Nucleon-Nucleon Correlations and the origins of the EMC Effect

Axel Schmidt

2019 Frontiers and Careers, Paphos Cyprus

October 27, 2019

The EMC Effect:
a major open puzzle in nuclear physics

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THE RATIO OF THE NUCLEON STRUCTURE FUNCTIONS F_2^N FOR IRON AND DEUTERIUM

The European Muon Collaboration

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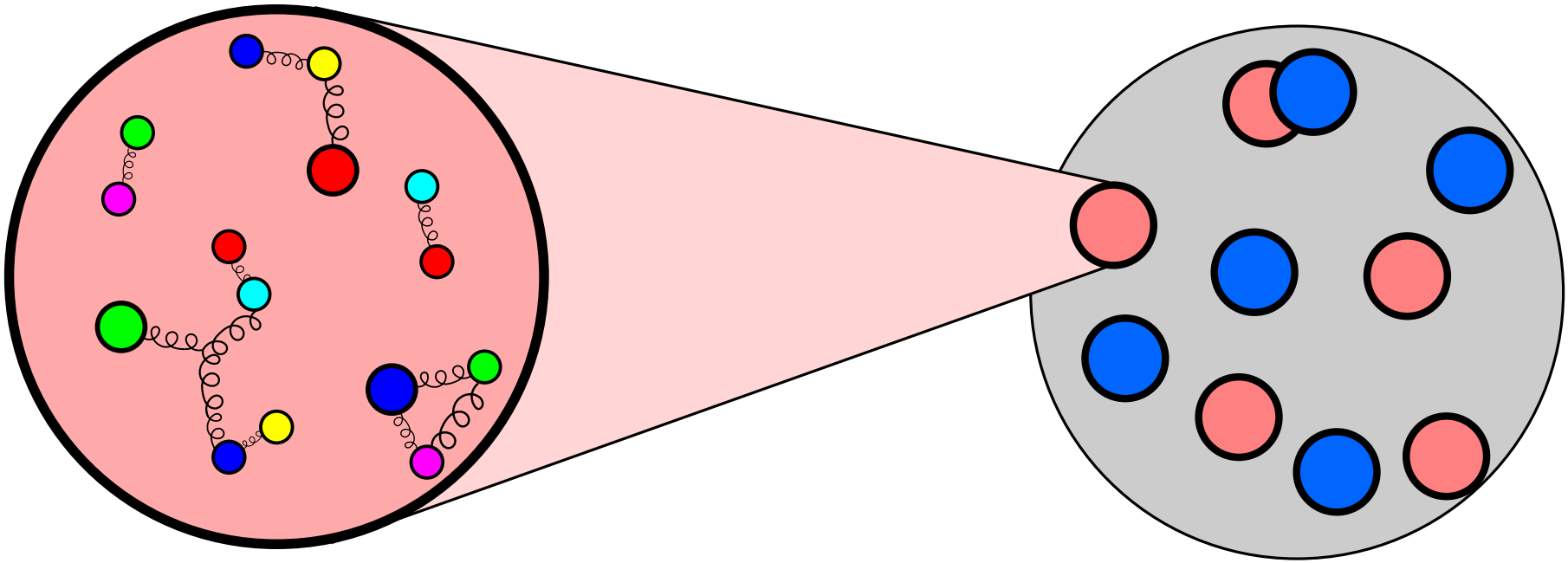
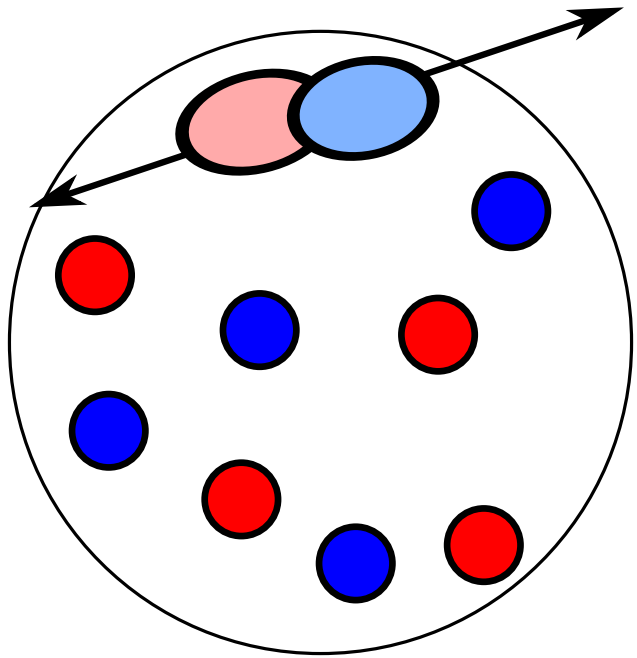
CERN [a]–DESY (Hamburg) [b]–Freiburg [c]–Kiel [d]–Lancaster [e]–LAPP (Annecy) [f]–Liverpool [g]–Marseille [h]–Oxford [i]–Rutherford [j]–Sheffield [k]–Turin [ℓ]–Wuppertal [m]

Quarks and nuclei are scale-separated.



Gigaelectron-Volt scale (GeV) $\gg$ Megaelectron-Volt scale (MeV)

Short-range correlations are ubiquitous in nuclei.



In my talk today:

1. Background
   - Review of structure functions and the EMC Effect
2. The SRC-EMC Connection
   - Could the EMC Effect stem from nuclear correlations?
3. Experiment
   - How to put this hypothesis to the test.

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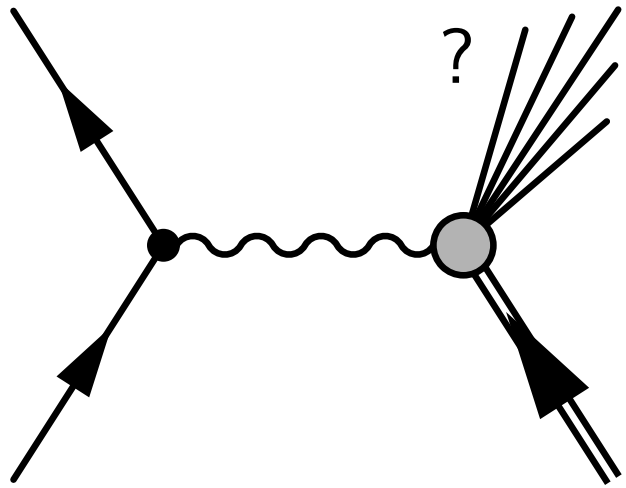
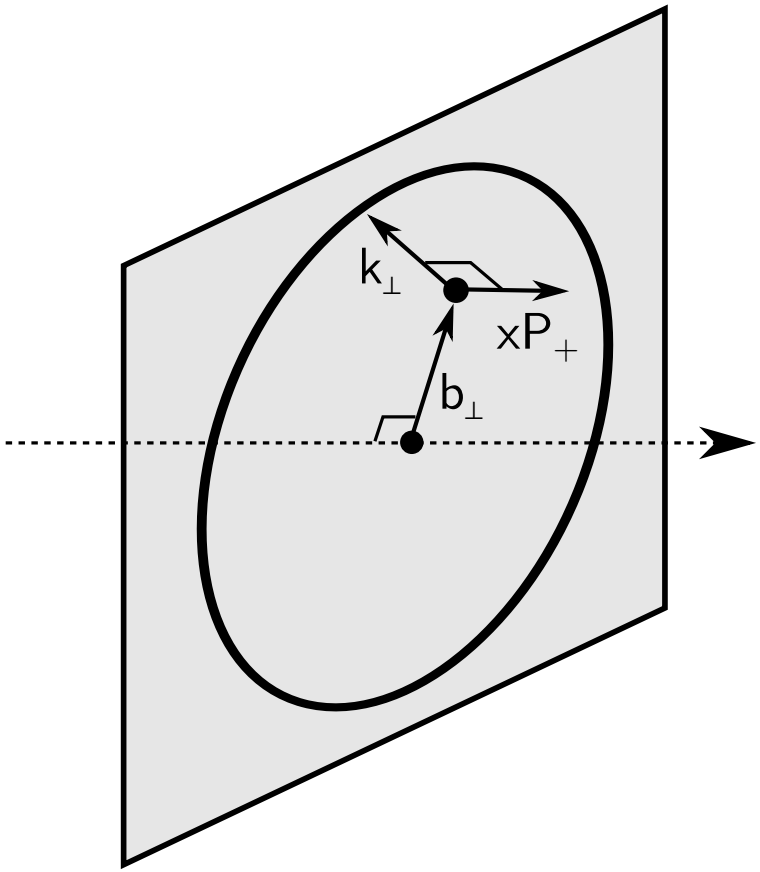
Structure functions "veil our ignorance."



"A successful theory must enable us to calculate the structure functions and form factors. . ."

–David Griffiths, Intro to Elementary Particles

We can connect structure functions to internal parton distributions.



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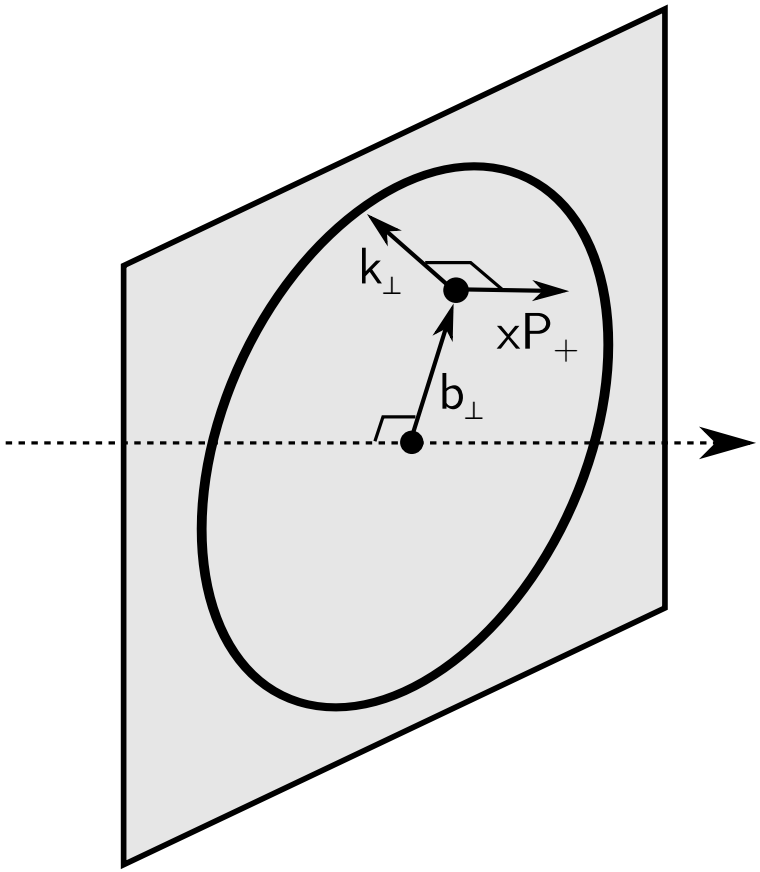

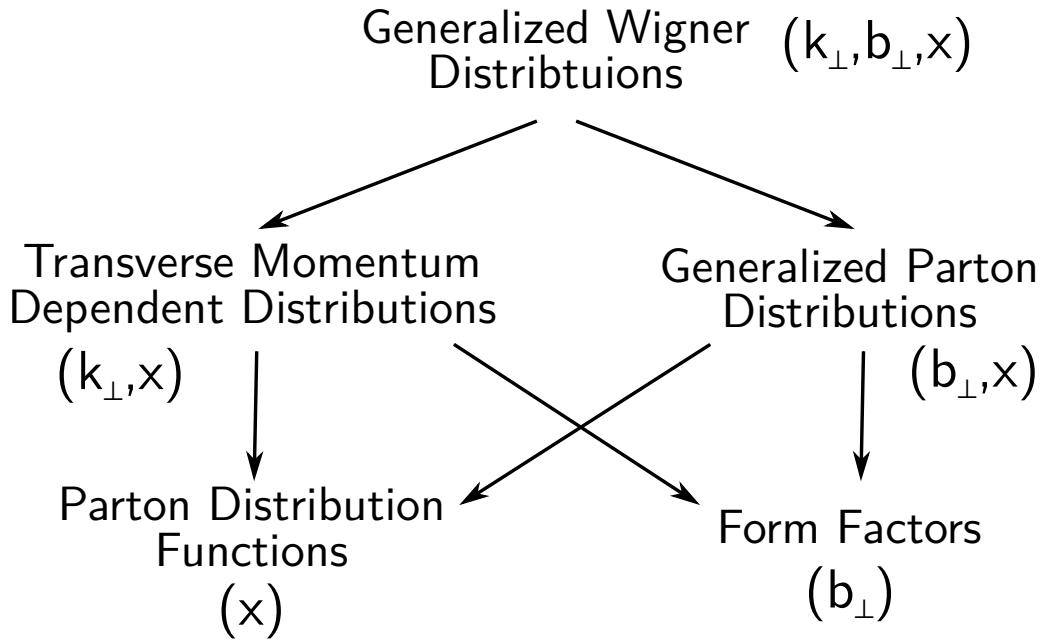

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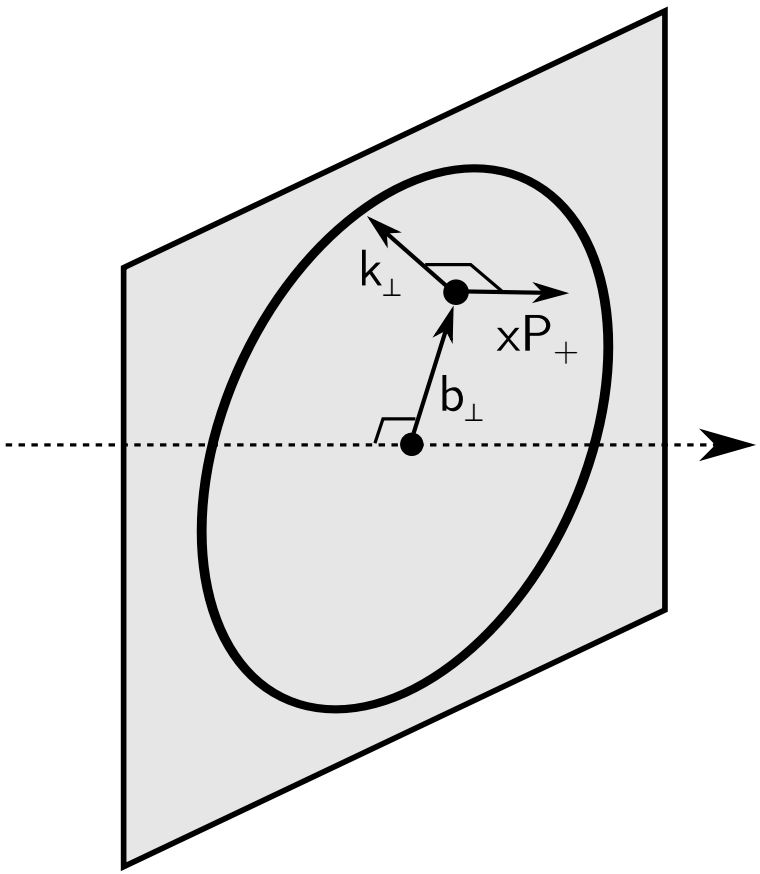
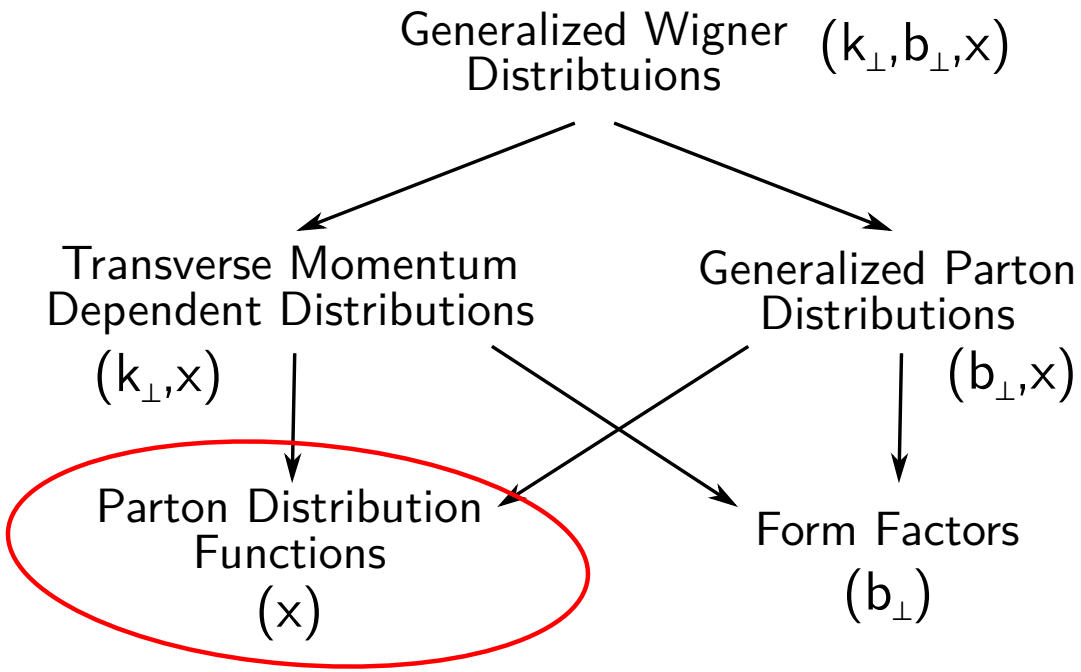
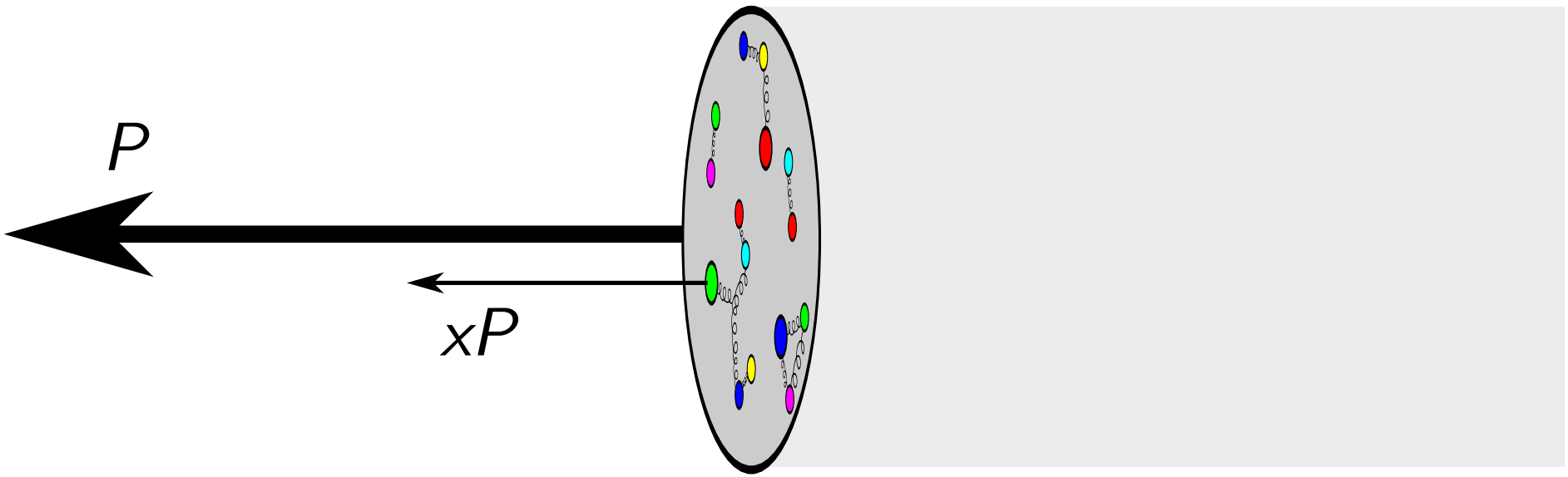




Proton structure is simplified in the "infinite momentum frame"



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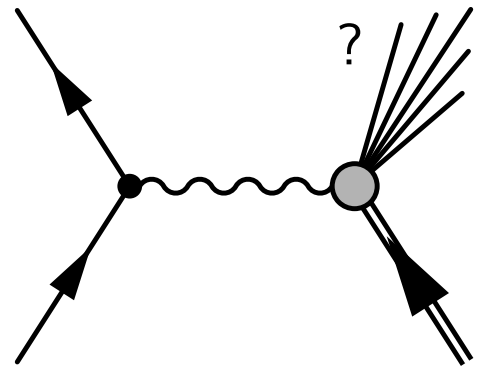

For very large energy and momentum transfers:

$$\frac{d\sigma}{d\Omega dE'} = \frac{E'\alpha^2}{MEQ^4}\left[\frac{Q^2}{x} + 2xM^2\left(\frac{EE'}{Q^2} - 1\right)\right]F_2(x)$$

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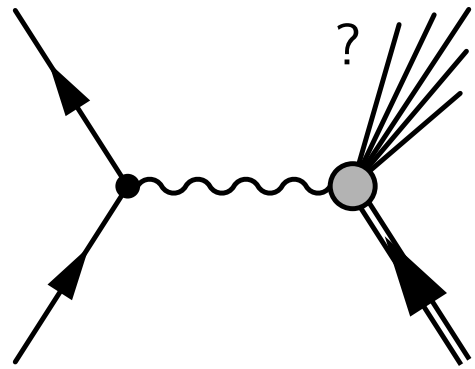

For very large energy and momentum transfers:

$$\frac{d\sigma}{d\Omega dE'} = \qquad\qquad K(E,\theta,E') \times F_2(x)$$

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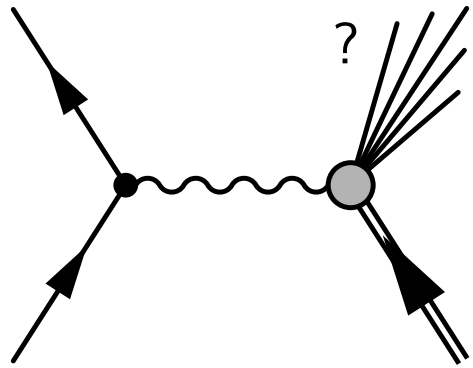
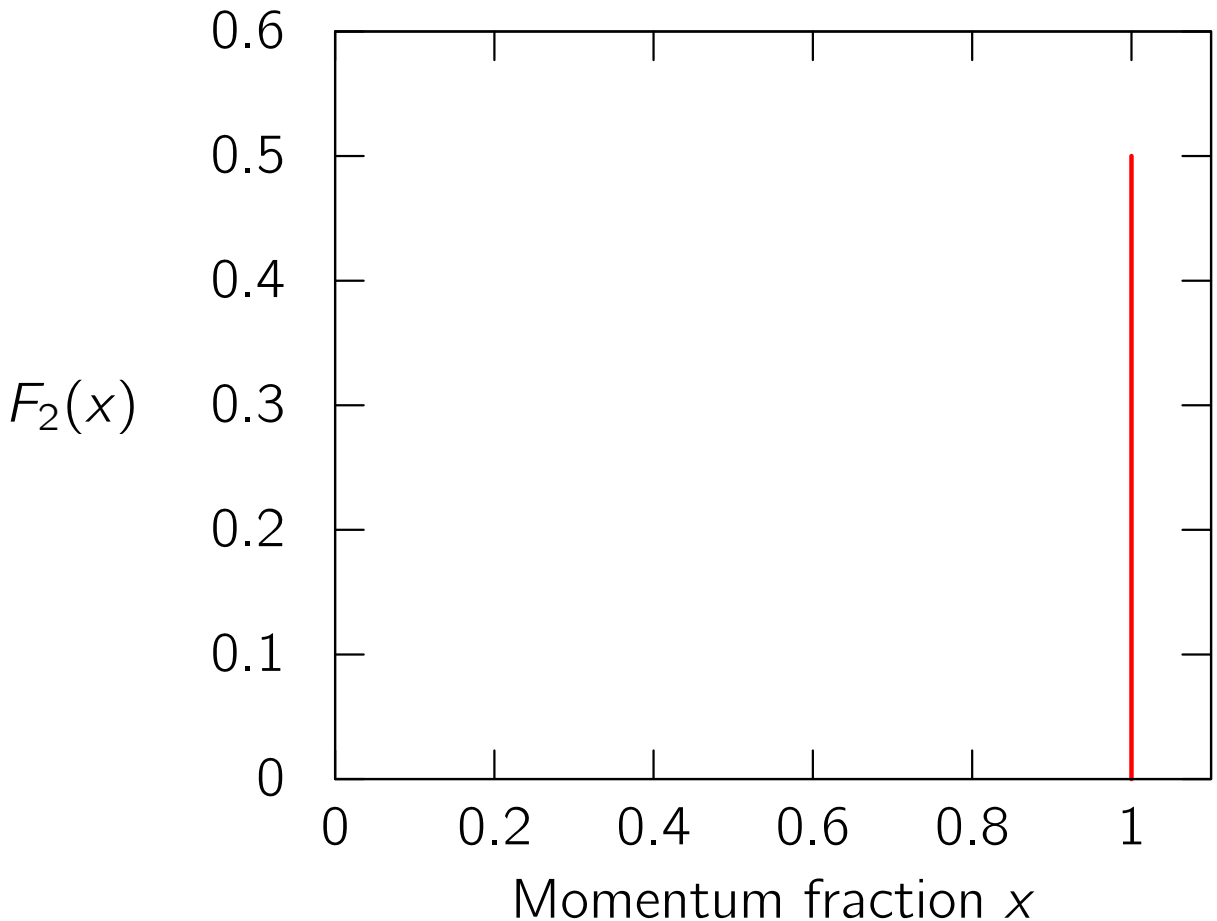
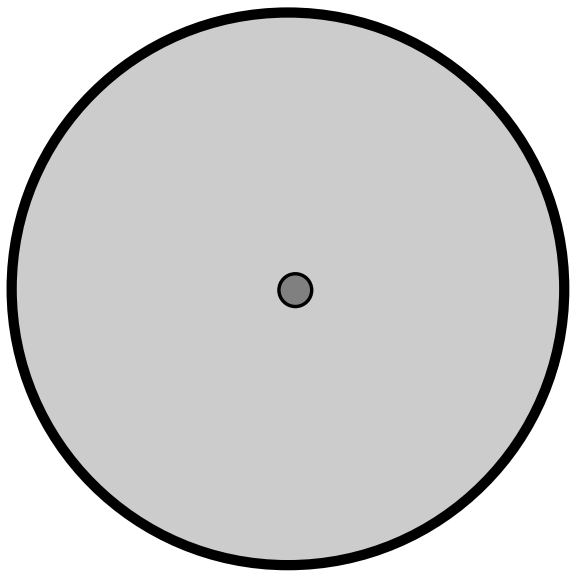


For very large energy and momentum transfers:

$$\frac{d\sigma}{d\Omega dE'} = \quad K(E,\theta,E') \times \sum_f x e_f^2 (q(x) + \bar{q}(x))$$

Momentum distribution, F_2, can tell us about the structure of the proton.





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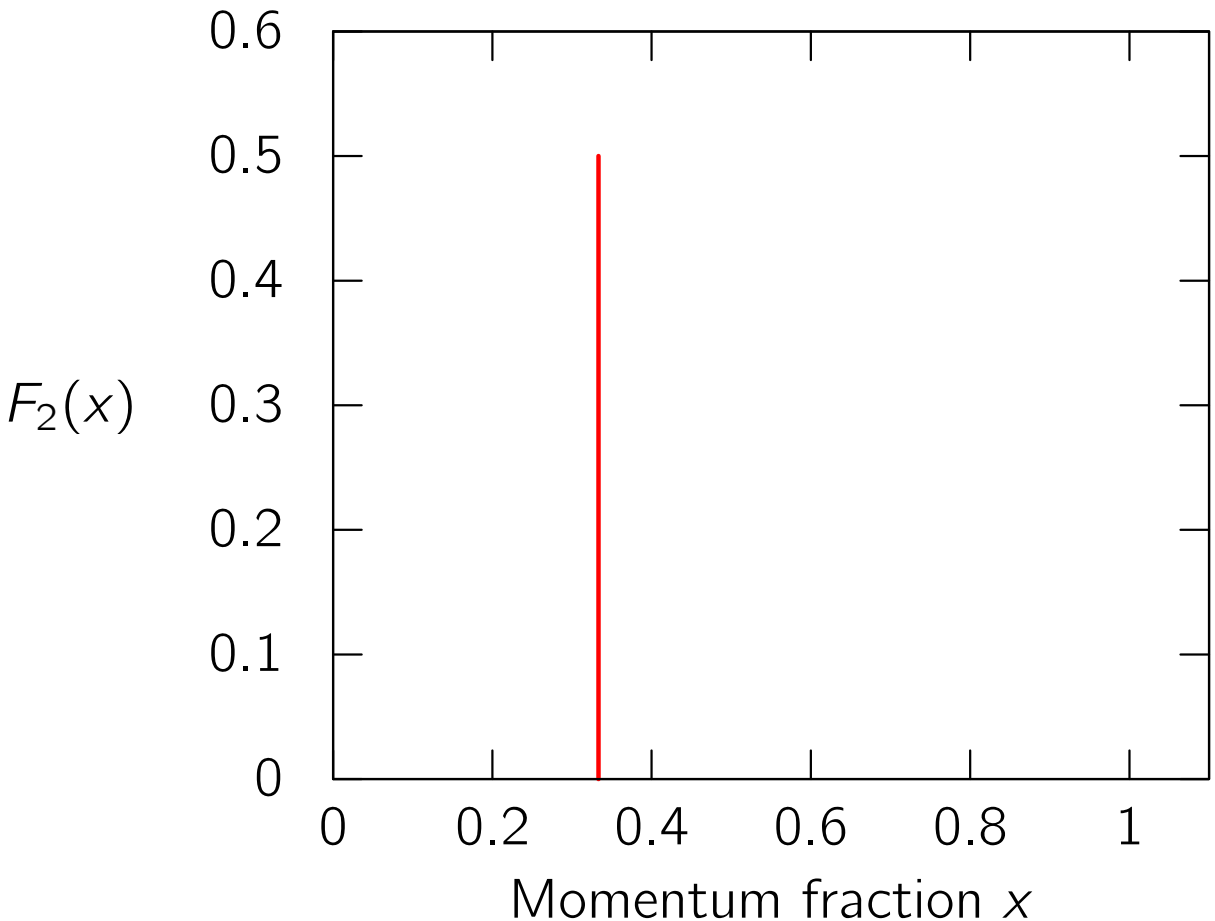

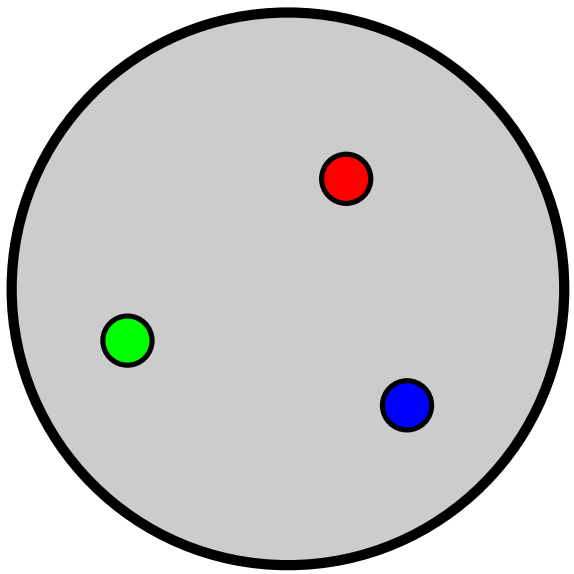

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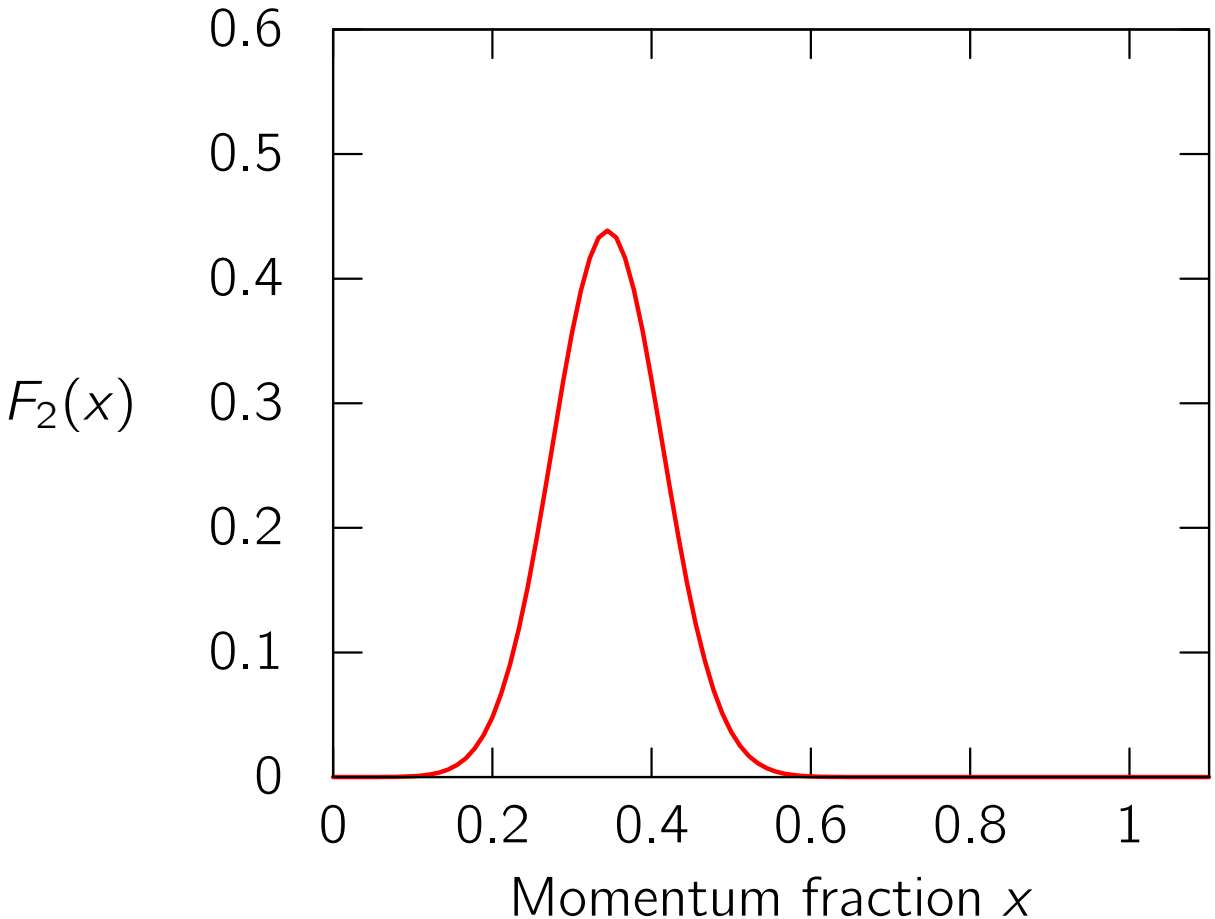

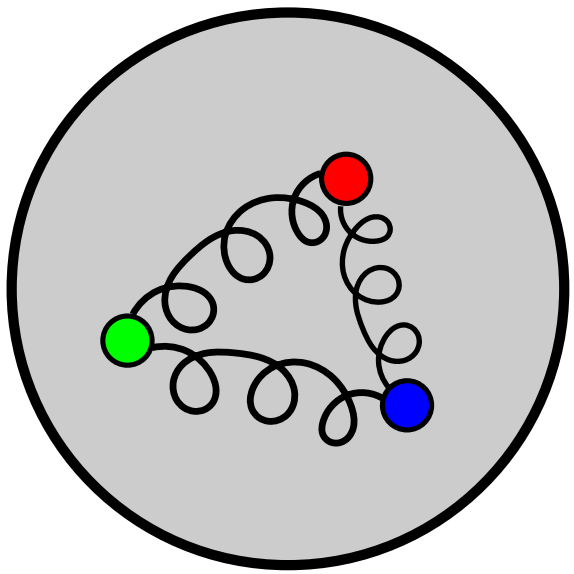

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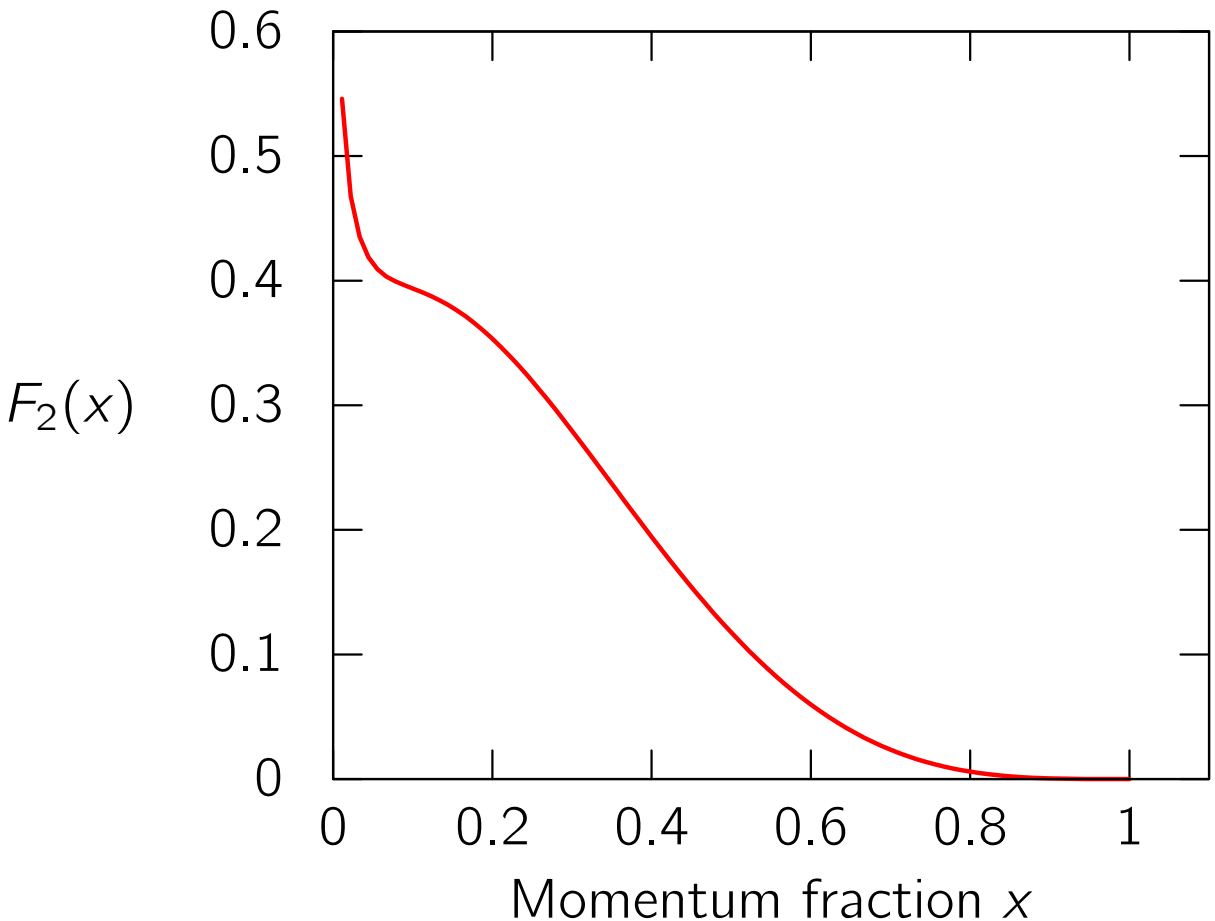

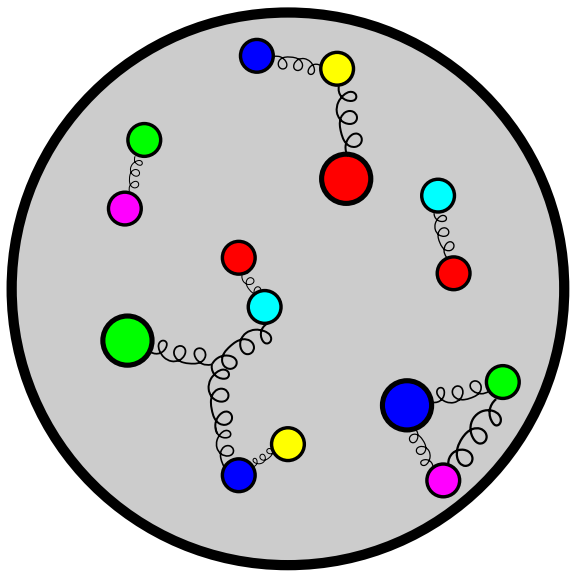

When learning about a new structure function ask questions!

- What experimental cross-section?
- What connection to hadron structure?
- In what limits is this connection accurate?

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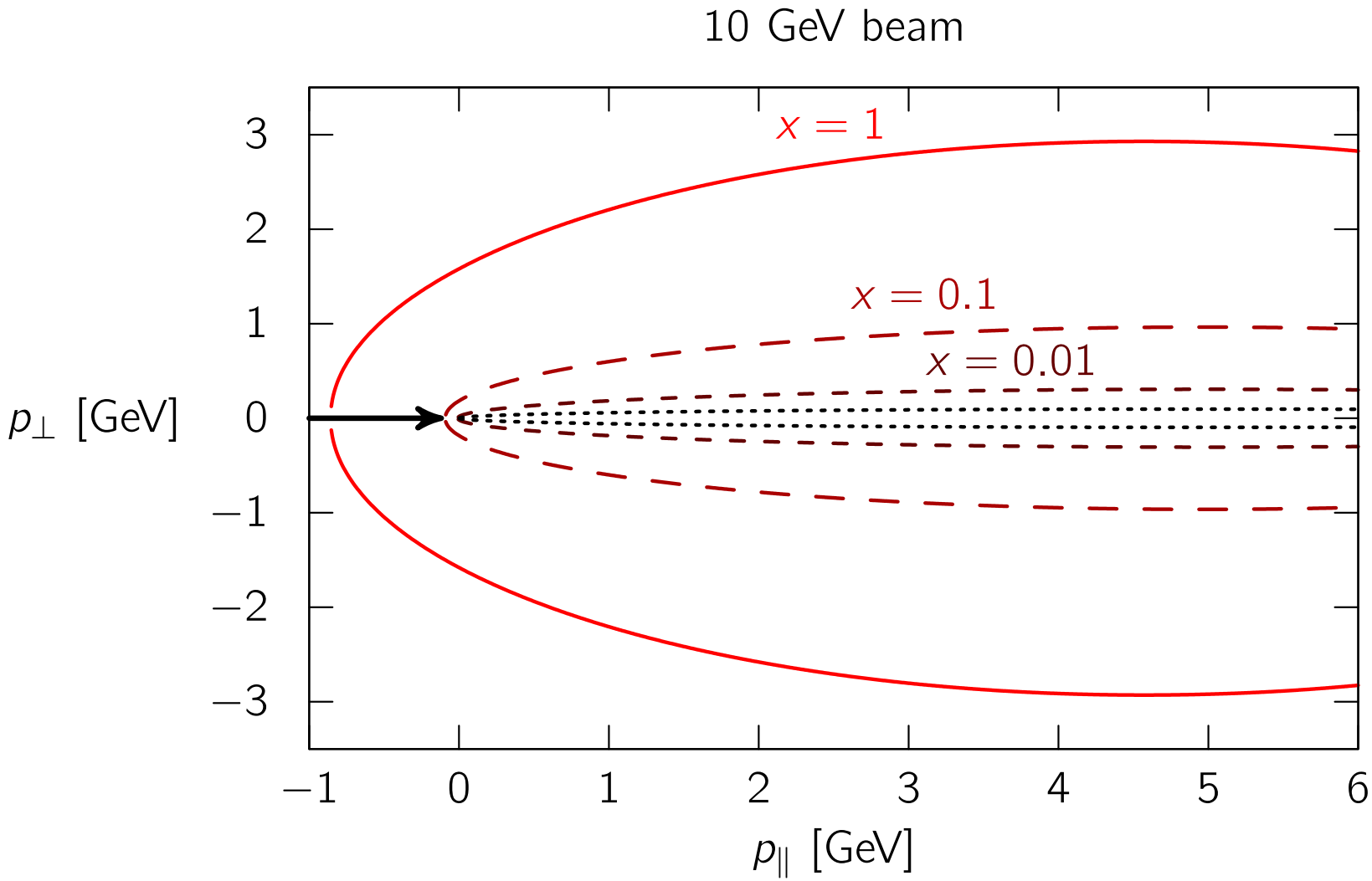
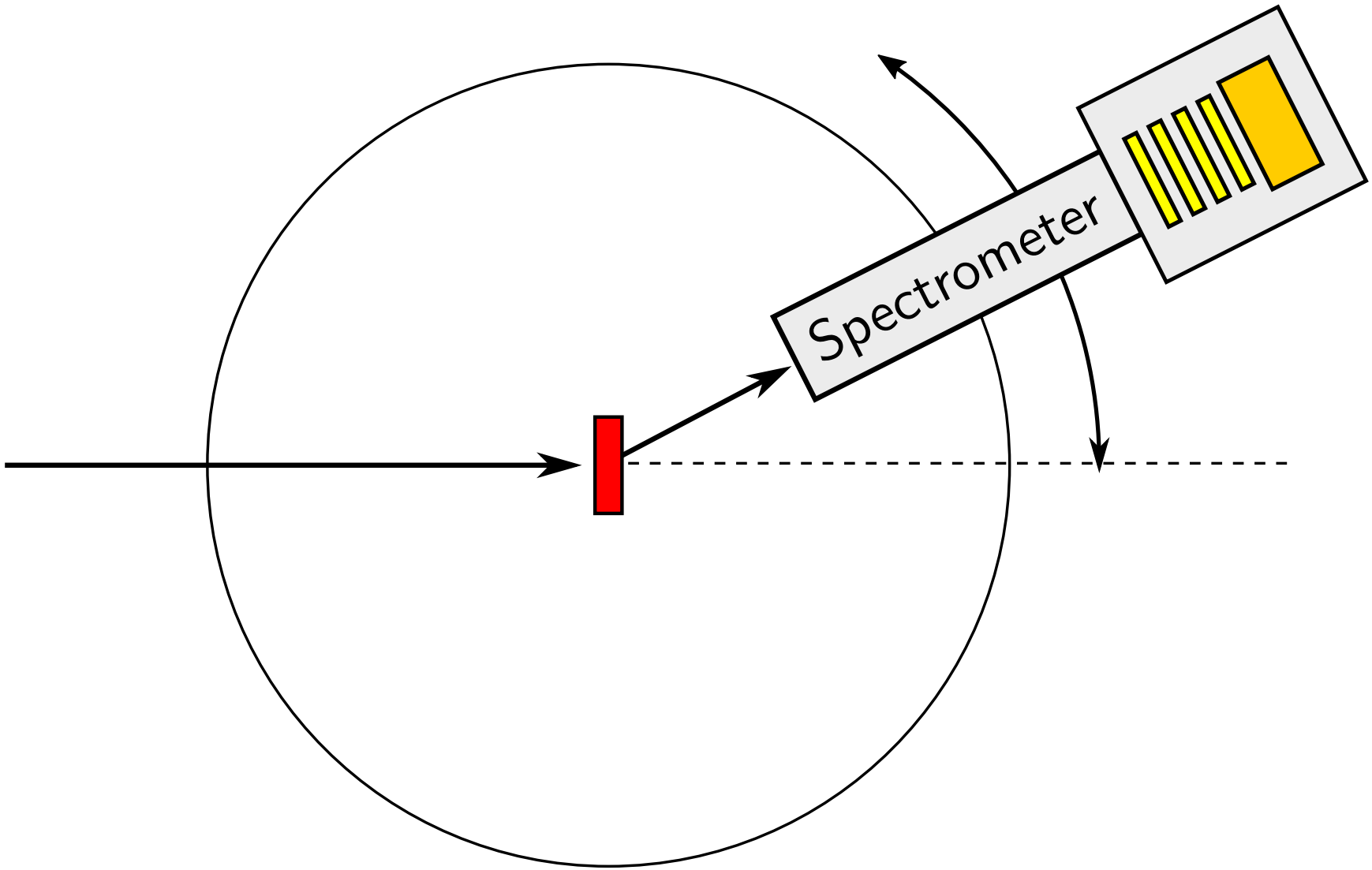
  Distribution of momentum fraction, x
- In what limits is this connection accurate?
  $Q^2 \longrightarrow \infty$, $\omega \longrightarrow \infty$

The set-up can be configured to select x.



Cross-sections can be measured
with high-resolution spectrometers.



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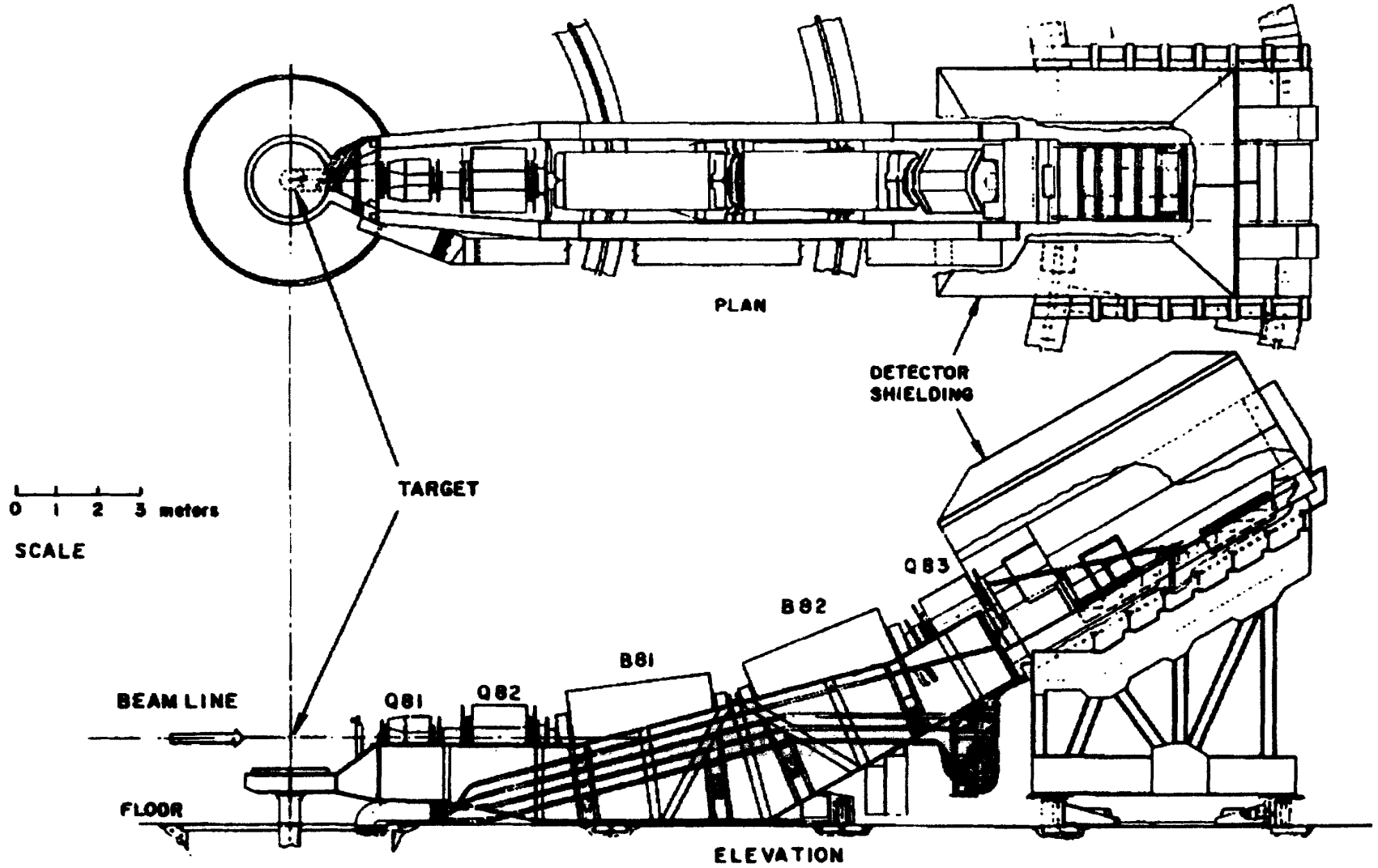

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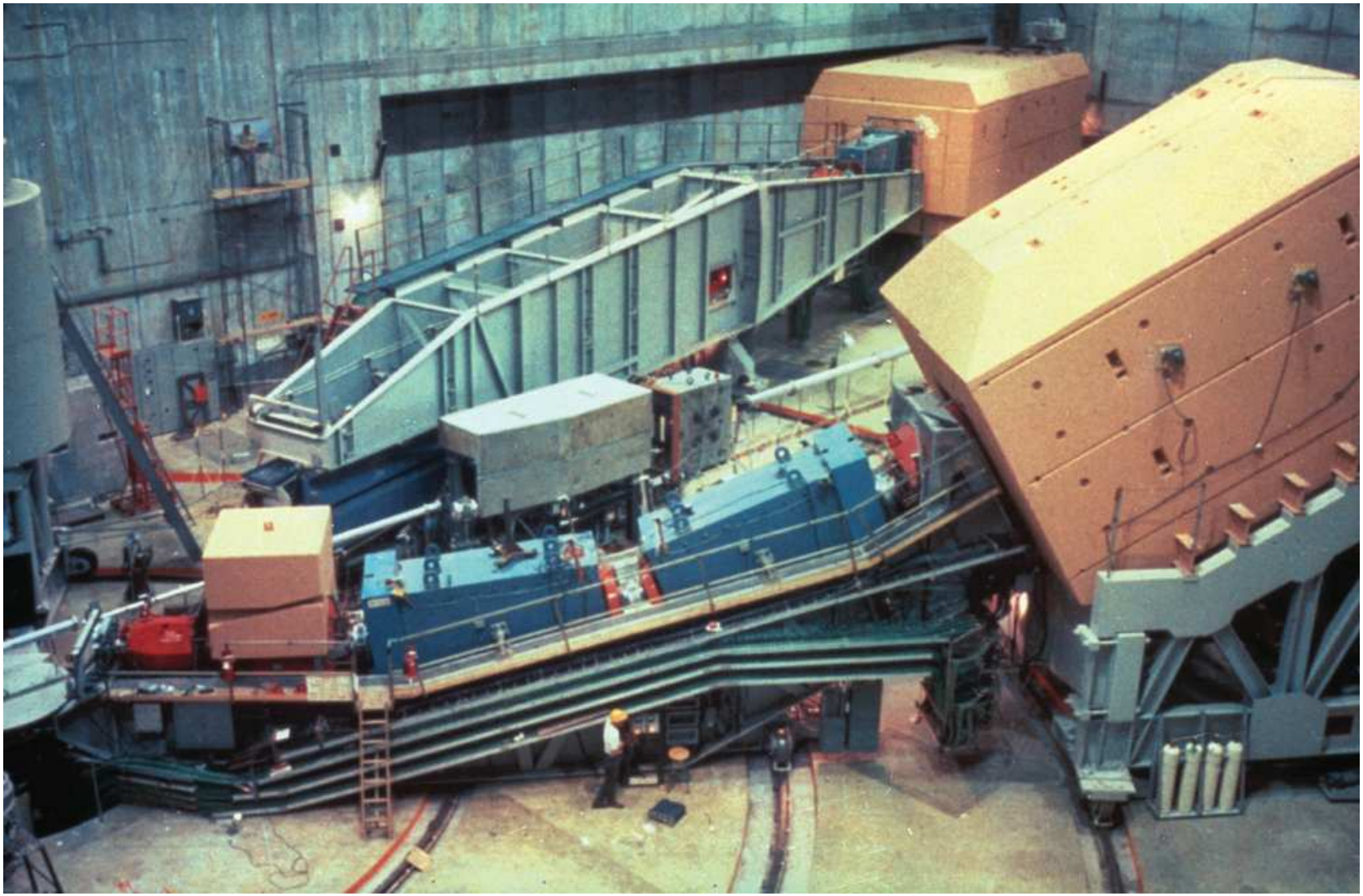
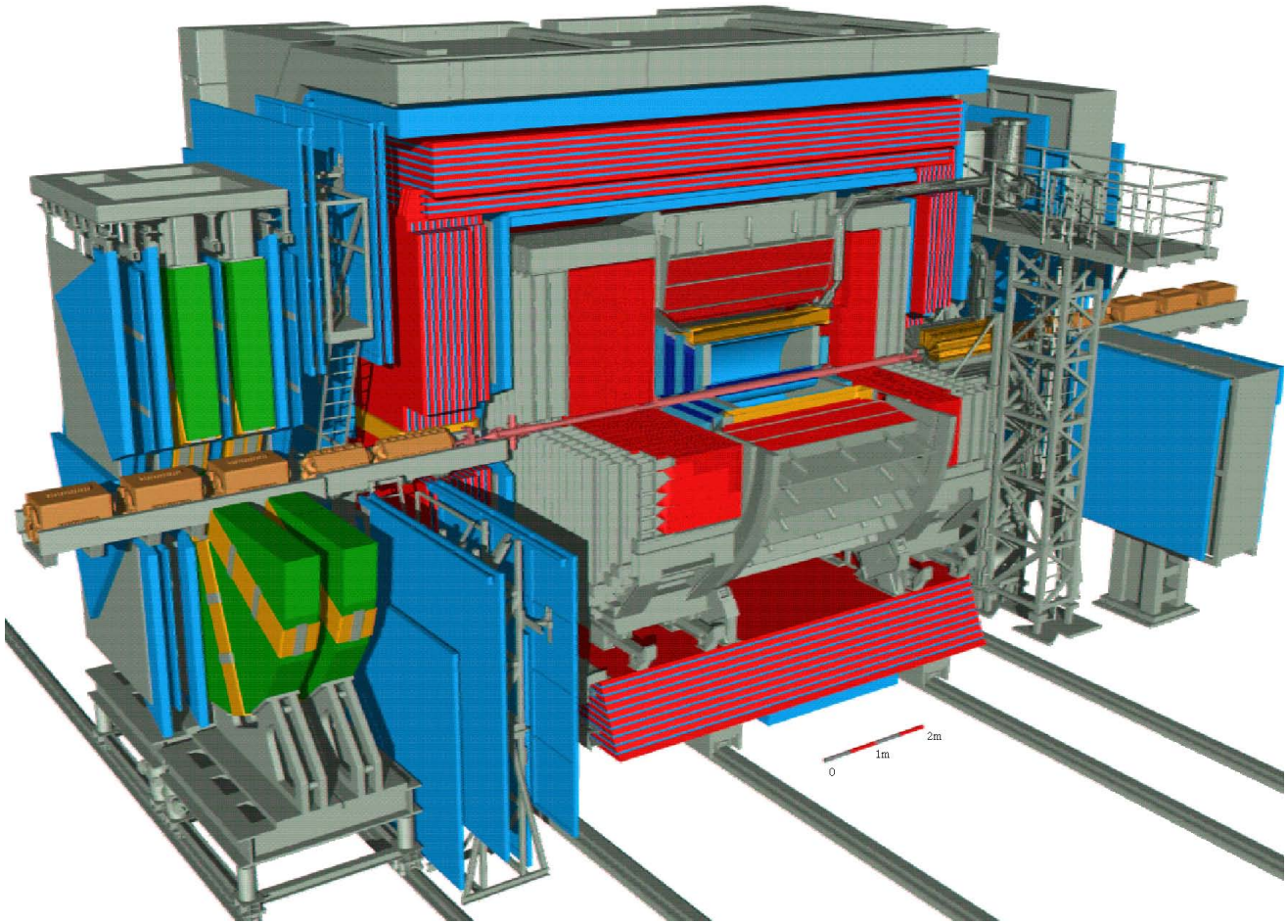
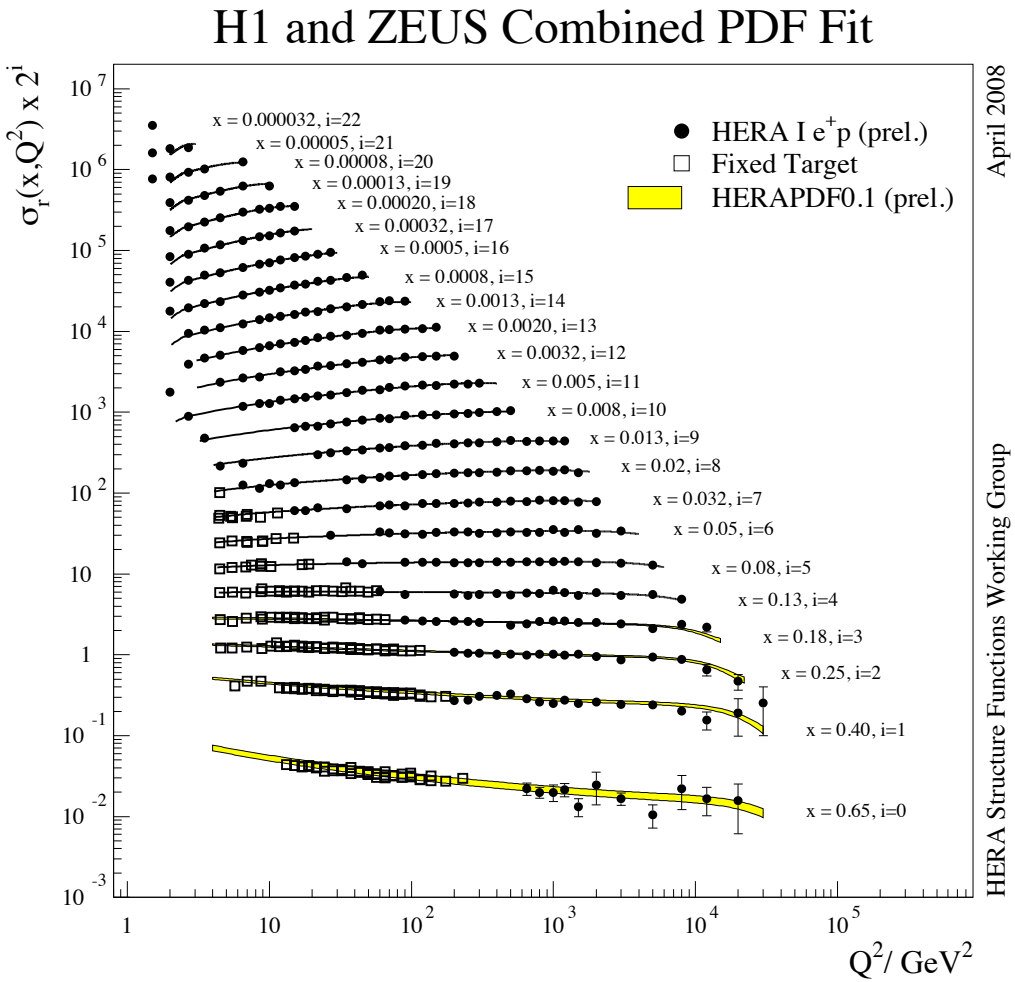


Alternatively, trade resolution for acceptance.

ZEUS Experiment, DESY



Mapping out the quark momentum in protons has been a triumph of DIS and QCD.



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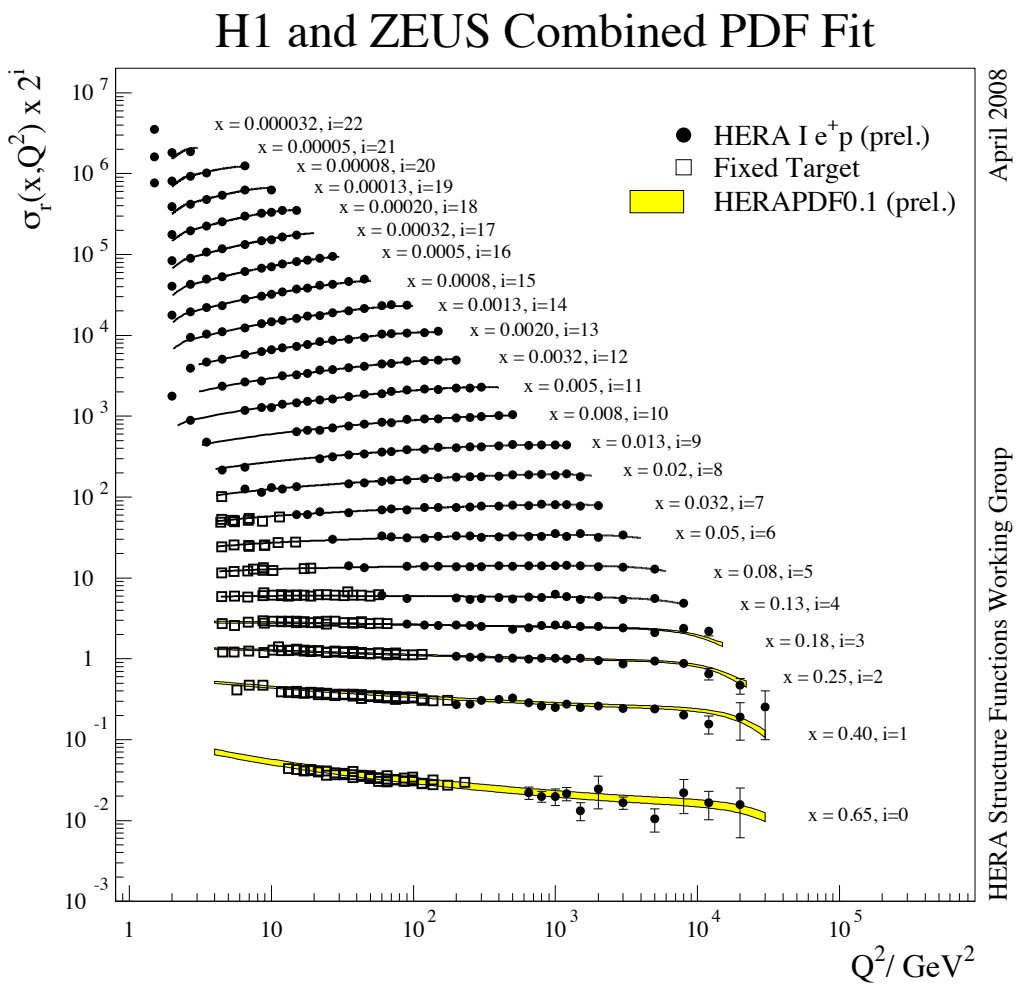
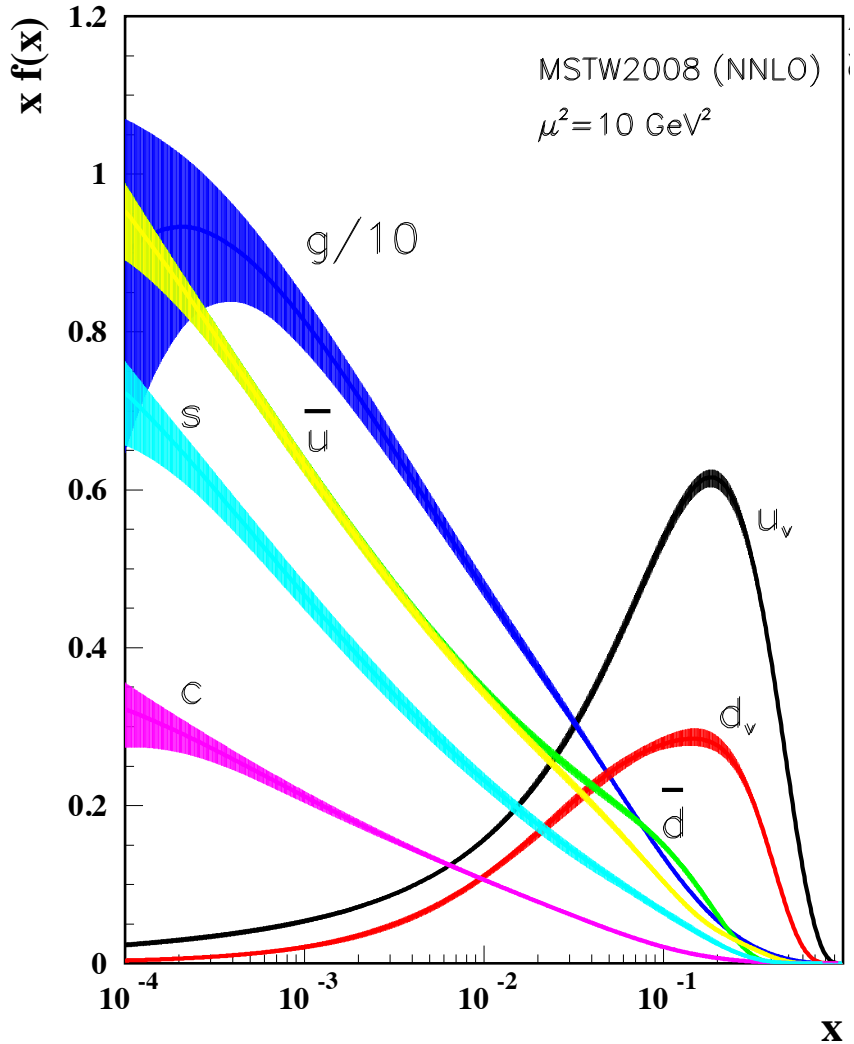
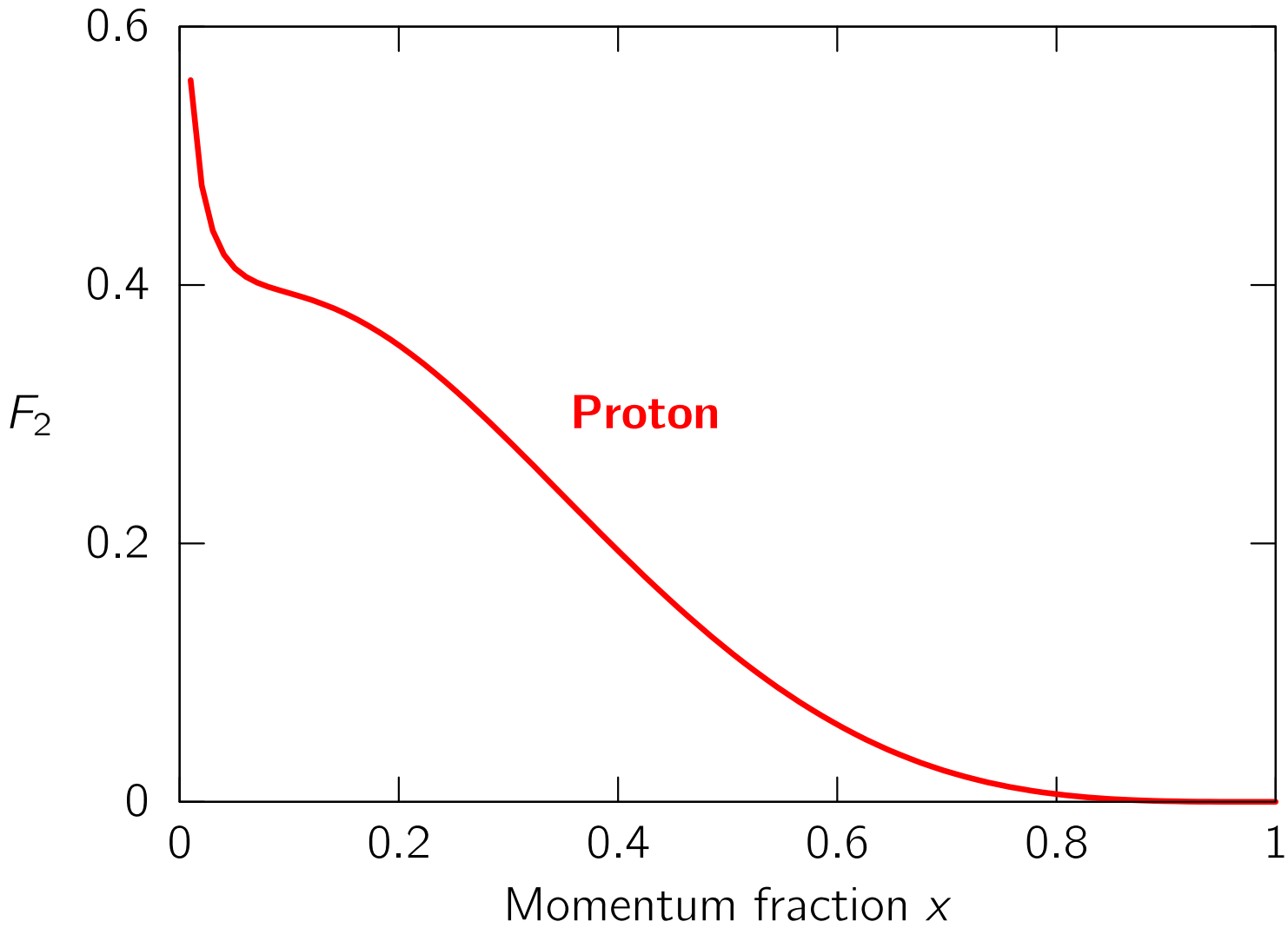




What is F_2 for a nucleus?



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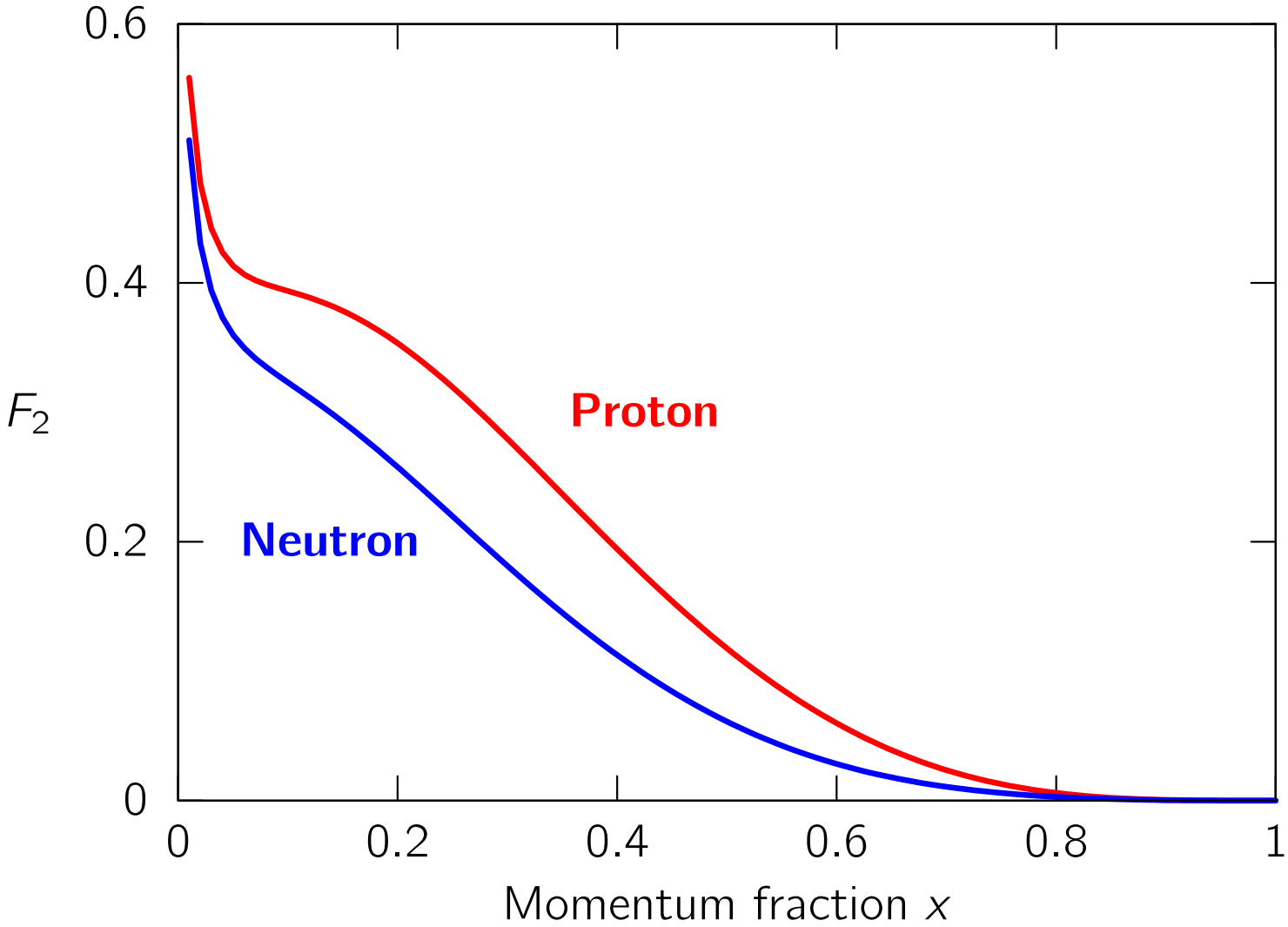

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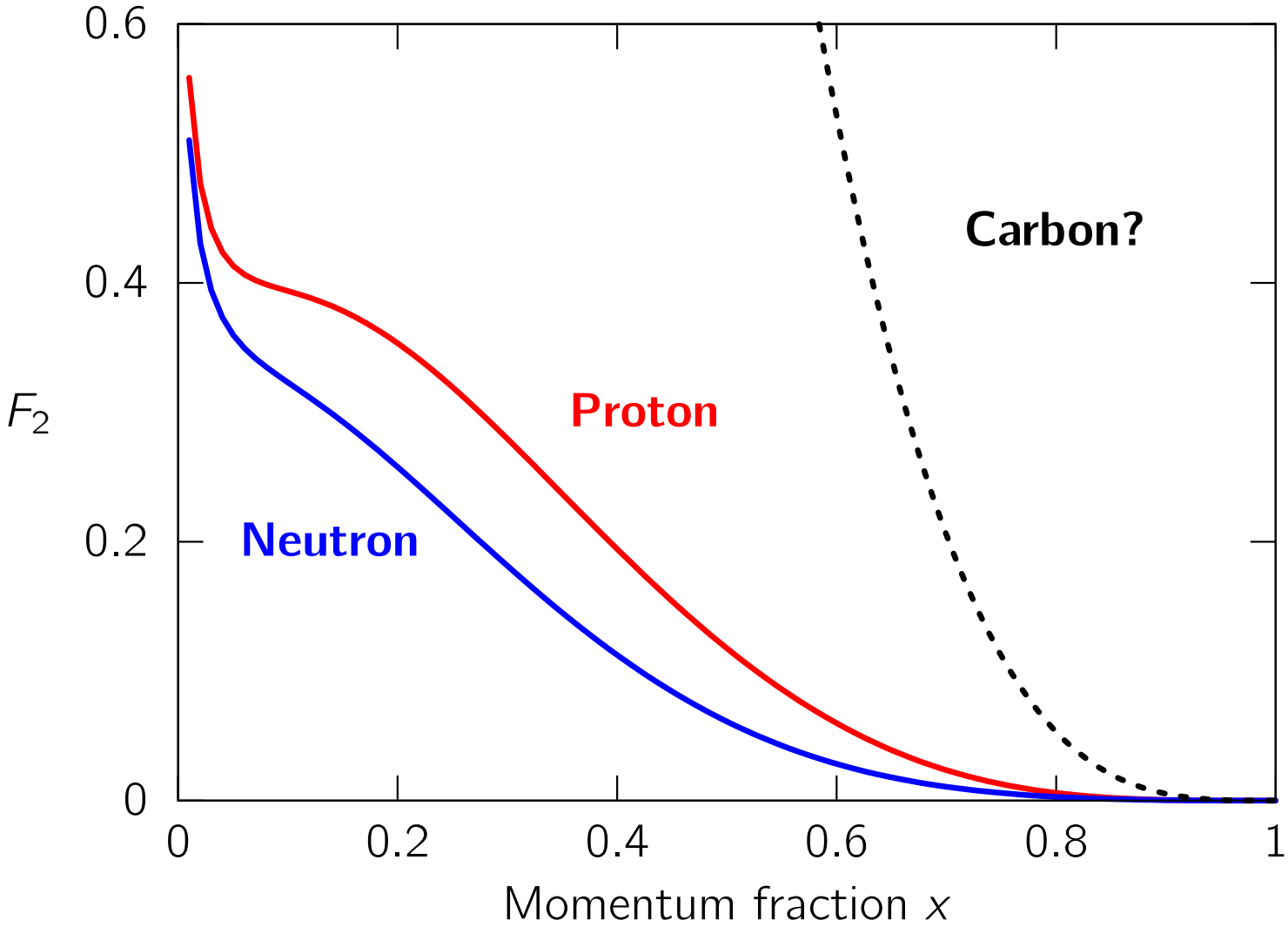

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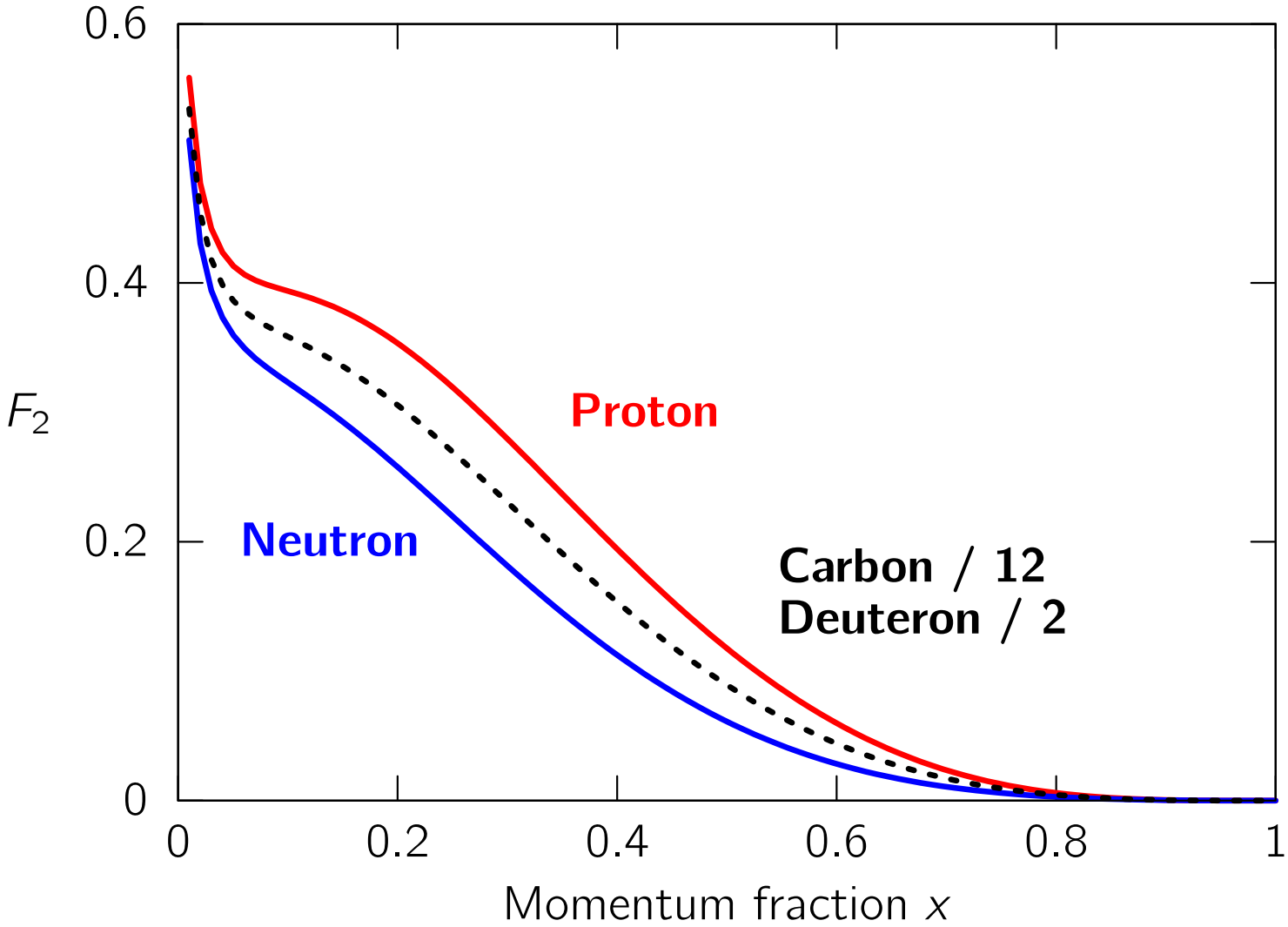
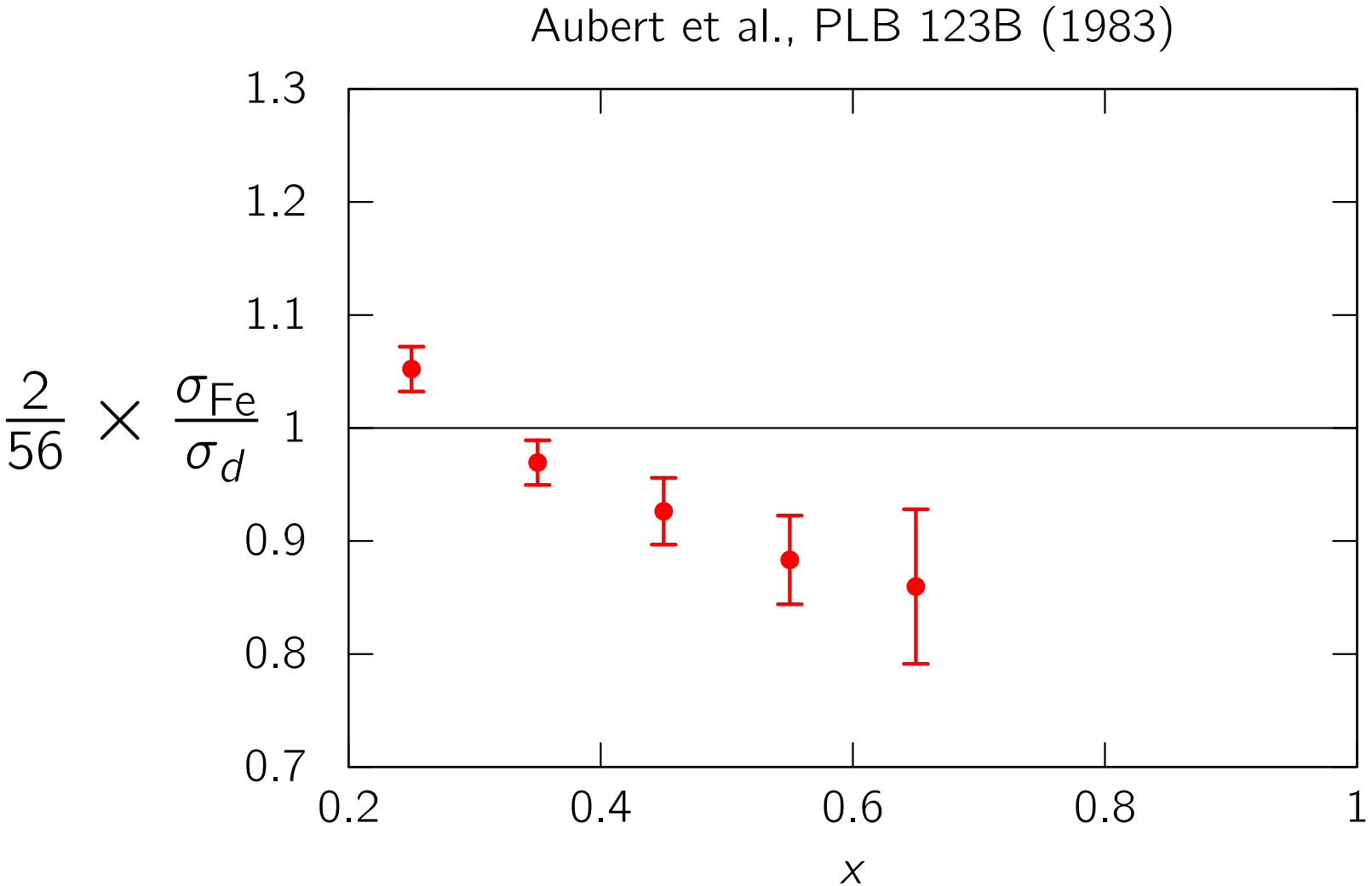
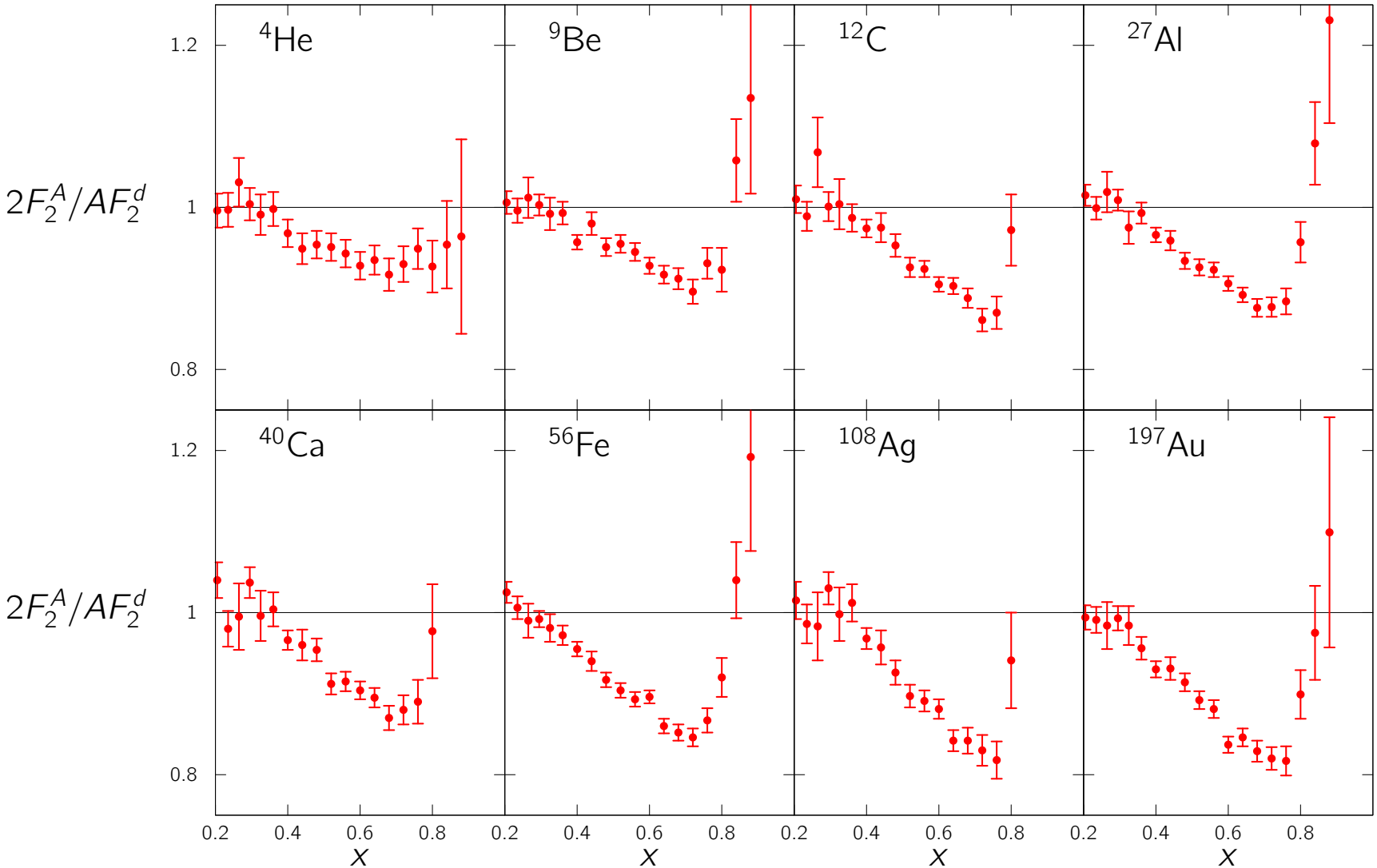


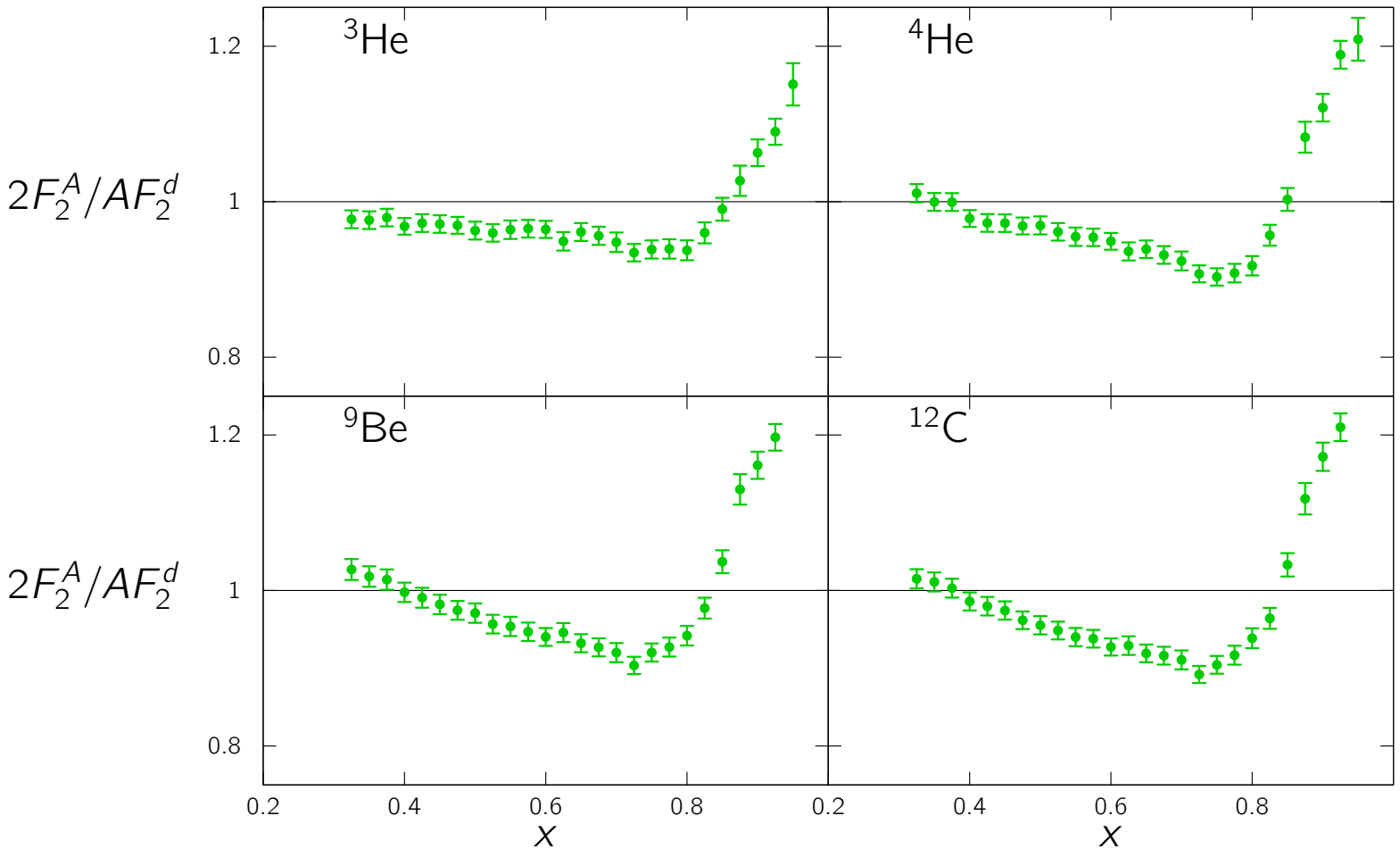
Nuclear F_2 does not scale with that of deuterium.



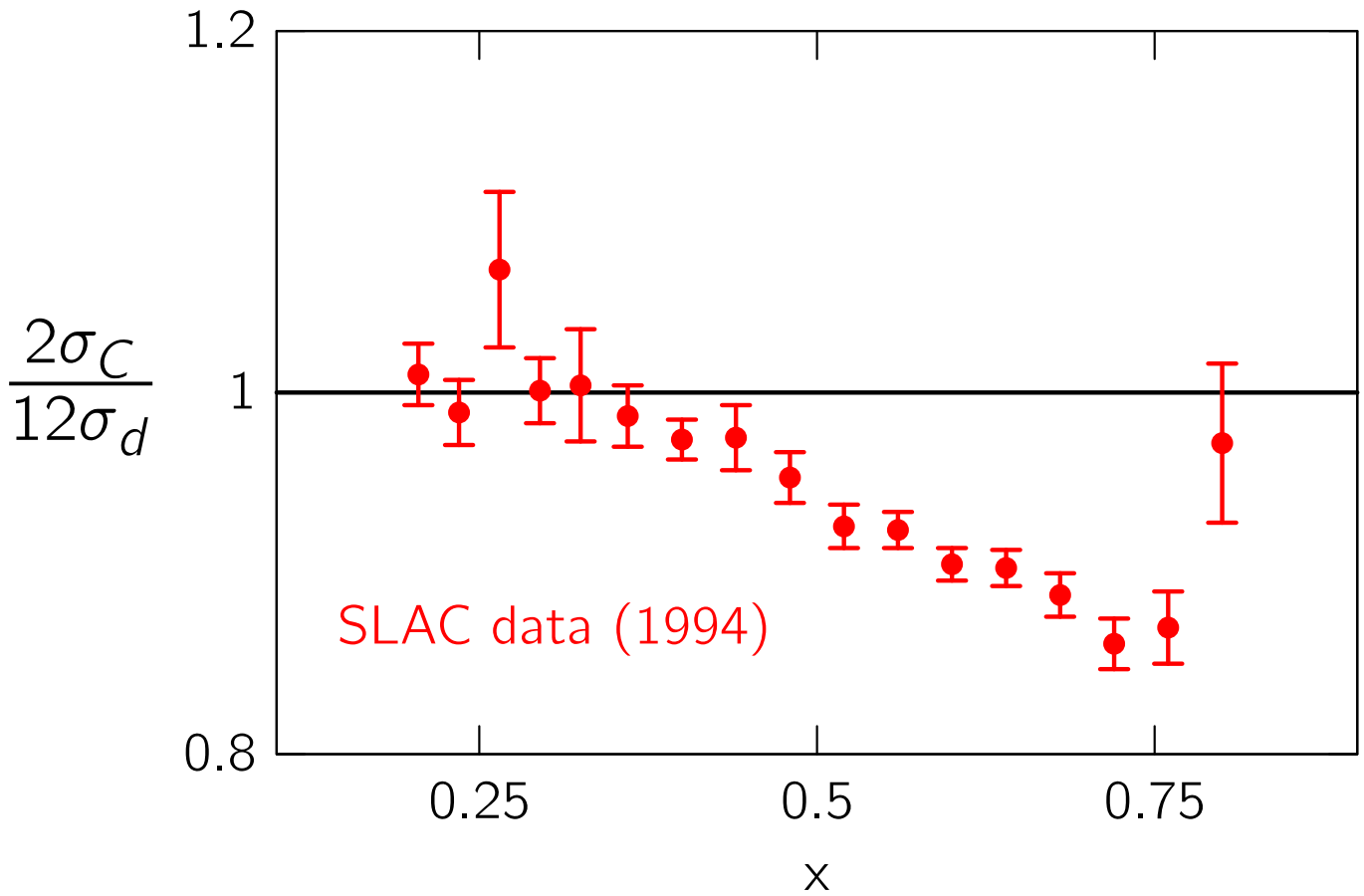
SLAC Measurements (Gomez et al., 1994)



Jefferson Lab Hall C (Seely et al., 1999)



We use the slope to characterize the size of the EMC Effect.



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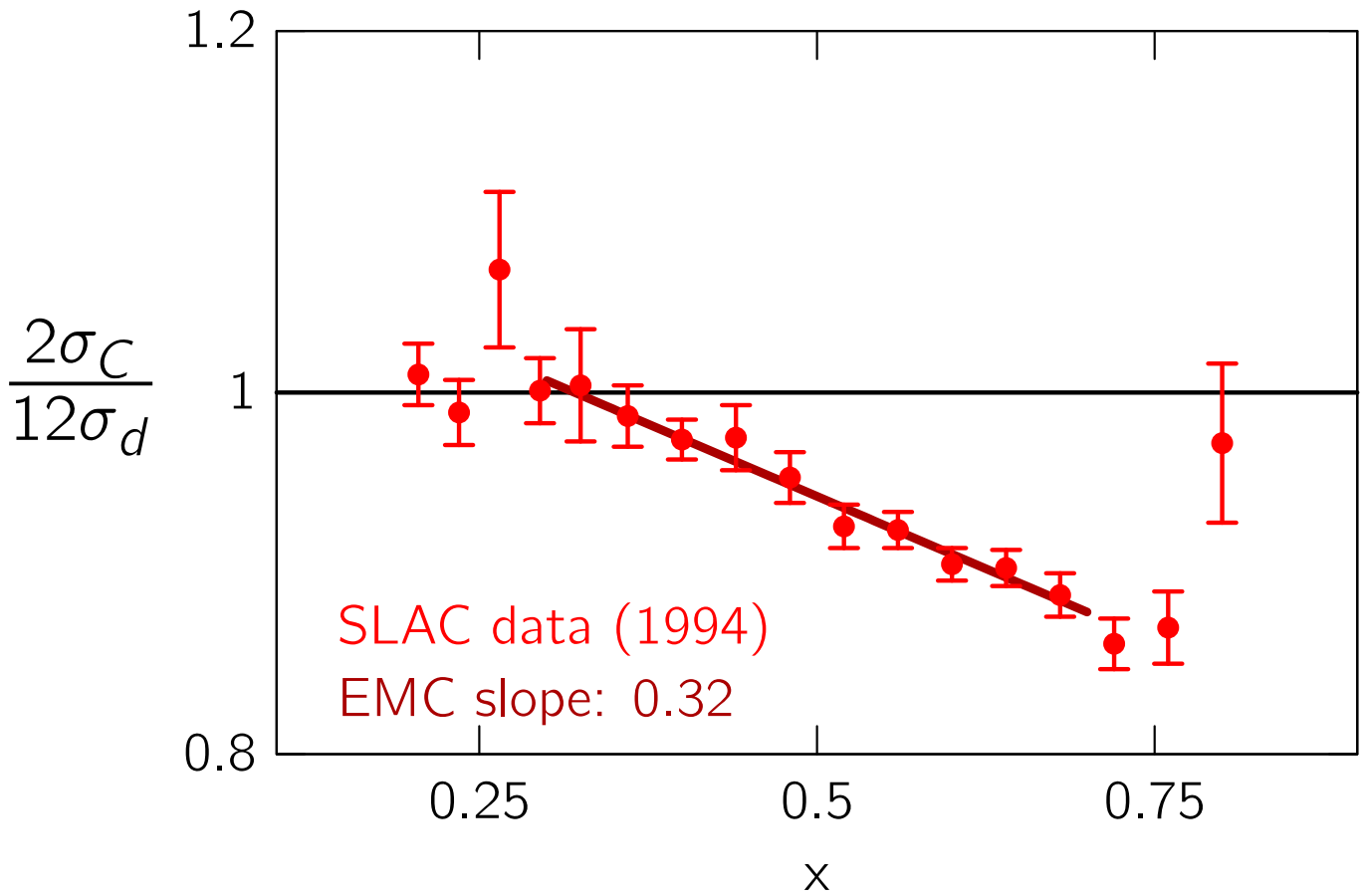
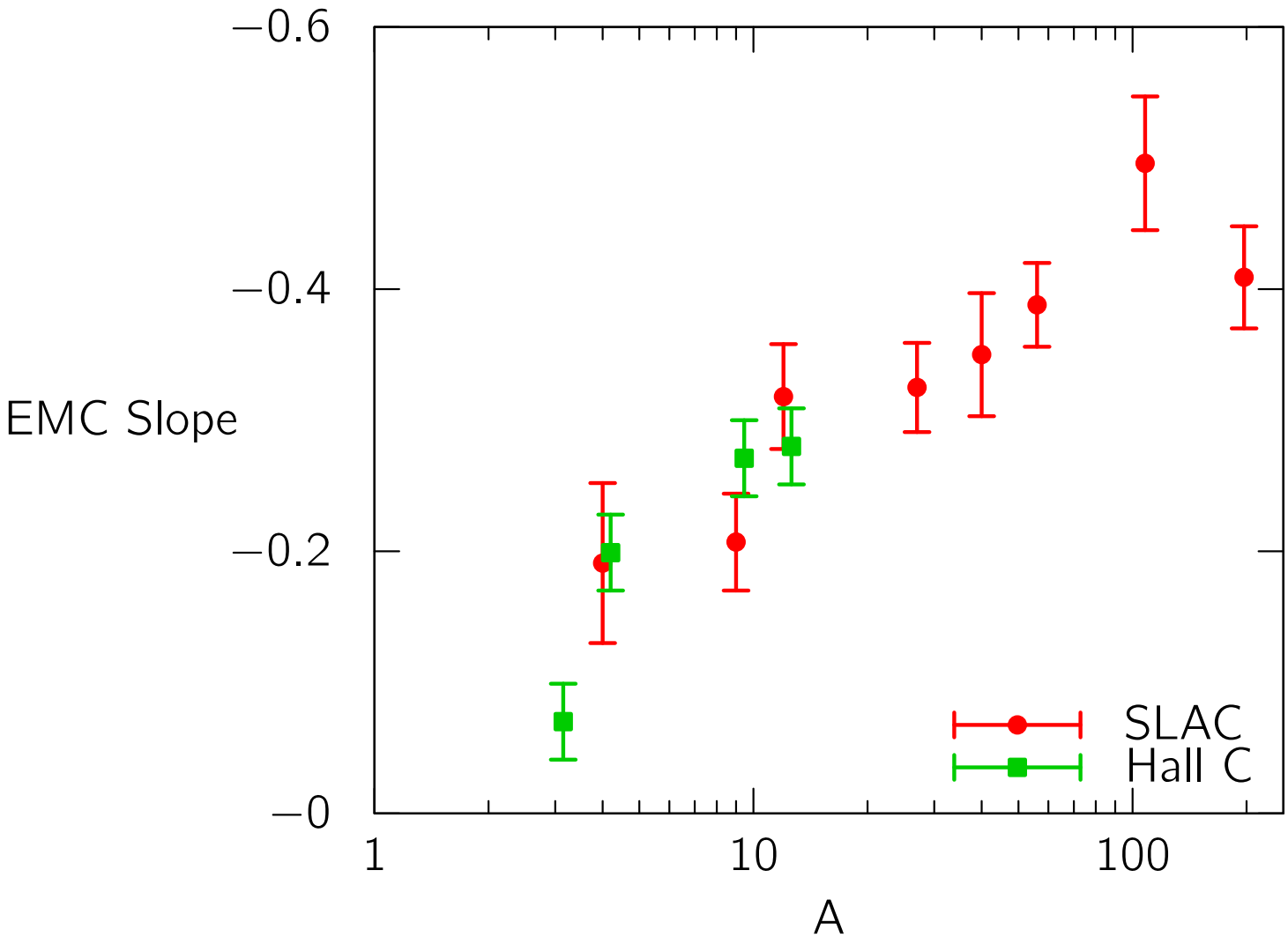
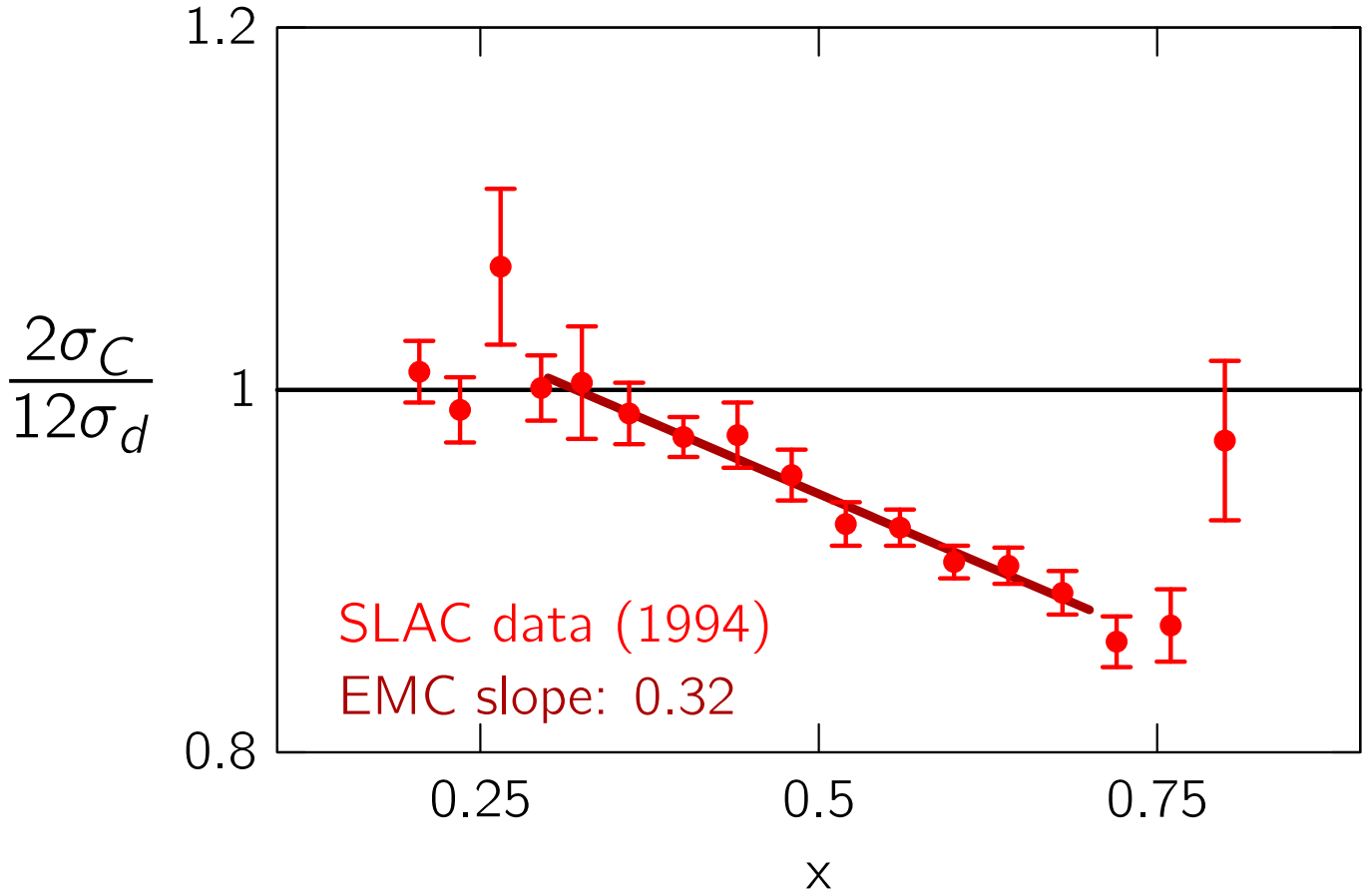


The EMC Effect grows with nuclear size.



Can Fermi-motion explain the effect?



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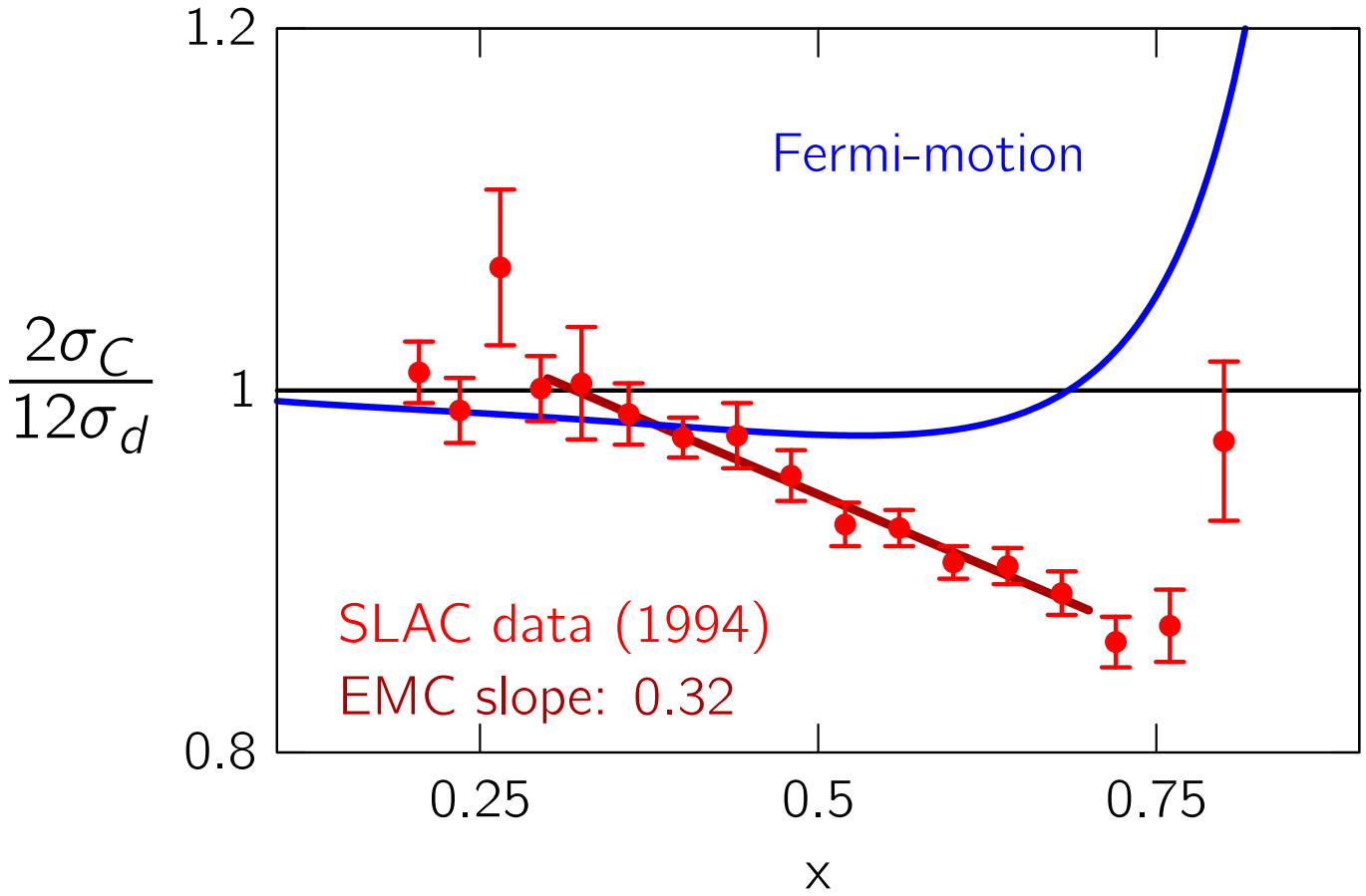

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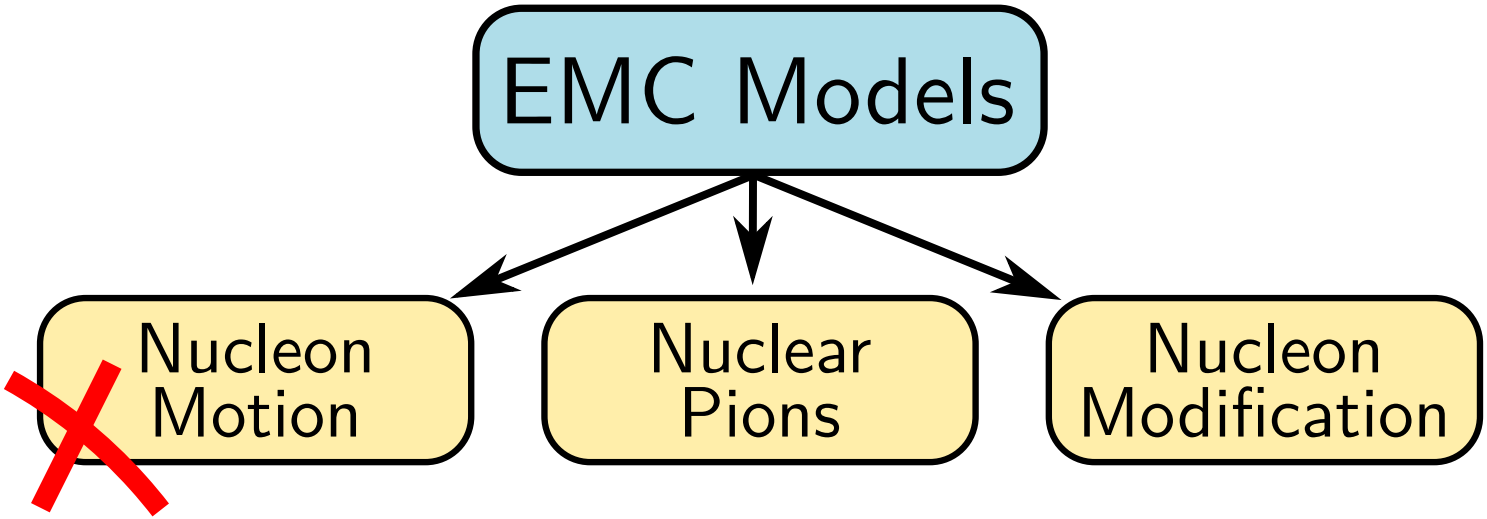

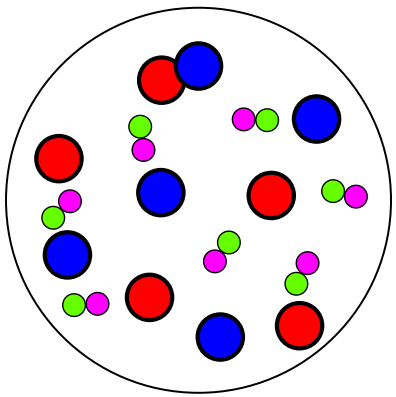

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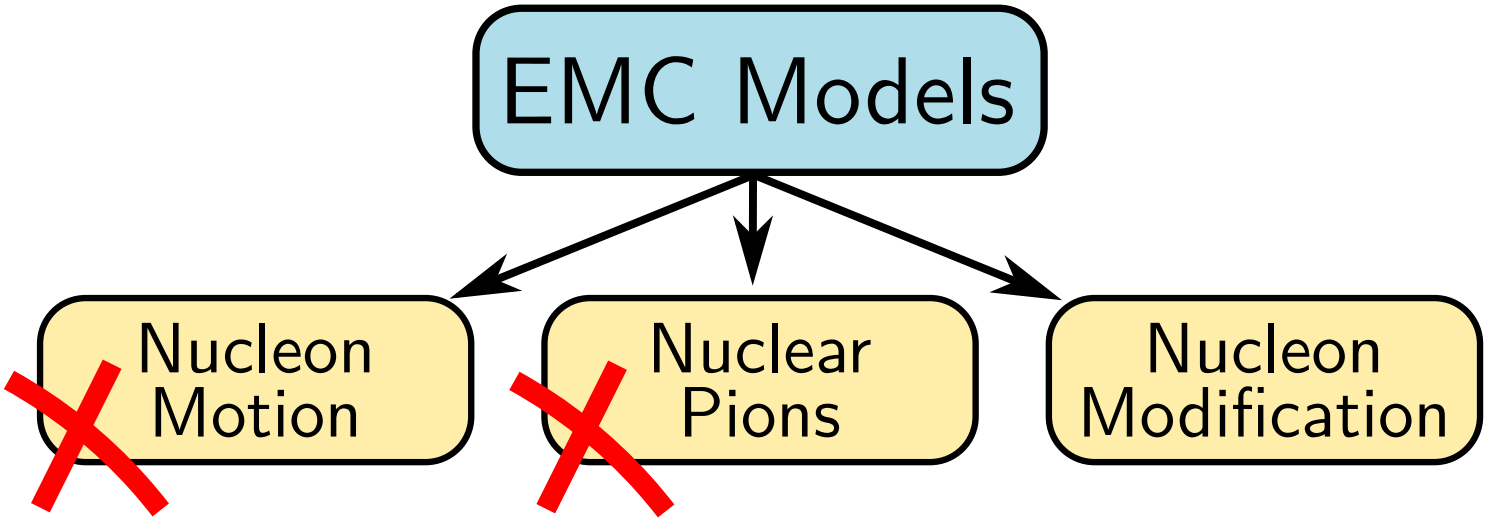

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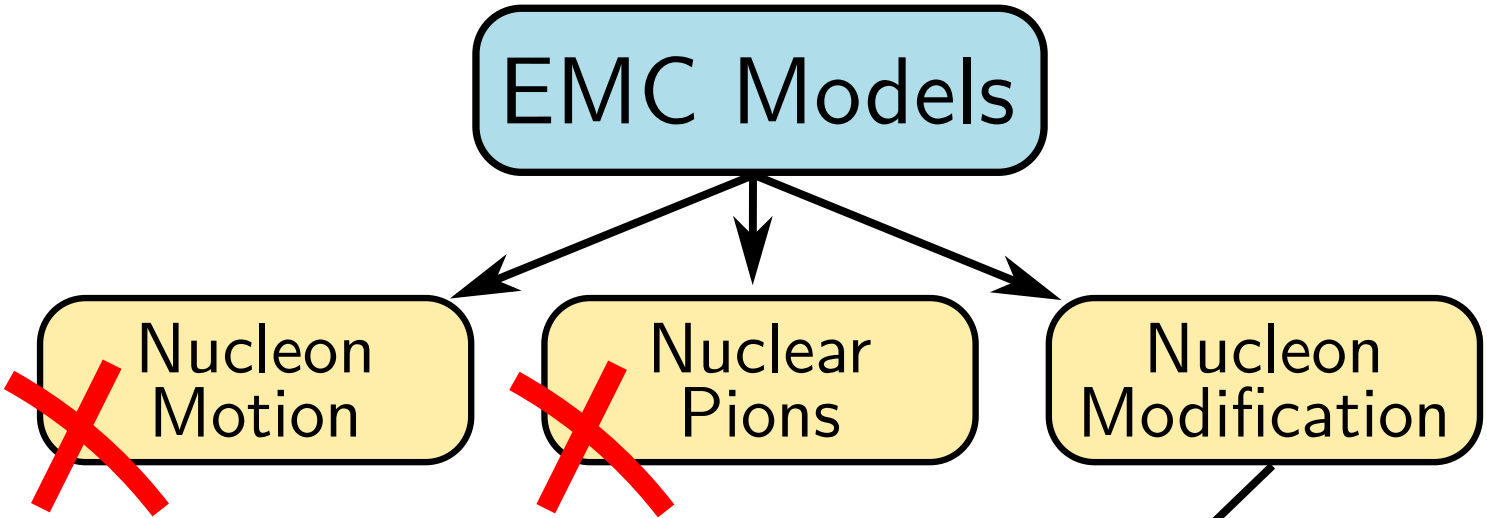

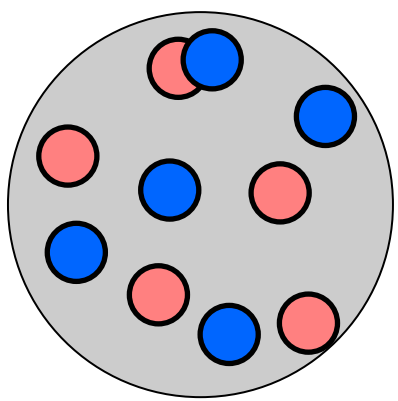

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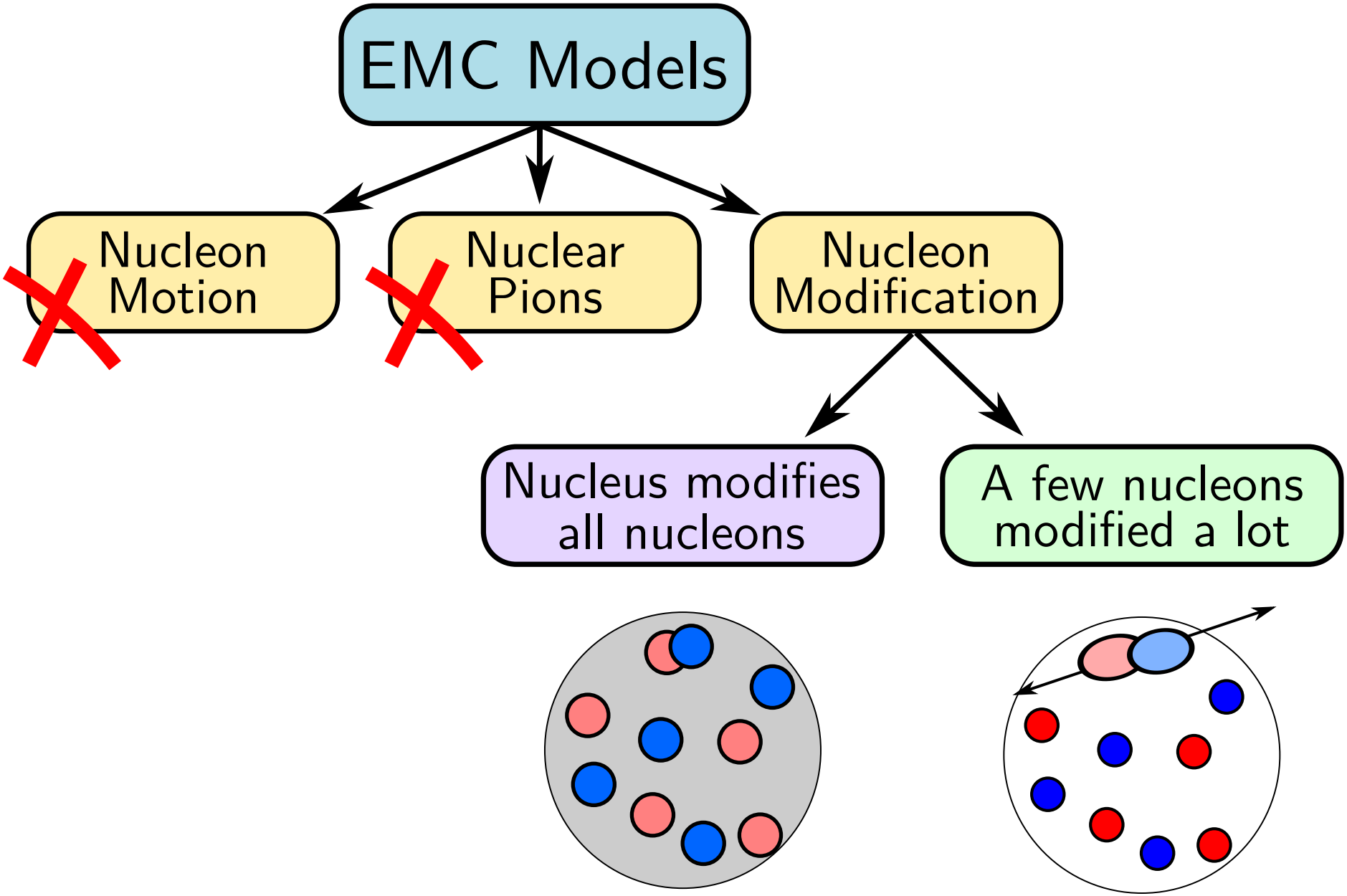

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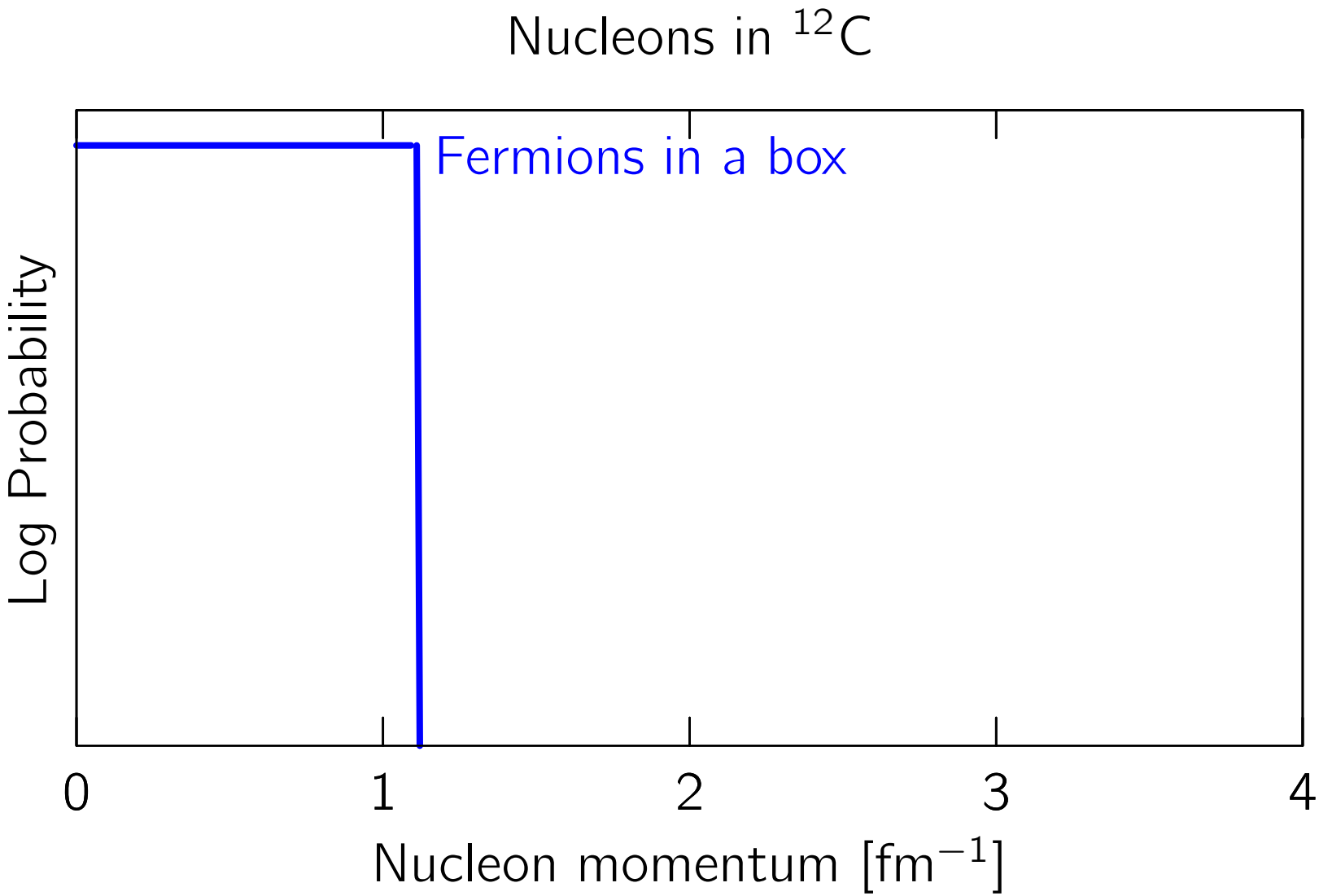
The nucleus as a box of fermions.



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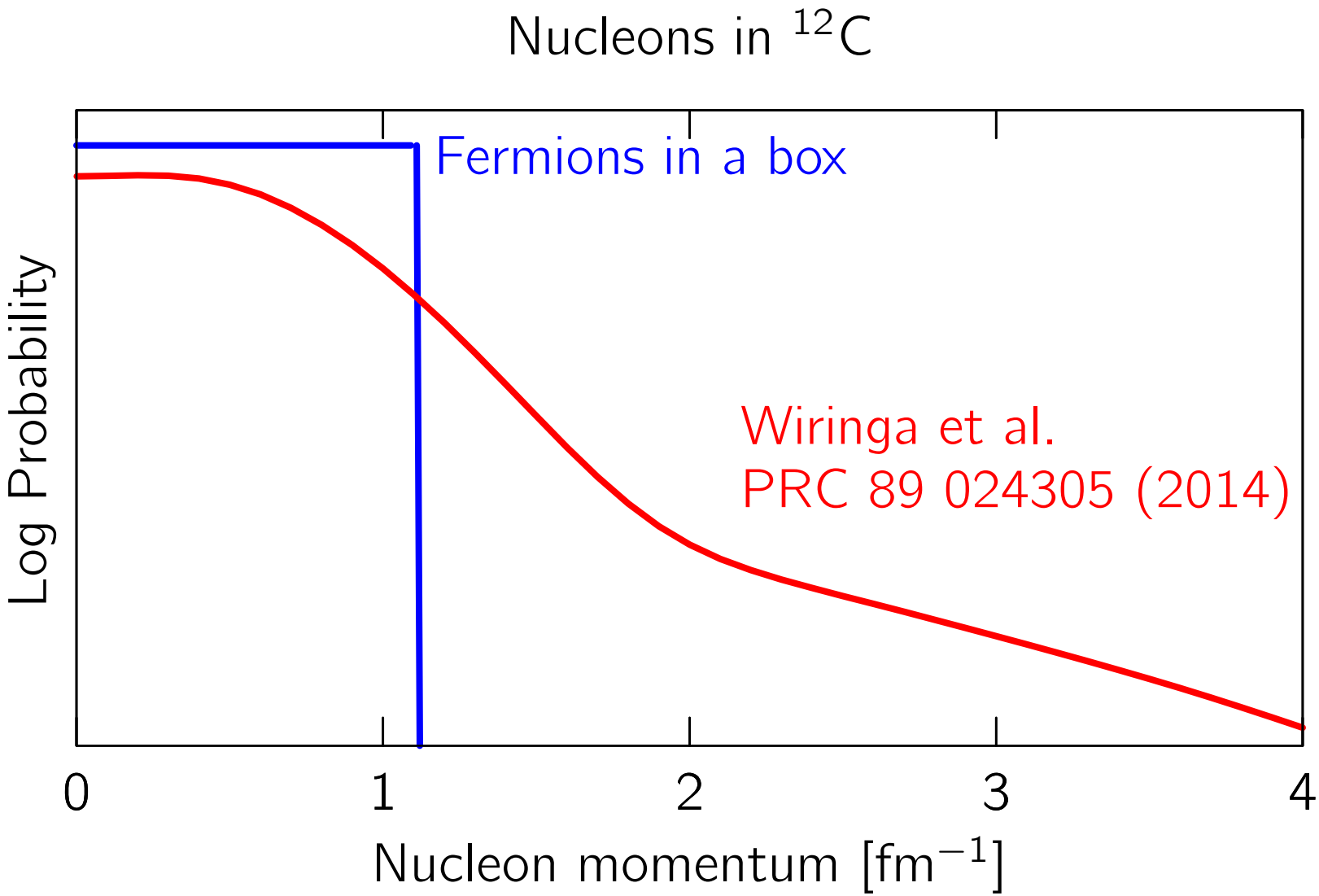
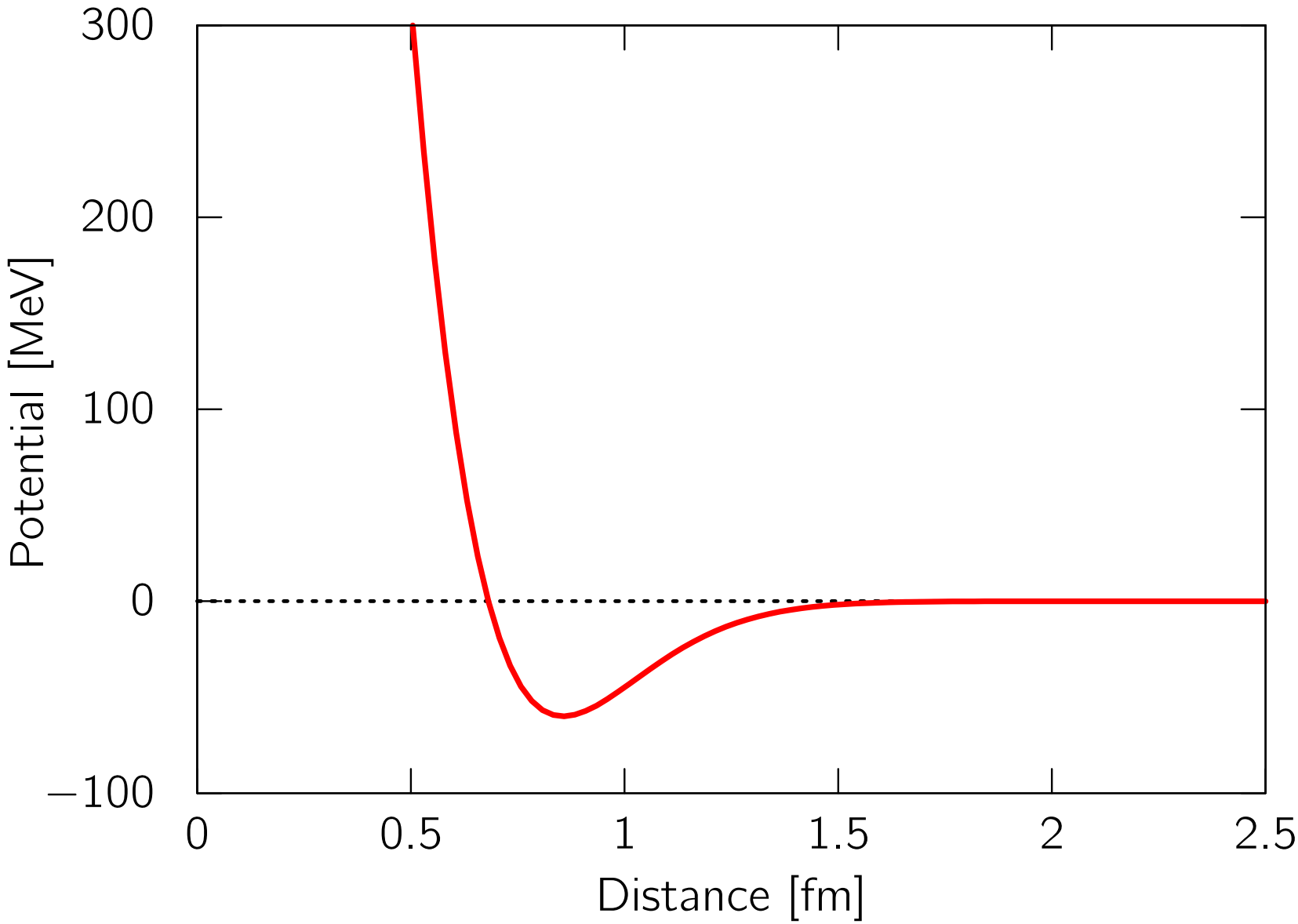


The *NN* force has a repulsive core.



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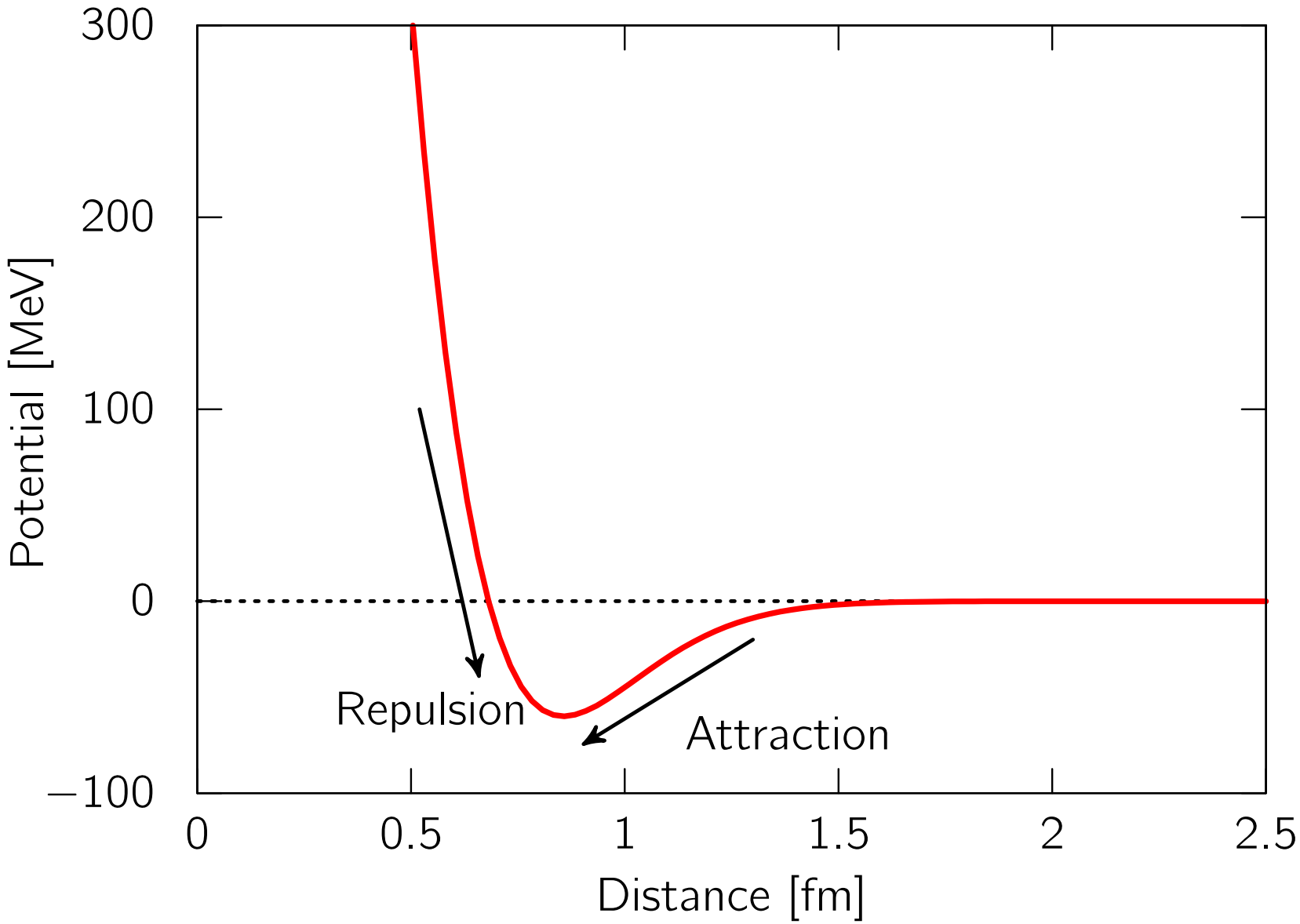

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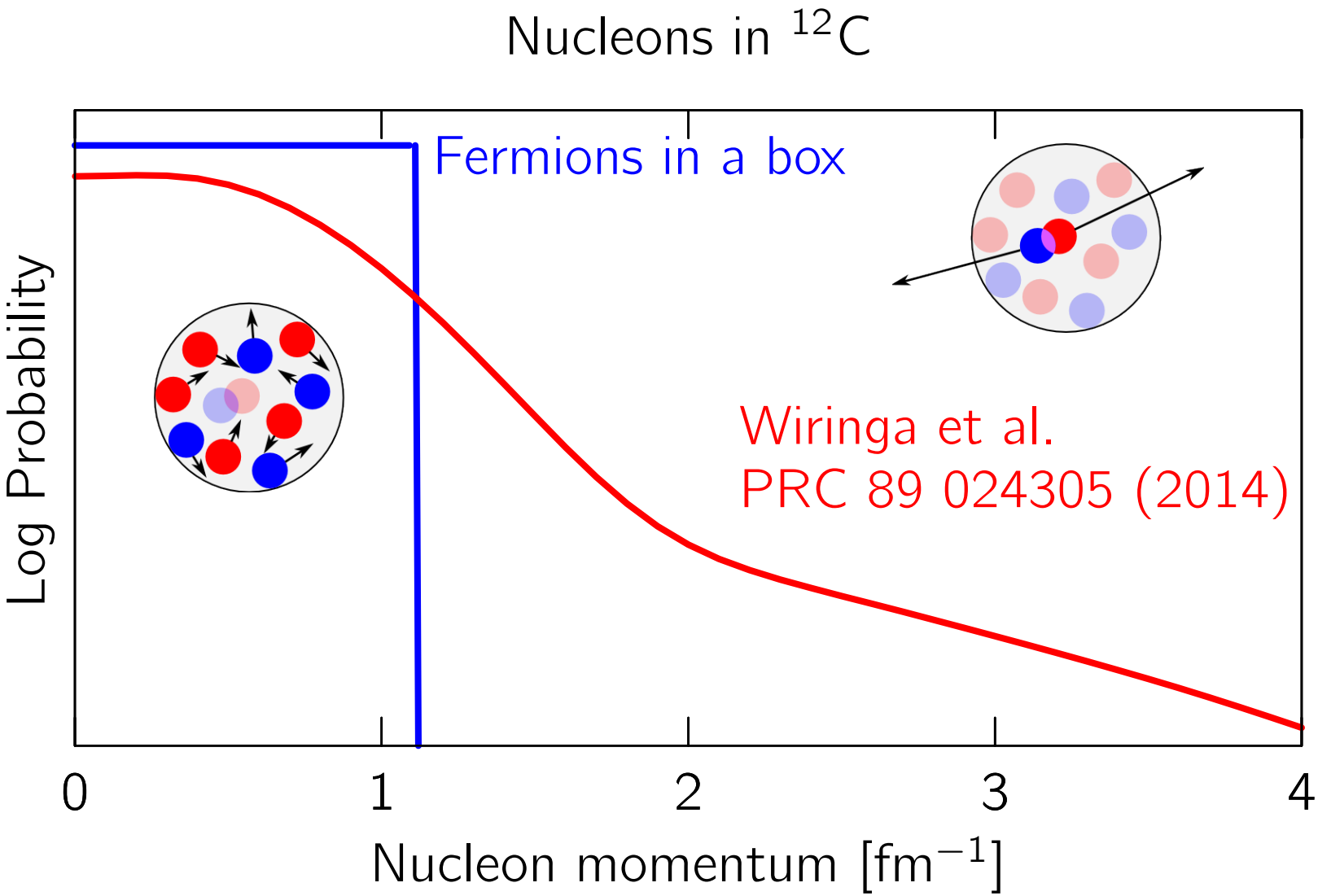
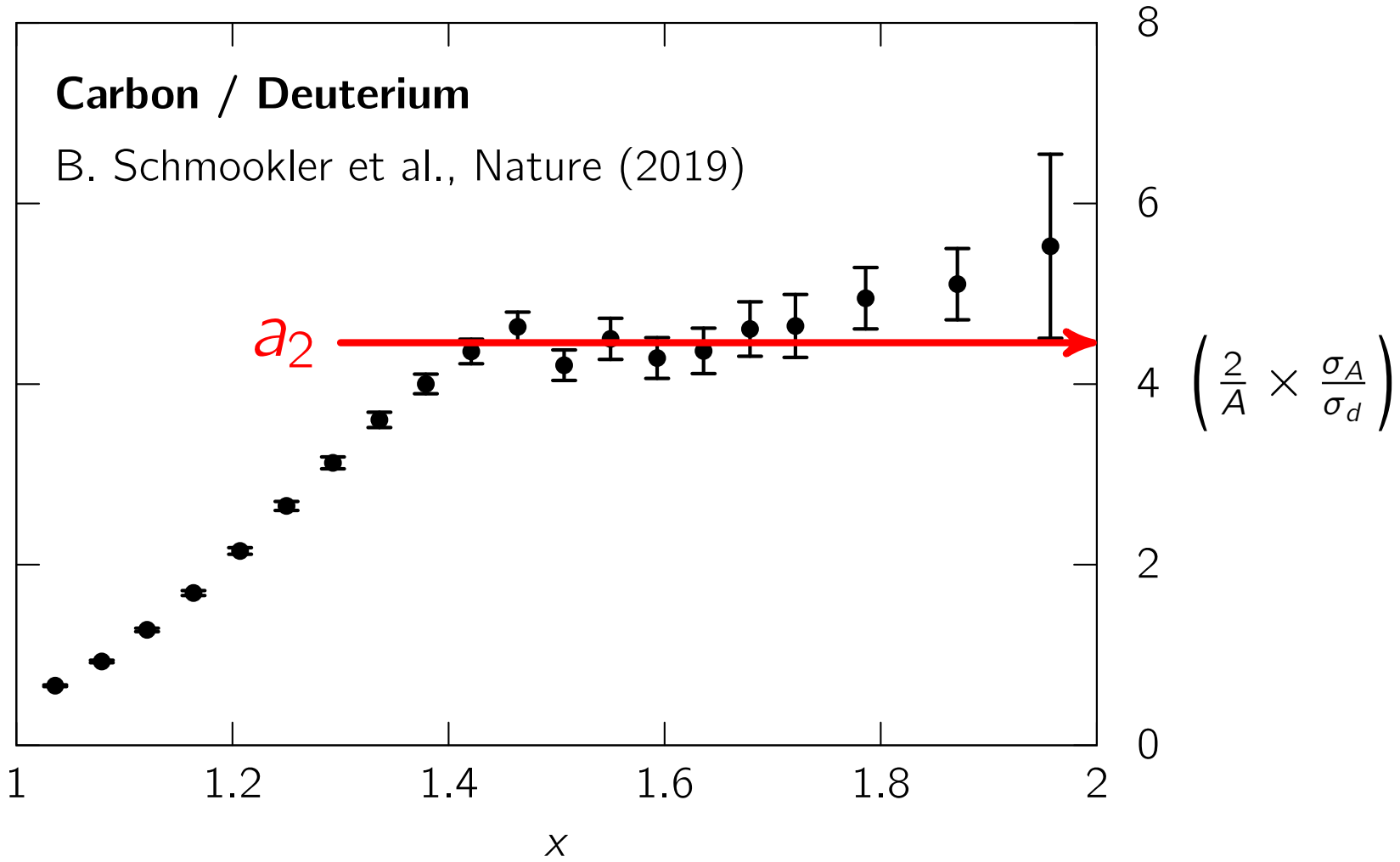
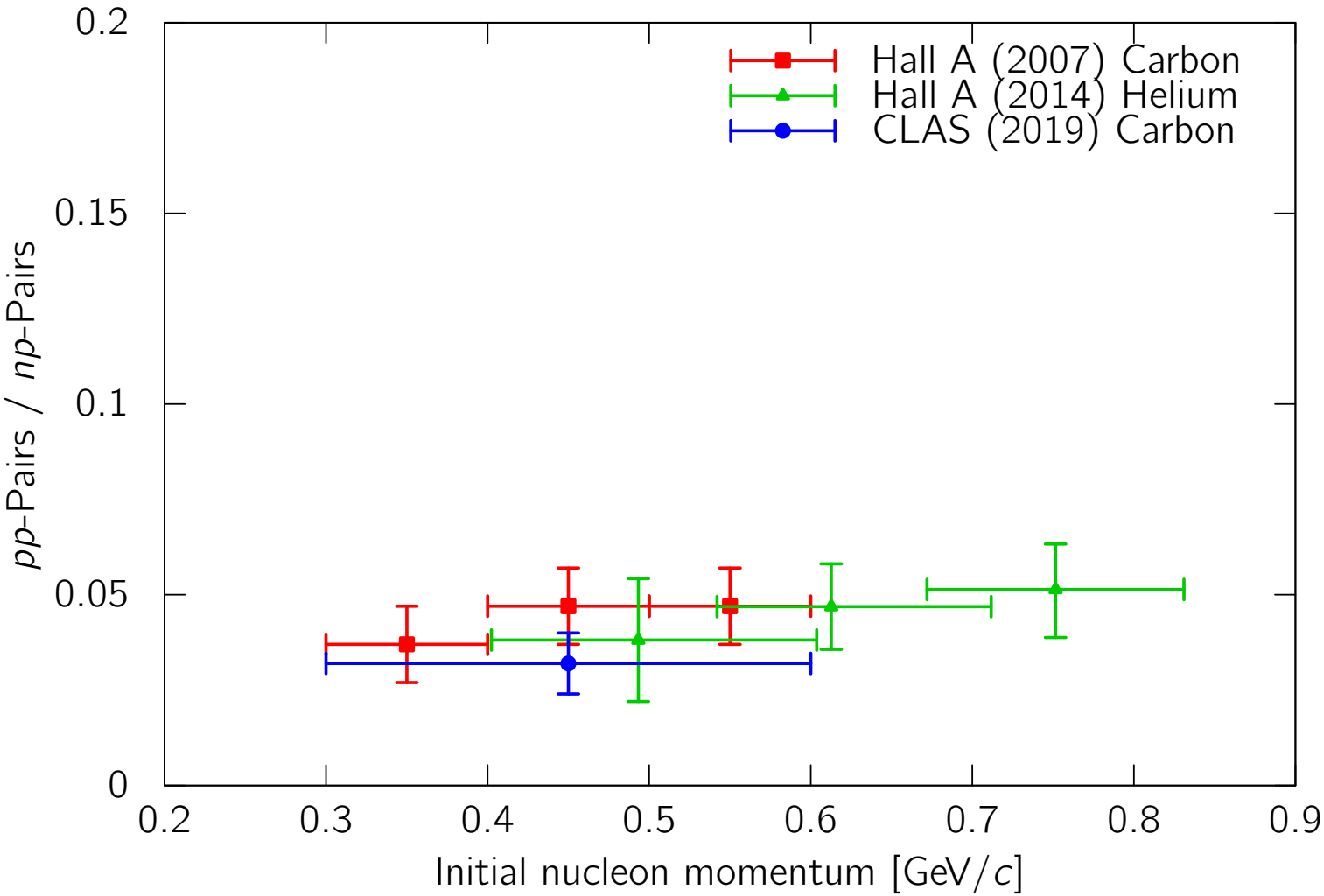


How often do nucleons correlate?

$\longrightarrow$ About 4–5 times more than in deuterium.



Proton-neutron pairs are much more likely than proton-proton or neutron-neutron.



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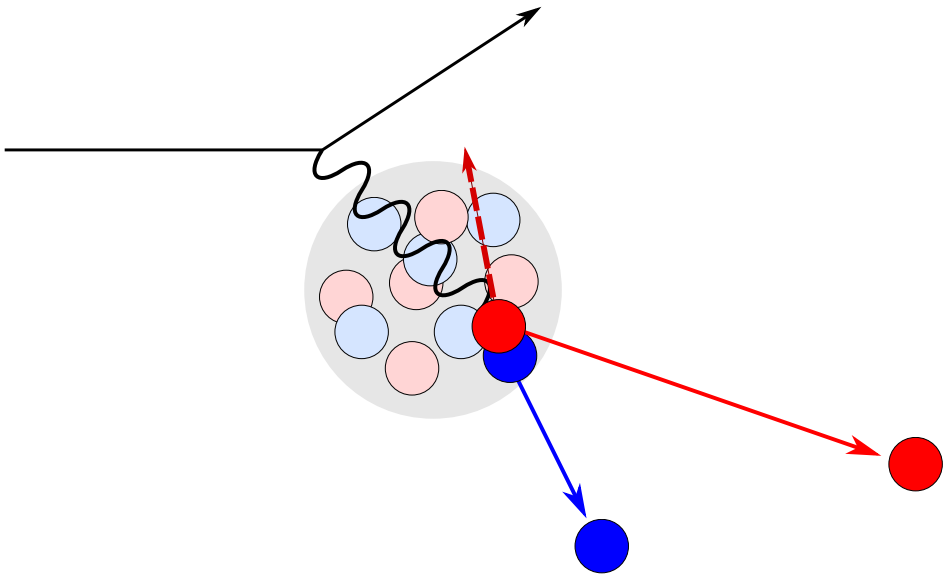

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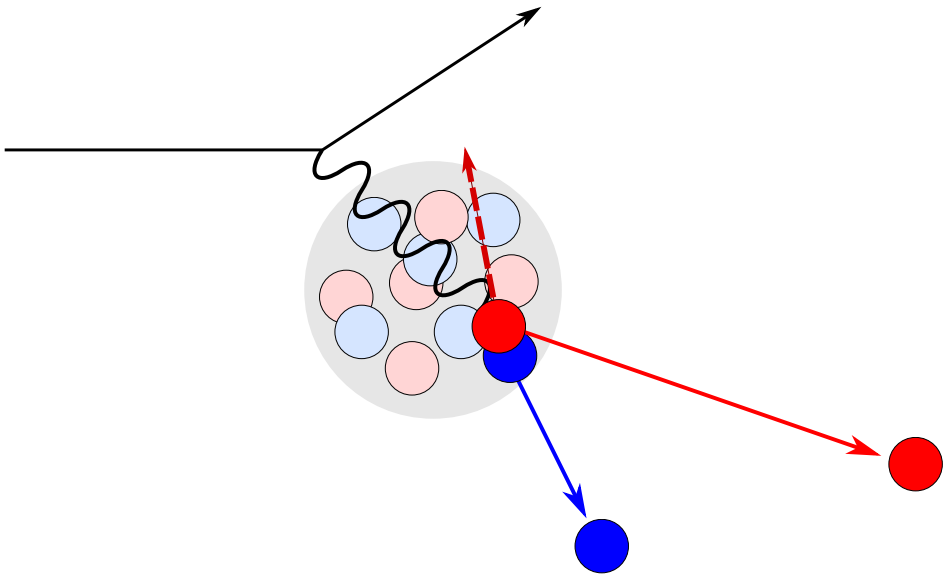
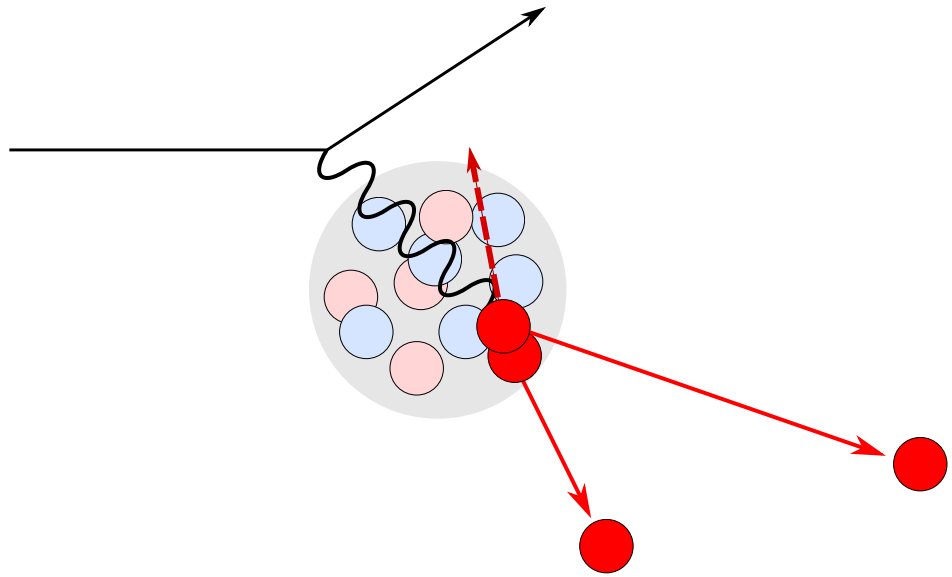
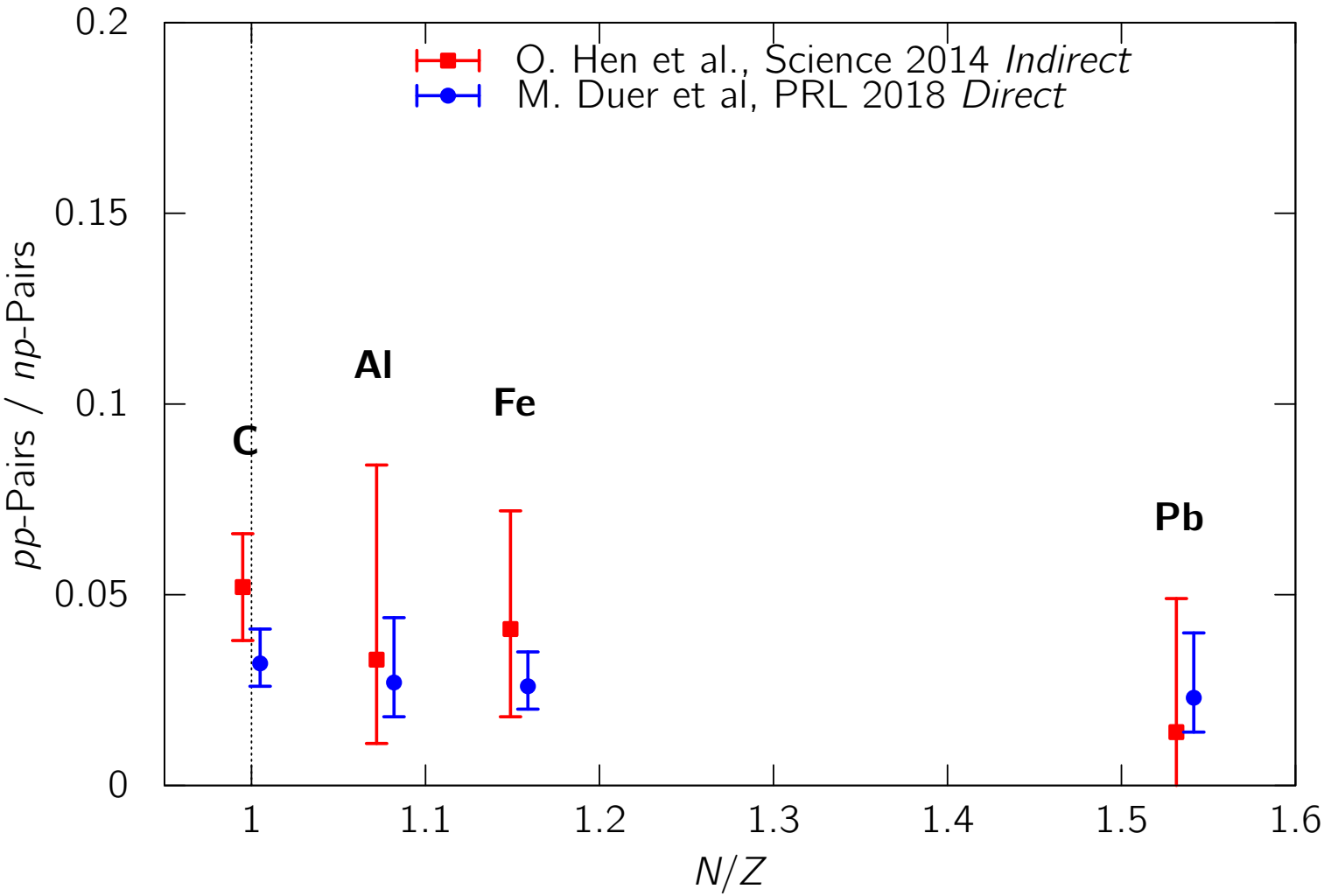




"*np*-Dominance" has been confirmed even in very neutron-rich neuclei.



Key facts about short-range correlations

1. Universal feature of nuclei
2. Interactions within the pair $\gg$ rest of the nucleus
3. *np*-pairs predominate by 20$\times$

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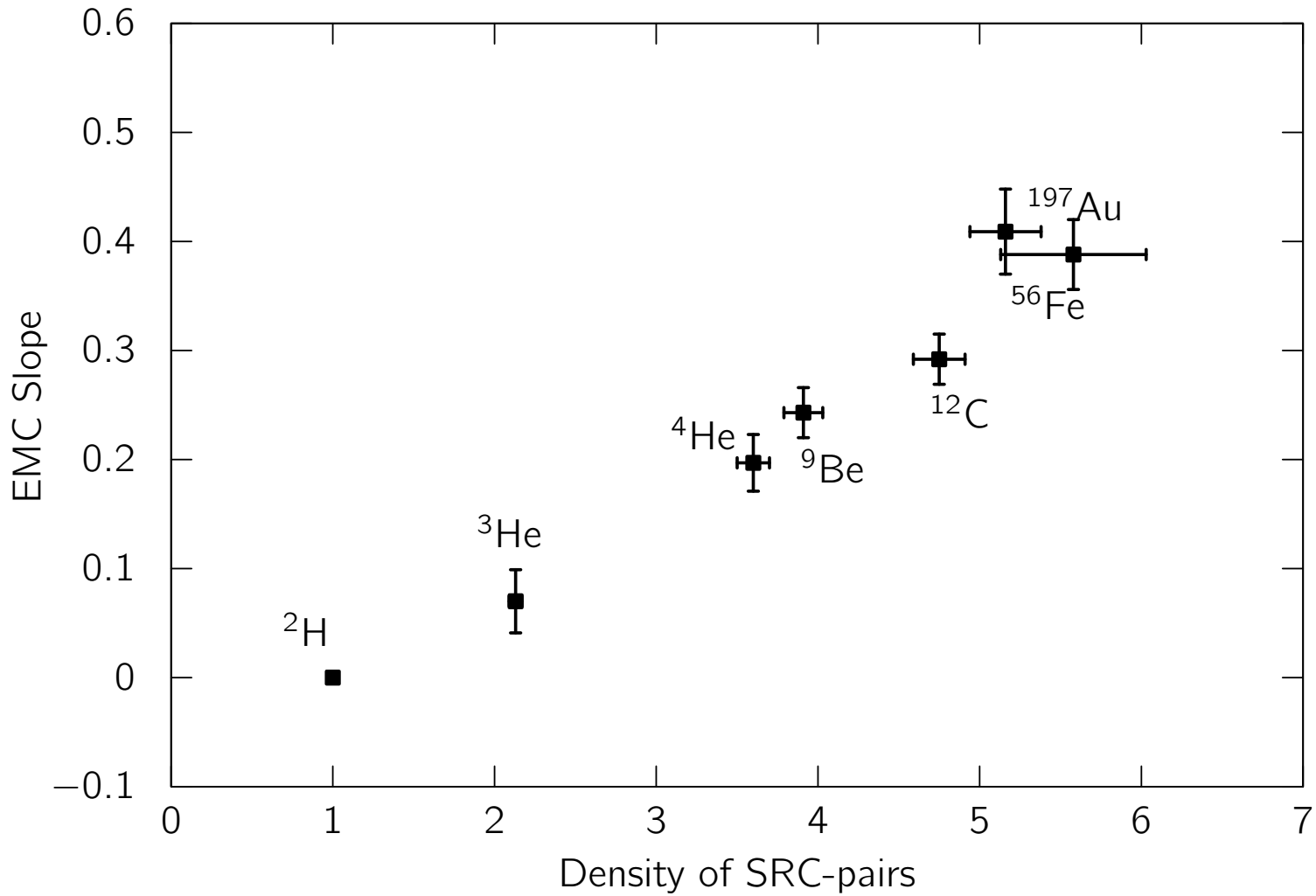
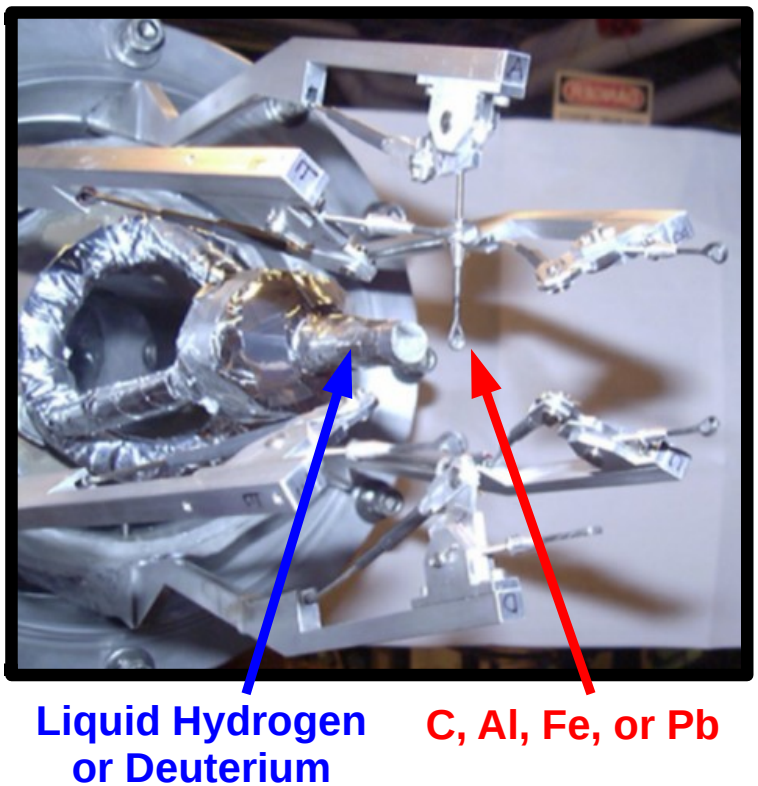
1. Universal feature of nuclei
2. Interactions within the pair $\gg$ rest of the nucleus
3. *np*-pairs predominate by 20$\times$
4. Pair density *correlates with the EMC Effect*

SRC pair density correlates with the EMC Effect.



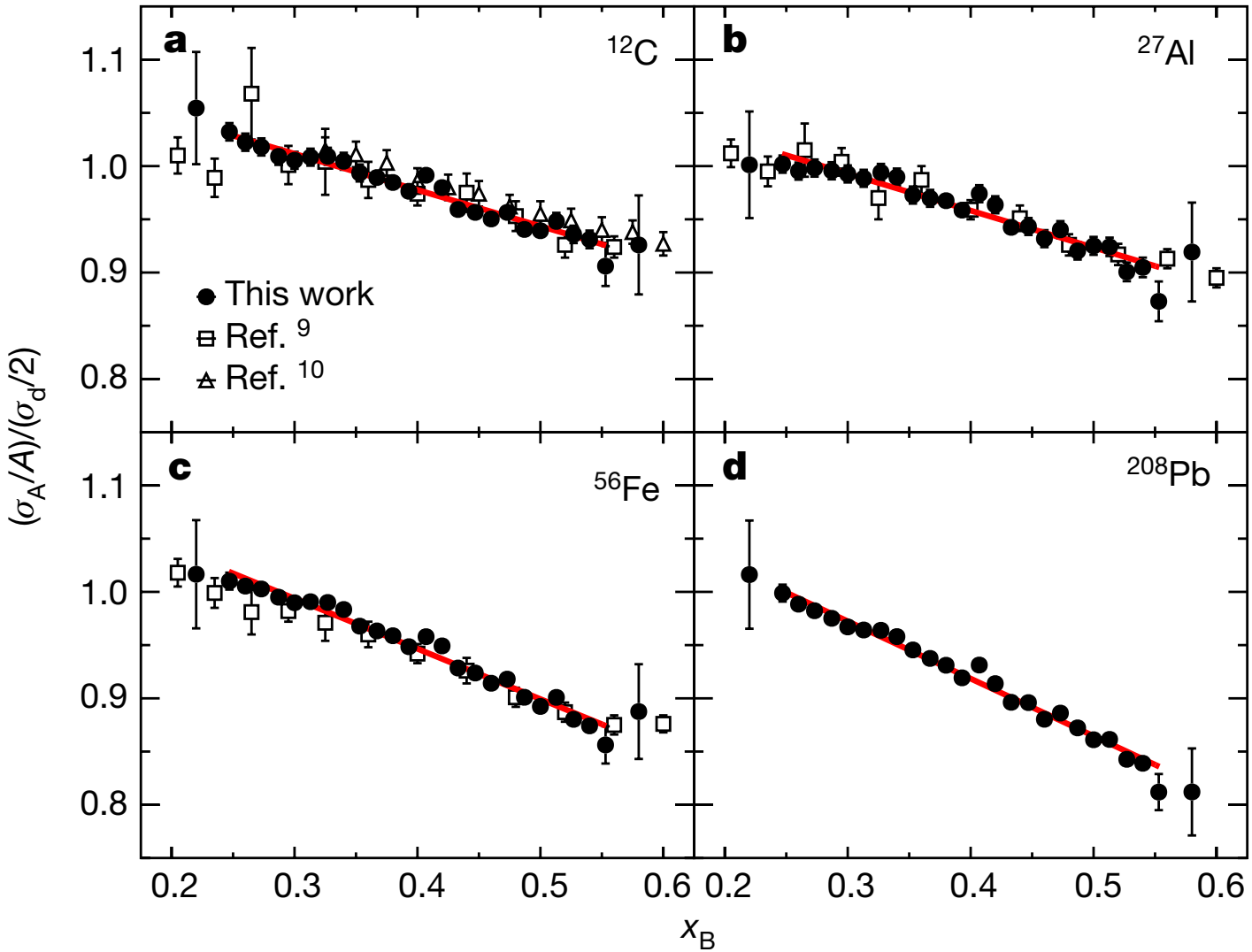
We studied this trend through data mining.

work led Barak Schmookler
MIT PhD 2016
Nature 566 p. 354 (2019)



- 5 GeV e^- beam
- Deuterium target AND
  C, Al, Fe, Pb
- CLAS detector
- Measured quark distributions
  and SRC pair density

We measured the EMC Effect and pair densities.



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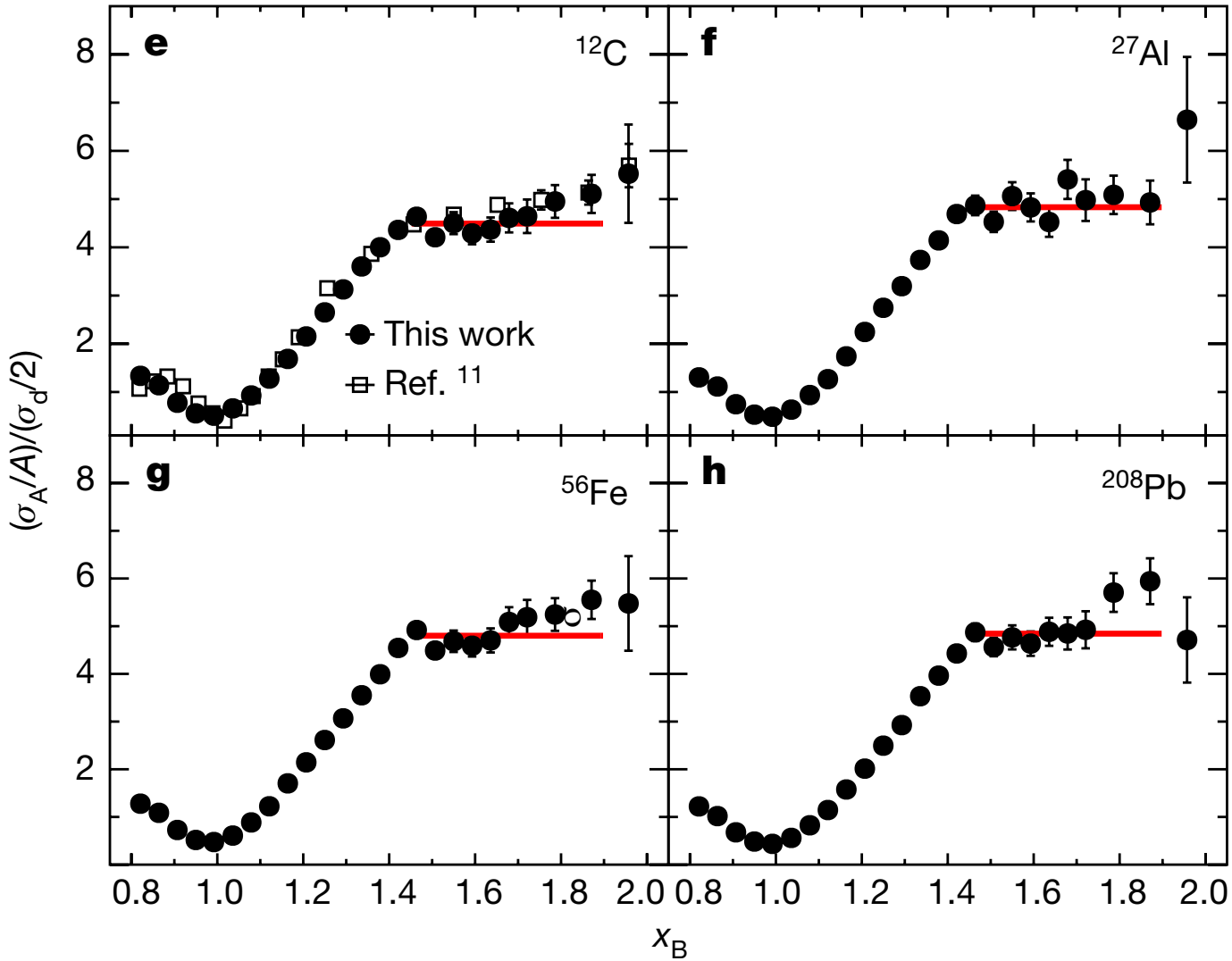

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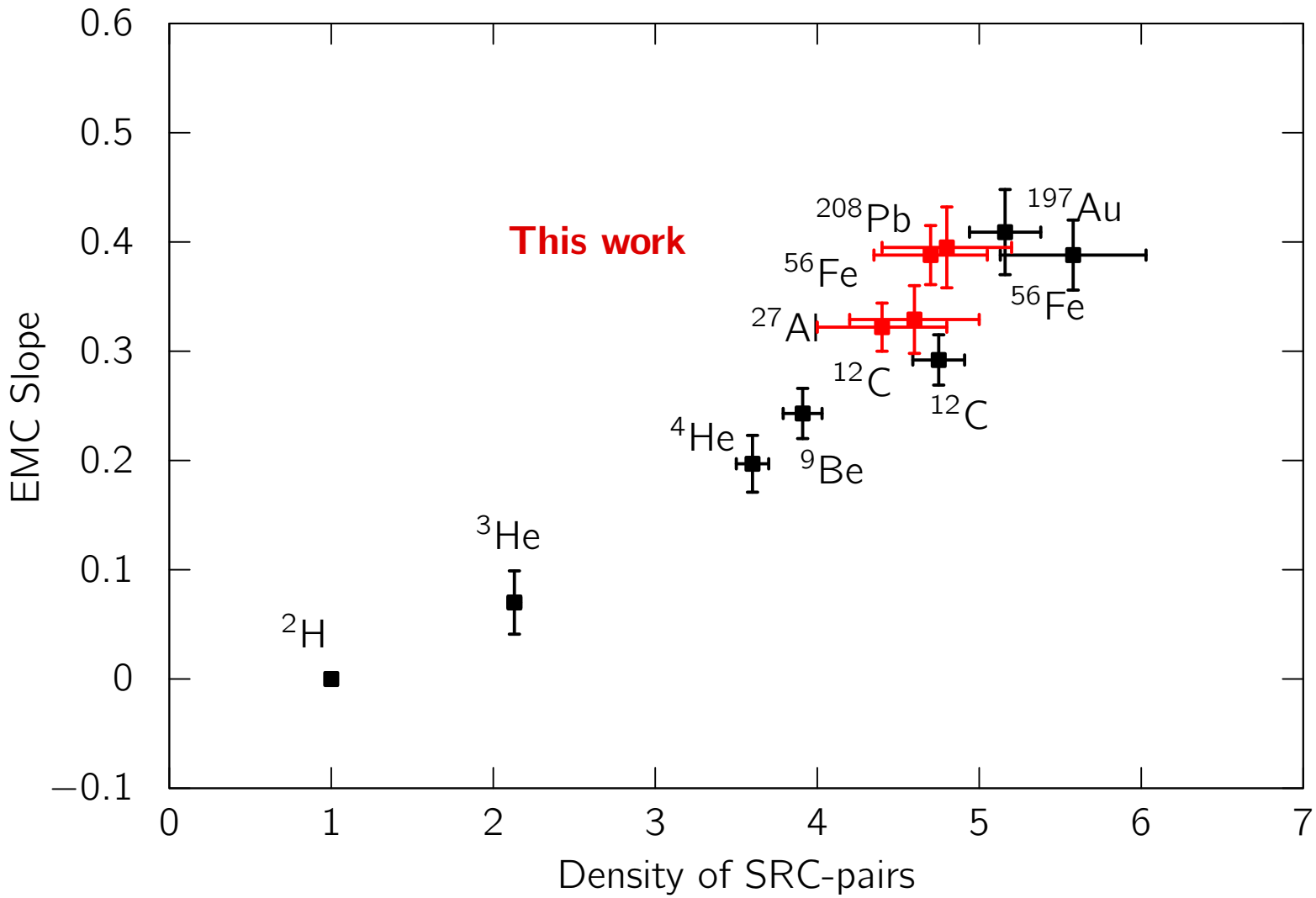
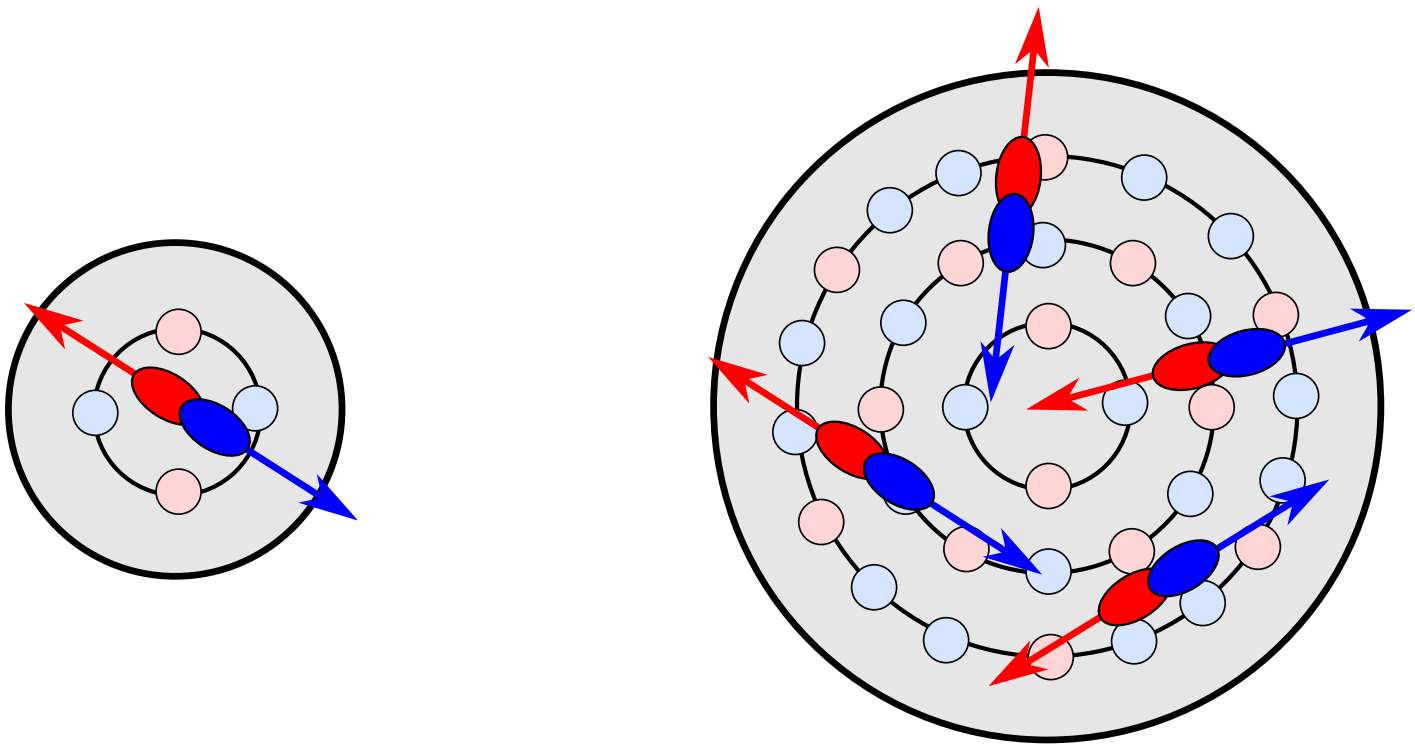


The SRC-EMC hypothesis predicts "Universal Modification"



The modification of an SRC pair should be independent of nuclear structure.

Isolating the modification of an individual pair:

Assume *only np* pairs

$$F_2^A = (Z - n_{\mathrm{SRC}}^A)F_2^p + (N - n_{\mathrm{SRC}}^A)F_2^n + n_{\mathrm{SRC}}^A(F_2^{p*} + F_2^{n*})$$

Isolating the modification of an individual pair:

Assume *only np* pairs

$$F_2^A = ZF_2^p + NF_2^n + n_{\mathrm{SRC}}^A(\Delta F_2^p + \Delta F_2^n)$$

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Assume *only np* pairs

$$F_2^A = ZF_2^p + NF_2^n + n_{\mathrm{SRC}}^A(\Delta F_2^p + \Delta F_2^n)$$

$$F_2^n = F_2^d - F_2^p - n_{\mathrm{SRC}}^d(\Delta F_2^p + \Delta F_2^n)$$

Isolating the modification of an individual pair:

$$\frac{n_{\mathrm{src}}^{d}(\Delta F_2^p + \Delta F_2^n)}{F_2^d} = \left[R_{\mathrm{EMC}} - \frac{2(Z-N)}{A}\frac{F_2^p}{F_2^d} - \frac{2N}{A} \right] / \left[a_2 - 2N/A \right]$$

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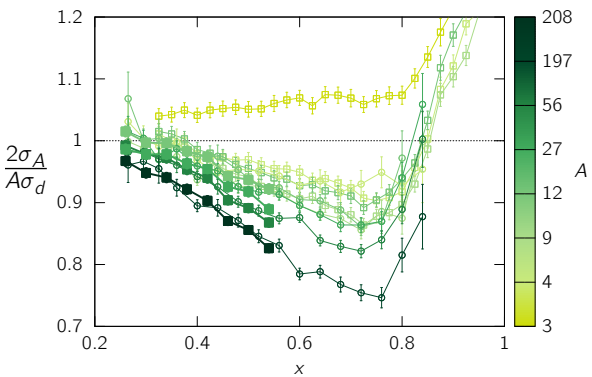

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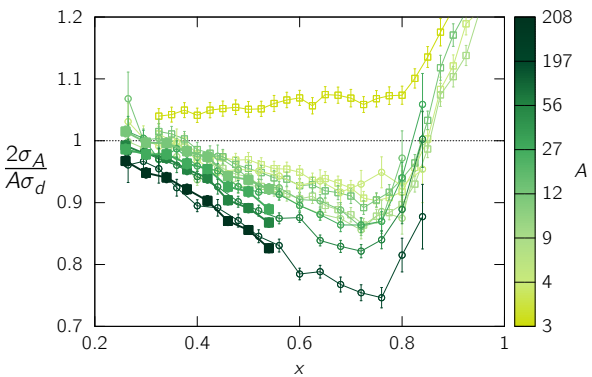

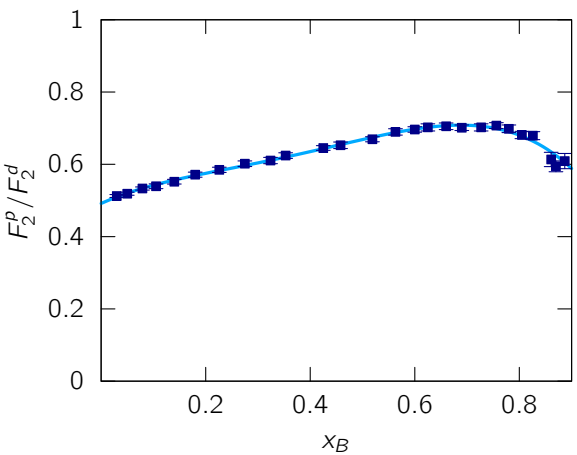

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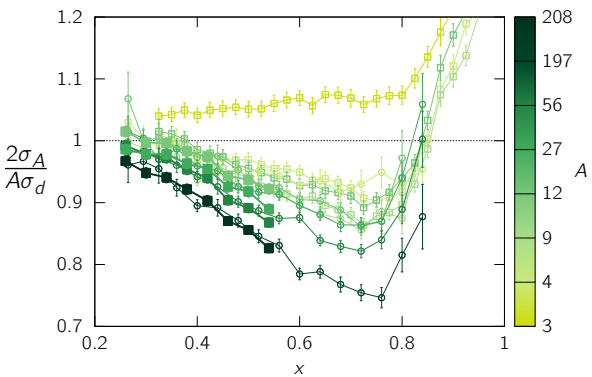
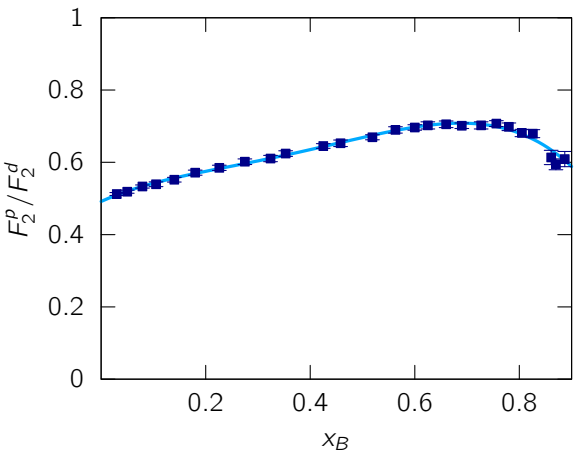
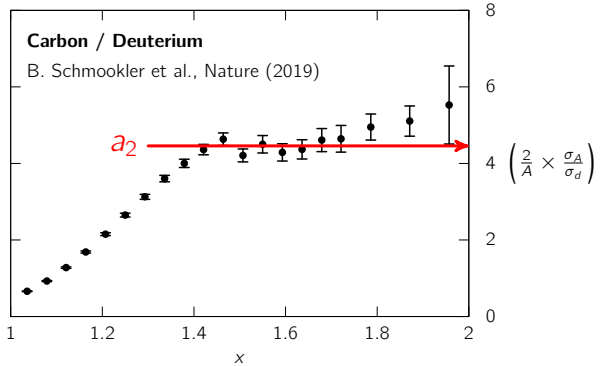
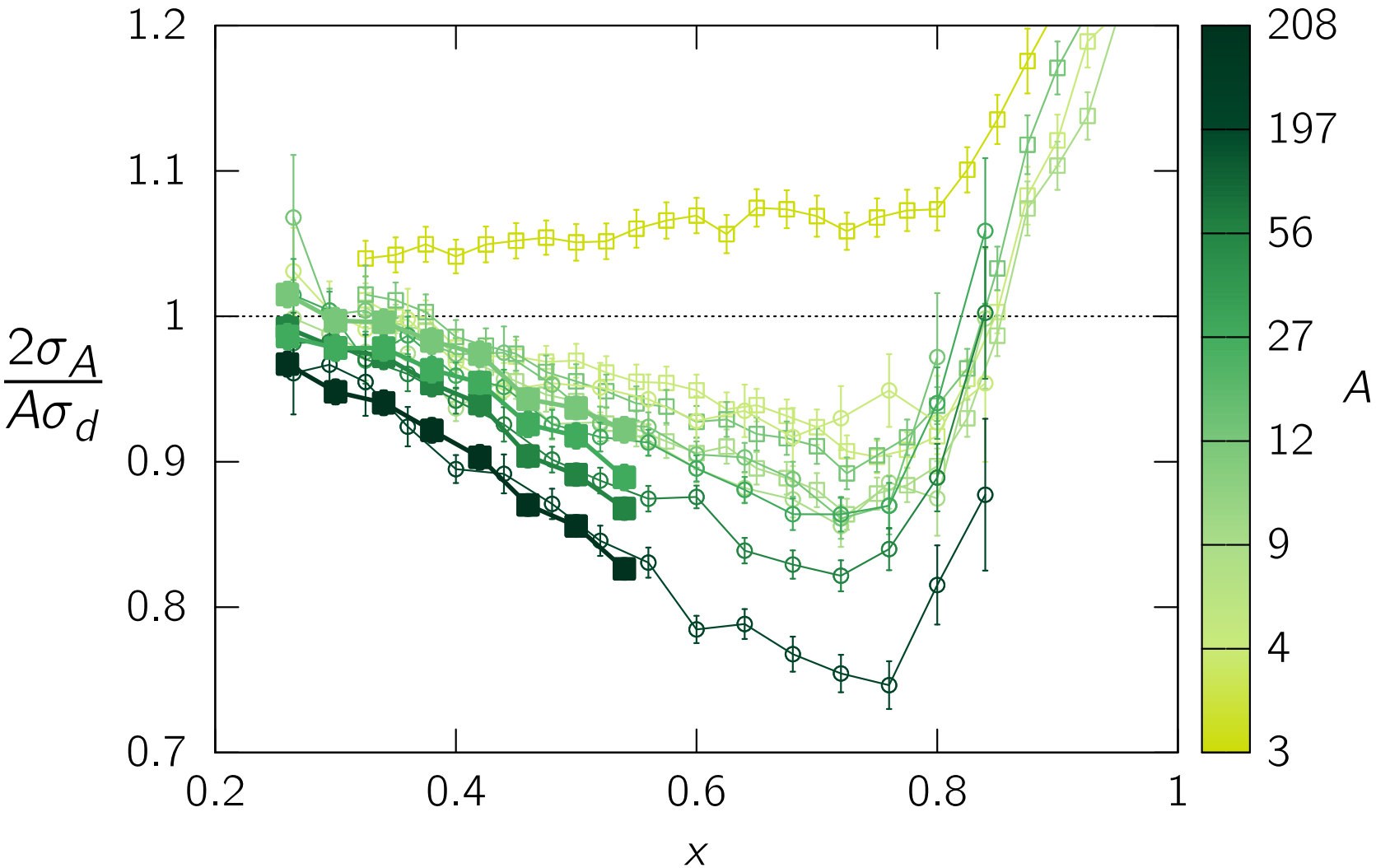


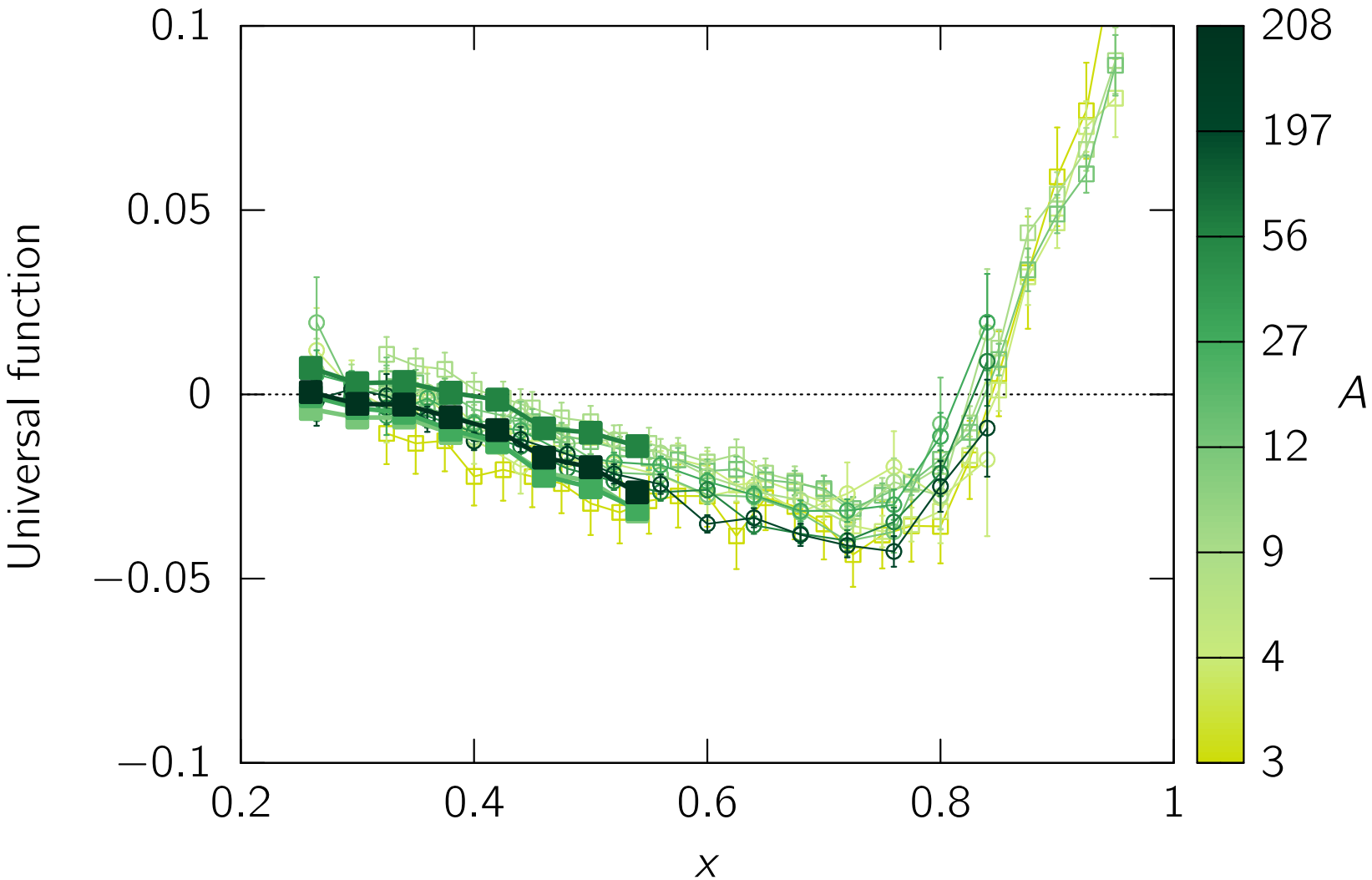




EMC Data vary significantly by nucleus.



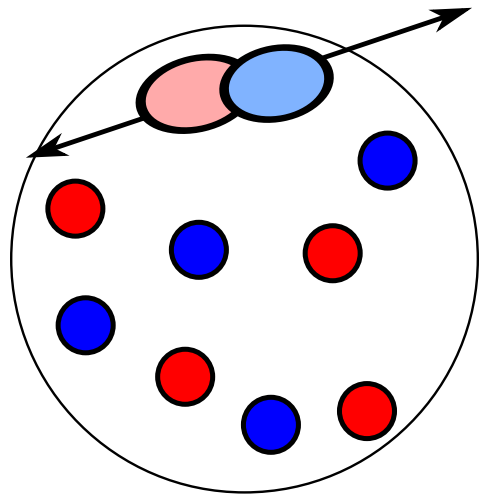
The modification of SRC pairs is universal!



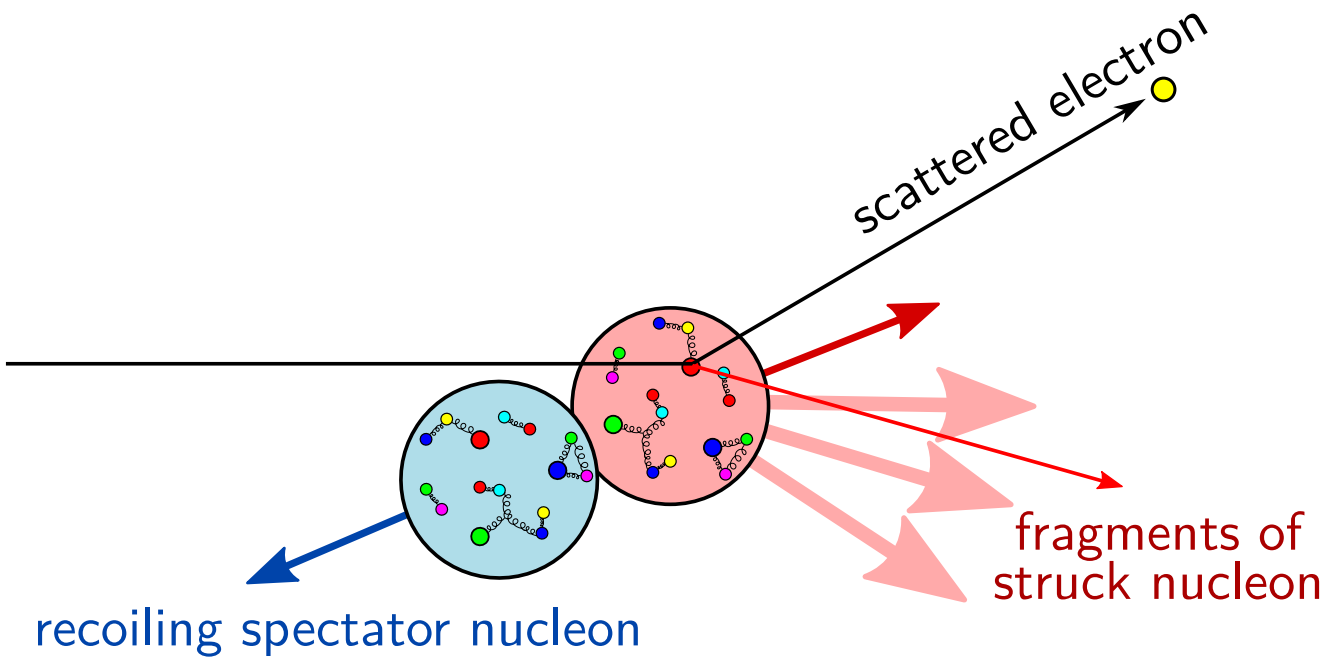
In my talk today:

1. Background
   - Review of structure functions and the EMC Effect
2. The SRC-EMC Connection
   - Could the EMC Effect stem from nuclear correlations?
3. **Experiment**
   - **How to put this hypothesis to the test.**

We need to measure the EMC Effect in SRC nucleons specifically!



We can isolate SRC nucleons by "tagging" a correlated partner.



1. Mom. of the scattered e^- $\longrightarrow$ determine quark momentum
2. Mom. of the spectator $\longrightarrow$ determine if SRC configuration

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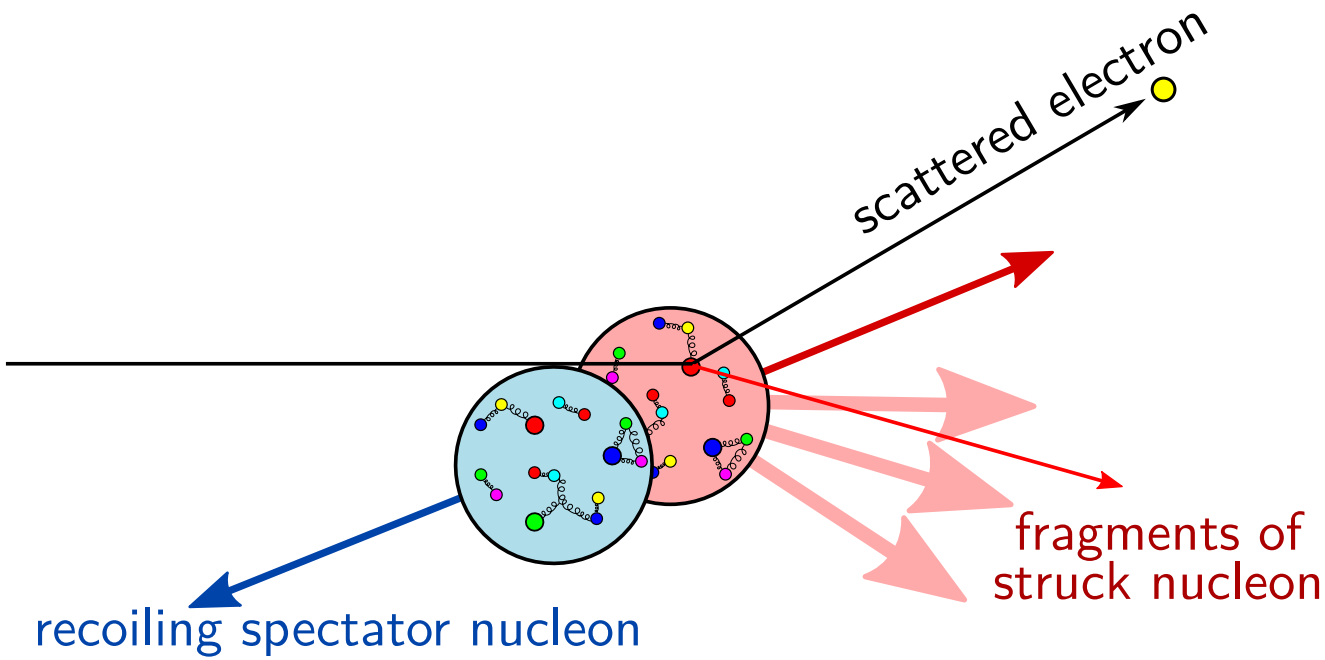

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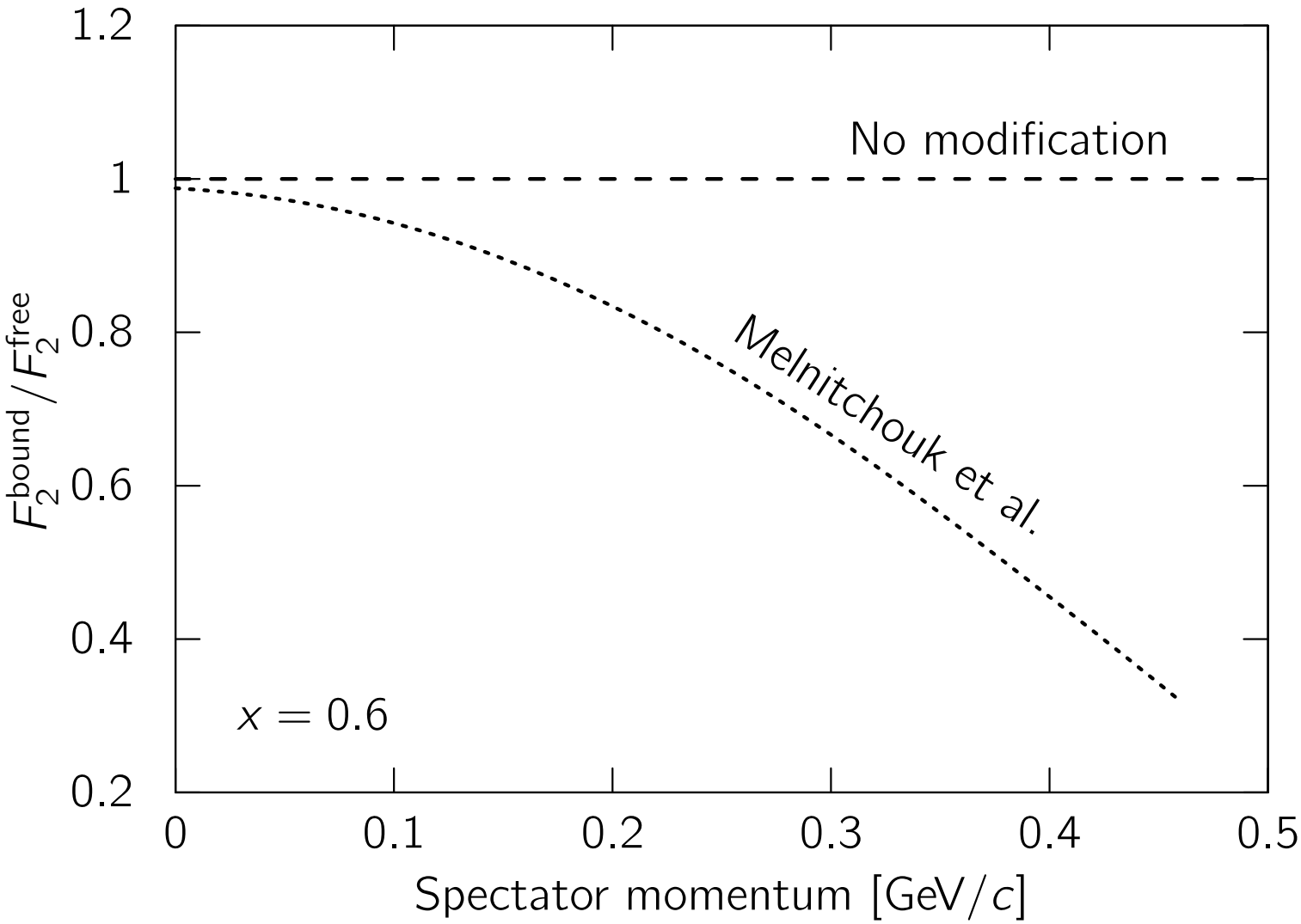


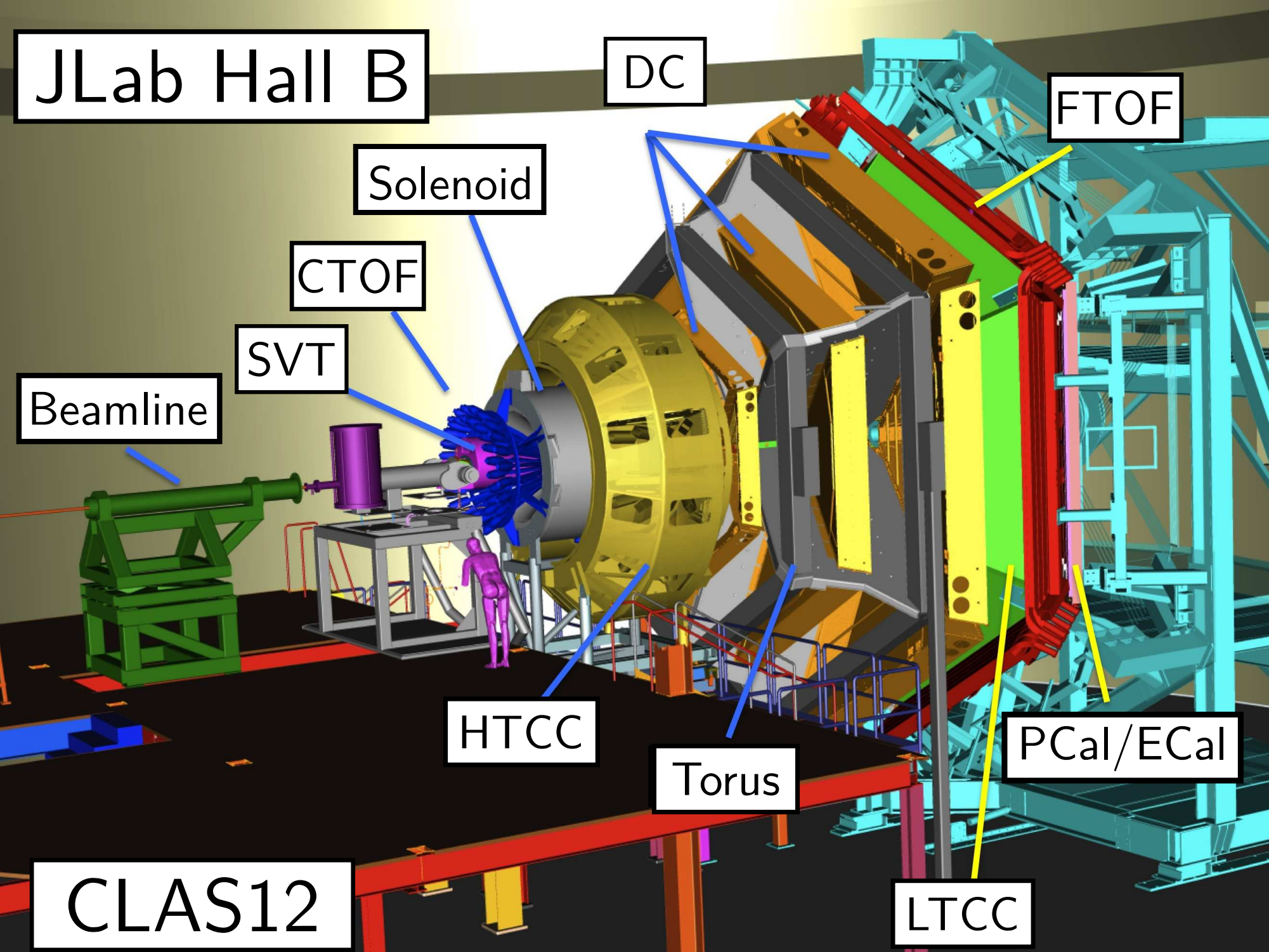
Two upcoming experiments at Jefferson Lab will complement each other.

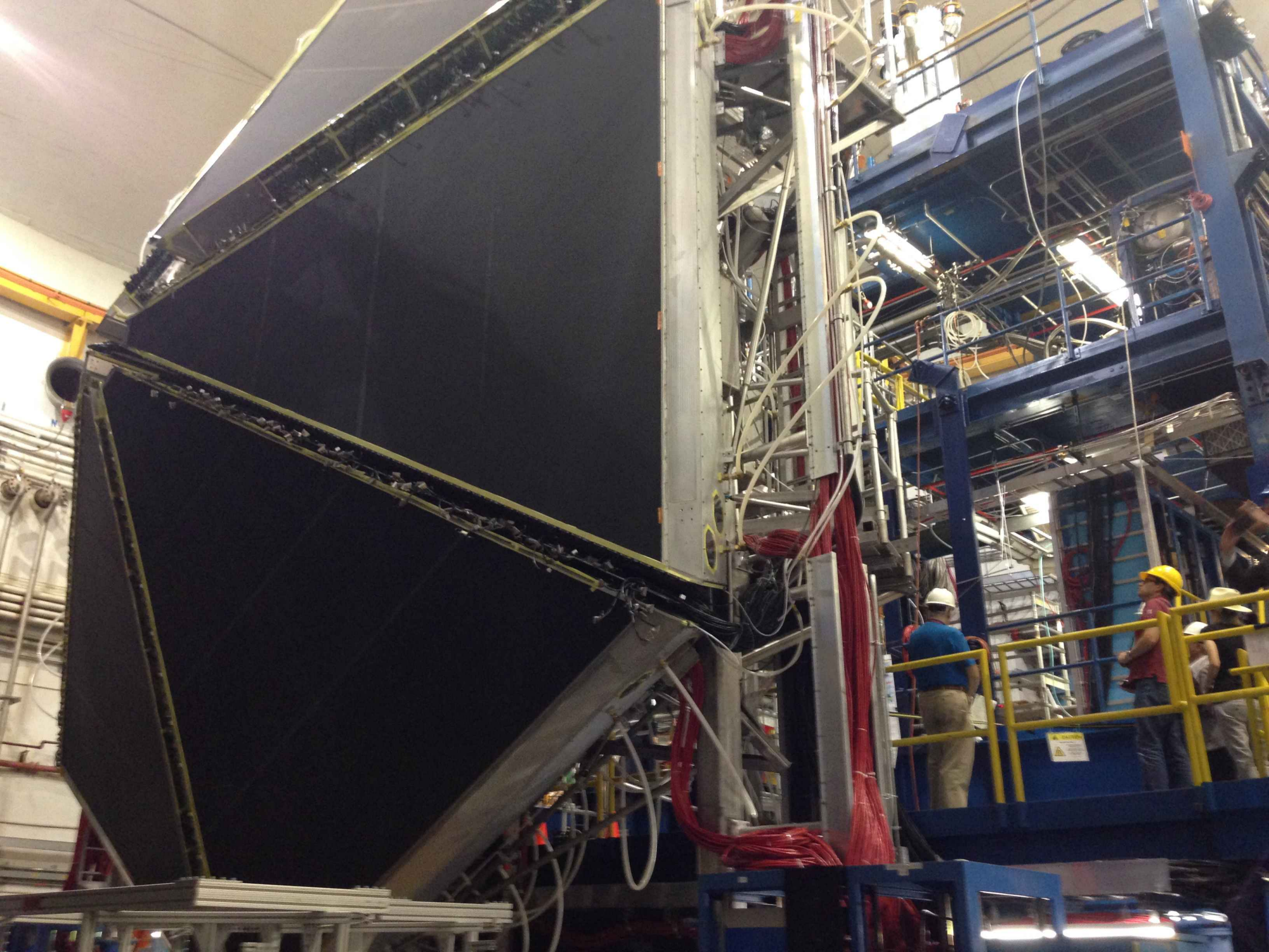
BAND

- quarks in protons
- detect recoil neutrons
- JLab Hall B
- Data taking just started!

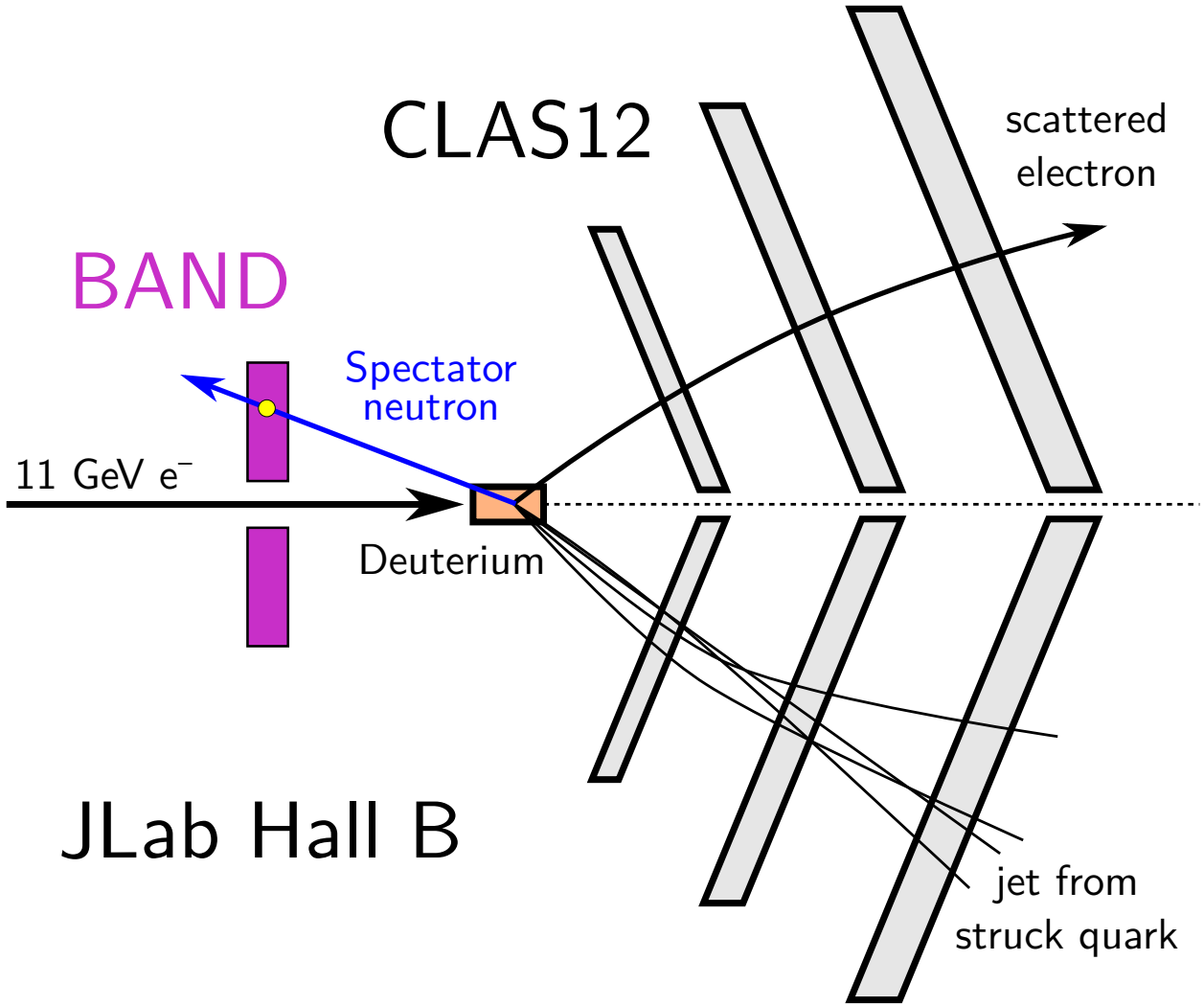
LAD

- quarks in neutrons
- detect recoil protons
- JLab Hall C
- Data taking $\approx$ 2021

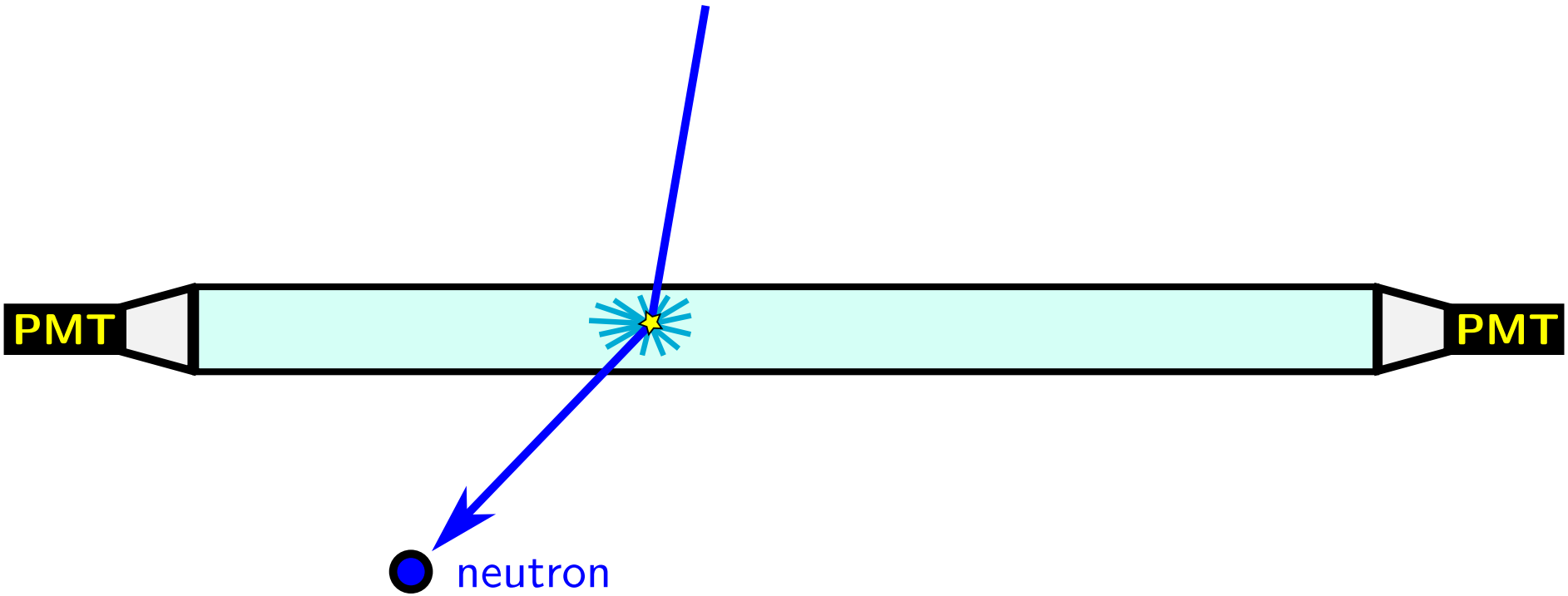

JLab Hall B
DC
FTOF
Solenoid
CTOF
SVT
Beamline
HTCC
Torus
PCal/ECal
LTCC
CLAS12



“Backward Angle Neutron Detector” will detect recoiling spectator neutrons

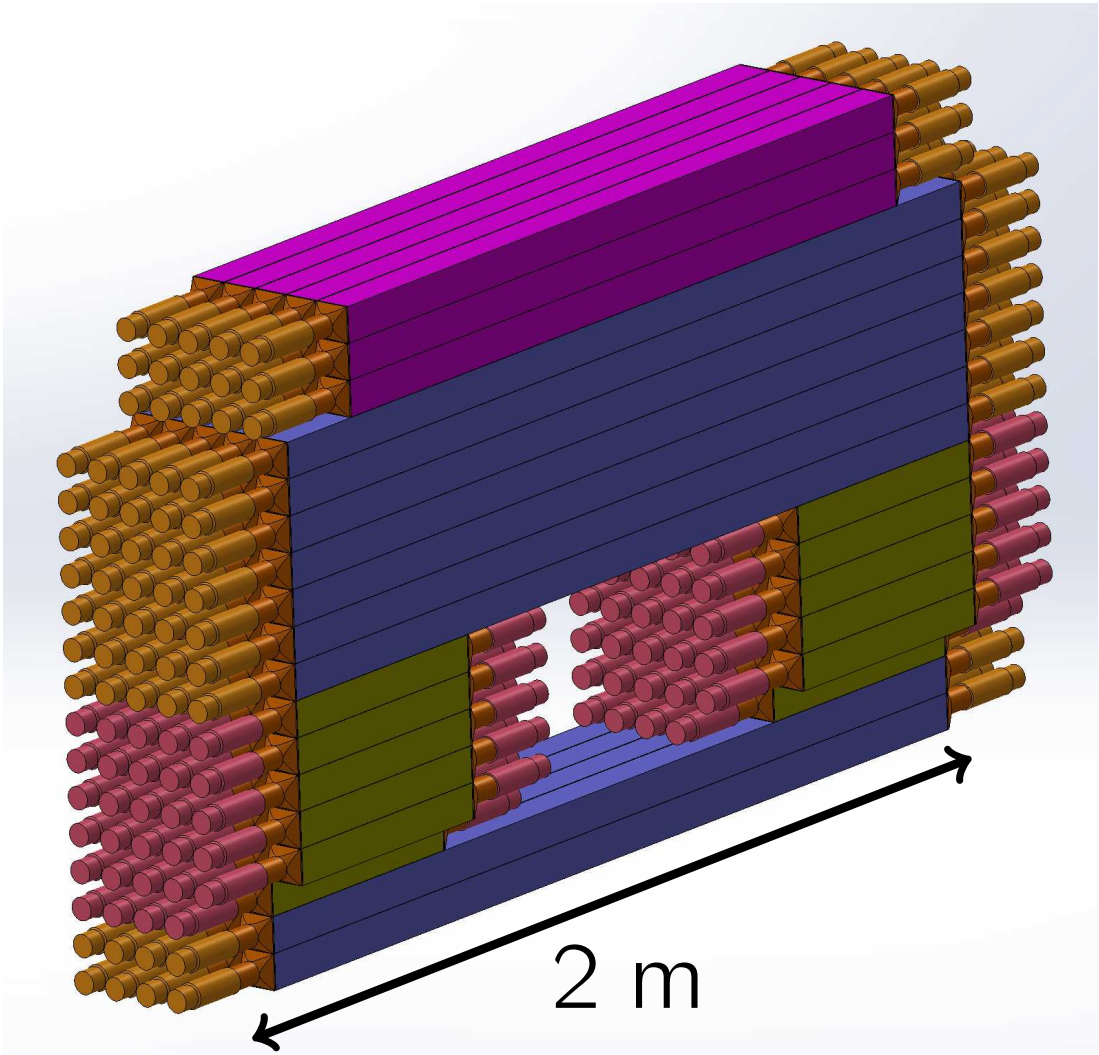


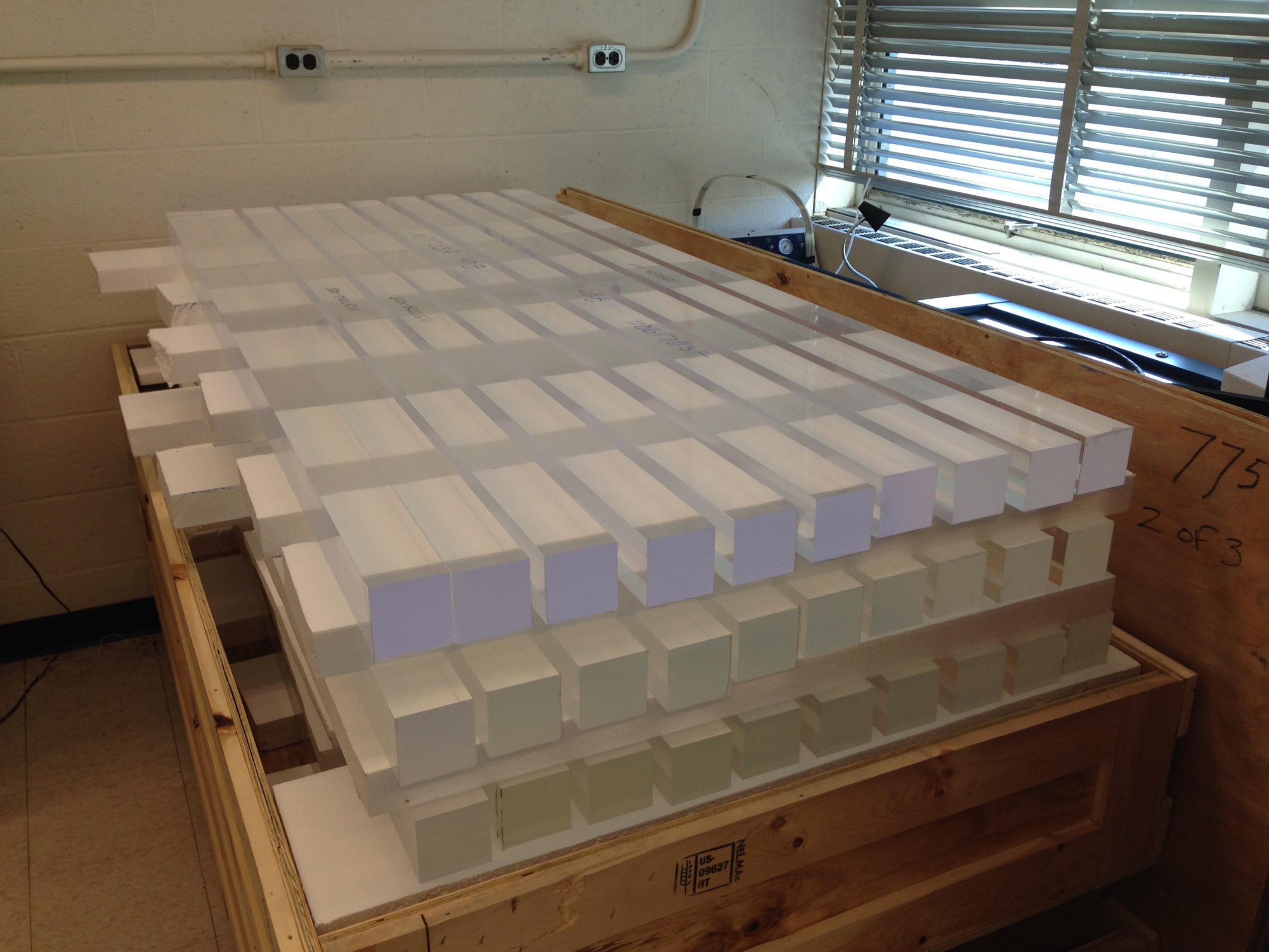
BAND is made up of modular bars made of scintillating plastic.

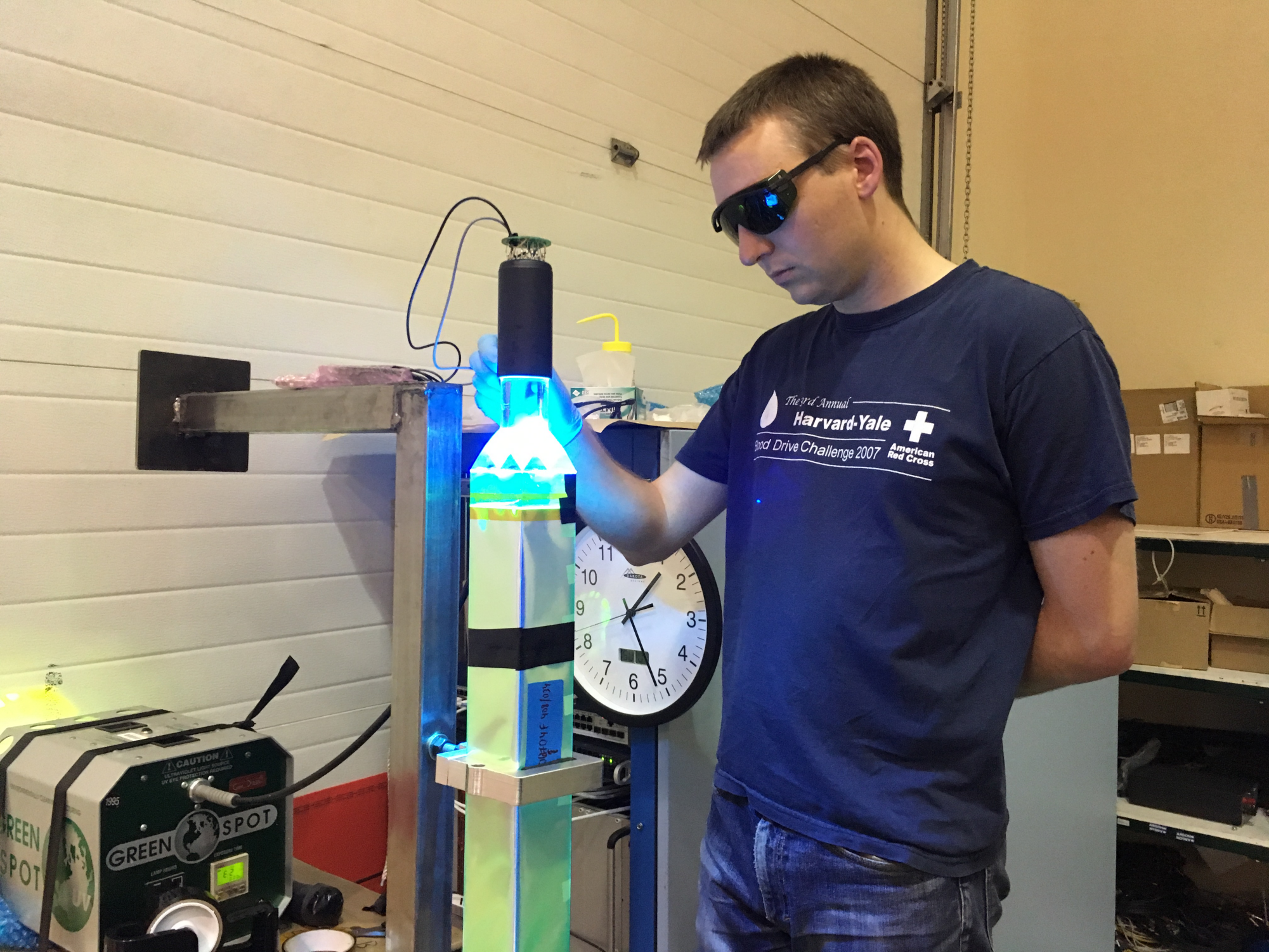


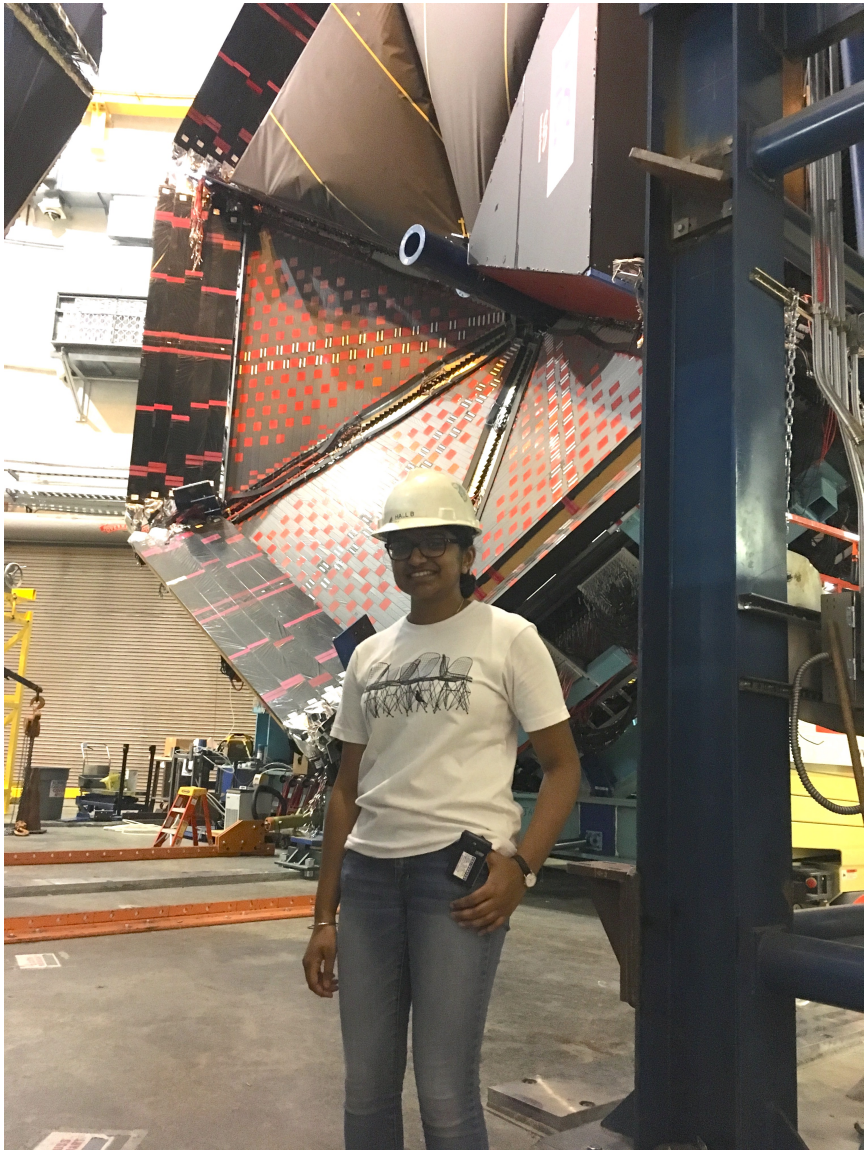
- $t_L - t_R \longrightarrow$ position
- $\frac{1}{2}(t_L + t_R) \longrightarrow$ flight time $\longrightarrow$ momentum

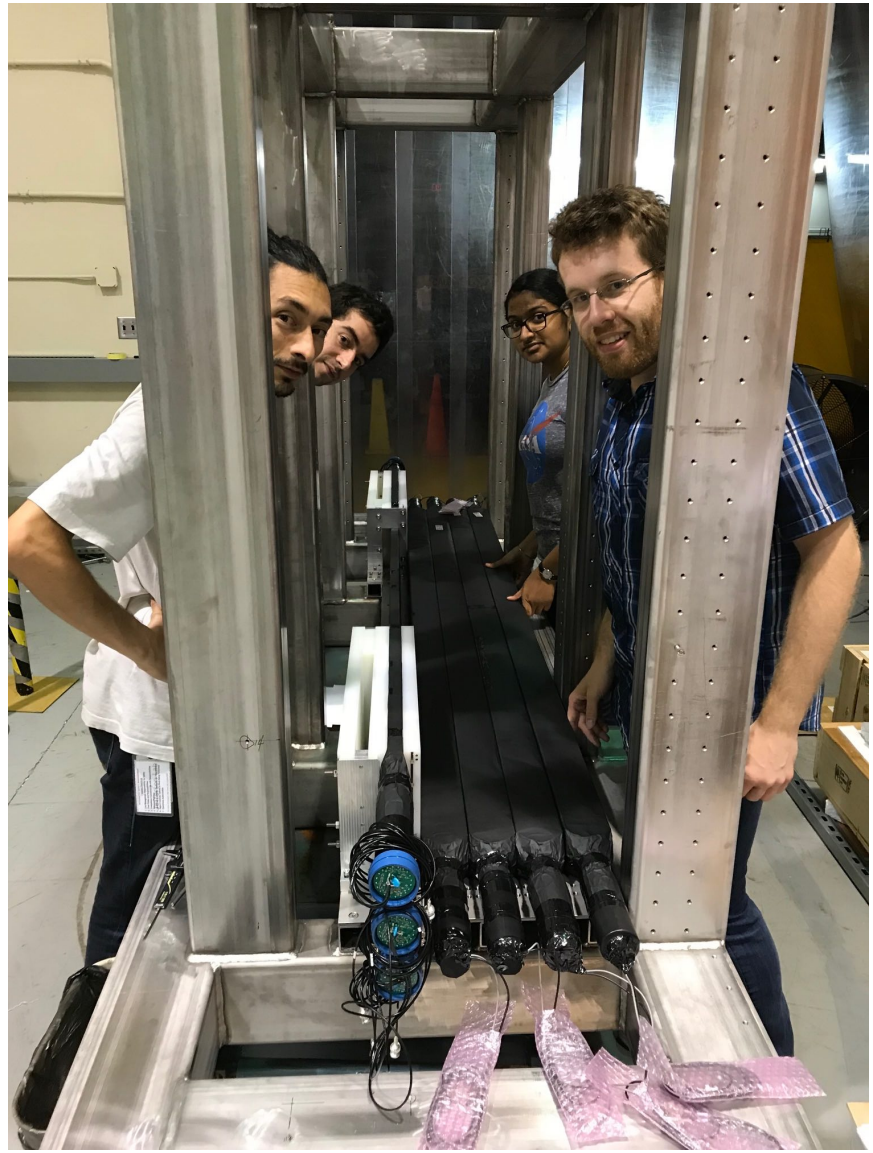
BAND is made up of modular bars made of scintillating plastic.

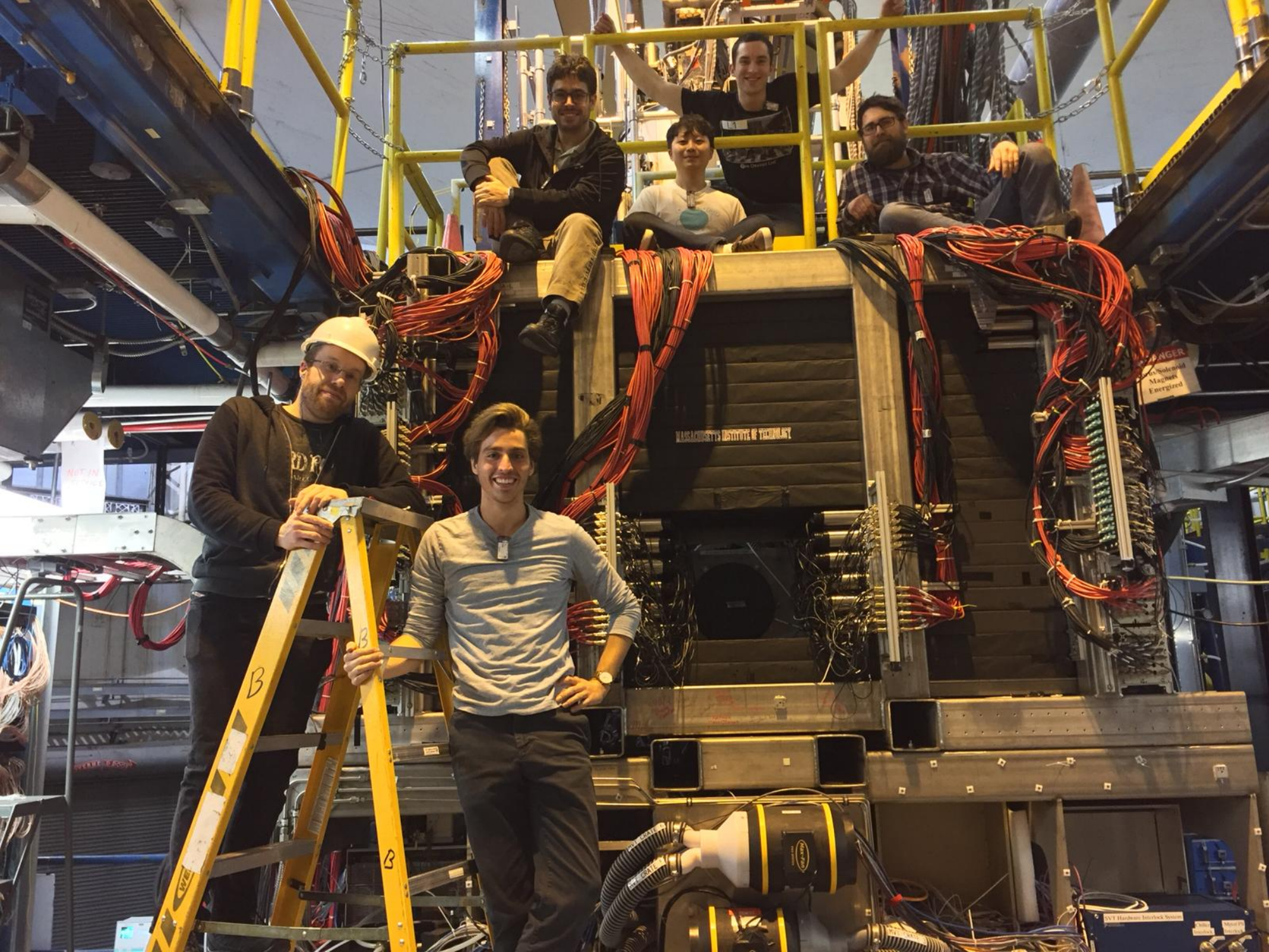



775
2 of 3
US-09627
NELMAR

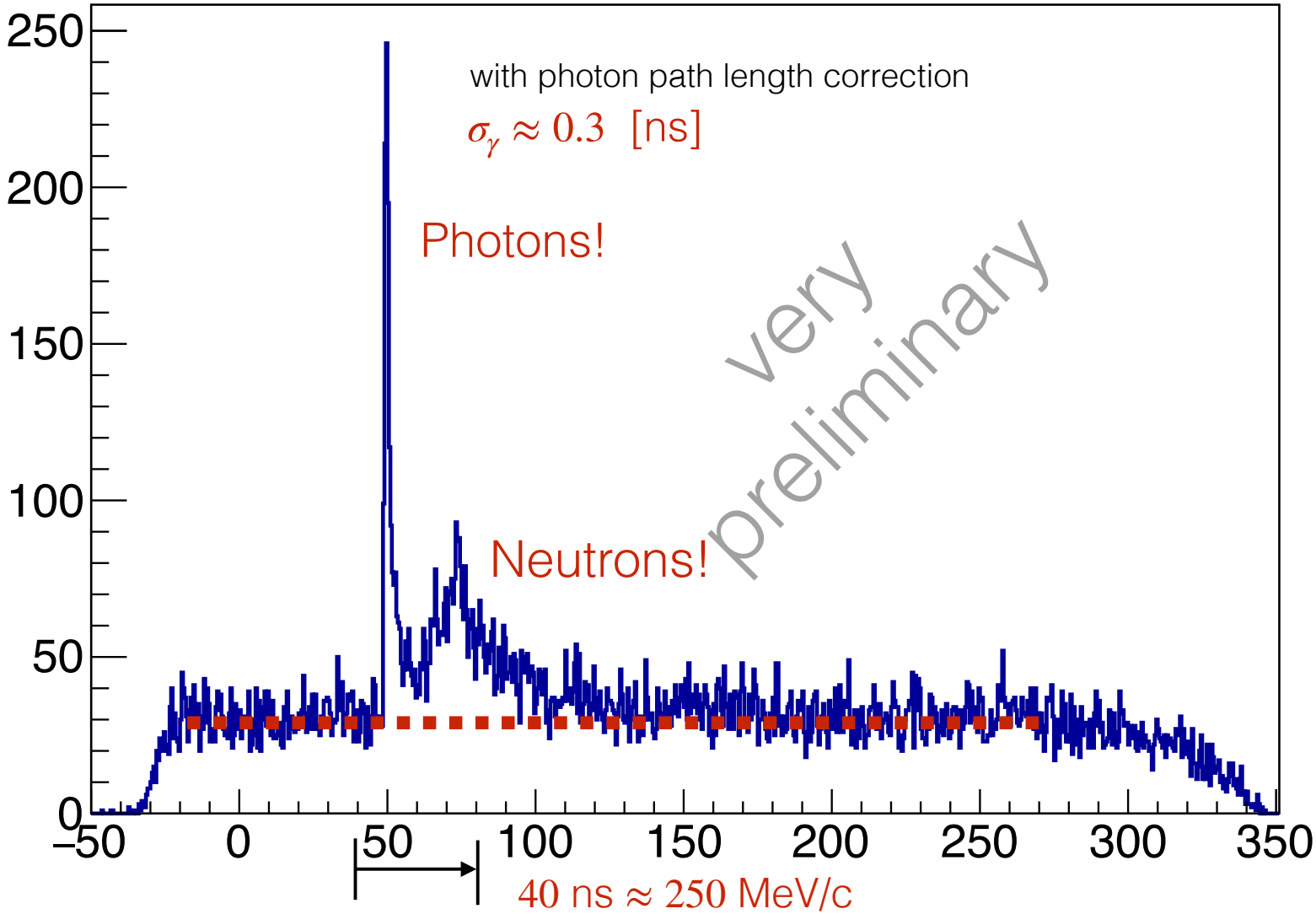

The 3rd Annual
Harvard-Yale
Blood Drive Challenge 2007
American Red Cross
GREEN SPOT
CAUTION
ULTRAVIOLET LIGHT SOURCE
UV EYE PROTECTION REQUIRED



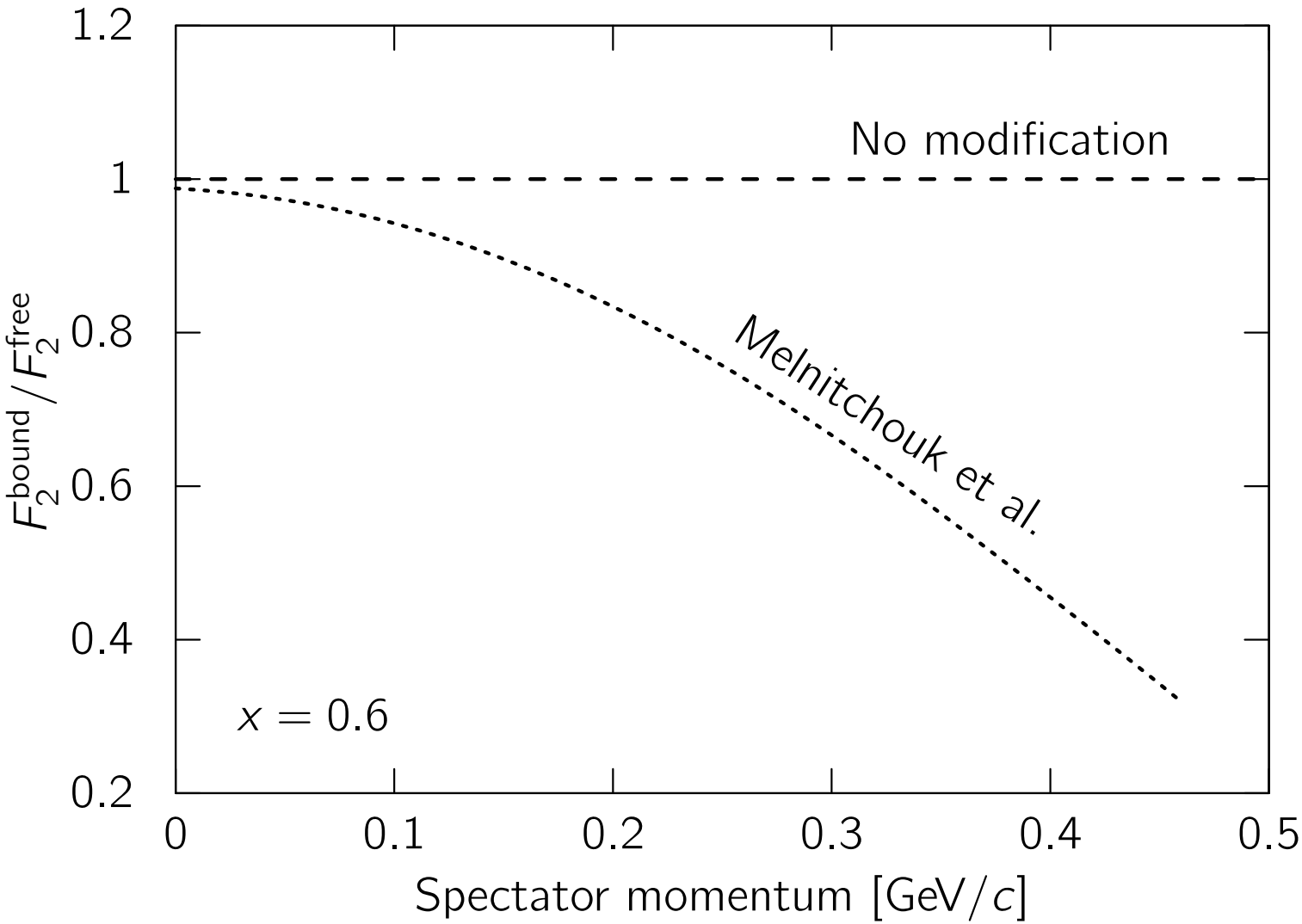



DANGER
Solenoid
Magnet
Energized
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SVT Hardware Interlock System

BAND just started taking data and we see neutrons!



The SRC hypothesis predicts more modification with larger spectator momentum.



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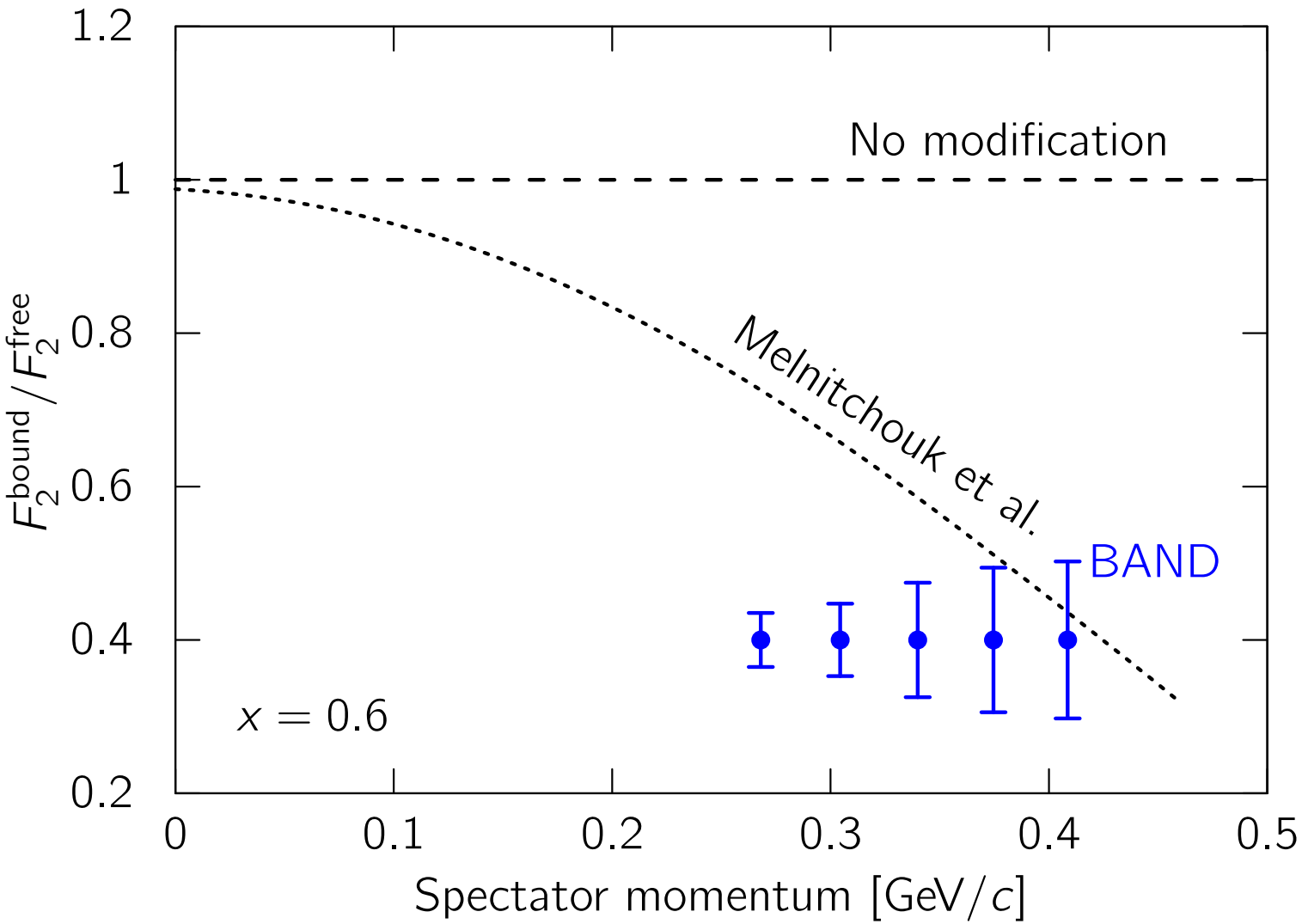
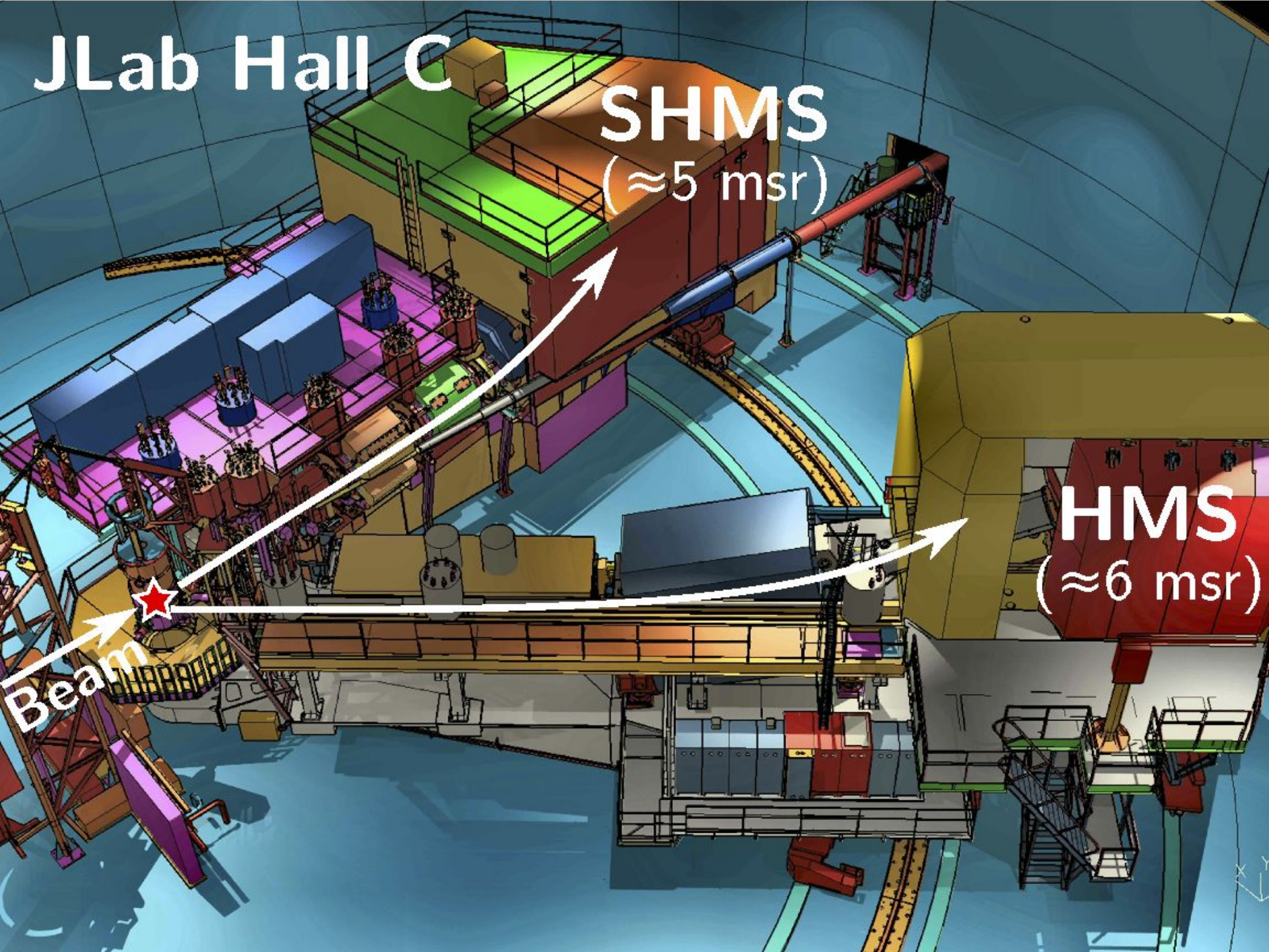
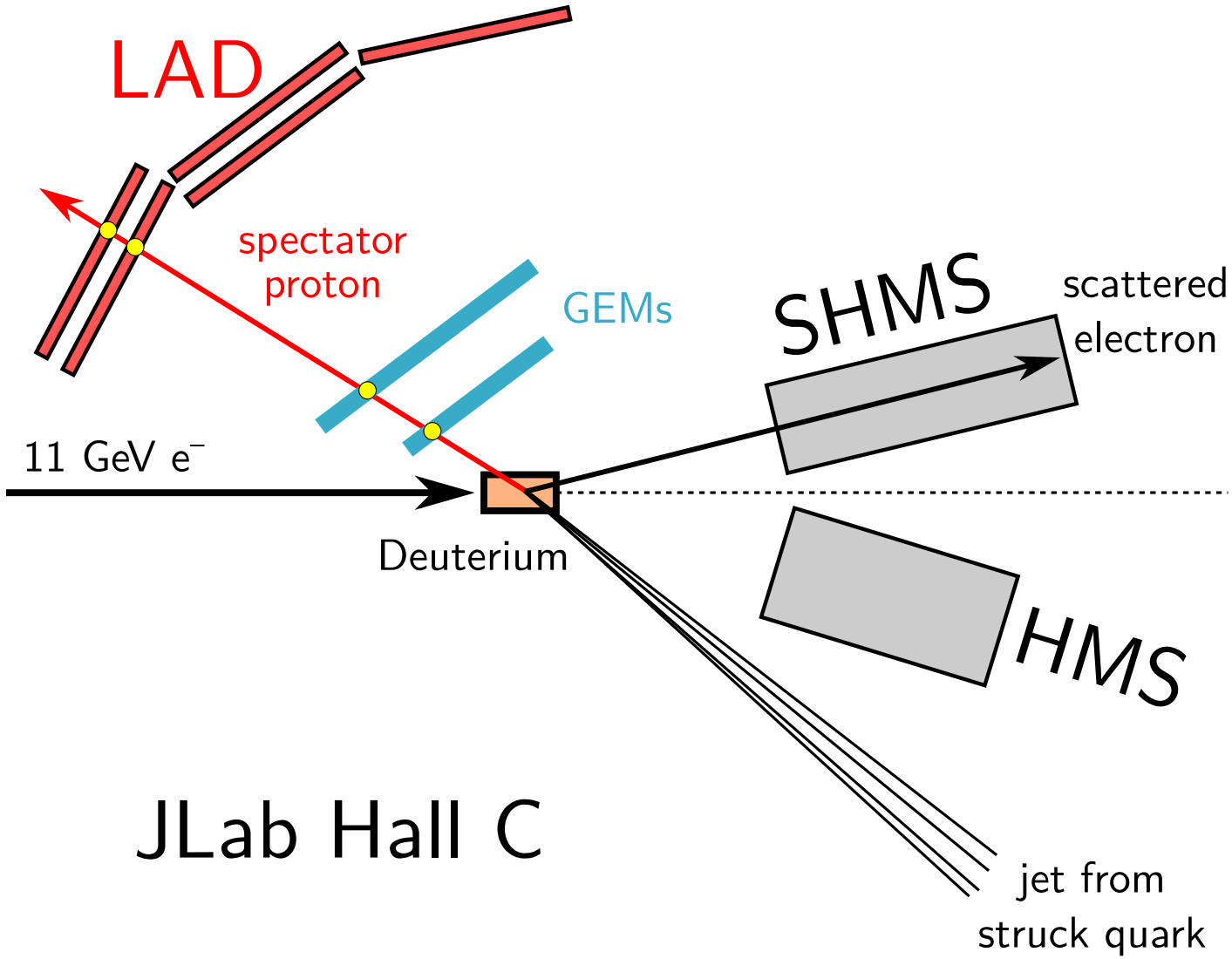


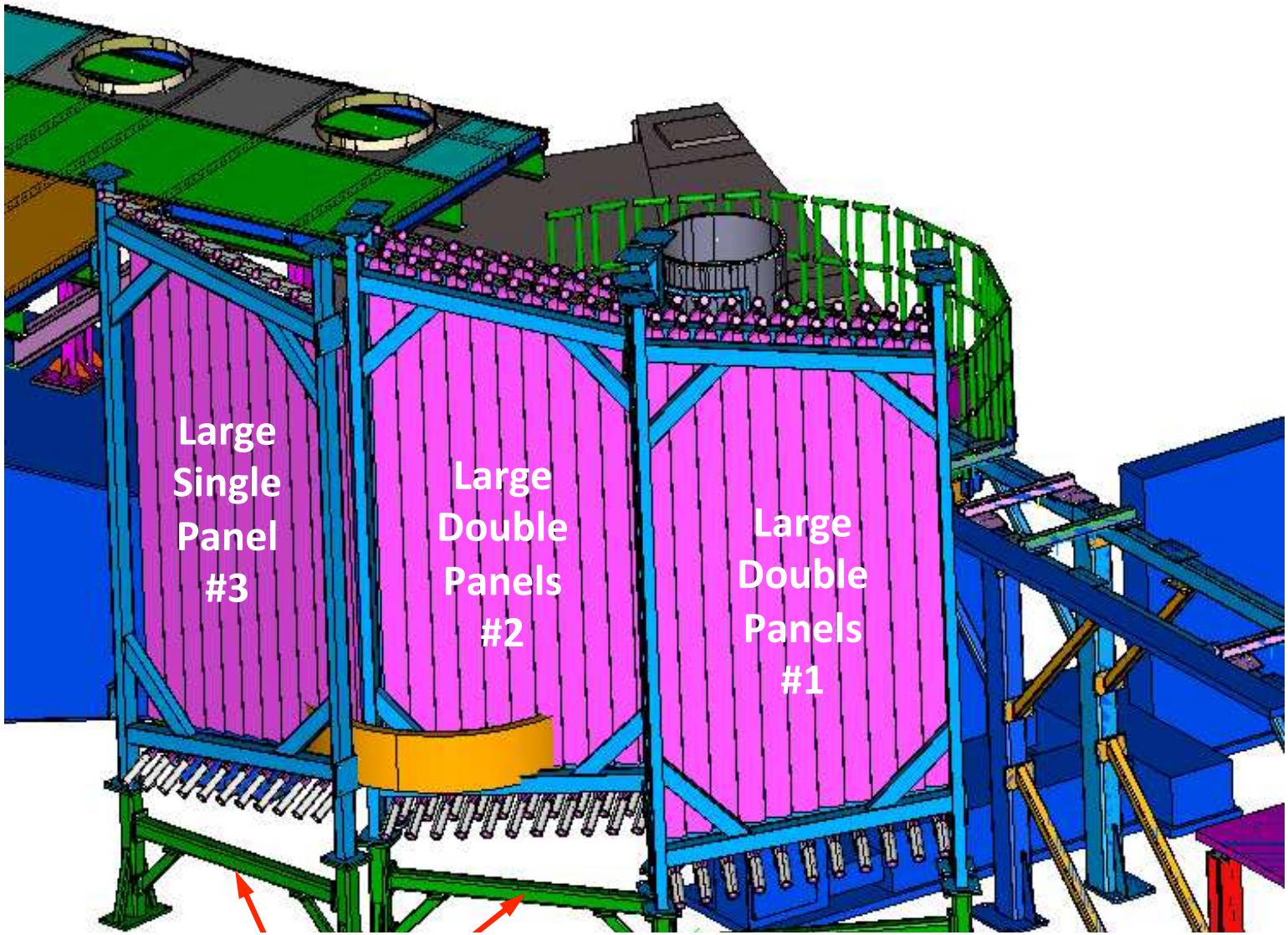

JLab Hall C
SHMS
(≈5 msr)
HMS
(≈6 msr)
Beam

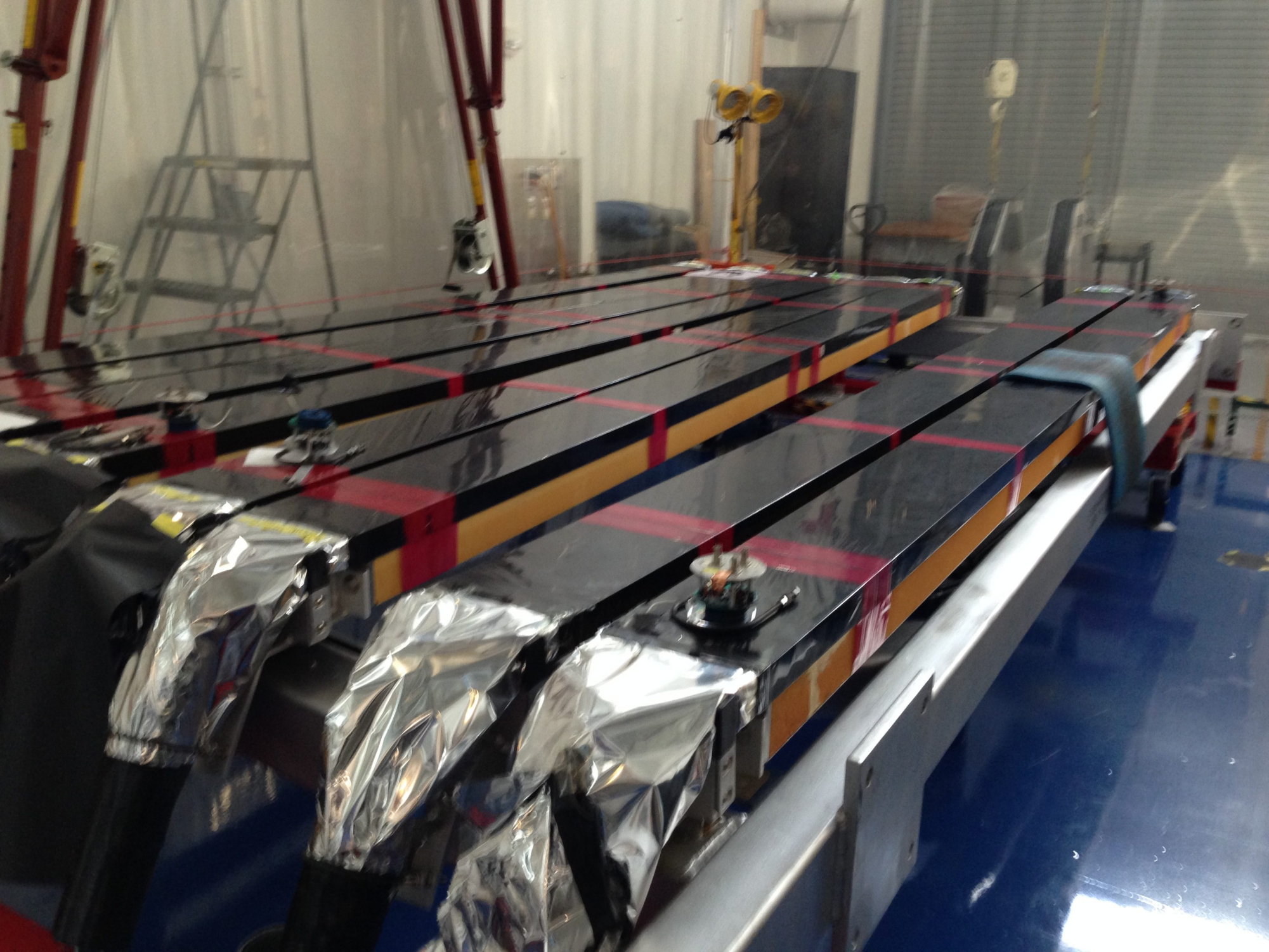
"Large Acceptance Detector"
will detect recoiling spectator protons.



JLab Hall C

LAD is three panels of scintillator bars, reused from the original CLAS.





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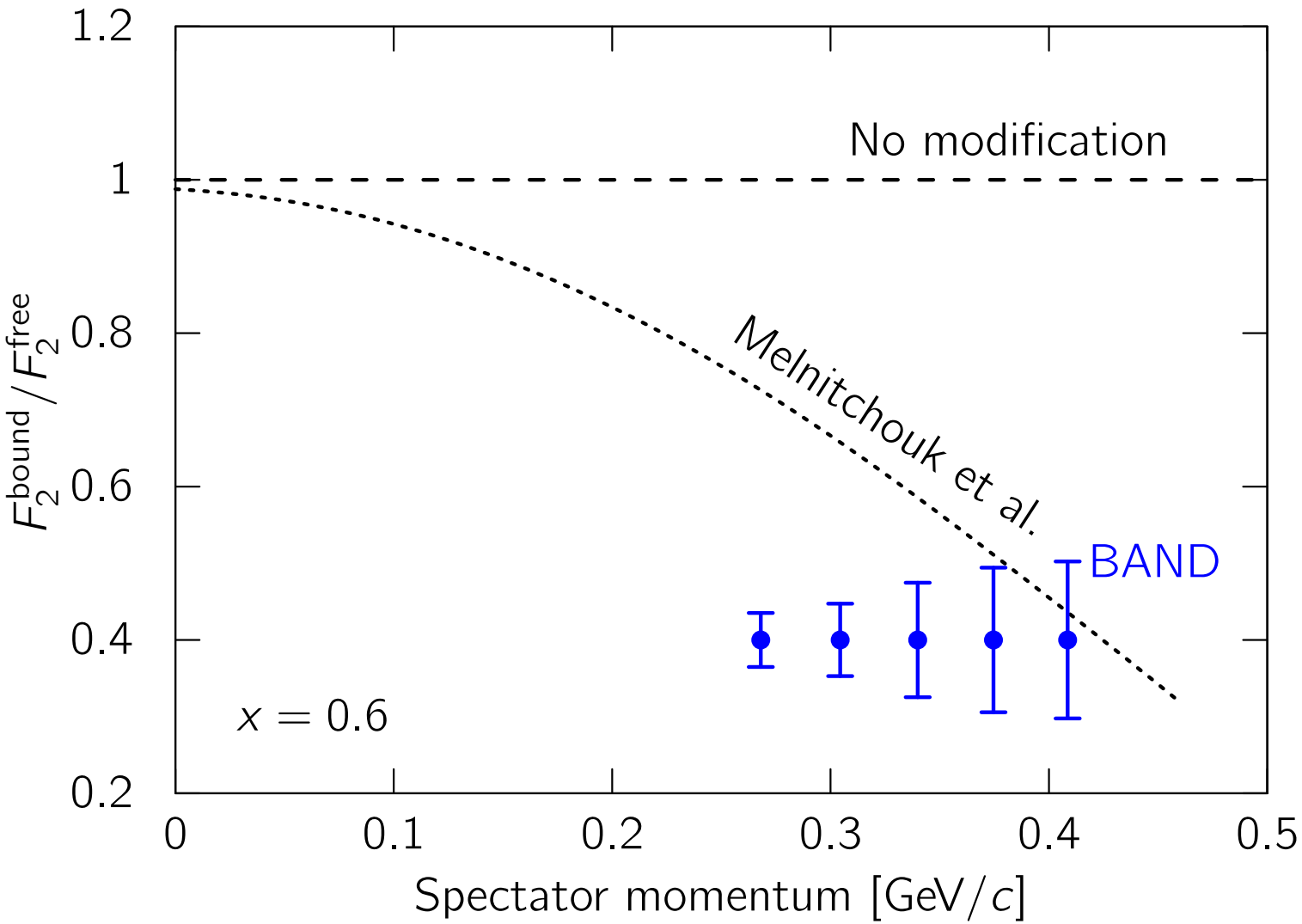

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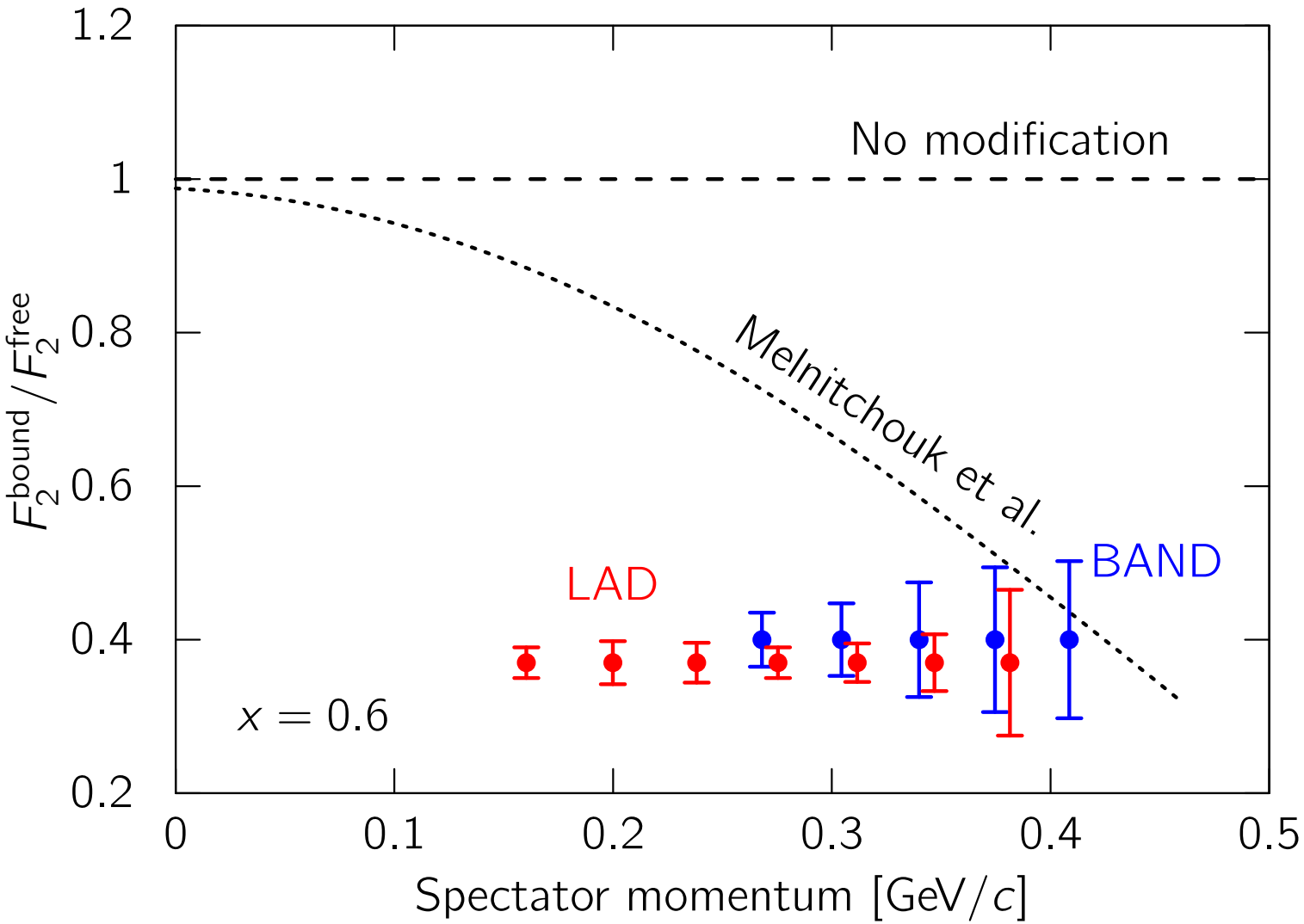
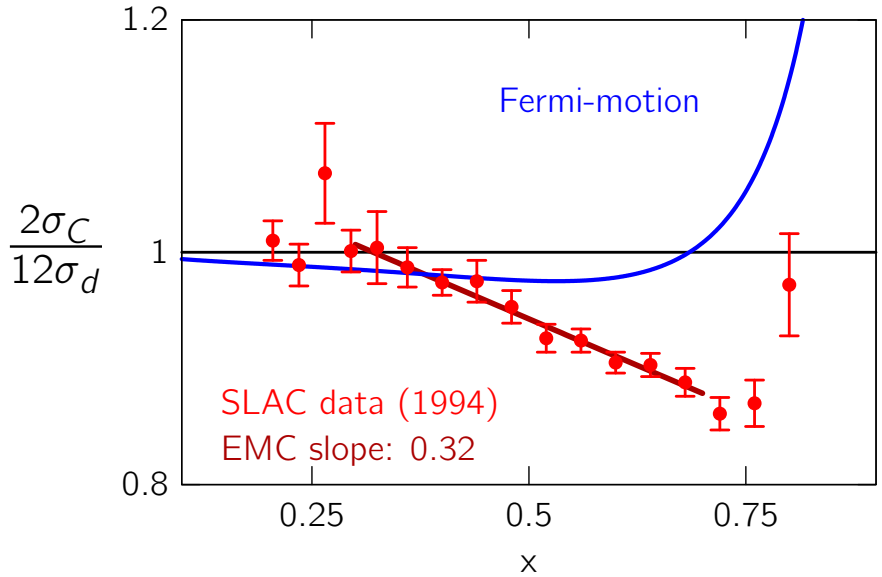


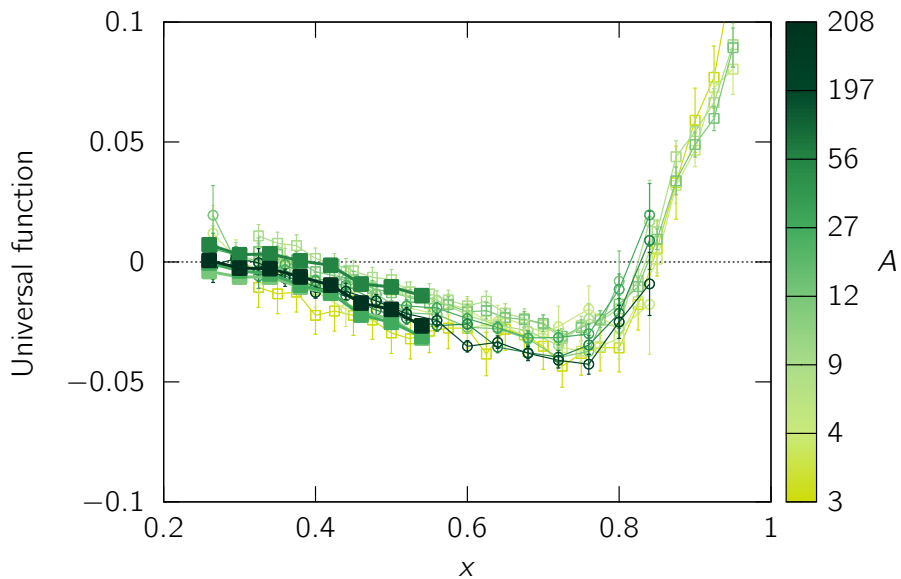
To Recap:

- The EMC Effect
- The SRC-EMC hypothesis
- Experimental tests



To Recap:

- The EMC Effect
- The SRC-EMC hypothesis
- Experimental tests



To Recap:

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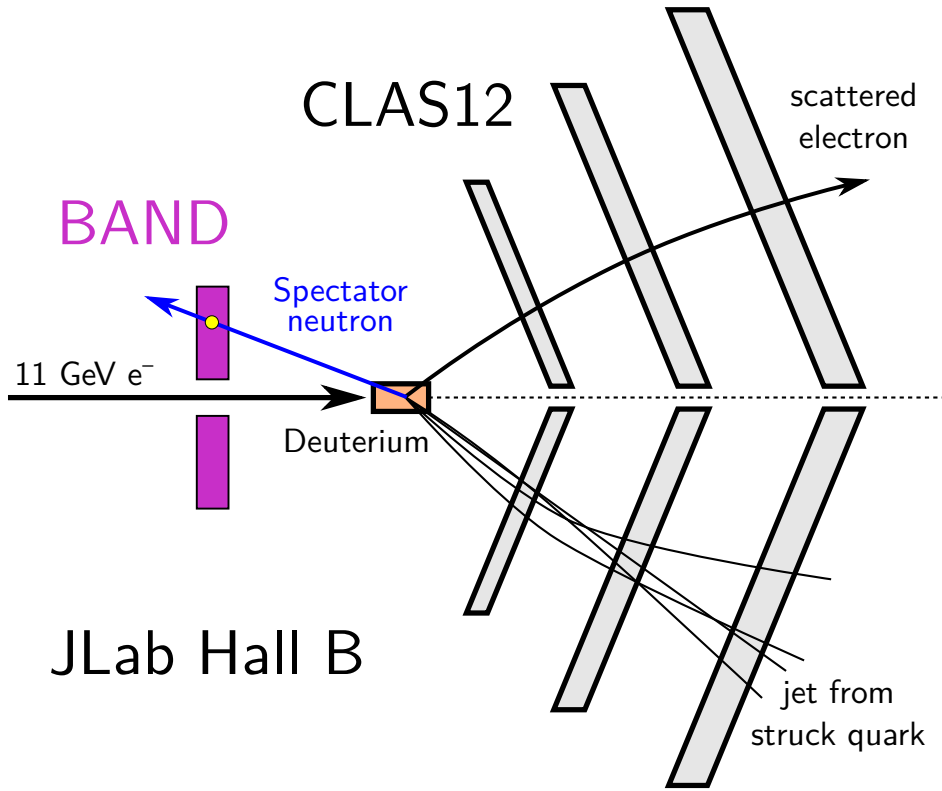

To Recap:

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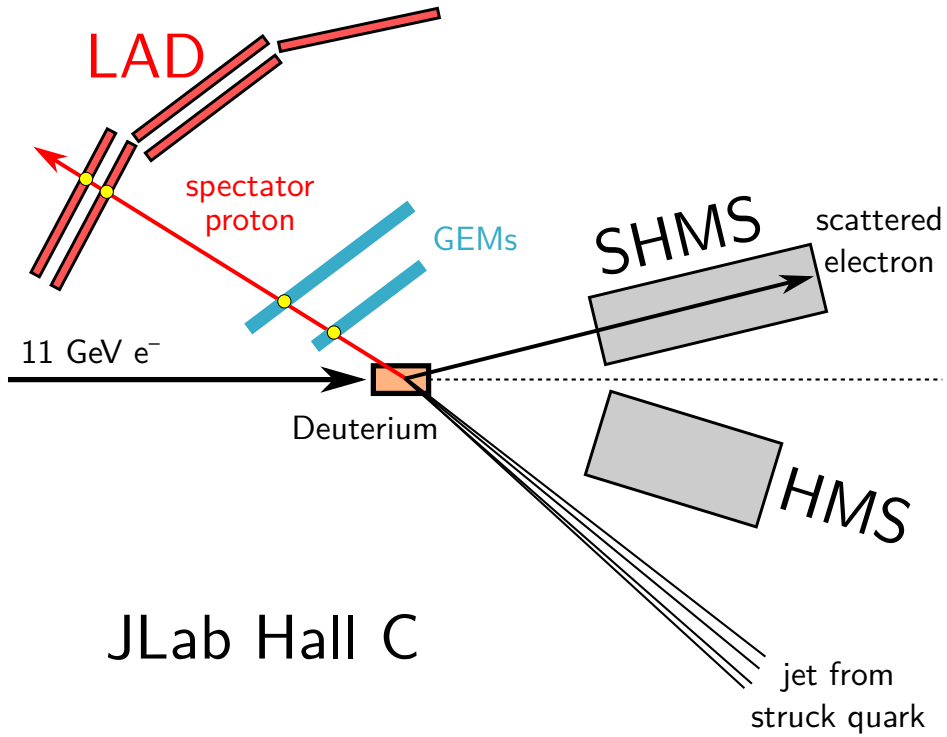

To Recap:

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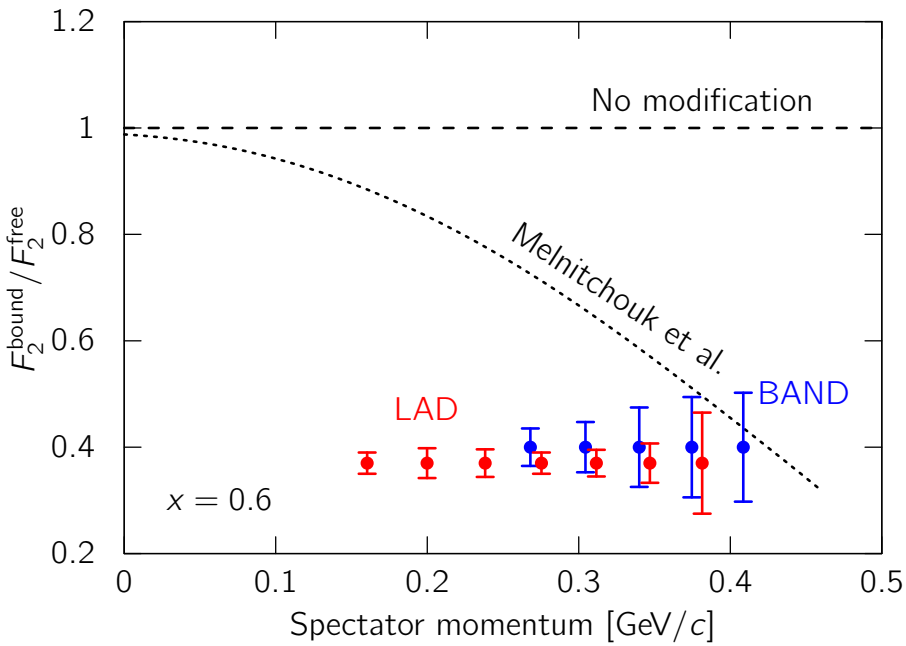
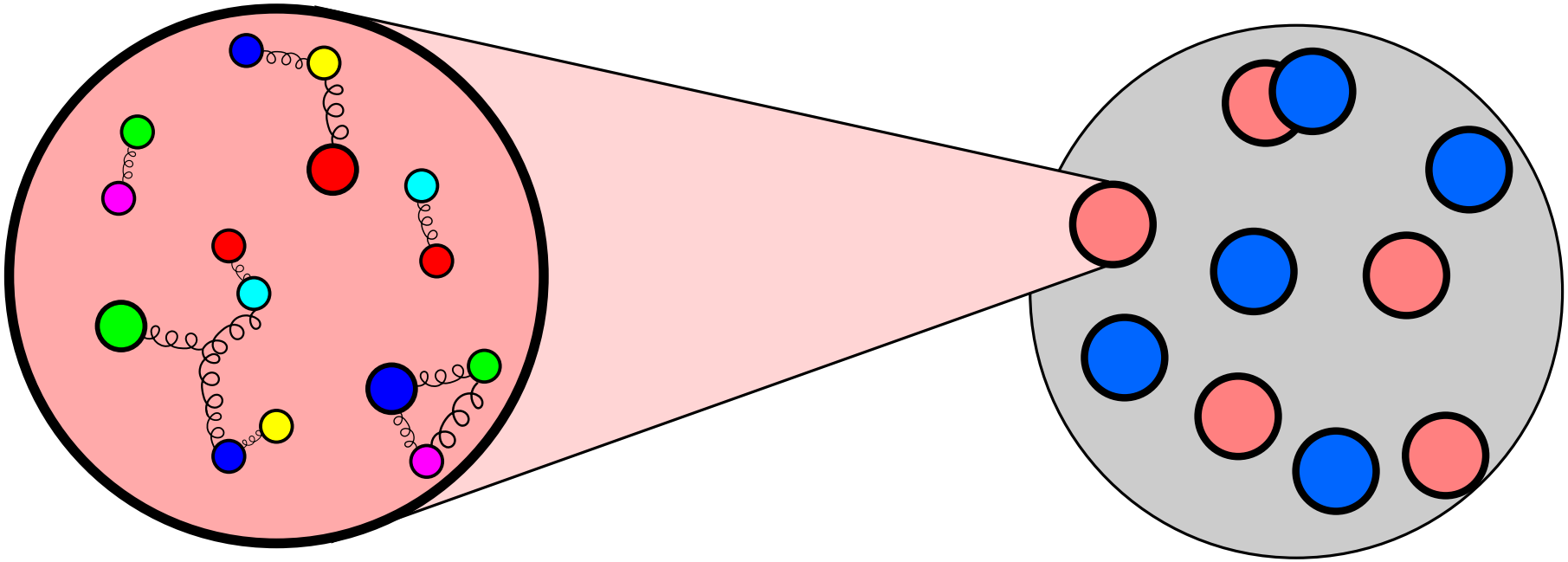


We will have a definitive test of the SRC-EMC hypothesis in the *next few years!*



Gigaelectron-Volt scale (GeV) $\gg$ Megaelectron-Volt scale (MeV)

Will it explain why scale separation is violated?