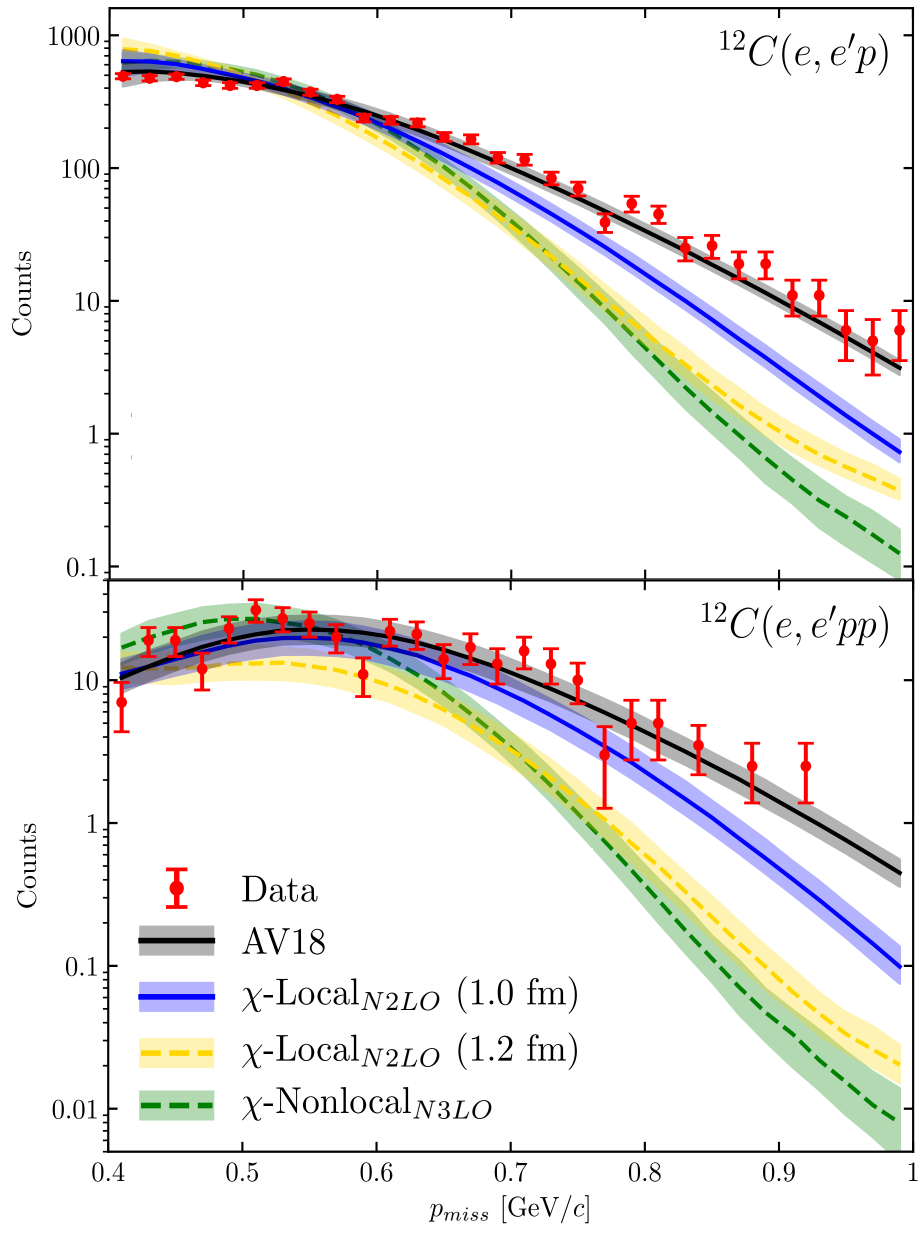
New results on short-range correlations

Or Hen (MIT)

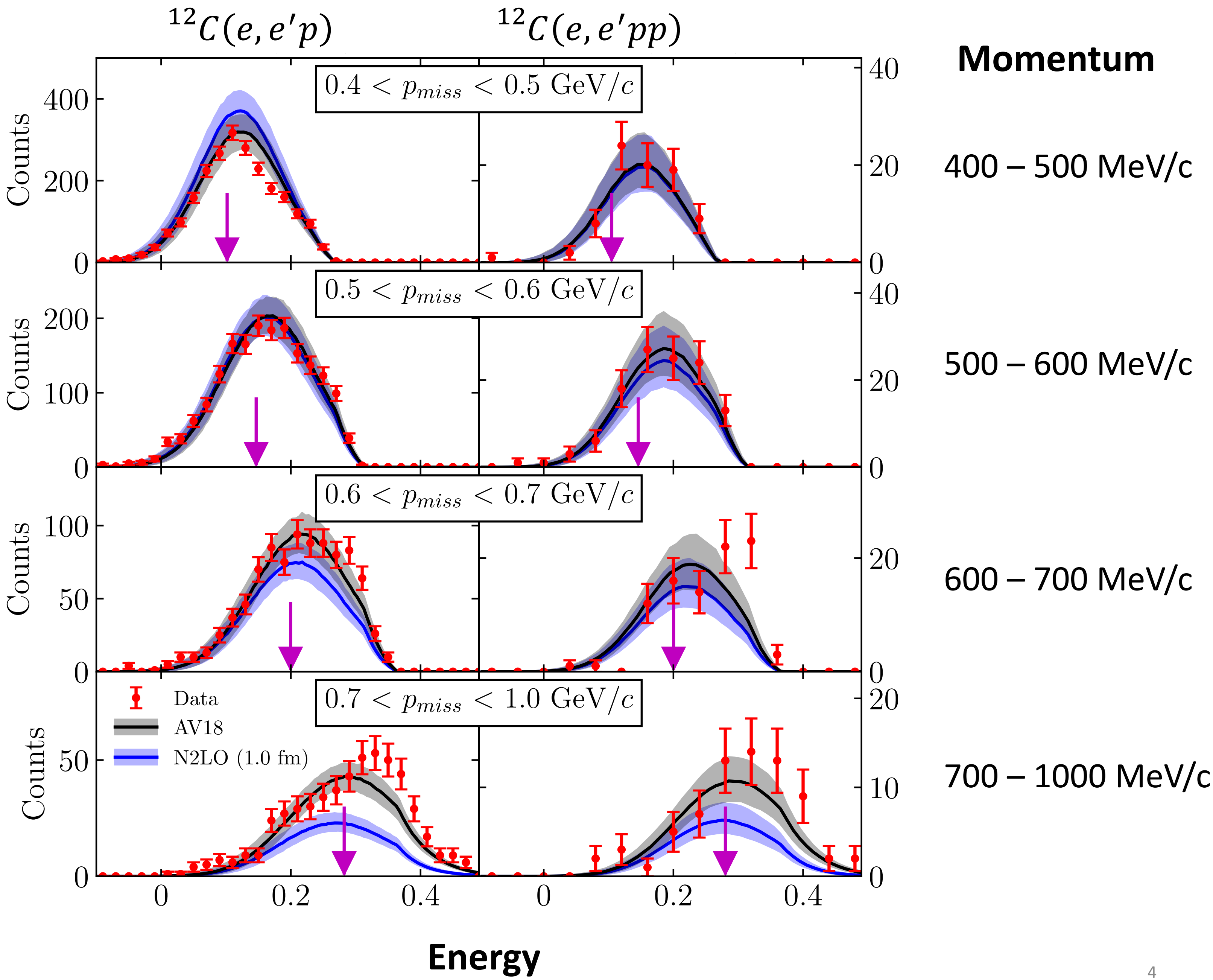
Lepton Interactions With Nucleons and Nuclei, Elba, Italy, June 25th 2019.

Starting from the end…

Measurements of exclusive electron scattering reactions can test, and constrain, the NN interaction and many-body theory.



$^{12}C(e,e'p)$
$^{12}C(e,e'pp)$
Counts
Counts
1000
100
10
1
0.1
10
1
0.1
0.01
0.4
0.5
0.6
0.7
0.8
0.9
1
p_{miss} [GeV/c]
Data
AV18
χ-Local$_{N2LO}$ (1.0 fm)
χ-Local$_{N2LO}$ (1.2 fm)
χ-Nonlocal$_{N3LO}$



$^{12}C(e,e'p)$
$^{12}C(e,e'pp)$
$0.4 < p_{miss} < 0.5$ GeV/c
$0.5 < p_{miss} < 0.6$ GeV/c
$0.6 < p_{miss} < 0.7$ GeV/c
$0.7 < p_{miss} < 1.0$ GeV/c
Counts
Data
AV18
N2LO (1.0 fm)
Momentum
400 – 500 MeV/c
500 – 600 MeV/c
600 – 700 MeV/c
700 – 1000 MeV/c
Energy

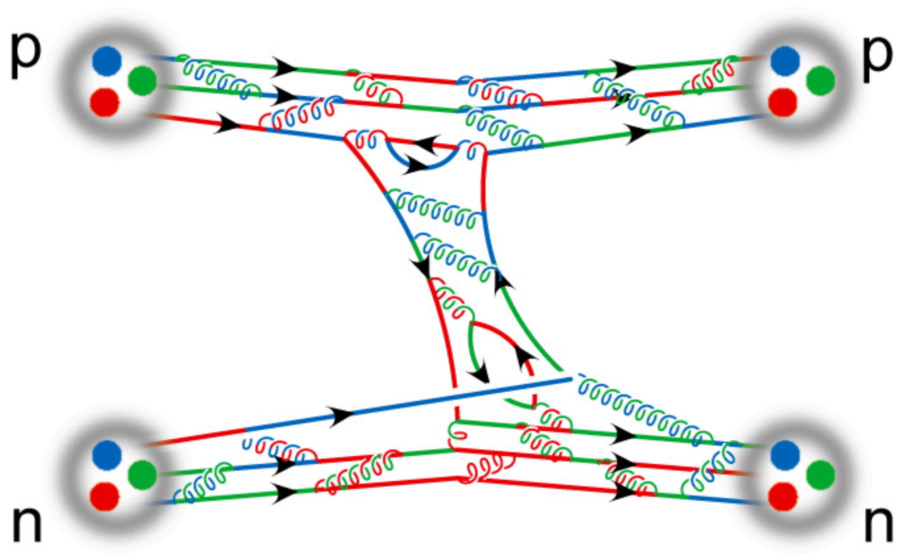
… Now, to the beginning

The Nuclear Challenge

1. Many-body problem

$$\sum_i \left\{ -\frac{\hbar^2}{2m_i} \nabla_i^2 \Psi(\vec{r}_1, \dots, \vec{r}_N, t) \right\} + U(\vec{r}_1, \dots, \vec{r}_N) \Psi(\vec{r}_1, \dots, \vec{r}_N, t) = i\hbar \frac{\partial}{\partial t} \Psi(\vec{r}_1, \dots, \vec{r}_N, t)$$

2. Complex QCD interaction

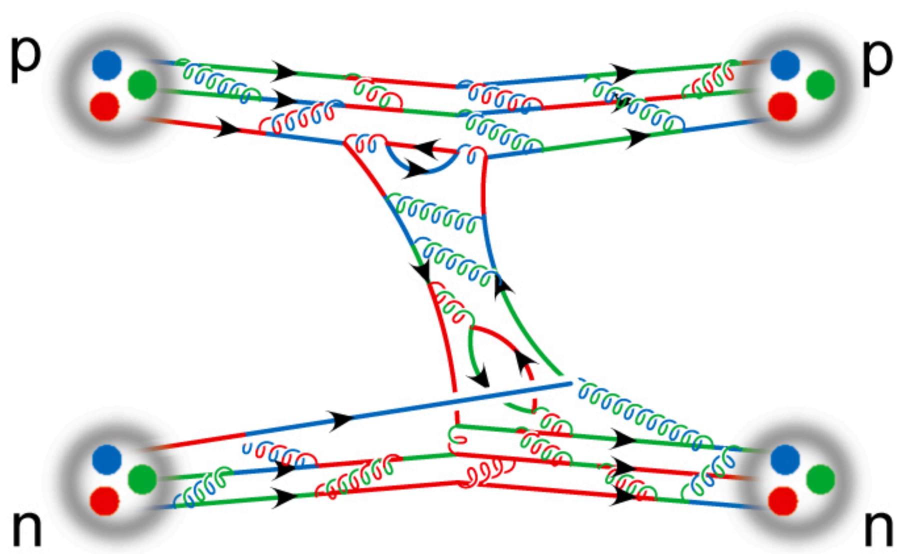


The Nuclear Challenge

1. Many-body problem

   ➔ Numerical Technics (Quantum Monte Carlo, Lattice, Coupled Clusters, …)

2. Complex QCD interaction

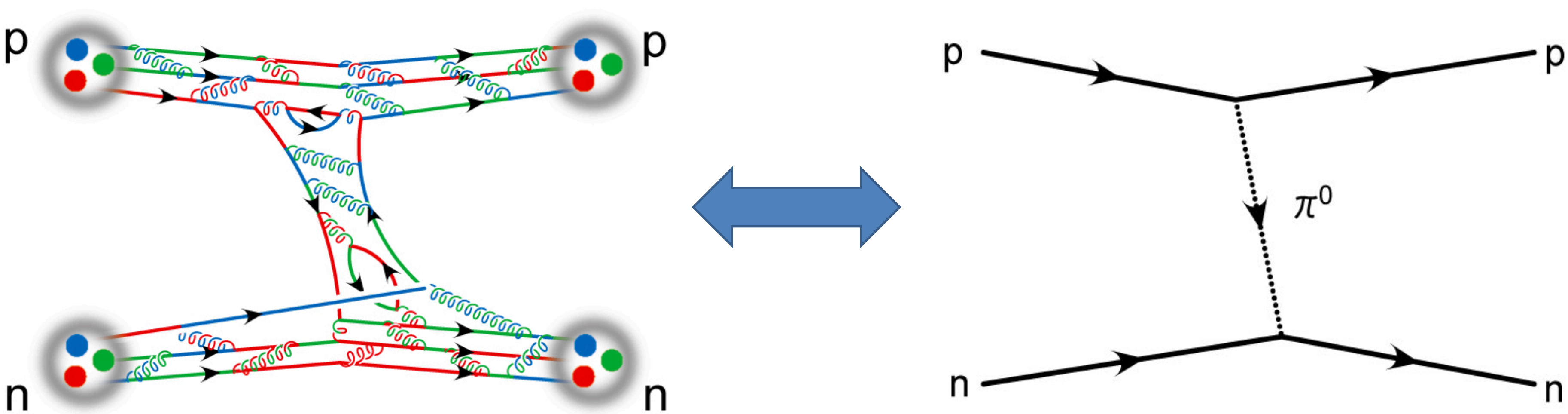


The Nuclear Challenge

1. Many-body problem

   ➔ Numerical Technics

2. Complex ~~QCD~~ Effective interaction

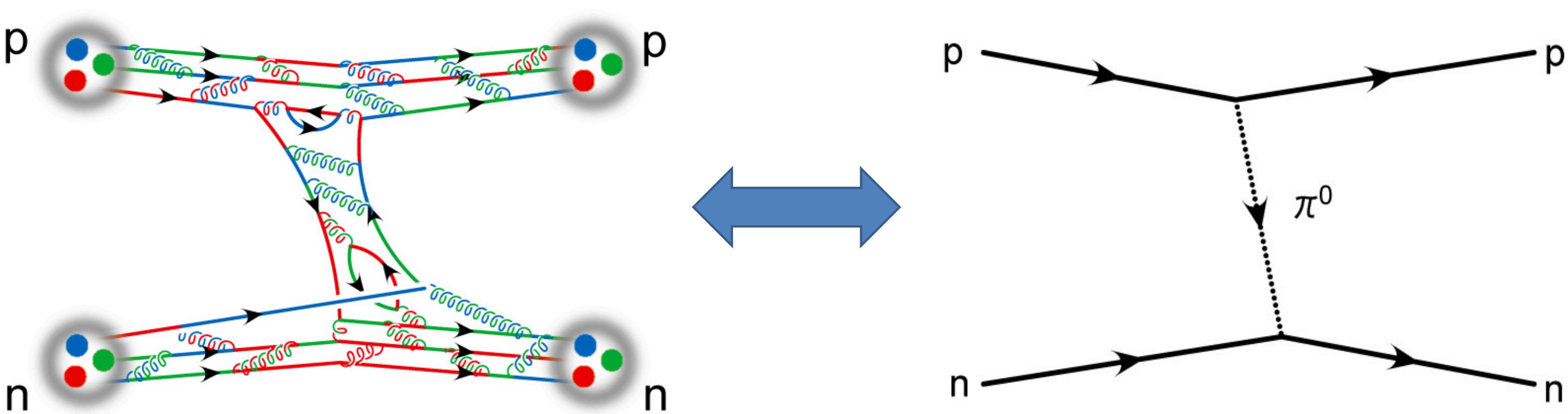


The Nuclear Challenge

1. Many-body problem

   → **Numerical Technics**

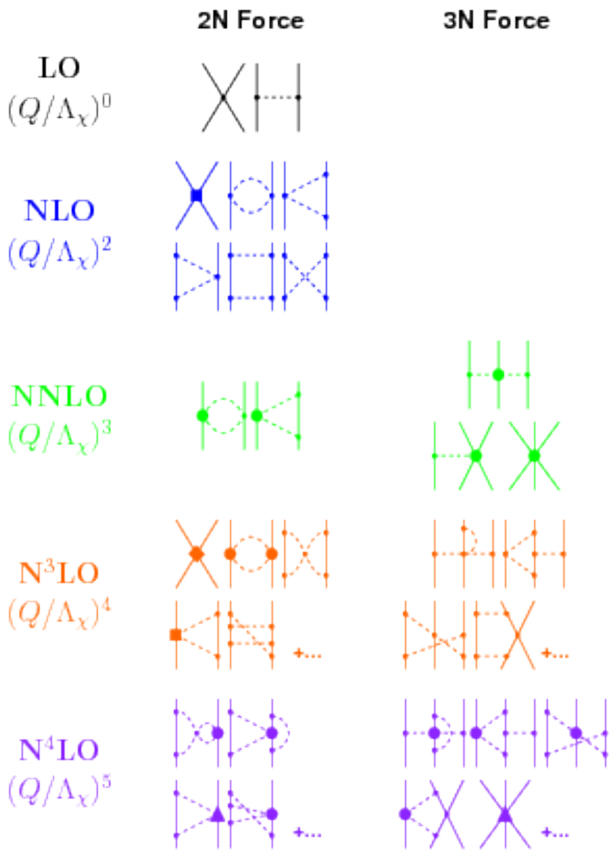
2. Complex ~~QCD~~ **Effective interaction**



The Nuclear Interaction

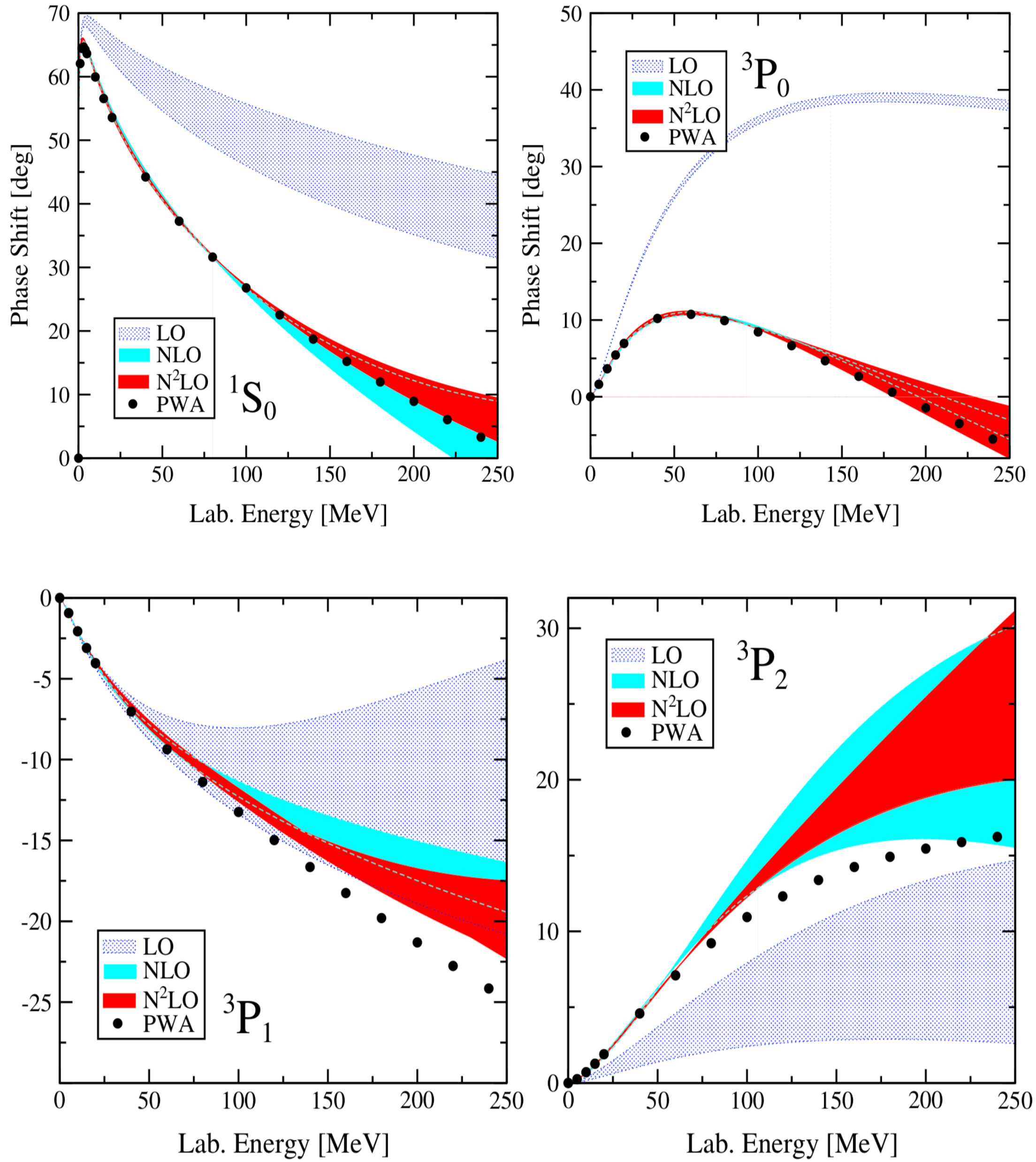
Many ways to derive an effective interaction.

All models contain experimentally determined parameters.



NN phase shifts constrain models up to pion threshold (~**400 MeV/c** c.m.)

No significant constrains @ higher momenta.



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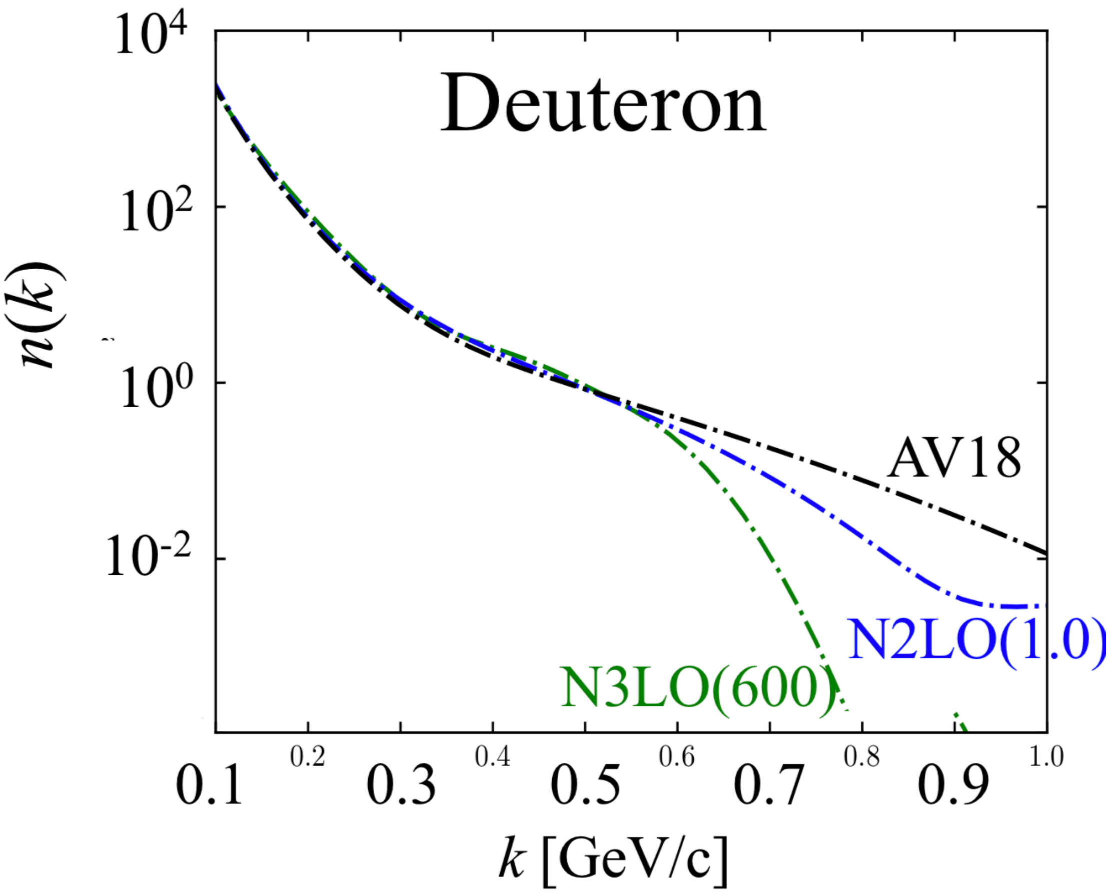
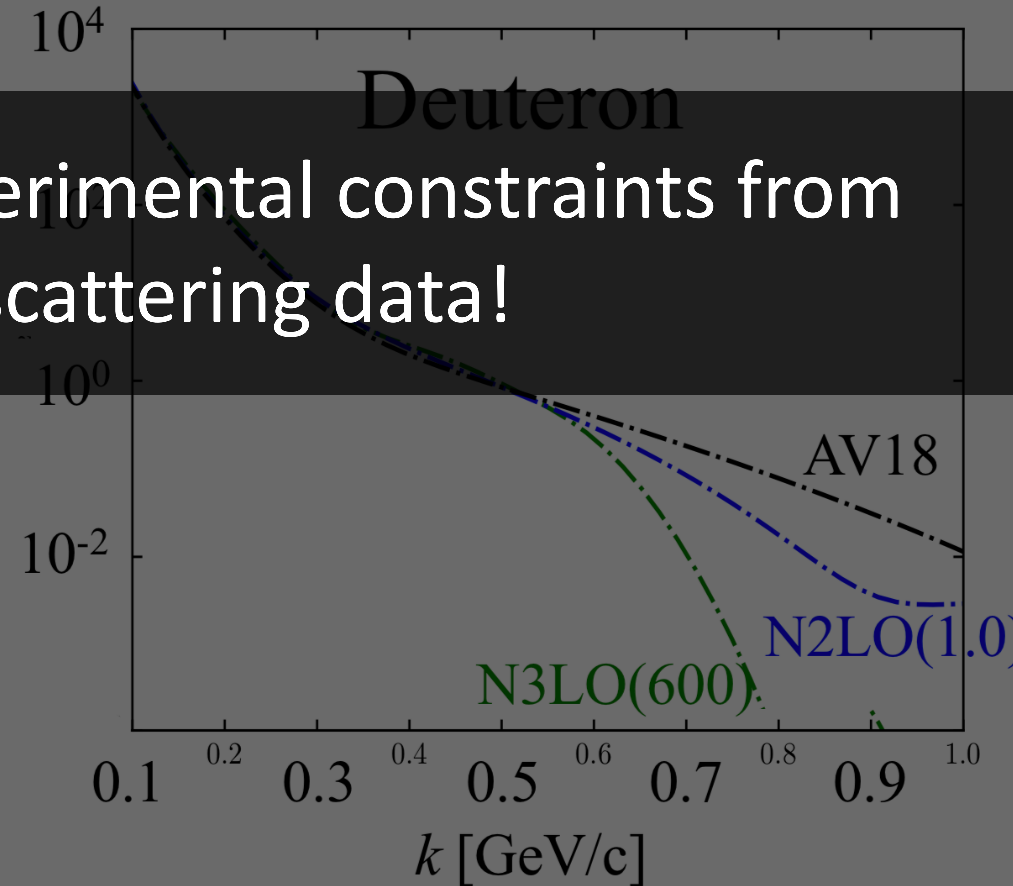


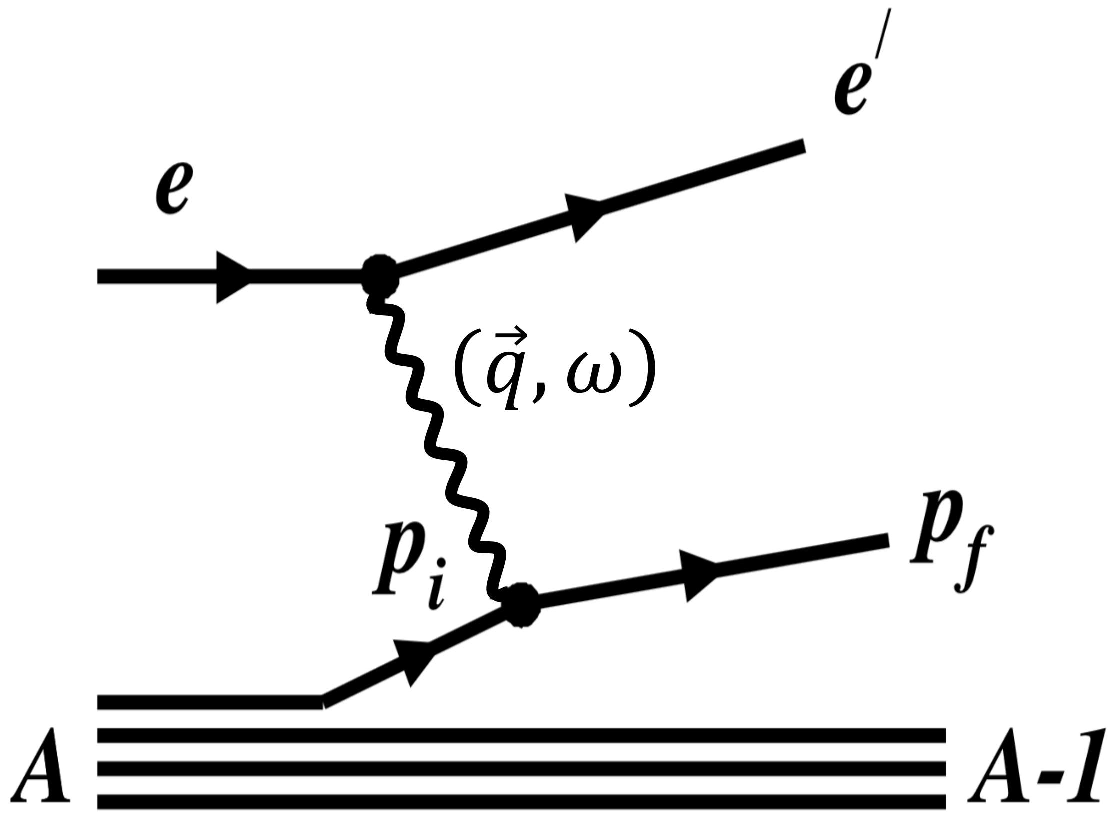
NN phase shifts constrain models up to pion threshold (~400MeV/c c.m.)

We provide new experimental constraints from electron scattering data!

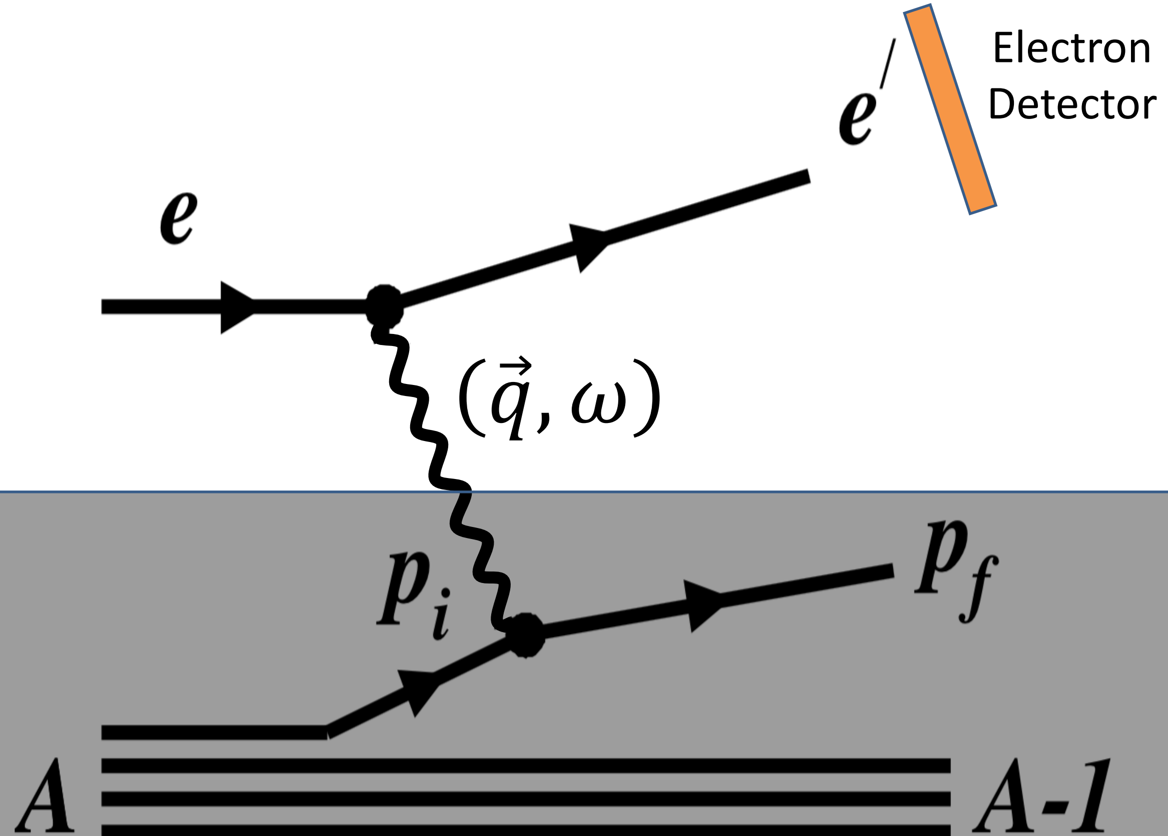
No significant constrains @ higher momenta.



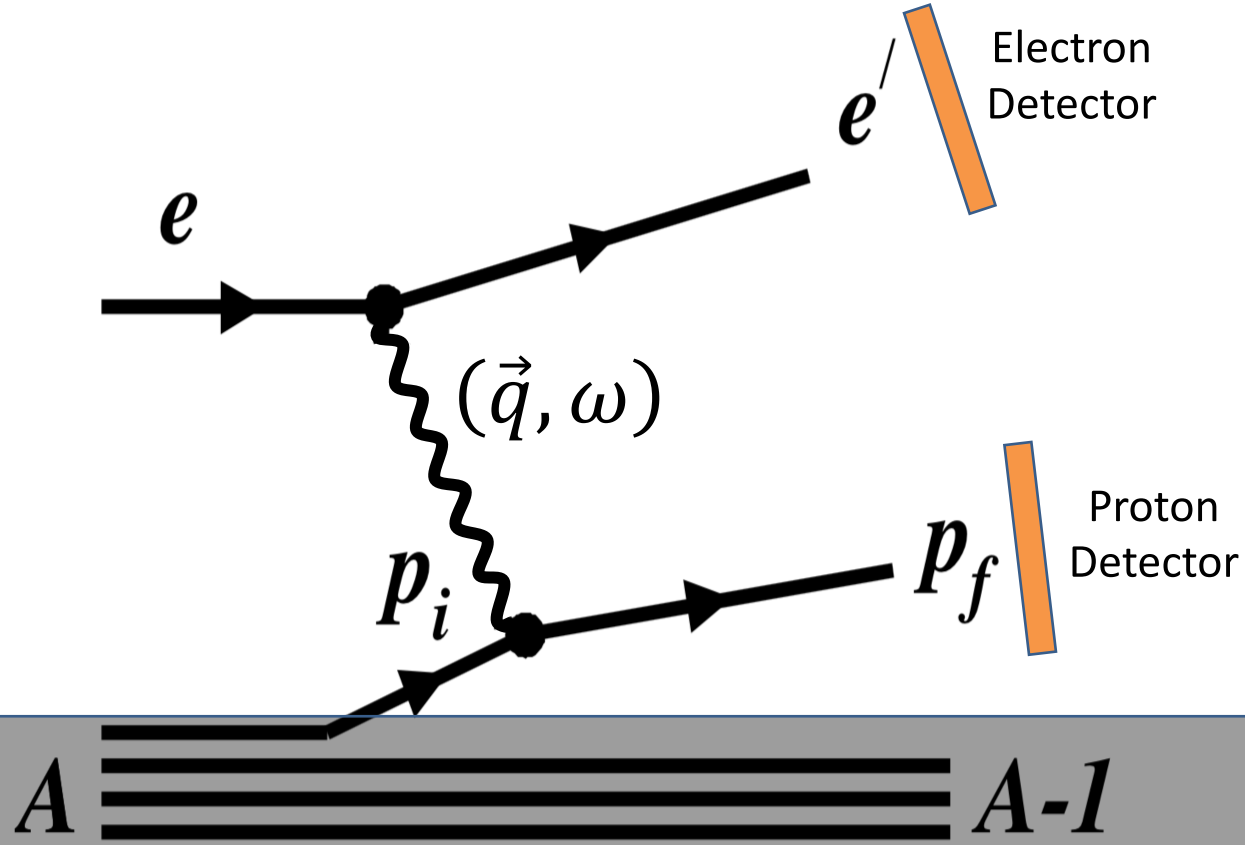
High-Energy Electron Scattering 101



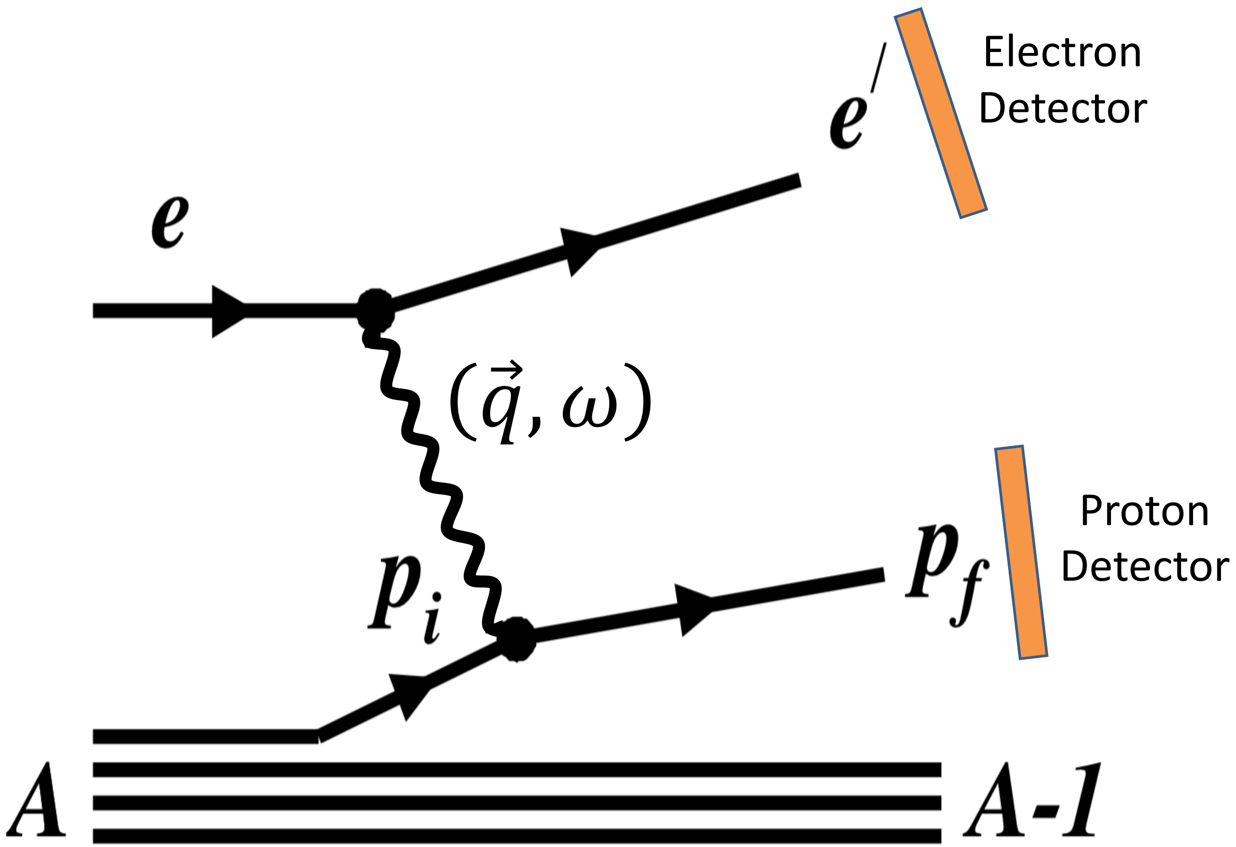
High-Energy Electron Scattering 101



High-Energy Electron Scattering 101



High-Energy Electron Scattering 101

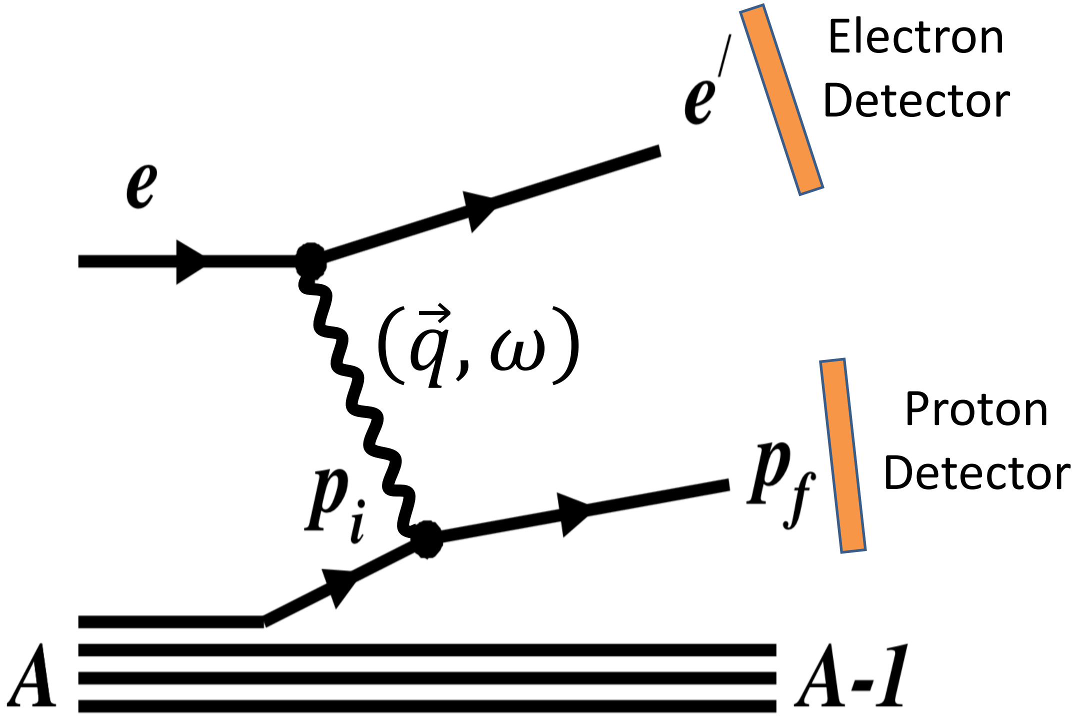


High-Energy Electron Scattering 101

Cross-section =

Probability of finding a proton with P_i in the nucleus

X Probability for P_i to absorb q (momentum transfer)



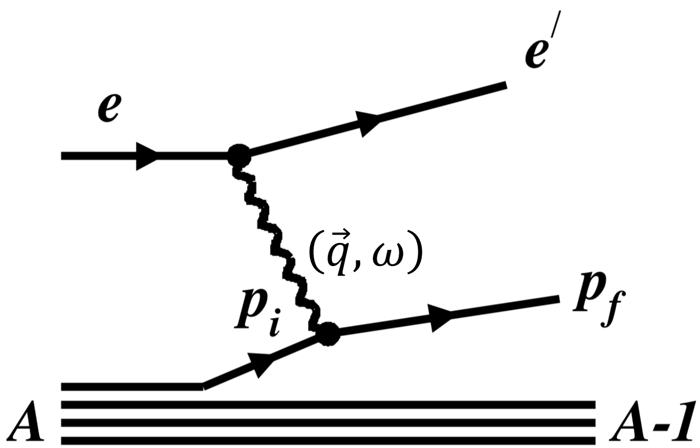
High-Energy Electron Scattering 101

$$\underbrace{\frac{d^4\sigma}{d\Omega_{k'} d\epsilon_{k'} d\Omega_{p_i} d\epsilon_i}}_{\text{Exp cross-section}} \cong \underbrace{\boldsymbol{S^N(p_i, \epsilon_i)}}_{\text{Spectral-Function}} \times \underbrace{[p_i \epsilon_i \cdot \sigma_{eN}]}_{\text{"Kinematics"}}$$

Exp cross-section

Spectral-Function

"Kinematics"



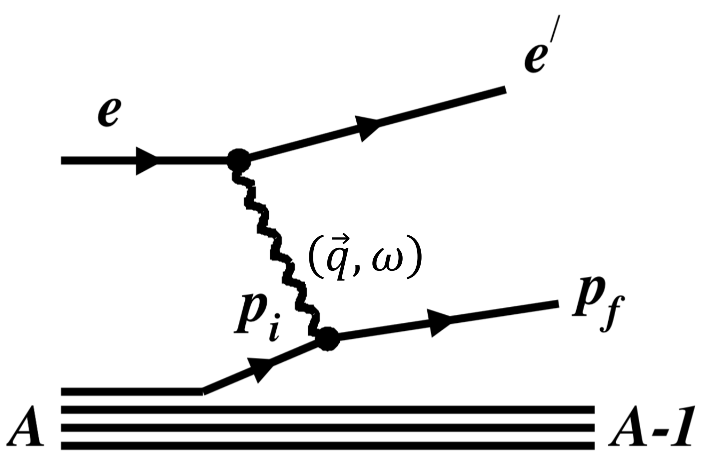
High-Energy Electron Scattering 101

$$\underbrace{S^N(p_i,\epsilon_i)}_{\text{Spectral-Function}} \cong \underbrace{\frac{d^4\sigma}{d\Omega_{k'}d\epsilon_{k'}d\Omega_{p_i}d\epsilon_i}}_{\text{Exp cross-section}} \Big/ \underbrace{p_i\epsilon_i\cdot\sigma_{eN}}_{\text{"Kinematics"}}$$

Spectral-Function

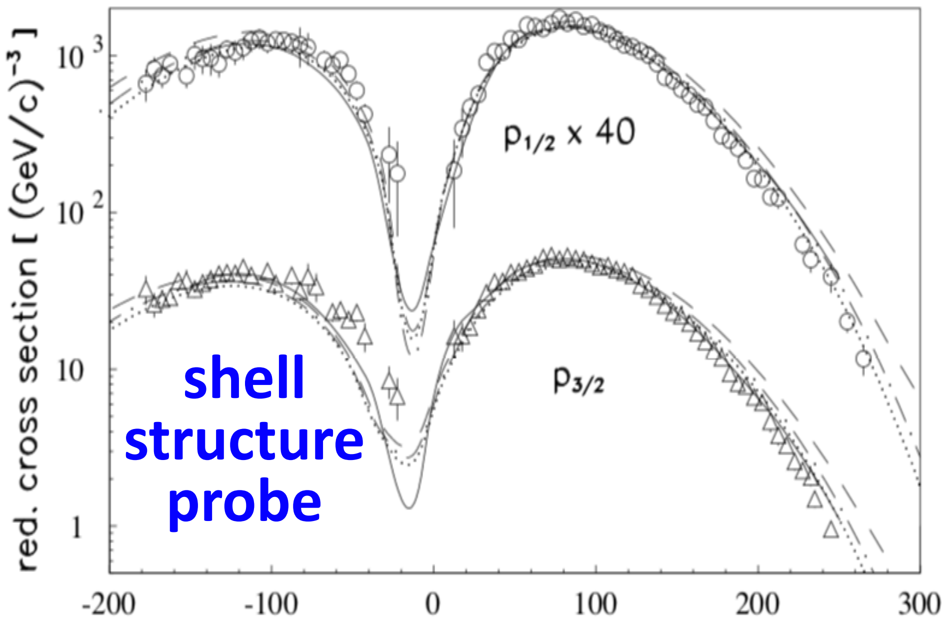
Exp cross-section

"Kinematics"

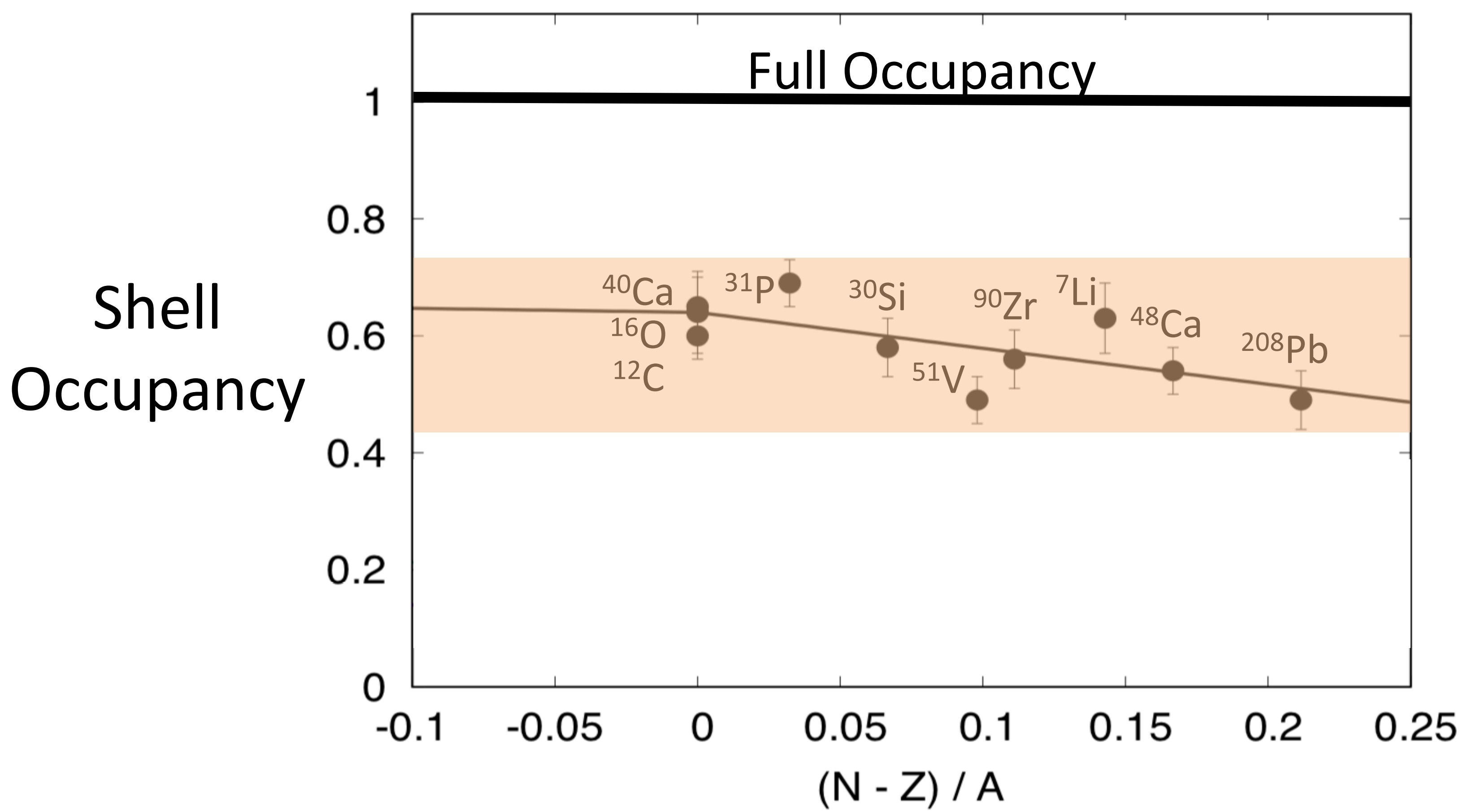


High-Energy Electron Scattering 101

$$\underbrace{S^N(p_i, \epsilon_i)}_{\text{Spectral-Function}} \cong \underbrace{\frac{d^4\sigma}{d\Omega_{k'} d\epsilon_{k'} d\Omega_{p_i} d\epsilon_i}}_{\text{Exp cross-section}} \Big/ \underbrace{p_i \epsilon_i \cdot \sigma_{eN}}_{\text{"Kinematics"}}$$

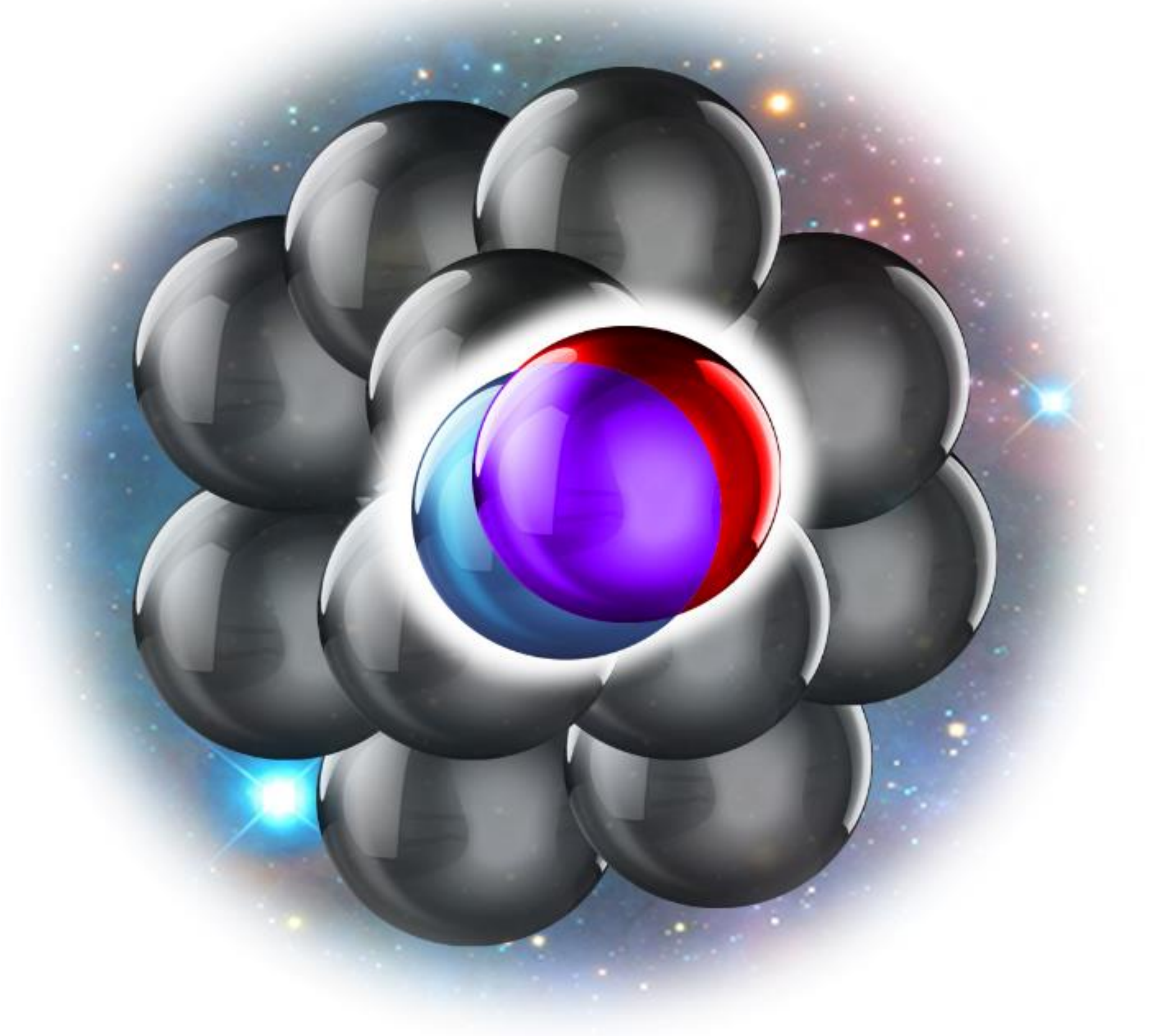


But.... Shells are not fully occupied!



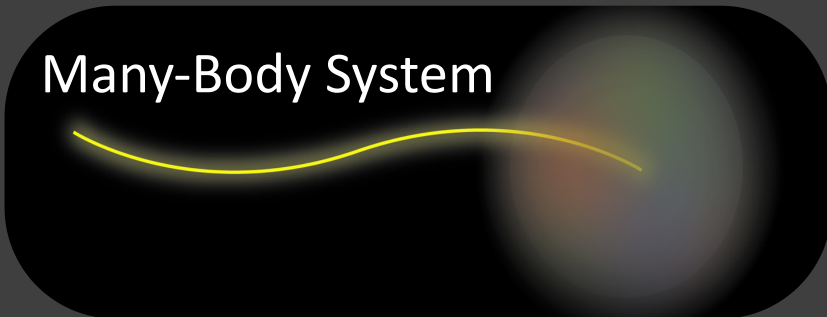
Paschalis, Petri, Macchiavelli, Hen, and Piasetzky, arXiv 1812.08051 (2018)

Short-Range Correlations (SRC)

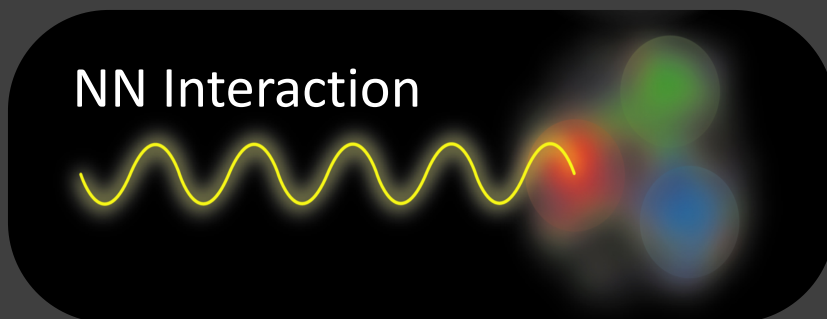


Today: Short-Ranged Interactions Across Resolutions

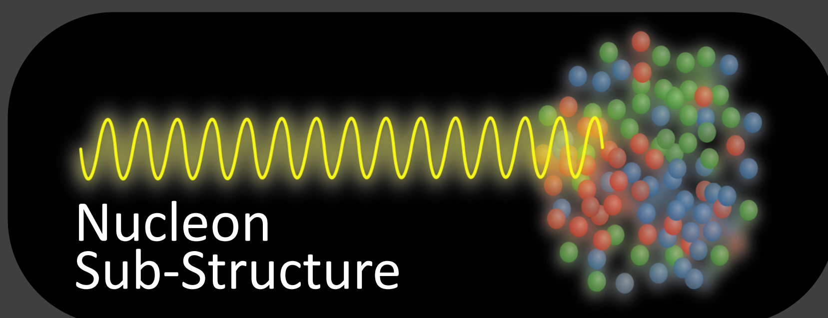
(1)



(2)



(3)



Focus on 2018/19 results

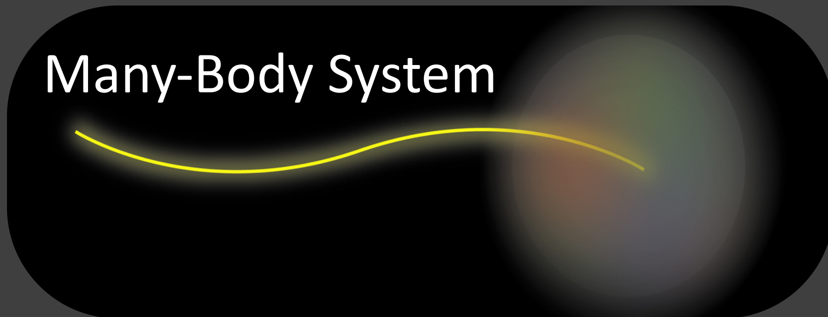
<u>Data:</u>

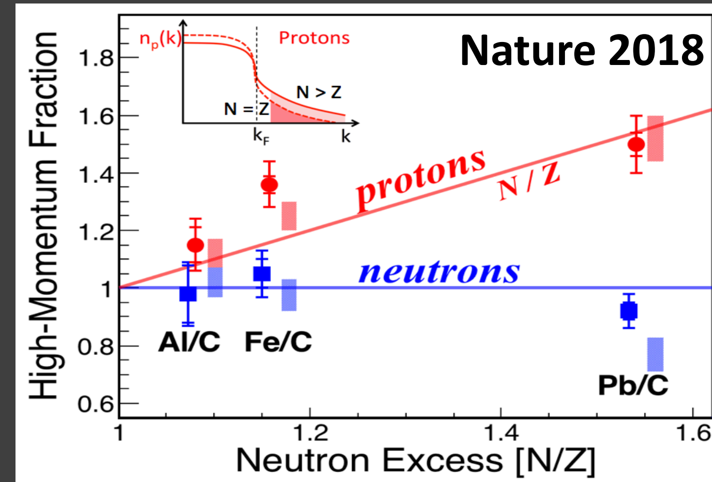
- Nature 566, 354 (2019)
- Nature 560, 617 (2018)
- PRL 122, 172502 (2019)
- PRL 121, 09201 (2018)
- arXiv: 1811.01823
  1902.06358

<u>Theory:</u>

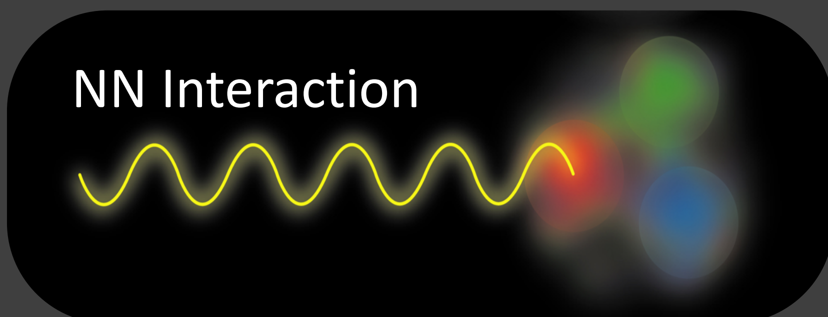
- Phys. Lett. B 791, 242 (2019)
- Phys. Lett. B 793, 360 (2019)
- Phys. Lett. B 780, 211 (2018)
- Phys. Lett. B 785, 304 (2018)
- arXiv: 1812.08051

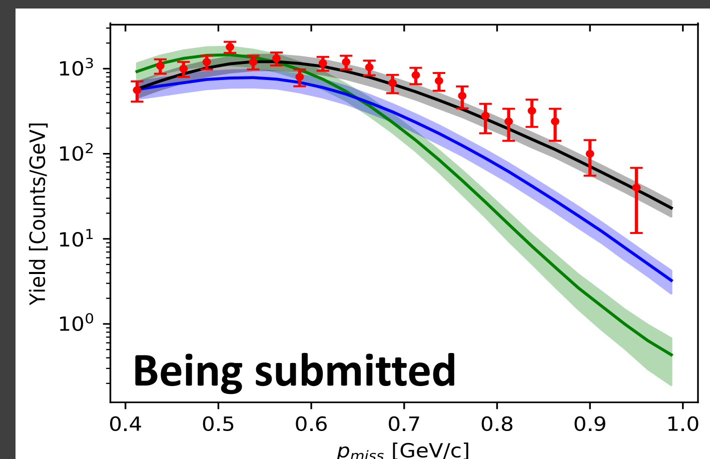
(1)


Many-Body System

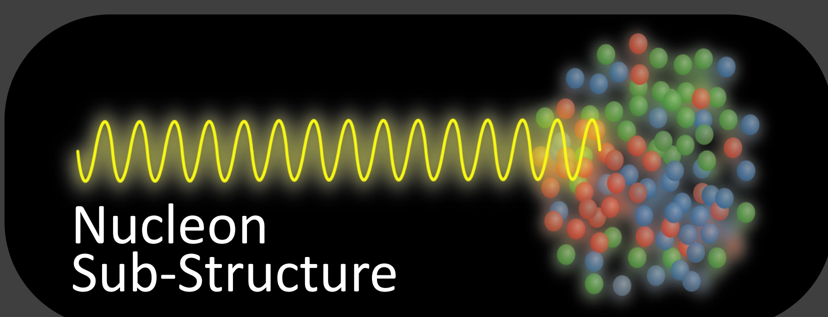

Nature 2018
High-Momentum Fraction
Neutron Excess [N/Z]
$n_p(k)$
Protons
N > Z
N = Z
k_F
k
protons
N / Z
neutrons
Al/C
Fe/C
Pb/C
1.8
1.6
1.4
1.2
1
0.8
0.6
1
1.2
1.4
1.6

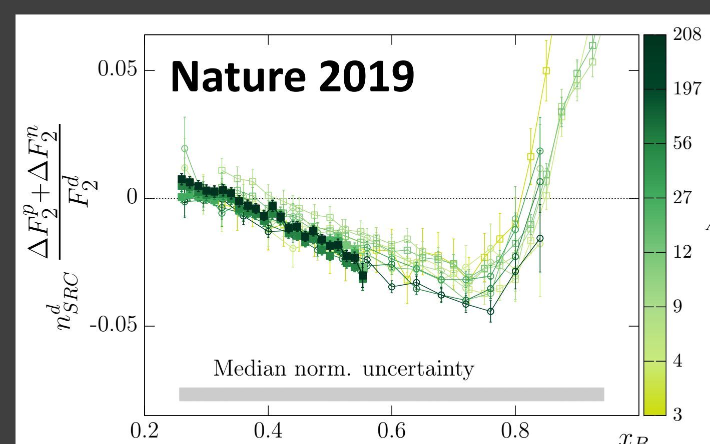
(2)

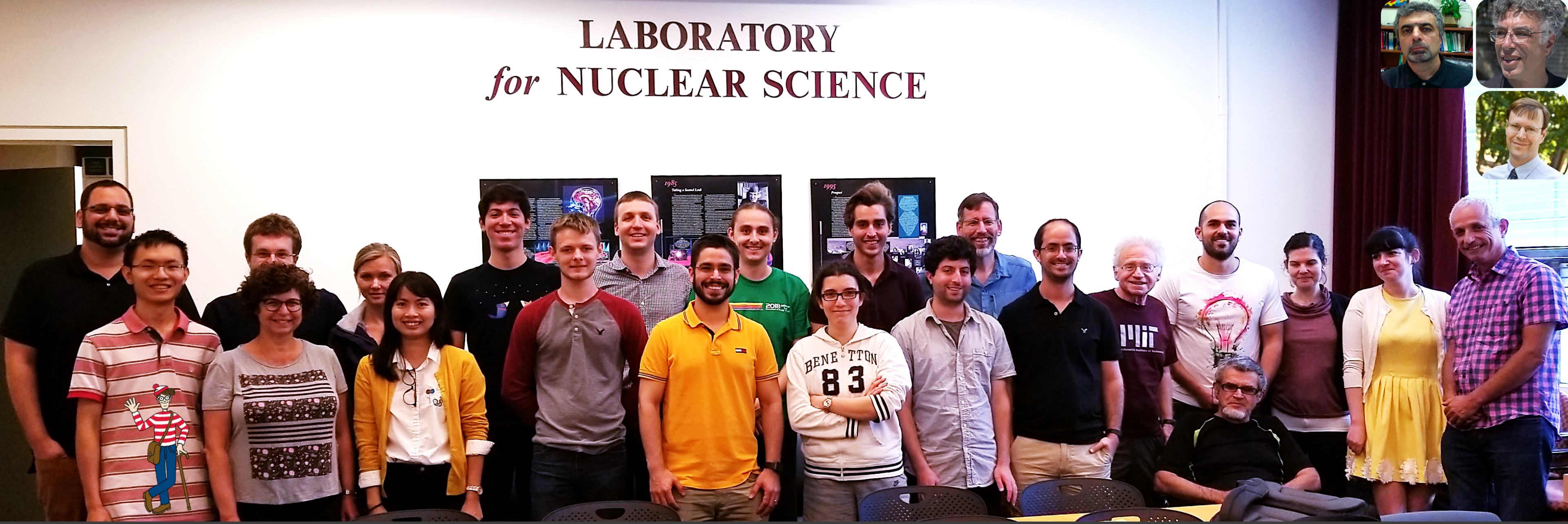

NN Interaction


Being submitted
Yield [Counts/GeV]
p_{miss} [GeV/c]
10^3
10^2
10^1
10^0
0.4
0.5
0.6
0.7
0.8
0.9
1.0

(3)


Nucleon
Sub-Structure


Nature 2019
$n^d_{SRC} \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}$
x_B
Median norm. uncertainty
0.05
0
-0.05
0.2
0.4
0.6
0.8
208
197
56
27
12
9
4
3
A




Dr. Adi Ashkenazy

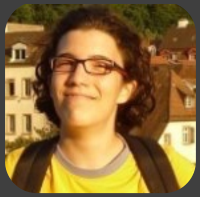

Dr. Dien Nguyen


Dr. Axel Schmidt

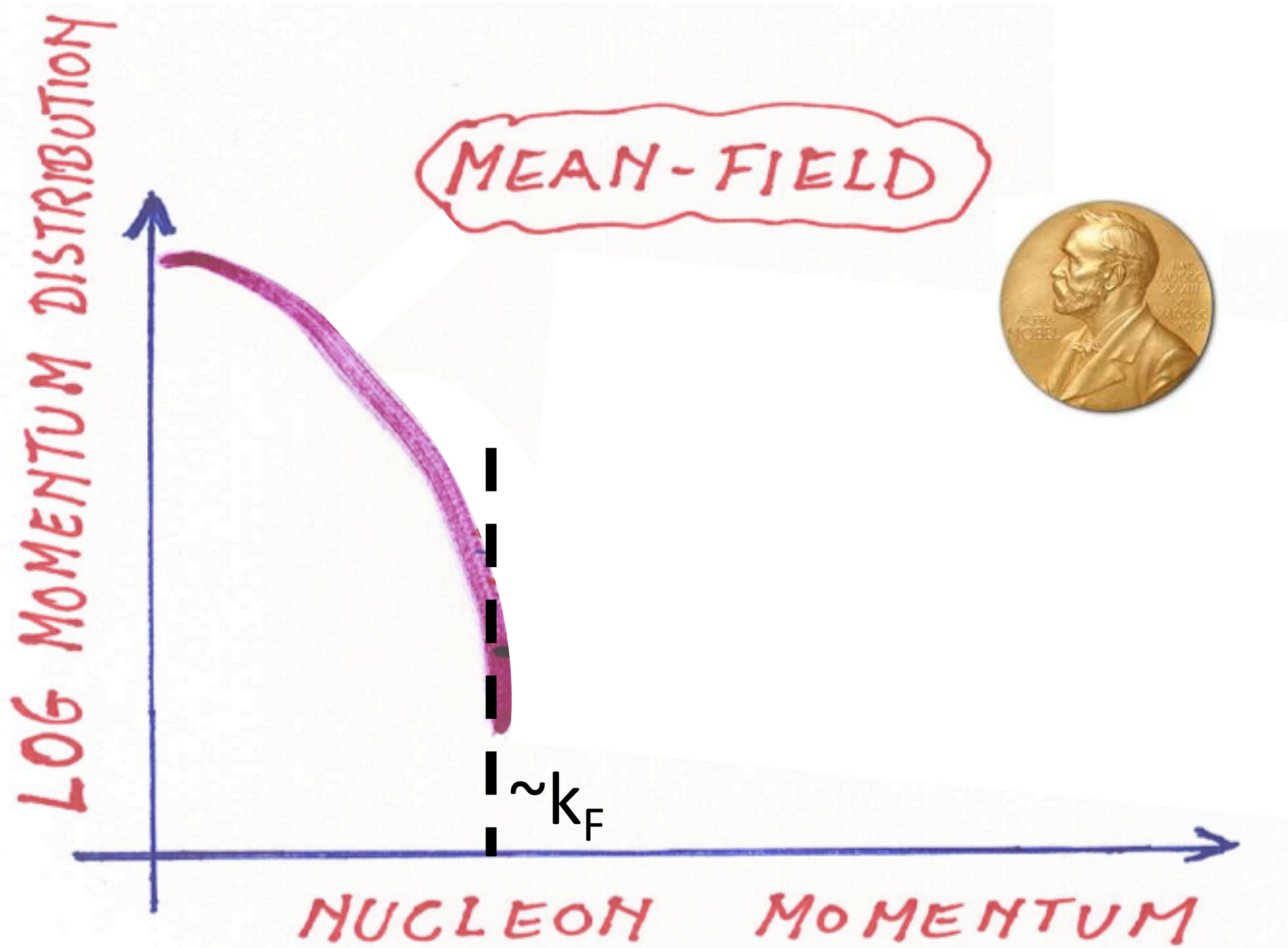

Reynier Cruz-Torres

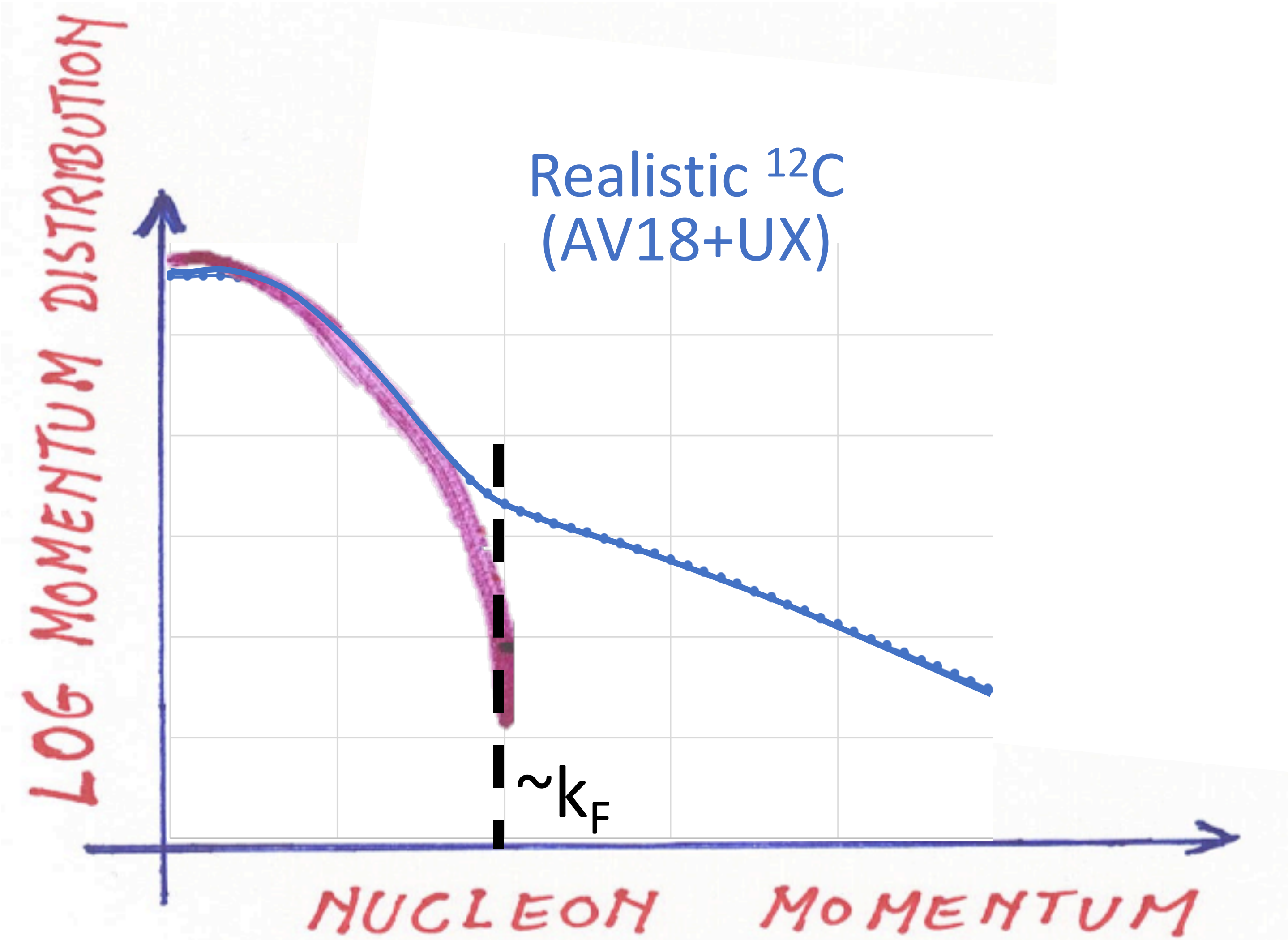

Efrain Segarra


Jackson Pybus

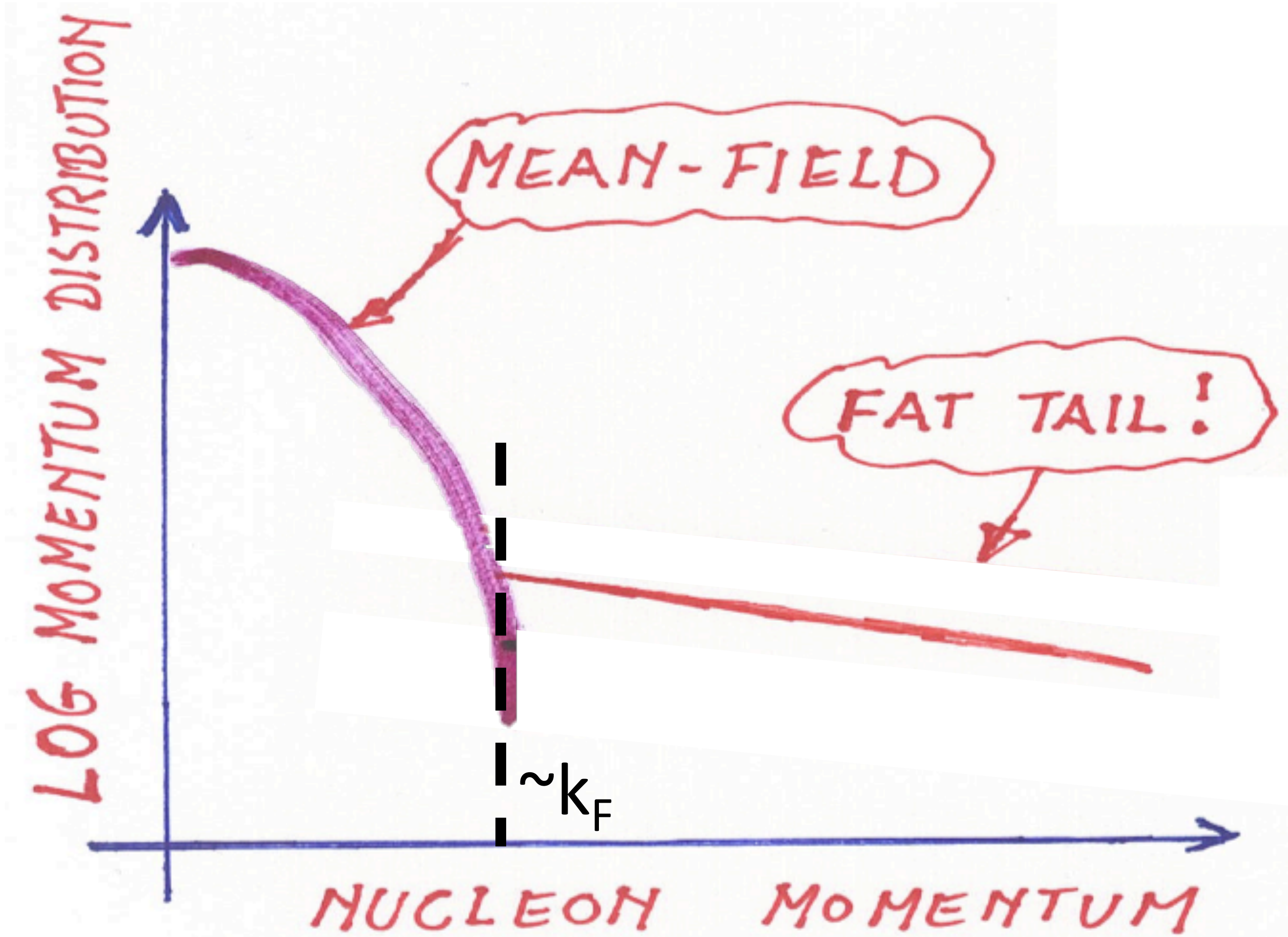

Afroditi Papadopoulou

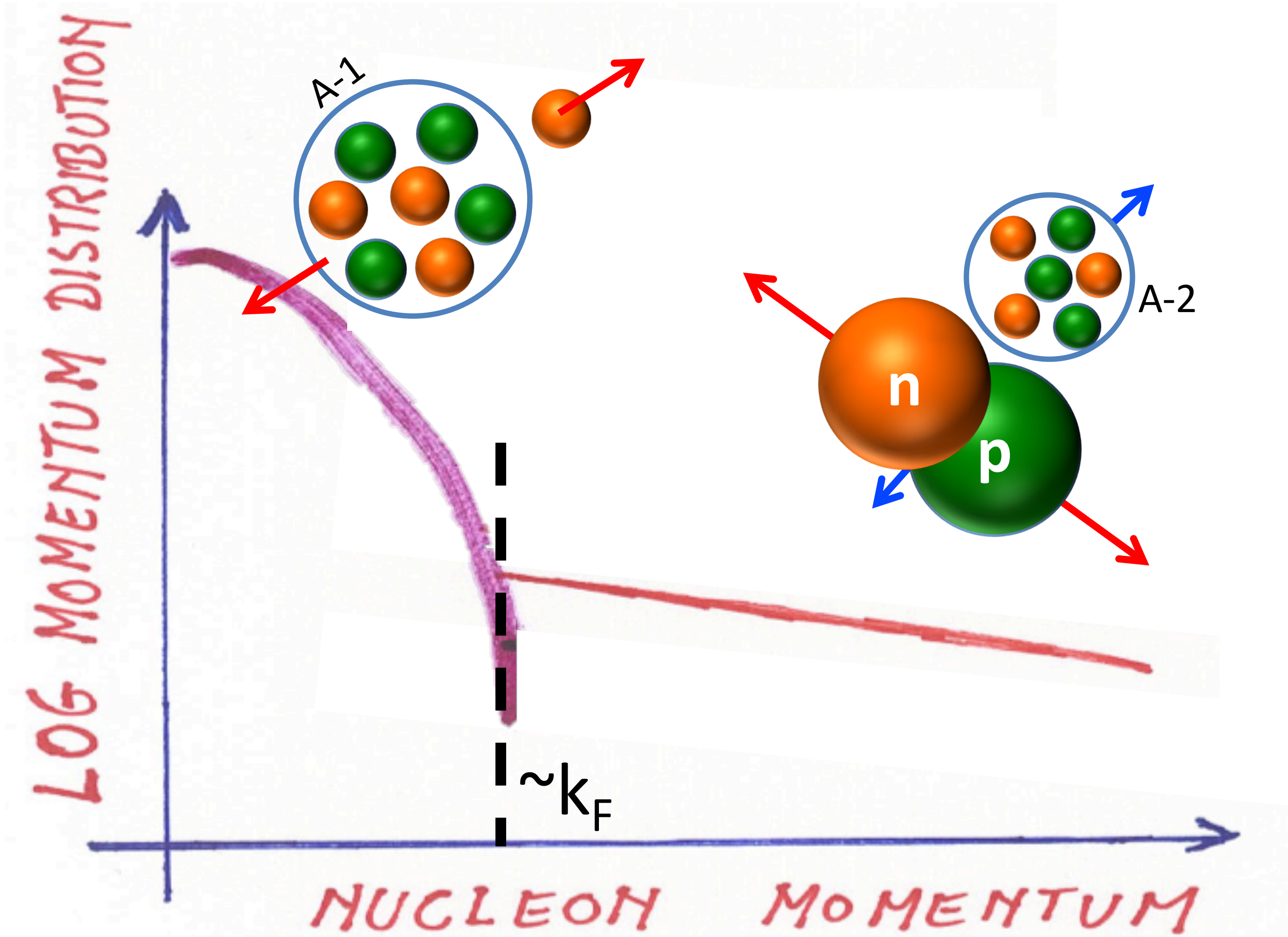

Andrew Denniston


LOG MOMENTUM DISTRIBUTION
MEAN-FIELD
~k_F
NUCLEON MOMENTUM



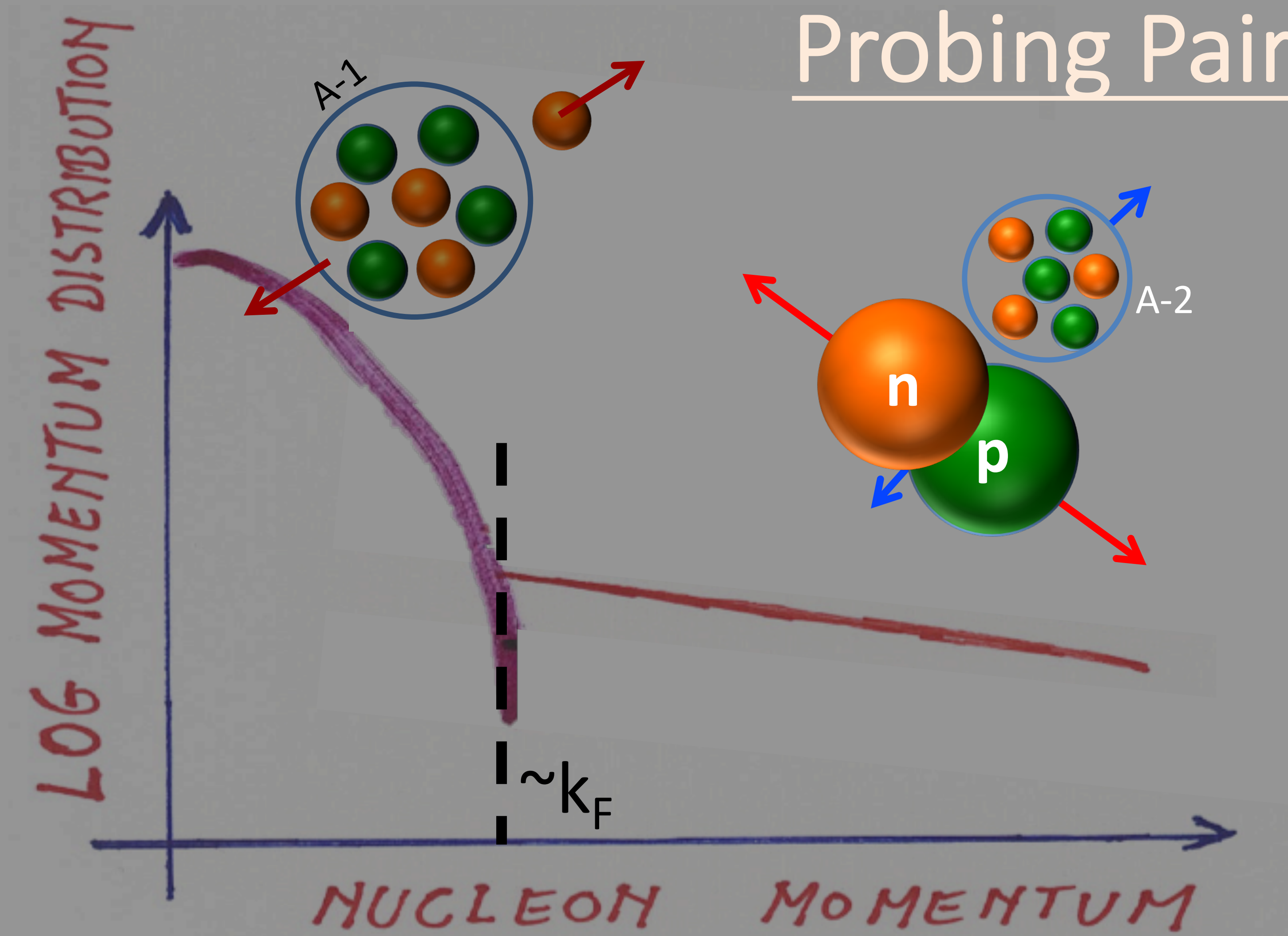
Wiringa, PRC (2014); Carlson, RMP (2015).


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



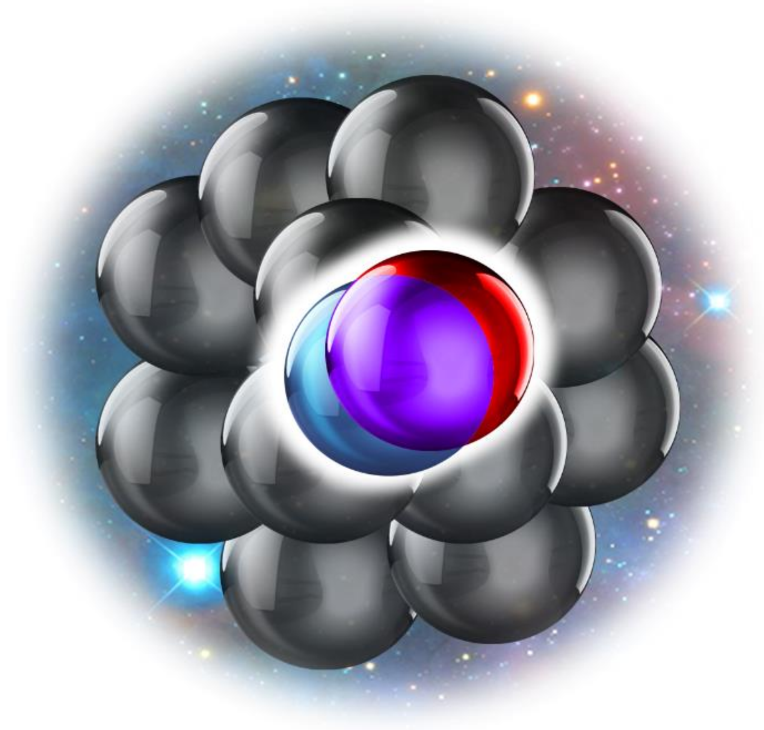
LOG MOMENTUM DISTRIBUTION
NUCLEON MOMENTUM
A-1
A-2
n
p
~k_F

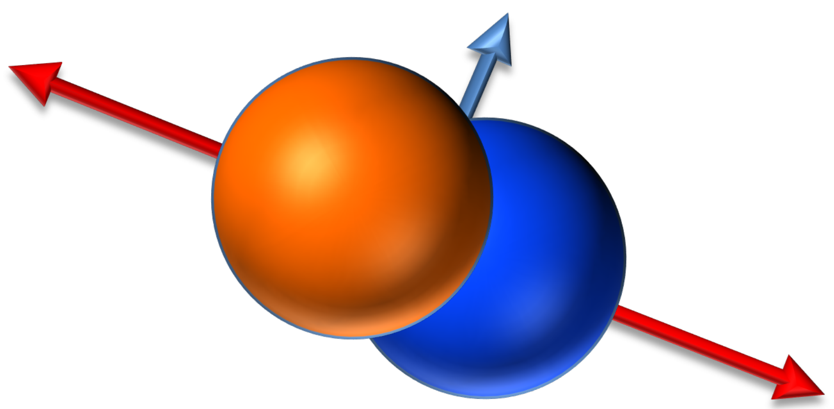
Probing Pairs



Nucleon pairs that are close together in the nucleus

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

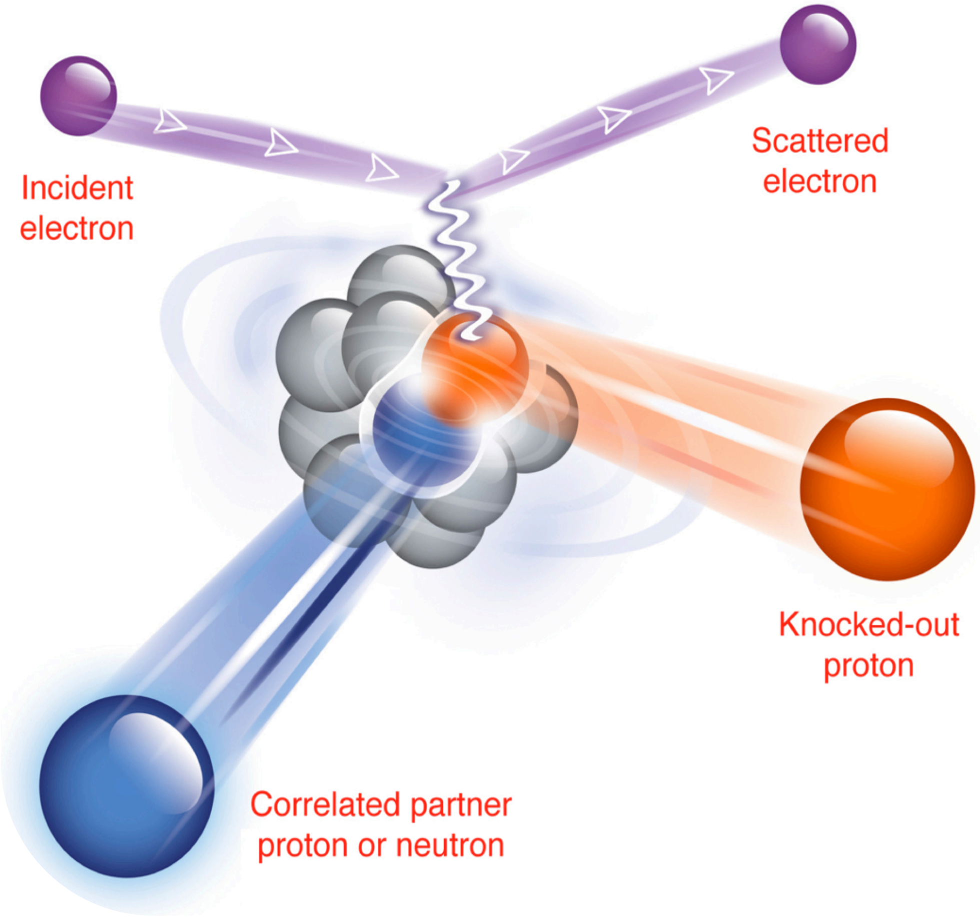




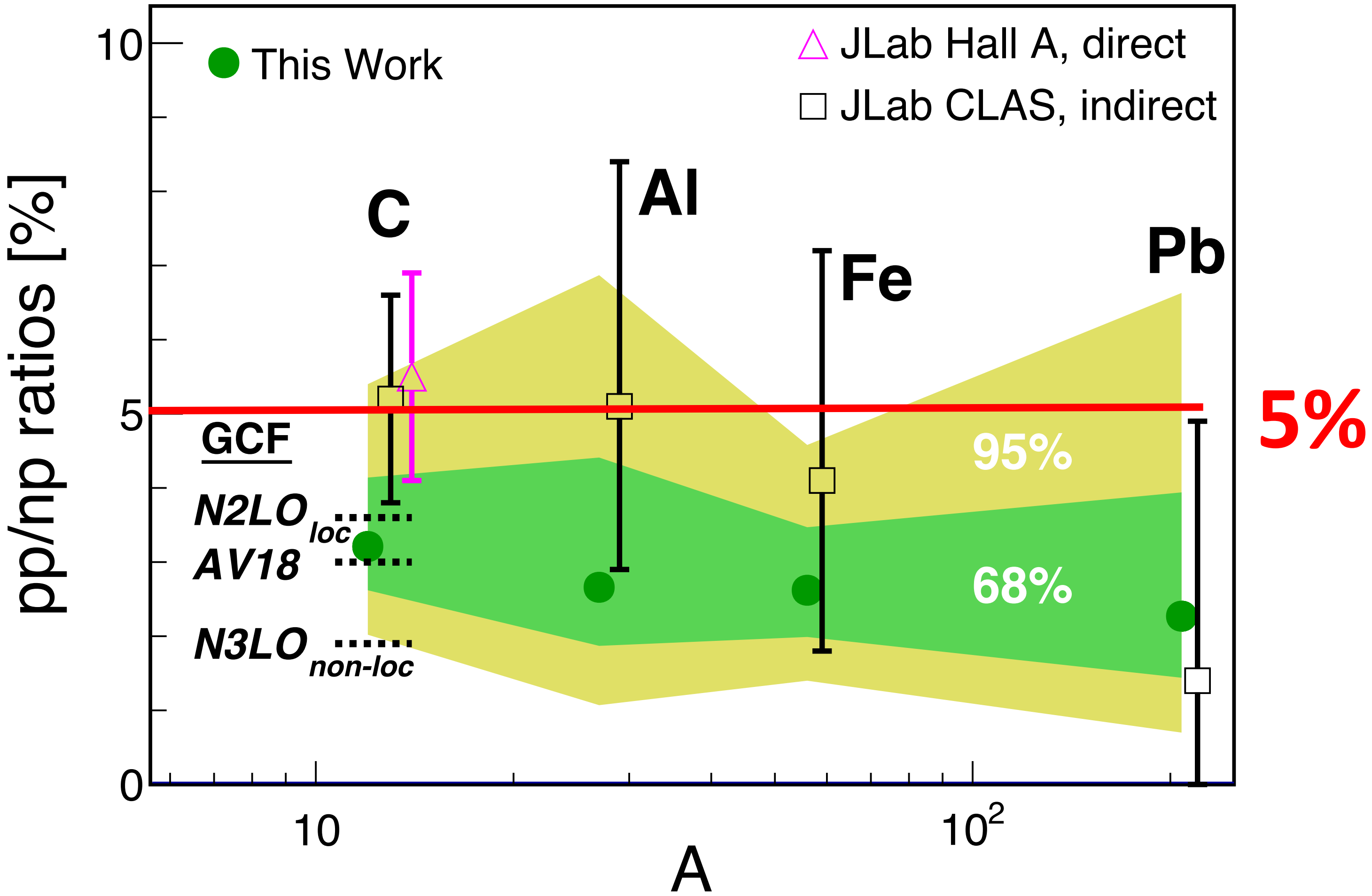
Breakup the pair =>

Detect ***both*** nucleons =>

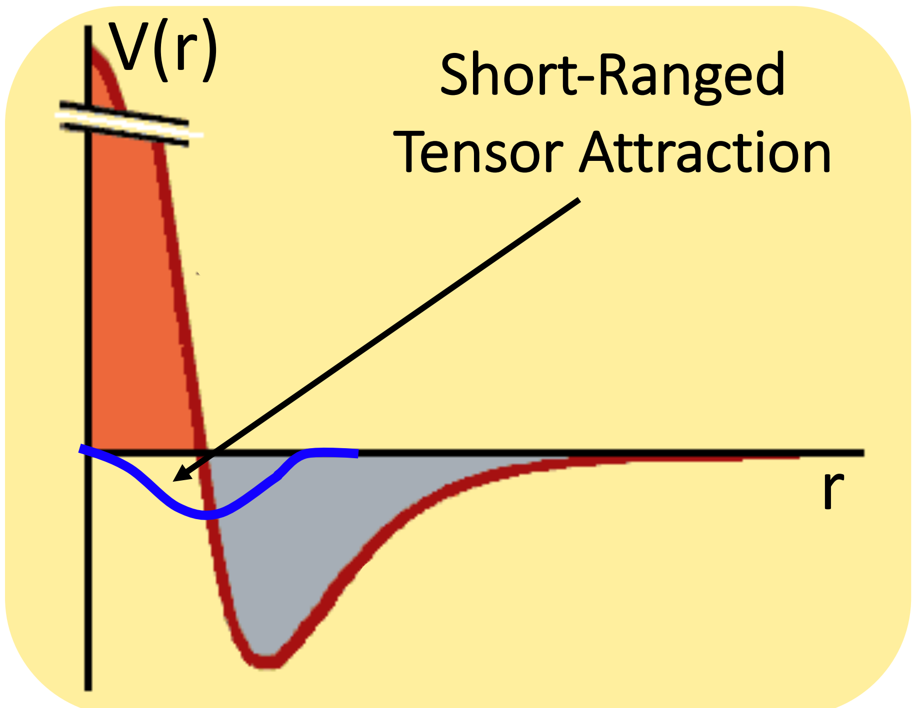
Reconstruct 'initial' state



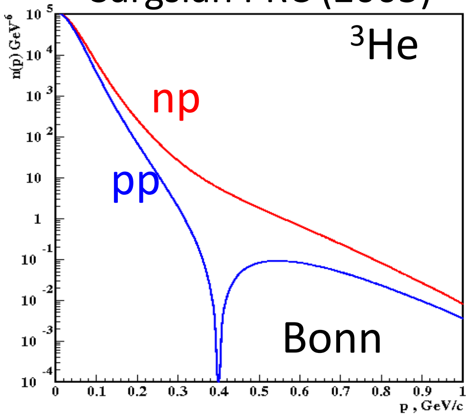
np dominance



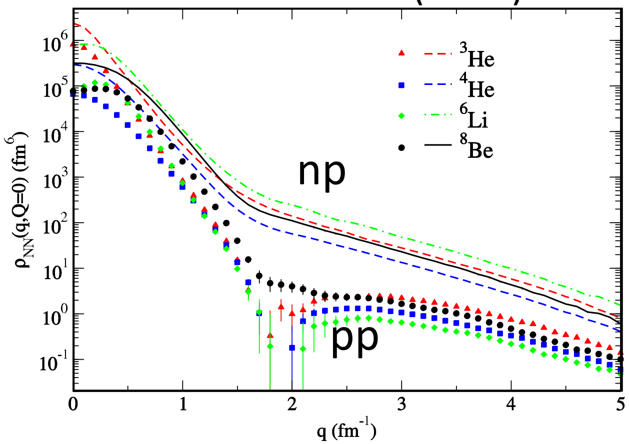
Duer, PRL (2019); Duer, Nature (2018); Hen, Science (2014); Korover, PRL (2014); Subedi, Science (2008); Shneor, PRL (2007); Piasetzky, PRL (2006); Tang, PRL (2003); Review: Hen RMP (2017);



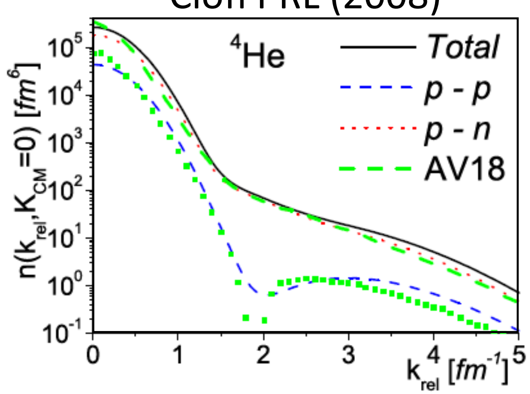
Sargsian PRC (2005)

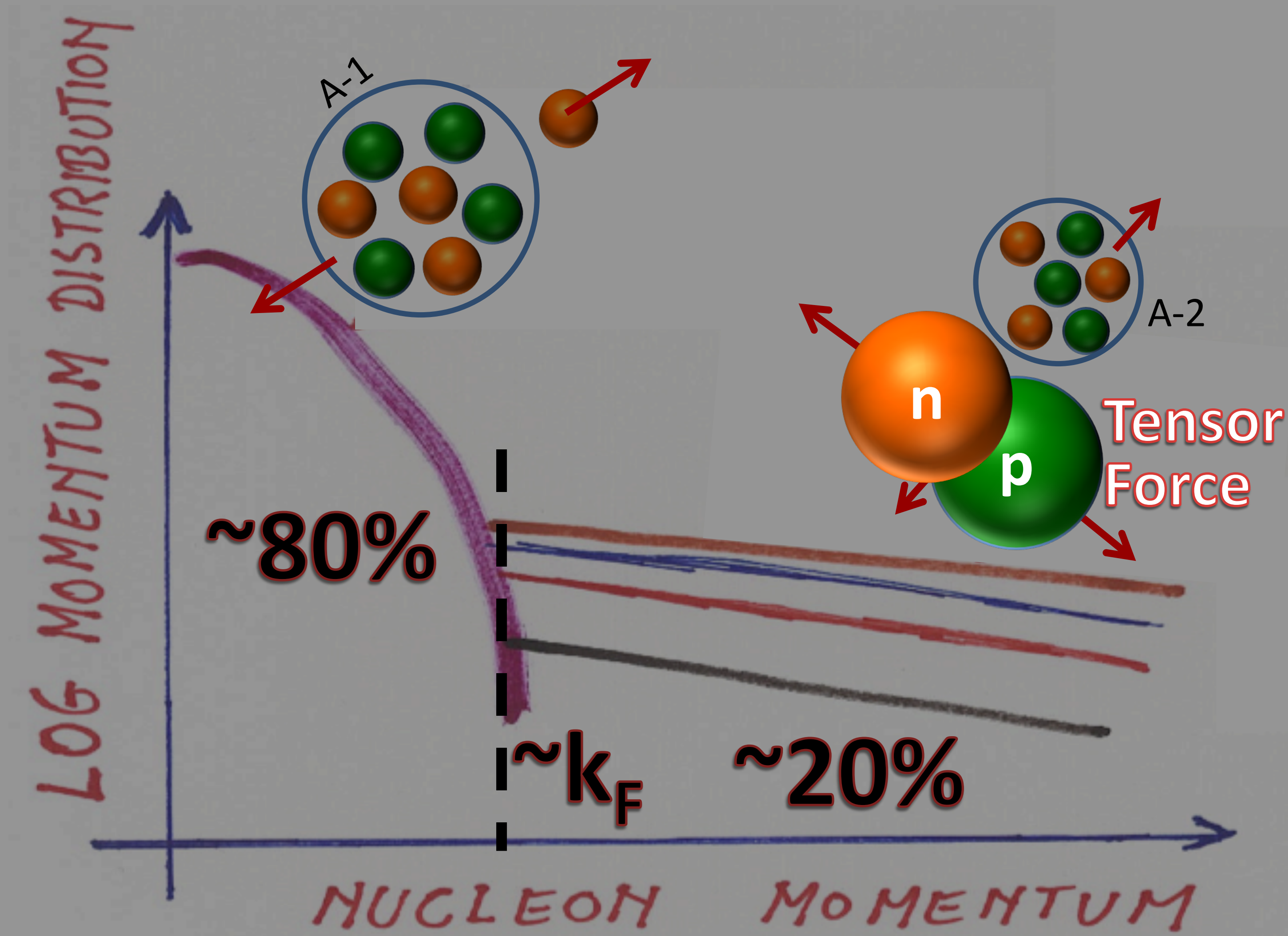


Schiavilla PRL (2007)

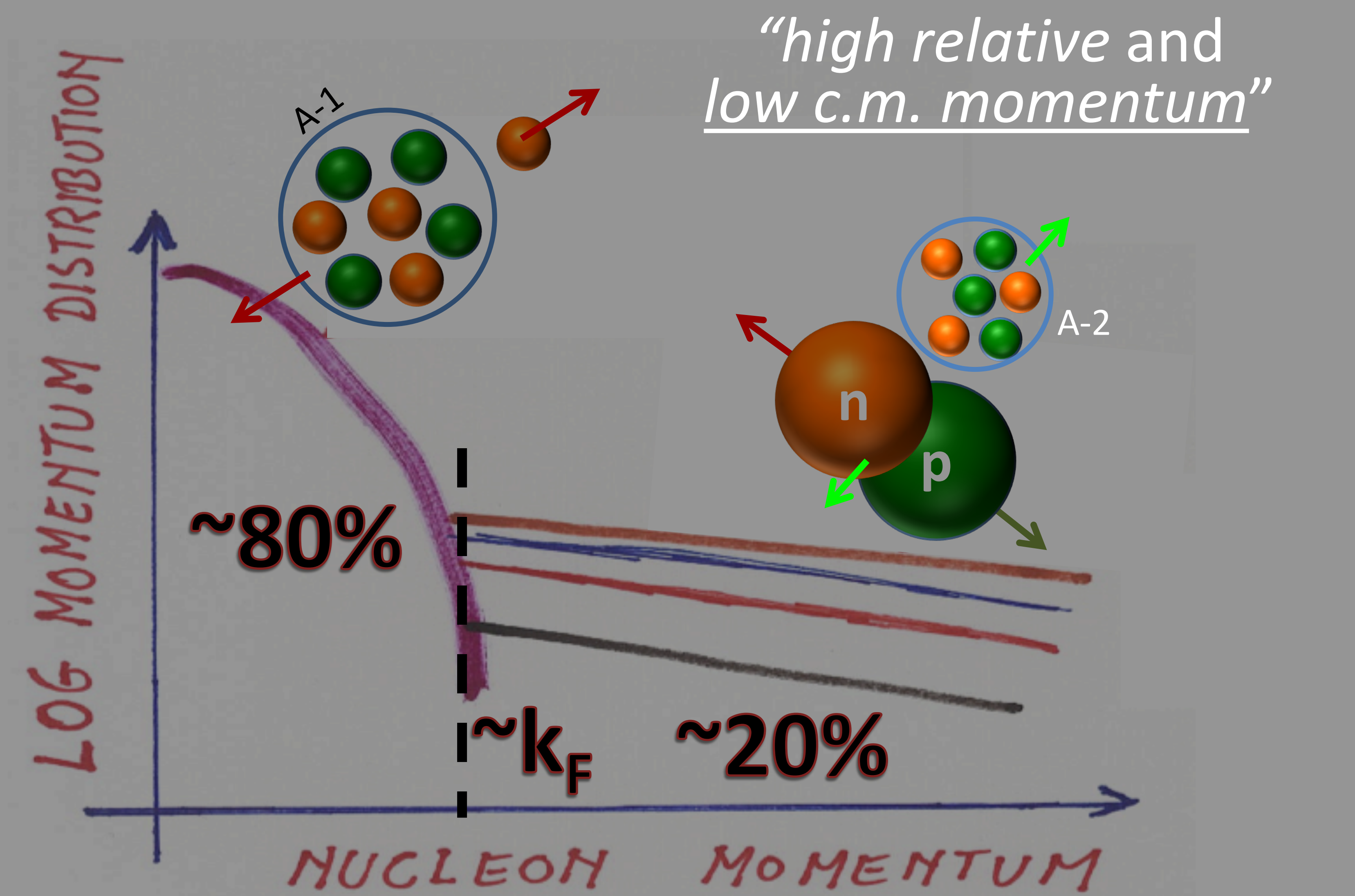


Ciofi PRL (2008)

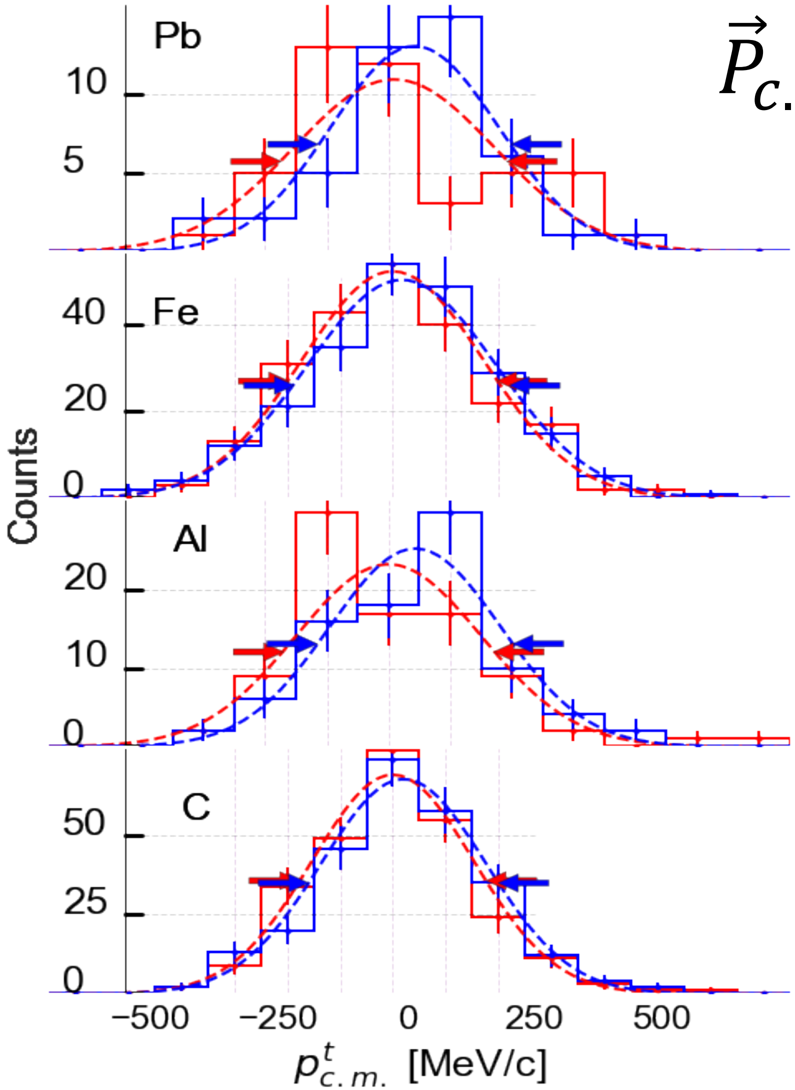




LOG MOMENTUM DISTRIBUTION
A-1
A-2
n
p
Tensor
Force
~80%
~k_F
~20%
NUCLEON MOMENTUM


"*high relative* and
<u>*low c.m. momentum*</u>"
A-1
A-2
n
p
LOG MOMENTUM DISTRIBUTION
~80%
~k_F
~20%
NUCLEON MOMENTUM

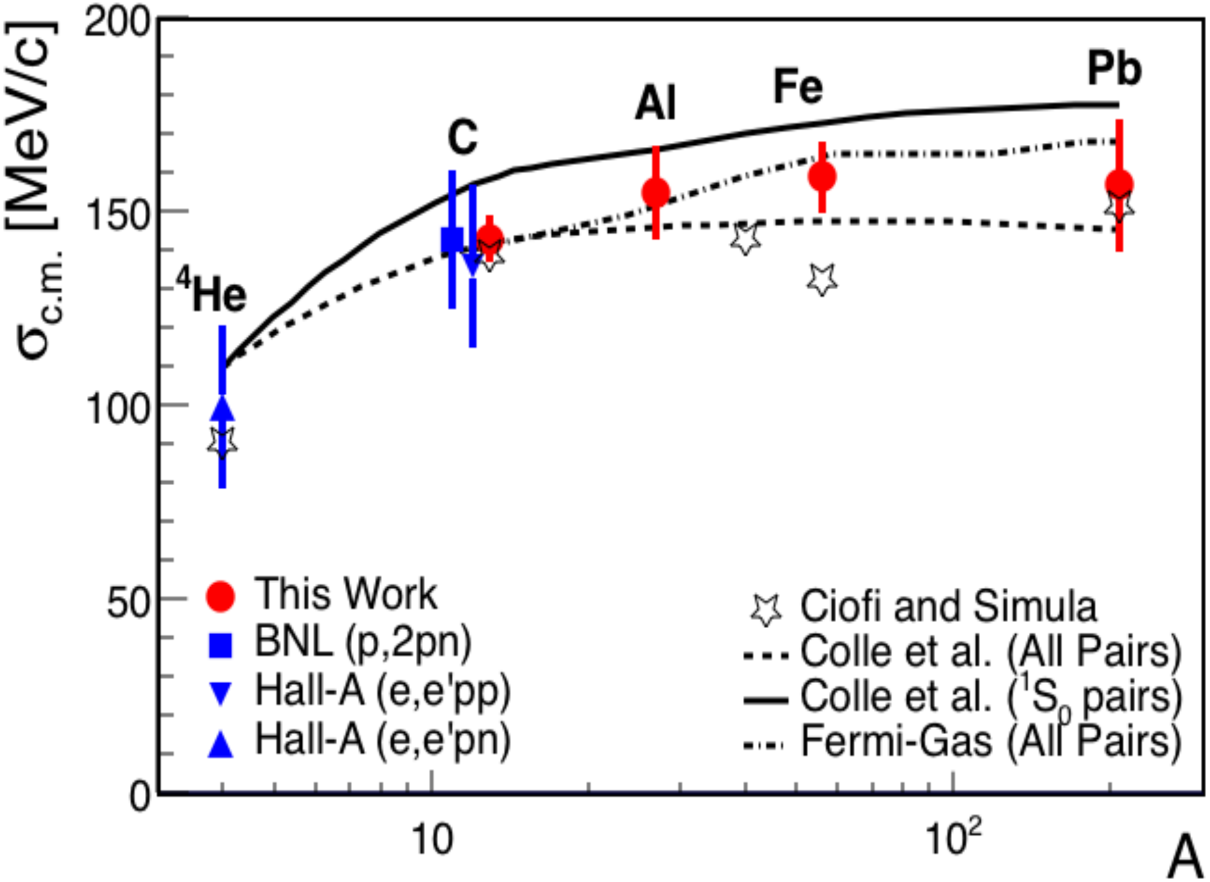
Low Pair C.M. Motion

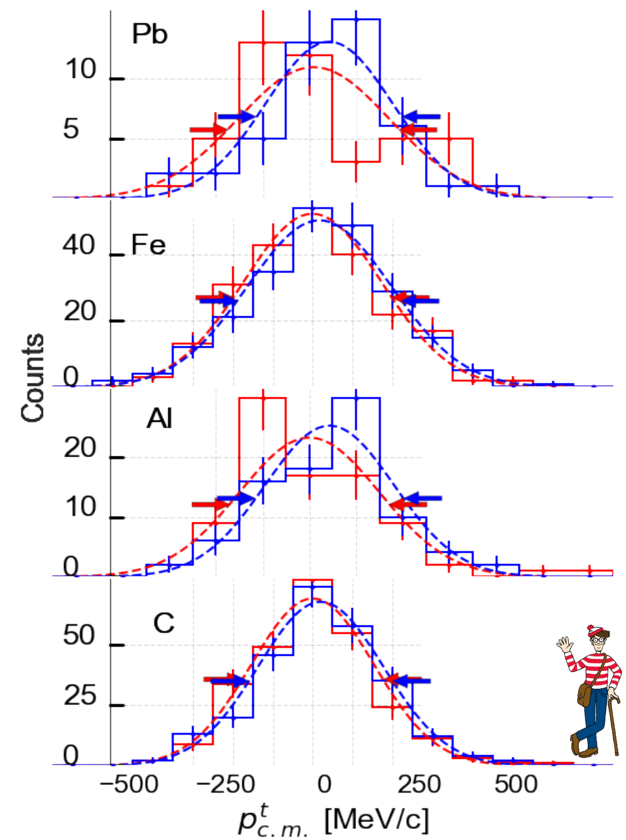


$$\vec{P}_{c.m.} = \vec{P}_{N1} + \vec{P}_{N2}$$

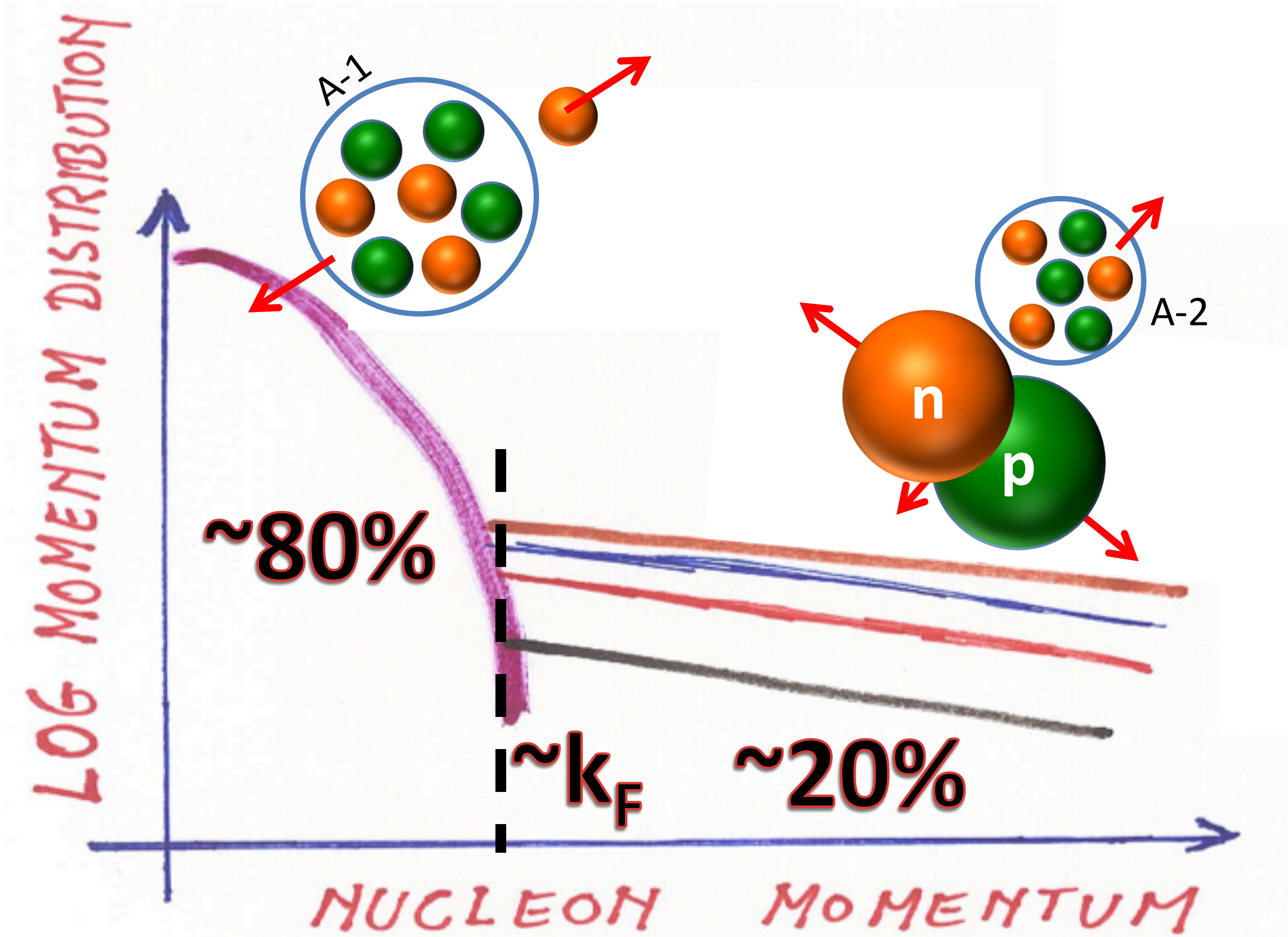
Cohen, PRL (2018).

Low Pair C.M. Motion





Cohen, PRL (2018).



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

Going neutron rich:

What do excess neutrons do?

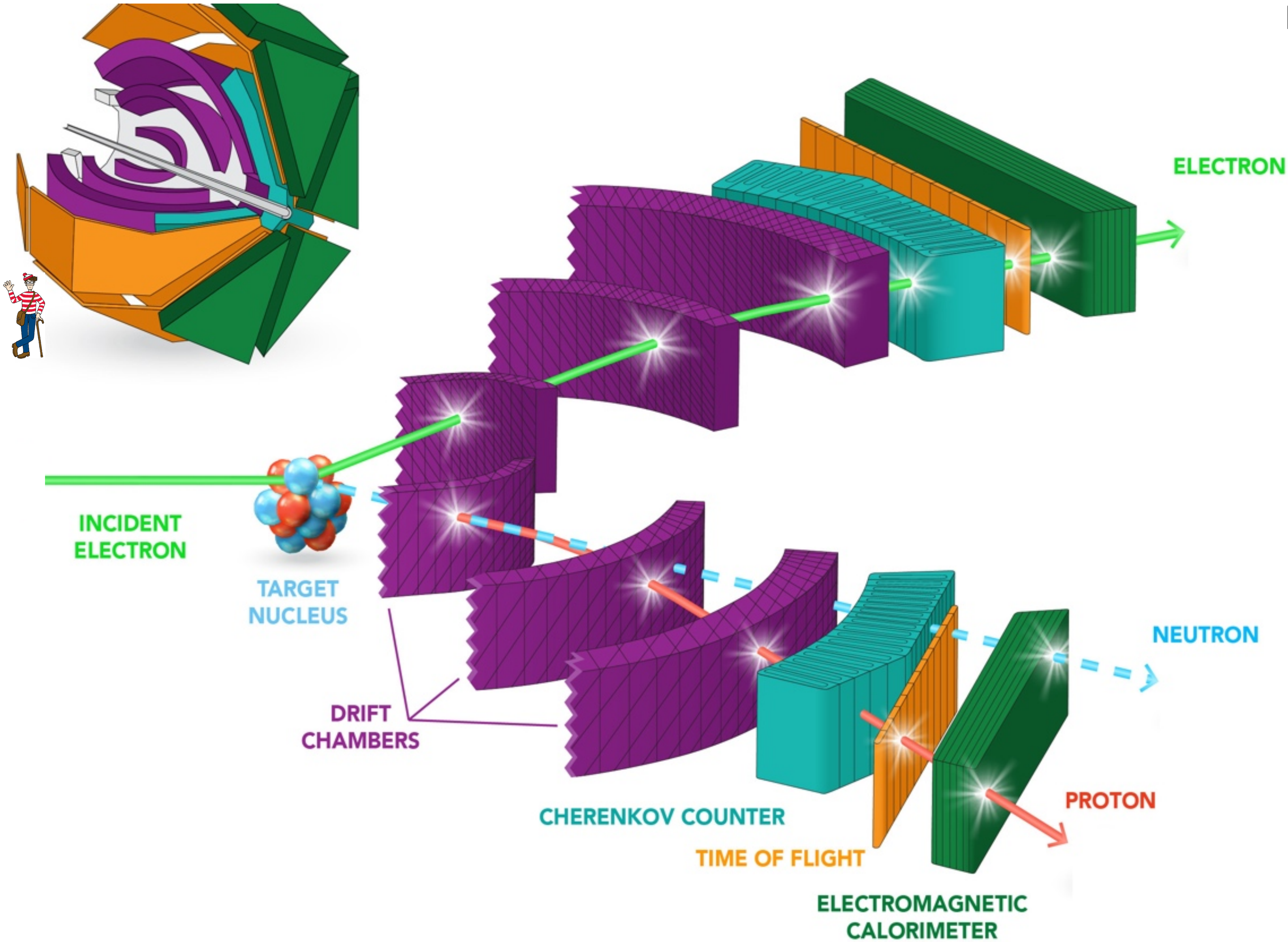
don't correlate?

correlate with each other?

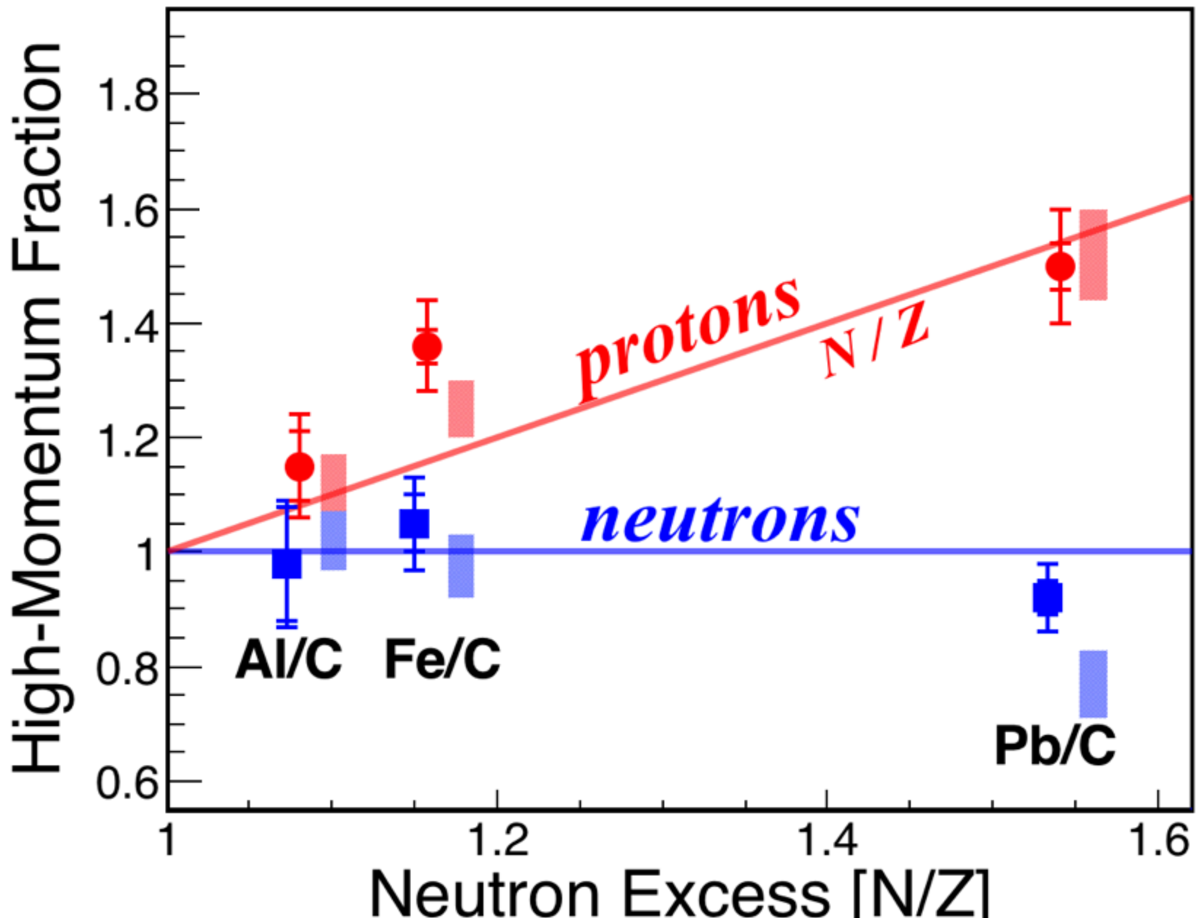
correlate with core protons?

Proton vs. Neutron Knockout

M. Duer

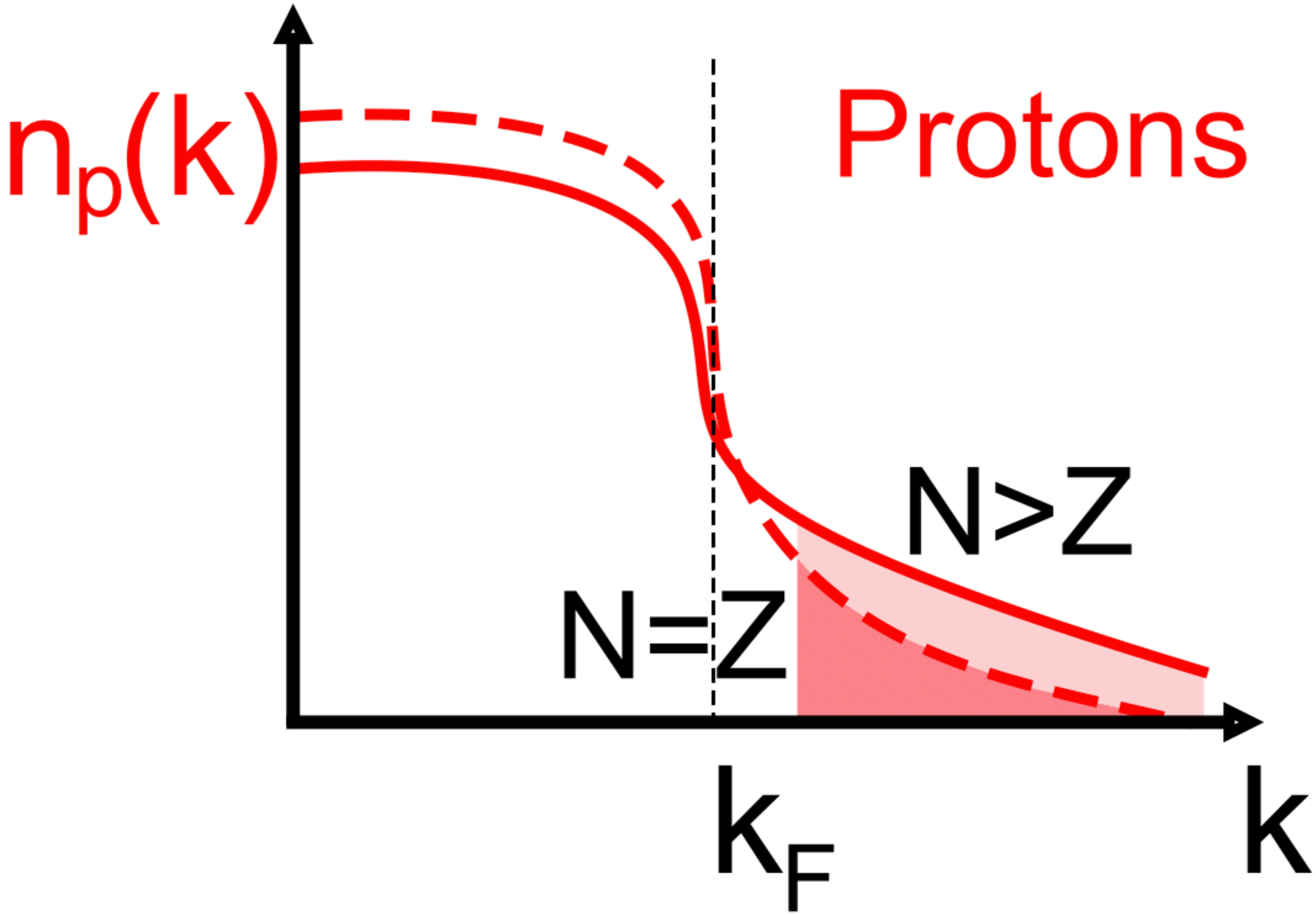


Correlation Probability:
Neutrons saturate Protons grow



Duer et al., Nature (2018)

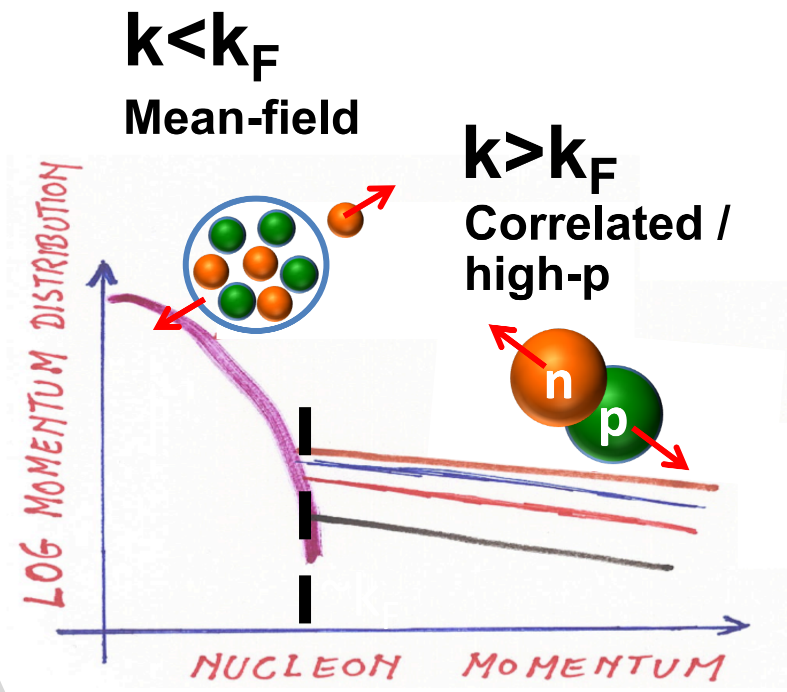
Protons ‘Speed-Up’ In Neutron-Rich Nuclei



Duer et al., Nature (2018)

Interim Summary

- Nuclear momentum distribution have two distinct regions.



Interim Summary

- Nuclear momentum distribution have two distinct regions.
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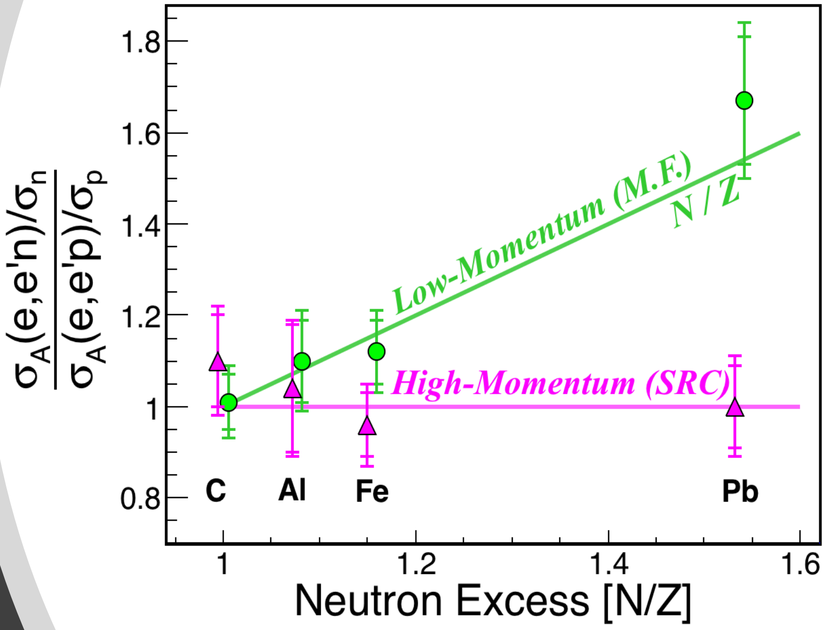

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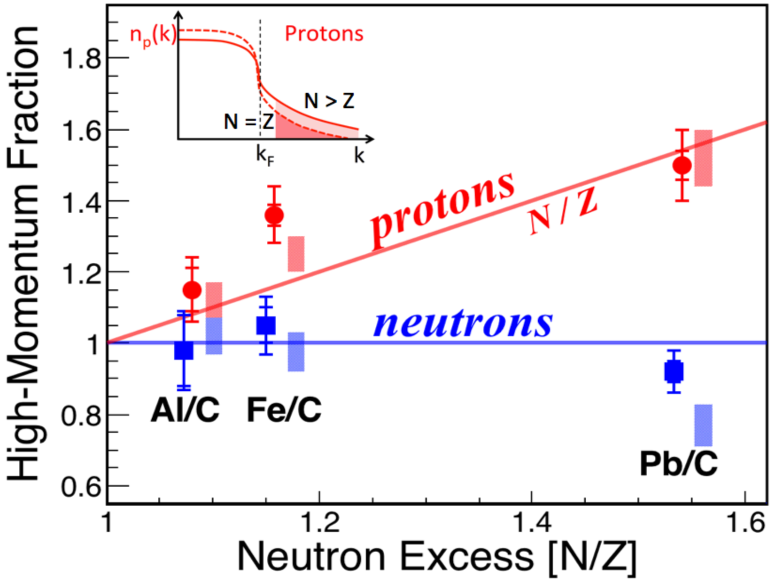

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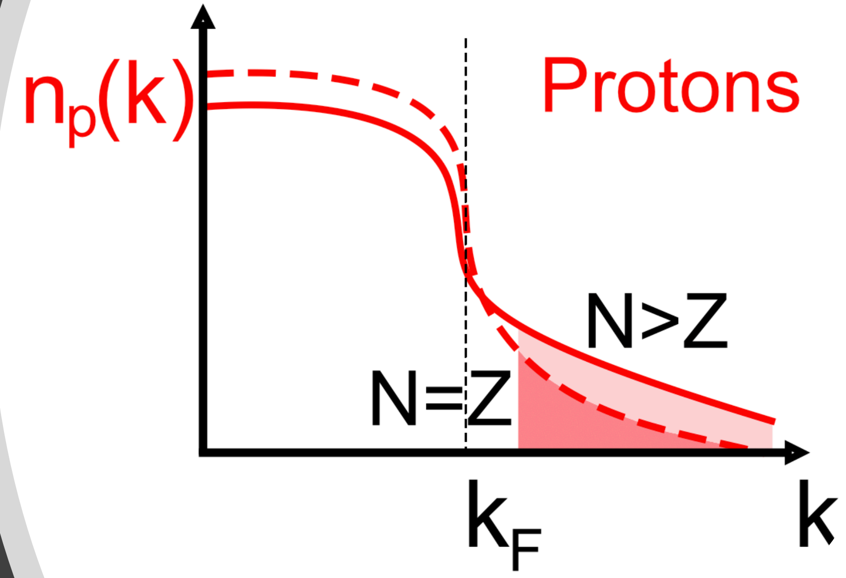
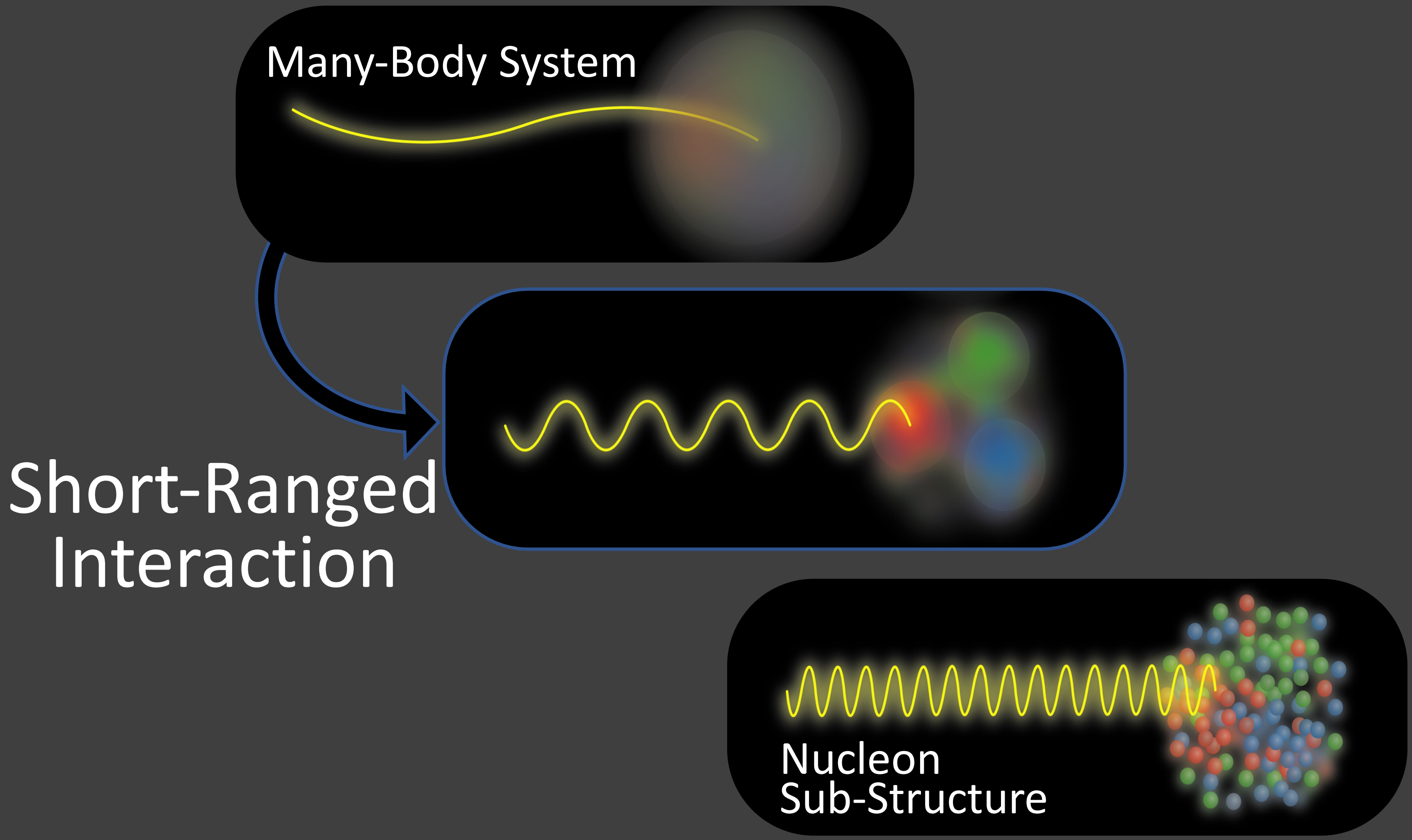
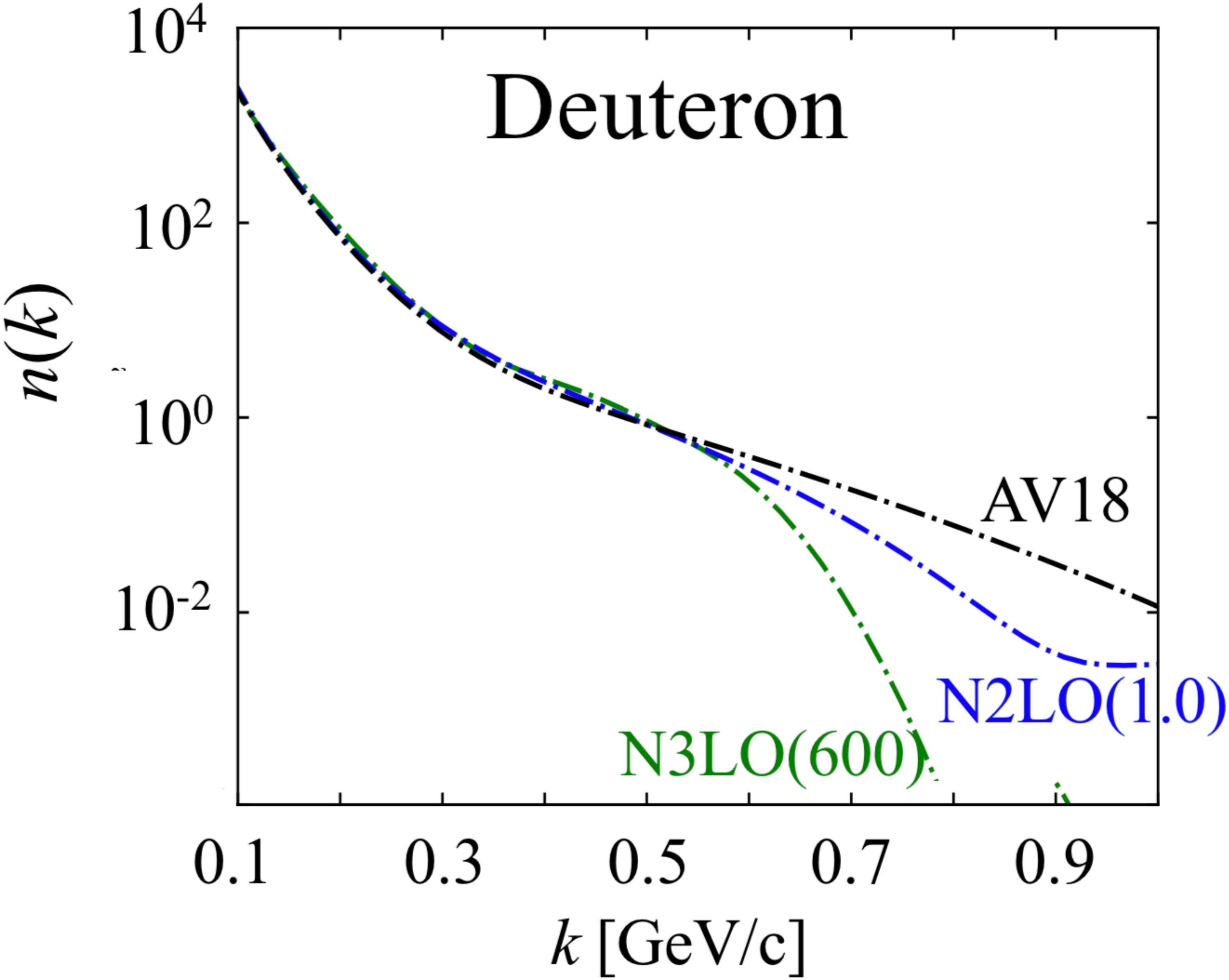



Many-Body System
Short-Ranged Interaction
Nucleon Sub-Structure


Deuteron
10^4
10^2
10^0
10^{-2}
$n(k)$
AV18
N2LO(1.0)
N3LO(600)
0.1
0.3
0.5
0.7
0.9
k [GeV/c]

Probing the NN Interaction

- Measure one- and two-nucleon knockout cross-sections.
- Compare with calculations using different NN interactions.
- See which one works best

Probing the NN Interaction

What's needed?

- Ab-initio cross-section calculations

- Data

Probing the NN Interaction

What's needed?

- ~~Ab-initio cross-section calculations~~
  => Plain-wave \w spectral functions from NN interaction

- Data

$$\frac{d^4\sigma}{d\Omega_{k'}\, d\epsilon'_k\, d\Omega_{p'_1}\, d\epsilon'_1} = p'_1 \epsilon'_1 \sigma_{eN} S^N(\boldsymbol{p}_1, \epsilon_1)$$

Probing the NN Interaction

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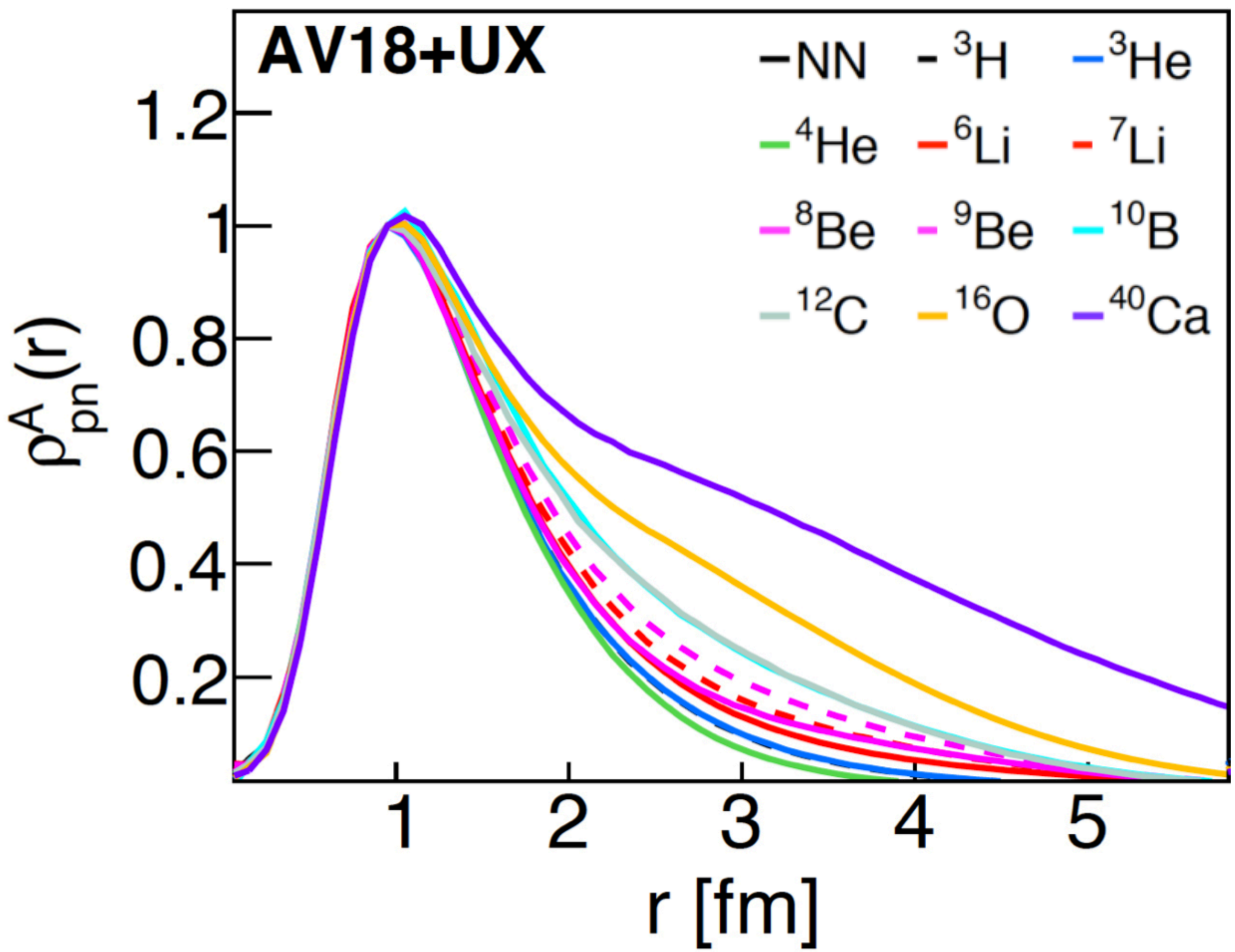
Scale and Scheme Independence and Position-Momentum Equivalence of Nuclear Short-Range Correlations

R. Cruz-Torres,[1] D. Lonardoni,[2,3] R. Weiss,[4] N. Barnea,[4] D. W. Higinbotham,[5]
E. Piasetzky,[6] A. Schmidt,[1] L. B. Weinstein,[7] R. B. Wiringa,[8] and O. Hen[1,*]

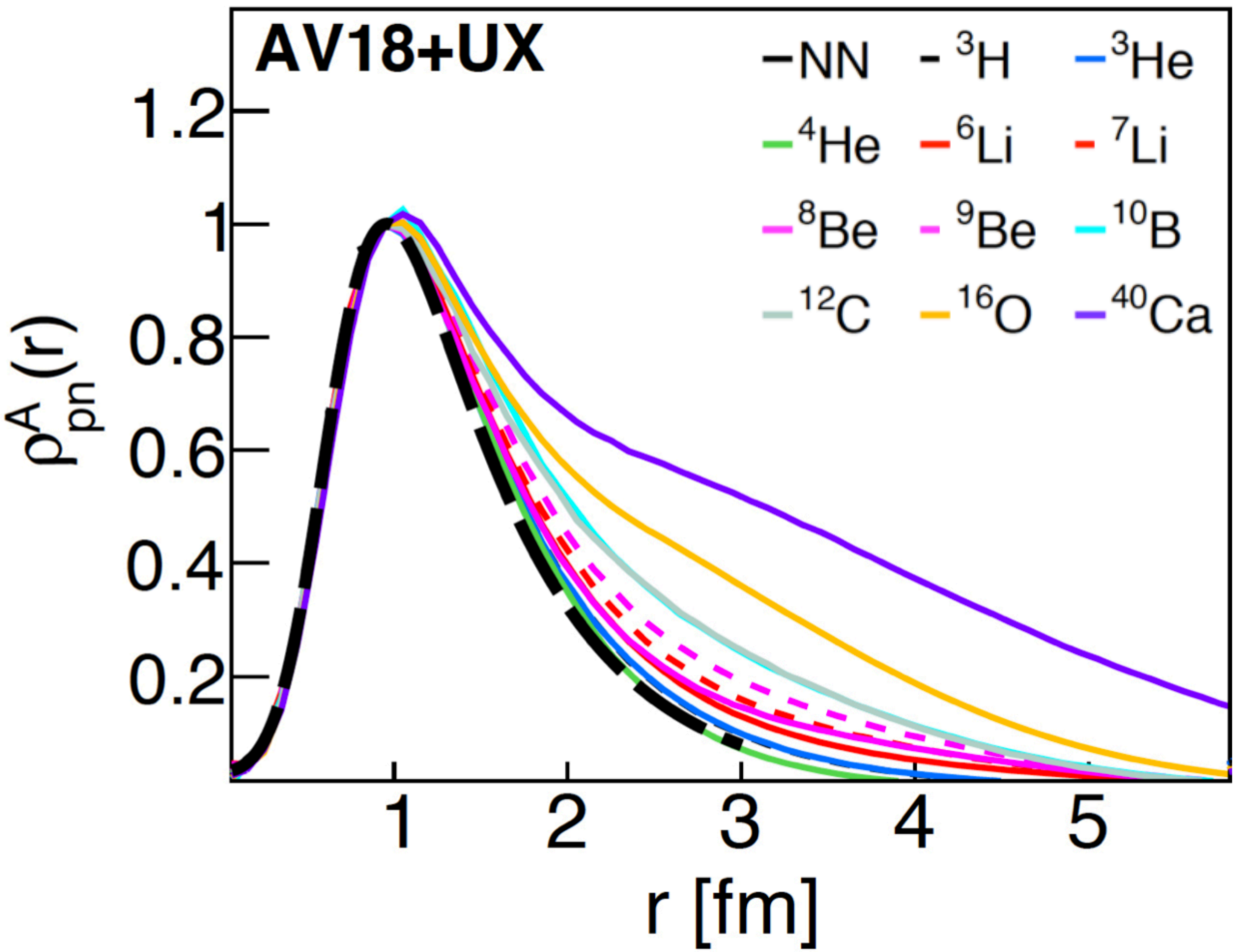
Ab-initio Quantum Monte Carlo (QMC) calculations of nuclei from deuterium to ^{40}Ca, obtained using four different phenomenological and local chiral nuclear potentials, are analyzed using the Generalized Contact Formalism (GCF). We extract spin- and isospin-dependent "nuclear contact terms" for each interaction in both coordinate and momentum space. The extracted contact terms, that count the number of short-range correlated (SRC) pairs with different quantum numbers, are dependent on the nuclear interaction model used in the QMC calculation. However, the ratios of contact terms for a nucleus A to deuterium (for spin-1 pn pairs) or to ^{4}He (for all NN pairs) are independent of the nuclear interaction model and are the same for both short-distance and high-momentum pairs. This implies that the relative abundance of *short-range* pairs in the nucleus is a *long-range* (mean-field) quantity that is insensitive to the short-distance nature of the nuclear force. Measurements of exclusive $(e, e'NN)$ pair breakup processes are instead more sensitive to short-range dynamics.

QMC Pair distance distributions



Cruz Torres and Lonardoni et al. (2019)

QMC Pair distance distributions



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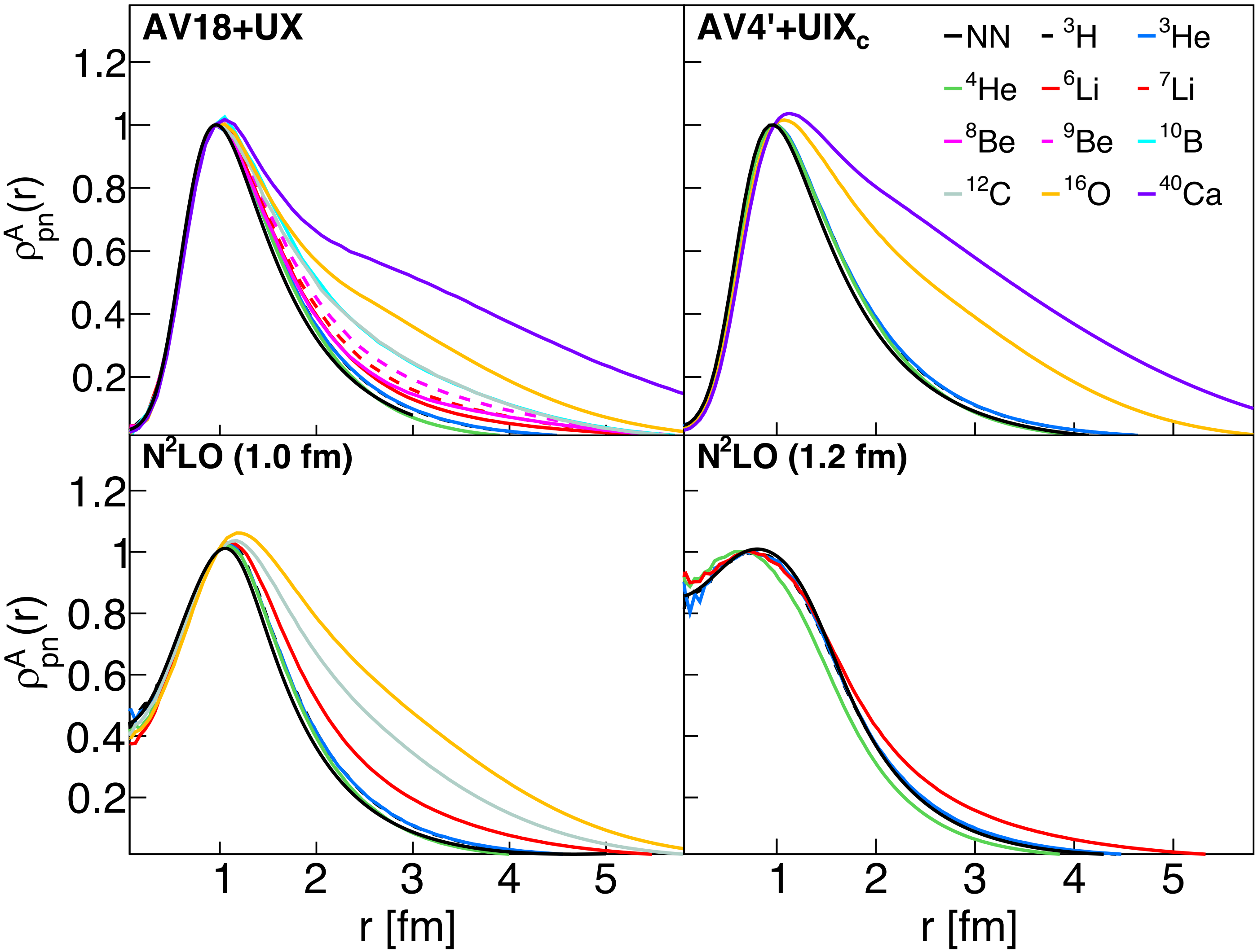
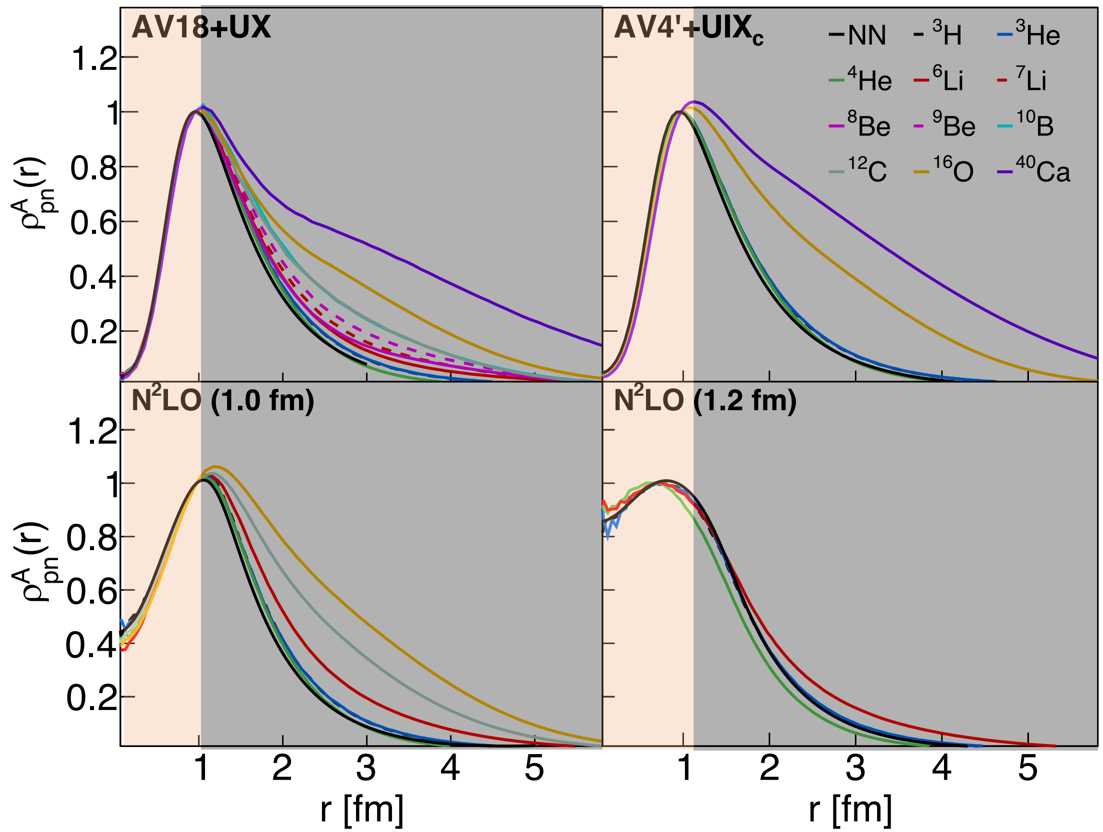


Cruz Torres and Lonardoni et al. (2019)

GCF Factorization

$$\rho_A^{NN,\alpha}(r) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(r)|^2$$



Weiss et al., Phys. Lett. B (2018);
Cruz Torres et al., Phys. Lett B (2018);
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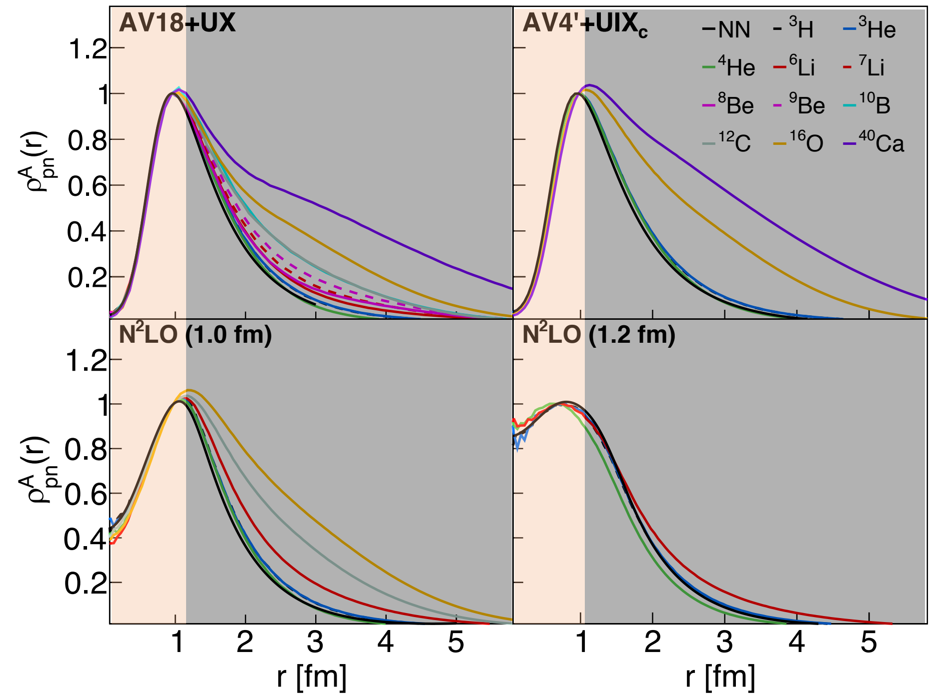

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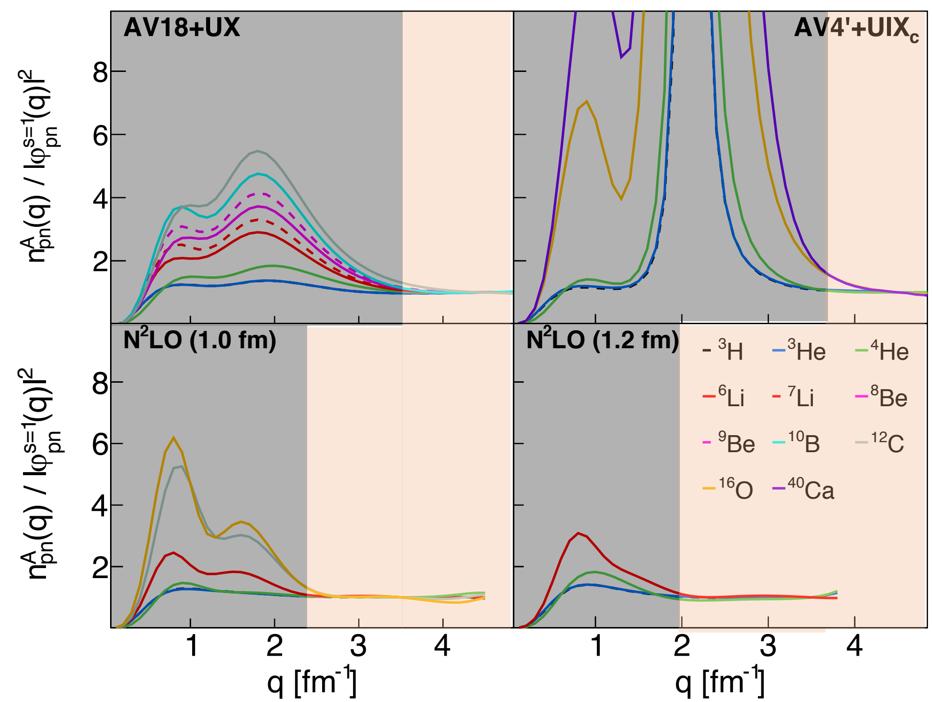

$$n_A^{NN,\alpha}(q) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(q)|^2$$

Weiss et al., Phys. Lett. B (2018);
Cruz Torres et al., Phys. Lett B (2018);
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P-A-I-R-S

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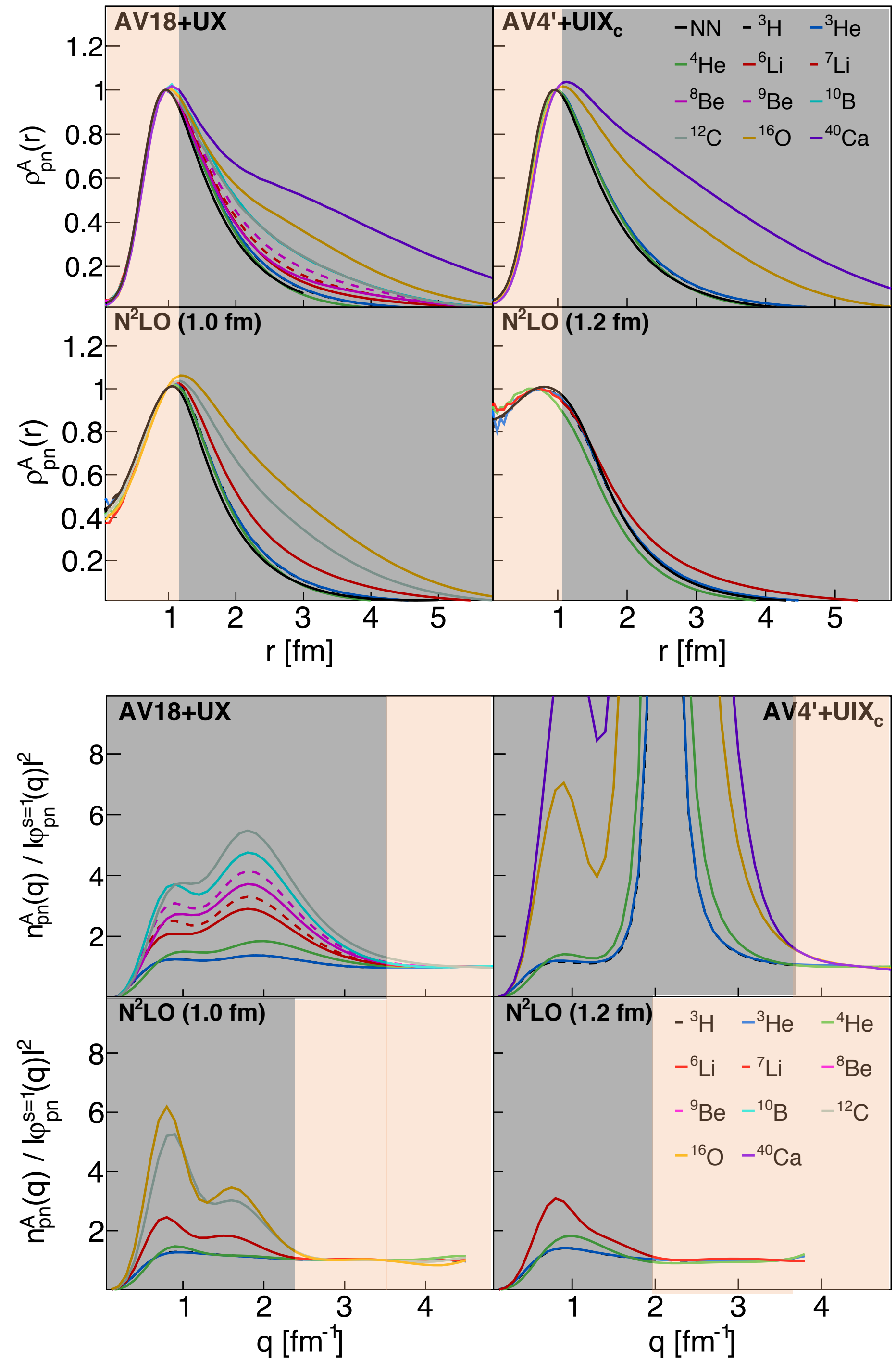

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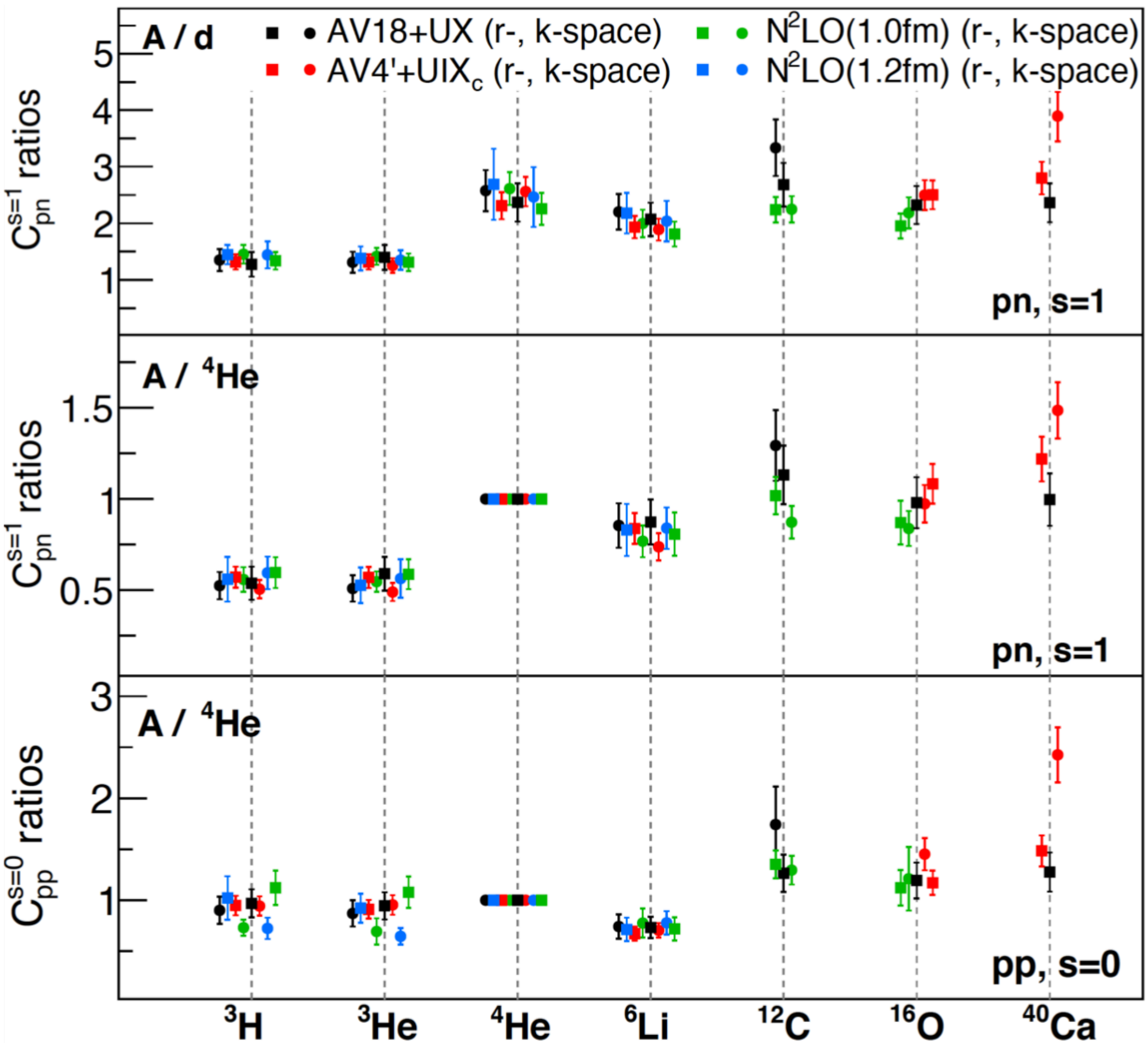
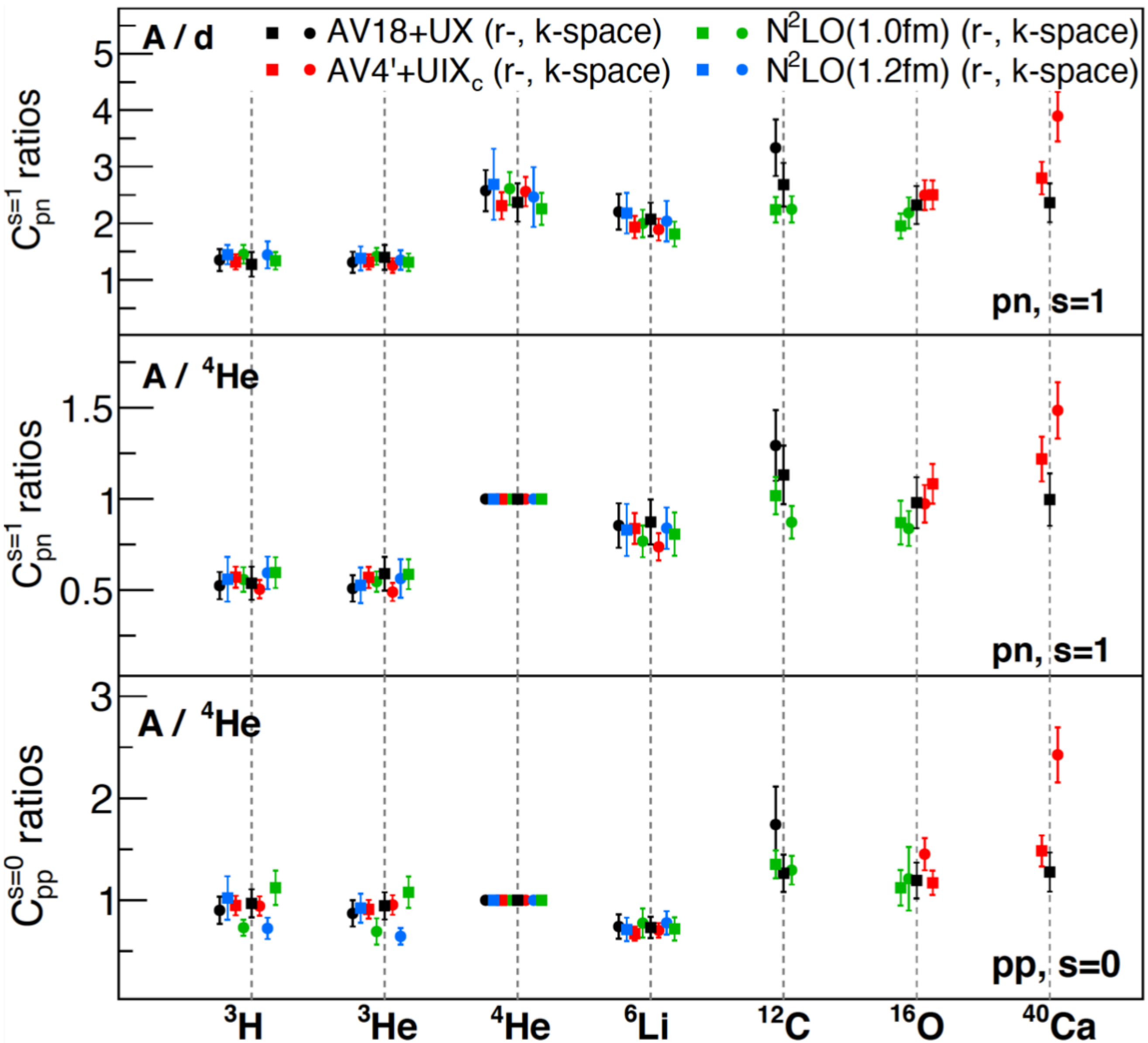
Scale & Scheme Independence



Cruz Torres and Lonardoni et al. (2019)

Momentum–Position Equivalence



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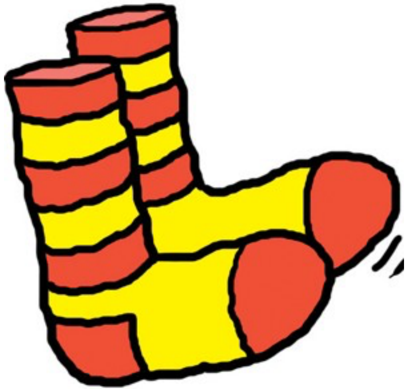

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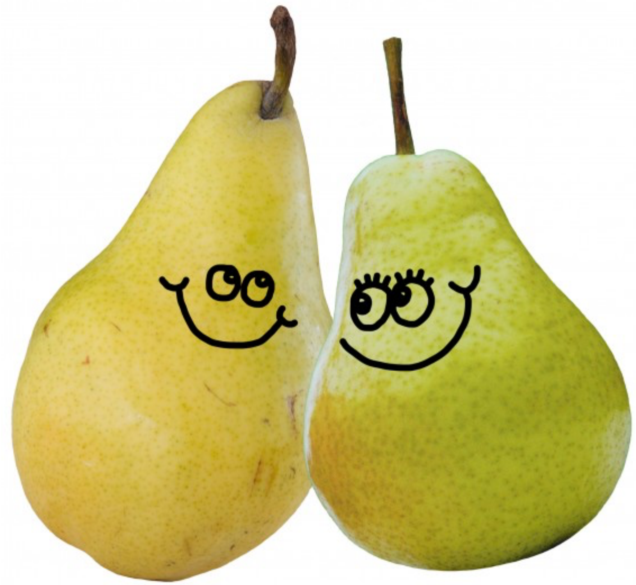

GCF: Pairs Spectral Functions

$$
\begin{aligned}
S^{p}(p,\varepsilon) \quad = \quad & C_A^{pn,\,s=1} \cdot S_{pn}^{s=1}(p,\varepsilon) + \\
& C_A^{np,\,s=0} \cdot S_{pn}^{s=0}(p,\varepsilon) + \\
& 2C_A^{pp,\,s=0} \cdot S_{pp}^{s=0}(p,\varepsilon)
\end{aligned}
$$

Weiss, Phys. Lett. B (2018); Cruz Torres, Phys. Lett B (2018); Weiss Phys. Lett B (2019).

GCF: Pairs Spectral Functions

$$S^p(p,\varepsilon) \;=\; C_A^{pn,\,s=1} \cdot S_{pn}^{s=1}(p,\varepsilon) + C_A^{np,\,s=0} \cdot S_{pn}^{s=0}(p,\varepsilon) + 2C_A^{pp,\,s=0} \cdot S_{pp}^{s=0}(p,\varepsilon)$$

Each pair is convoluted with c.m. motion:

$$S_{ab}^{\alpha} = \frac{1}{4\pi} \int \frac{d\boldsymbol{p}_2}{(2\pi)^3} \delta(f(\boldsymbol{p}_2)) \left|\tilde{\varphi}_{ab}^{\alpha}(|(\boldsymbol{p}_1 - \boldsymbol{p}_2)/2|)\right|^2 n_{ab}^{\alpha}(\boldsymbol{p}_1 + \boldsymbol{p}_2)$$

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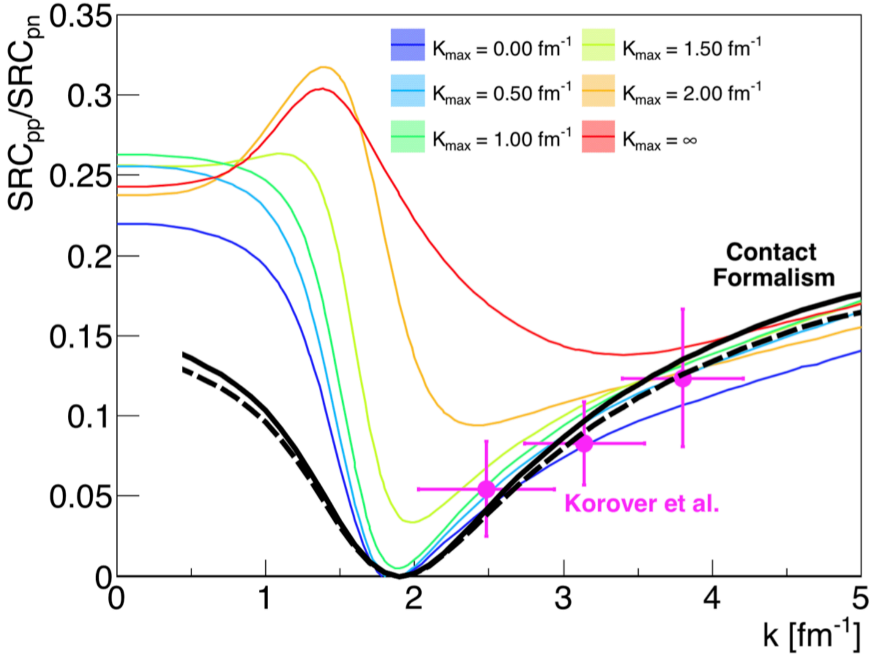
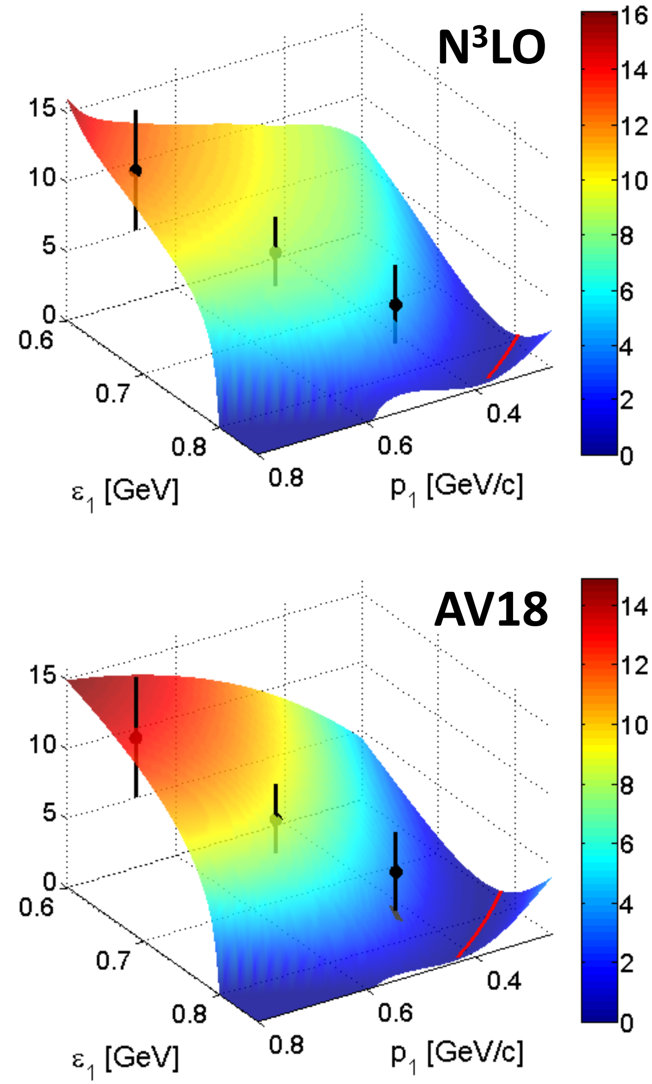
$$

Weiss, Phys. Lett. B (2018); Cruz Torres, Phys. Lett B (2018); Weiss Phys. Lett B (2019).

GCF: Realistic Spectral Functions





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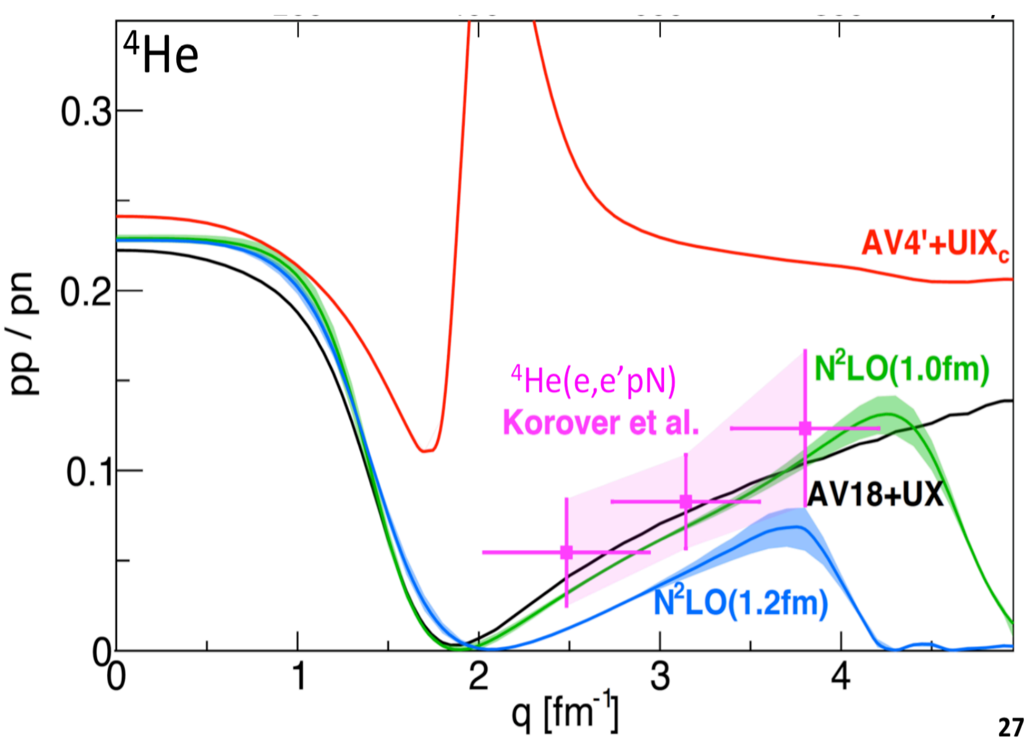

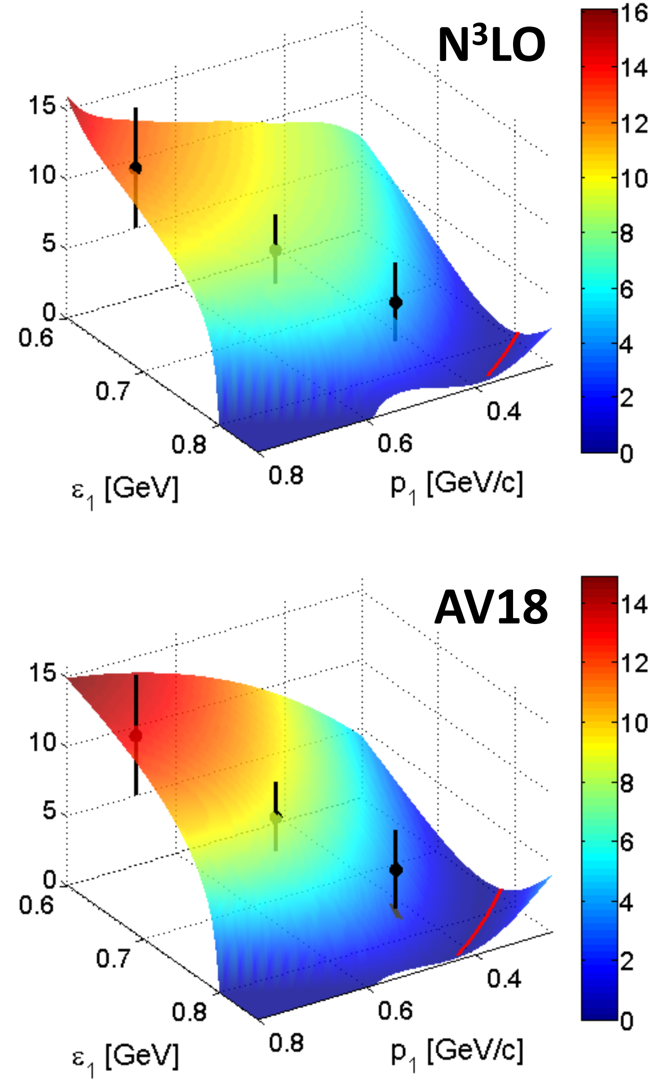

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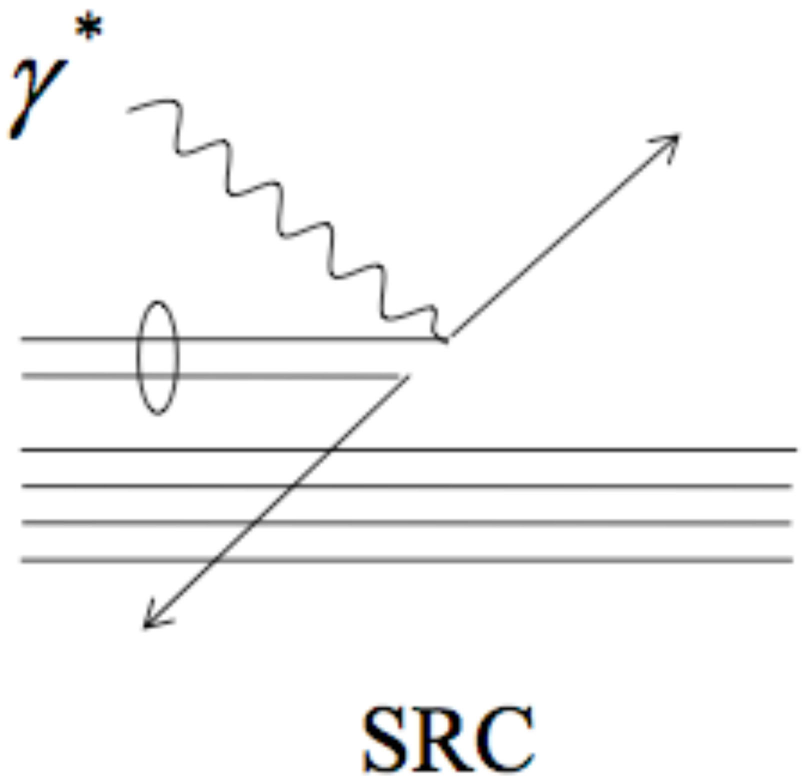
Two-Nucleon Knockout



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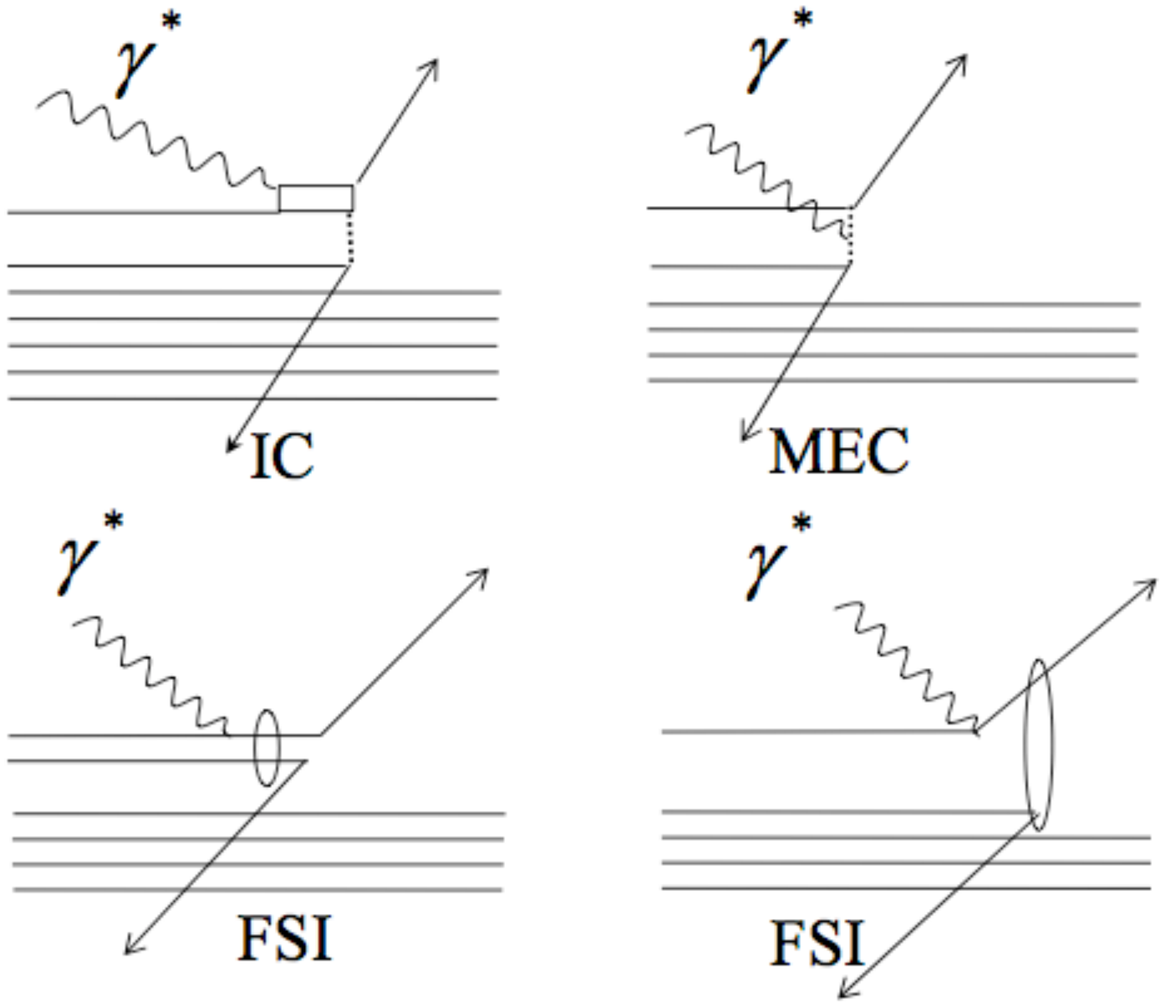

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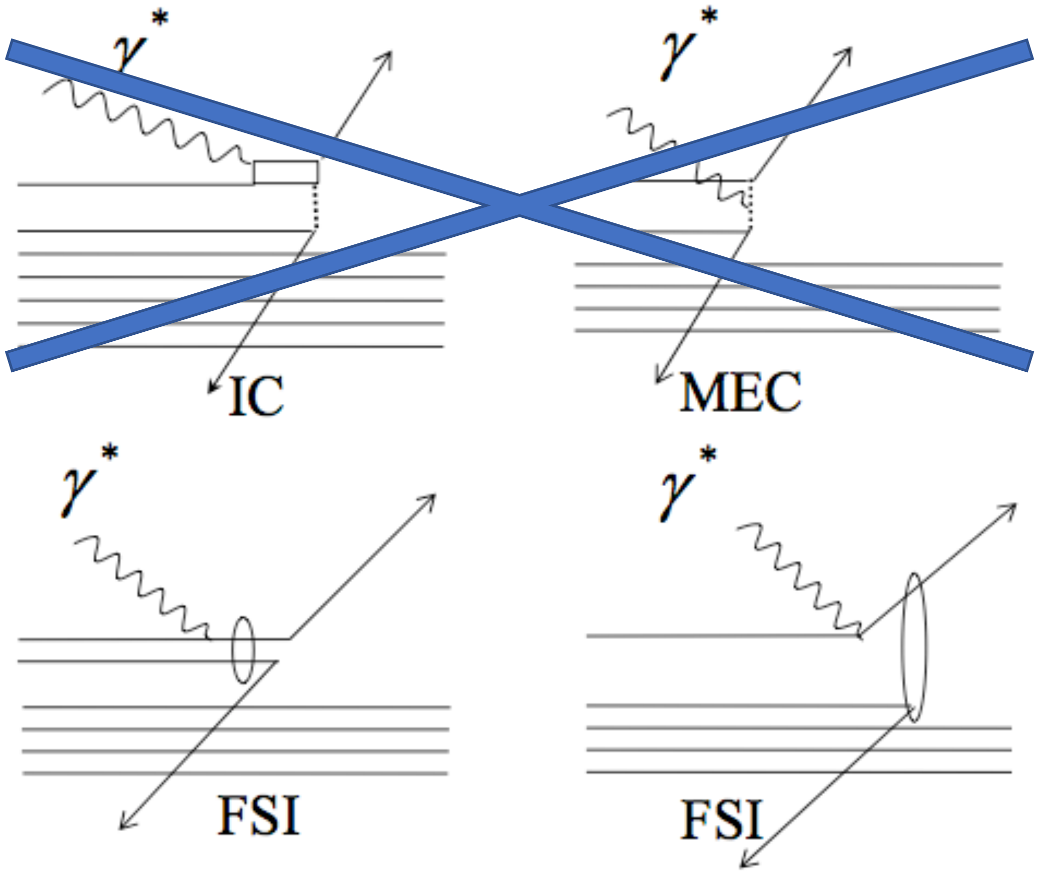

MEC suppressed @ **high-Q^2**, IC suppressed at **$x_B > 1$.**

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

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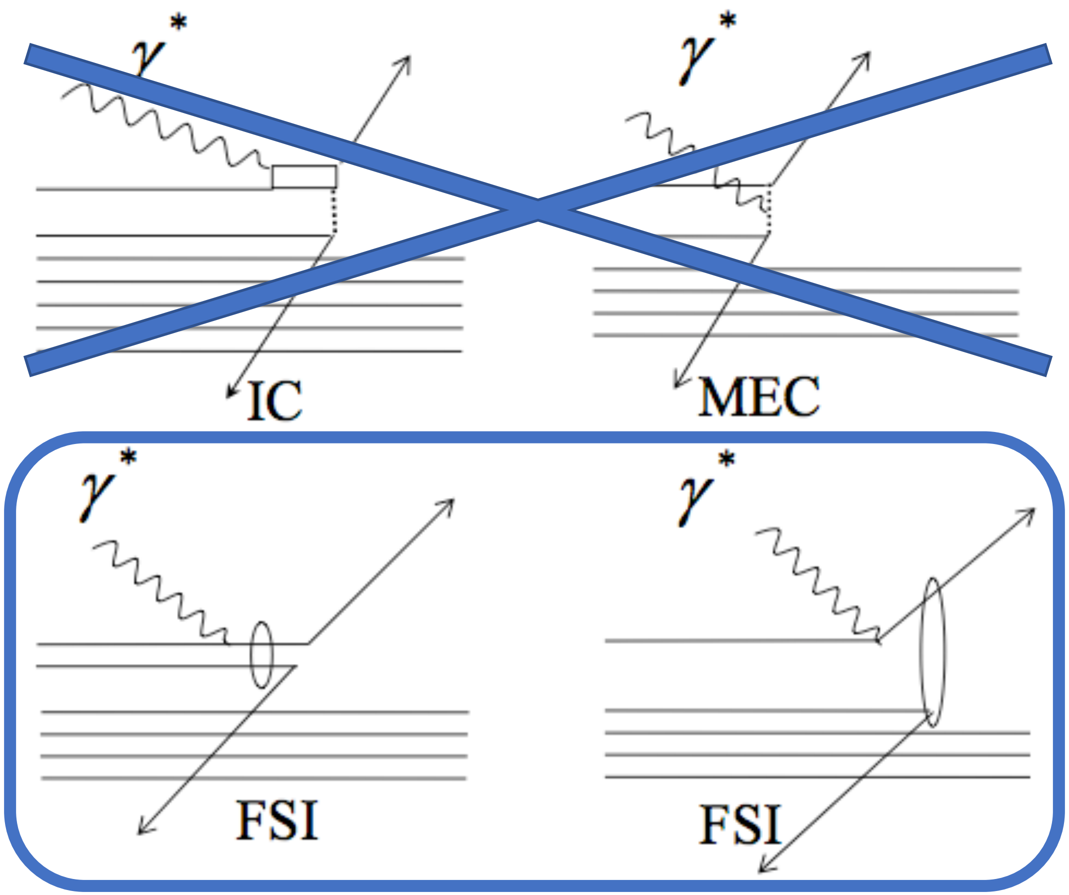


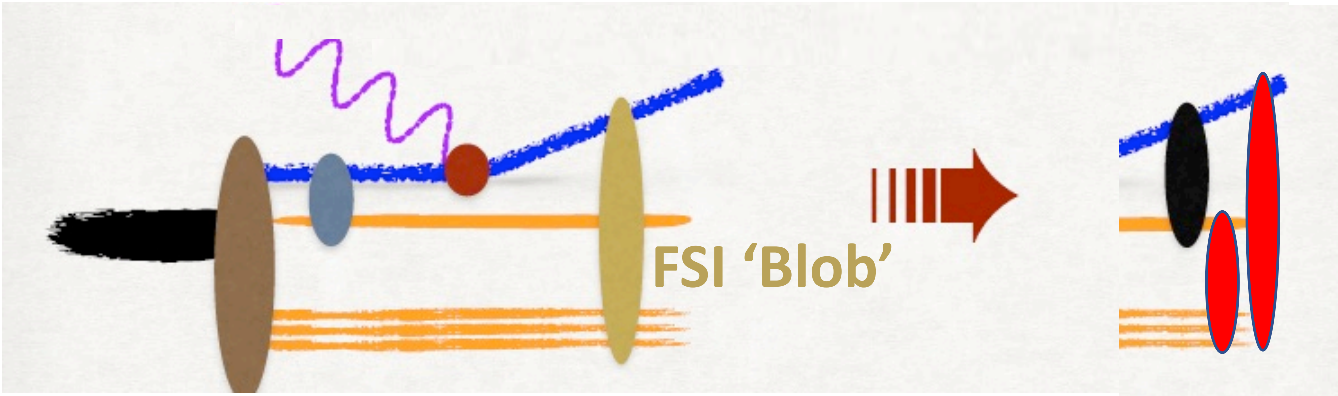
MEC suppressed @ **high-Q^2**, IC suppressed at **$x_B > 1$.**

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

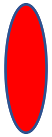
Frankfurt, Sargsian, and Strikman PRC **56**, 1124 (1997).
Colle, Cosyn, and Ryckebusch, PRC **93**, 034608 (2016).

FSI: Theory Guidance

For large Q^2, x>1



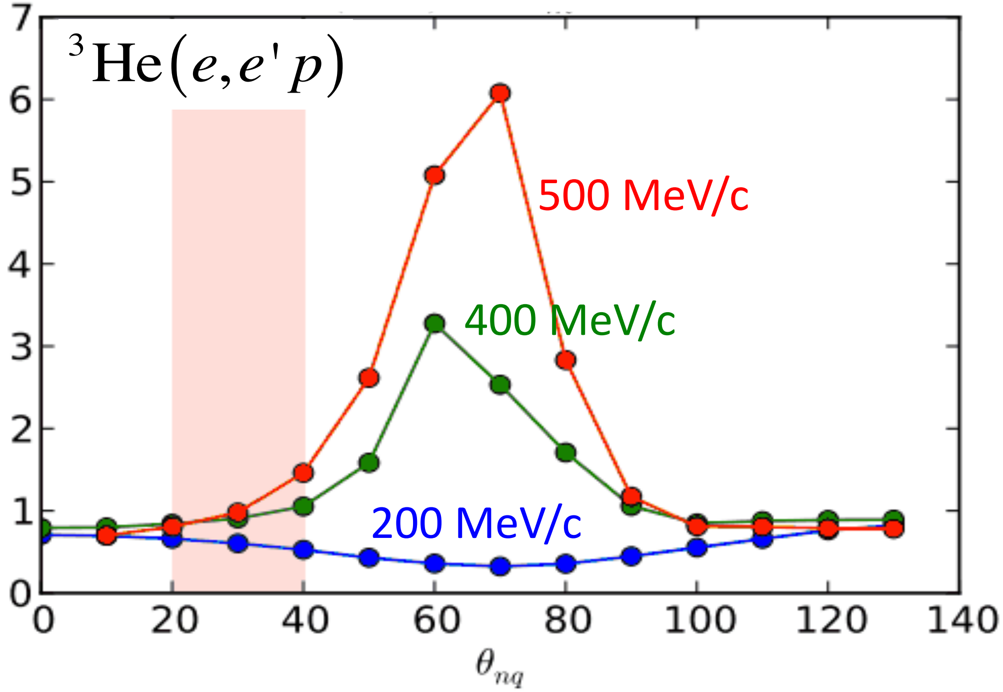
Pair rescattering:
Minimize by choosing correct kinematics

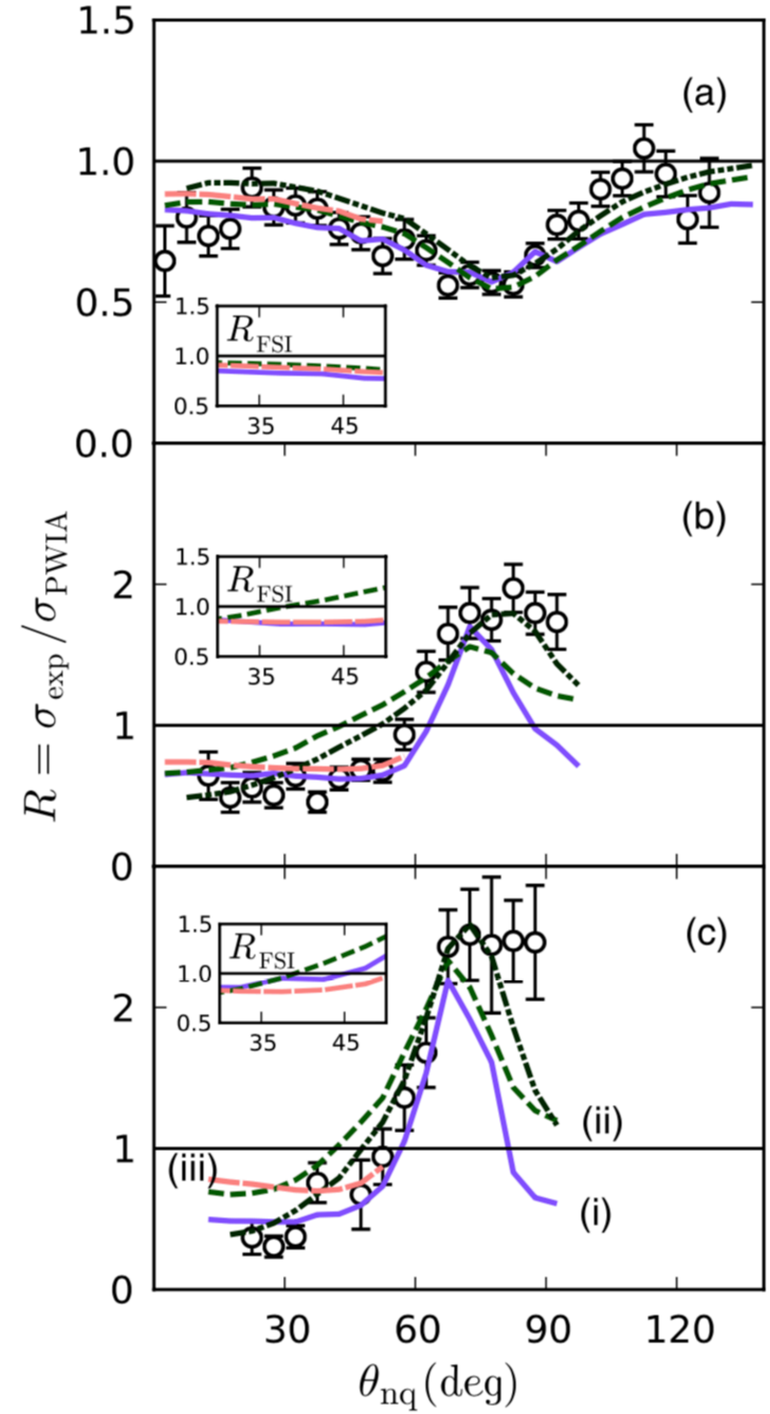


Attenuation:
Calculate using Glauber.

Pair Rescattering

$R = \sigma_{Full} / \sigma_{PWIA}$

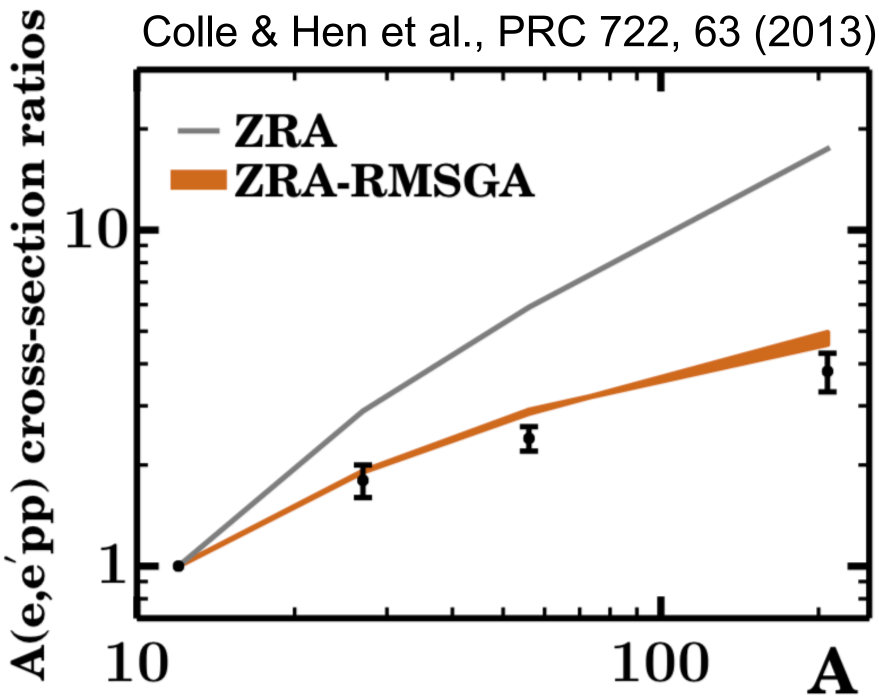


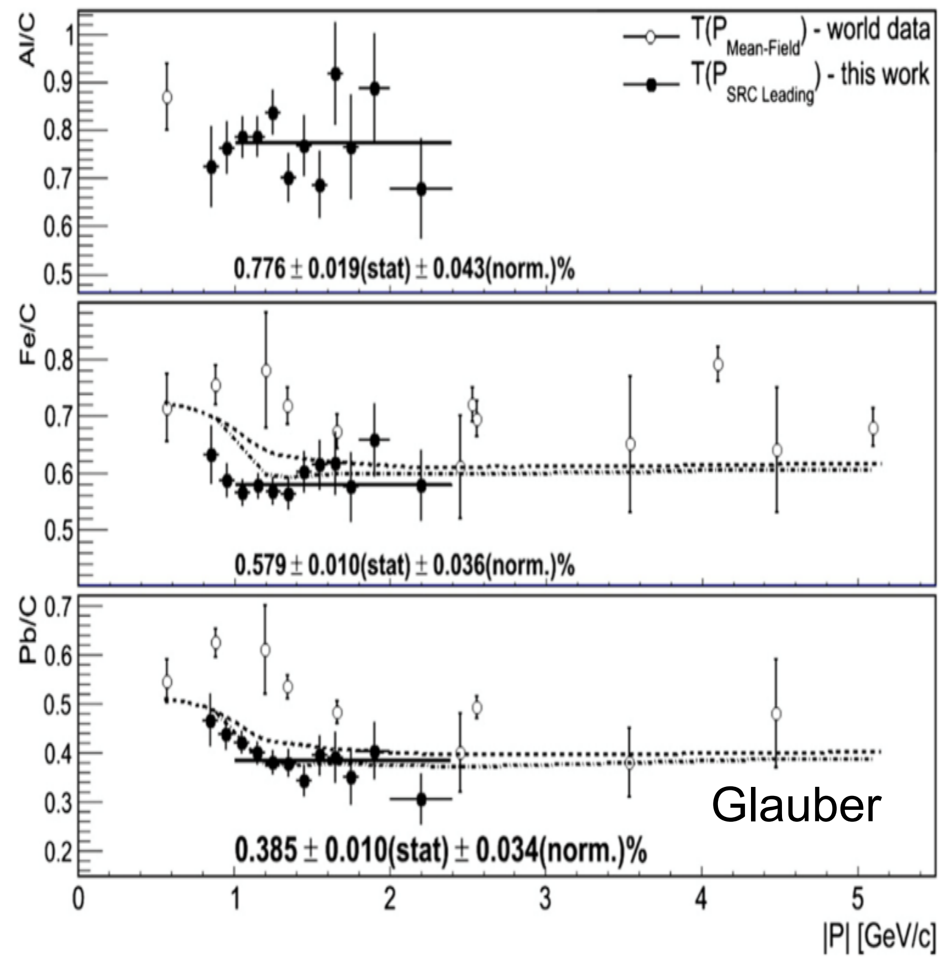


M. Sargsian; Boeglin PRL (2011).

Attenuation: Glauber

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





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

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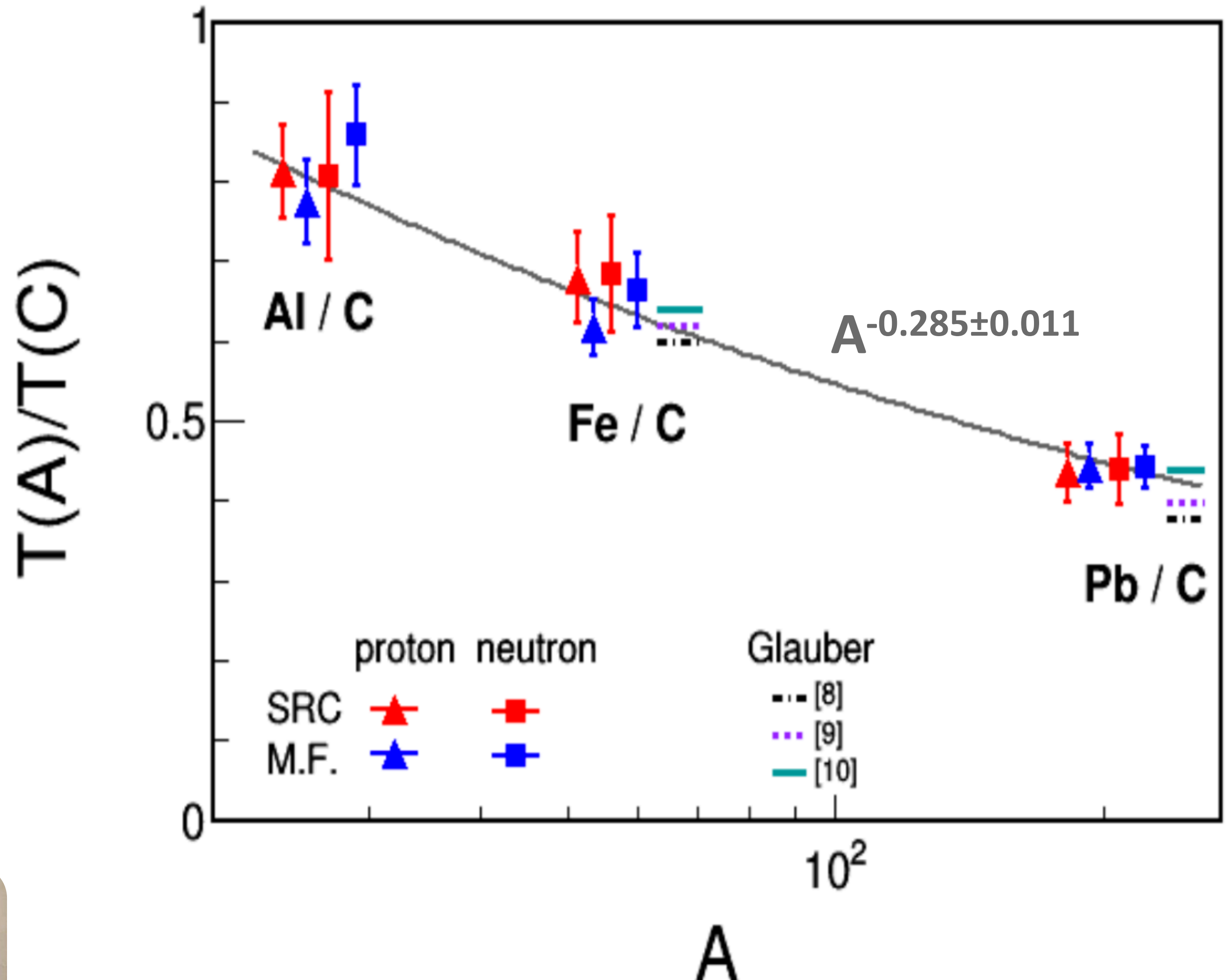

M. Duer et al., submitted (2018)

Probing the NN Interaction

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Theory-Data Comparisons

Experiments usually correct data for detector acceptance and reaction mechanism effect before comparing with theory.

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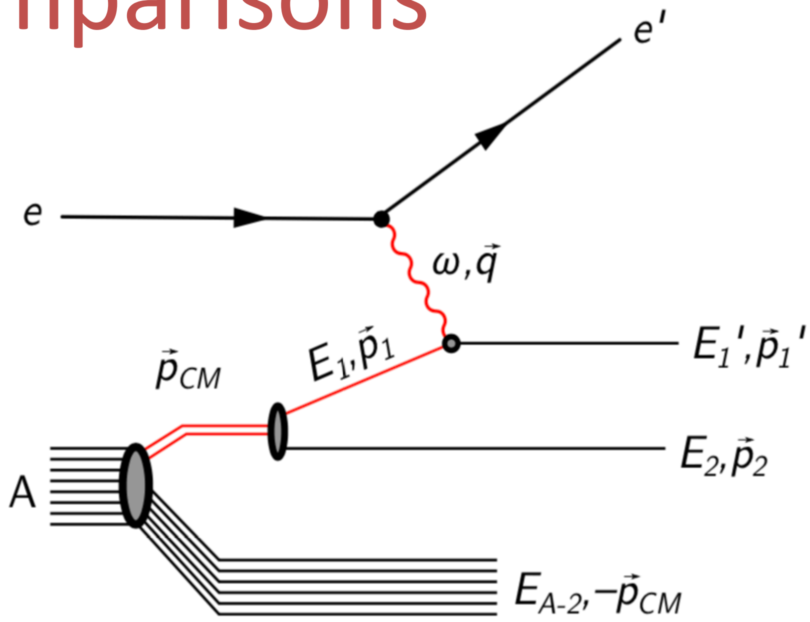
This often leads to ‘model dependent data’ 😬

Theory-Data Comparisons



We bring the theory to the data:

- Generate PWIA A(e,e'NN) events.
- Run through detector simulation.
- Weigh by GCF cross-sections + reaction effects (transparency & single charge exchange)
- Apply event selection cuts

  & overlay on data.

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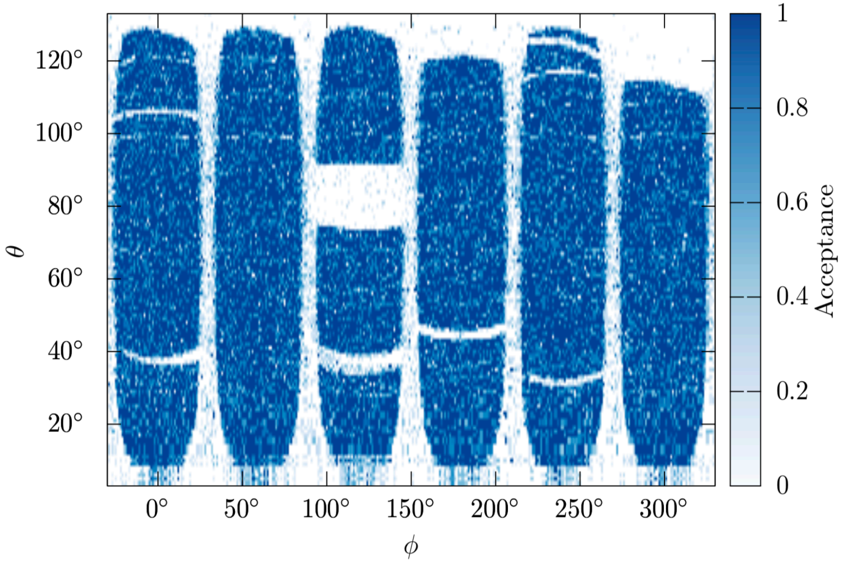

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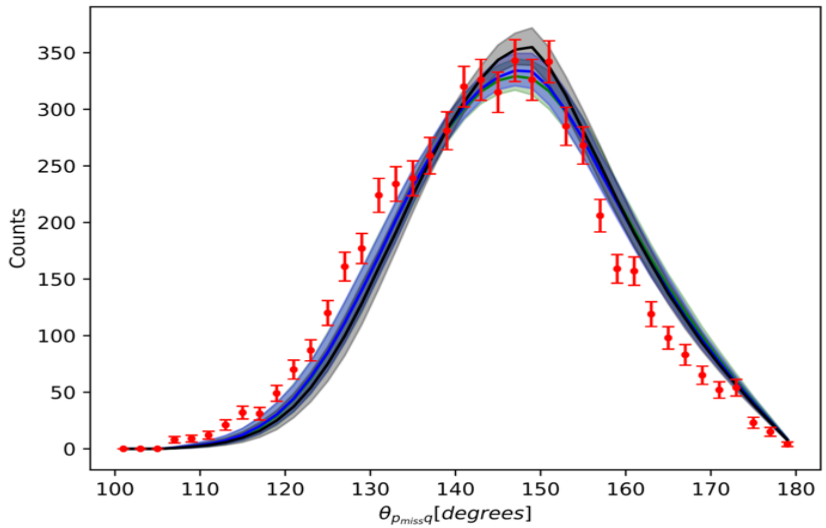
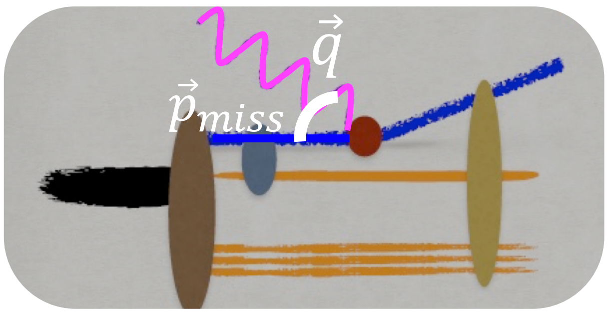
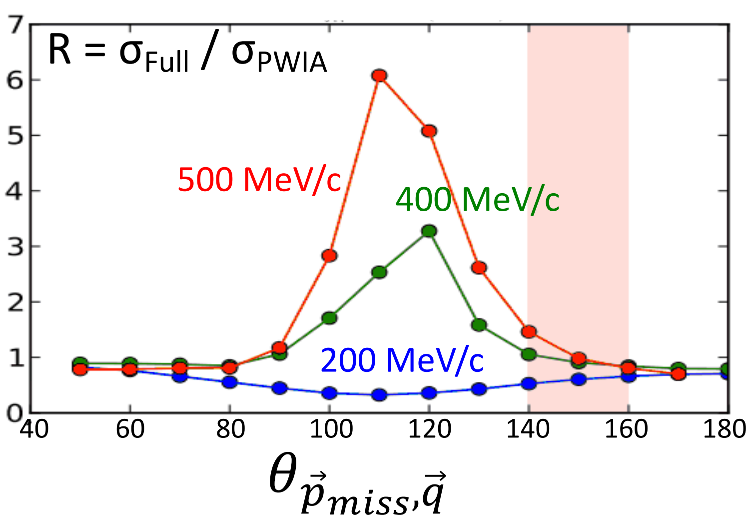
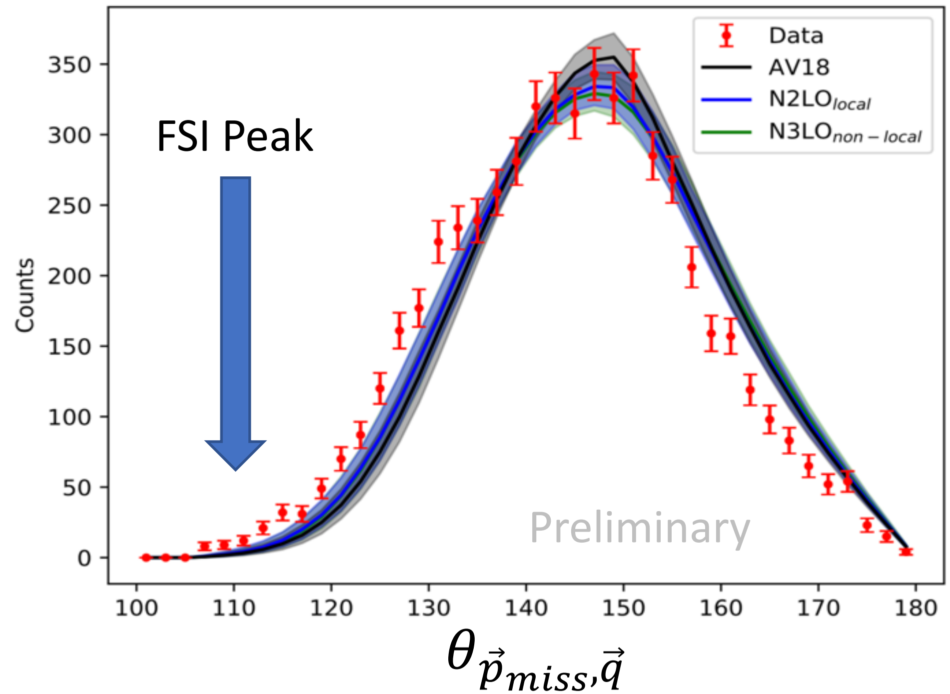


No evidence of FSI enhancements

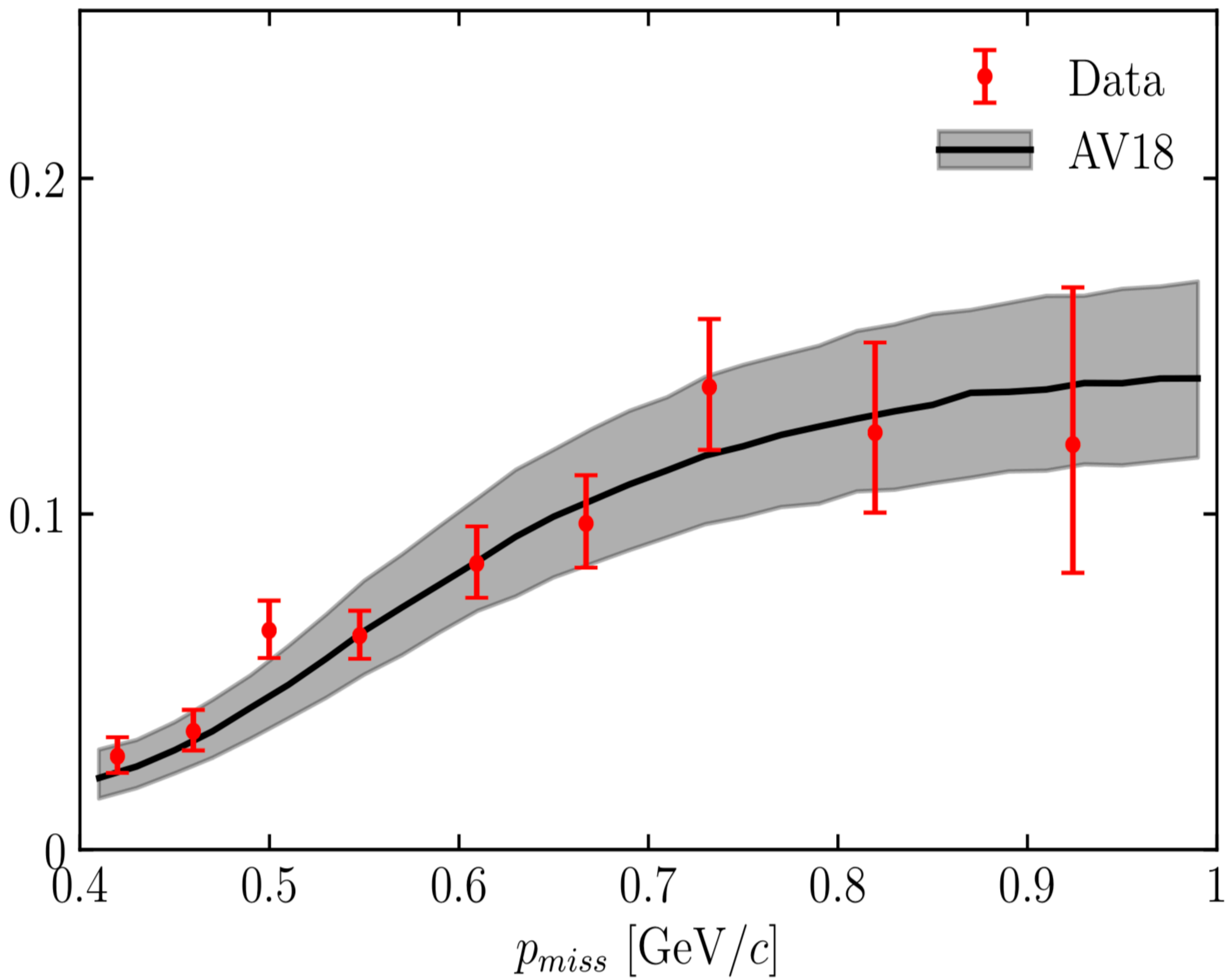






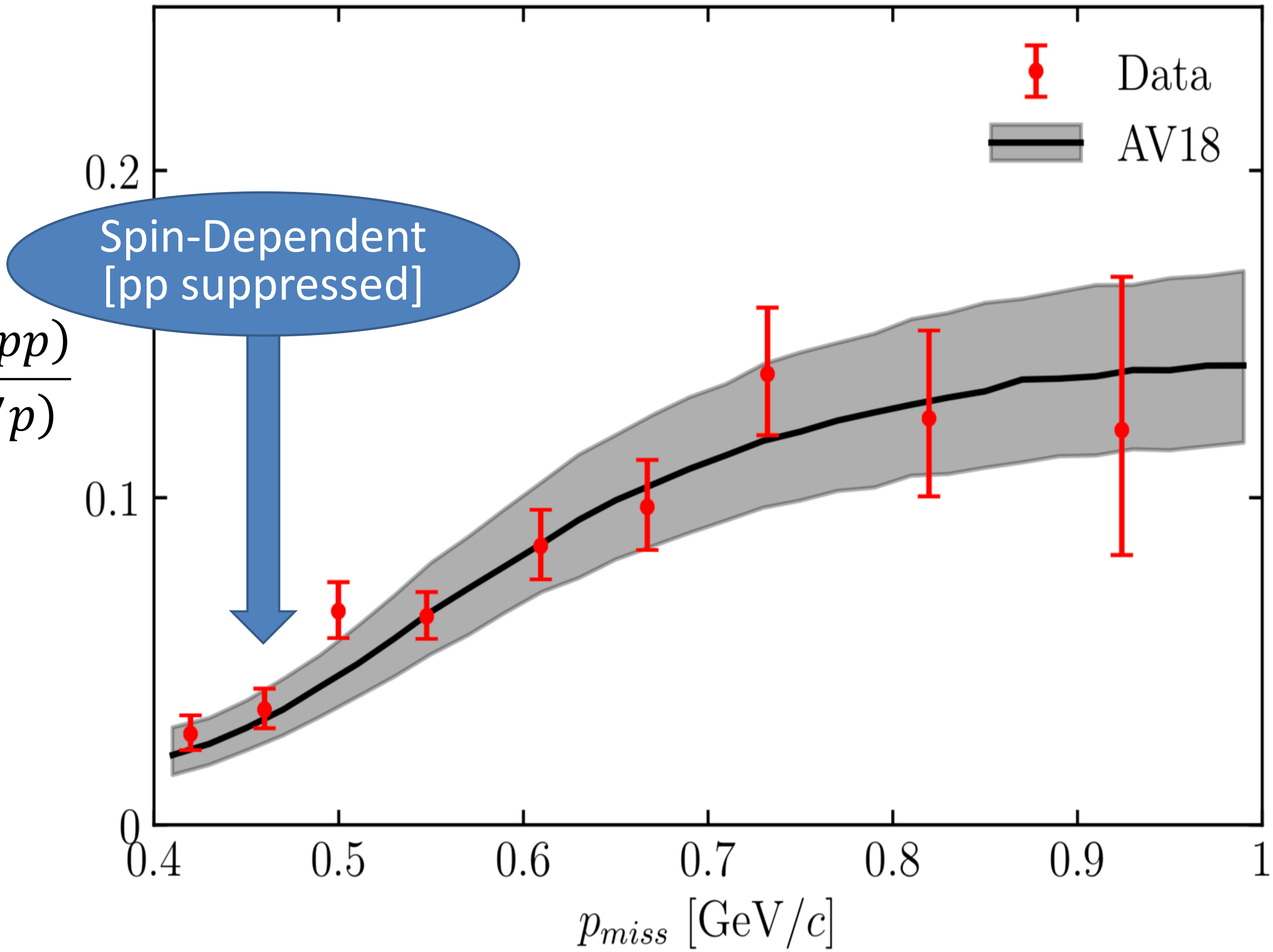
Reaching the Repulsive Core

$$\frac{^{12}C(e,e'pp)}{^{12}C(e,e'p)}$$



A. Schmidt

Reaching the Repulsive Core



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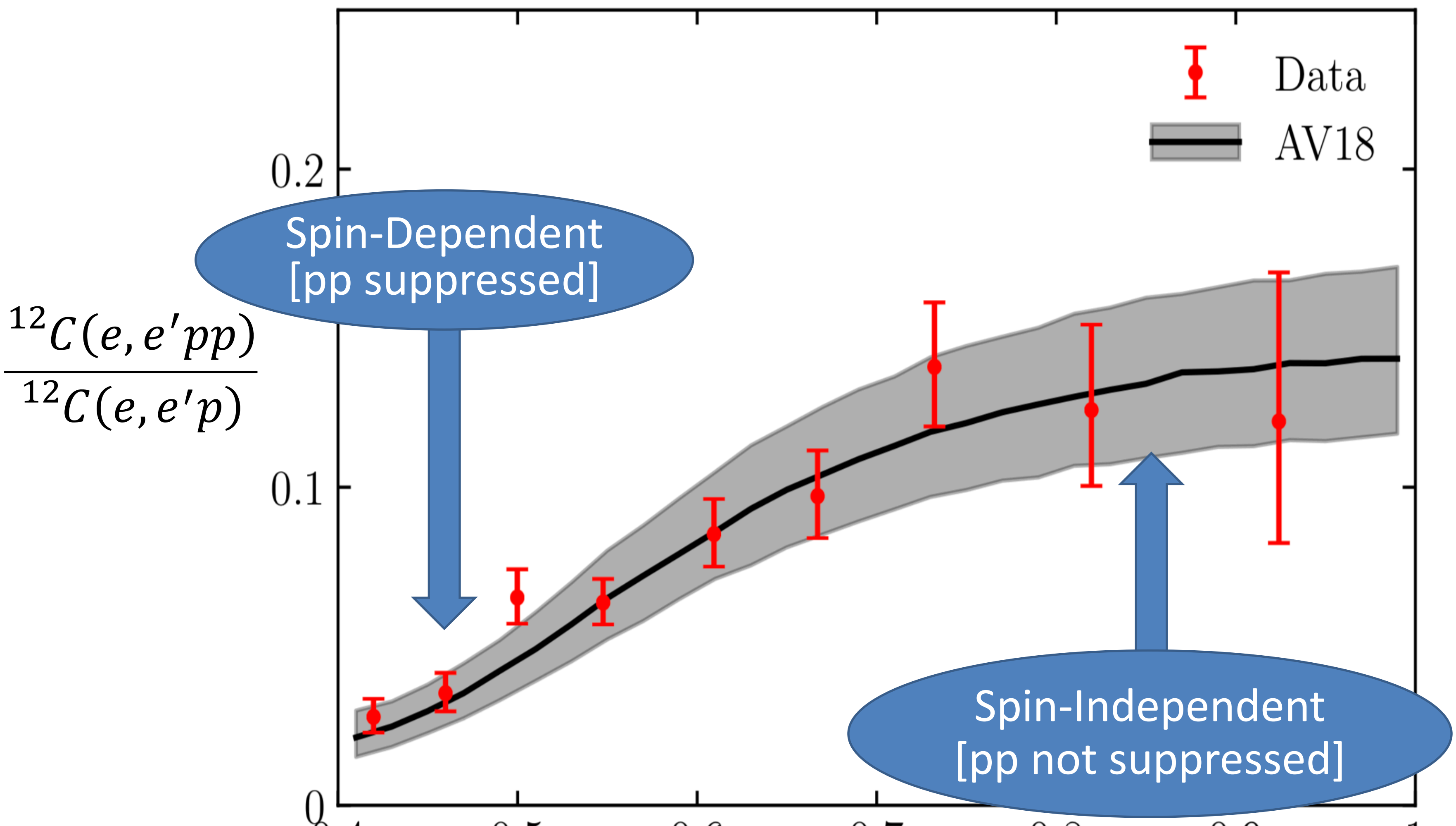

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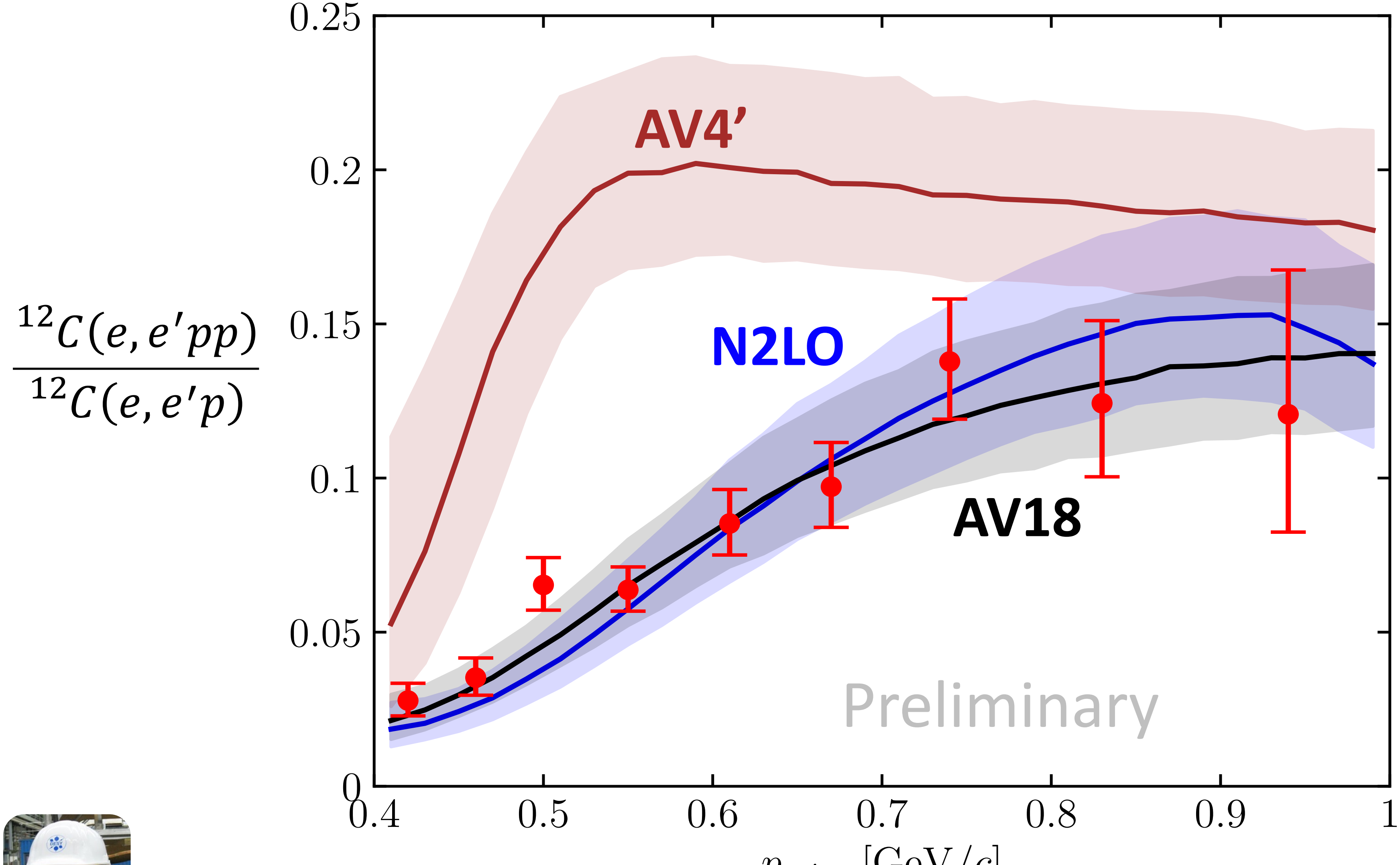

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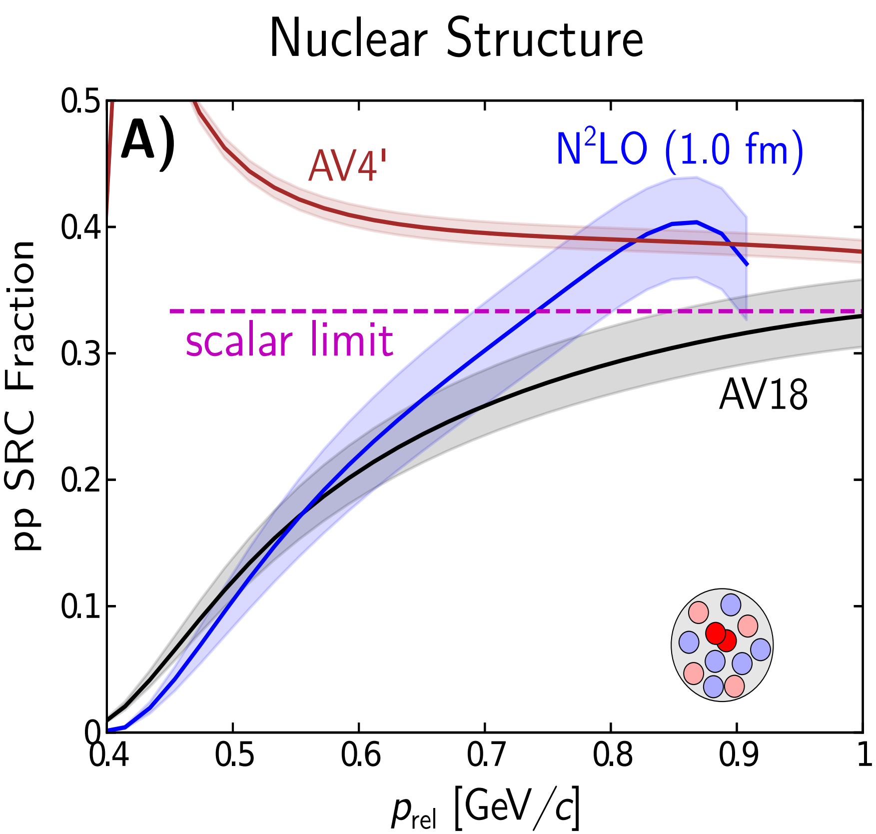
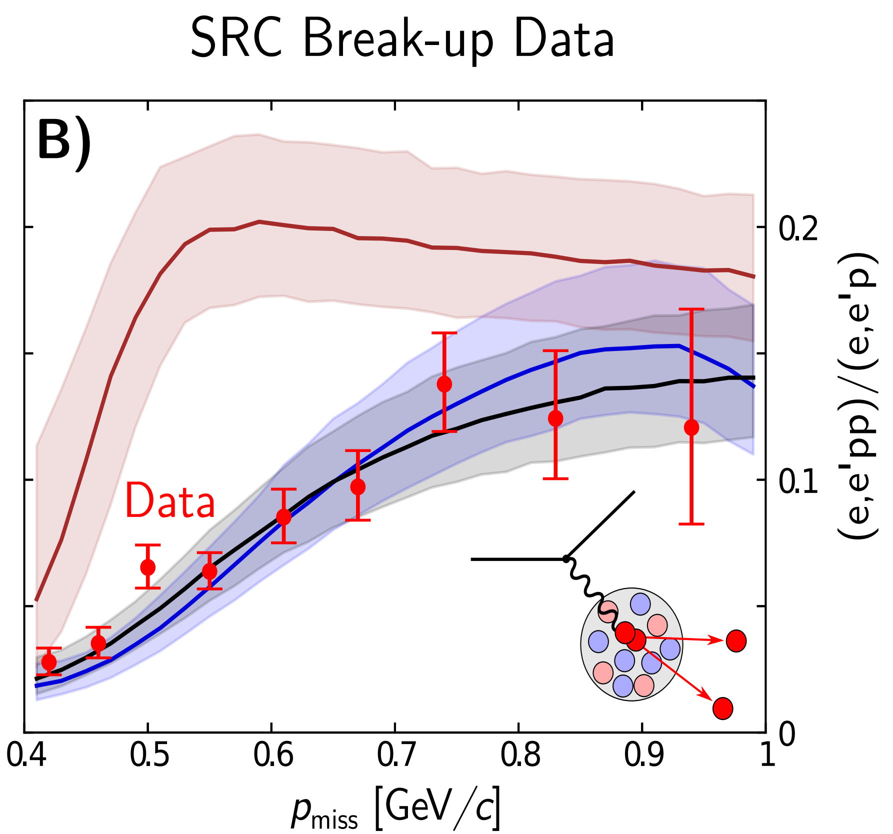
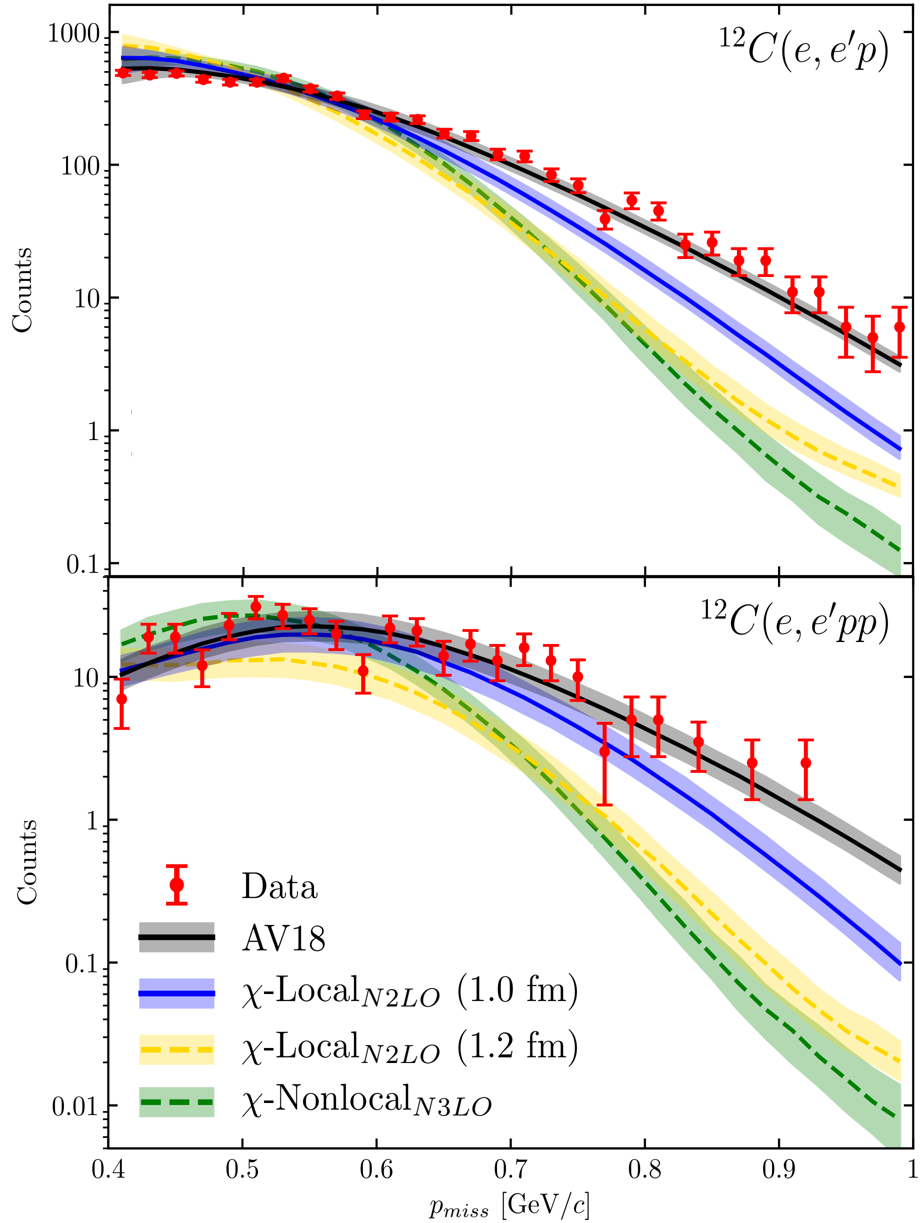




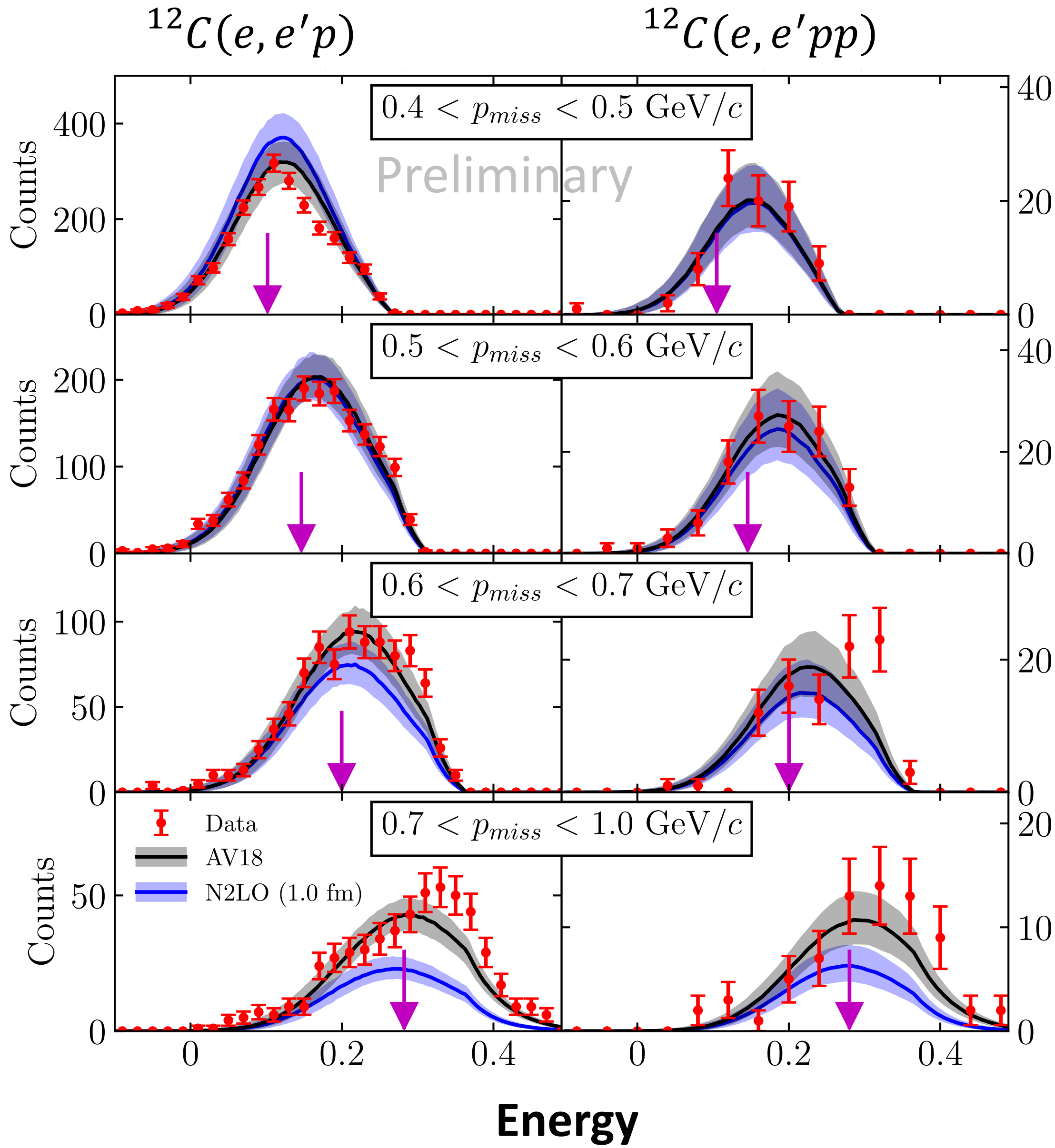
A. Schmidt

Reaching the Repulsive Core



A. Schmidt

Reaching the Repulsive Core



Momentum

400 – 500 MeV/c

500 – 600 MeV/c

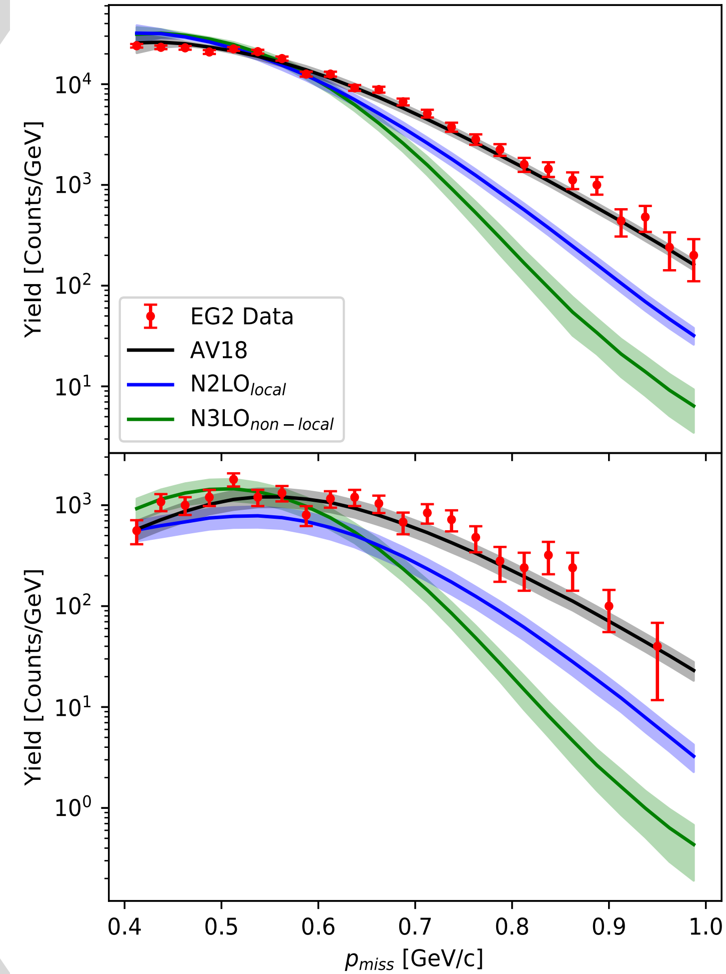
600 – 700 MeV/c

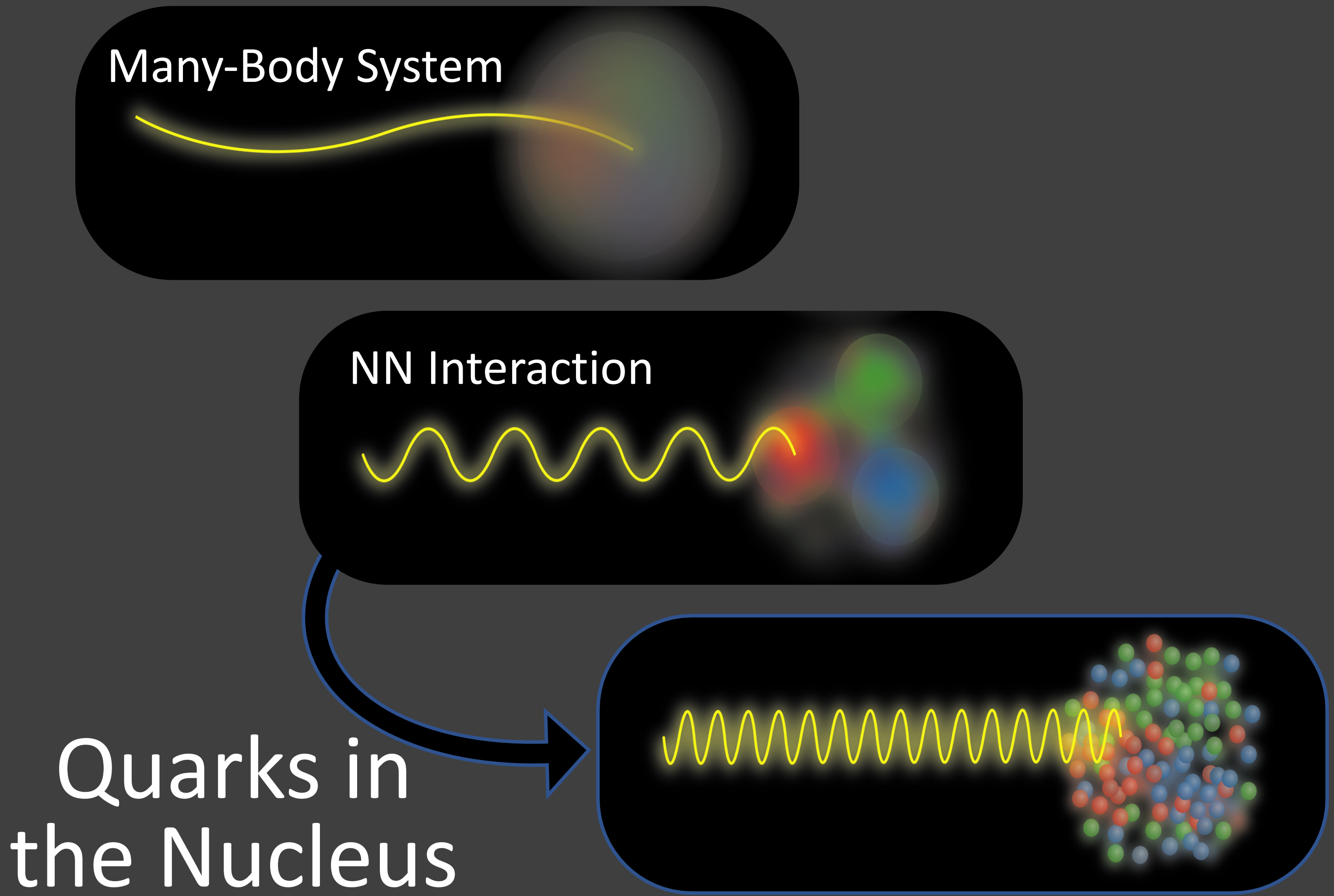
700 – 1000 MeV/c

Interim Summary

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

+ First probe of NN models up to 1 GeV/c.

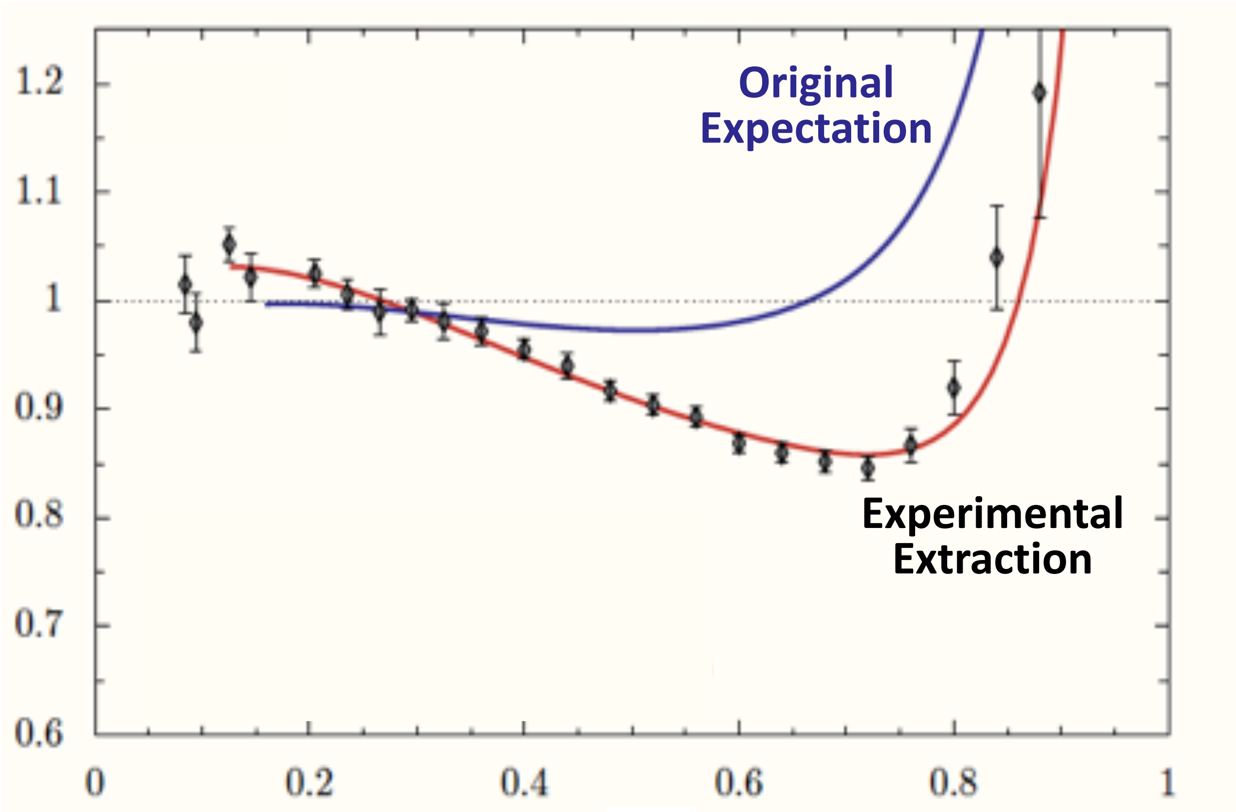




Many-Body System
NN Interaction
Quarks in the Nucleus

EMC Effect:

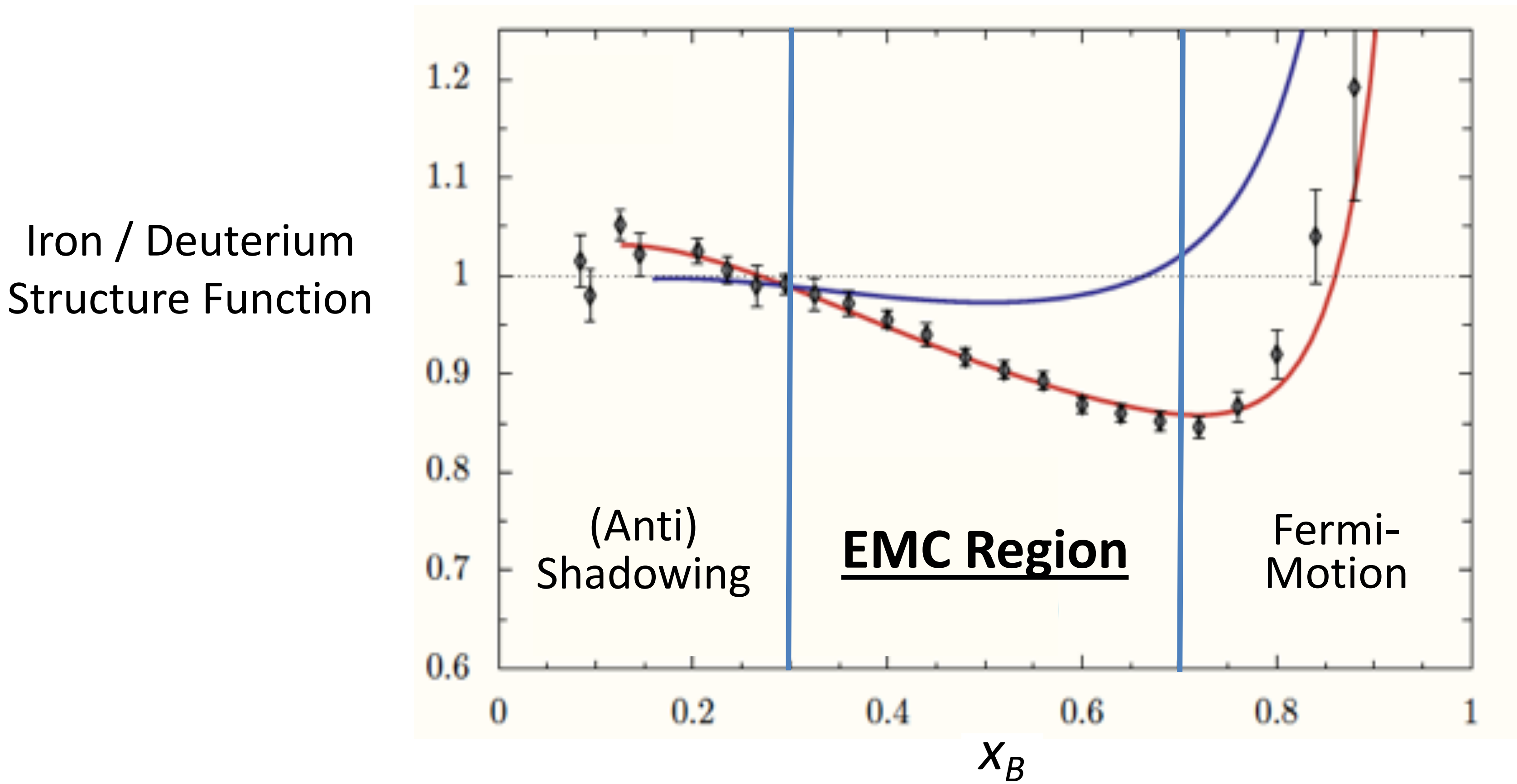
Iron / Deuterium Structure Function



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)

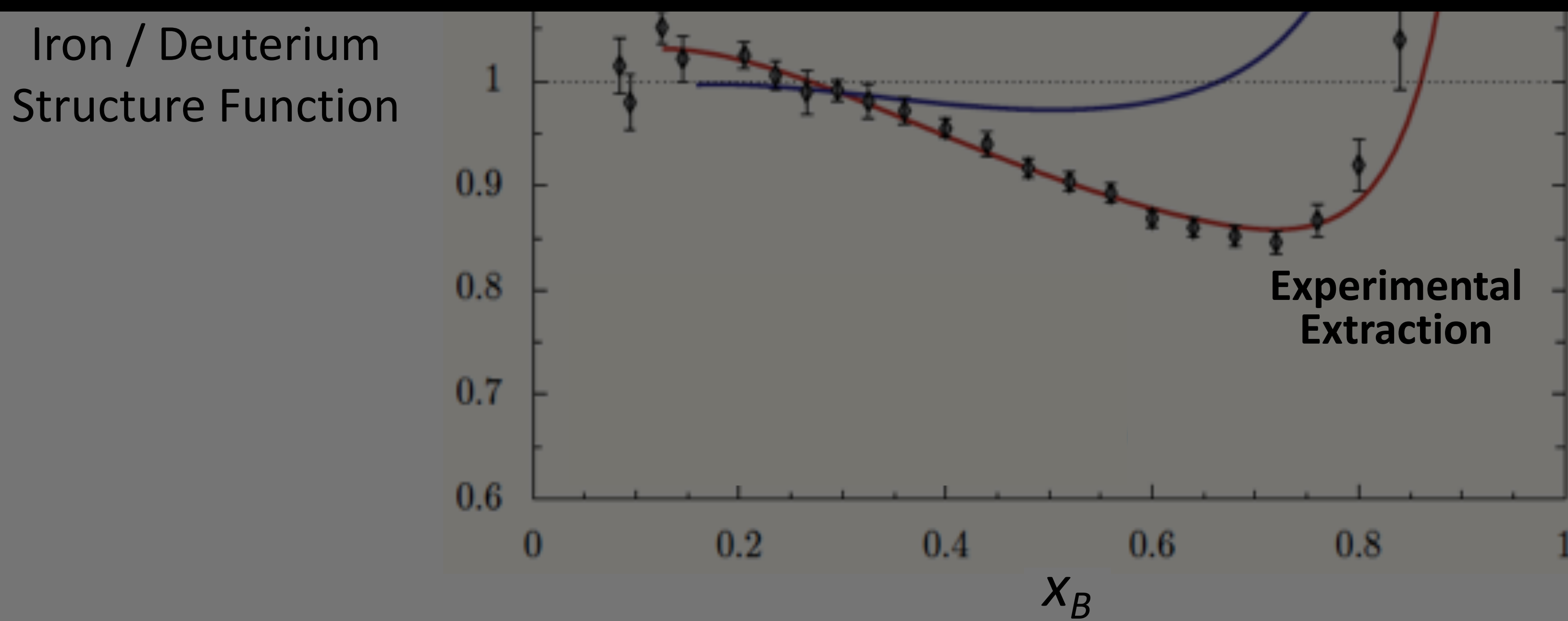
EMC Effect:



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 underlying cause



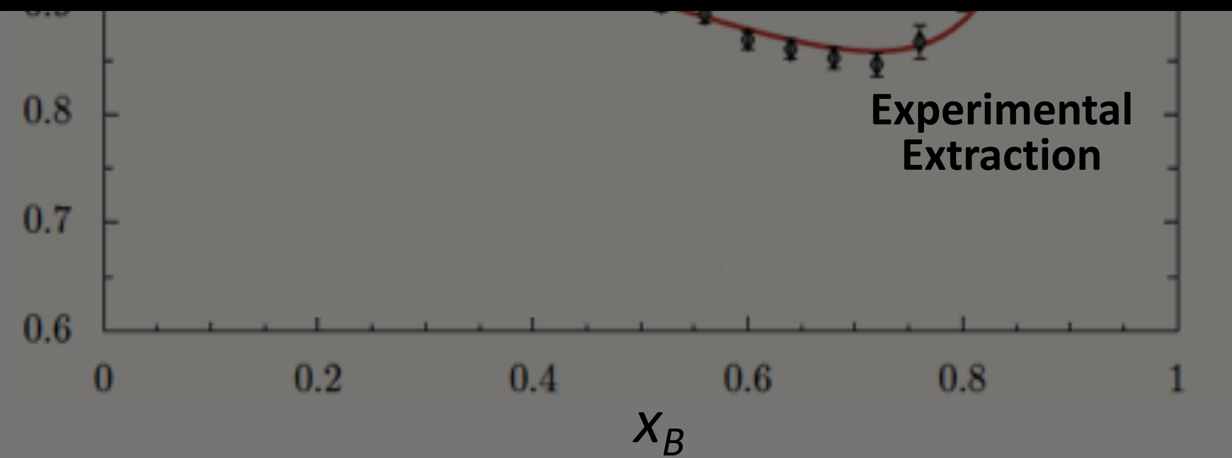
Hen et al., Rev. Mod. Phys. 89, 045002 (2017)

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 underlying cause

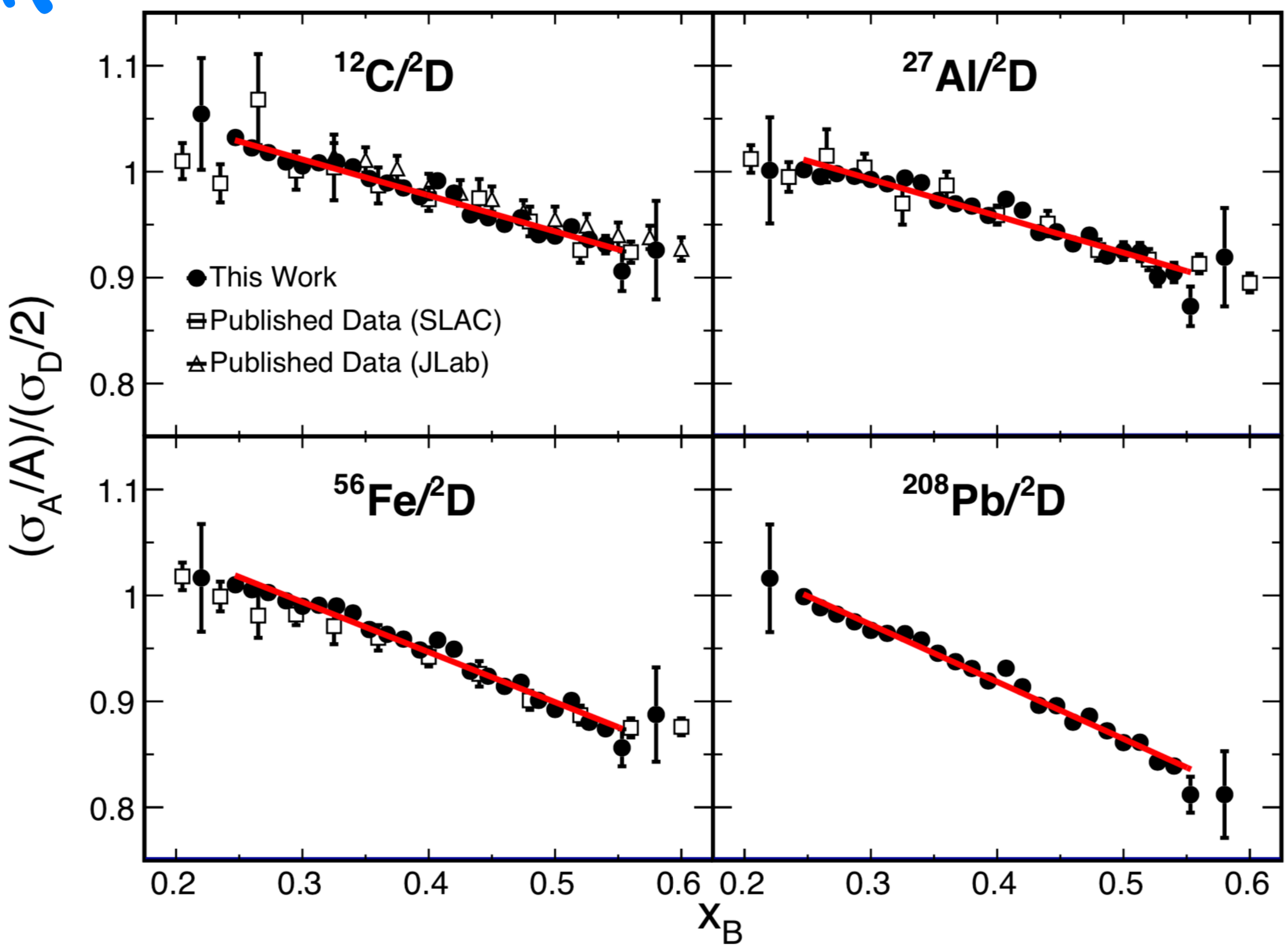
But… Lots of data!



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

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)

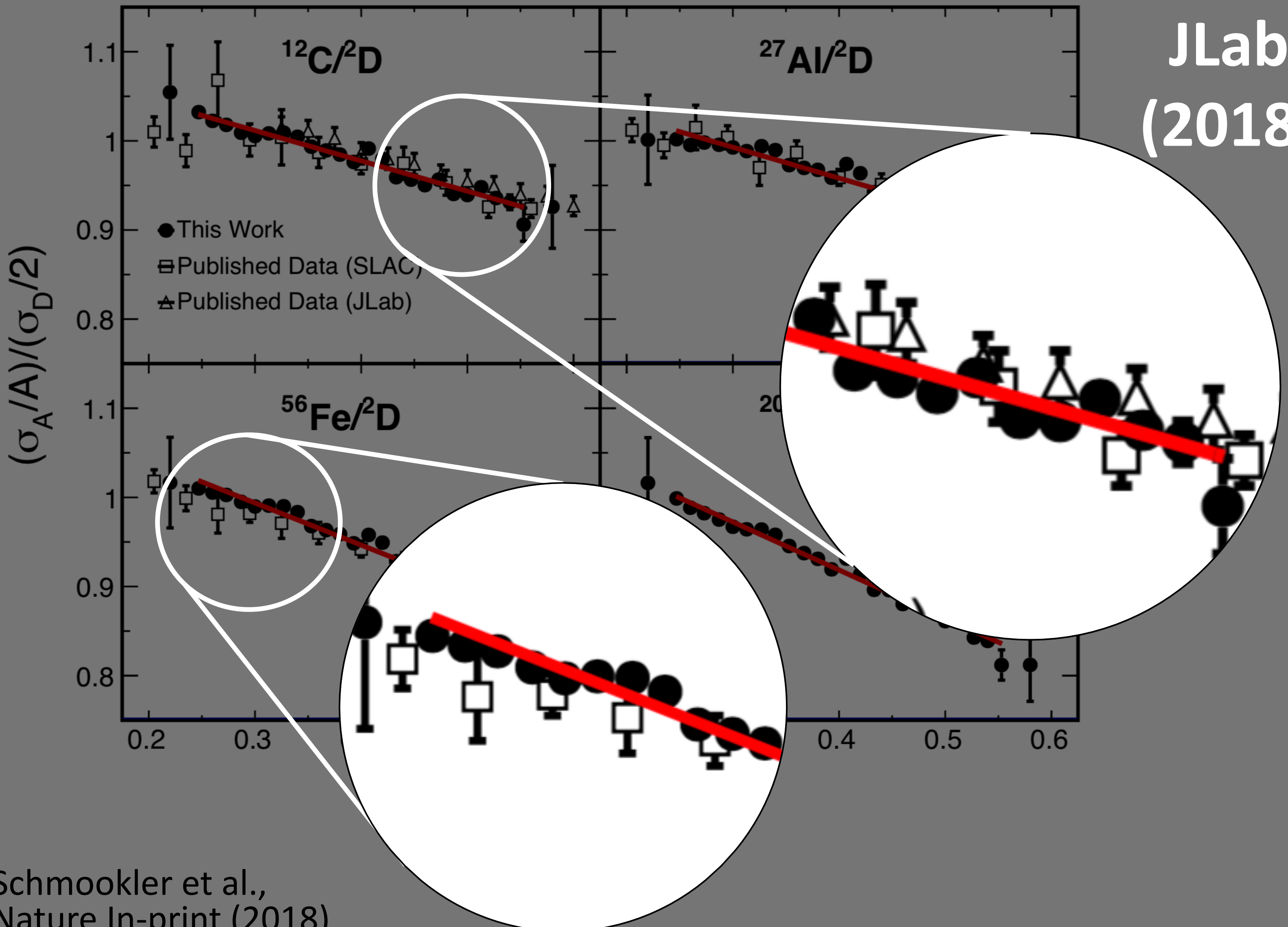
High Precision data!



JLab (2018)

Schmookler et al.,
Nature In-print (2018)

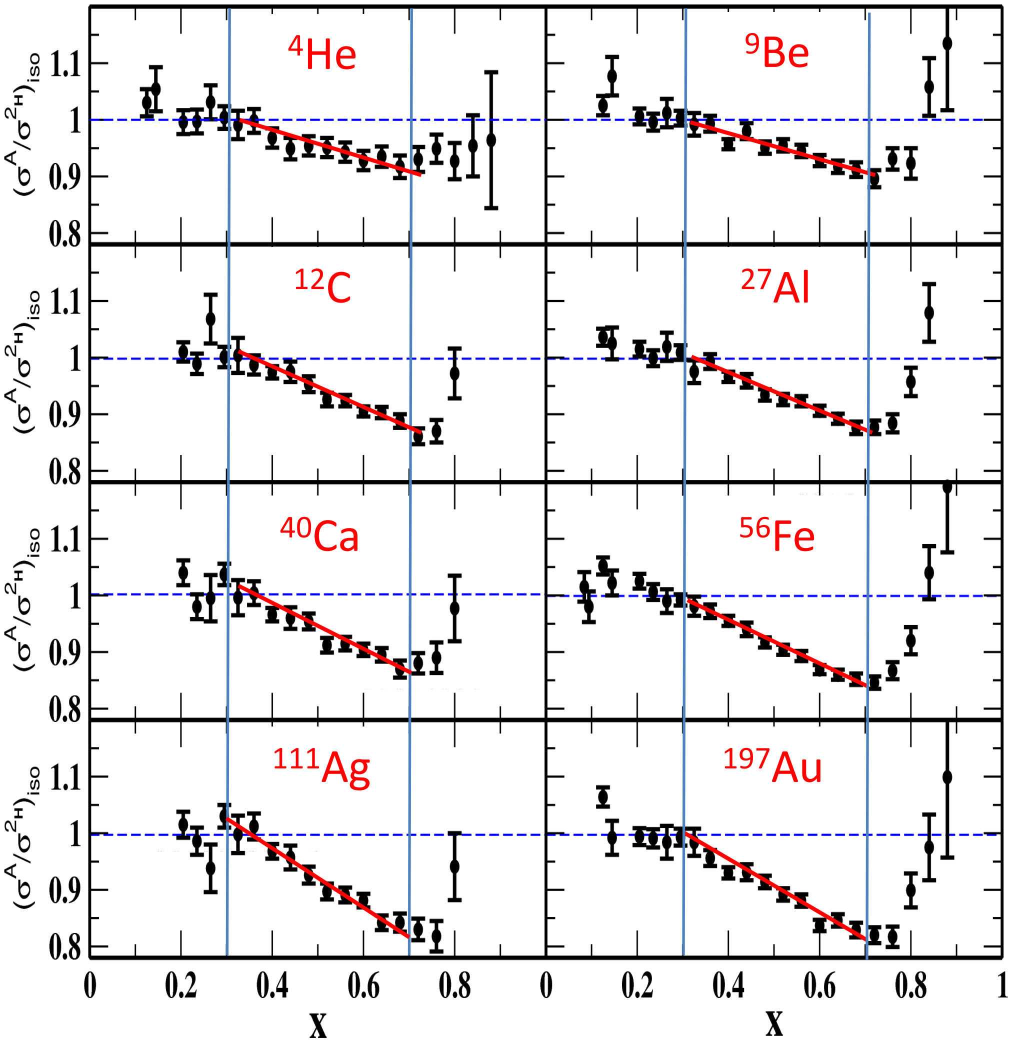
High Precision data!



JLab (2018)

Schmookler et al.,
Nature In-print (2018)

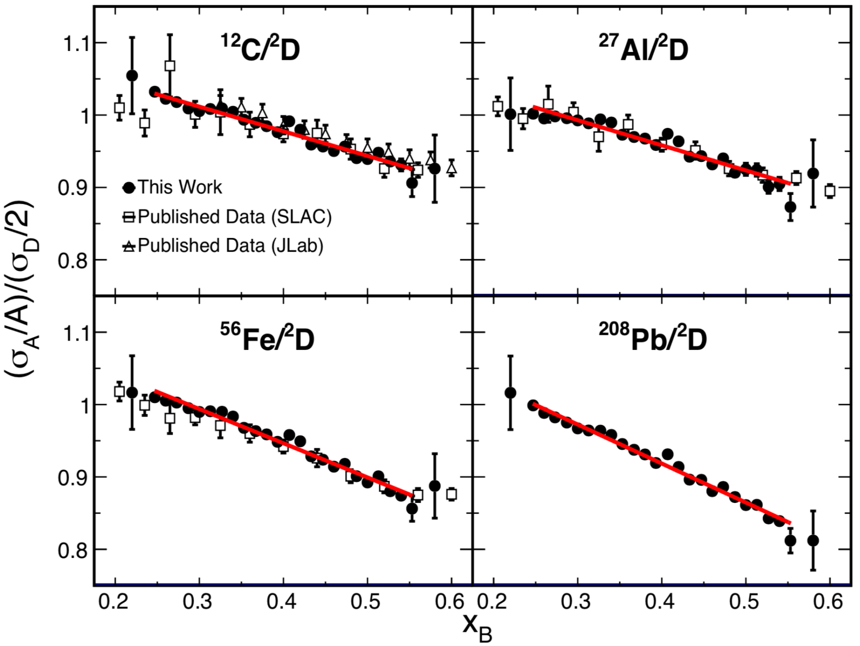
‘Global’ EMC Data



Gomez PRD (1994)

SLAC (1994)

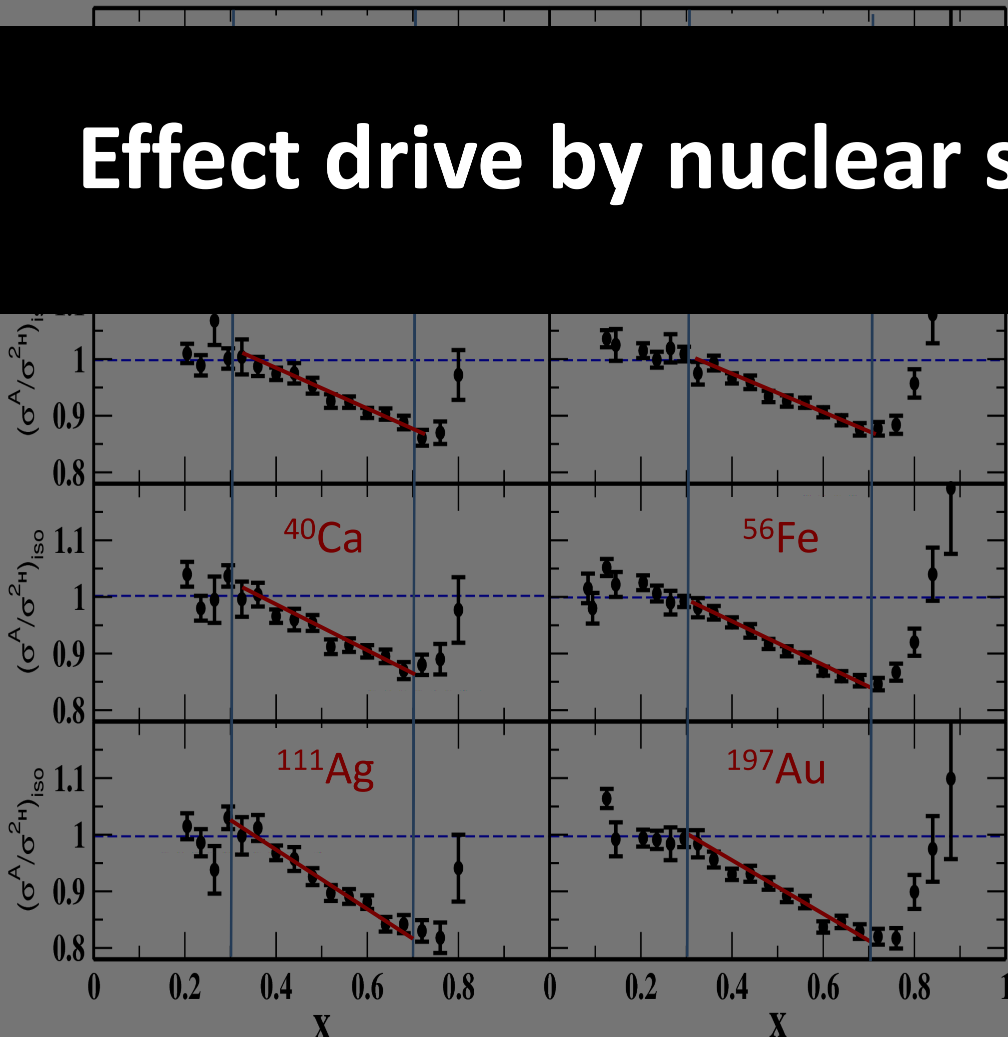
JLab (2018)



Schmookler, Nature
In-print (2018)

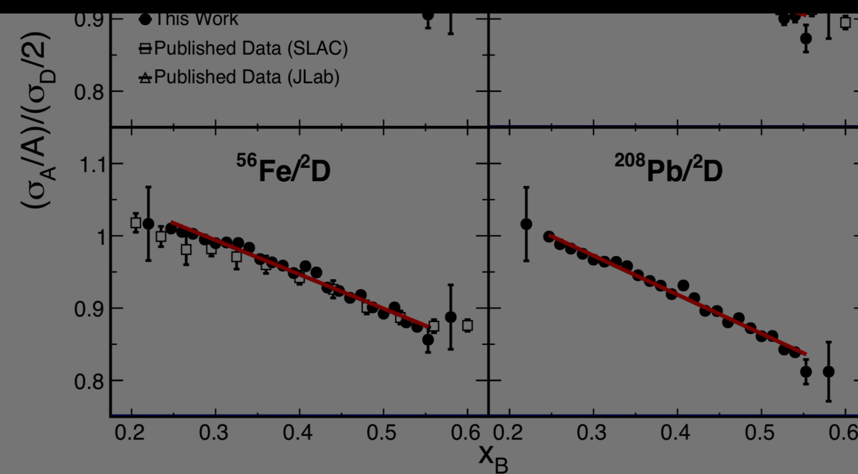
‘Global’ EMC Data

Effect drive by nuclear structure & dynamics



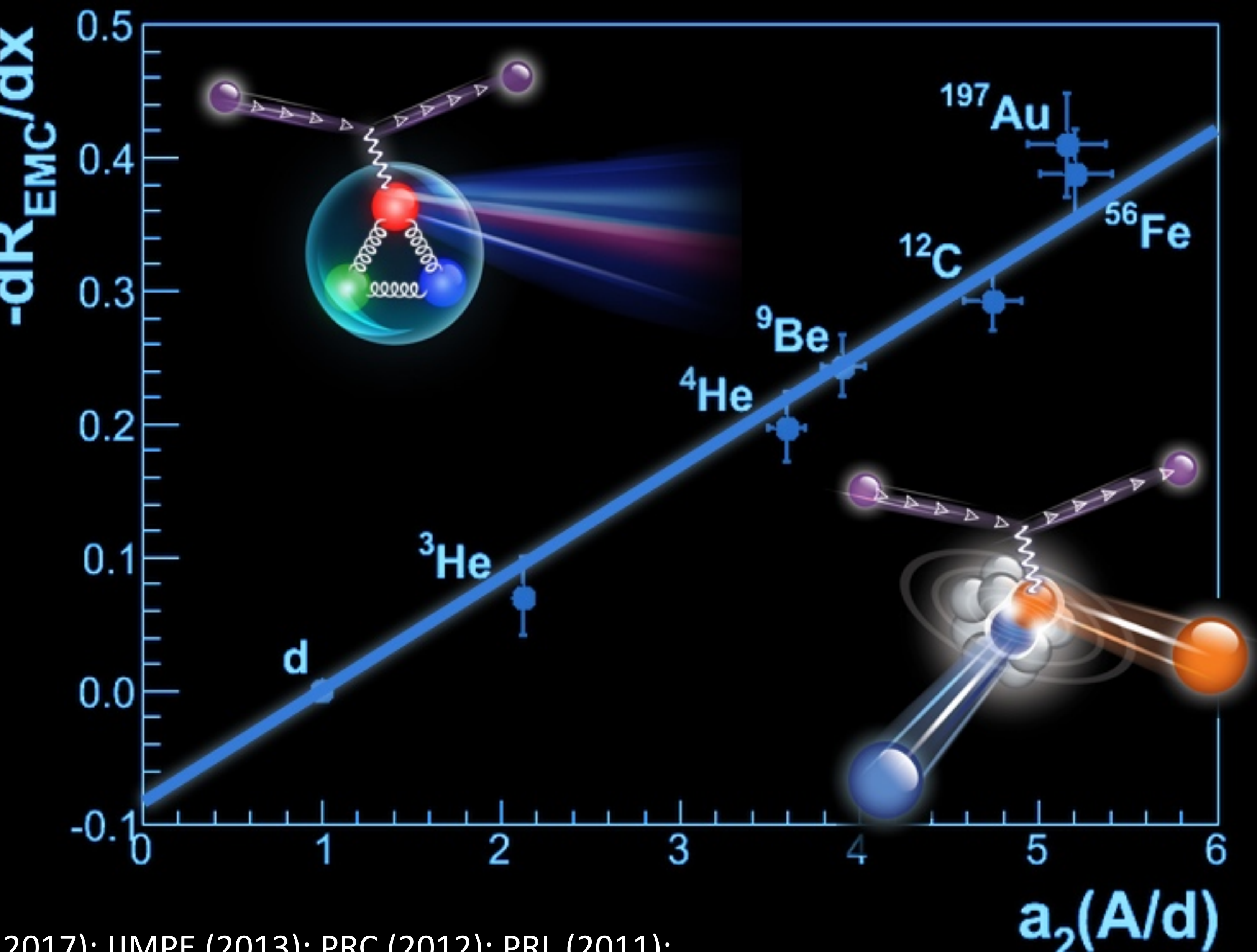
Gomez PRD (1994)

SLAC (1994)



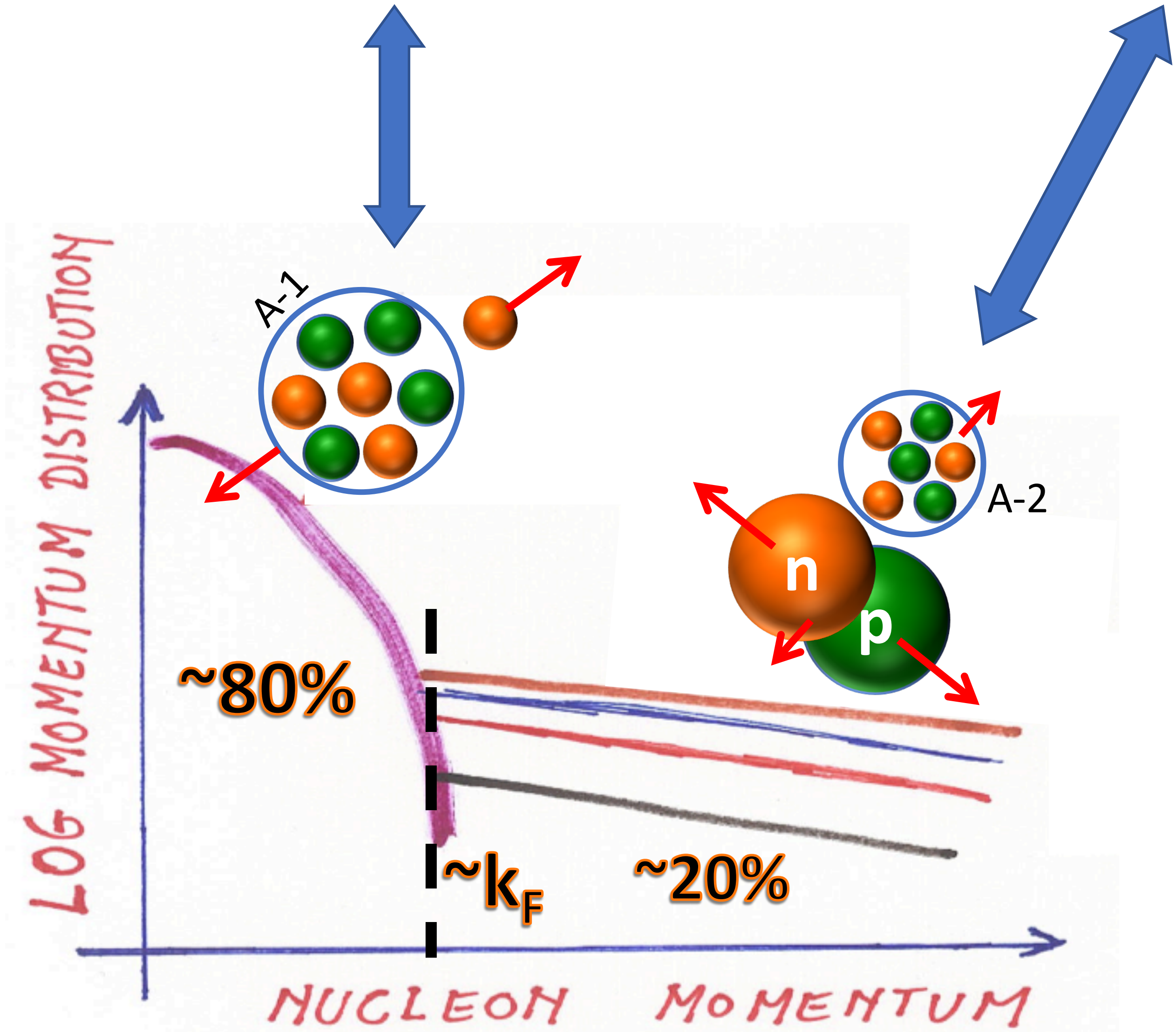
Schmookler, Nature
In-processing (2018)

EMC – SRC Correlation

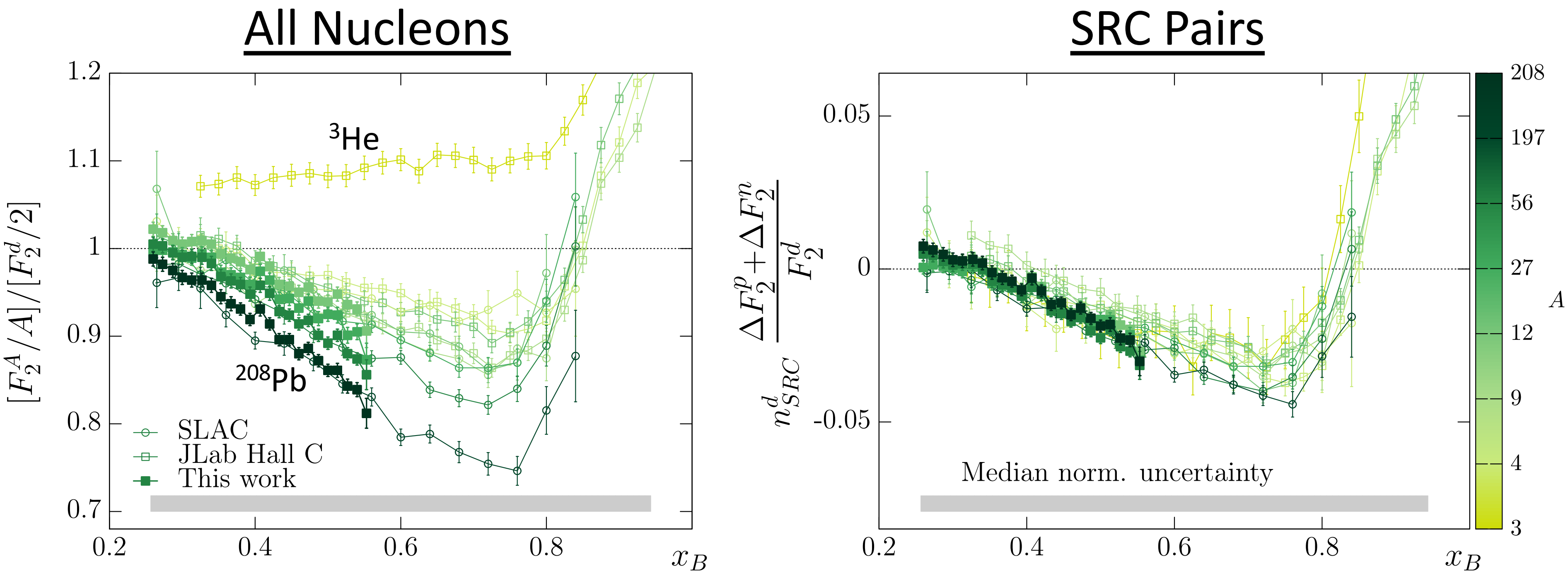


RMP (2017); IJMPE (2013); PRC (2012); PRL (2011);

Bound = 'quasi Free' + Modified SRCs

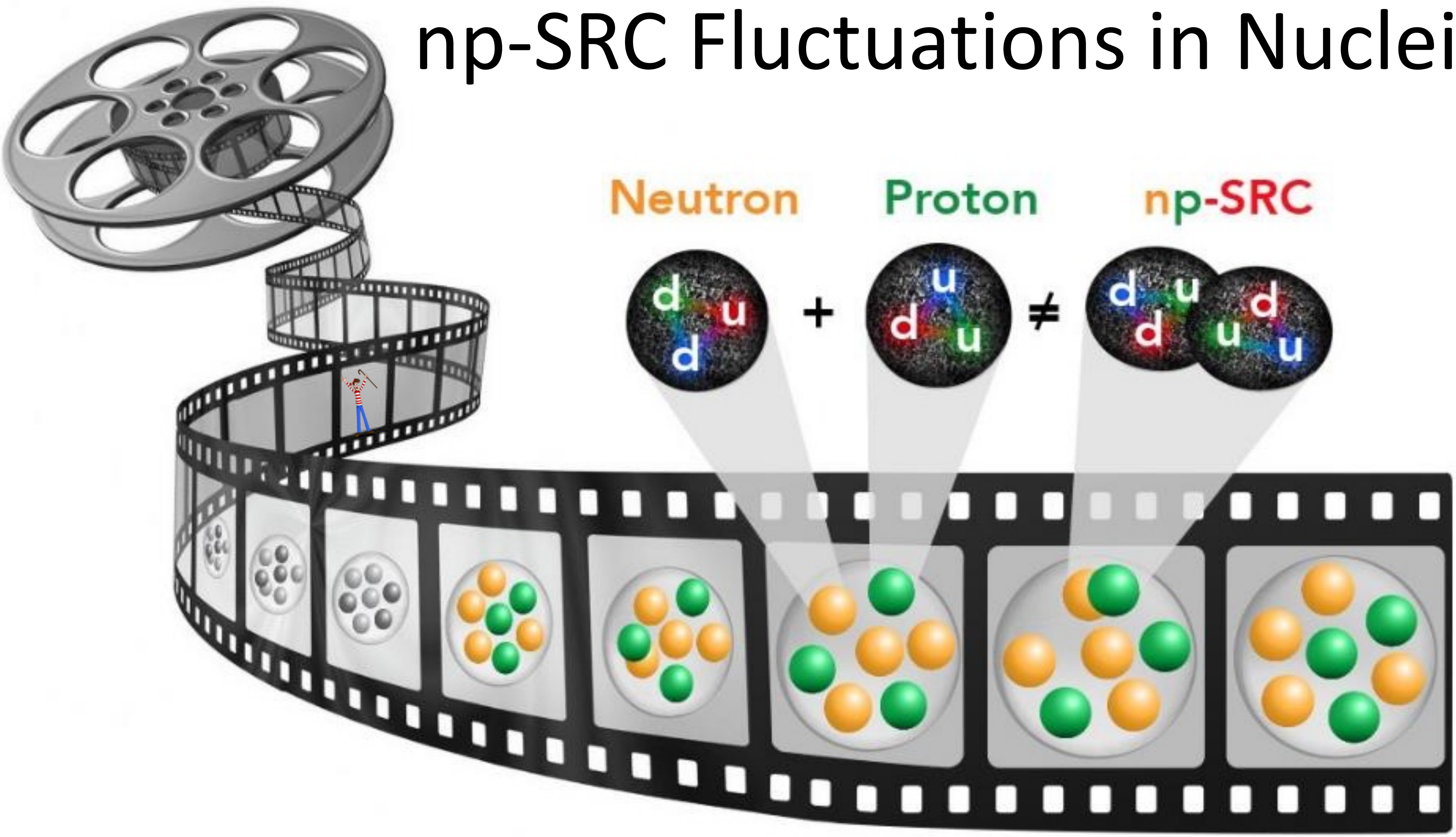


All Nucleons | SRC Pairs

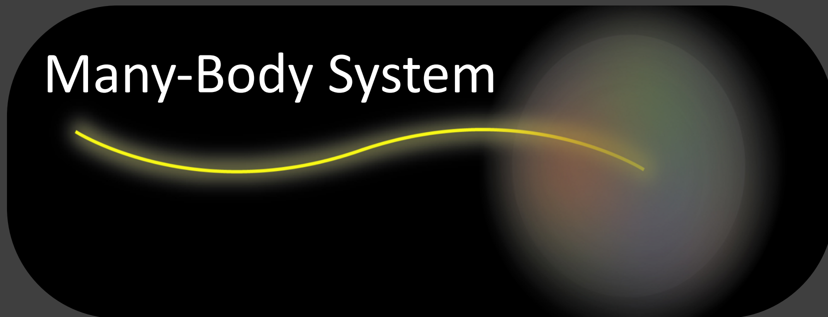


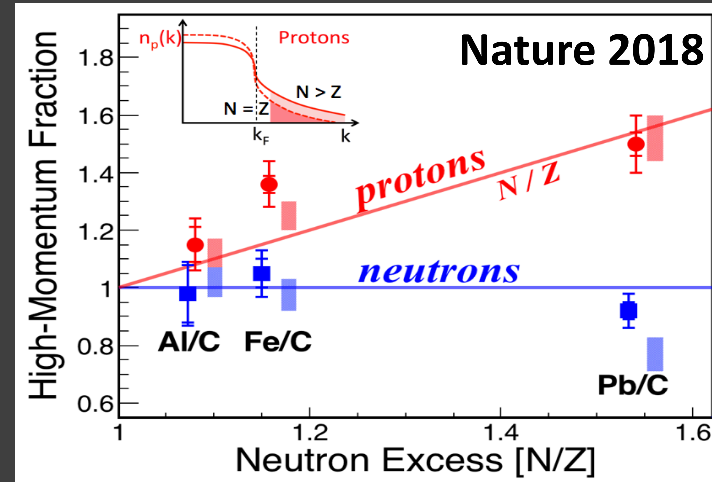
Schmookler et al., Nature In-print (2018)

np-SRC Fluctuations in Nuclei

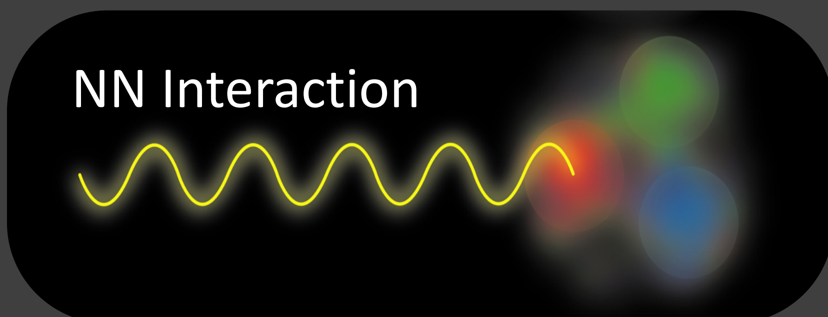


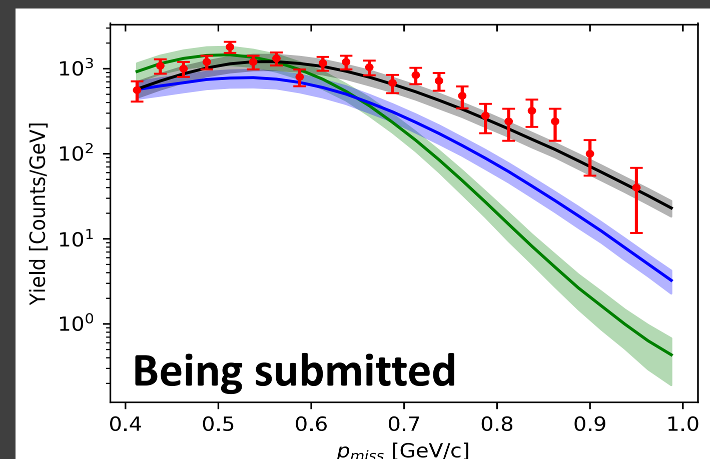
(1)


Many-Body System

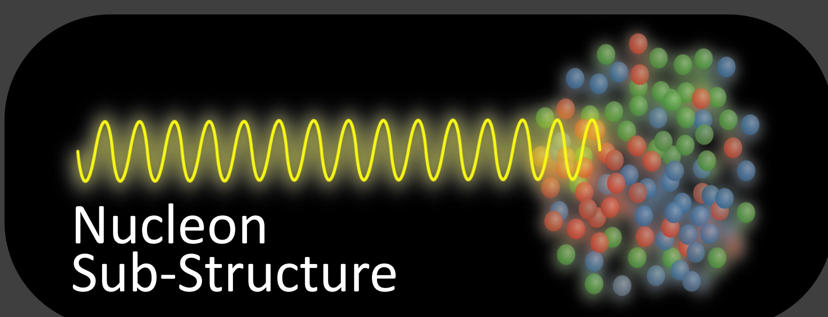

Nature 2018
High-Momentum Fraction
Neutron Excess [N/Z]
Protons
N > Z
N = Z
protons
N / Z
neutrons
Al/C
Fe/C
Pb/C

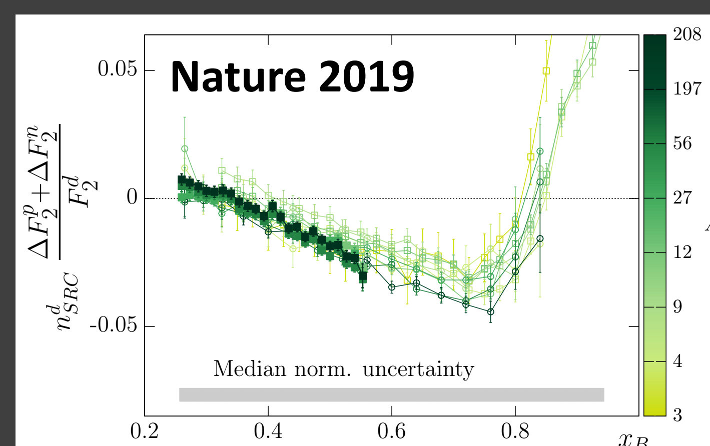
(2)


NN Interaction

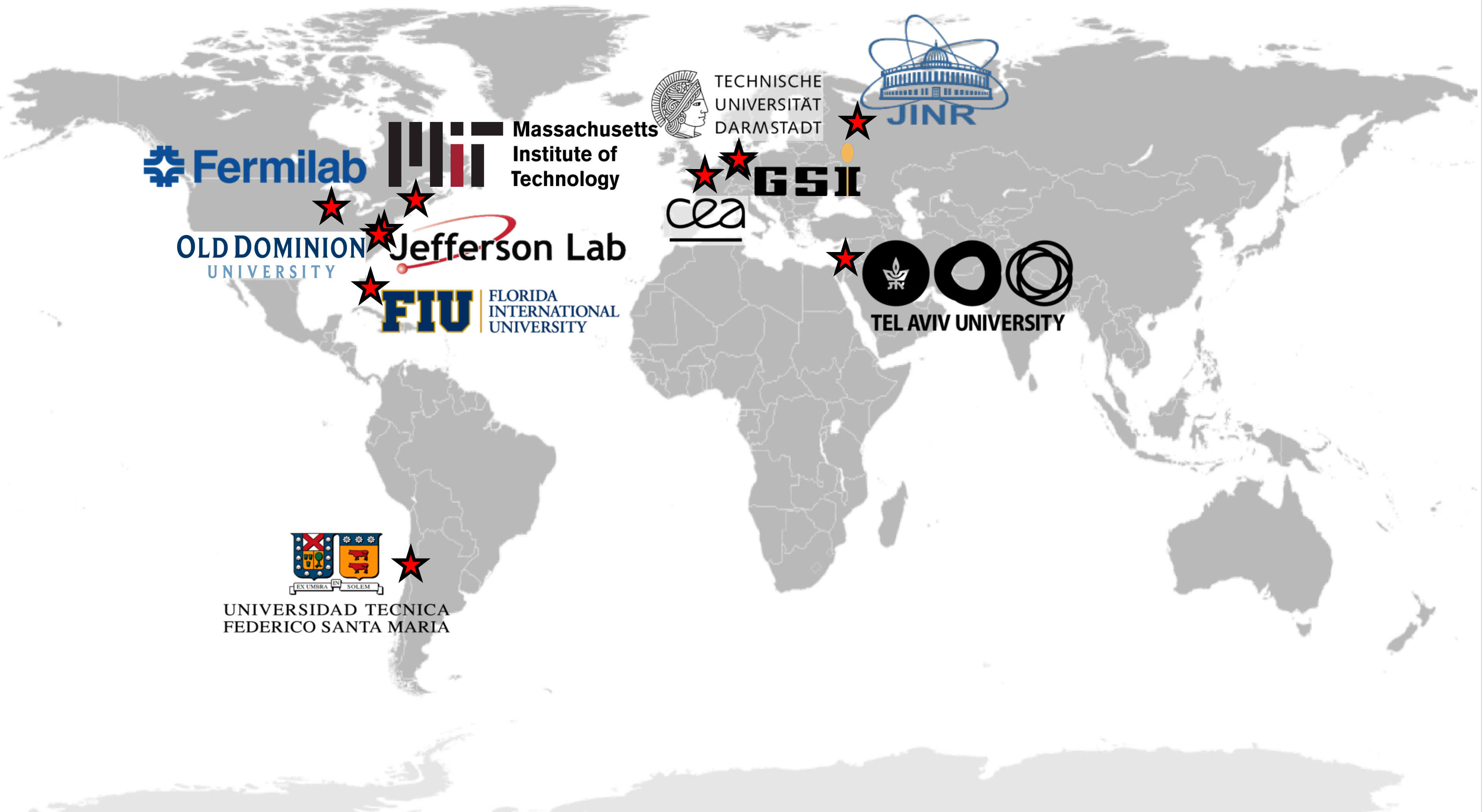

Yield [Counts/GeV]
p_{miss} [GeV/c]
Being submitted

(3)

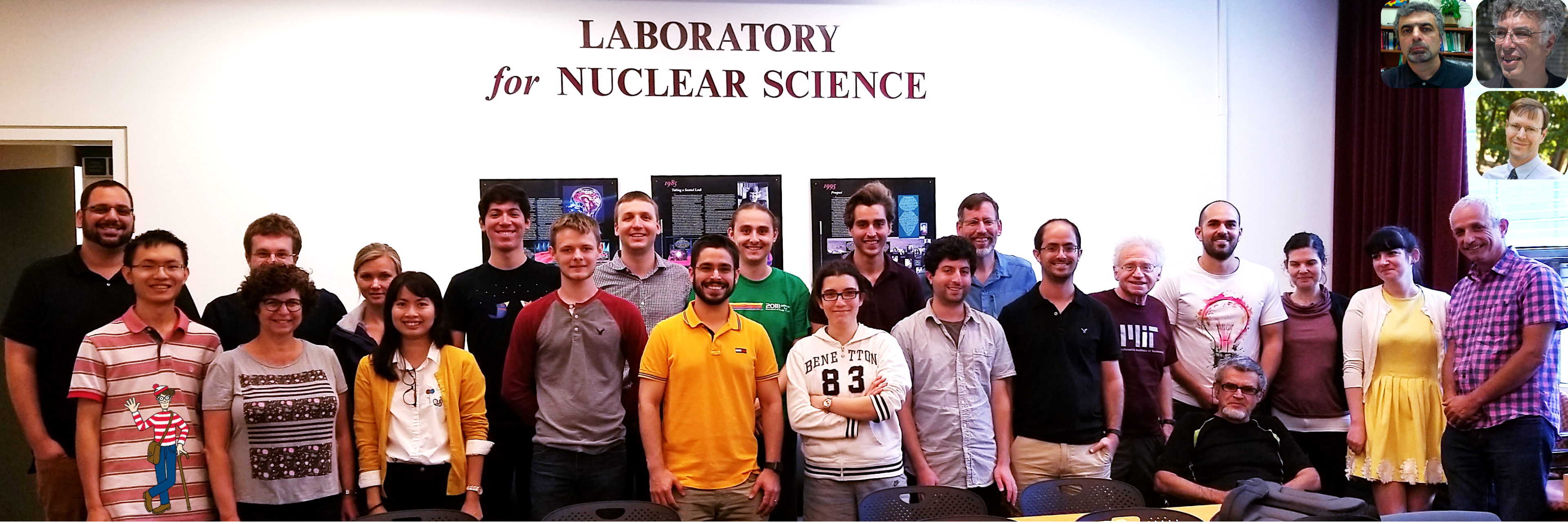

Nucleon
Sub-Structure


Nature 2019
$n^d_{SRC} \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}$
x_B
A
Median norm. uncertainty

The SRC World



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




Dr. Adi Ashkenazy


Dr. Dien Nguyen


Dr. Axel Schmidt

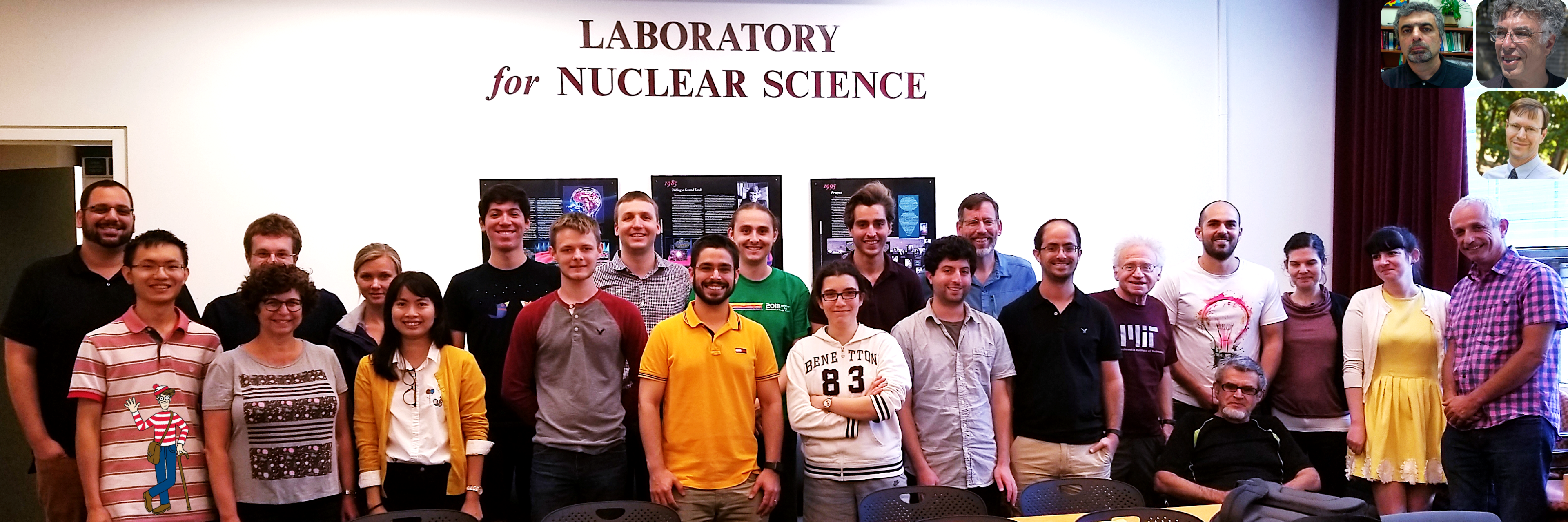

Reynier Cruz-Torres

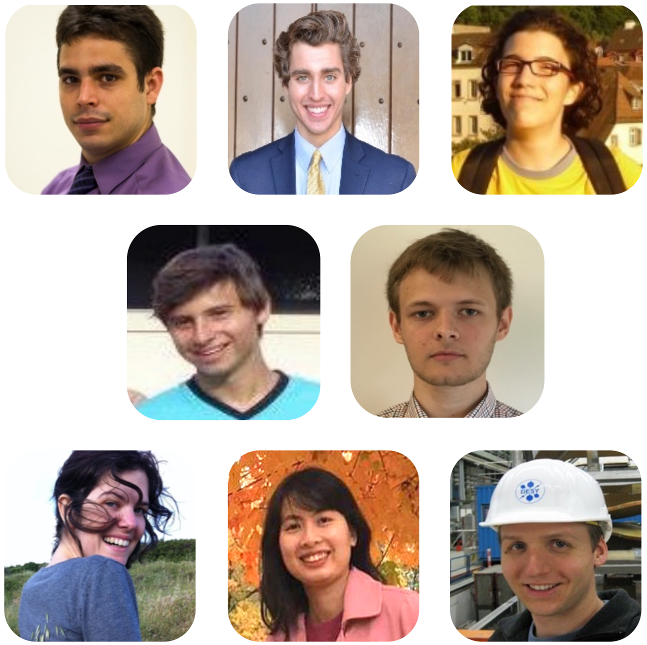

Efrain Segarra


Jackson Pybus


Afroditi Papadopoulou


Andrew Denniston





2018/19 SRC Publications:

- Nature, 566, 354 (2019)
- Nature 560, 617 (2018)
- Phys. Rev. Lett. 122, 172502 (2019)
- Phys. Rev. Lett. 121, 092501 (2018)
- Physics Letters B 791, 242 (2019)
- Physics Letters B 793, 360 (2019)
- Physics Letters B 785, 304 (2018)
- Physics Letters B 780, 211 (2018)
- Chin Phys. C 42, 064105 (2018)

arXiv: 1811.01823; 1812.08051; 1902.06358