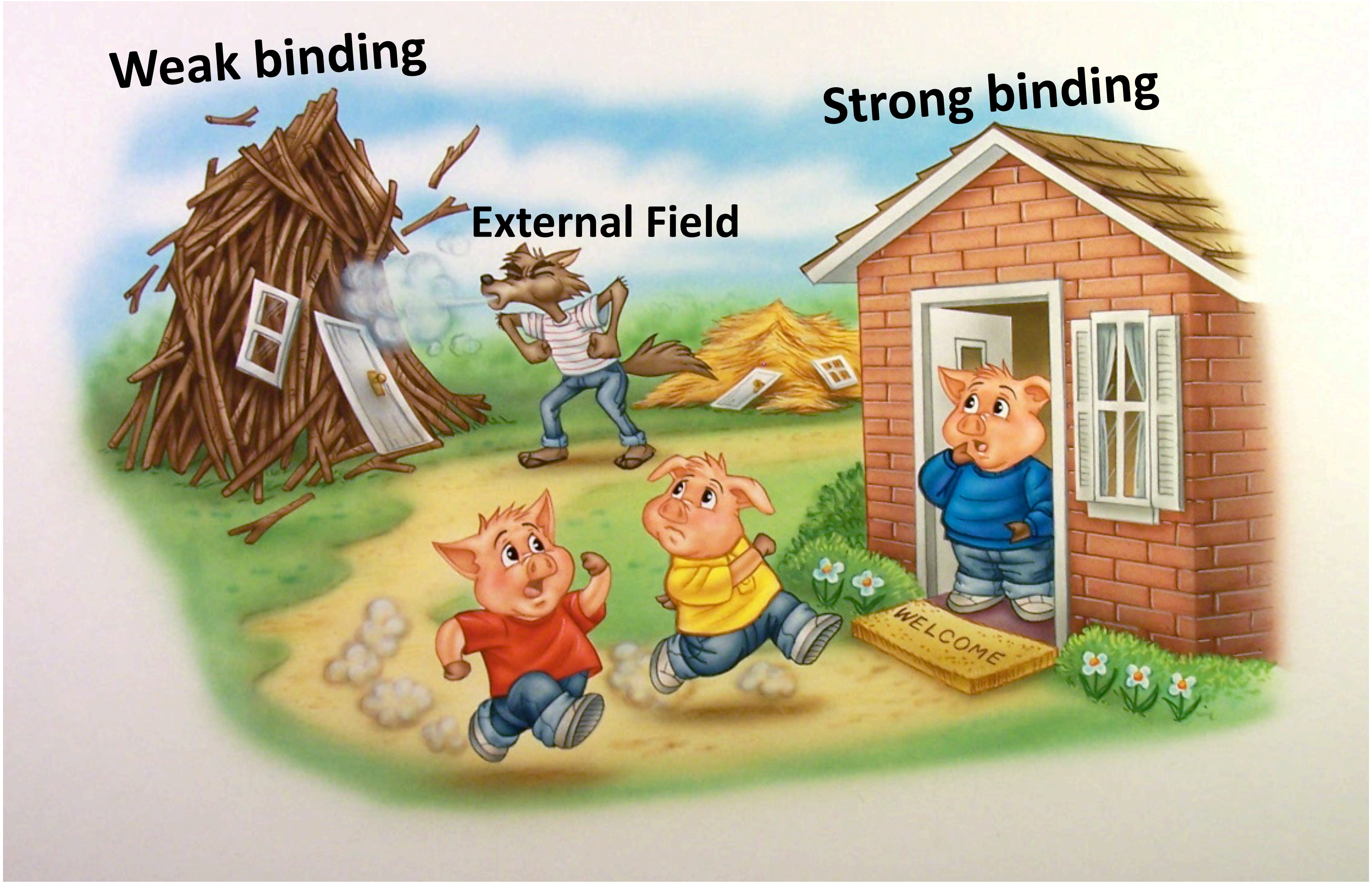
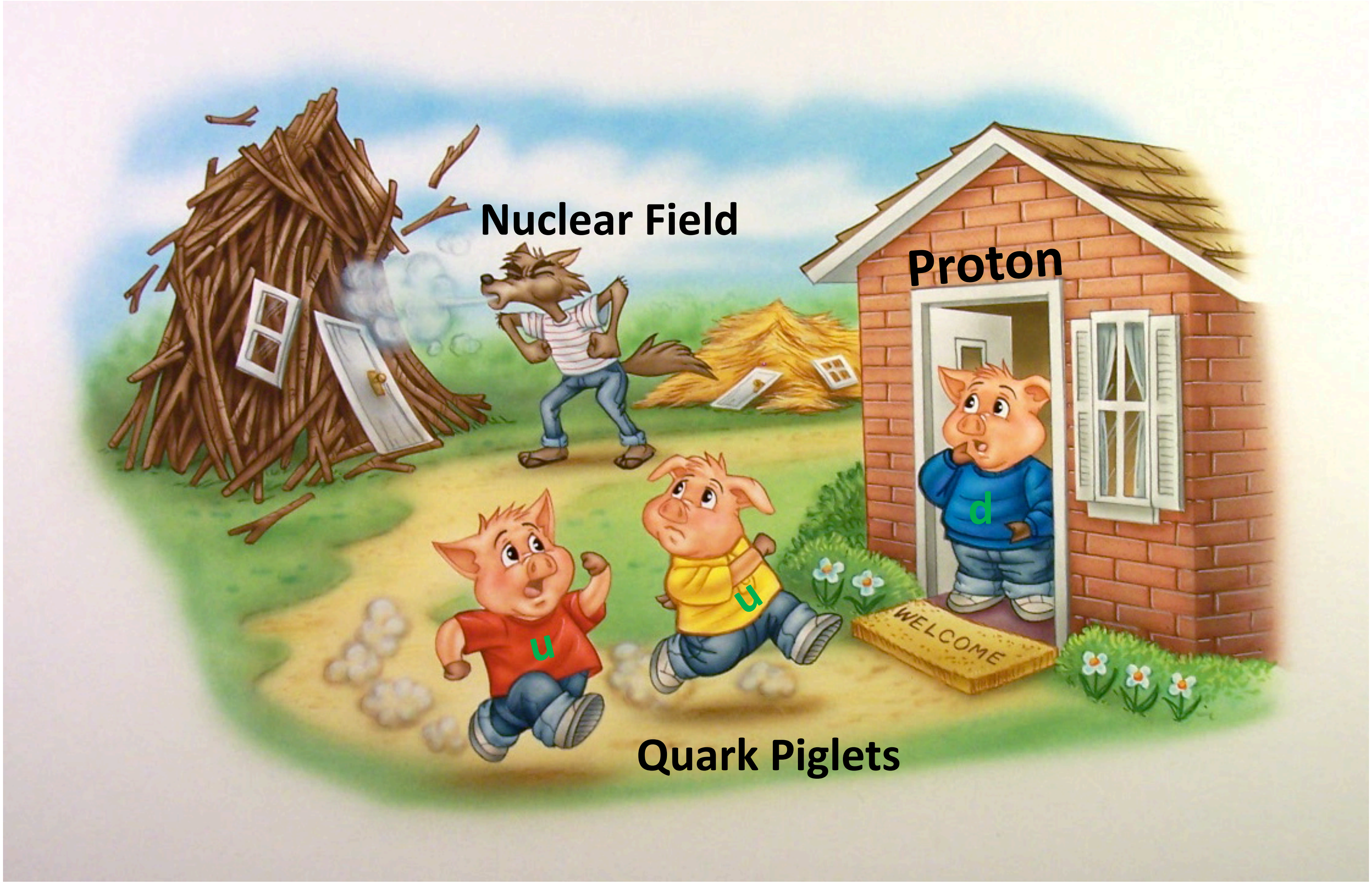
EMC & SRC: New Results from EIC Phase-0

Or Hen - MIT

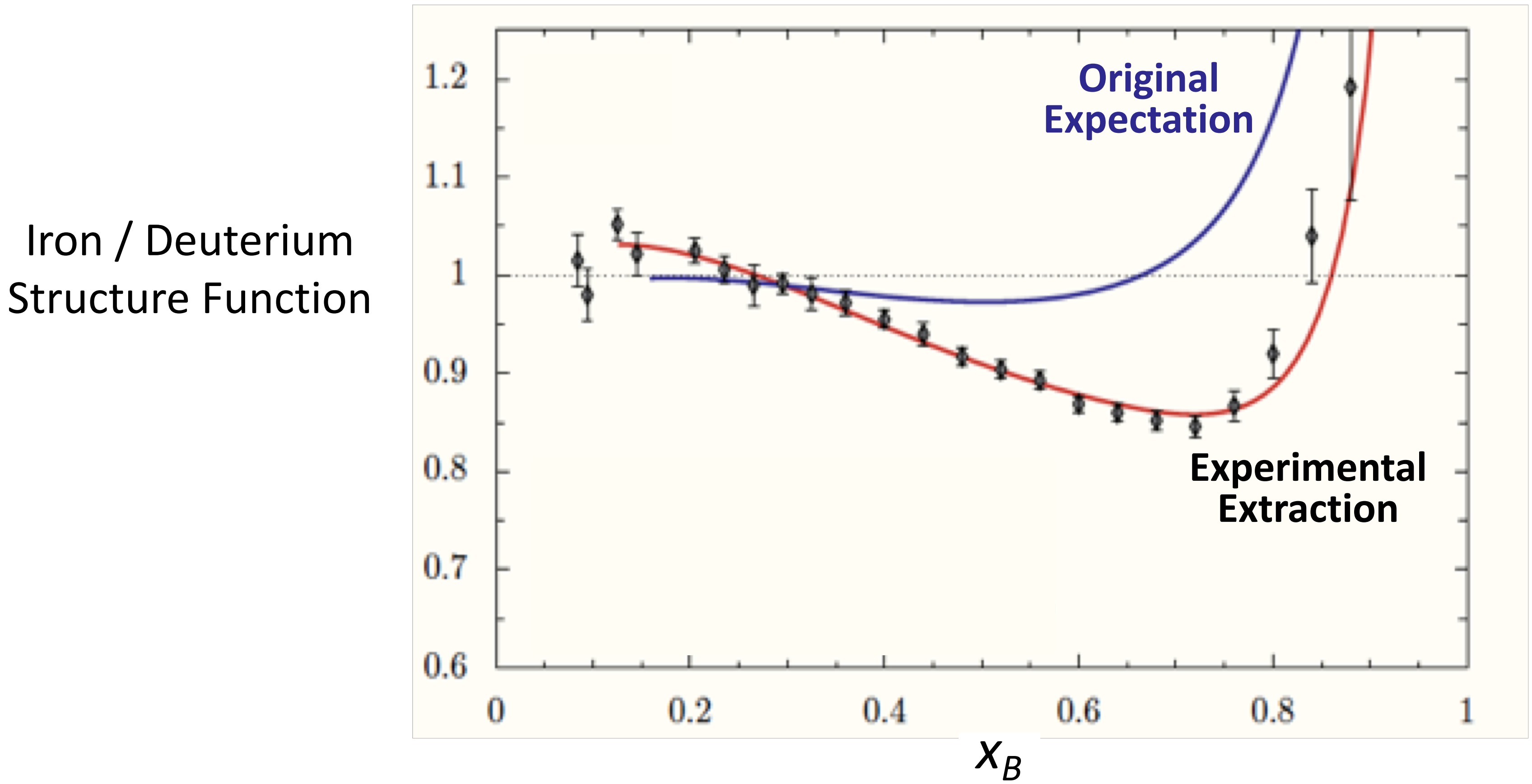
Probing Nucleons and Nuclei in High Energy Collisions, INT, Oct. 29th 2018.

Scale Separation and Confinement


Weak binding
External Field
Strong binding
WELCOME


Nuclear Field
Proton
d
u
u
WELCOME
Quark Piglets

EMC Effect:



Aubert et al., PLB (1983); Ashman et al., PLB (1988); Arneodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et al., PRD (1994); Seely et al., PRL (2009); Schmookler et al., Submitted (2018)

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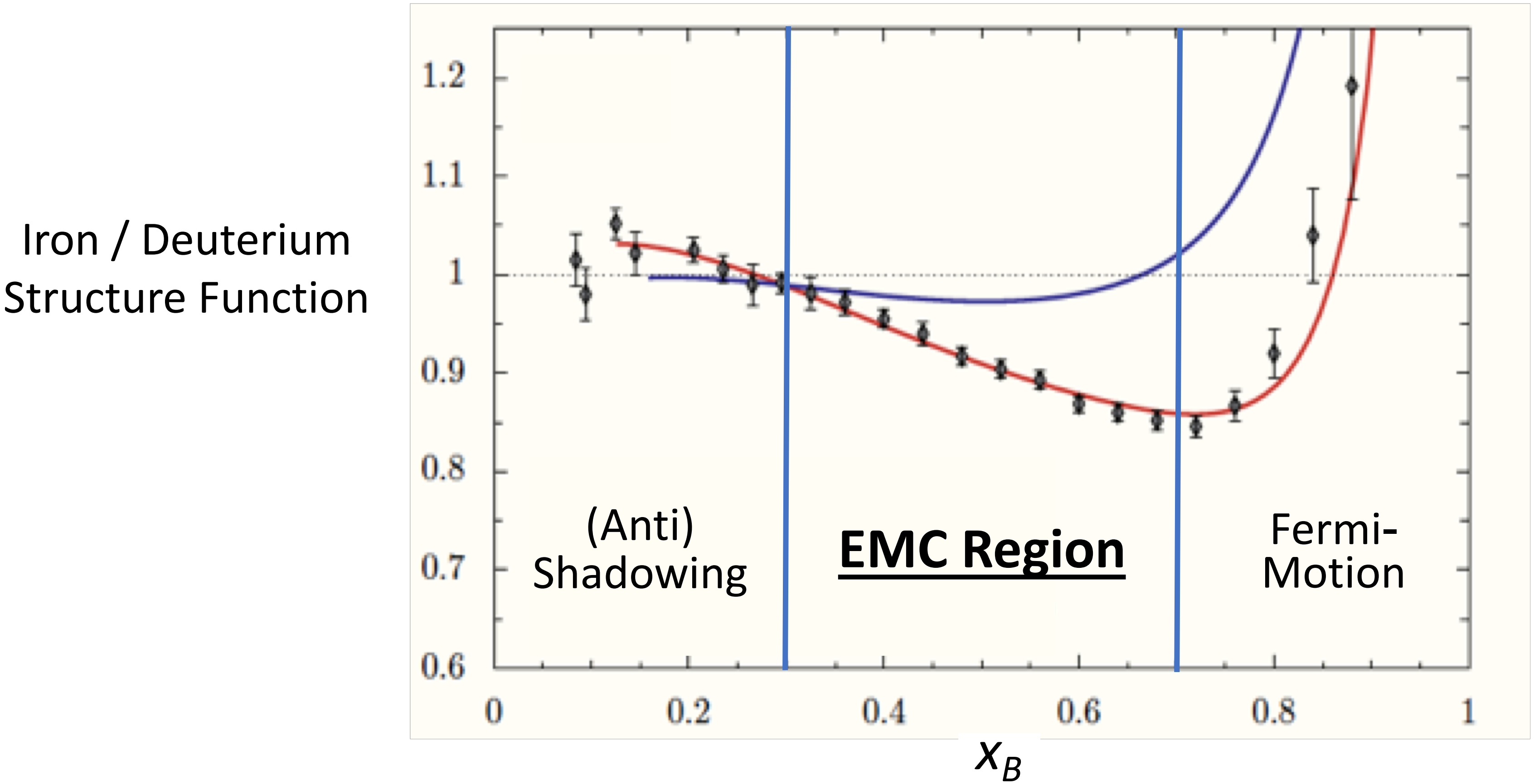

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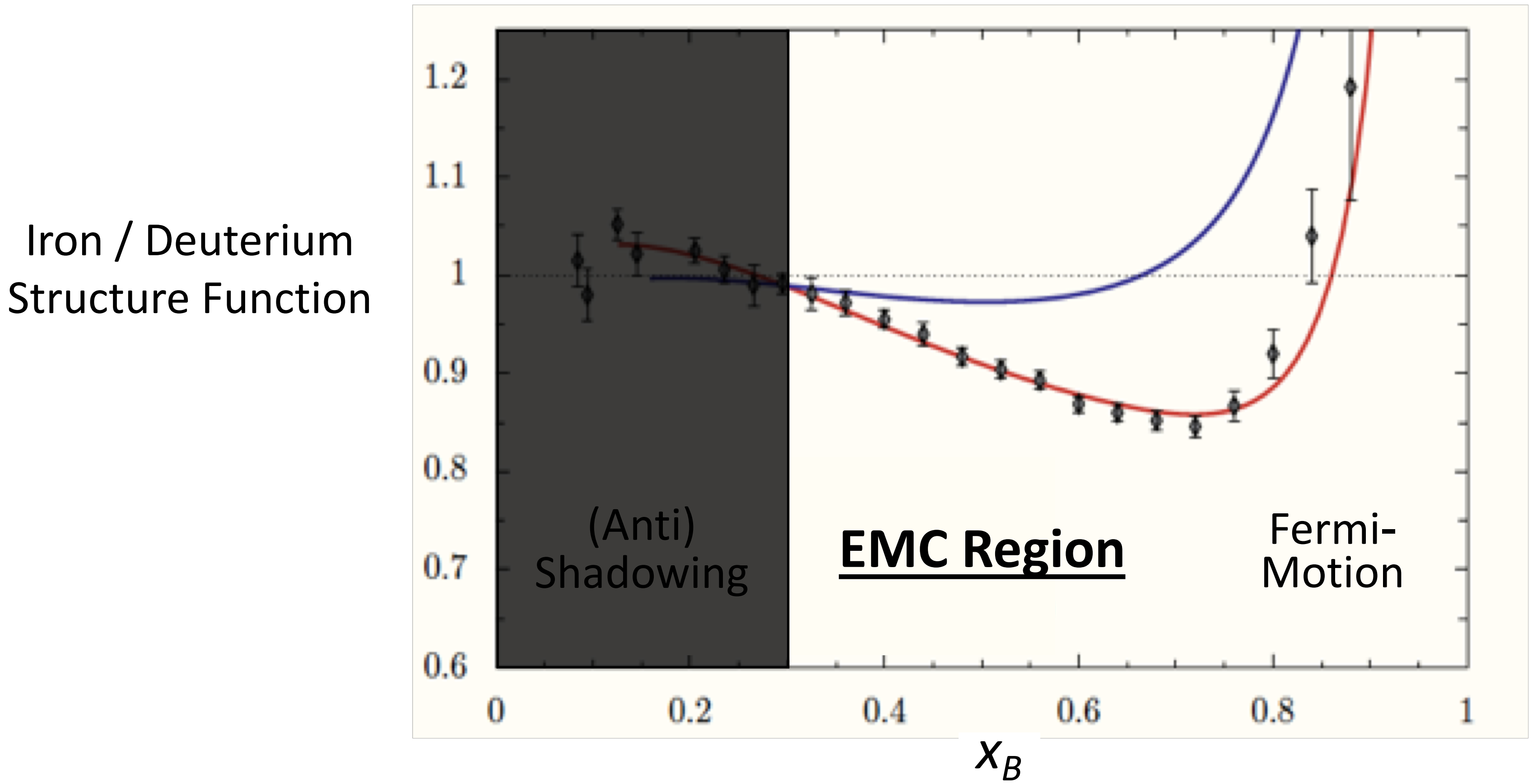
EMC Effect:



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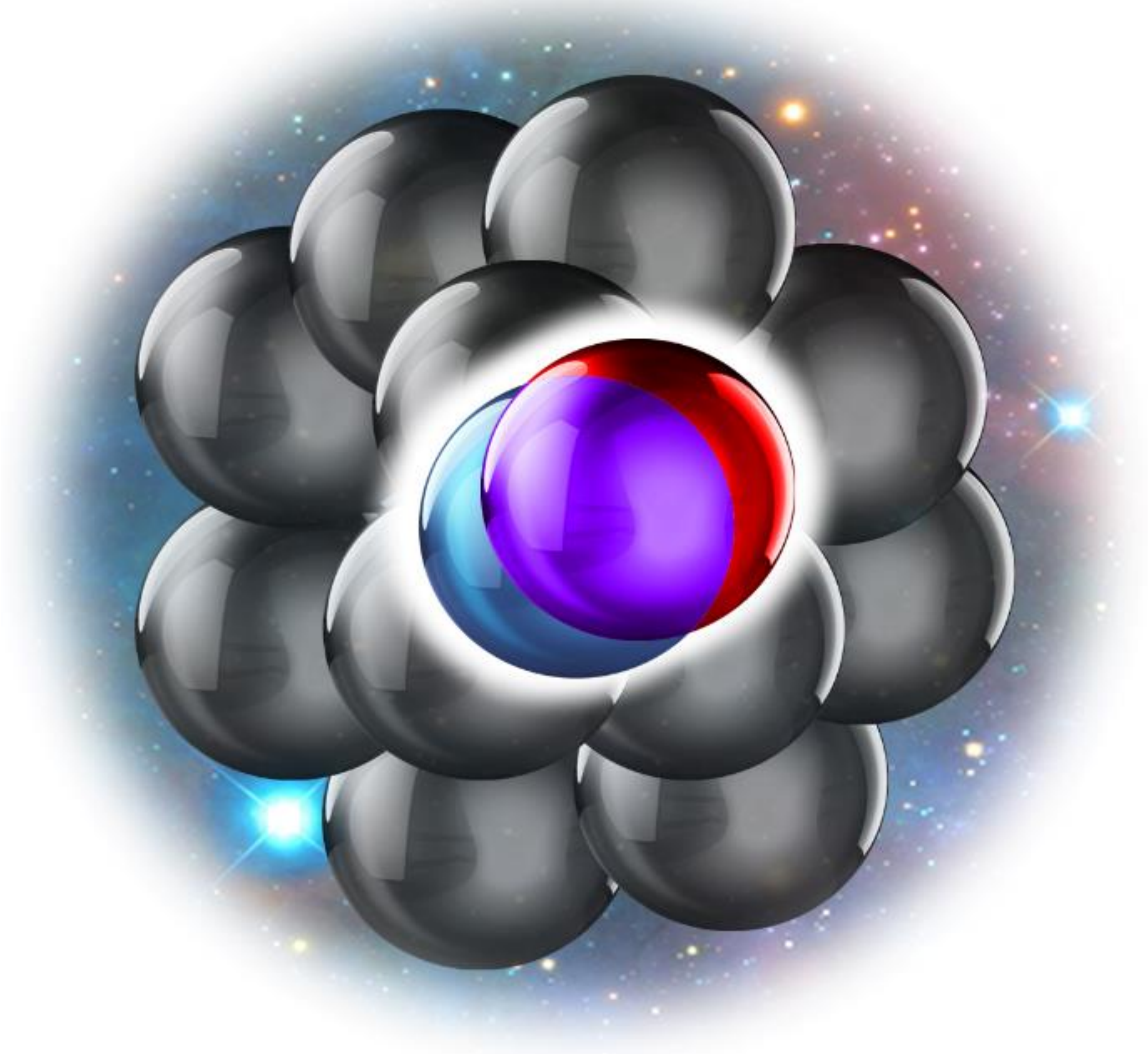
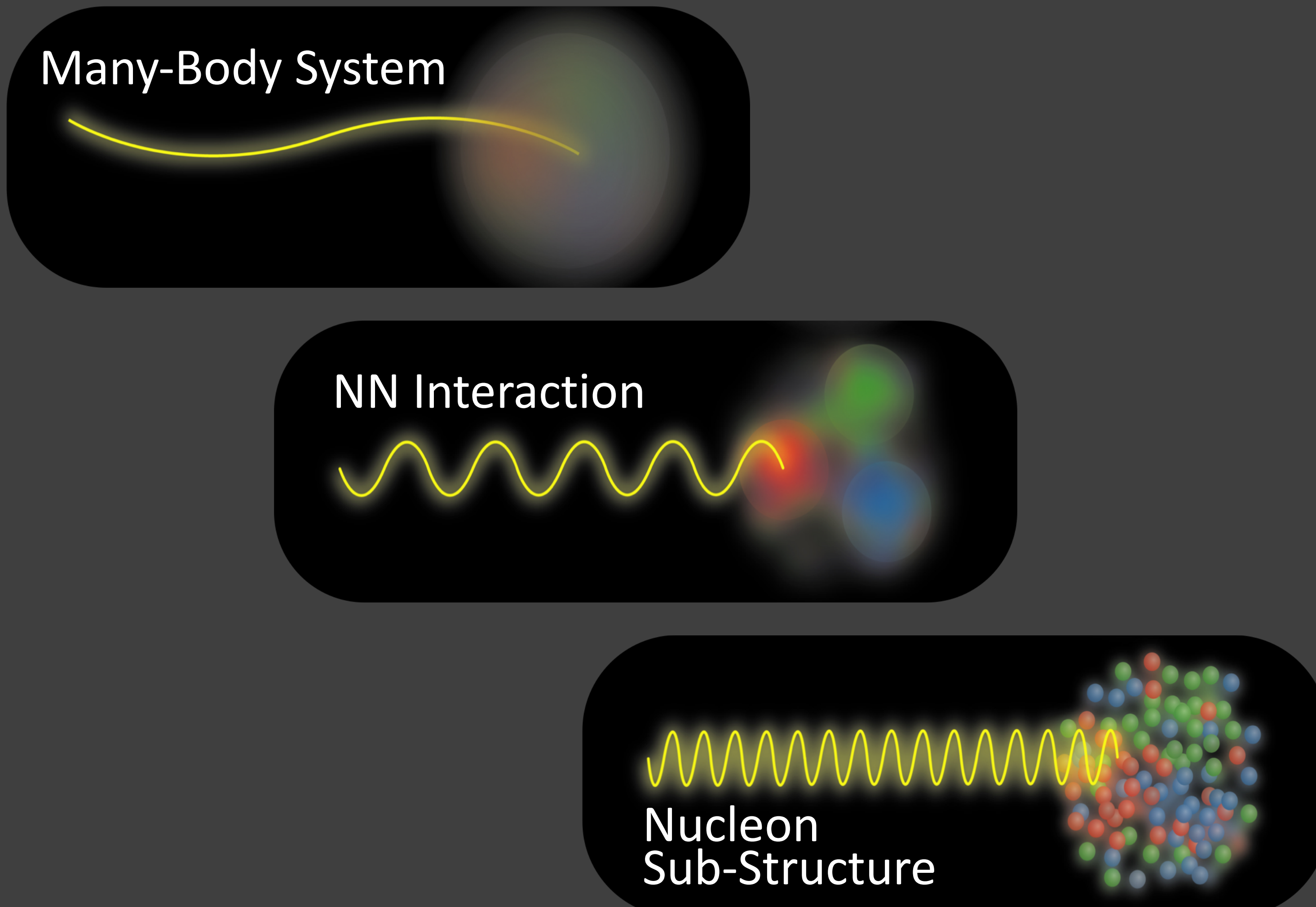
Short-Range Correlations (SRC)



Today: Short-Ranged Interactions Across Resolutions



(1) New SRC & EMC data.

- Nature 560, 617 (2018)
- PRL 121, 09201 (2018)
- arXiv: 1810.05343 (2018)

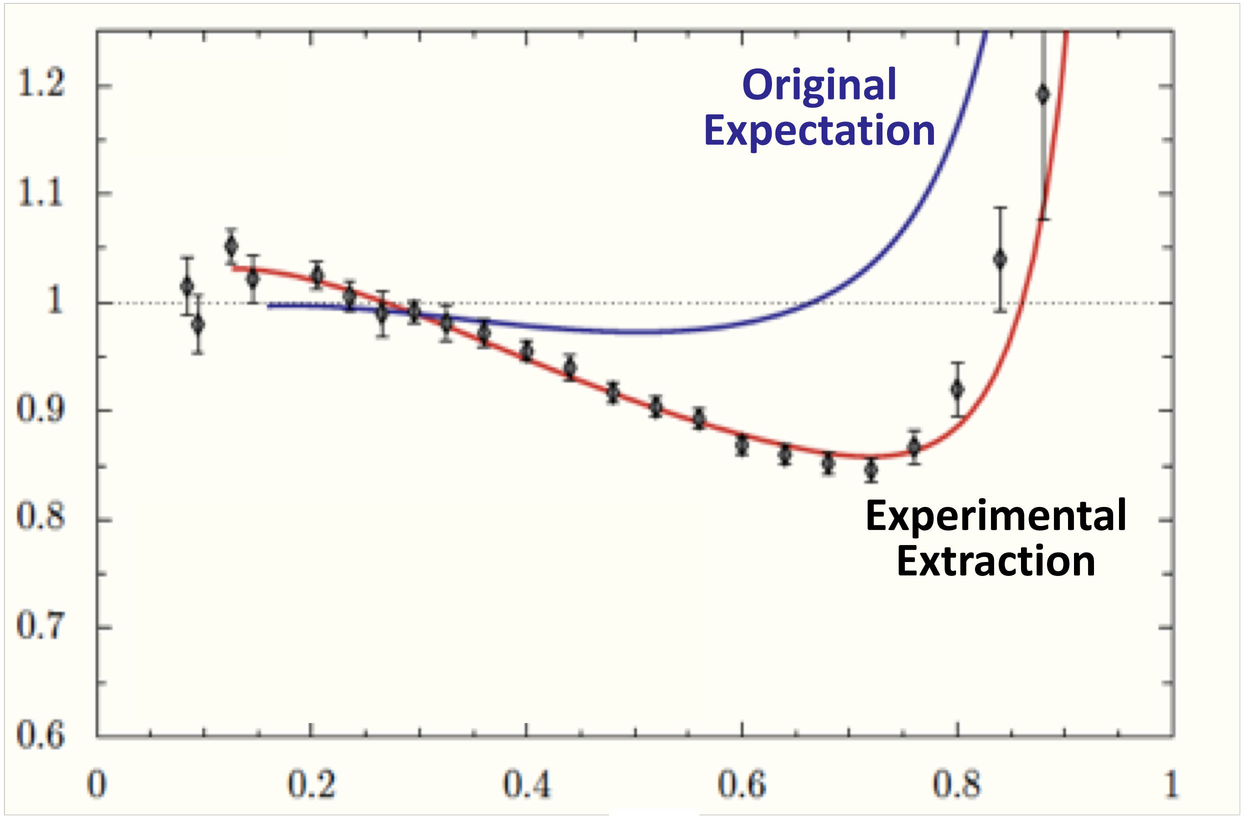
\+ 3 not on arXiv

(1) New SRC & EMC data.

(2) SRC as a new bridge between nuclear-structure and quark-gluon dynamics.

EMC Effect:

Iron / Deuterium Structure Function



x_B

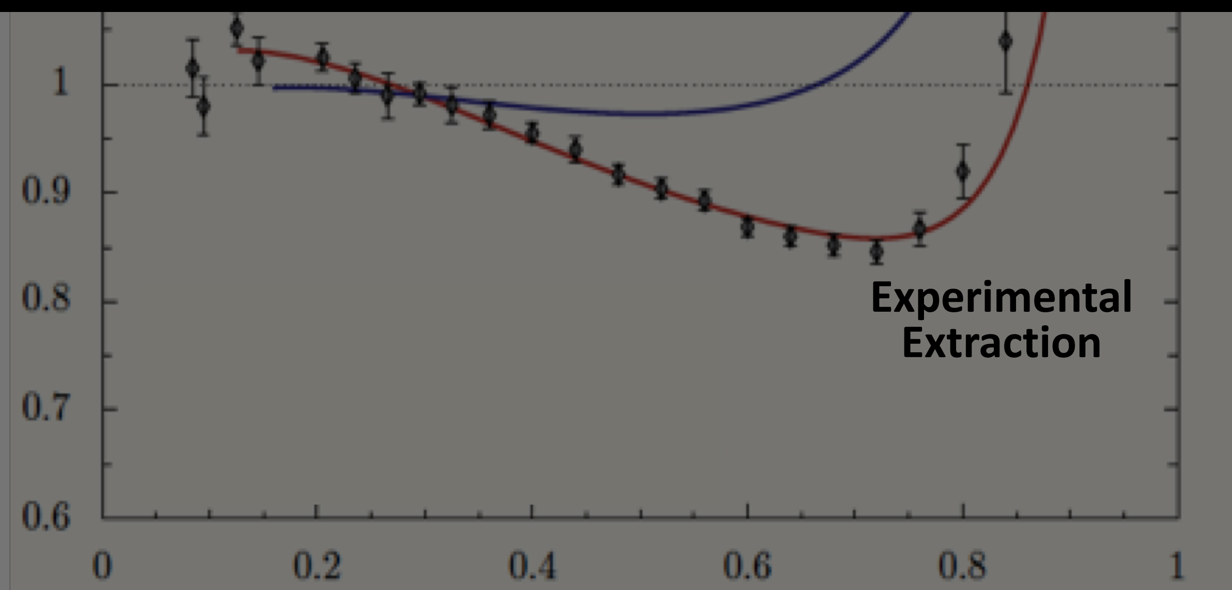
Aubert et al., PLB (1983); Ashman et al., PLB (1988); Arneodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et al., PRD (1994); Seely et al., PRL (2009); Schmookler et al., Submitted (2018)

EMC Effect:

35 years after discovery:

>1000 papers; No consensus on underlaying cause

Iron / Deuterium Structure Function



x_B

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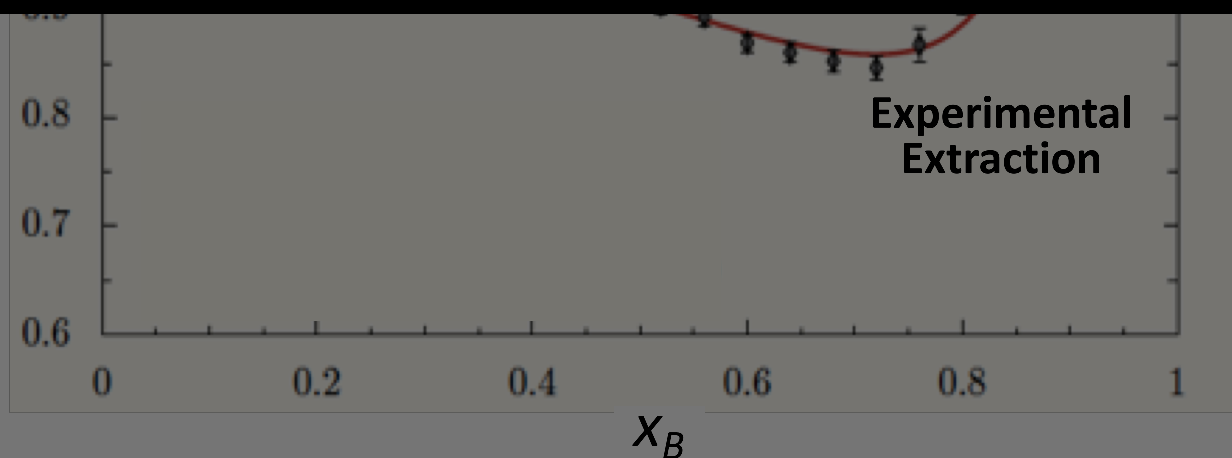
EMC Effect:

35 years after discovery:

>1000 papers; No consensus on underlaying cause

But… Lots of data!



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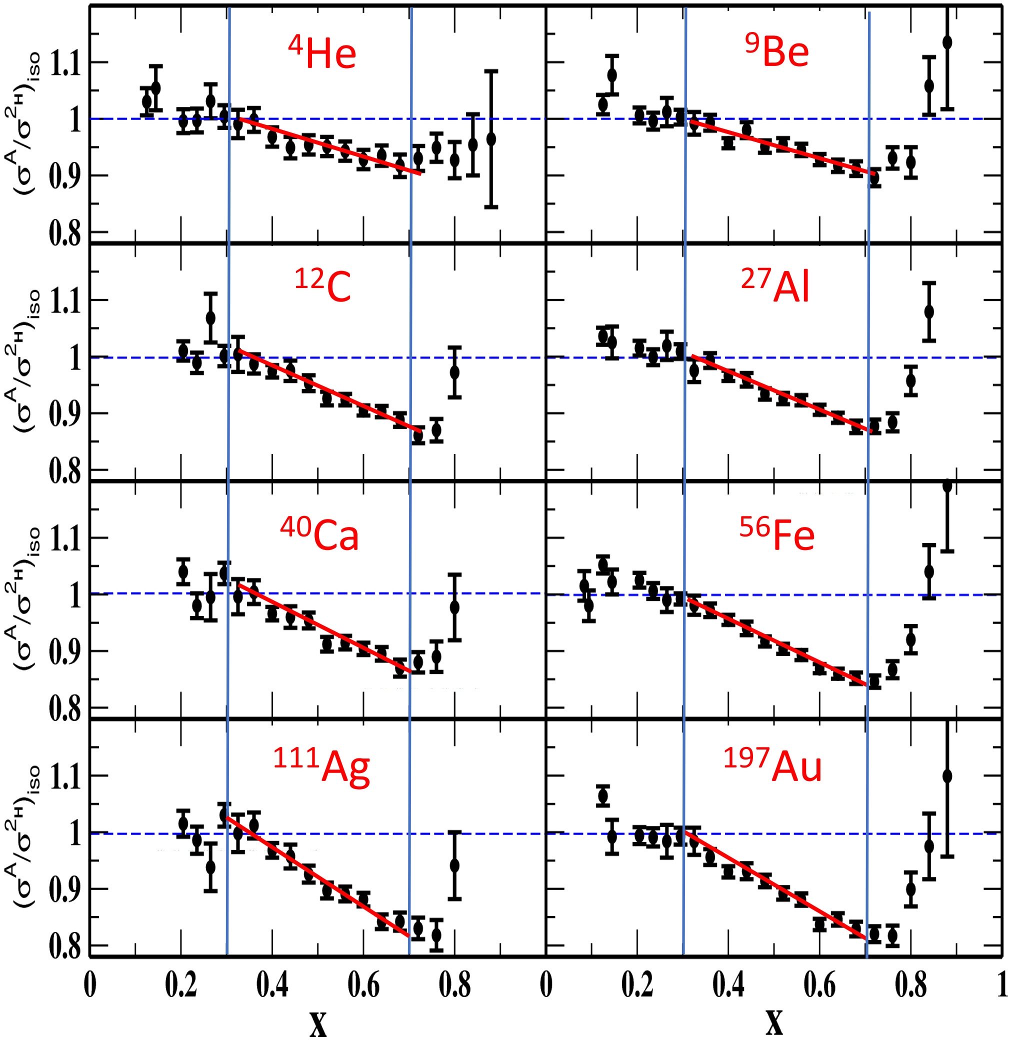
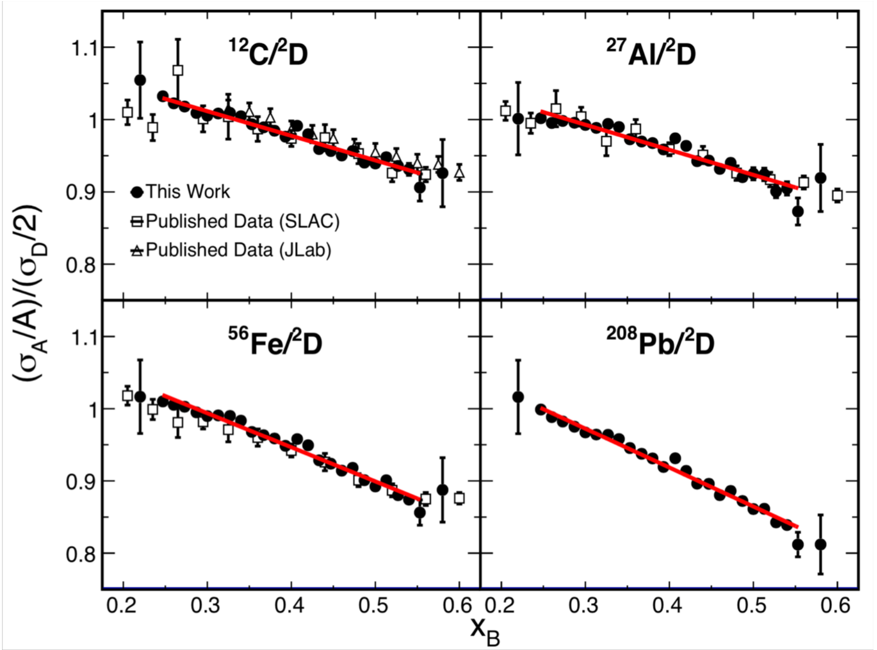
EMC Data



Gomez PRD (1994)

SLAC (1994)

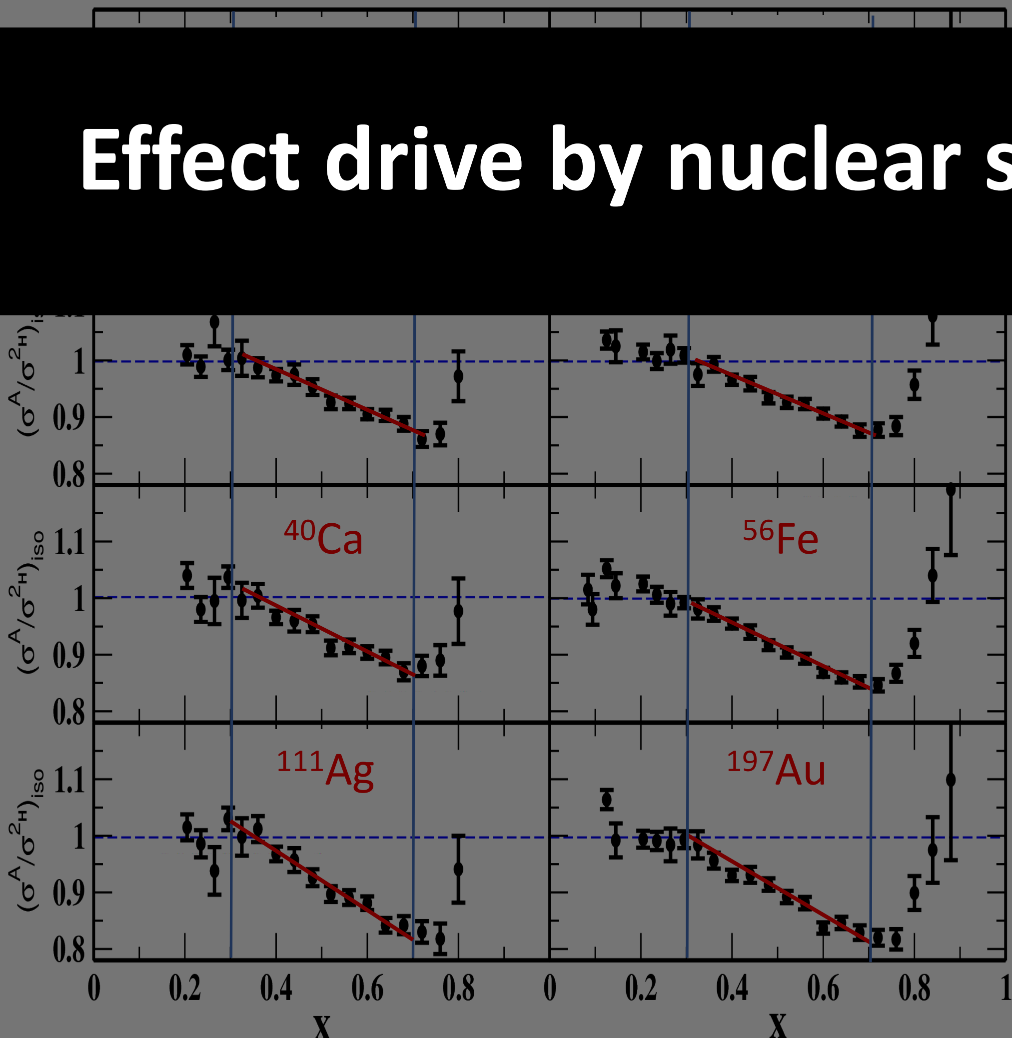
JLab (2018)



Schmookler, submitted (2018)

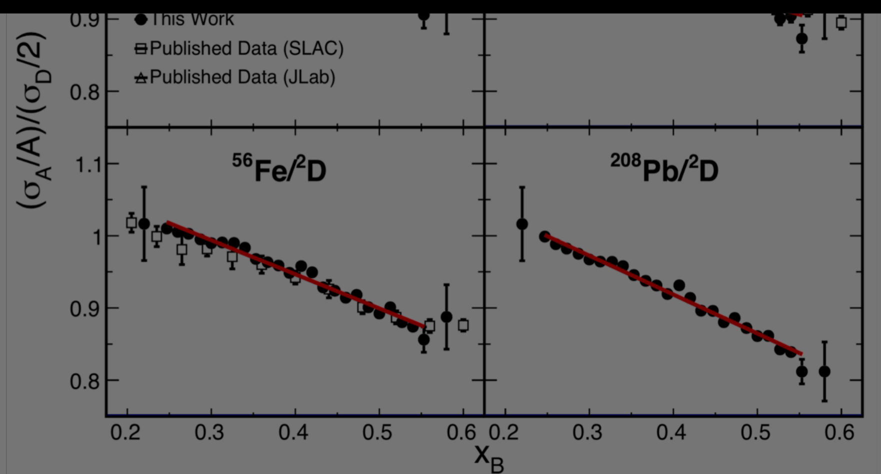
EMC Data

Effect drive by nuclear structure & dynamics

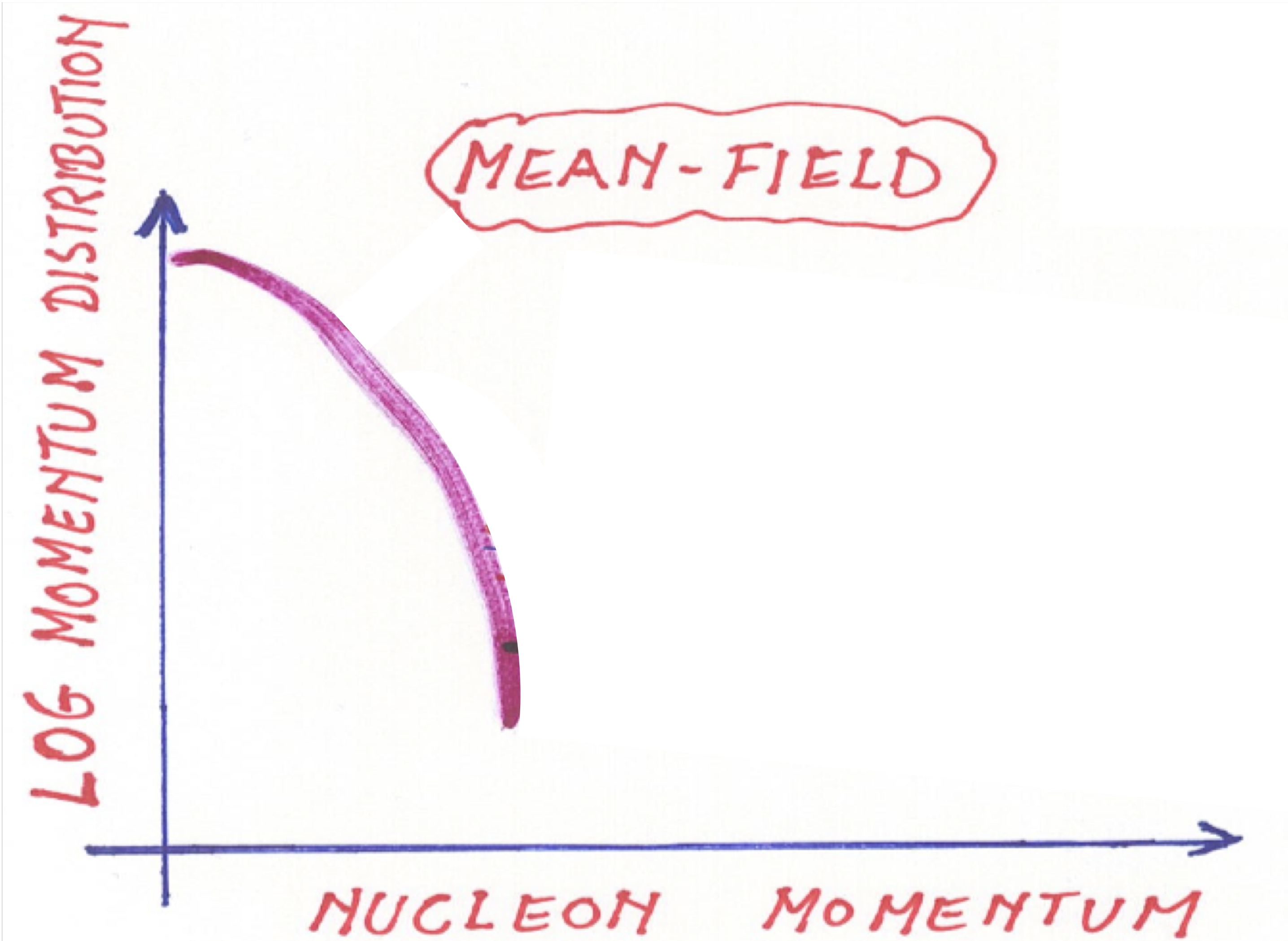


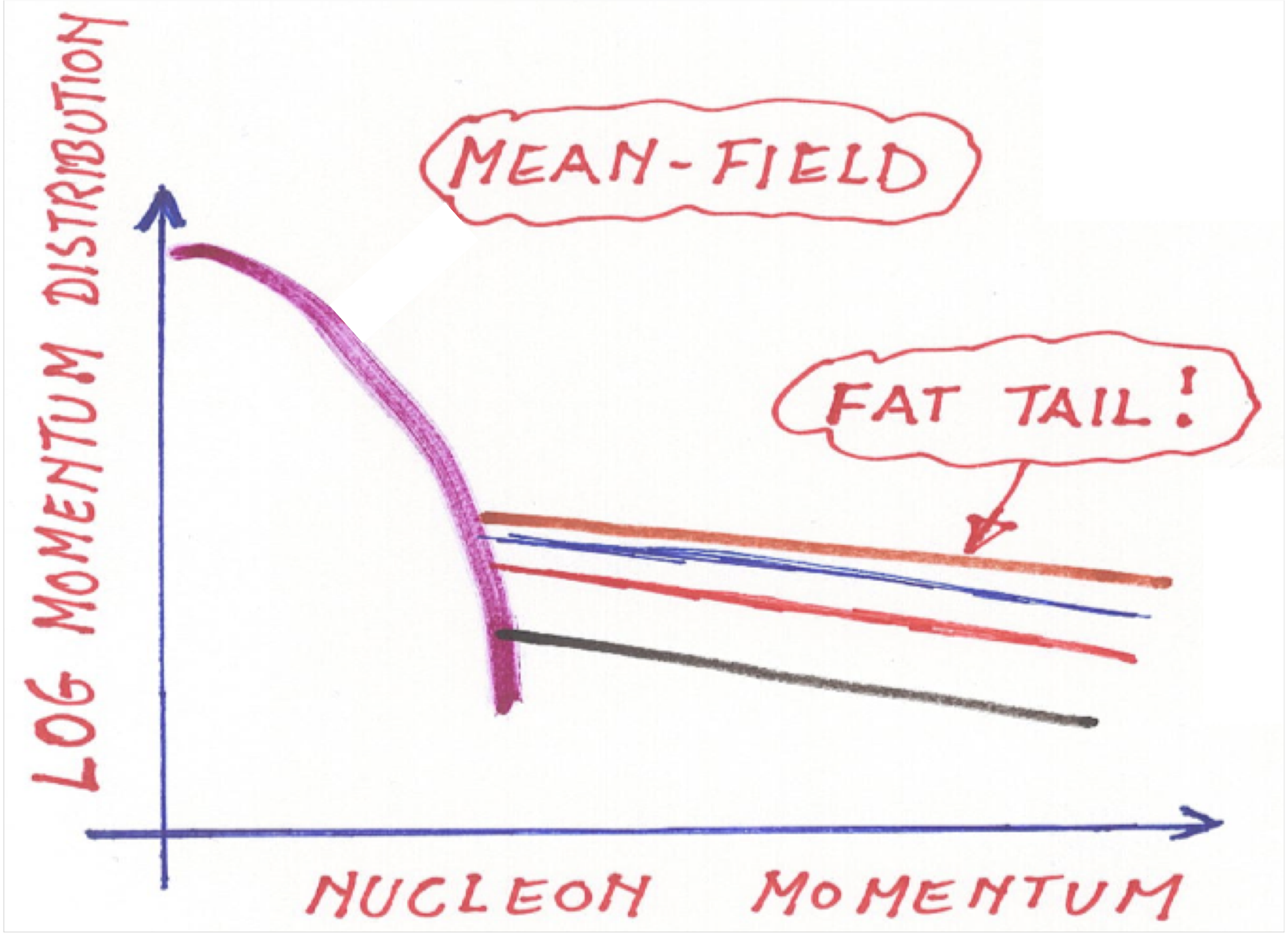
Gomez PRD (1994)

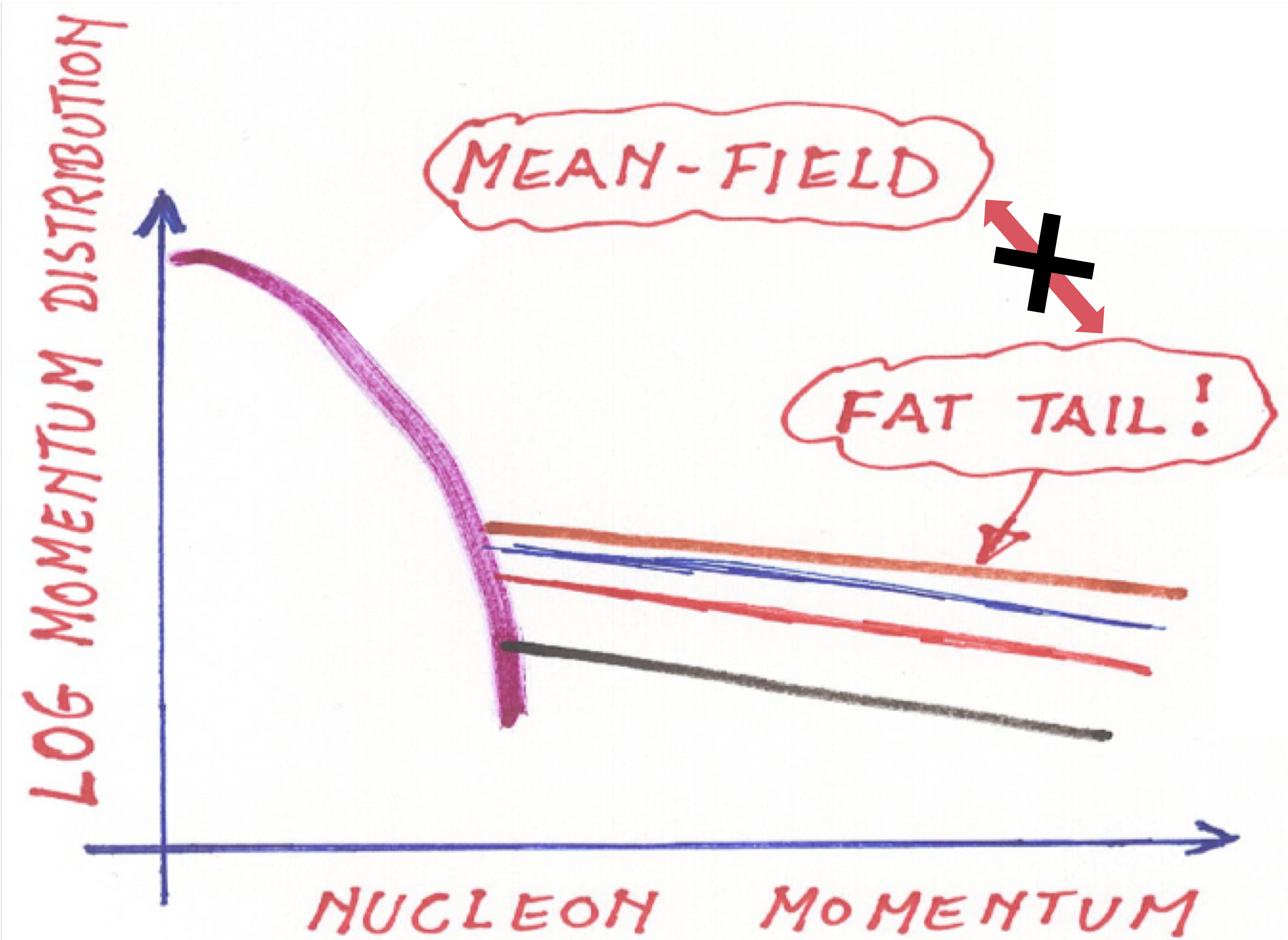
SLAC (1994)



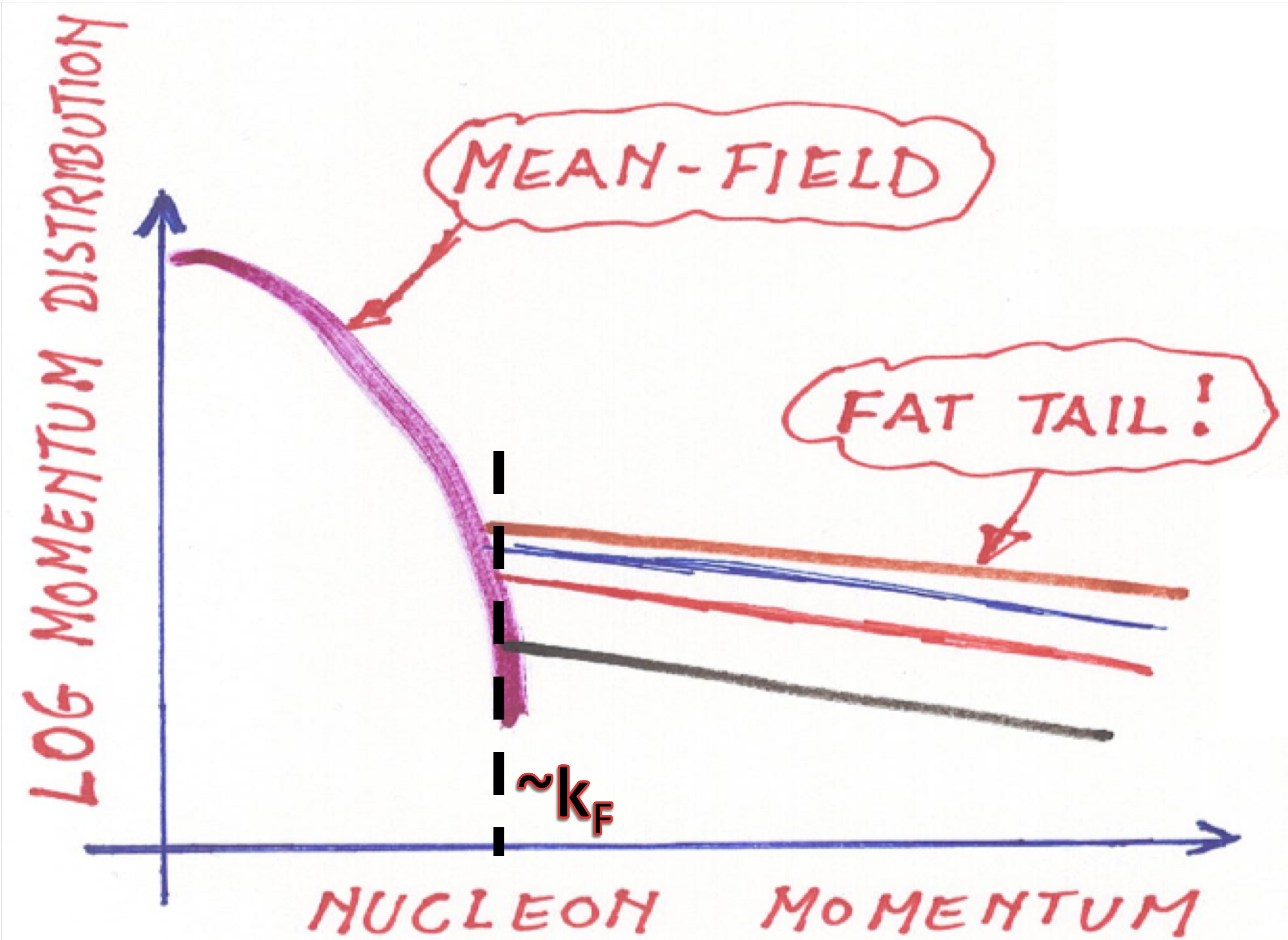
Schmookler, submitted (2018)


MEAN-FIELD
LOG MOMENTUM DISTRIBUTION
NUCLEON MOMENTUM

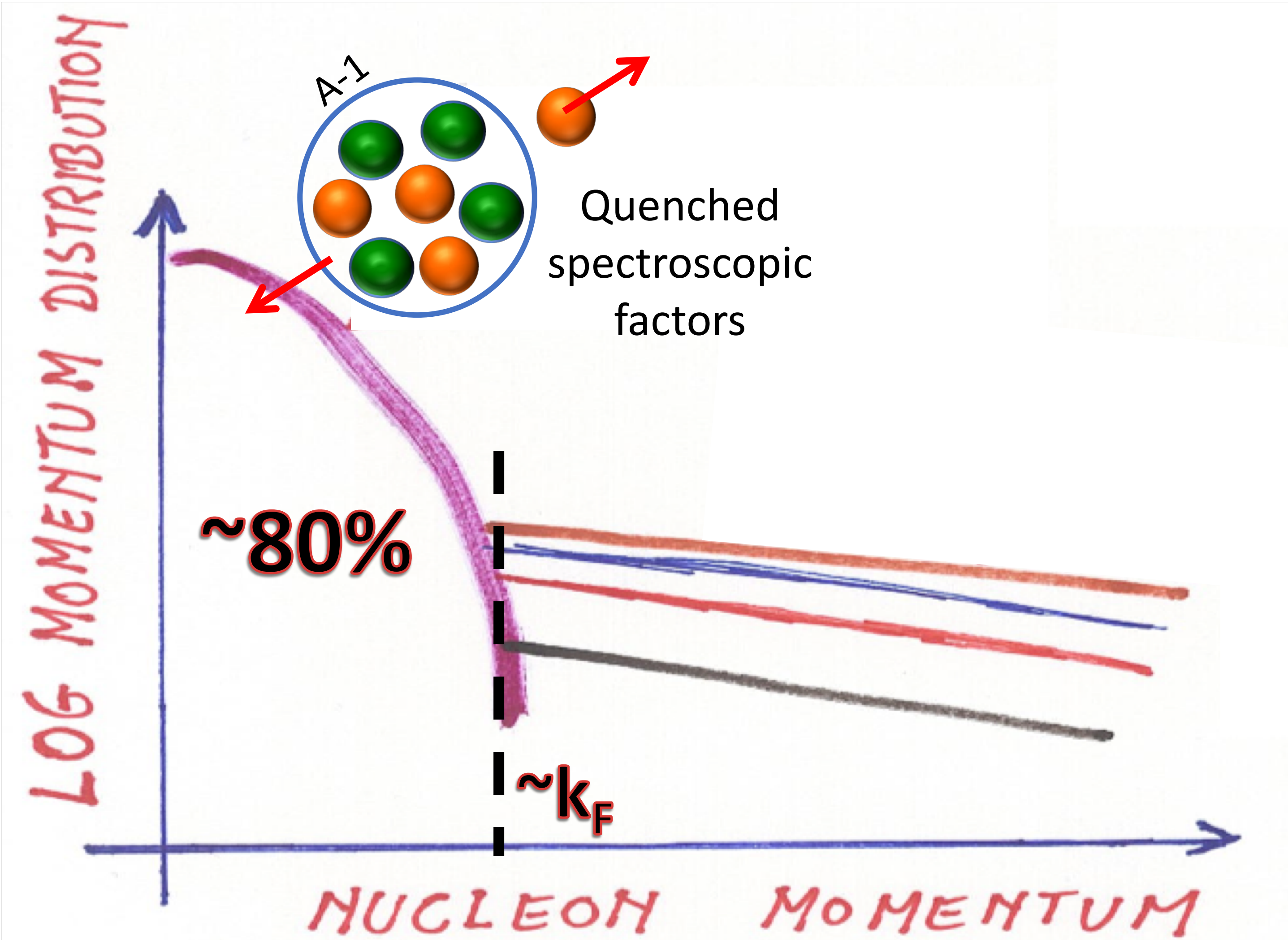

LOG MOMENTUM DISTRIBUTION
MEAN-FIELD
FAT TAIL!
NUCLEON MOMENTUM



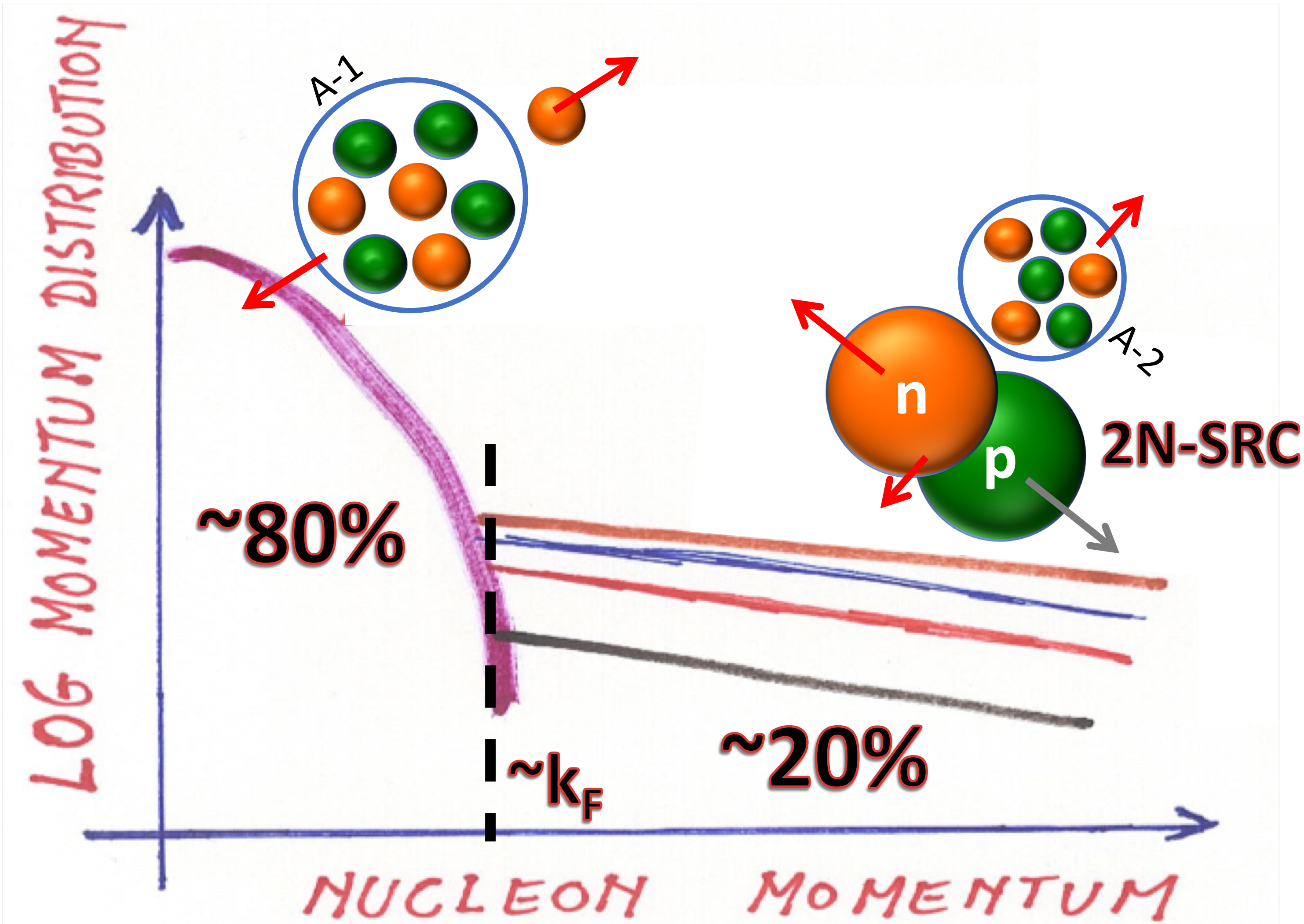
LOG MOMENTUM DISTRIBUTION
MEAN-FIELD
FAT TAIL!
NUCLEON MOMENTUM



LOG MOMENTUM DISTRIBUTION
MEAN-FIELD
FAT TAIL!
~k_F
NUCLEON MOMENTUM



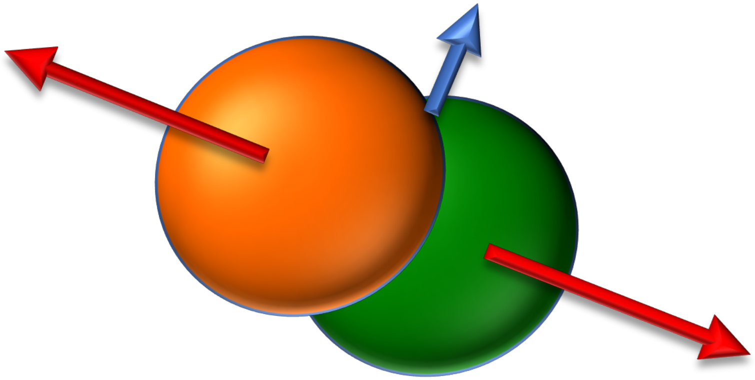
LOG MOMENTUM DISTRIBUTION
A-1
Quenched
spectroscopic
factors
~80%
~k$_F$
NUCLEON MOMENTUM


LOG MOMENTUM DISTRIBUTION
A-1
~80%
~k_F
~20%
n
p
A-2
2N-SRC
NUCLEON MOMENTUM

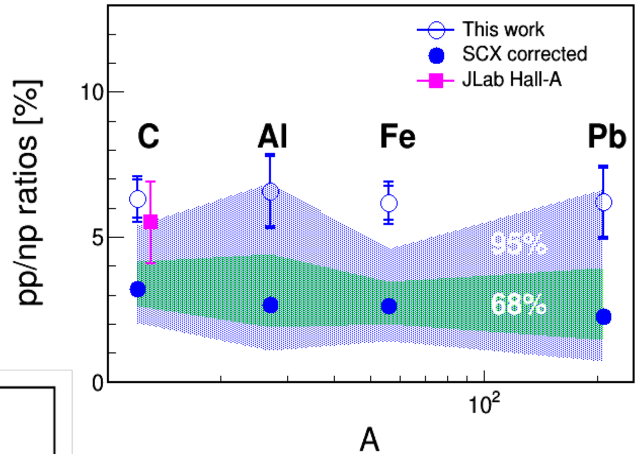
Short-Range Correlations (SRC)

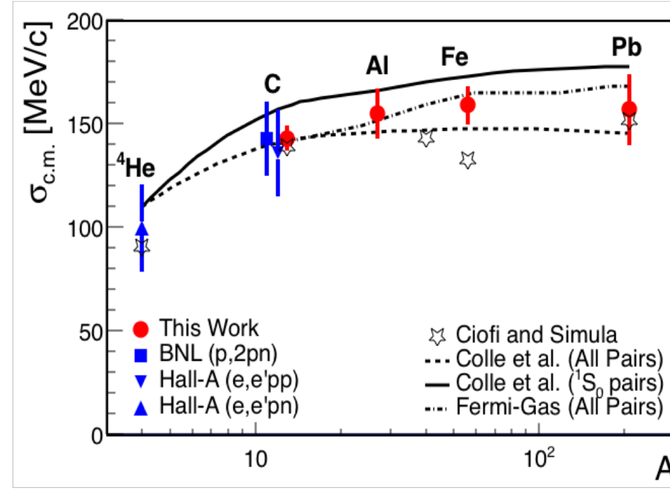
Nucleon pairs that are close together in the nucleus

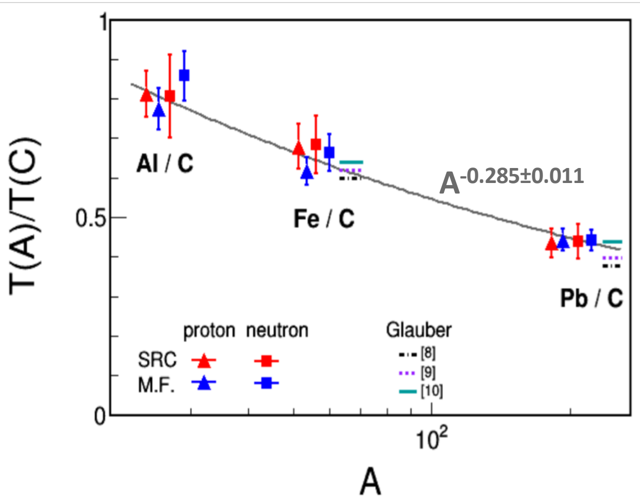
Momentum space: *high relative* and *low c.m. momentum,* compared to the Fermi momentum (k_F)

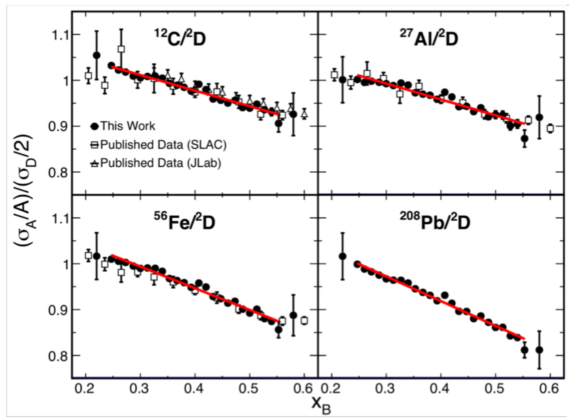


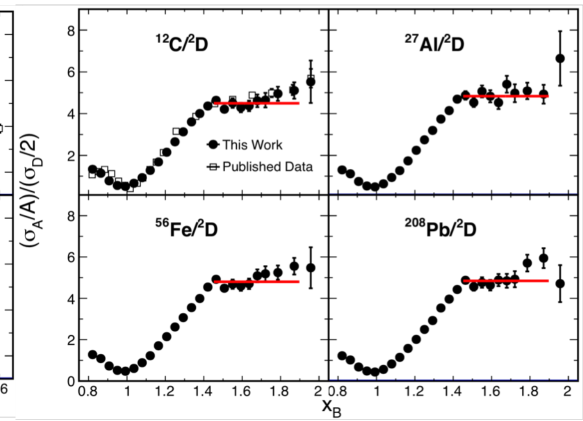
2018 Data-Mining

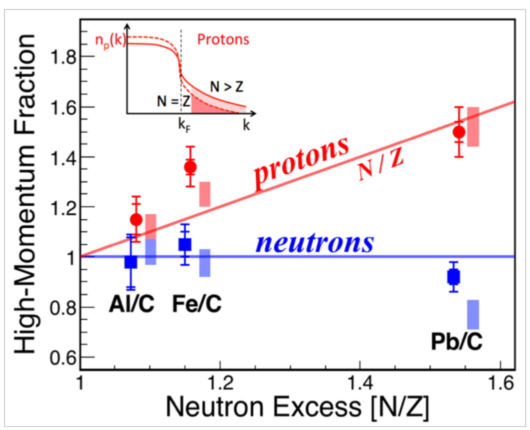


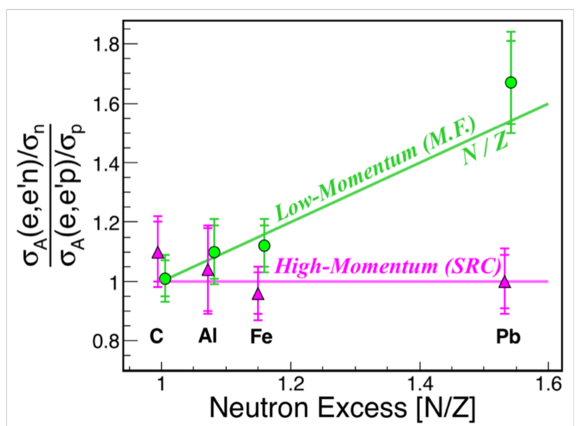


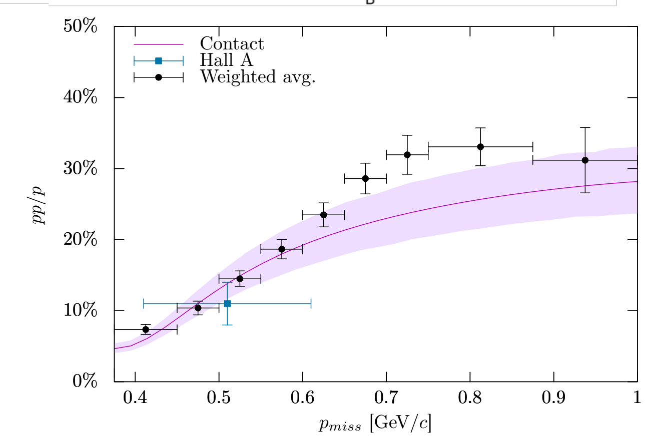






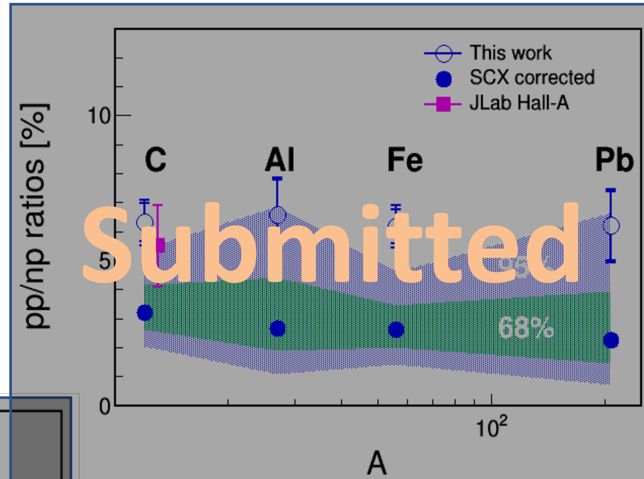


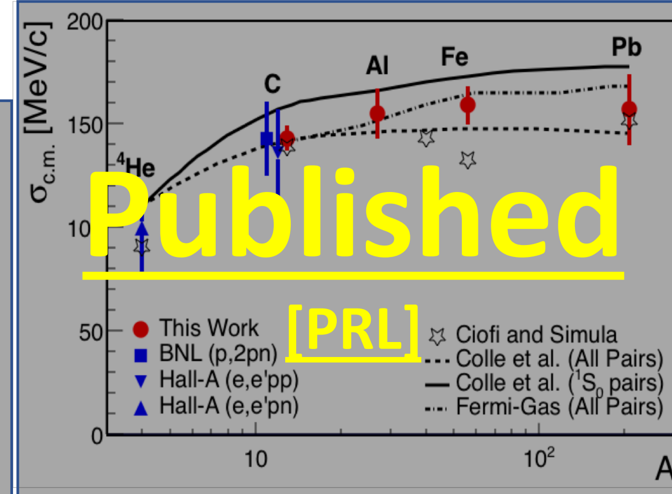


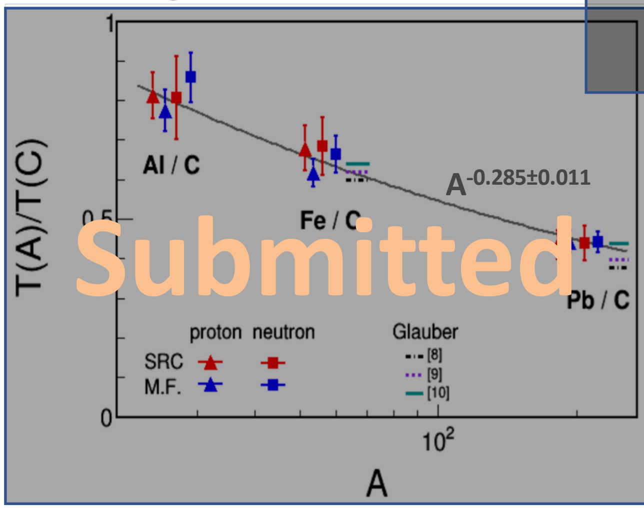


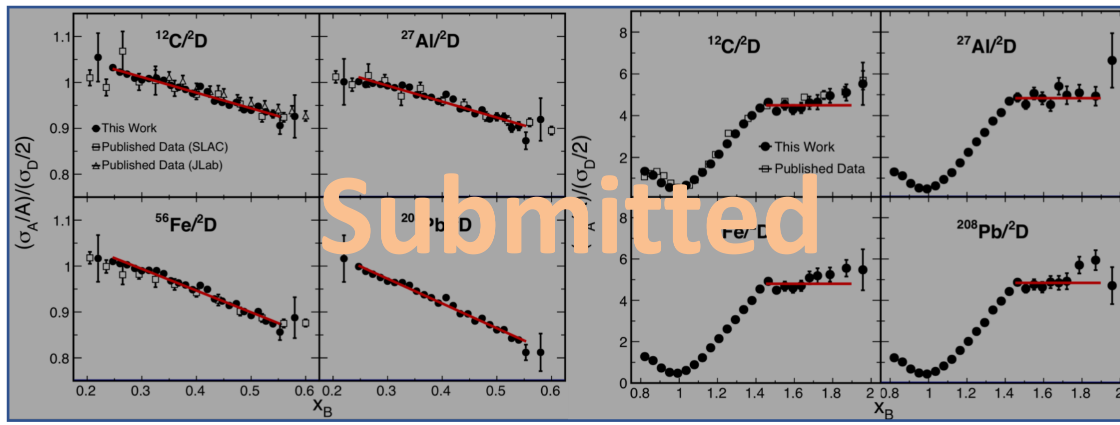
2018 Data-Mining

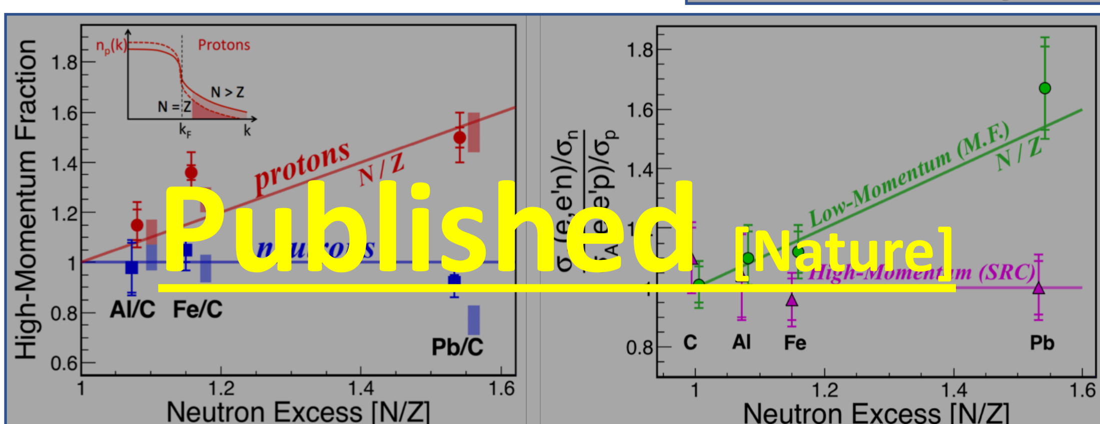
NEW!

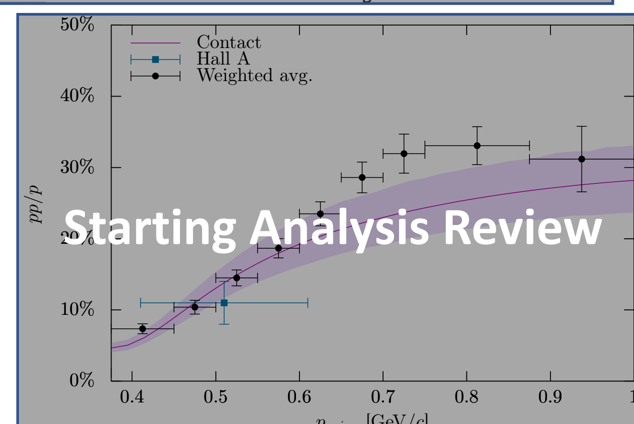




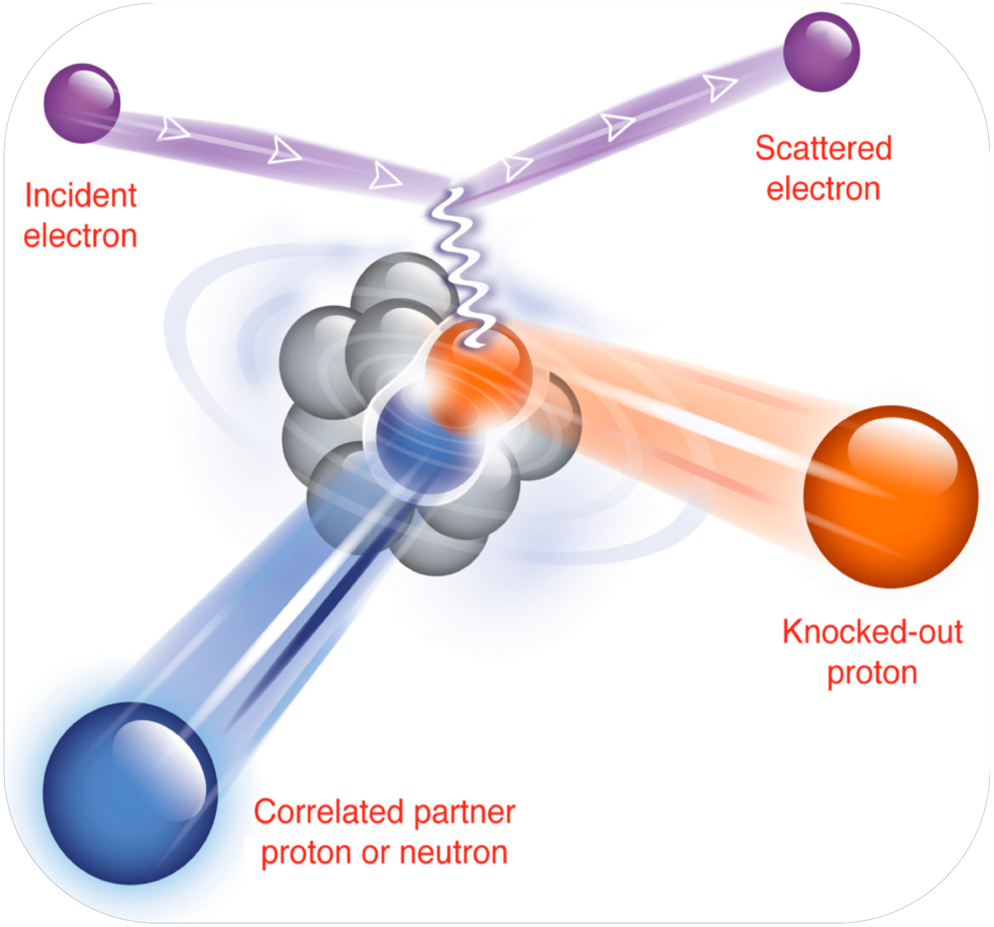








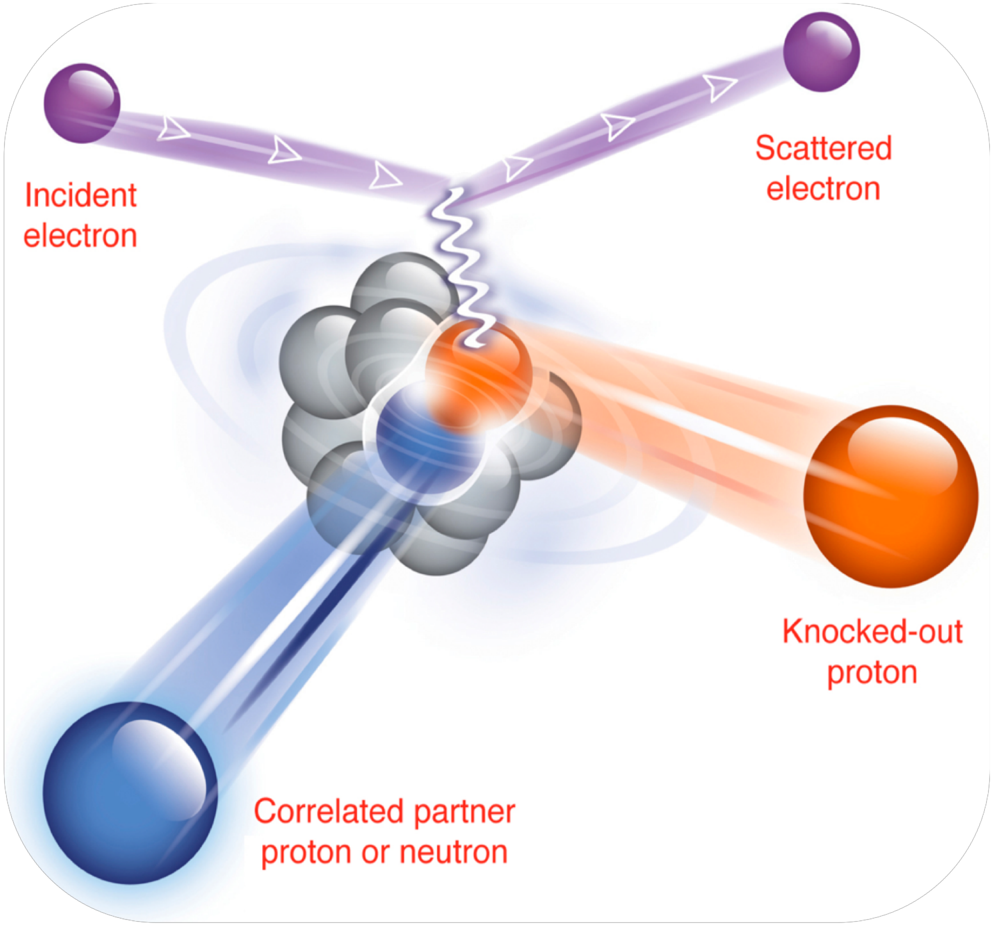
Probing Correlations Using Hard Knockout Reactions



Breakup the pair =>

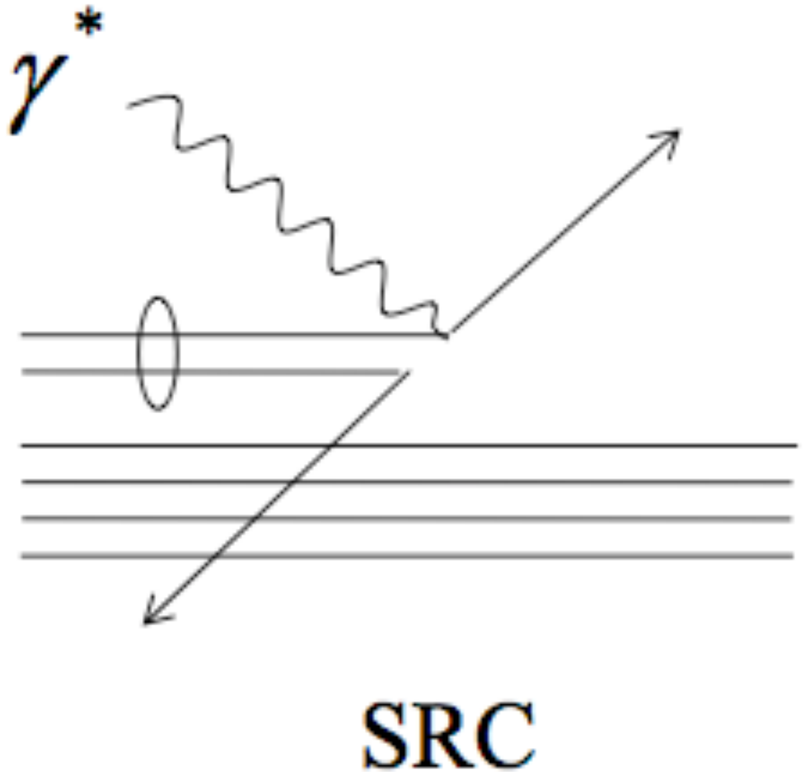
Detect ***both*** nucleons =>

Reconstruct 'initial' state



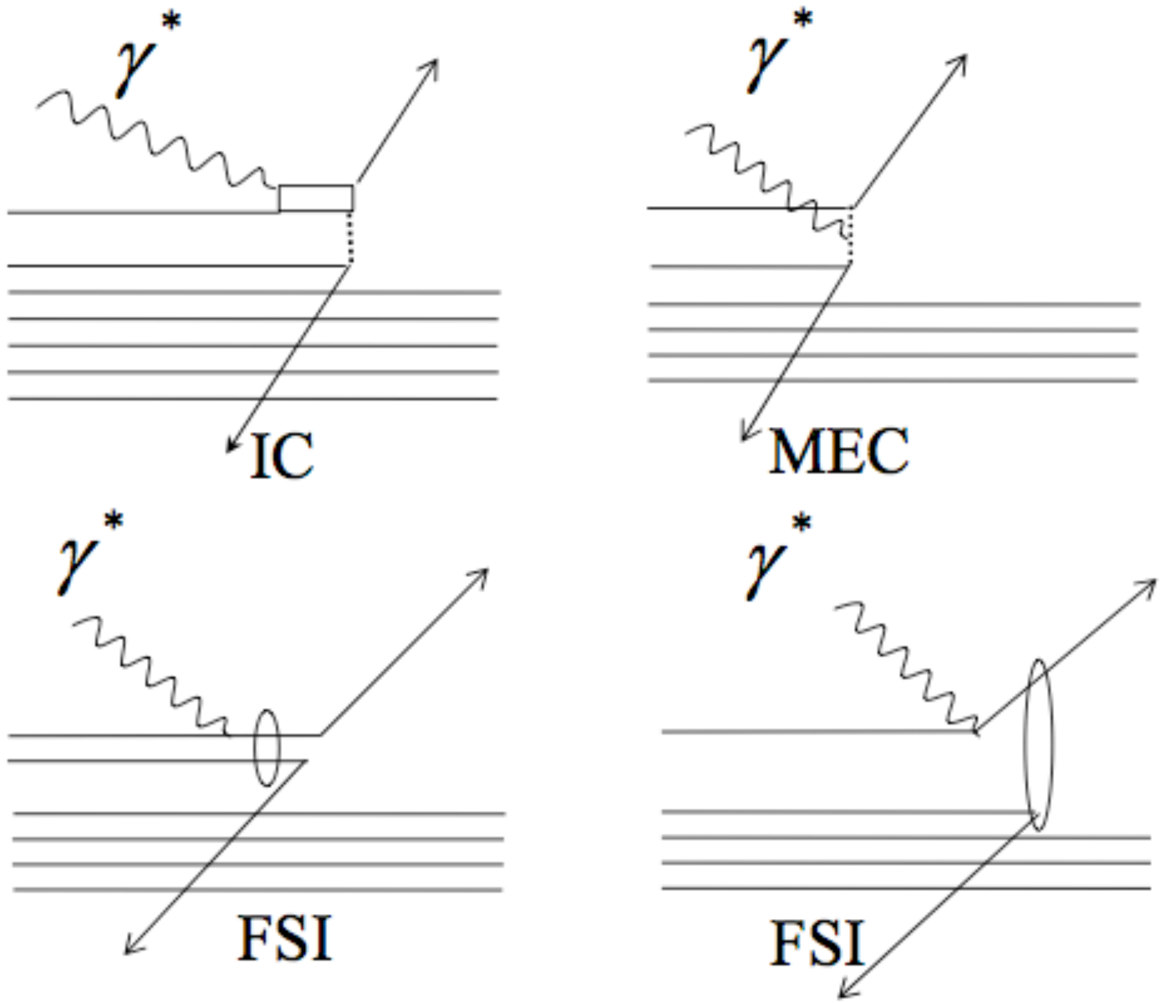
Interlude: Reaction Mechanisms

What we want:

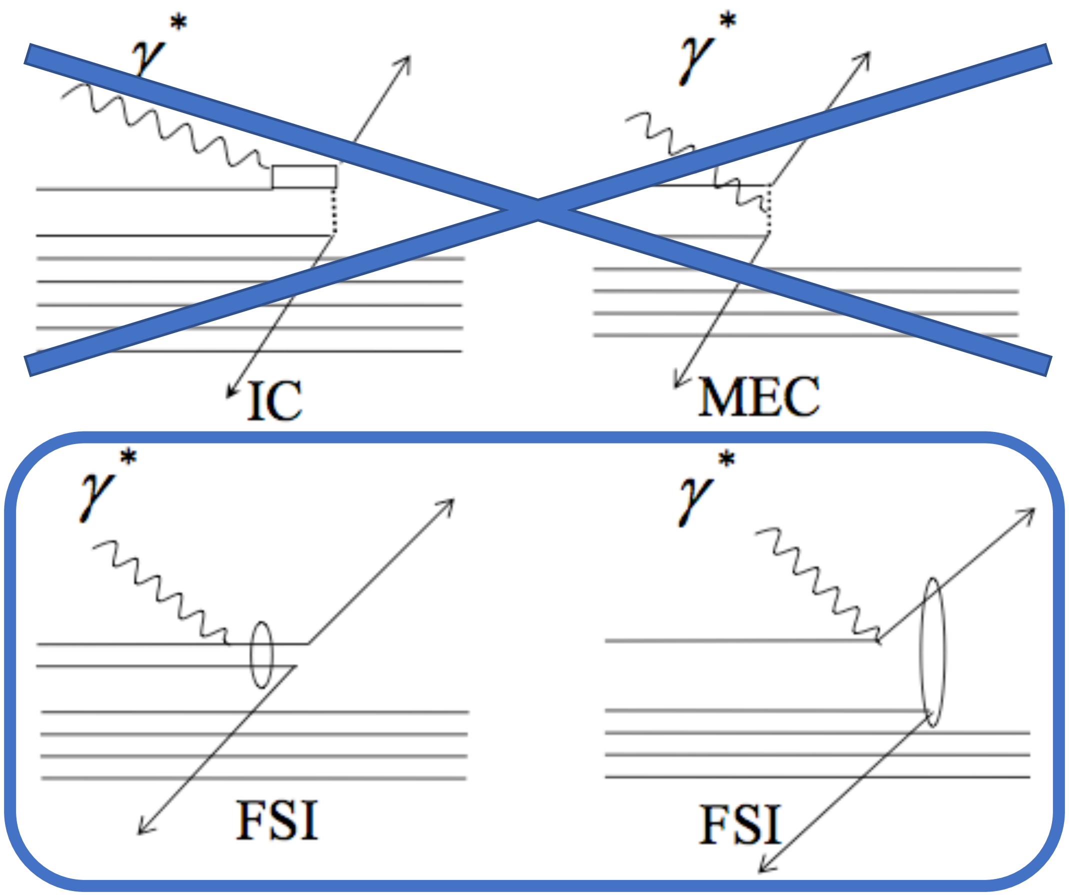


Interlude: Reaction Mechanisms

What we (might) get:



Interlude: Reaction Mechanisms



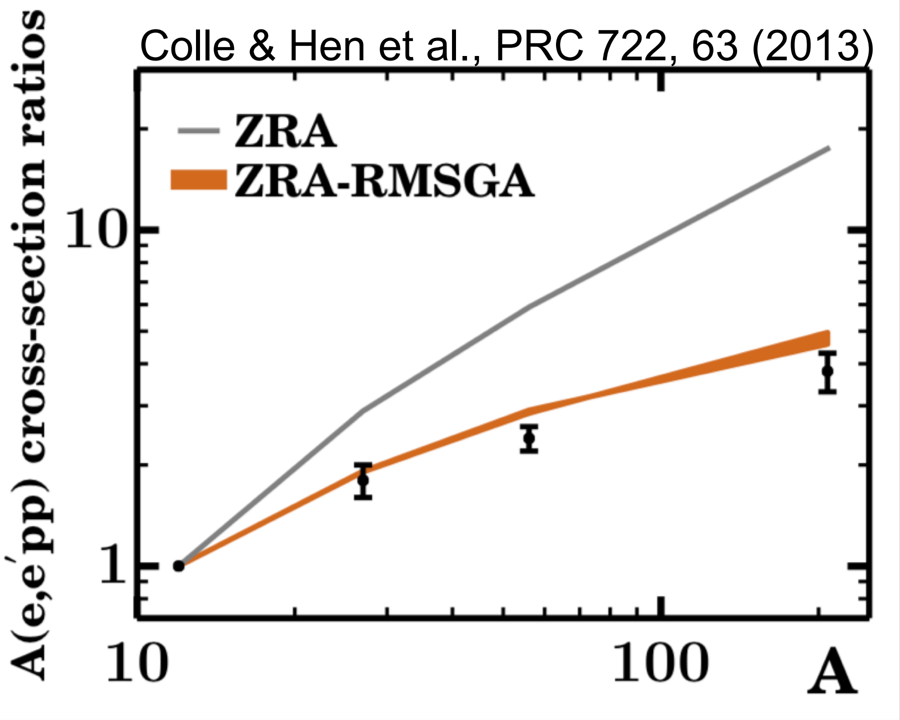
MEC suppressed @ **high-Q^2**, IC suppressed at **$x_B > 1$.**

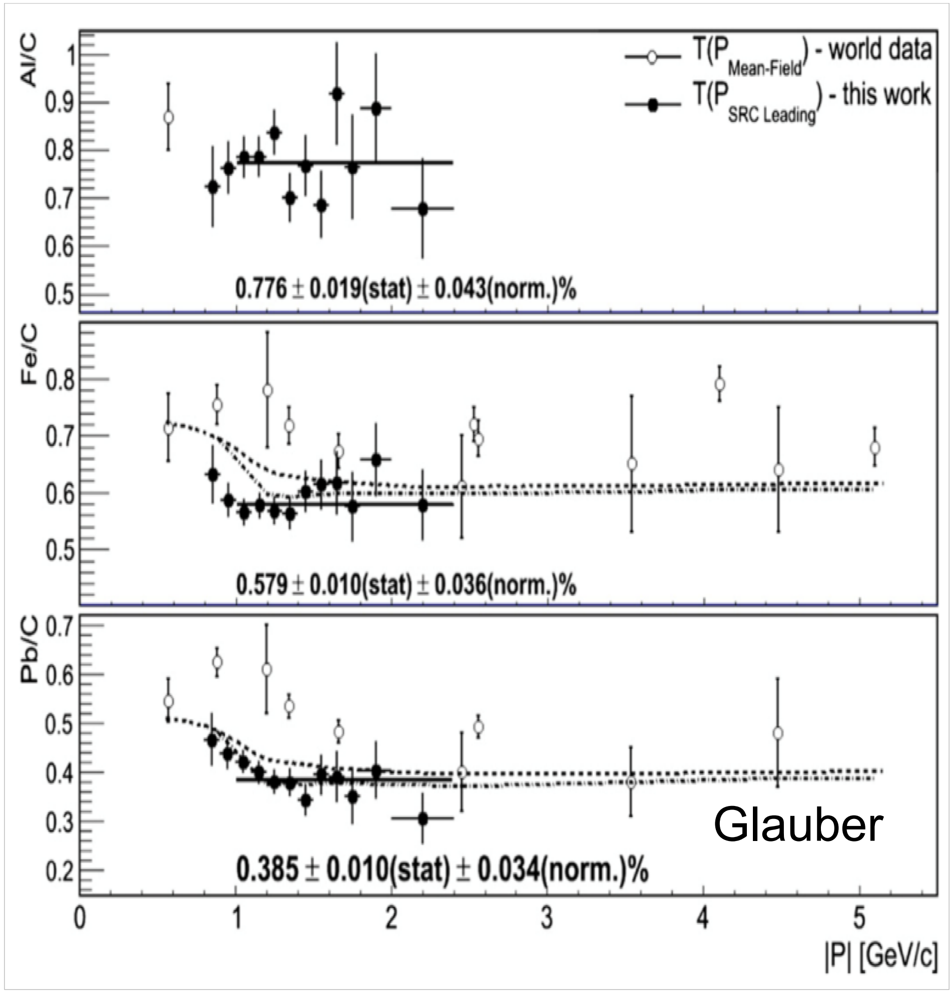
FSI suppressed in **anti-parallel** kinematics. Treated using **Glauber** approximation.

Frankfurt, Sargsian, and Strikman PRC **56**, 1124 (1997).
Colle, Cosyn, and Ryckebusch, PRC **93**, 034608 (2016).

Glauber agrees with data!

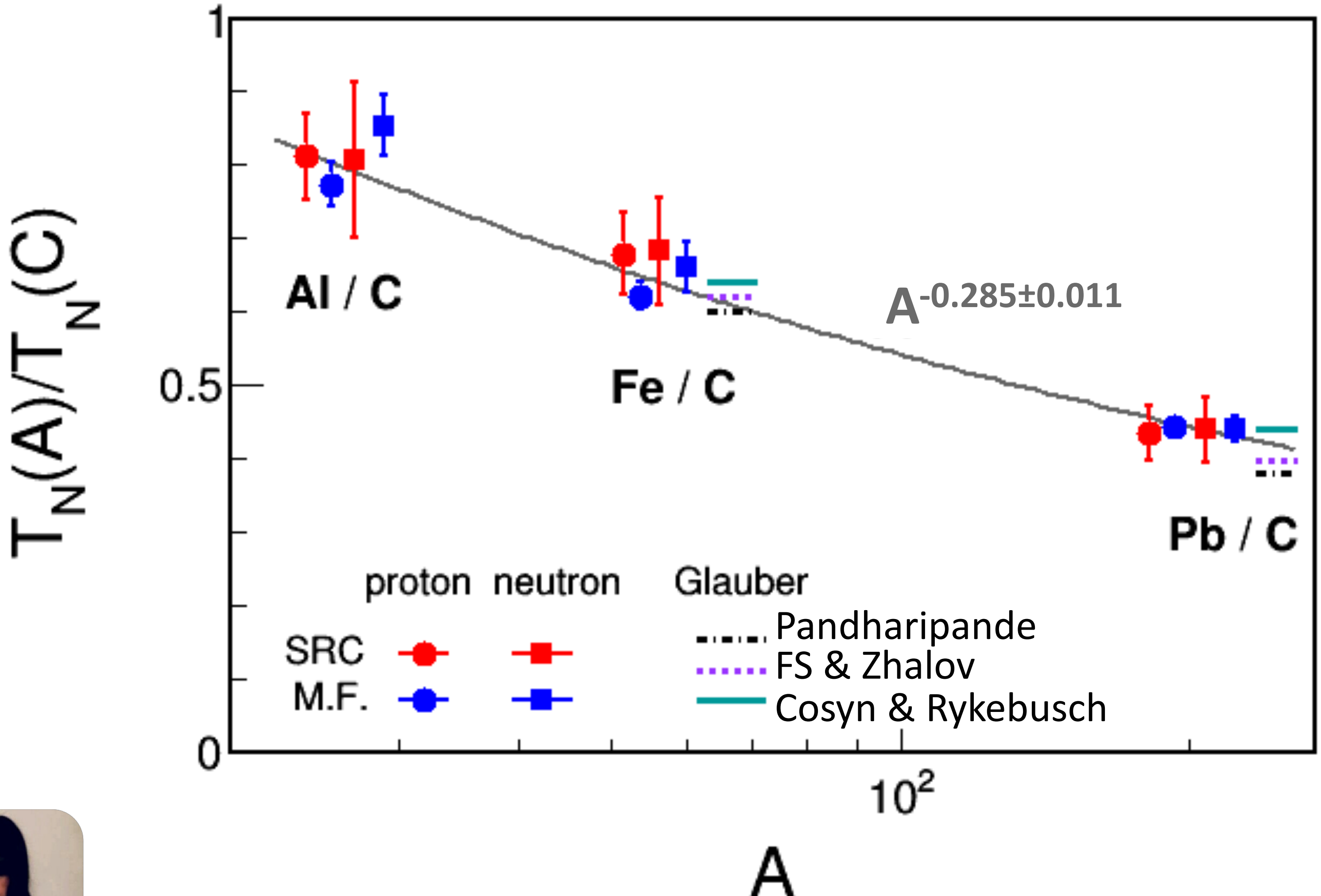
Colle & Hen et al., PRC 722, 63 (2013)





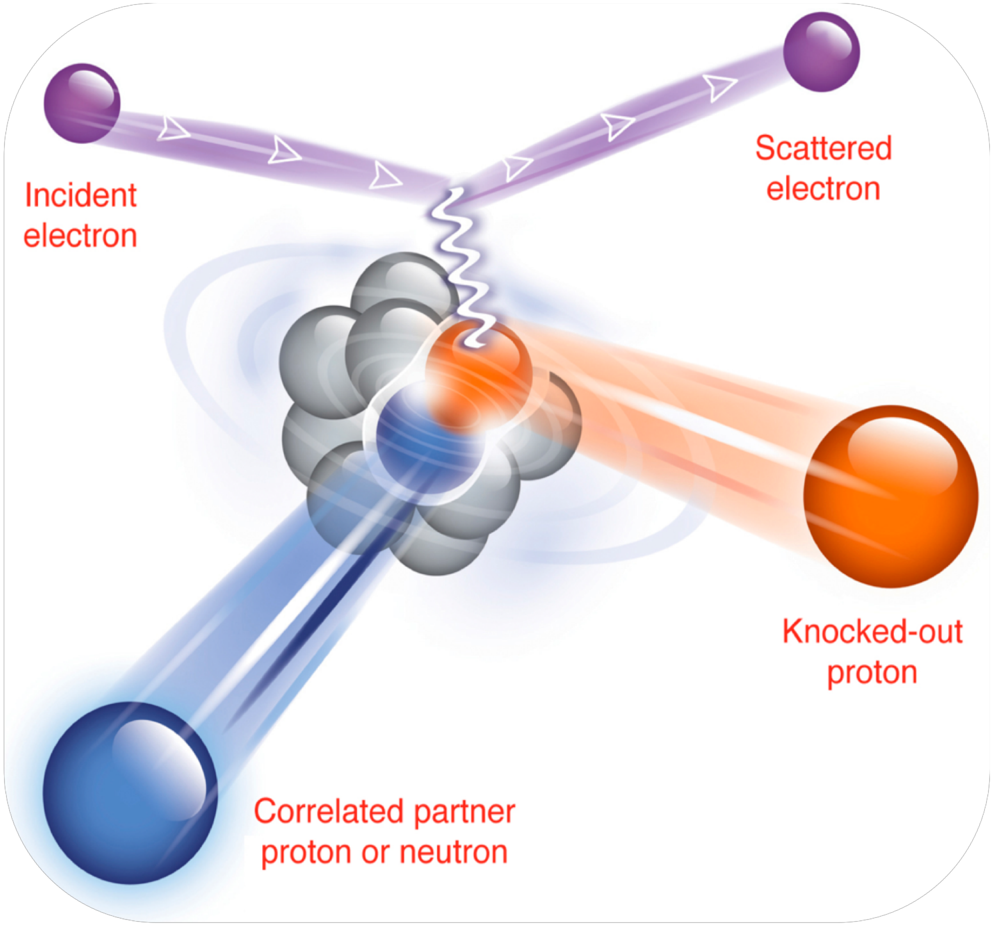
Hen et al., Phys. Lett. B 722, 63 (2013)

Glauber agrees with data!

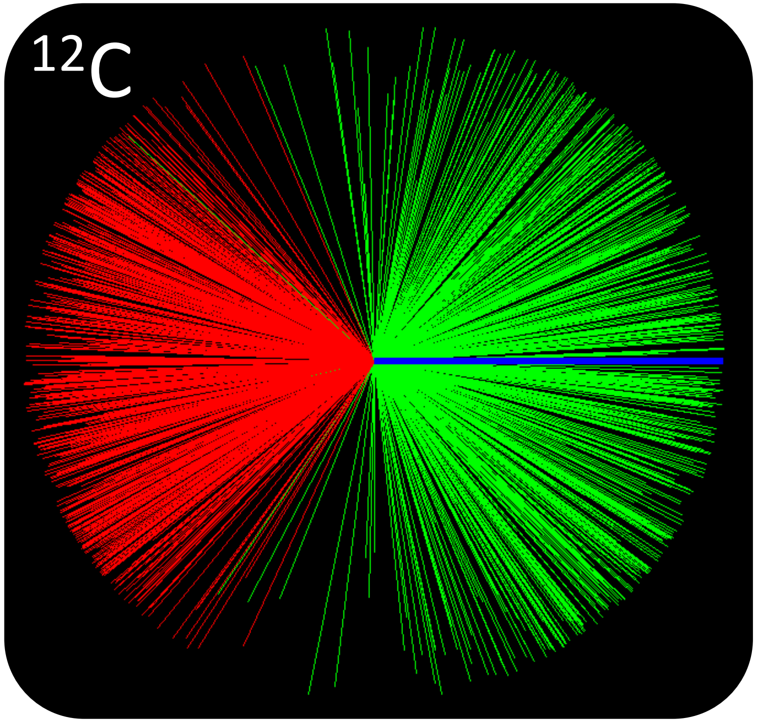


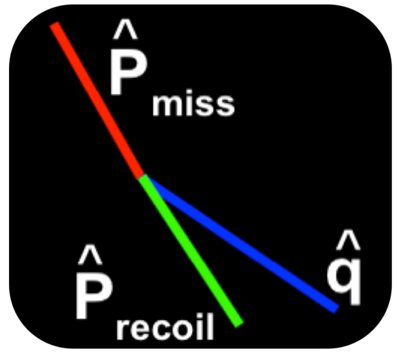
M. Duer et al.

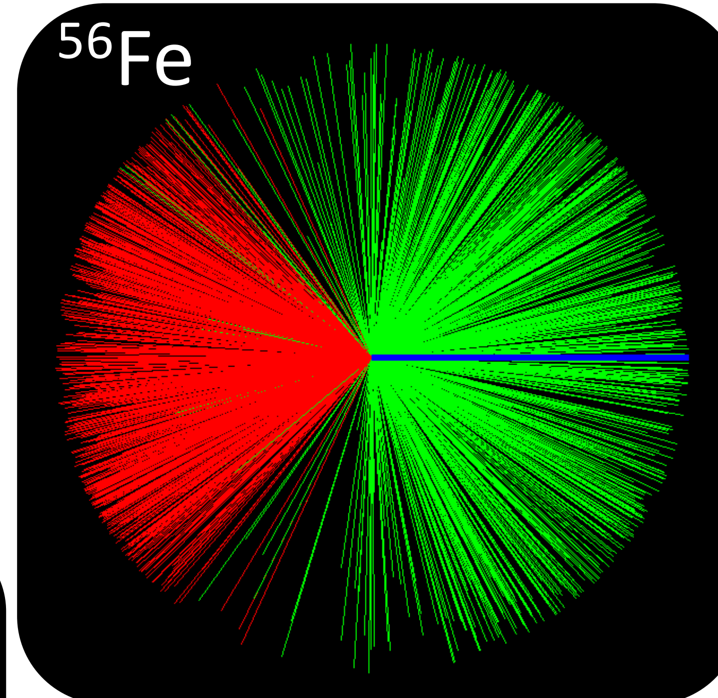
Breakup the pair =>
Detect ***both*** nucleons =>
Reconstruct ‘initial’ state

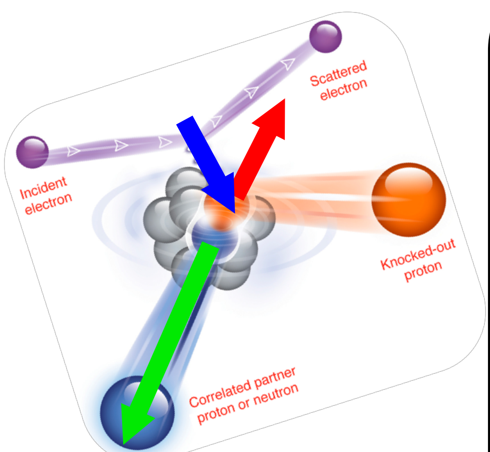


3D Reconstruction



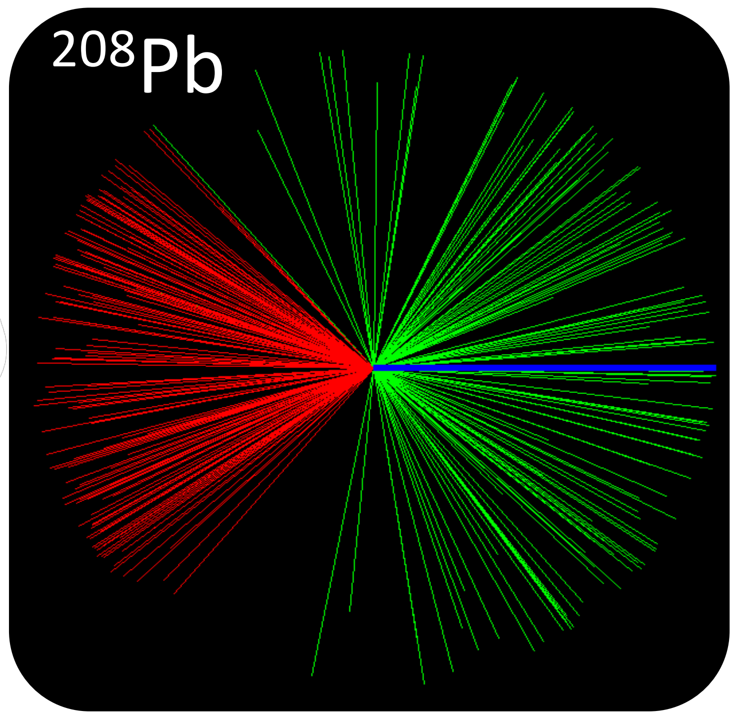


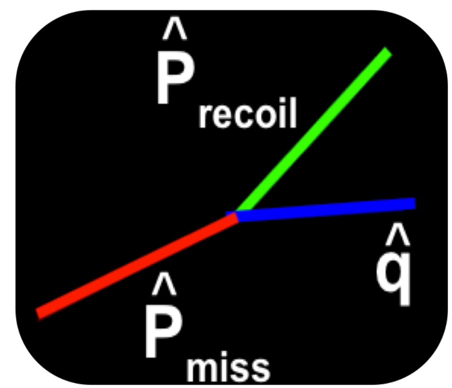




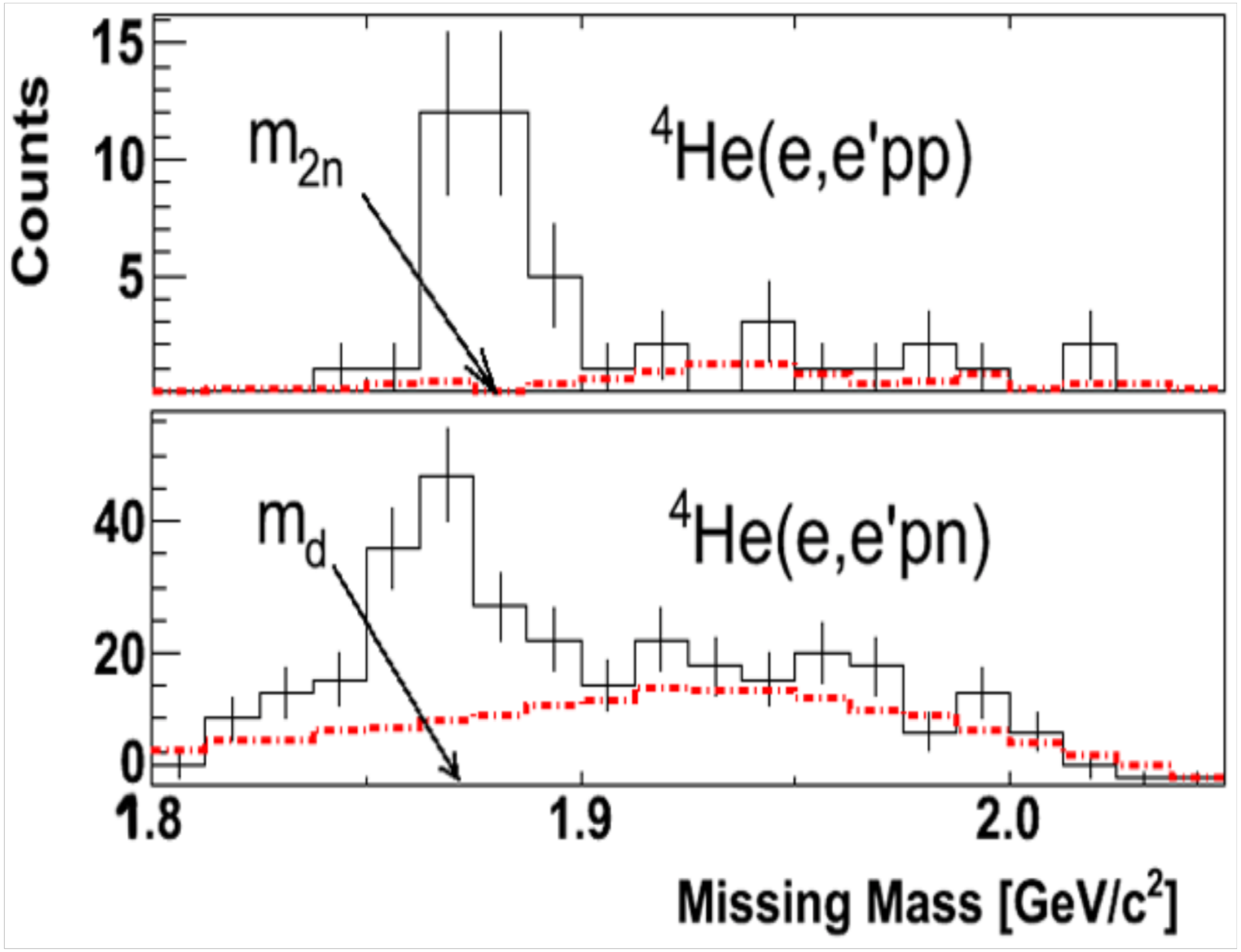
Back-to-back =

SRC pairs!



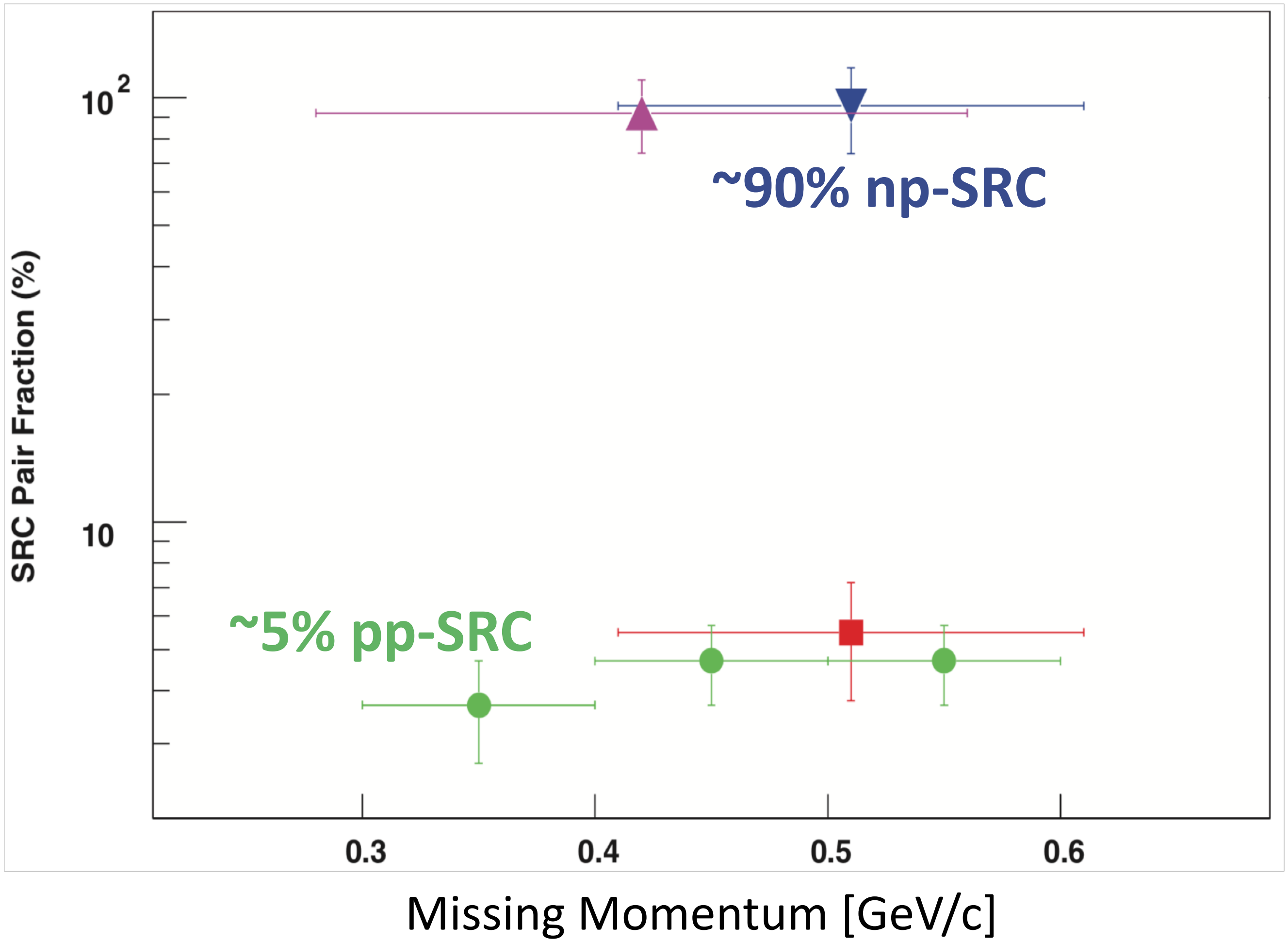


“Clean” Breakup



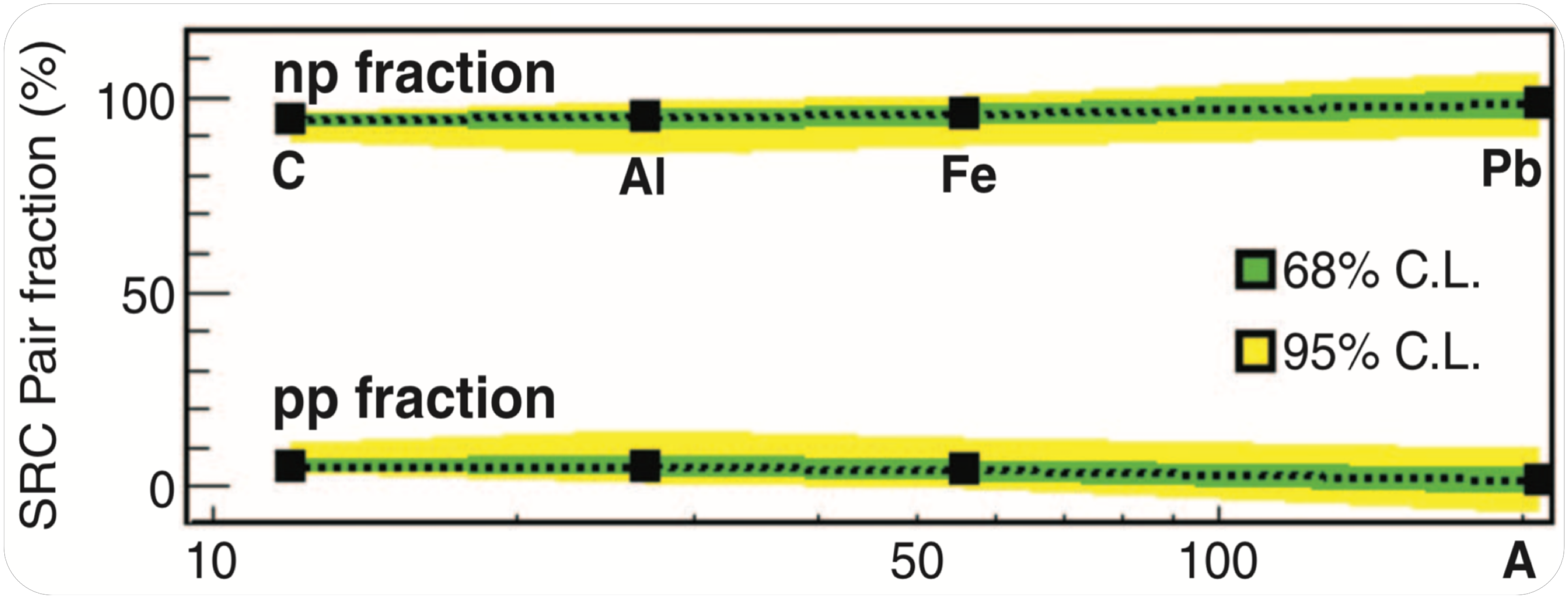
Korover PRL (2014)

np dominance (^{12}C)



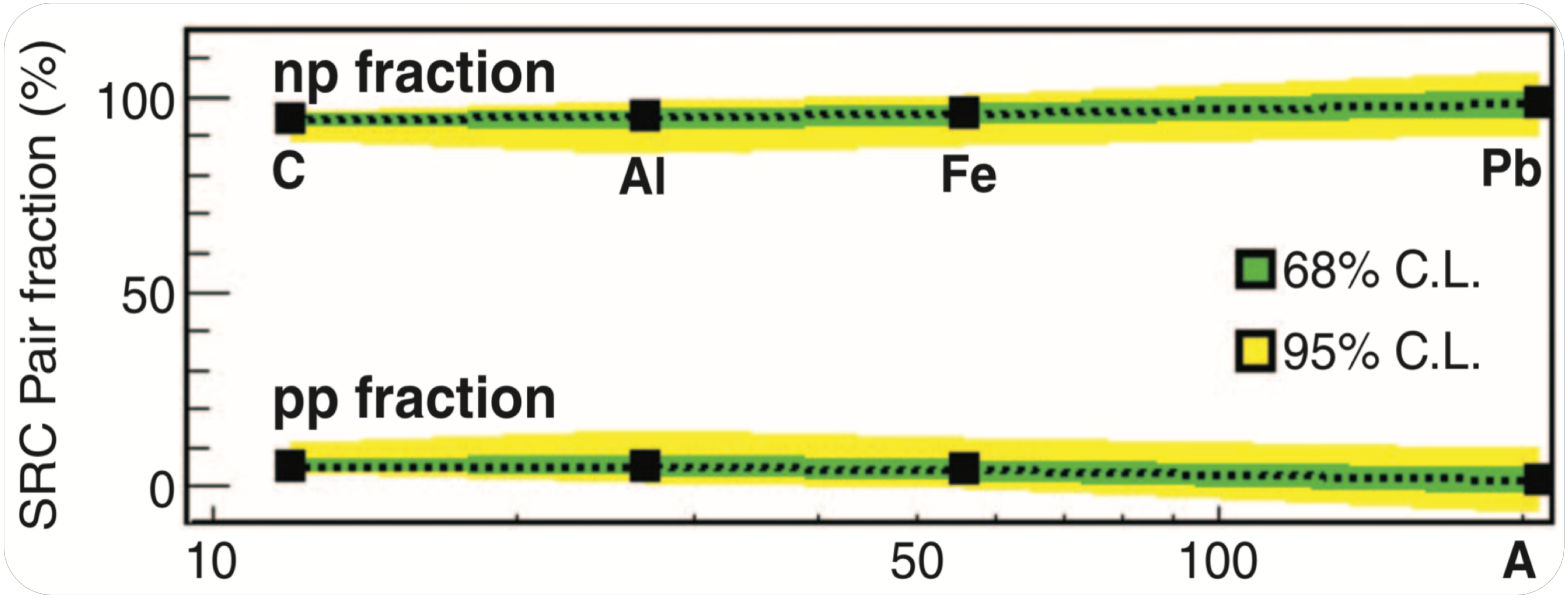
Subedy Science (2008); Shneor PRL (2007); Piasetzky PRL (2006); Tang PRL (2003).

np dominance (A≥12)



Hen Science (2014)

np dominance (A≥12)



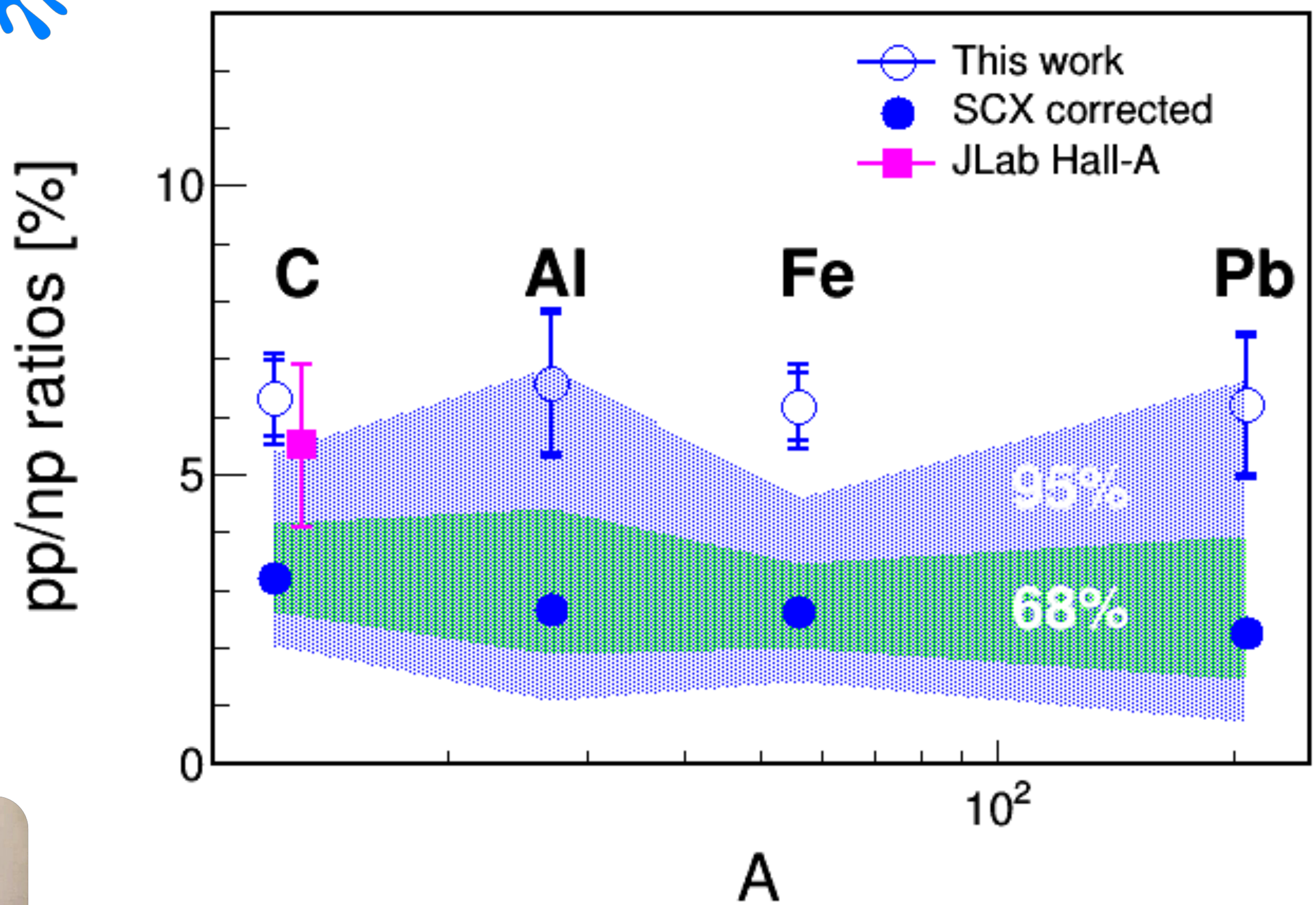
*Deduced from observing a low (e,e’pp) / (e,e’p) ratio

Hen Science (2014)

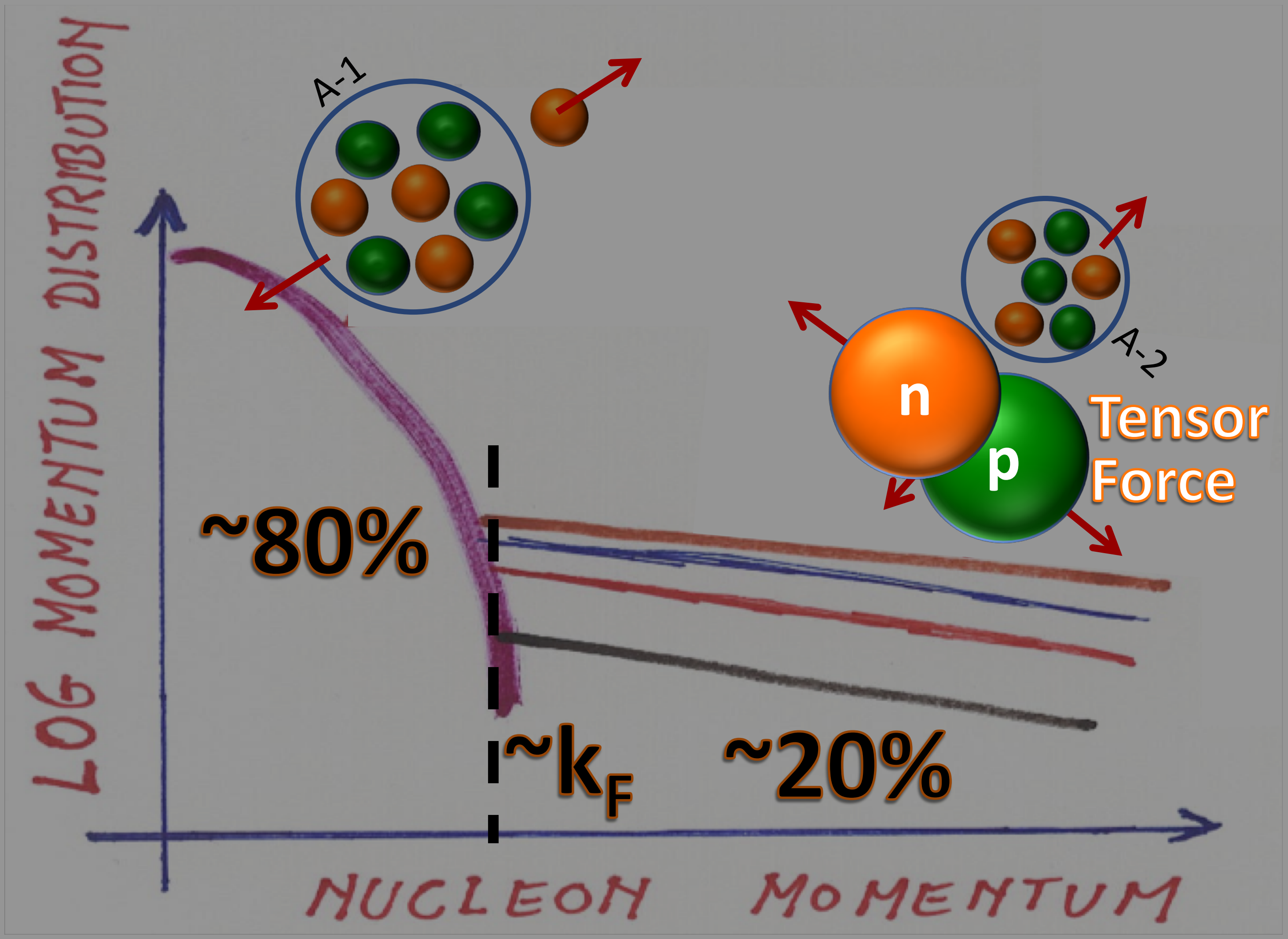

BRACE YOURSELF
(New) DATA
~~WINTER~~ IS COMING
Troll.me

(e,e’Np): DIRECT Observation

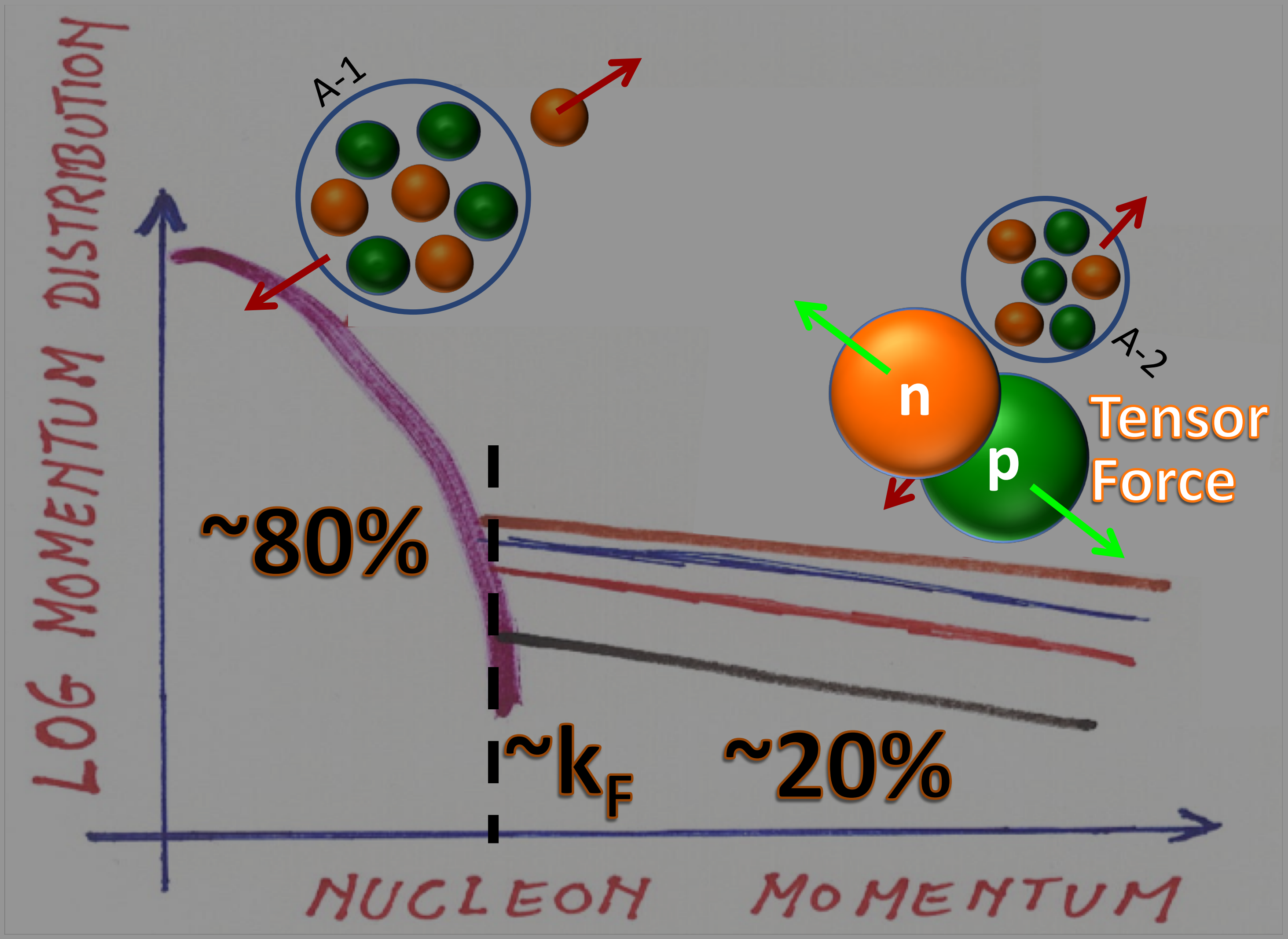
NEW!



M. Duer et al.,
arXiv: 1810.05343 (2018)



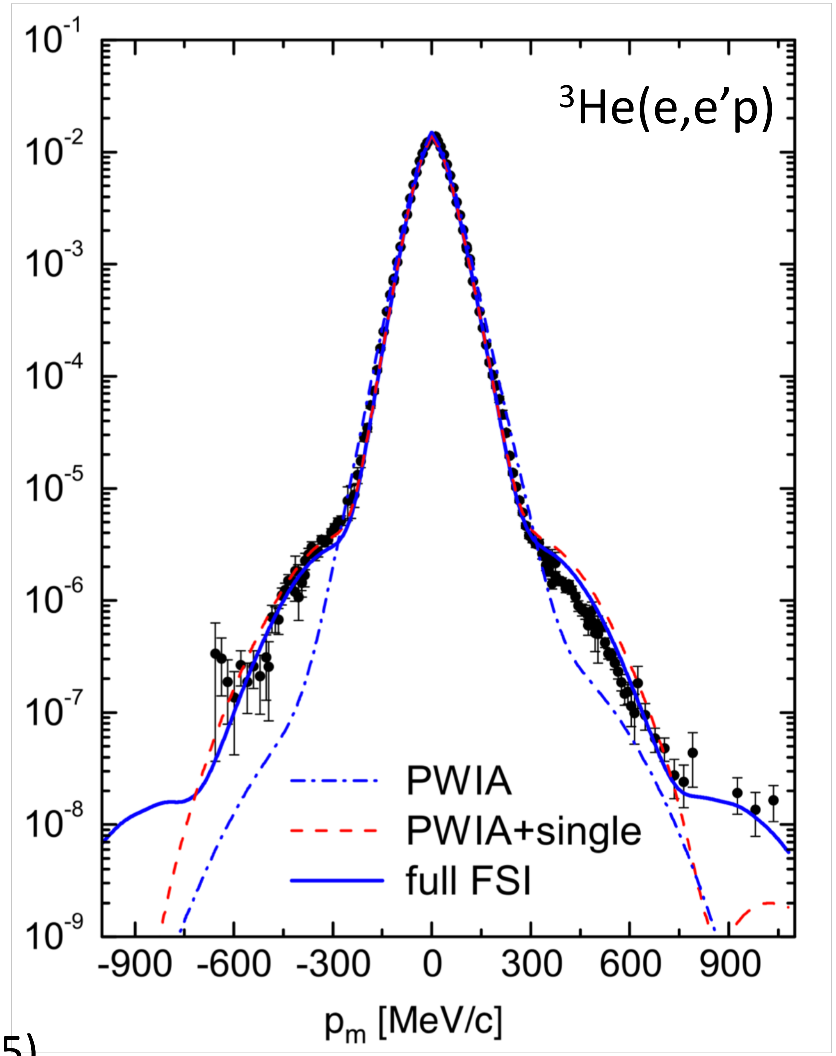
LOG MOMENTUM DISTRIBUTION
A-1
A-2
n
p
Tensor Force
~80%
~k_F
~20%
NUCLEON MOMENTUM



LOG MOMENTUM DISTRIBUTION
A-1
A-2
n
p
Tensor Force
~80%
~k_F
~20%
NUCLEON MOMENTUM

Past attempts of high-p probs

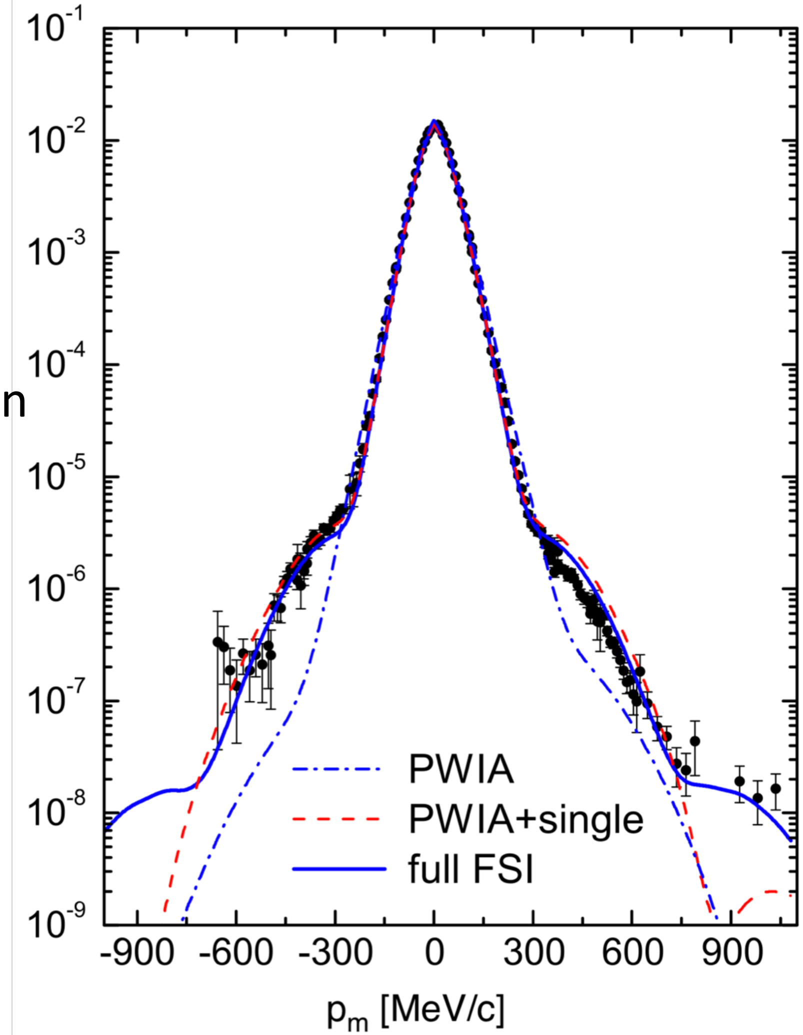
Reduced Cross-section



Exp: Benmokhtar PRL (2005)
Calc: Ciofi degli Atti PRL (2005)

Past attempts of high-p probs

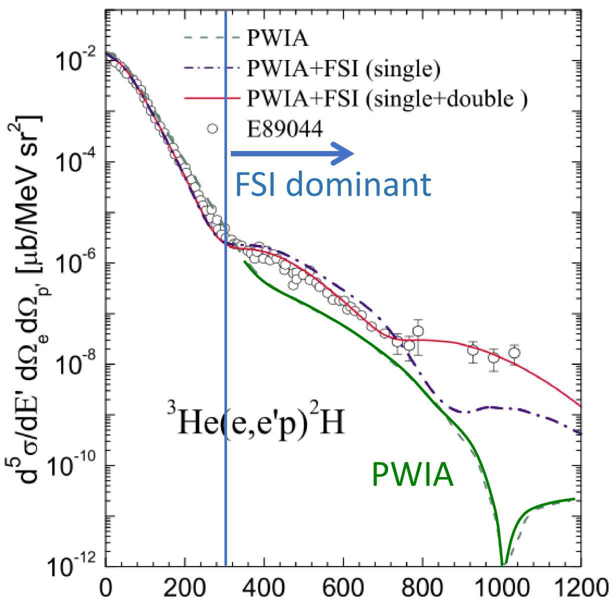
Reduced Cross-section



Logarithmic reaction effects @ high-k / short-distance!

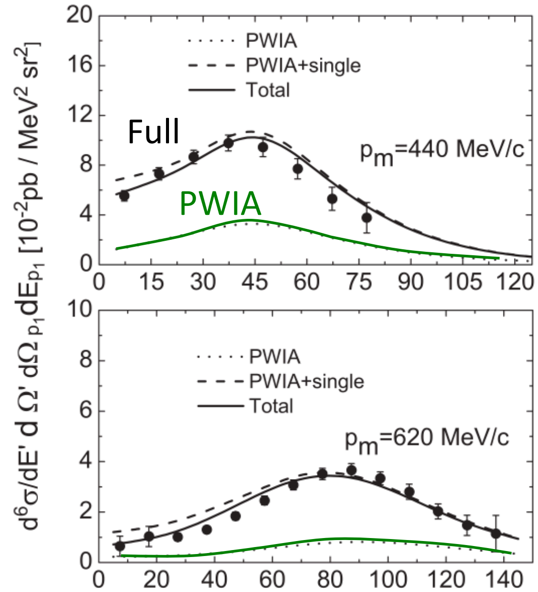
(e,e’p): large FSI at high-momentum

^{3}He(*e,e’p*)*d*



p_m [MeV/c]

^{3}He(*e,e’p*)*np*



E_m [MeV]

p_m = 440 MeV/c

p_m = 620 MeV/c

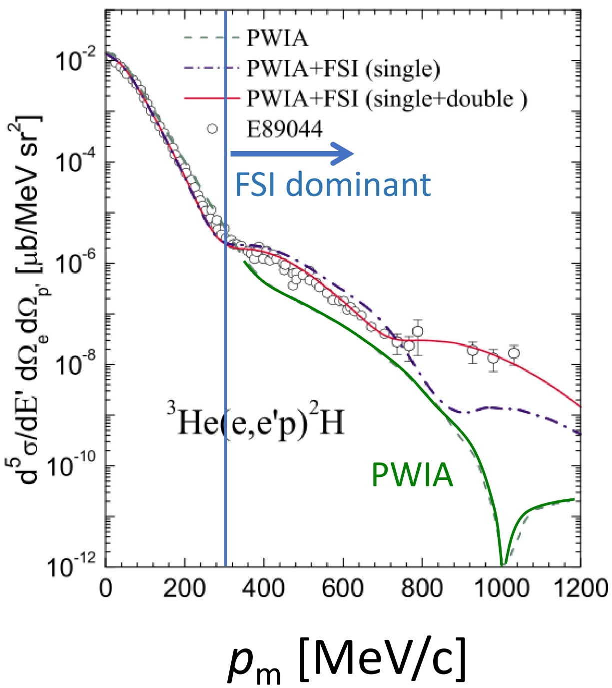
Dominated by FSI at large missing momentum

Data: Rvachev *et al.*, PRL94 192302 ; Benmokhtar *et al.*, PRL94 082305

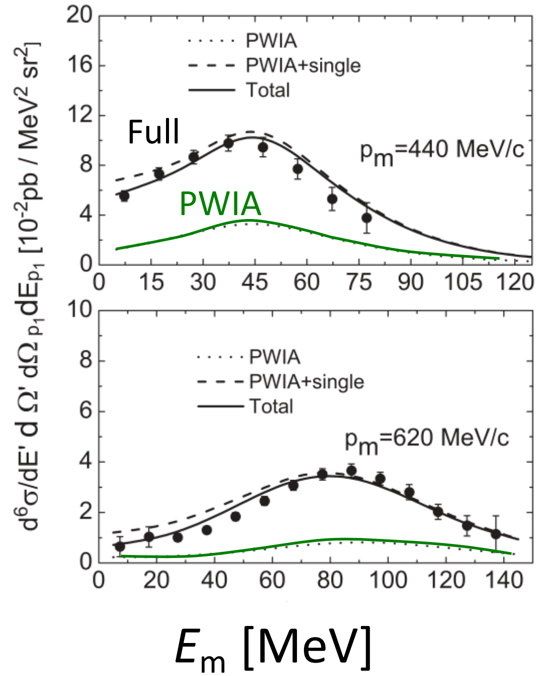
Theory: Ciofi degli Atti and Kaptari, PRL95 052502 ; Alvioli *et al.*, PRC81 021001 ; Laget, PLB609 49 (not shown)

(e,e'p): large FSI at high-momentum

^{3}He(*e,e'p*)*d*



^{3}He(*e,e'p*)*np*



p_m = 440 MeV/c

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Dominated by FSI at large missing momentum

Well described by calculation

Data: Rvachev *et al.*, PRL94 192302 ; Benmokhtar *et al.*, PRL94 082305

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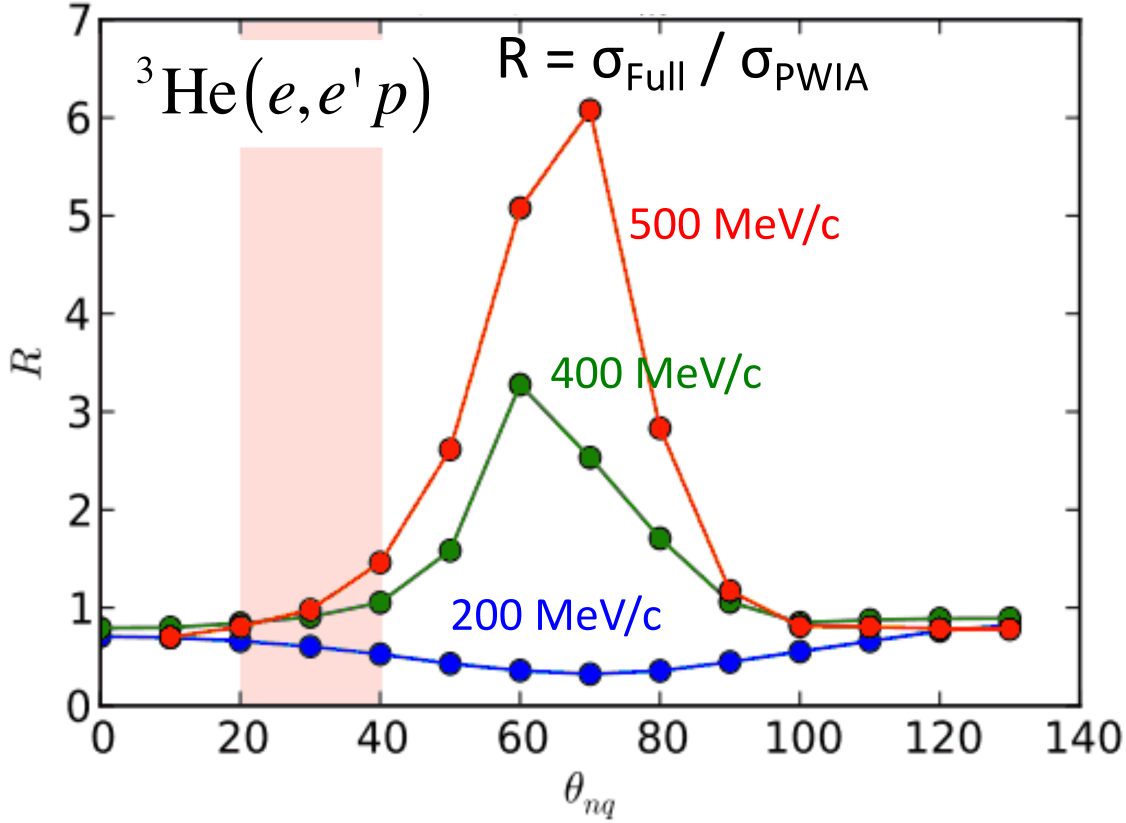
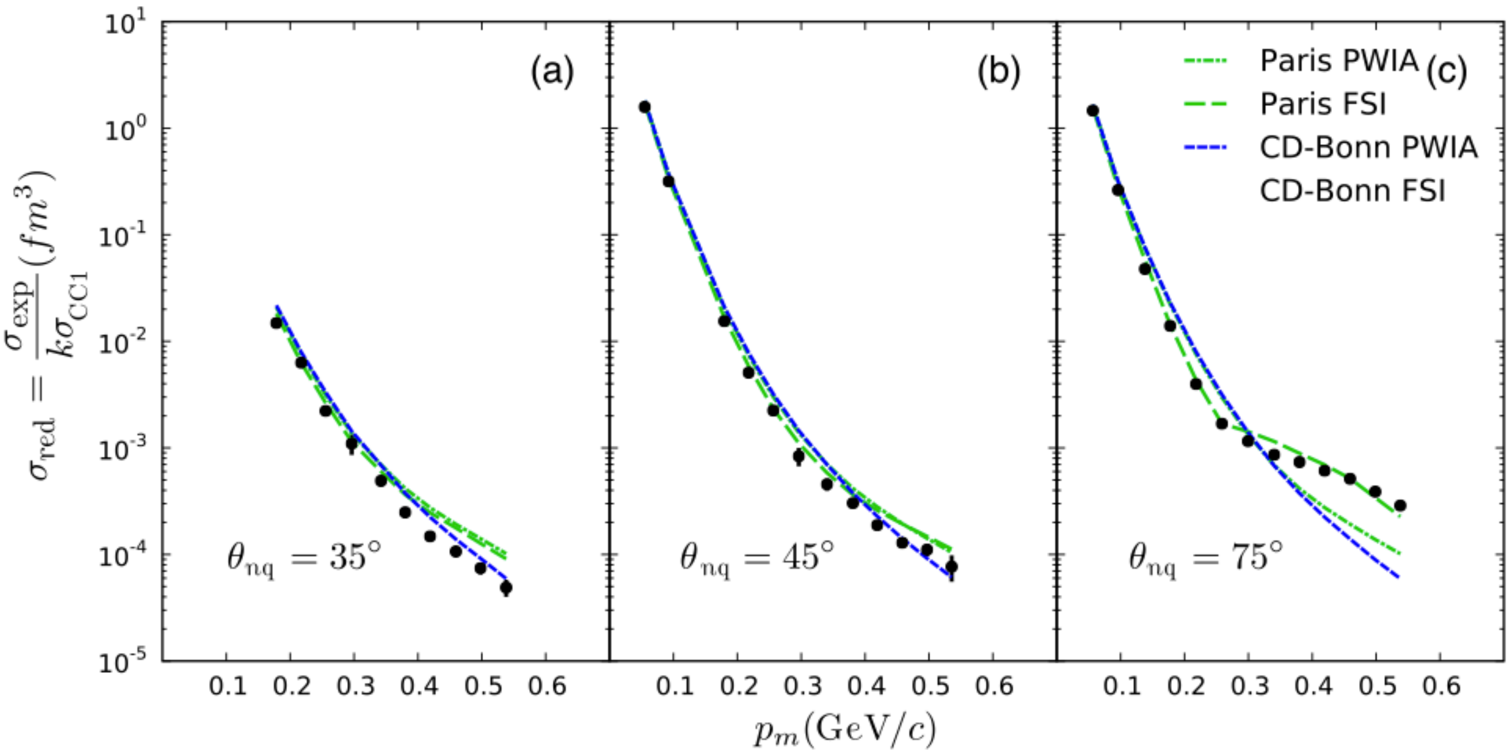
Magic Kinematics?



M. Sargsian

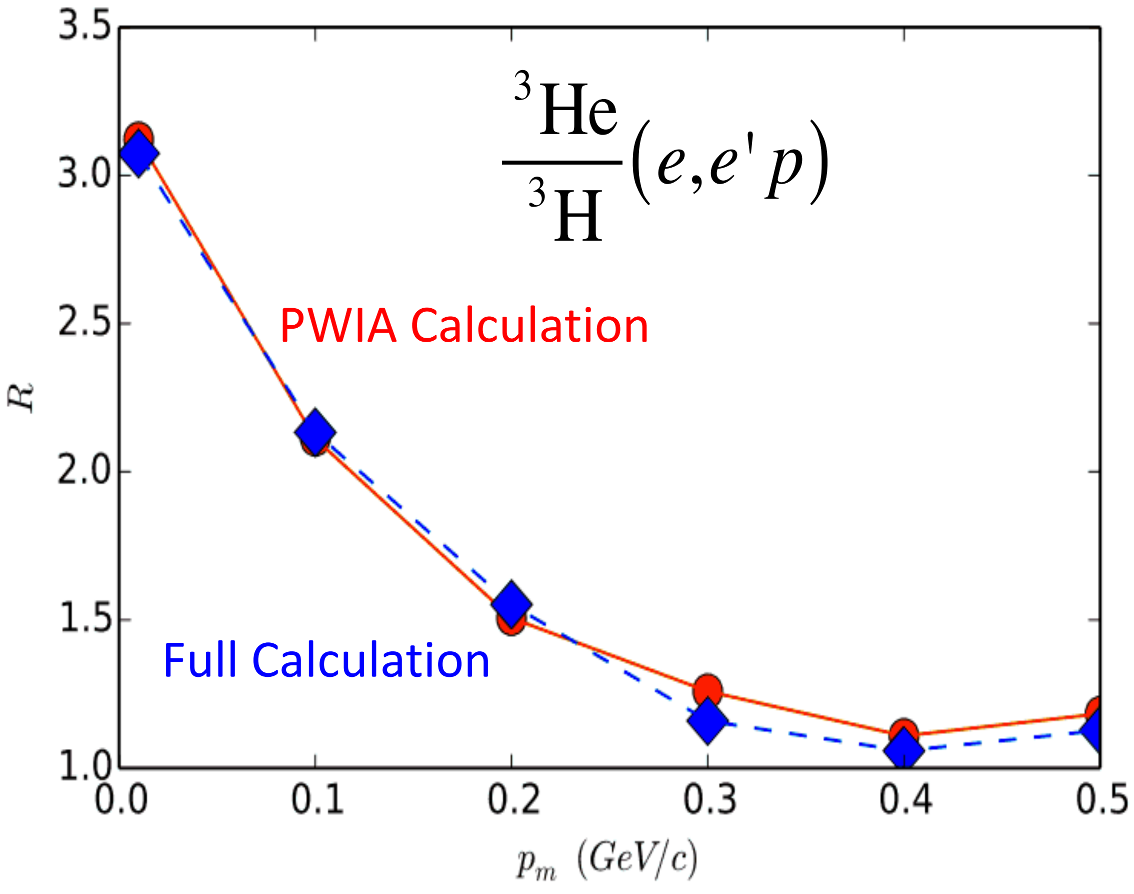
Magic Kinematics!



$P_{\rm miss}$ (GeV/c)

Boeglin et al., PRL (2011)

Magic Ratios?



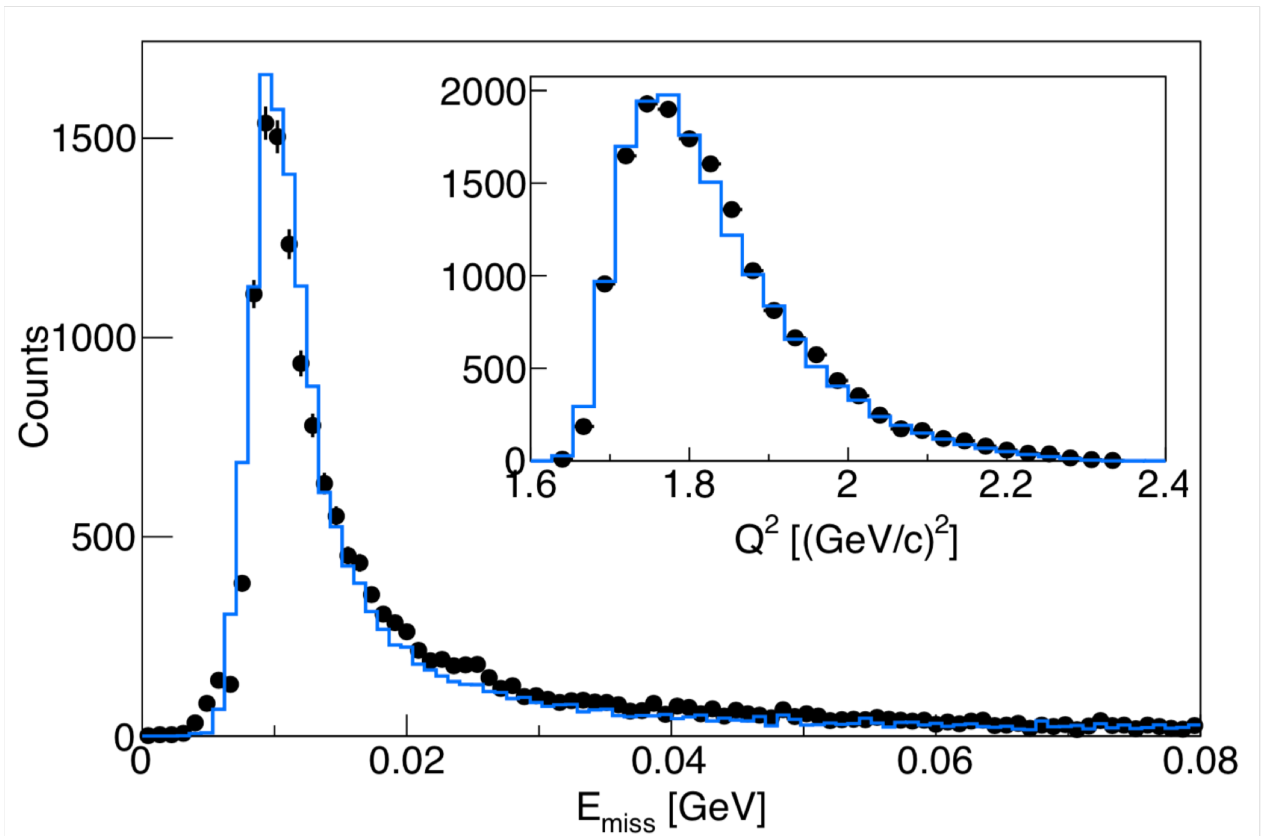
M. Sargsian

Probing nucleon momentum distributions in $A = 3$ nuclei via ^{3}He and ^{3}H$(e, e'p)$ measurements

R. Cruz-Torres,[1] S. Li,[2] F. Hauenstein,[3] A. Schmidt,[1] D. Abrams,[4] H. Albataineh,[5] S. Alsalmi,[6] D. Androic,[7]

⋮

(Jefferson Lab Hall A Tritium Collaboration)
[1]*Massachusetts Institute of Technology, Cambridge, MA*
[2]*University of New Hampshire, Durham, NH*
[3]*Old Dominion University, Norfolk, VA*



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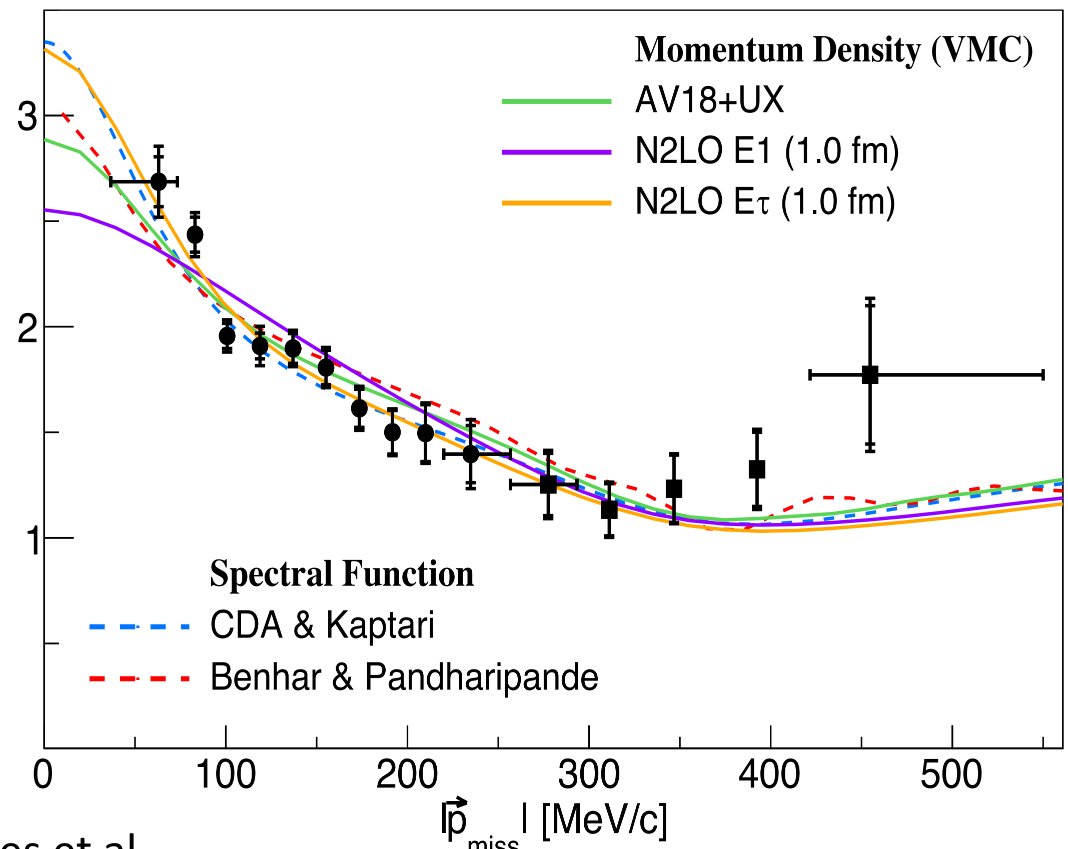
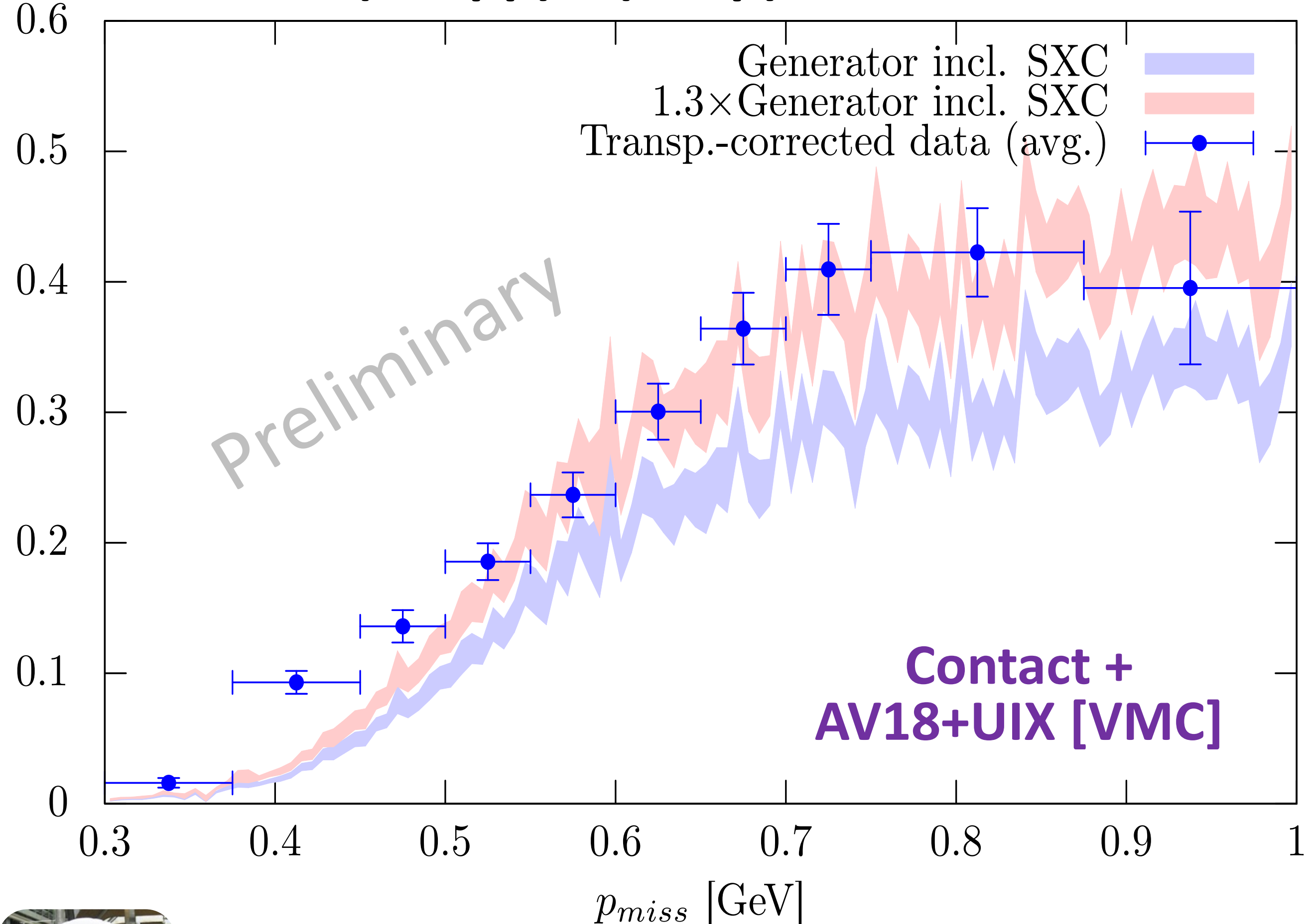
^{3}He / ^{3}H (e,e'p)



R. Cruz Torres et al.

Probing even higher momenta

A (e,e'pp) / (e,e'p) [C, Al, Fe, Pb]



Remarkable (preliminary) agreement \w ab-initio calculations @ high-momenta

A. Schmidt et al.

NEW!

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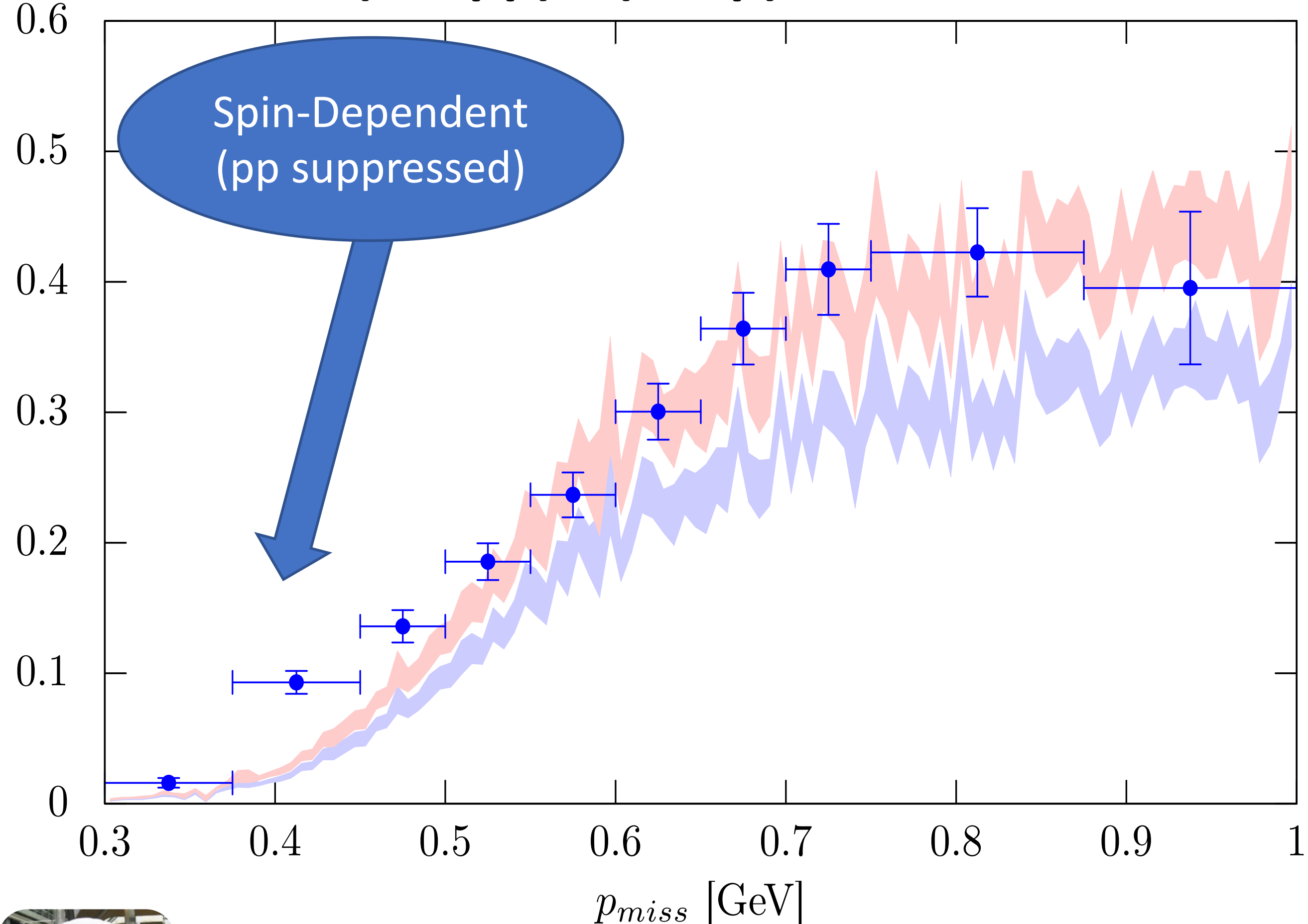

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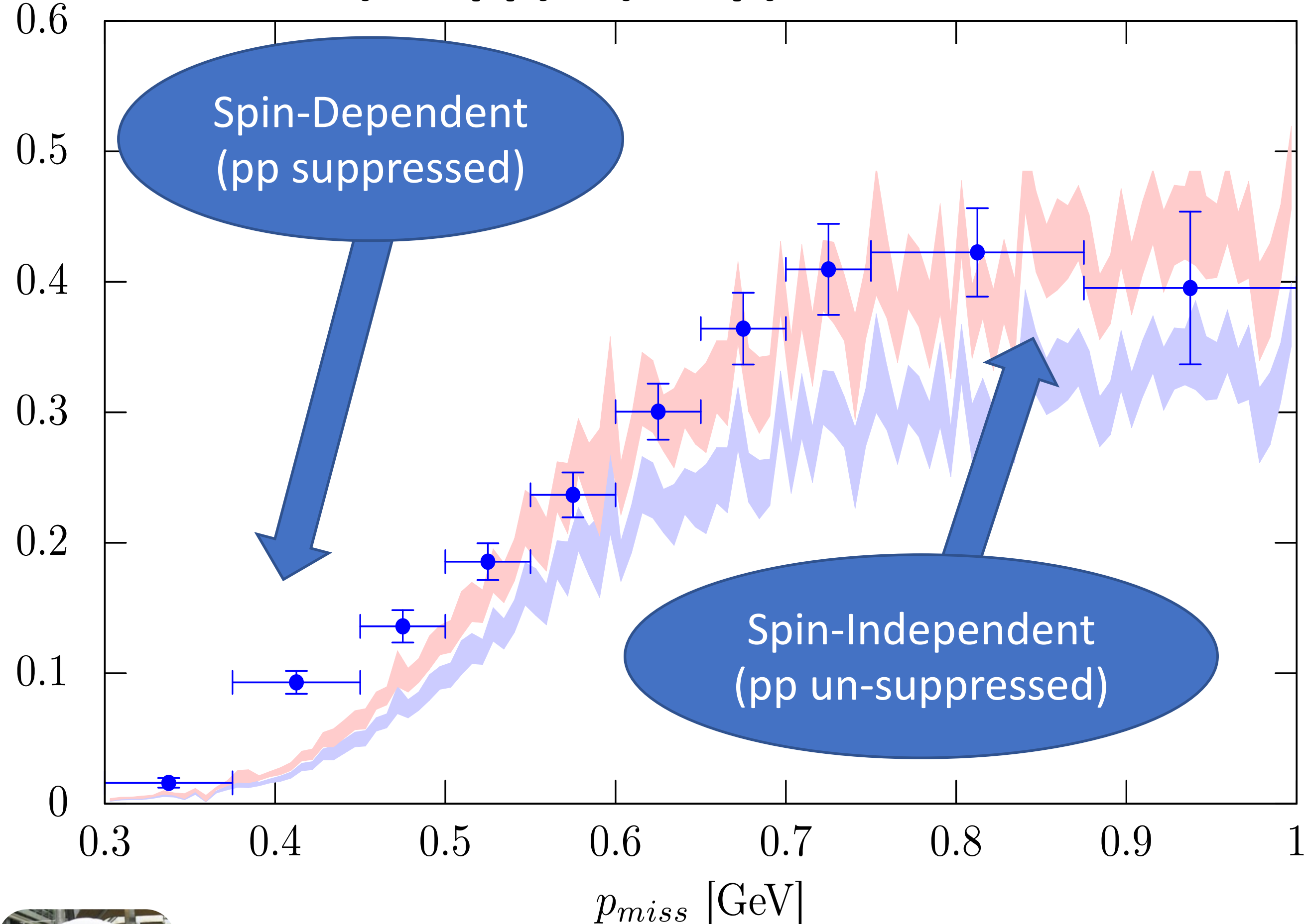

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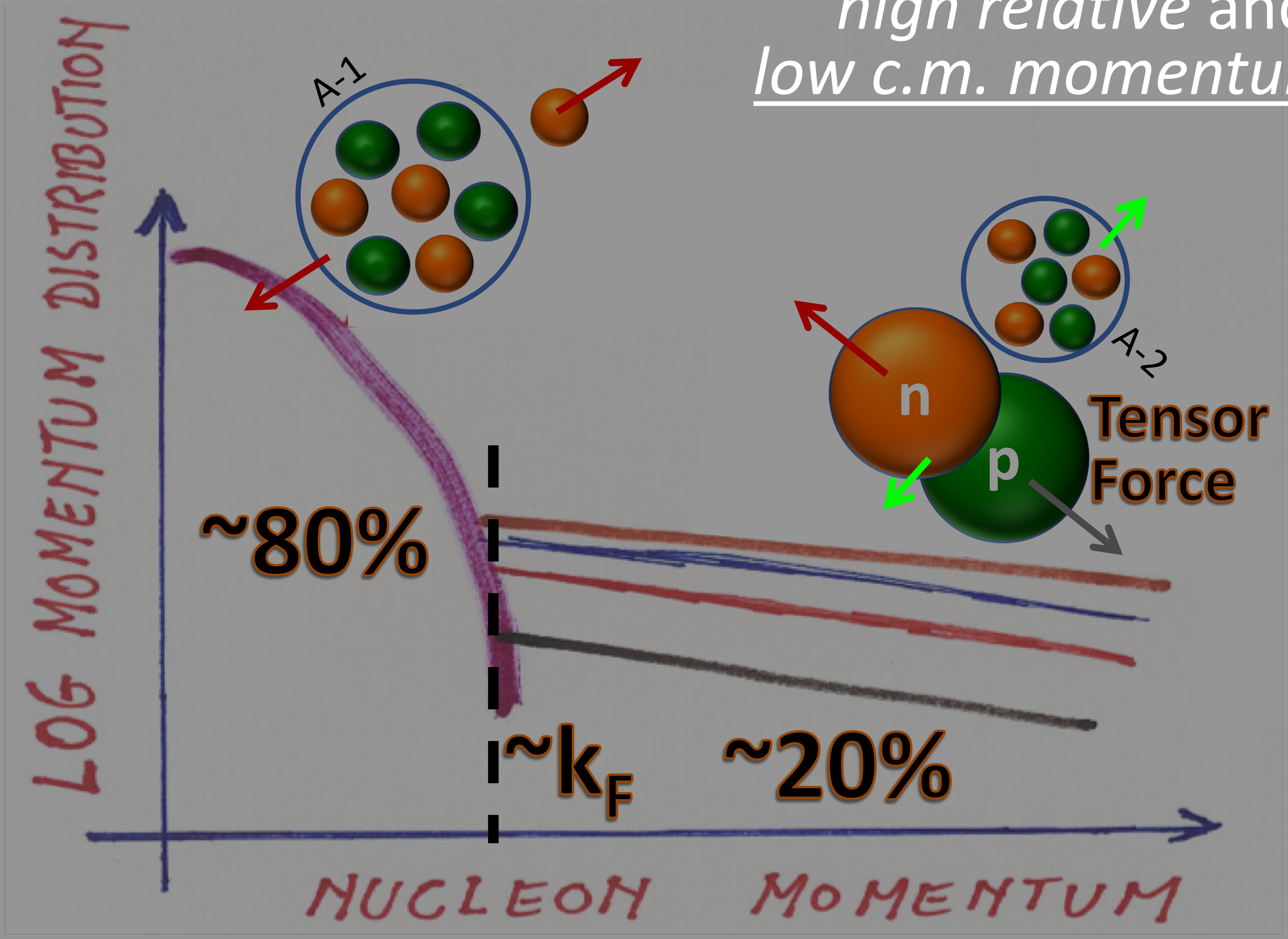
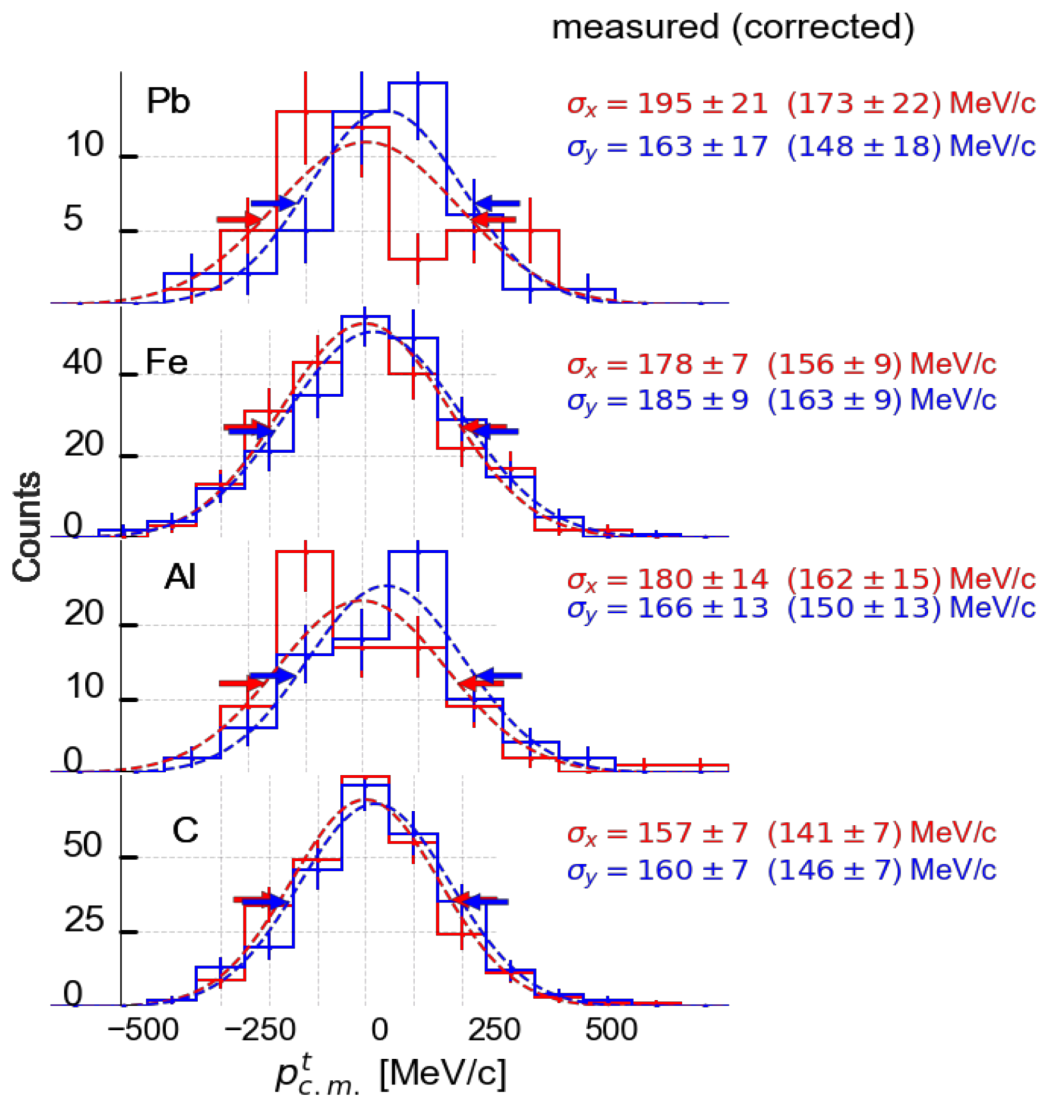
A. Schmidt et al.

"high relative and
low c.m. momentum"

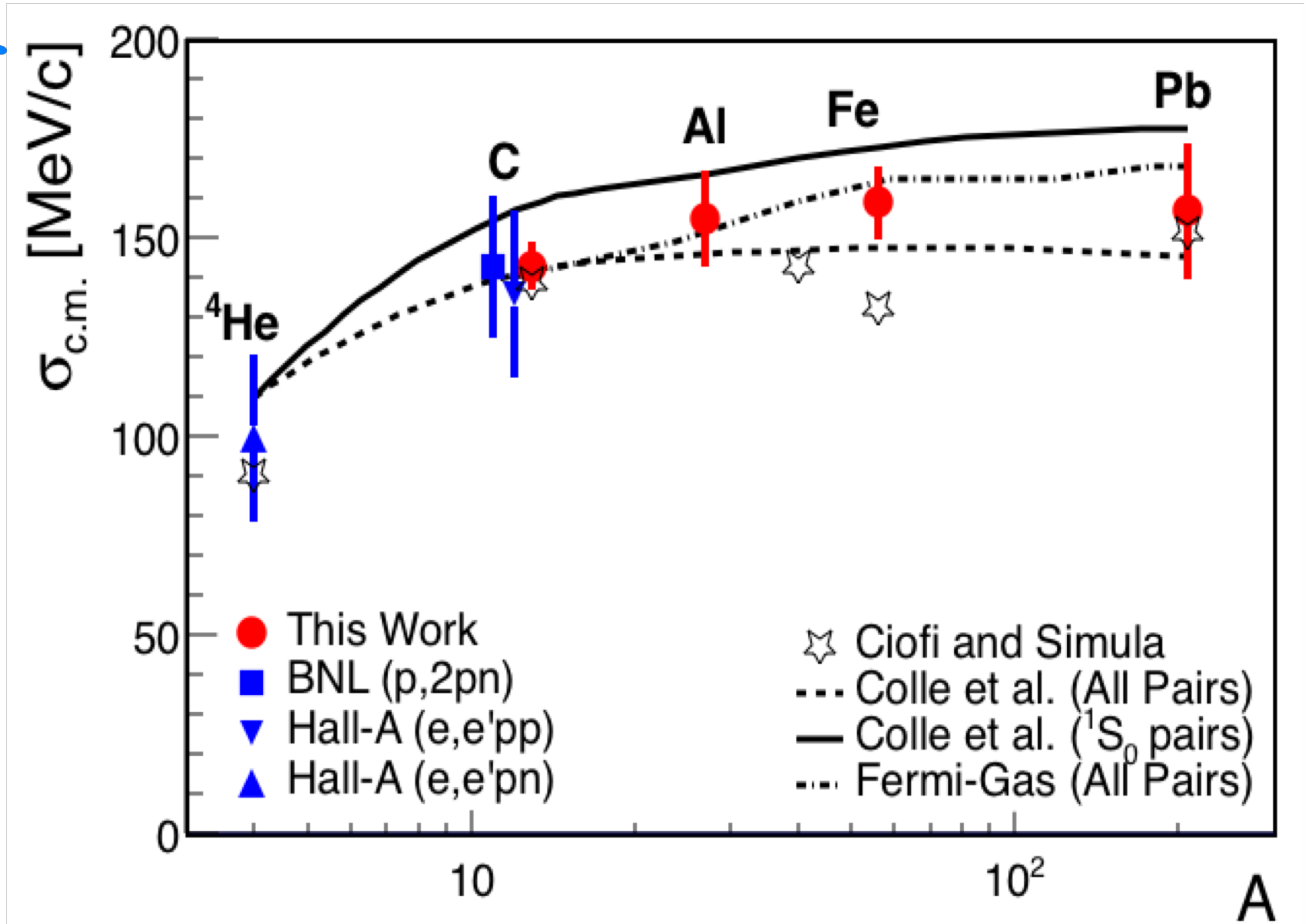


Low Pair C.M. Motion



E. Cohen, PRL (2018).

Consistent with Mean-Field Calculations



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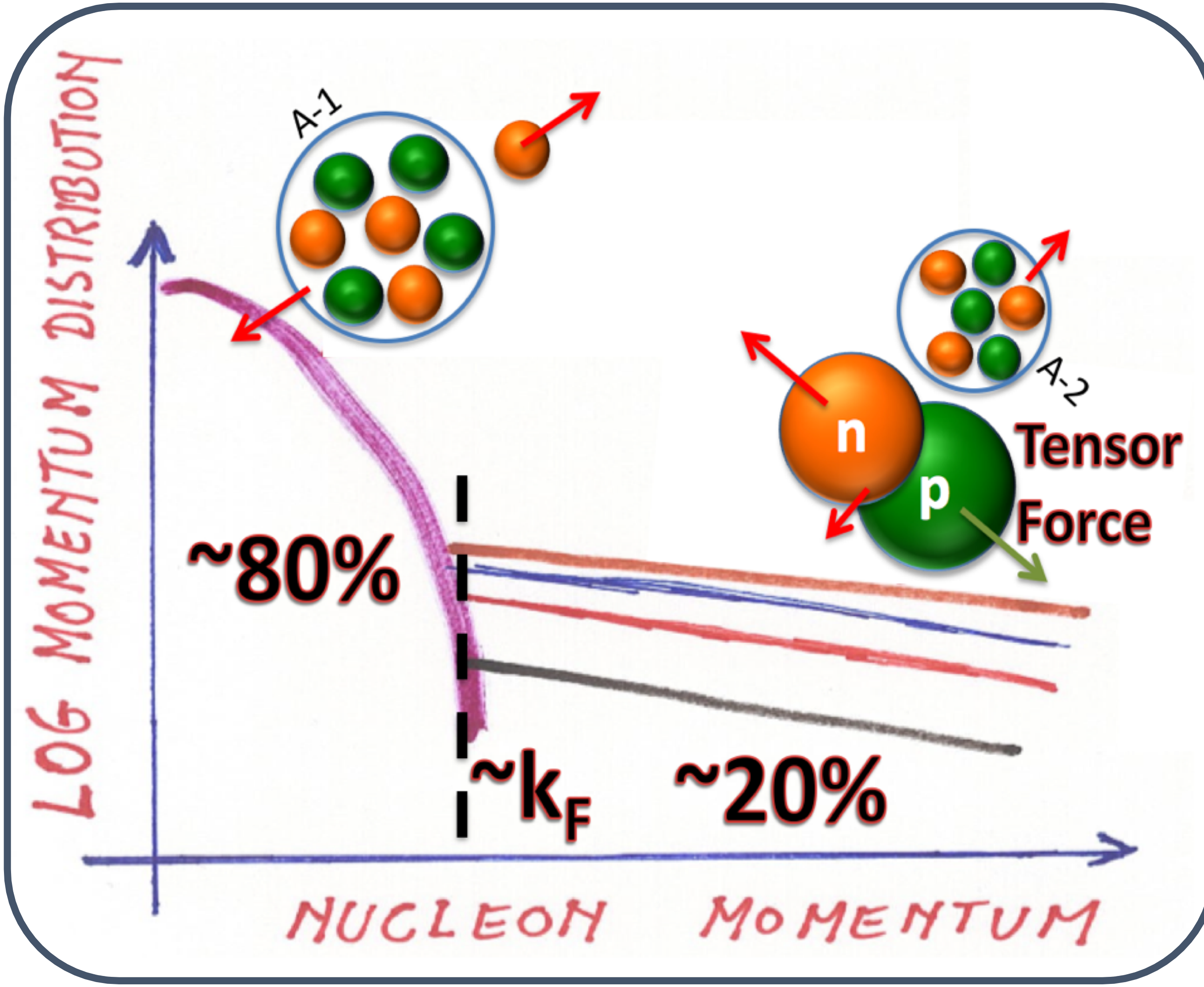
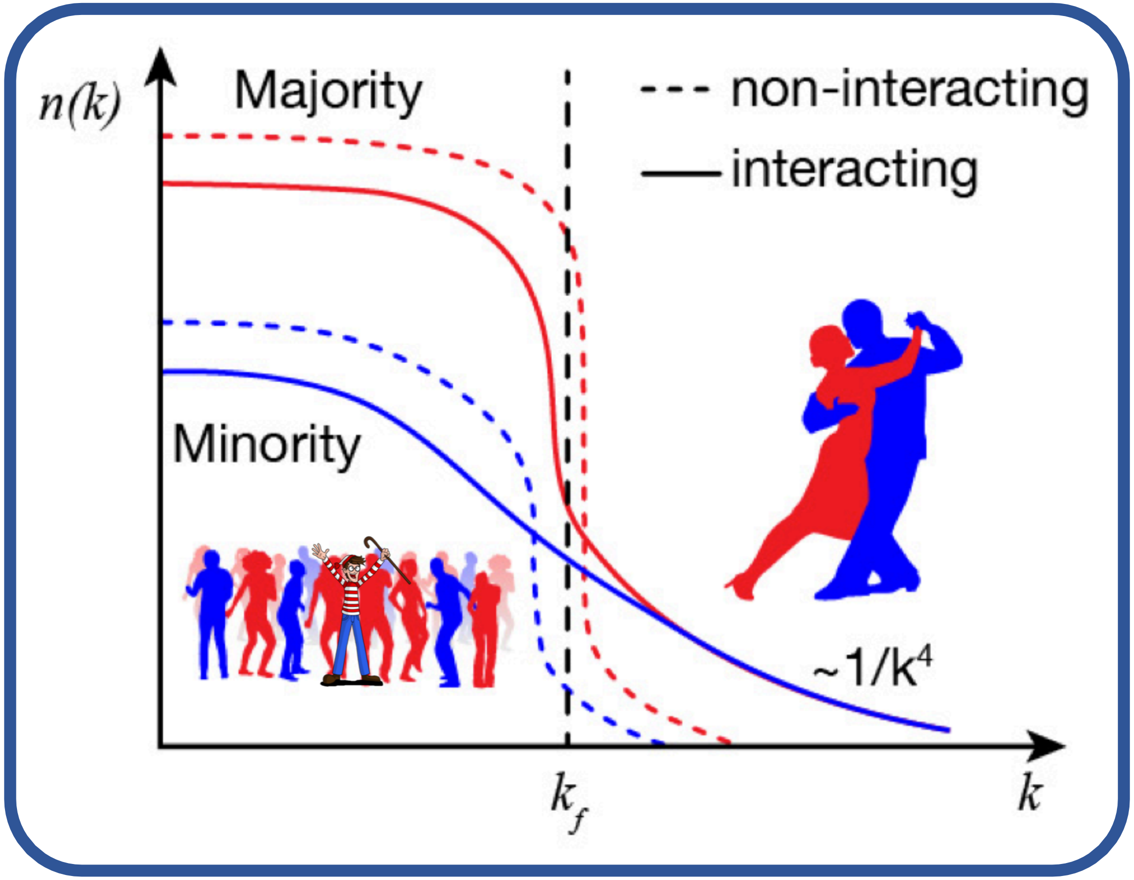
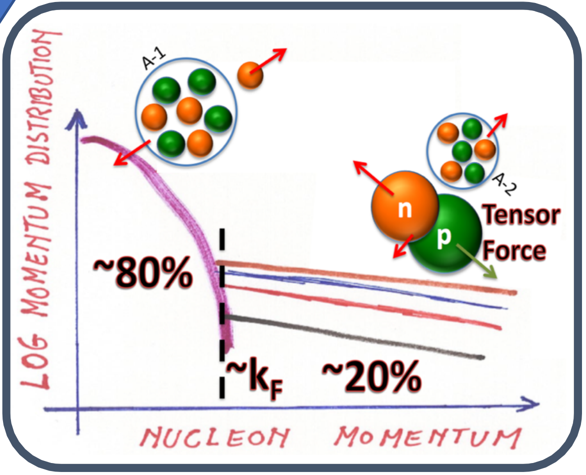


LOG MOMENTUM DISTRIBUTION
A-1
A-2
n
p
Tensor
Force
~80%
~k_F
~20%
NUCLEON MOMENTUM

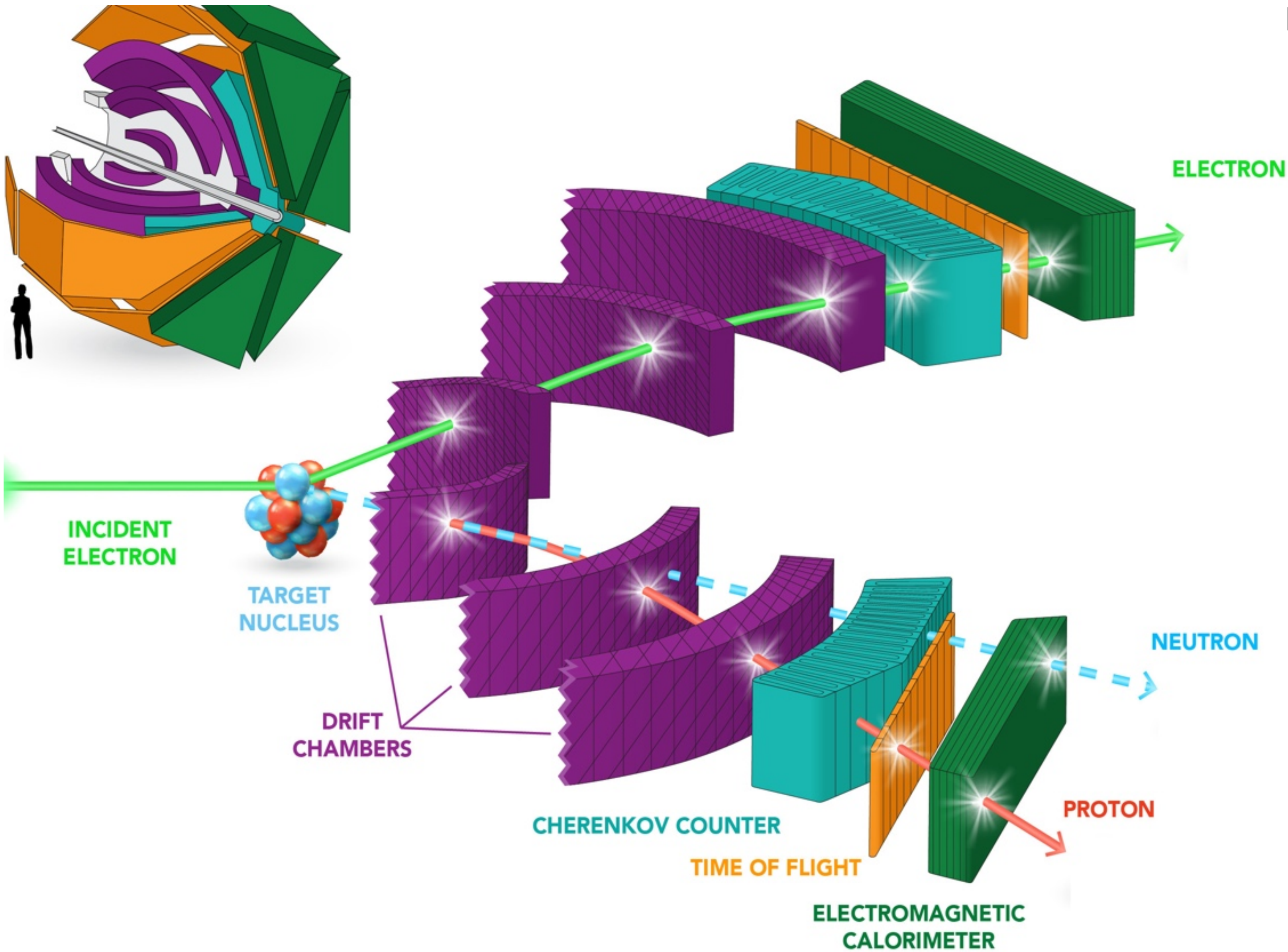
Asymmetric Nuclei?



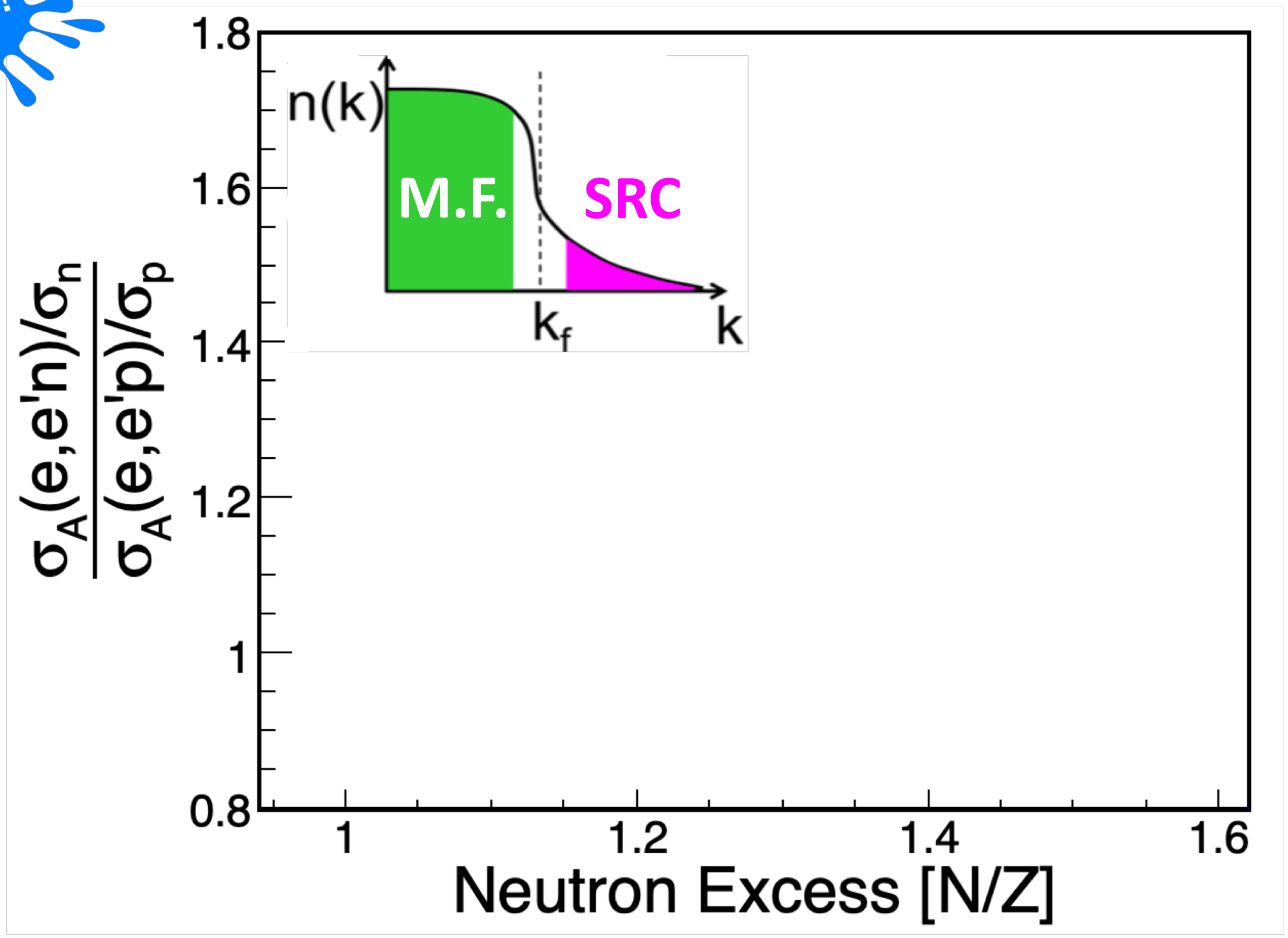


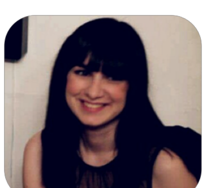
Proton vs. Neutron Knockout

M. Duer



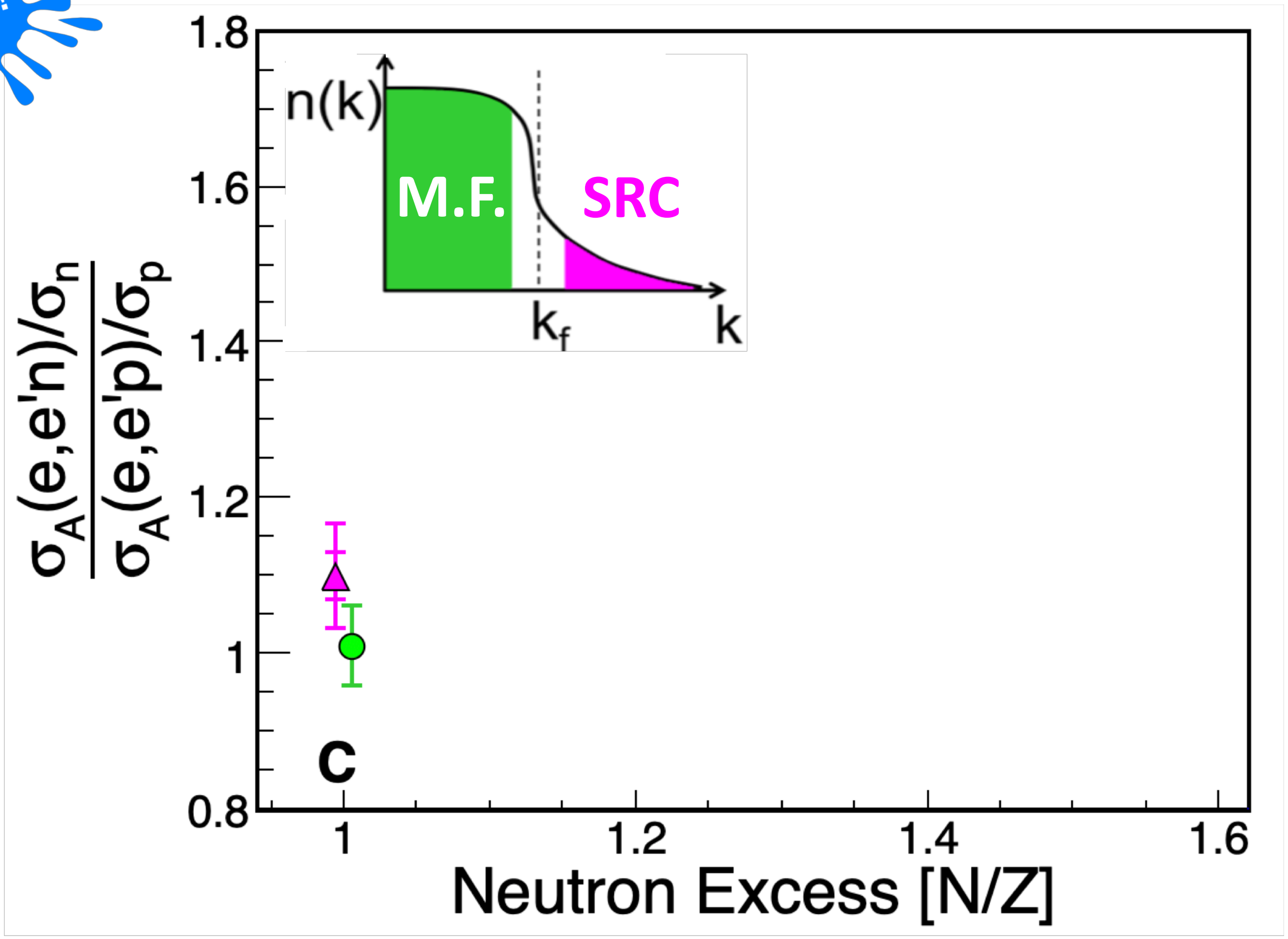
Proton / Neutron Populations





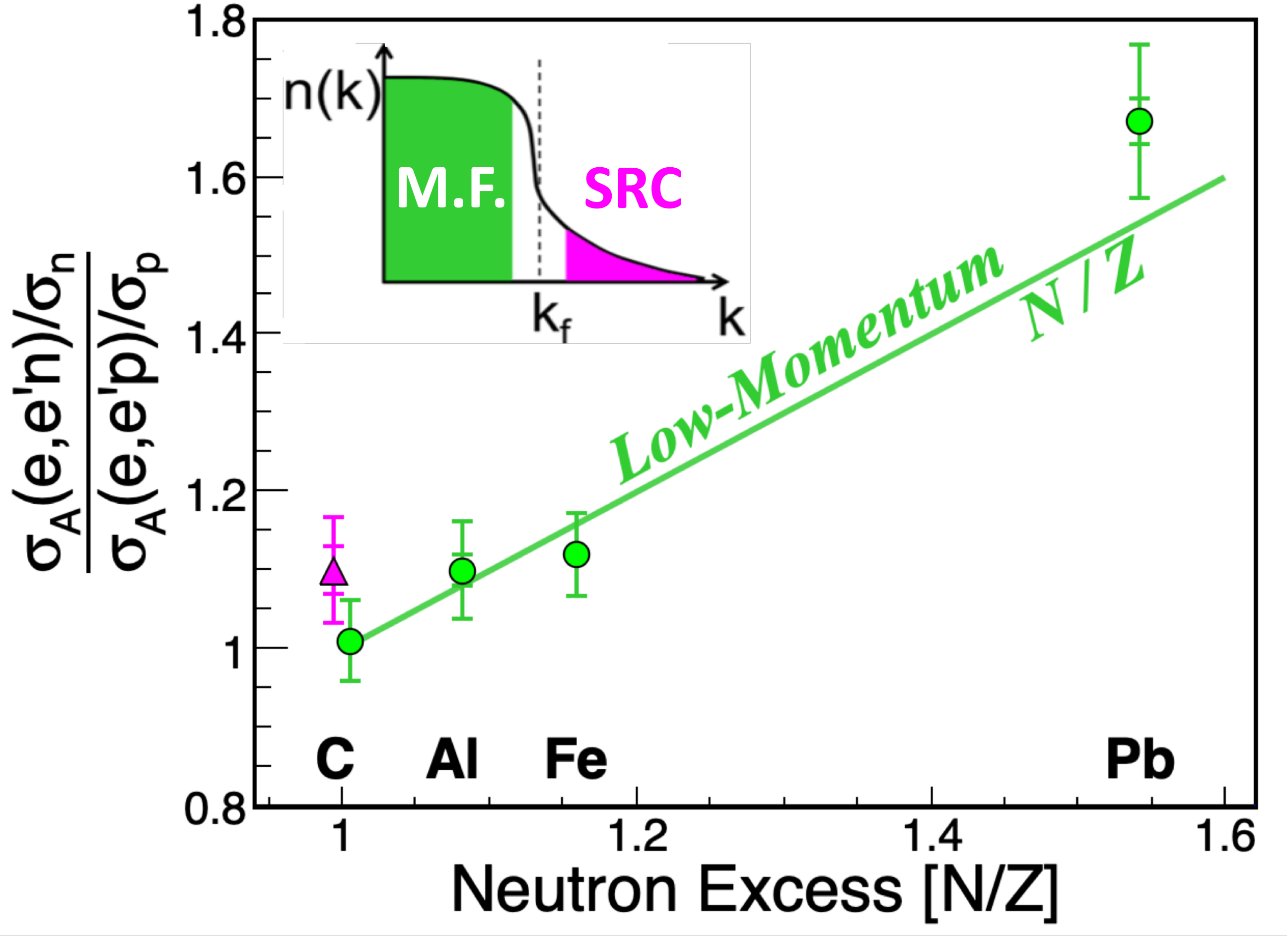
Duer et al.,
Nature (2018)

Symmetric: n/p = 1



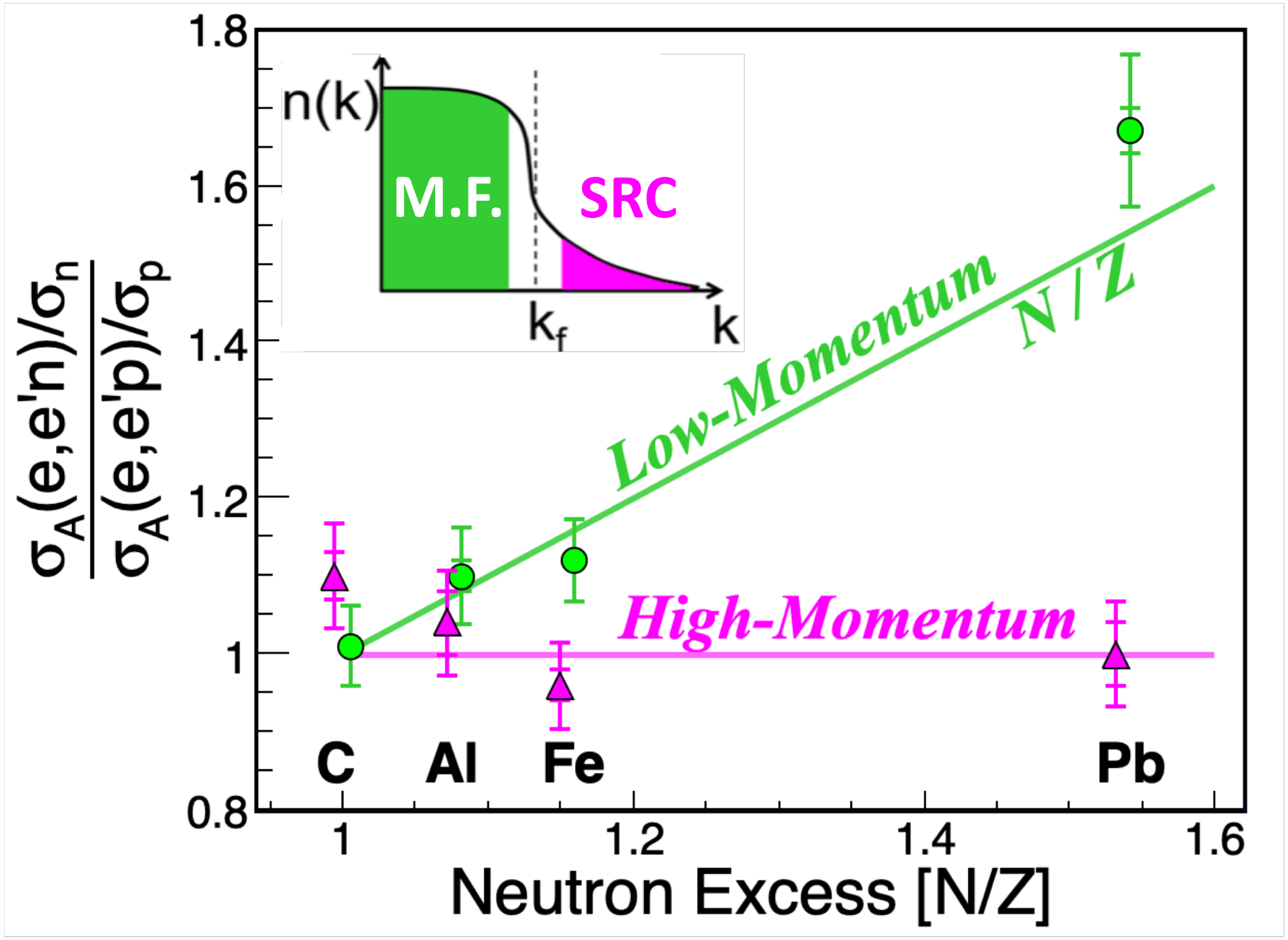
Duer et al.,
Nature (2018)

Mean-Field: n/p = N/Z



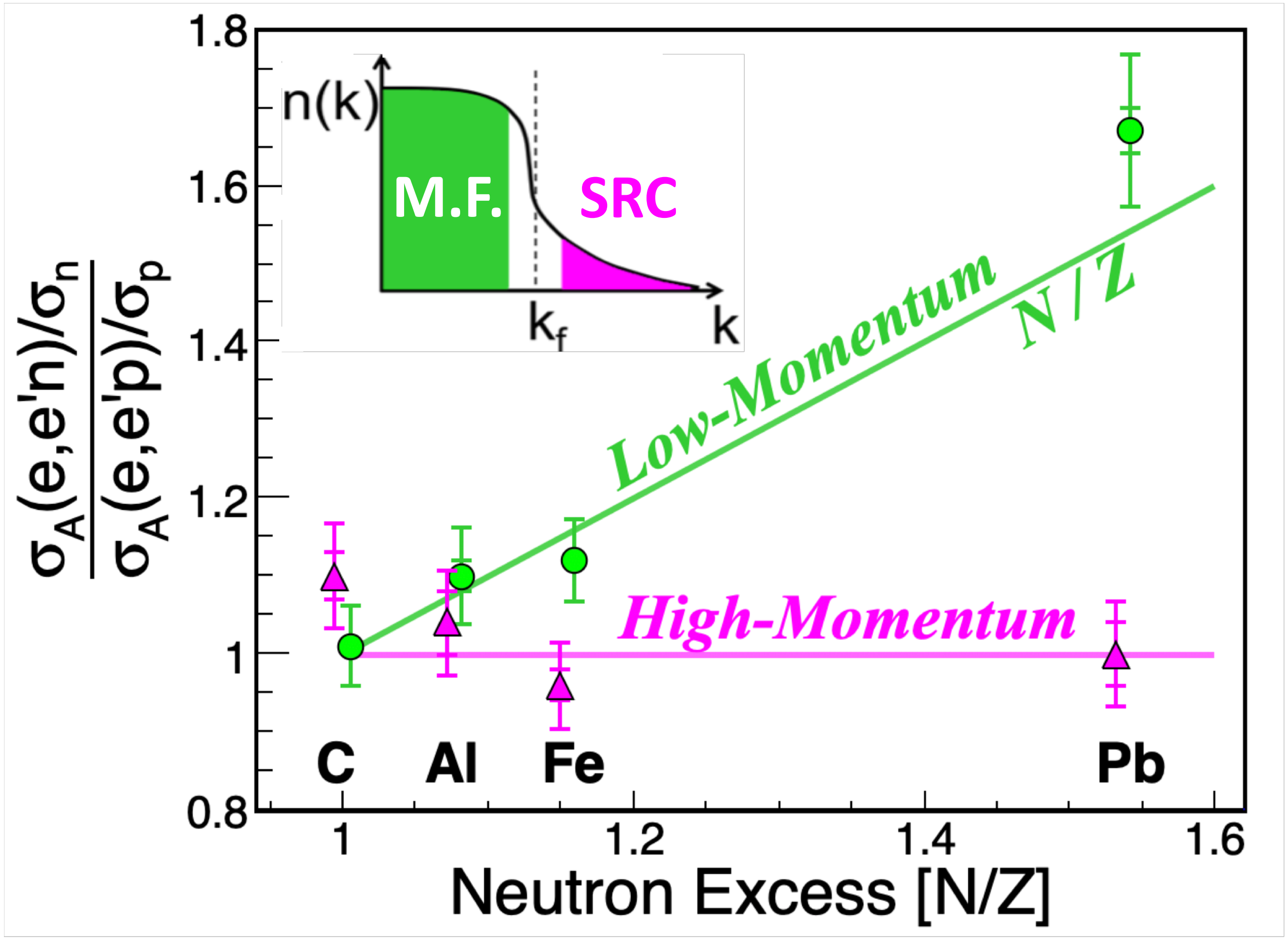
Duer et al.,
Nature (2018)

SRC: n/p = 1



Duer et al.,
Nature (2018)

➔ Same # of high-momentum protons and neutrons



Duer et al.,
Nature (2018)

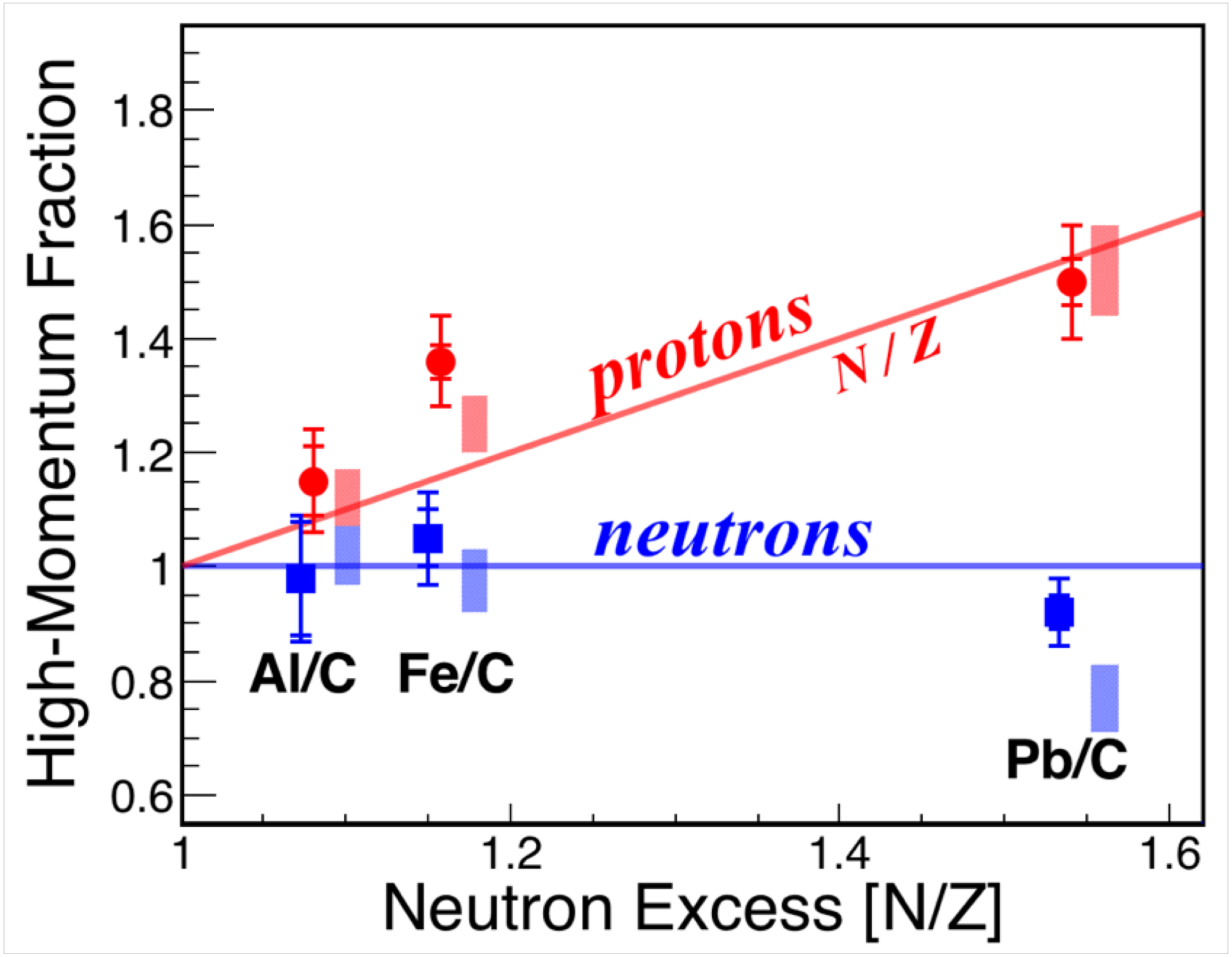
What do the outer neutrons do?

don't correlate?

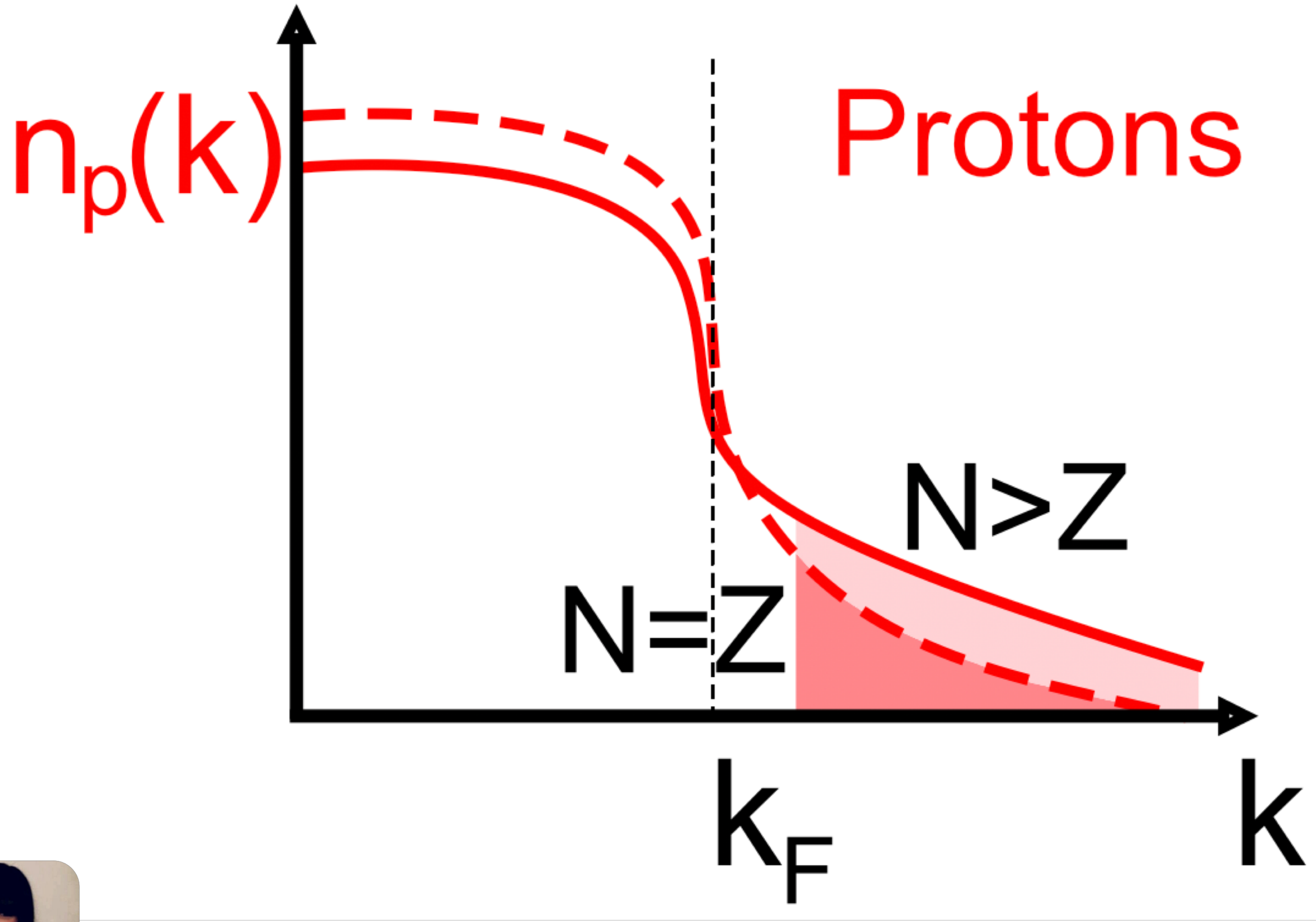
correlate with core protons?

Duer et al.,
Nature (2018)

Correlation Probability:
Neutrons saturate Protons grow



Duer et al.,
Nature (2018)

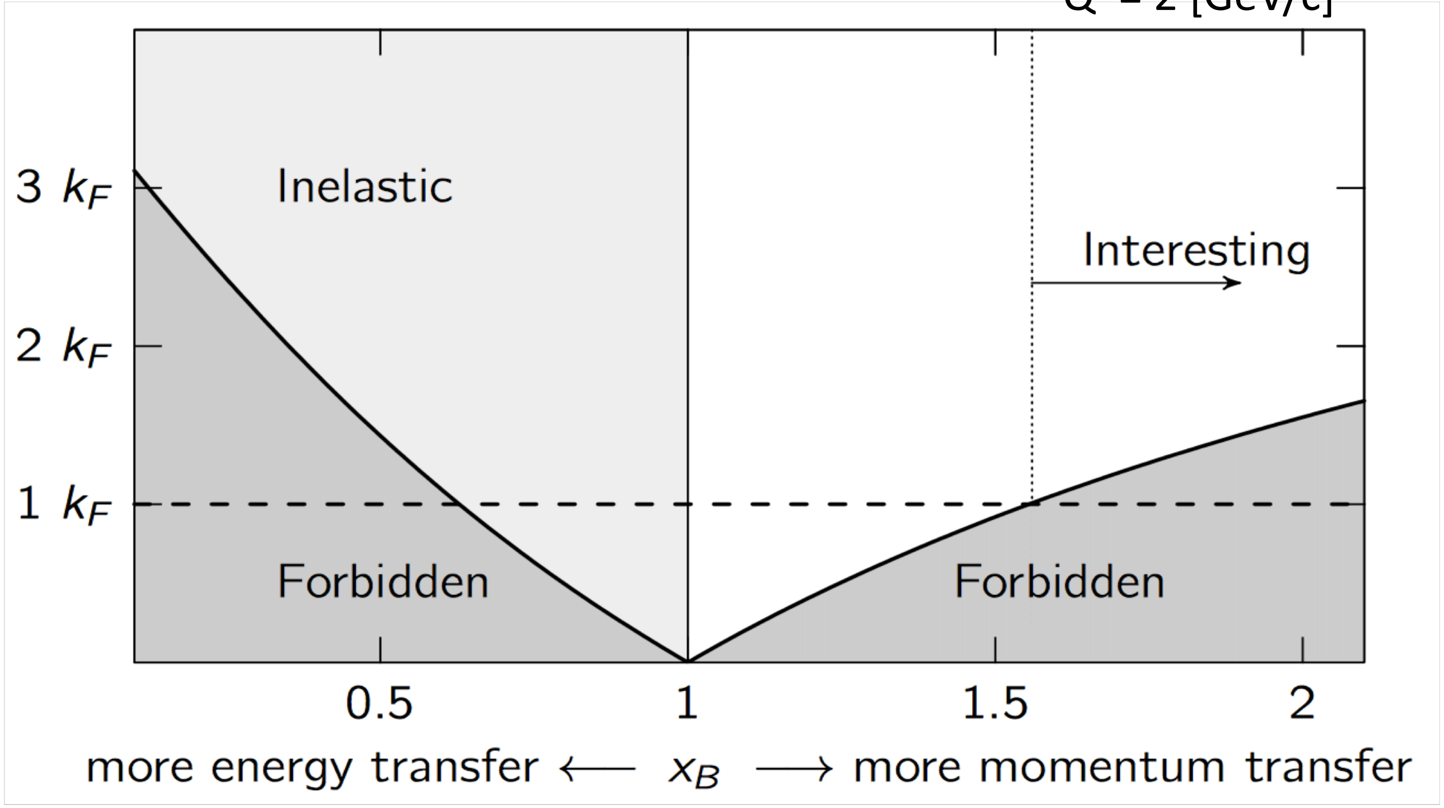


Duer et al.,
Nature (2018)

(e,e'): x_B correlates with initial momenta

Q^2 = 2 [GeV/c]^2

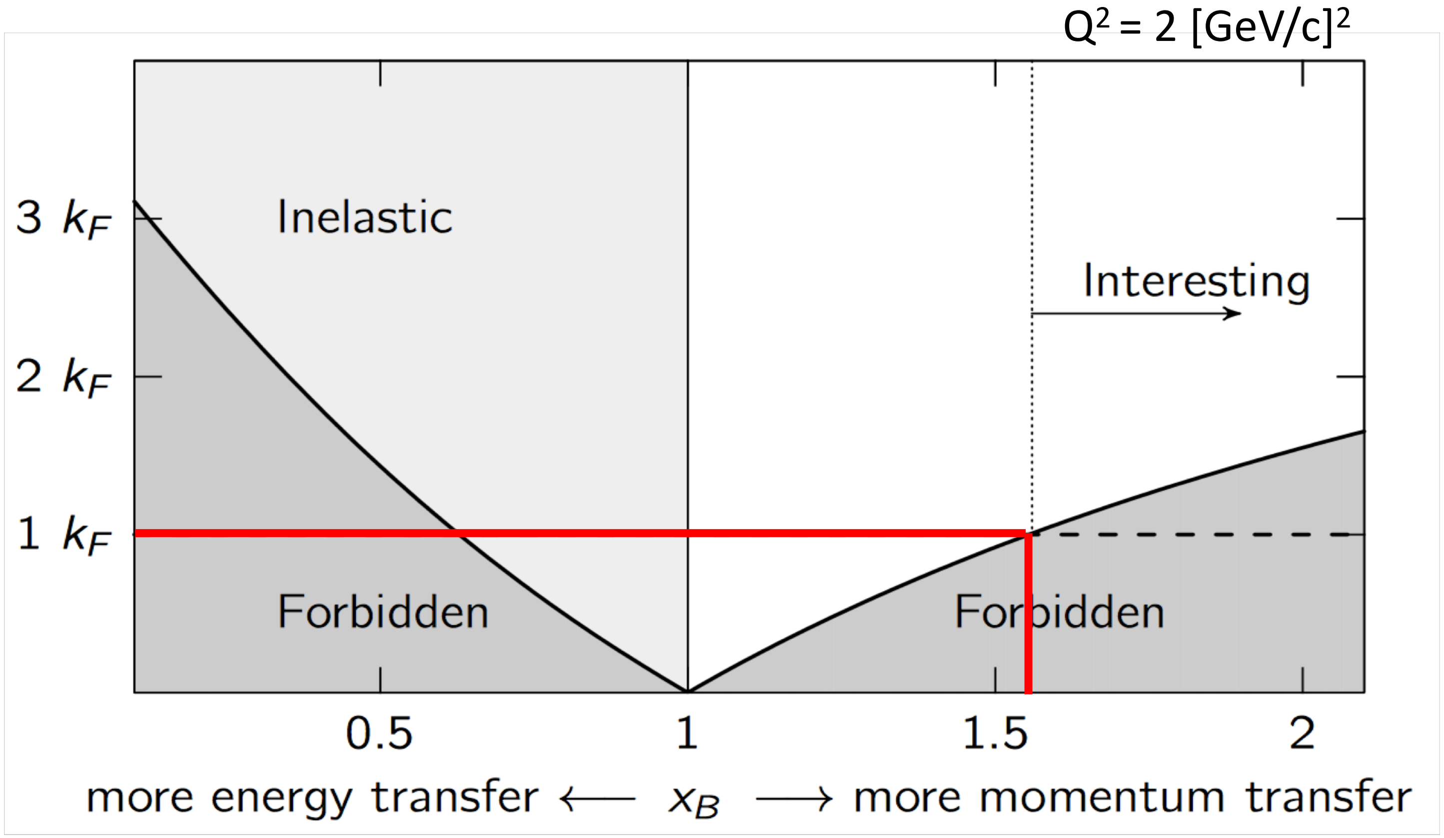
Struck nucleon minimal momentum



$$(q+p_A-p_{A-1})^2=p_f^2=m_N^2$$

High x_B ⇔ High initial momenta

Struck nucleon minimal momentum



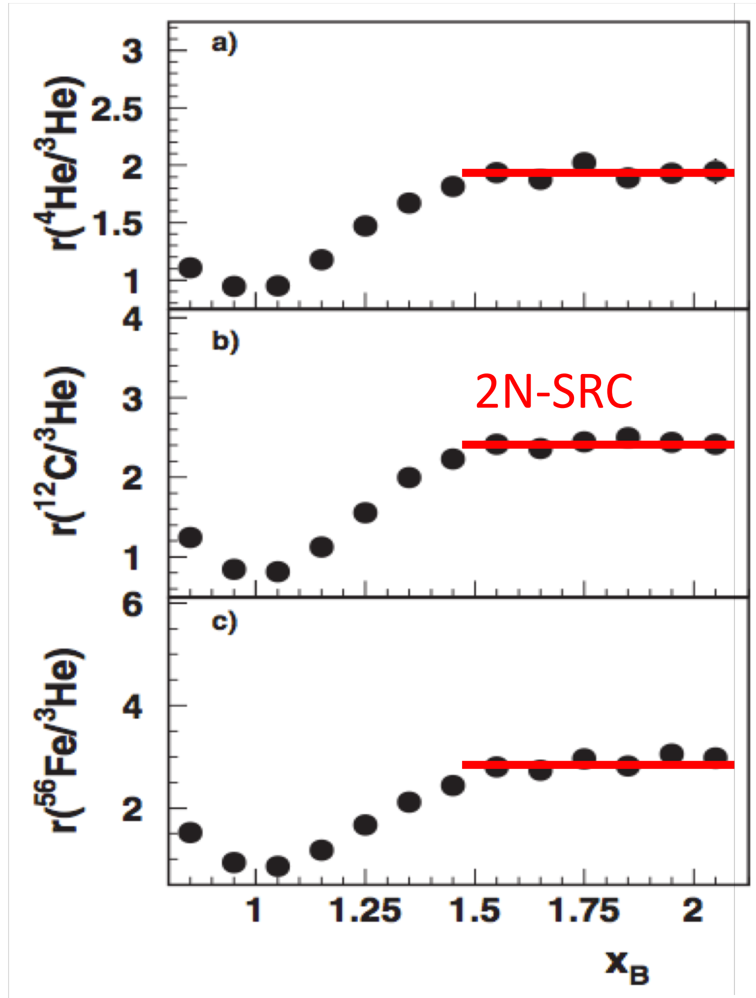
$$(q+p_A-p_{A-1})^2=p_f^2=m_N^2$$

High-Momentum Scaling

- A/d (e,e') cross section ratios sensitive to $n_A(k)/n_d(k)$

- Observed scaling for $x_B \geq 1.5$.

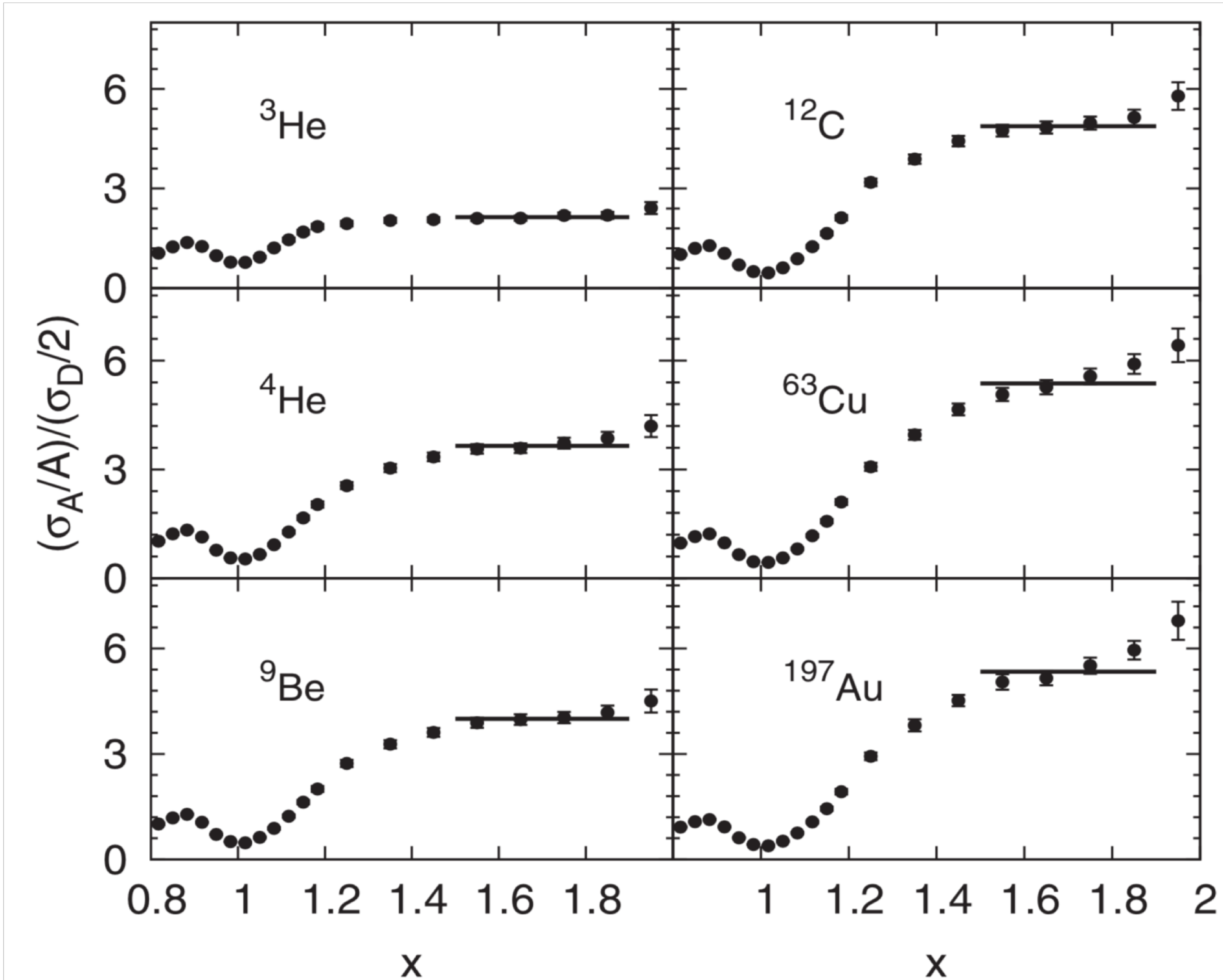
=> $n_A(k>k_F) = a_2(A) \times n_d(k)$



Egiyan et al., PRL (2006)

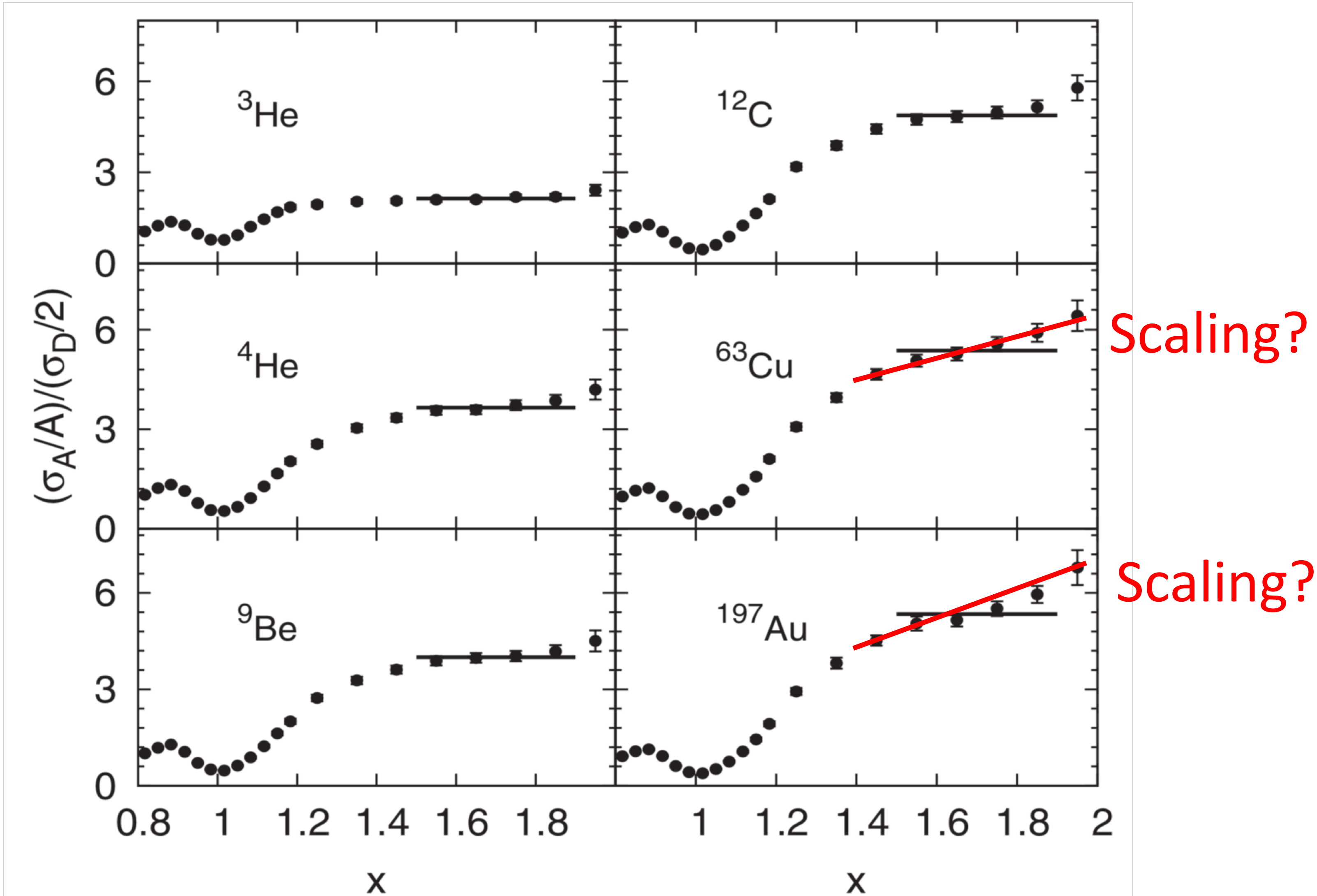
Frankfurt et al., PRC (1993); Egiyan et al., PRC (2003); Fomin et al., PRL (2012).

2012 High-Momentum [almost] Scaling



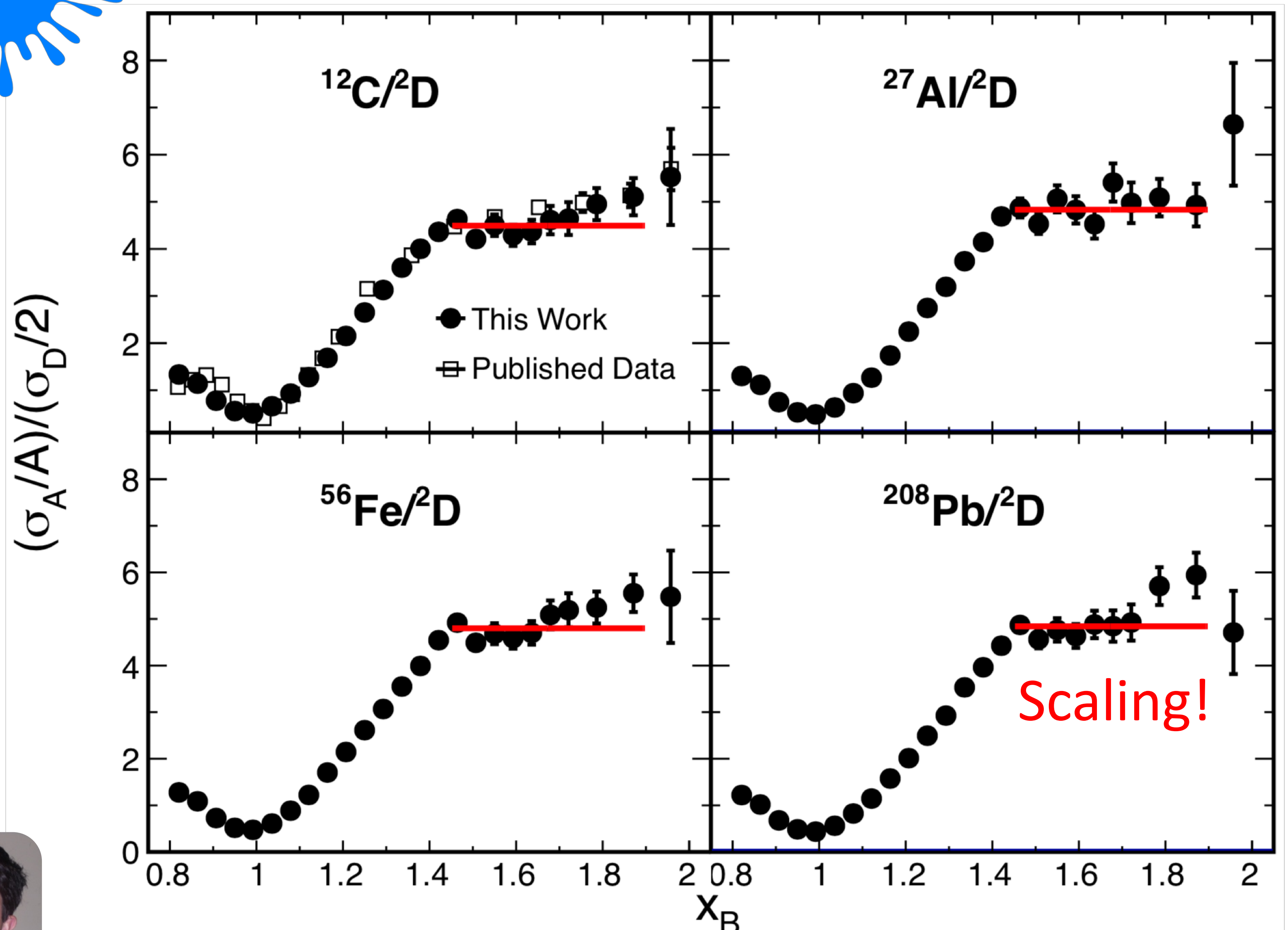
Fomin, PRL (2012)

2012 High-Momentum [almost] Scaling



Fomin, PRL (2012)

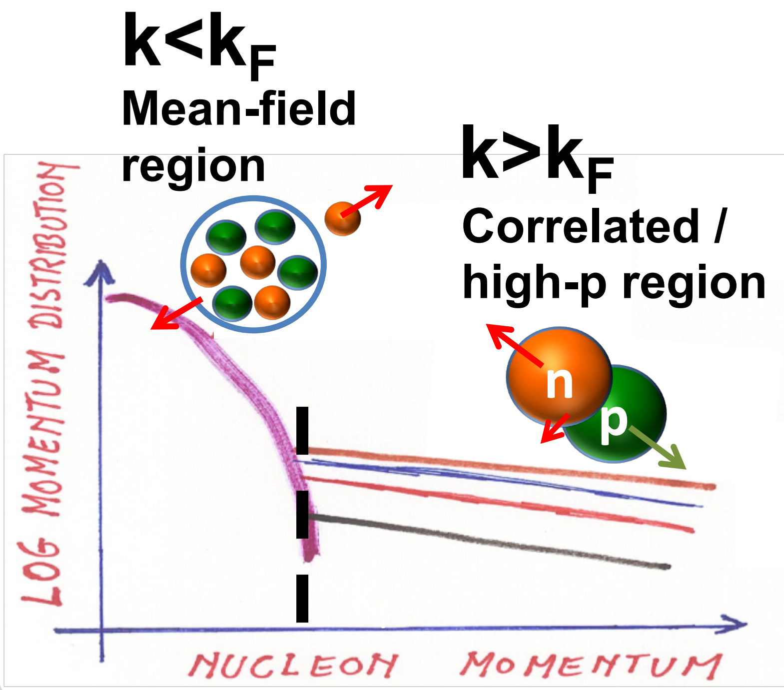
2018 High-Momentum Scaling



Schmookler et al., (2018)

Interm Summary

- Nuclear momentum distribution can be divided into two distinct regions.



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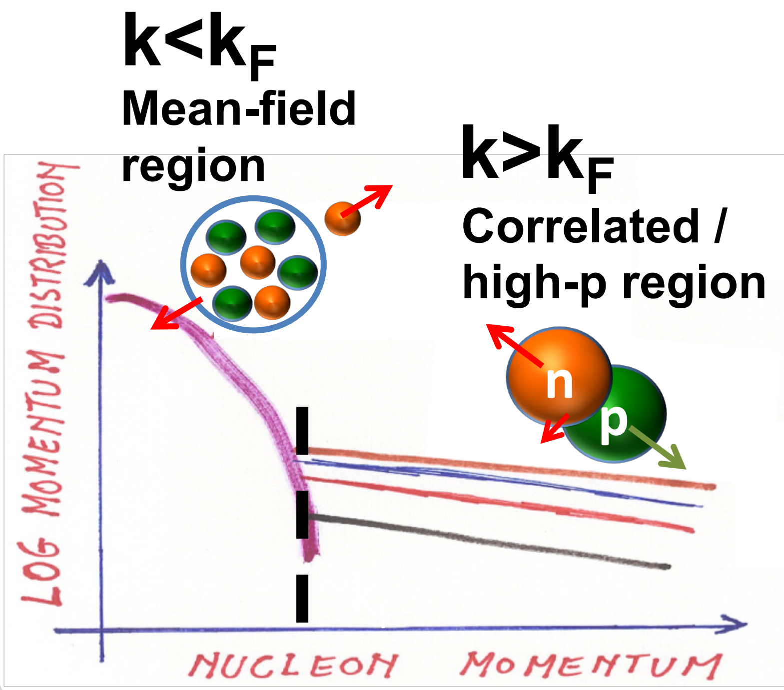
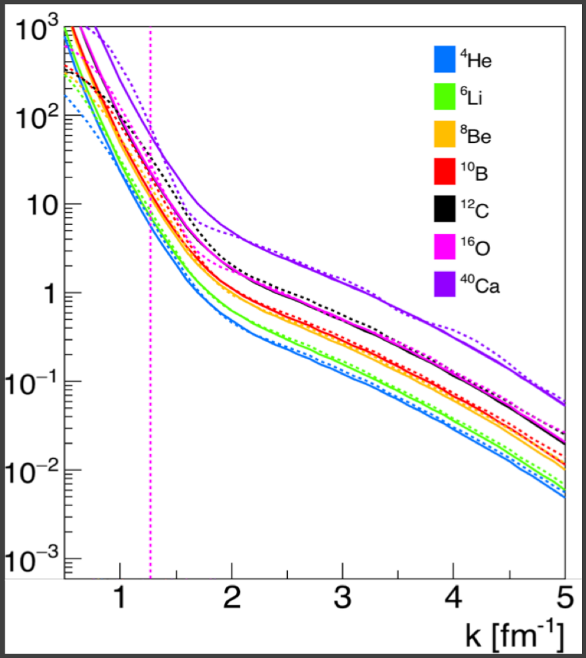
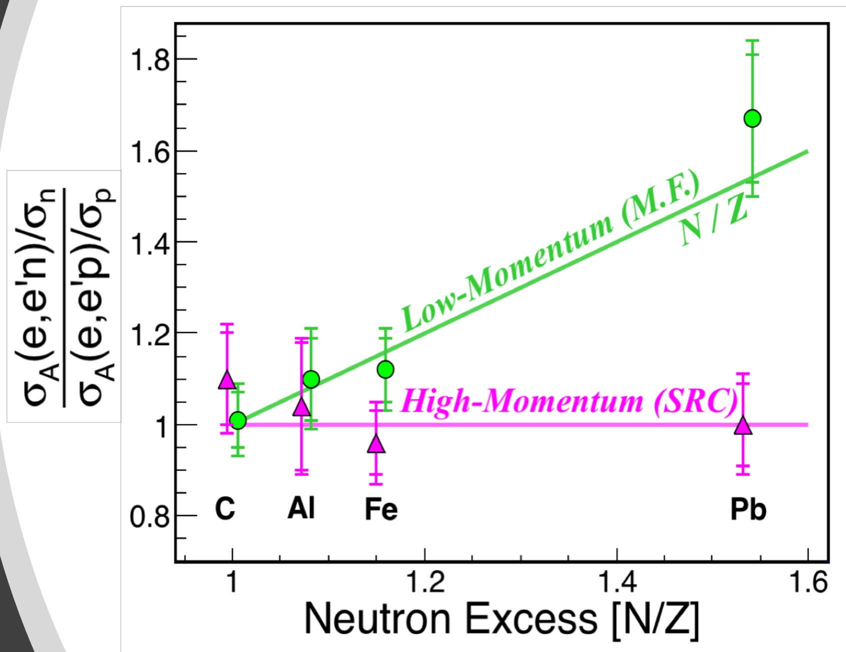




Also seen in calculations (e.g. QMC, Contact, SCGF etc.)

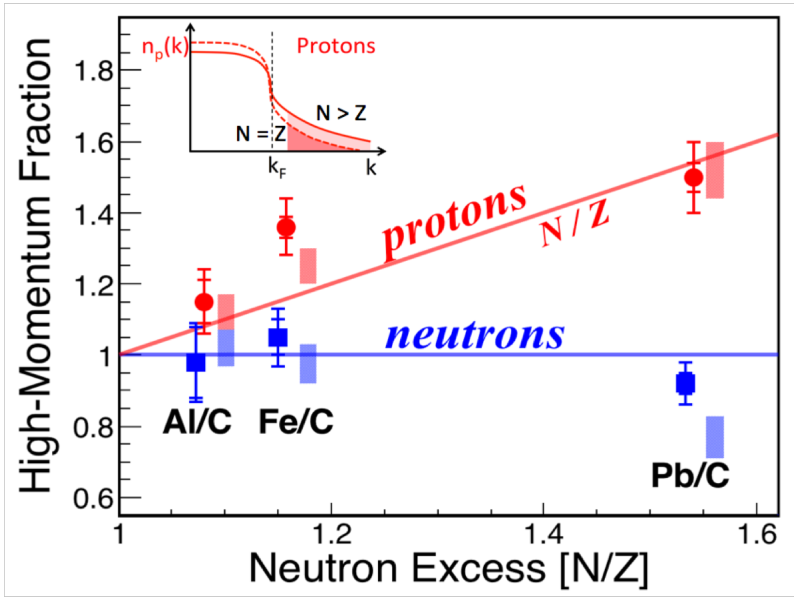
Interm Summary

- Nuclear momentum distribution can be divided into two distinct regions.
- #protons = #neutrons, irrespectively of neutron excess.



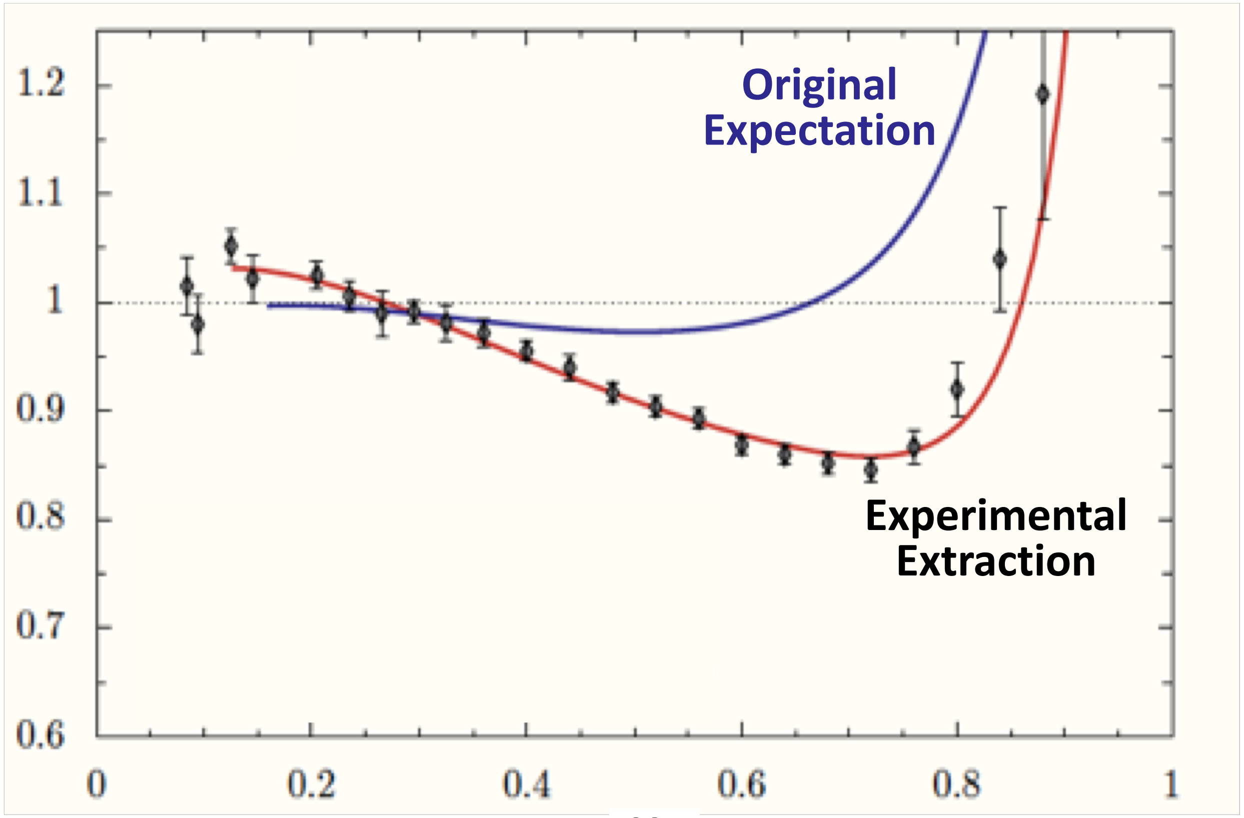
Interm Summary

- Nuclear momentum distribution can be divided into two distinct regions.
- #protons = #neutrons, irrespectively of neutron excess.
- The fraction of correlated
  protons / neutrons
  grow / saturate
  with neutron excess.



Back to the EMC

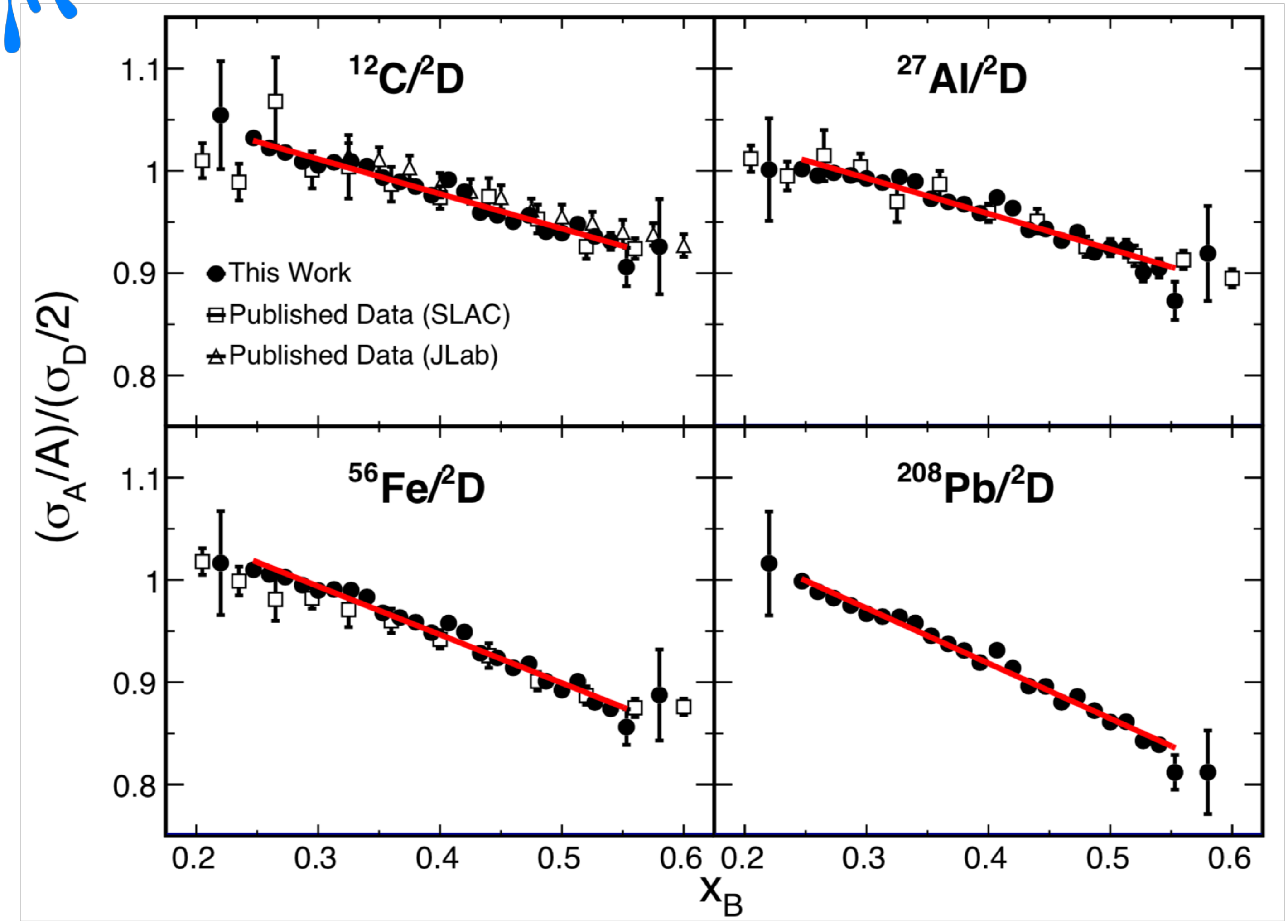
Iron / Deuterium
quark k-distribution



x_B 'quark velocity'

Aubert et al., PLB (1983); Ashman et al., PLB (1988); Arneodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et al., PRD (1994); Seely et al., PRL (2009); Schmookler et al., Submitted (2018)

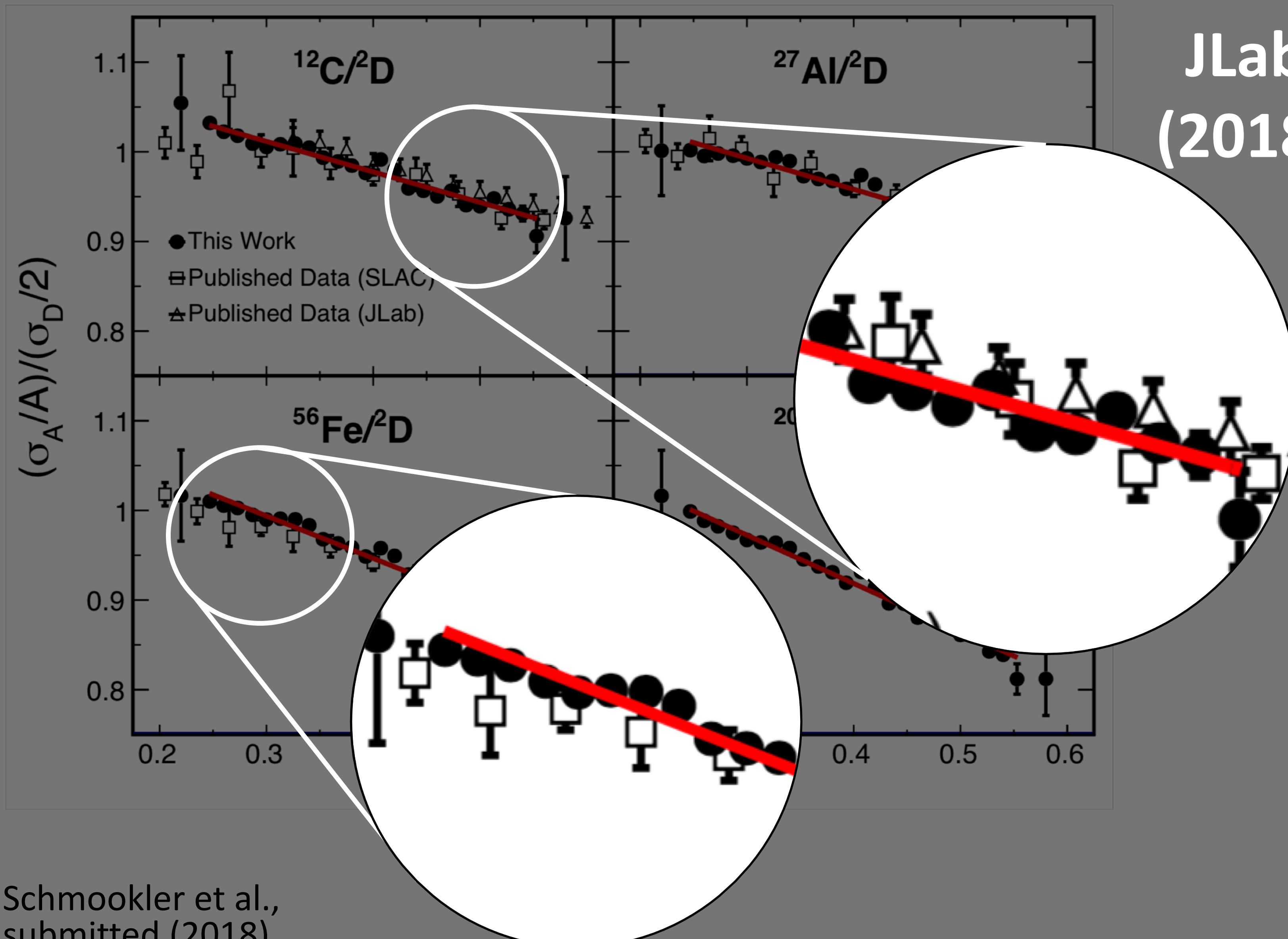
High Precision data!



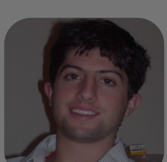
JLab (2018)

Schmookler et al., submitted (2018)

High Precision data!



JLab (2018)



Schmookler et al., submitted (2018)

35 years, 1000 papers, 3 Ideas

1. Proper treatment of 'known' nuclear effects
   [explain some of the effect, up to x≈0.5]
   - Nuclear Binding and Fermi motion, Pions, Coulomb Field.
   - **No modification of bound nucleon structure.**

2. Short-Range Correlations
   - Beyond the mean-field.
   - Momentum dependent.
   - **Dynamical Modification!**

3. Bound Nucleons are 'larger' than free nucleons.
   - Larger confinement volume => slower quarks.
   - Mean-Field effect.
   - Momentum Independent.
   - **Static Modification.**

O. Hen et al., Rev. Mod. Phys. 89, 045002 (2017)

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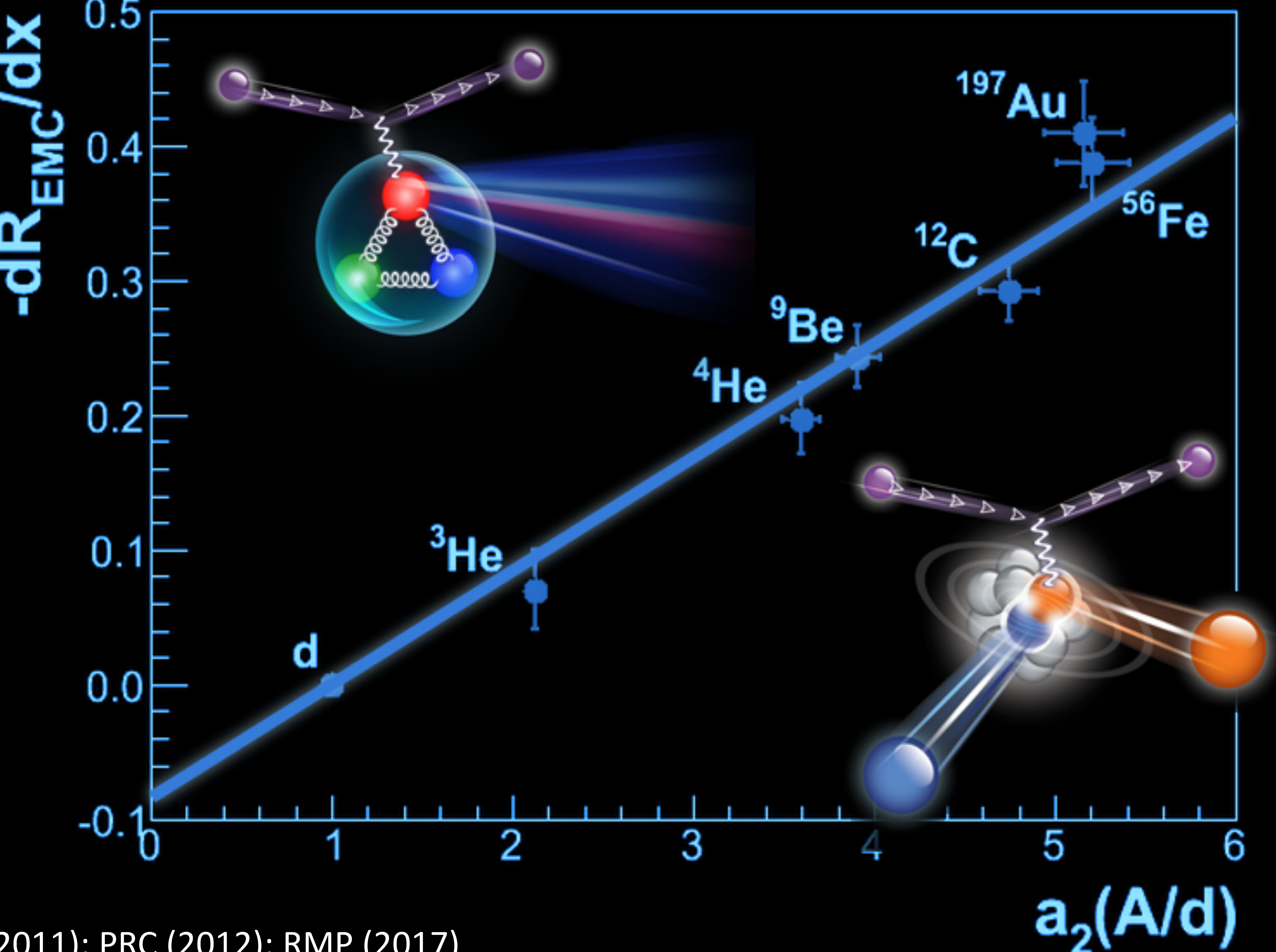
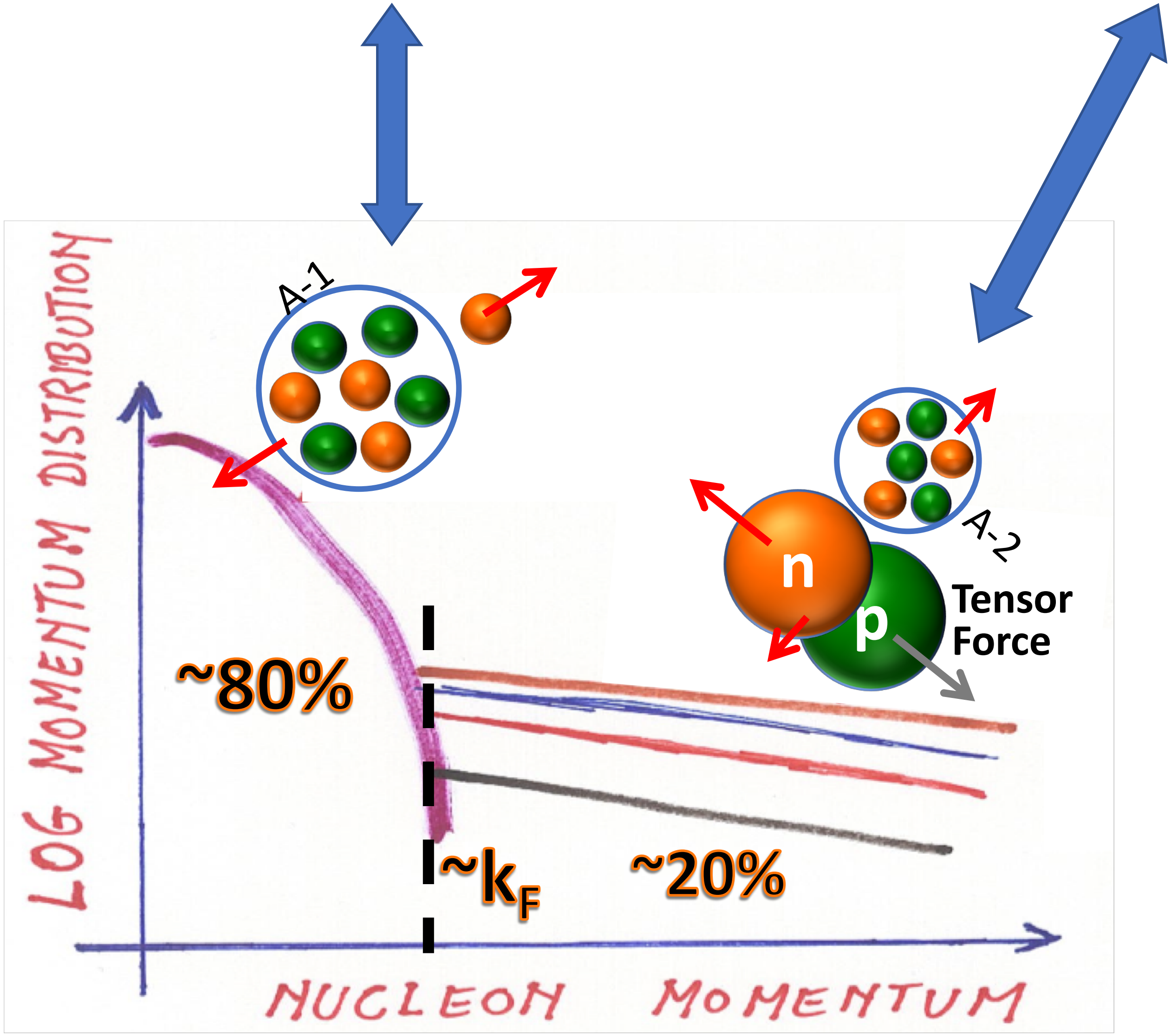
O. Hen et al., Rev. Mod. Phys. 89, 045002 (2017)

EMC – SRC Correlation



PRL (2011); PRC (2012); RMP (2017)

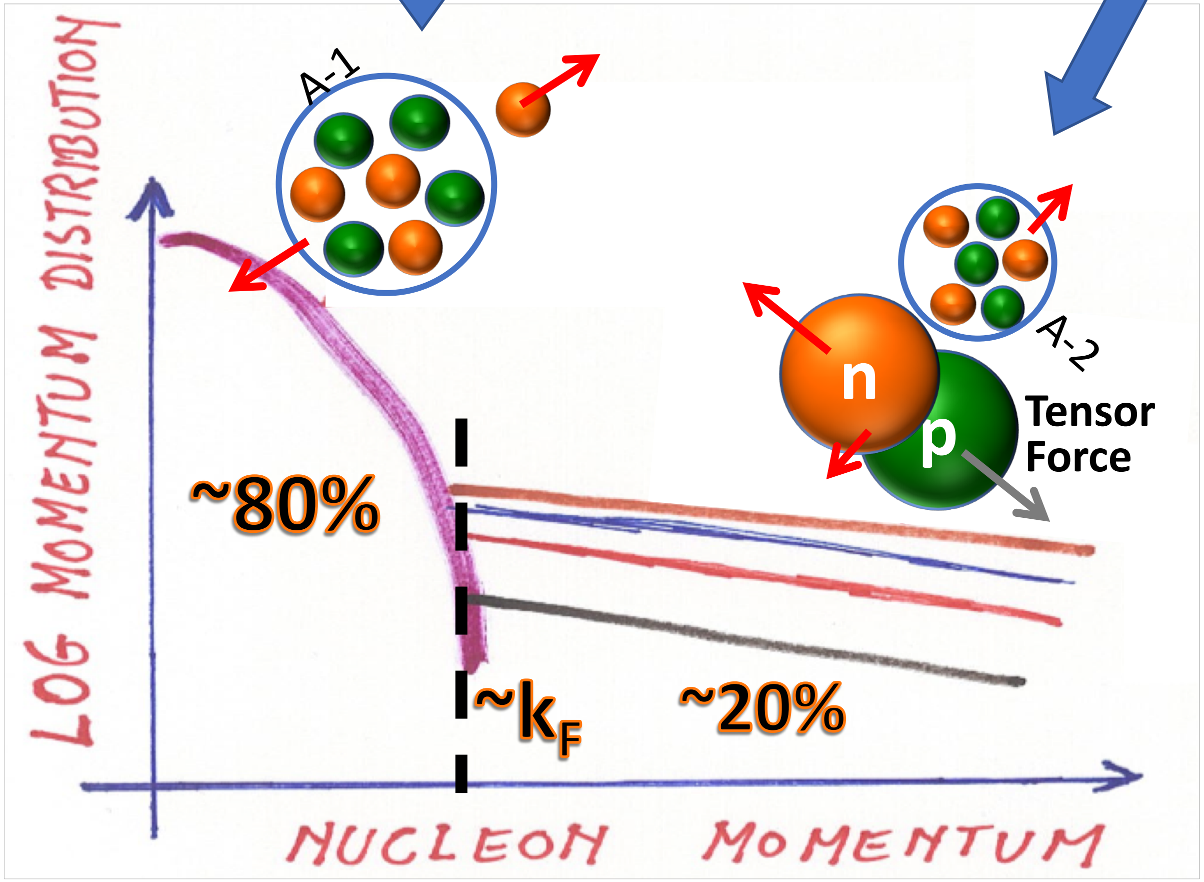
Bound = 'quasi Free' + Modified SRCs



Bound = 'quasi Free' + Modified SRCs

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

$$\Delta F_2^N = F_2^{N*} - F_2^N$$



Bound = 'quasi Free' + Modified SRCs

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

Previously Measured **Universal?**

Bound = 'quasi Free' + Modified SRCs

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

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

Bound = 'quasi Free' + Modified SRCs

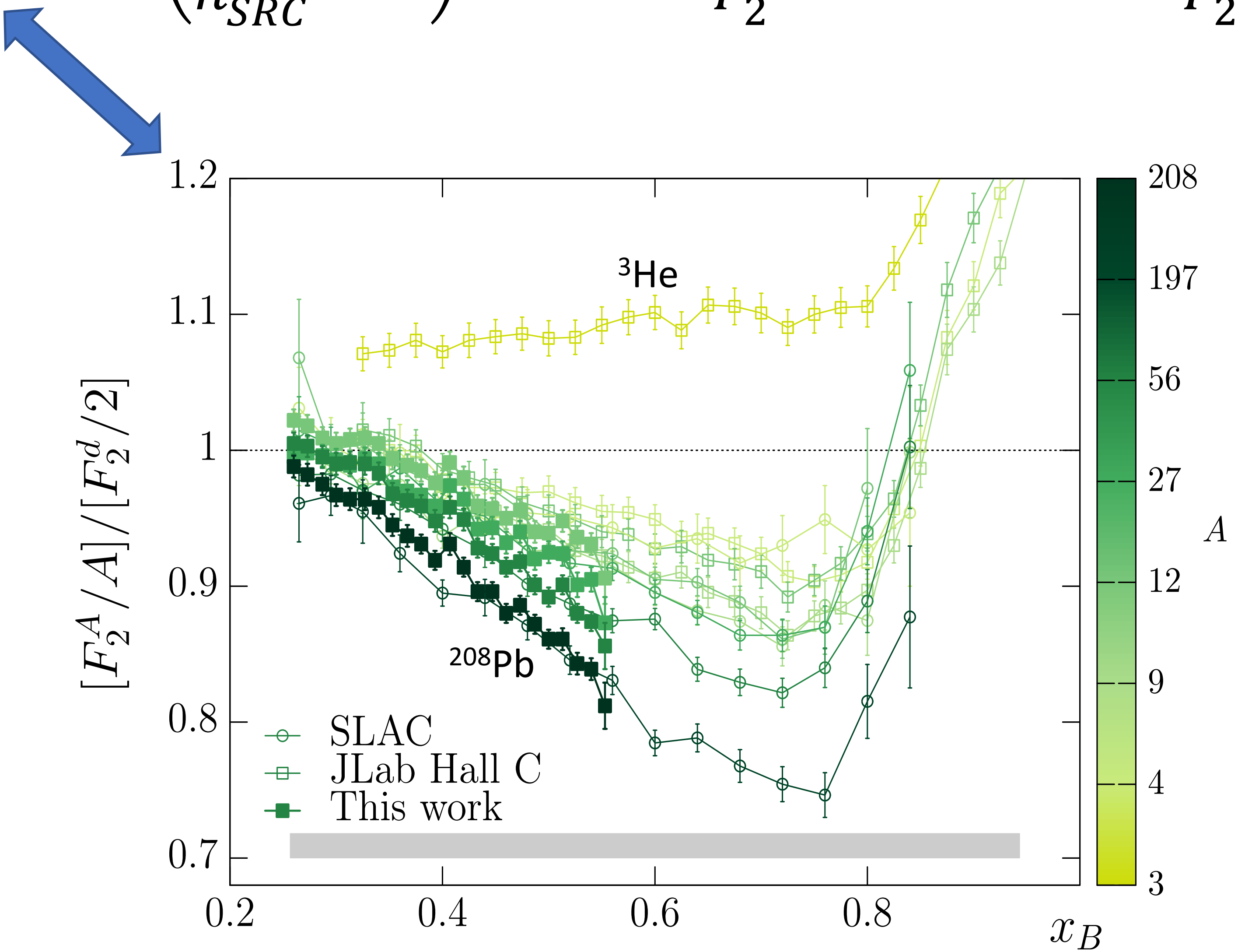
$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A\left(\Delta F_2^p + \Delta F_2^n\right)$$

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

Bound = 'quasi Free' + Modified SRCs

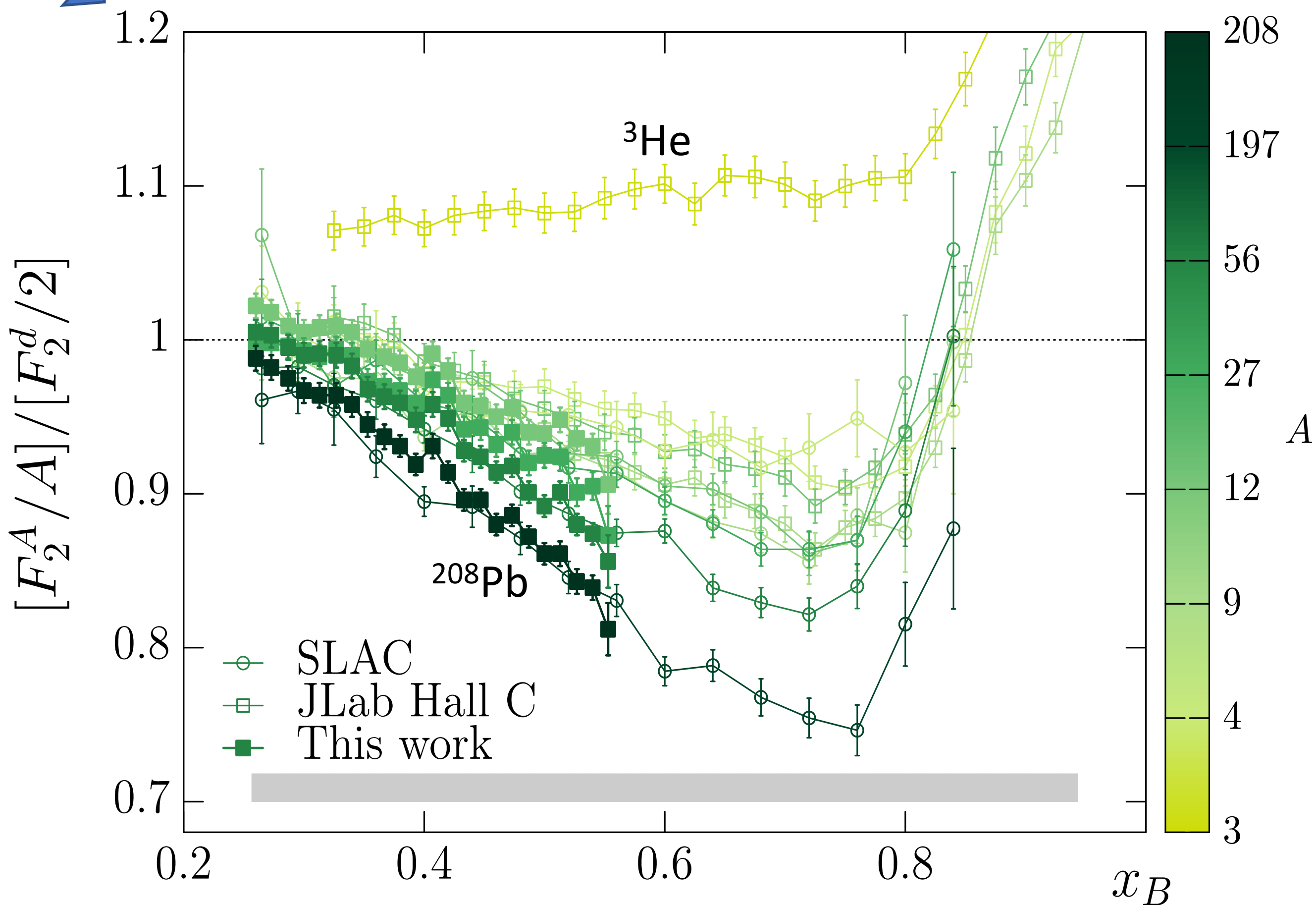
$$\frac{F_2^A}{F_2^d} = \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right) n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} + (Z - N)\frac{F_2^p}{F_2^d} + N$$

$$\frac{F_2^A}{F_2^d} = \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right) n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} + (Z - N)\frac{F_2^p}{F_2^d} + N$$



SRC Scaling | **Universal(?) Mod.** | **Isospin Term**

$$\frac{F_2^A}{F_2^d} = \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right) n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} + (Z-N)\frac{F_2^p}{F_2^d} + N$$



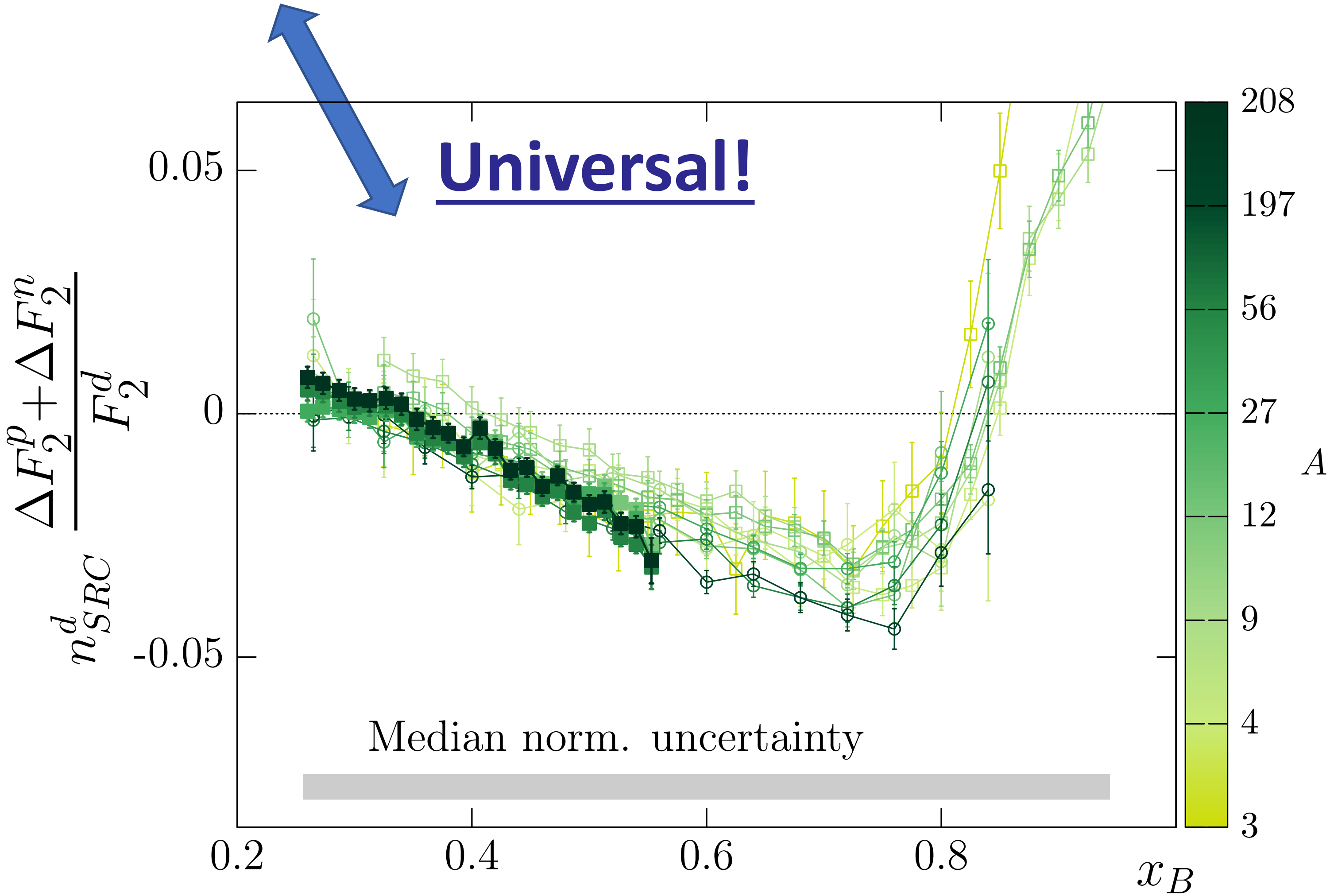
$$\frac{F_2^A}{F_2^d} = \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right) n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} + (Z - N)\frac{F_2^p}{F_2^d} + N$$

$$n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} = \left(\frac{F_2^A}{F_2^d} - (Z - N)\frac{F_2^p}{F_2^d} - N\right) \Big/ \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right)$$

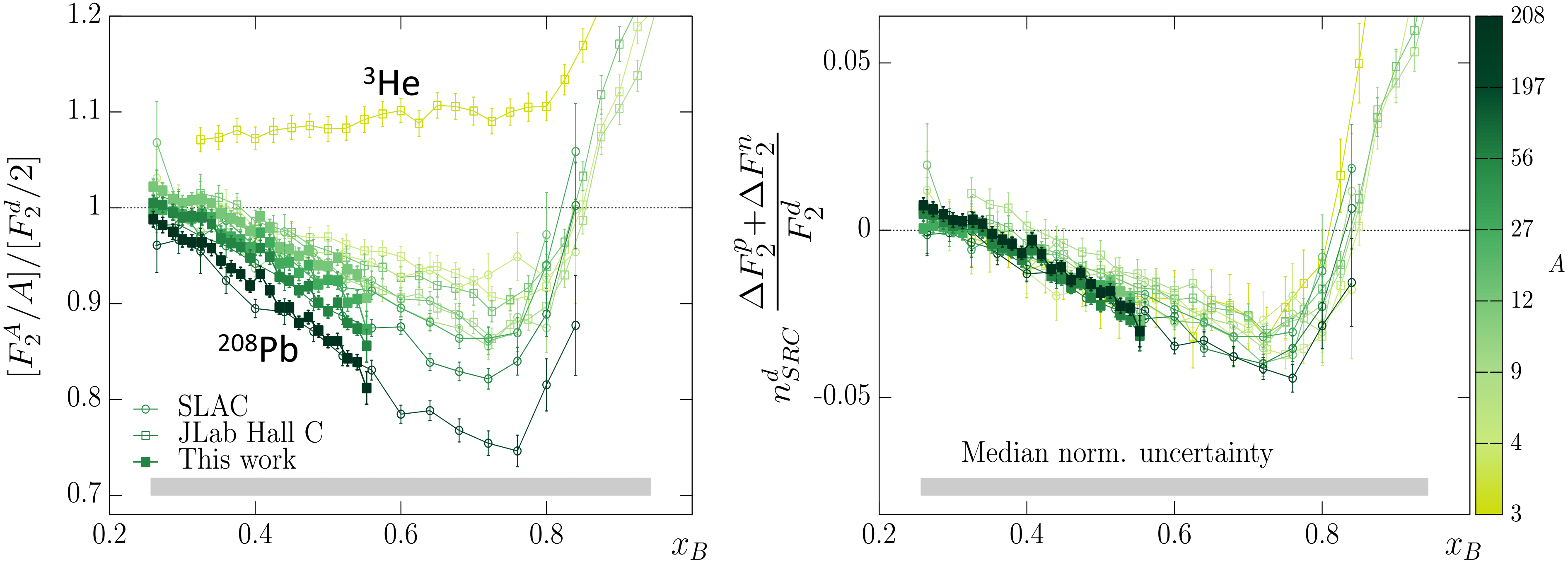
Universal?

Previously Measured A-Dependent terms

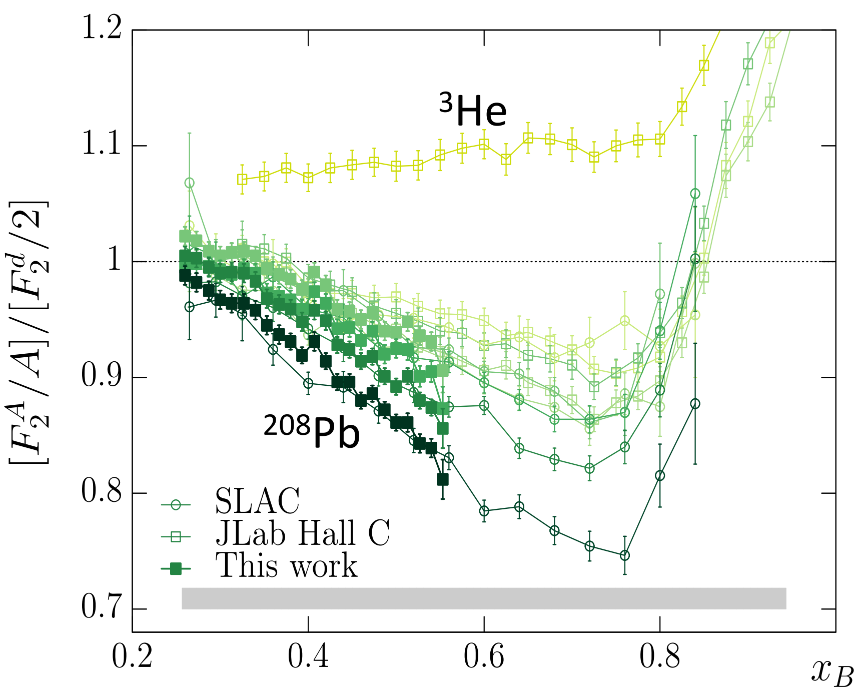
$$n_{SRC}^{d}\frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} = \left(\frac{F_2^A}{F_2^d} - (Z-N)\frac{F_2^p}{F_2^d} - N\right) \Big/ \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right)$$

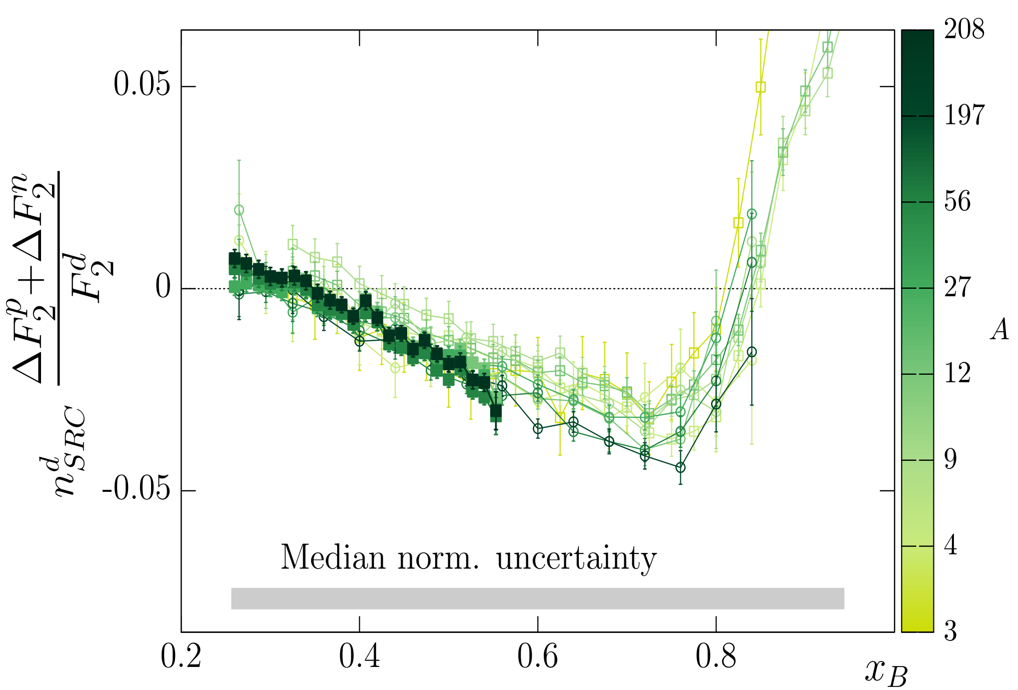



ONE
RING
Function
TO
RULE
THEM
ALL

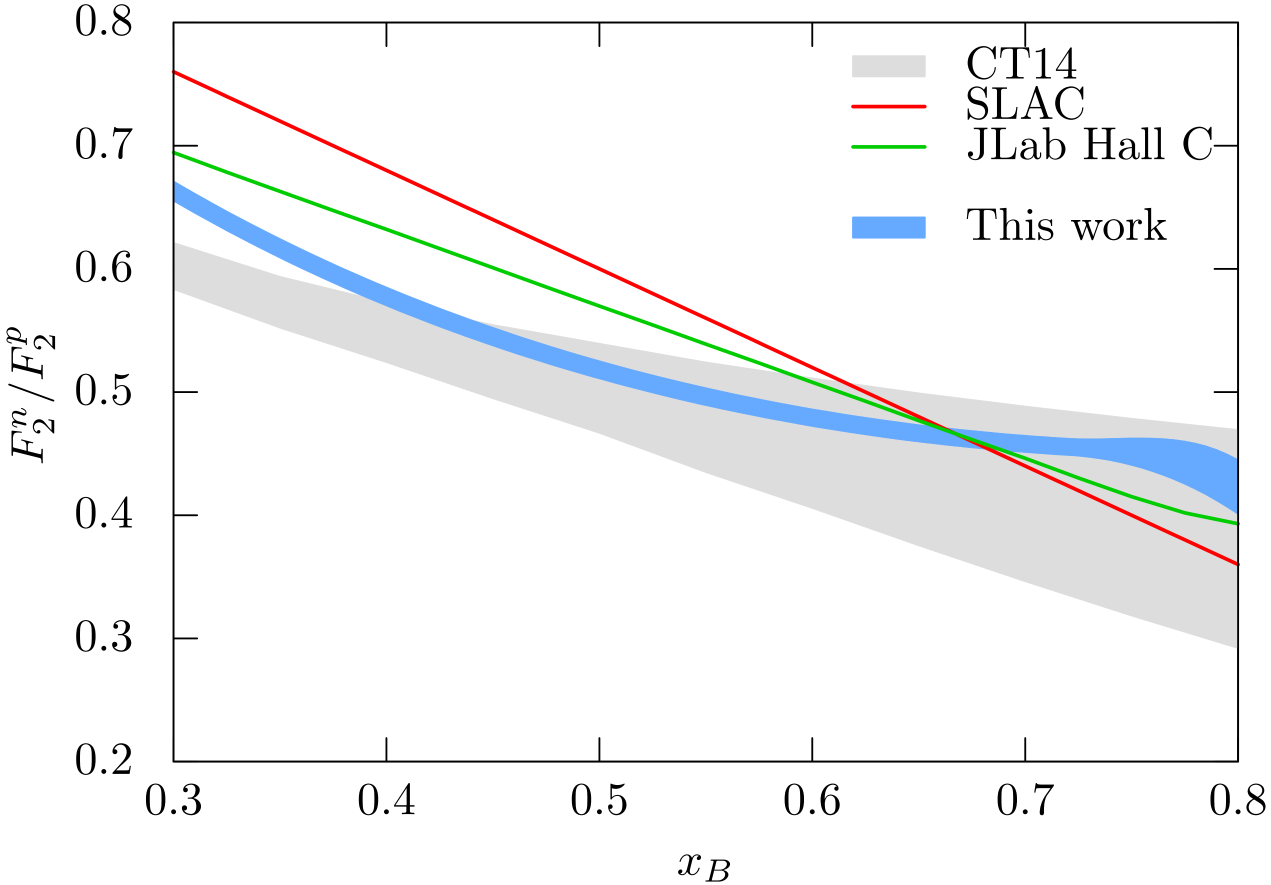

^{3}He
^{208}Pb
SLAC
JLab Hall C
This work
$[F_2^A/A]/[F_2^d/2]$
x_B
$n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}$
Median norm. uncertainty
A

- EMC can be explained by a universal modification of SRC nucleons.
- Universality seems to hold also for x > 0.7 (Fermi-motion ~ <T>)



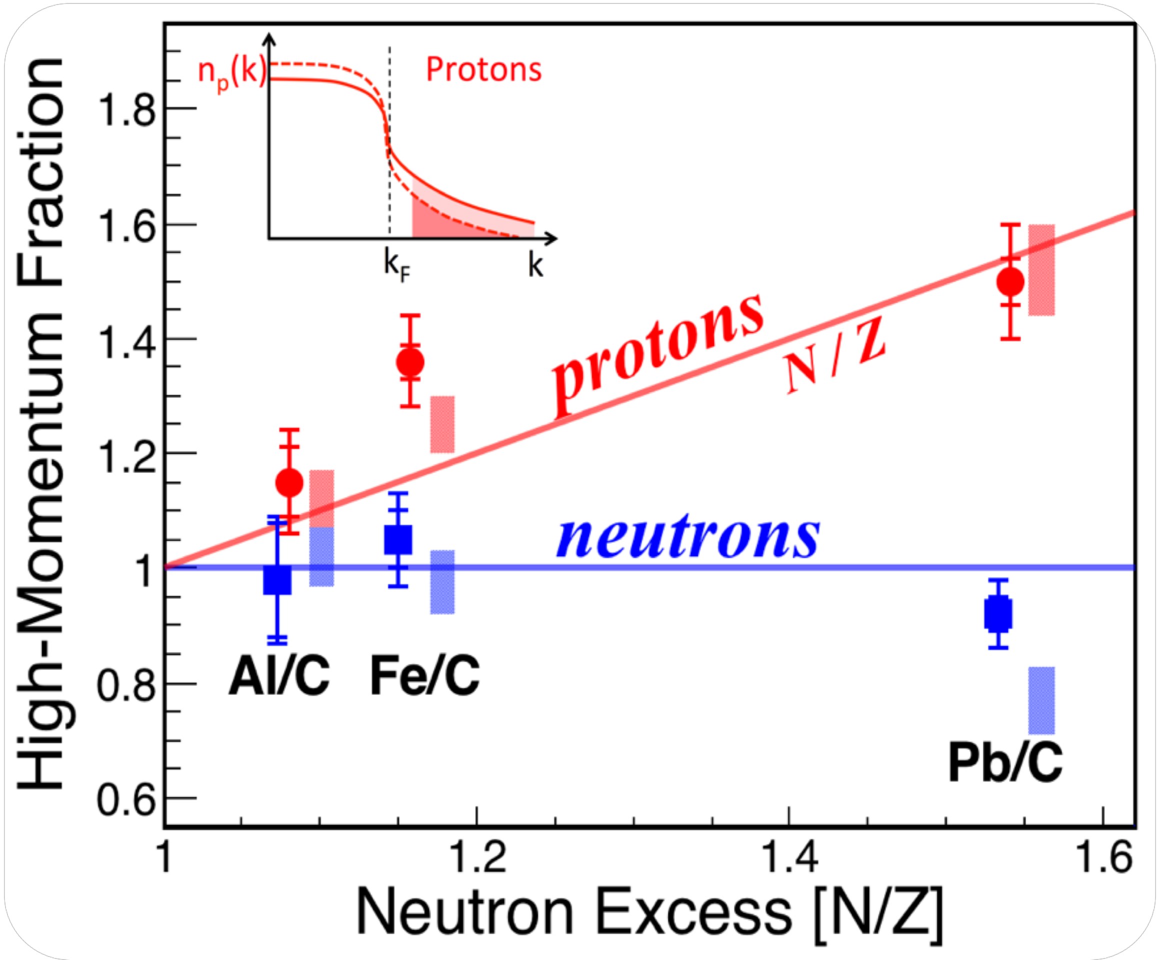


Free neutron extraction

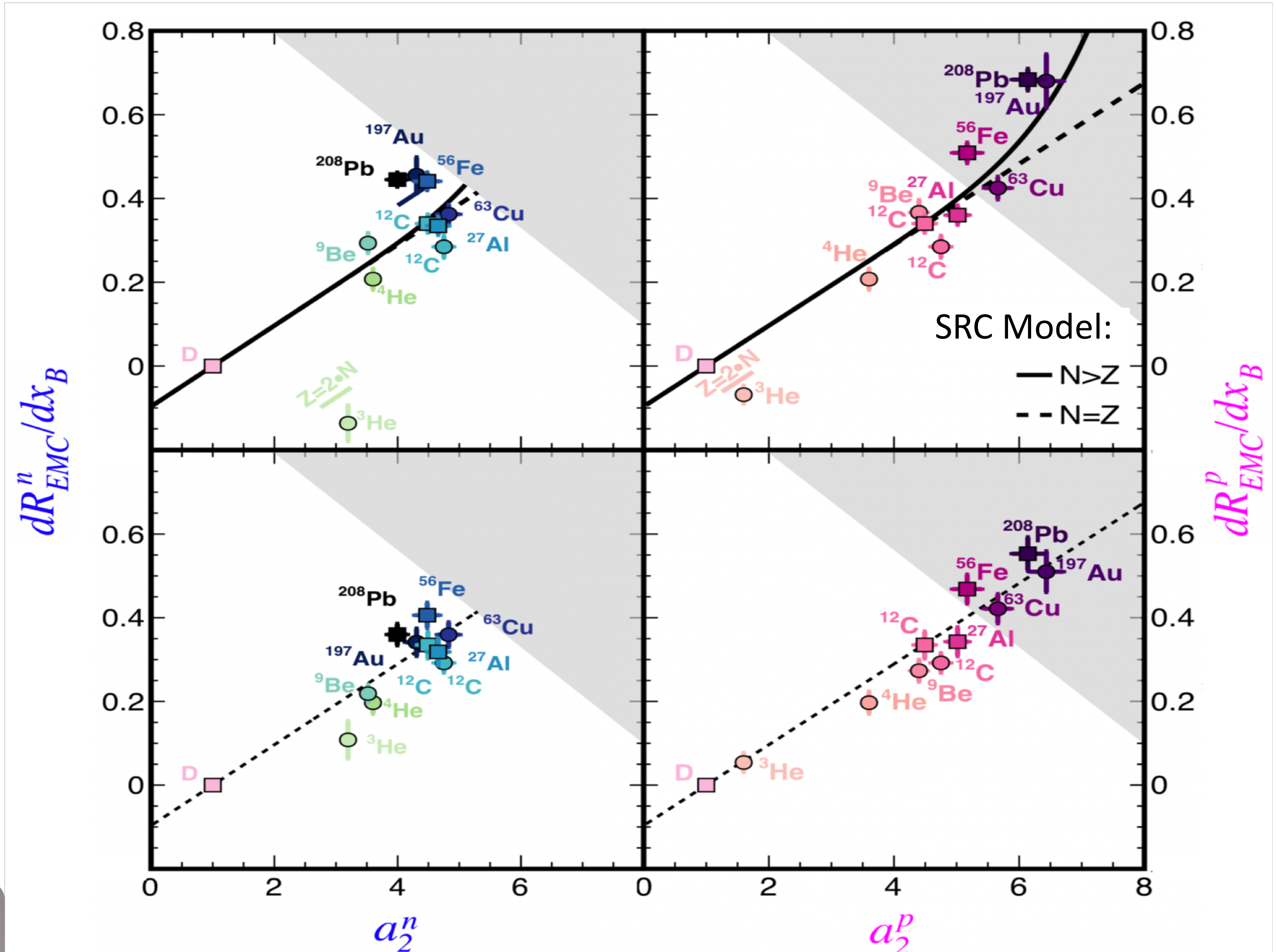


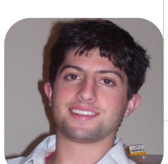
Back to QE

'Prediction':
EMC effect should saturate for neutrons and grow for protons



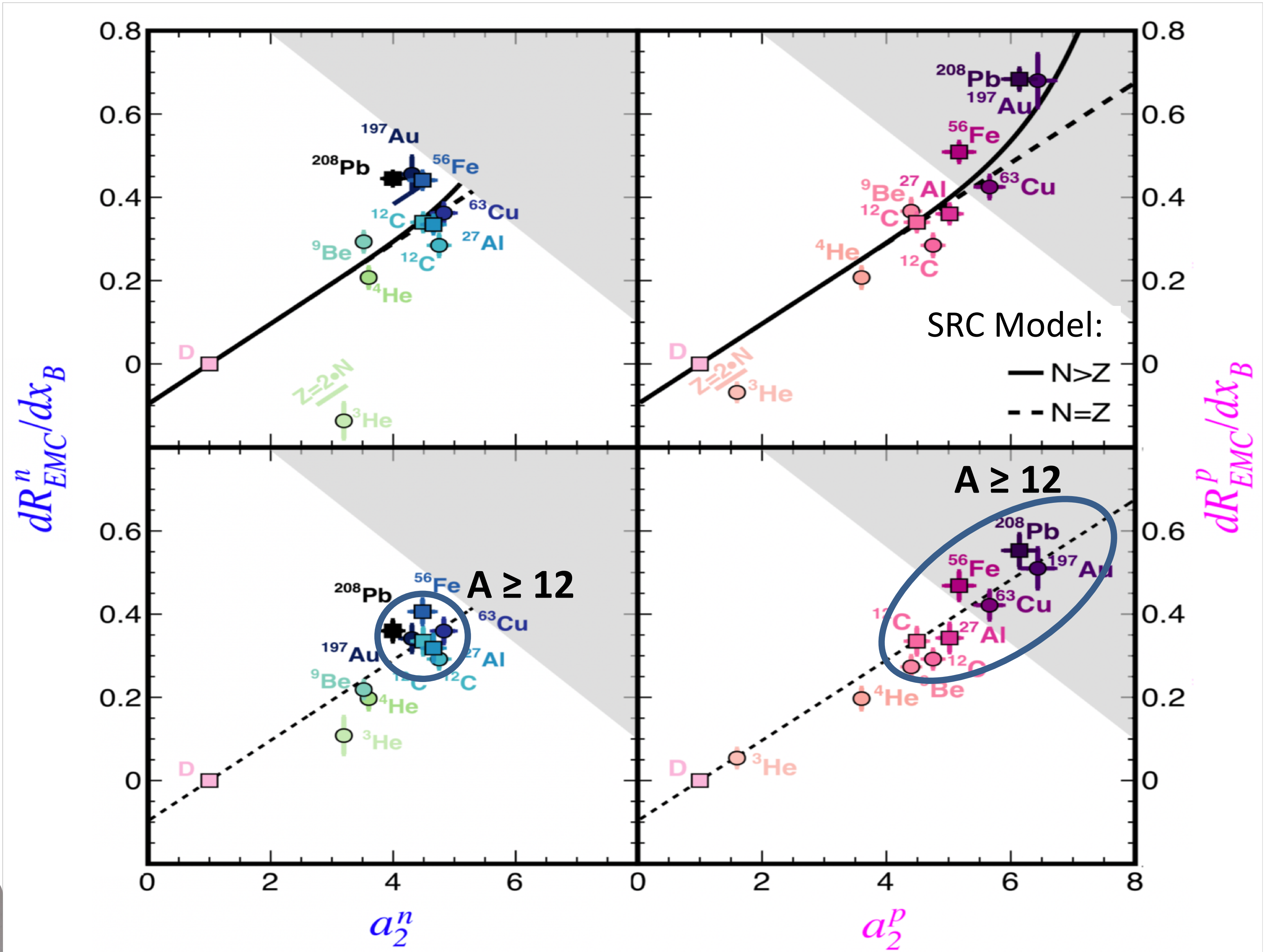
Neutrons Saturate; Protons Grow

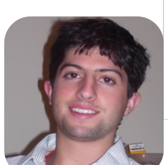




Schmookler et al., (2018)

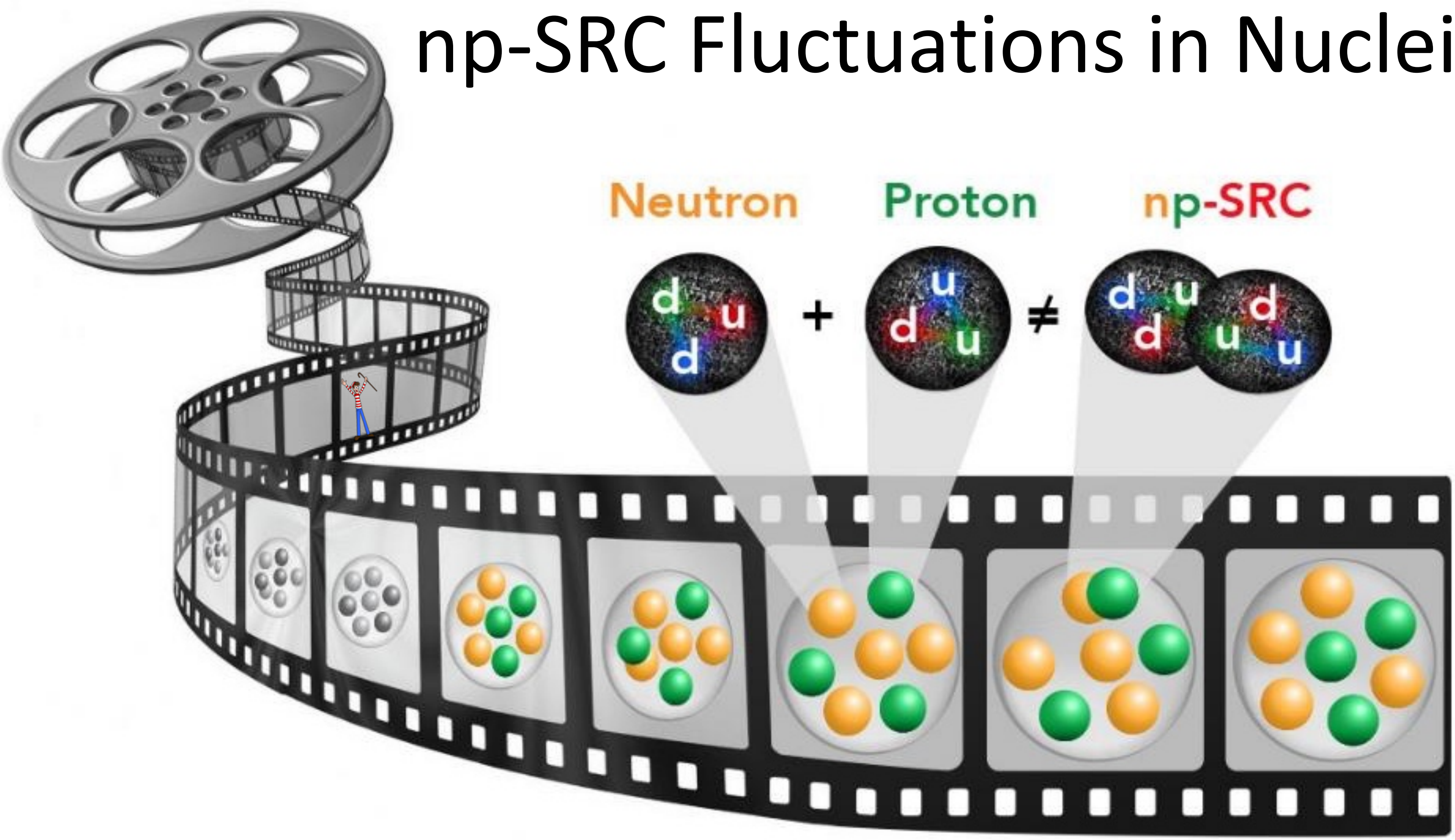
N/Z dependence of nuclear PDFs!



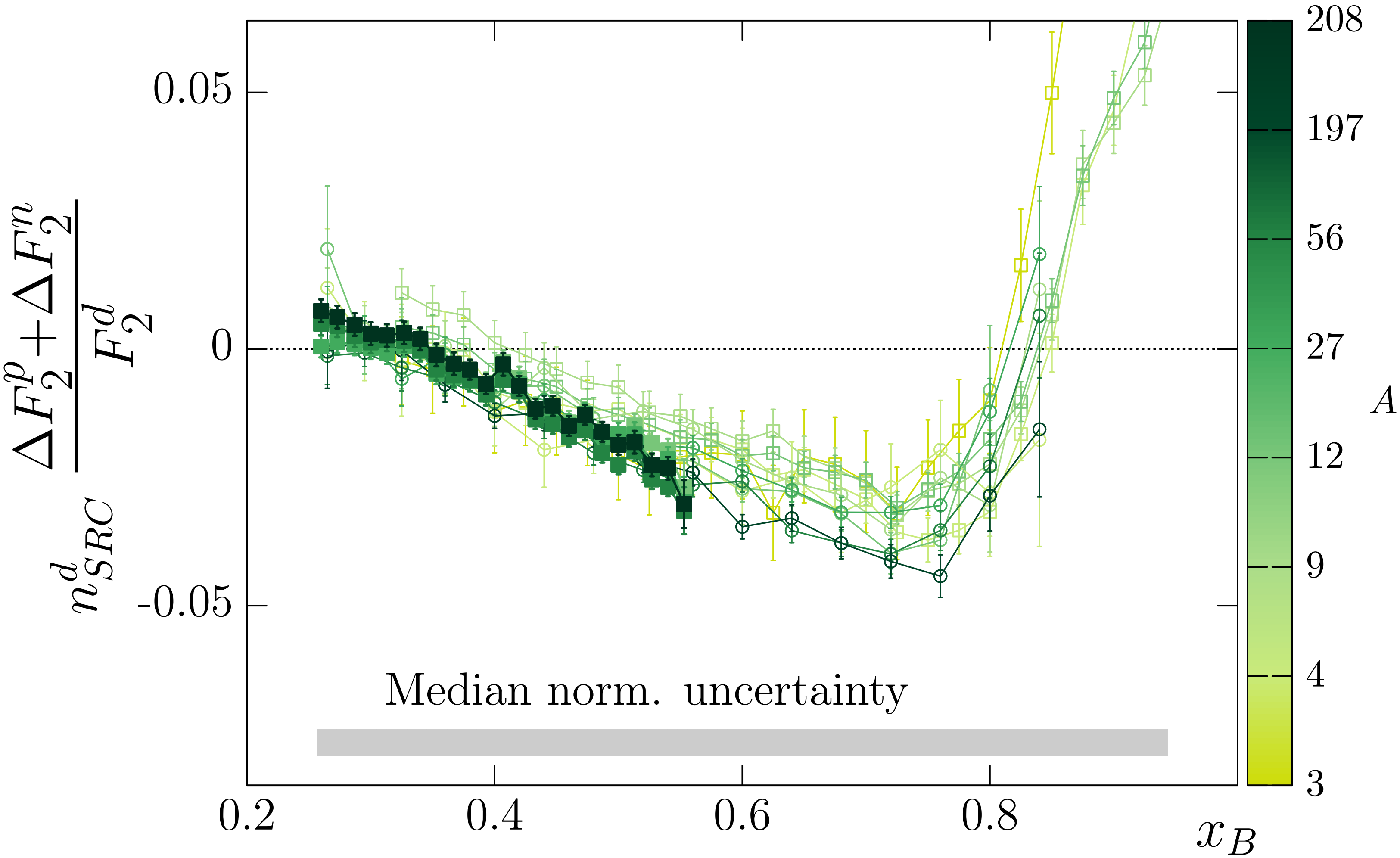


Schmookler et al., (2018)

np-SRC Fluctuations in Nuclei



Universal Modification Tests



Jefferson Lab

2018: Few Body

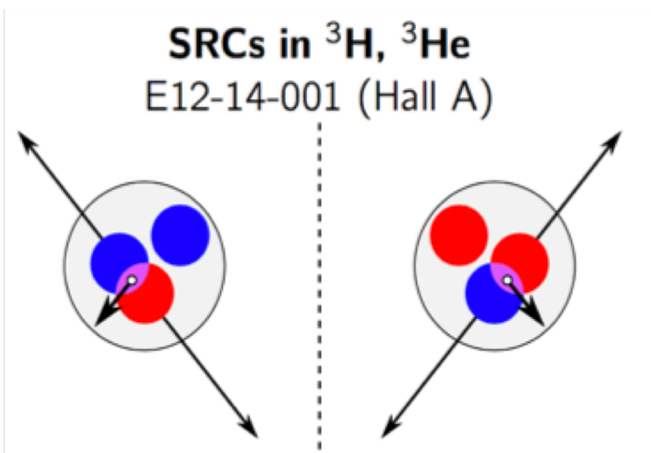
Probing np interactions:

Mirror nuclei: $^{3}He - {}^{3}H$

Proton addition: $d - {}^{3}He$

Neutron addition: $d - {}^{3}H$

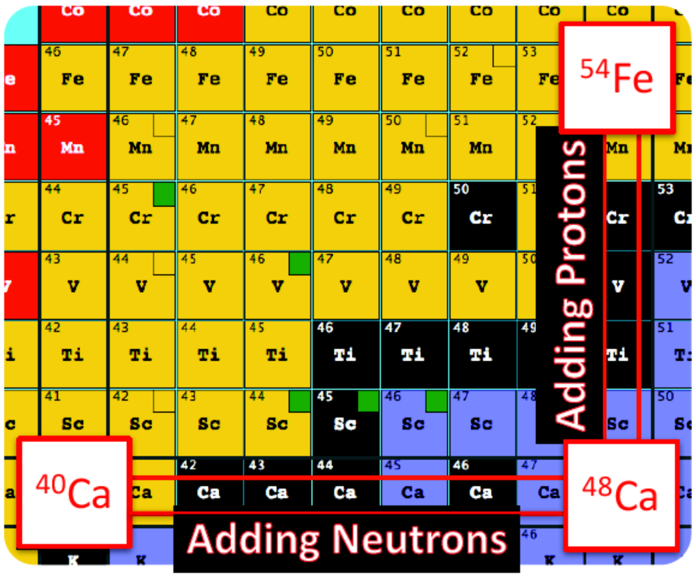
$^{3}He - {}^{4}He$



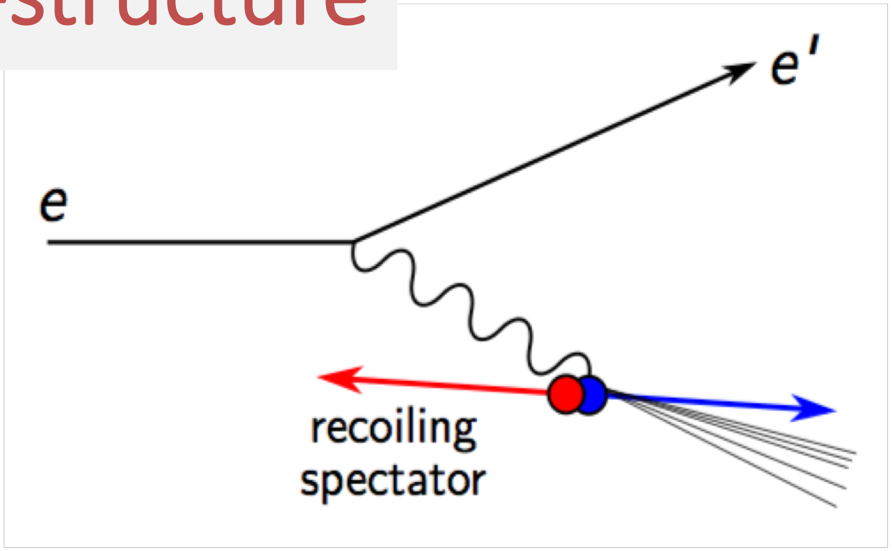
2019: Asymmetric Nuclei

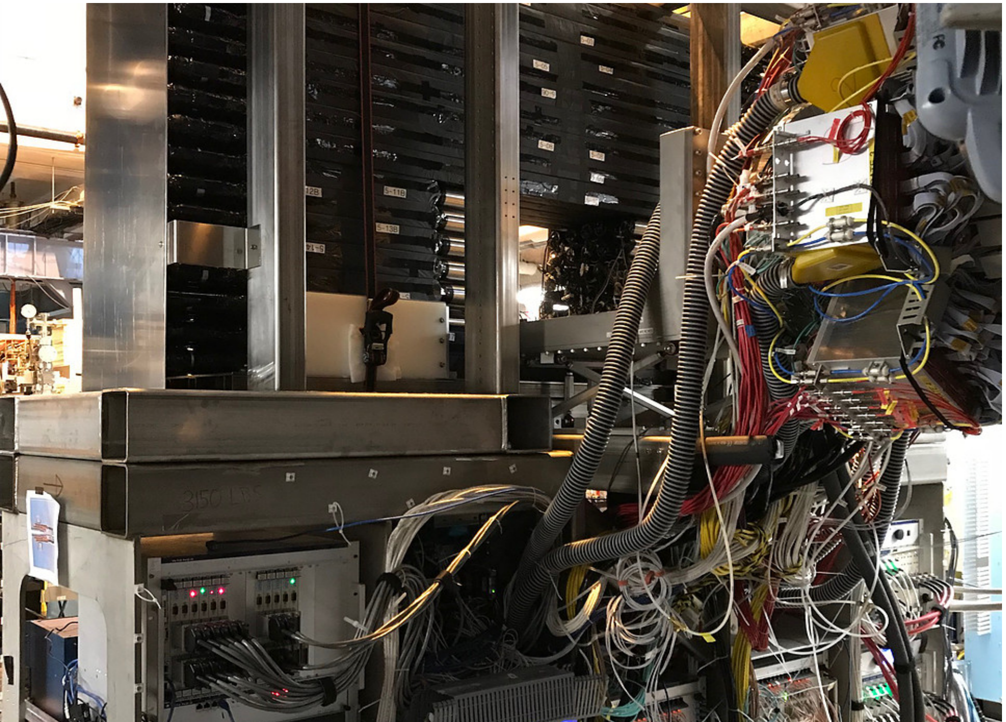
Probing many-body dynamics:

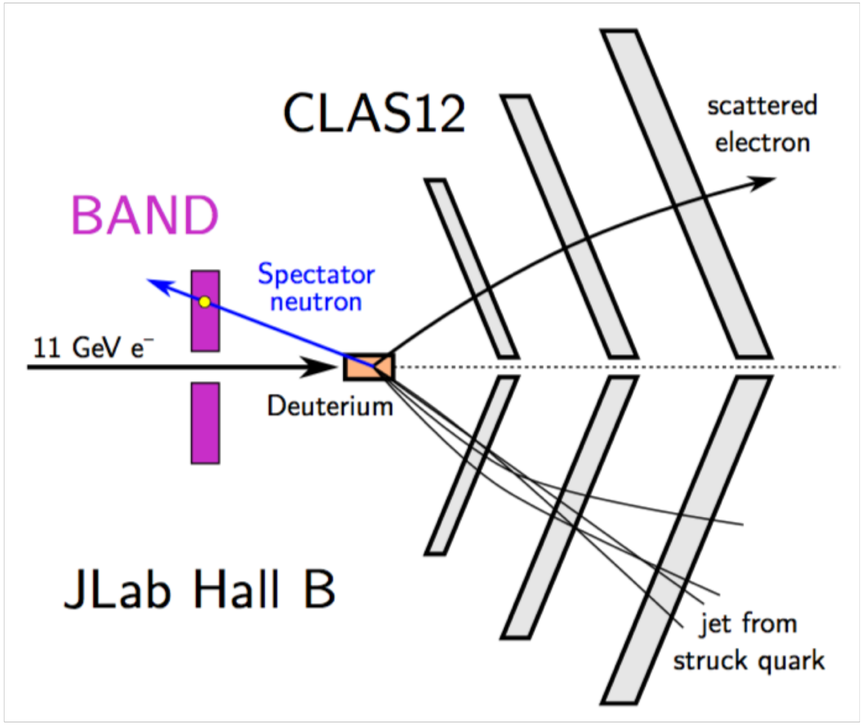
- $^{40}Ca \rightarrow {}^{48}Ca \rightarrow {}^{54}Fe$
- Paring from different orbitals
- Disentangle asymmetry and mass number dependence



SRC parton-structure

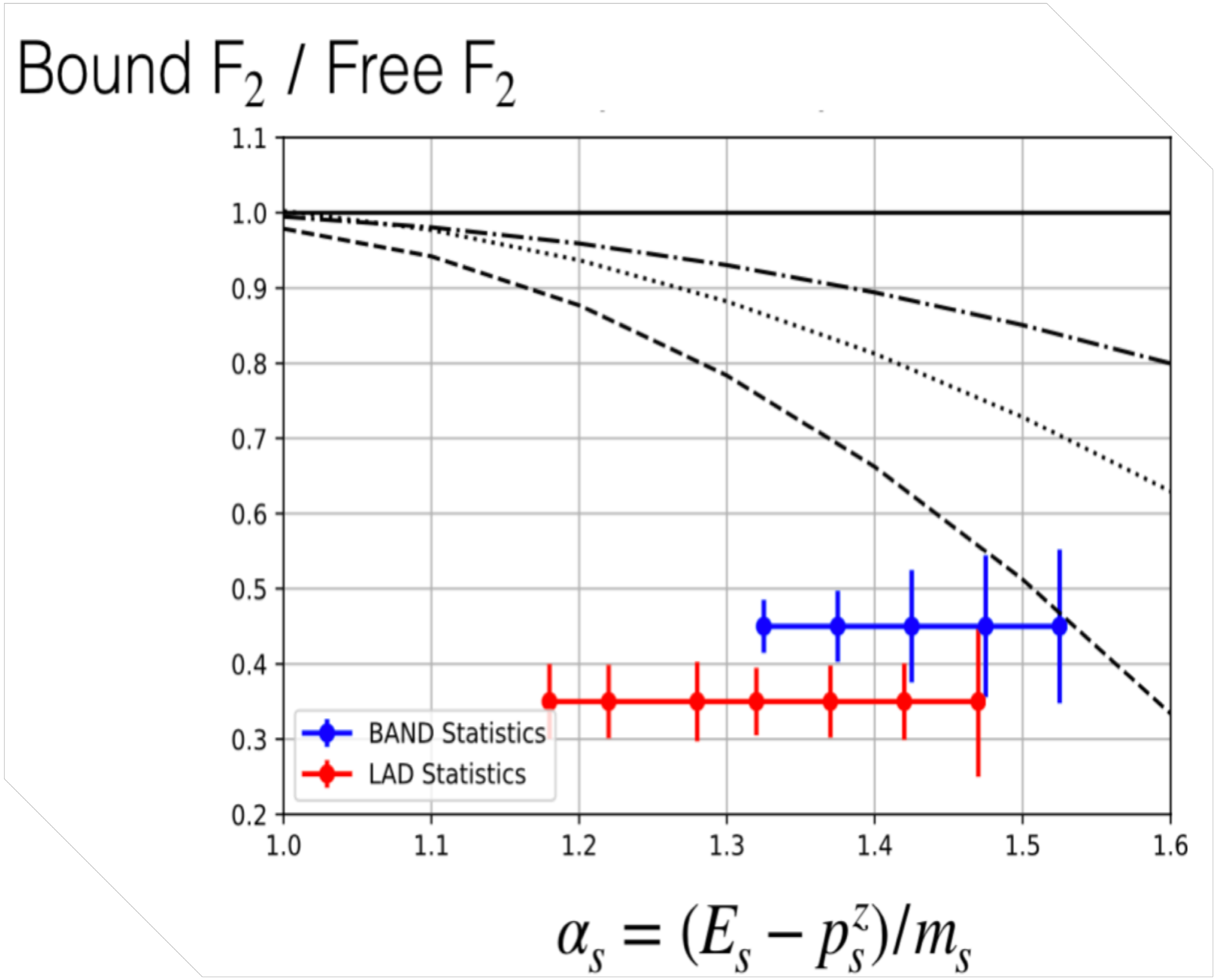




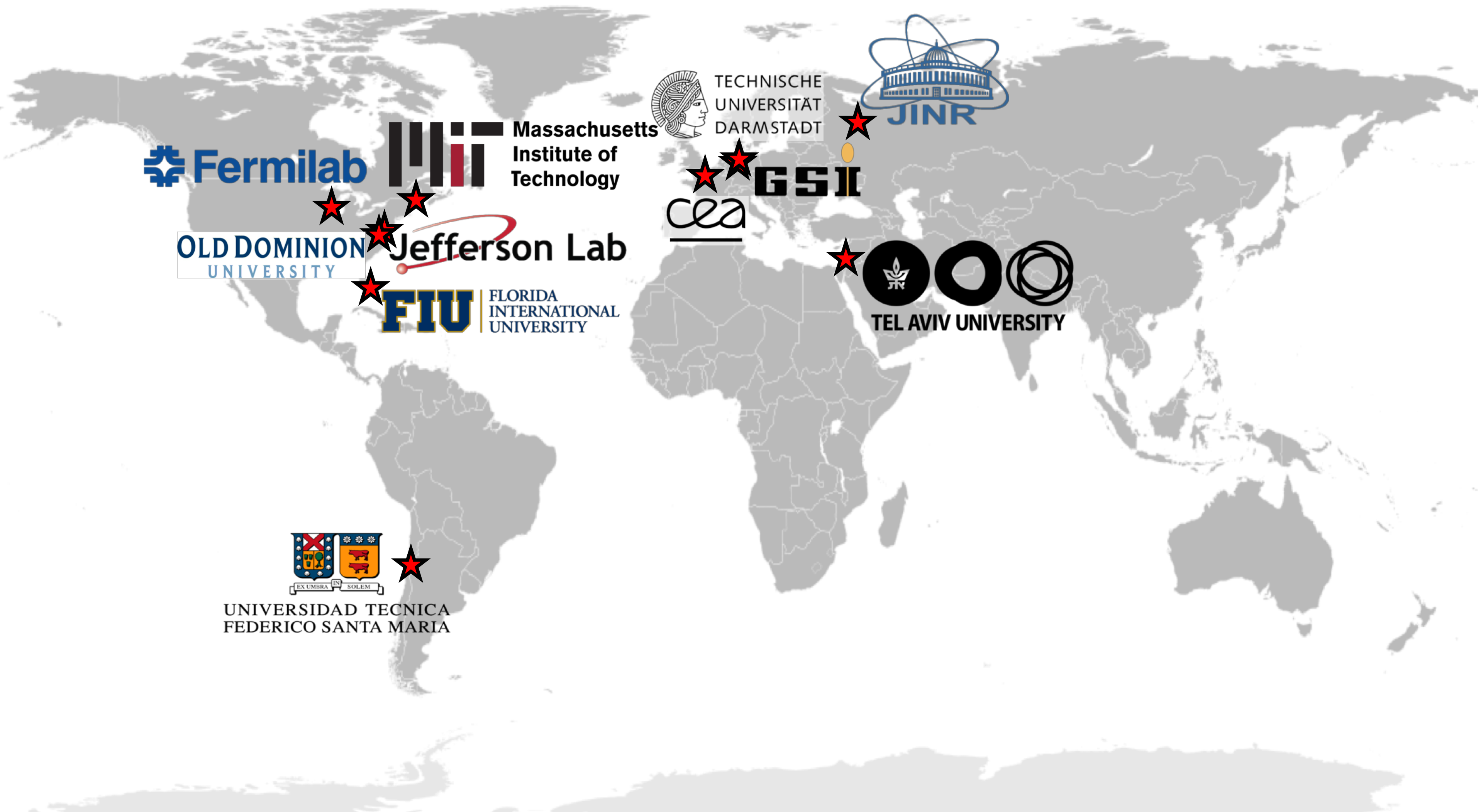


BAND @ CLAS12

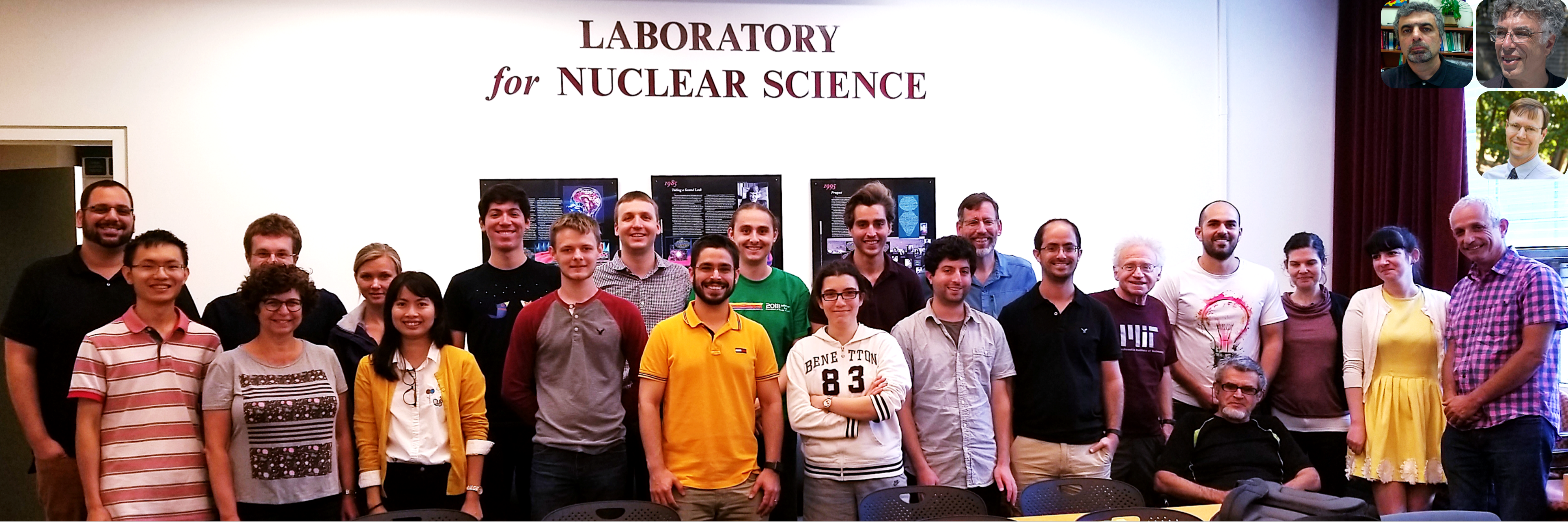
SRC parton-structure



(some of) The SRC World



+ Many Theory Collaborators: UW, Penn State, Huji, Gent, FIU, Perugia, …

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Andrew Denniston


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Dr. George Laskaris


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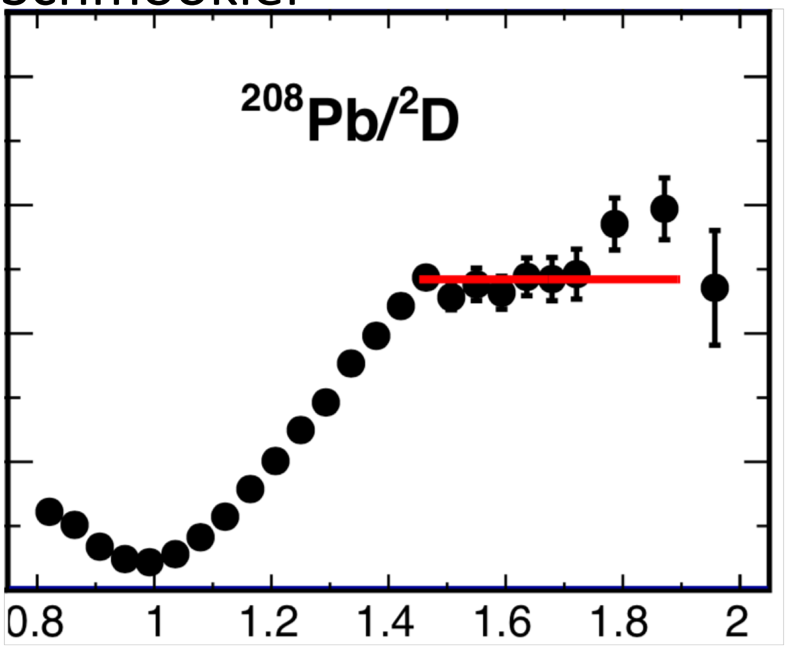
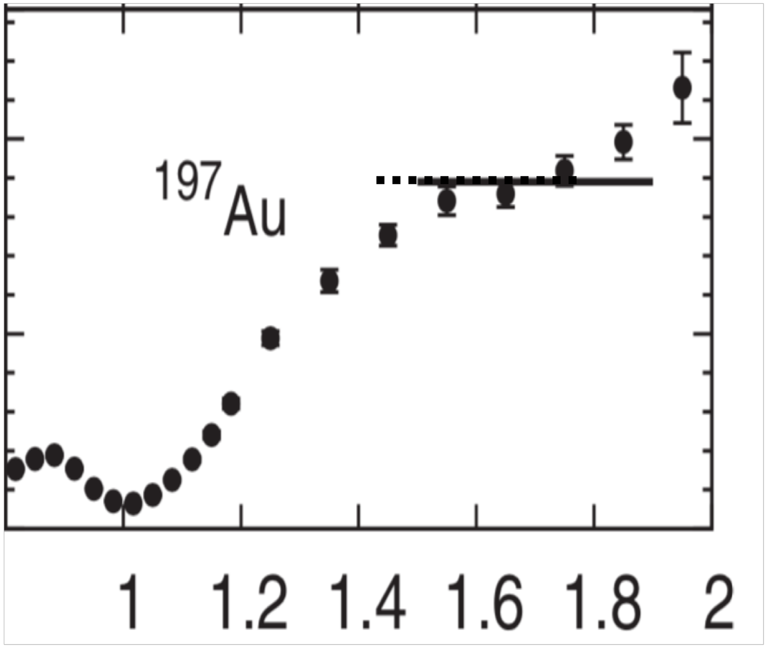
2018 High-Momentum Scaling

Schmookler

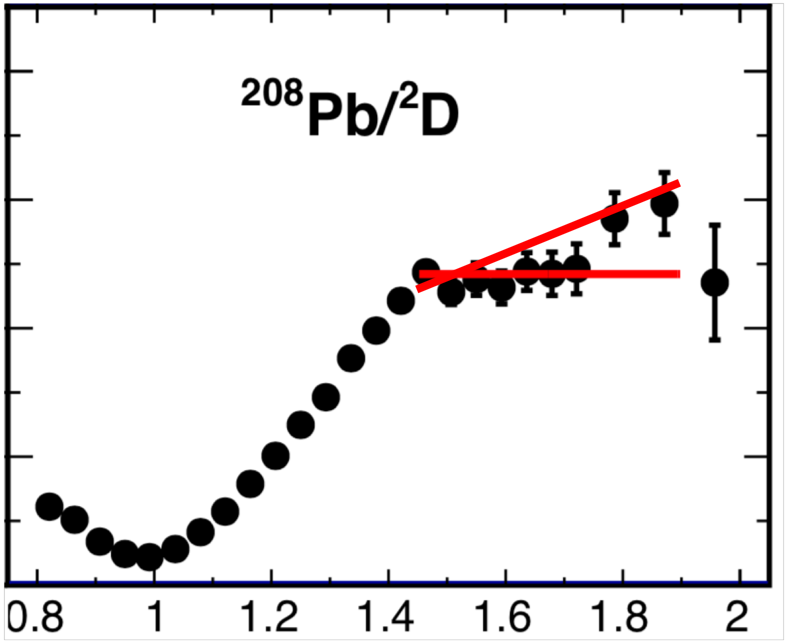


Fomin



2018 High-Momentum Scaling

Schmookler



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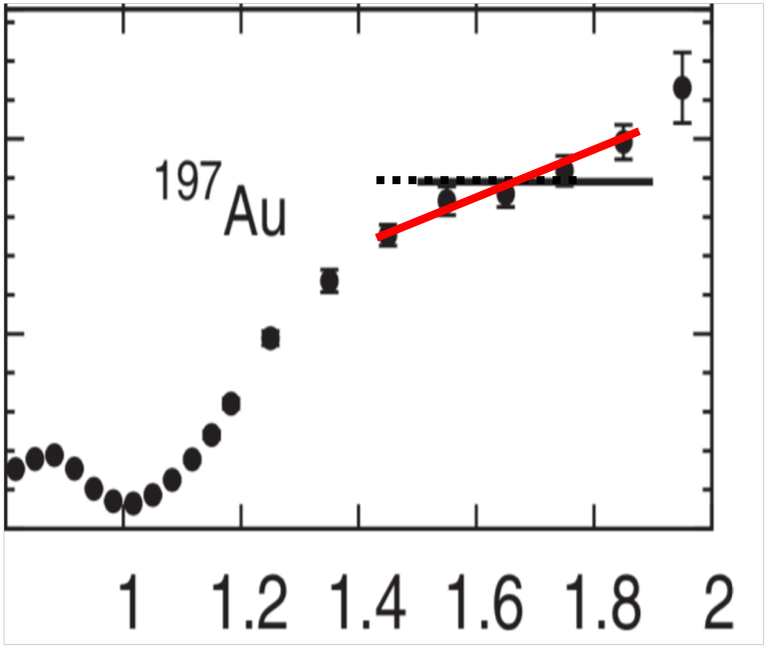

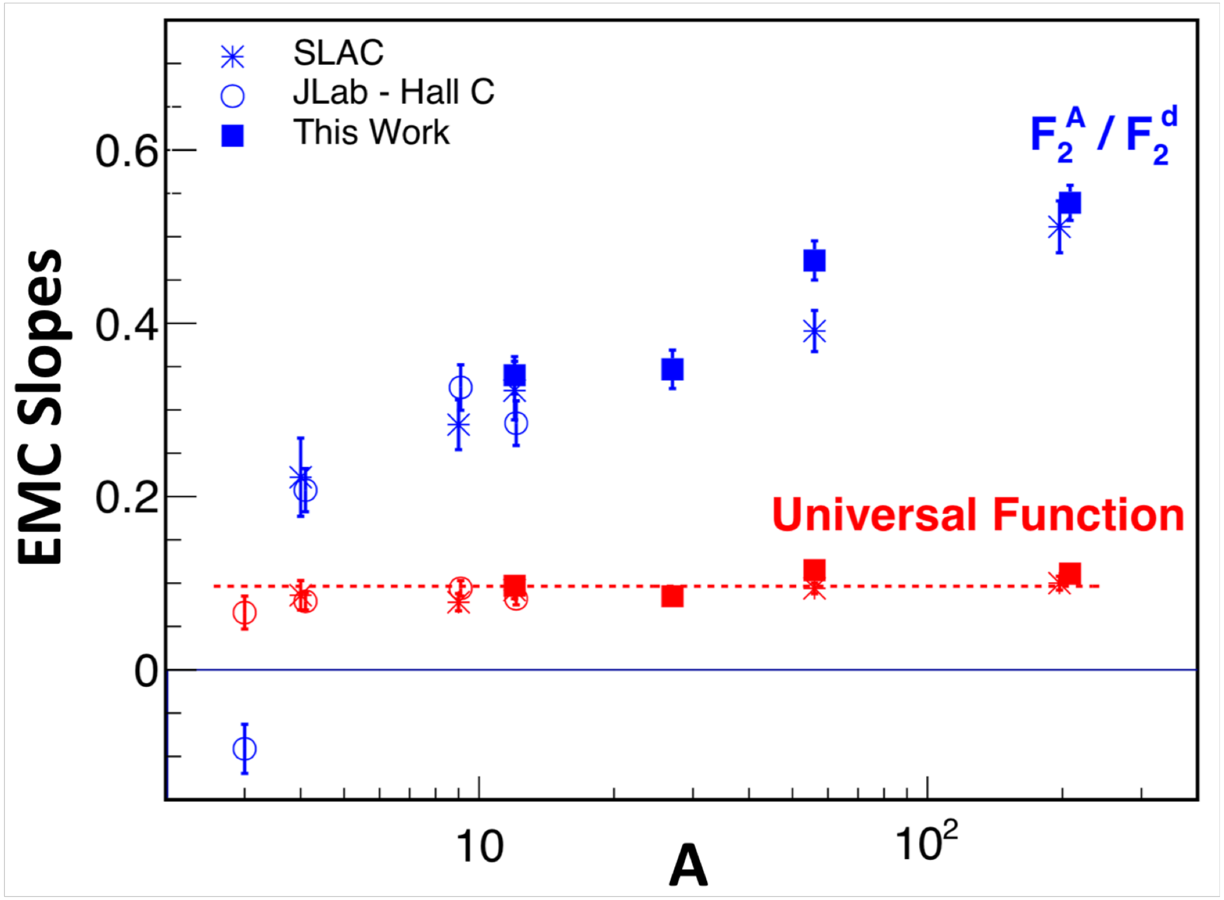

SLAC
JLab - Hall C
This Work
F_2^A / F_2^d
Universal Function
EMC Slopes
0.6
0.4
0.2
0
10
10^2
A