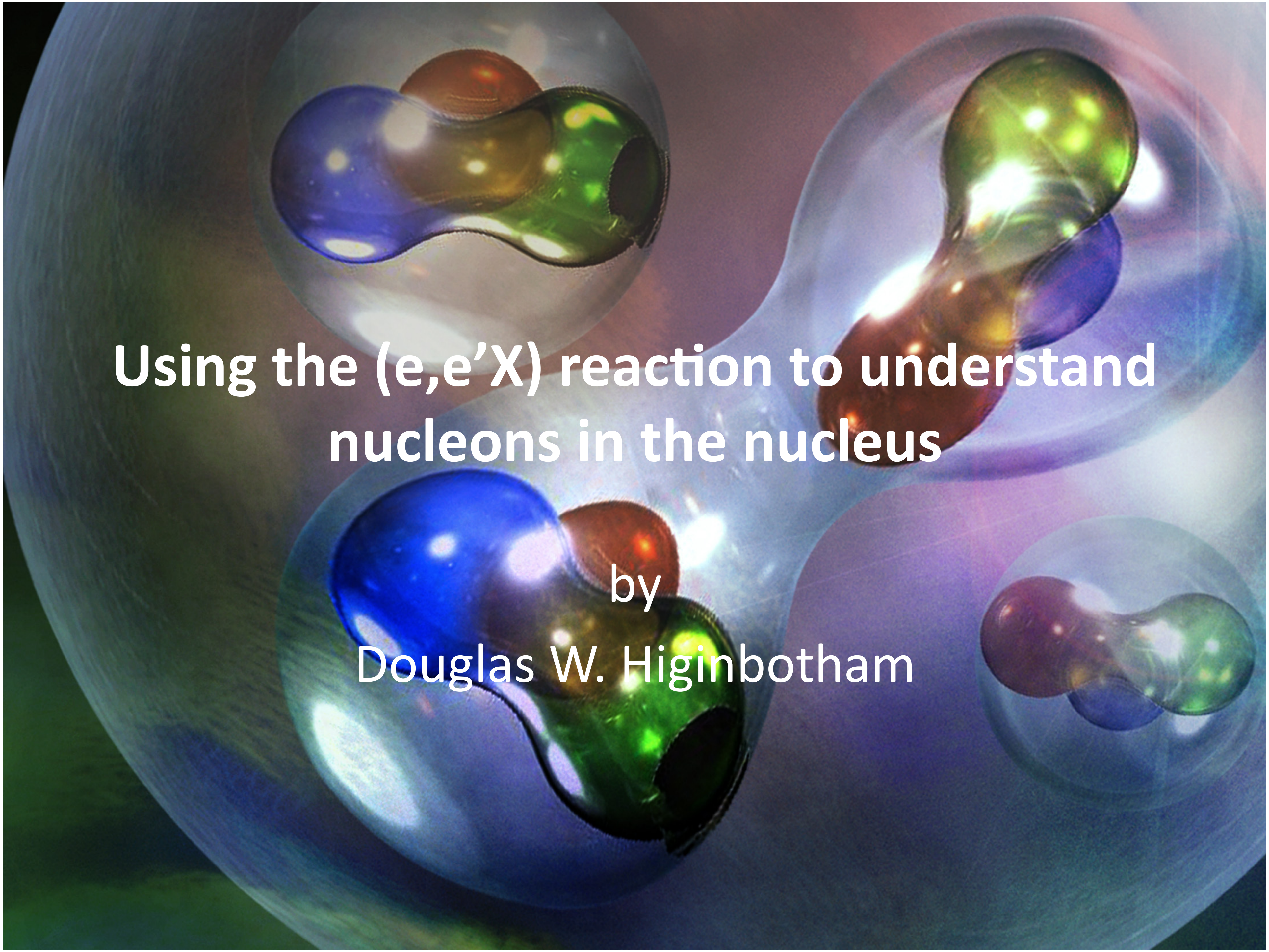


Using the (e,e'X) reaction to understand nucleons in the nucleus

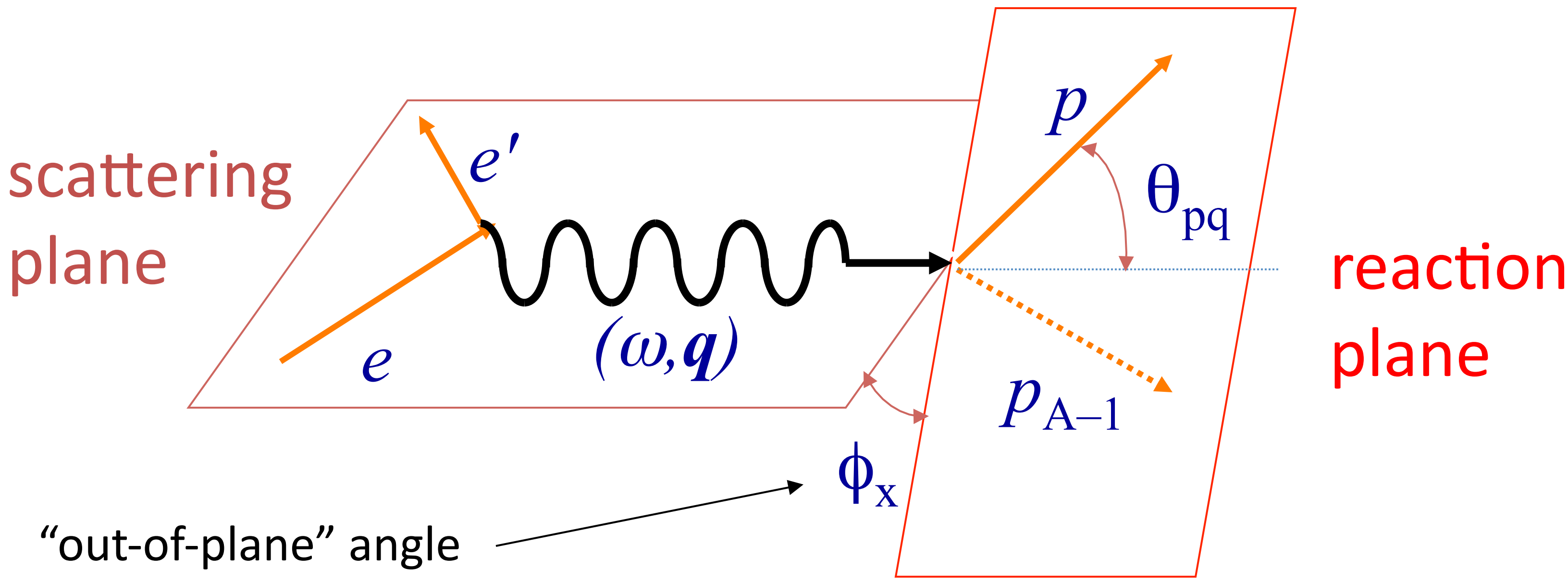
by

Douglas W. Higinbotham

Thoughts in my head from yesterday…

- In electron scattering, how would I get the correct free proton form factors (or cross section) from (e,e'p) if I didn't even know my beam energy?! Wow!
- Electron scattering physicists have become masters of enhancing or suppressing effects such as FSI, MEC, etc. by tuning the kinematics of the experiment. (Forced on us by nature not being a simple as we would like).
- The kinematics of two final-state high momentum nucleons is extreme.
- Neutrino energies are close to JLab electron energies.
- At high energy continuum dominates over the bound states.
- FSI is constrained by electron data. (i.e. you can fold Ingo's spectral function with Omar's FSI calculations to cross sections, we do not just "tweak" the FSI to match data)
- CLAS (e,e'), (e,e'p), (e,e'pn) data at high energy coming soon for a variety of nuclei! (was just shown at CLAS meeting last week and will be discussed at photonuclear Gordon conference)
- In electron scattering we worry a lot about getting neutron information from D & 3He.

Electron Scattering Kinematics



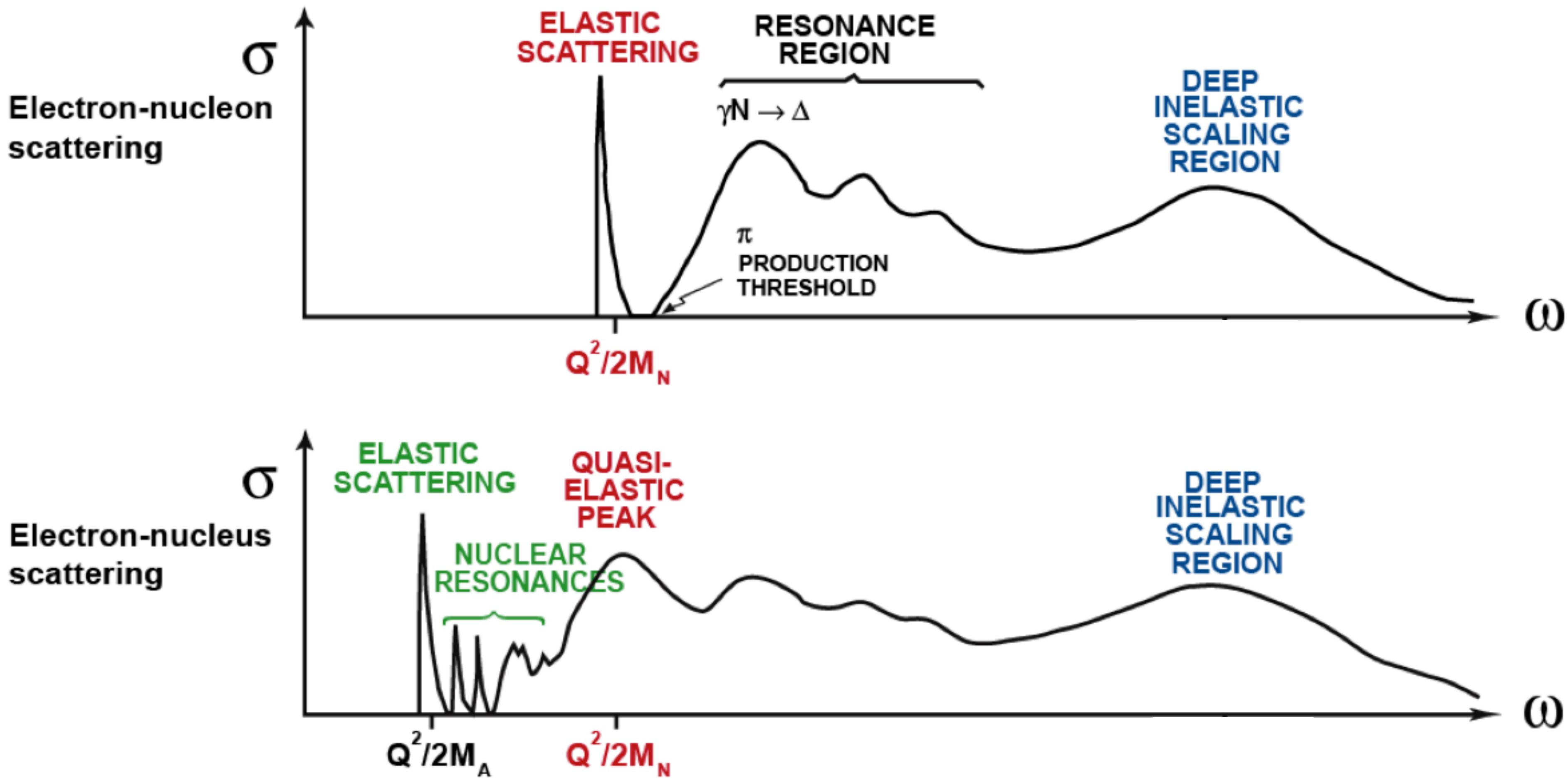
Energy transfer: $\omega = e - e'$

Four-momentum transfer: $Q^2 \equiv -q_\mu q^\mu = \boldsymbol{q}^2 - \omega^2$

Missing momentum: $\boldsymbol{p}_m = \boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{A-1}$

Bjorken x: $x_B = Q^2/2m\omega$ ***(just kinematics!)***

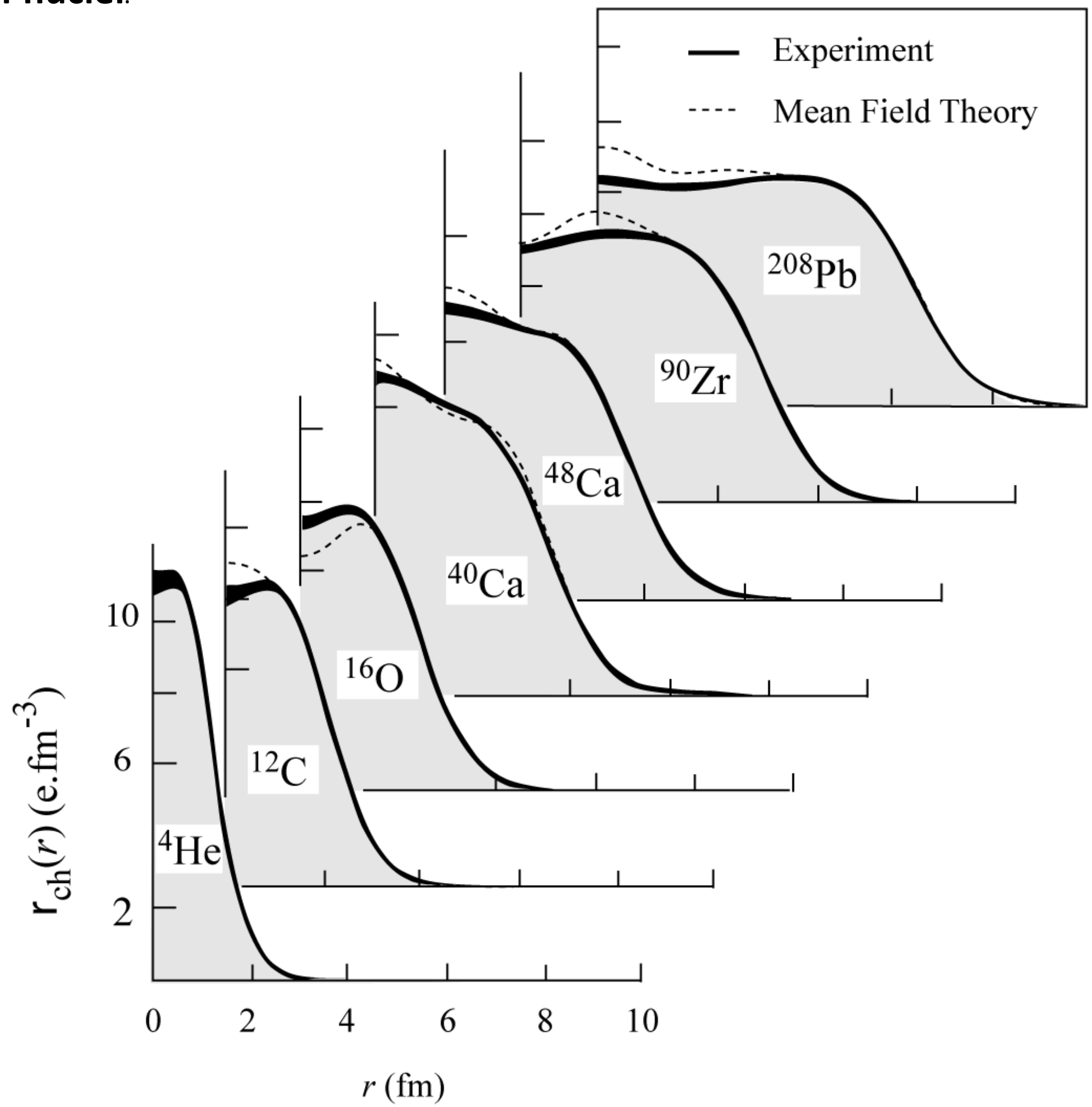
Electron Scattering Regions



$\mathbf{x_B = Q^2/2m\omega}$ $x_B > 1$ $x_B = 1$ $x_B < 1$

Nuclear Charge Distributions

In '70s large data set was acquired on elastic electron scattering (mainly at Saclay) over large Q^2-range and for variety of nuclei.



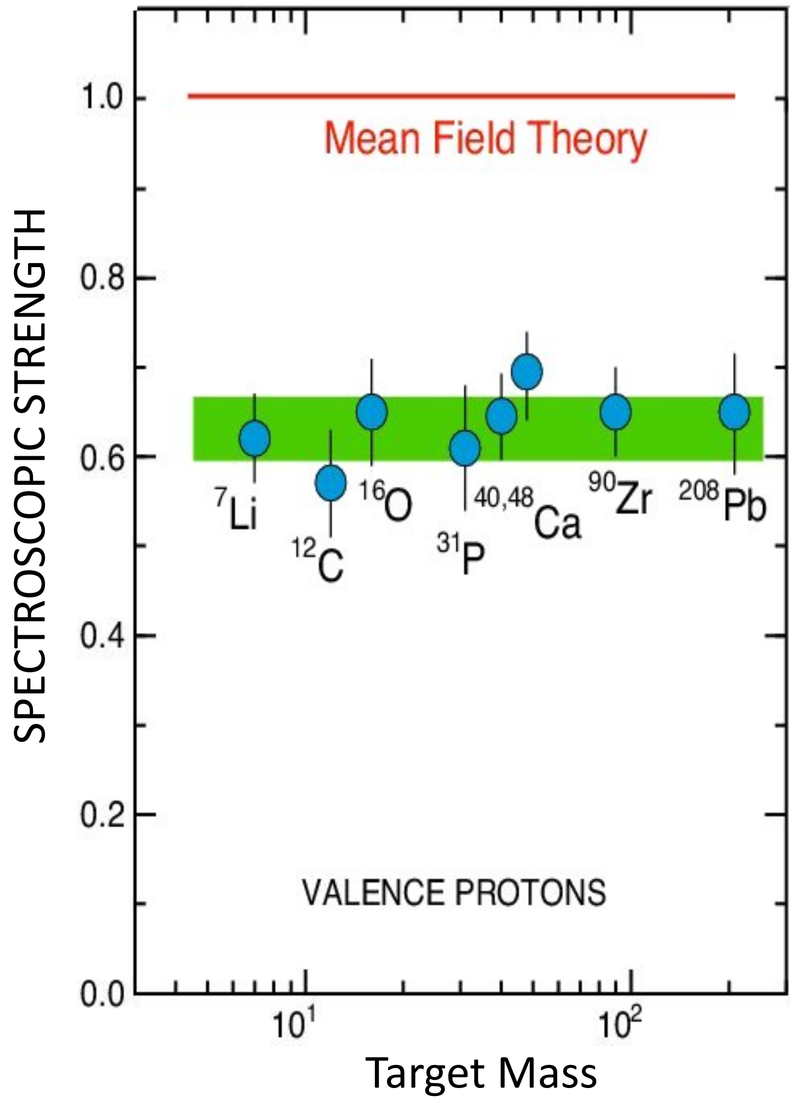
Classic A(e,e'p)A-1 Results

L. Lapikas, Nucl. Phys. A553 (1993) 297.

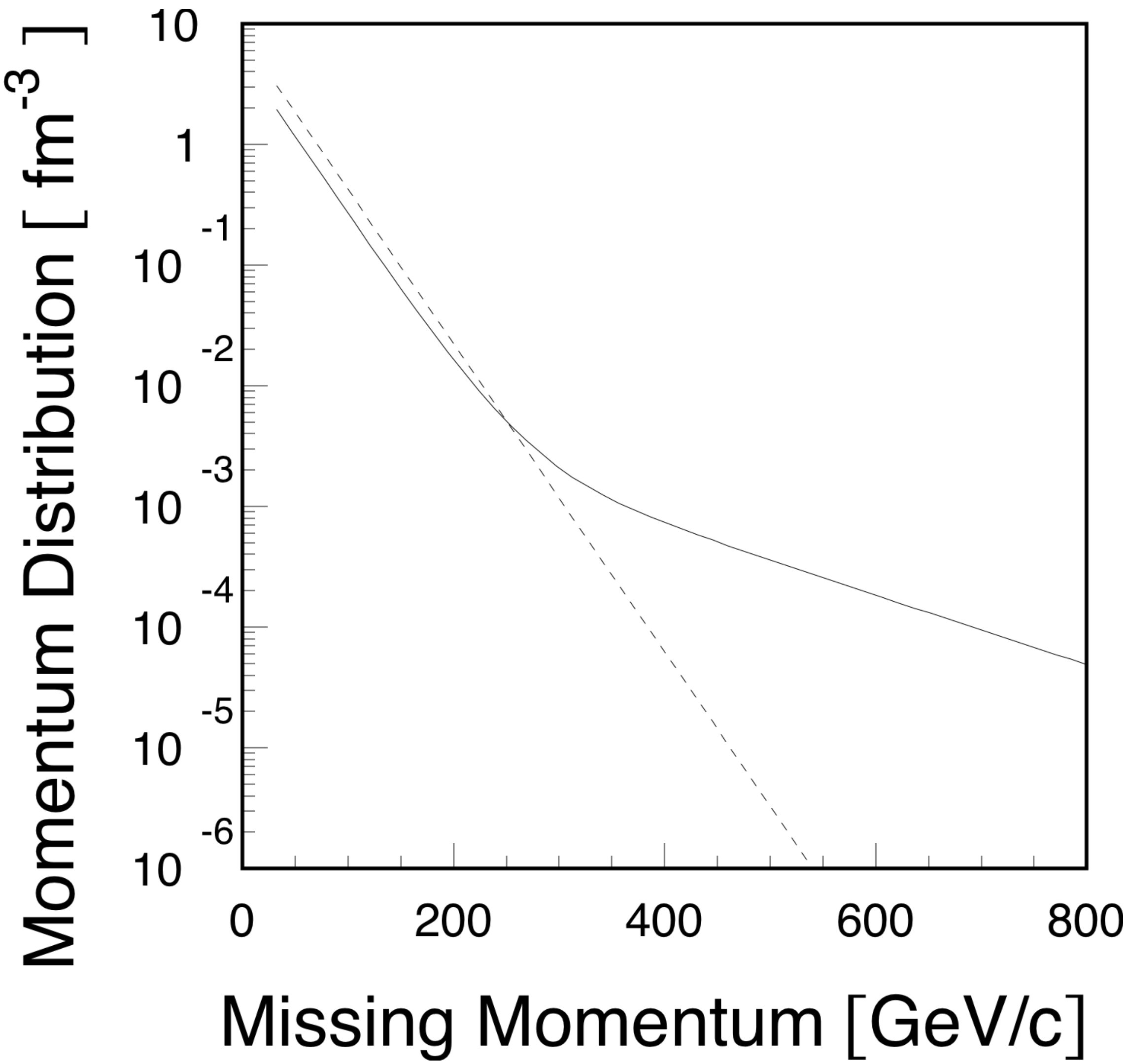
Independent-Particle Shell-Model
is based upon the assumption that each nucleon moves independently in an average potential (mean field) induced by the surrounding nucleons

The (e,e'p) data for knockout of valence and deeply bound orbits in nuclei gives spectroscopic factors that are 60 – 70% of the mean field prediction.

Next Step: Add Correlations Between Nucleons



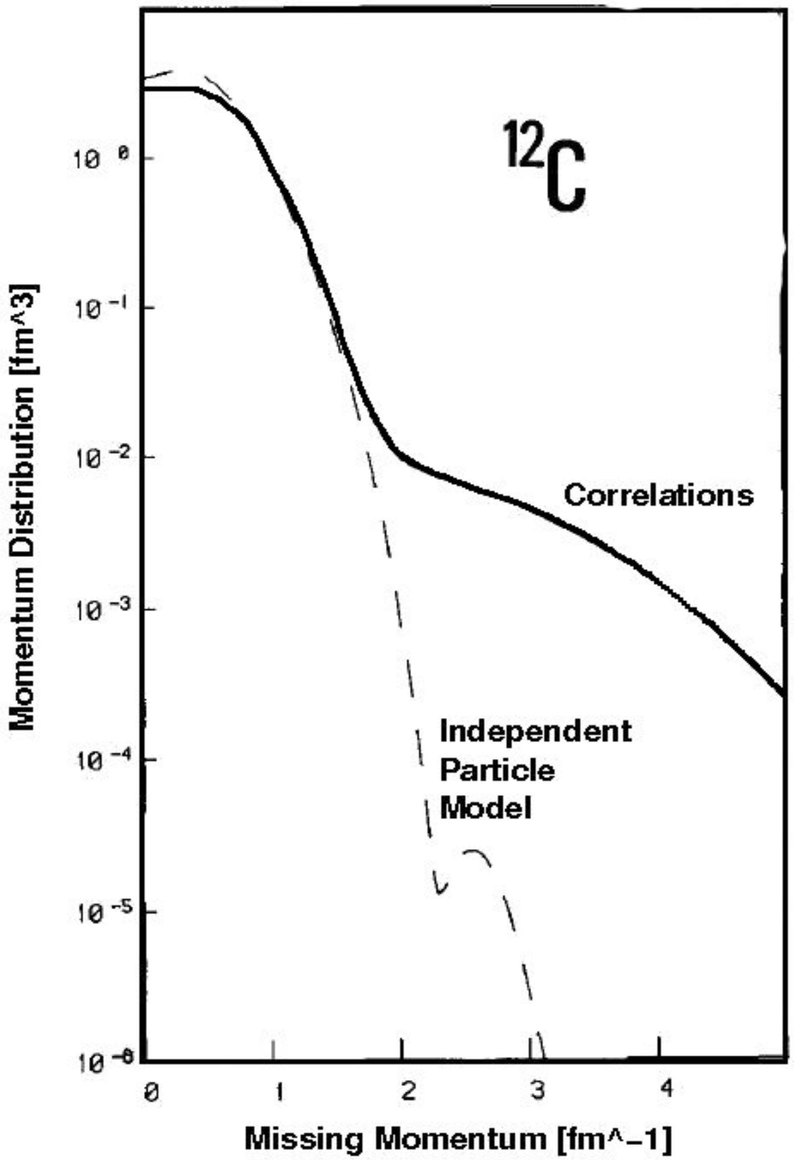
A Toy Model Momentum Distribution



By Uncertainty Principle High Momentum Region Dominated by Short Distance Phenomena

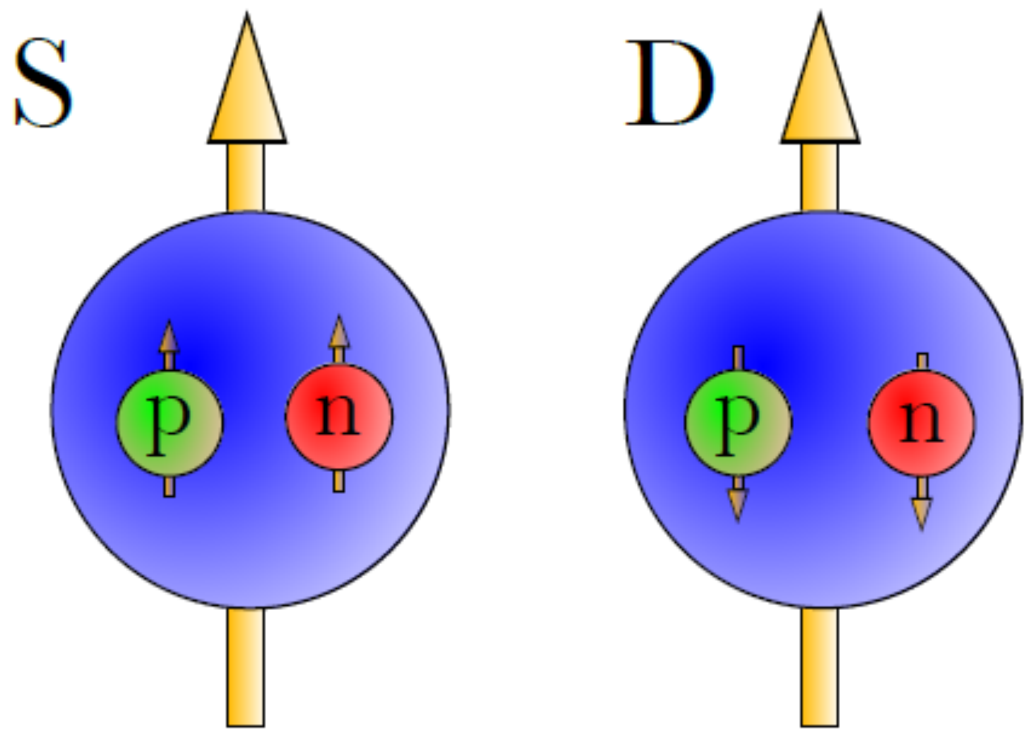
Realistic Momentum Distribution

Benhar et al., Phys. Lett. **B** 177 (1986) 135.



Vector Polarized Deuterium

Spin-1 Particle, 2 spin-$^{1}/_{2}$ Nucleons (Proton and Neutron)



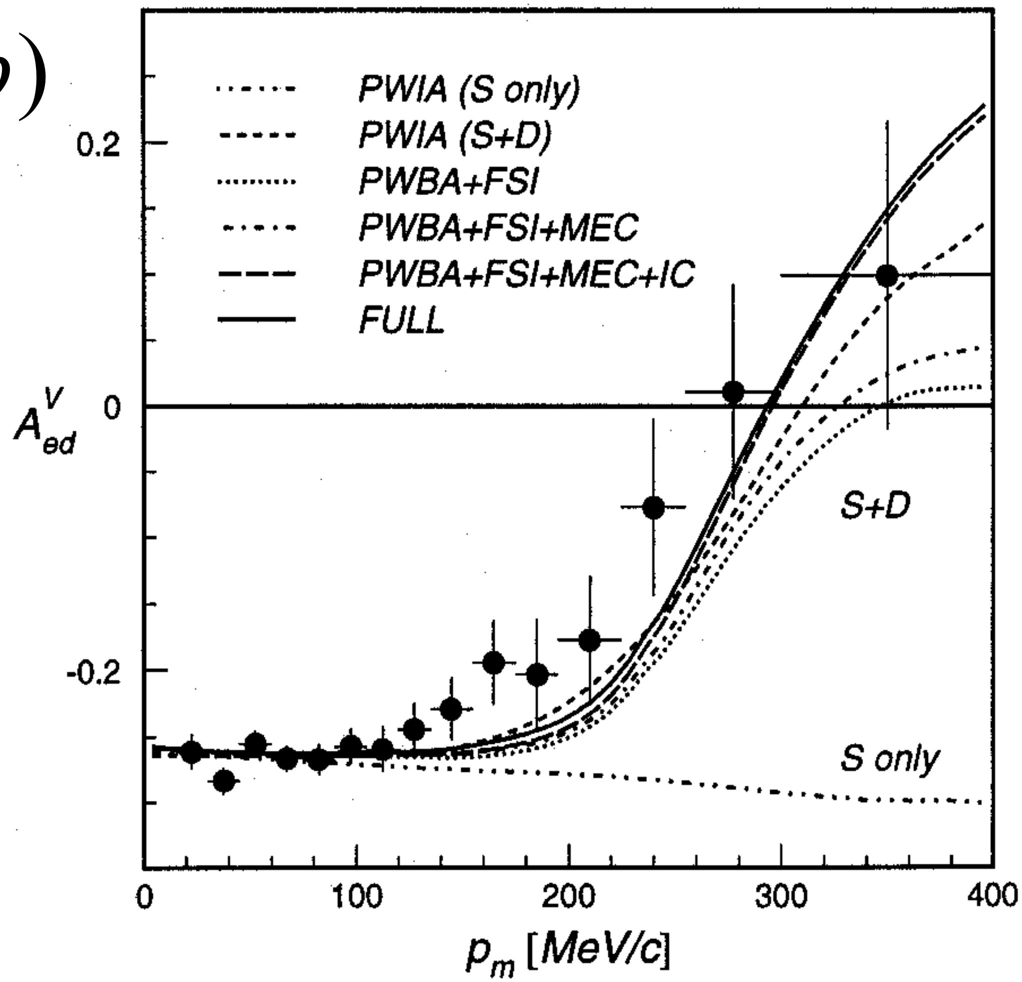
l=0
~90%

l=2
~10%

Deuteron Asymmetry Data

I. Passchier *et al.*, Phys. Rev. Lett. **88** (2002)102302.
(repeated at MIT Bates with BLAST and better statistics)

$$^2\vec{\mathrm{H}}(\vec{e},e'p)$$

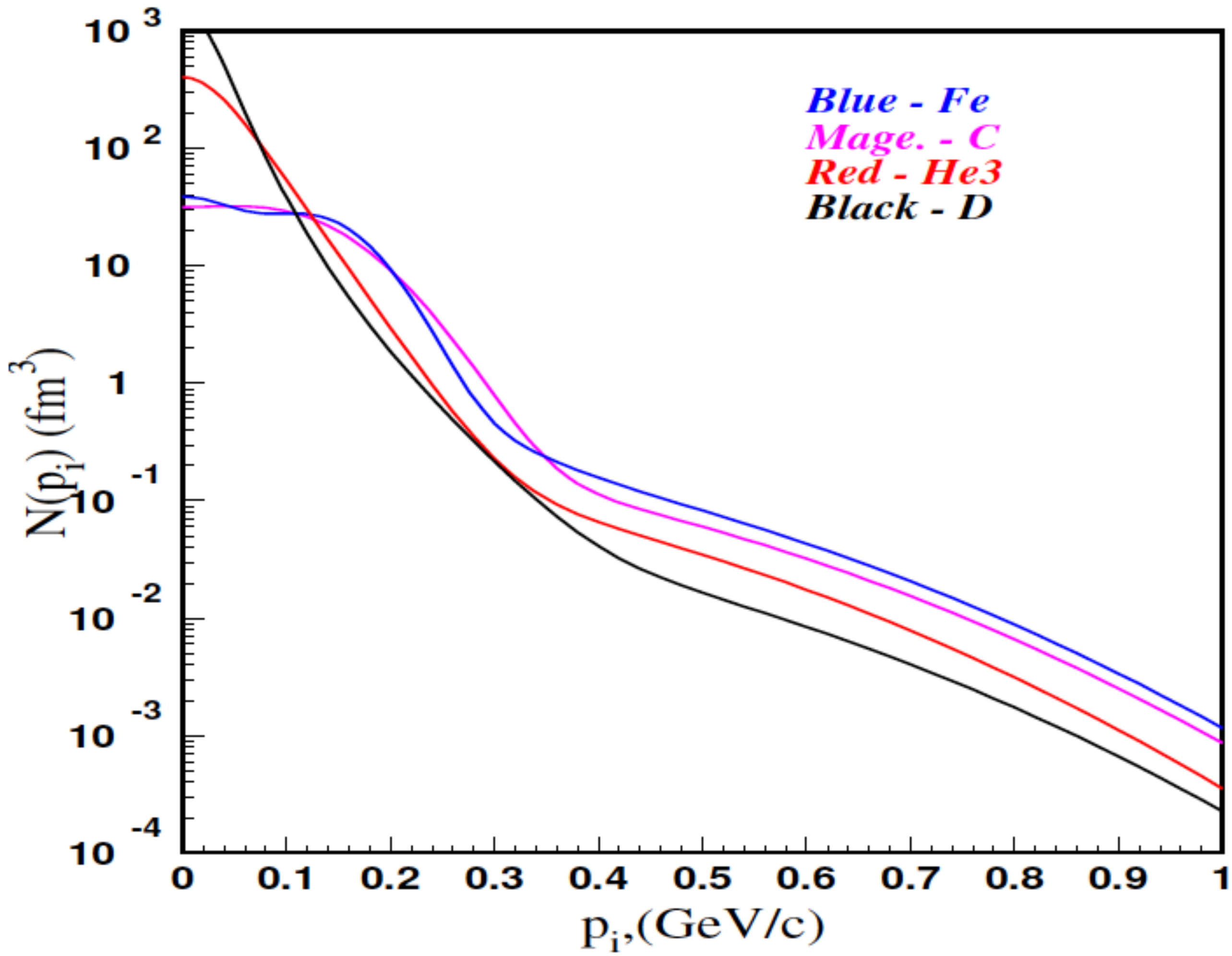


Q^2 = 0.2 GeV/c

x_B = 1

Momentum Distributions

C. Ciofi degli Att and S. Simula, *Phys. Rev. C* **53** (1996) 1689.

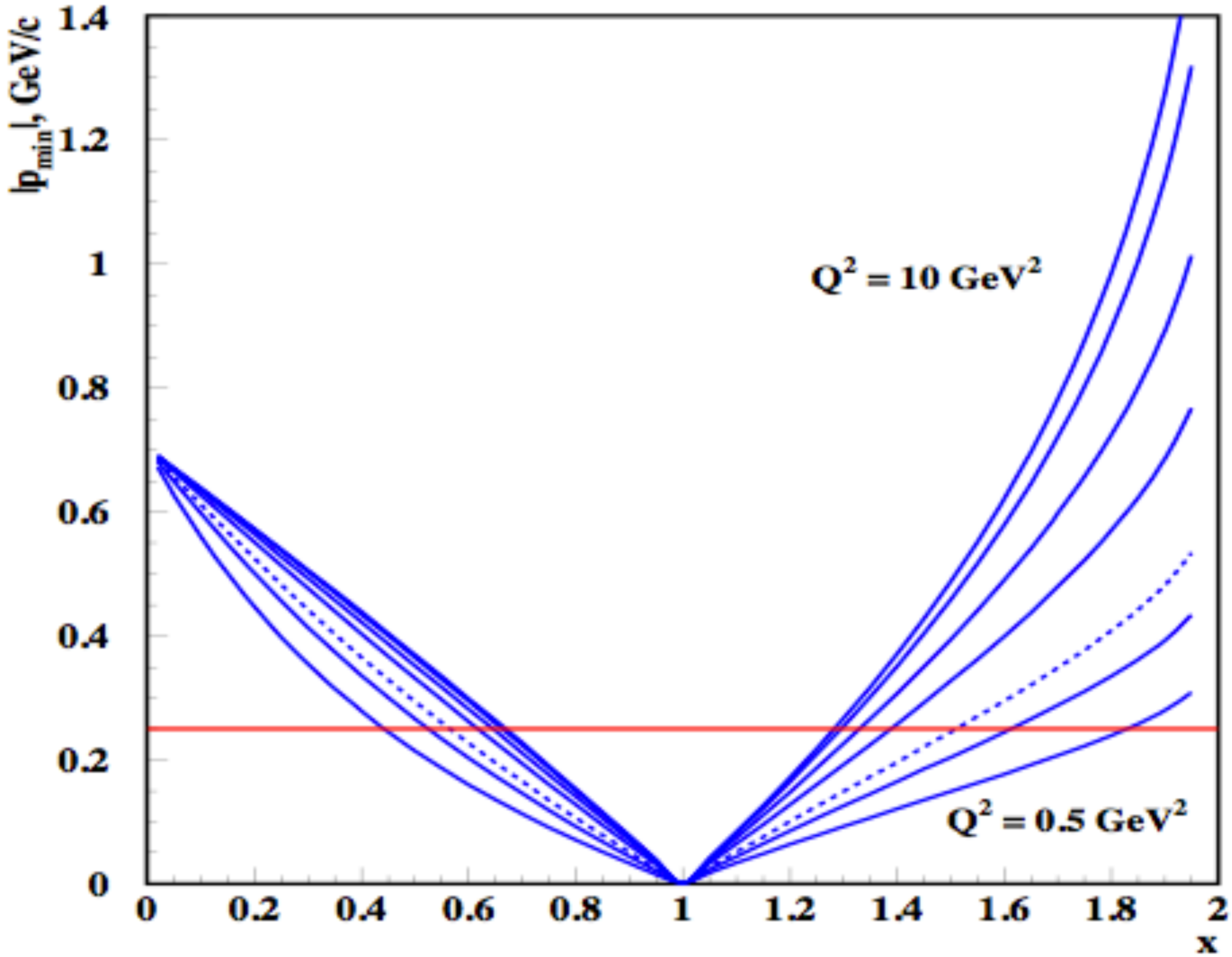


At high *initial* momentums $\mathbf{n_A(p) = N * n_D(p)}$

Jefferson Lab

Minimum Missing Momentum

Assuming a (e,e'p) reaction, inclusive (e,e') can set limits on recoiling system's momentum.

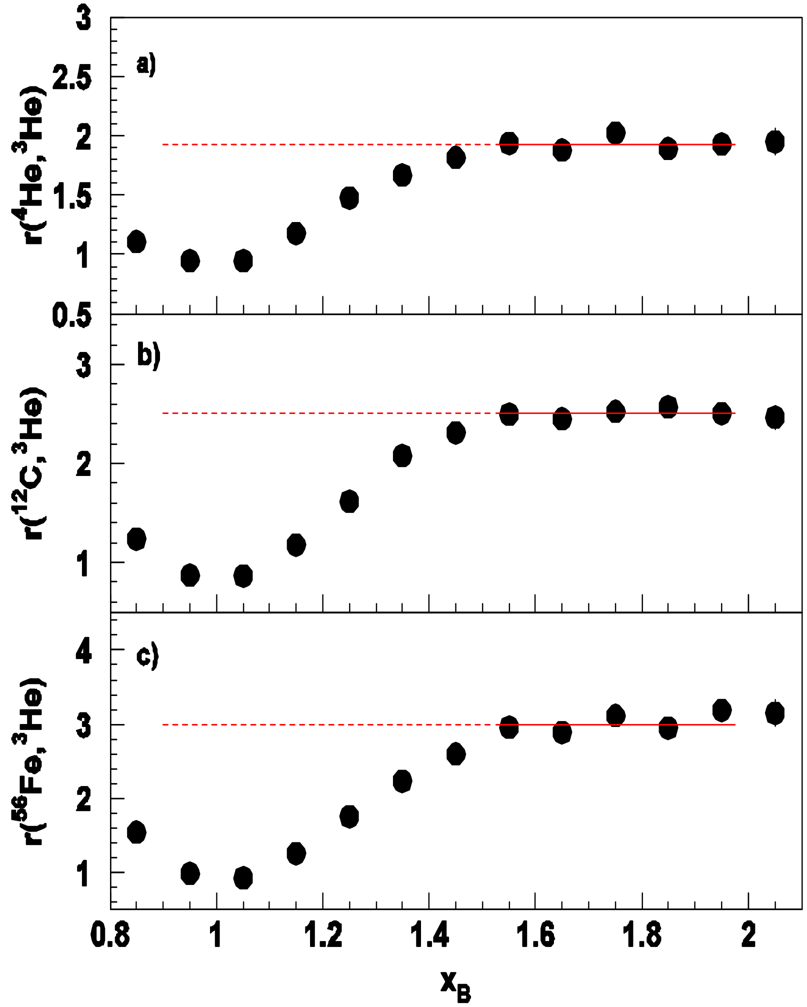


Jefferson Lab

Nuclear Scaling Plateaus from CLAS

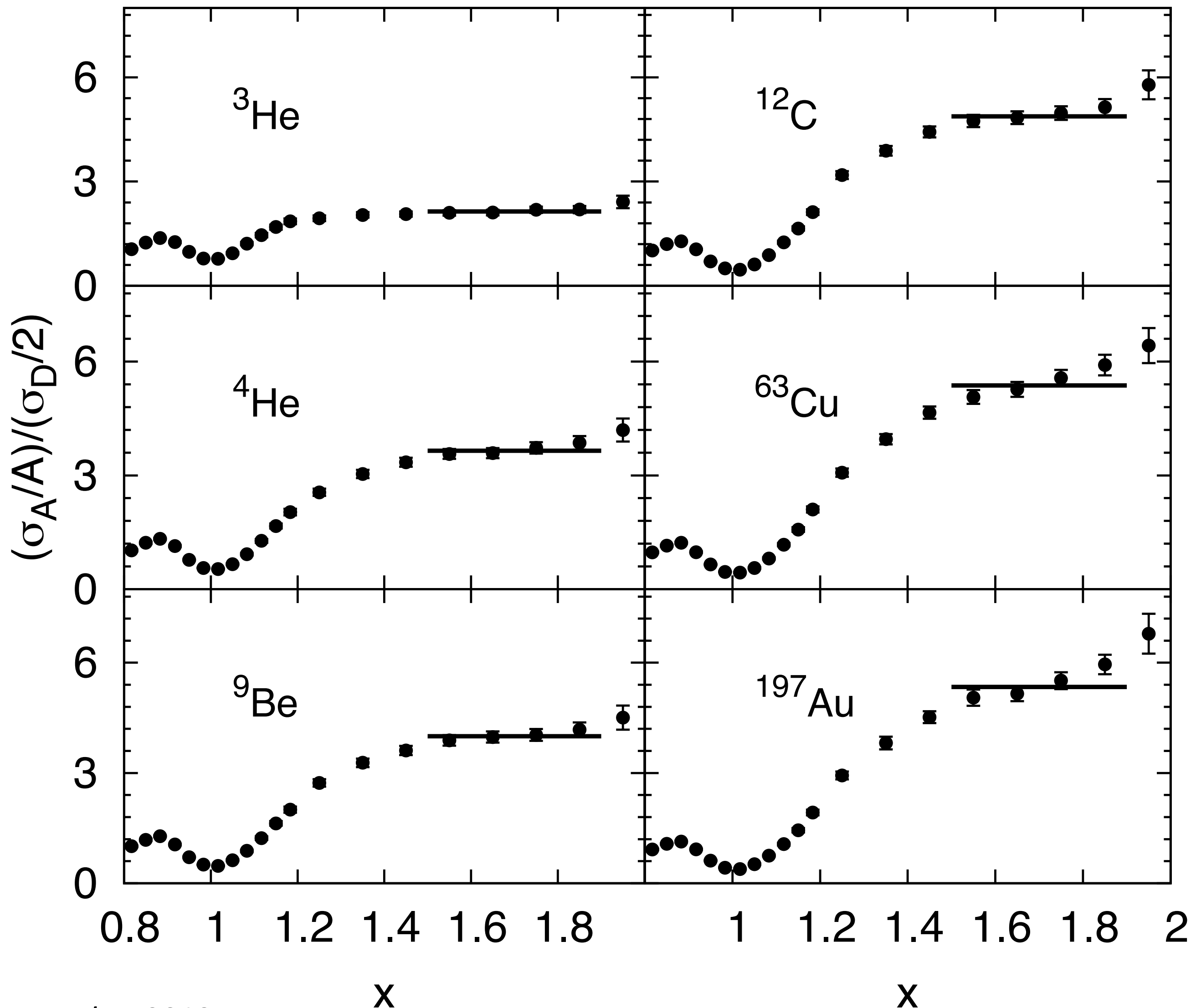
K. Sh. Egiyan *et al.,* Phys. Rev. C **68** (2003) 014313.

Originally done with SLAC data by Frankfurt et al., Phys. Rev. C **48** (1993) 2451.



New Results From JLab Hall-C

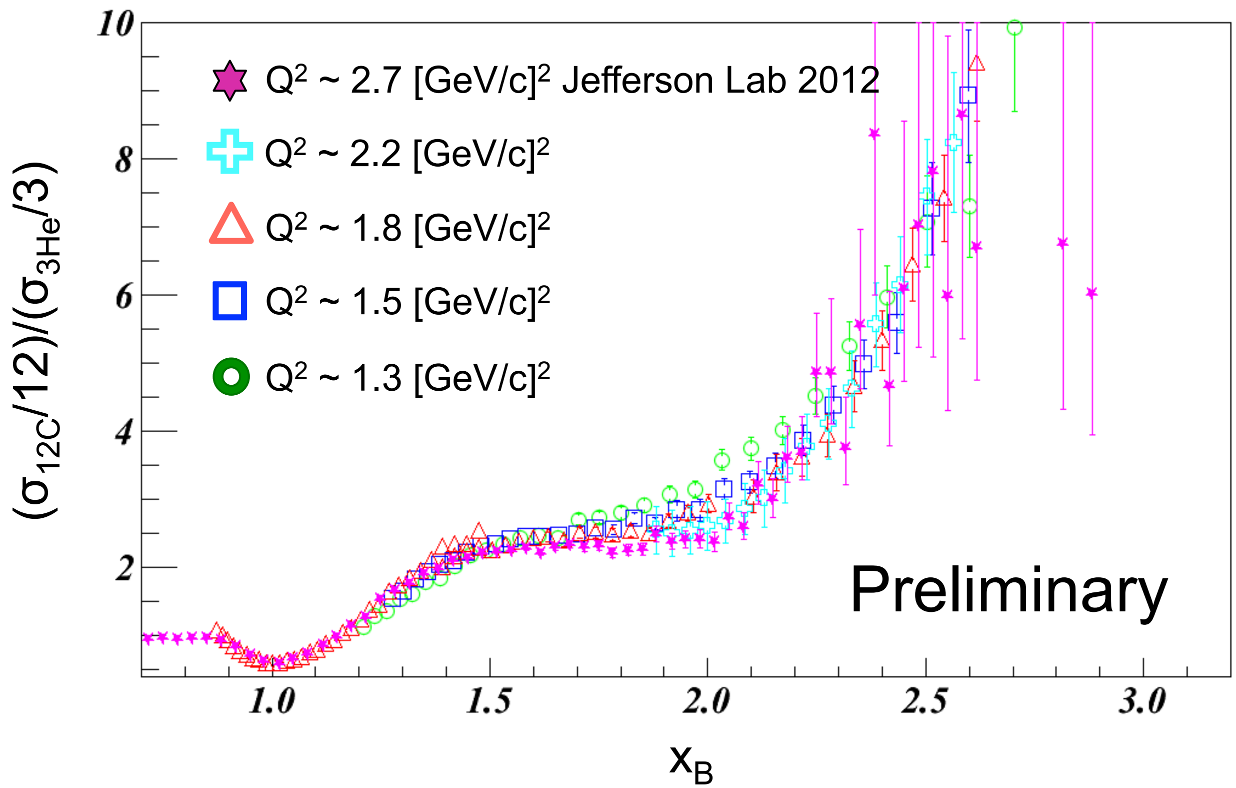
N. Fomin et al., Phys. Rev. Lett. **108** (2012) 092502.



Jefferson Lab

Analysis in Progress

- **E07-006**: SRC 2^{nd} Generation (e,e'pN) Triple Coincidence Experiment
  - Goal to further probe the repulsive part of the nucleon-nucleon potential with a few body, ^4He, target.
- **E08-014**: SRC (e,e') x_B >1 & 2 data on ^3He, ^4He, ^{40}Ca, & ^{48}Ca
  - Goal to study Q^2, x_B > 2 region, and the A/Z dependence of the SRC plateaus.

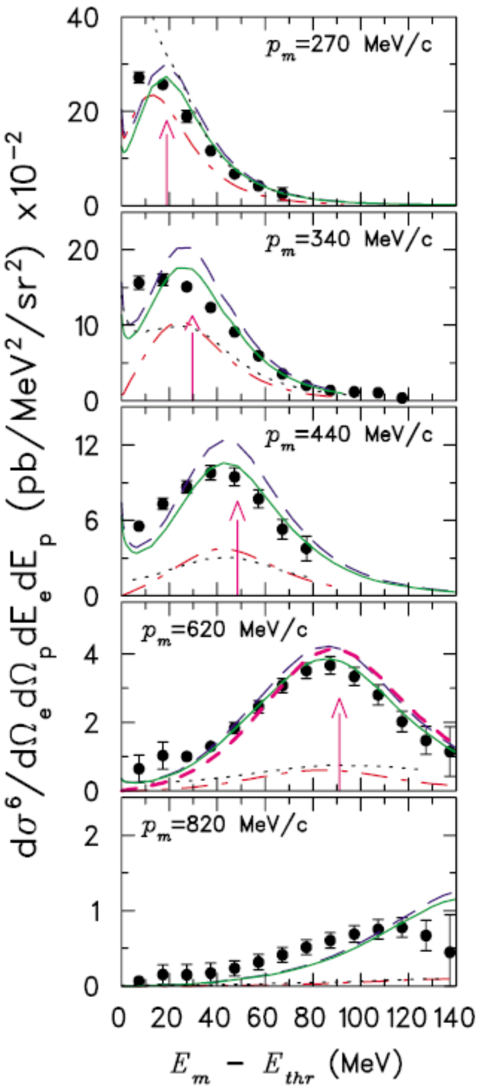


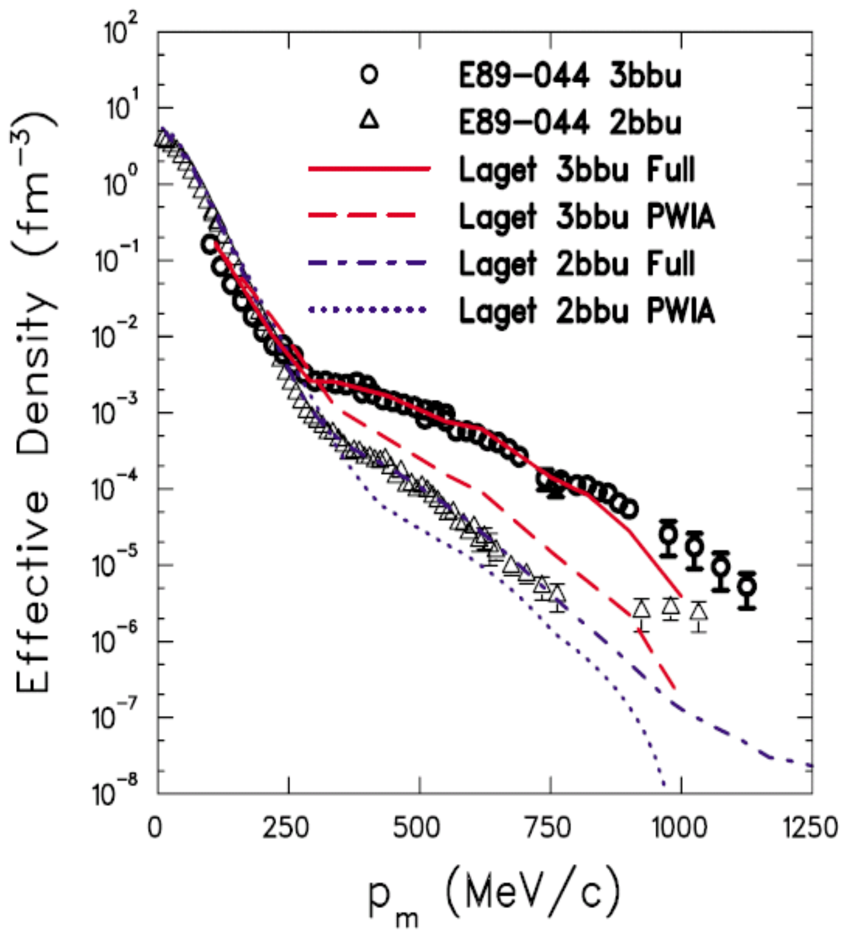
It's this just final-state interactions?

- You definitely need final-state interactions.
- And models will show final-state interactions are important even in these kinematics BUT
- The final-state interactions are part of the story with the rest of the nuclear physics taken together correctly [i.e. you wouldn't get the correct cross section in most kinematics without putting all the ingredients together correctly]

E89-044 $^3He(e,e'p)pn$ Results (HallA)

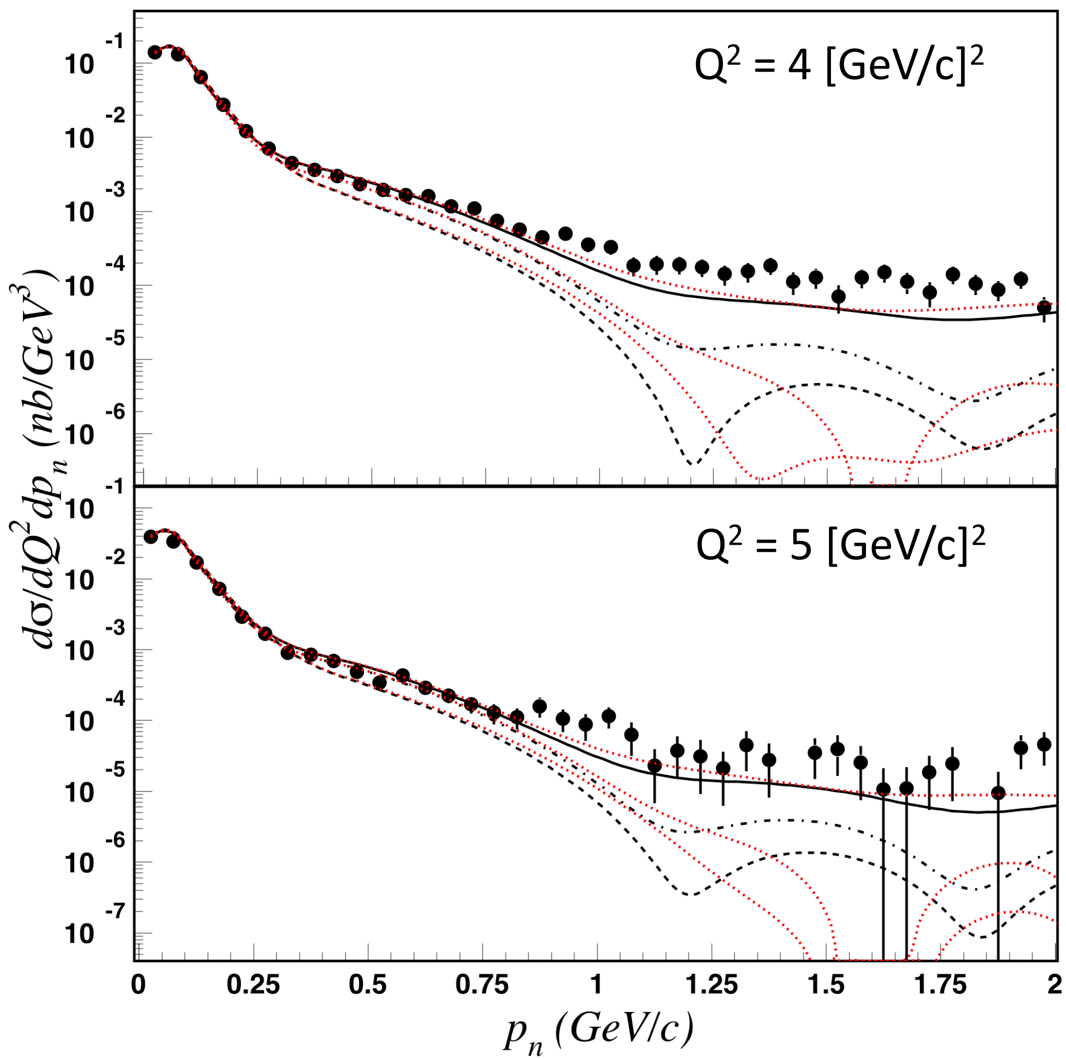
F. Benmokhtar *et al*., Phys. Rev. Lett. **94** (2005) 082305. [x=1, q=1.5 GeV, w=0.84 GeV.]





Hall B (CLAS) D(e,e'p)n x<1 Data

K. Sh. Egiyan *et al.*, Phys. Rev. Lett. **98** (2007) 262502.

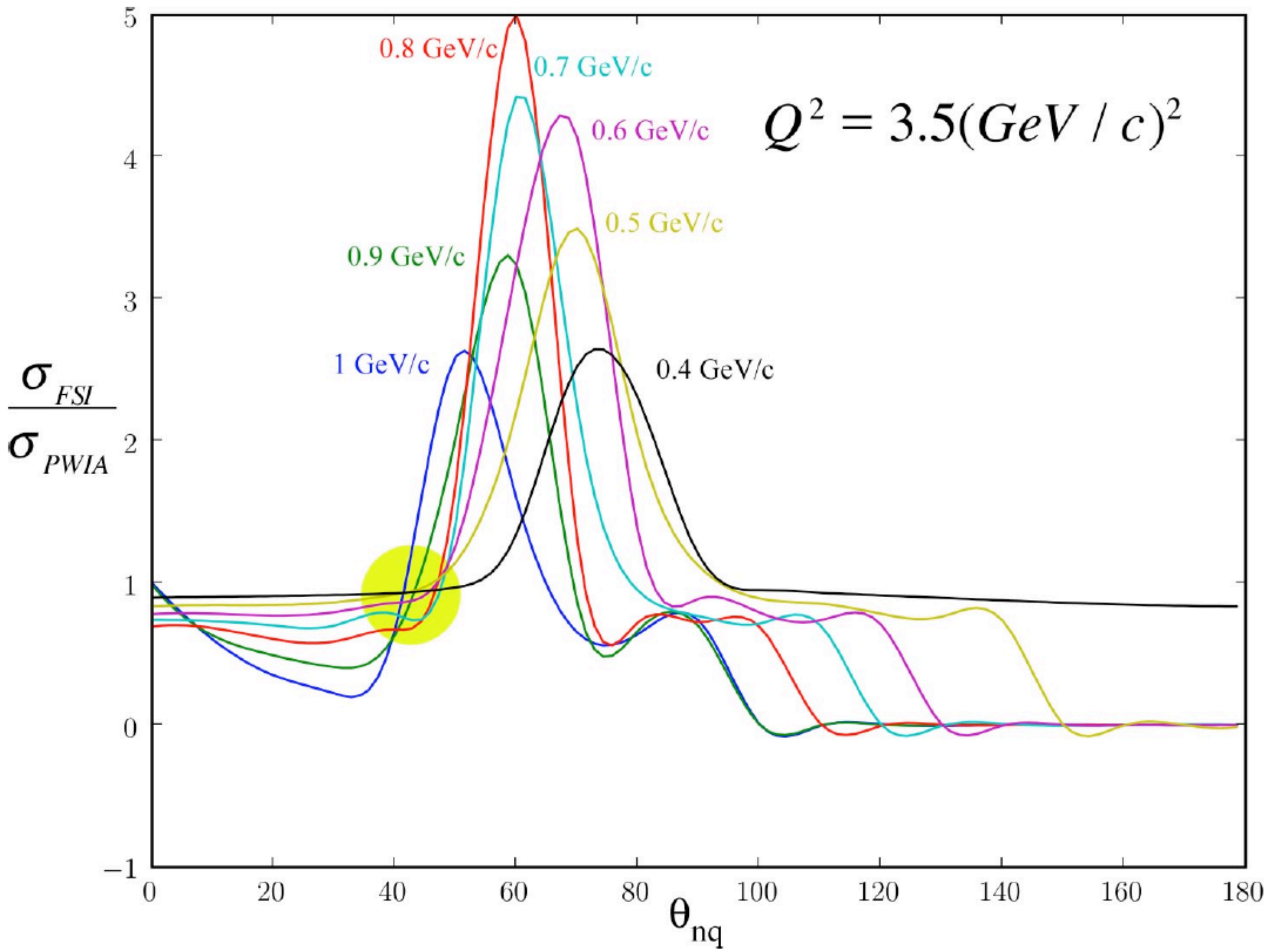


Black Paris Potential
Red AV-18 Potential

From Lowest To Highest
PWIA
PWIA+FSI
PWIA+FSI+MEC+NΔ

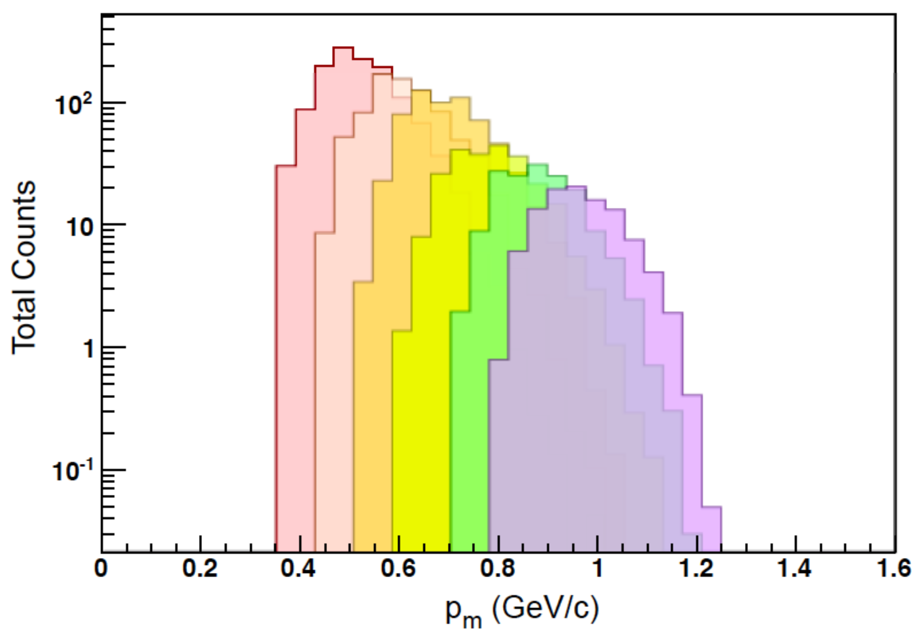
Calculation of D(e,e'p)n FSI Ratio

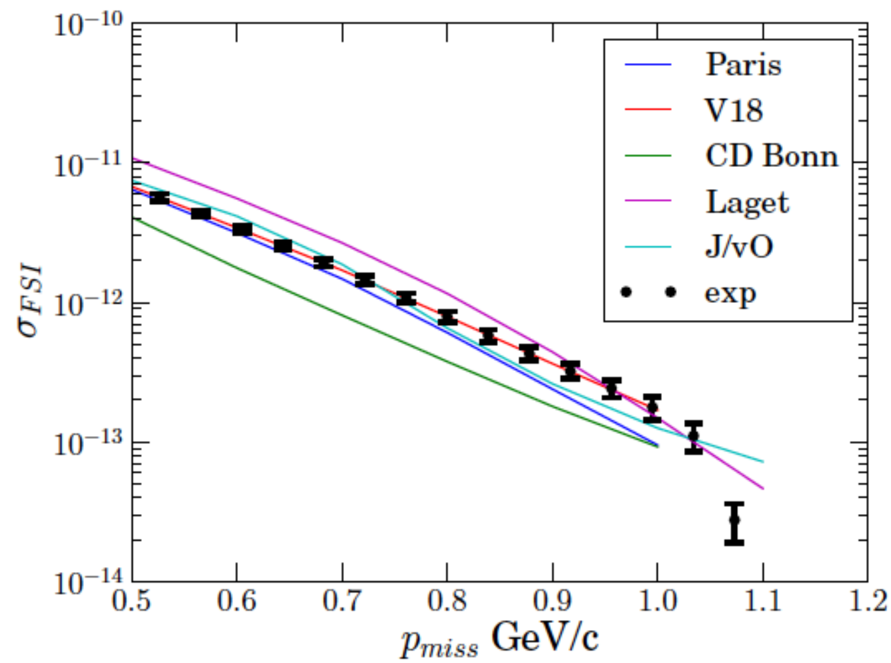
By Misak Sargasian using AV18 to get a momentum distribution and x>1 kinematics



E12-10-003: D(e,e'p)n at x>1 & Q^2=4 GeV/c

21 PAC Days, 11 GeV beam and Hall C with 6 settings of the spectrometers

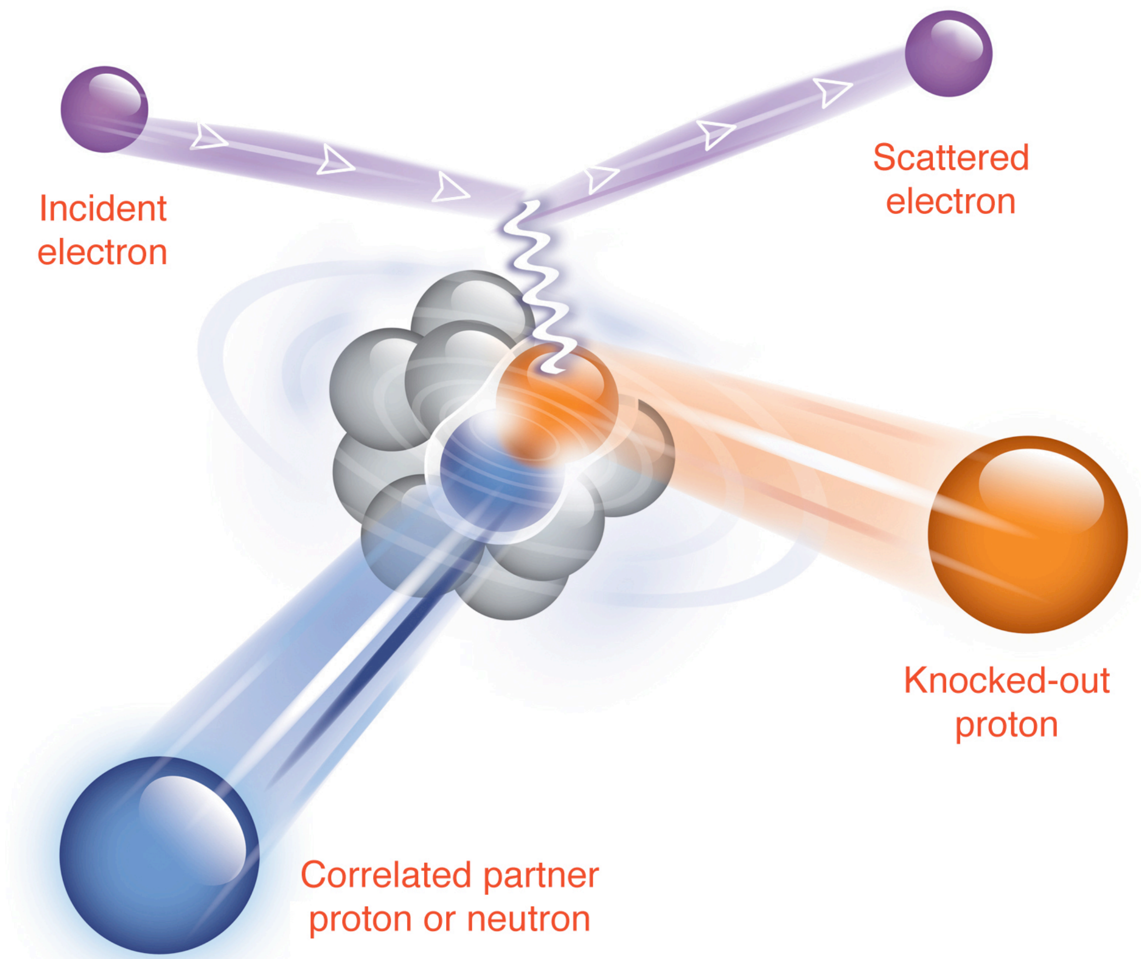




Kinematics where FSI is minimized (though still calculated) and sensitive to initial state ingredients.

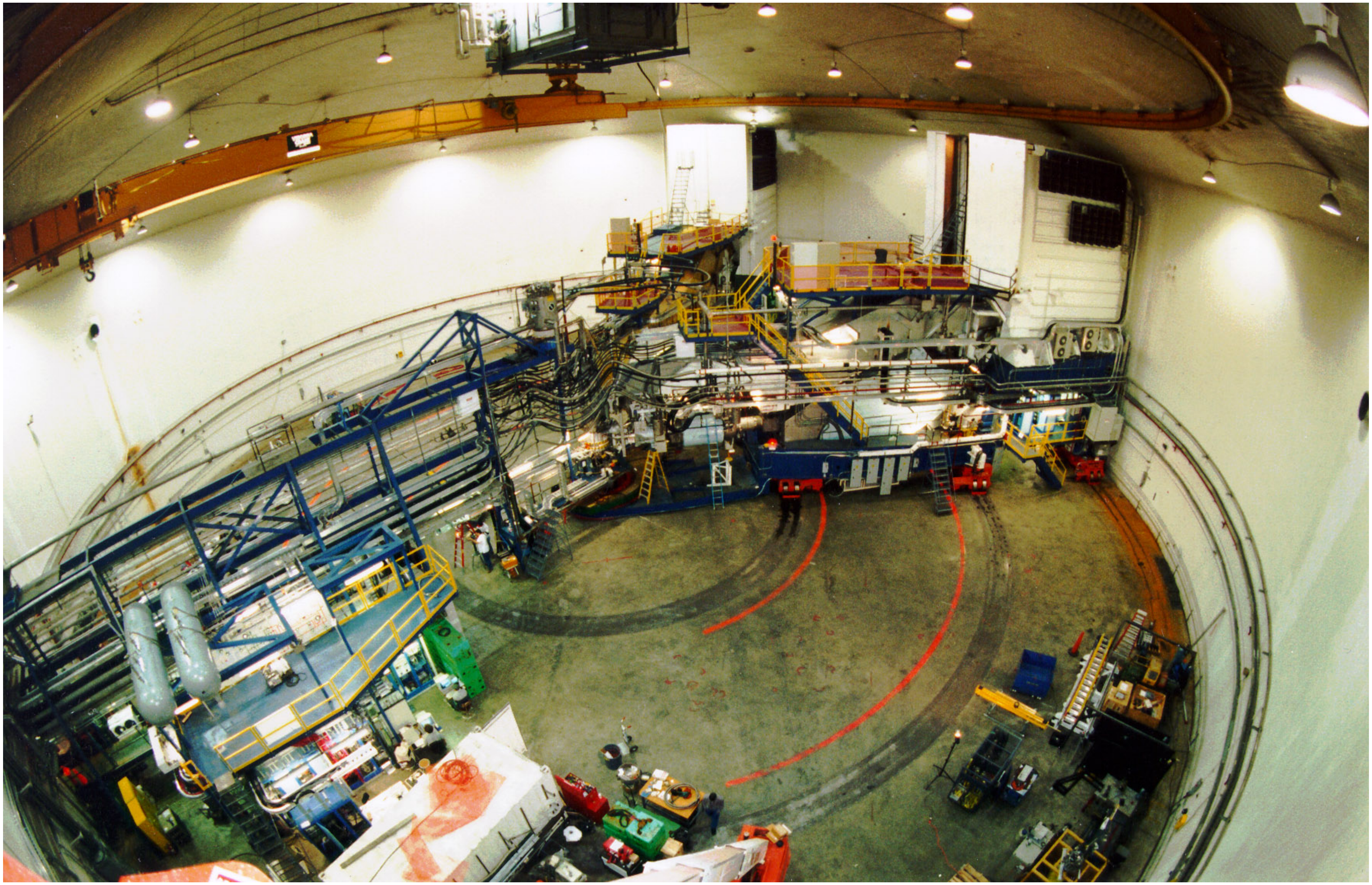
Coincidence (e,e’pN) Measurement

To study nucleon pairs and the fraction that contribute to momentum tail.

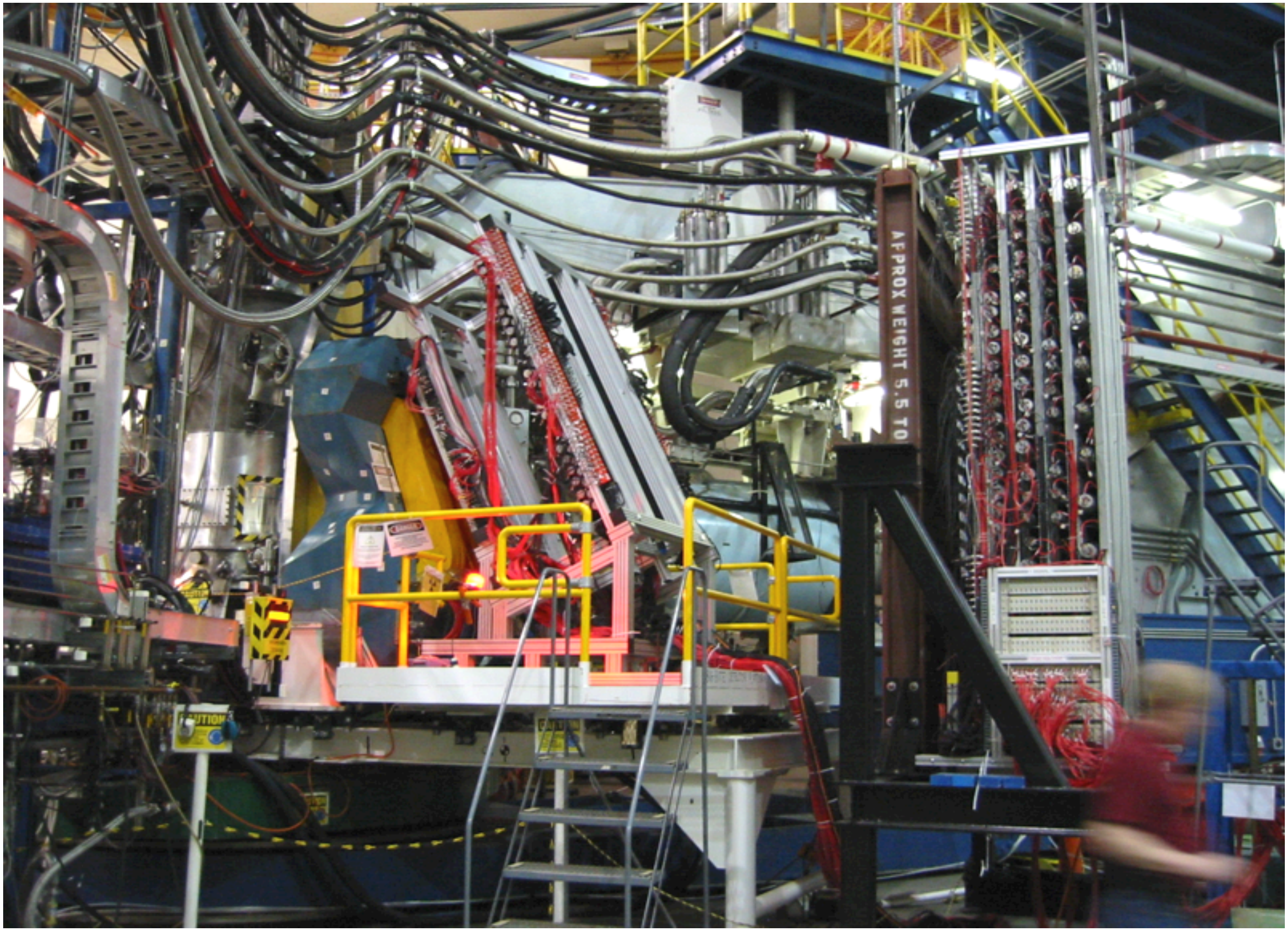


$x > 1$, $Q^2 = 1.5\ [\mathrm{GeV/c}]^2$ and missing momentum of 500 MeV/c

Jefferson Lab's Hall A

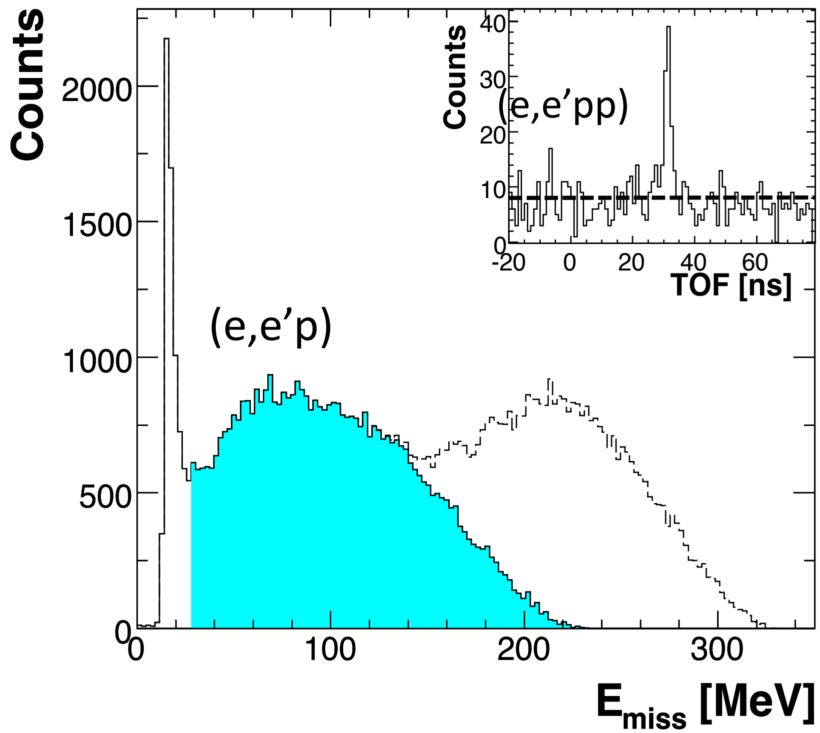


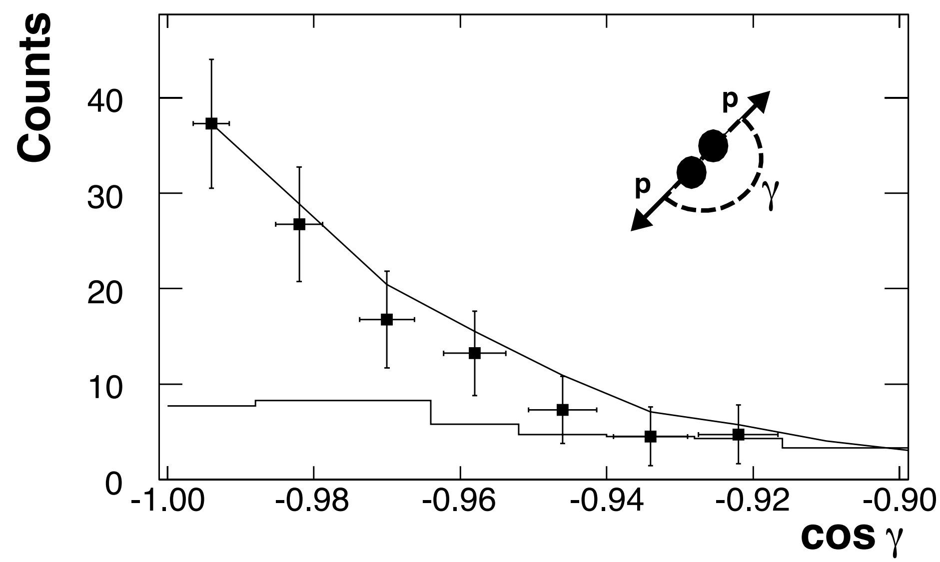
Acceptance matched np detectors.



(e,e'p) & (e,e'pp) Data

R. Shneor *et al.*, Phys. Rev. Lett. **99** (2007) 072501.





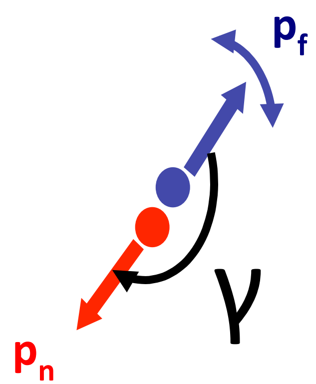
Strong back-to-back correlation!

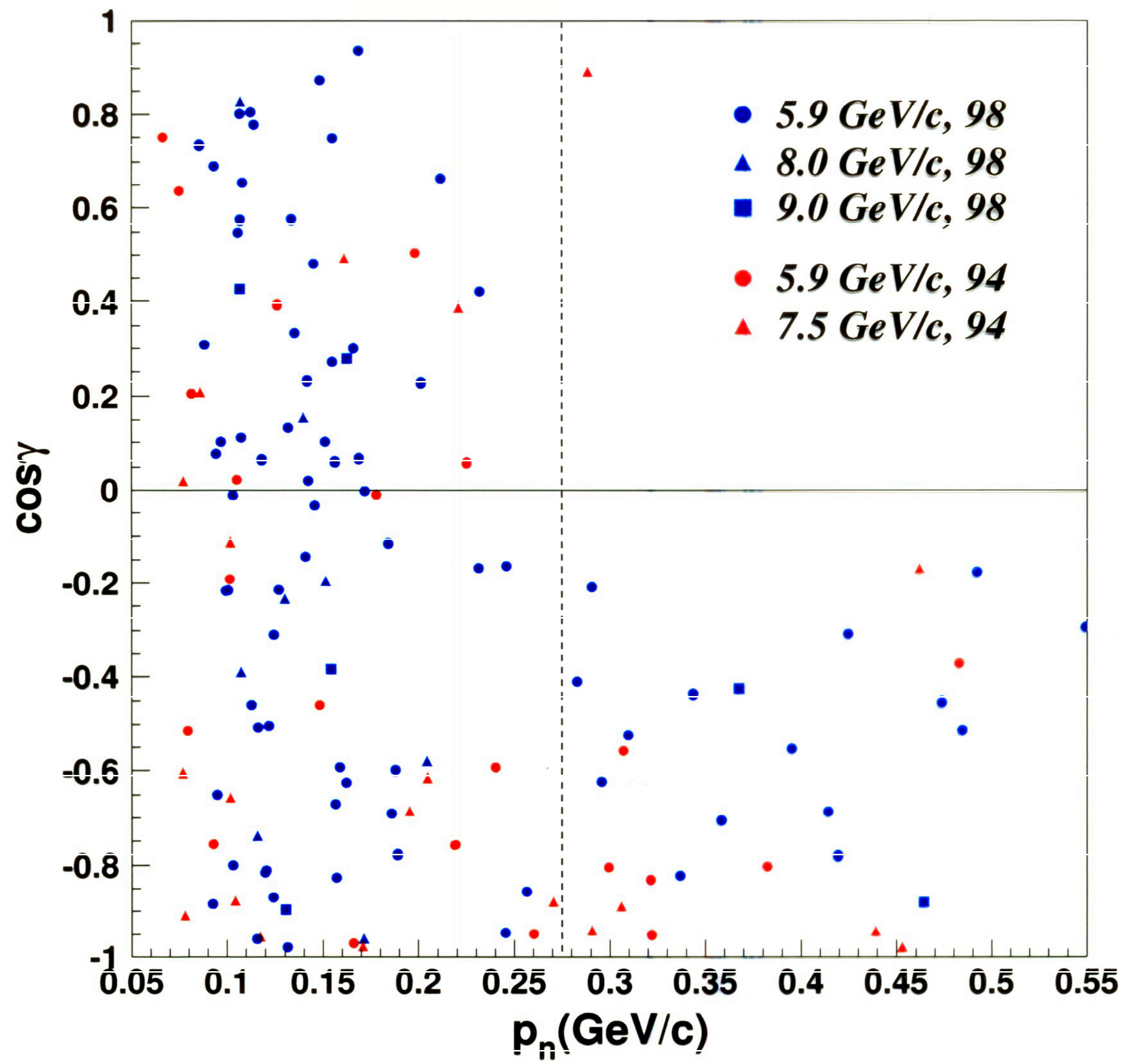
- ^{12}C(e,e'p)
- Quasi-Elastic Shaded In Blue
- Resonance Even at x_B>1

Brookhaven EVA Collaboration Result

A. Tang *et al*., Phys. Rev. Lett. **90** (2003) 042301.

$^{12}C(p,2p+n)$ Reaction





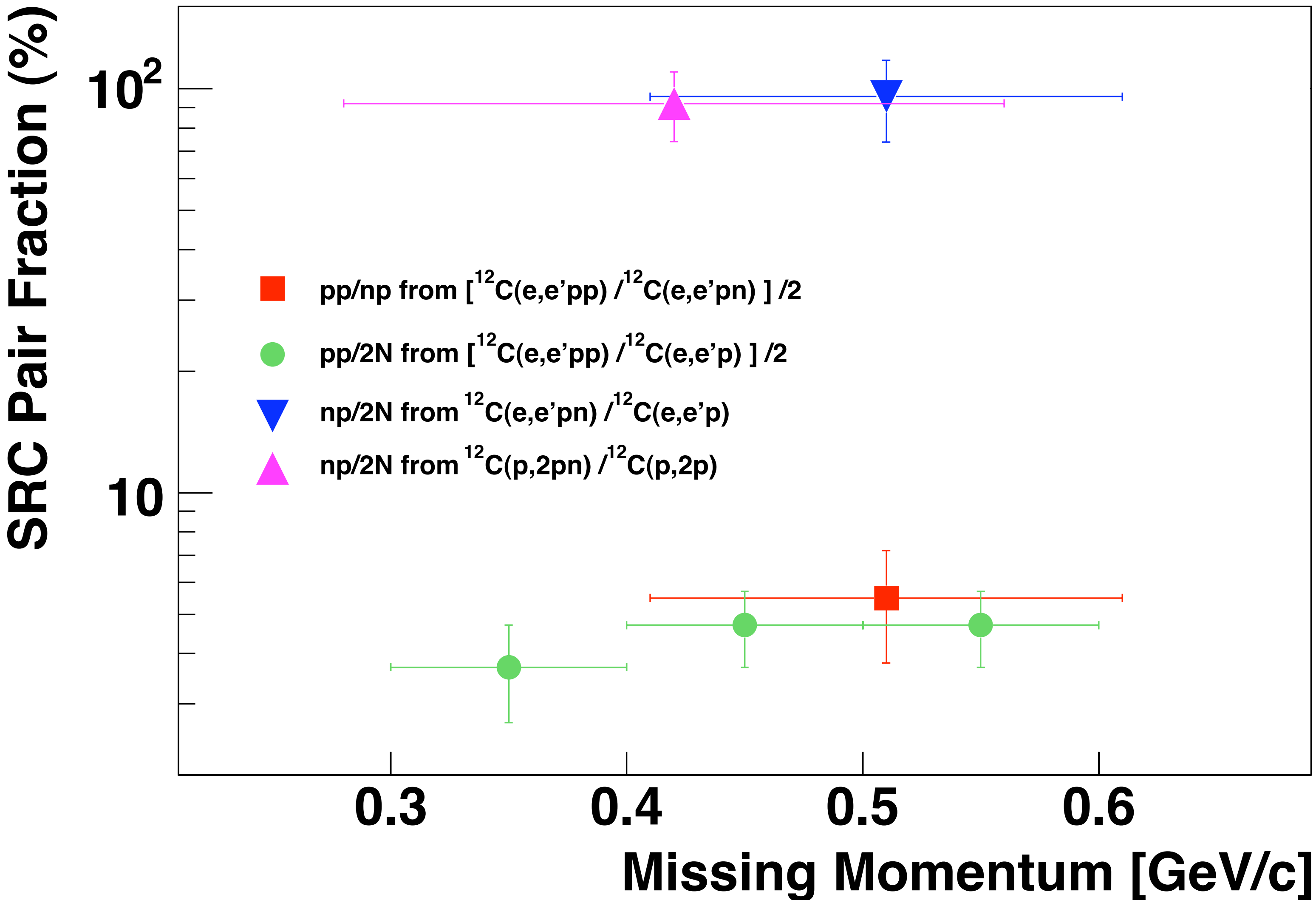
$p_f = p_1 + p_2 - p_0$

p_0 = incident proton

p1 and p2 are detected

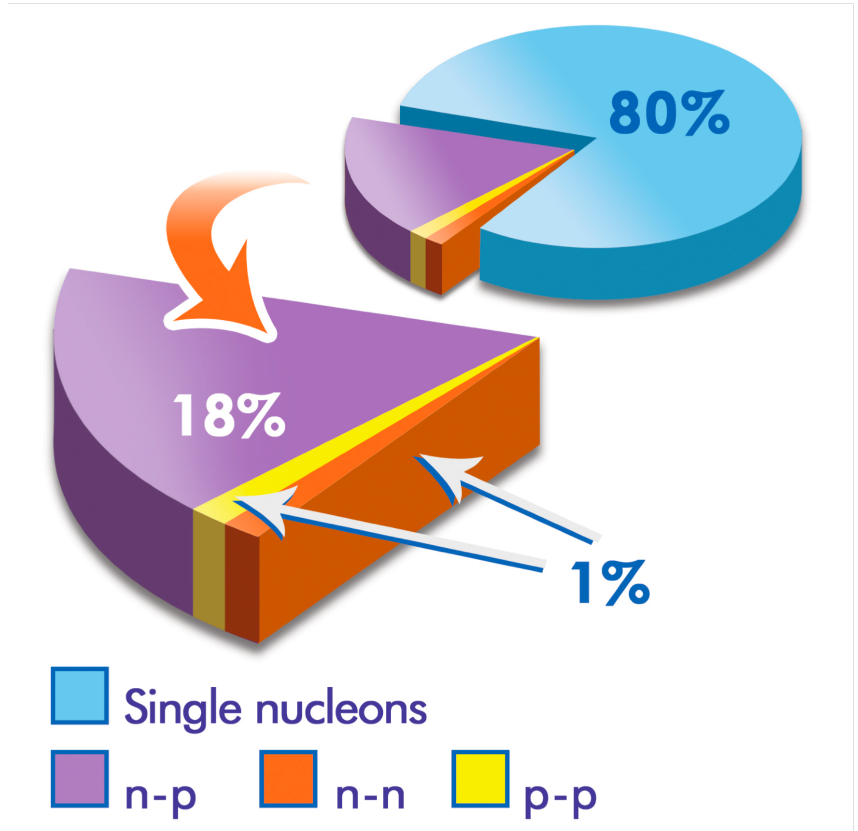
High p_m (e,e'p) events have recoiling neutrons.

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

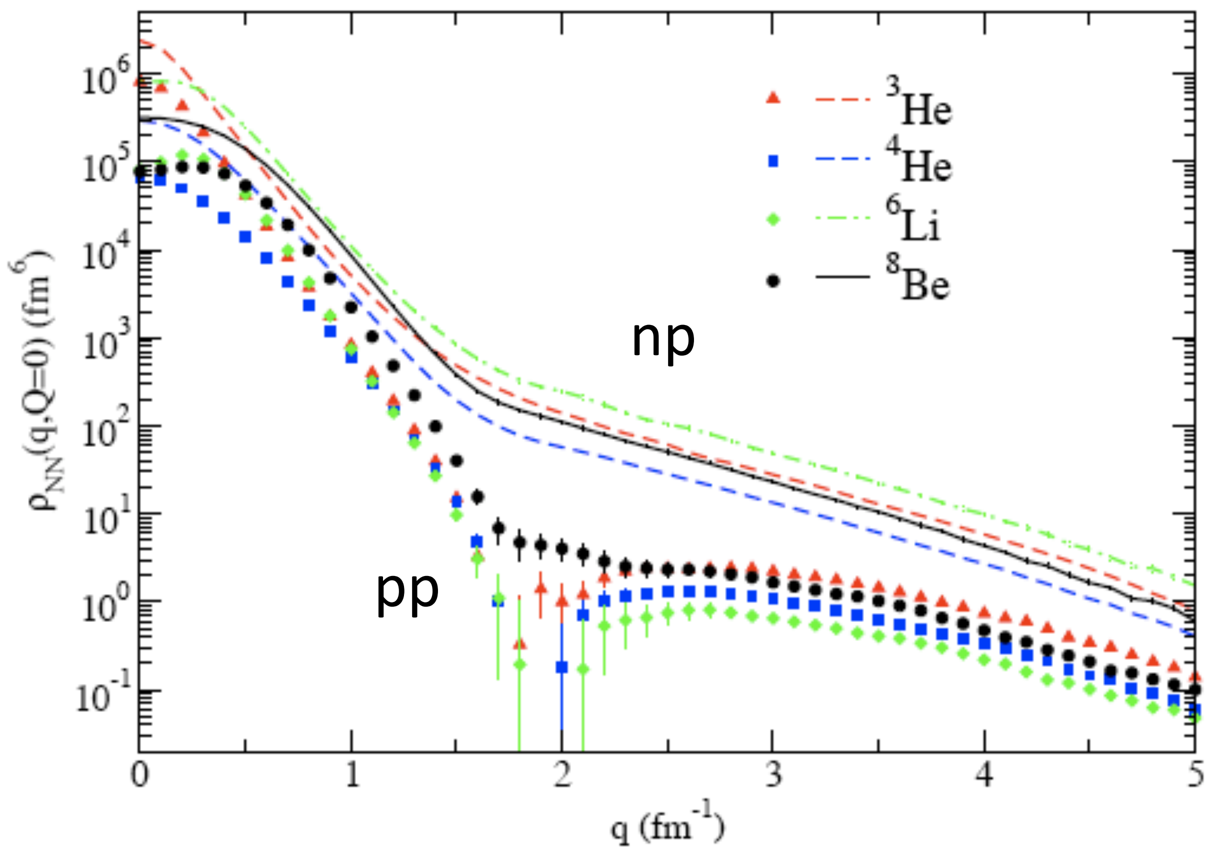


^{12}C From (e,e'), (e,e'p), and (e,e'pN) Results

- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - 18% np pairs (quasi-deuteron)
  - 1% pp pairs
  - 1% nn pairs (from isospin symmetry)
- Less than 1% multi-nucleon correlations



Importance of Correlations

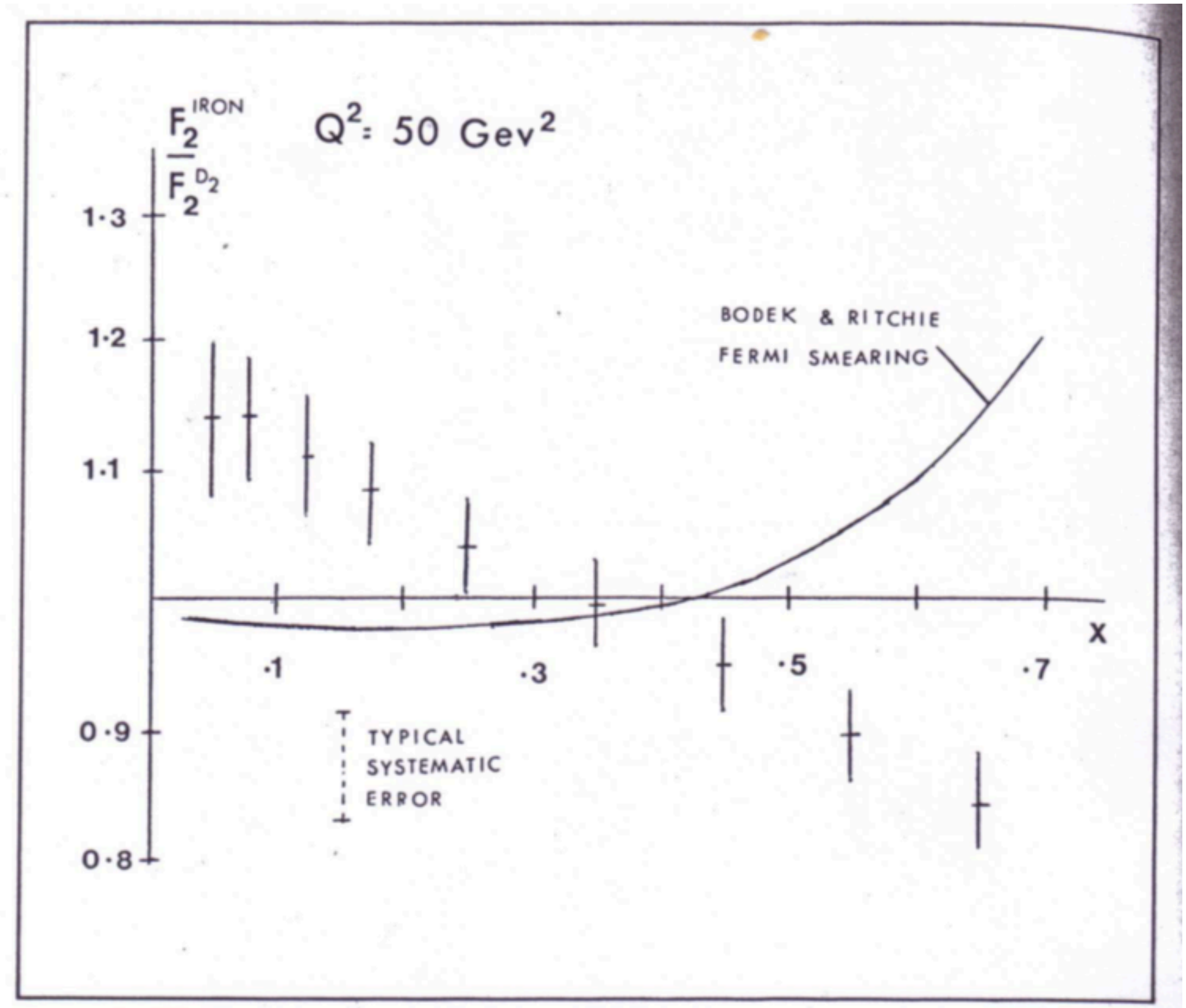


- R. Schiavilla *et al.*, Phys. Rev. Lett. 98 (2007) 132501.
- M. Sargsian *et al.*, Phys. Rev. C (2005) 044615.
- M. Alvioli *et al.*, Phys. Rev. Lett. 100 (2008) 162503.

If the x>1 results are proportional to local density effects, then it seems reasonable to look for connections to other possible local density effects.

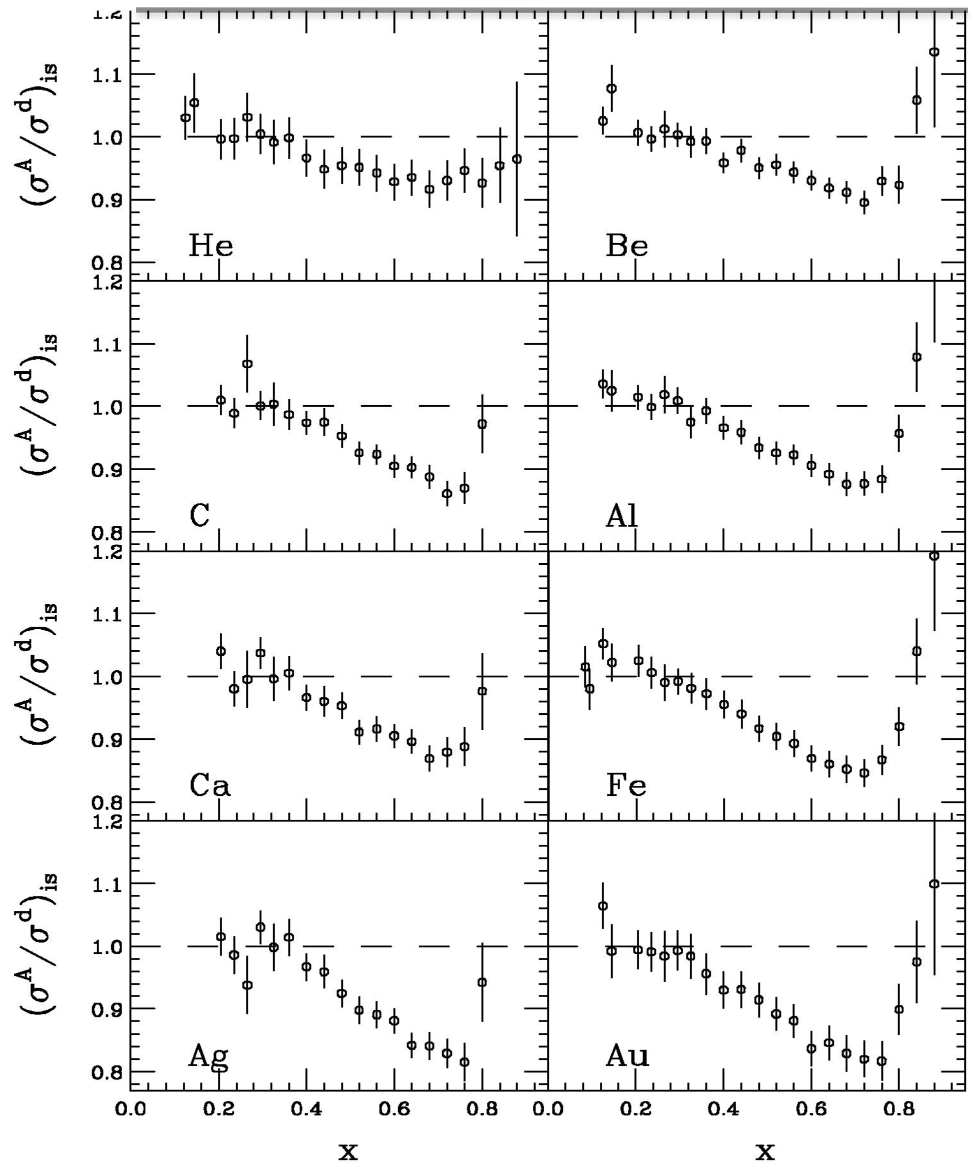
What is the EMC effect?

CERN Courier, Nov. 1982 (shown) and then J.J. Aubert *et al.*,Phys. Lett. B **123** (1983) 275.



Effect Reproduced Many Times

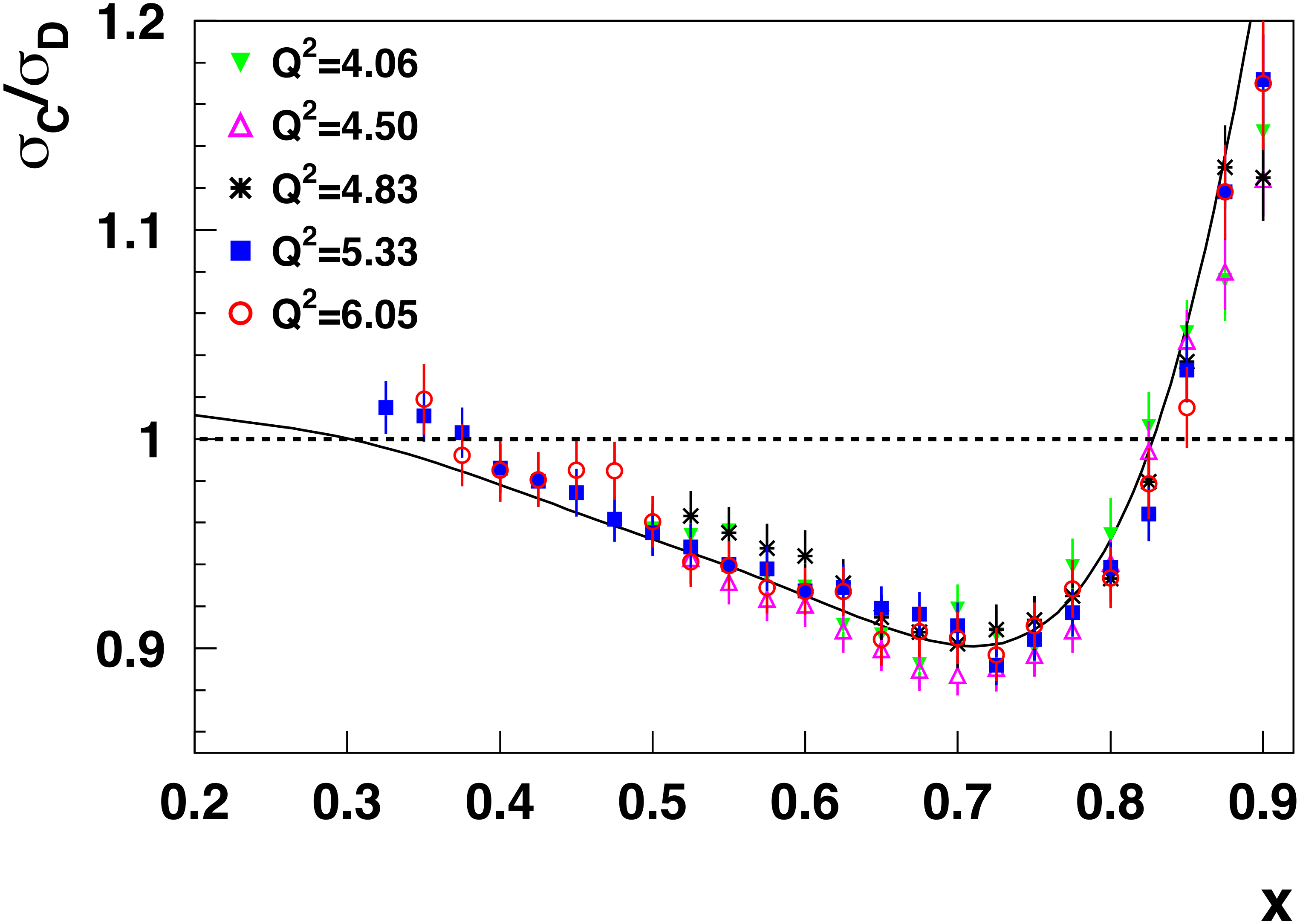
- **EMC effect is simply the fact the ratio of DIS cross sections is not one**
  - J.J. Aubert et al. PLB 123 (1983) 275.
  - Simple Parton Counting Expects One
  - **MANY Explanations**
- **SLAC E139**
  - J. Gomez et al., PRD 49 (1994) 4348.
  - Precise large-x data
  - Nuclei from A=4 to 197
- **Conclusions from SLAC data**
  - Q^2-independent
  - Universal x-dependence (shape)
  - Magnitude varies with A
  - Average Nuclear Density Effect



Jefferson Lab

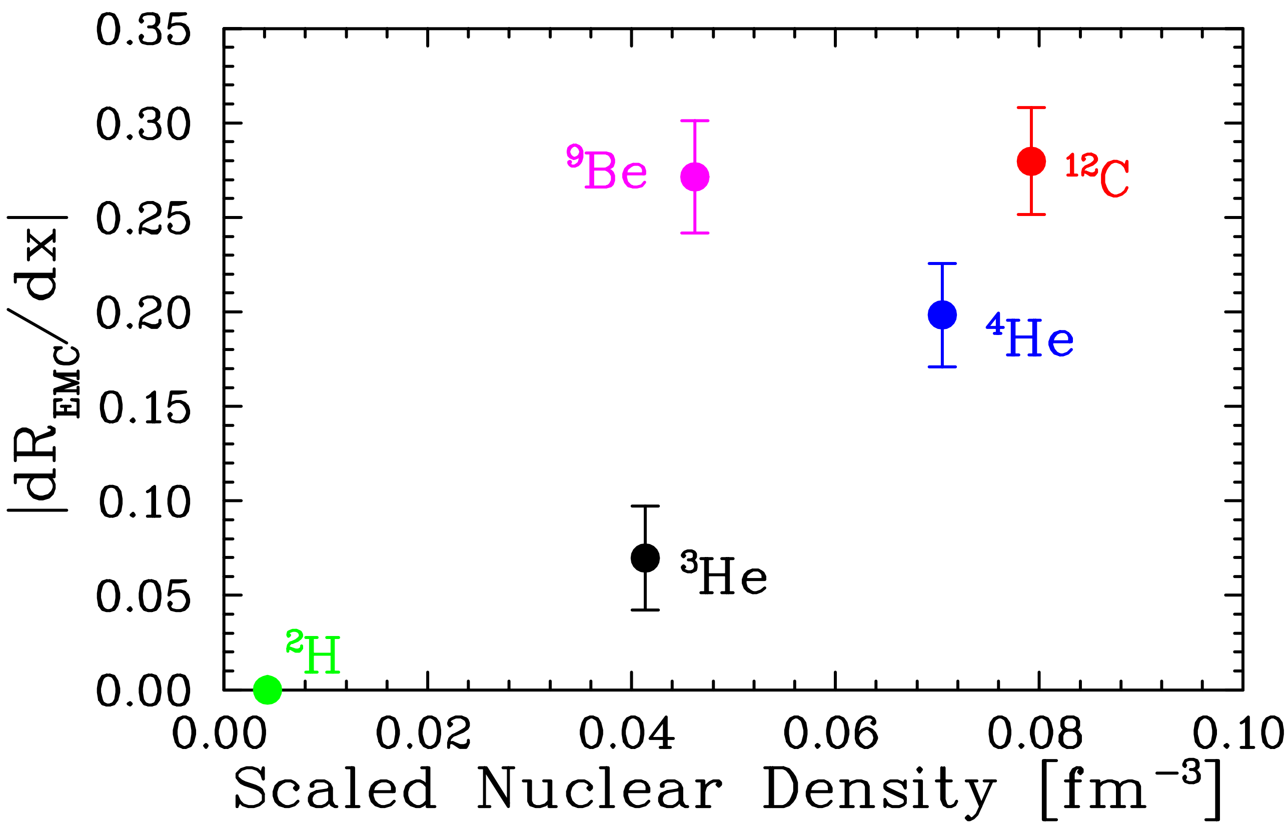
New Jefferson Lab EMC Effect Data

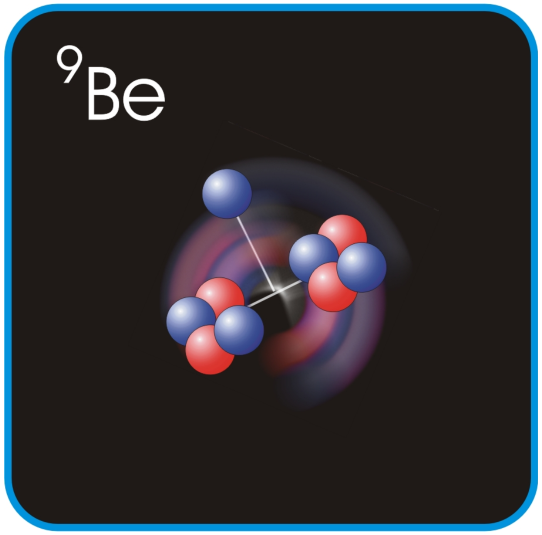
J. Seely *et al.*, Phys, Rev. Lett. **103** (2009) 202301.



New Jefferson Lab EMC Effect Data

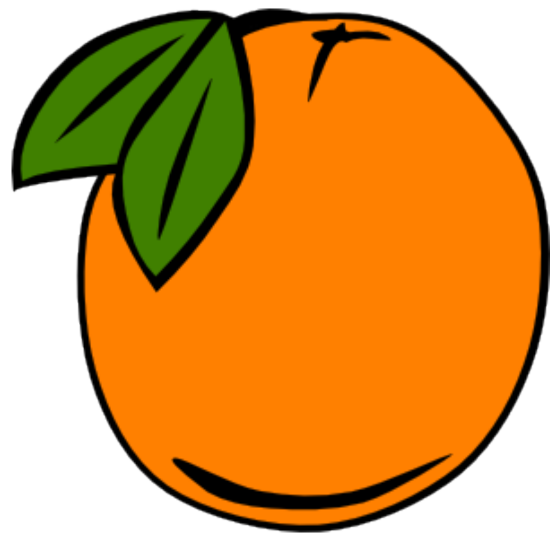
J. Seely *et al.*, Phys, Rev. Lett. **103** (2009) 202301.





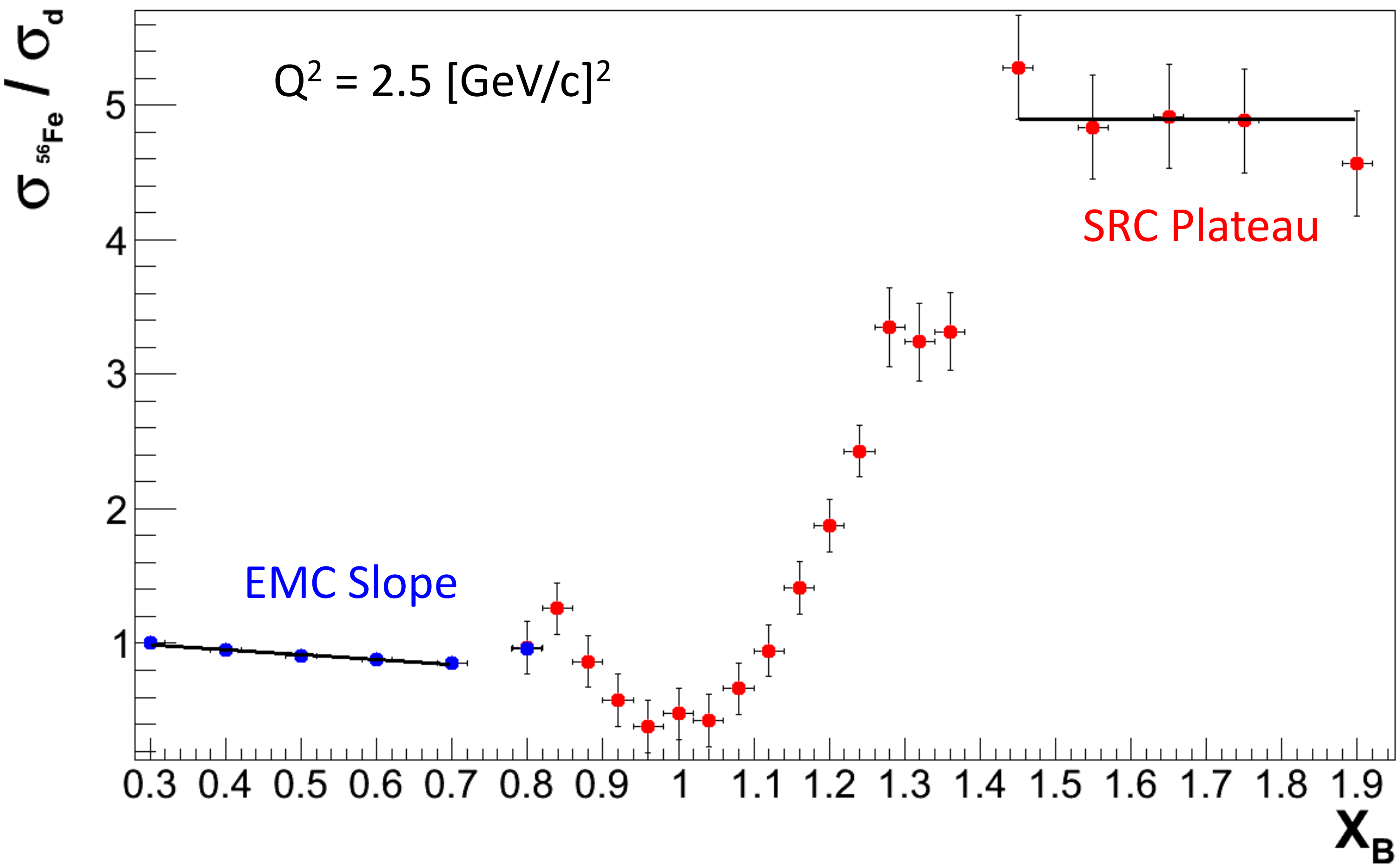
- Plot shows slope of ratio σ_A/σ_D at EMC region.
- EMC effect correlated with **local density** not average density.

So How These “DIS” Results Relate To The “SRC” Results?!



Holistic View of the EMC & SRC Data

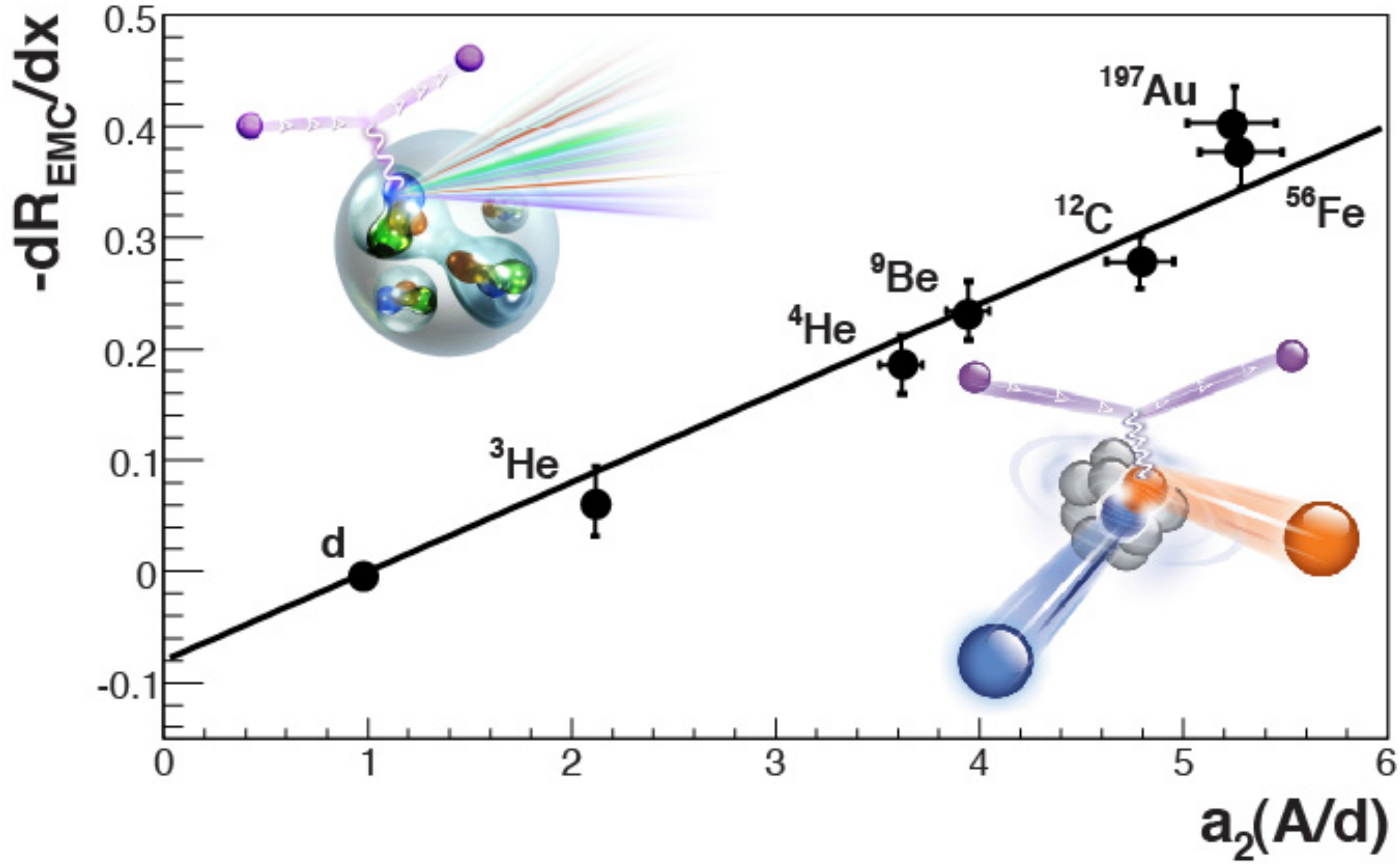
D. Higinbotham *et al.*, arXiv:1003.4497



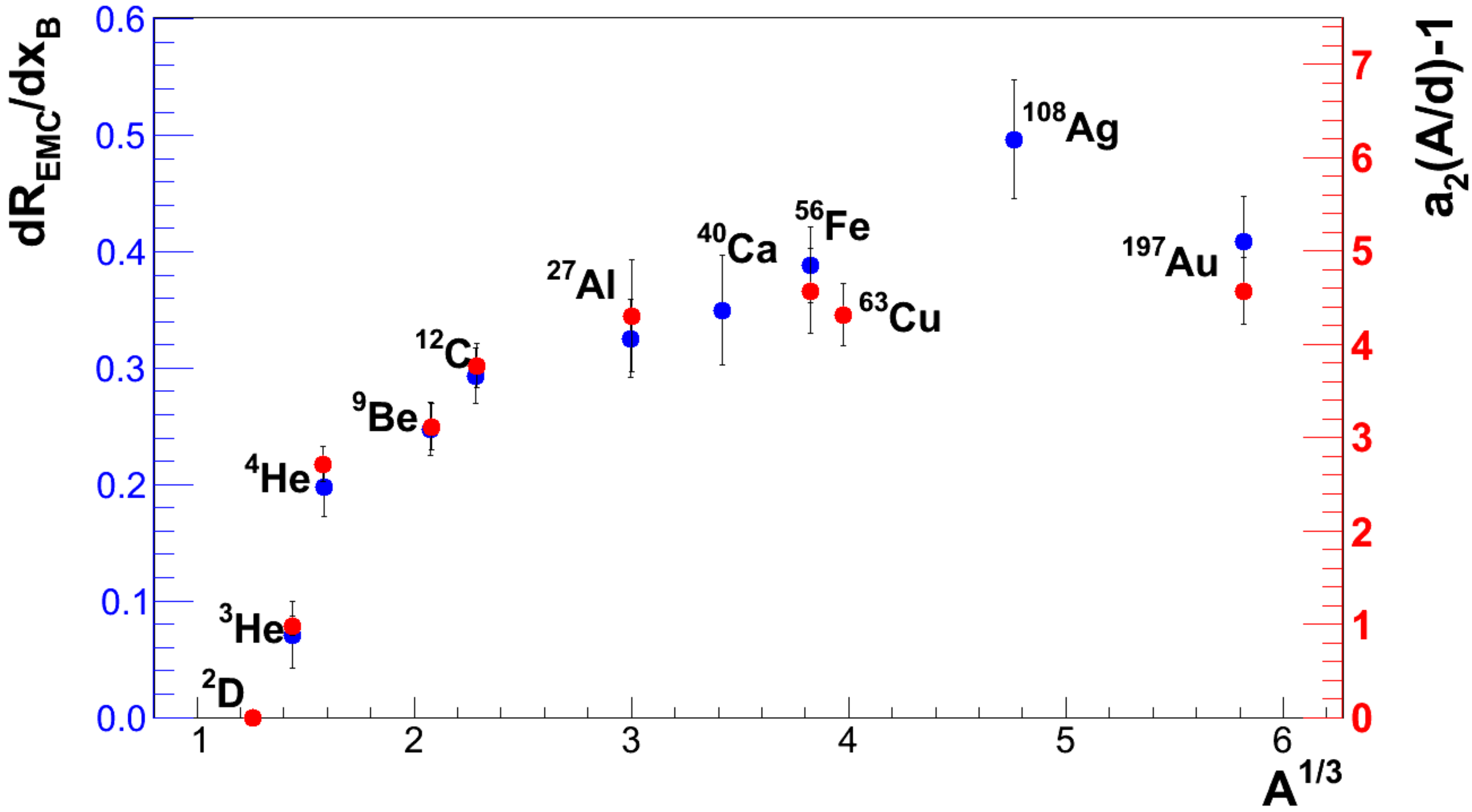
- Scaling plateaus are likely due to proton-nucleon **local density** correlations
- So could the **EMC** slopes (x_B<0.7) and **SRC plateaus** (x_B>1.5) correlated?!

SRC and EMC Correlation

L. Weinstein *et al.*, Phys. Rev. Lett. **106** (2011) 052301.

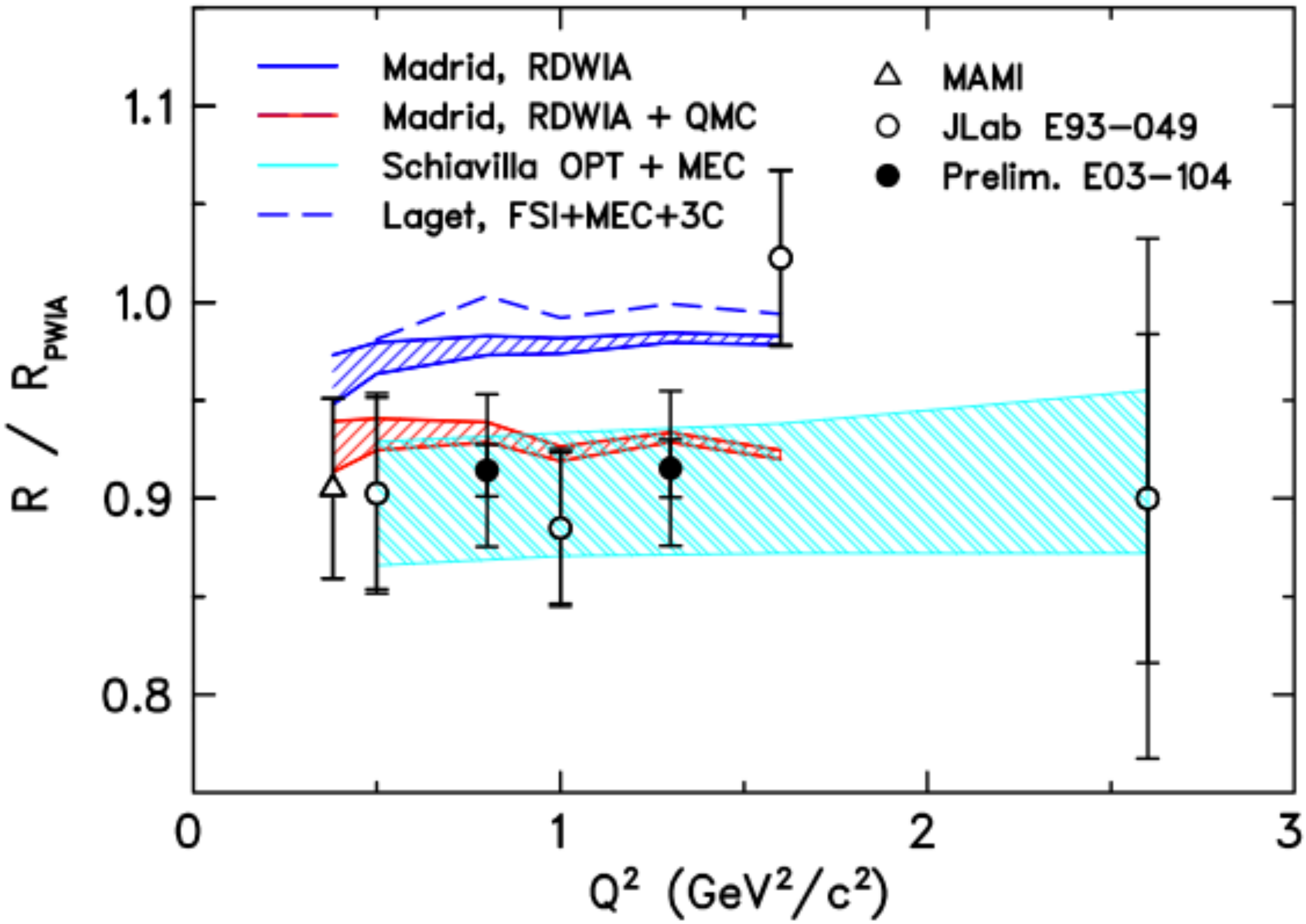


EMC Slopes & SRC Plateaus



Medium Modified Form Factors

Polarization Transfer Measurements on $^4He(e,e'p)^3H$ around the QE peak



Answer depends on your basis as both Madrid and Schiavilla can describe the data.

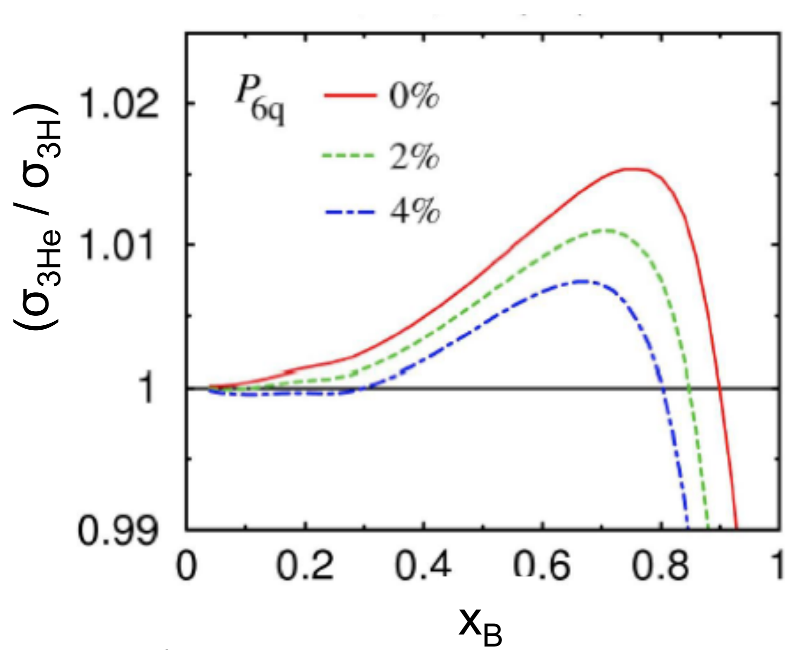
Summary

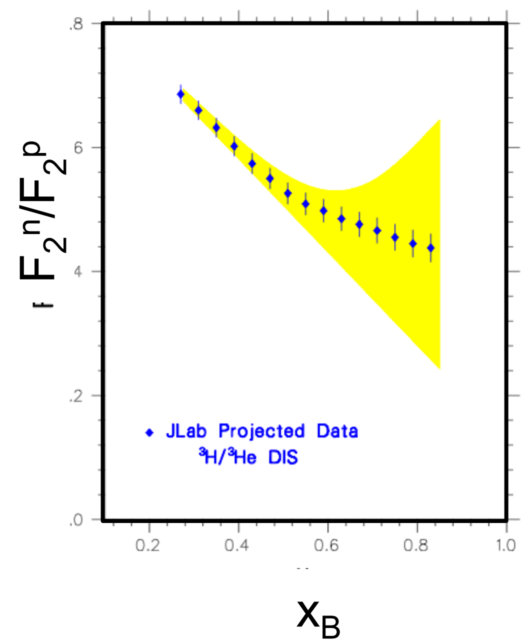
- There is a wealth of electron scattering data available and MANY codes with parameterizations of the measured cross sections. (e.g. XEMC has a amazing amount of (e,e') data parameterized)
- Mean field is a great starting point, but it is not the whole story.
- Interest new results show EMC & SRC effects to be strongly correlated. (i.e. nuclear effects even in DIS kinematics!)
- Open Questions
  - What exactly is the high momentum tail?

    (i.e. for momentum $p >> p_{fermi}$ $n_A(p) = N * n_D(p)$)
  - Is it hadronic, partonic , or some combination both?!
  - Can we use this correlation to make even more insights?!
- Many New EMC (x<1) and SRC (x>1) Experiments Coming with 12GeV Jefferson Lab, including ^3H & ^3He also well as A(e,e'X) data mining of 6 GeV CLAS data.
- **And yes, Jefferson Lab could do argon measurements of (e,e'X) but it would need to be well thought out experiment [range of Q2, parallel & perp. kinematics, etc].**

Select Upcoming 12GeV Experiments

- **E12-10-103 & E12-11-112** plans ^3He & ^3H (e,e') SRC & EMC Measurements
  - DIS 3He/3H is a text book u/d experiment
  - x>1 to further investigate SRC and possible link EMC effect
- **E12-10-008 & E12-06-105** plans a survey of (e,e') nuclei from light to heavy.
  - Exact list being optimized, but goal is to cover EMC x < 1 and SRC x > 1 for each nucleus
- **E12-11-002** recoil polarization in the 4He(e,e'p)3H, 2H(e,e'p)n, and 1H(e,e'p) reactions
  - Classic medium modification experiment pushed to higher precision and higher missing momentum
- **E12-10-003** will measure D(e,e'p)n to extreme large missing momentum.

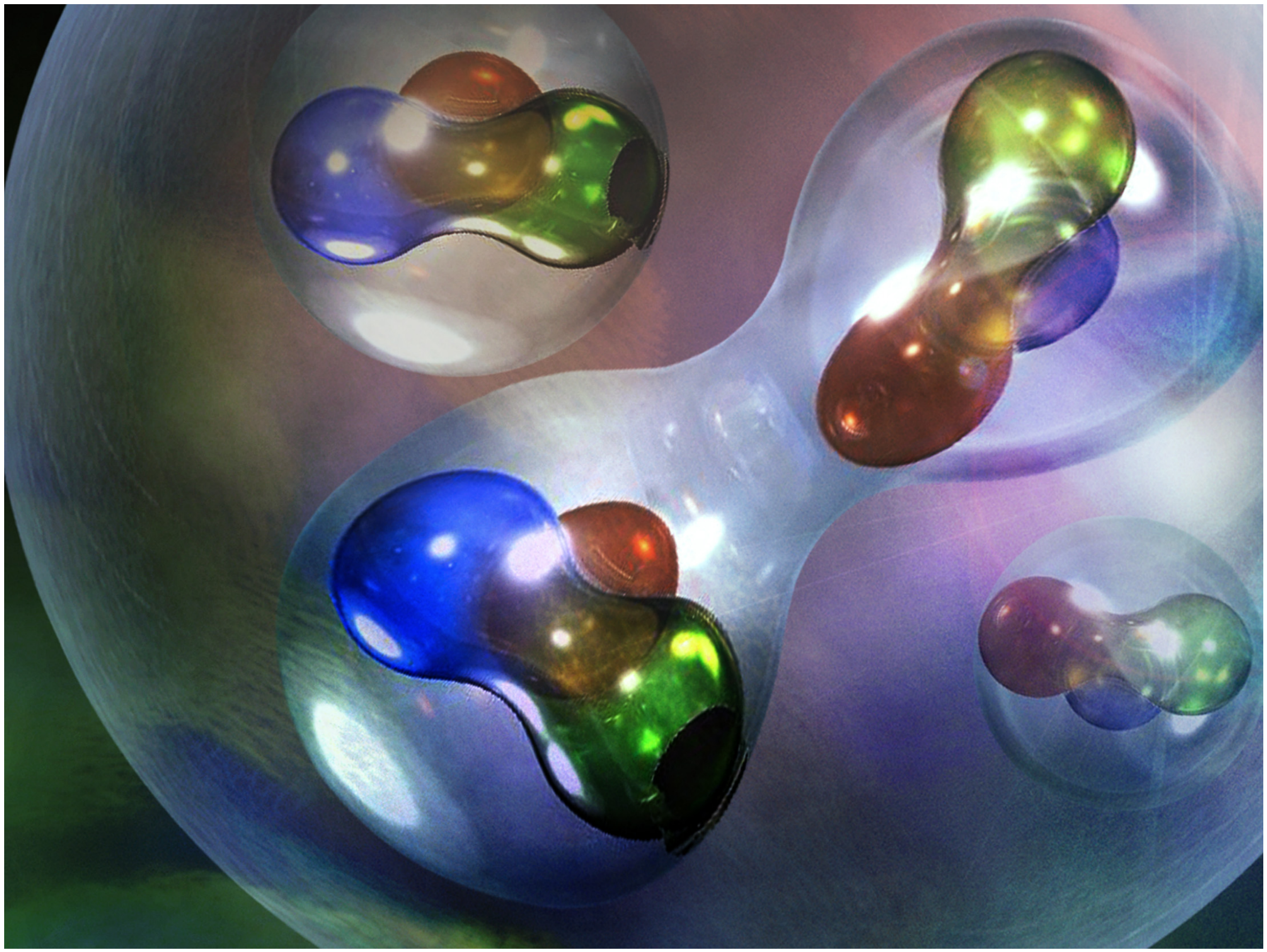




Backup Slides

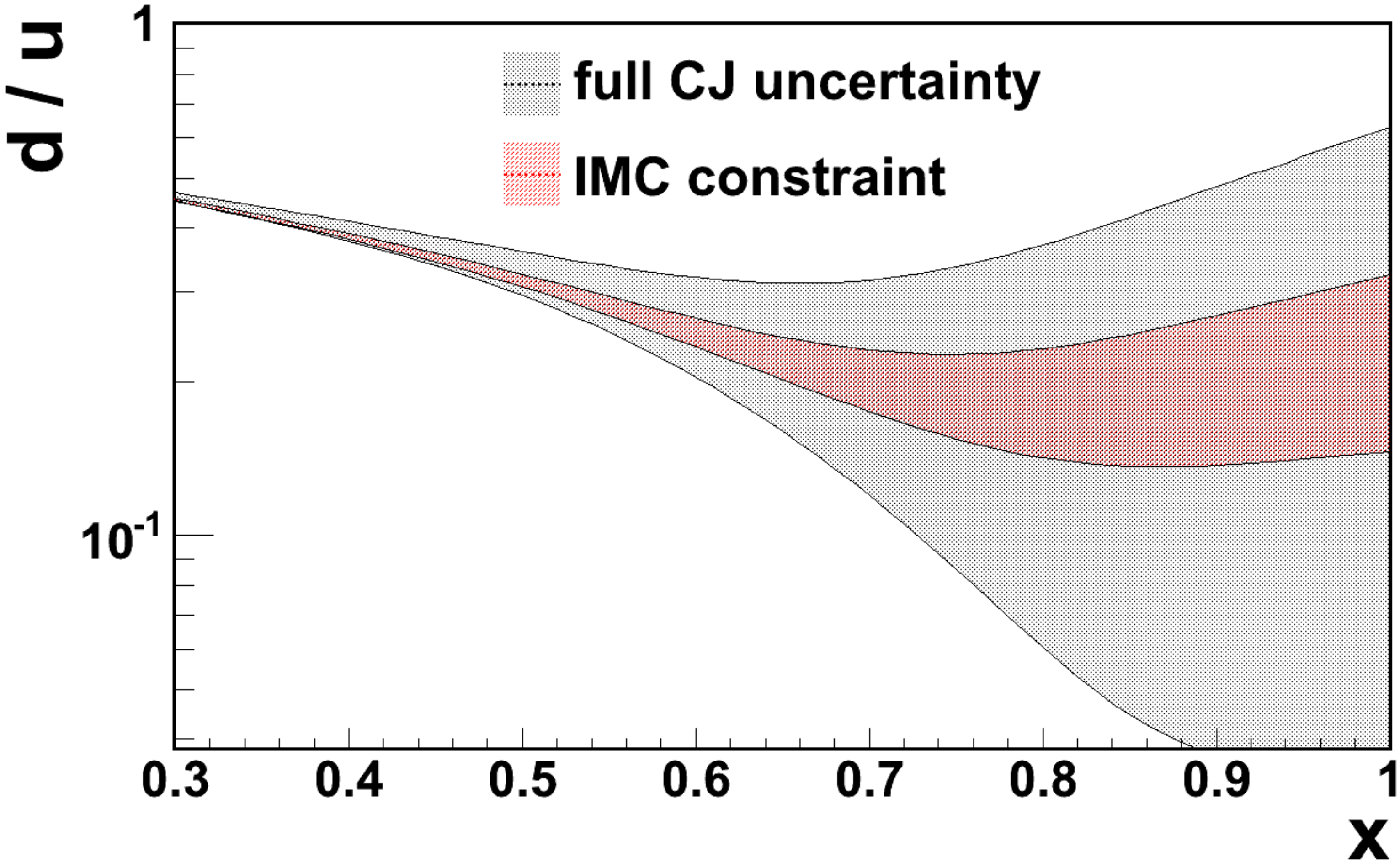
Revisiting the bag model (v2.0).

Discussions with A. Kerman with artwork by Joanne Griffen (Jefferson Lab)



Using SRC & EMC to get d/u ratios

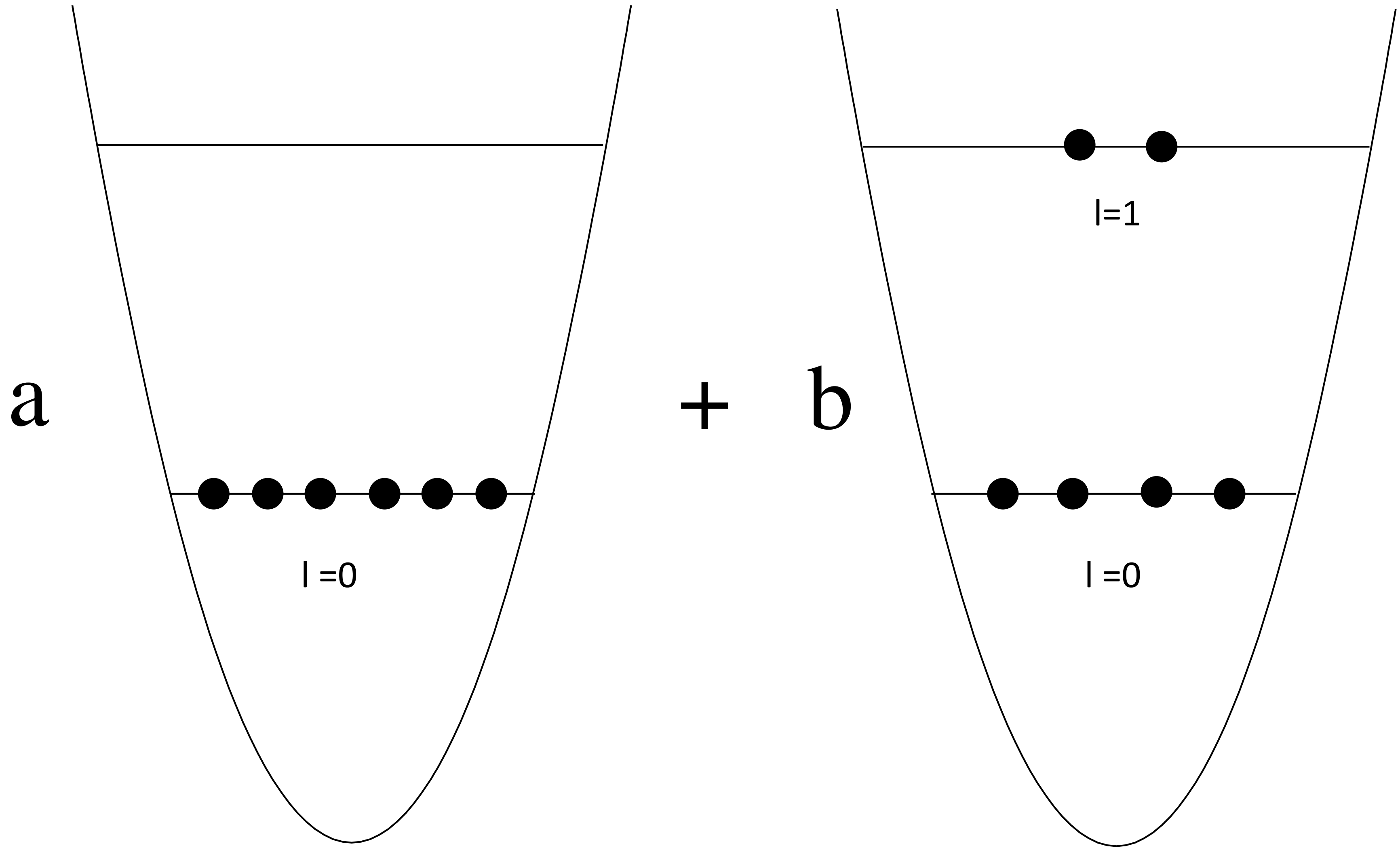
CTEQ-Jefferson Lab (CJ): A. Accardi *et al*., Phys. Rev. D **84**, 014008 (2011).
In-Medium Correction (IMC): O. Hen *et al*., Phys. Rev. D **84** (2012) 117501.



Result is between the SU(6) symmetry limit of ½ and the scalar di-quark dominance limit of 0.

Quark State of Overlapping Nucleons

Deuteron Has Quadripole Moment In All Frames Of Reference



^{40}Ca to ^{48}Ca (e,e') Preliminary Ratios