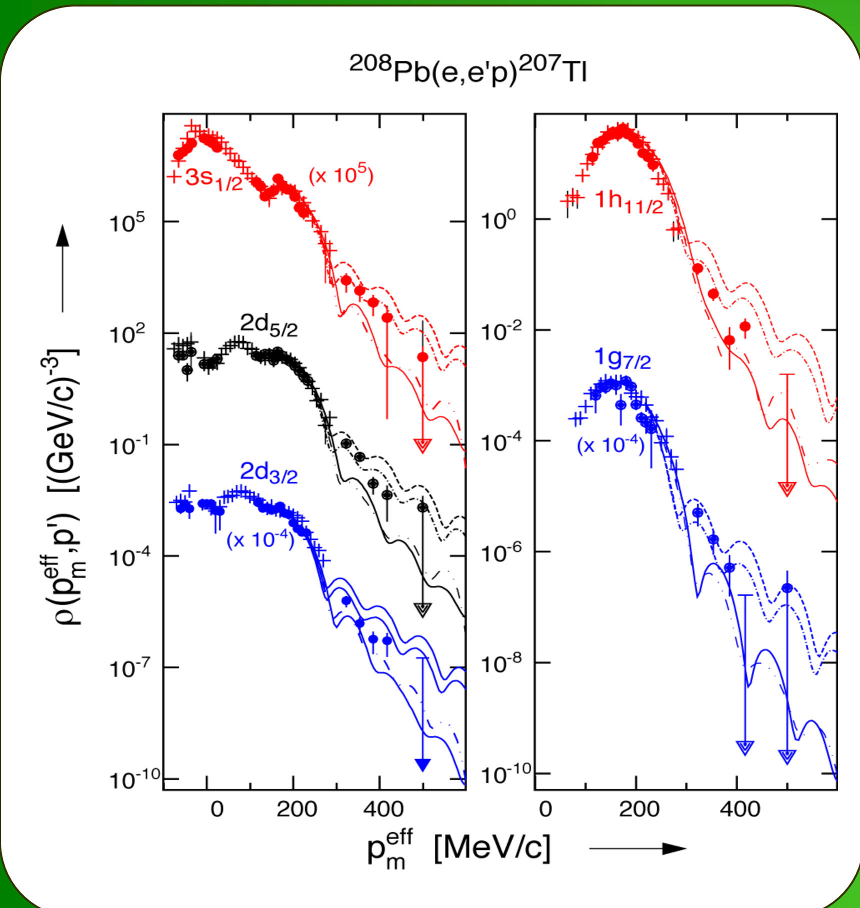
High Energy Nuclear Physics with Spectator Tagging

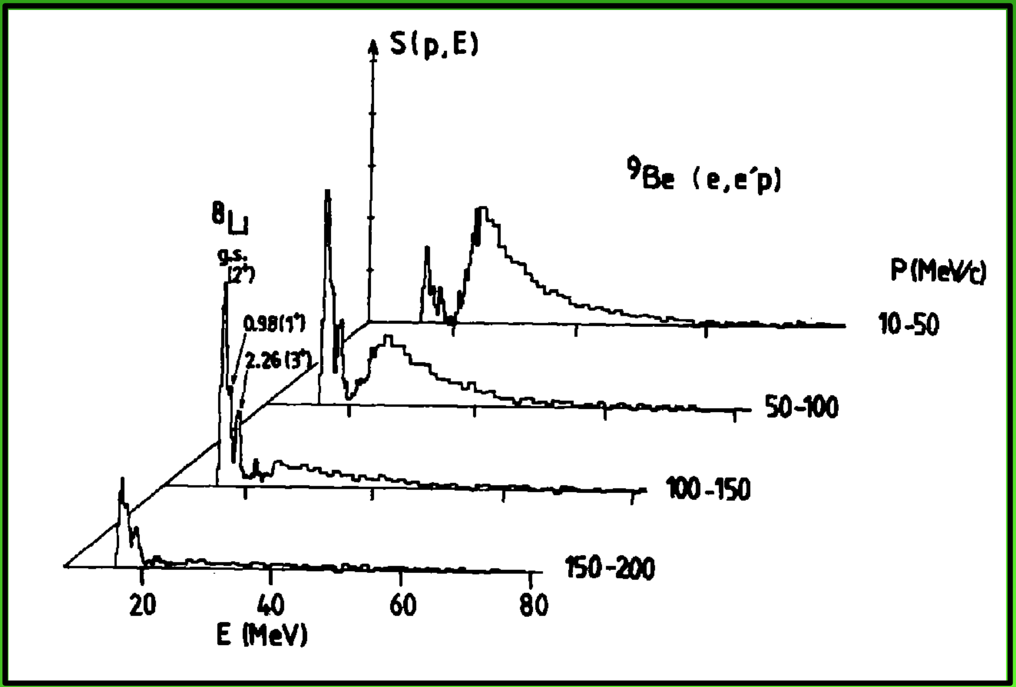
March 10th, 2015

High momentum nucleons – where do they come from?

Independent Particle Shell Model :

$$S_\alpha = 4\pi \int S(E_m, p_m) p_m^2 dp_m \delta(E_m - E_\alpha)$$



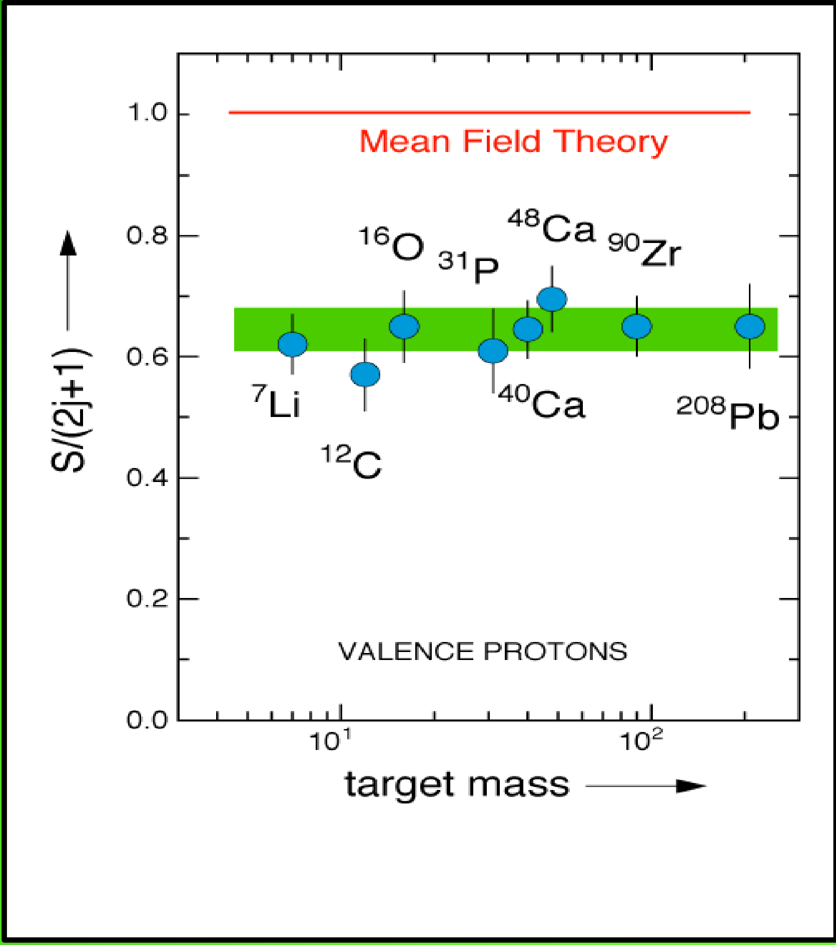


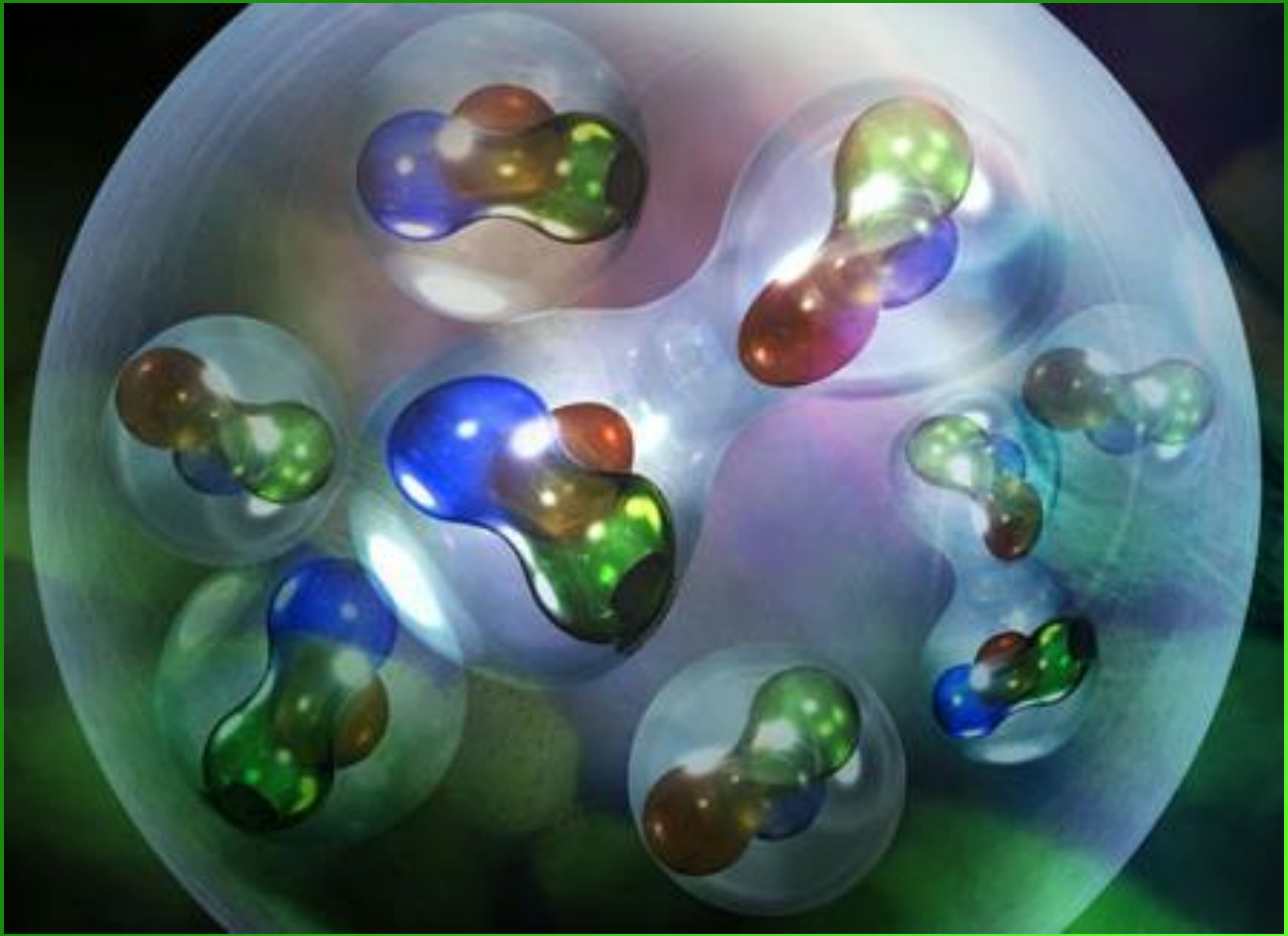
Proton E_m,p_m distribution modeled as sum of independent shell contributions (arbitrary normalization)

Independent Particle Shell Model :

$$S_\alpha = 4\pi \int S(E_m, p_m) p_m^2 dp_m \delta(E_m - E_\alpha)$$

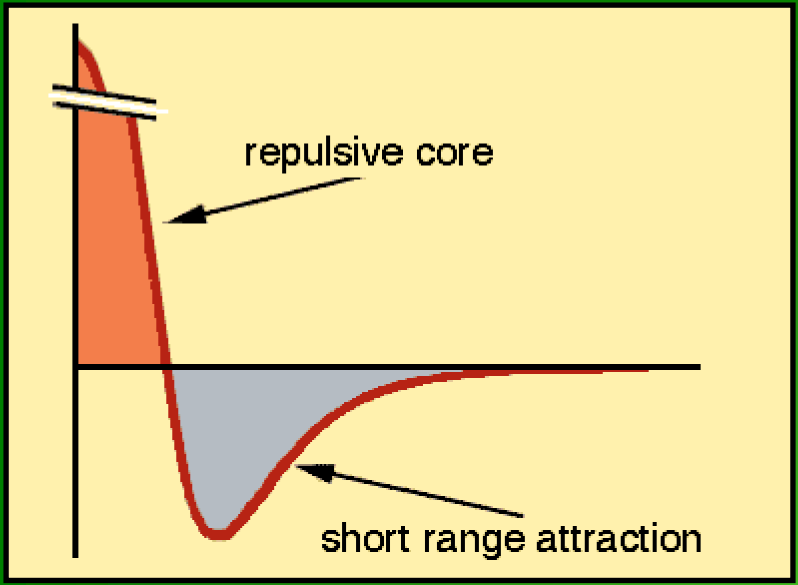
- For nuclei, S_α should be equal to ***2j+1*** => number of protons in a given orbital
- However, it as found to be only ~2/3 of the expected value
- The bulk of the missing strength it is thought to come from **short range correlations**

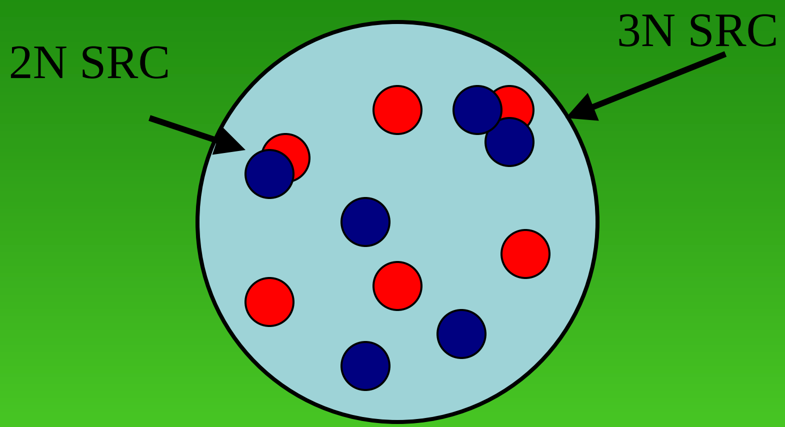


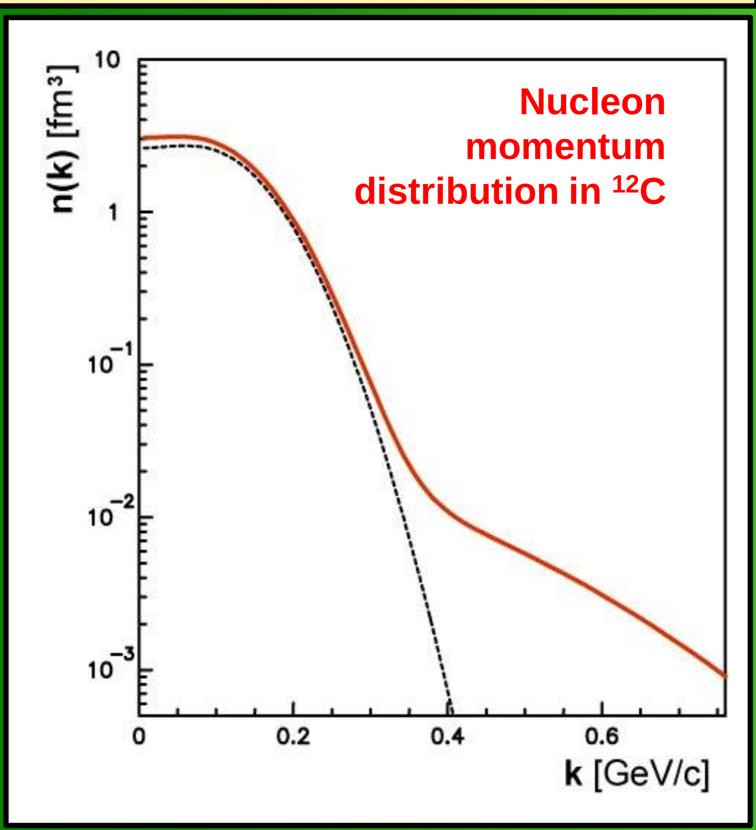


High momentum nucleons

- Short Range Correlations







High momentum tails in A(e,e'p)

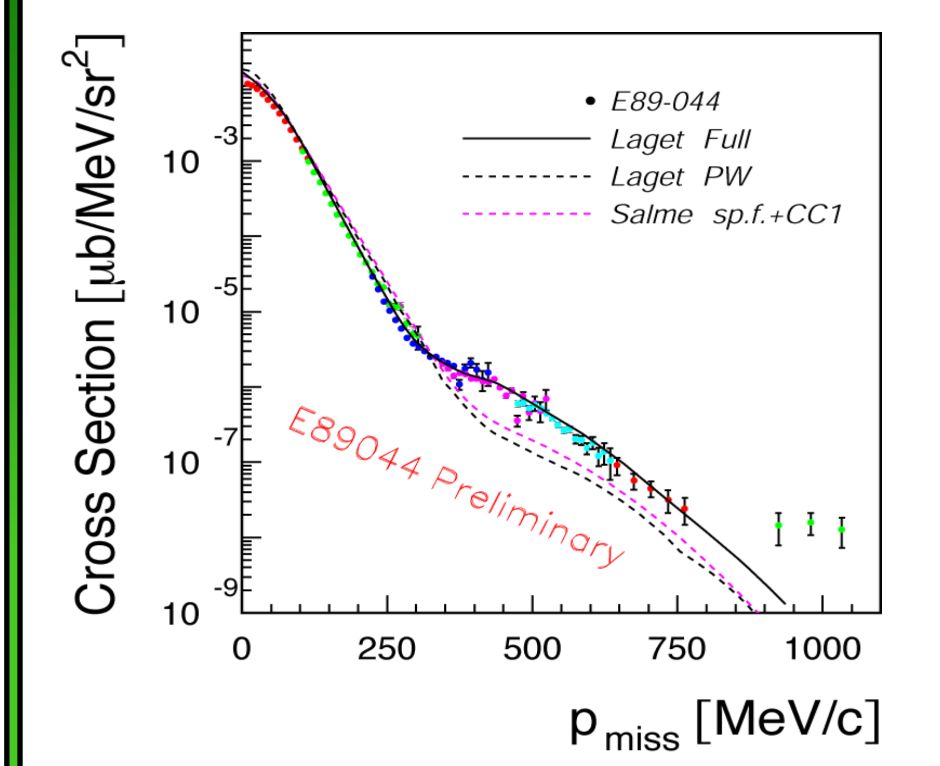
- E89-004: Measure of ^{3}He(e,e'p)d
- Measured far into high momentum tail: Cross section is ~5-10x expectation

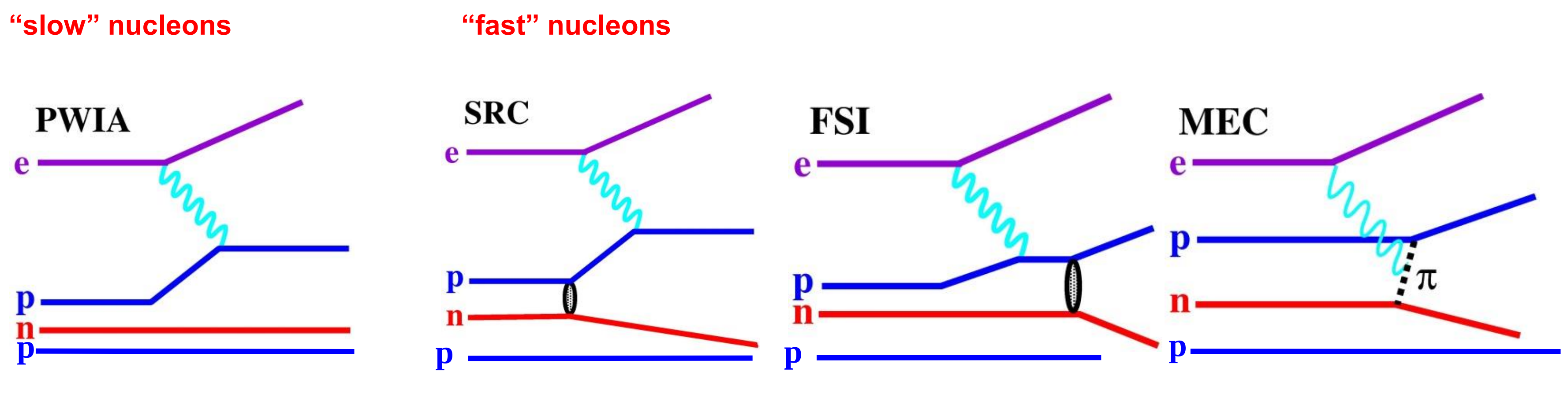
Difficulty

- High momentum pair can come from SRC (initial state)

OR

- Final State Interactions (FSI) and Meson Exchange Contributions (MEC)





A(e,e'p)

^{2}H(e,e'p) Mainz
PRC 78 054001 (2008)

E =0.855 GeV
θ = 45°
E'=0.657 GeV
Q^2=0.33 GeV^2
x=0.88

Unfortunately: FSI, MECs overwhelm the high momentum nucleons

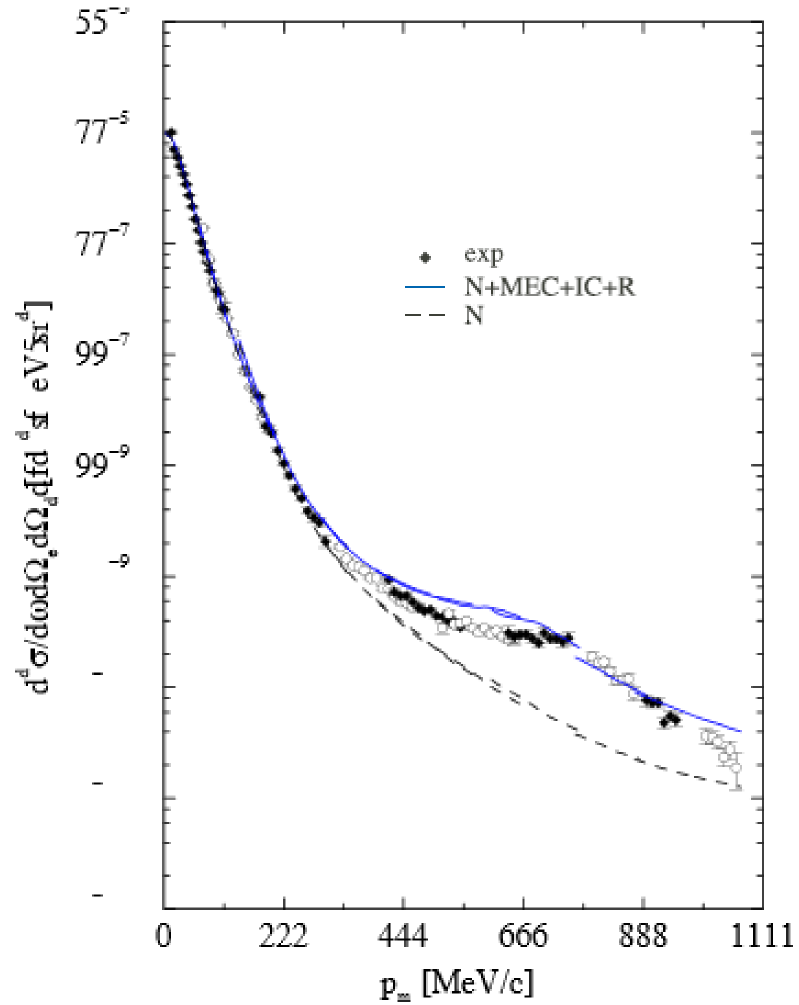


FIG. 1: The experimental D(e,e′p)n cross section as a function of missing momentum measured at MAMI for $Q^2 = 0.33$ $(\mathrm{GeV}/c)^2$ [4] compared to calculations [7] with (solid curve) and without (dashed curve) MEC and IC. Both calculations include FSI. The low p_m data have been re-analyzed and used in this work to determine f_{LT} (color online).

Past A(e,e'p) experiments in Hall A

E89-003	Study of the Quasielastic $(e,e'p)$ reaction in ^{16}O at High Recoil Momentum
E89-044	Selected Studies of the ^{3}He and 4He Nuclei through ...
E97-111	Systematic Probe of Short-Range Correlations via the Reaction ^{4}He$(e,e'p)^3H$
E00-102	Testing the limits of the Single Particle Model in ^{16}O$(e,e'p)$
E03-104	Probing the Limits of the Standard Model of Nuclear Physics with the ^{4}He$(e,e'p)^3$H Reaction
E04-004	In-Plane Separations and High Momentum Structure in d$(e,e'p)$n
E06-007	Impulse Approximation limitations to the $(e,e'p)$ on ^{208}Pb, ...

E89-003	Study of the Quasielastic $(e, e'p)$ reaction in ^{16}O at High Recoil Momentum
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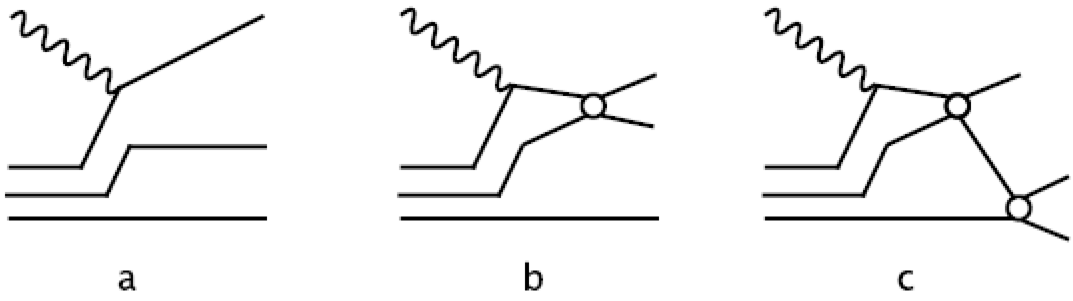


FIG. 1: Feynman diagrams for a) direct disintegration, b) rescattering, and c) rescattering with the spectator nucleon.

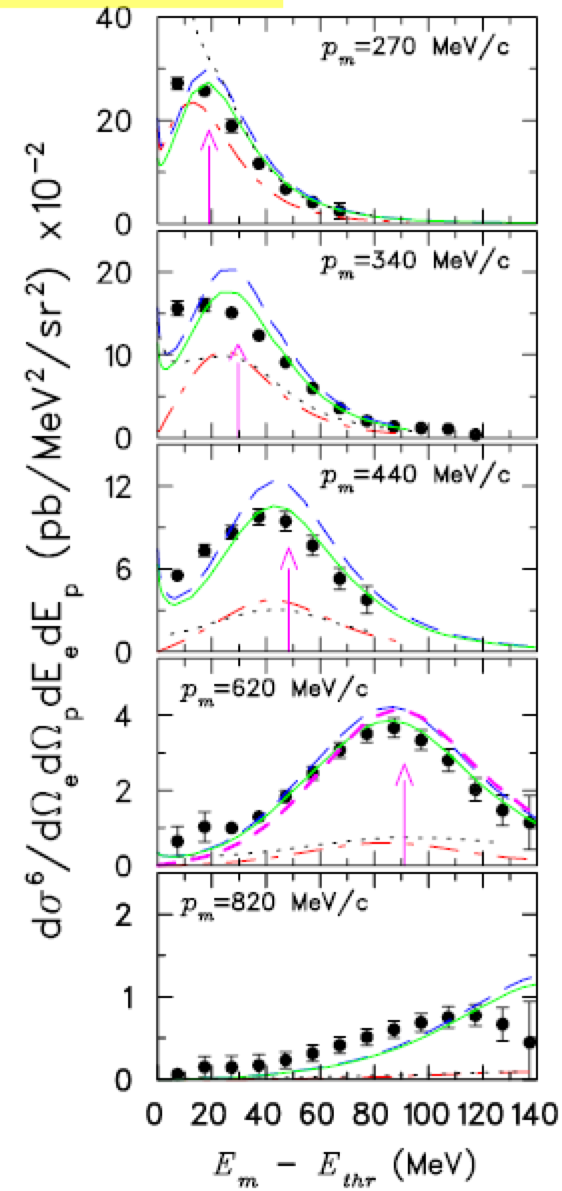
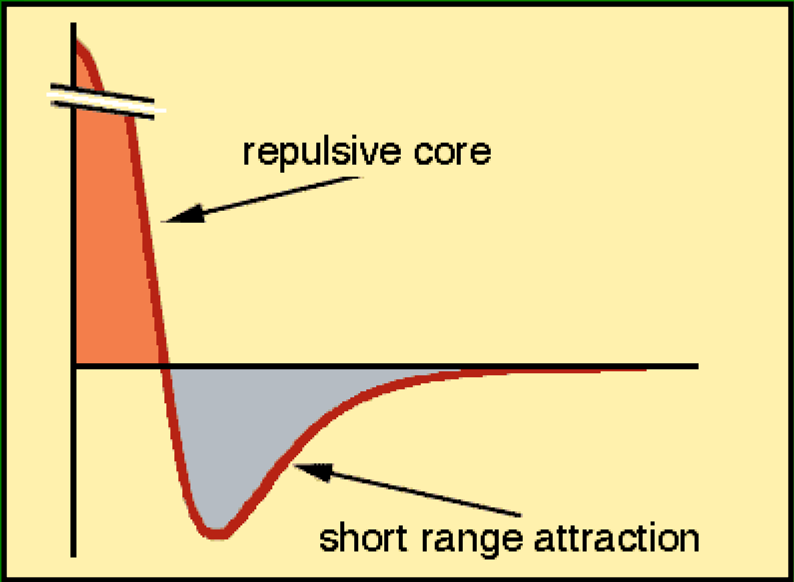
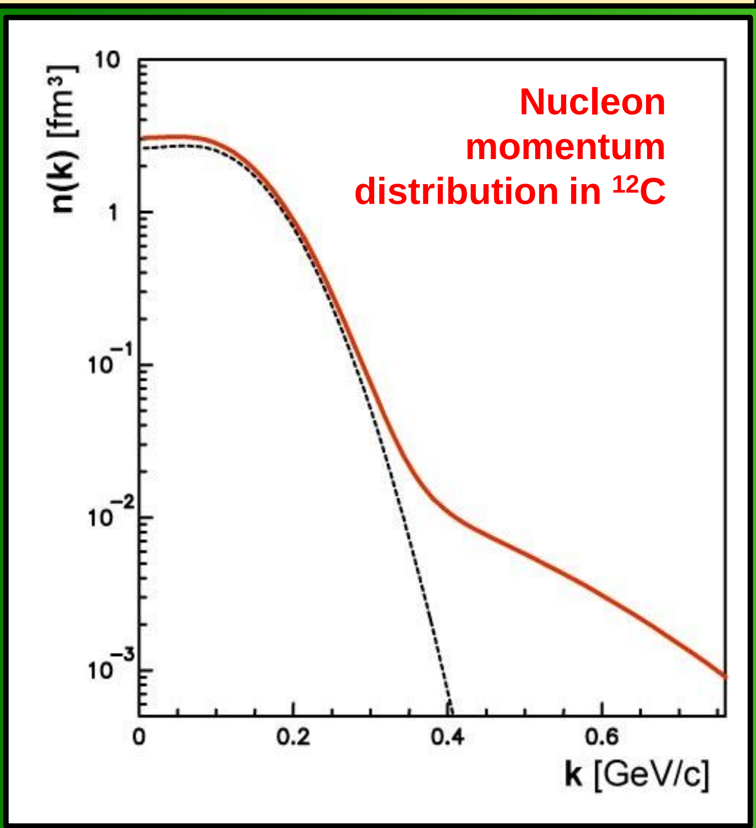


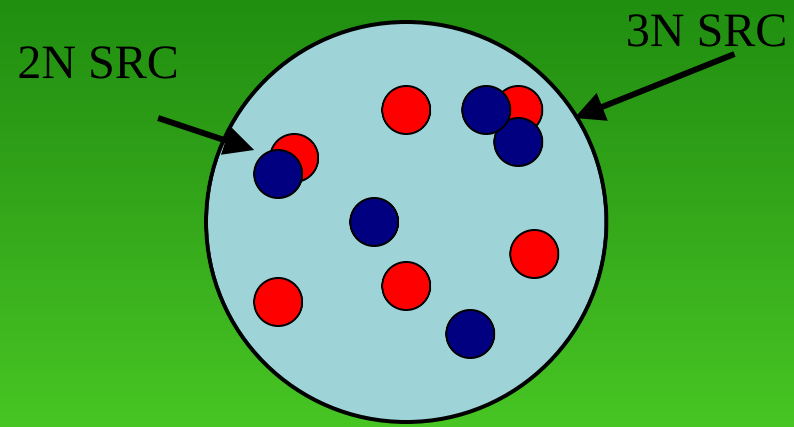
FIG. 2: (color online). Cross-section results for the ^{3}He$(e, e'p)pn$ reaction versus missing energy E_m. The vertical arrow gives the peak position expected for disintegration of correlated pairs. The dotted curve presents a PWIA calculation using Salme's spectral function and σ_{cc1} electron-proton off-shell cross section. Other curves are recent theoretical predictions of J. M. Laget [19] from the PWIA (dash dot) to PWIA + FSI (long dash) to full calculation (solid), including meson exchange current and final state interactions. In the 620 MeV/c panel, the additional short dash curve is a calculation with PWIA + FSI only within the correlated pair.

High momentum nucleons

- Short Range Correlations



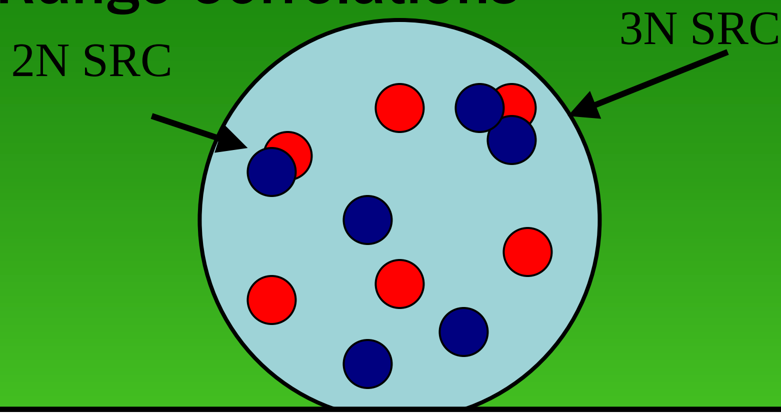




Try inclusive scattering!
Select kinematics such that the initial nucleon momentum $> \boldsymbol{k_f}$

High momentum nucleons

- Short Range Correlations



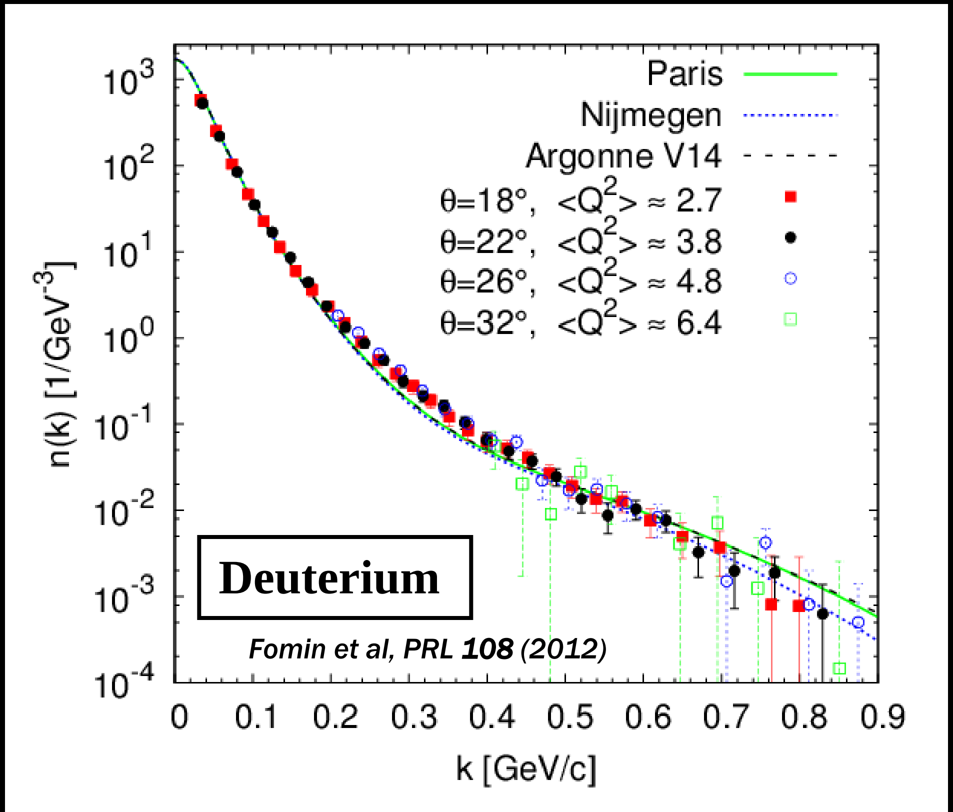
$$\frac{d\sigma^{QE}}{d\Omega dE'} \propto \int d\vec{k} \int dE \sigma_{ei} S_i(k,E)\delta(Arg)$$

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

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

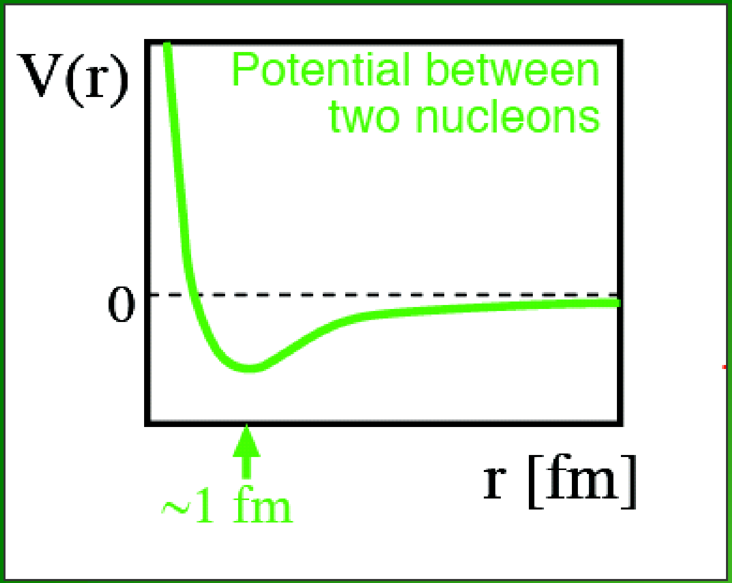
$$= 2\pi \int_{|y|}^{\infty} n(k) k dk$$

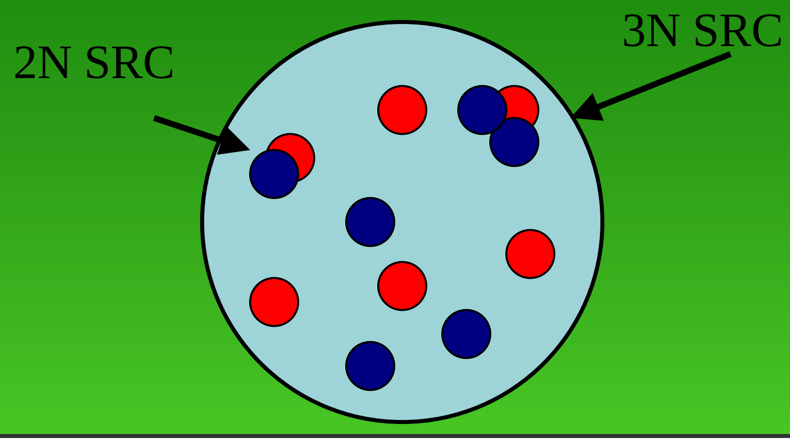
Ok for A=2

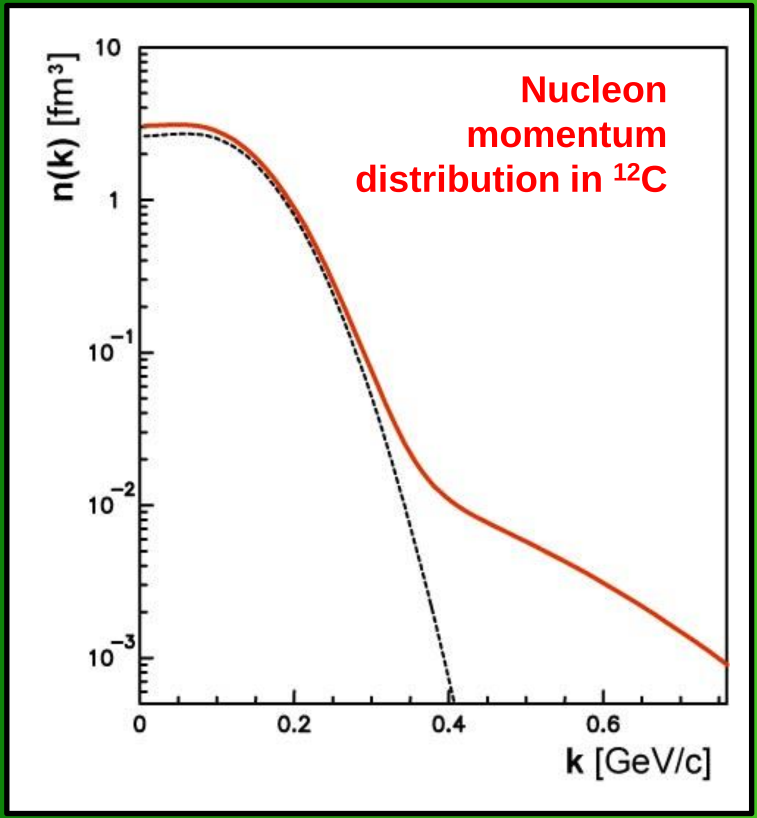


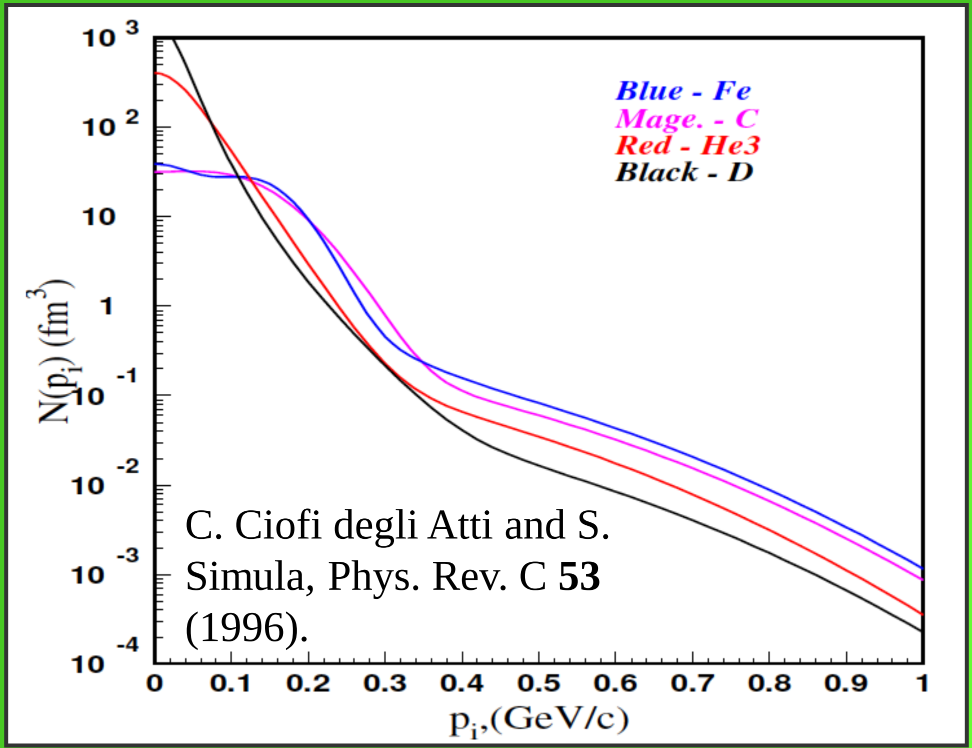
High momentum nucleons

- Short Range Correlations



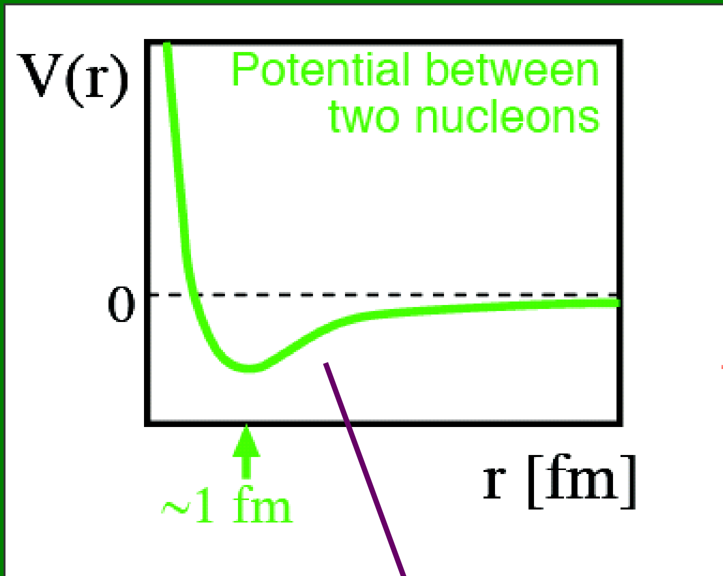


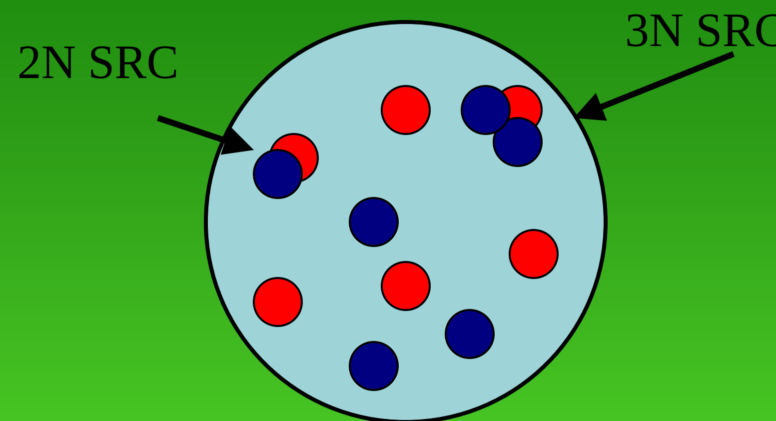


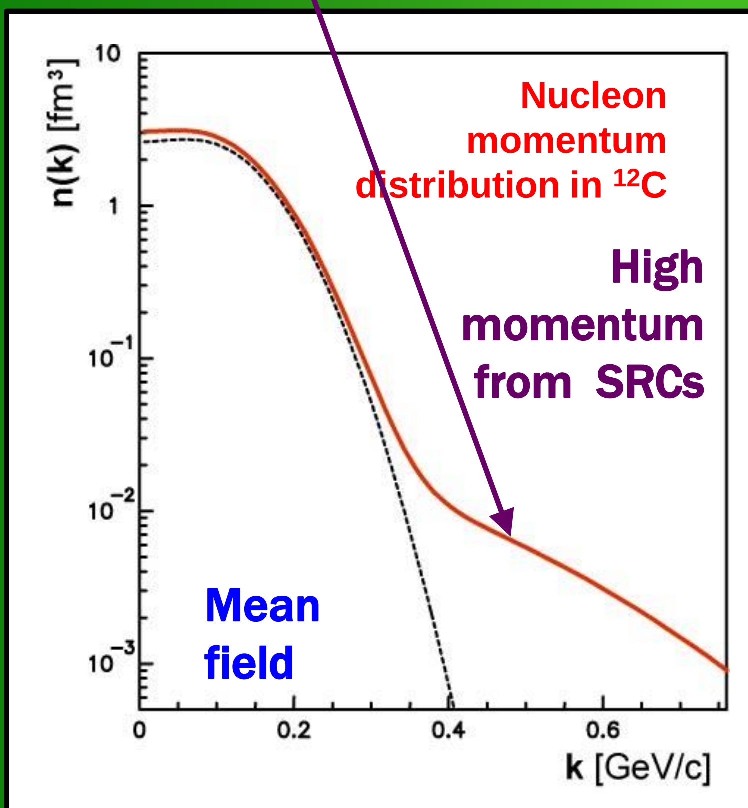


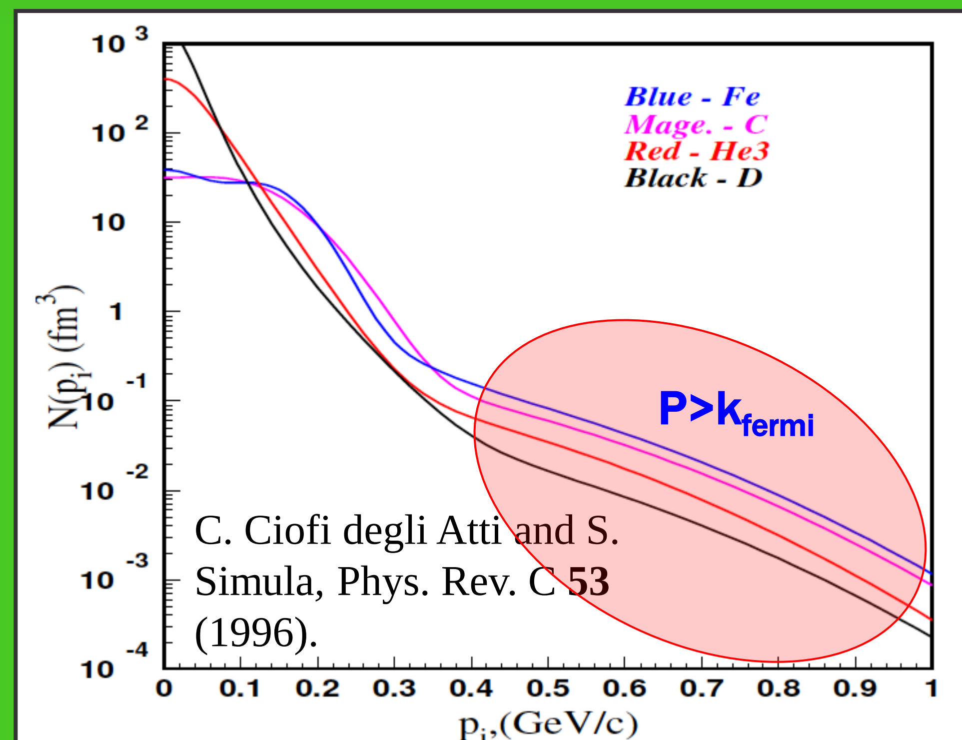
High momentum nucleons

- 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).*
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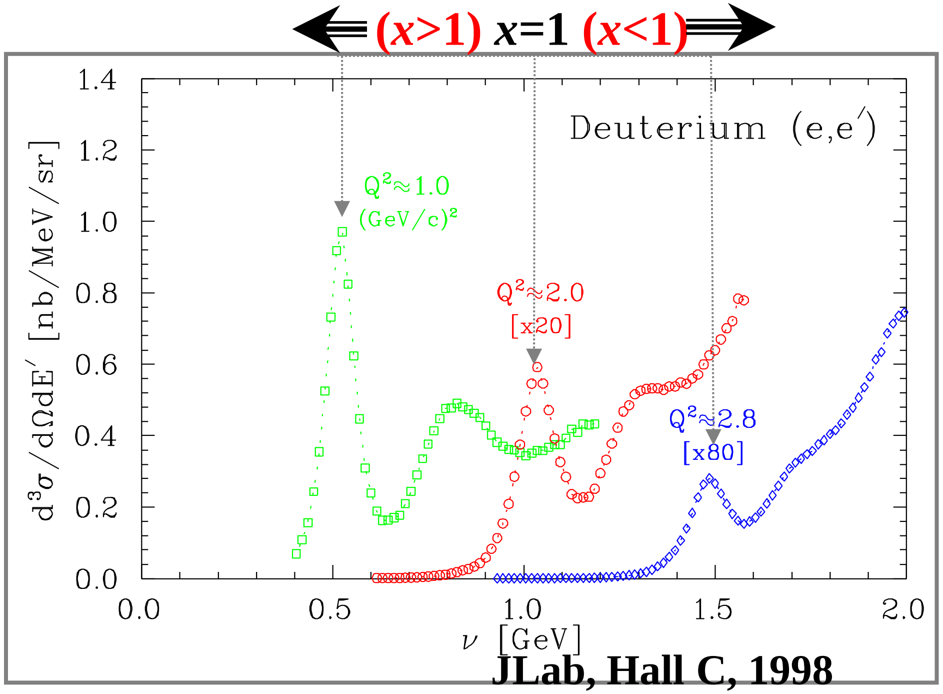
- *C. C. degli Atti and S. Simula, Phys. Rev. C 53, 1689 (1996).*

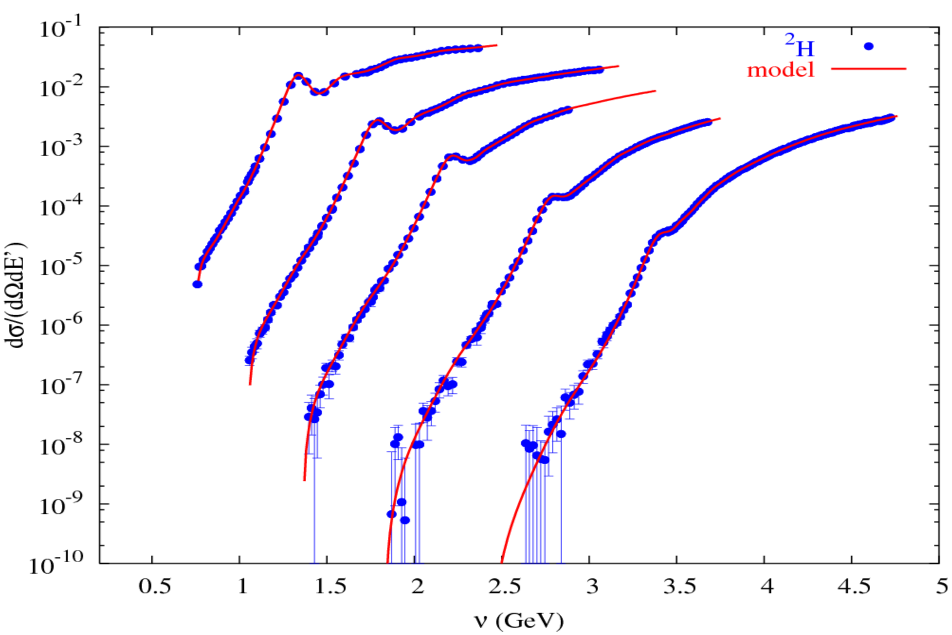
$$\sigma(x, Q^2) = \sum_{j=1}^{A} A \frac{1}{j} a_j(A)\sigma_j(x, Q^2)$$

$$= \frac{A}{2} a_2(A)\sigma_2(x, Q^2) + \frac{A}{3} a_3(A)\sigma_3(x, Q^2) + \ldots.$$

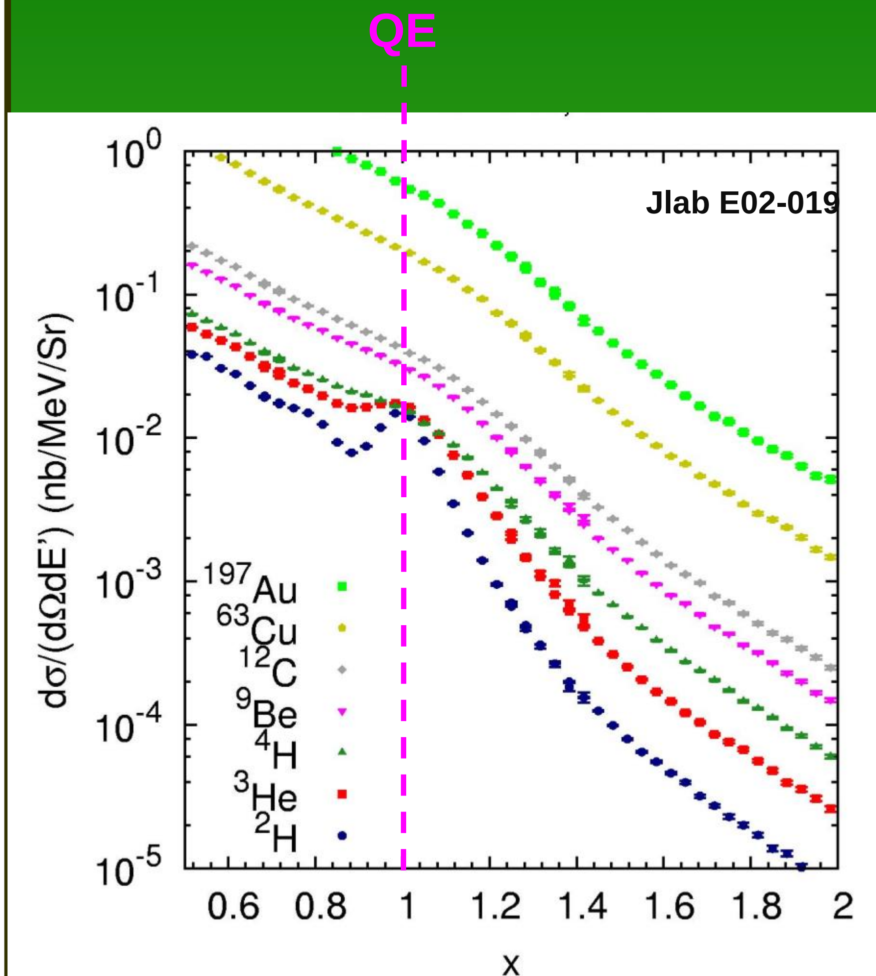
$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A)$$



(x>1) x=1 (x<1)
Deuterium (e,e′)
Q²≈1.0 (GeV/c)²
Q²≈2.0 [x20]
Q²≈2.8 [x80]
d³σ/dΩdE′ [nb/MeV/sr]
ν [GeV]
JLab, Hall C, 1998

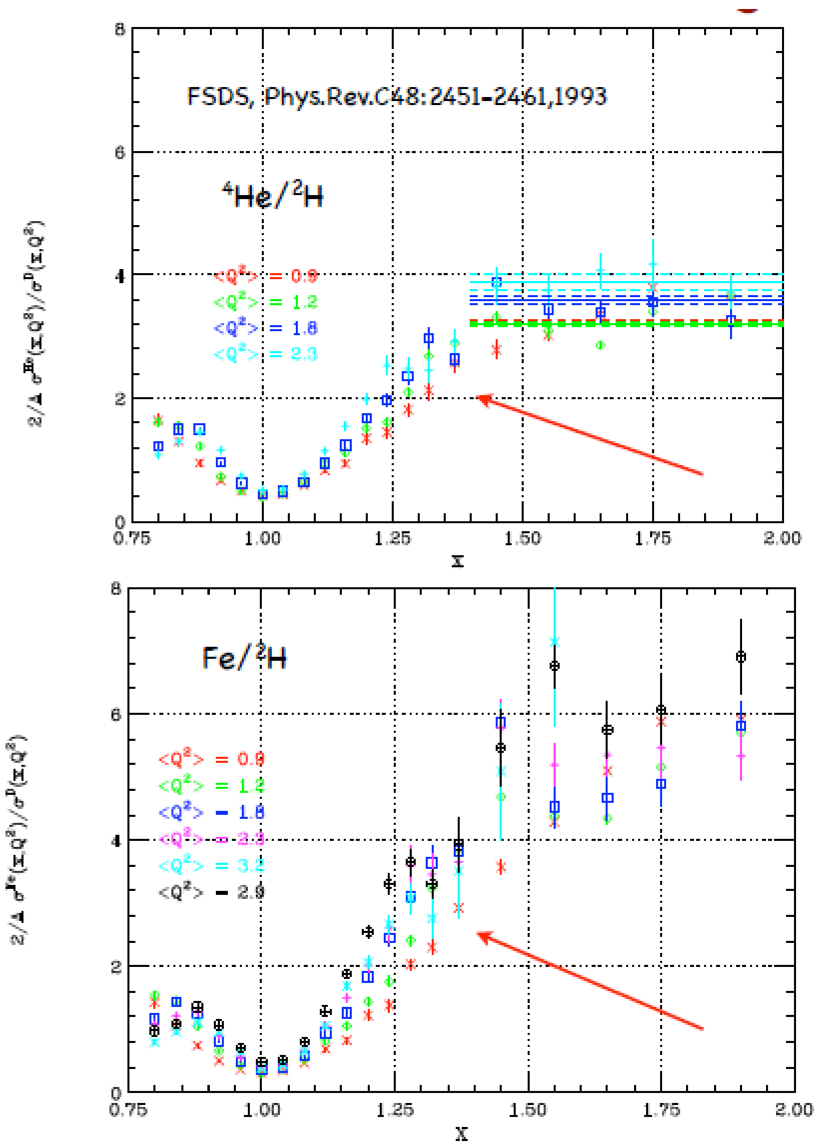


²H
model
dσ/(dΩdE′)
ν (GeV)



QE
Jlab E02-019
dσ/(dΩdE') (nb/MeV/Sr)
x
¹⁹⁷Au
⁶³Cu
¹²C
⁹Be
⁴H
³He
²H

Before my time



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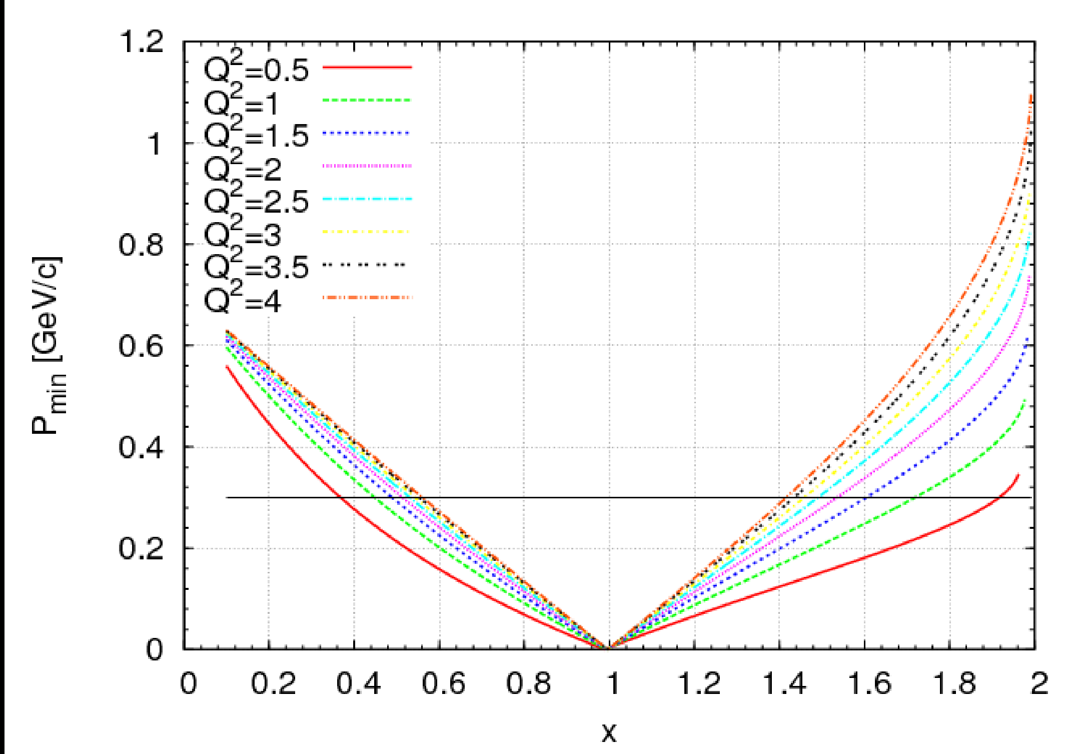
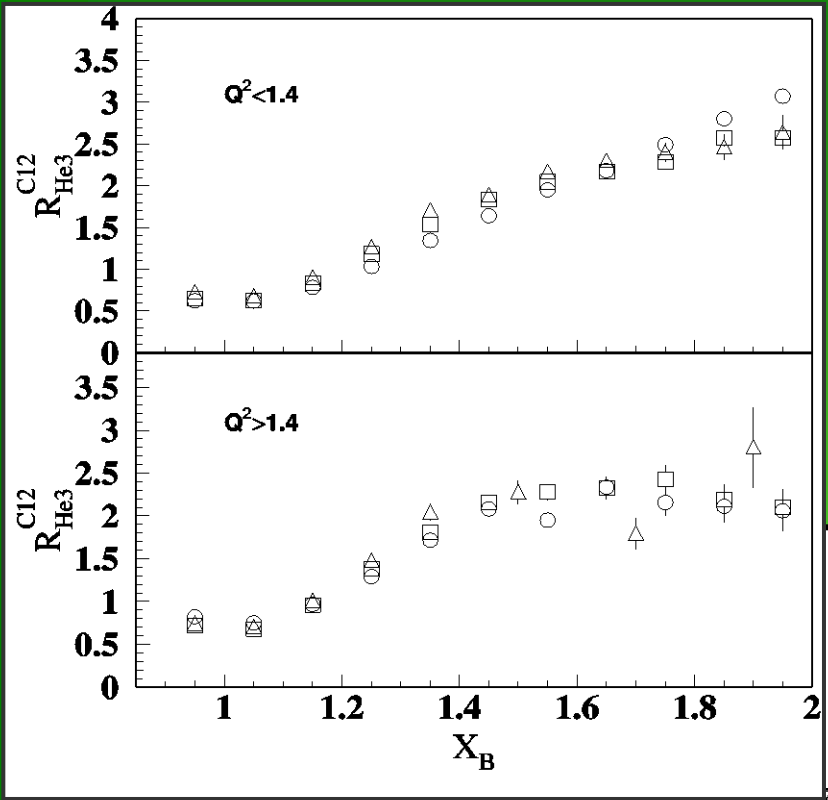


$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A)$$

Previous measurements



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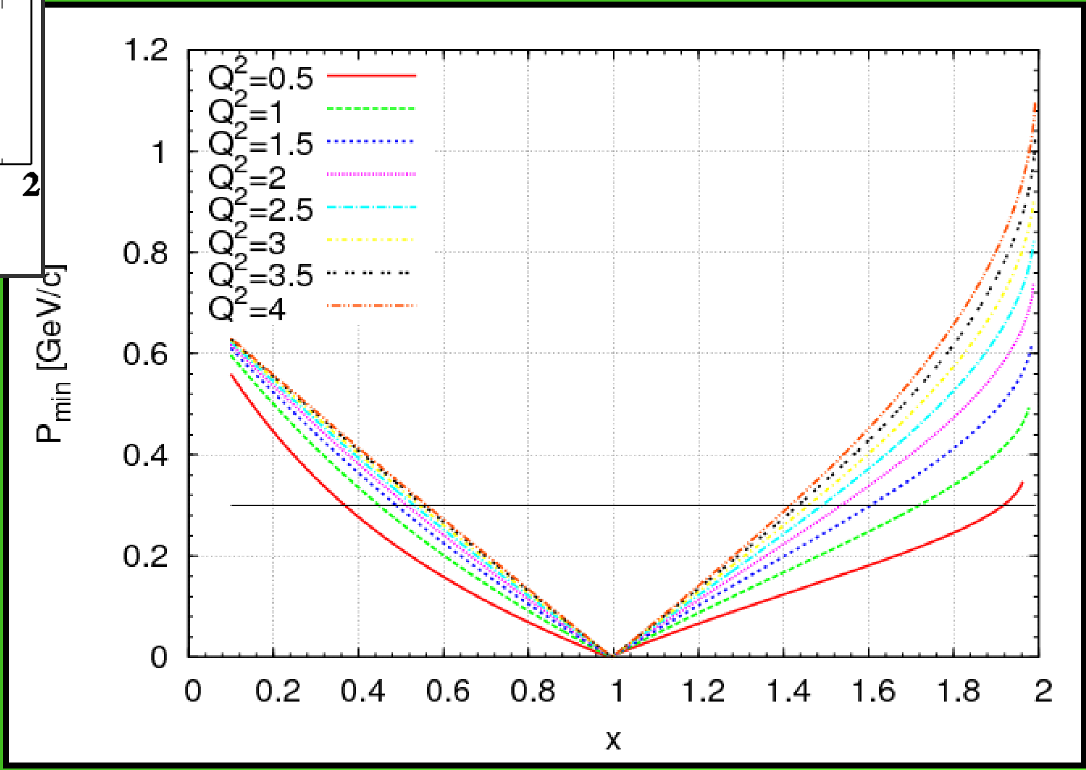
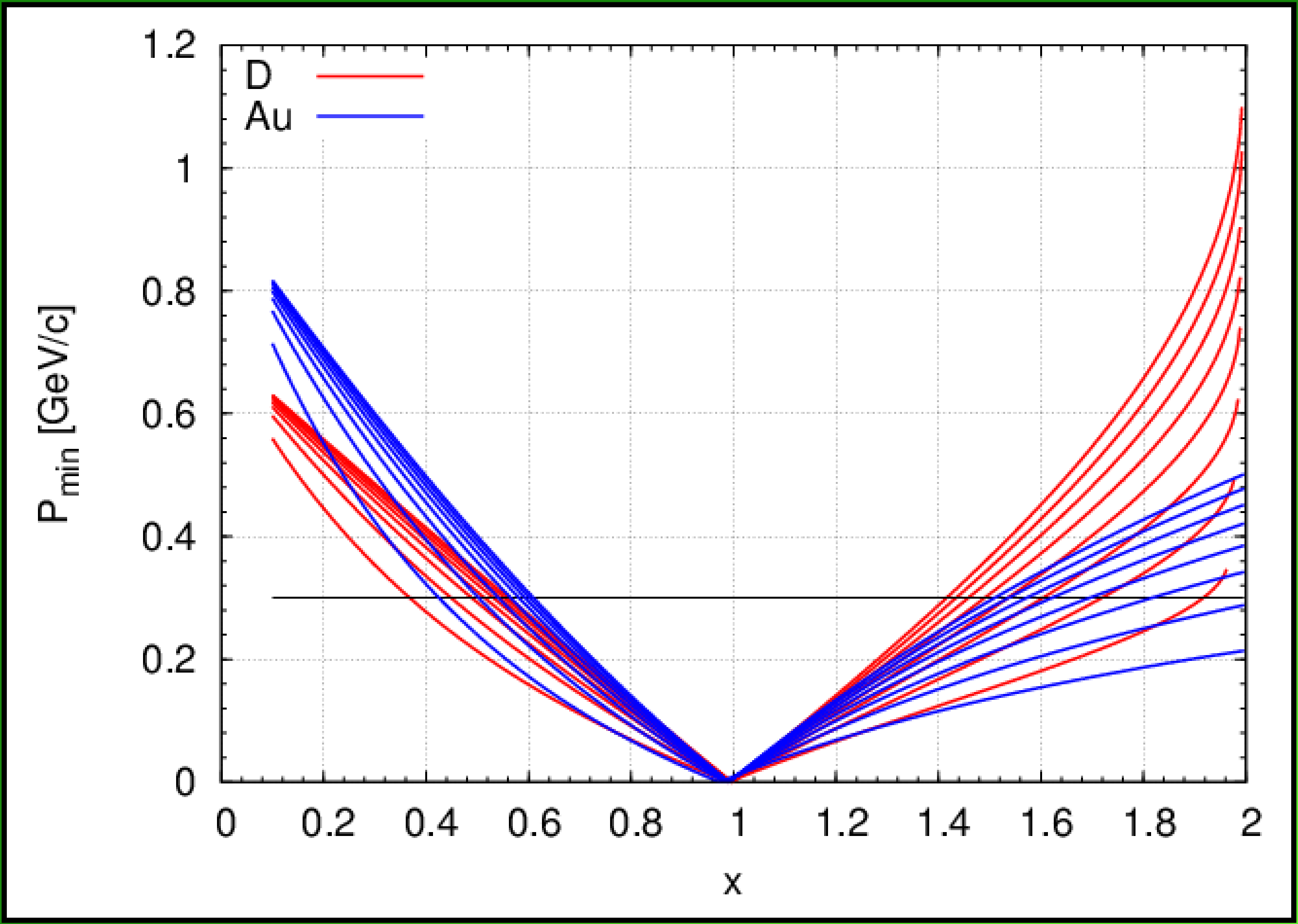
Egiyan et al, Phys.Rev.C68, 2003



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

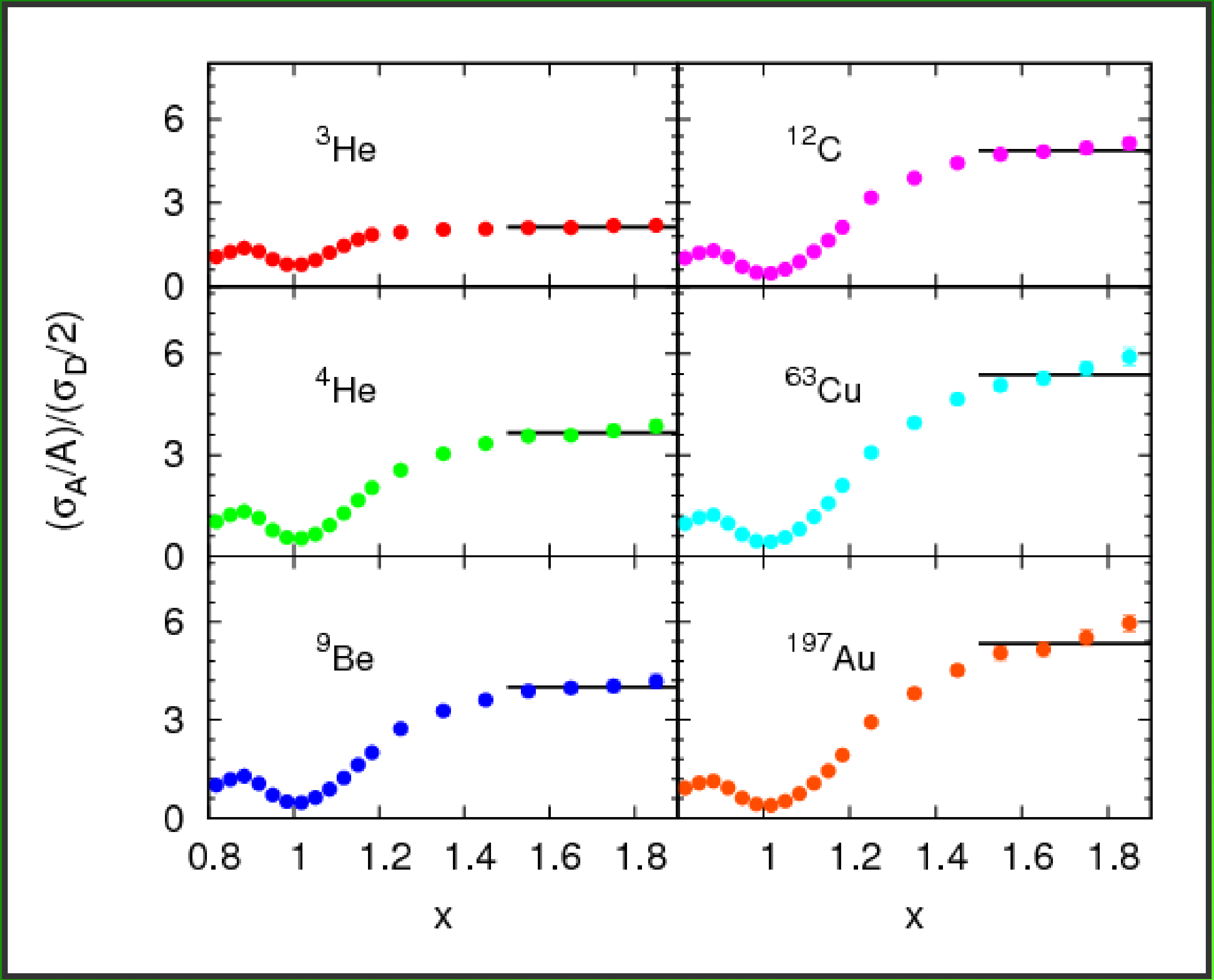
Kinematic cutoff is A-dependent



- 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



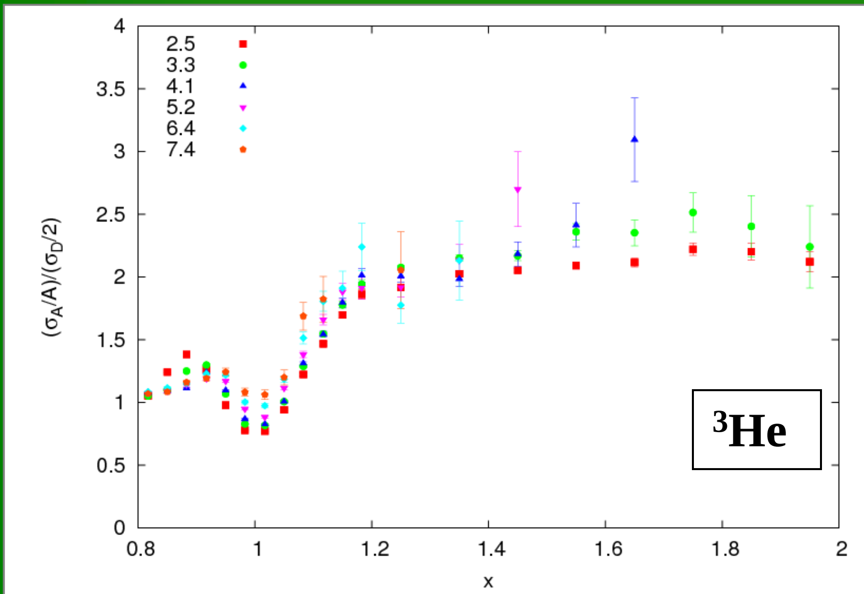
Fomin et al, PRL ***108*** *(2012)*

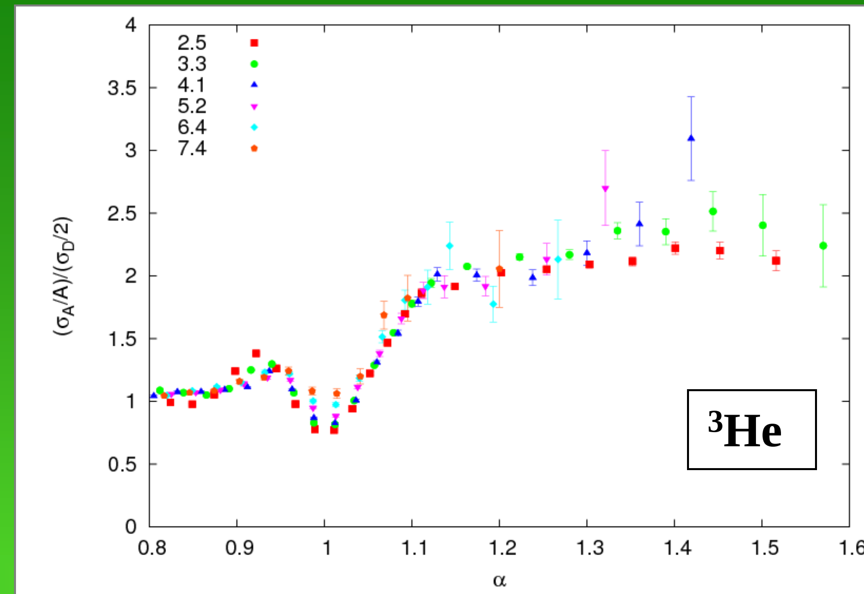
Jlab E02-019

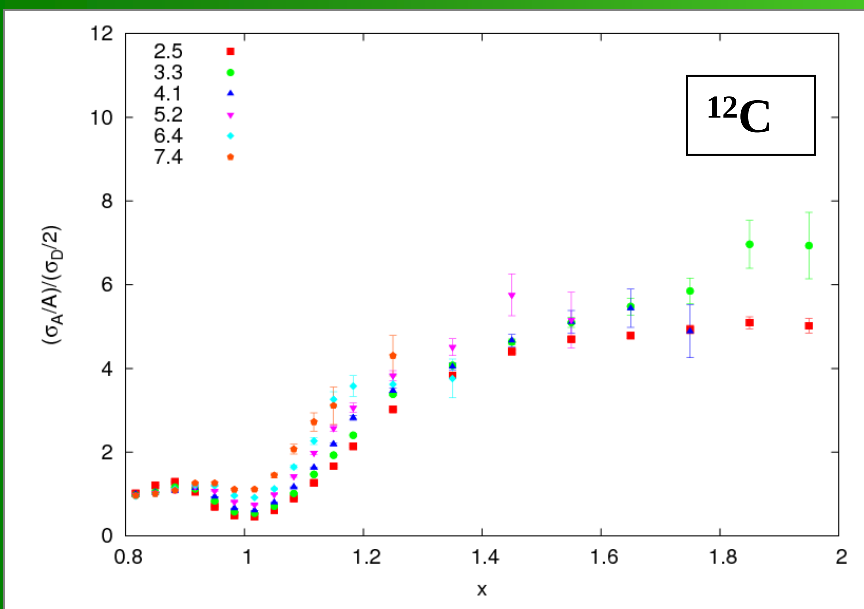
$<Q^2>=2.7\ \mathrm{GeV}^2$

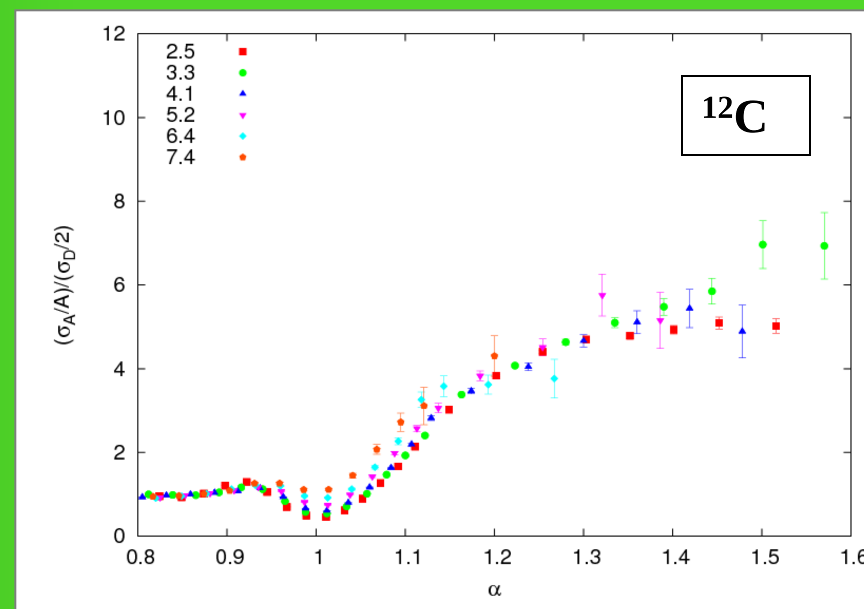
Q^2 dependence features

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



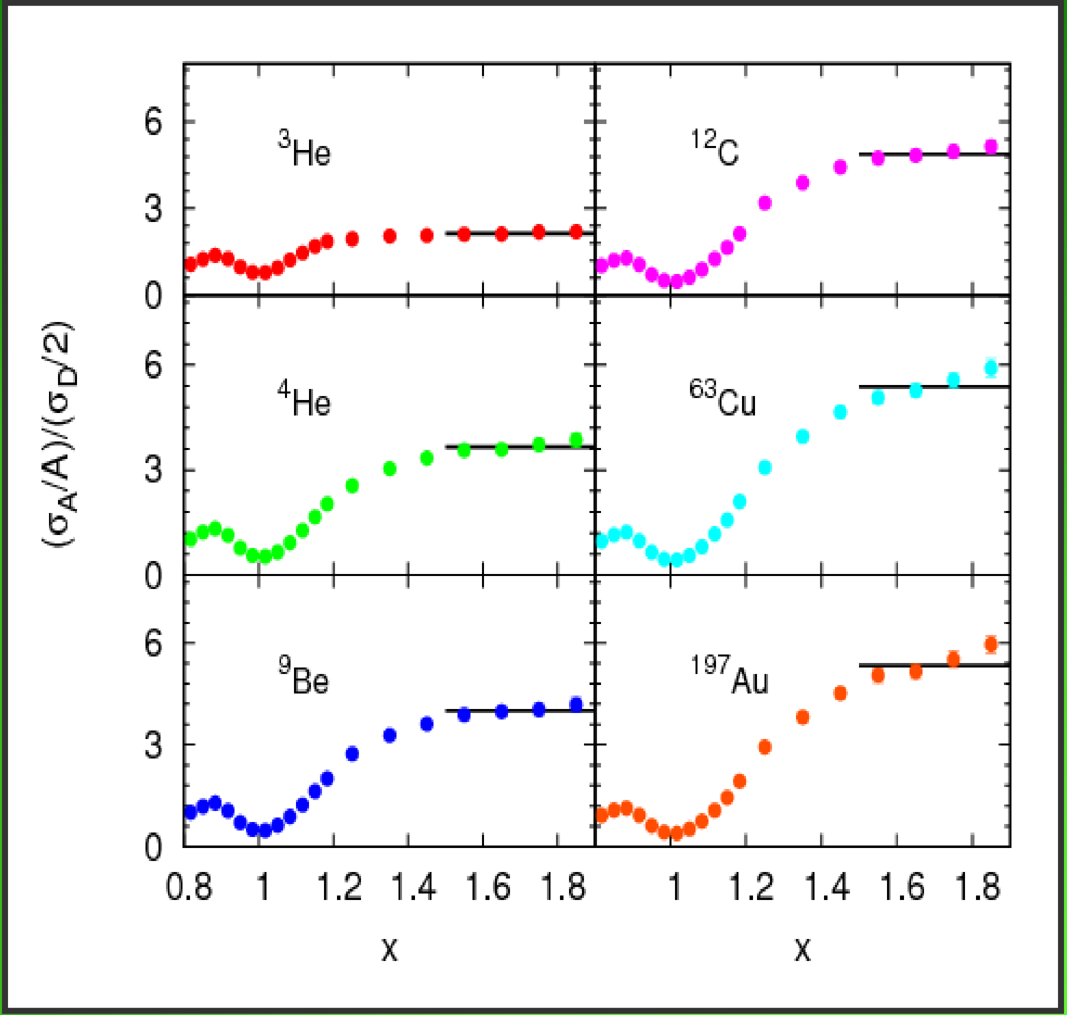






E02-019: 2N correlations in A/D ratios

A	θ_e=18°
^{3}He	2.14±0.04
^{4}He	3.66±0.07
Be	4.00±0.08
C	4.88±0.10
Cu	5.37±0.11
Au	5.34±0.11
$\langle Q^2 \rangle$	2.7 GeV^2
x_{min}	1.5

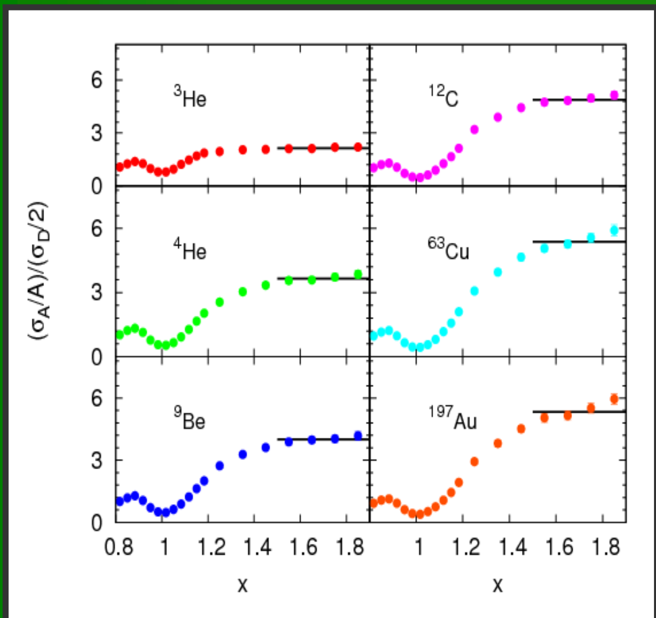


*Fomin et al, PRL **108** (2012)*

Jlab E02-019

$<Q^2>=2.7$ GeV^2

Look at nuclear dependence of NN SRCs



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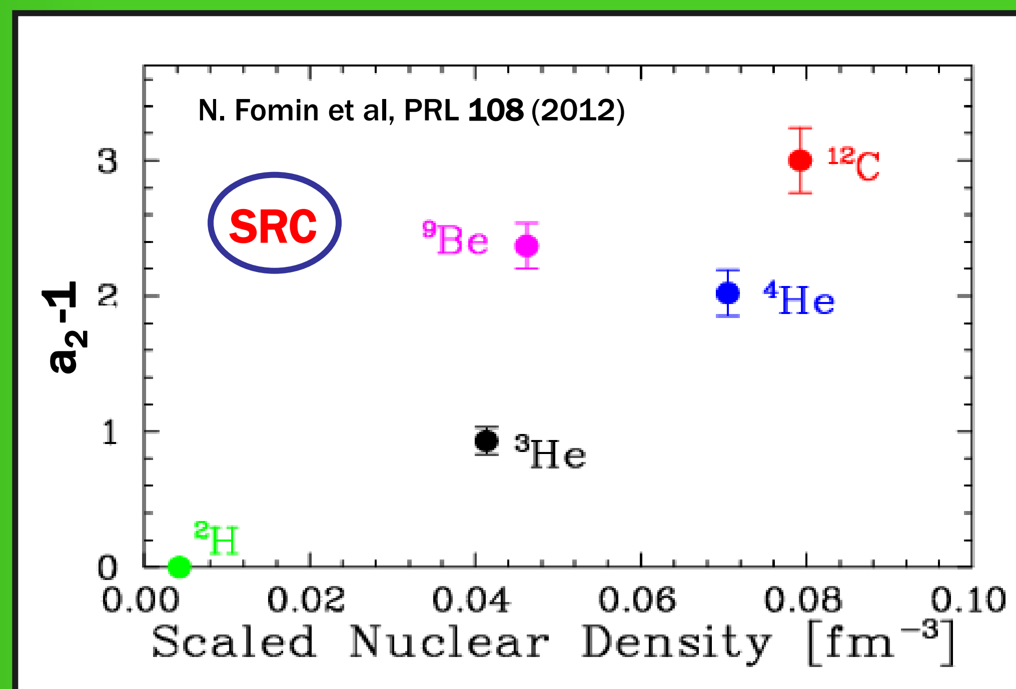
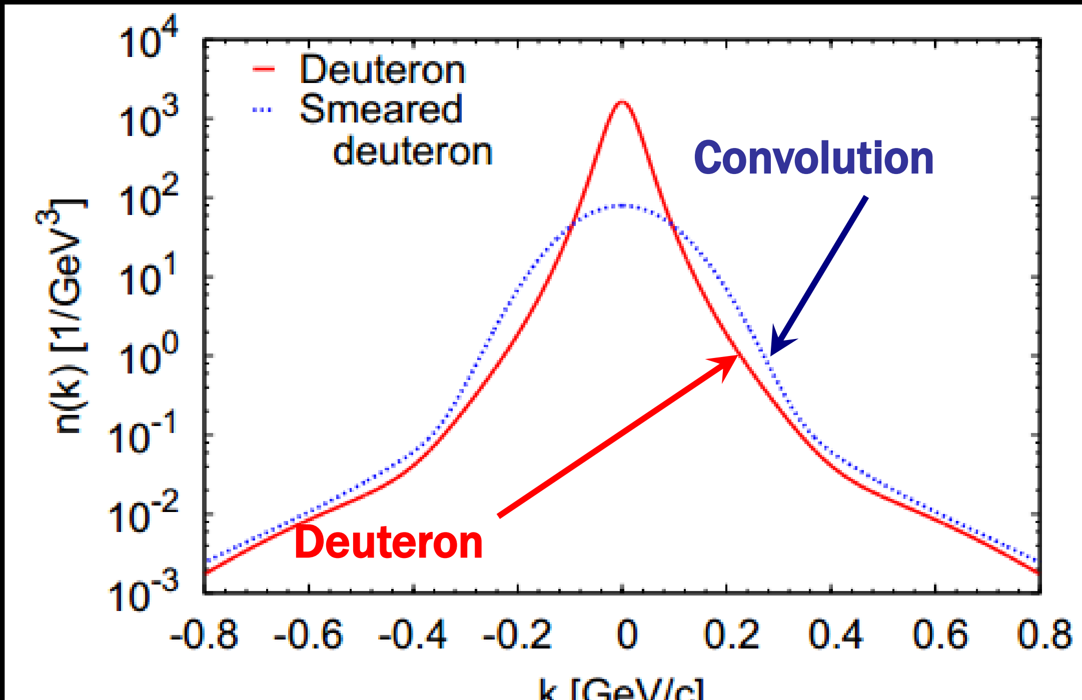


($a_2=\sigma_A/\sigma_D$)!= Relative #of SRCs



$n_D^{CONV}(k)$ 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)

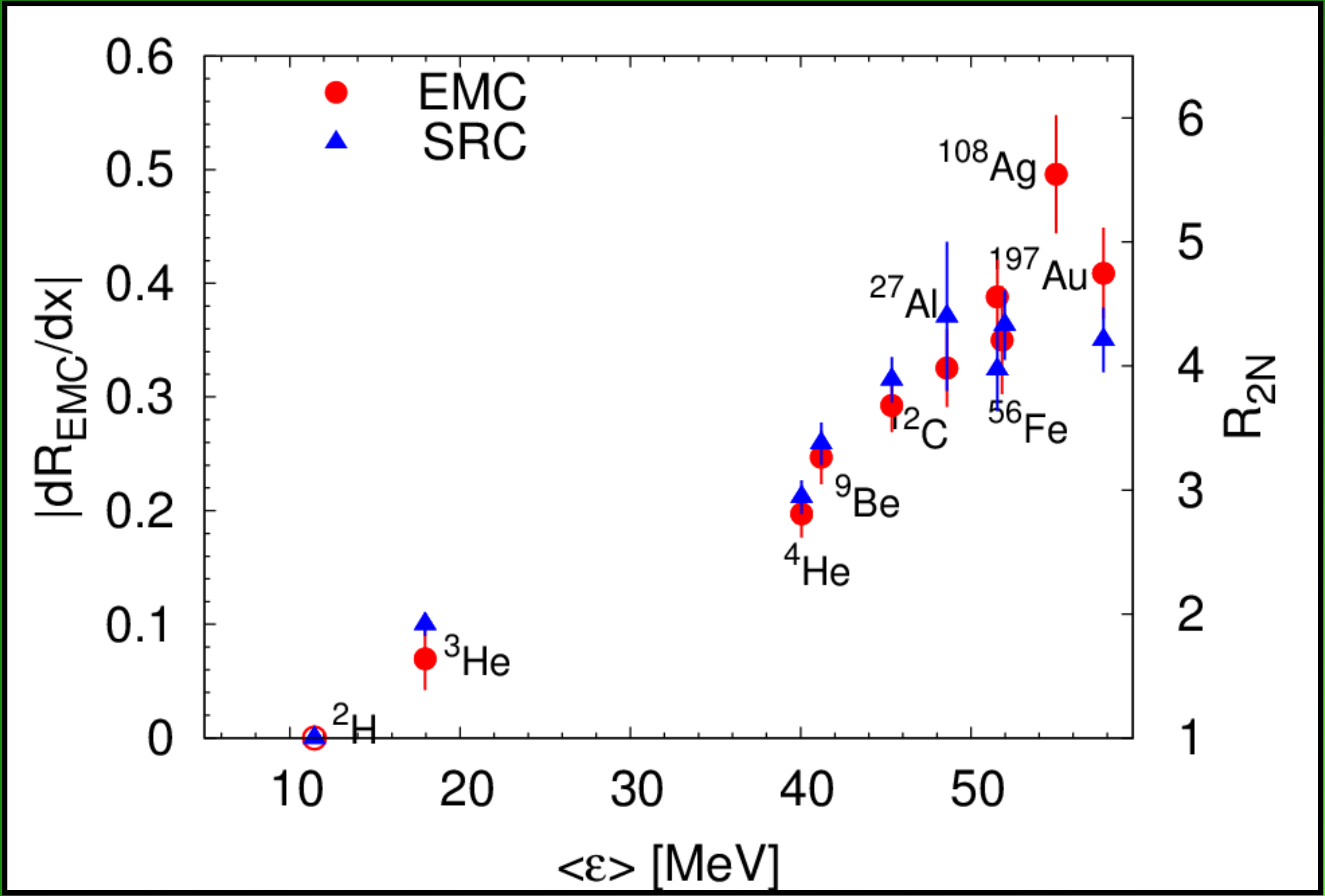
	E02-019	SLAC	CLAS	R_{2N}-ALL	a_2-ALL
^{3}He	1.93±0.10	1.8±0.3	–	1.92±0.09	2.13±0.04
^{4}He	3.02±0.17	2.8±0.4	2.80±0.28	2.94±0.14	3.57±0.09
Be	3.37±0.17	–	–	3.37±0.17	3.91±0.12
C	4.00±0.24	4.2±0.5	3.50±0.35	3.89±0.18	4.65±0.14
Al	–	4.4±0.6	–	4.40±0.60	5.30±0.60
Fe	–	4.3±0.8	3.90±0.37	3.97±0.34	4.75±0.29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

Both driven by a similar underlying cause?

Separation Energy

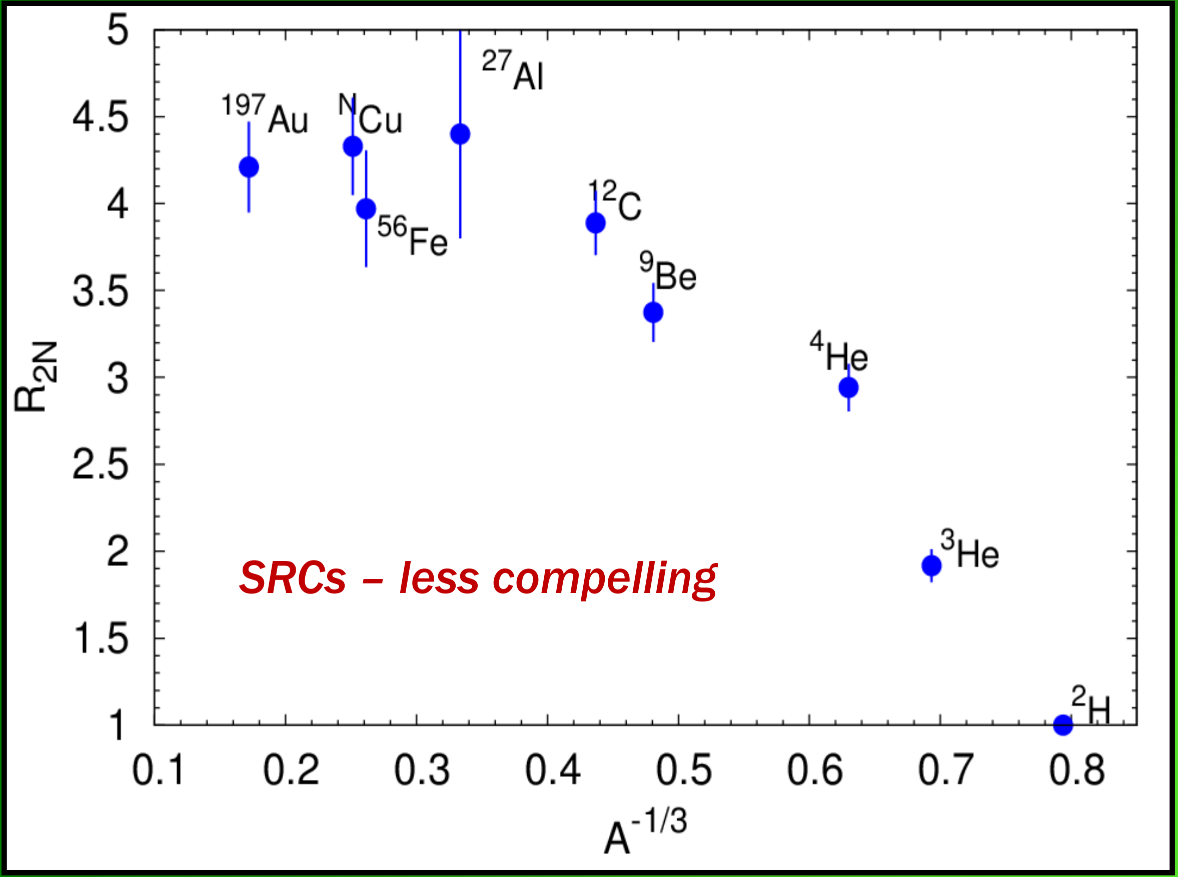


For SRCs, a linear relationship with <ε> is less suggestive

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

Both driven by a similar underlying cause?

$A^{-1/3}$

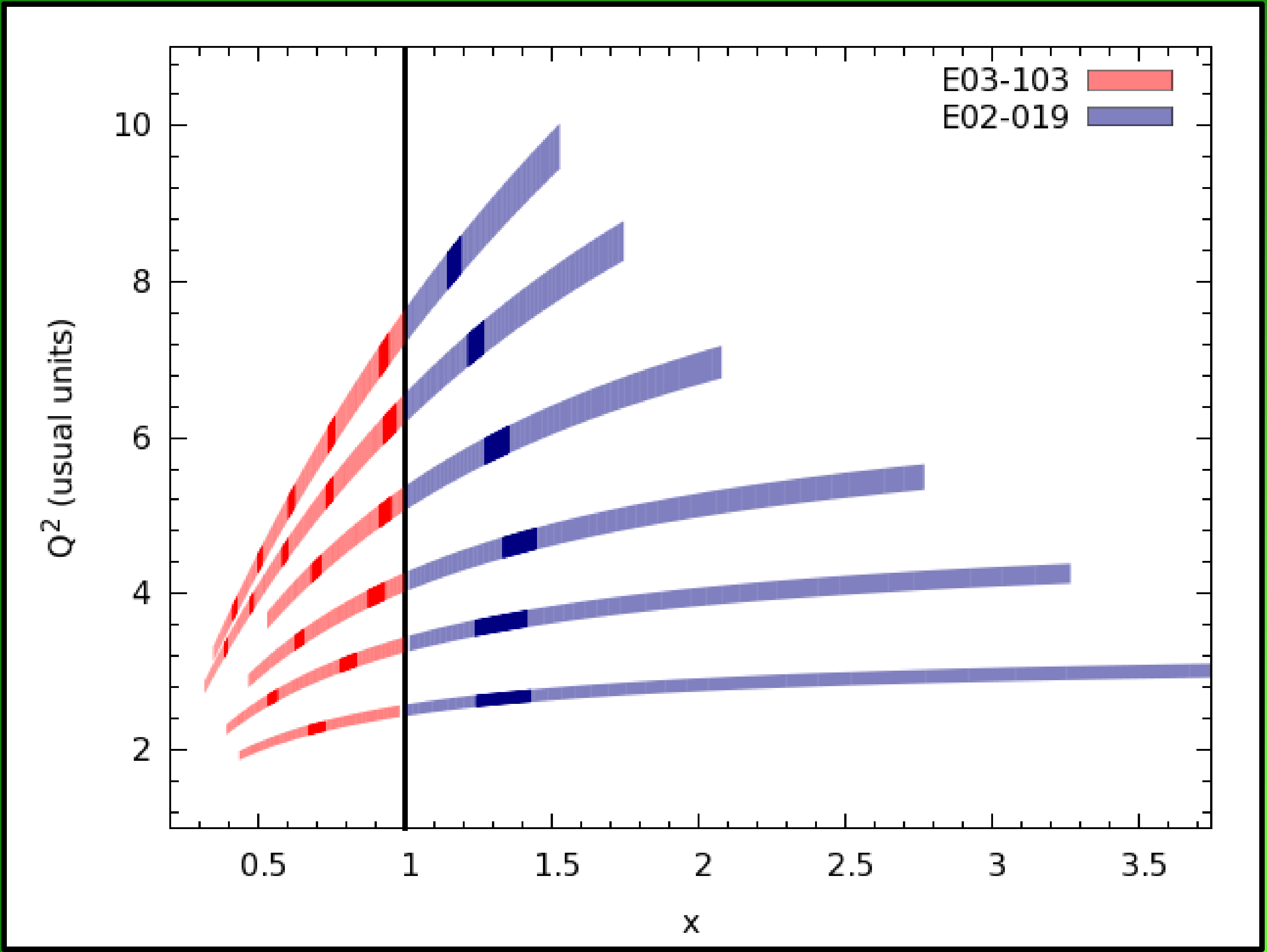


Apply exact NM calculations to finite nuclei via LDA

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

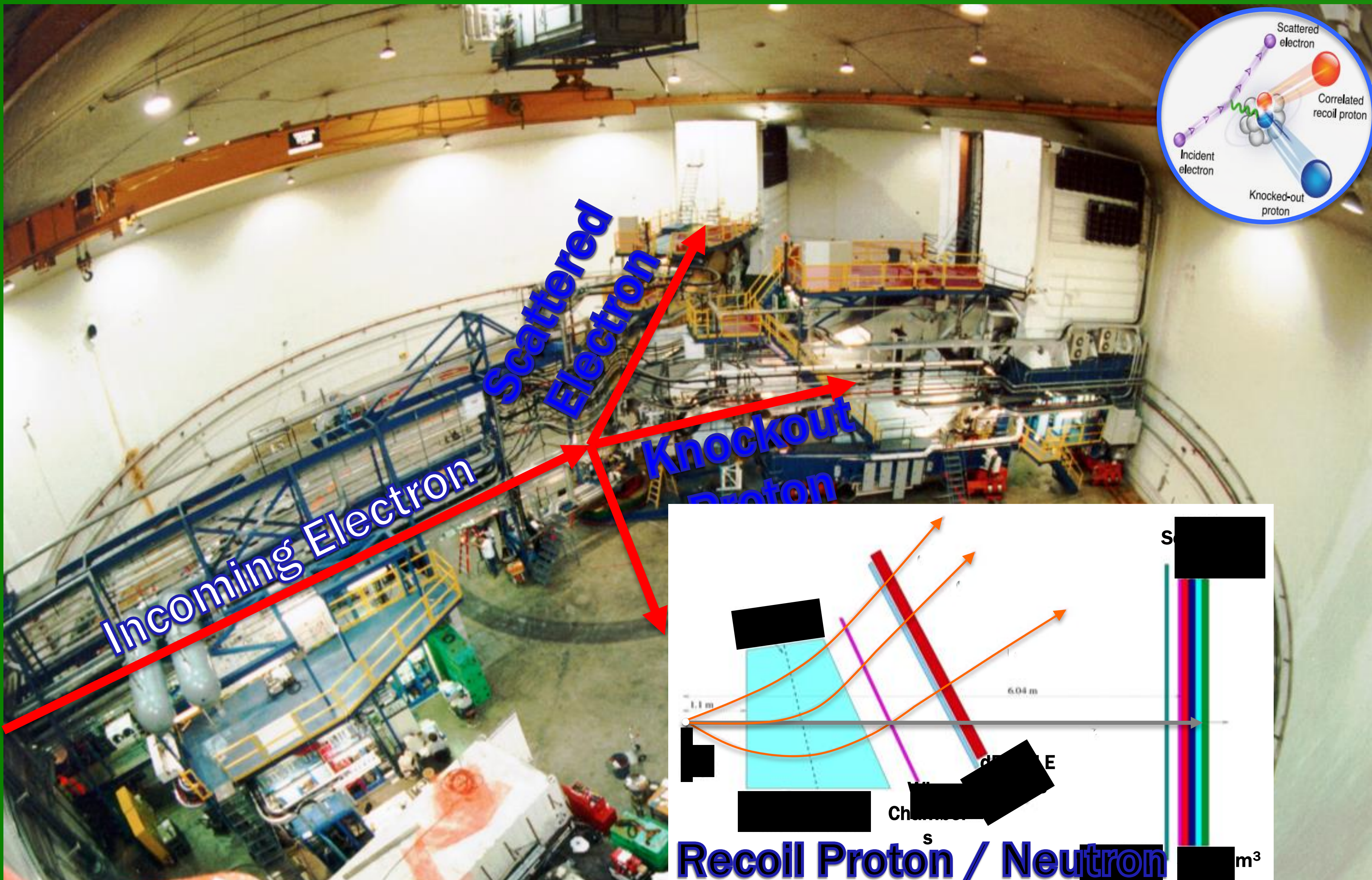
- For A>12, the nuclear density distribution has a common shape; constant in the nuclear interior (bulk)
  → ***Scale with A***
- Nuclear surface contributions grow ***as*** $A^{2/3}$ (R^2)
- σ per nucleon would be constant with small deviations that go with $A^{-1/3}$

10+ years ago....in Hall C



^{2}H
^{3}He
^{4}He
^{9}Be
^{12}C
^{27}Al*
^{63}Cu
^{197}Au

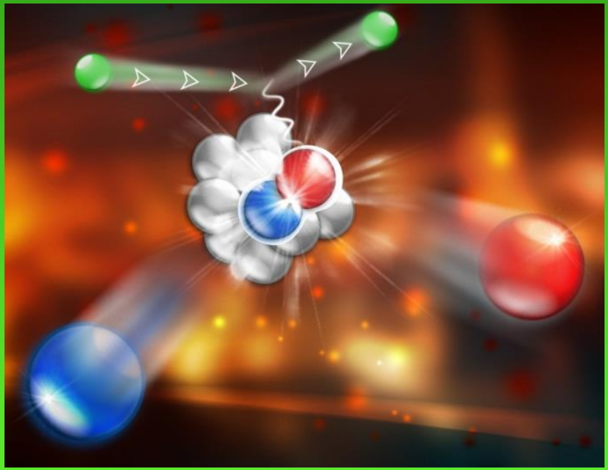
Physics Tend to Fill the Open Space



2N knockout experiments establish NP dominance

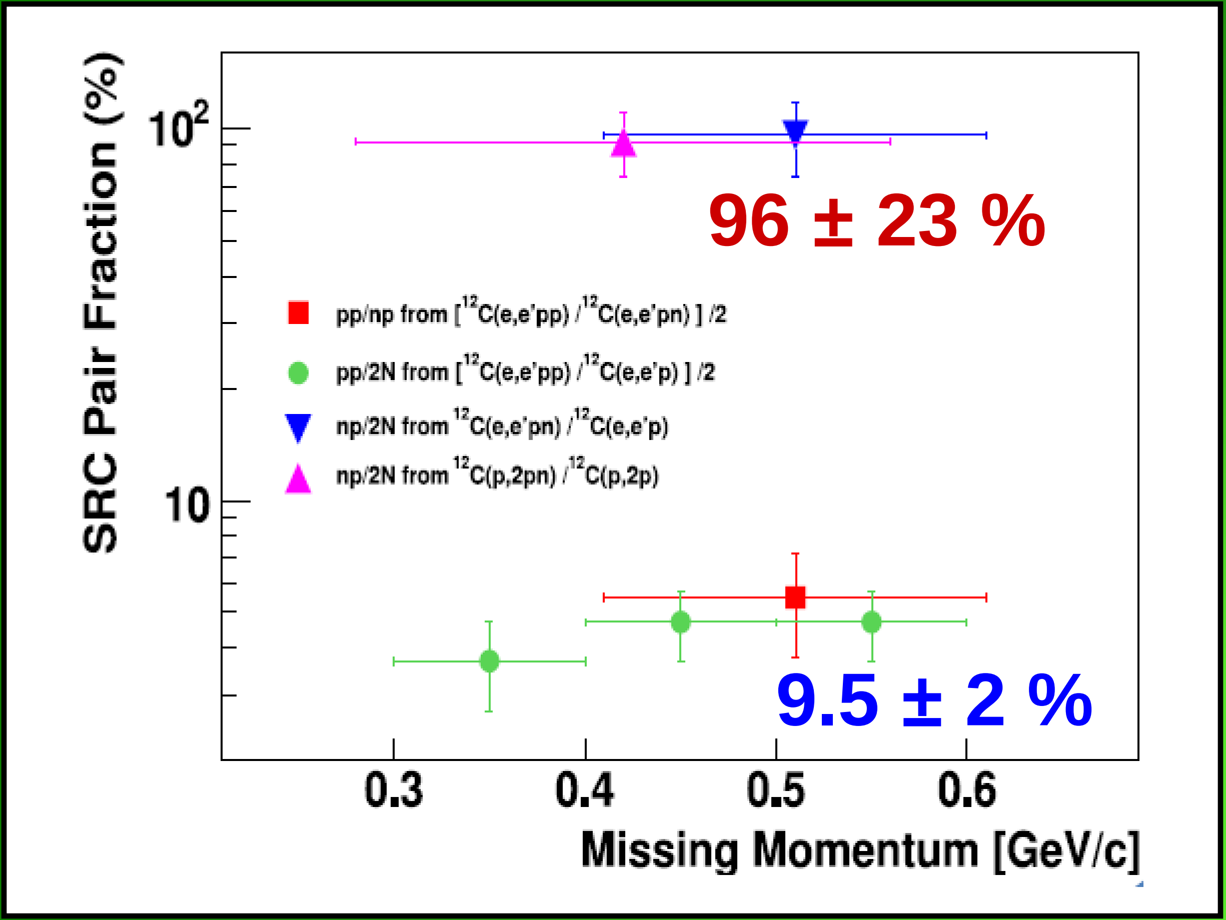
- Knockout high-initial-momentum proton, look for correlated nucleon partner.
- For 300 < P_{miss} < 600 MeV/c all nucleons are part of 2N-SRC pairs: 90% np, 5% pp (nn)

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

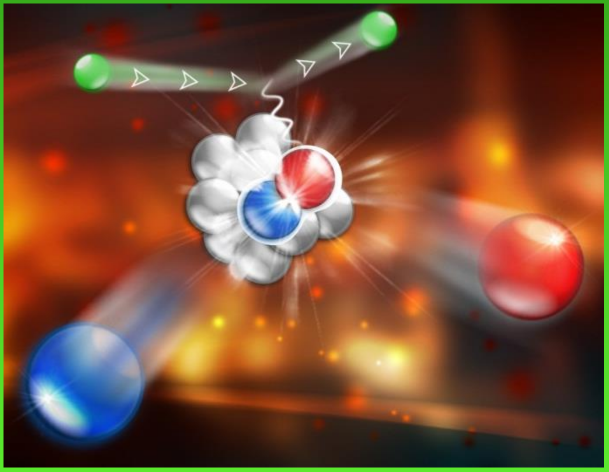


R. Shneor et al., PRL 99, 072501 (2007)

2N knockout experiments establish NP dominance

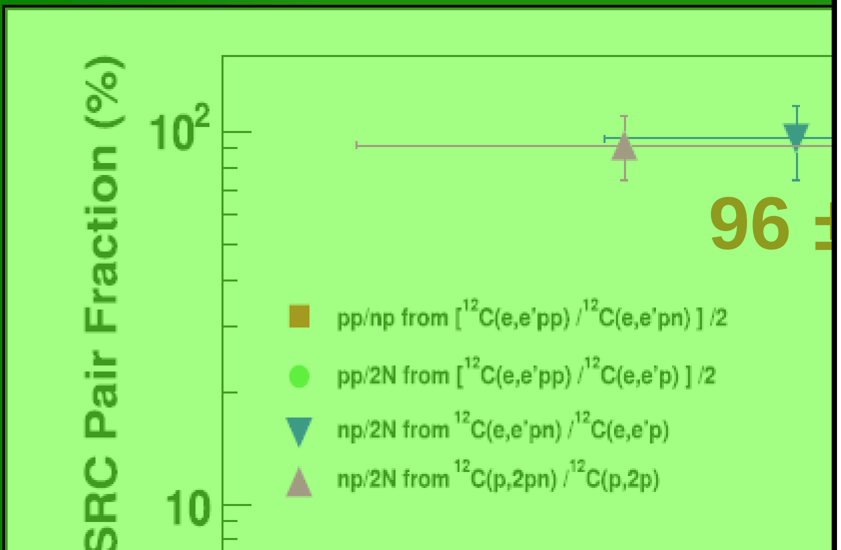


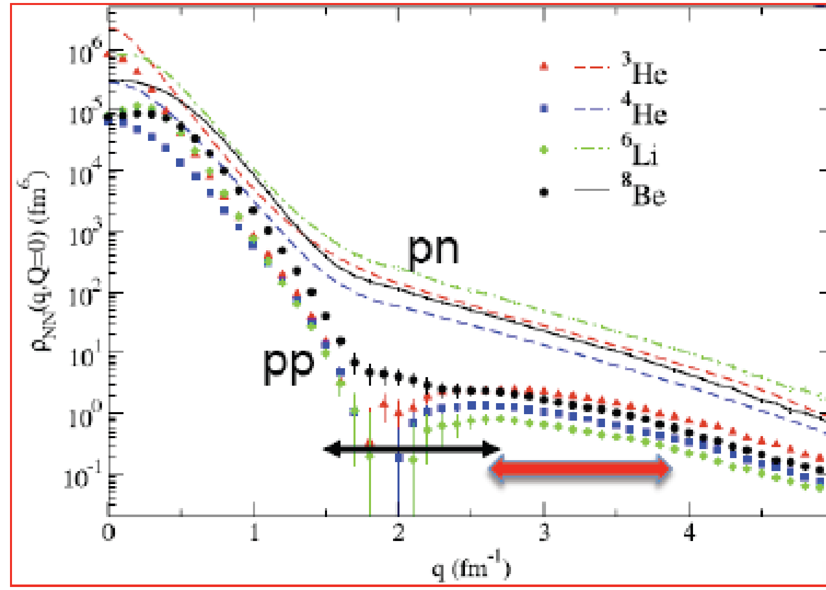
R. Subedi et al., Science 320, 1476 (2008)



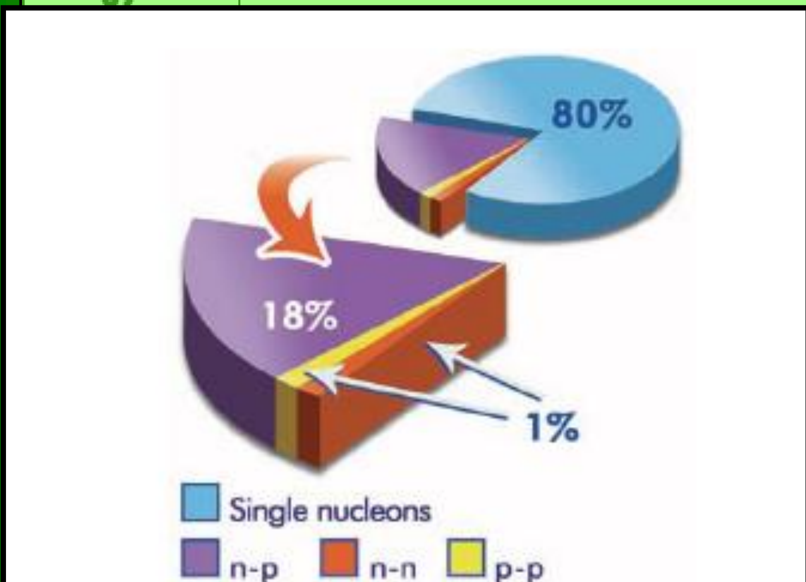
R. Shneor et al.,
PRL 99, 072501 (2007)

NP dominance





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

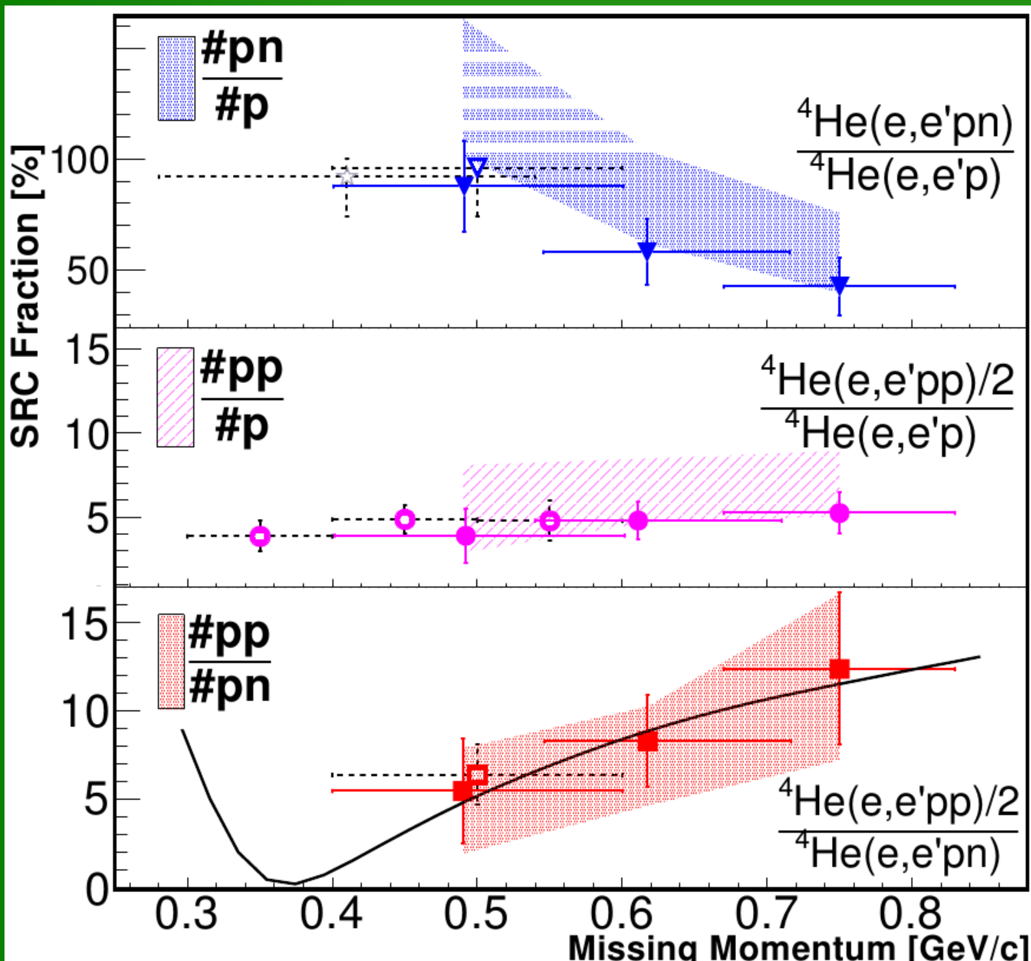


also

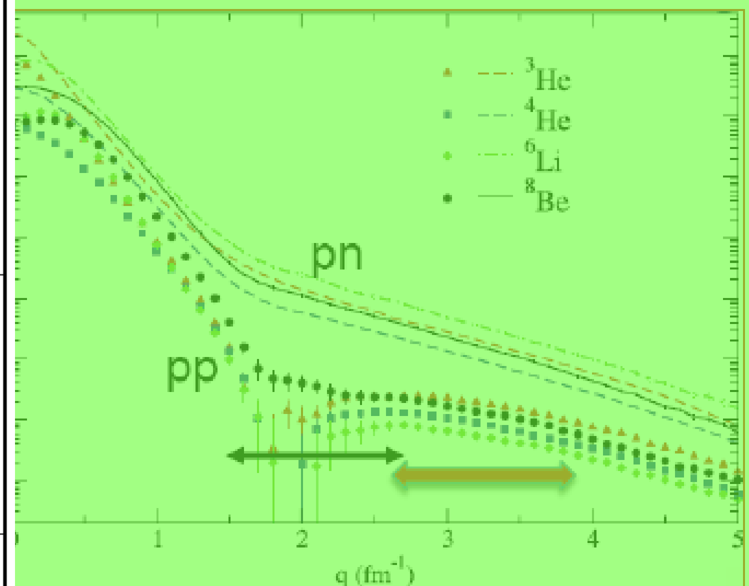
→ Ciofi and Alvioli PRL 100, 162503 (2008)

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

NP dominance: momentum dependent



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



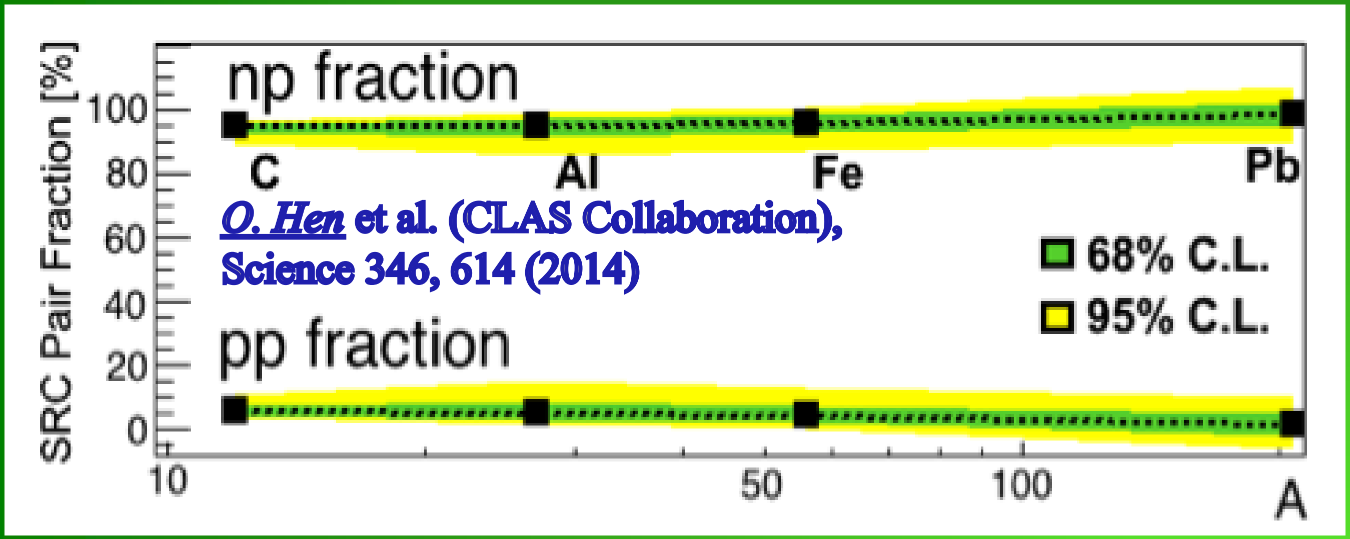
chiavilla, R. B. Wiringa, S. C. Pieper, J.
son, Phys. Rev. Lett. **98** (2007) 132501

also

→ C.Ci... i and Alvioli PRL 100, 162503 (2008)

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

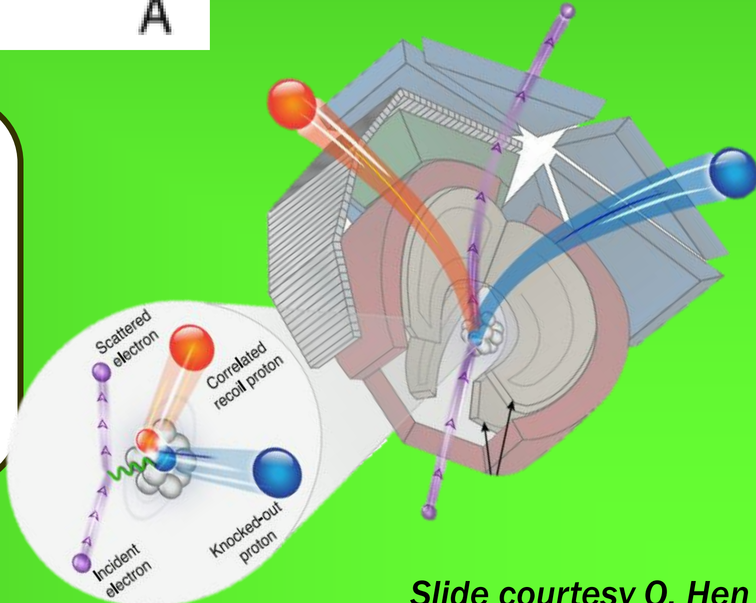
Data mining using CLAS
NP dominance continues for heavy nuclei



Assuming scattering off 2N-SRC pairs:

- **(e,e'p) is sensitive to *np* and *pp* pairs**
- **(e,e'pp) is sensitive to *pp* pairs alone**

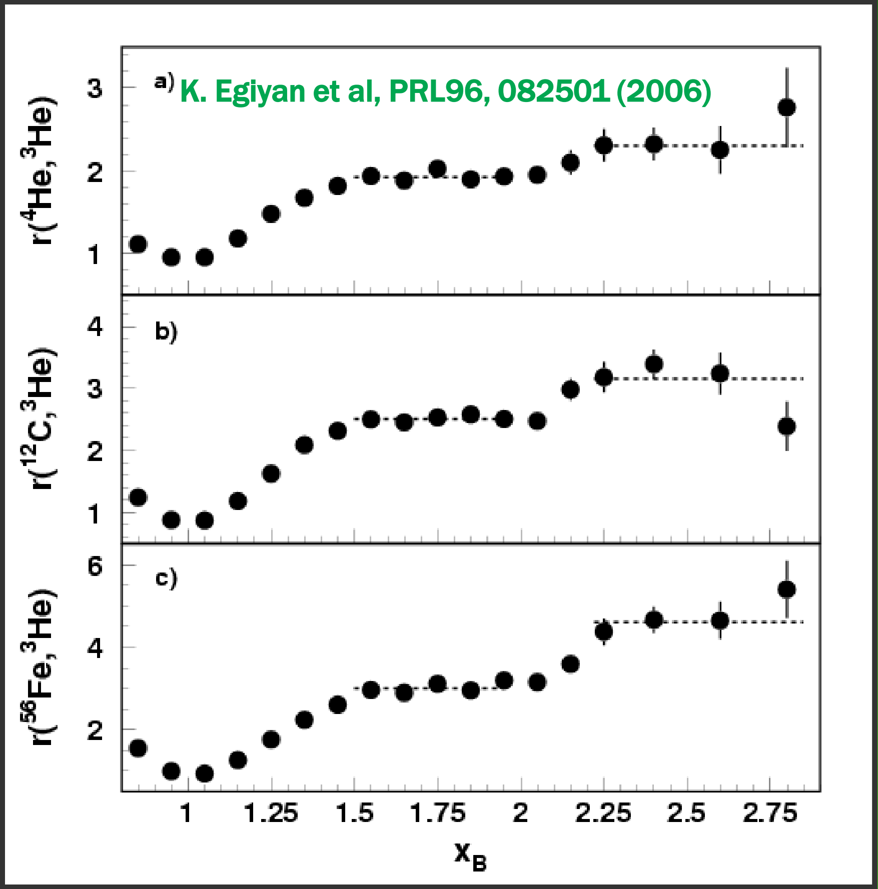
=> (e,e'pp)/(e,e'p) ratio is sensitive to the *np*/*pp* ratio



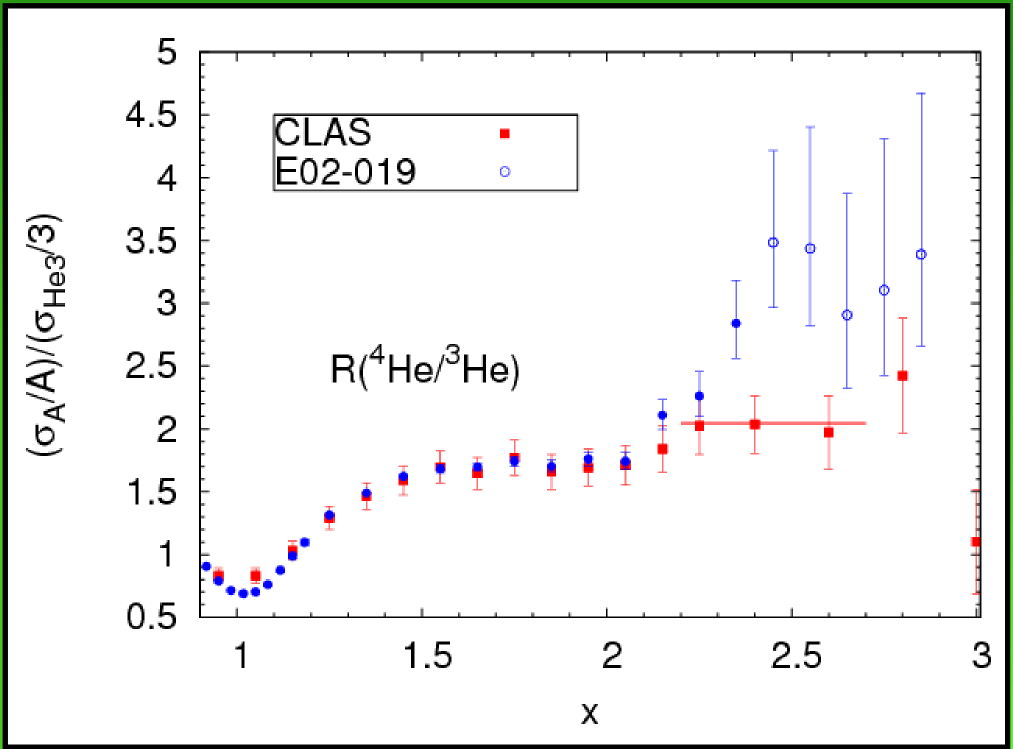
Slide courtesy O. Hen

Why not more nucleons in a correlation?

Further evidence of multi-nucleon correlations



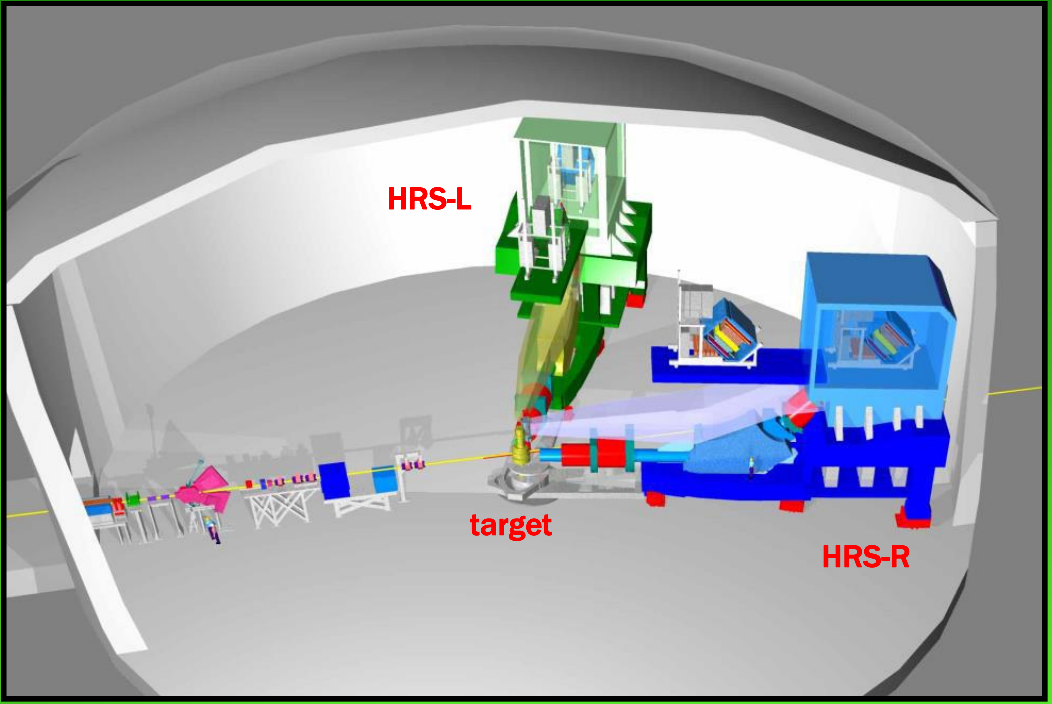
<Q^2> (GeV^2): ***CLAS: 1.6*** ***E02-019: 2.7***



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

E08-014: Study 3N correlations

- Map Q^2 dependence of 3N plateau
- Verify Isospin Dependence with ^{40}Ca and ^{48}Ca

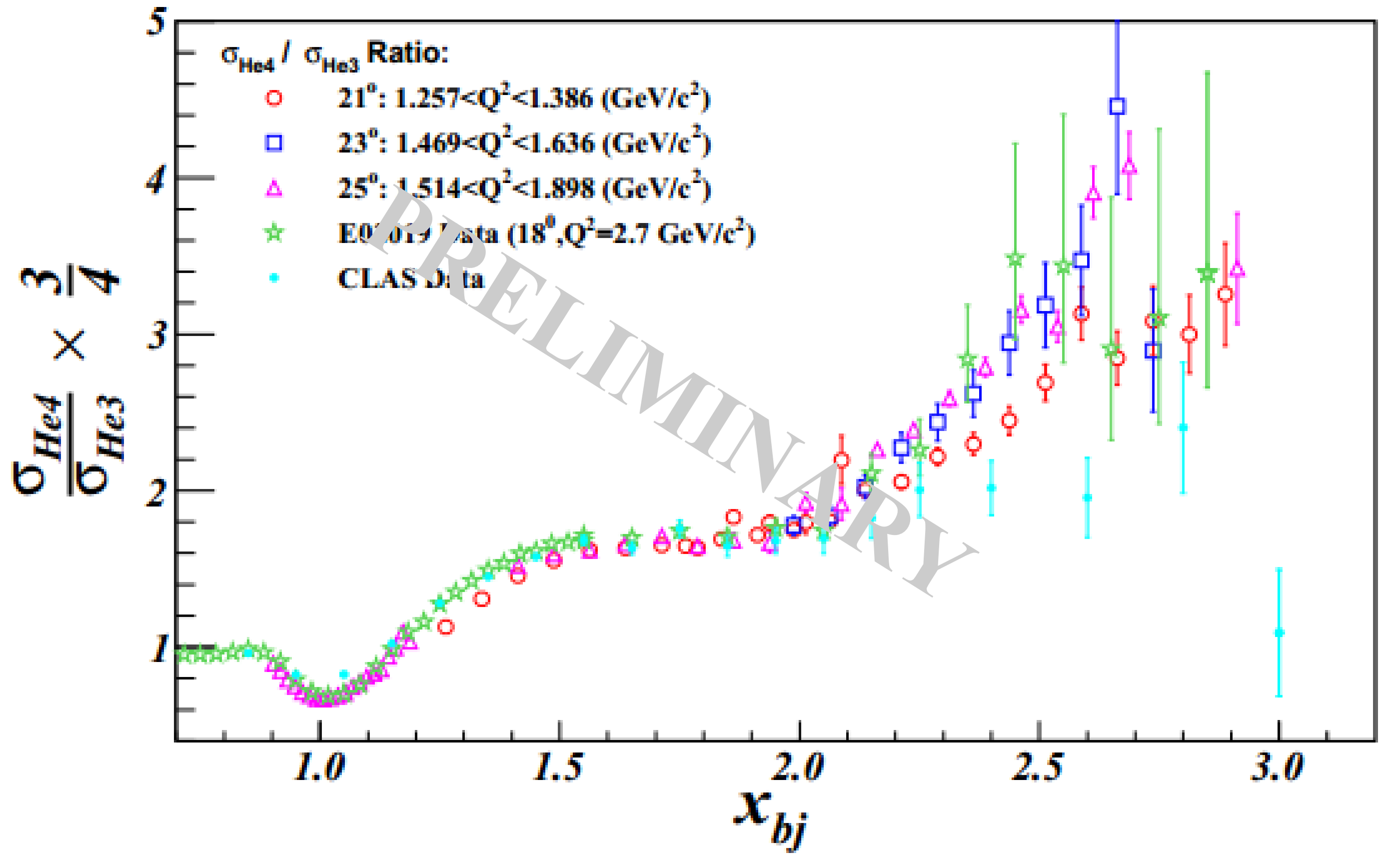


Analysis in final stages

If independent: $$\frac{\sigma_{Ca48}/48}{\sigma_{Ca40}/40} = \frac{(20\sigma_p + 28\sigma_n)/48}{(20\sigma_p + 20\sigma_n)/40} \xrightarrow{\sigma_p \approx 3\sigma_n} 0.92$$

If dependent: $$\frac{\sigma_{Ca48}/48}{\sigma_{Ca40}/40} = \frac{(20\times 28)/48}{(20\times 20)/40} \longrightarrow 1.17$$

E08-014: Study 3N correlations

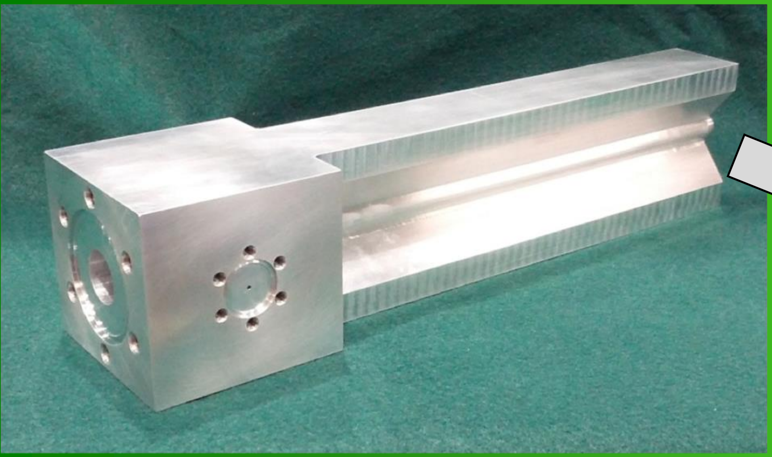


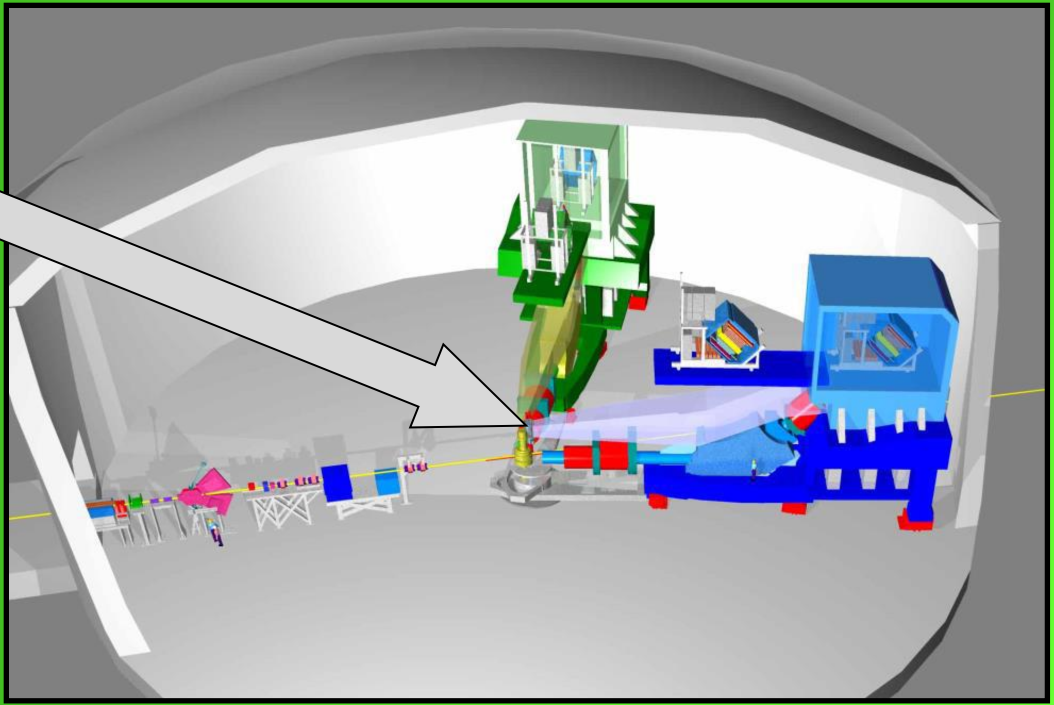
Plot courtesy of Z. Ye

Coming soon at 12 (well….11) GeV

Coming very soon: [Jlab E12-11-112]

- Quasielastic electron scattering with ^3H and ^3He
- Study isospin dependence of 2N and 3N correlations
- Test calculations of FSI for well-understood nuclei





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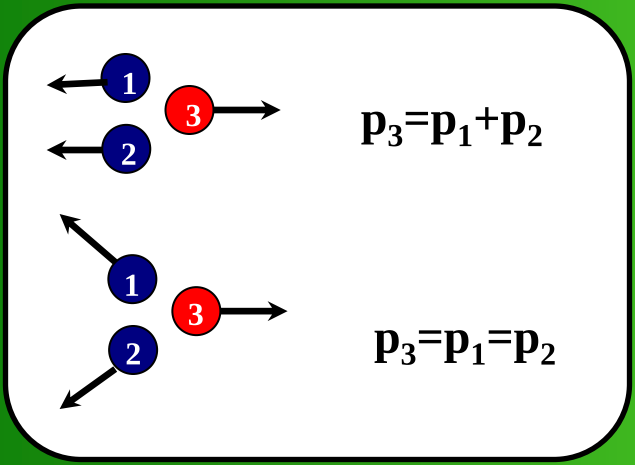
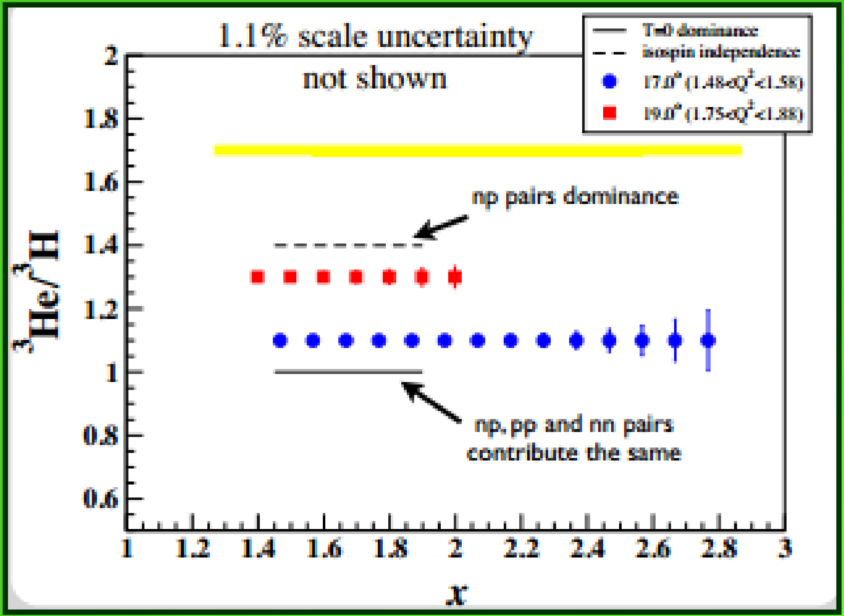
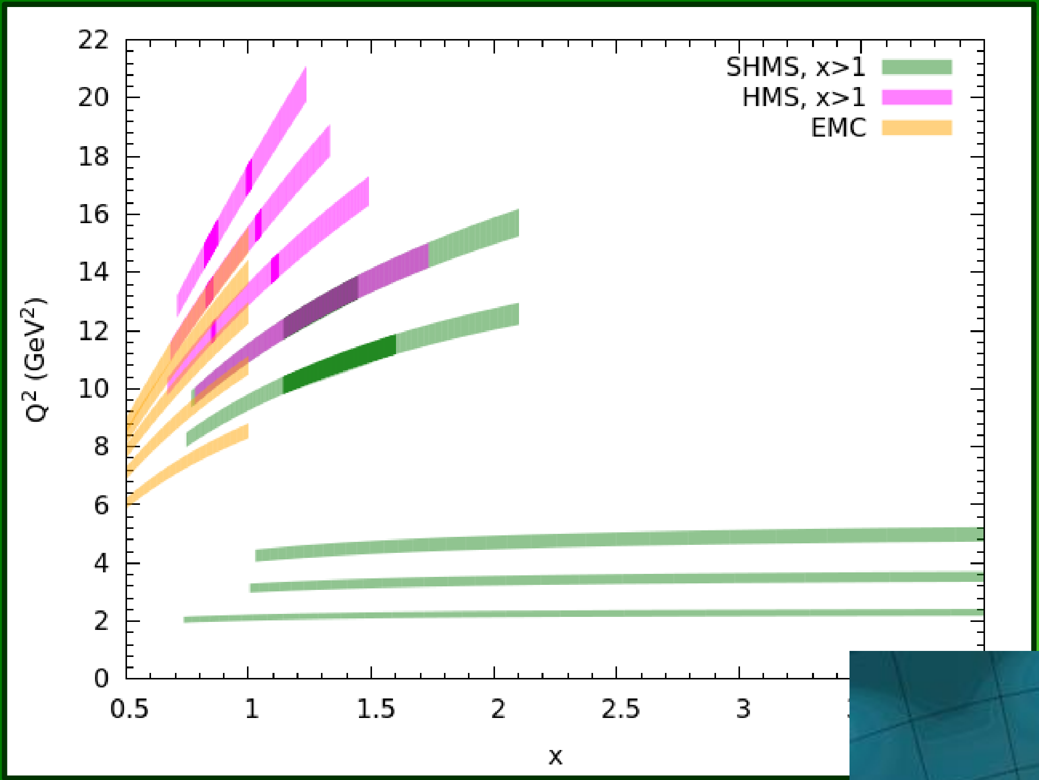
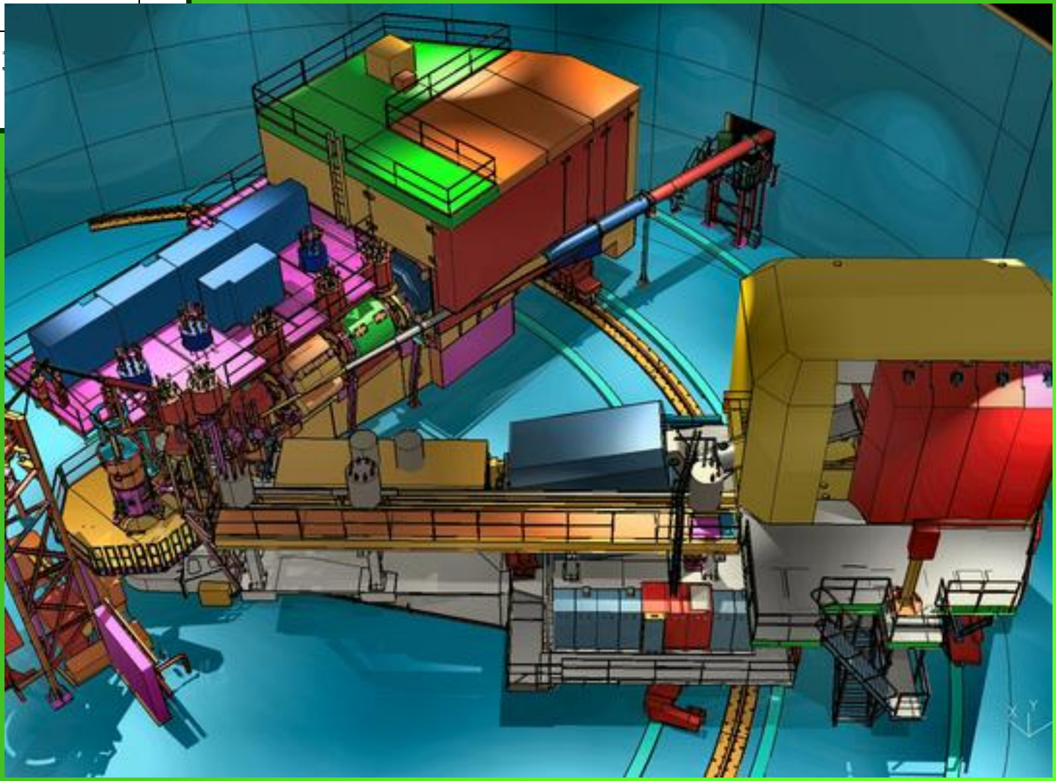


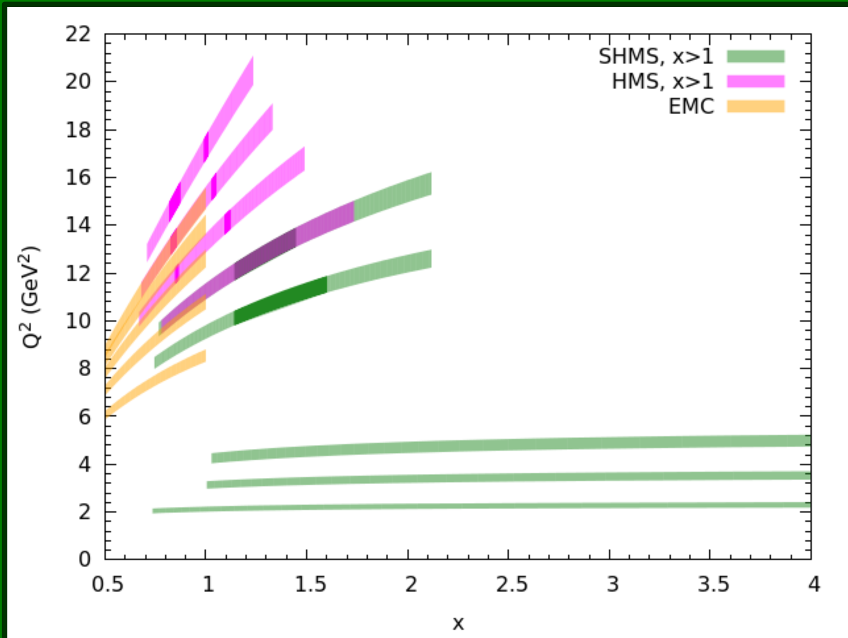




Jlab E12-06-105

- short-range nuclear structure
  - Isospin dependence
  - A-dependence
- Super-fast quarks





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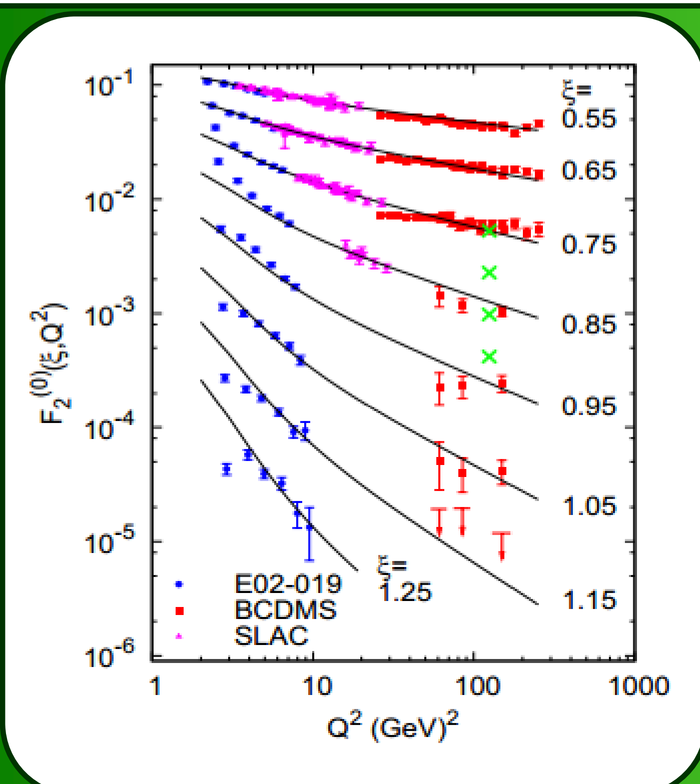
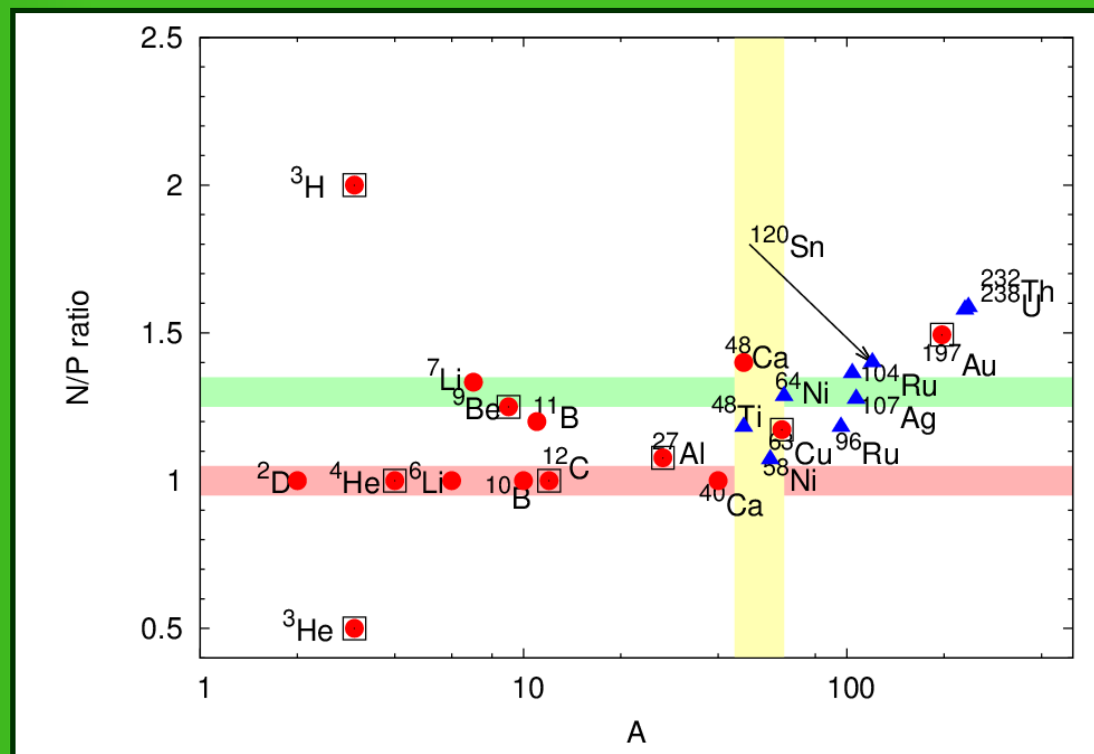
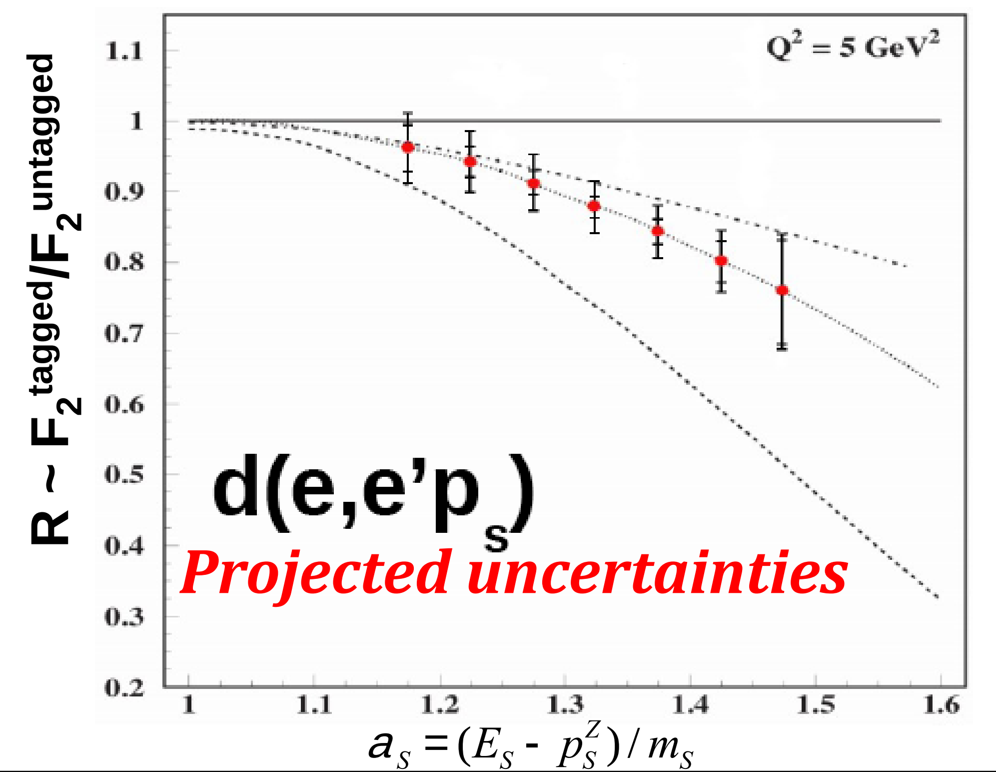


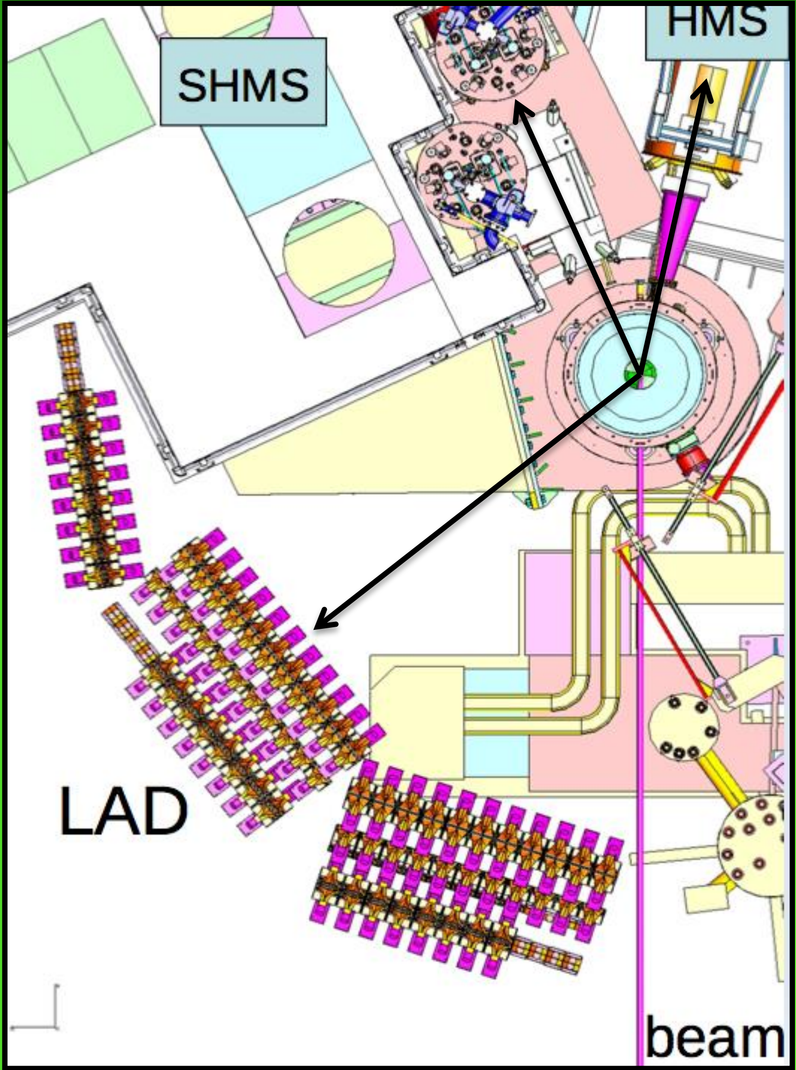


In-Medium Nucleon Structure Functions

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

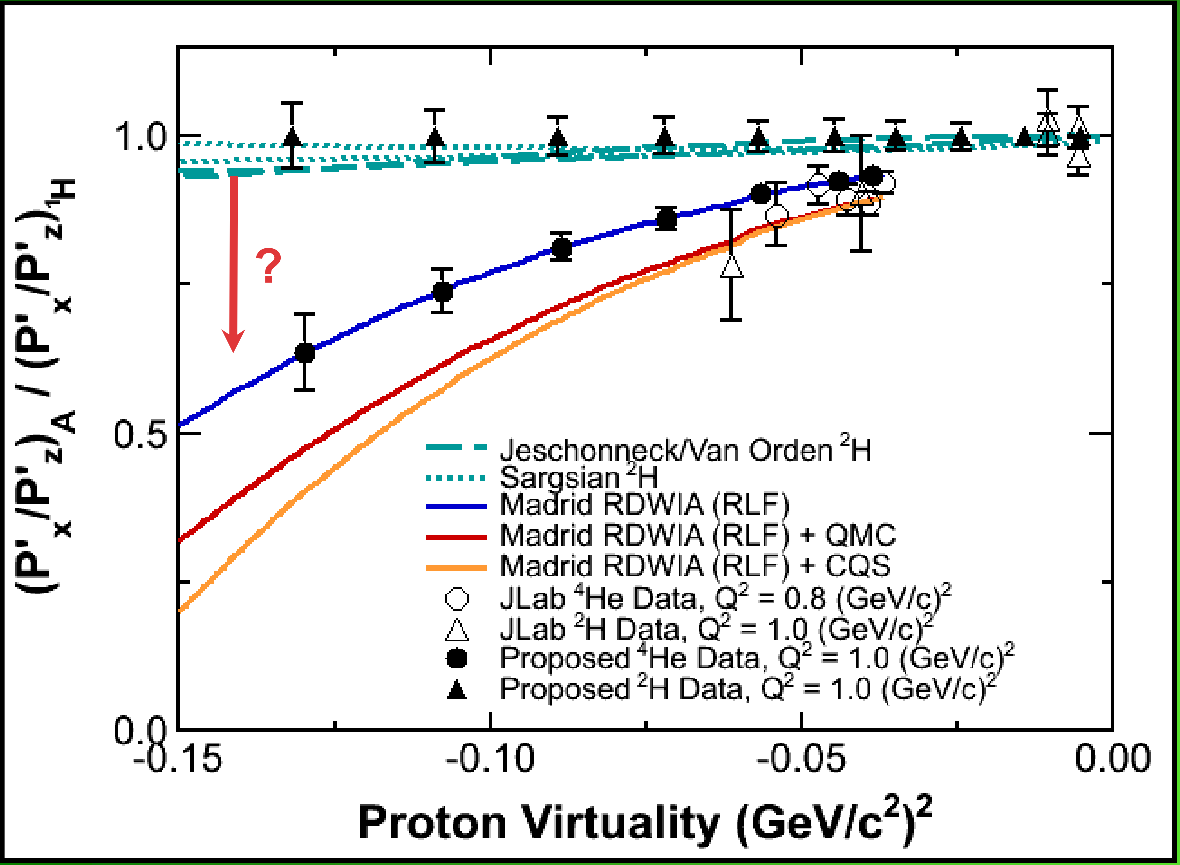
- **DIS scattering from nucleon in deuterium**
- **Tag high-momentum struck nucleons by detecting backward "spectator" nucleon in Large-Angle Detector**





In-Medium Nucleon Form Factors

[E11-002: E. Brash, G. M. Huber, R. Ransom, S. Strauch]



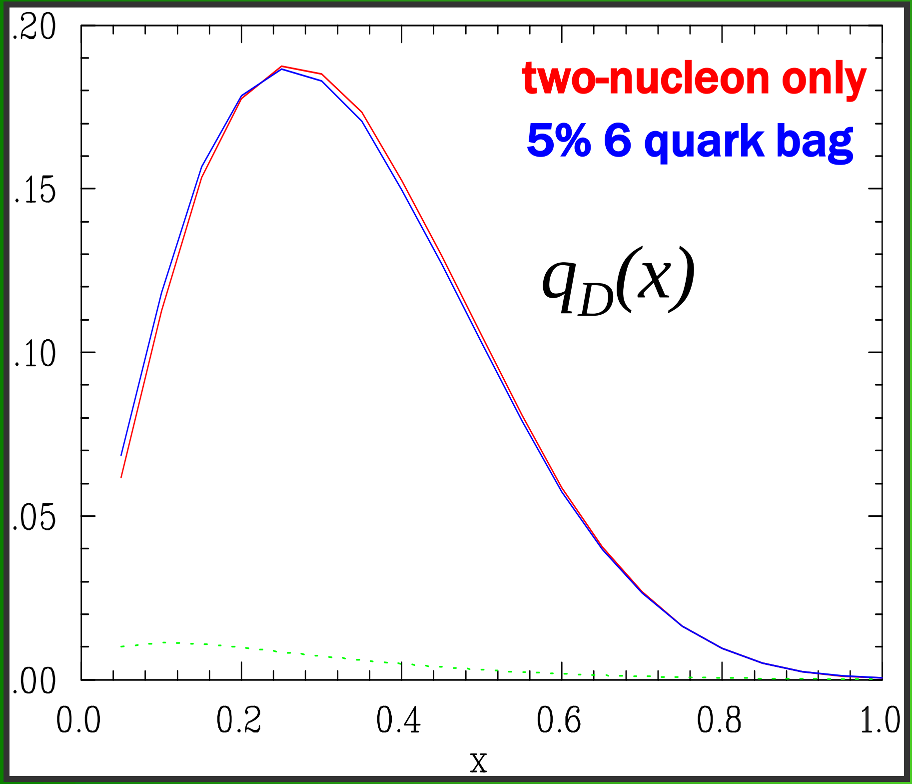
- Compare proton knock-out from dense and thin nuclei: *^{4}He(e,e′p)^{3}H* and *^{2}H(e,e′p)n*
- Modern, rigorous ^{2}H(e,e'p)n calculations show reaction-dynamics effects and FSI will change the ratio at most 8%
- QMC model predicts 30% deviation from free nucleon at large virtuality

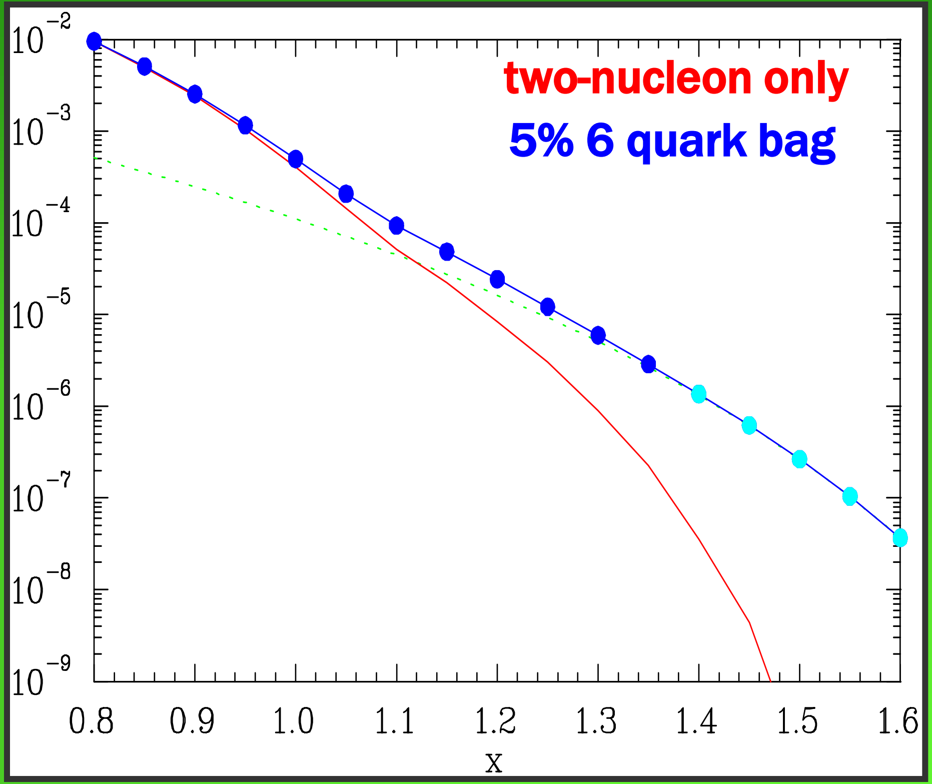
S. Jeschonnek and J.W. Van Orden, Phys. Rev. C 81, 014008 (2010) and Phys. Rev. C 78, 014007 (2008); M.M. Sargsian, Phys. Rev. C82, 014612 (2010)

Summary

- SRCs have been under the microscope for many decades – 6GeV era at Jlab has yielded interesting data
- 12 GeV experiments continue the search
- New results in the next few years!

Overlapping nucleons ⟶ enhancement of F_2 structure function





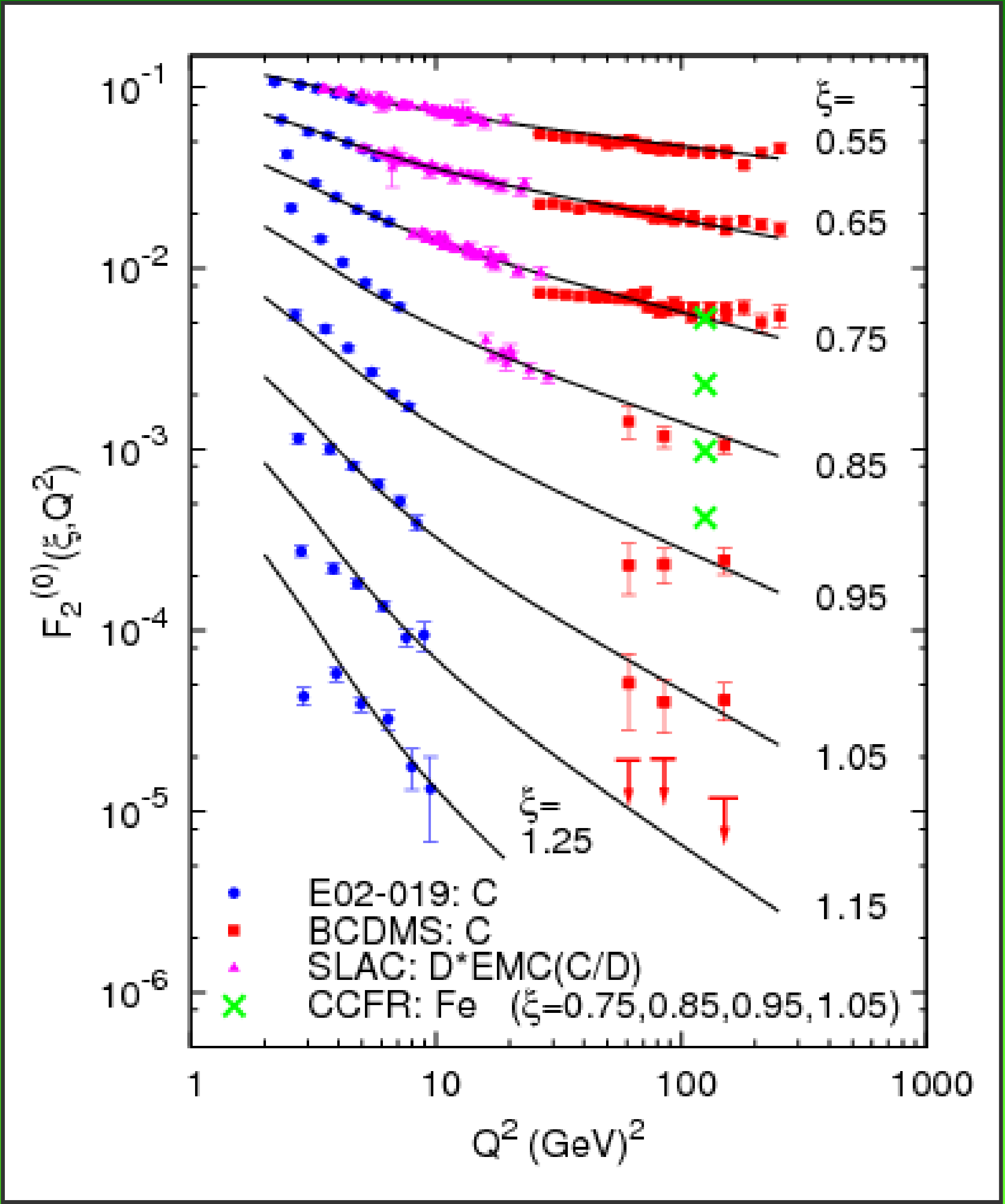
Small effect, possible contribution to EMC effect?

Noticeable effect at x>1

"Superfast" quarks

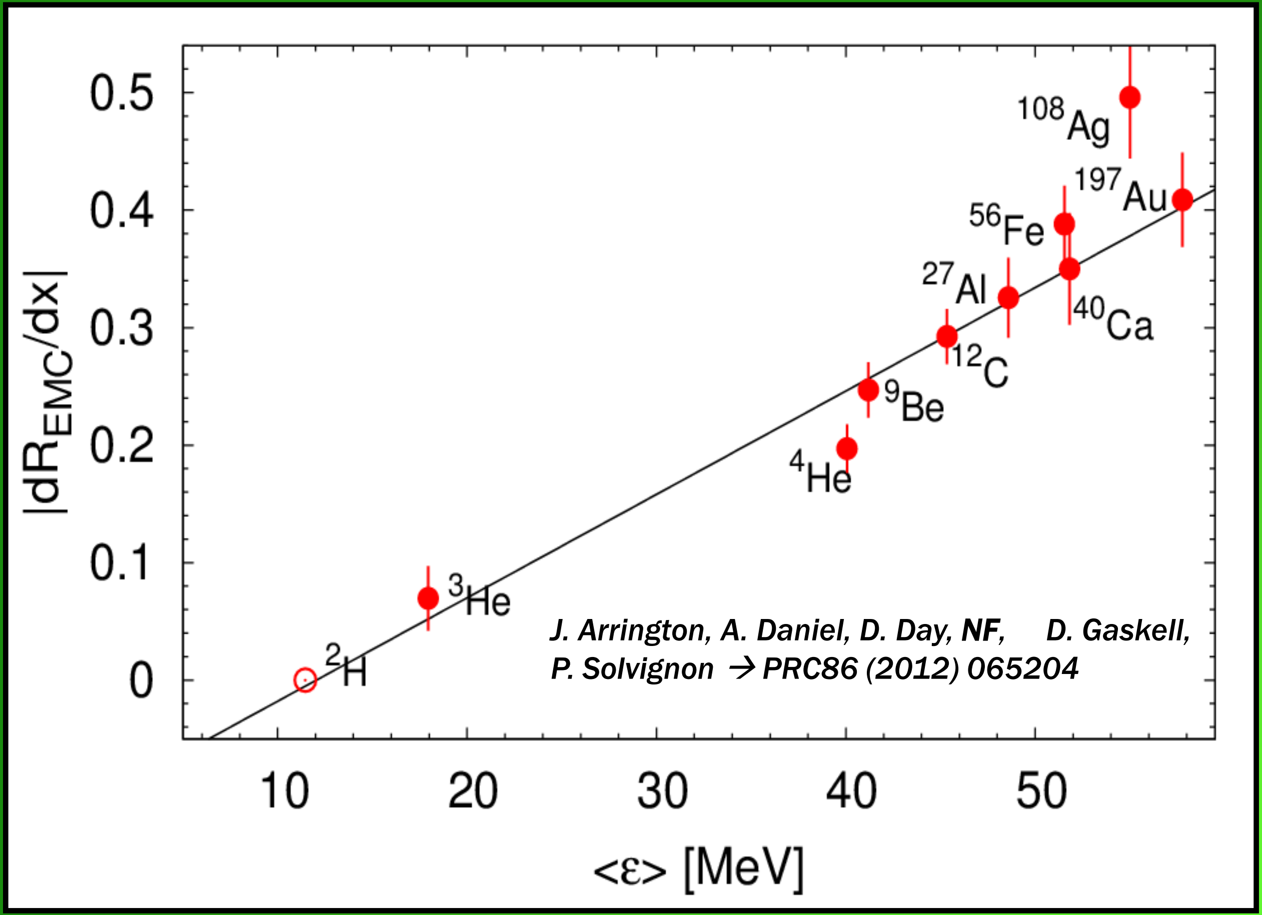
Current data at highest Q^2 (JLab E02-019) already sensitive to partonic behavior at x>1

N. Fomin et al, PRL 105, 212502 (2010)



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)