SRCs in x>1 Inclusive Processes

Nadia Fomin
University of Tennessee

Next generation nuclear physics with JLab12 and EIC
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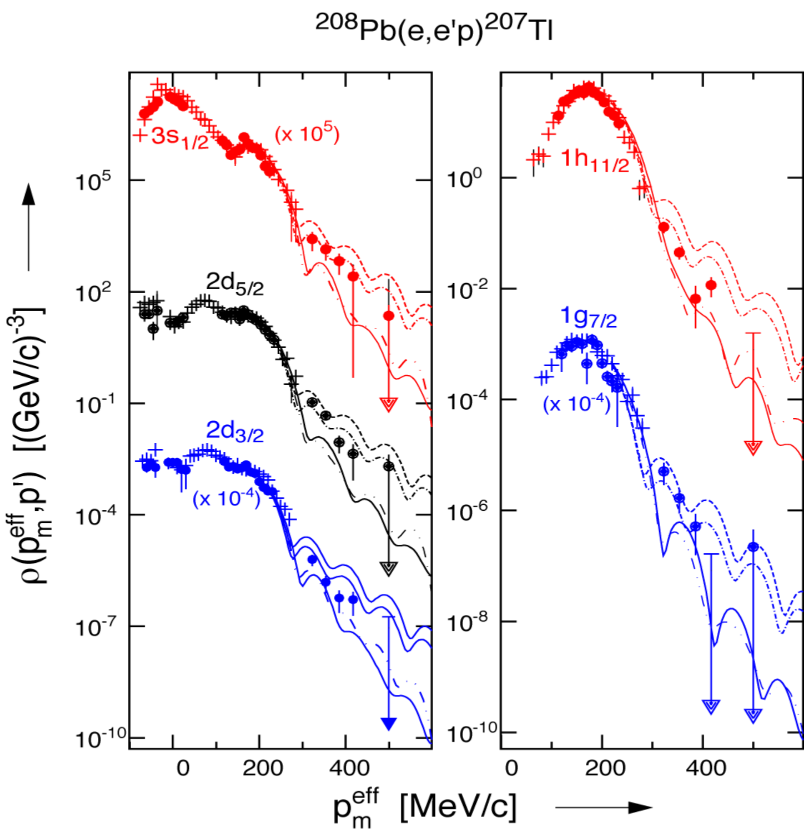
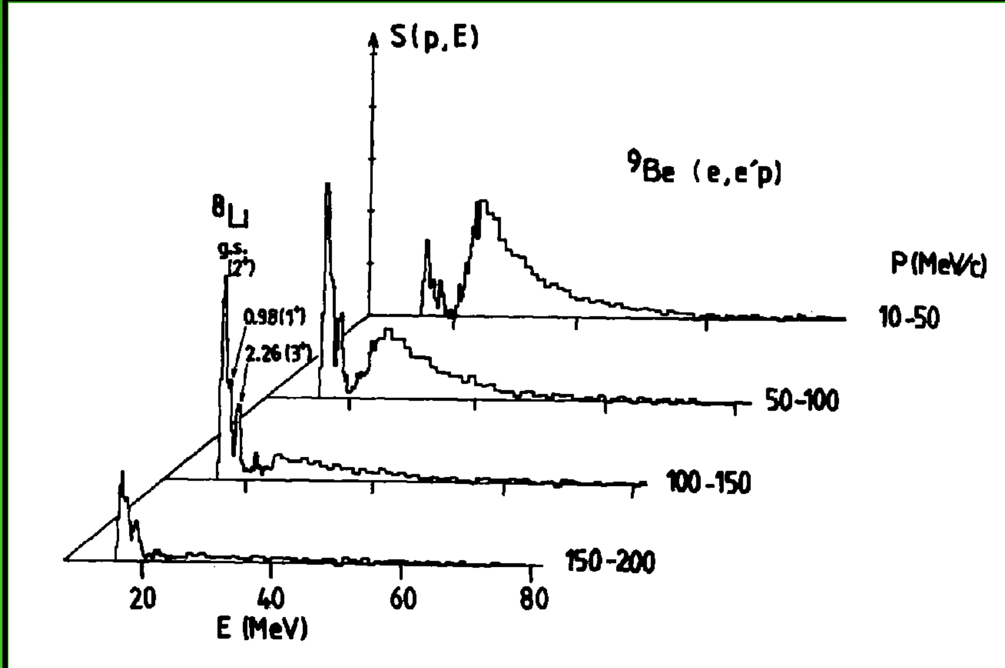
High momentum nucleons – where do they come from?

Independent Particle Shell Model :

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



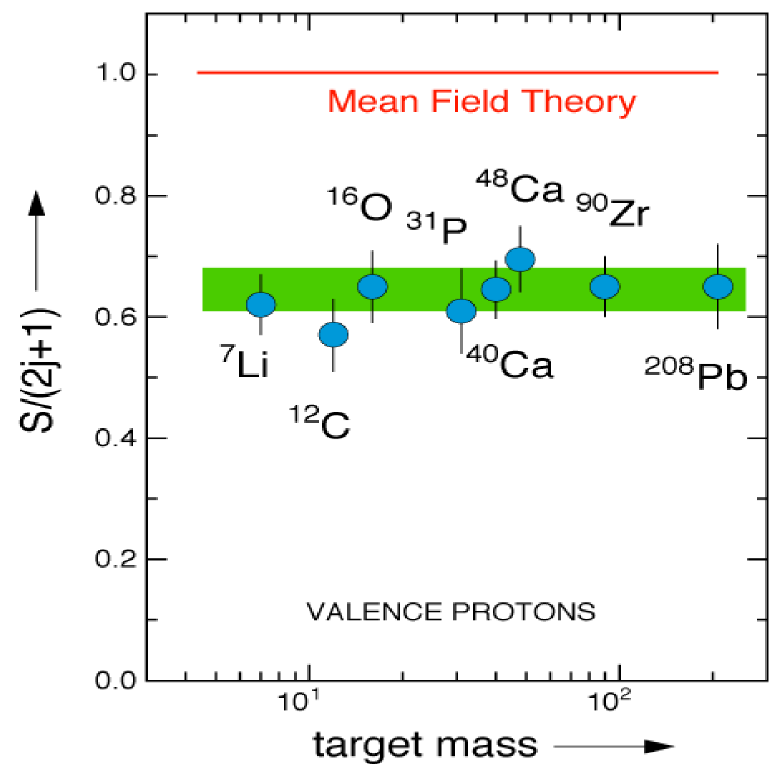


Proton E_m,p_m distribution modeled as sum of independent shell contributions (arbitrary normalization)

Independent Particle Shell Model :

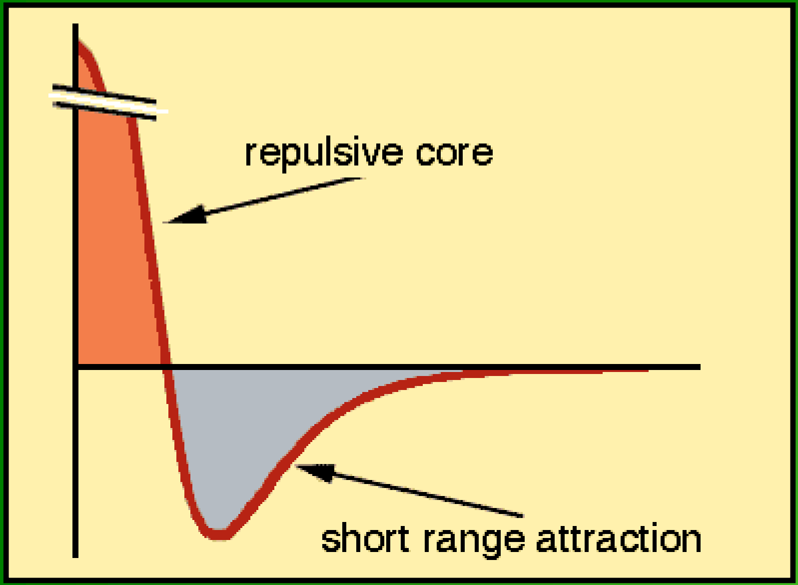
$$S_\alpha = 4\pi \int S(E_m, p_m) p_m^2 dp_m \delta(E_m - E_\alpha)$$

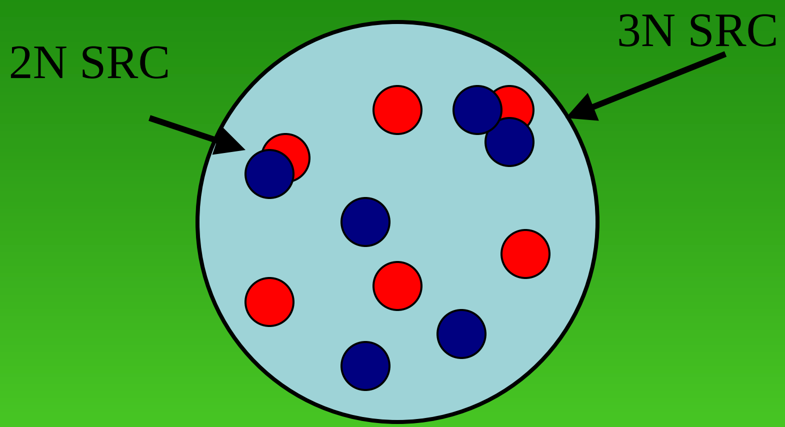
- For nuclei, S_α should be equal to ***2j+1*** => number of protons in a given orbital
- However, it as found to be only ~2/3 of the expected value
- The bulk of the missing strength it is thought to come from **short range correlations**

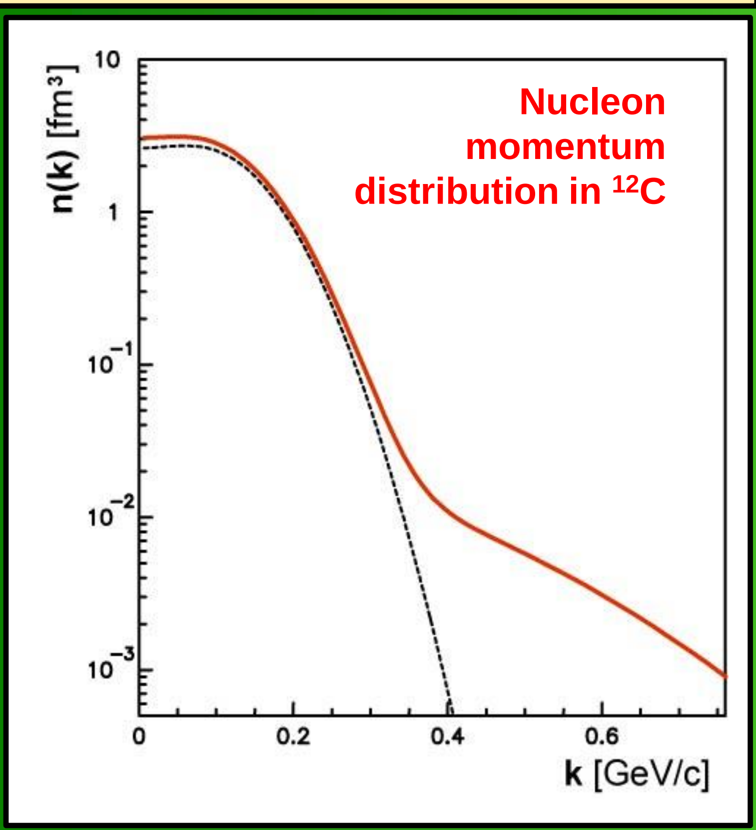


High momentum nucleons

- Short Range Correlations







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

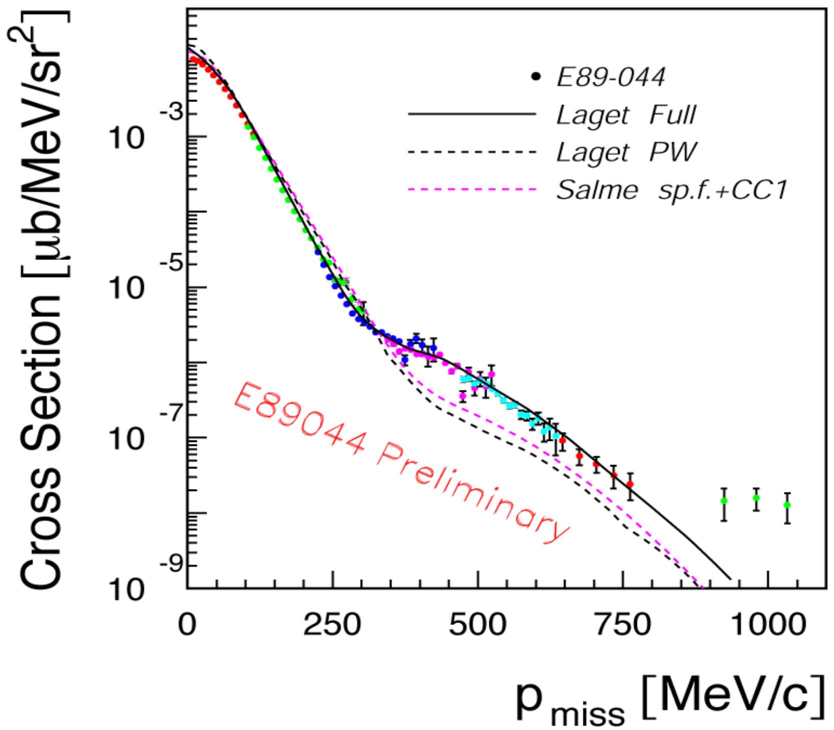
- E89-004: Measure of ^{3}He(e,e'p)d
- Measured far into high momentum tail: Cross section is ~5-10x expectation

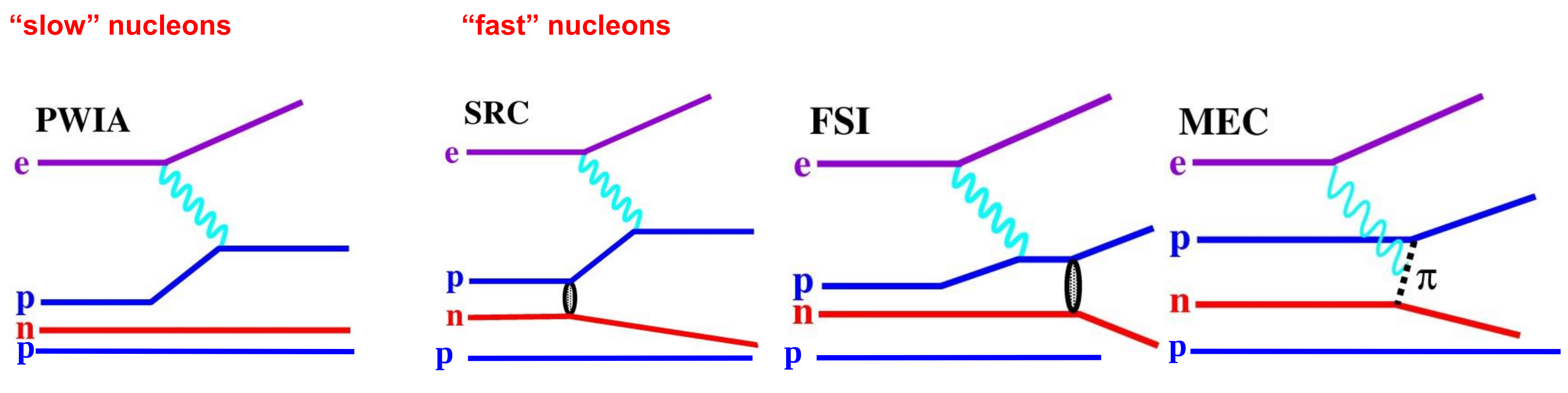
<u>Difficulty</u>

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

OR

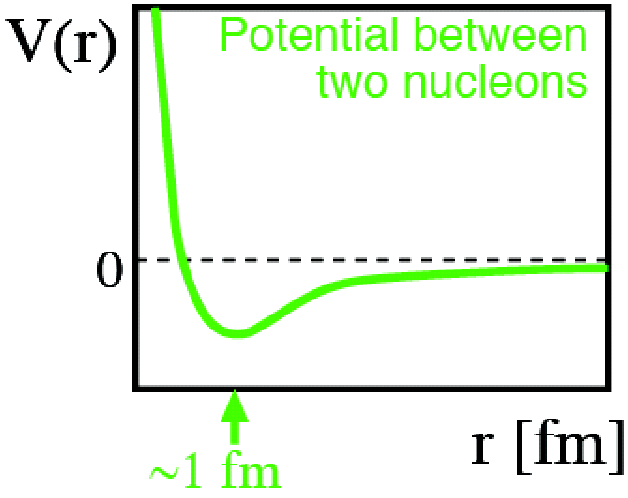
- Final State Interactions (FSI) and Meson Exchange Contributions (MEC)

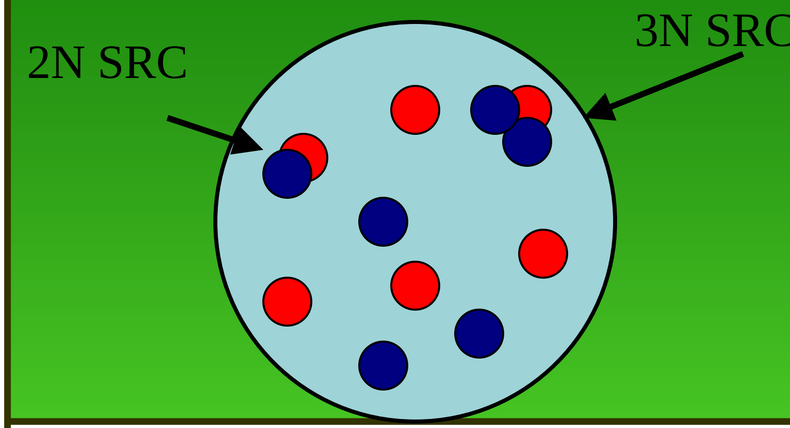


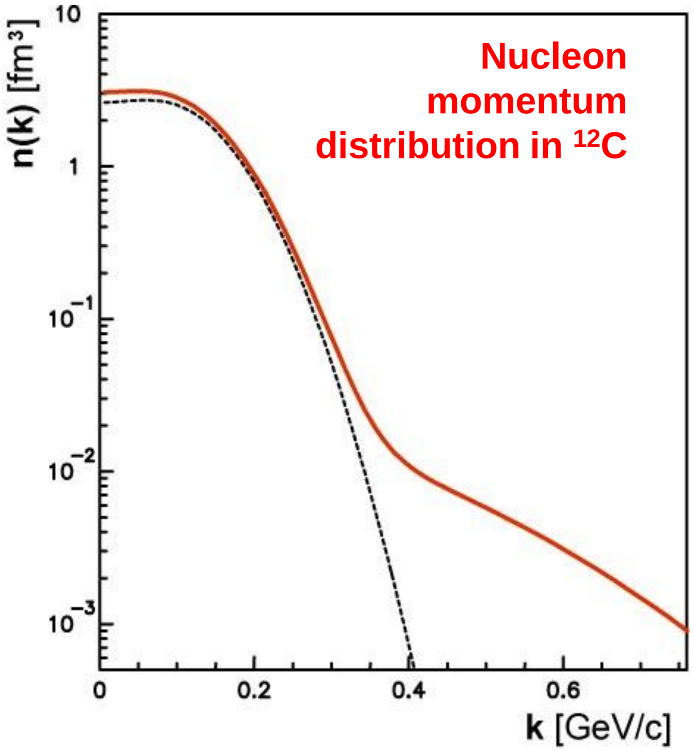


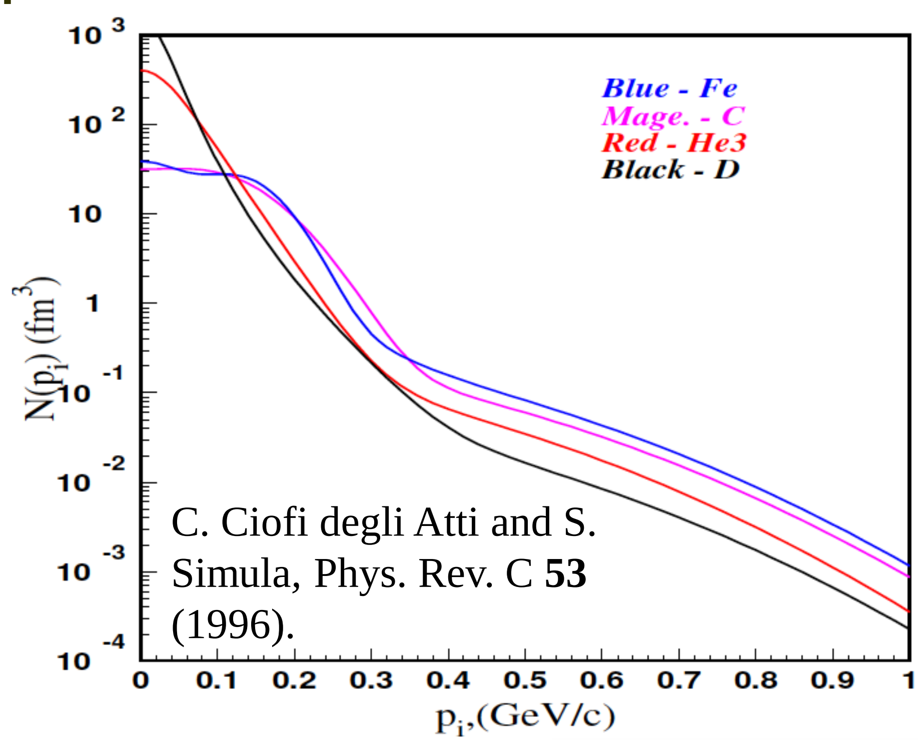
High momentum nucleons

- Short Range Correlations



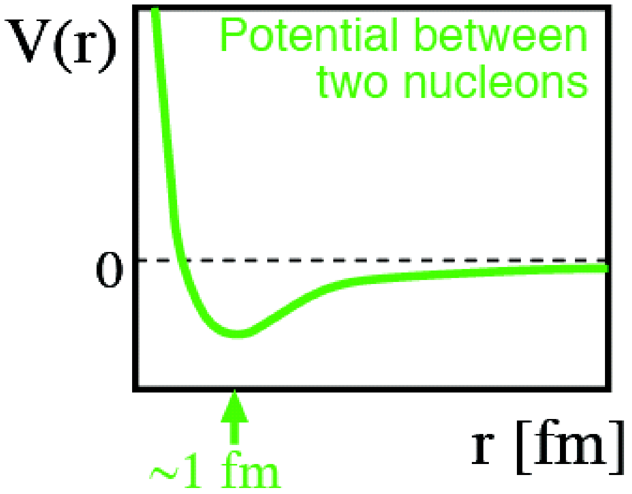


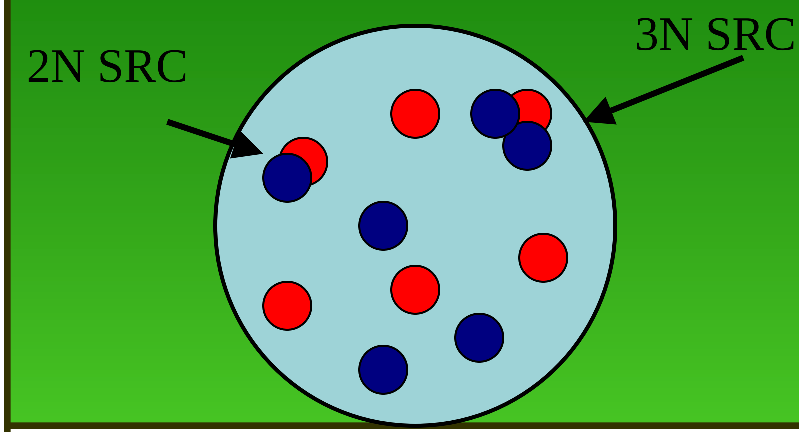


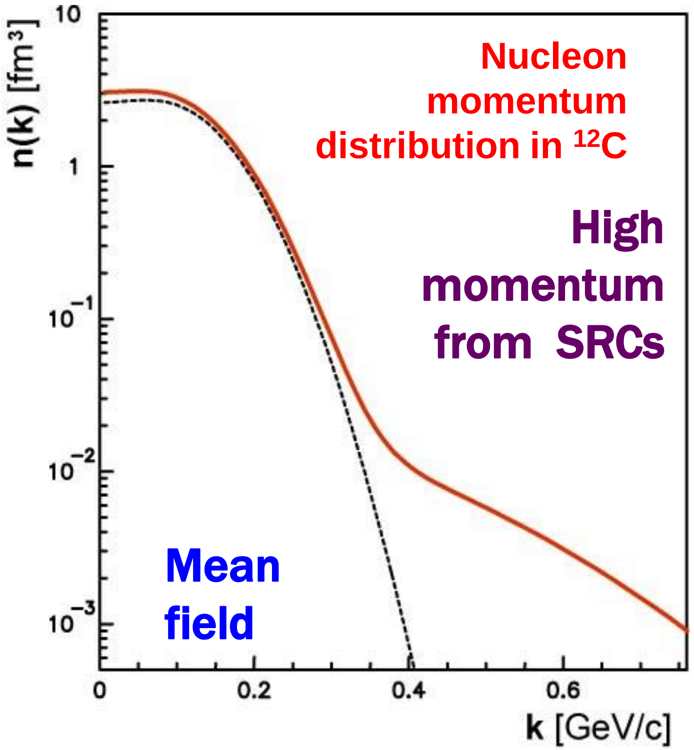


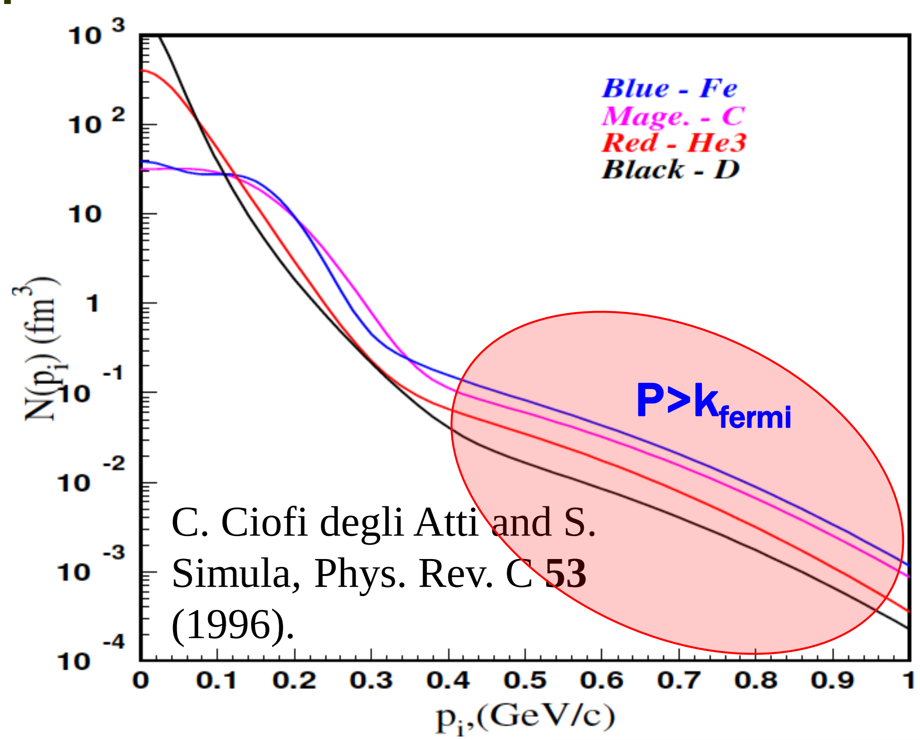
High momentum nucleons

- Short Range Correlations



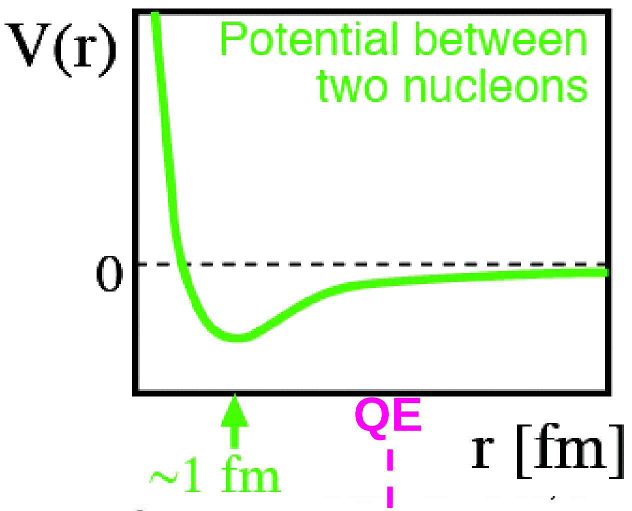


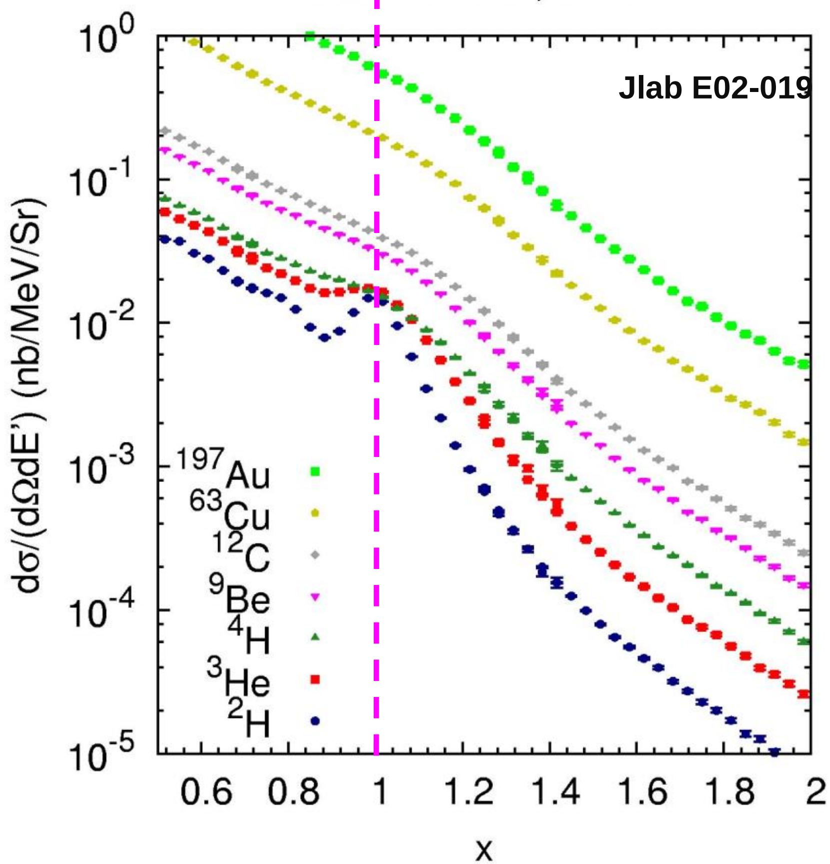


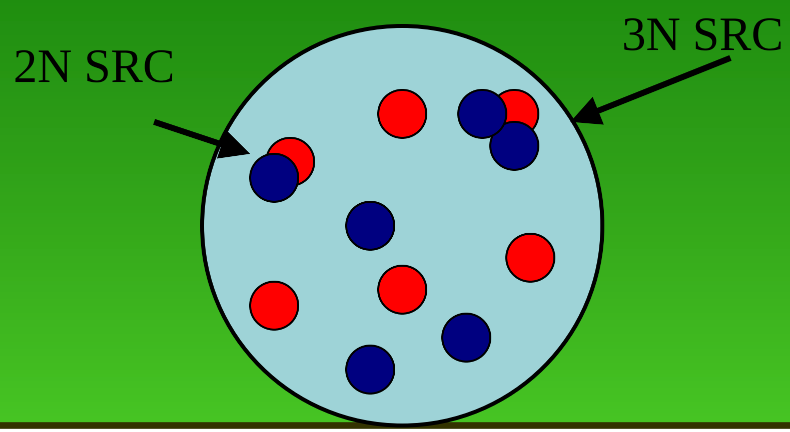


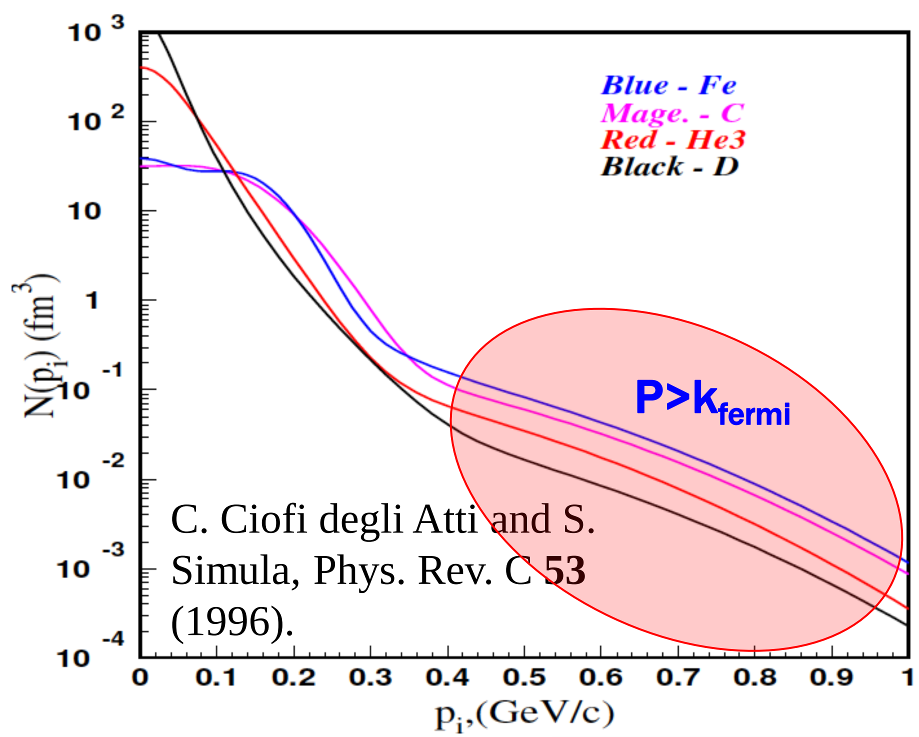
High momentum nucleons

- 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

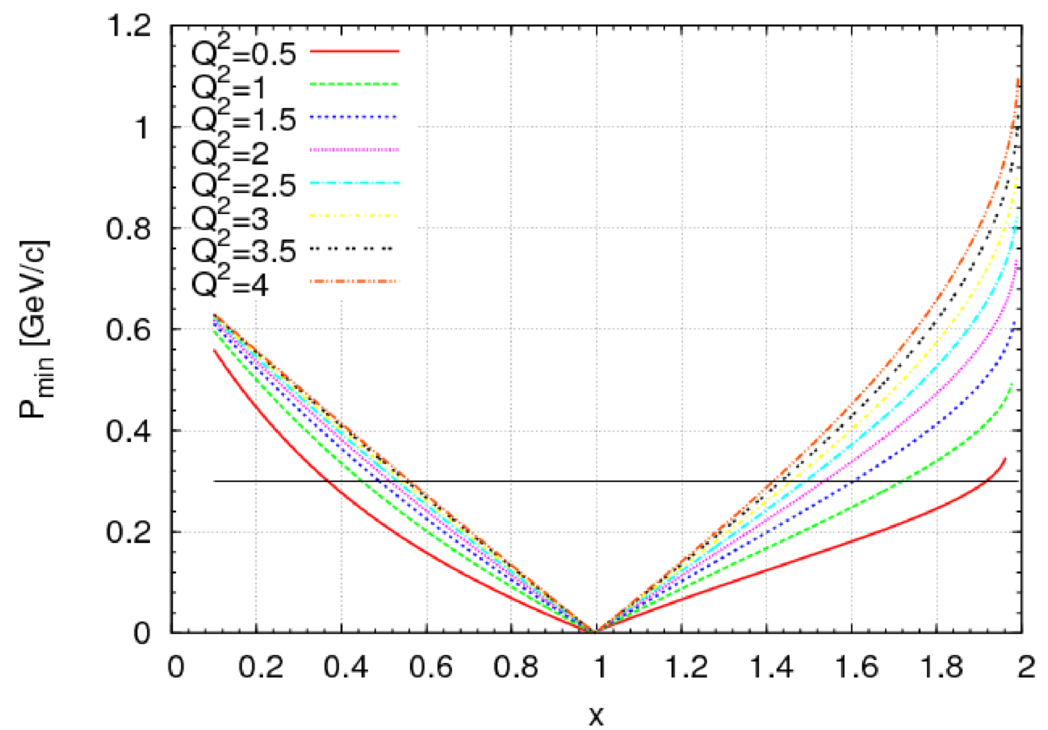
- In the high momentum region, FSIs are thought to be confined to the SRCs and therefore, cancel in the cross section ratios

1.4<x<2 => 2 nucleon correlation

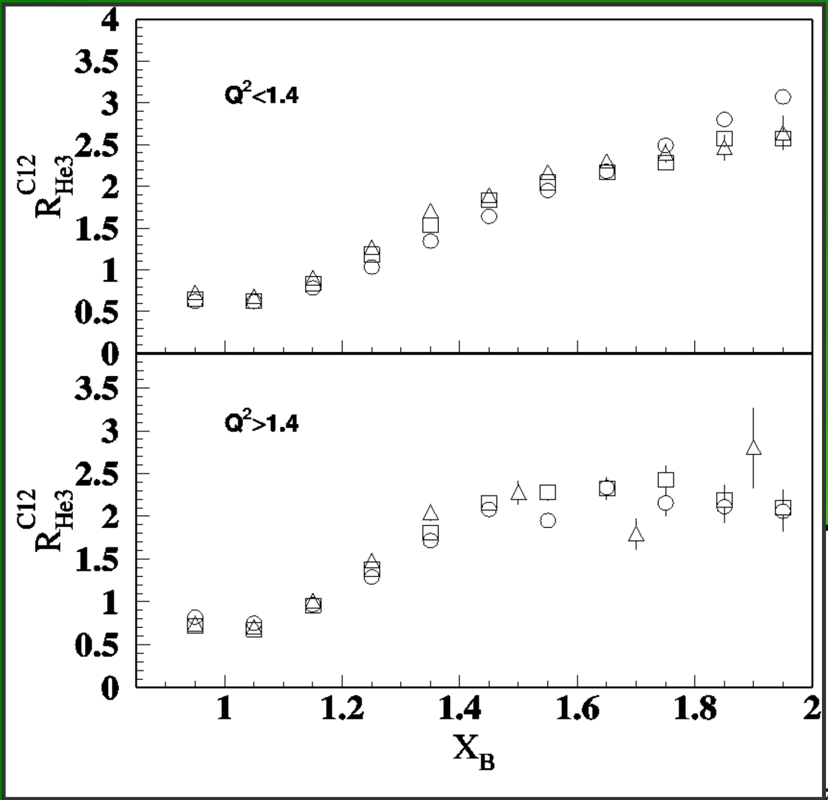
2.4<x<3 => 3 nucleon correlation

- *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).*
- *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

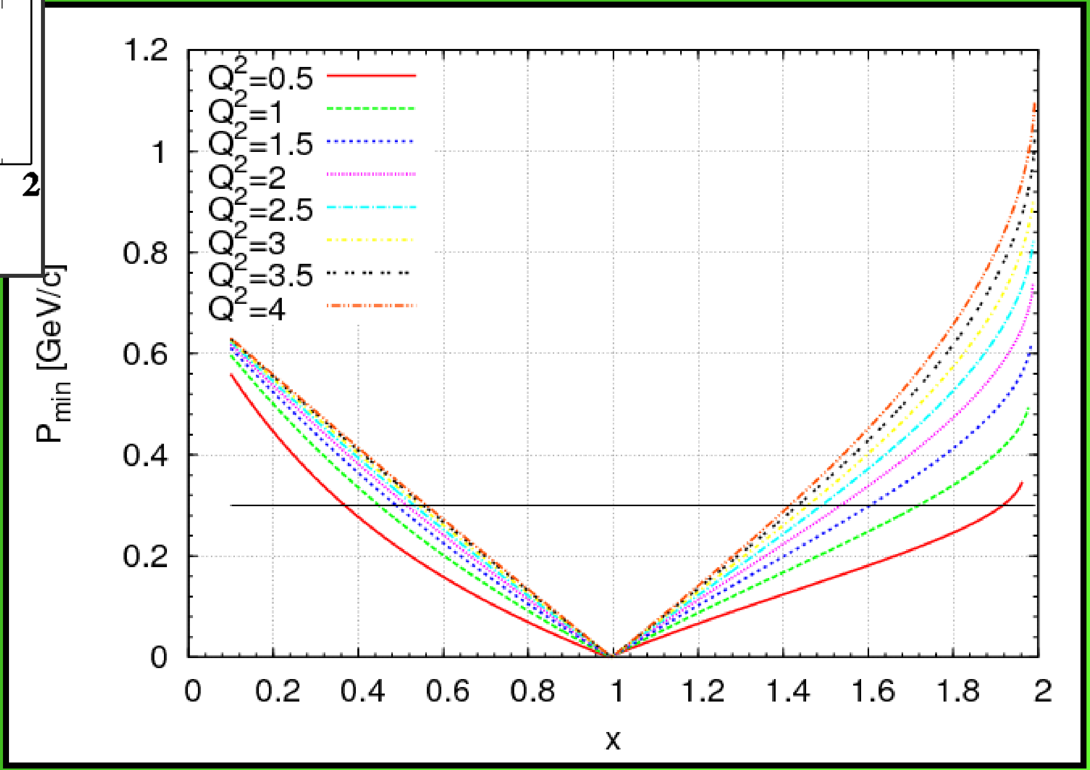


1.4<x<2 => 2 nucleon correlation

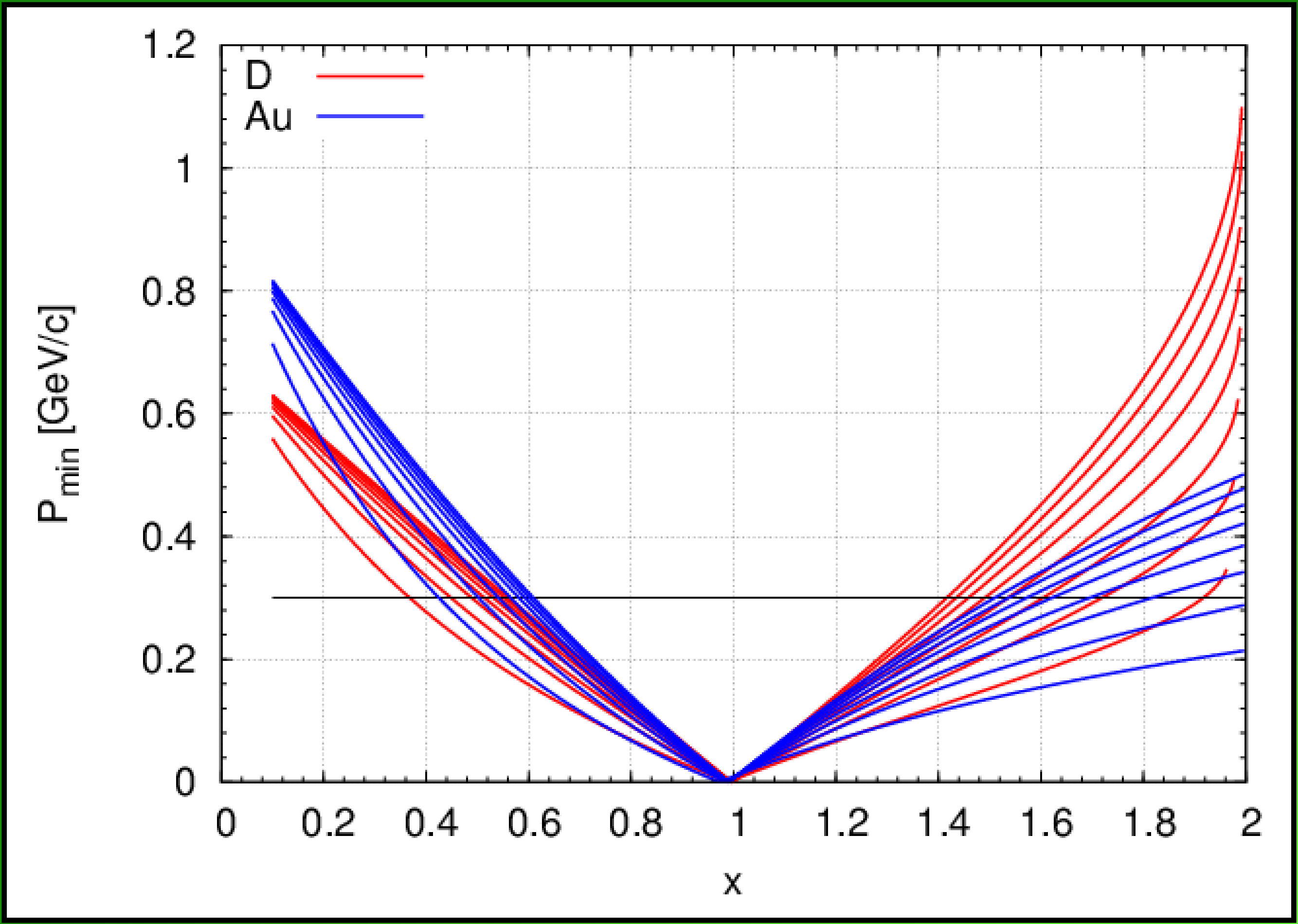
2.4<x<3 => 3 nucleon correlation

Egiyan et al, Phys.Rev.C68, 2003

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

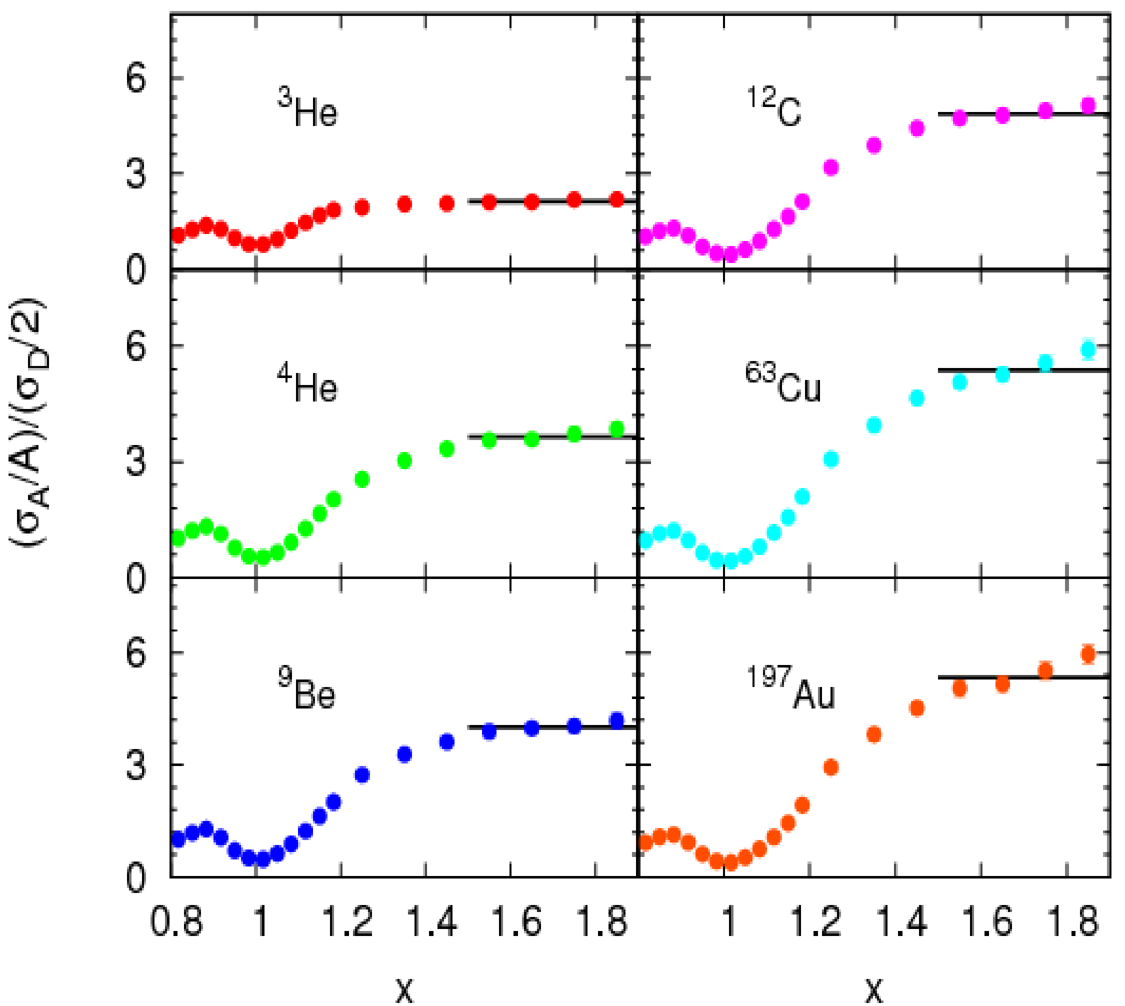


Kinematic cutoff is A-dependent



- 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



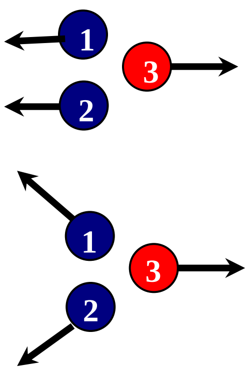
NF et al, PRL **108** (2012)

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

Jlab E02-019

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

Why not more than two nucleons in a correlation?



$p_3 = p_1 + p_2$

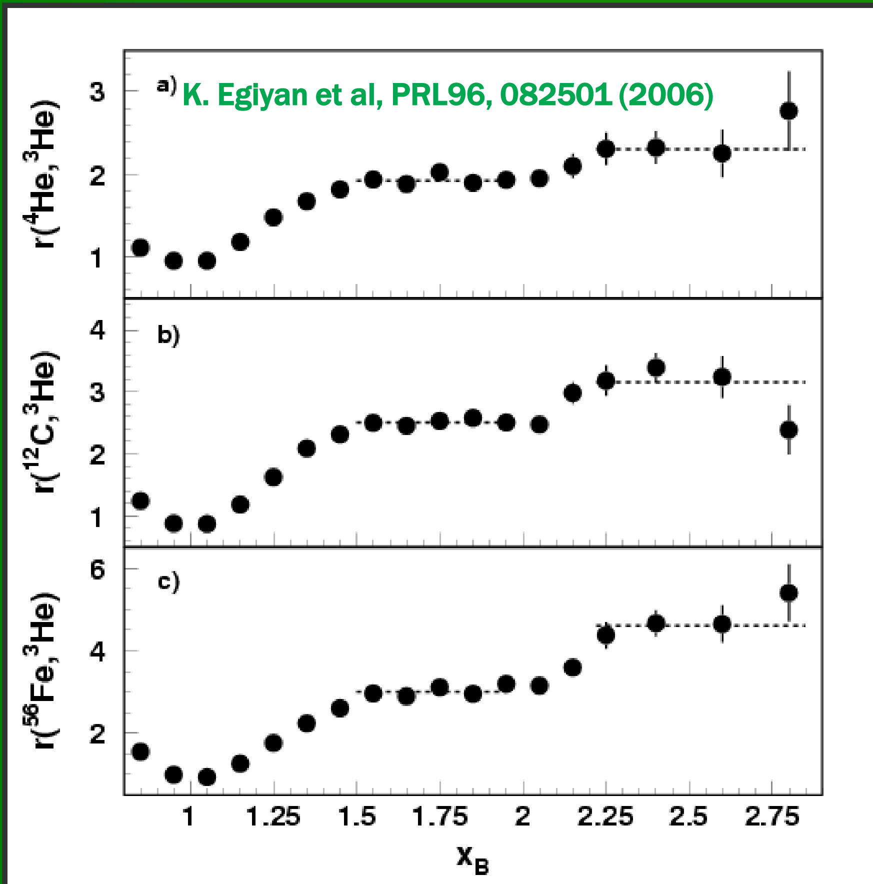
$p_3 = p_1 = p_2$

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

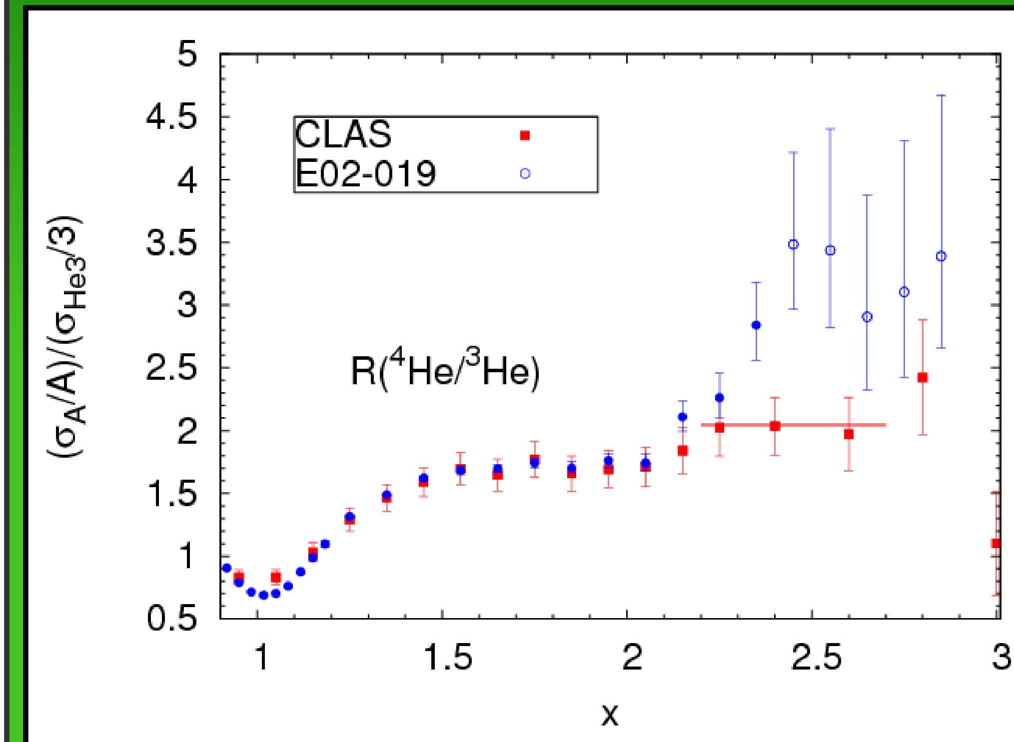
$$= \frac{A}{2} a_2(A) \sigma_2(x, Q^2) +$$

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

Further evidence of multi-nucleon correlations

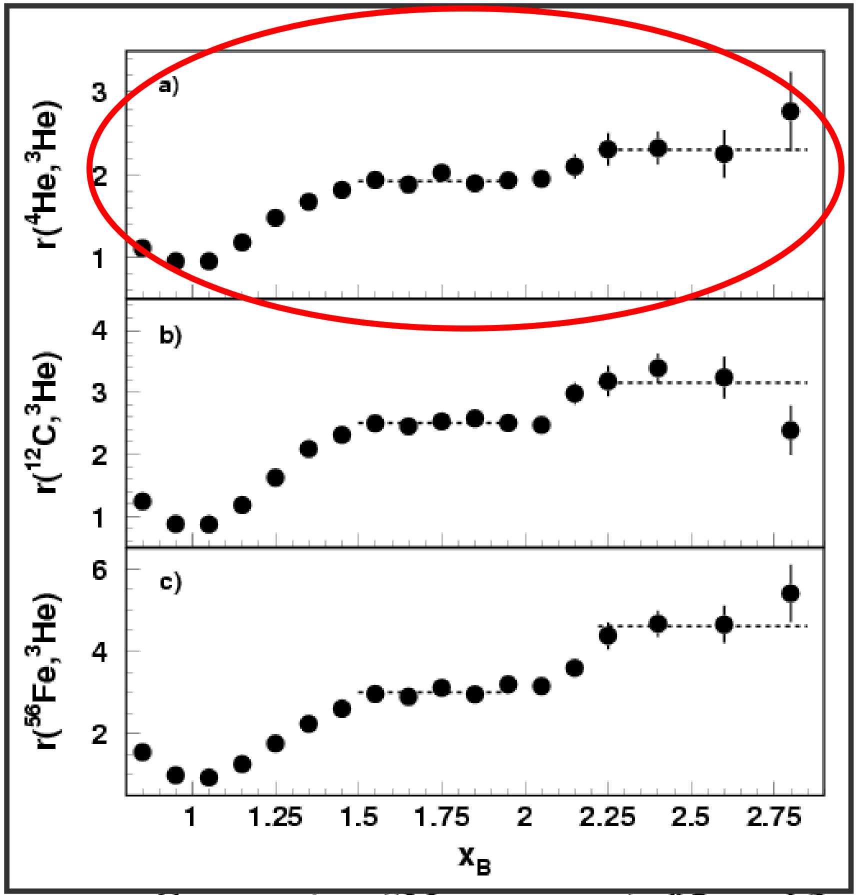


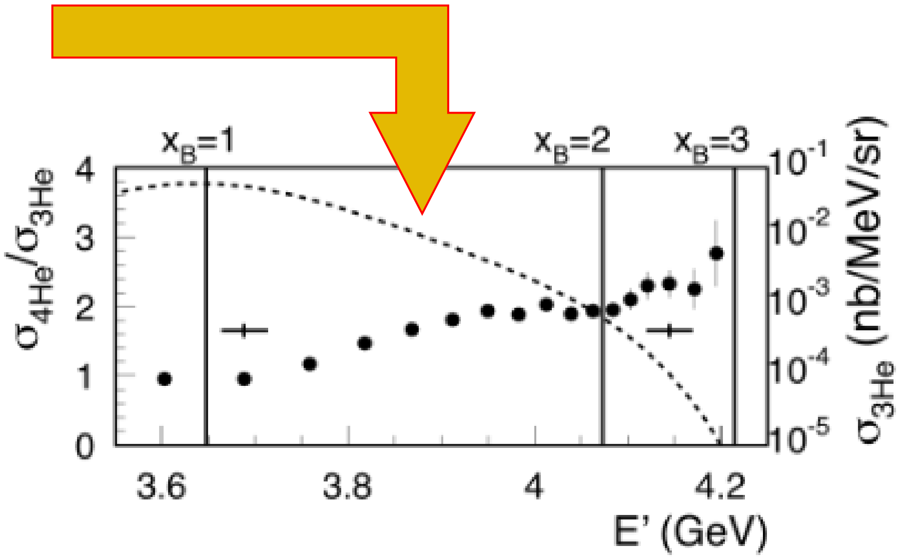
$\langle Q^2\rangle$ (GeV^2): ***CLAS: 1.6*** ***E02-019: 2.7***



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

Have we actually seen 3N SRC in ratios?

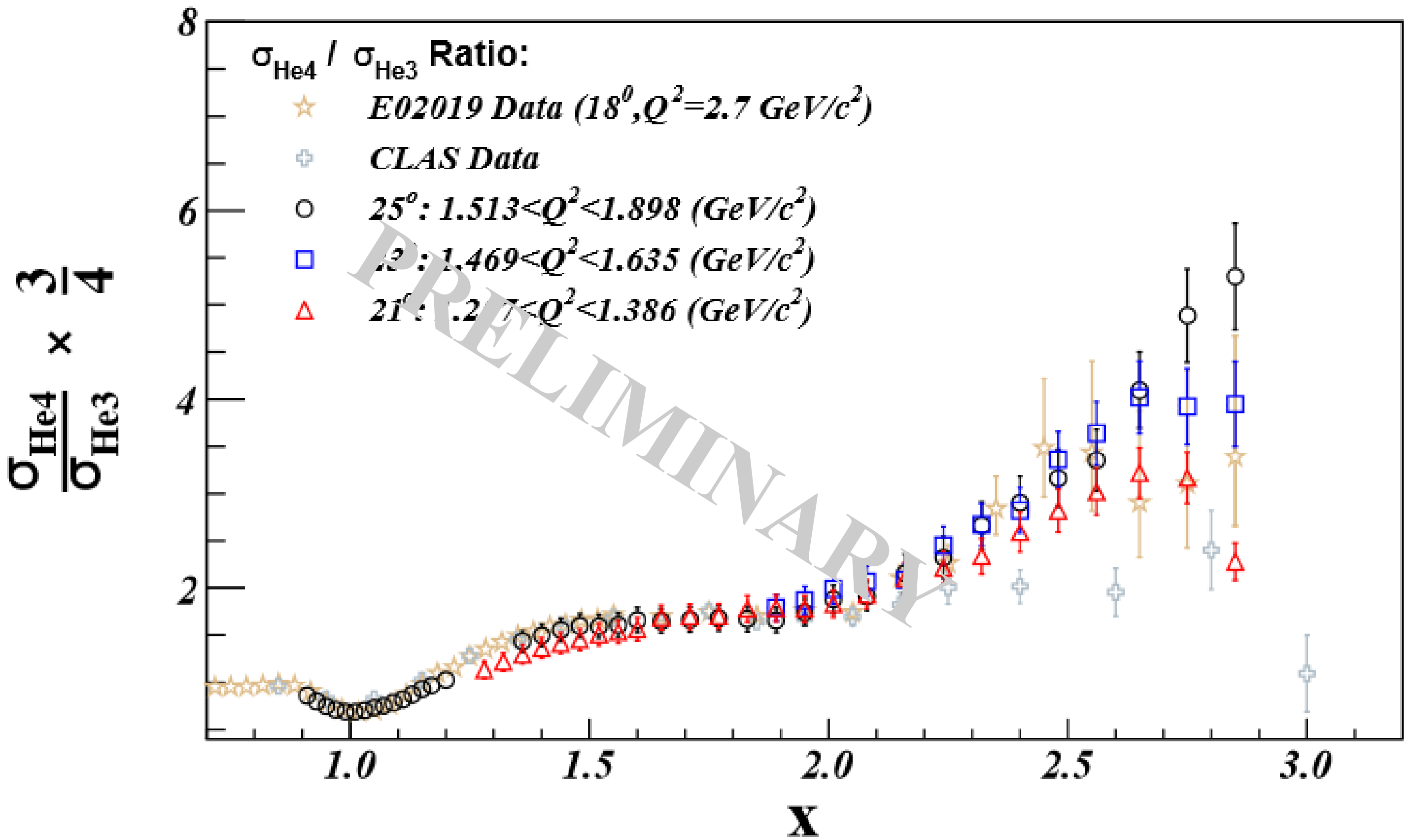




Comment on "Measurement of 2- and 3-nucleon short range correlation probabilities in nuclei"

Douglas W. Higinbotham[1] and Or Hen[2]

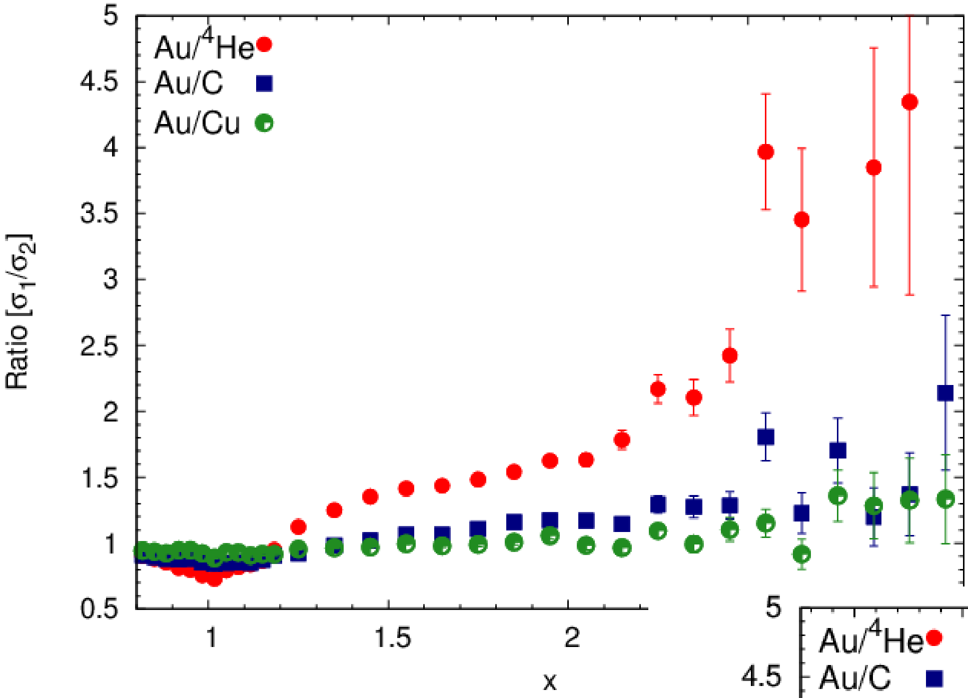
E08-014: Study Q^2 dependence of 3N SRC



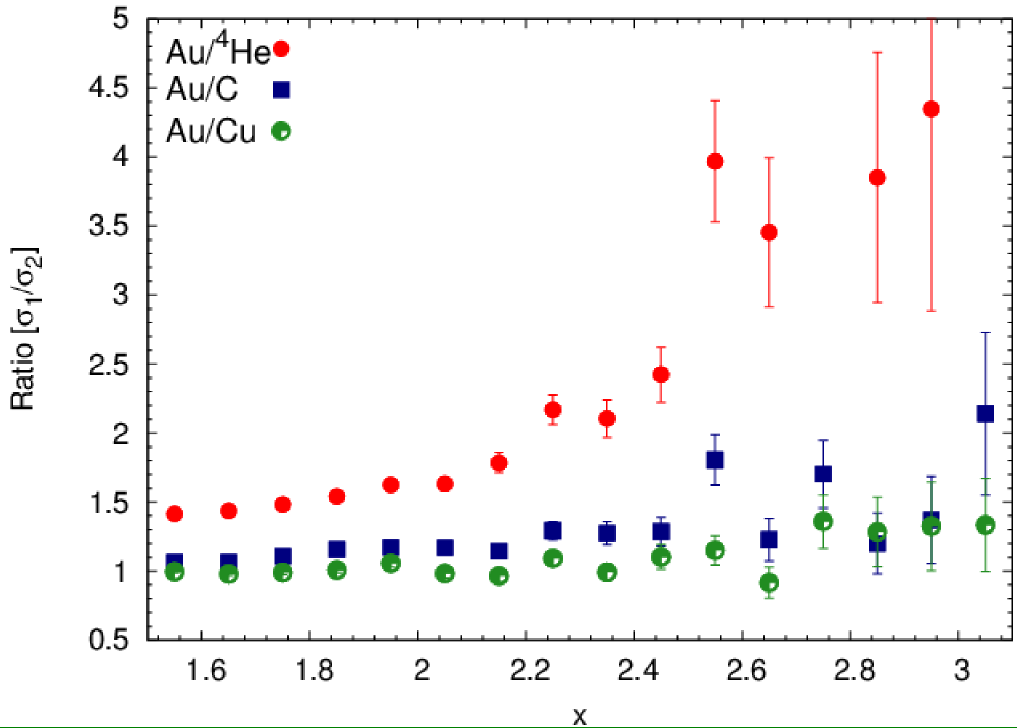
More results in D. Day's and P. Solvignon's talks

Plot courtesy of Z. Ye

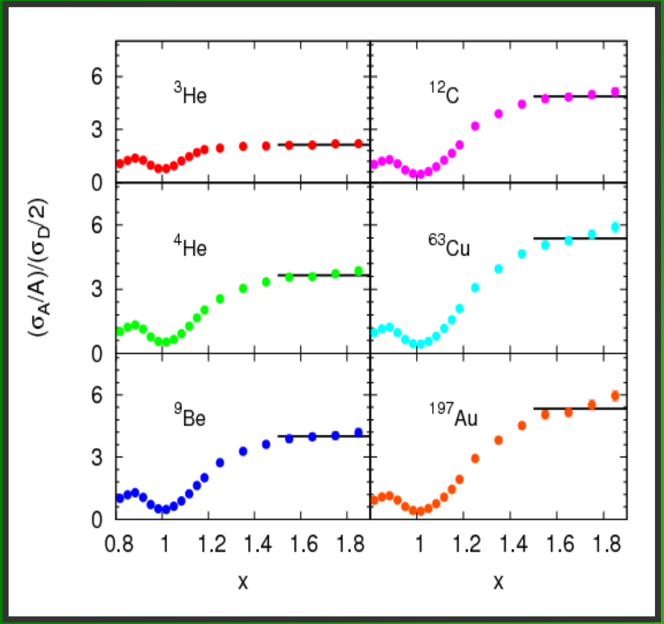
By popular demand σ_{A1}/σ_{A2}



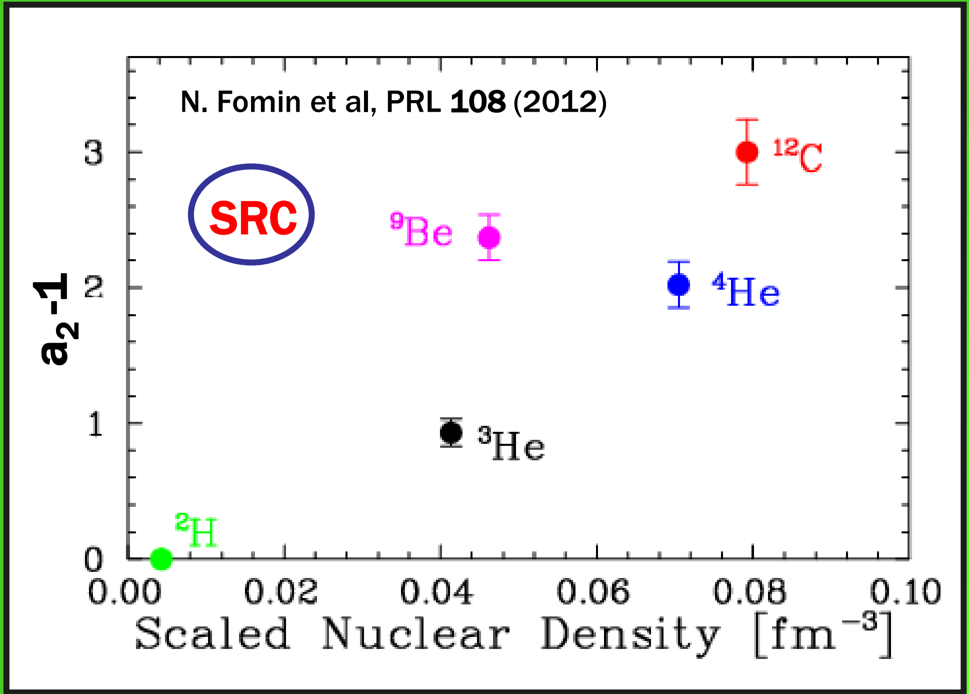
No hint of a second plateau at x>1.6 for Au/(A>=12)



Look at nuclear dependence of NN SRCs



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



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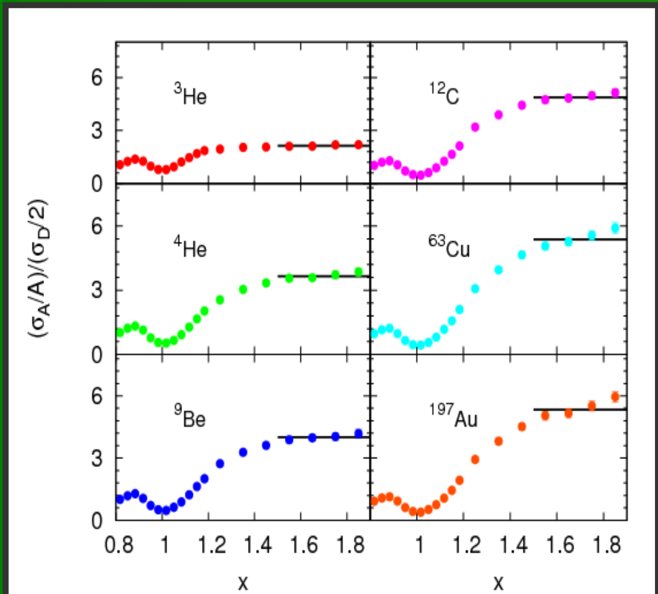

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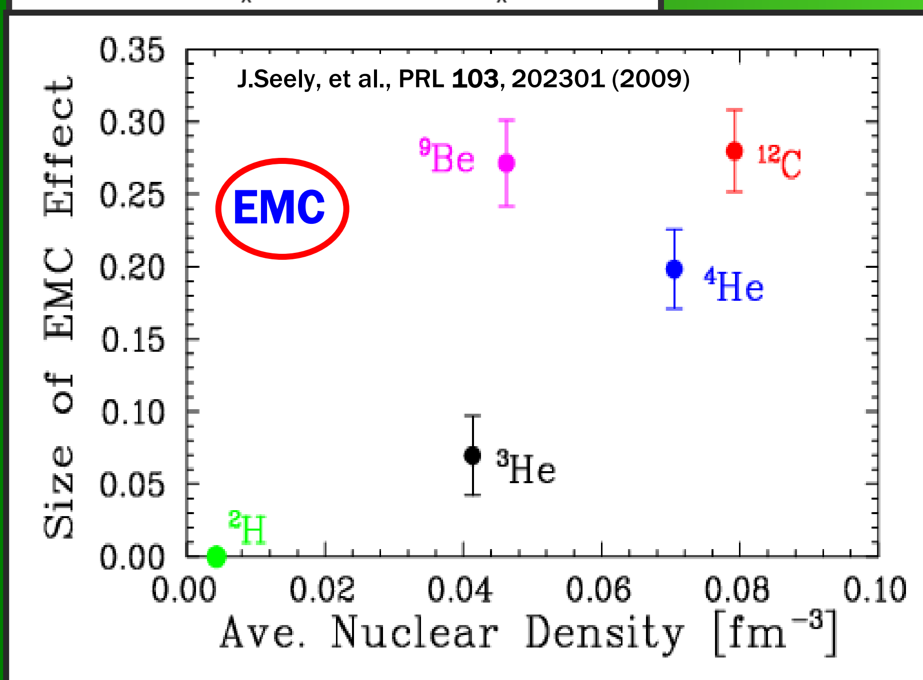
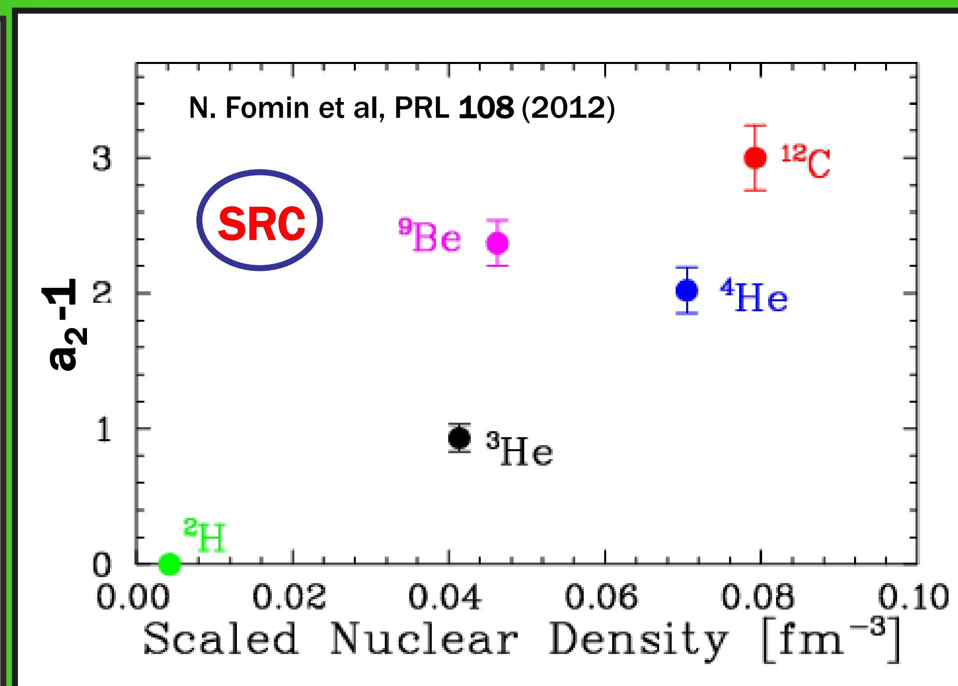
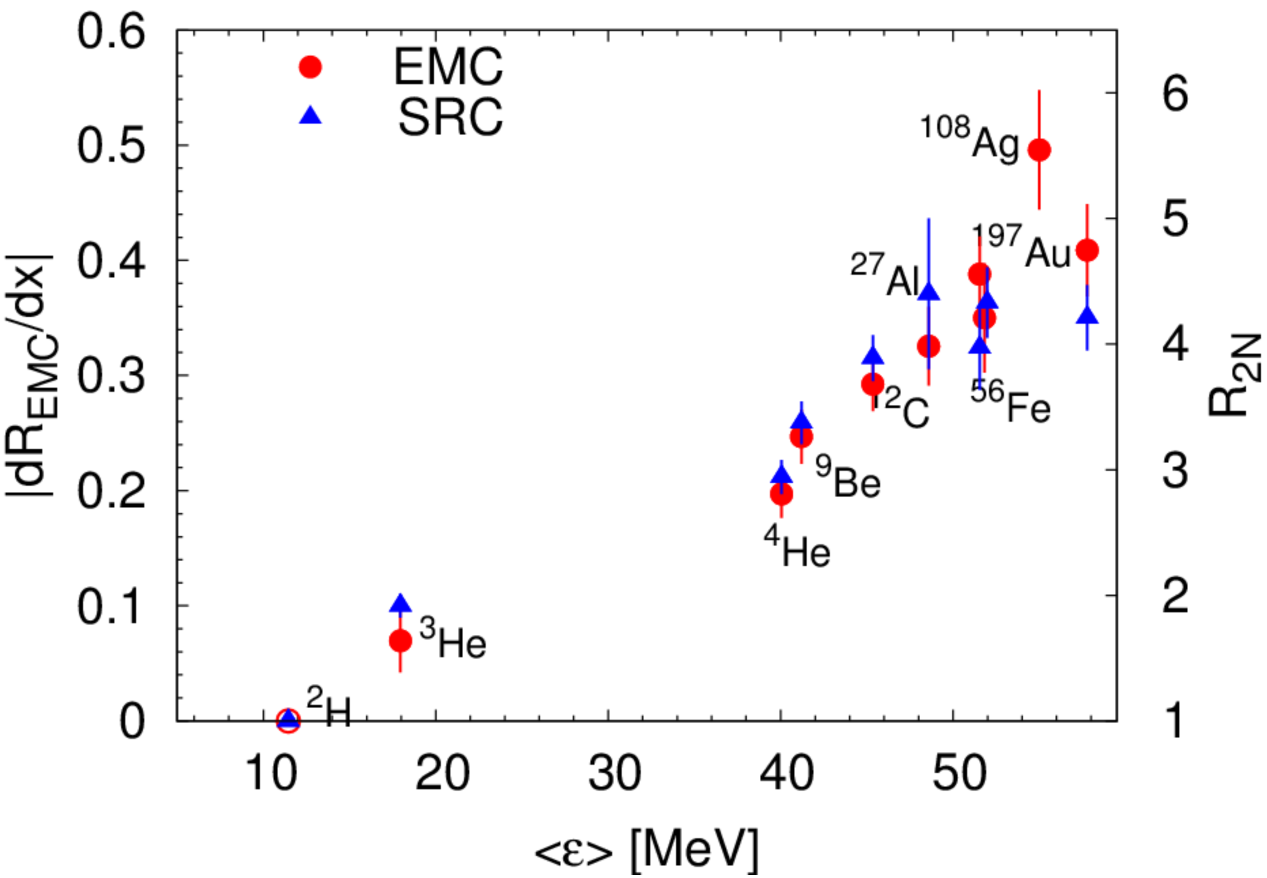




Both driven by a similar underlying cause?

Separation Energy



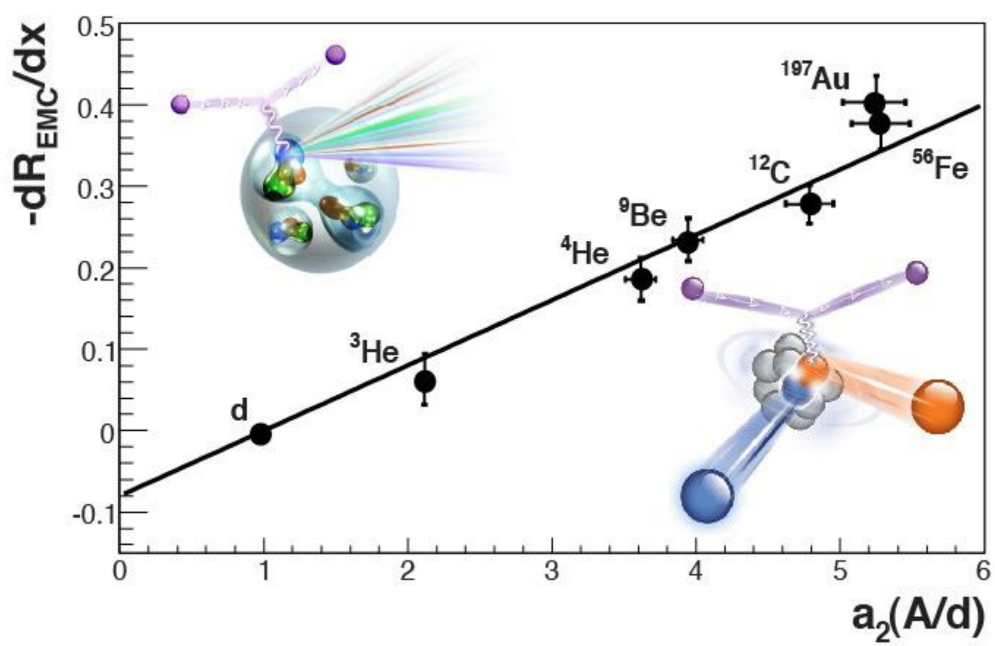
Also Tried:

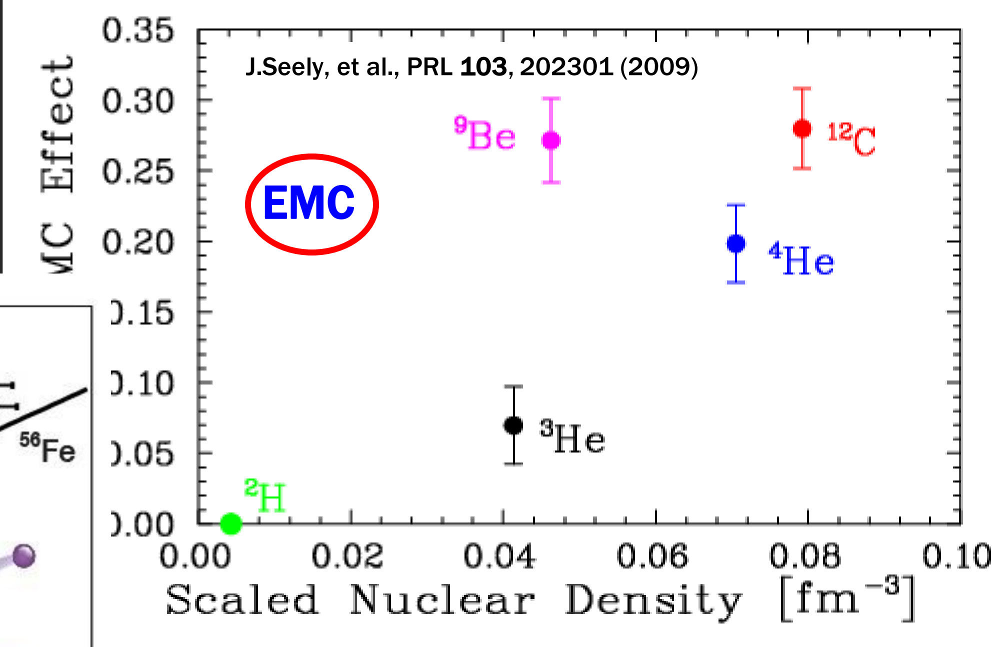
- ***density***
- ***A***
- ***Binding Energy***
- ***Kinetic Energy***
- $A^{-1/3}$

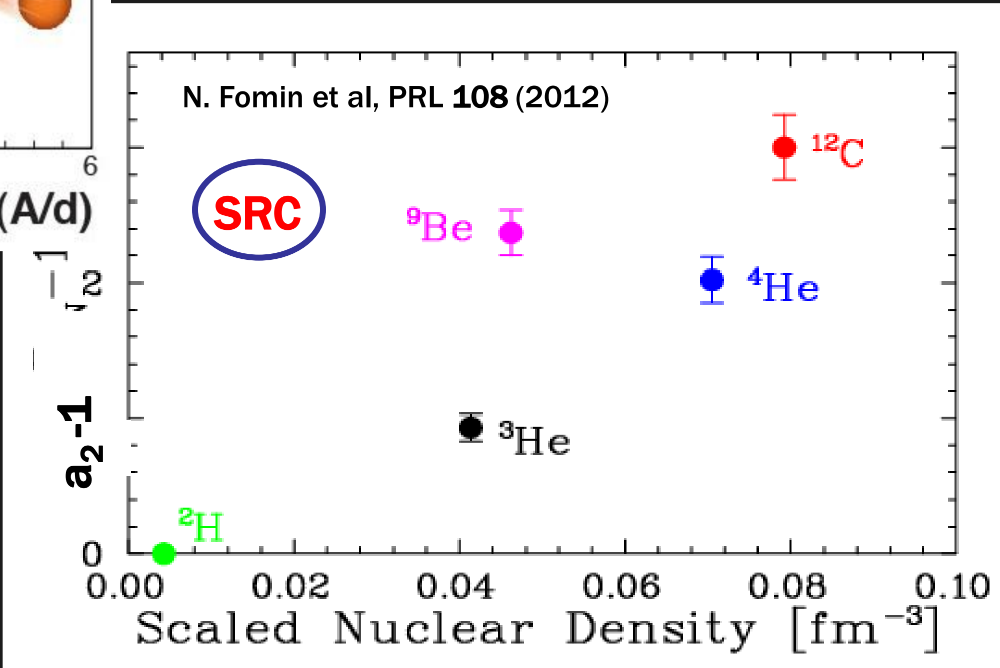
For SRCs, a linear relationship with <ε> is less suggestive

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

Enter ^{9}Be







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

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

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

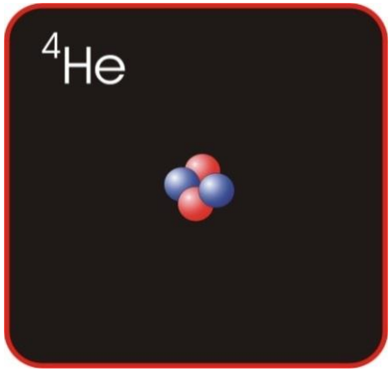
O. Hen, et al, PRC 85, 047301 (2012)
L. Weinstein, et al., PRL 106, 052301 (2011)

Two Hypotheses (that remain)

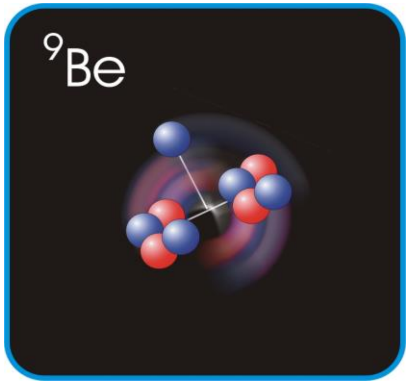
0. Both quantities are functions of nuclear density - *data rules it out*

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

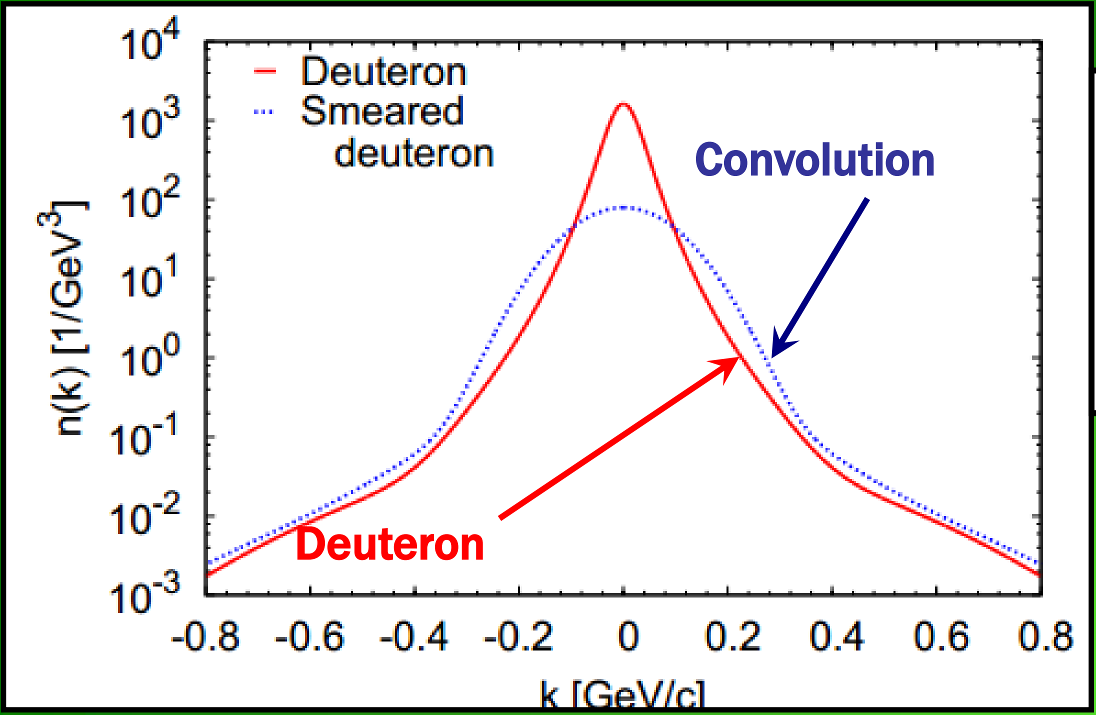
2. EMC effect is driven by ***"local density"***
   - SRCs are sensitive to high density configurations, but MUST remove the center of mass motion smearing to get ***R*$_{2N}$**
     – measure of correlated pairs relative to the deuteron
   - EMC effect samples ***all*** the nucleons, whereas ***R*$_{2N}$** is only sensitive to *np* pairs, a subset of all possible NN configurations



The data show a weak preference for "local density" hypothesis



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



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

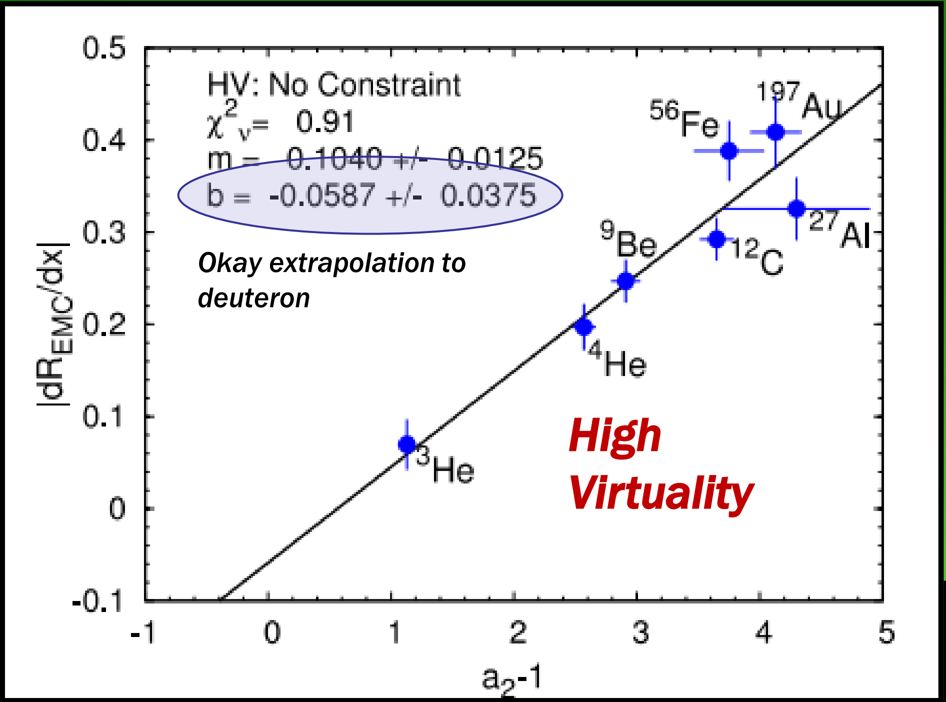
Following prescription from C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53 (1996)

	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*

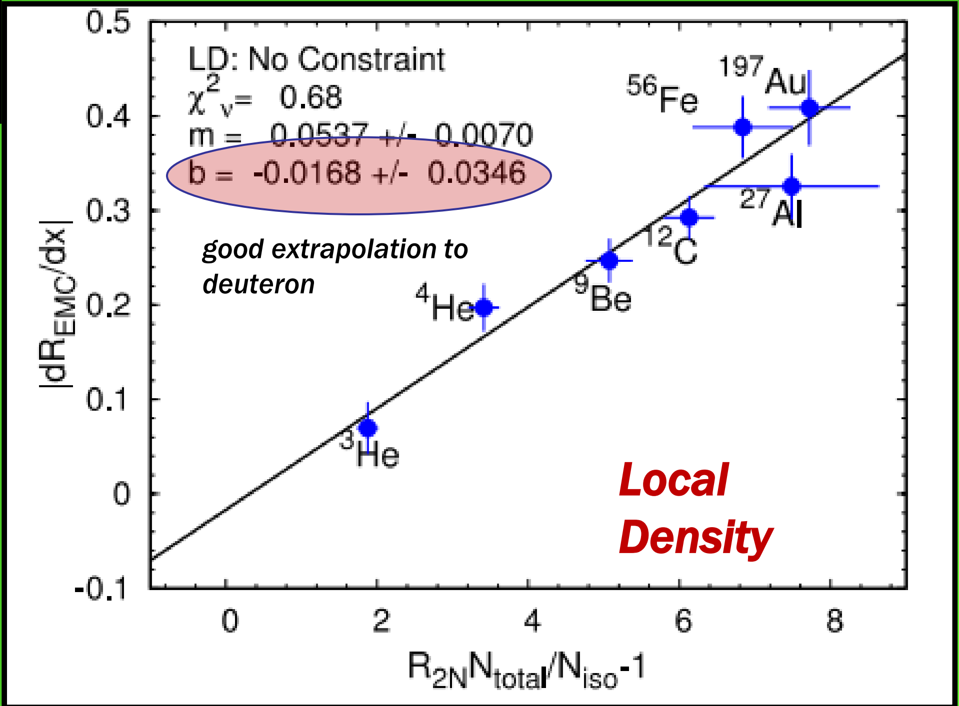
R_{2n} → *relative measure of correlated pairs*

Two hypotheses

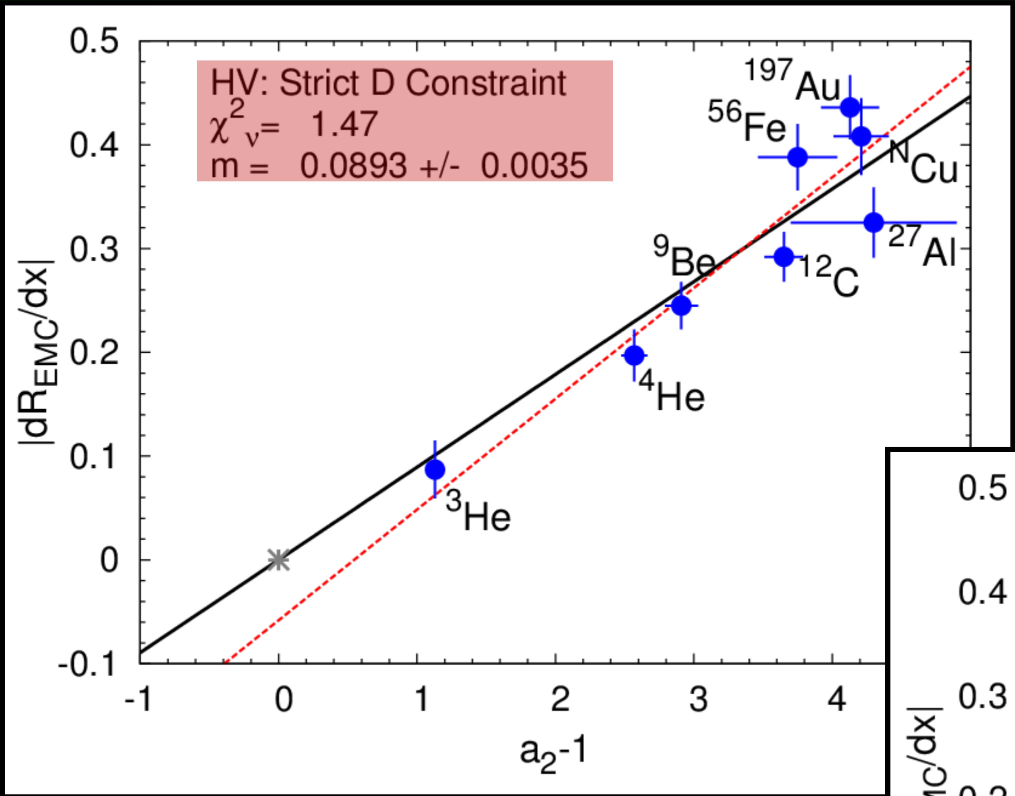


1. Both quantities reflect ***virtuality*** of the nucleons (*L. Weinstein et al, PRL 106:052301,2011*)
   - ***a_2 is a measure of high momentum nucleons relative to the deuteron***

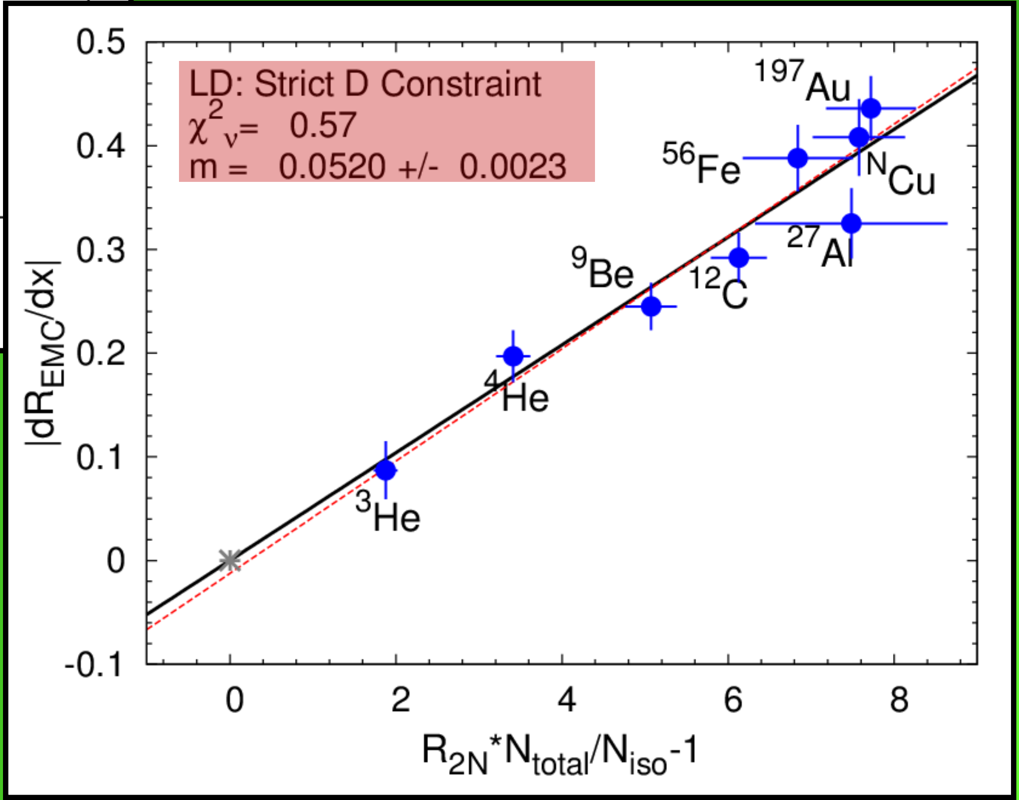
2. A measure of "***local density***"
   R_{2N}
   – measure of correlated pairs relative to the deuteron
   *- Only sensitive to **np** pairs, scale by N_{total}/N_{iso}.*



New Data are helping and more data will help even further

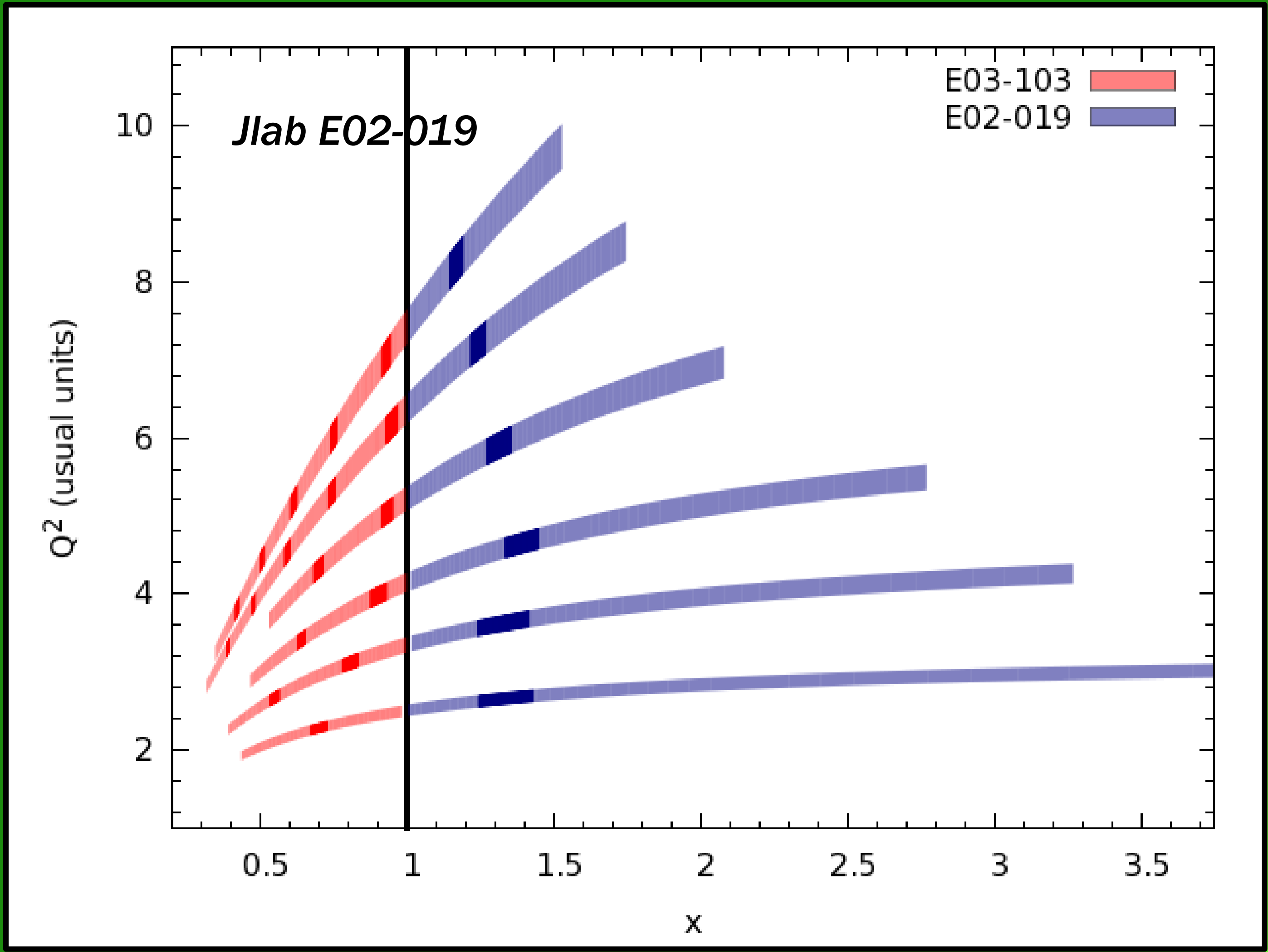


Heavy target data from Jlab E03-103 (Cu, Au)

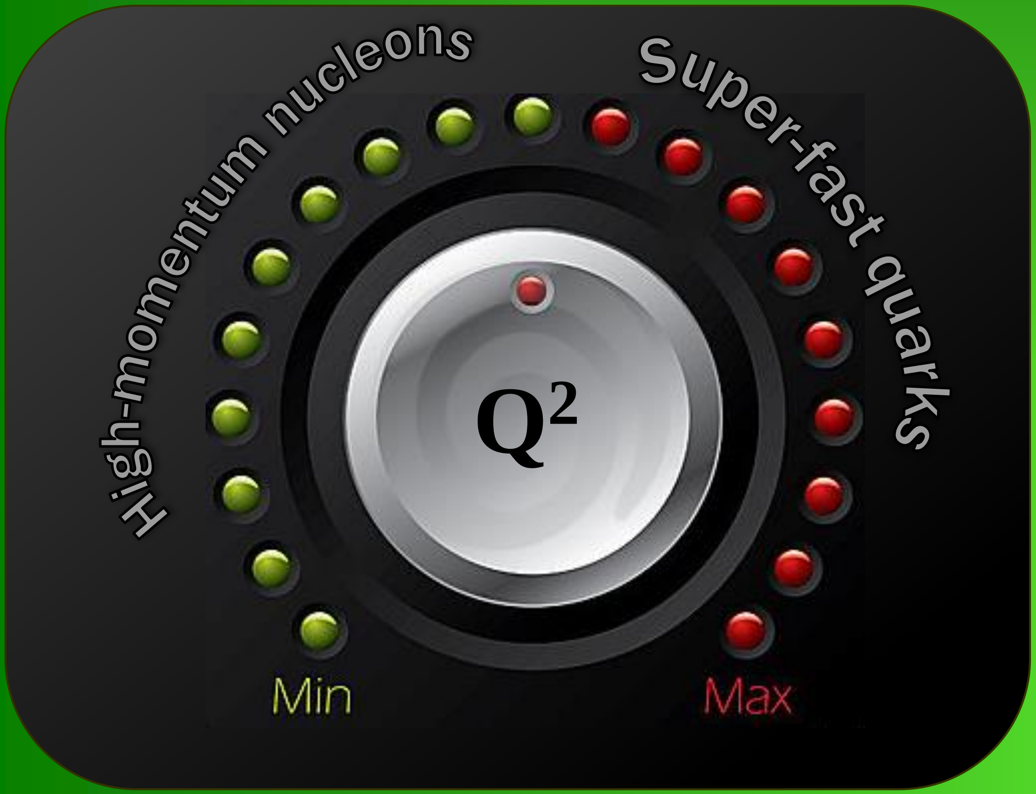


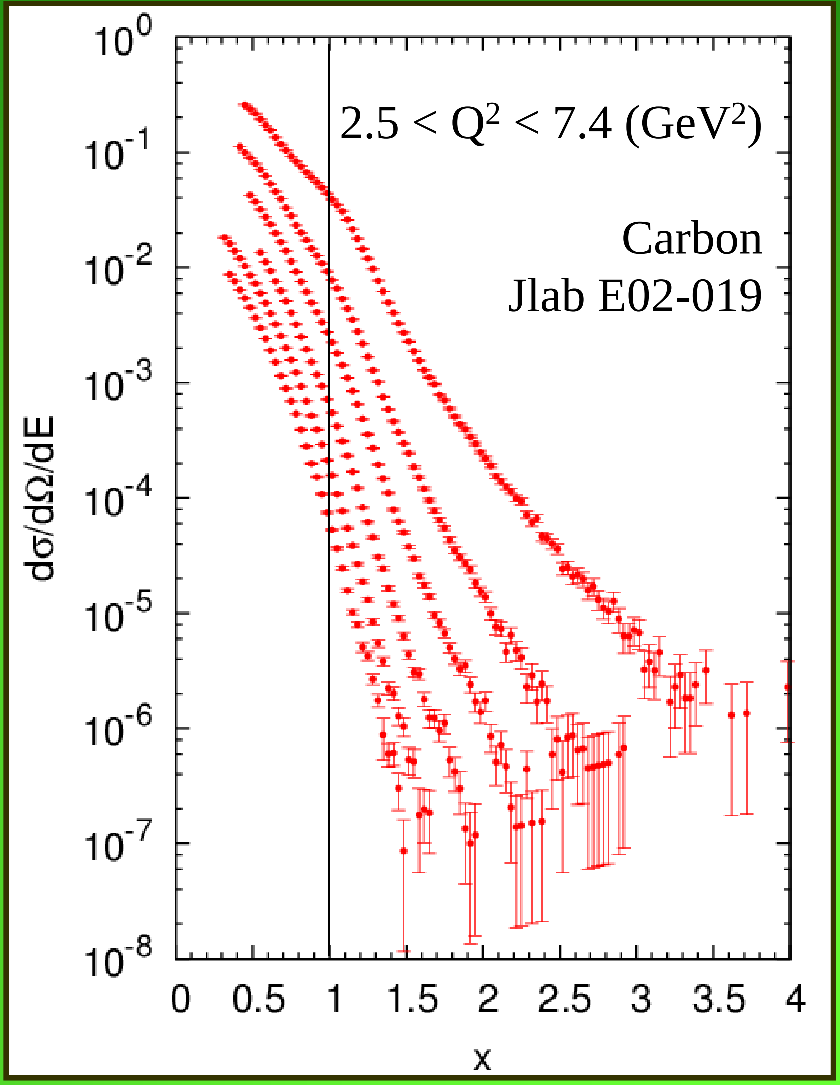
Compare χ^2 of **1.47 and 0.57** to χ^2 of **1.14 and 0.61**, respectively

The rest of 6 GeV inclusive data

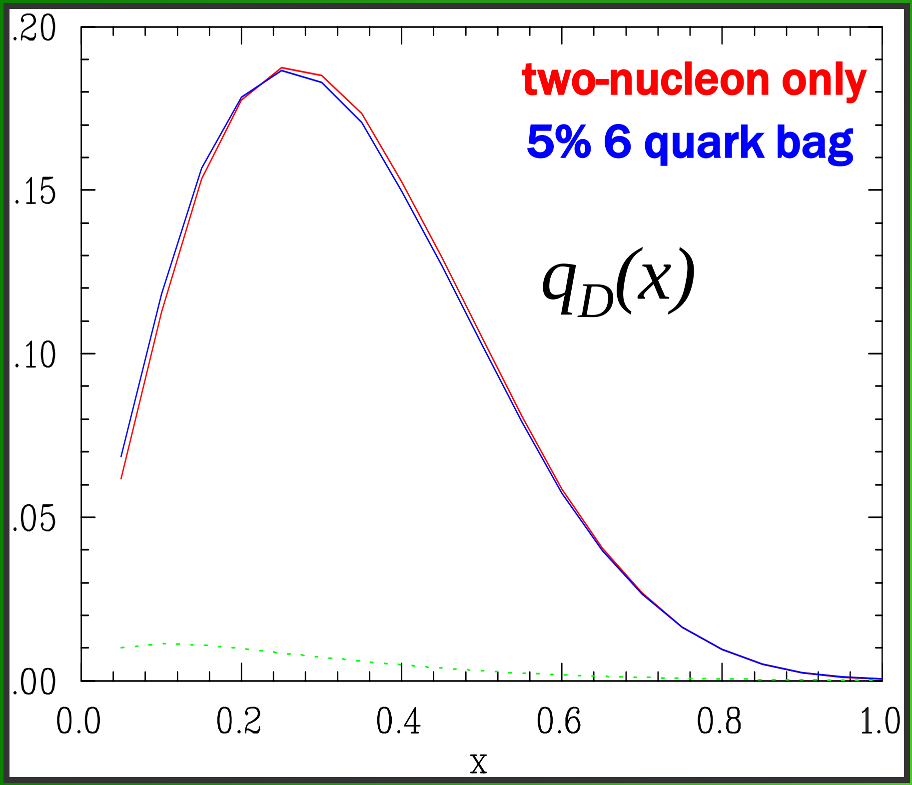


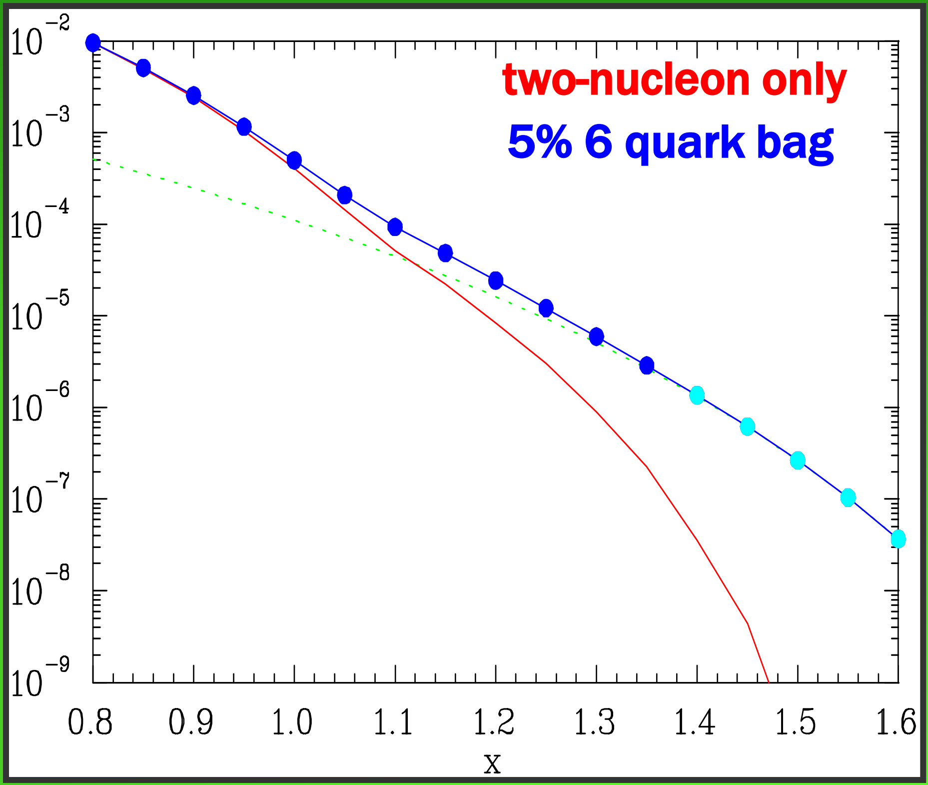
x > 1: Nuclear PDFs





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 $\boldsymbol{F_2^{(0)}}$, the scaling limit ($Q^2 \rightarrow \infty$) structure function as well as its Q^2 dependence

Schienbein et al, J.Phys, 2008

How do we get to SFQ distributions

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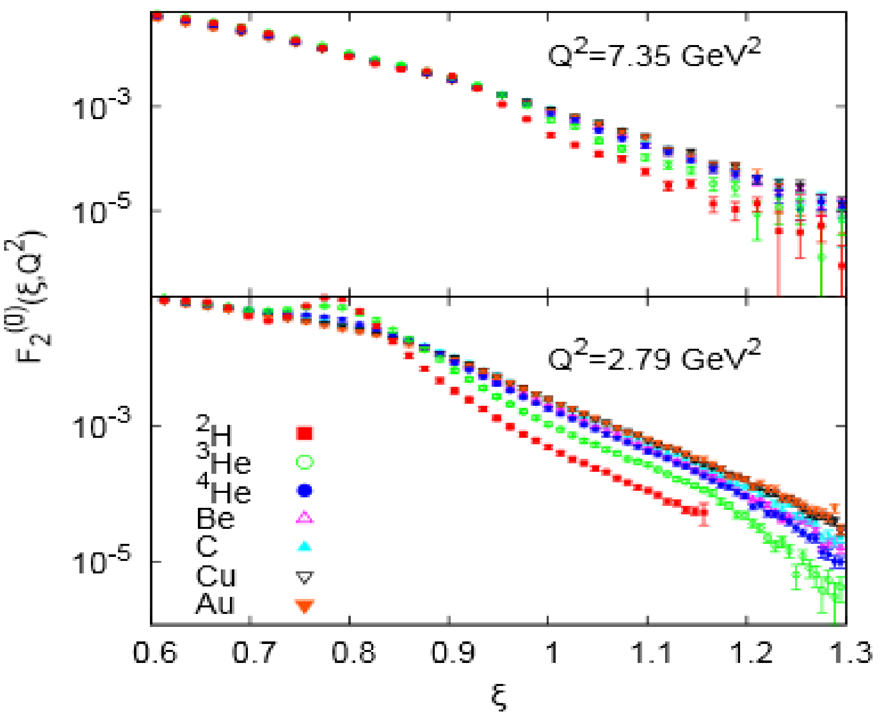


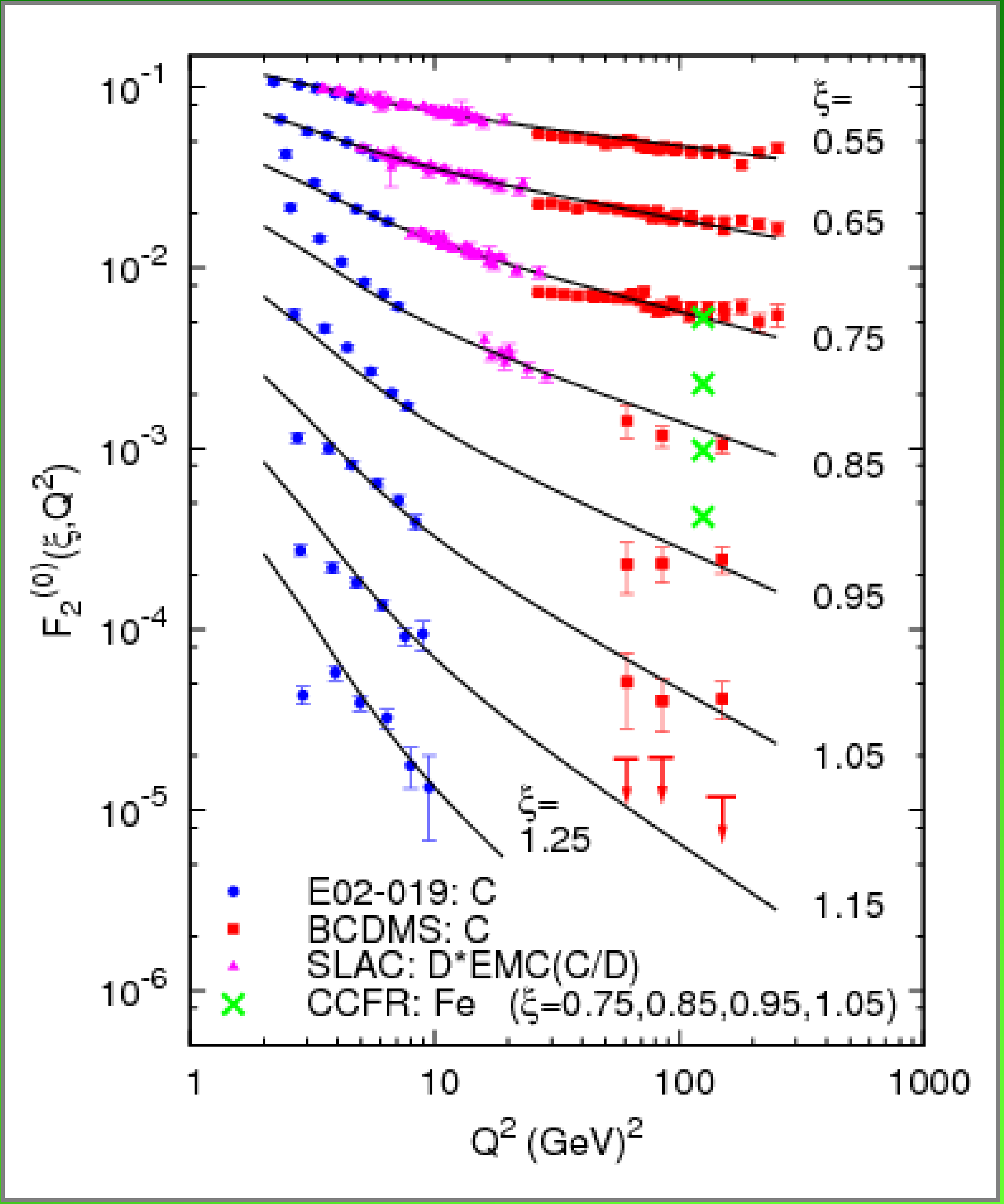
Produced a fit to the data for $F_2^0(\xi, Q^2=7)$

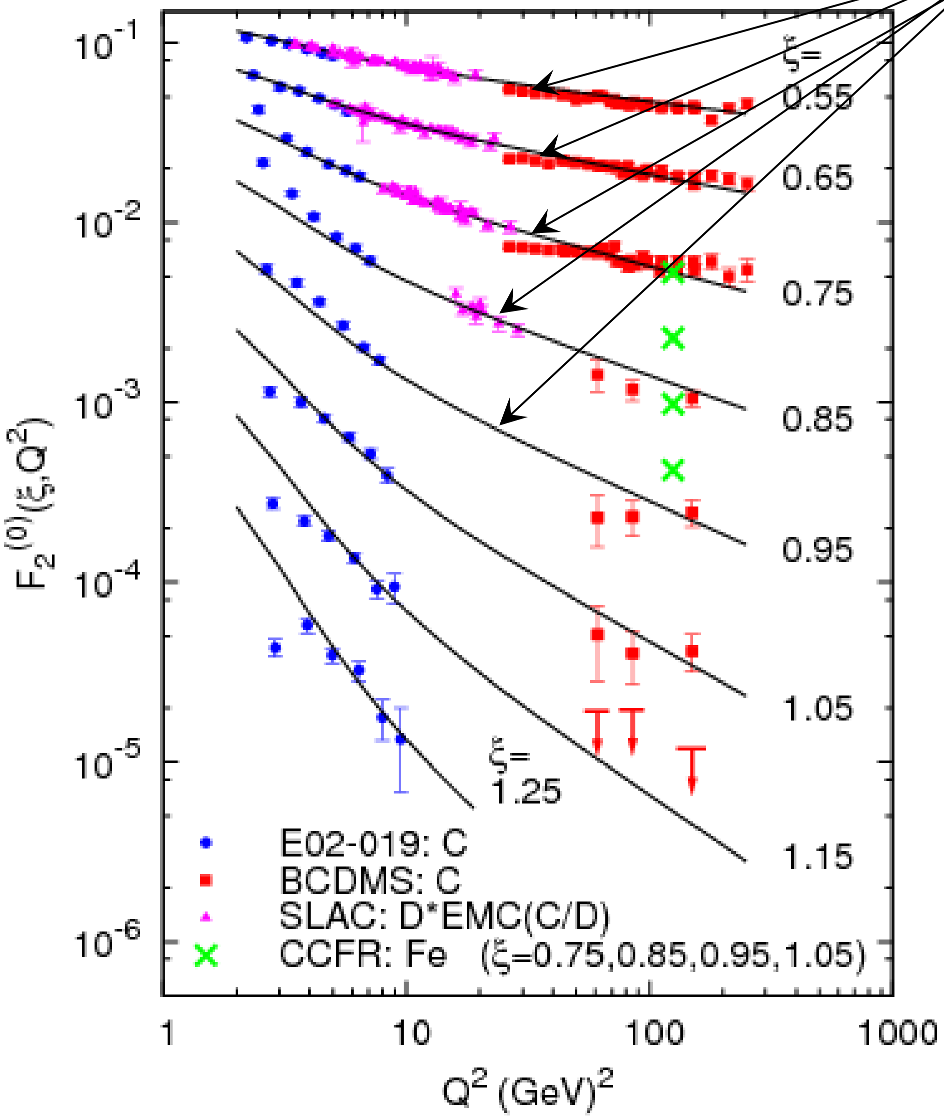
"Super-fast quarks"

• 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)



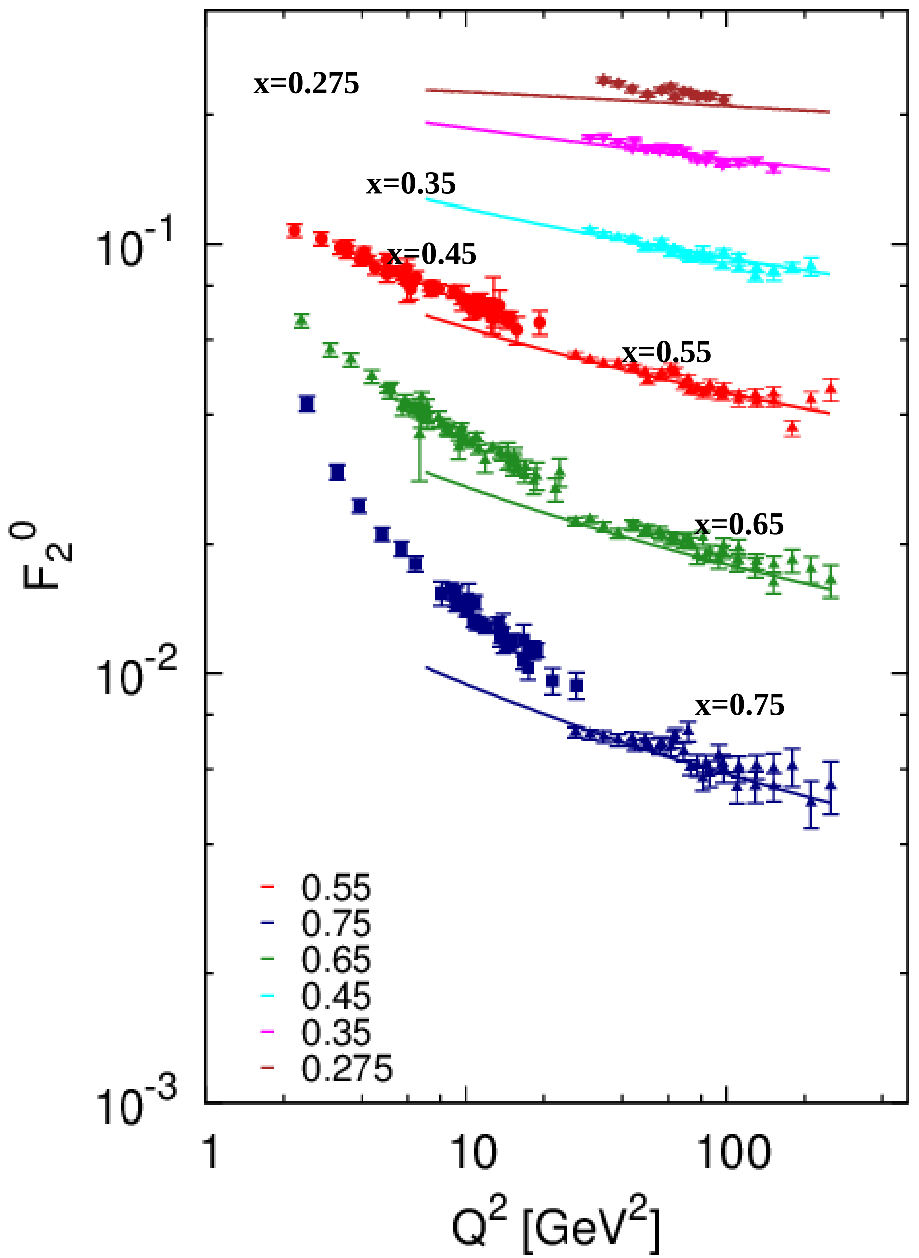


Next: Replace Q^2 dependent fit with non-singlet QCD evolution

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

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

Fix: use x_D, rather than x_p



Current Status

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

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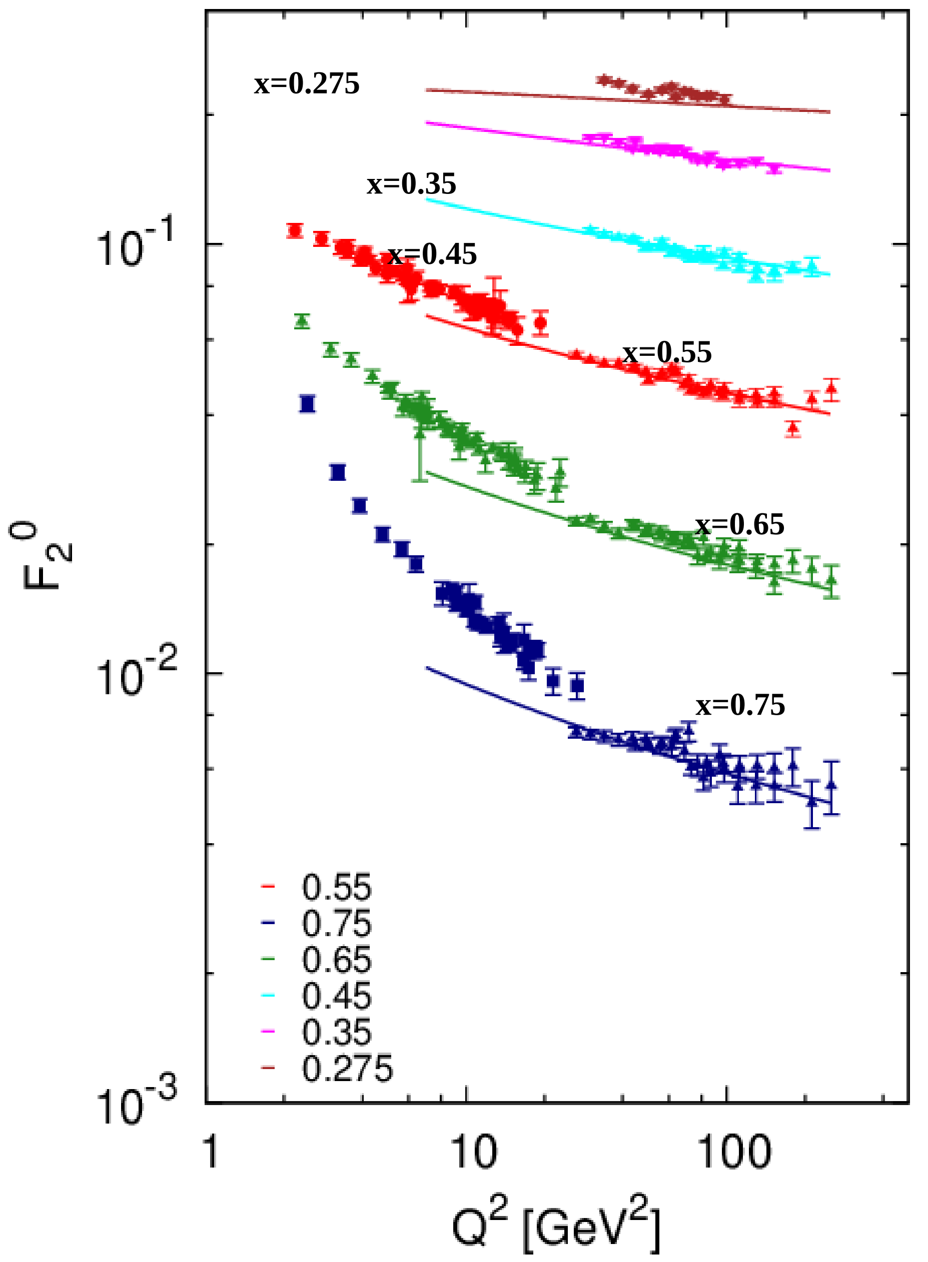
Fix: use x_D, rather than x_p

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

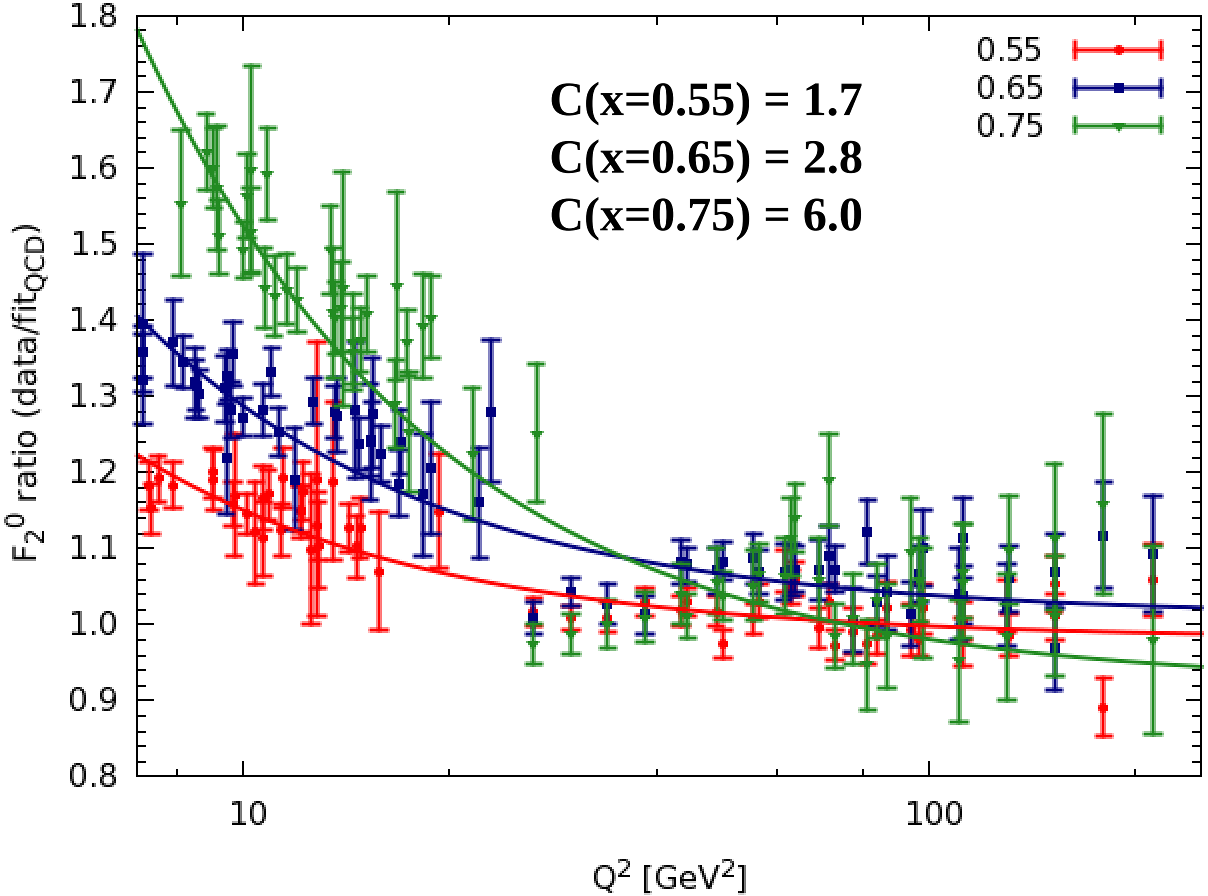


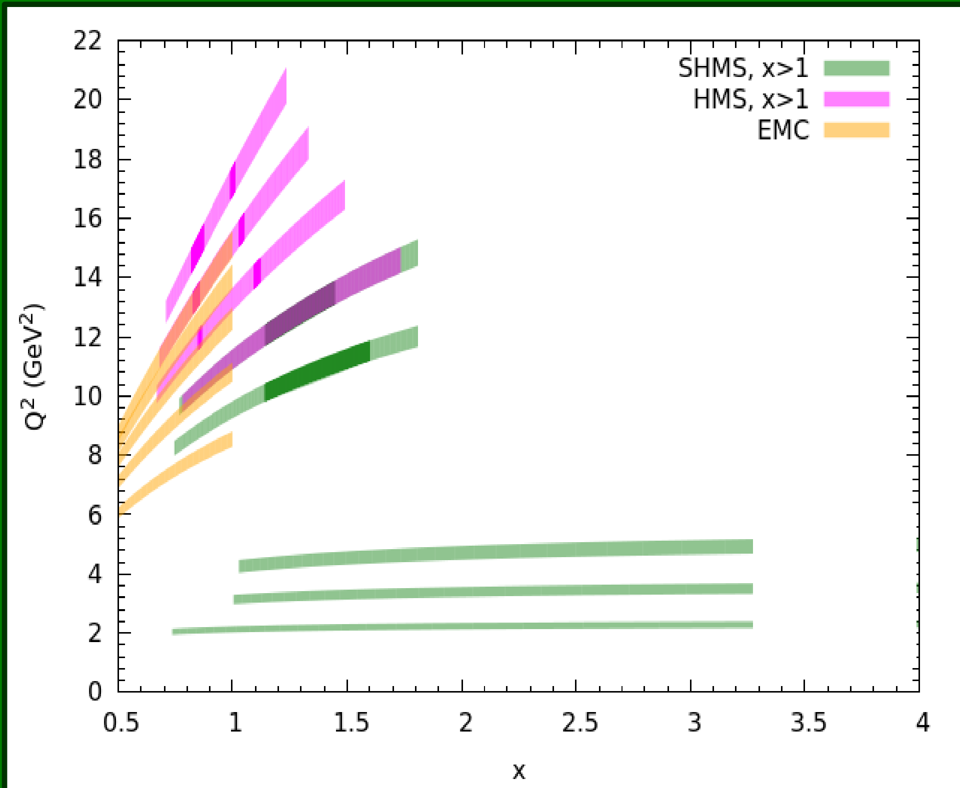
Current Status

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

Ratio fit to $1+C/Q^2$

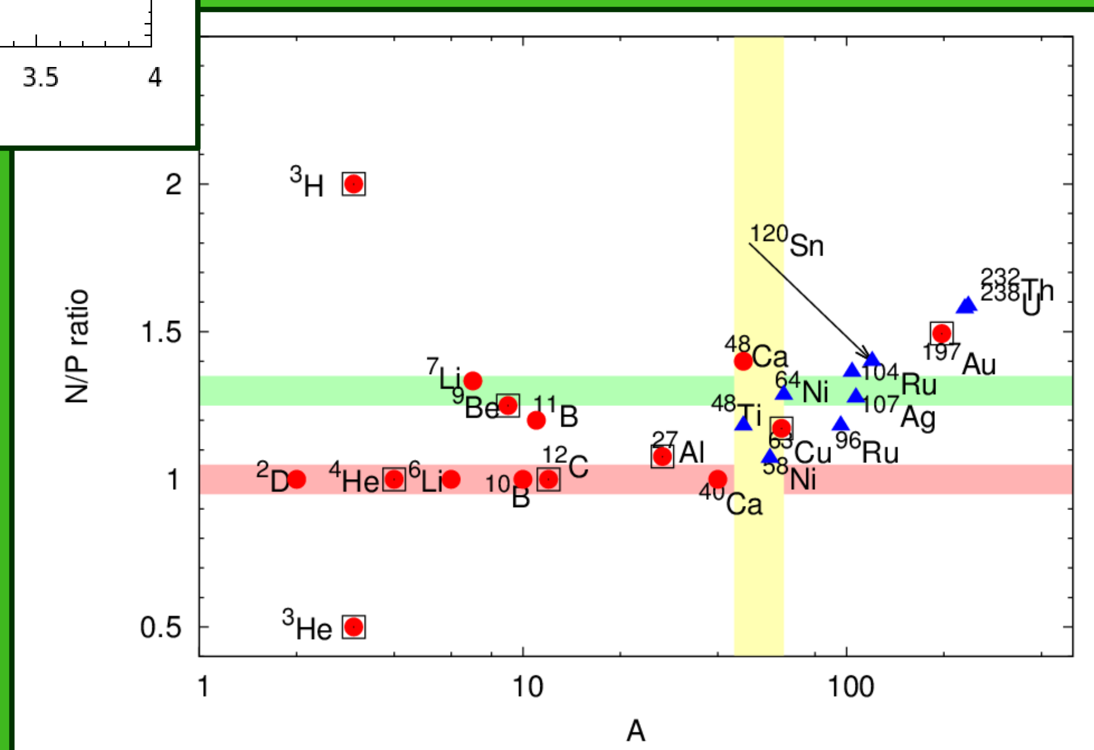
$$F_2(x,Q^2) = F_2^{LT}(x,Q^2) \times [1 + \frac{C(x)}{Q^2}]$$





Jlab E12-06-105

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



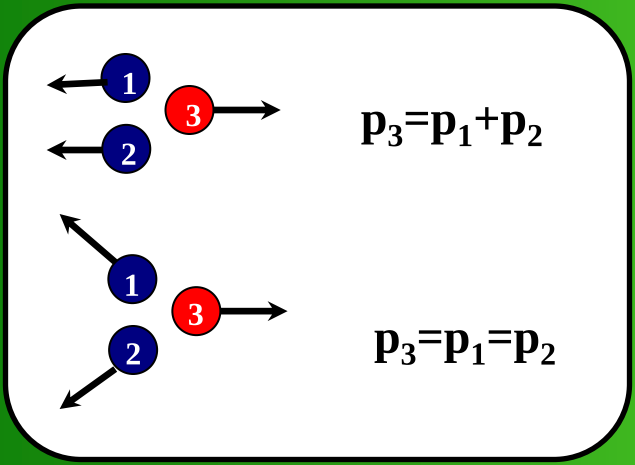
Summary

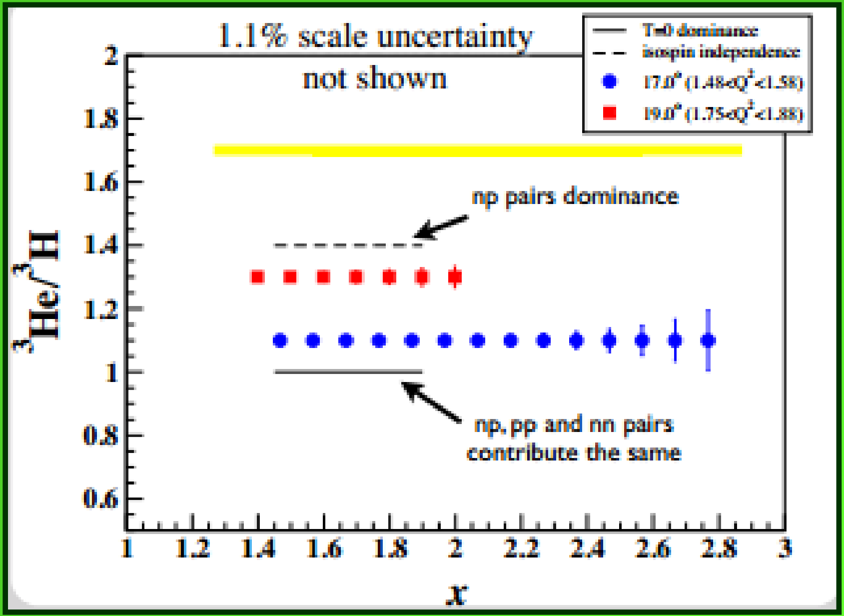
- SRCs have been under the microscope for many decades – 6GeV era at Jlab has yielded interesting data
- 12 GeV experiments continue the search
- New results in the next few years!

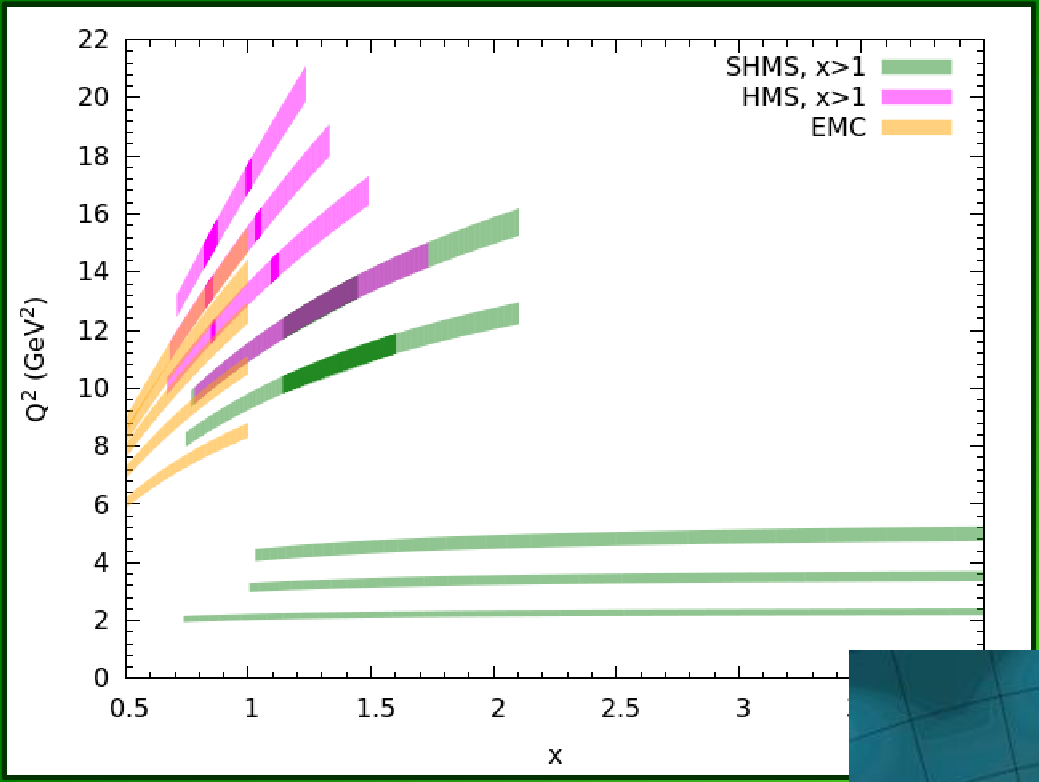
END

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

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







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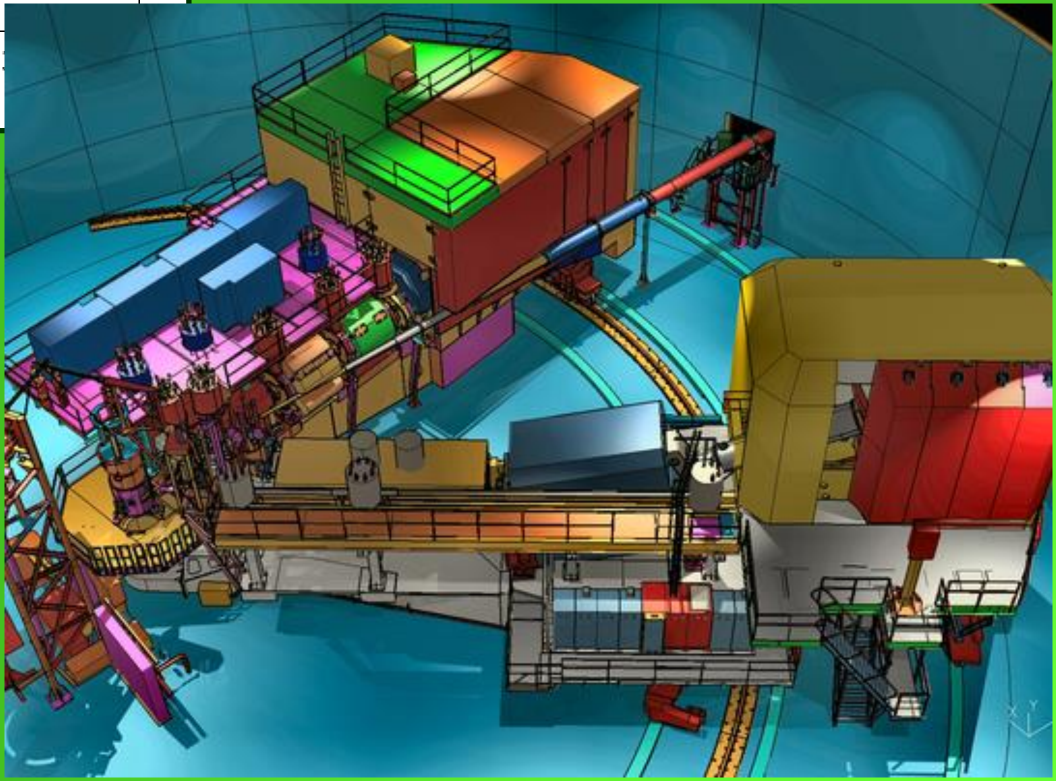
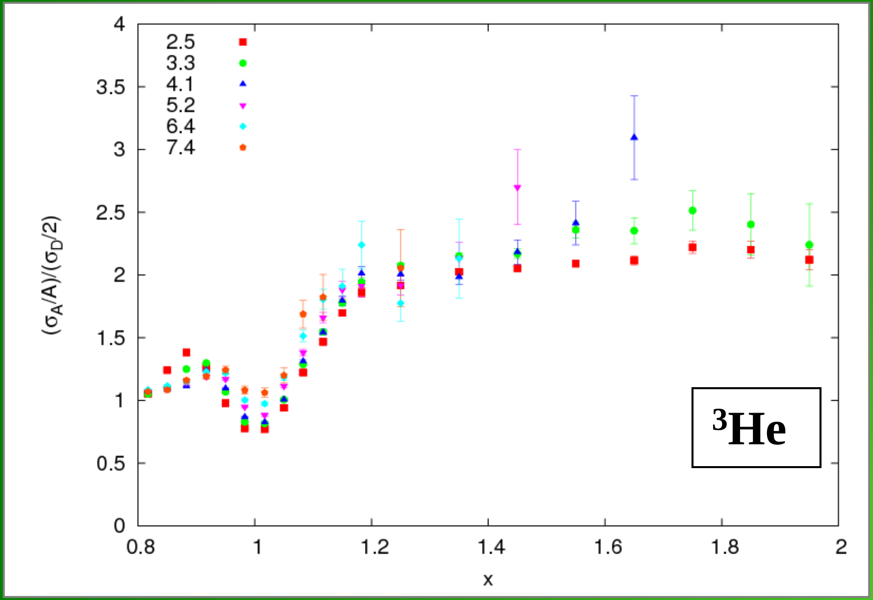
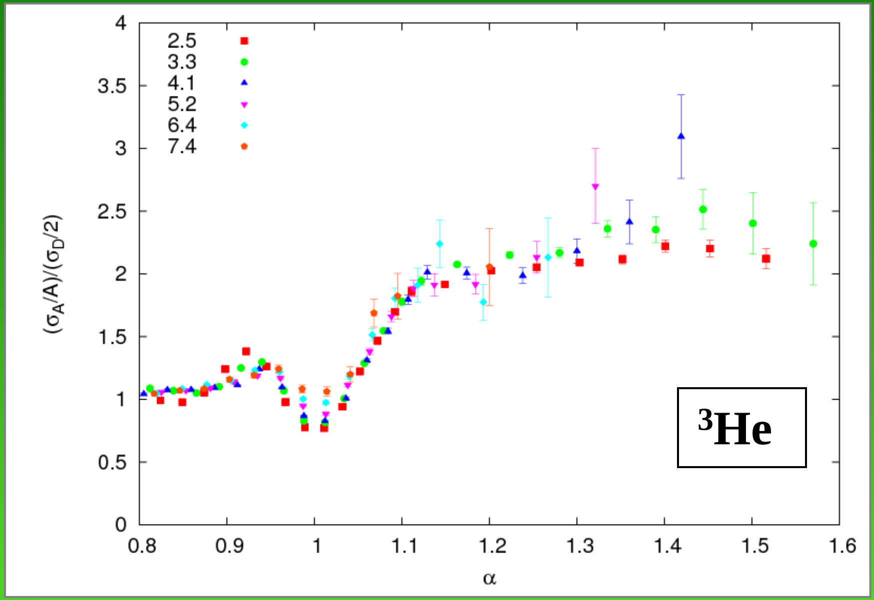
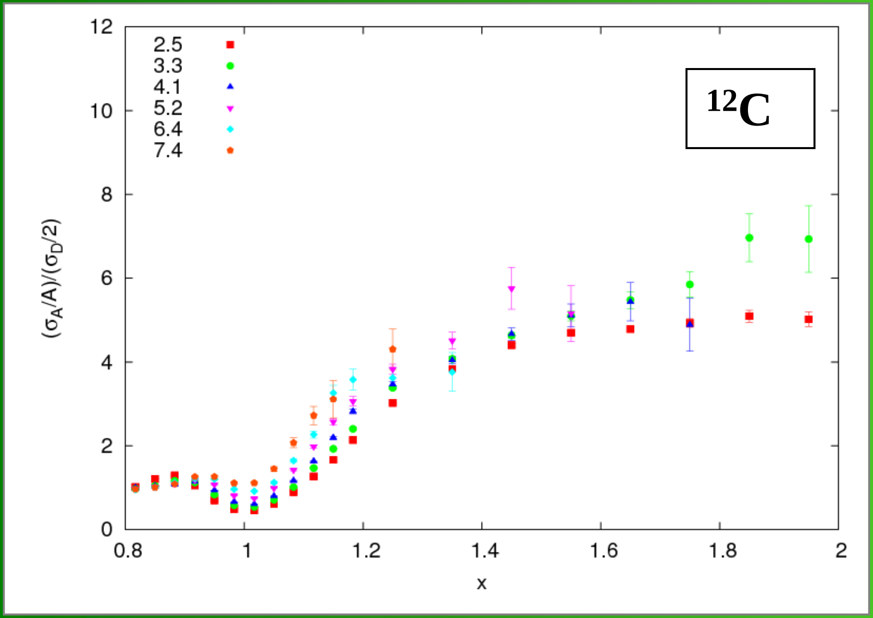


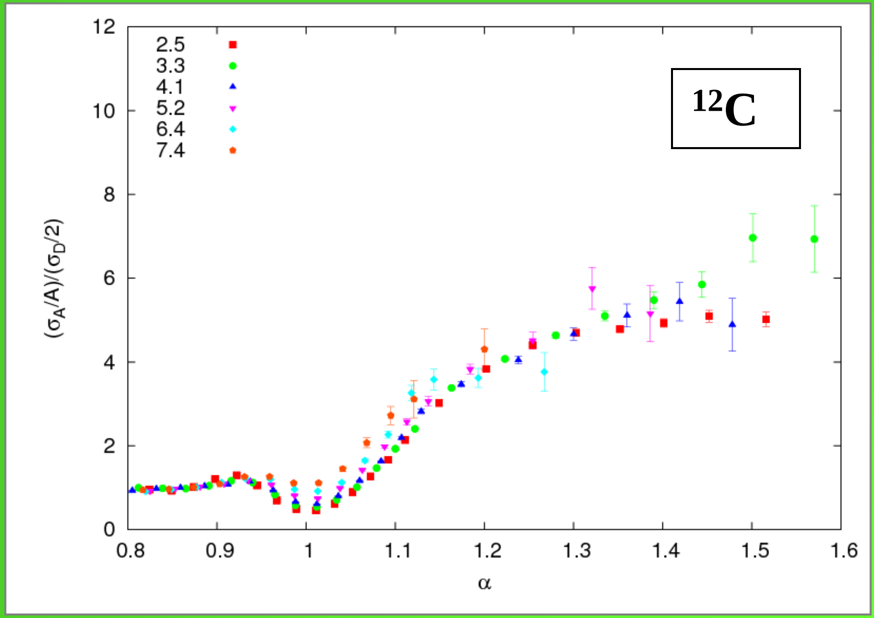
Q^2 dependence features

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

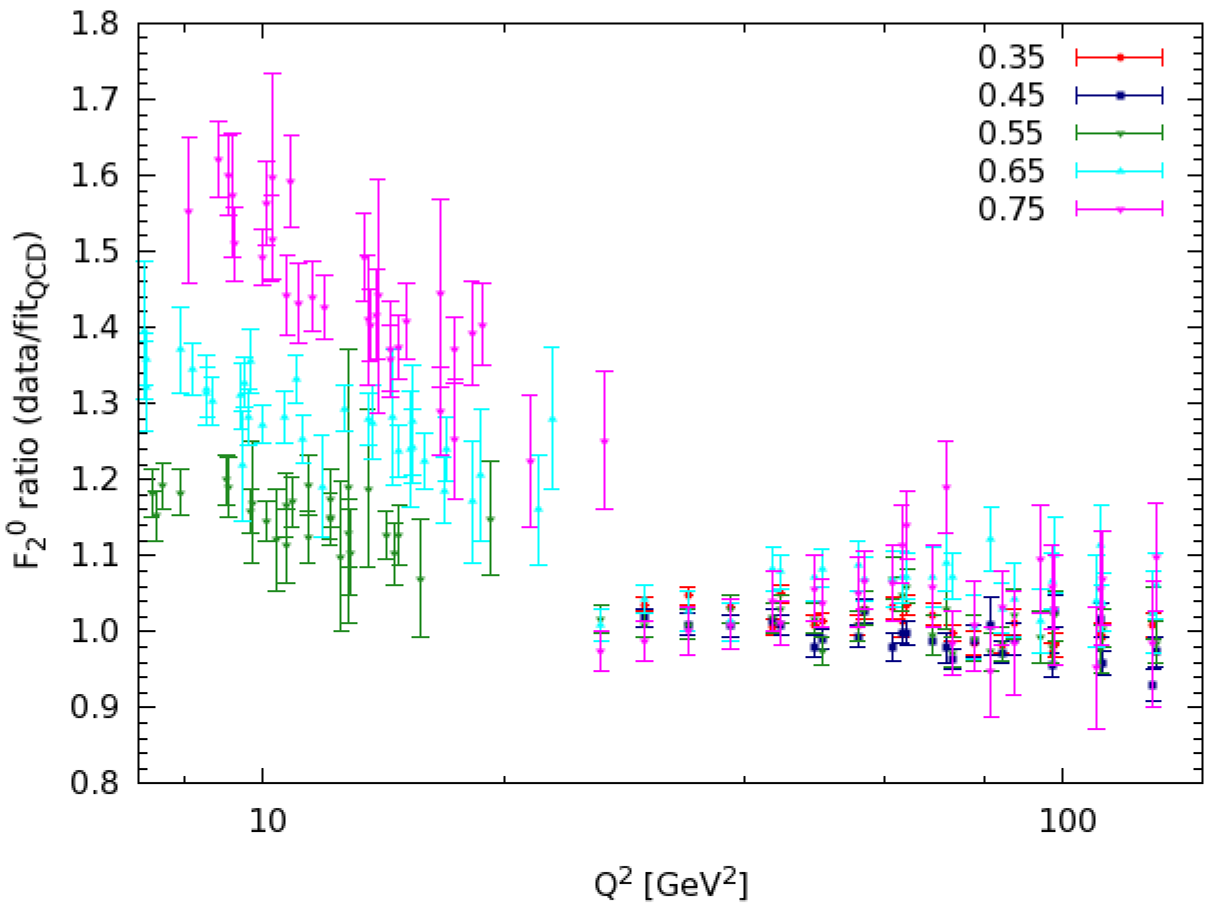








In progress



$$F_2(x,Q^2) = F_2^{LT}(x,Q^2) \times [1 + \frac{C(x)}{Q^2}]$$

$$C(x) = C_1 x^{C_2}(1 + C_3 x)$$