SRCs in x>1 Inclusive Processes

Nadia Fomin
University of Tennessee

EMMI Workshop
Cold dense nuclear matter:
from short-range nuclear correlations to neutron stars
October 13-16, 2015
GSI, Darmstadt

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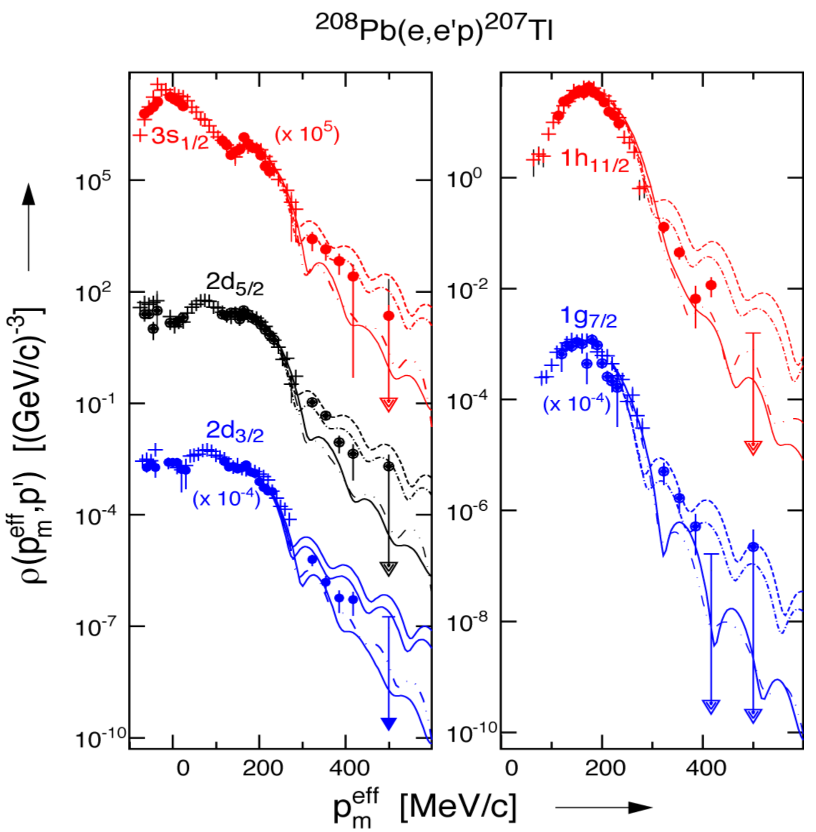
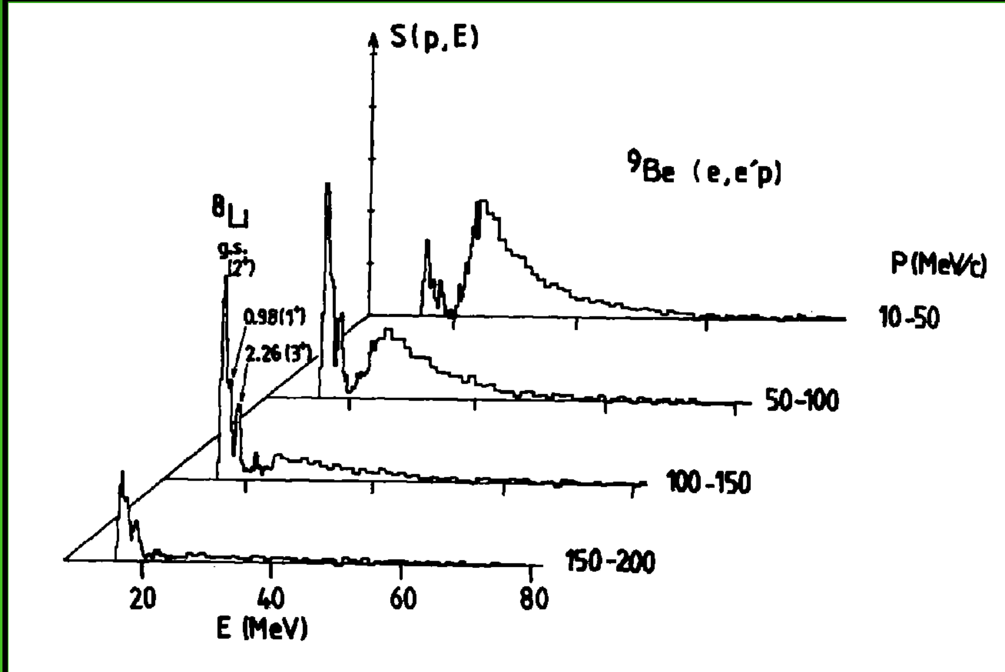
High momentum nucleons – where do they come from?

Independent Particle Shell Model :

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



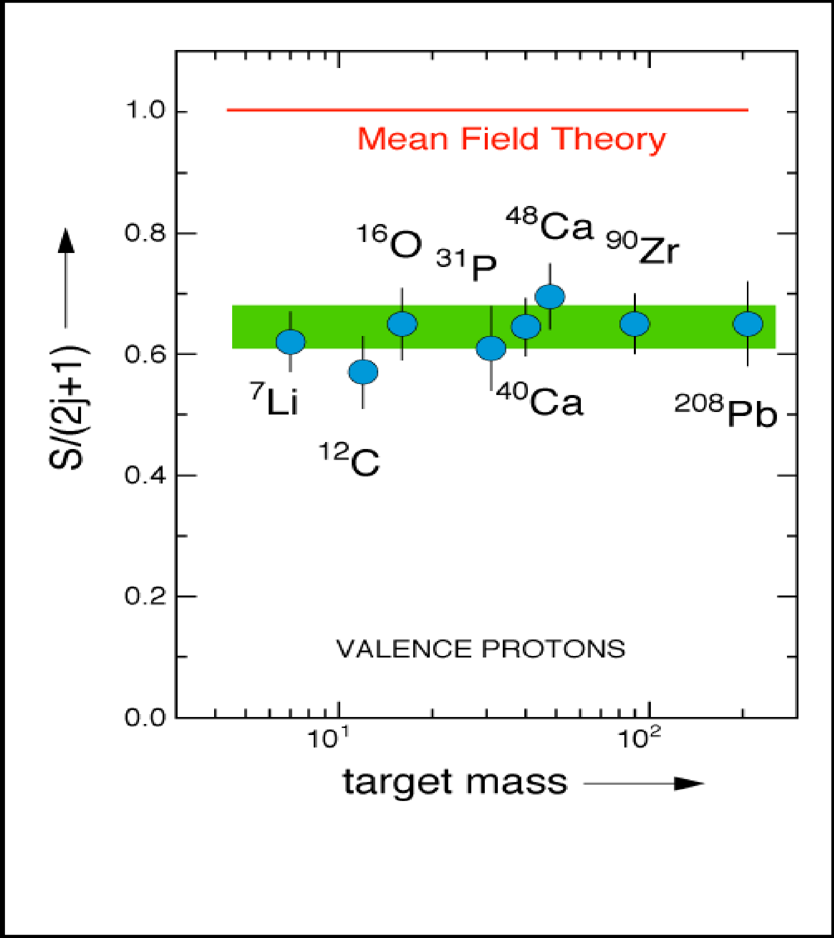


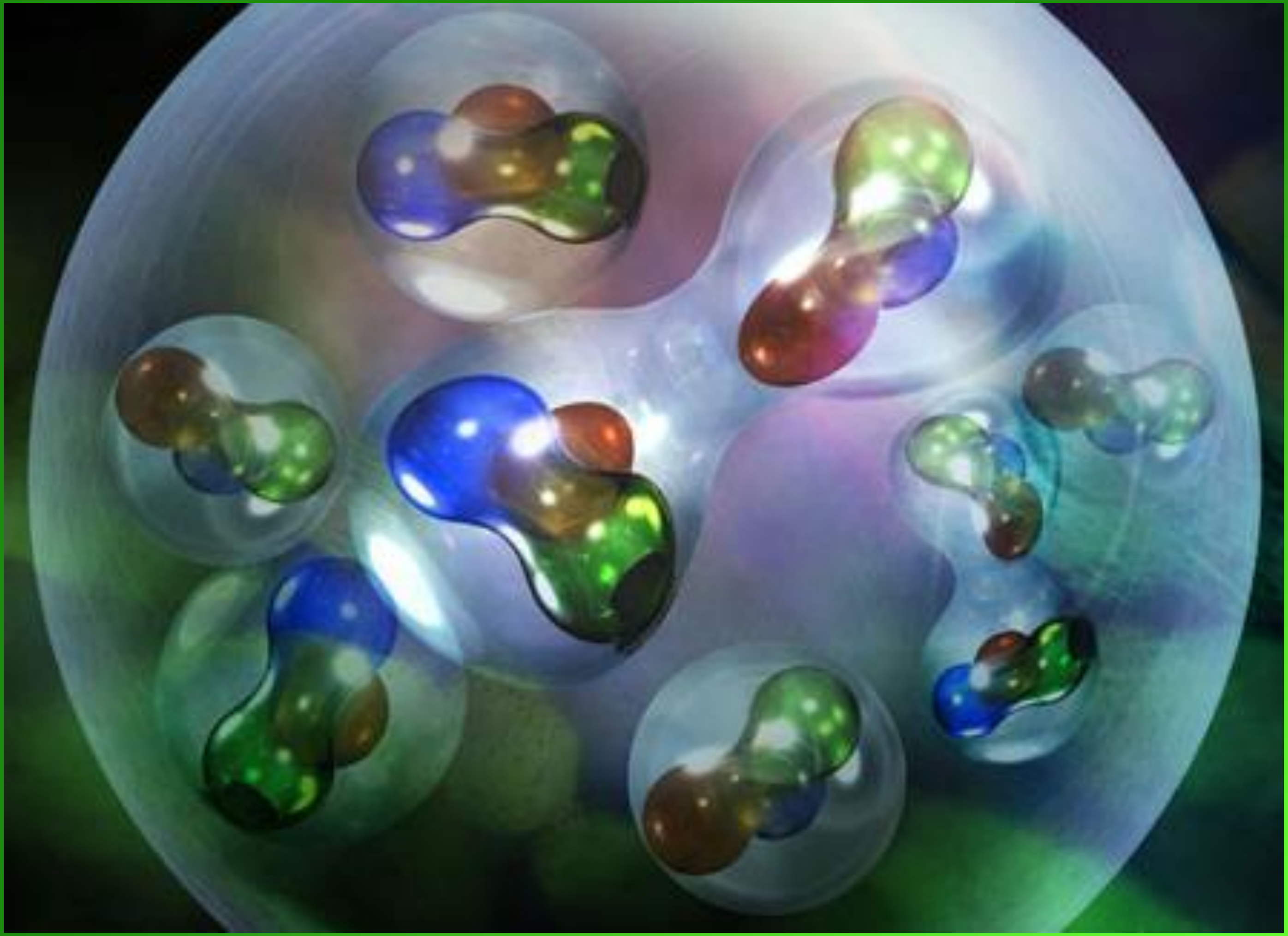
Proton E_m,p_m distribution modeled as sum of independent shell contributions (arbitrary normalization)

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**

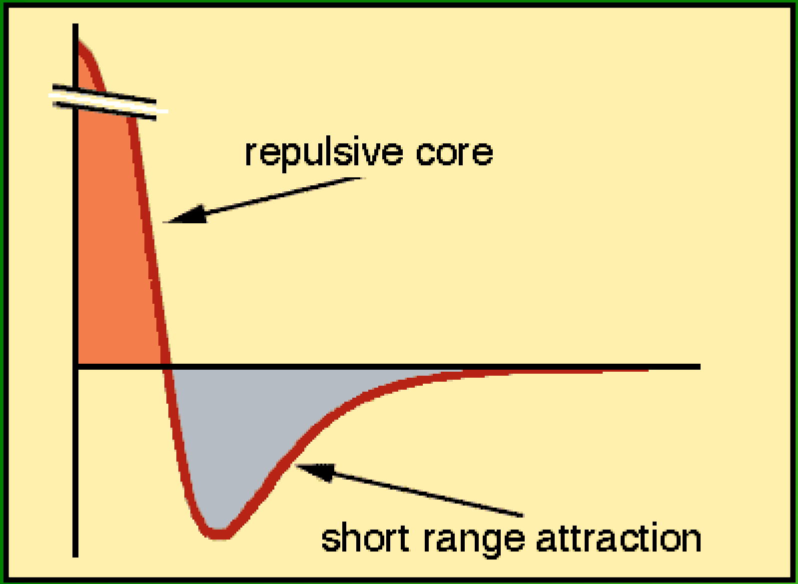


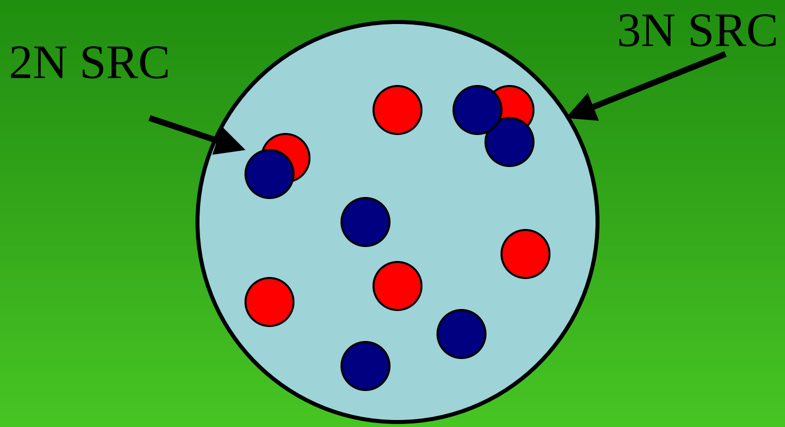


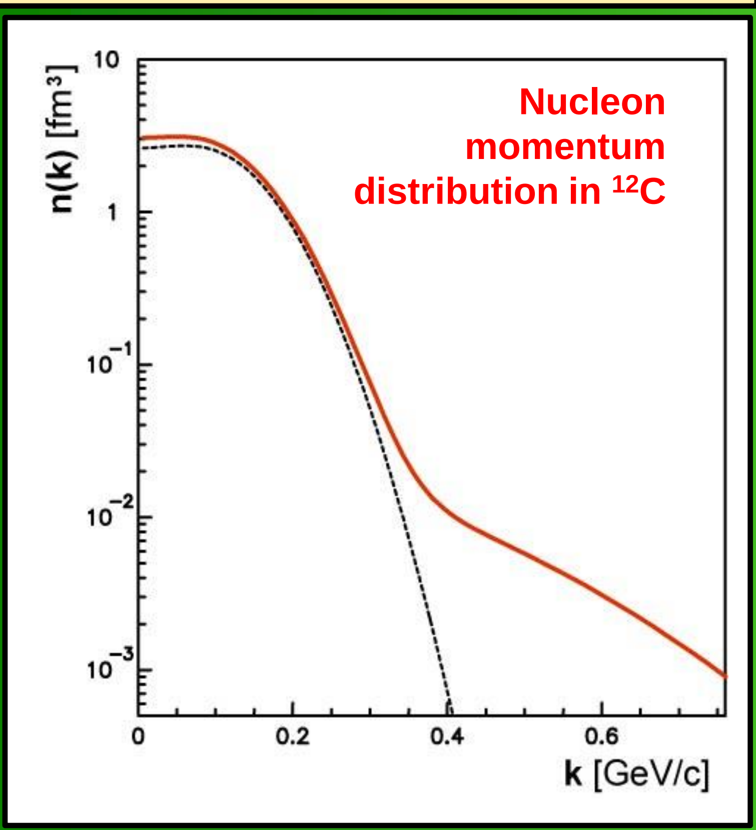
credit: Jonanna Griffin (Jefferson Lab)

High momentum nucleons

- Short Range Correlations







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

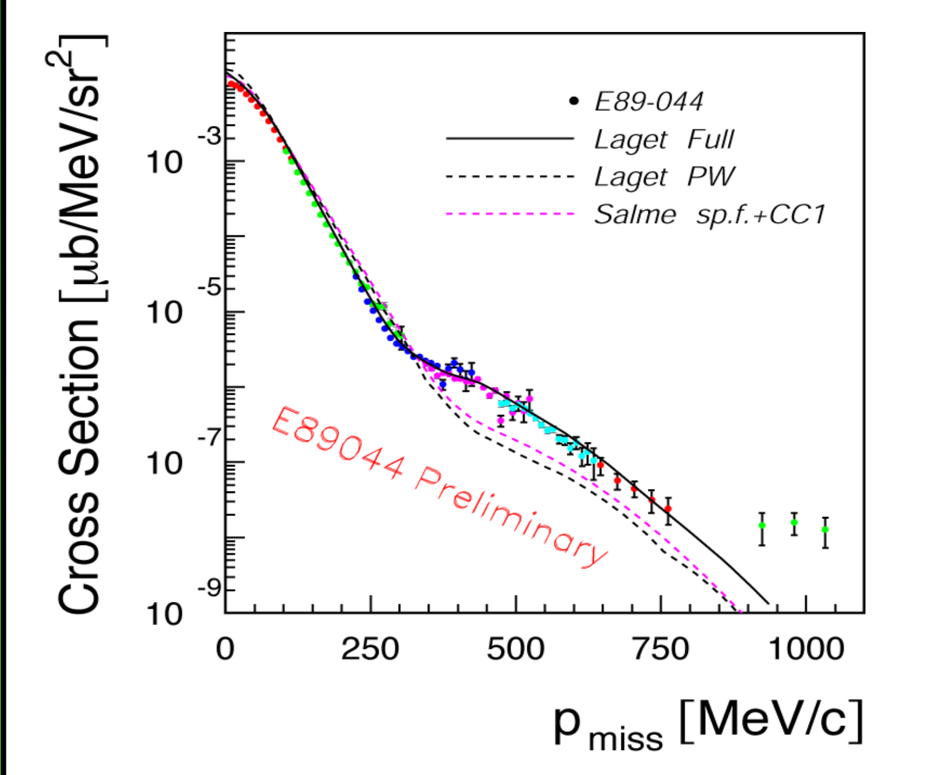
- E89-004: Measure of $^3He(e,e'p)d$
- Measured far into high momentum tail: Cross section is ~5-10x expectation

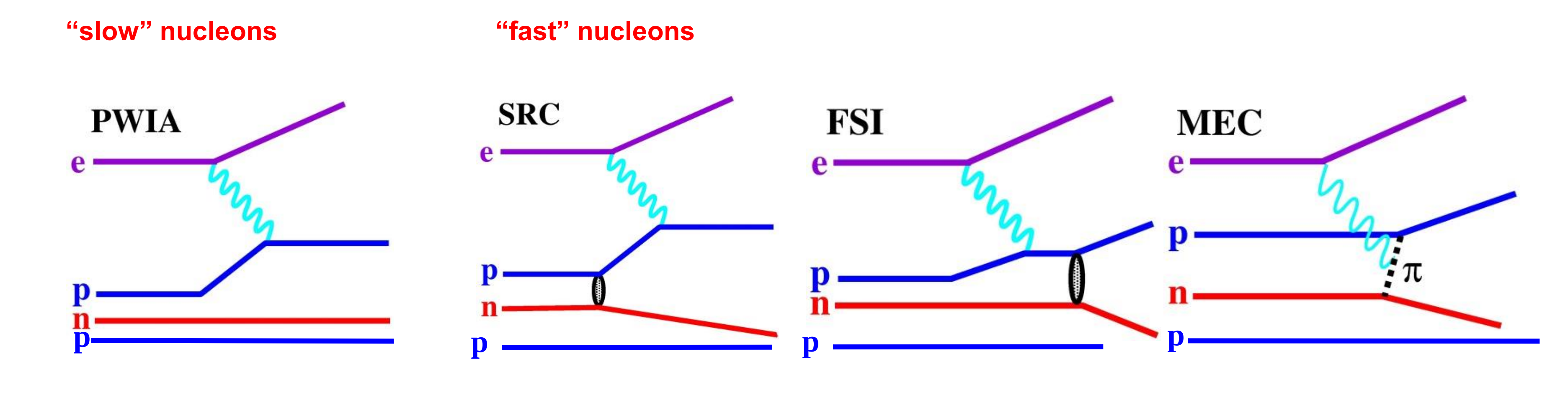
Difficulty

- 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

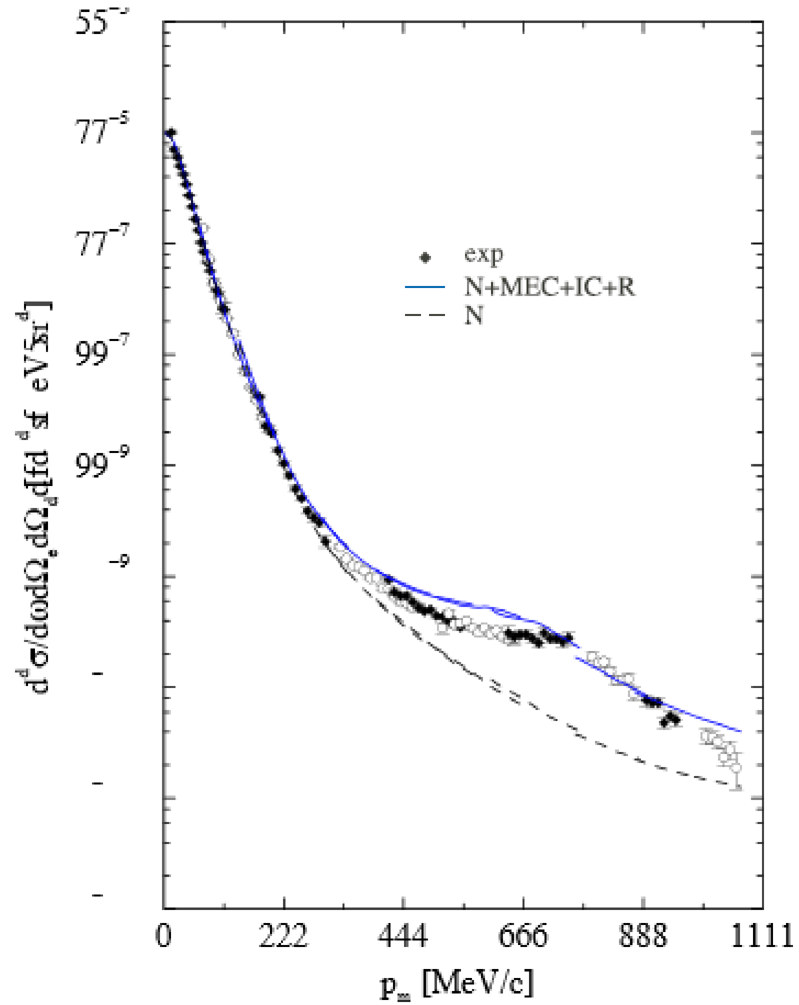
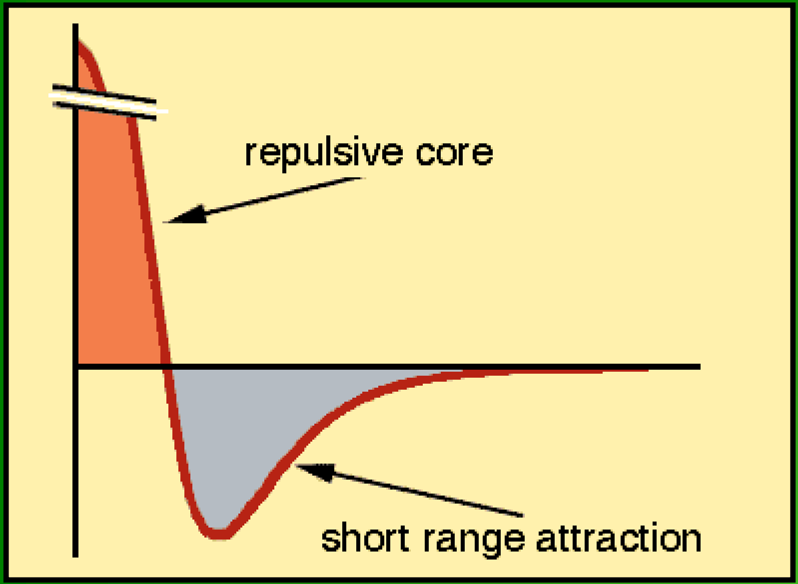
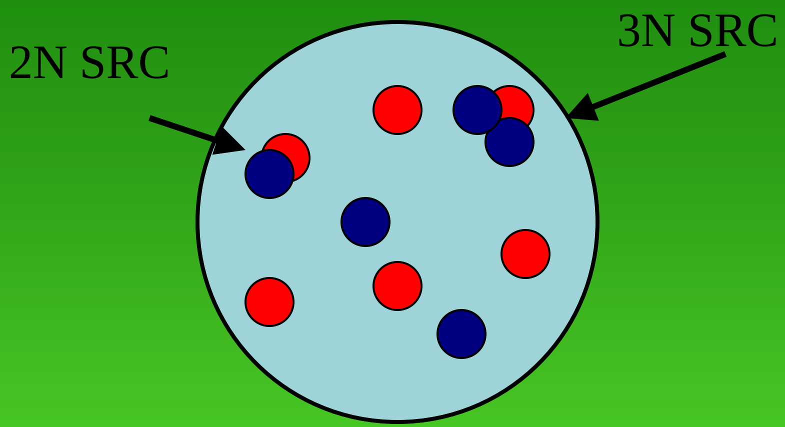


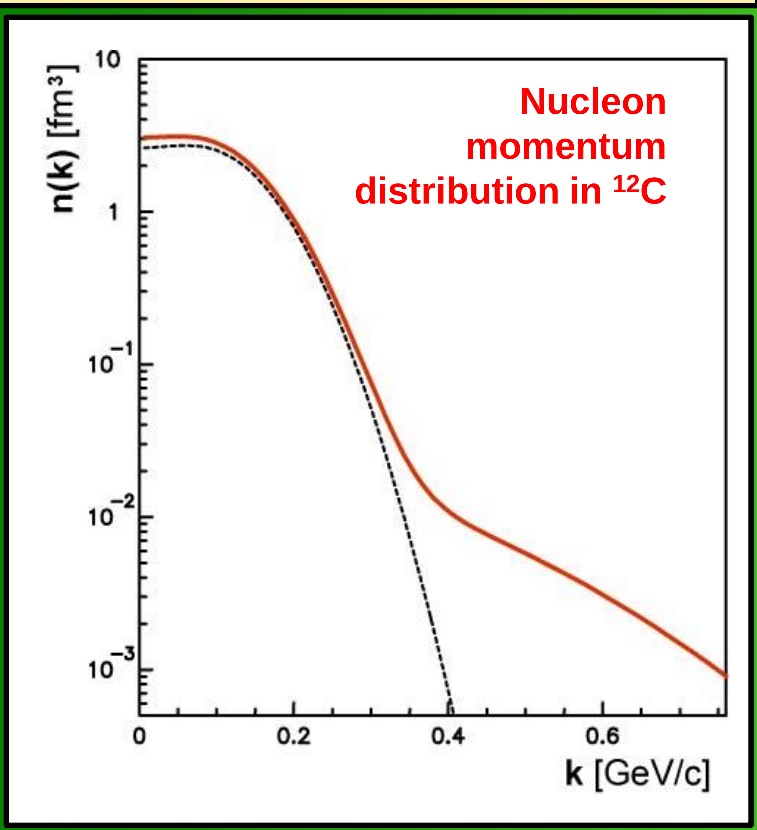
FIG. 1: The experimental D(e,e′p)n cross section as a function of missing momentum measured at MAMI for $Q^2 = 0.33$ $(\mathrm{GeV/c})^2$ [4] compared to calculations [7] with (solid curve) and without (dashed curve) MEC and IC. Both calculations include FSI. The low p_m data have been re-analyzed and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

High momentum nucleons

- Short Range Correlations



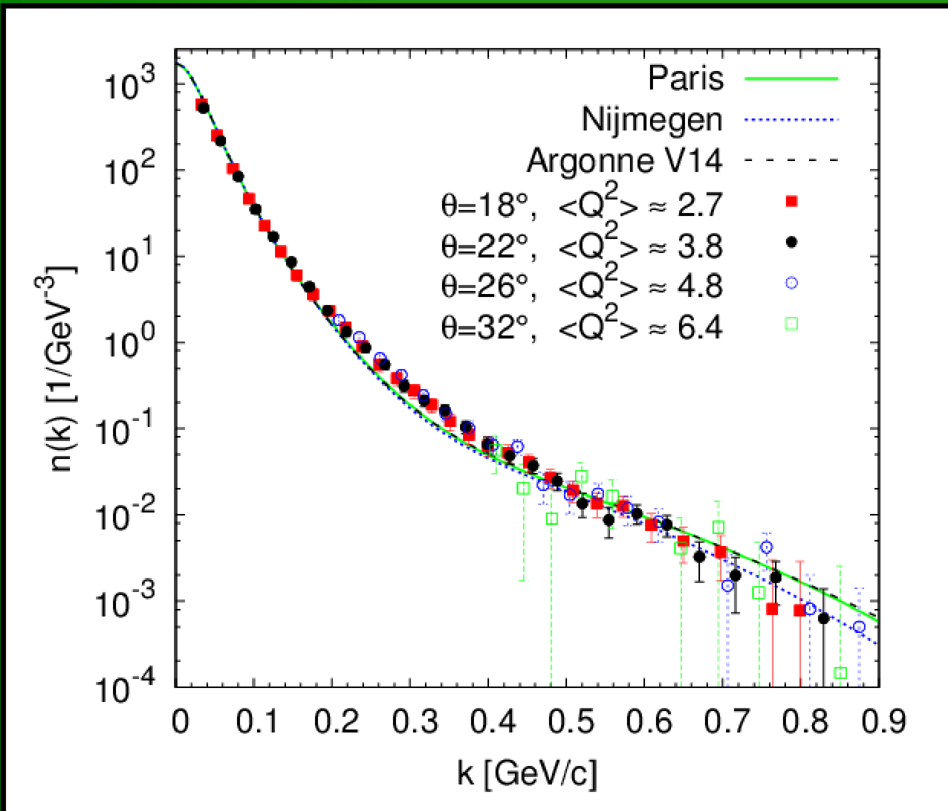


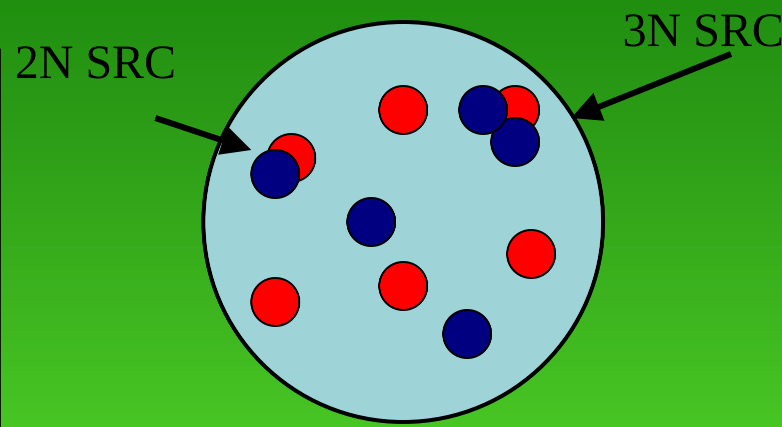


Try inclusive scattering!
Select kinematics such that the initial nucleon momentum $> \boldsymbol{k_f}$

High momentum nucleons

- Short Range Correlations





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

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

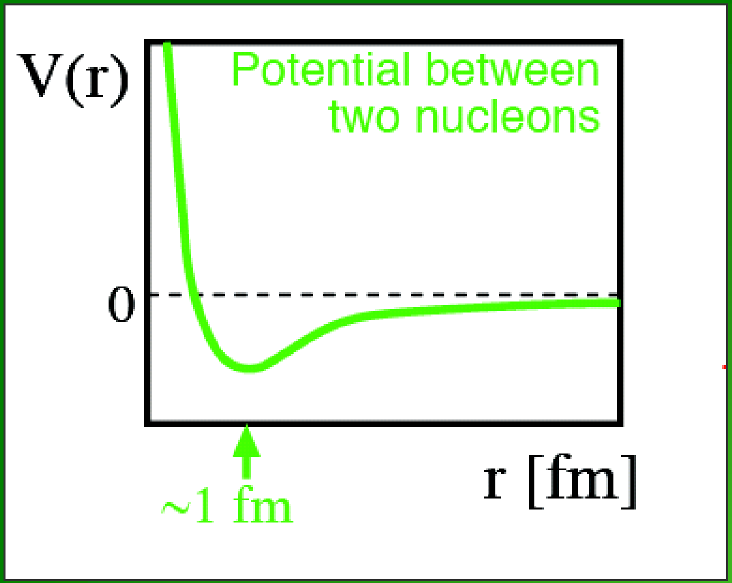
$$F(y,\mathbf{q}) = \frac{d^2\sigma}{d\Omega d\upsilon}\frac{1}{(Z\overline{\sigma}_p + N\overline{\sigma}_n)}\frac{\mathbf{q}}{\sqrt{M^2+(y+q)^2}}$$

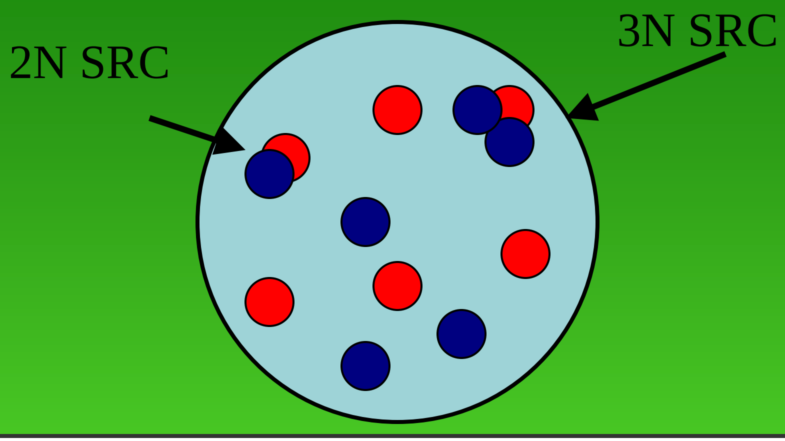
$$= 2\pi\int_{|y|}^{\infty} n(k)kdk$$

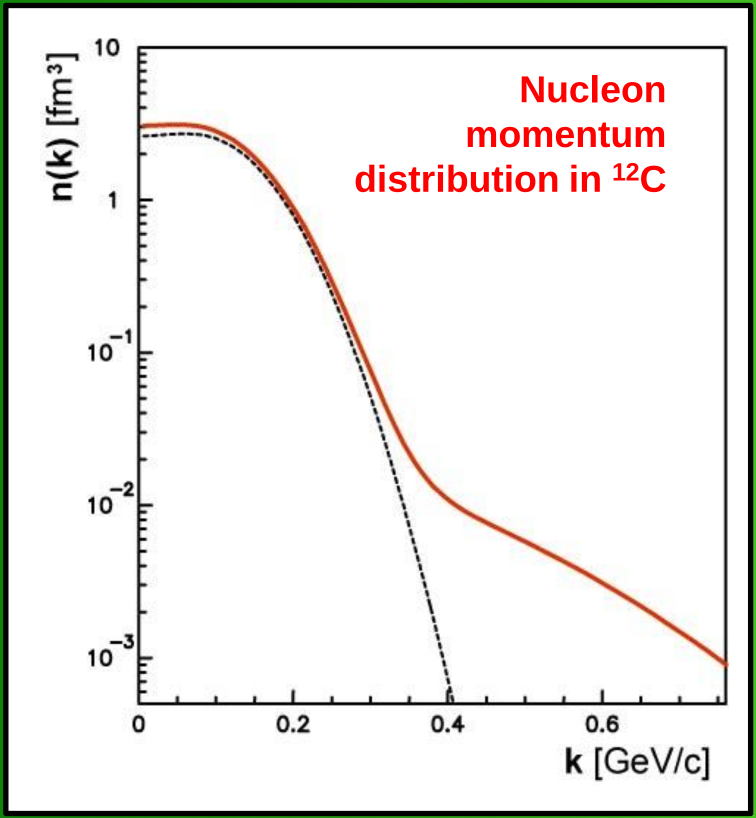
Ok for A=2

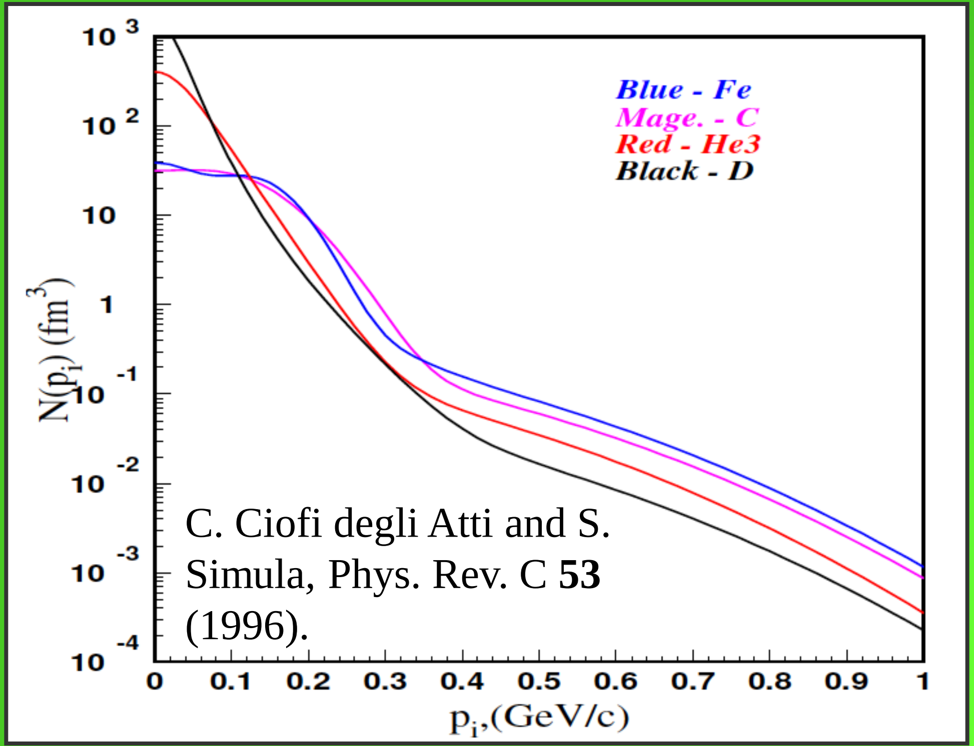
High momentum nucleons

- Short Range Correlations



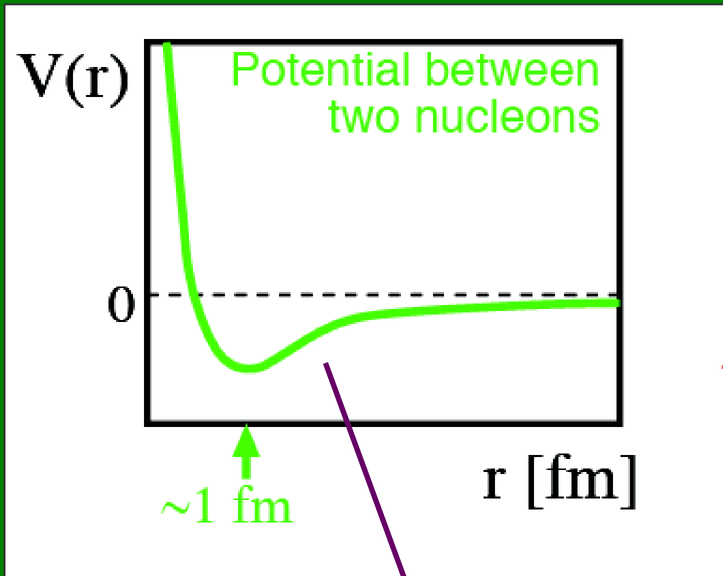


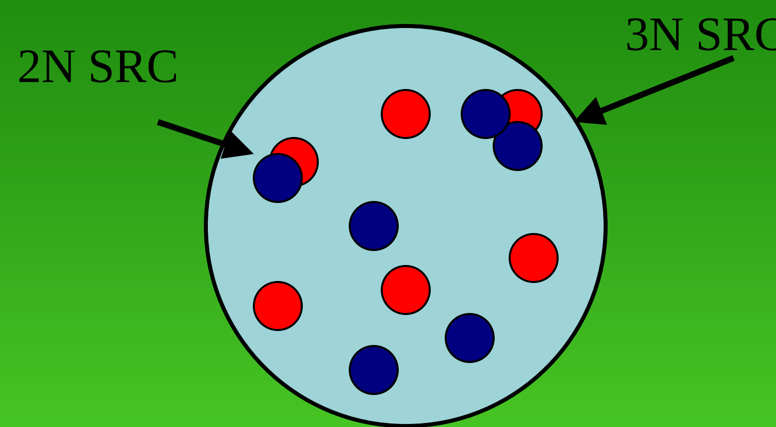


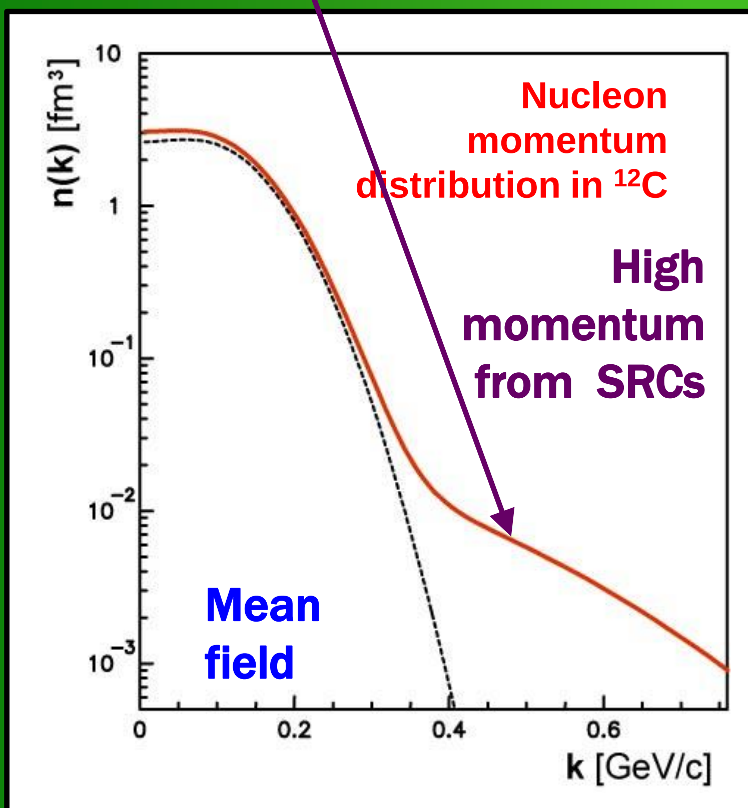


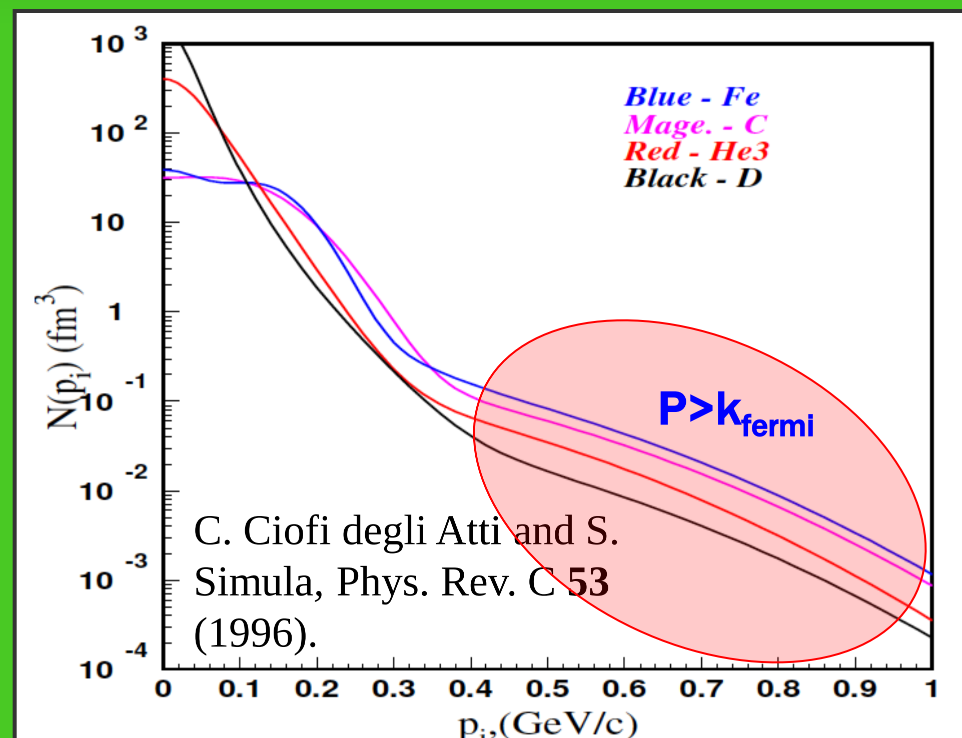
High momentum nucleons

- 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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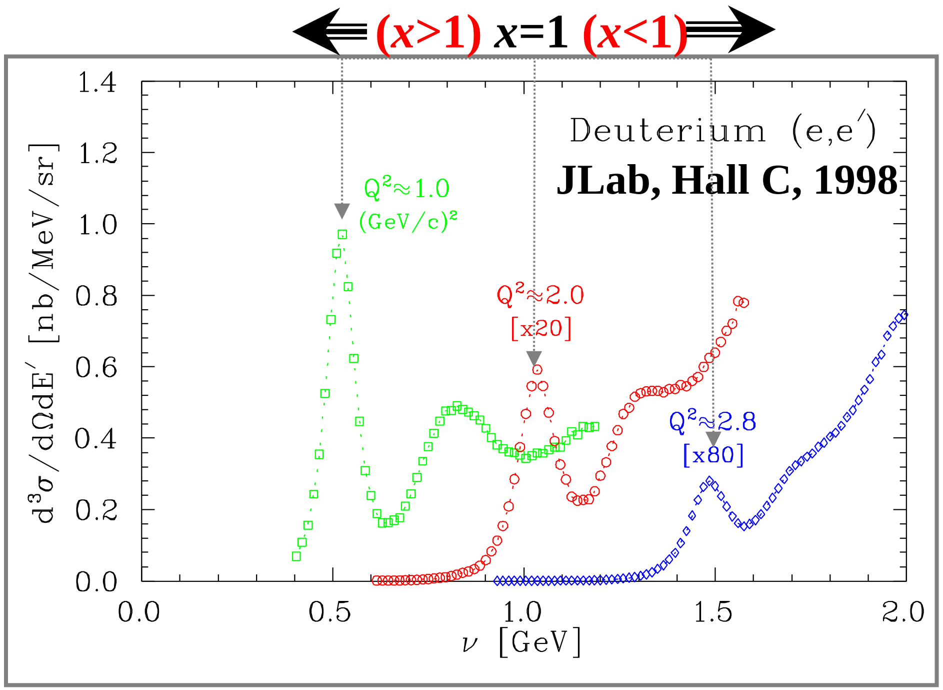
- *C. C. degli Atti and S. Simula, Phys. Lett. B 325, 276 (1994).*
- *C. C. degli Atti and S. Simula, Phys. Rev. C 53, 1689 (1996).*

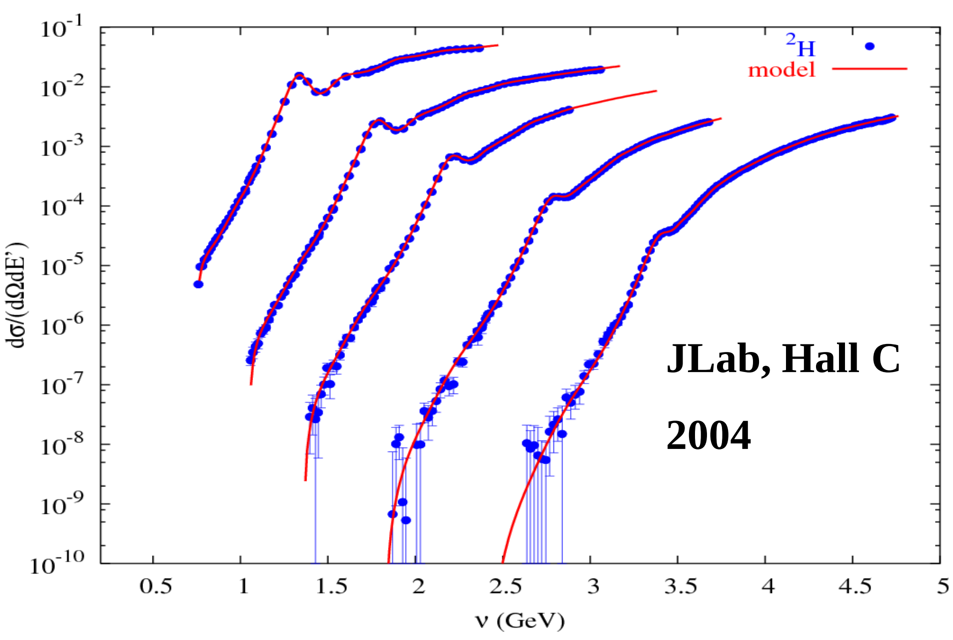
$$\sigma(x, Q^2) = \sum_{j=1}^{A} A \frac{1}{j} a_j(A) \sigma_j(x, Q^2)$$

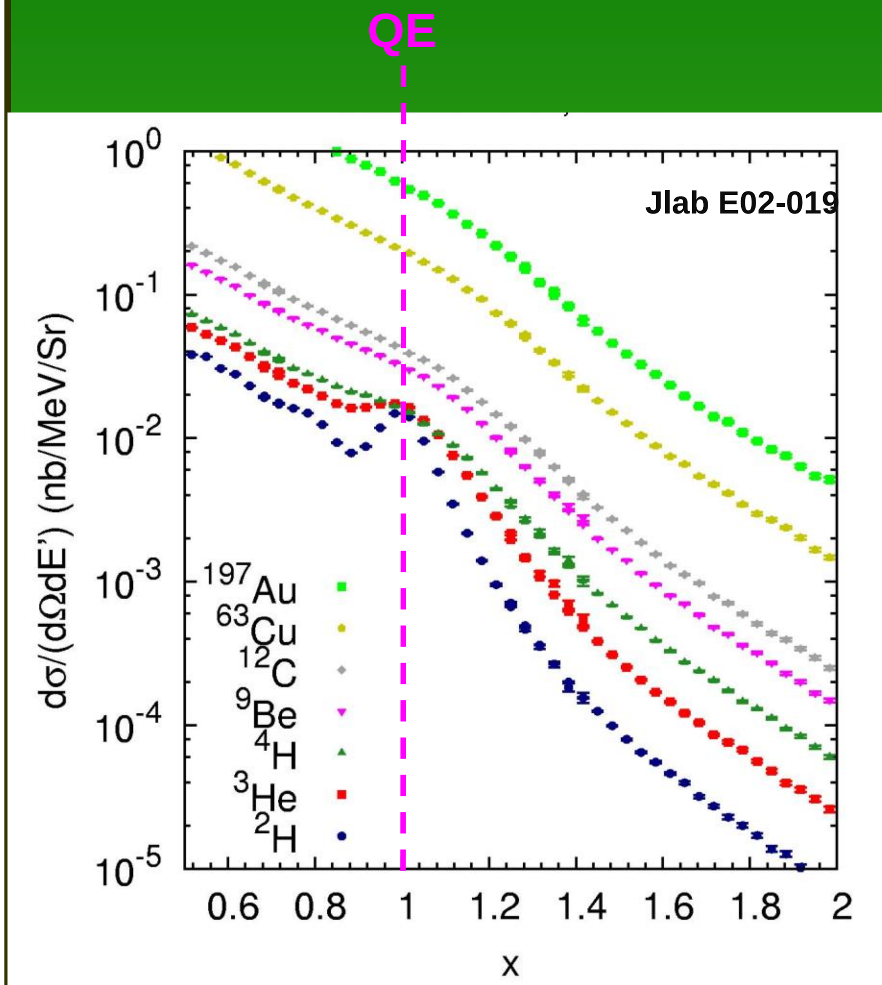
$$= \frac{A}{2} a_2(A) \sigma_2(x, Q^2) +$$

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

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


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


²H
model
JLab, Hall C
2004
dσ/(dΩdE′)
ν (GeV)


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

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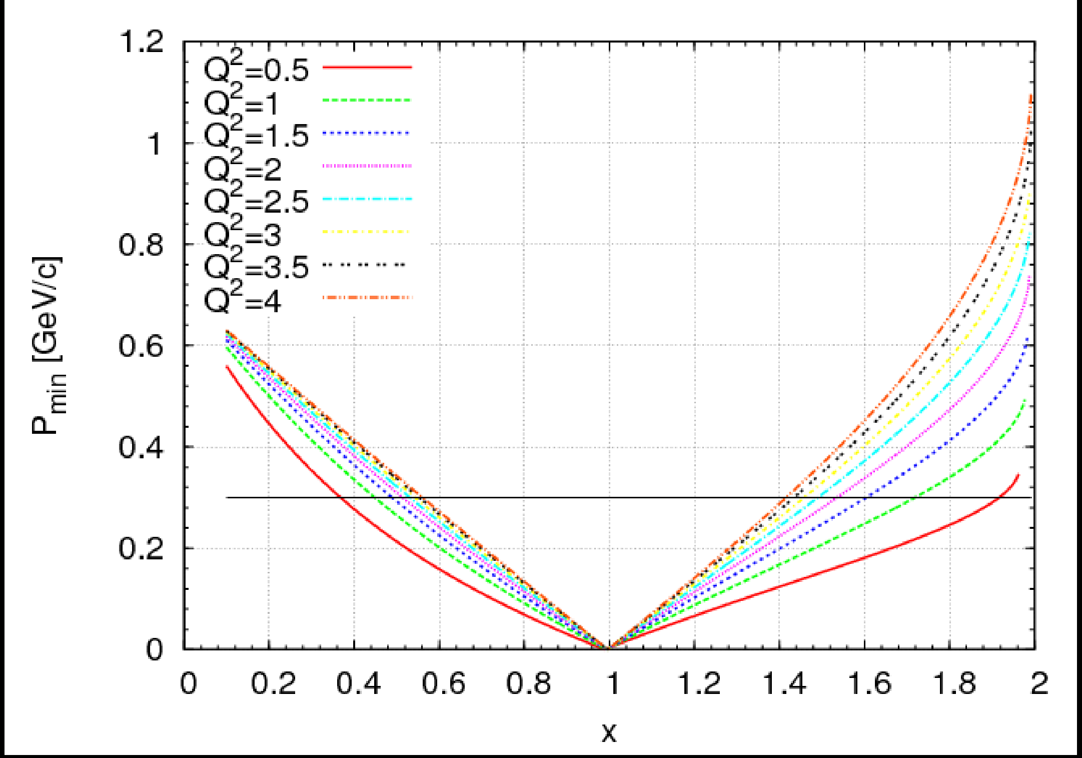
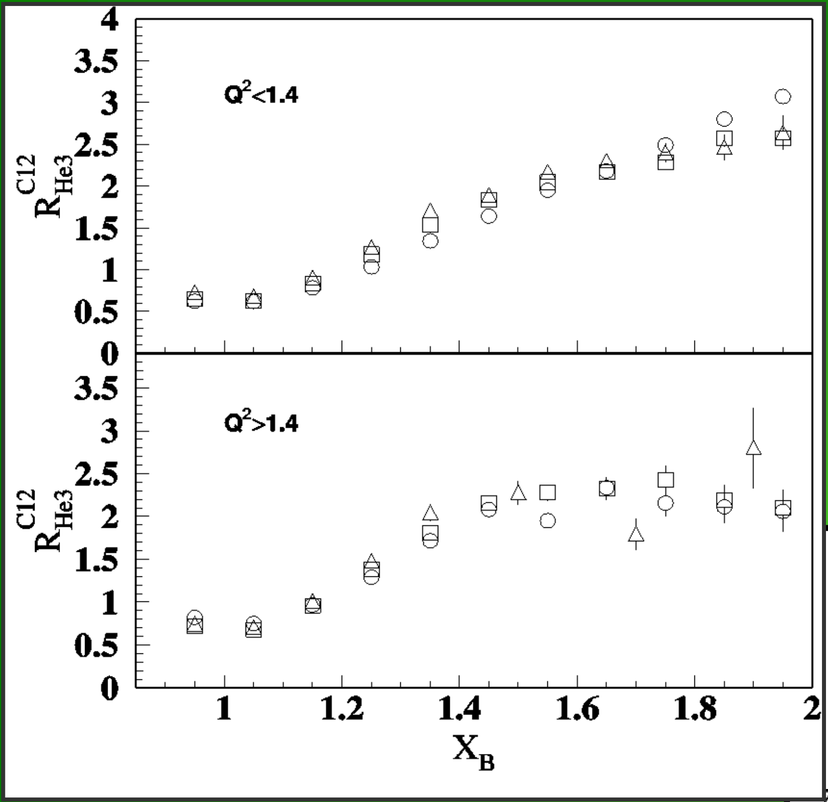
$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A)$$



Previous measurements

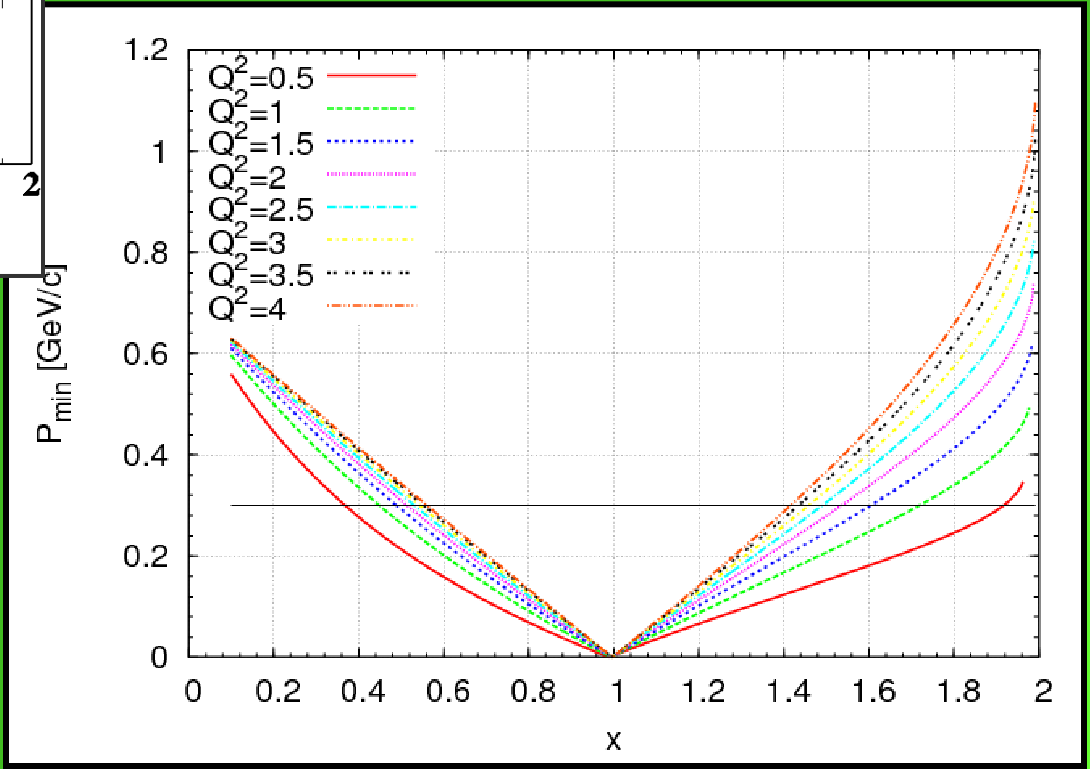


1.4<x<2 => 2 nucleon correlation

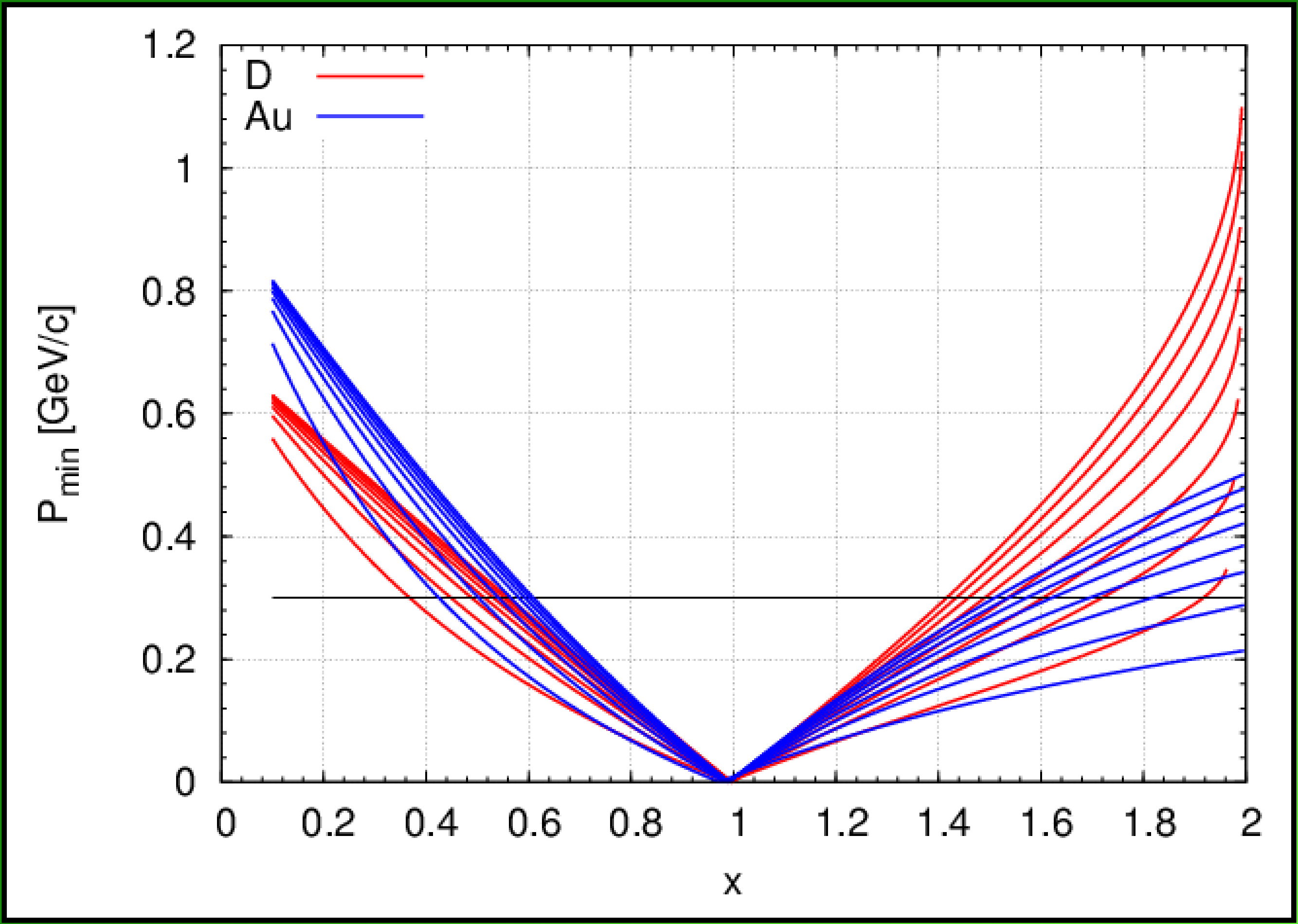
2.4<x<3 => 3 nucleon correlation

Egiyan et al, Phys.Rev.C68, 2003

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

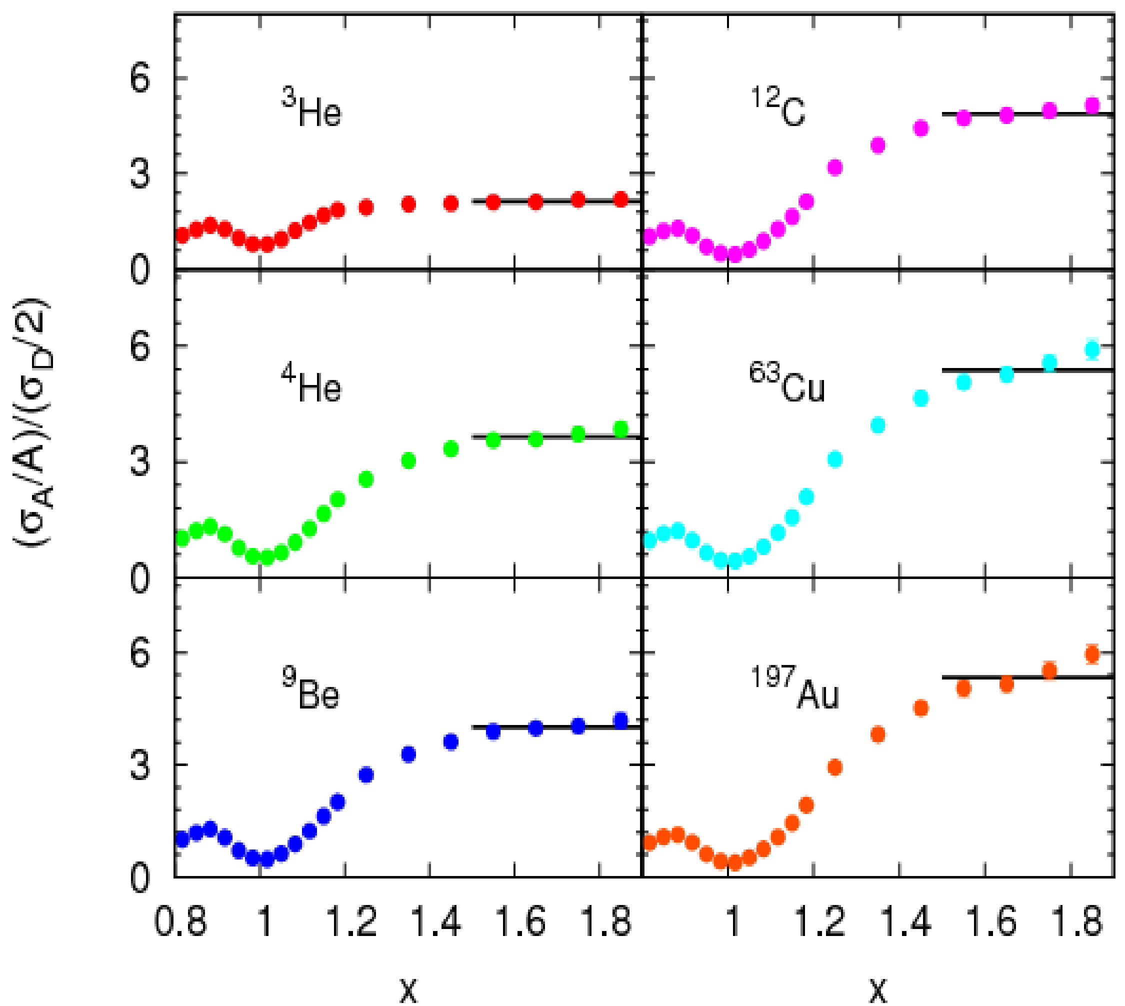


Kinematic cutoff is A-dependent



- 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



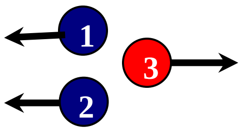
NF et al, PRL *108* (2012)

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

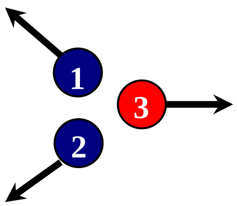
Jlab E02-019

$\langle Q^2 \rangle = 2.7\ \mathrm{GeV}^2$

Why not more than two nucleons in a correlation?



$p_3 = p_1 + p_2$



$p_3 = p_1 = p_2$

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

$$= \frac{A}{2} a_2(A)\sigma_2(x, Q^2) +$$

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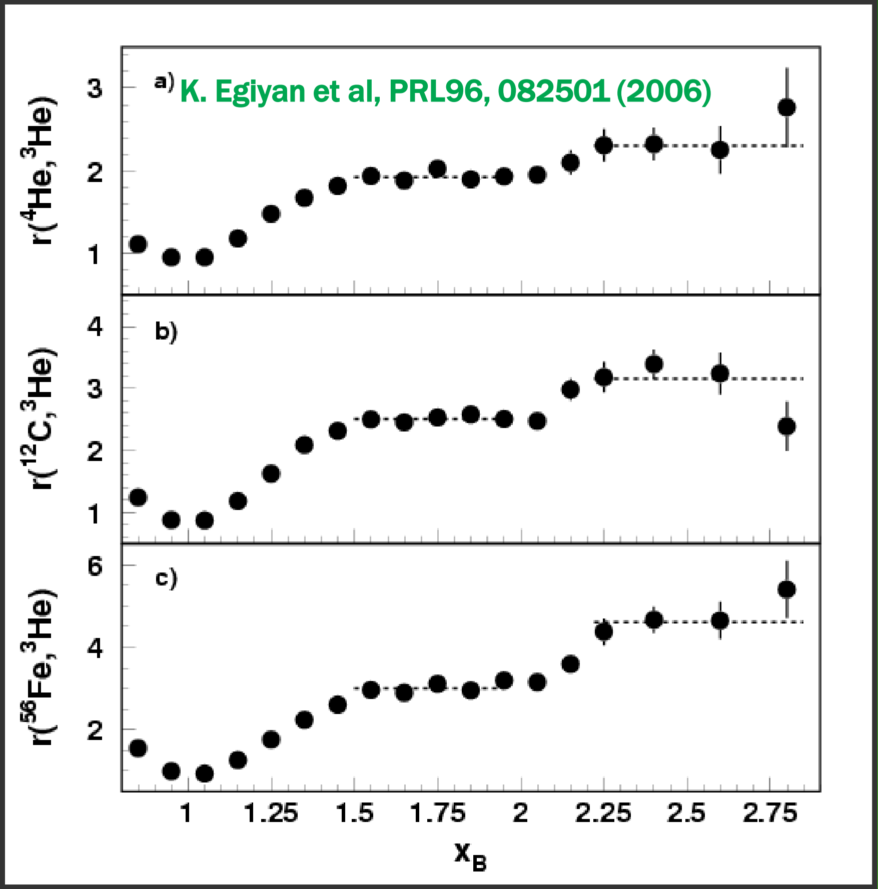
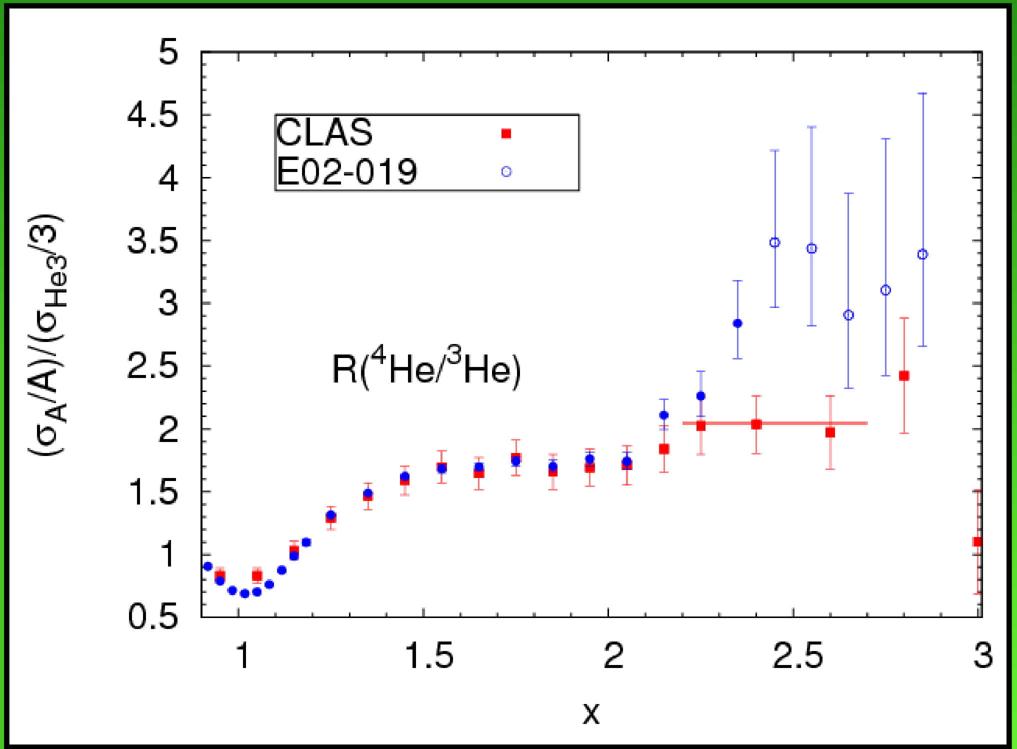
Further evidence of multi-nucleon correlations



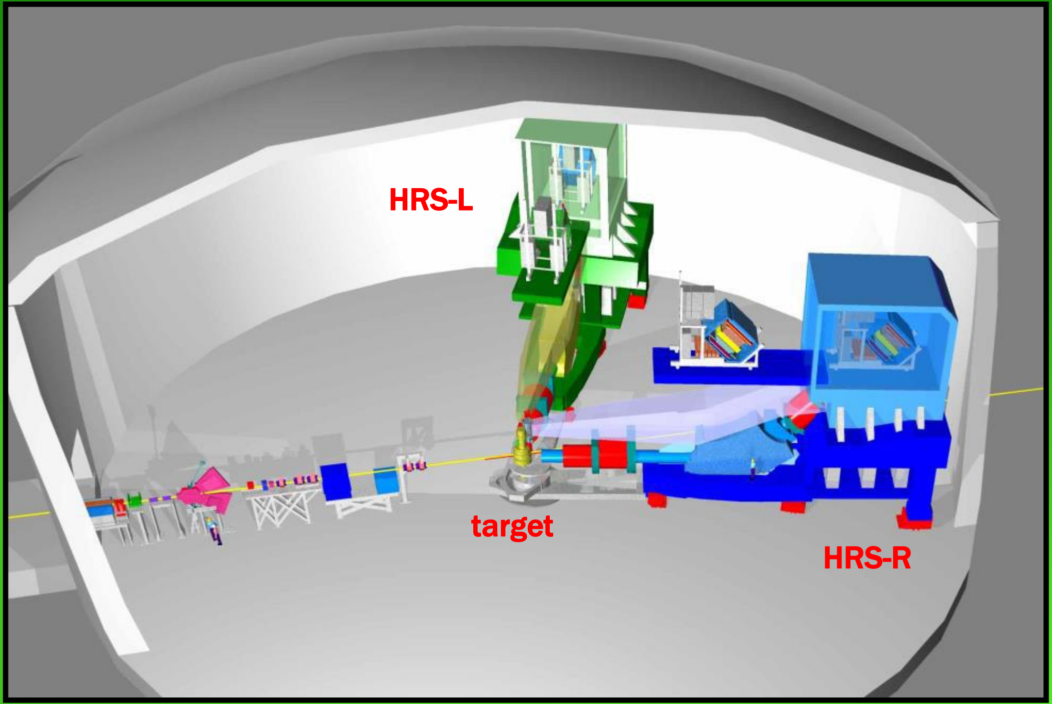
<Q^2> (GeV^2): *CLAS: 1.6* *E02-019: 2.7*



- 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

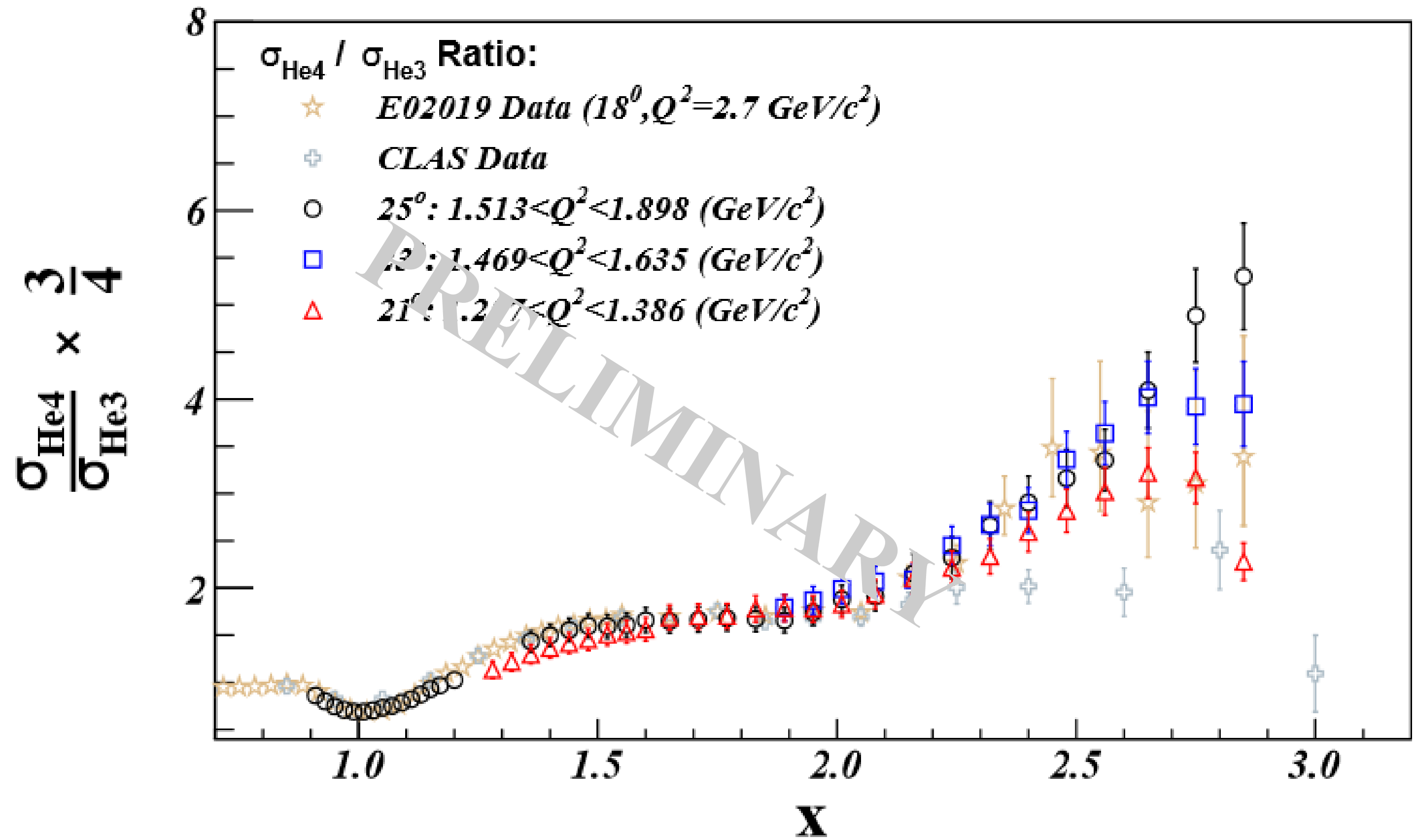


Analysis in final stages

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

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

E08-014: Study 3N correlations

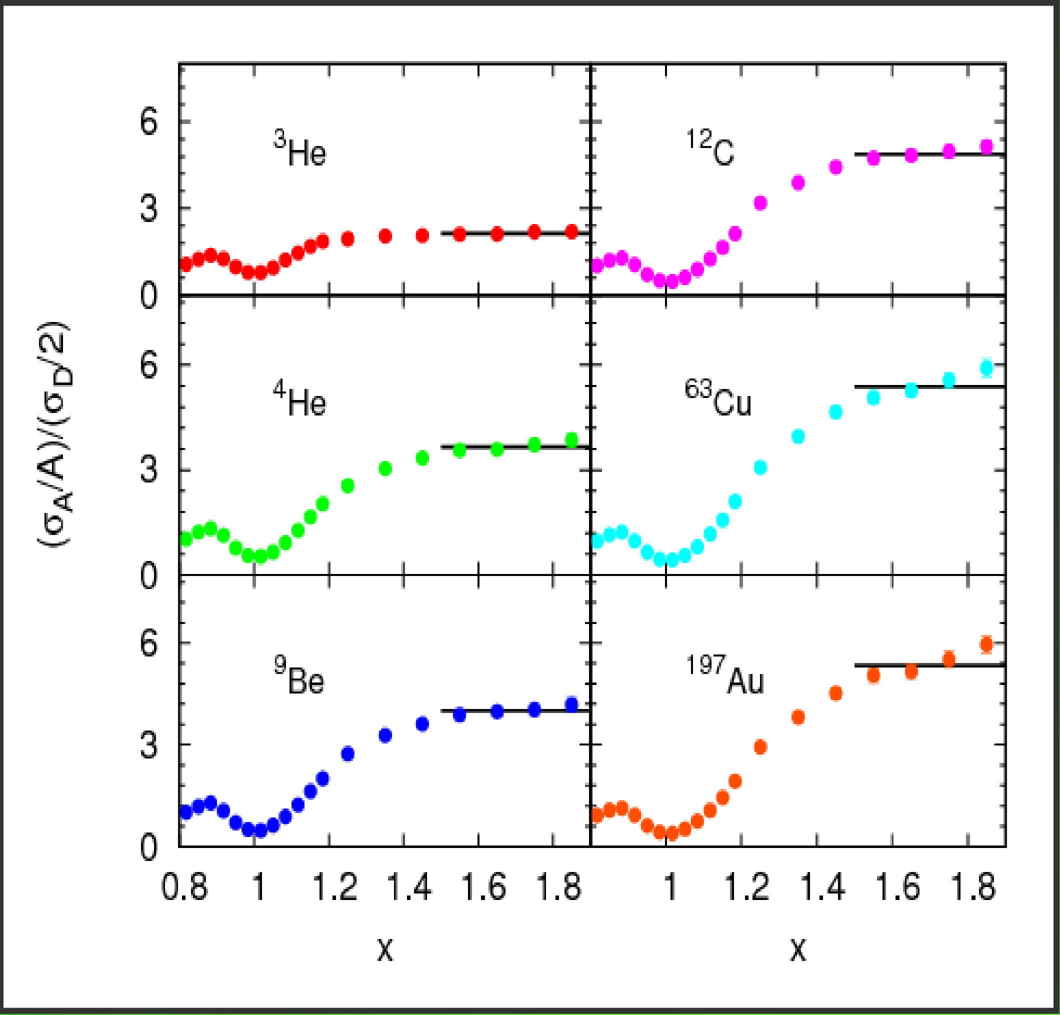


More results in D. Day's talk

Plot courtesy of Z. Ye

Back to precision 2N 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

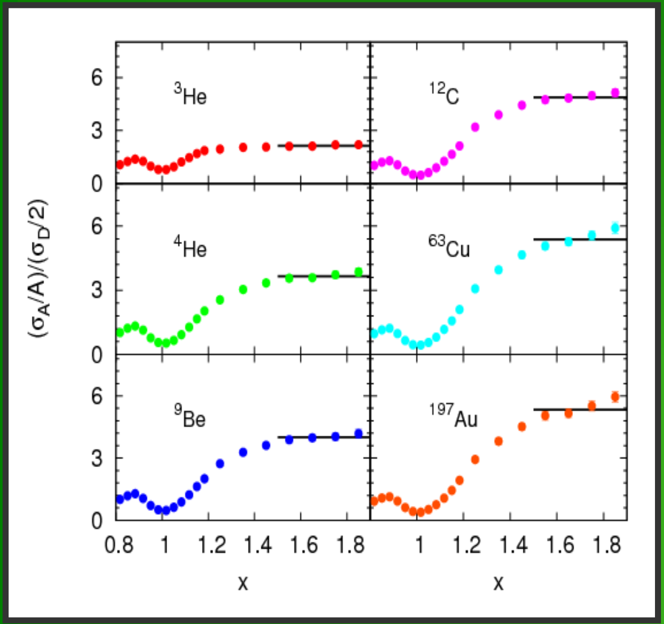


*Fomin et al, PRL **108** (2012)*

Jlab E02-019

<Q^2>=2.7 GeV^2

Look at nuclear dependence of NN SRCs



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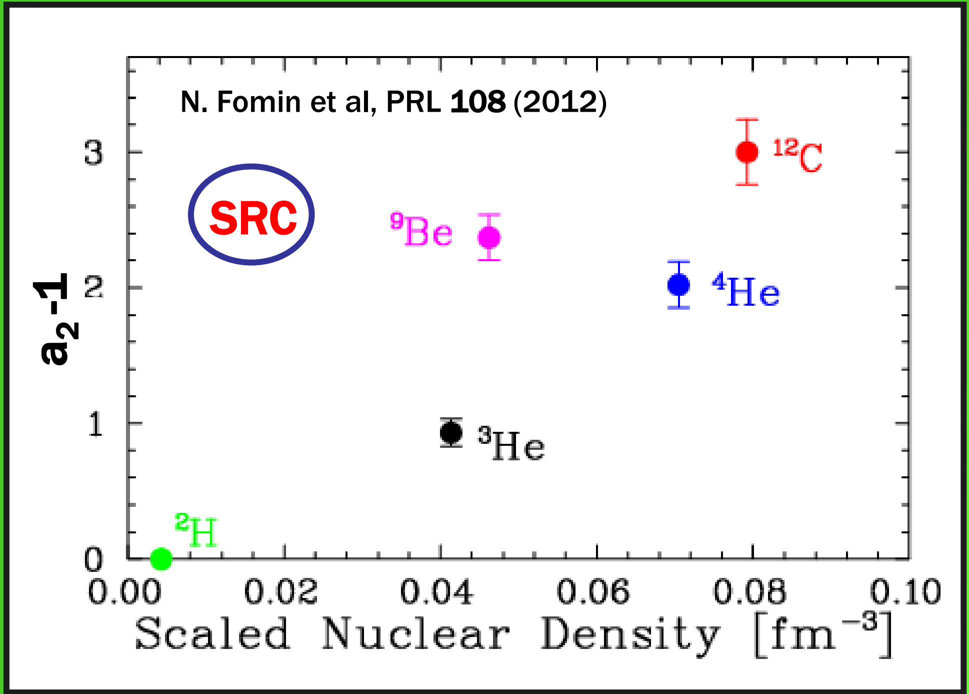

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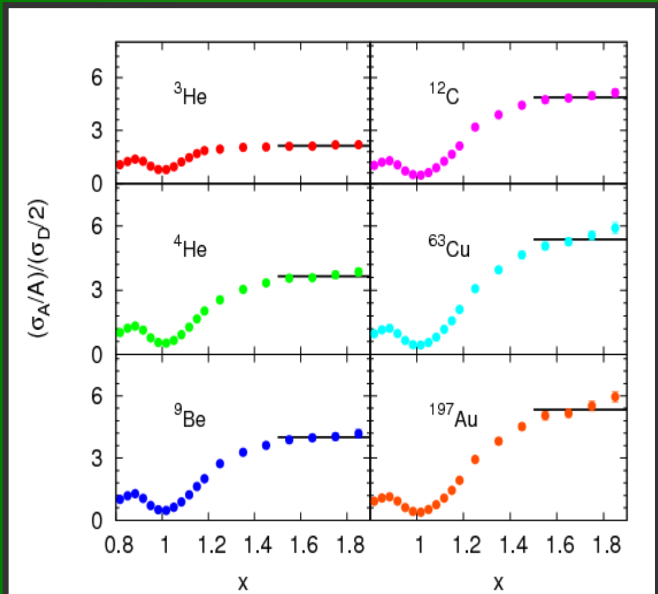

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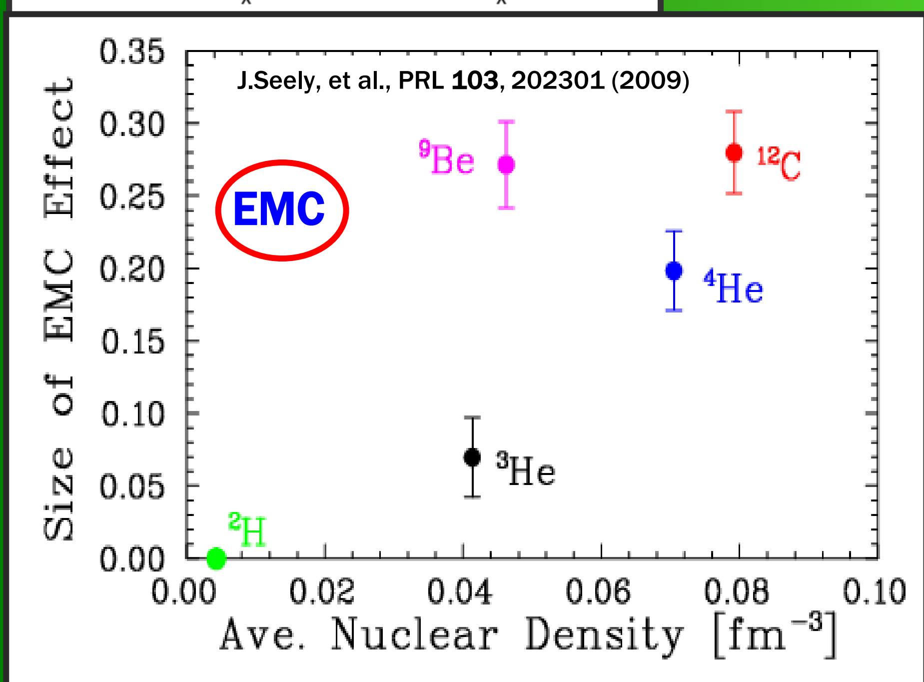
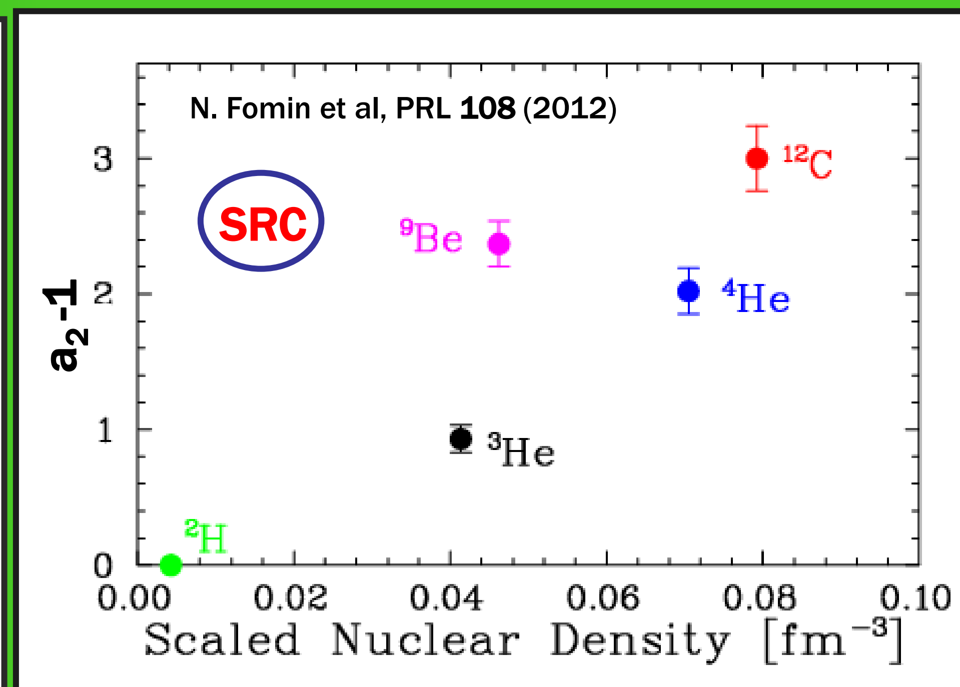
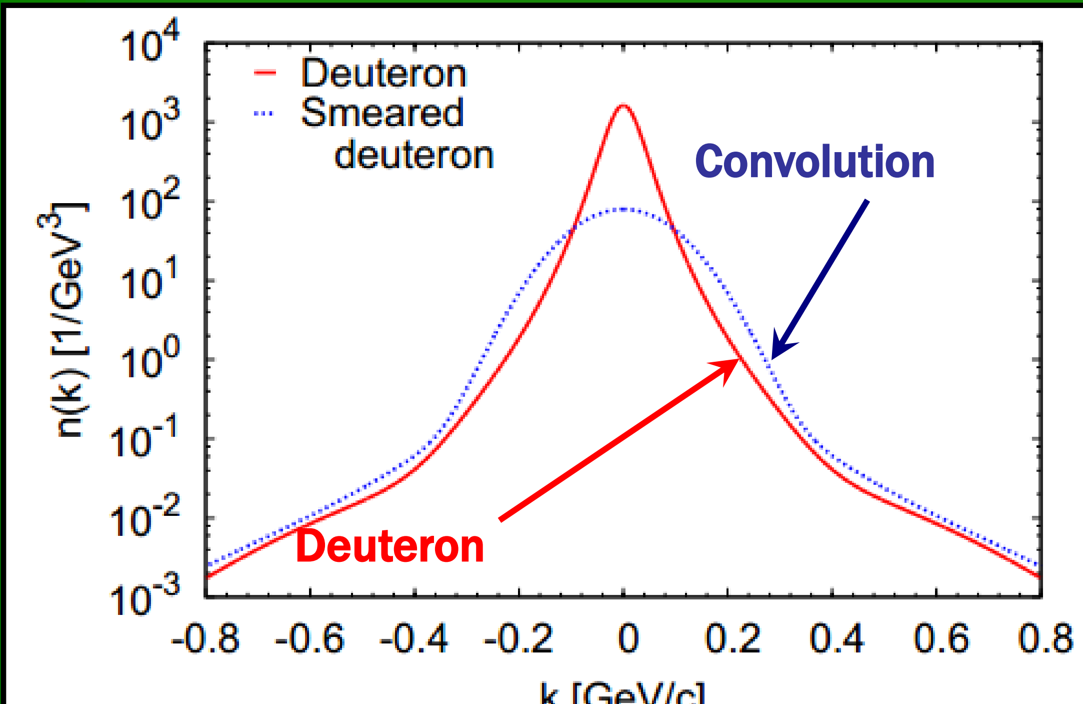




$(a_2=\sigma_A/\sigma_D)$!= Relative #of SRCs



$n_D^{CONV}(k)$ **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)

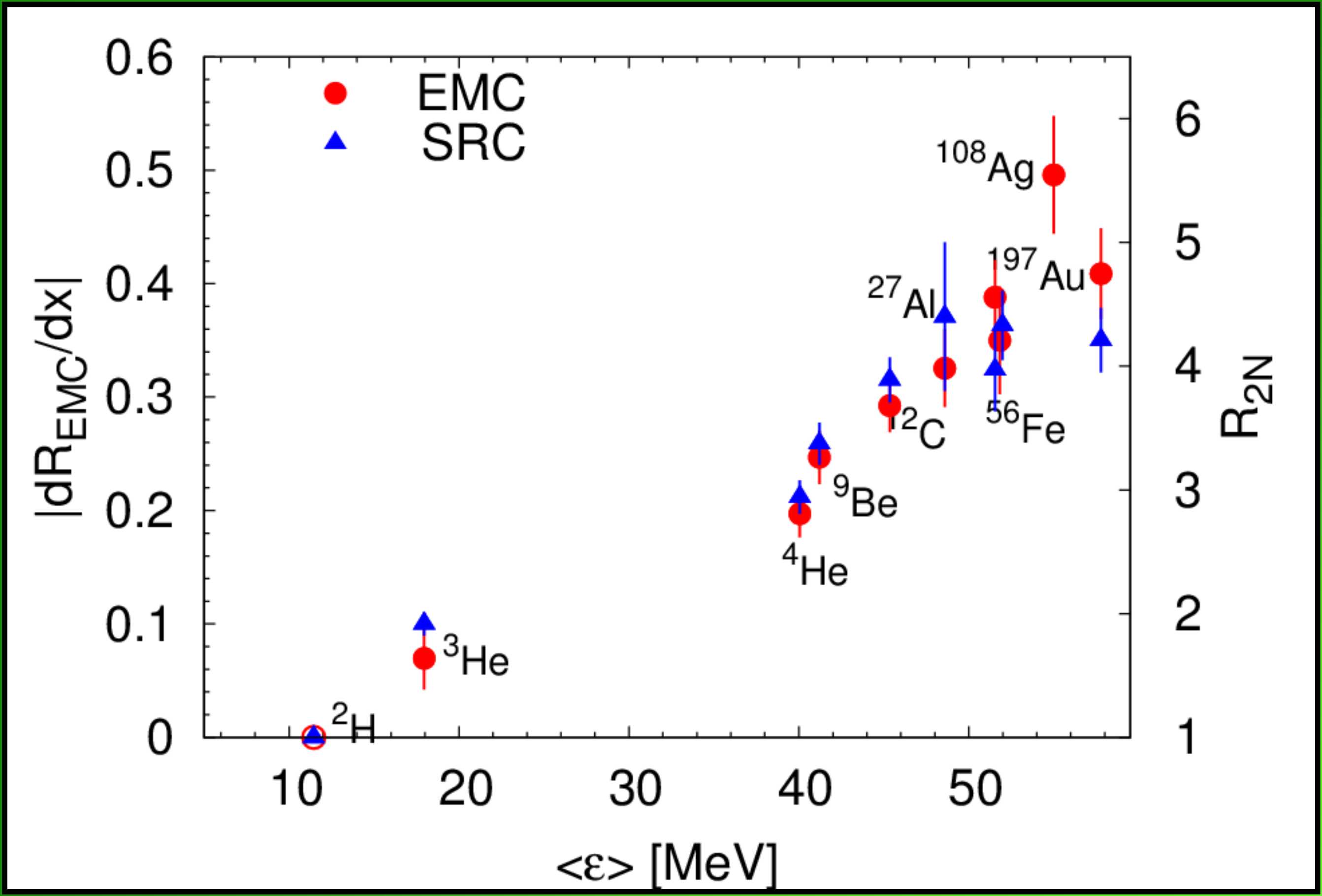
	E02-019	SLAC	CLAS	R_{2N}-ALL	a_2-ALL
^{3}He	1.93±0.10	1.8±0.3	–	1.92±0.09	2.13±0.04
^{4}He	3.02±0.17	2.8±0.4	2.80±0.28	2.94±0.14	3.57±0.09
Be	3.37±0.17	–	–	3.37±0.17	3.91±0.12
C	4.00±0.24	4.2±0.5	3.50±0.35	3.89±0.18	4.65±0.14
Al	–	4.4±0.6	–	4.40±0.60	5.30±0.60
Fe	–	4.3±0.8	3.90±0.37	3.97±0.34	4.75±0.29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

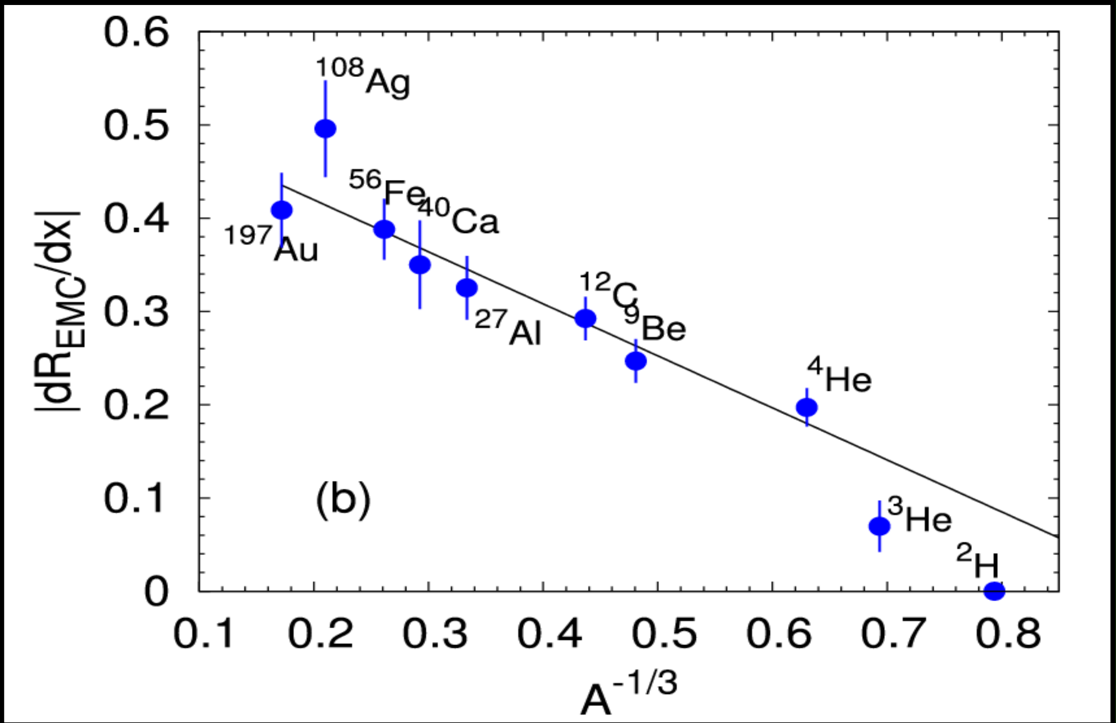
Separation Energy



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

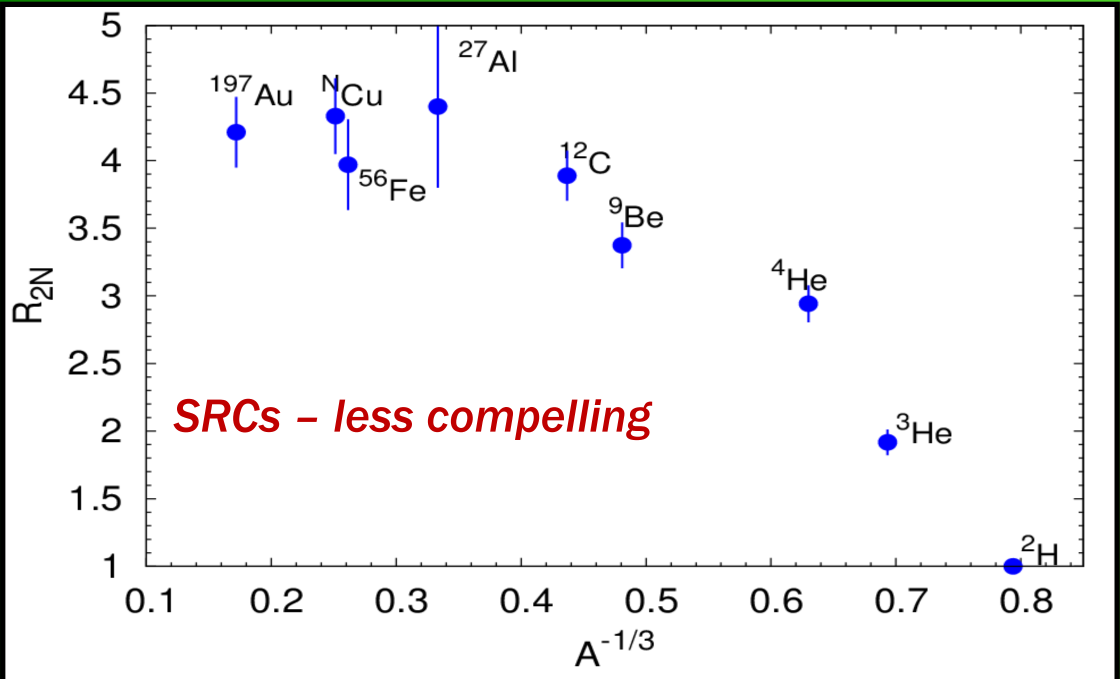
S.A. Kulagin and R. Petti, Nucl. Phys. A 176, 126 (2006)

A $^{-1/3}$



Apply exact NM calculations to finite nuclei via LDA

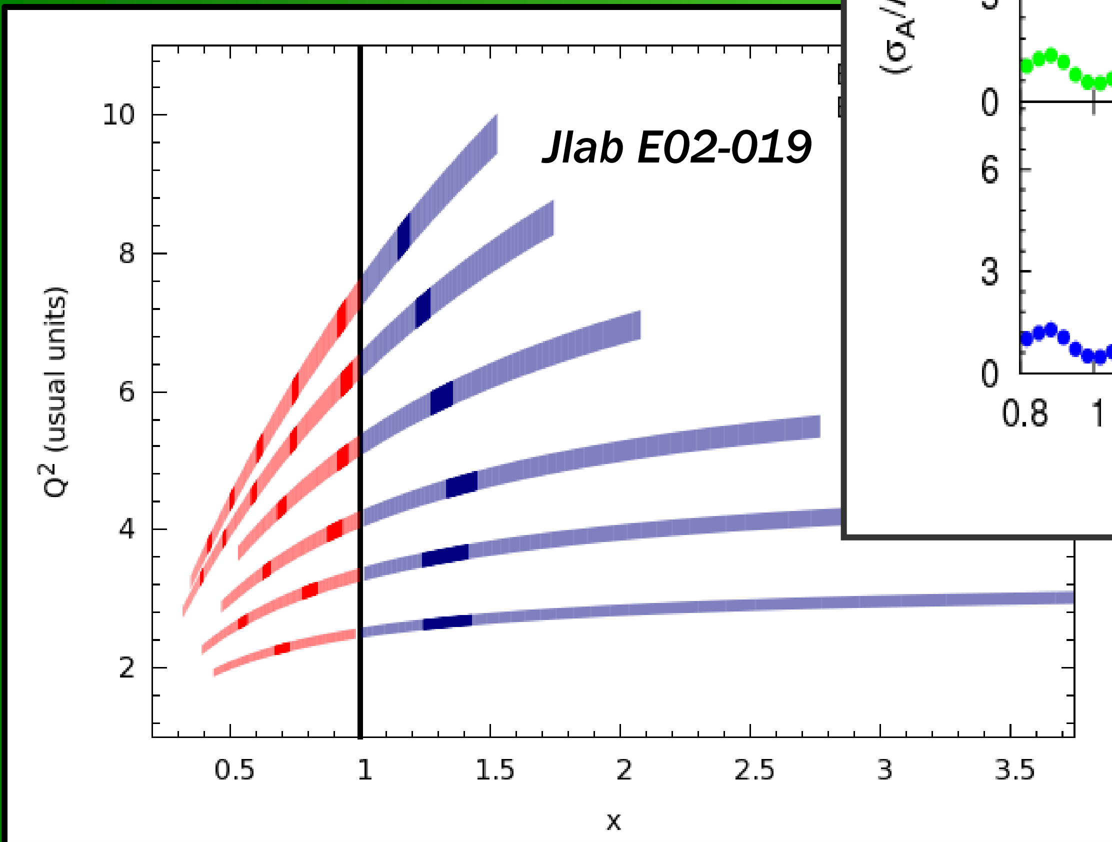
- *(A. Antonov and I. Petkov, Nuovo Cimento A 94, 68 (1986)*
- *(I. Sick and D. Day, Phys. Lett B 274, 16 (1992))*

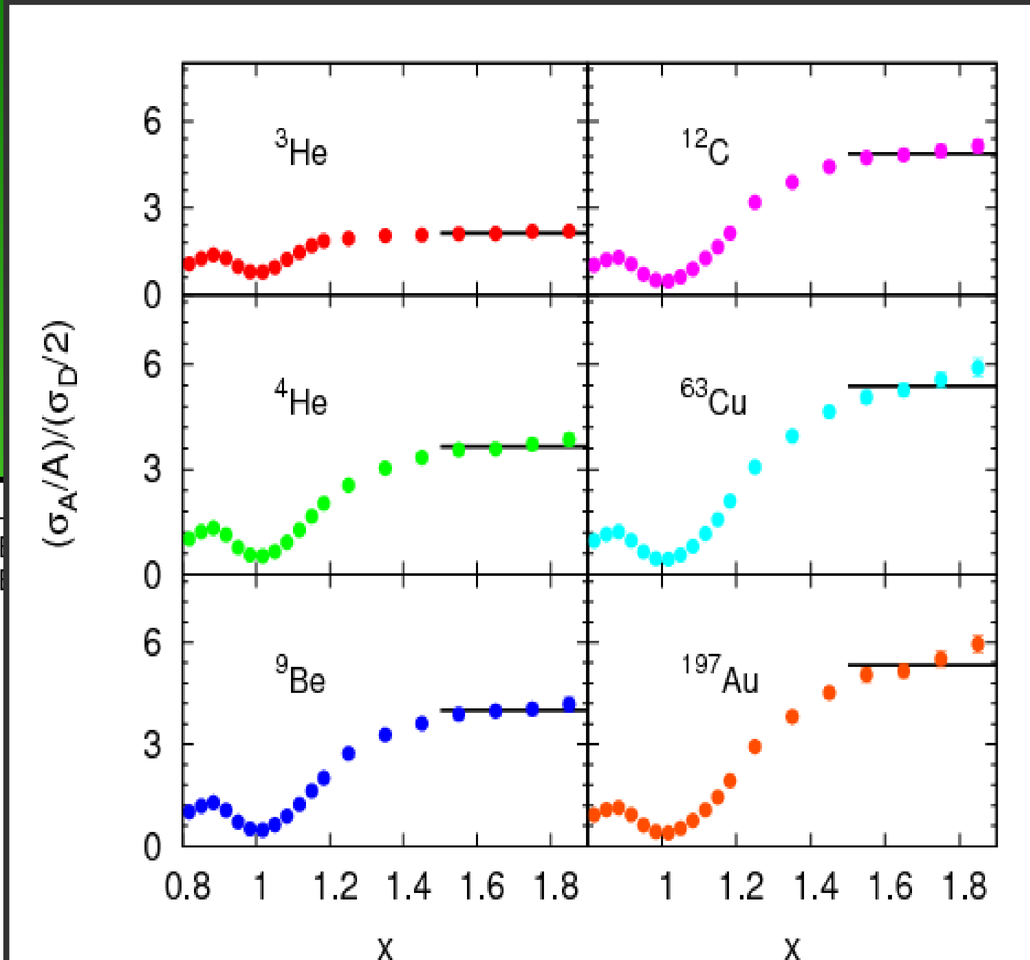


- For A>12, the nuclear density distribution has a common shape; constant in the nuclear interior (bulk)
  → ***Scale with A***
- Nuclear surface contributions grow ***as A$^{2/3}$*** (R^2)
- σ per nucleon would be constant with small deviations that go with A$^{-1/3}$

More details in J. Arrington's and O. Hen's talks (and probably others)

The rest of 6 GeV inclusive data



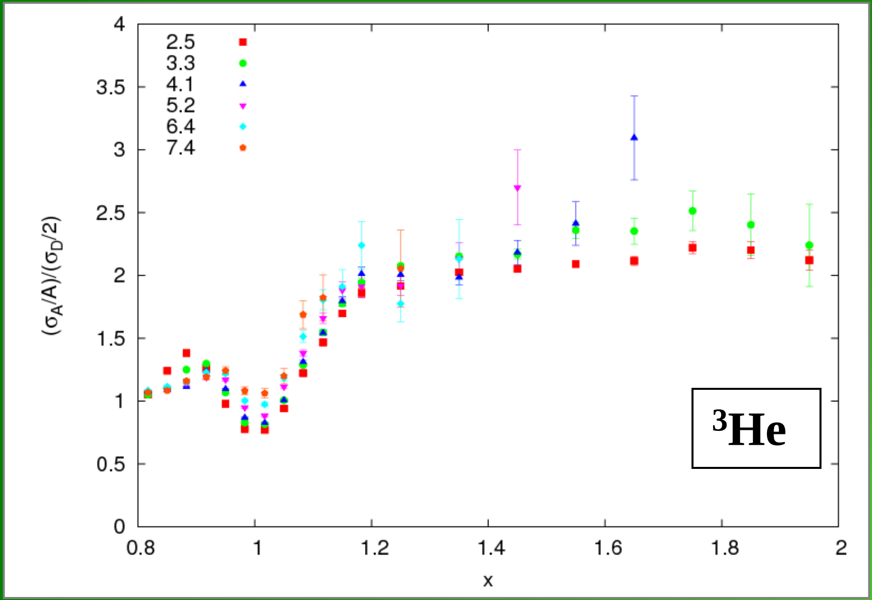


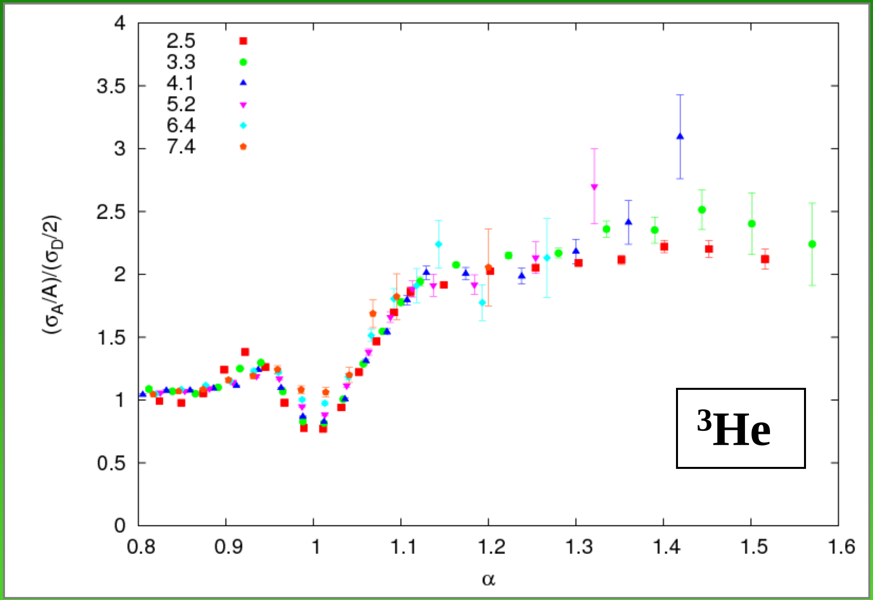
NF et al, PRL ***108*** *(2012)*

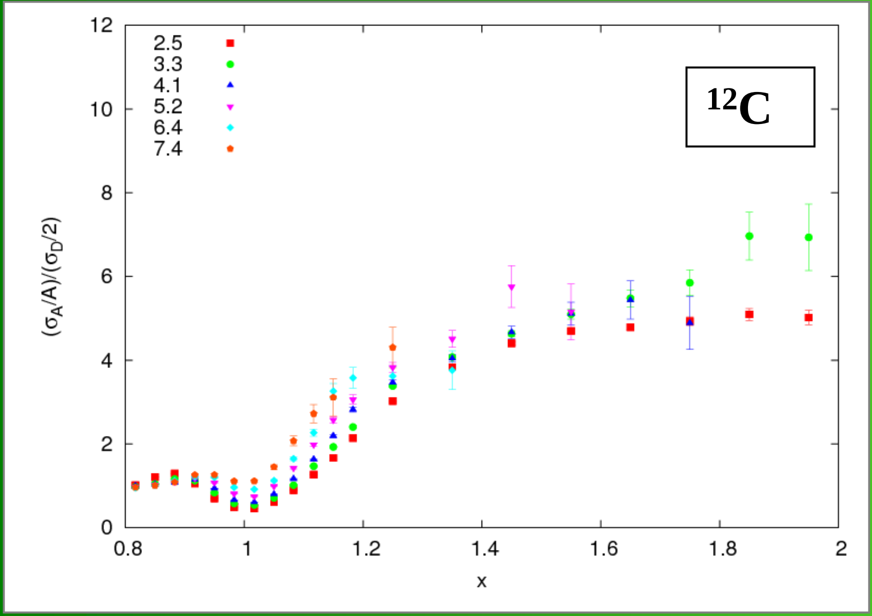
$<Q^2>=2.7\ GeV^2$

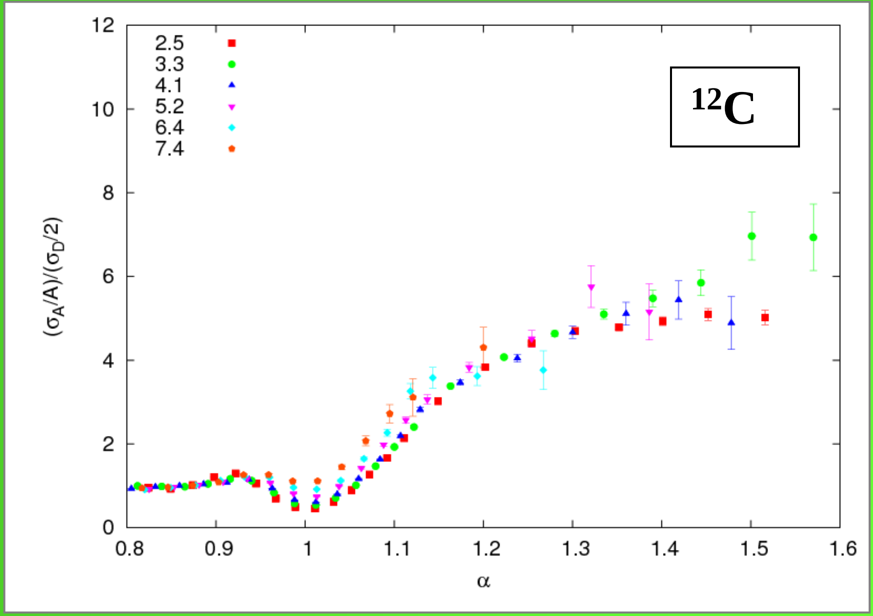
Q^2 dependence features

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

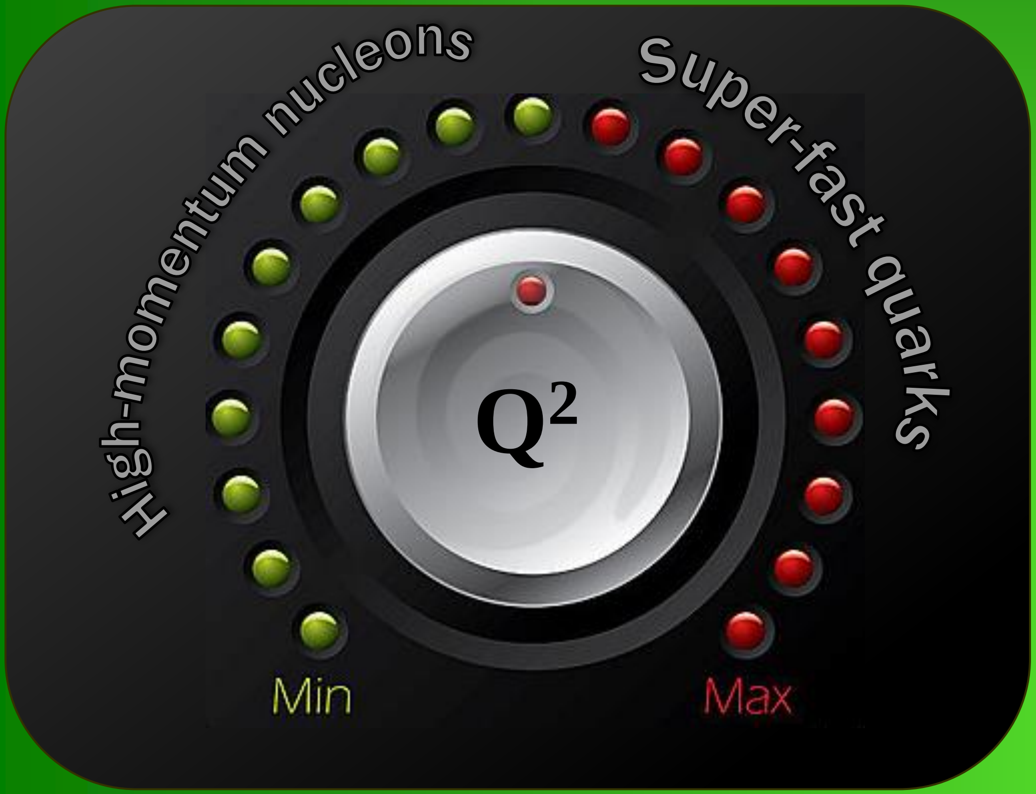


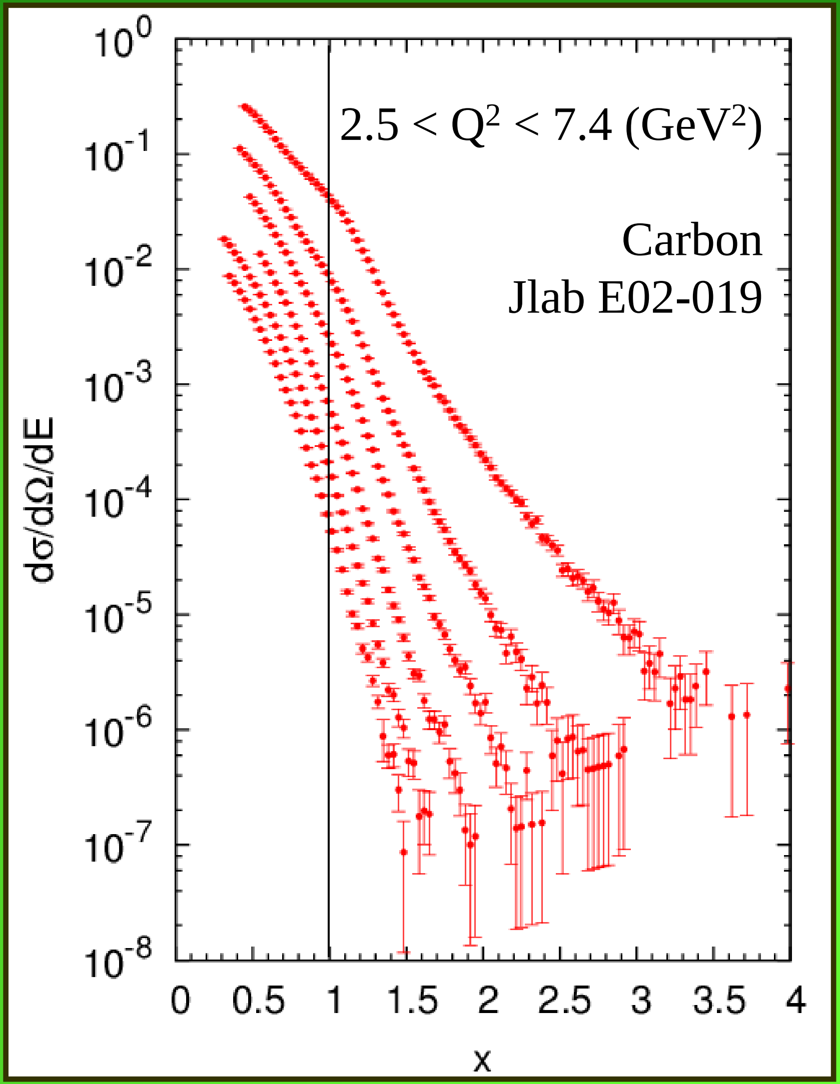




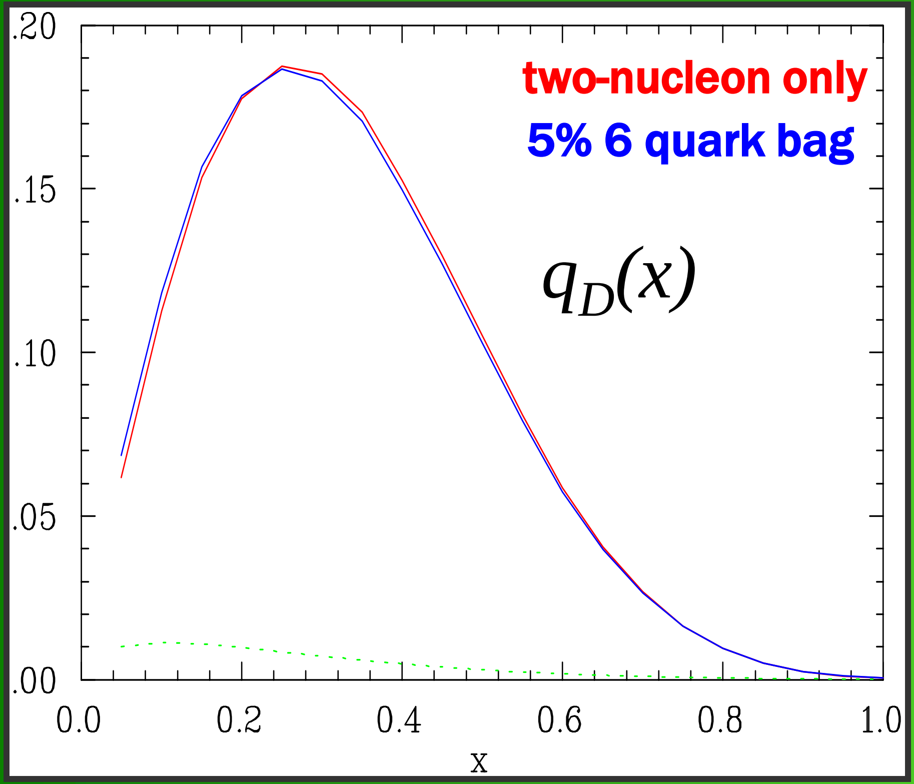


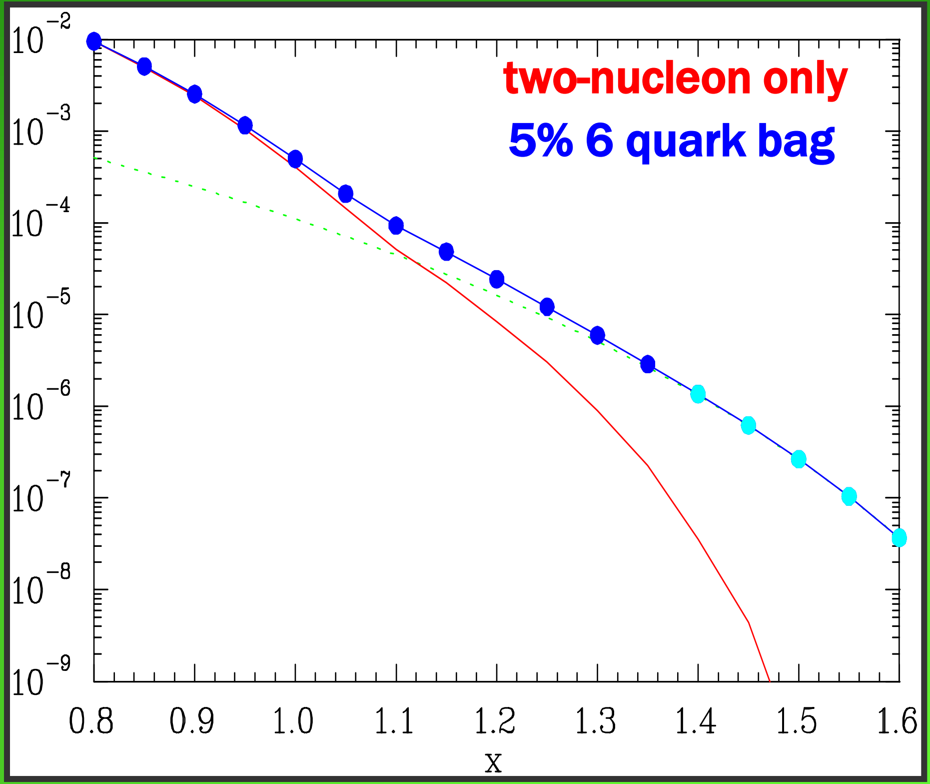
x > 1: Nuclear PDFs





Overlapping nucleons ⟶ enhancement of F_2 structure function





Small effect, possible contribution to EMC effect?

Noticeable effect at x>1

How do we get to SFQ distributions

$$F_2^{TMC}(x,Q^2) = \frac{x^2}{\xi^2 r^3} F_2^{(0)}(\xi) + \frac{6M^2x^3}{Q^2r^4} h_2(\xi) + \frac{12M^4x^4}{Q^4r^5} g_2(\xi)$$

Measured structure function

$$h_2(\xi,Q^2) = \int_\xi^1 du \frac{F_2^{(0)}(u,Q^2)}{u^2}$$

$$g_2(\xi,Q^2) = \int_\xi^1 dv(v-\xi) \frac{F_2^{(0)}(v,Q^2)}{v^2}$$

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

- We want $F_2^{(0)}$, the scaling limit ($Q^2 \to \infty$) structure function as well as its Q^2 dependence

Schienbein et al, J.Phys, 2008

From structure functions to quark distributions

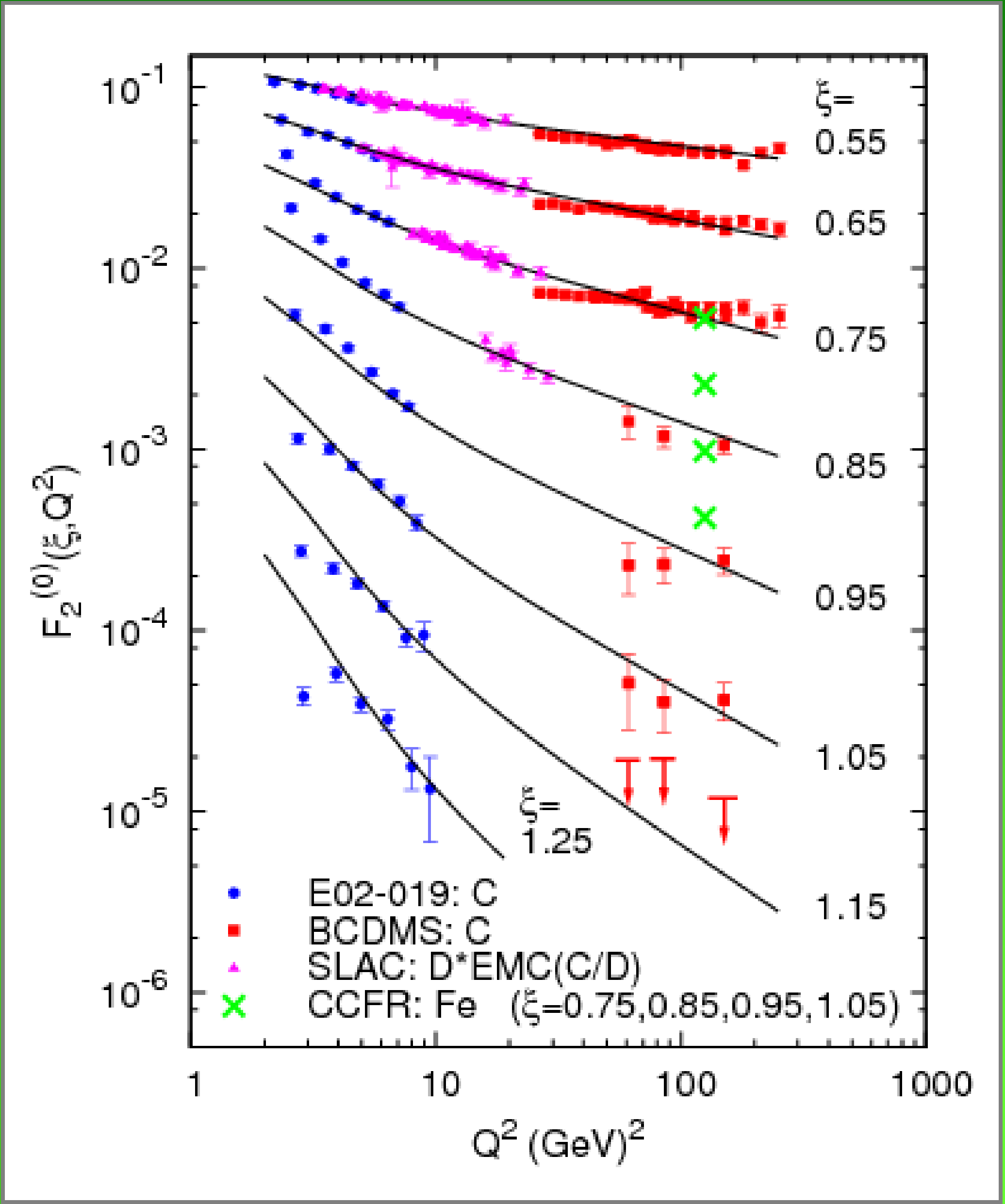
- 2 results for high *x* SFQ distributions (**CCFR** & **BCDMS**)
  - both fit F_2 to e^{-sx}, where s is the “slope” related to the SFQ distribution fall off.
  - **CCFR**: s=8.3±0.7 (Q^2=125 GeV/c^2)
  - **BCMDS**: s=16.5±0.5 (Q^2: 52-200 GeV/c^2)
- We can contribute something to the conversation if we can show that we’re truly in the scaling regime
  - Can’t have large higher twist contributions
  - Show that the Q^2 dependence we see can be accounted for by TMCs and QCD evolution

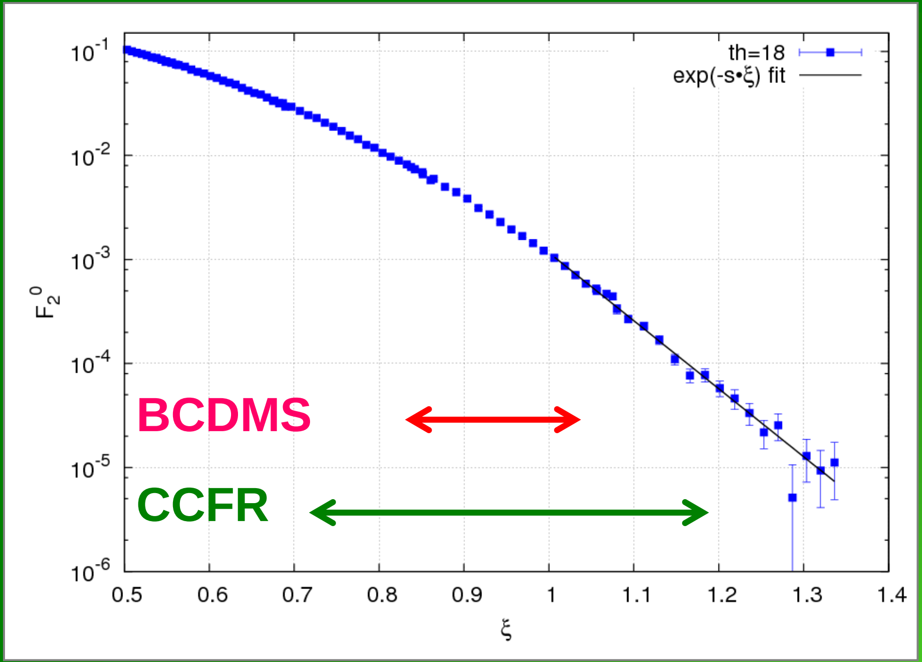
"Super-fast quarks"

- With all the tools in hand, we apply target mass corrections to the available data sets

- With the exception of low Q^2 quasielastic data – E02-019 data can be used for SFQ distributions

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





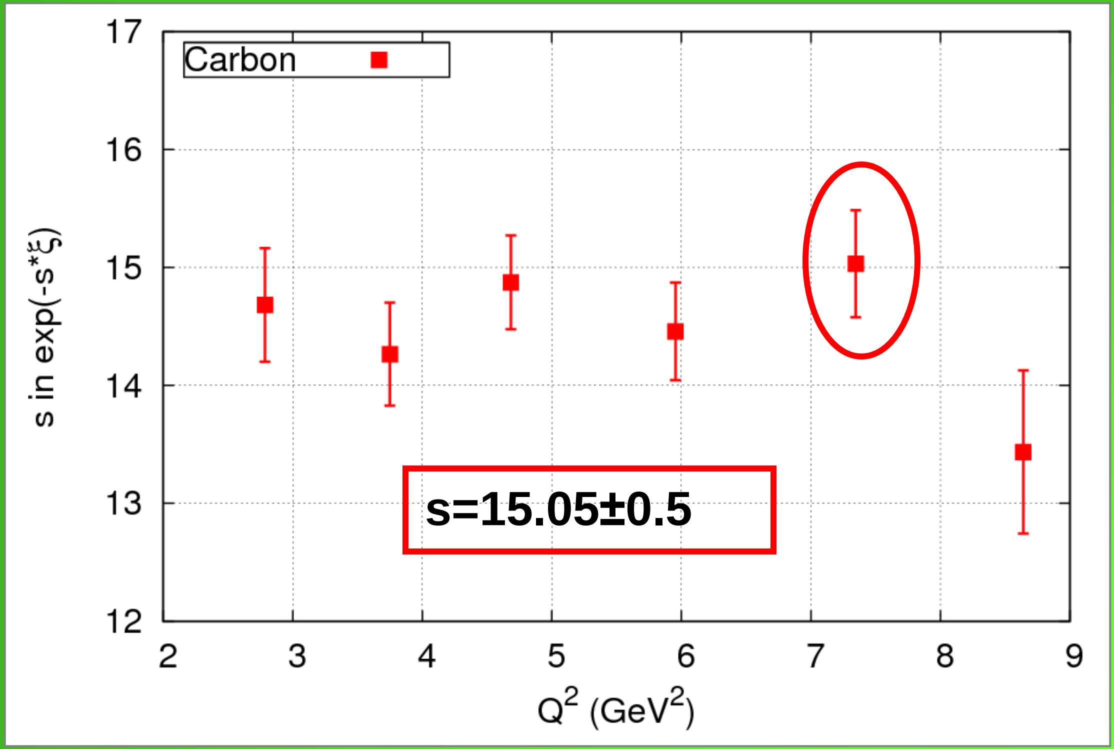
Final step: fit exp(-sξ) to $F_2{}^0$ and compare to **BCDMS** and **CCFR**

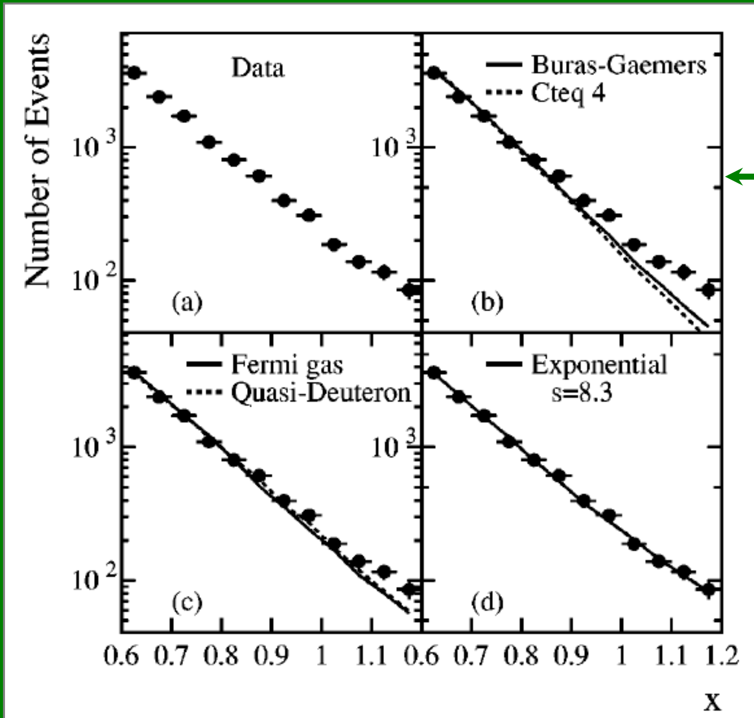
CCFR – (Q^2=125GeV^2)

s=8.3±0.7

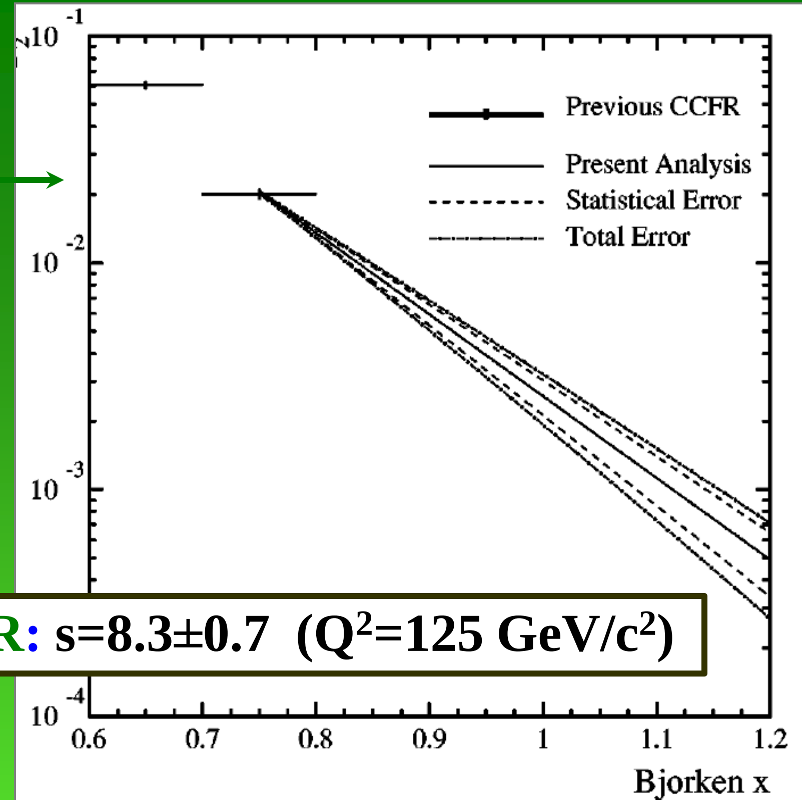
BCDMS – (Q^2: 52-200 GeV^2)

s=16.5±0.5



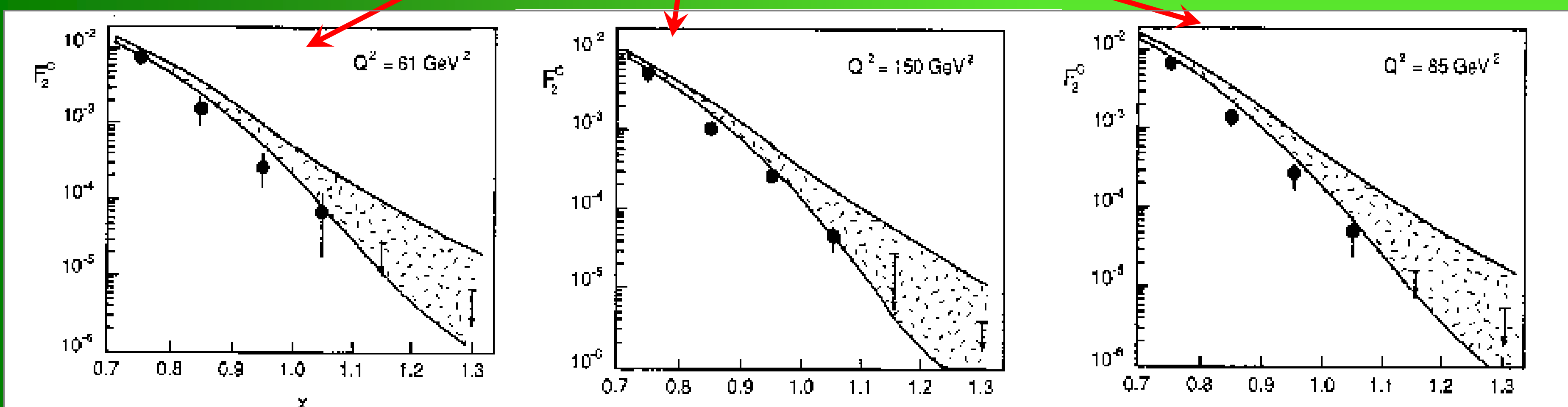


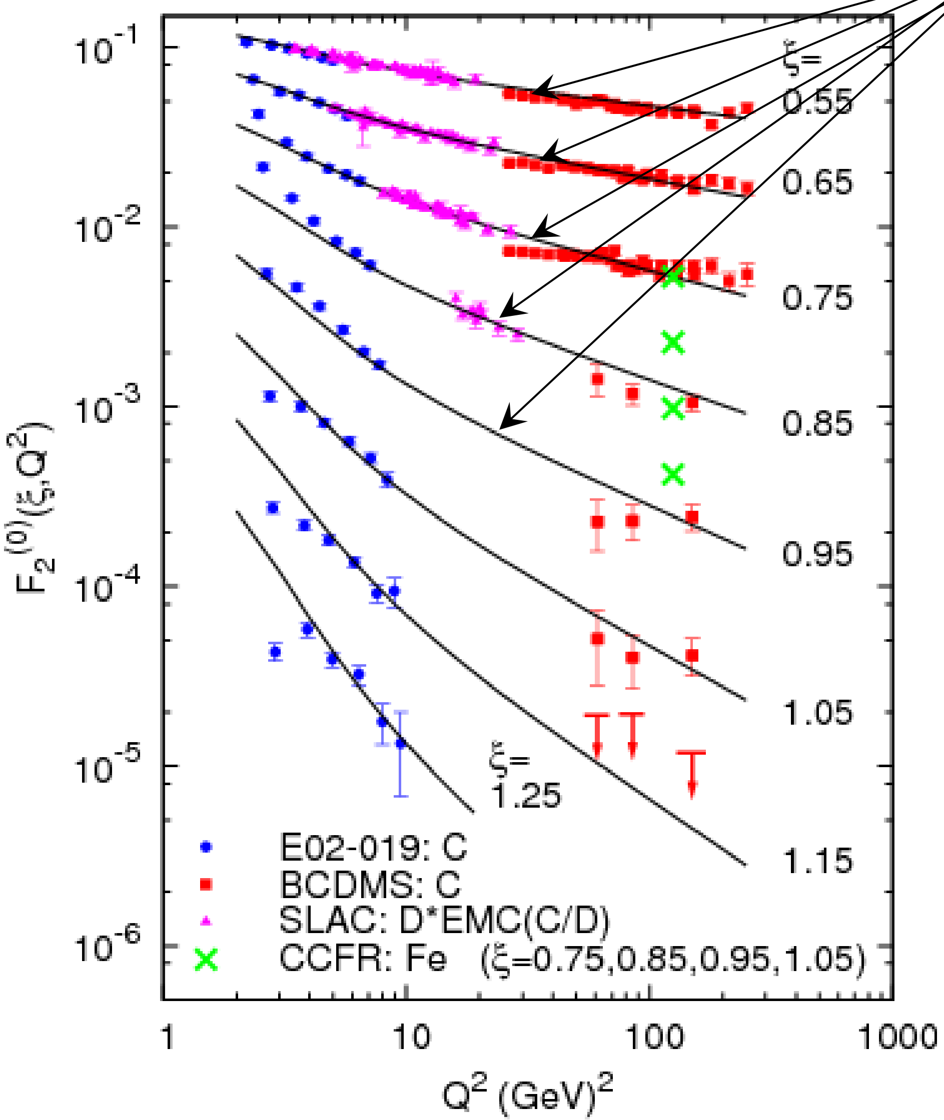
CCFR



CCFR: s=8.3±0.7 (Q^2=125 GeV/c^2)

BCDMS s=16.5±0.5 (Q^2: 52-200 GeV/c^2)



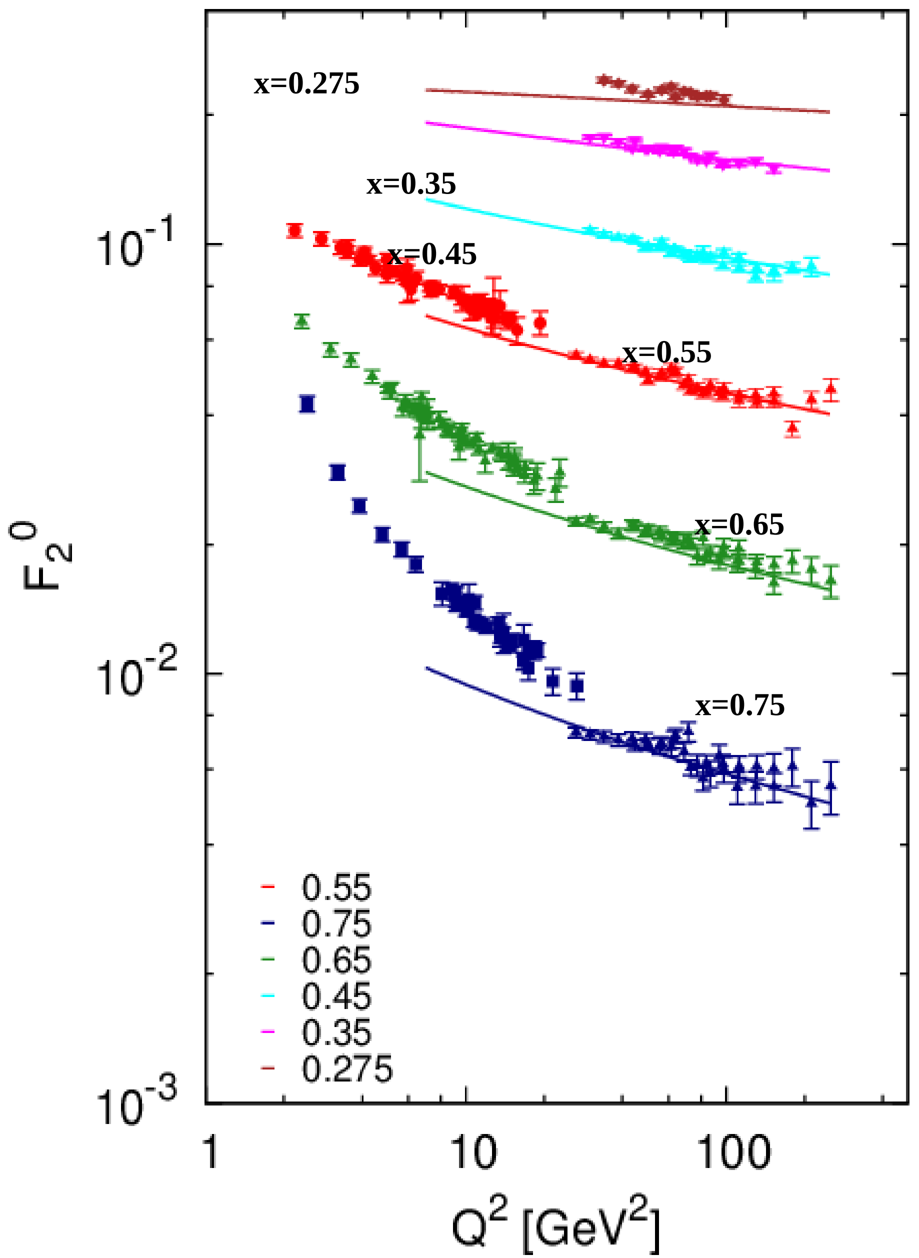


Next: Replace Q^2 dependent fit with non-singlet QCD evolution

$$\frac{\partial q_i^{\pm}(x)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dz}{z} P_{\pm}\left(\frac{x}{z}\right) q_i^{\pm}(z).$$

By definition, the result is only physical for x ≤ 1

Fix: use x_D, rather than x_p



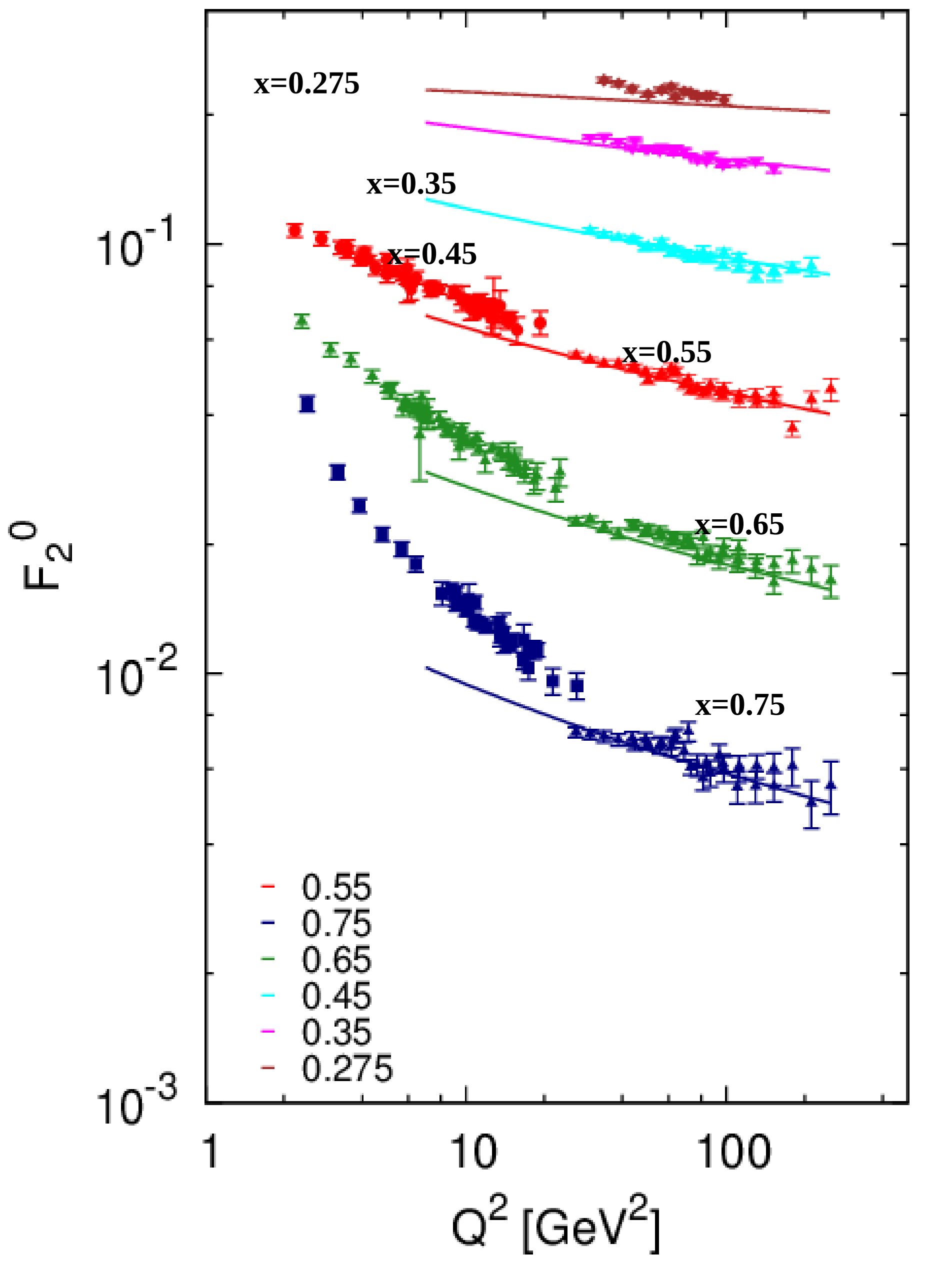
Current Status

$$\frac{\partial q_i^{\pm}(x)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dz}{z} P_{\pm}\left(\frac{x}{z}\right) q_i^{\pm}(z).$$

By definition, the result is only physical for x ≤ 1

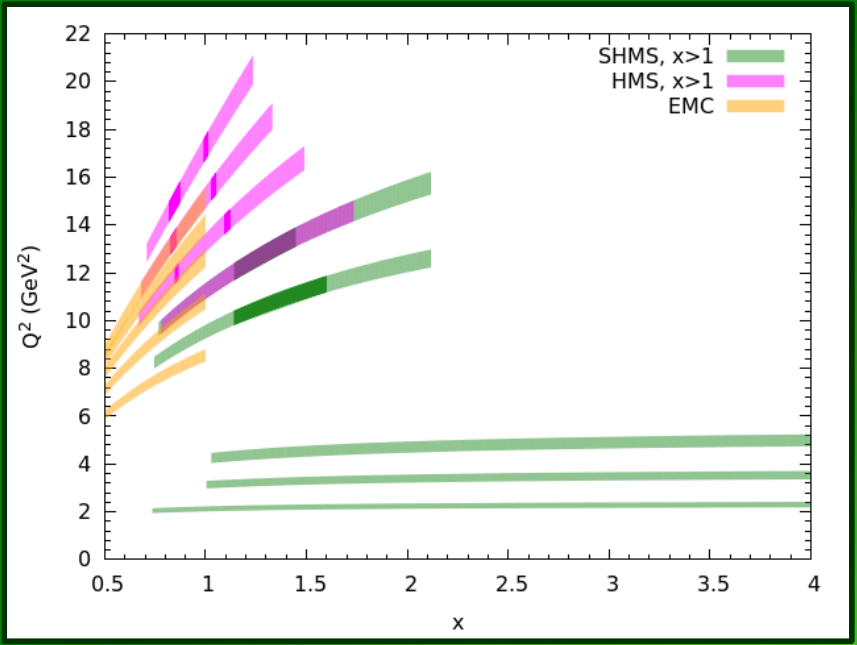
Fix: use x_D, rather than x_p

Rescale F_2^0 fit with x-dependent correction to match high Q^2 data



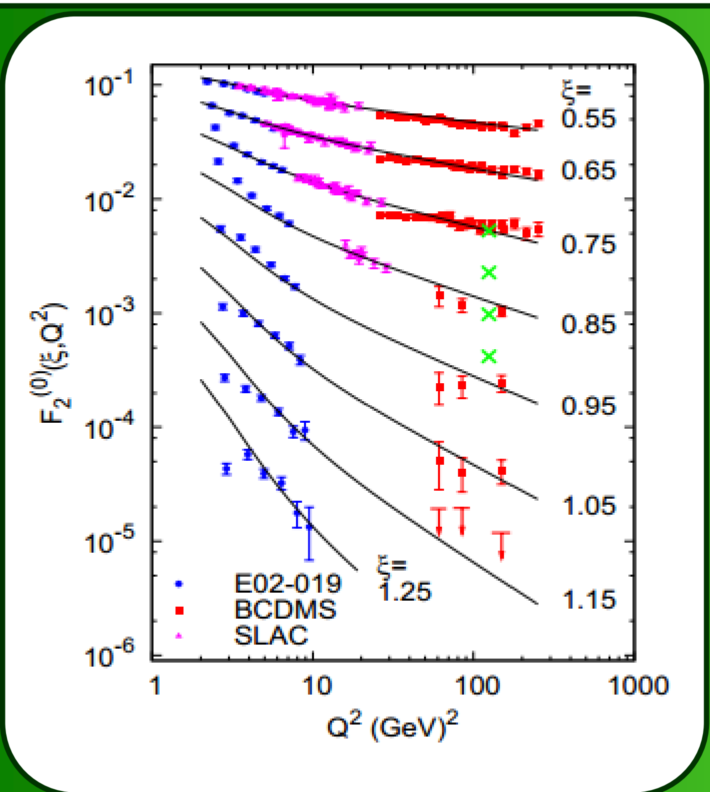
Current Status

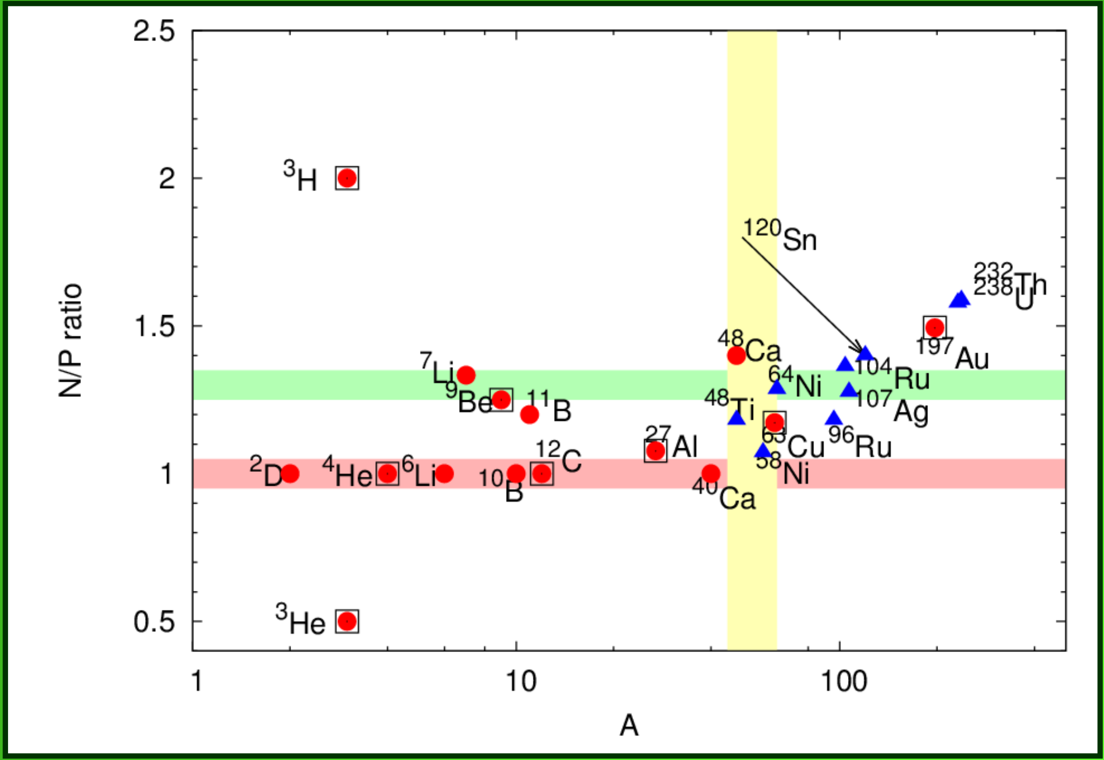
- Non-singlet QCD evolution appears to work for nuclear structure functions
- Higher twist contributions appear to persist to tens of GeV^2



Jlab E12-06-105

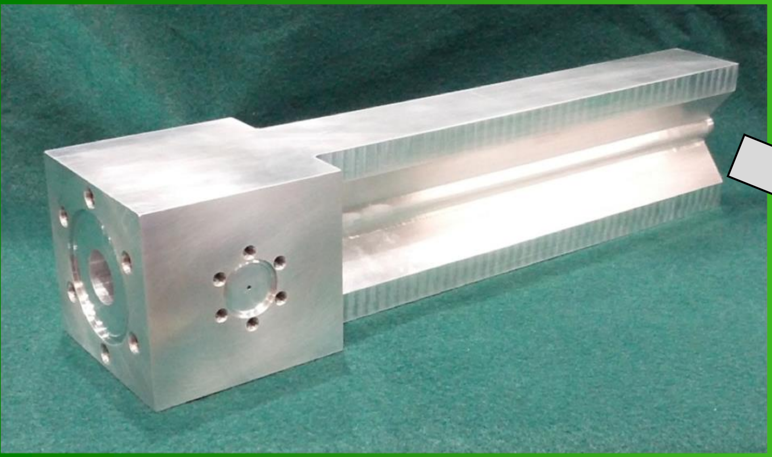
- short-range nuclear structure
  - Isospin dependence
  - A-dependence
- Super-fast quarks

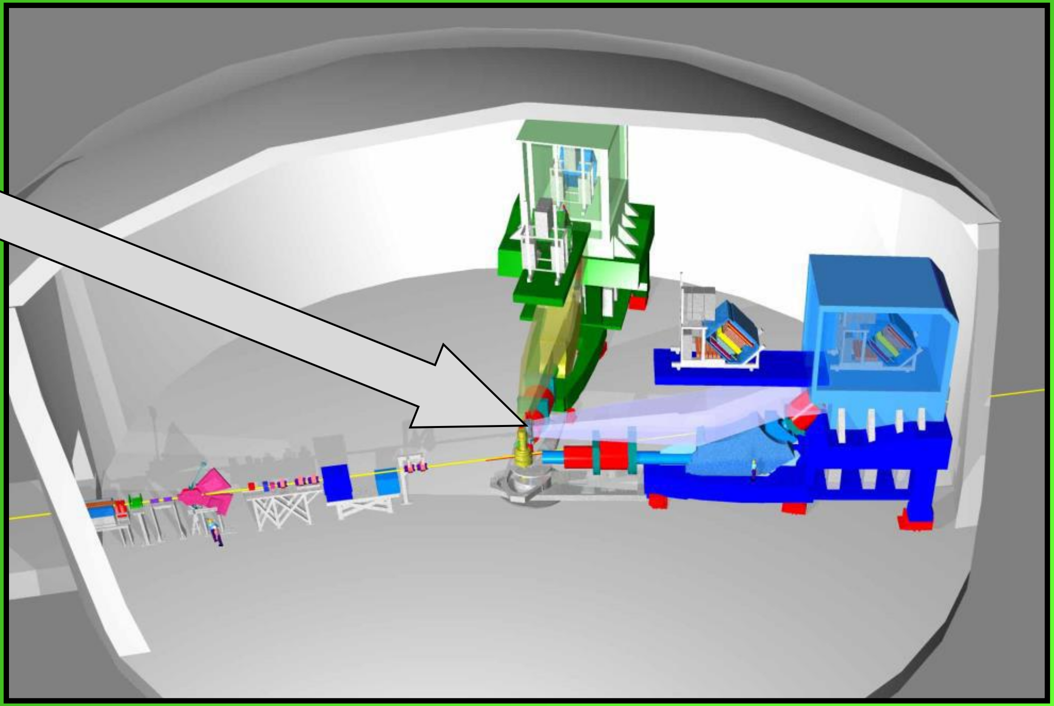




Coming very soon: [Jlab E12-11-112]

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





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!

END

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

- Quasielastic electron scattering with ^3H and ^3He
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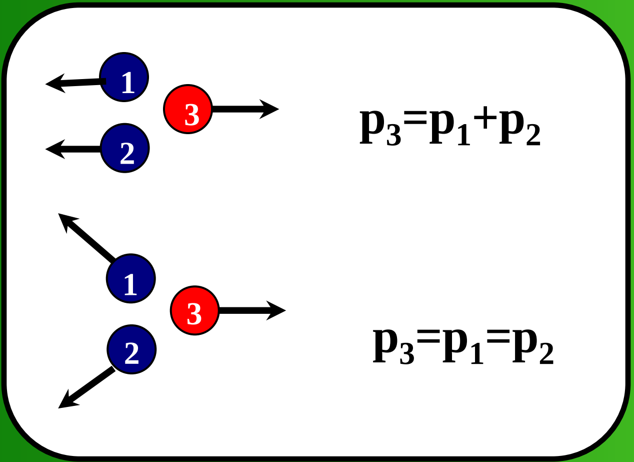

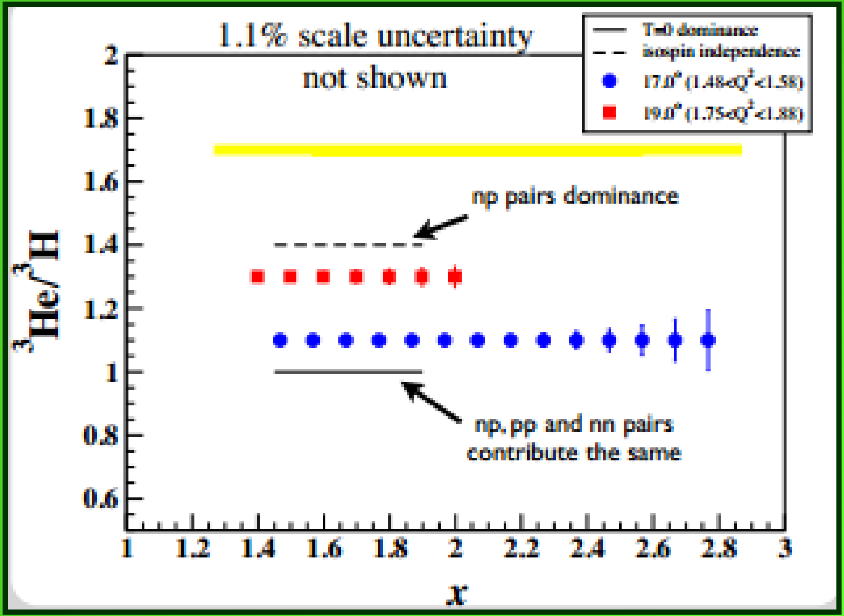

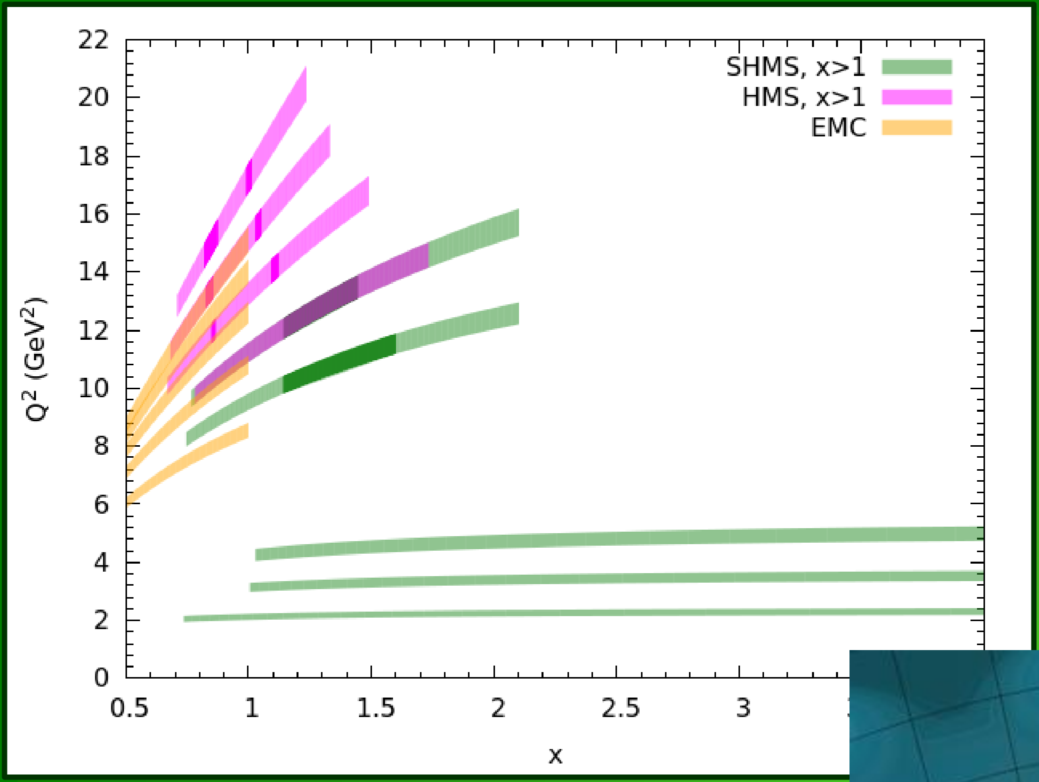

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