Short-Range Correlations

Or Hen (MIT)

- (new) Exp. results
- (new) Implications
- (new) Theory results

INT Workshop on Fundamental Physics with Electroweak Probes of Light Nuclei, July 2nd 2018.

Flower
Power
Flower
Power
Power
Peace Love Peace Love Peace Love Peace Love Peace Love Peace Love

What Are SRCs?

What Are SRCs?

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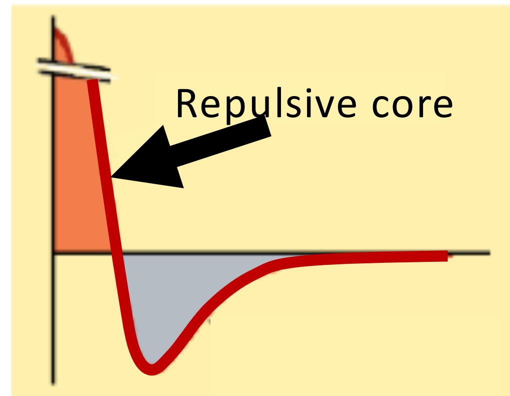

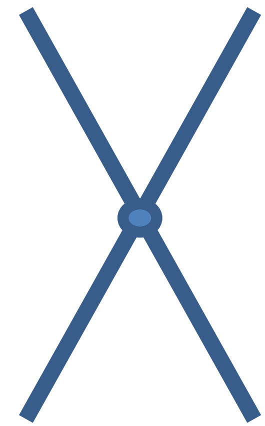

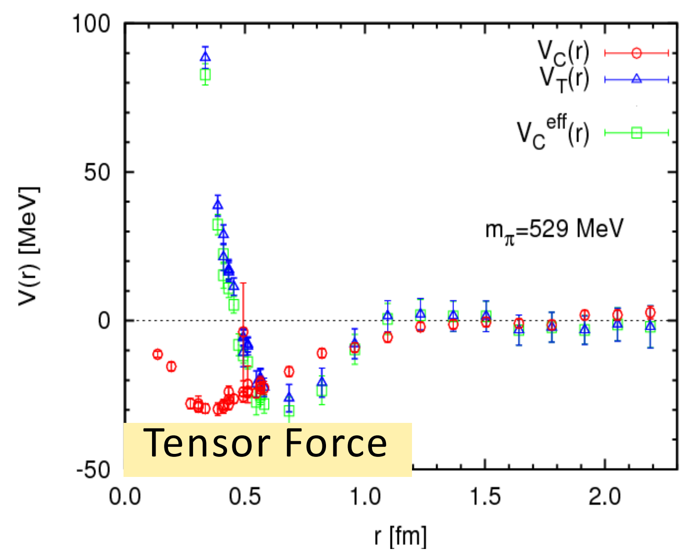

What Do I Mean by SRCs?

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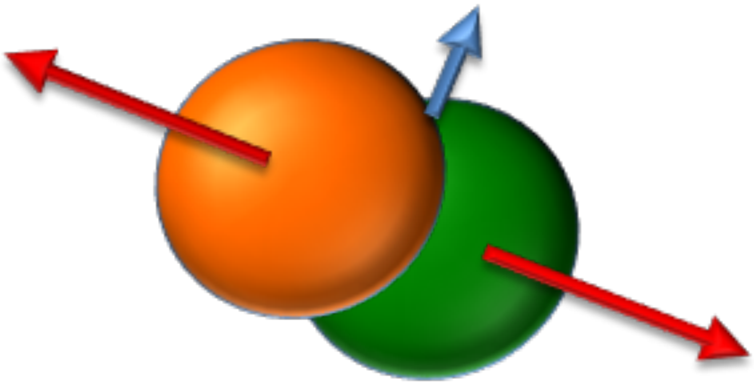
Nucleon pairs that are close together in the nucleus

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



Why Study SRCs?

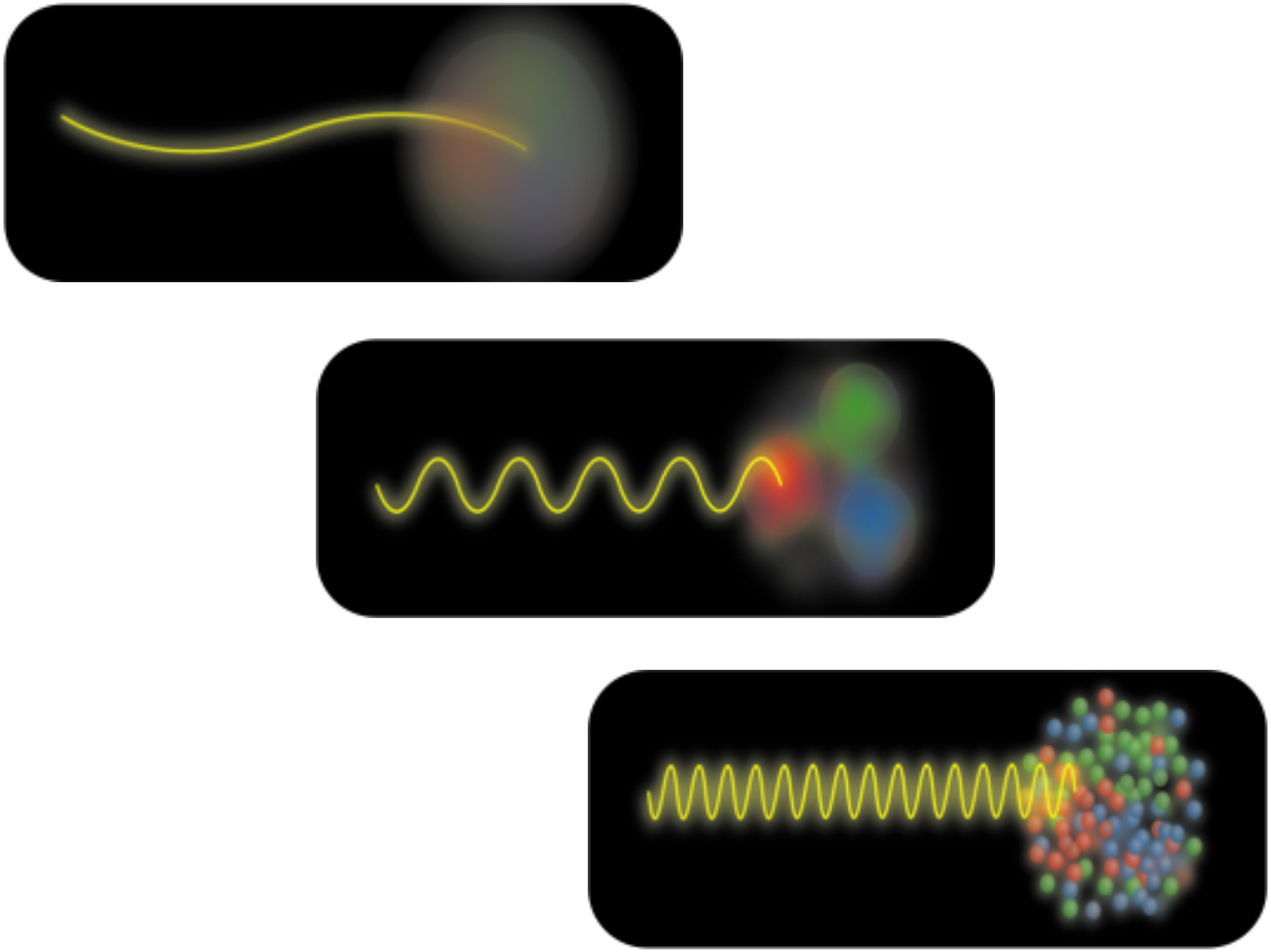
Why Study SRCs?

- Significant part of the nuclear w.f. / response
  [20% of the density; 40% of the amplitude]

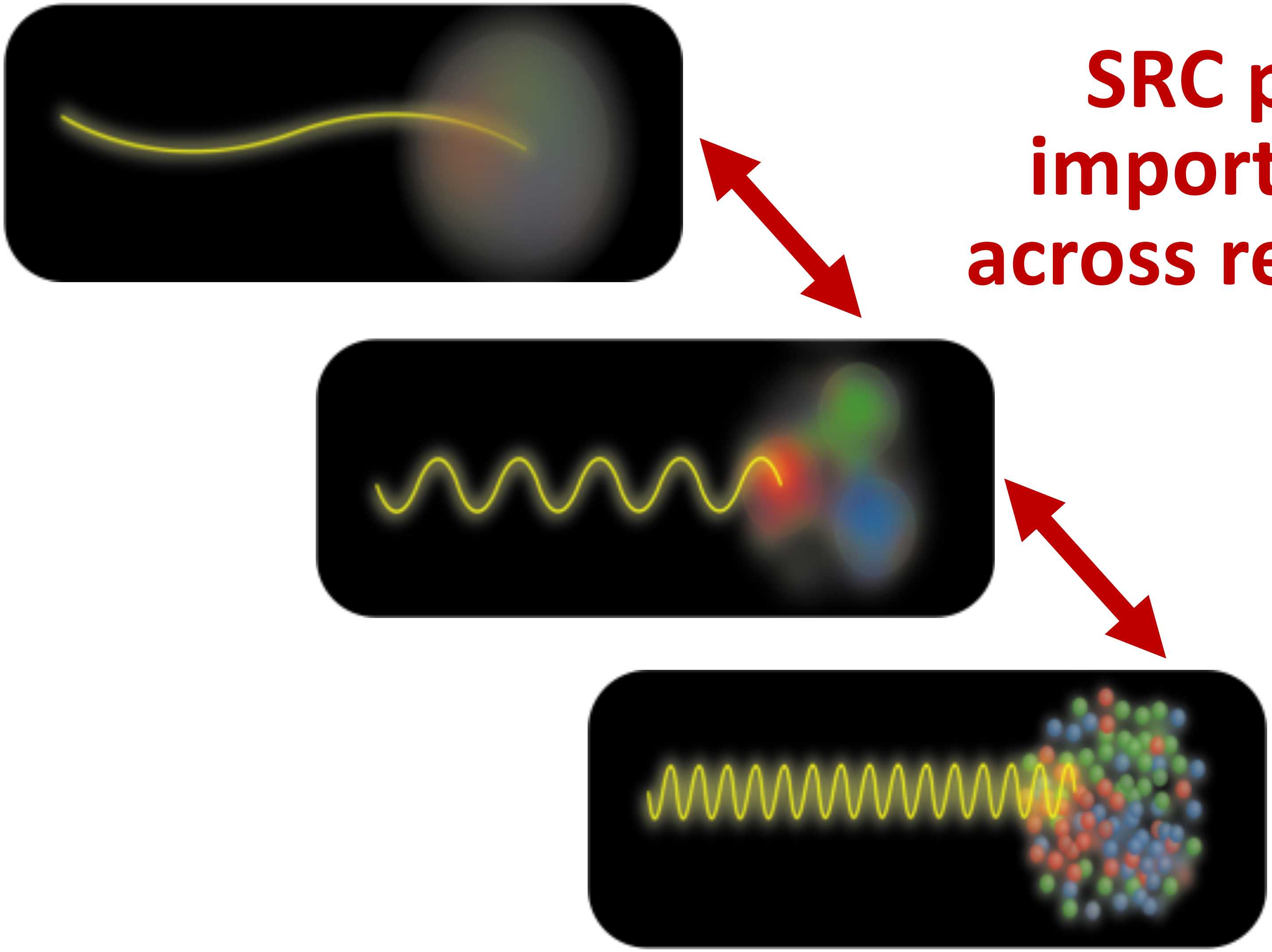
- NN interaction at short distances
  [/ effective short-distance operators in EFT]

- Implications
  - Bound nucleon structure; Nuclear matter EOS; ν-interactions; …

Physics is resolution dependent

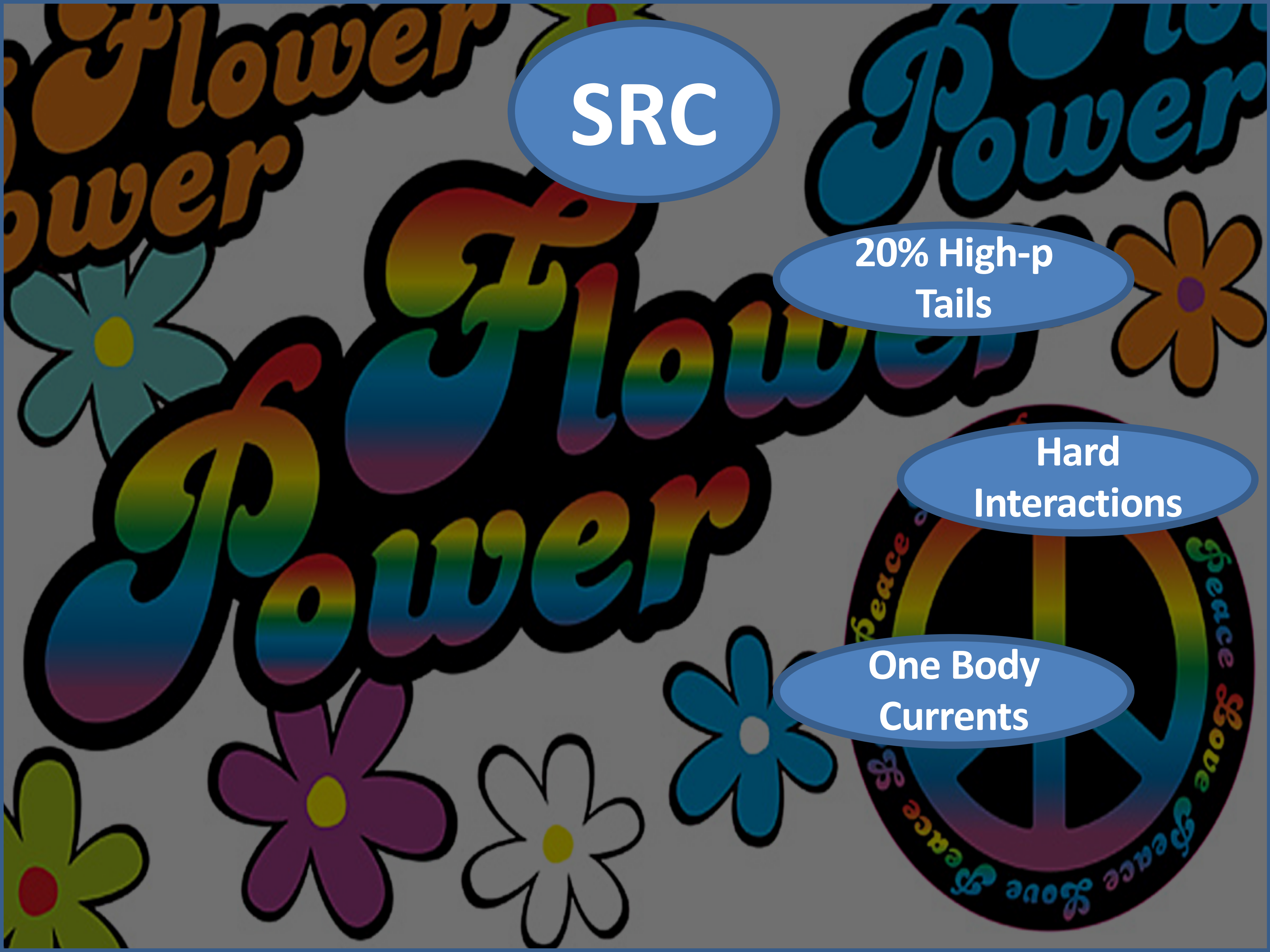


Physics is resolution dependent



SRC play an important role across resolutions


Flower
Flower Power
Power
Peace Love Peace Love Peace Love Peace Love Peace Love

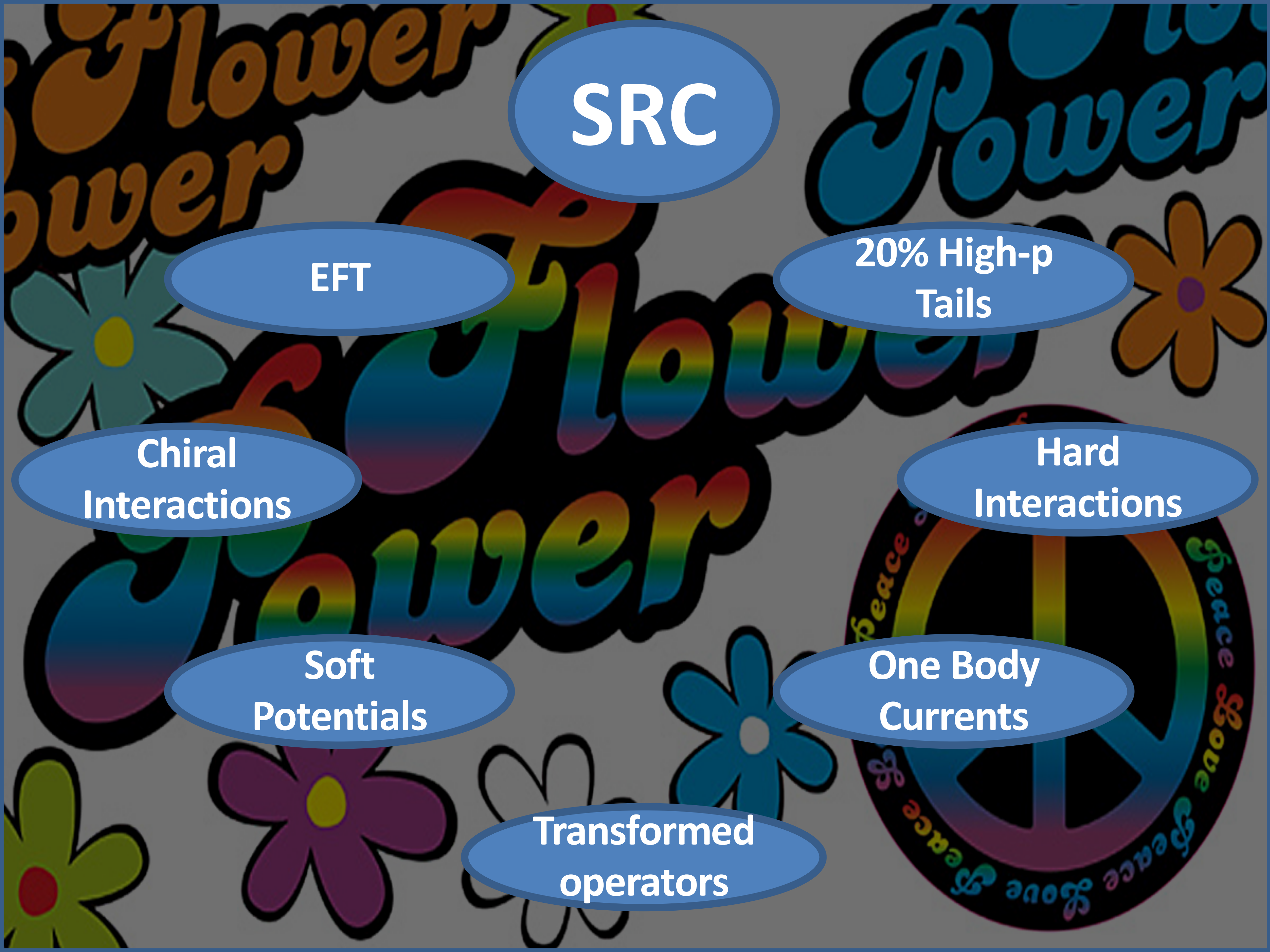


SRC

20% High-p Tails

Hard Interactions

One Body Currents


SRC
EFT
20% High-p Tails
Chiral Interactions
Hard Interactions
Soft Potentials
One Body Currents
Transformed operators
Flower Power

SRC

EFT

20% High-p Tails

Chiral Interactions

Hard Interactions

Soft Potentials

One Body Currents

Transformed operators

While differences still stand, many commonalities exist.

Data can guide & test theory!

My Goals for Today:

1. Present new data,
2. Showcase its importance,
3. Initiate discussion:
   - Data Interpretation?
   - Getting Quantitative!
   - Where we are and where we’re going?

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- **(new) Exp. results**
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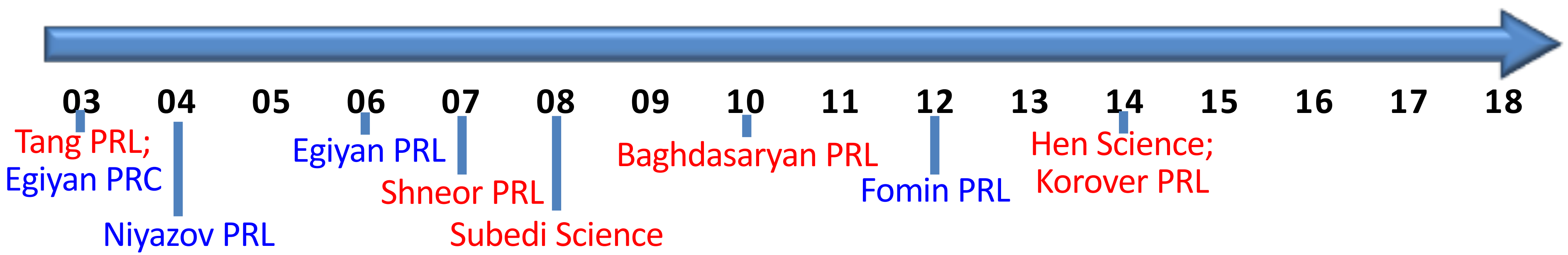
Past Data


03
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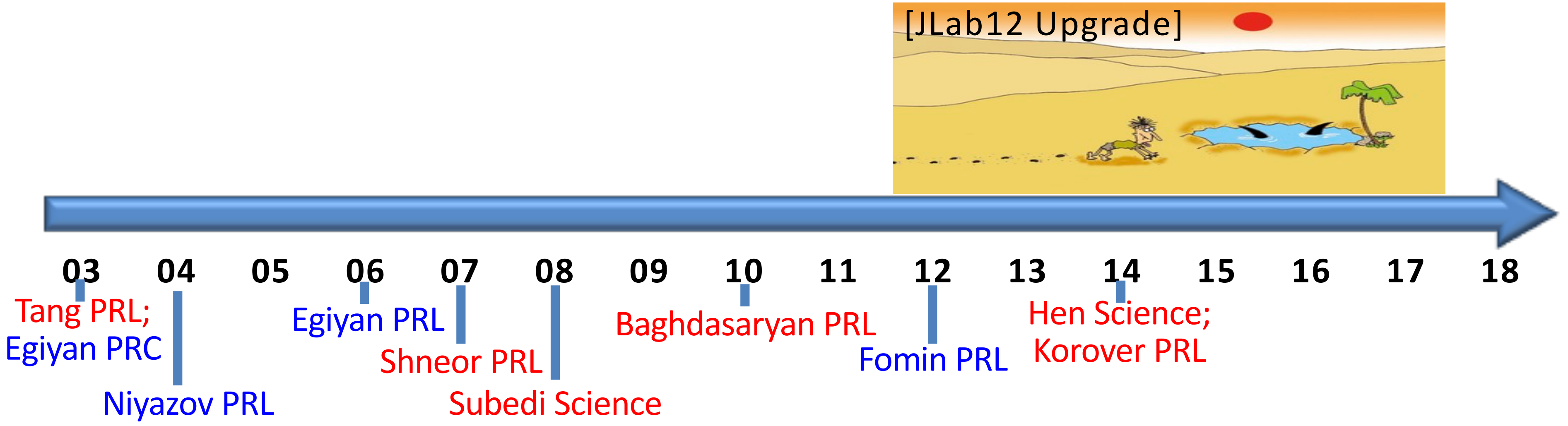
18
Tang PRL;
Egiyan PRC
Niyazov PRL
Egiyan PRL
Shneor PRL
Subedi Science
Baghdasaryan PRL
Fomin PRL
Hen Science;
Korover PRL

Past Data


[JLab12 Upgrade]
03
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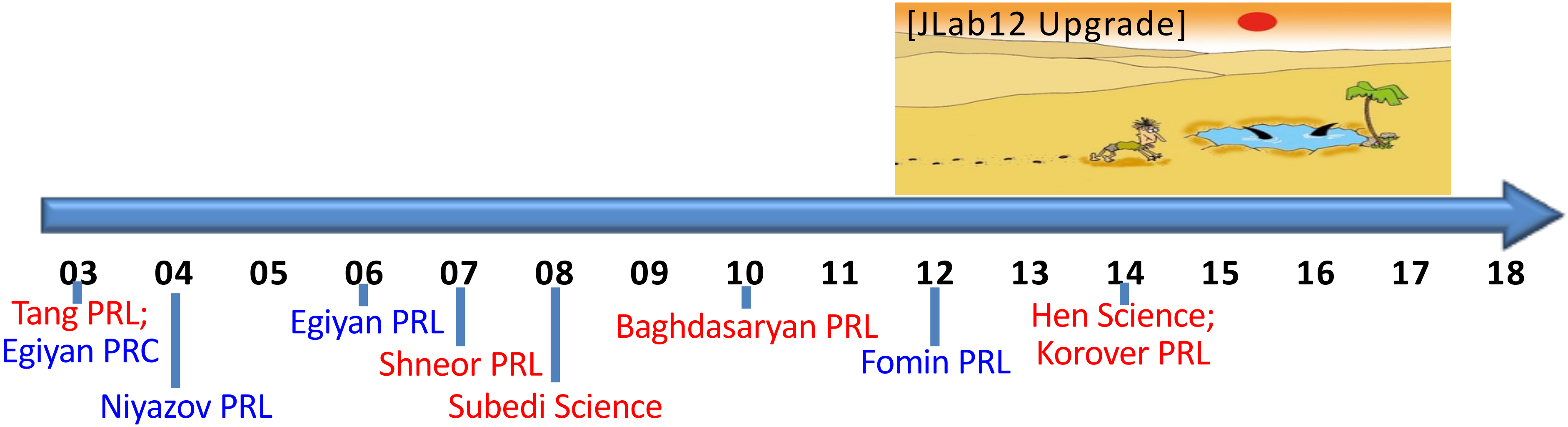
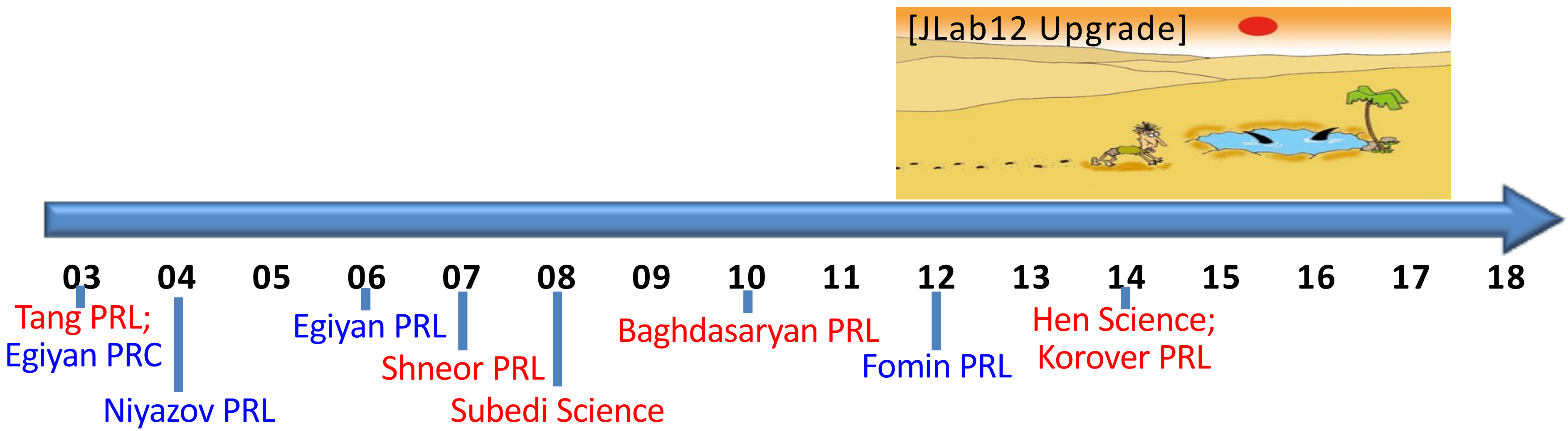


<u>10 papers in 15 years</u> 😬. Two main conclusions:

- Exclusive measurements: SRCs are np-pairs [Tensor Interaction]
- Inclusive measurements: Deuteron scaling-factors measured

Past Data

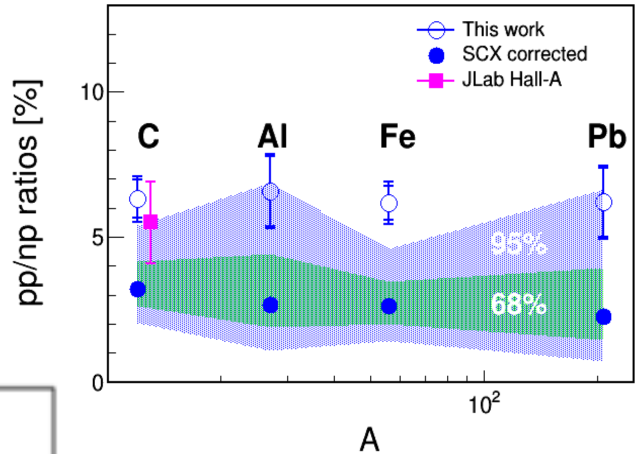


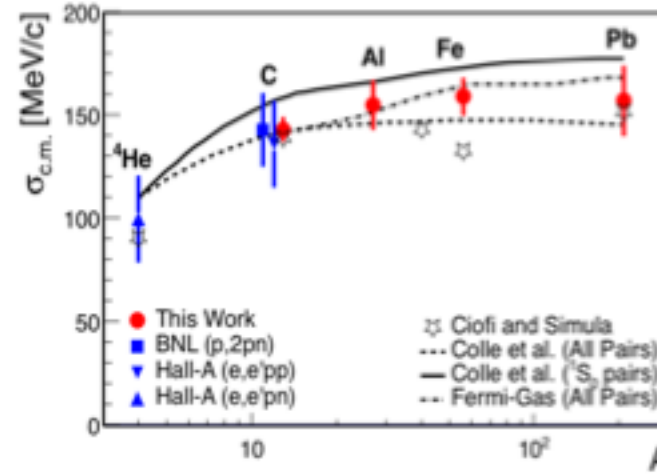
<u>10 papers in 15 years 😬</u>. Two main conclusions:

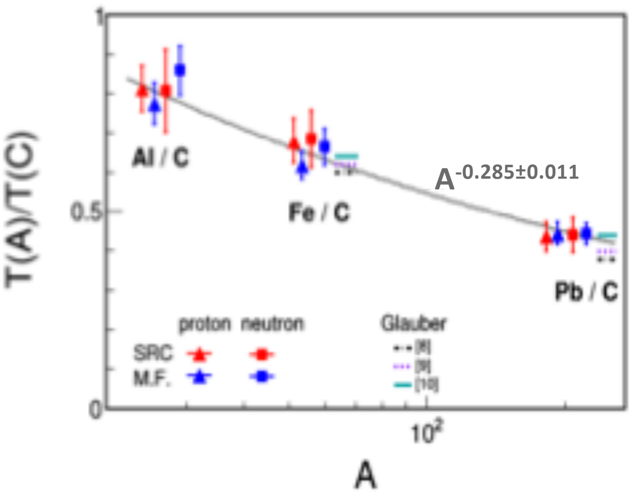
- Exclusive measurements: SRCs are np-pairs [Tensor Interaction]
- Inclusive measurements: Deuteron scaling-factors measured

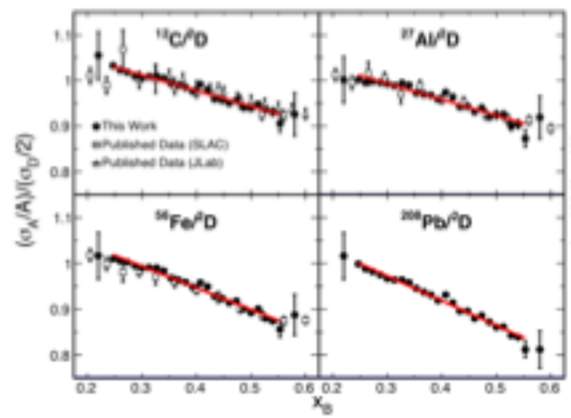
*On average, there's one review paper for every ~ two experimental papers 😬 😬

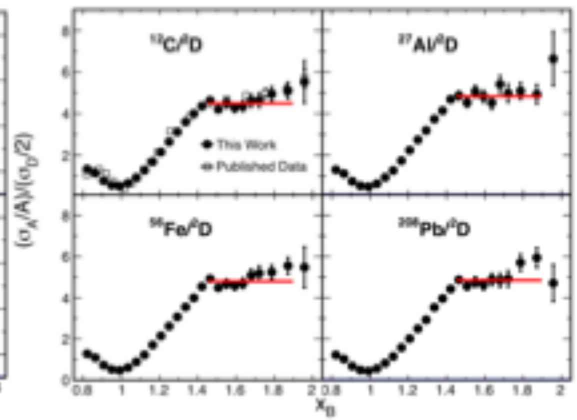
2018


This work
SCX corrected
JLab Hall-A
C
Al
Fe
Pb
95%
68%
pp/np ratios [%]
A


$\sigma_{c.m.}$ [MeV/c]
^{4}He
C
Al
Fe
Pb
This Work
BNL (p,2pn)
Hall-A (e,e'pp)
Hall-A (e,e'pn)
Ciofi and Simula
Colle et al. (All Pairs)
Colle et al. (^{1}S$_0$ pairs)
Fermi-Gas (All Pairs)
A


T(A)/T(C)
Al / C
Fe / C
Pb / C
$A^{-0.285\pm0.011}$
proton
neutron
Glauber
SRC
M.F.
A


^{12}C/^{2}D
^{27}Al/^{2}D
^{56}Fe/^{2}D
^{208}Pb/^{2}D
This Work
Published Data (SLAC)
Published Data (JLab)
$(\sigma_A/A)/(\sigma_D/2)$
x_B


^{12}C/^{2}D
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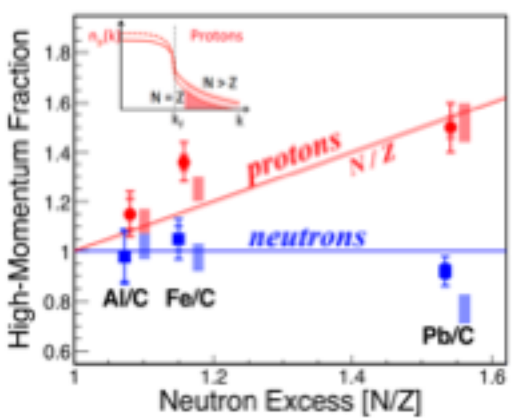
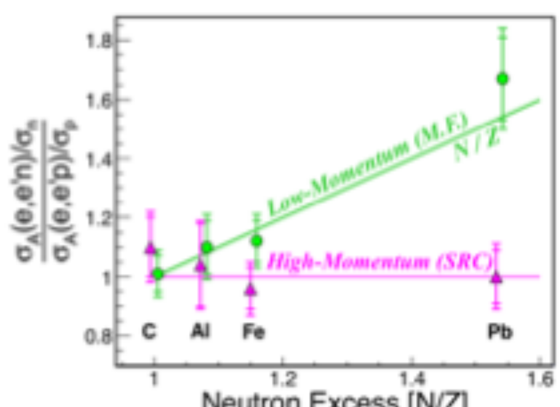
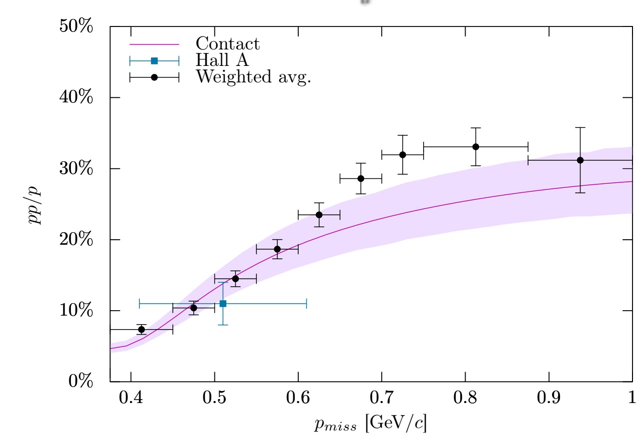
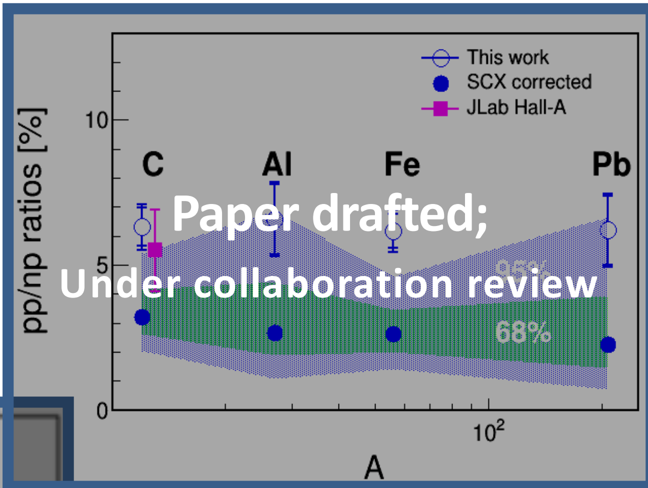

High-Momentum Fraction
Protons
N = Z
N > Z
protons
N / Z
neutrons
Al/C
Fe/C
Pb/C
Neutron Excess [N/Z]


$\frac{\sigma_A(e,e'n)/\sigma_n}{\sigma_A(e,e'p)/\sigma_p}$
Low-Momentum (M.F.)
N / Z
High-Momentum (SRC)
C
Al
Fe
Pb
Neutron Excess [N/Z]


Contact
Hall A
Weighted avg.
pp/p
p_{miss} [GeV/c]

2018


This work
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pp/np ratios [%]
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95%
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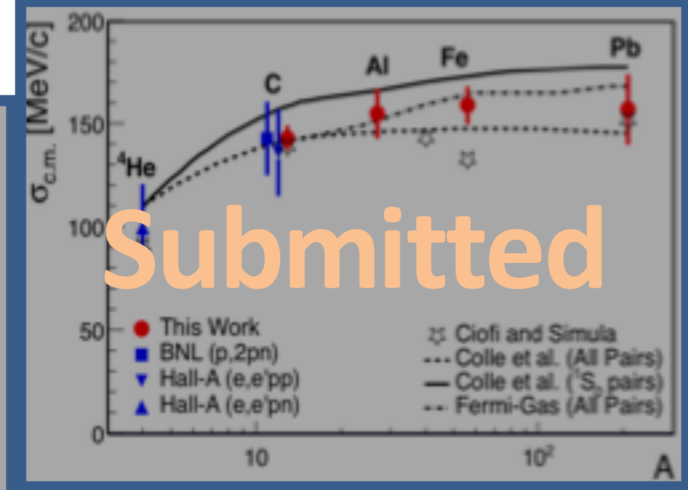
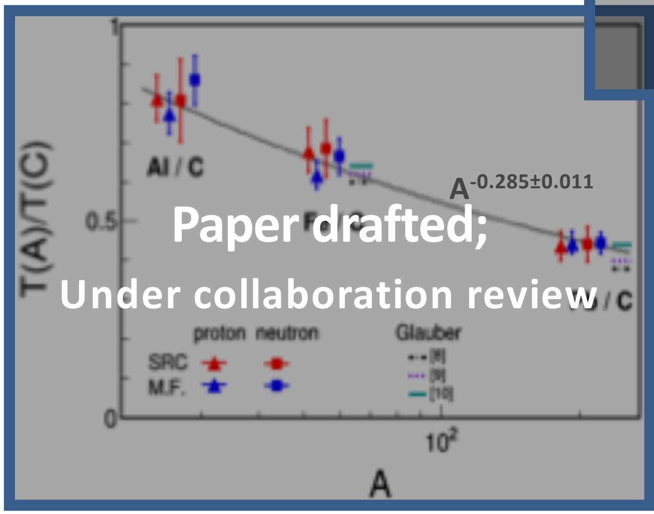
Paper drafted;
Under collaboration review


σc.m. [MeV/c]
⁴He
C
Al
Fe
Pb
This Work
BNL (p,2pn)
Hall-A (e,e'pp)
Hall-A (e,e'pn)
Ciofi and Simula
Colle et al. (All Pairs)
Fermi-Gas (All Pairs)
A
Submitted


T(A)/T(C)
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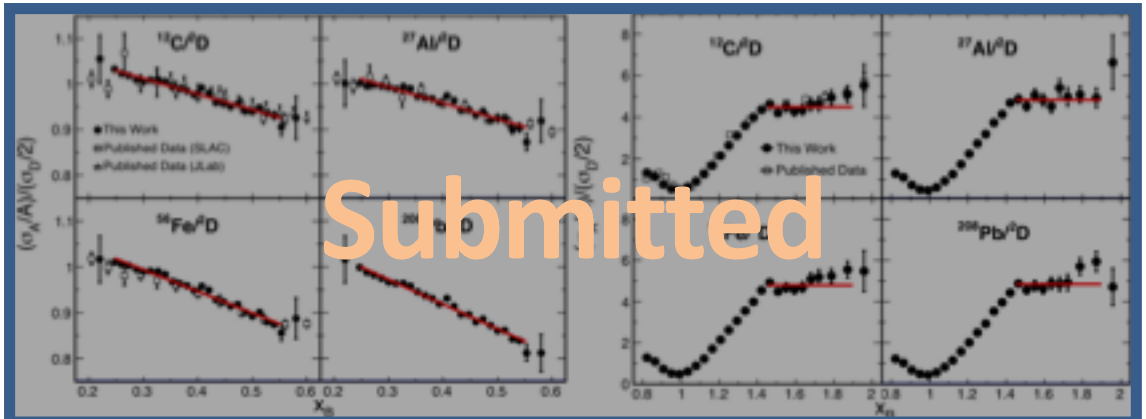
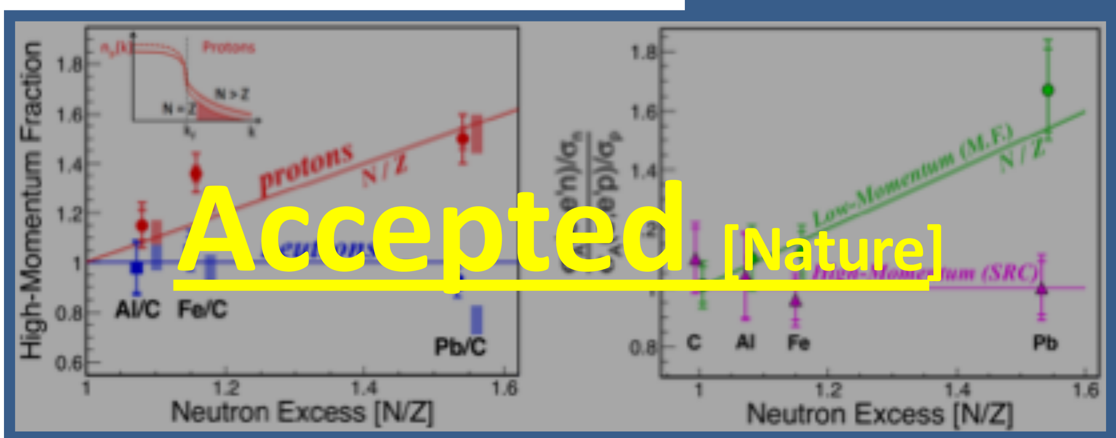

¹²C/²D
²⁷Al/²D
⁵⁶Fe/²D
²⁰⁸Pb/²D
This Work
Published Data
Submitted


High-Momentum Fraction
Protons
protons
N/Z
Low-Momentum (M.F.)
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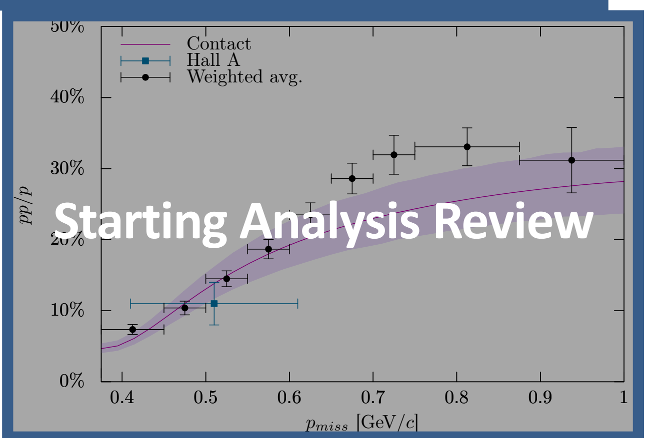
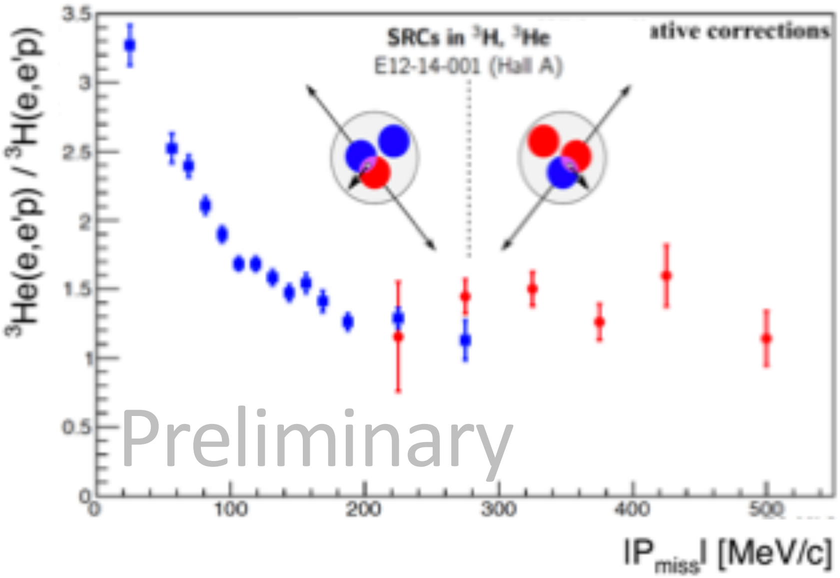
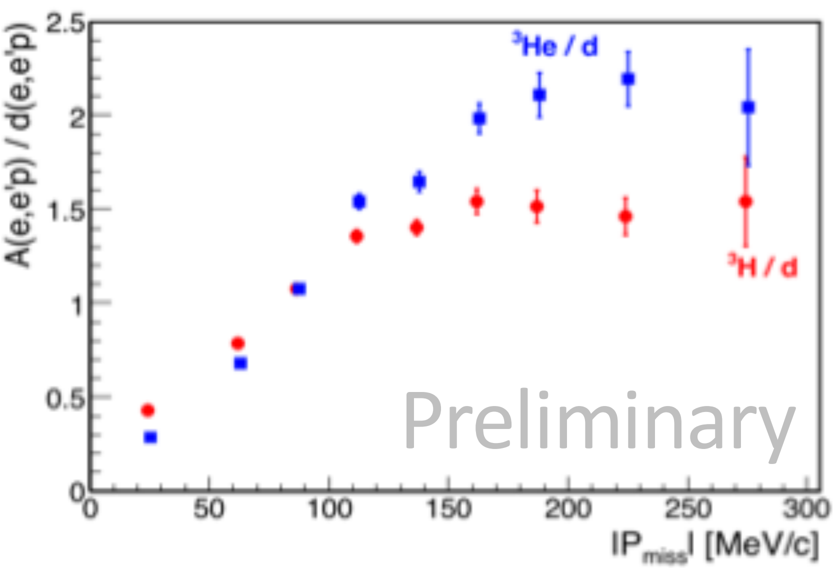
Al/C
Fe/C
Pb/C
C
Al
Fe
Pb
Neutron Excess [N/Z]
Accepted [Nature]

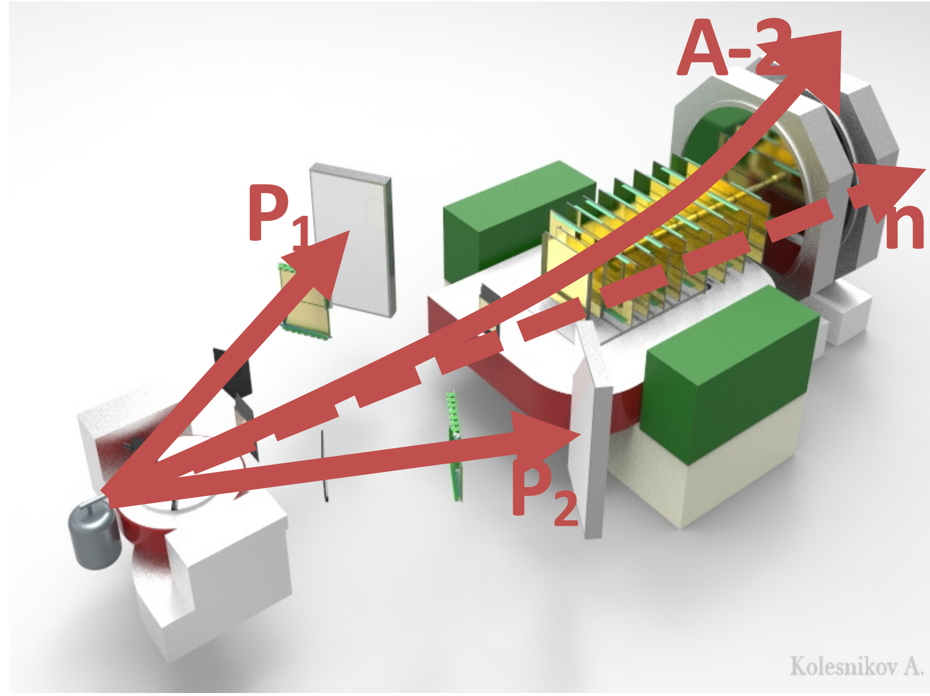

Contact
Hall A
Weighted avg.
pp/p
pmiss [GeV/c]
Starting Analysis Review

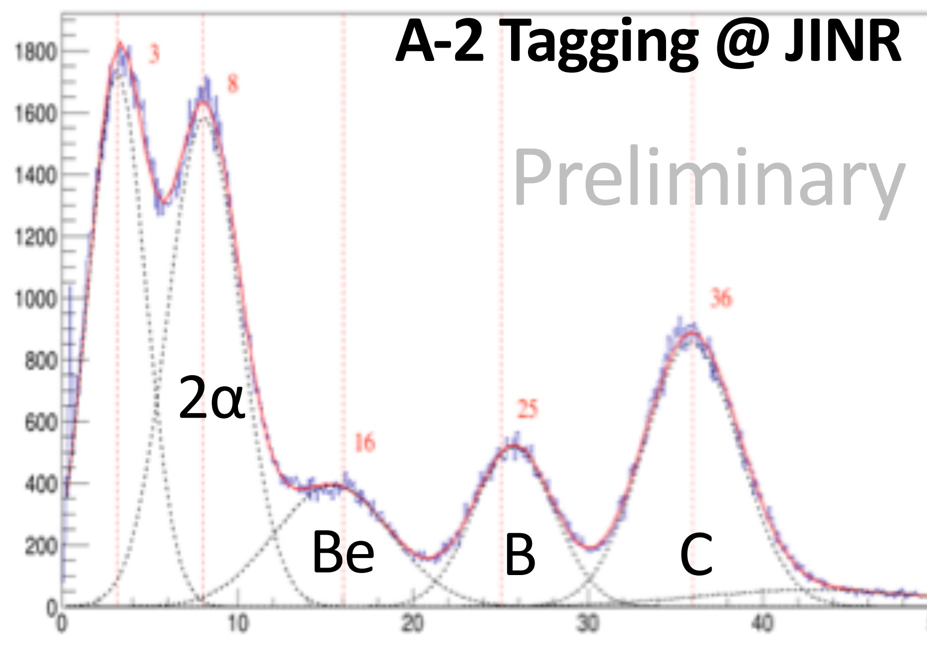
2018 Experiments

Few Body @ JLab

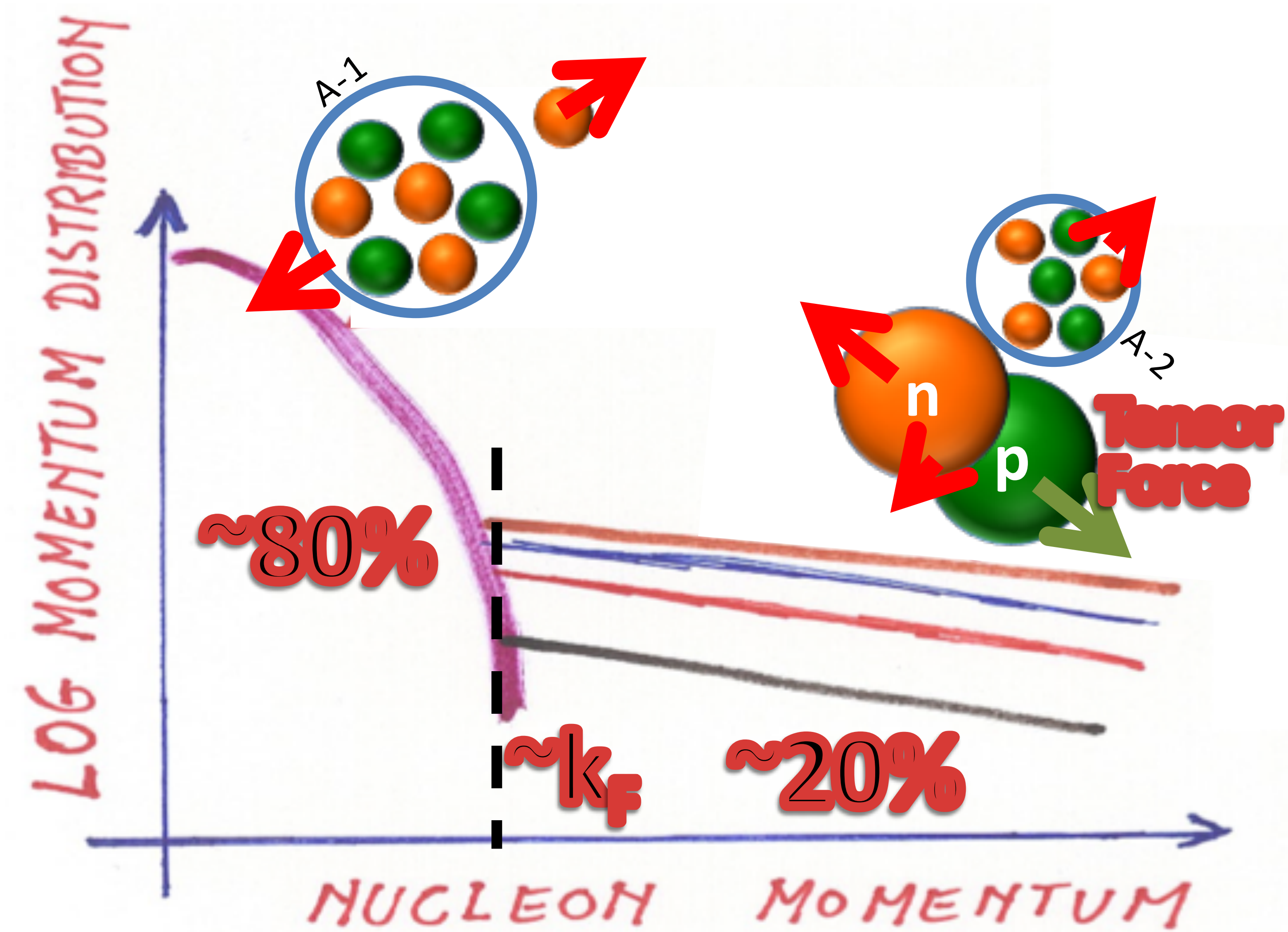




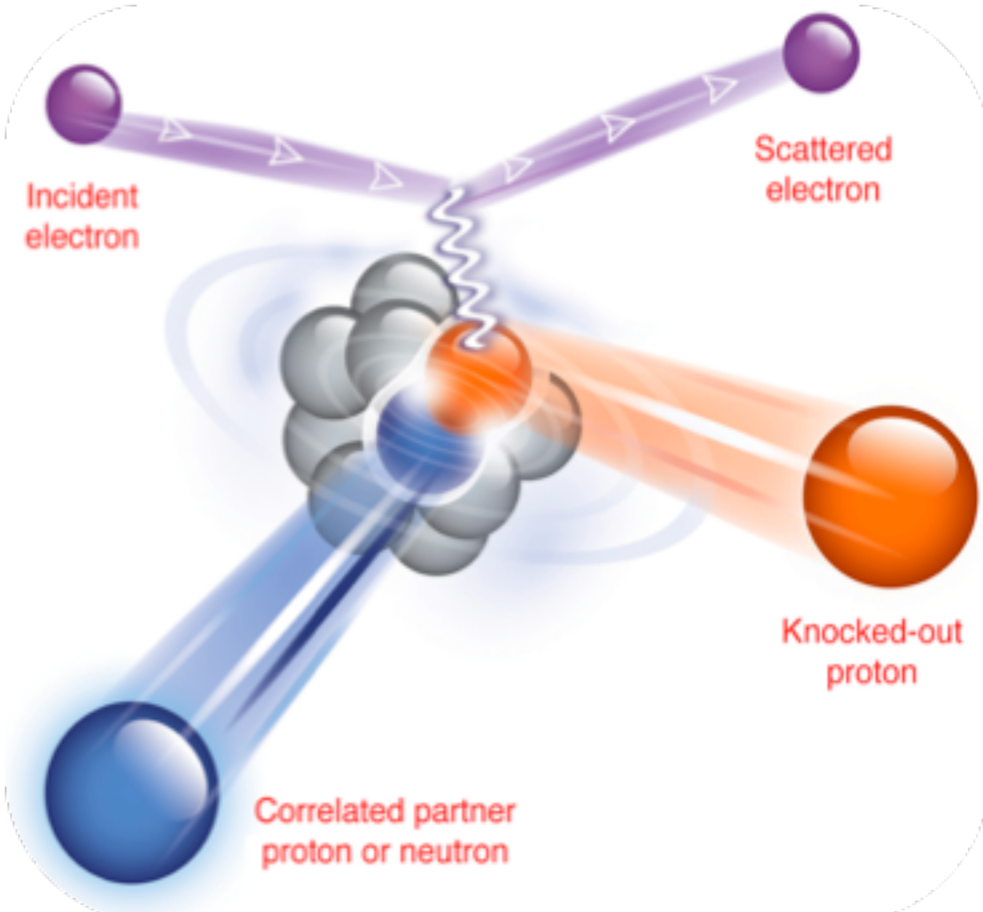




[one] Data Interpretation



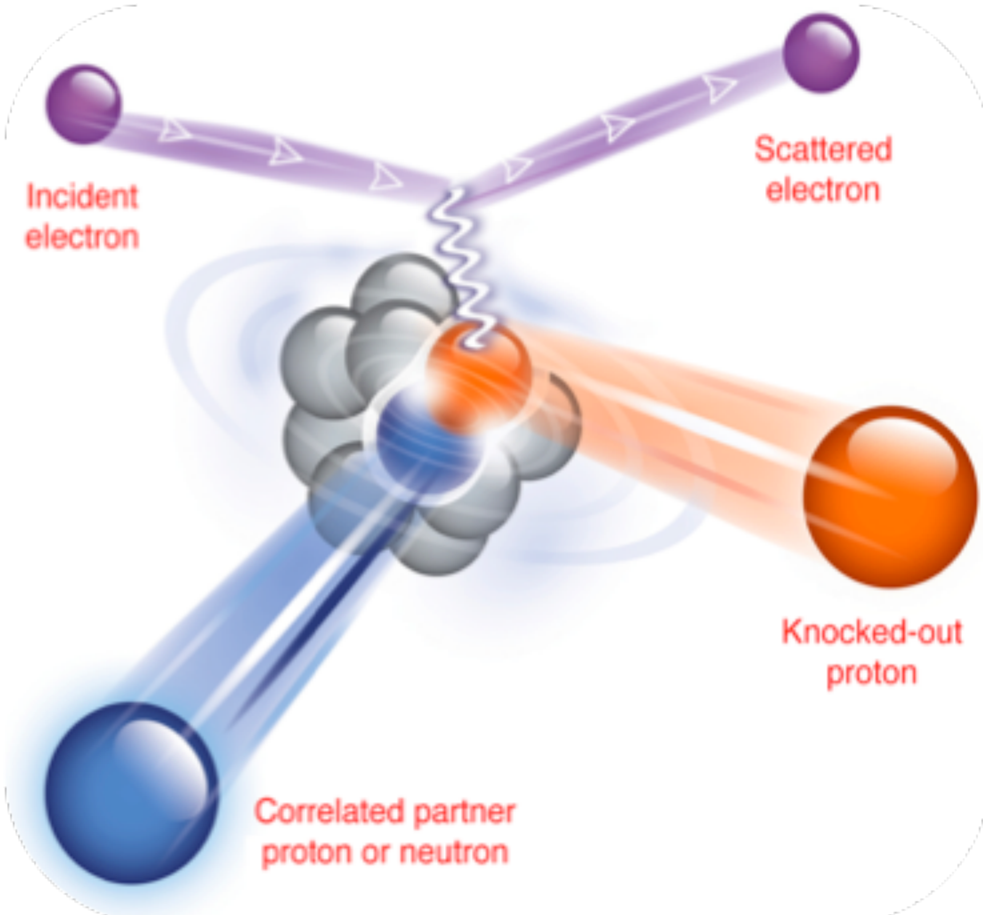
Probing Correlations Using Hard Knockout Reactions



Breakup the pair =>

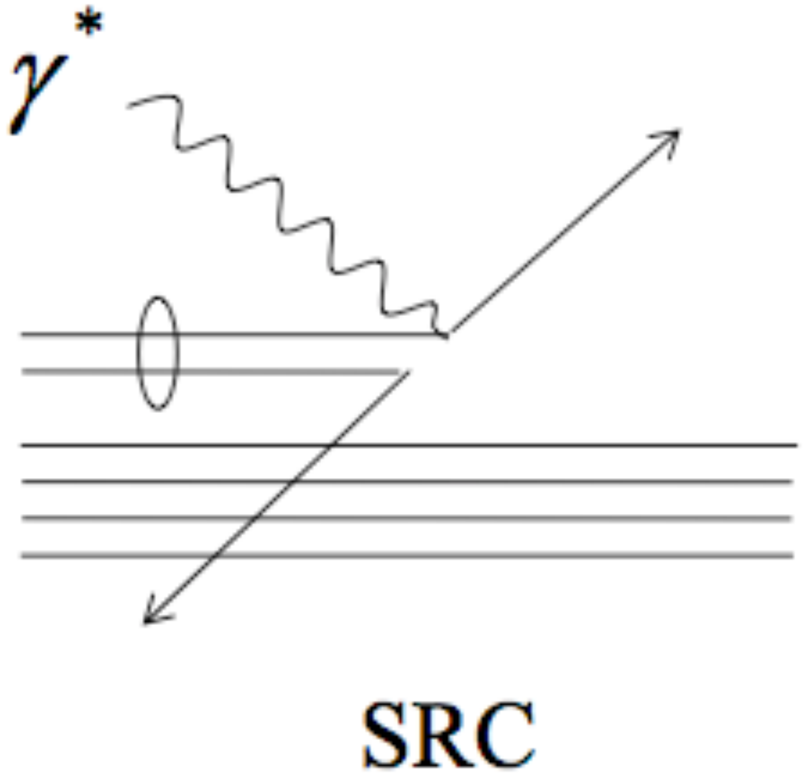
Detect <u>***both***</u> nucleons =>

Reconstruct 'initial' state



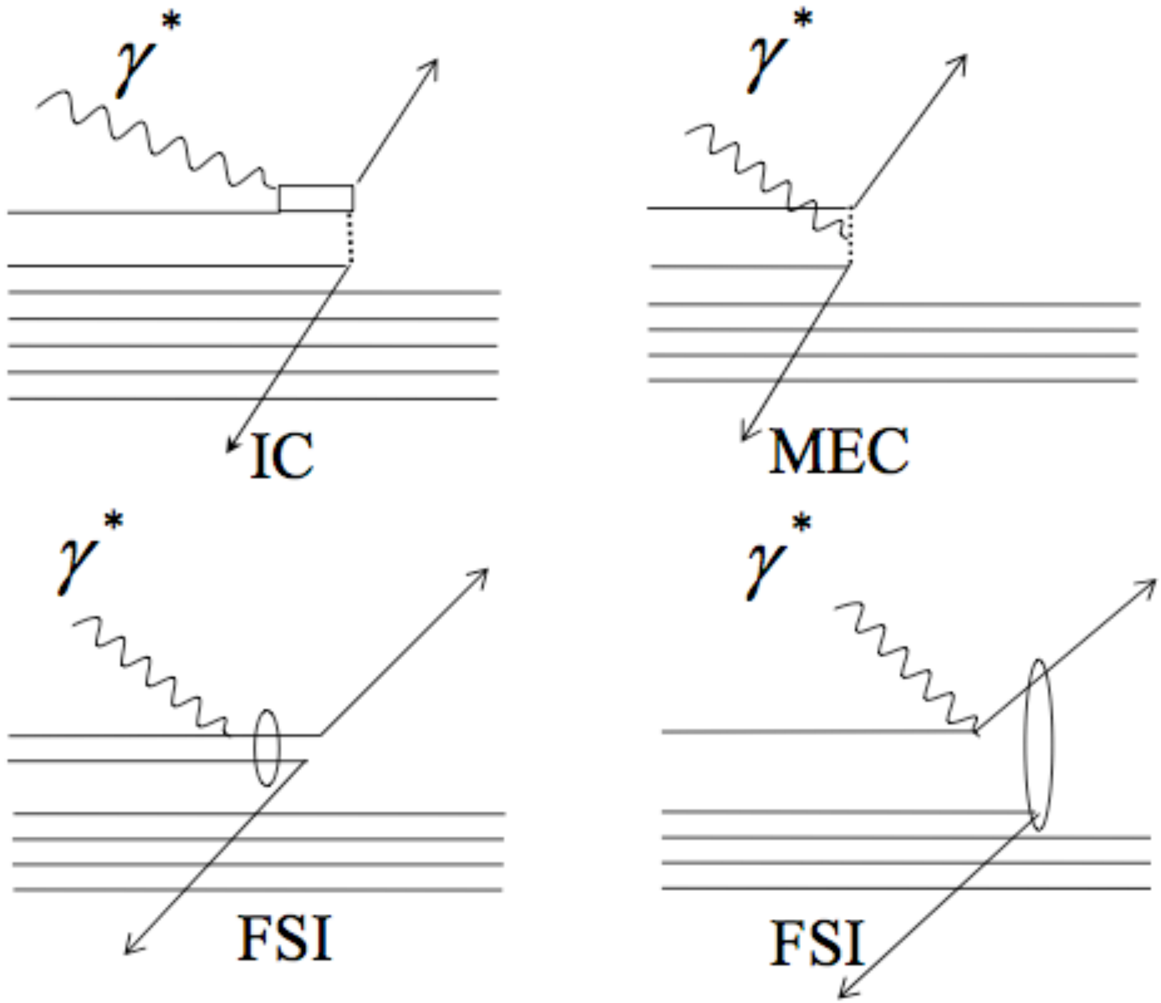
Interlude: Reaction Mechanisms

What we want:

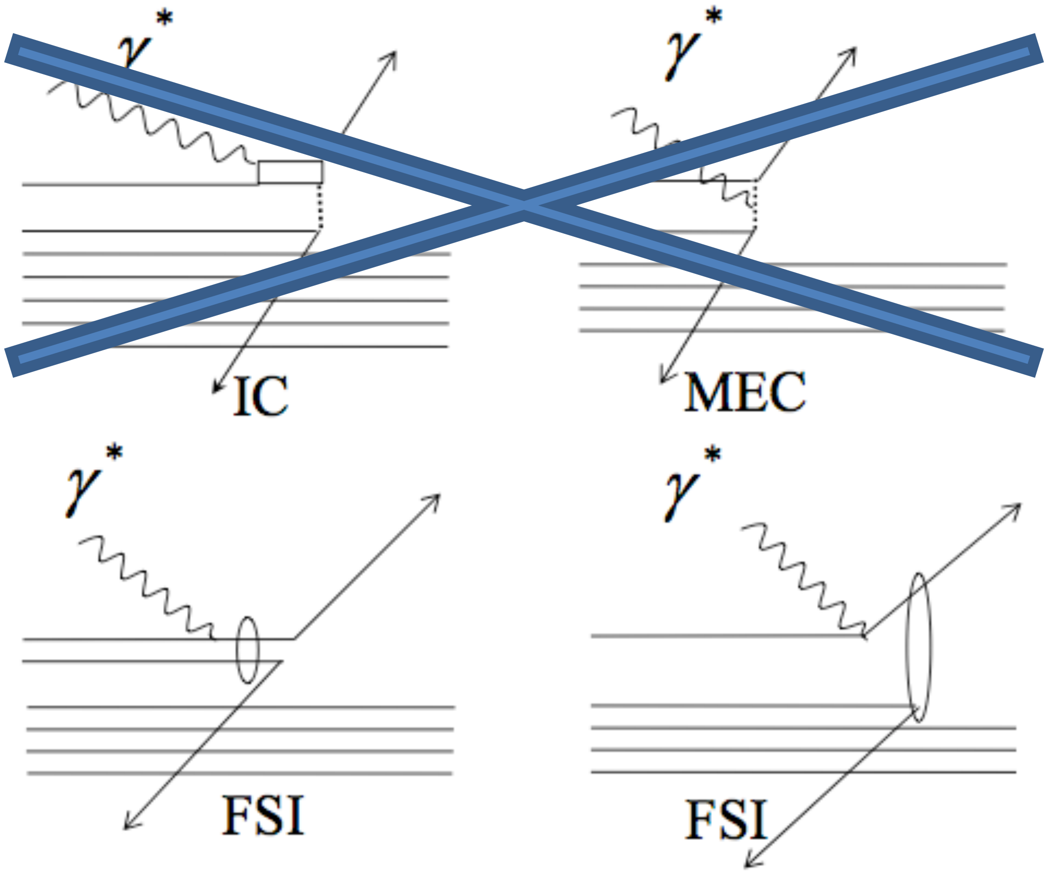


Interlude: Reaction Mechanisms

What we (might) get:



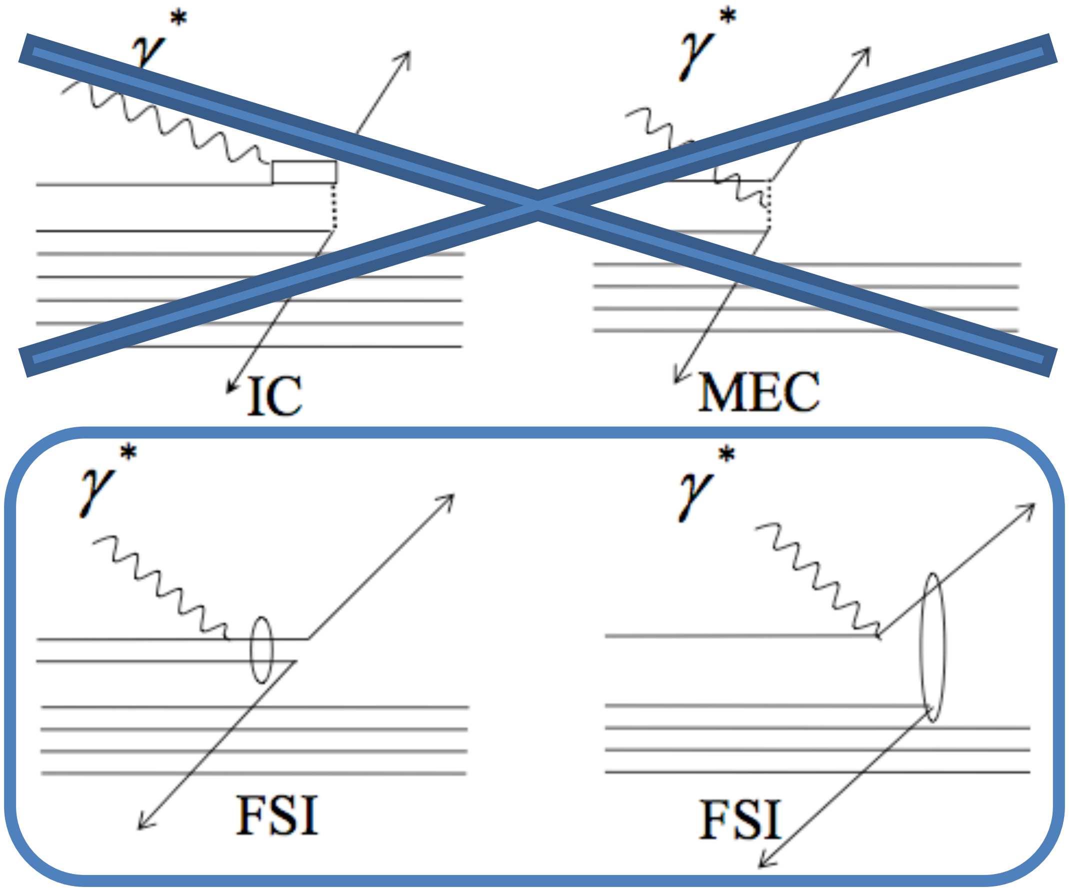
Interlude: Reaction Mechanisms



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

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

Interlude: Reaction Mechanisms



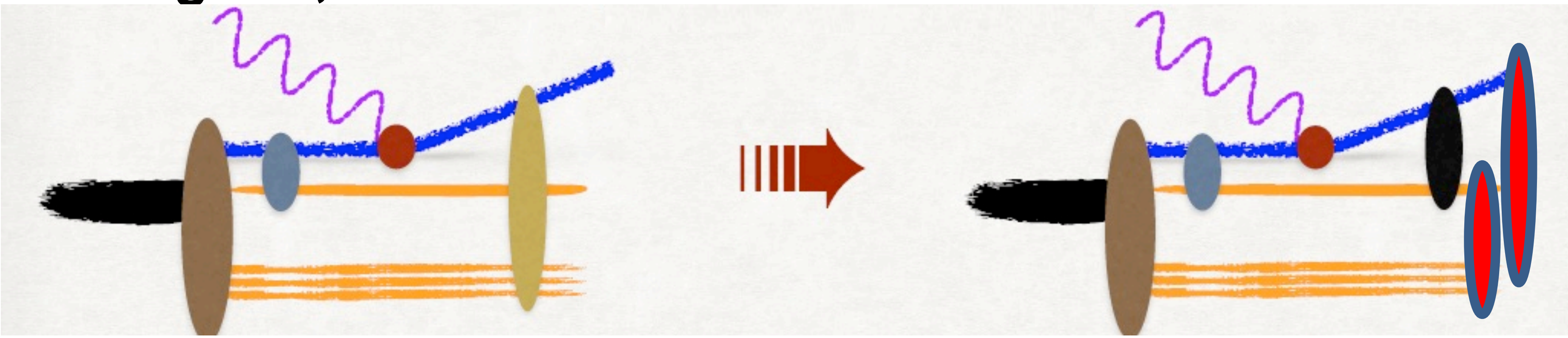
MEC suppressed @ **high-Q^2**, IC suppressed at **$x_B > 1$.**

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).

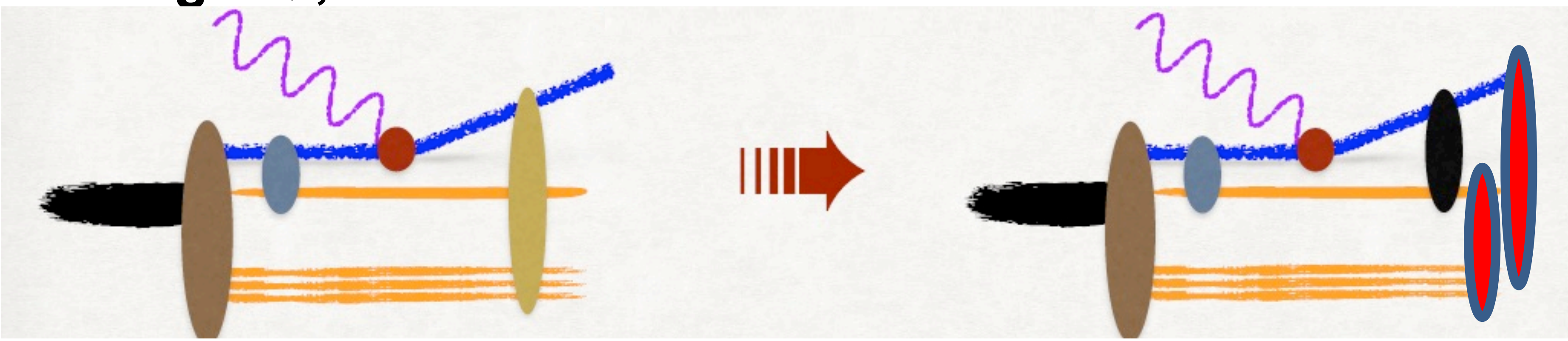
FSI: Theory Guidance

For large Q^2, x>1



FSI: Theory Guidance

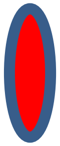
For large Q^2, x>1



$$r_{FSI} \sim \frac{1}{\Delta E v} \lesssim 1 \text{ fm}$$

[PRC 56 1124-1137 (1997), arXiv: 0806.4412]

$$\Delta E = -q_0 - M_A + \sqrt{m^2 + (p_i + q)^2} + \sqrt{M_{A-1}^2 + p_i^2}$$



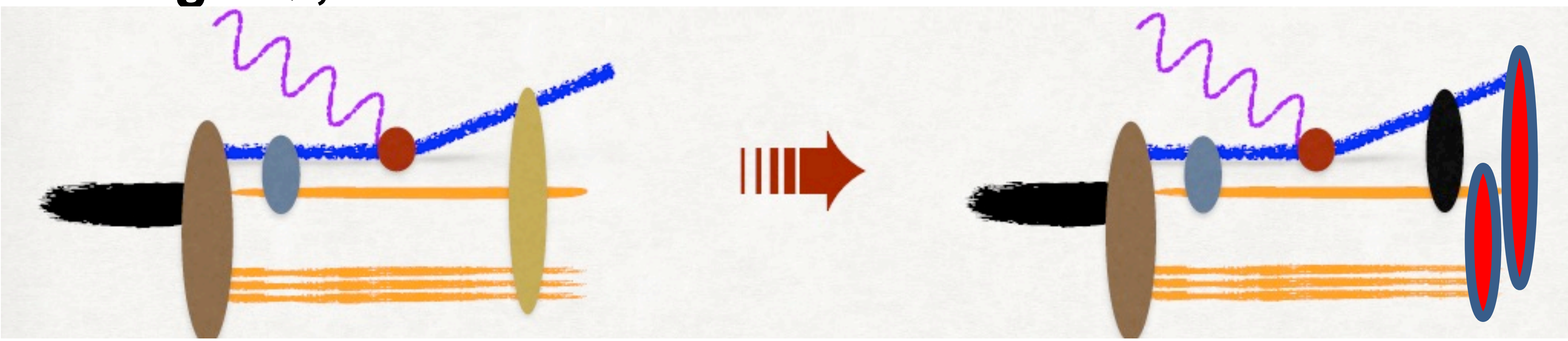
Can be approximated by Glauber (transparency)

Large but confined within the SRC pair

Rescattering do not produce 2N–SRC candidates due to high p_t

FSI: Theory Guidance

For large Q^2, $x>1$



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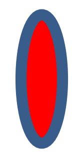

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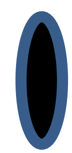
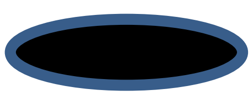


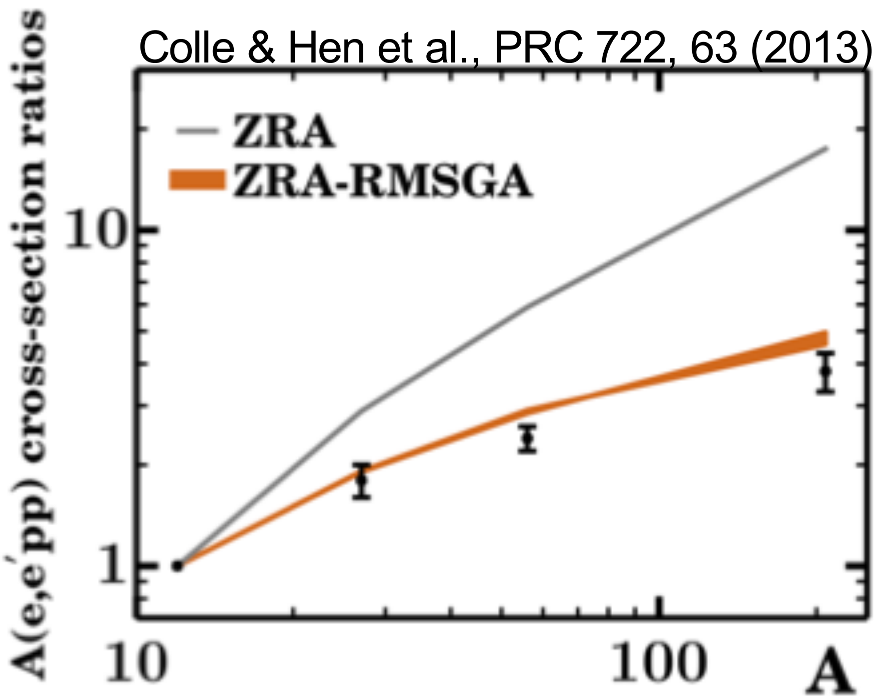
Large but confined within the SRC pair

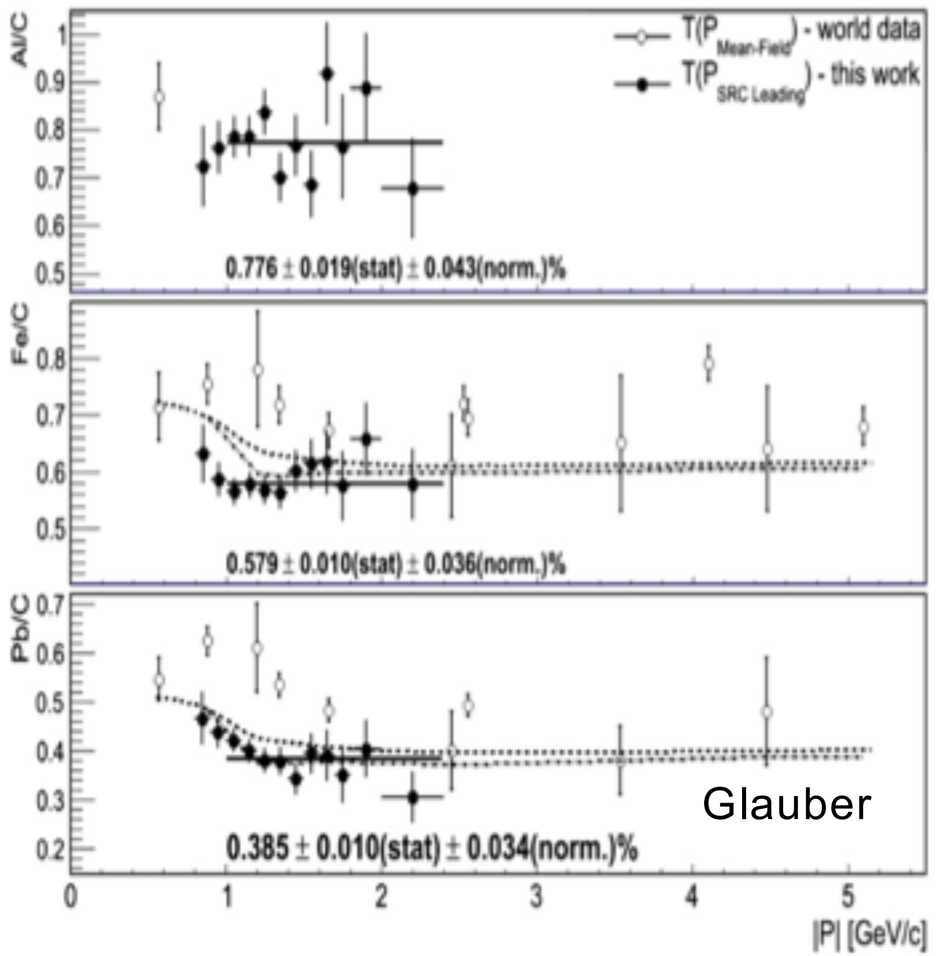
- **Choose kinematics to min FSI**
- **Choose observables not sensitive to** 

Rescattering do not produce 2N–SRC candidates due to high p_t

Glauber agrees with data!

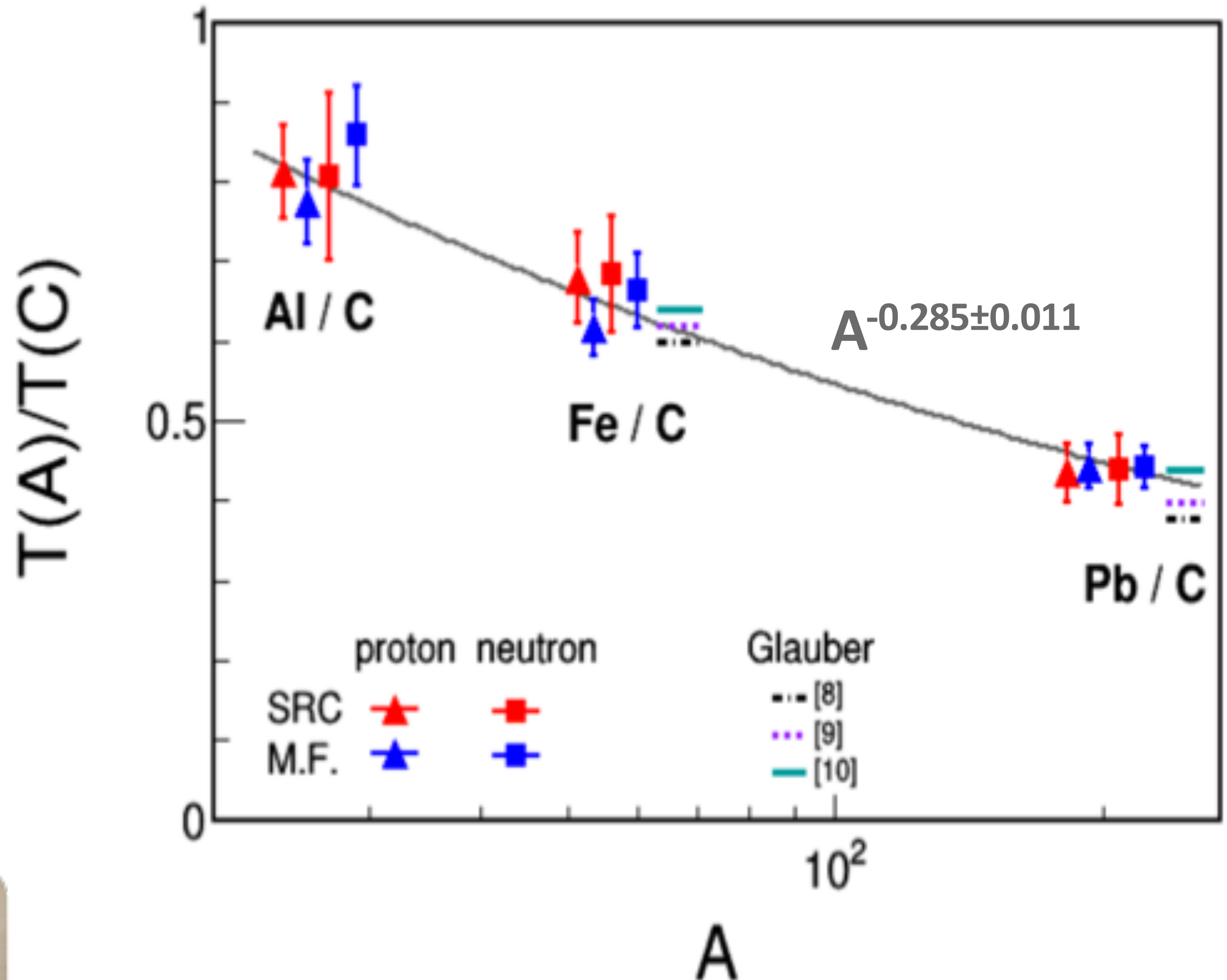
Colle & Hen et al., PRC 722, 63 (2013)





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

Glauber agrees with data!

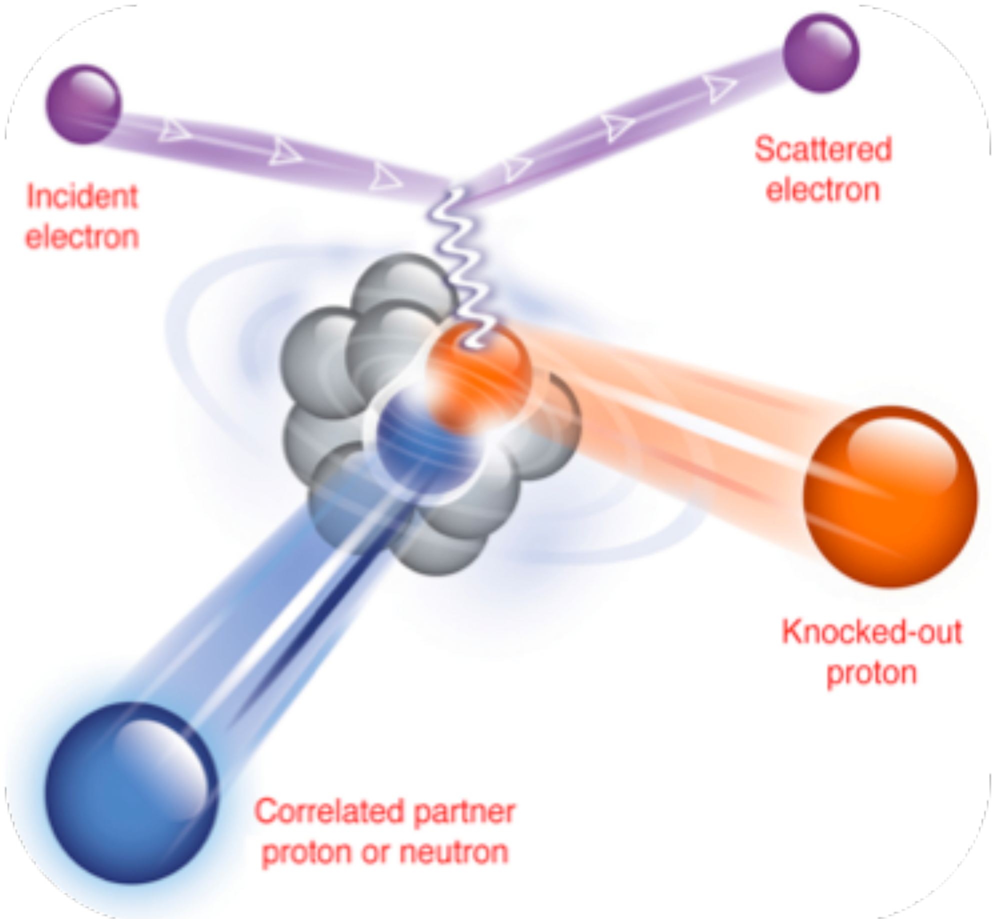


M. Duer et al.

Breakup the pair =>

Detect ***both*** nucleons =>

Reconstruct 'initial' state



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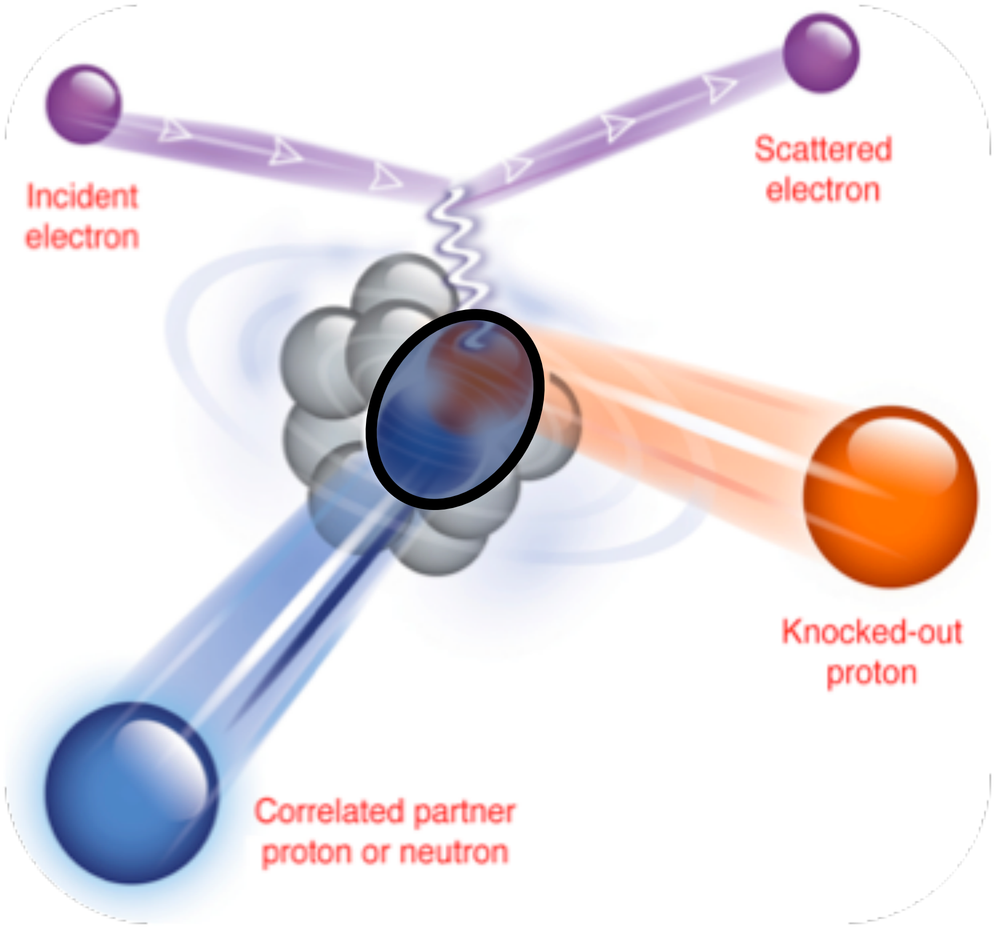


Unitary Interlude

- “high momentum” interpretation relies on *single nucleon* interaction operators.
  - Compatible \w calculation using hard potentials (e.g., AV18).
  - Difficult to go much beyond than C / Ca.

- Unitary transforms simplifies calculations of heavy nuclei at the expense of forming many-body operators.

  $$\langle\Psi|\tilde{O}|\Psi\rangle = \langle\Psi U^{\dagger}|U\tilde{O}U^{\dagger}|U\Psi\rangle$$

  - Transforms “high momentum” to “short range”

    Win: Simpler wave functions

    Lose: Complicated interaction operators

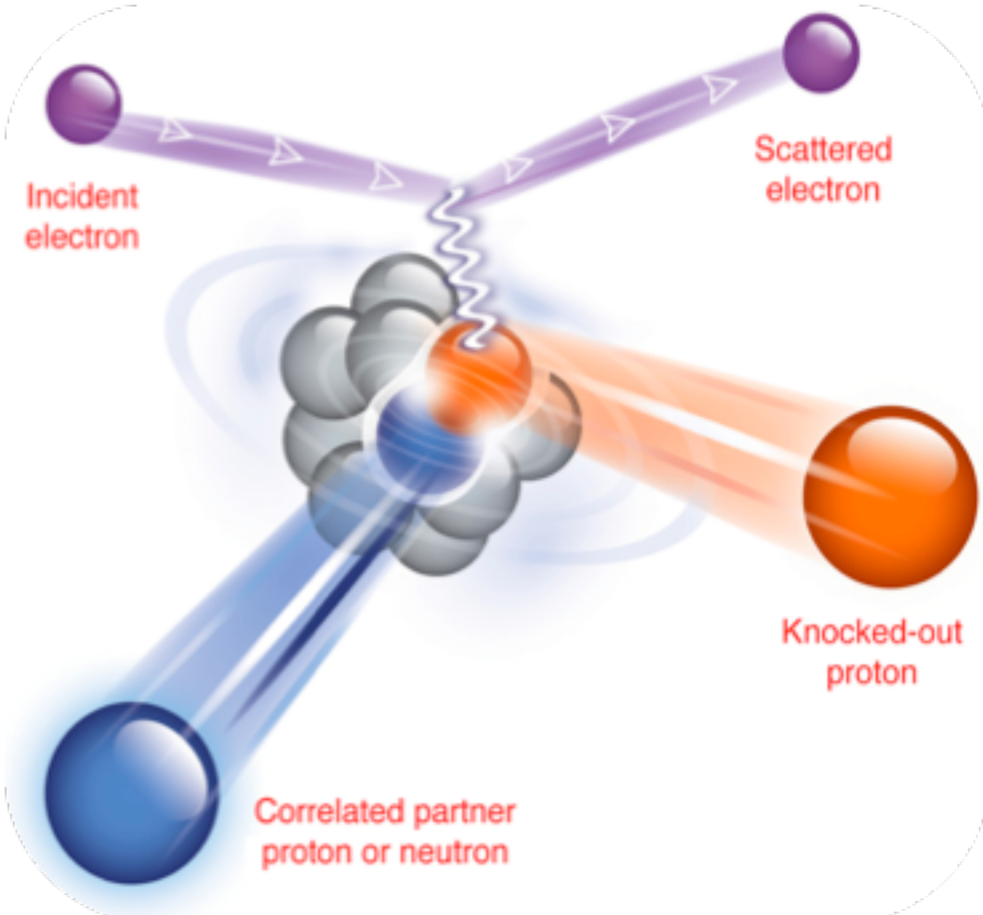
    Trick: Transform wave-function but not the operators 😬 😬
  - No calculations for e-scattering off heavier nuclei, yet.

- Complete physical equivalent.
  - Same cross sections
  - Different interpretations

Breakup the pair =>

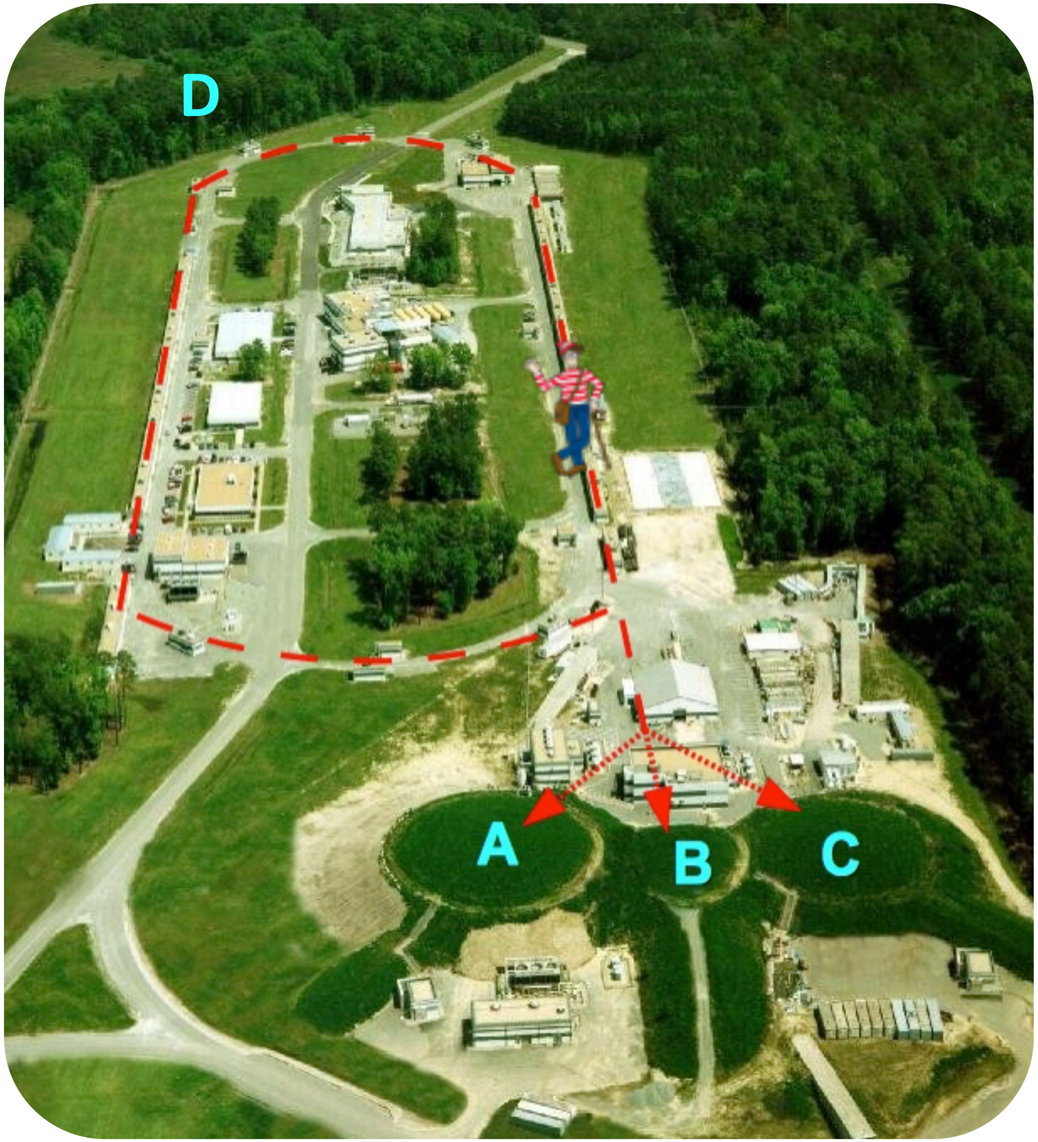
Detect ***both*** nucleons =>

Reconstruct 'initial' state

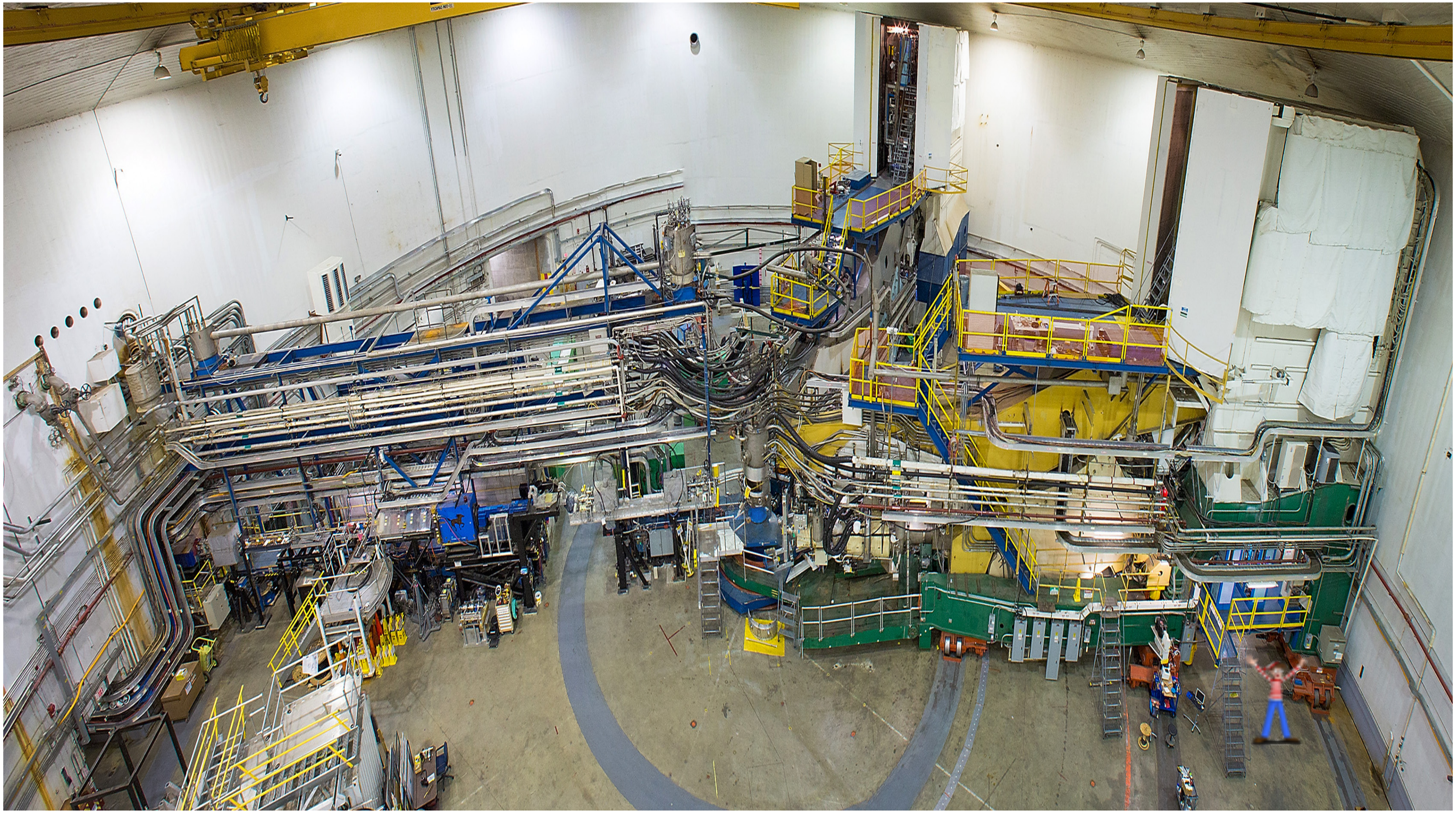


Jefferson-Lab National Accelerator Facility

- Located in Virginia USA
- 12 (6) GeV ~80 uA continues polarized electron beam
- Parallel operation of 4 experimental halls
- 12 GeV experiments recently started!
- Approved program for first 8 years of 12 GeV running

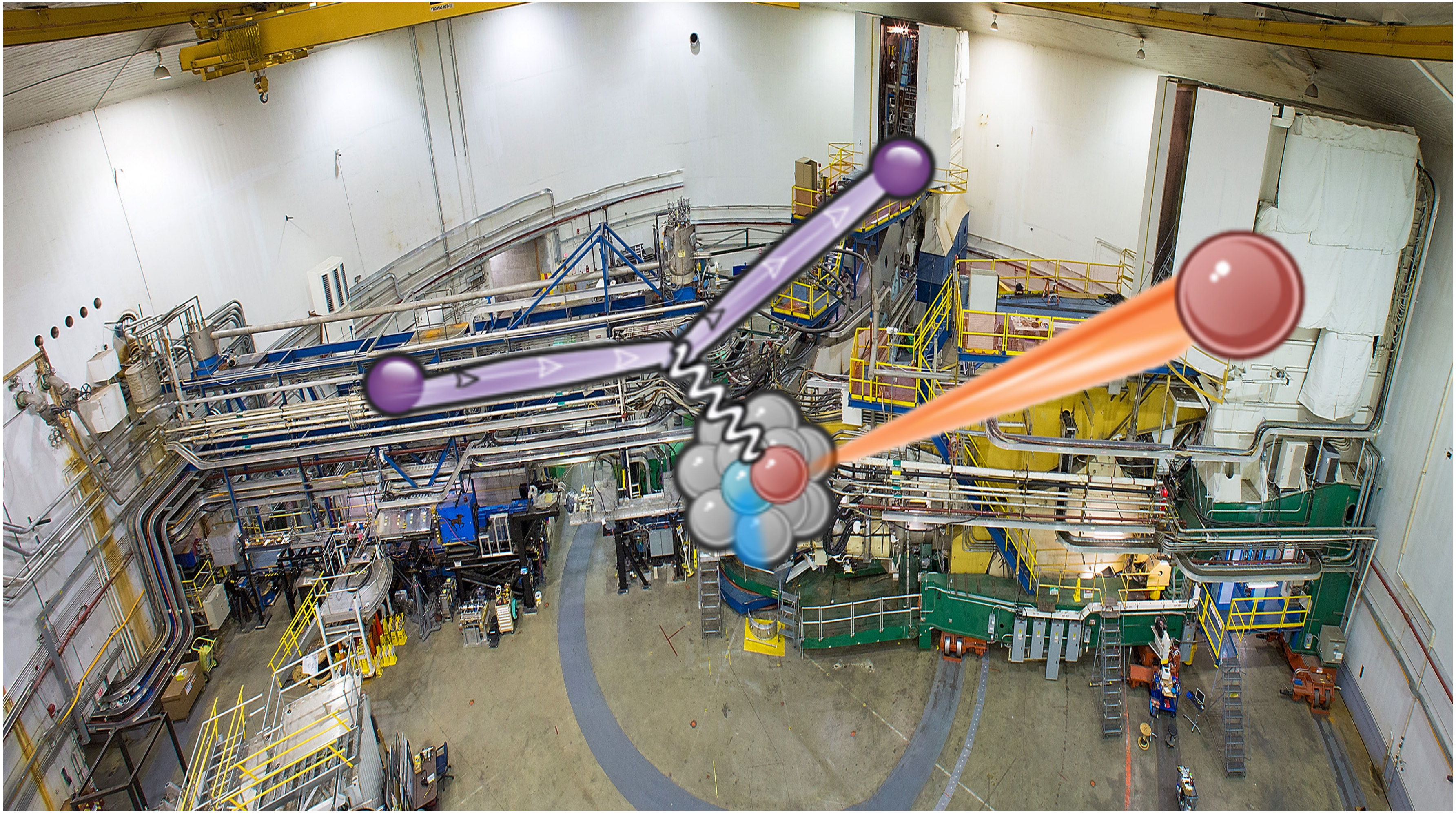


Hall-A: High-Resolution Spectrometers

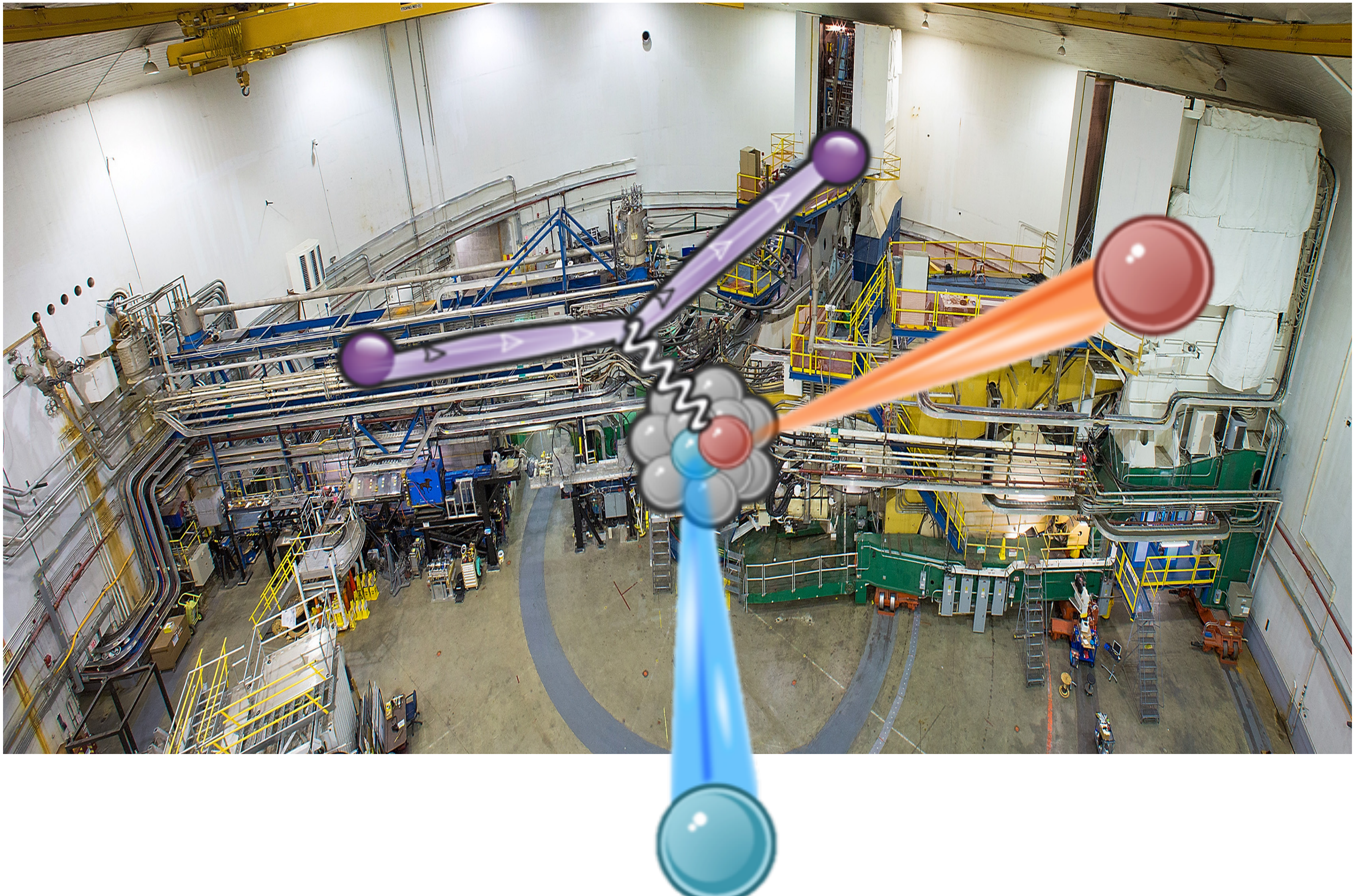


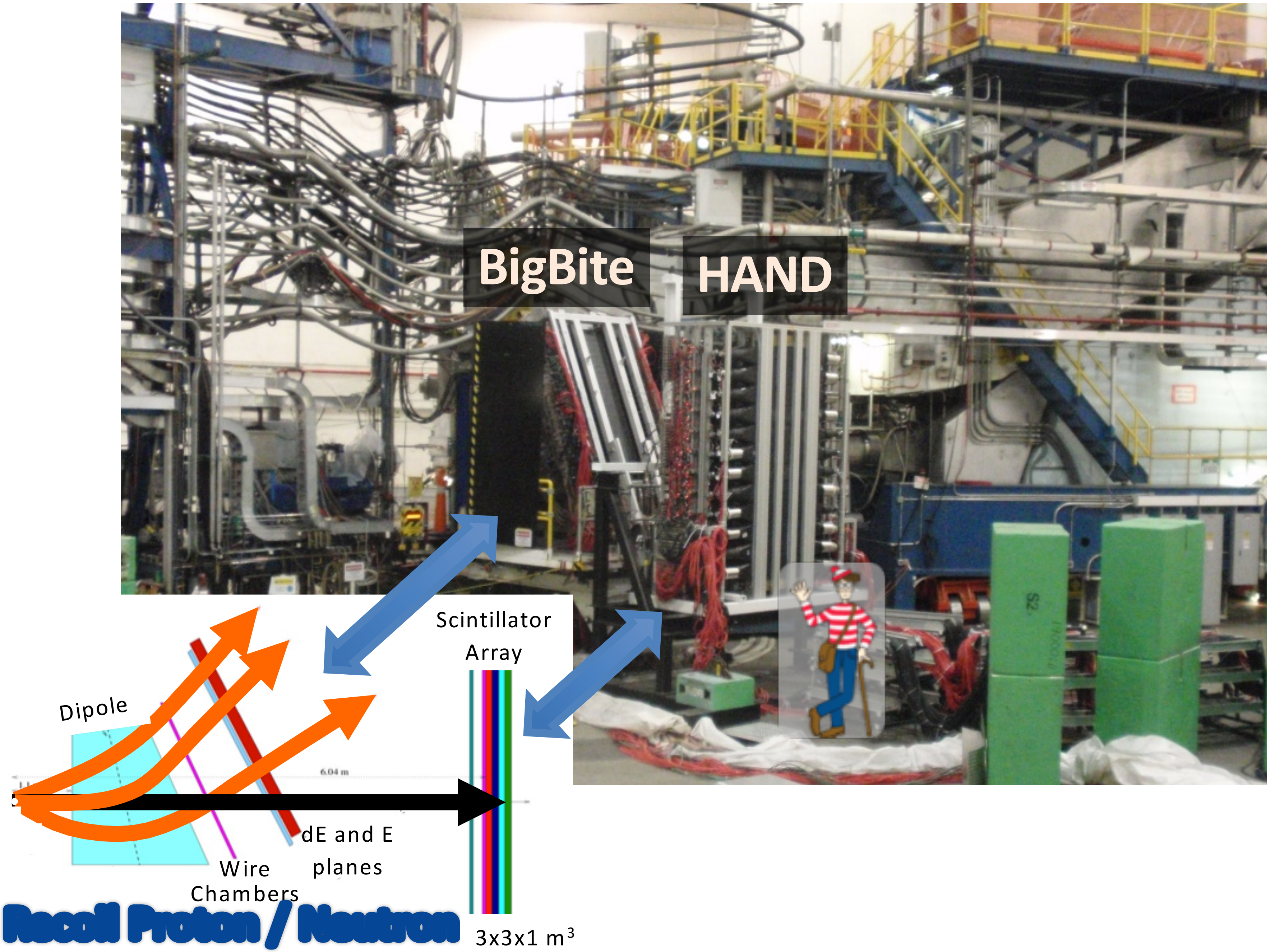
Hall-A: High-Resolution Spectrometers

Hall-A: High-Resolution Spectrometers



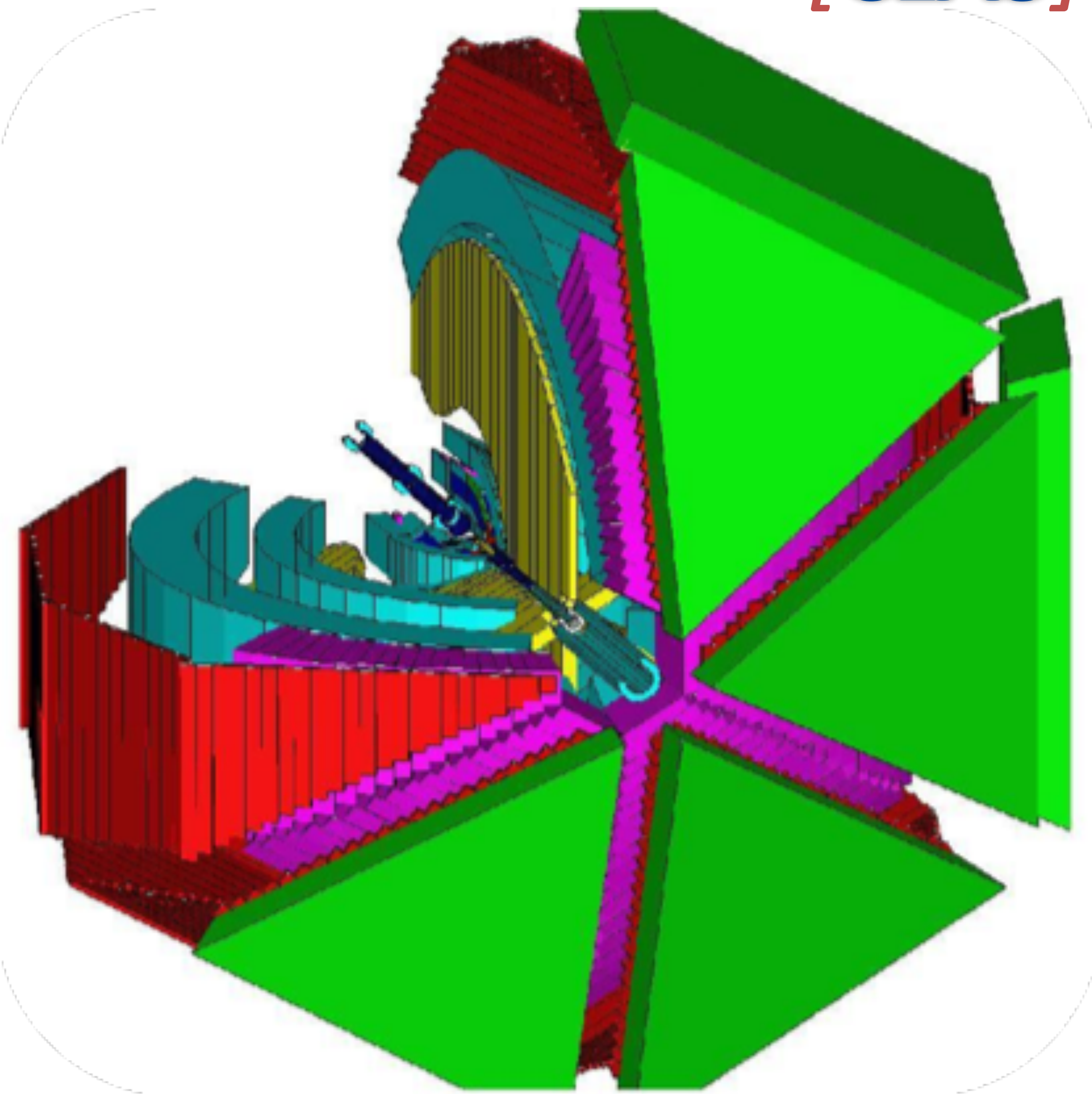
Hall-A: High-Resolution Spectrometers

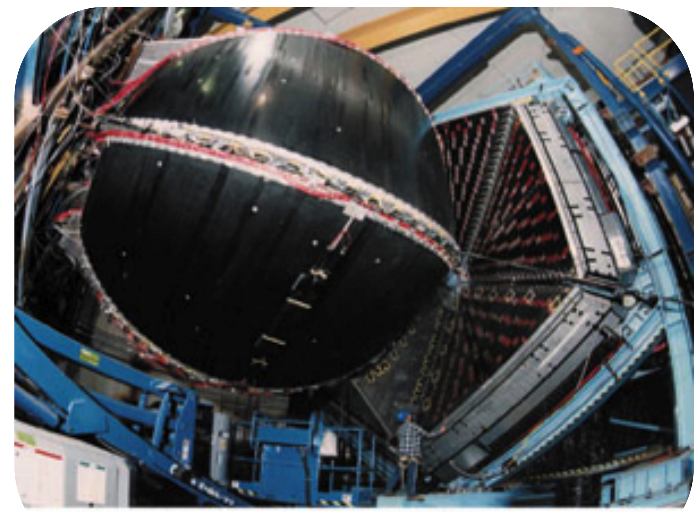




Recoil Proton / Neutron

CEBAF Large Acceptance Spectrometer [CLAS]

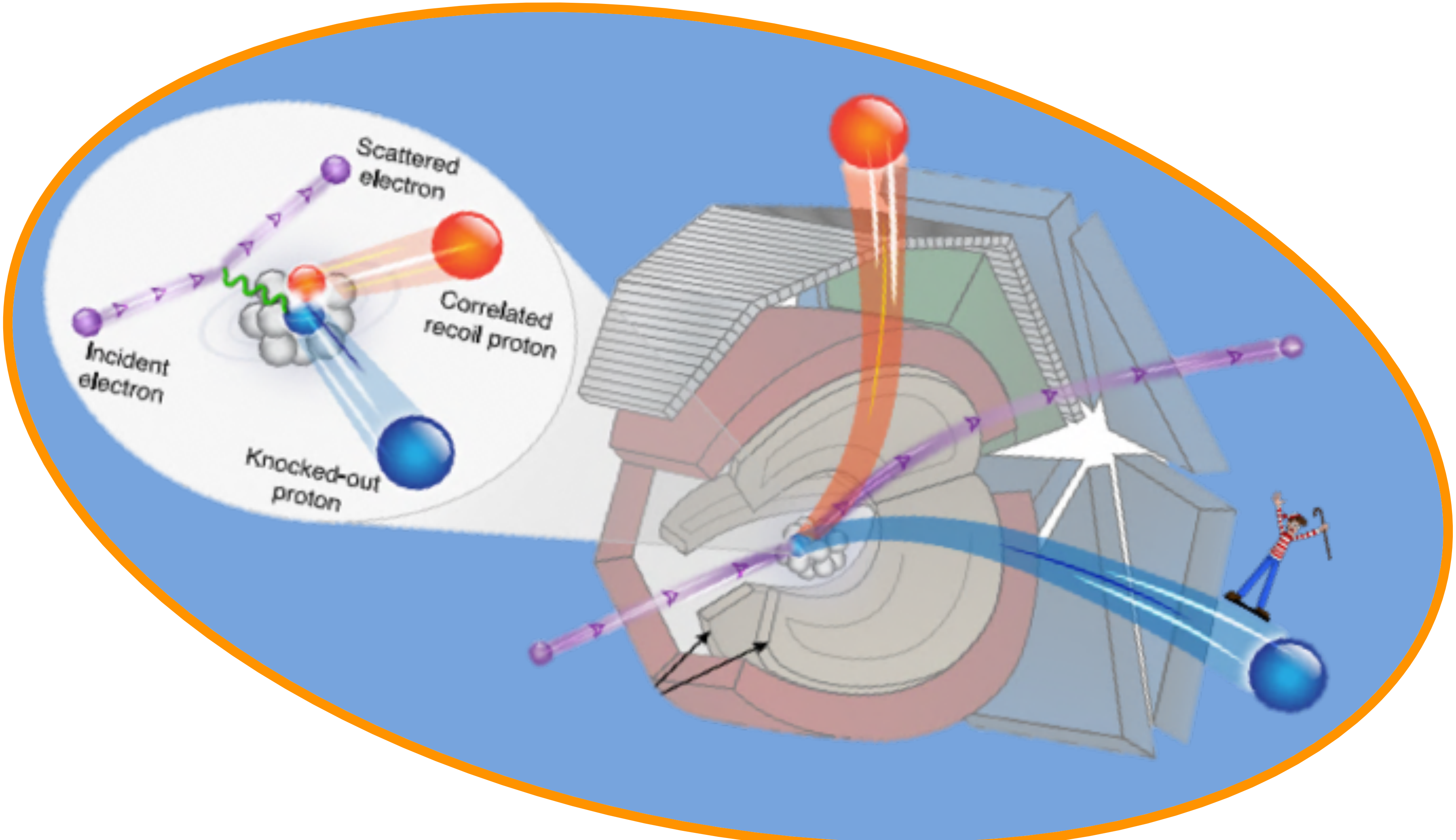




Hall B Large Acceptance Spectrometer

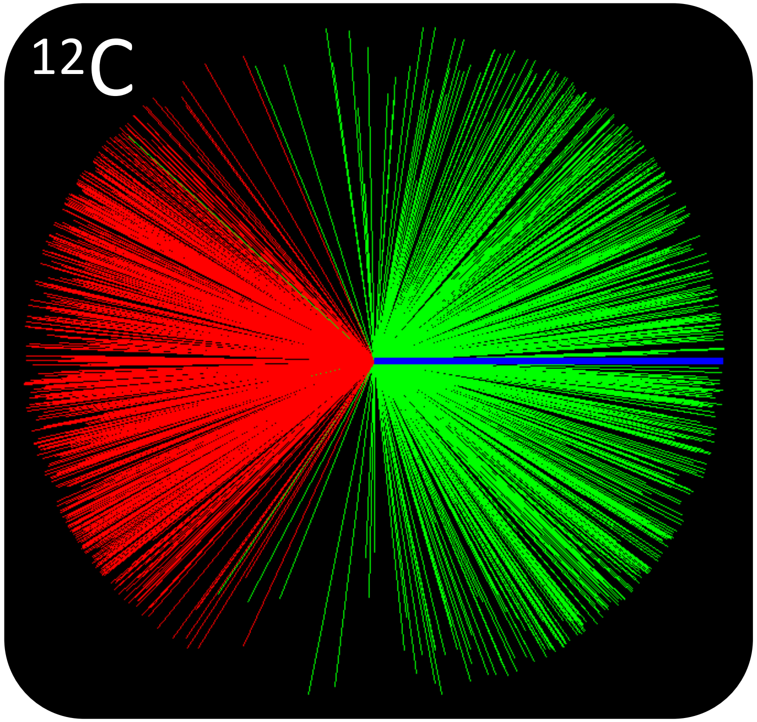
Open (e,e’) trigger, Large-Acceptance, Low luminosity (~10^{34} cm^{-2} sec^{-1})

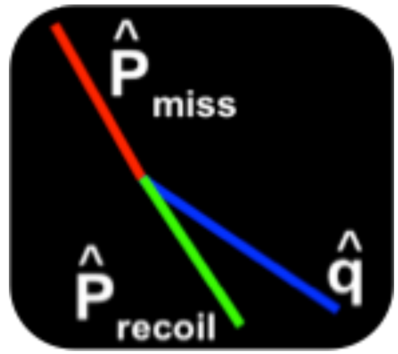
CEBAF Large Acceptance Spectrometer [CLAS]

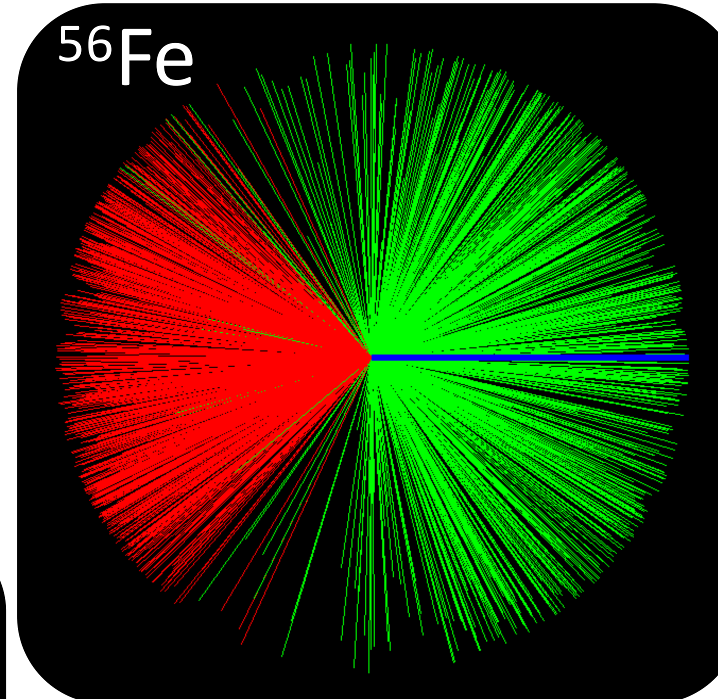


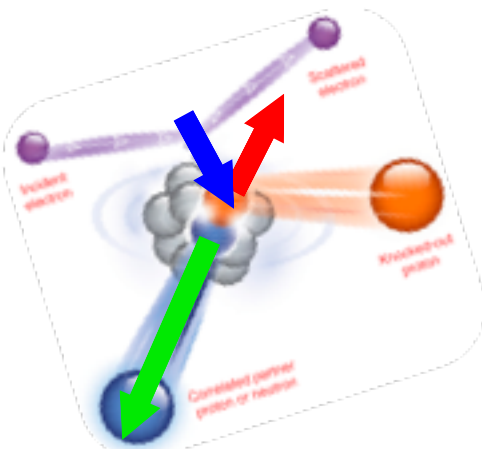
Open (e,e') trigger, Large-Acceptance, Low luminosity ($\sim 10^{34}$ cm^{-2} sec^{-1})

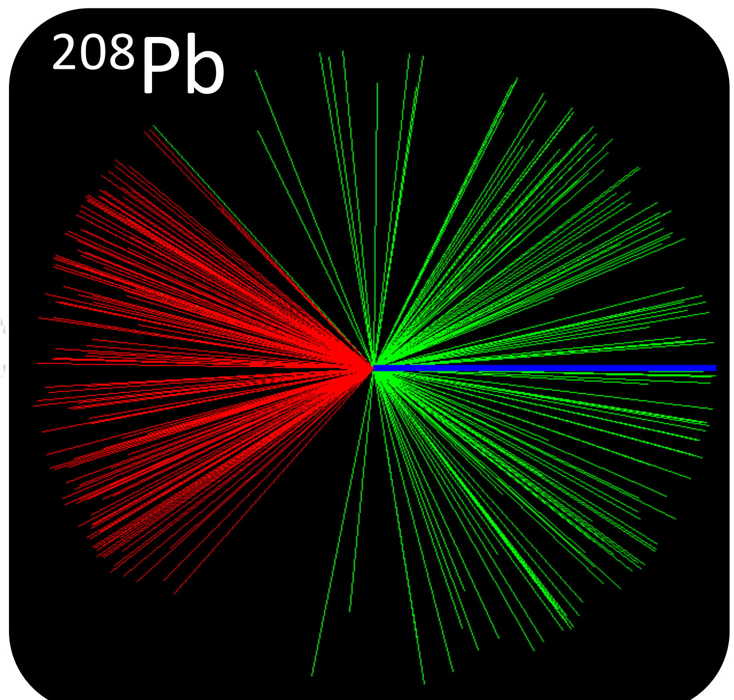
3D Reconstruction

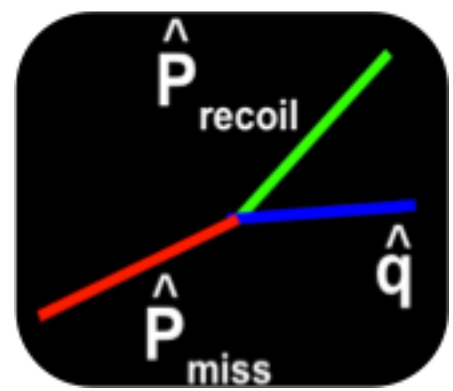






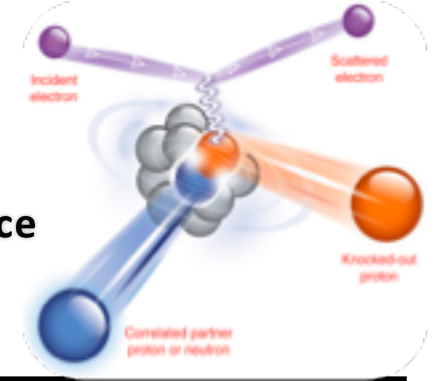


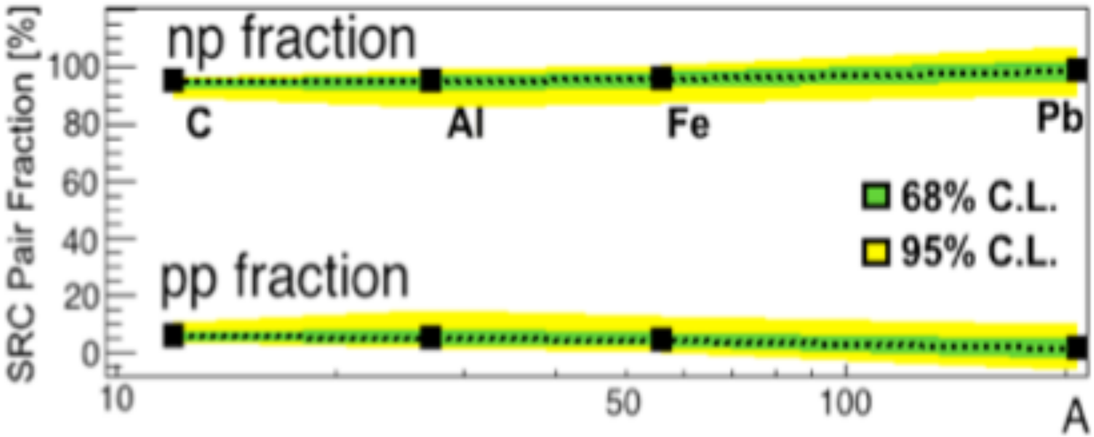




Back-to-back =
SRC pairs!

OLD np dominance results





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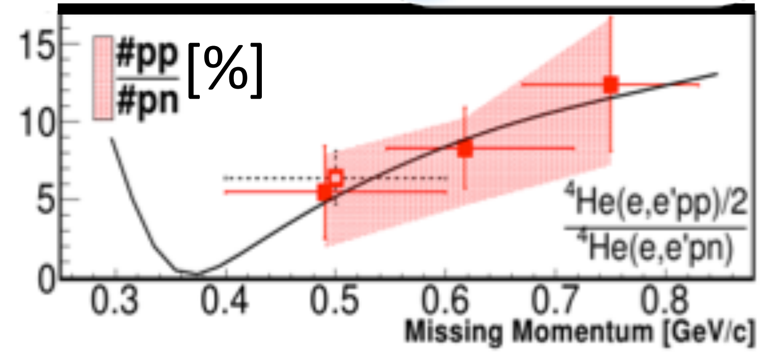
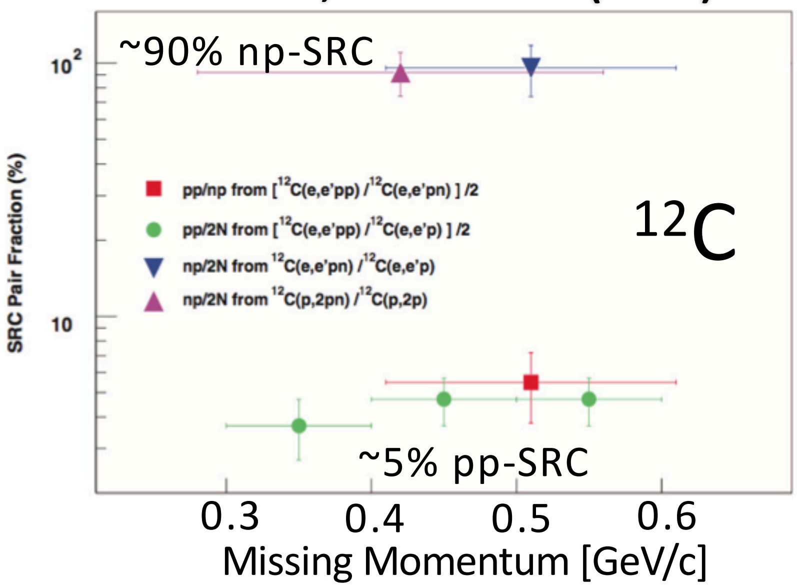
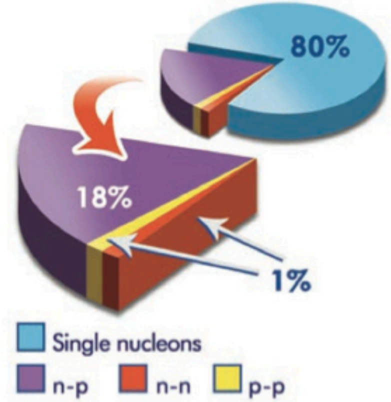
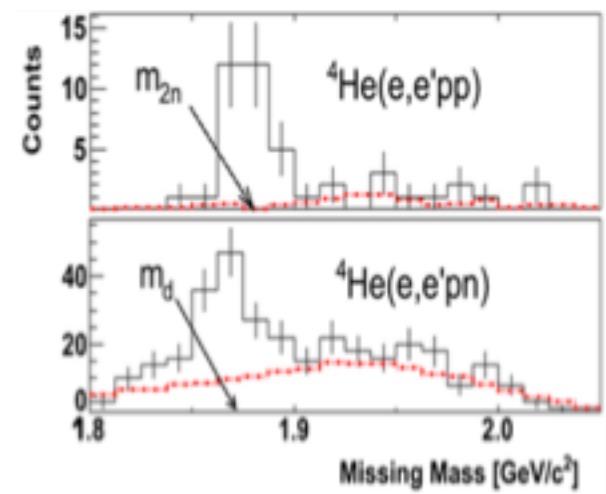


R. Subedi et al., Science 320 (2008) 1476

I. Korover et al., PRL 113 (2014) 022501

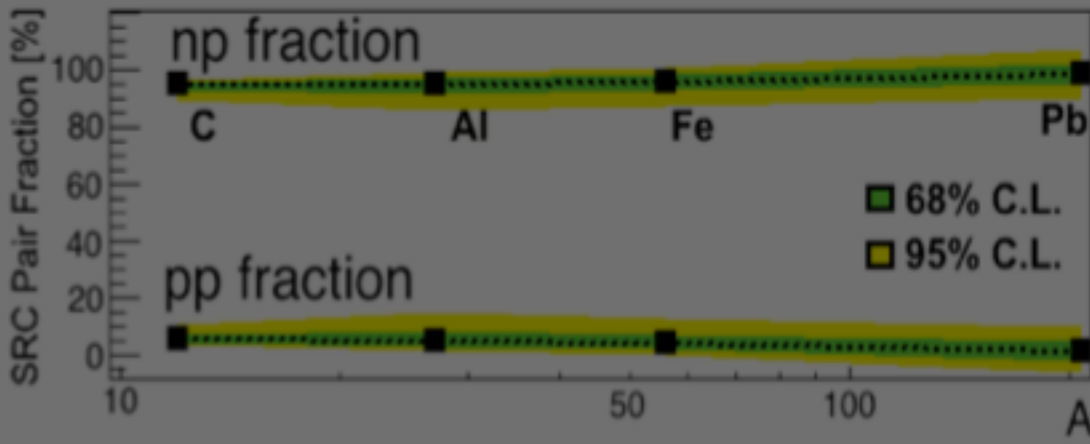


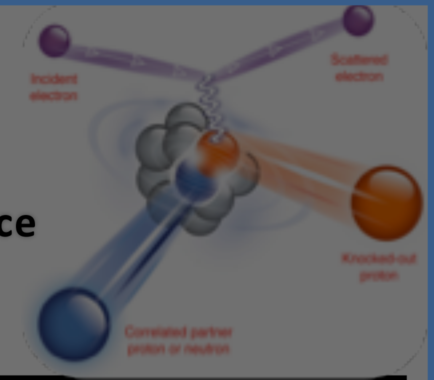




A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

np dominance results





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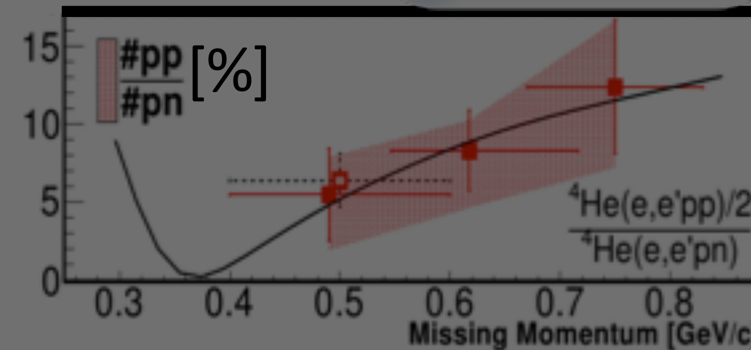

I. Korover et al., PRL 113 (2014) 022501

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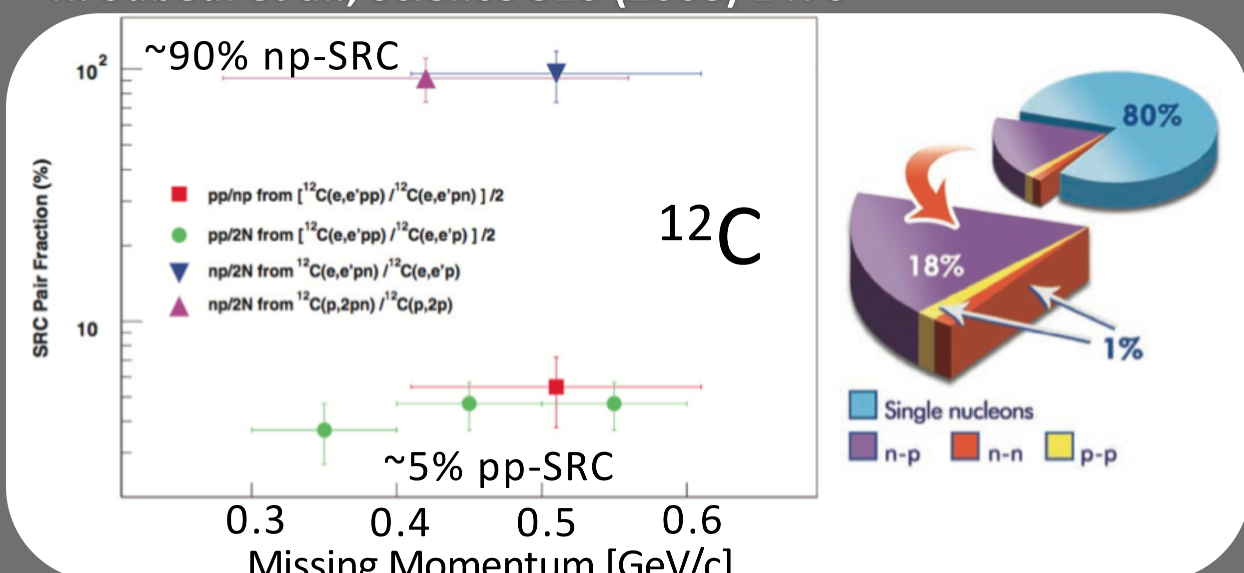

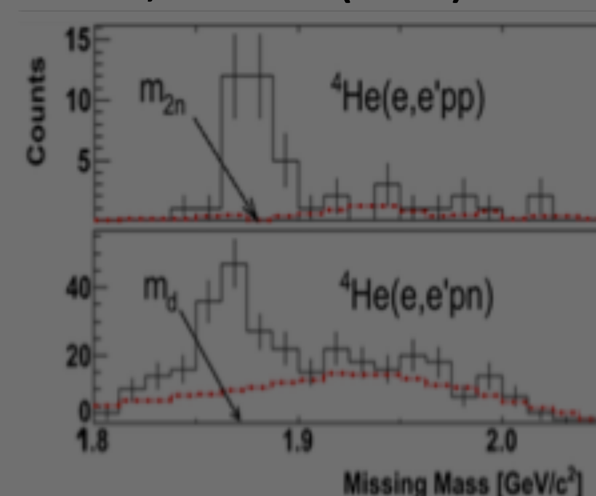

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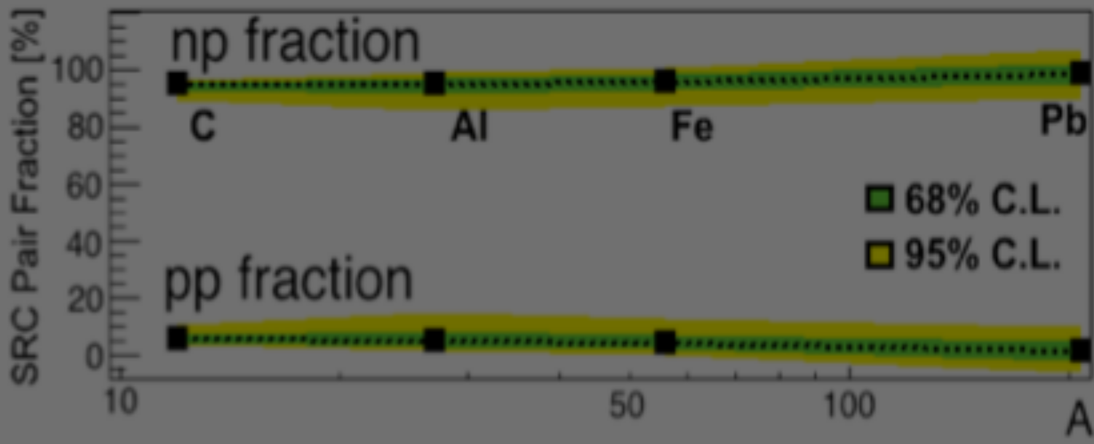
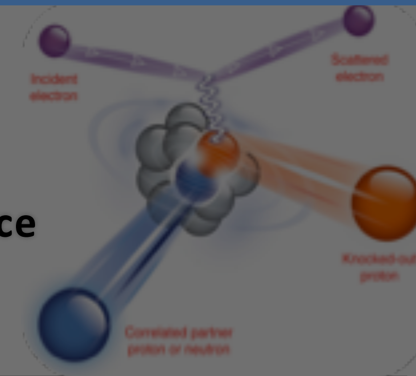
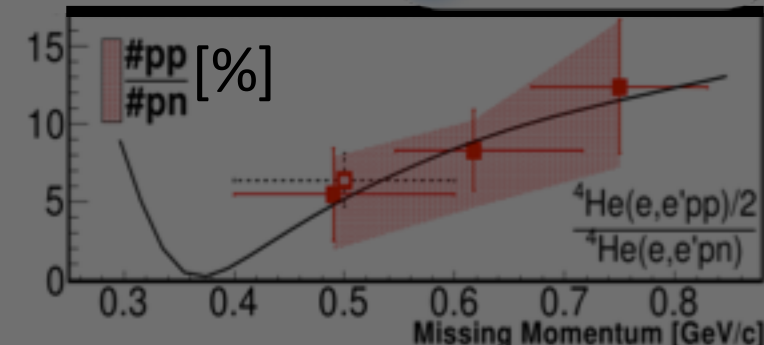


O. Hen et al., Science 364 (2014) 614





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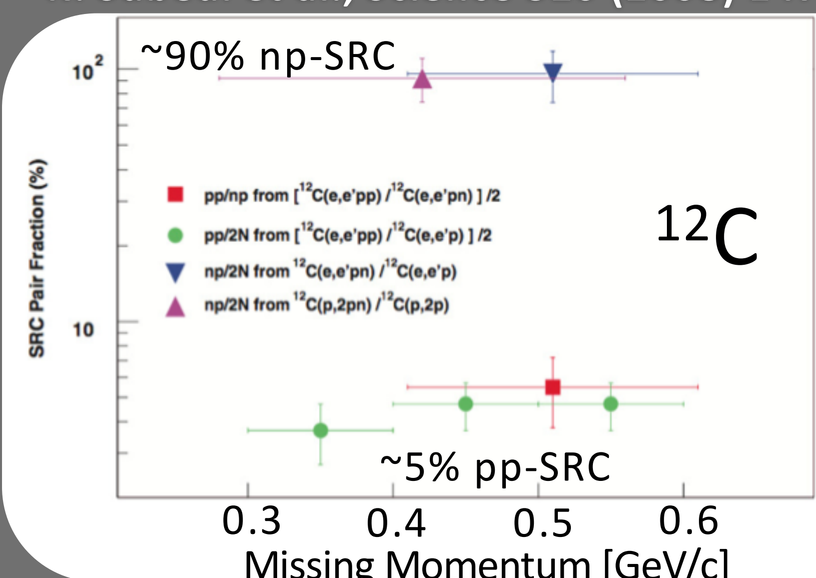
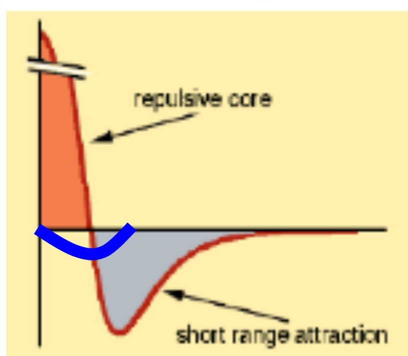
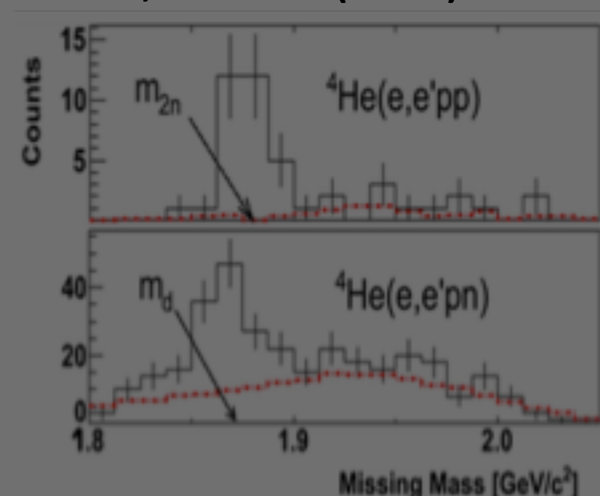
R. Subedi et al., Science 320 (2008) 1476







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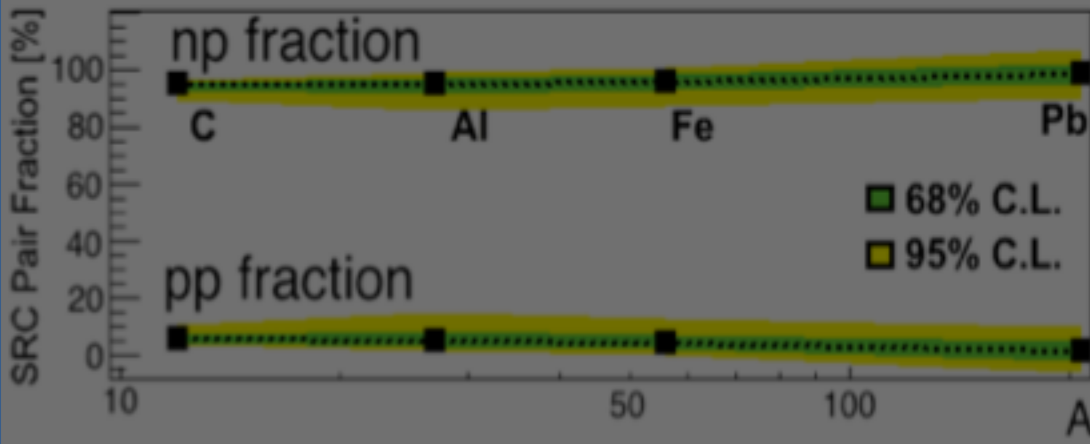
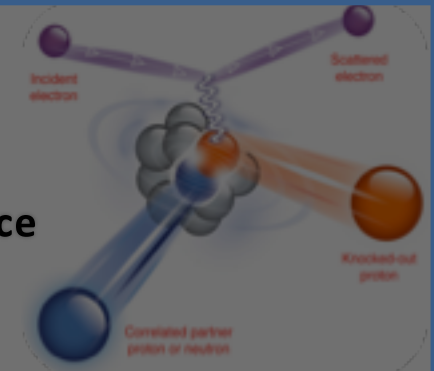
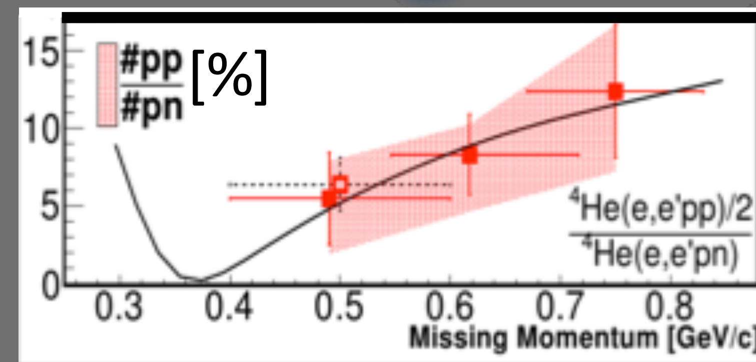
np dominance results



O. Hen et al., Science 364 (2014) 614





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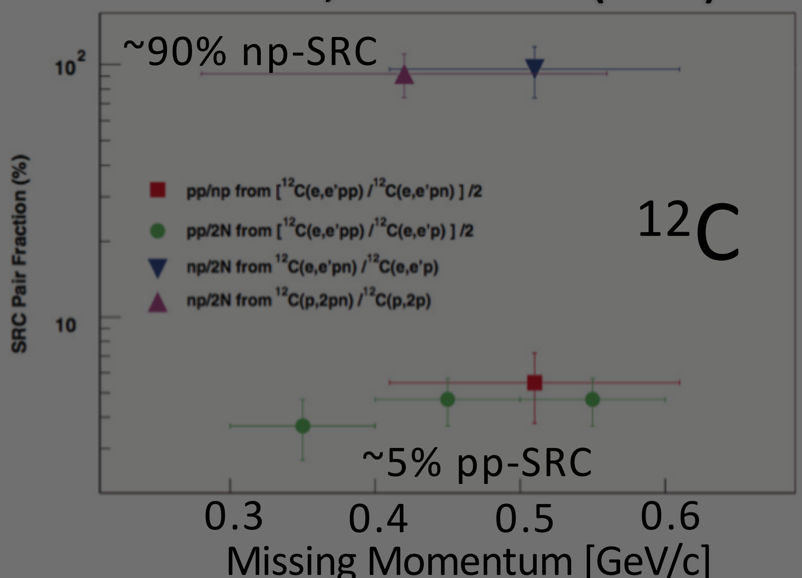

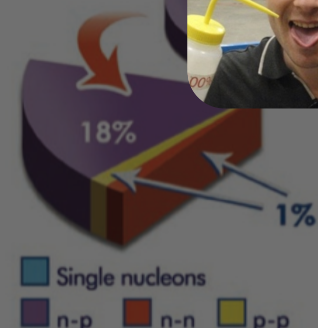

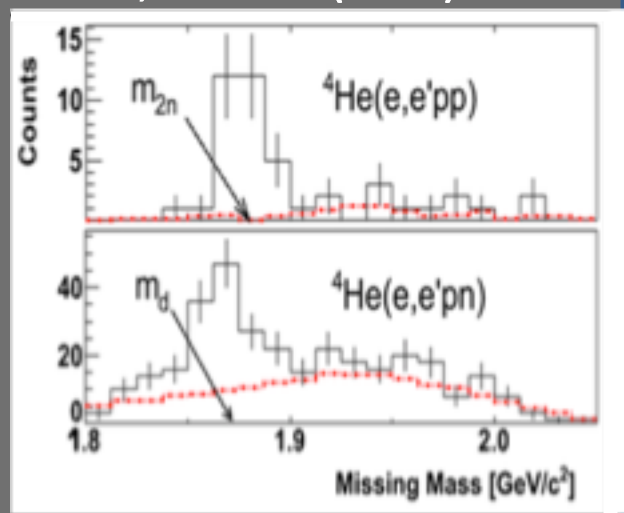

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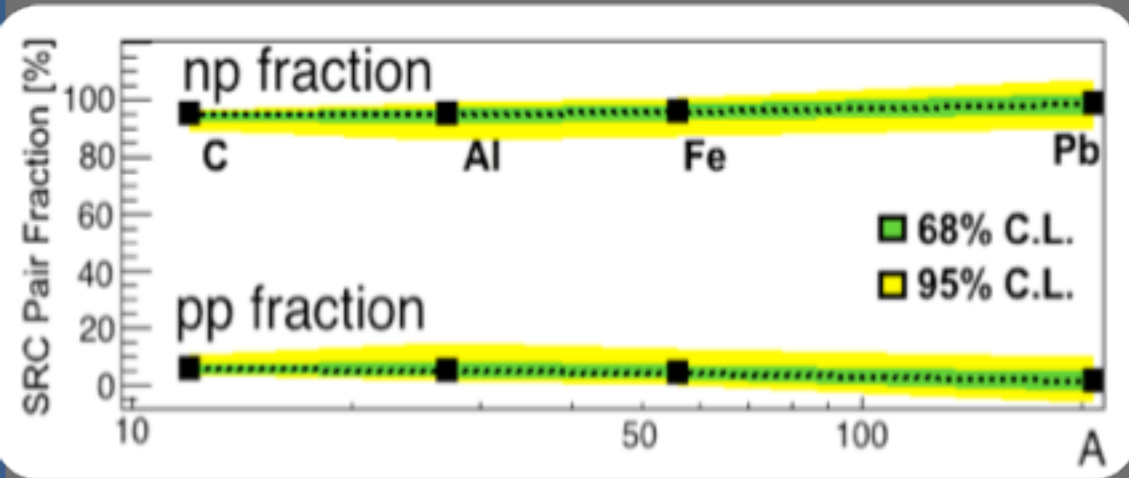
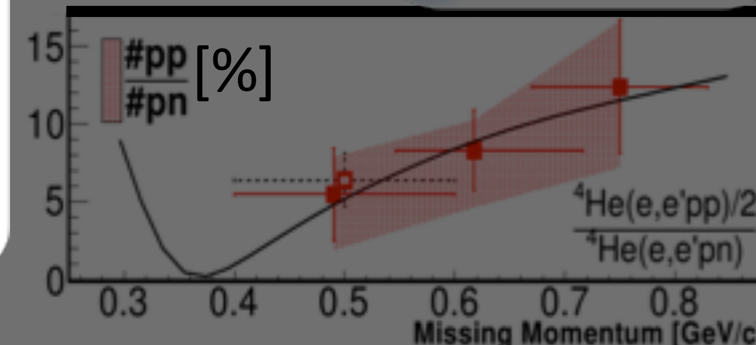
np dominance results



O. Hen et al., Science 364 (2014) 614



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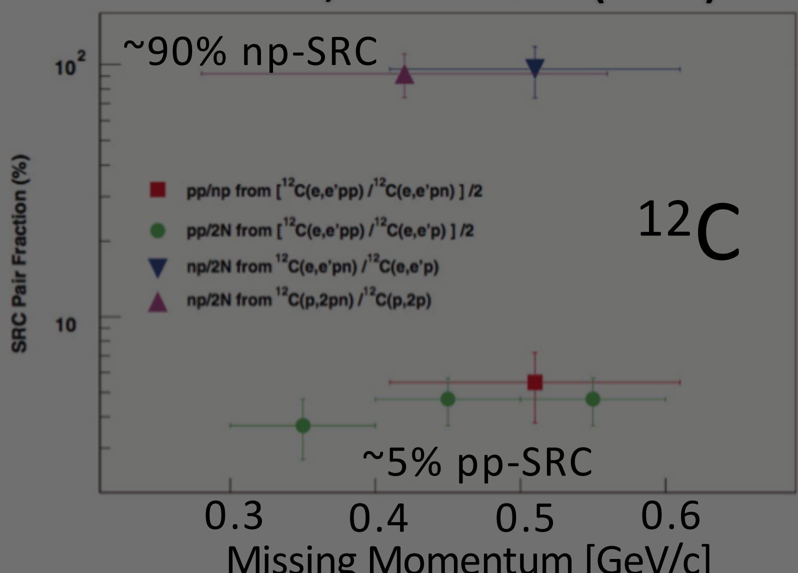

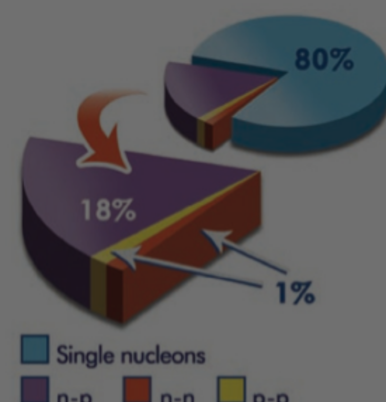

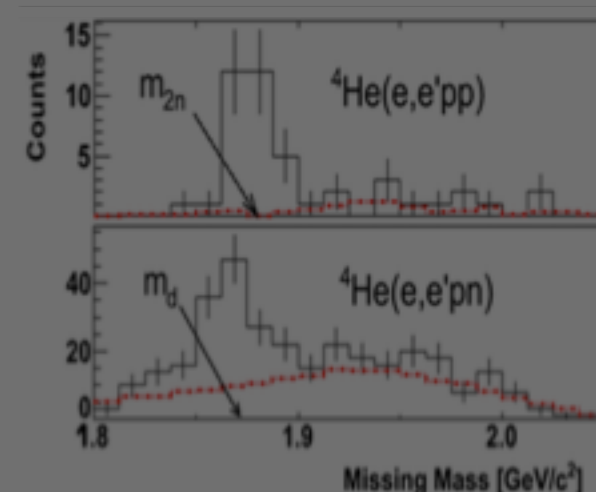

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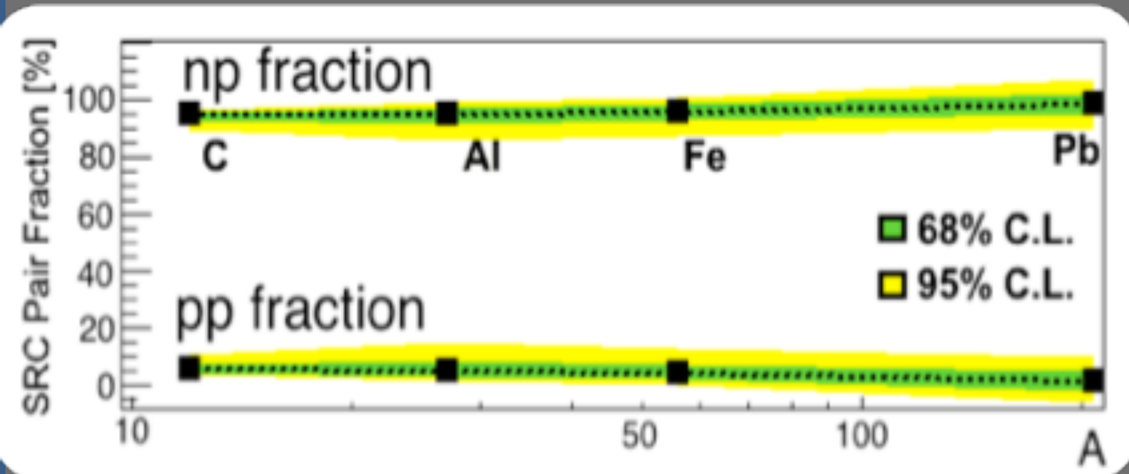
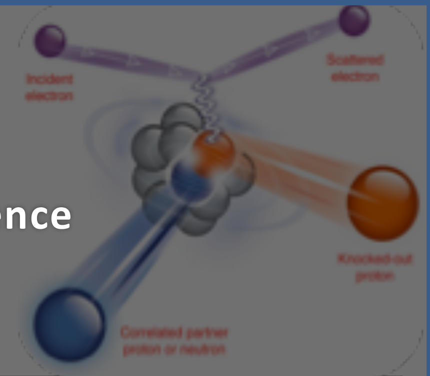
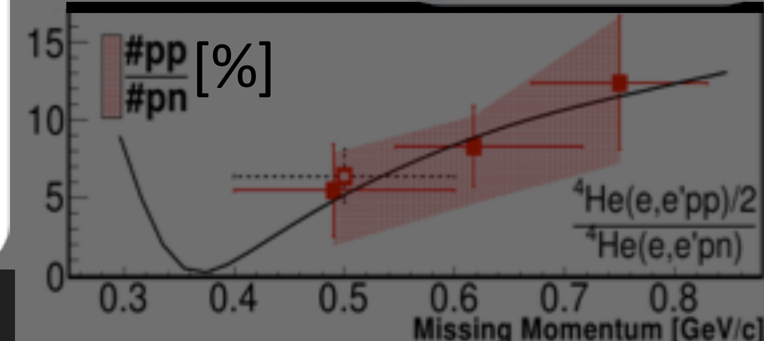




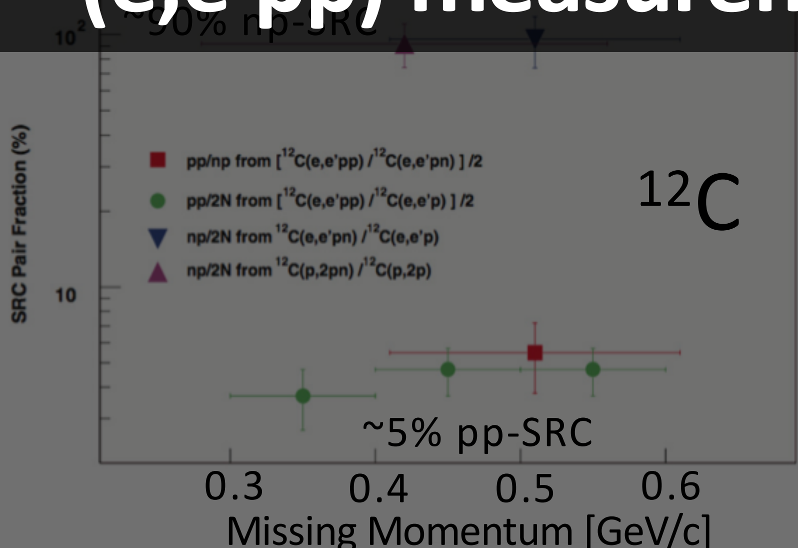
O. Hen et al., Science 364 (2014) 614

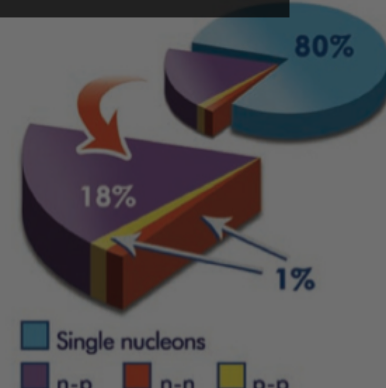


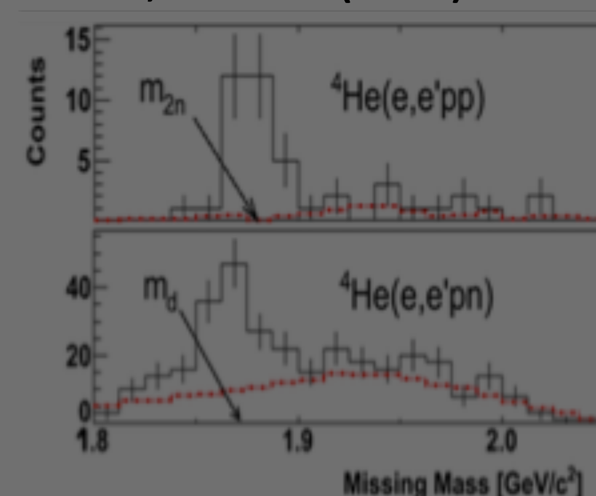
I. Korover et al., PRL 113 (2014) 022501

^^ Inferred from (e,e'p) & (e,e'pp) measurements

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

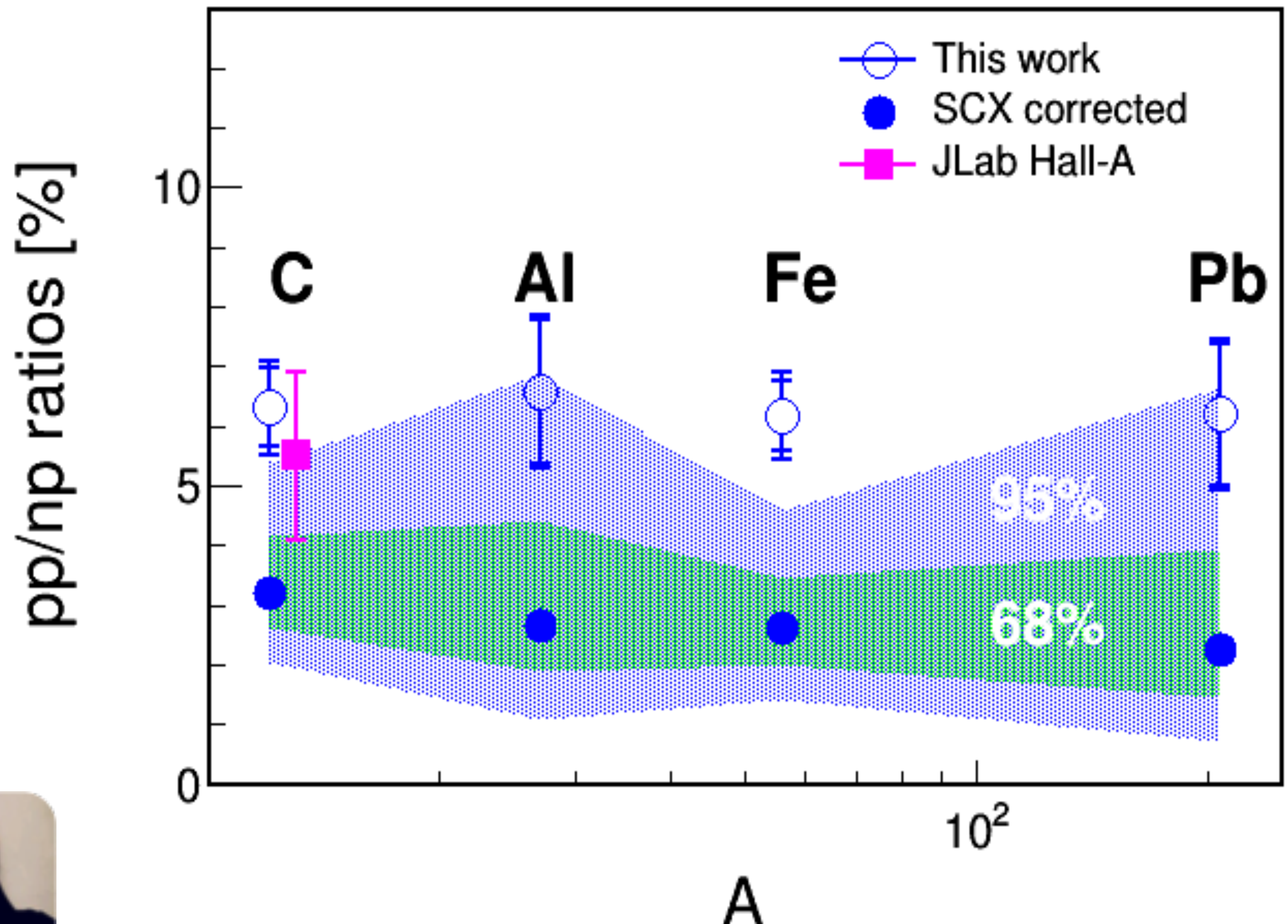




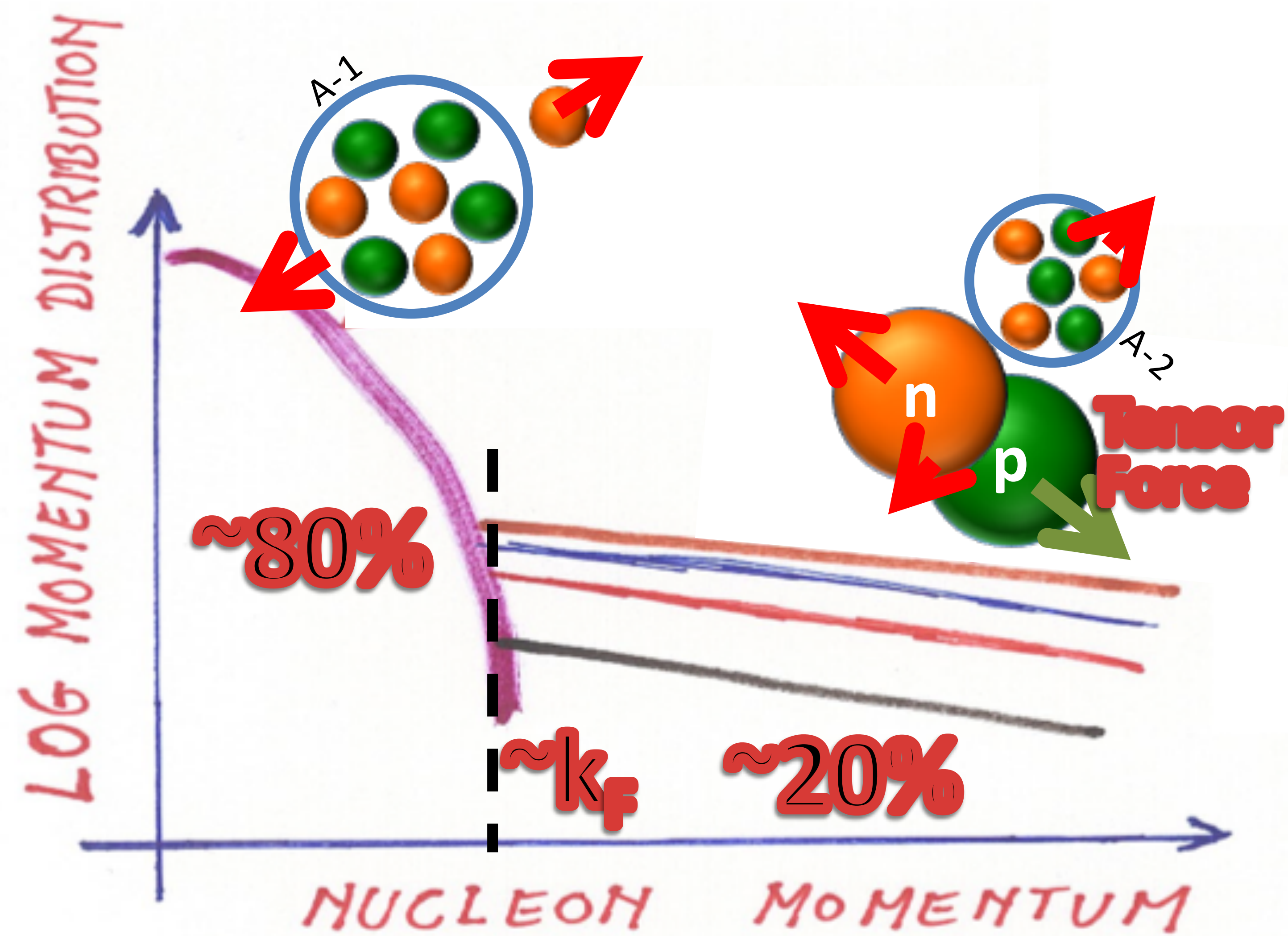


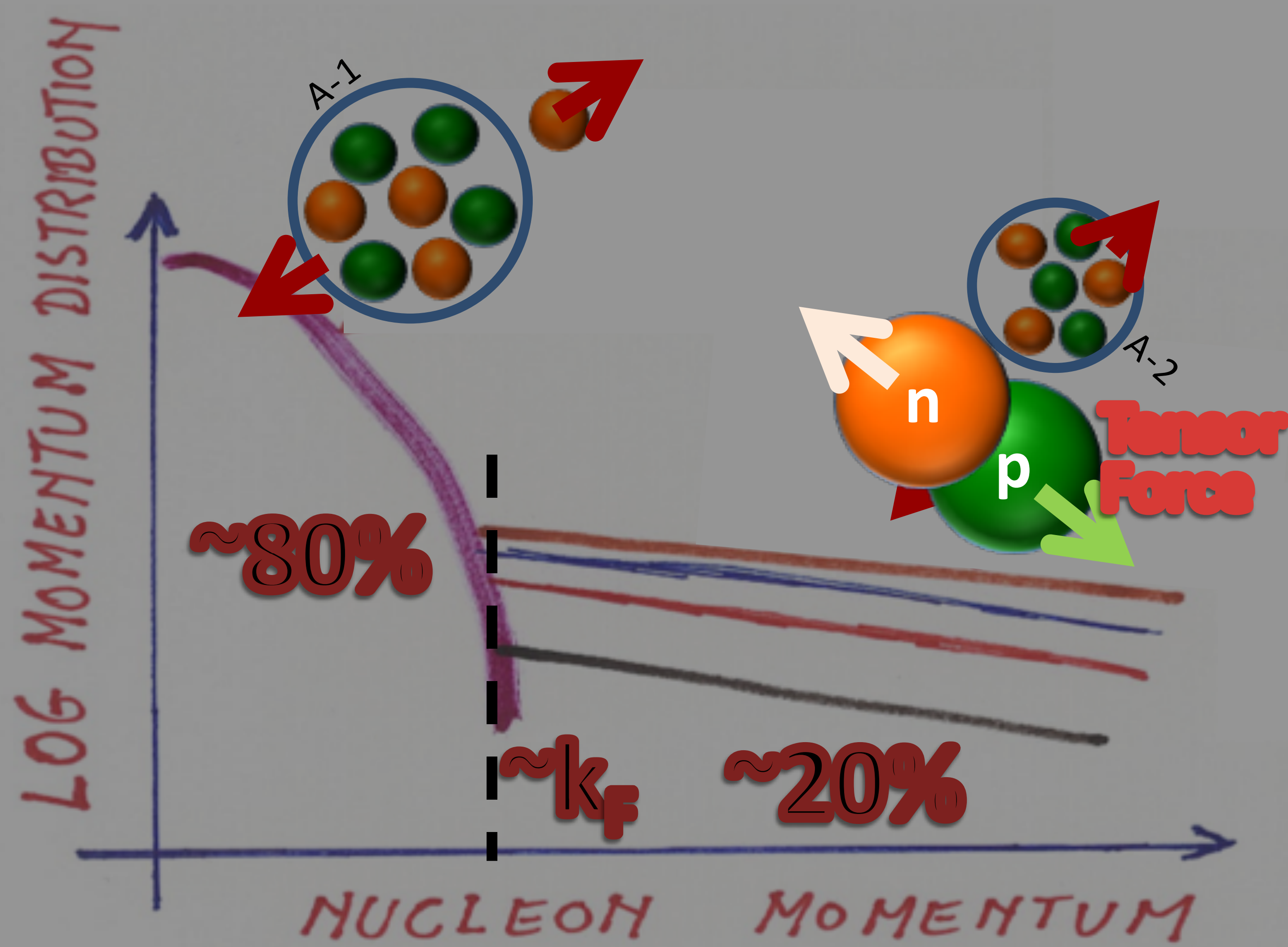
A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

D-I-R-E-C-T Observation of np-Dominance: (e,e'Np) Measurements



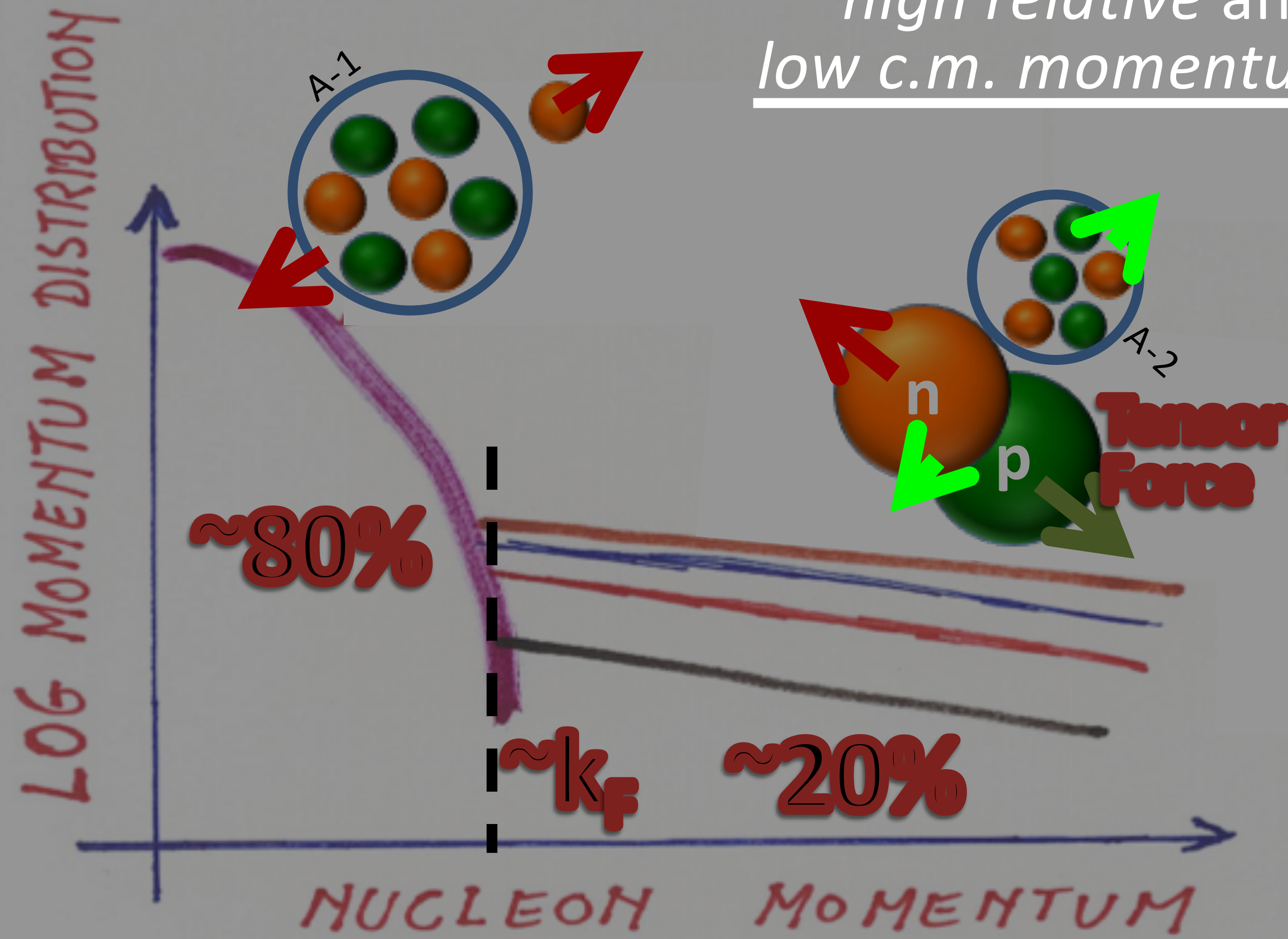
M. Duer et al.

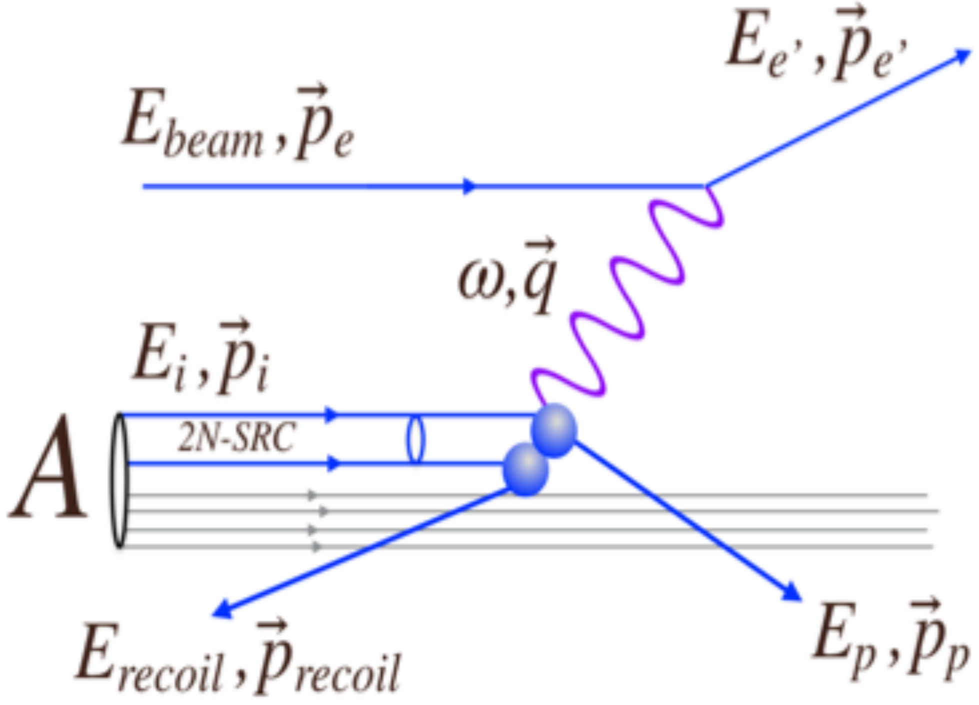

LOG MOMENTUM DISTRIBUTION
A-1
A-2
n
p
Tensor Force
~80%
~k_F
~20%
NUCLEON MOMENTUM



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

“high relative and *low c.m. momentum”*





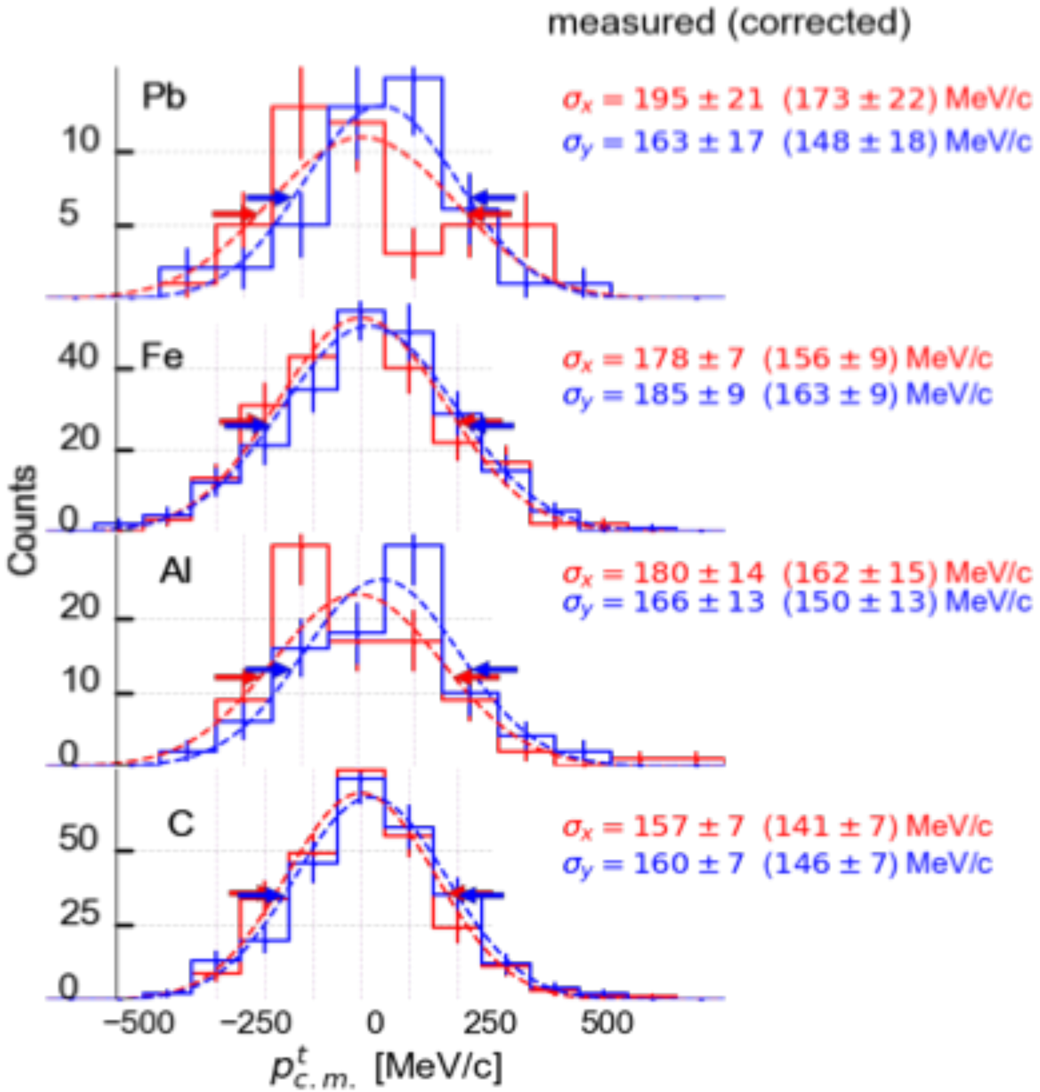
$$\vec{P}_{c.m.} = (\vec{P}_p - \vec{q}) + \vec{P}_{recoil}$$

FSI Between nucleons in the pair:

$$\vec{P}_p \rightarrow \vec{P}_p + \vec{\Delta}$$
$$\vec{P}_{recoil} \rightarrow \vec{P}_{recoil} - \vec{\Delta}$$

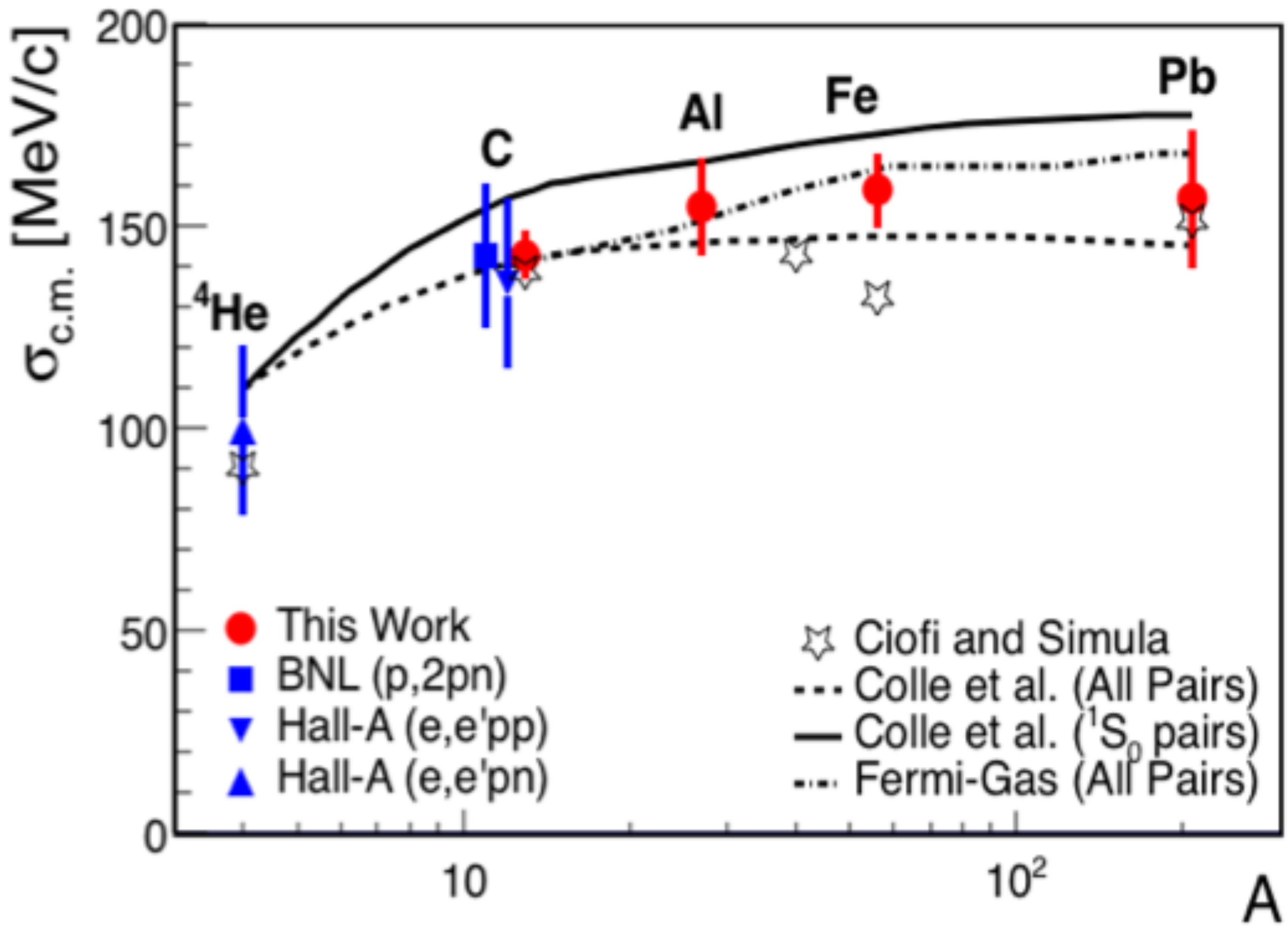
$$\Rightarrow \overrightarrow{\boldsymbol{P}}_{\boldsymbol{c.m.}}\ \boldsymbol{Invarient}$$

Low Pair C.M. Motion



E. Cohen et al. (CLAS Collaboration), submitted, arXiv: 1805.01981 (2018).

Consistent with Mean-Field Calculations



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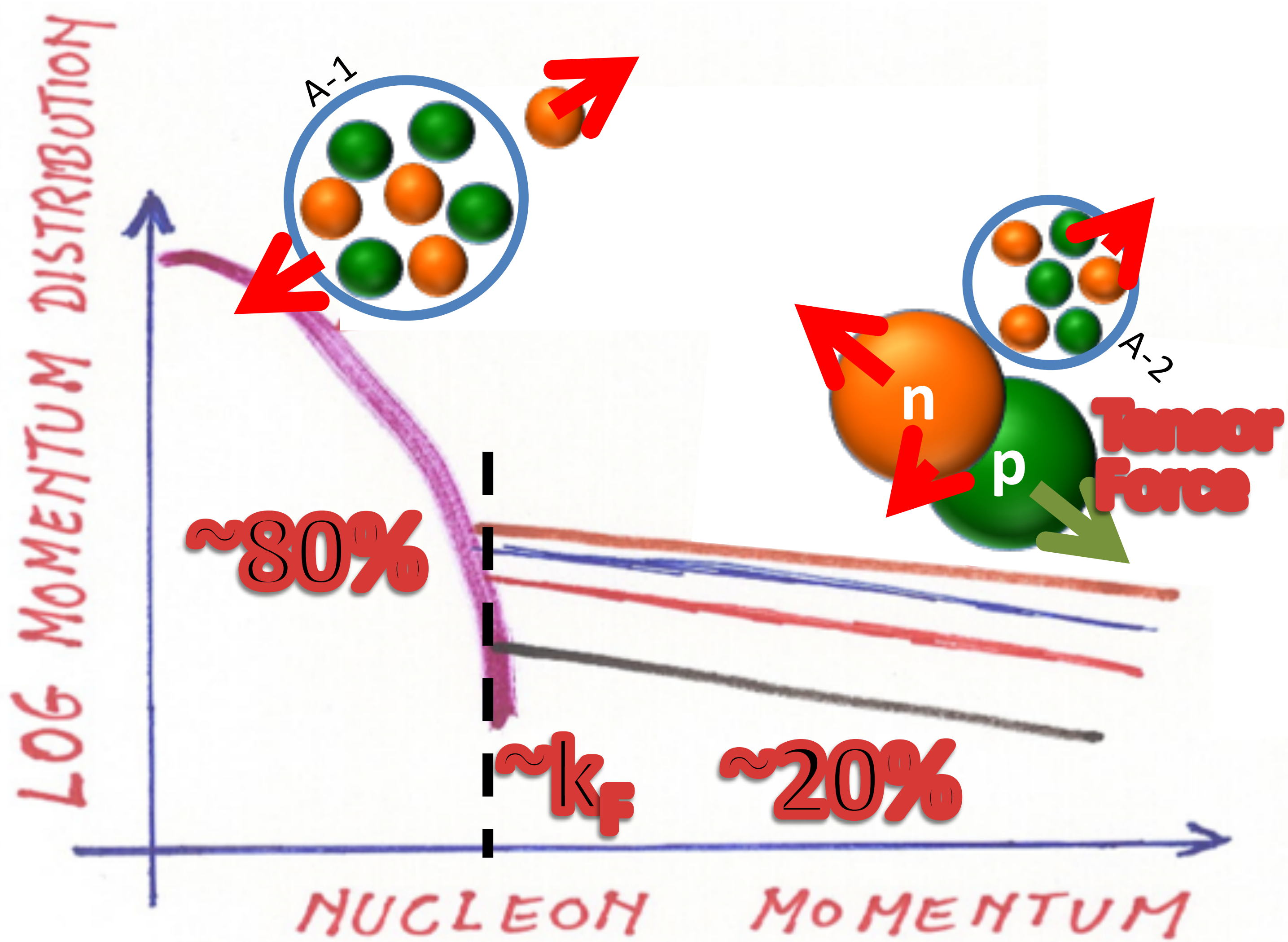
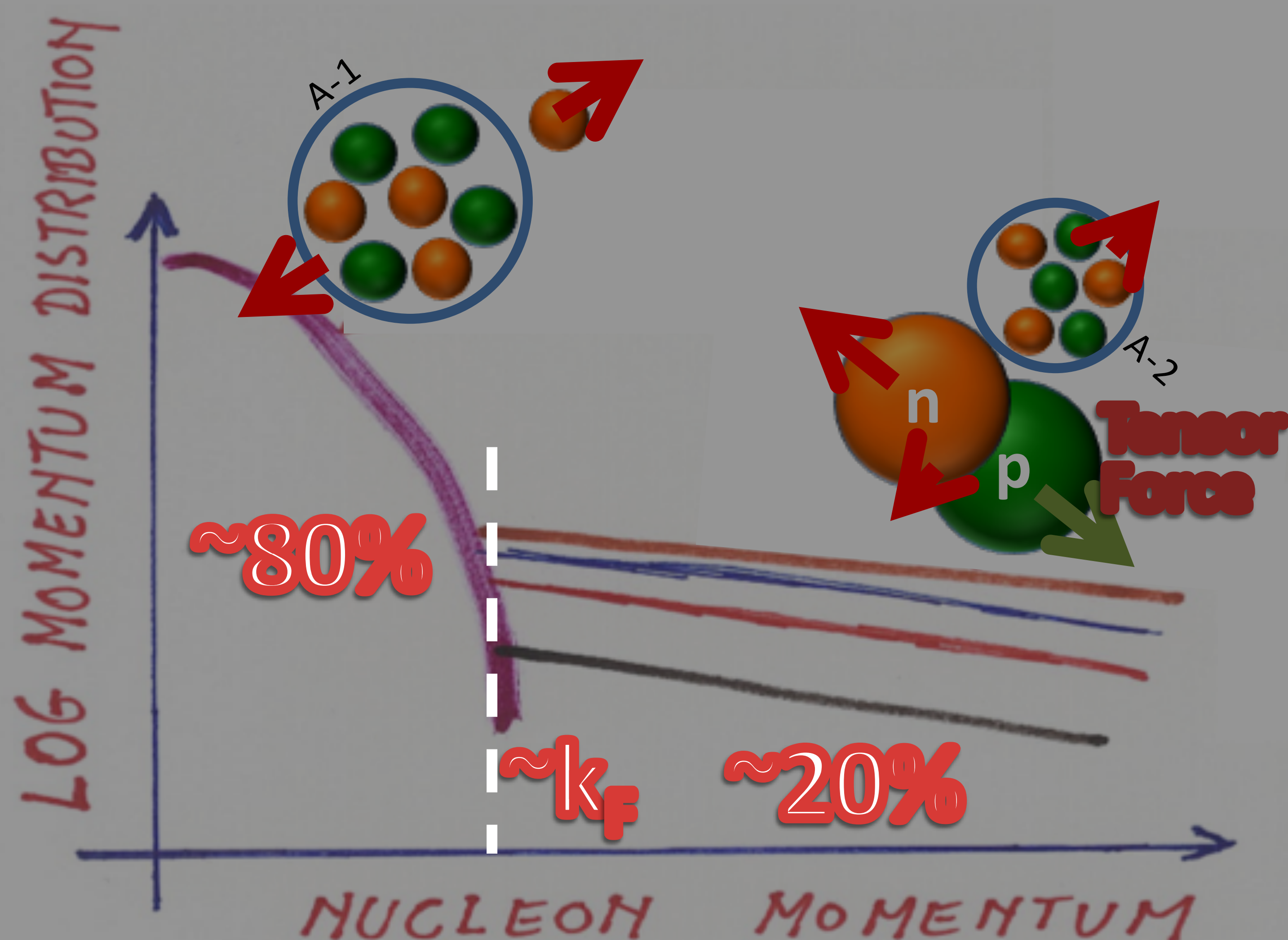
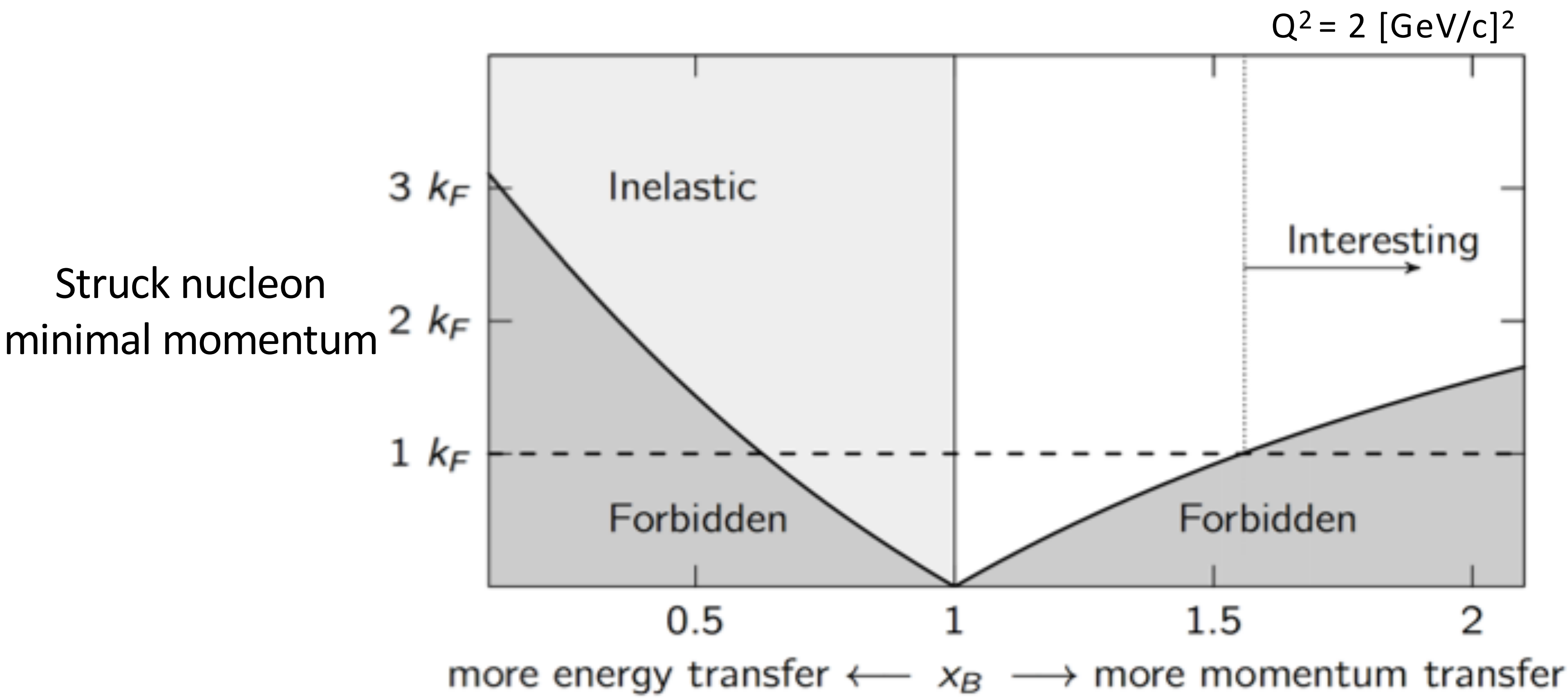


LOG MOMENTUM DISTRIBUTION
NUCLEON MOMENTUM
A-1
A-2
n
p
Tensor Force
~80%
~20%
~k_F



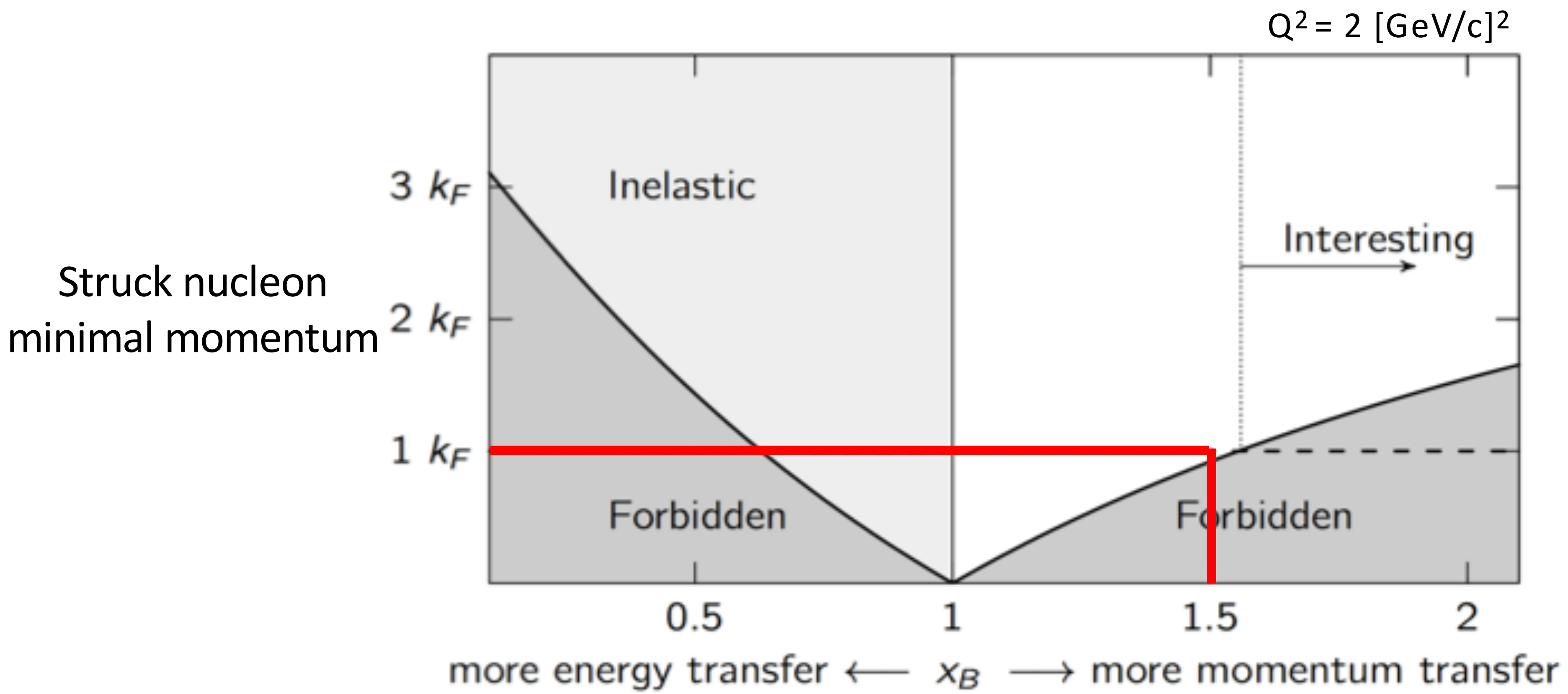
LOG MOMENTUM DISTRIBUTION
A-1
~80%
~k_F
~20%
n
p
A-2
Tensor Force
NUCLEON MOMENTUM

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



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

High x_B ⇔ High initial momenta



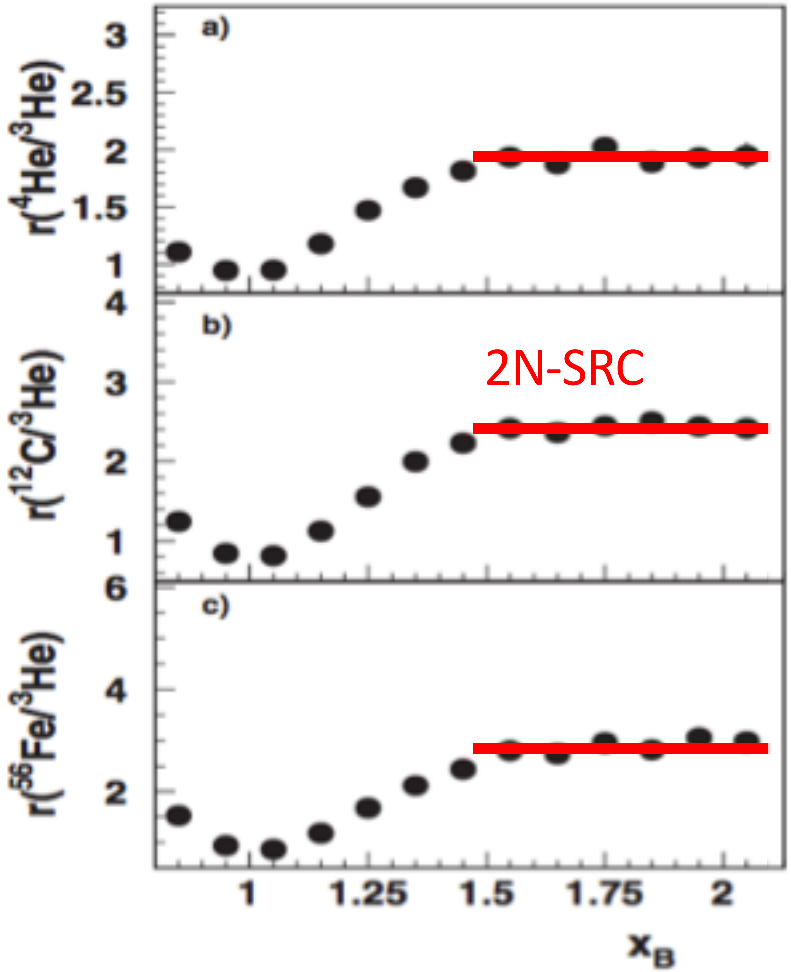
$$(q + p_A - p_{A-1})^2 = p_f^2 = m_N^2$$

High-Momentum Scaling

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

- Observed scaling for $x_B \geq 1.5$.

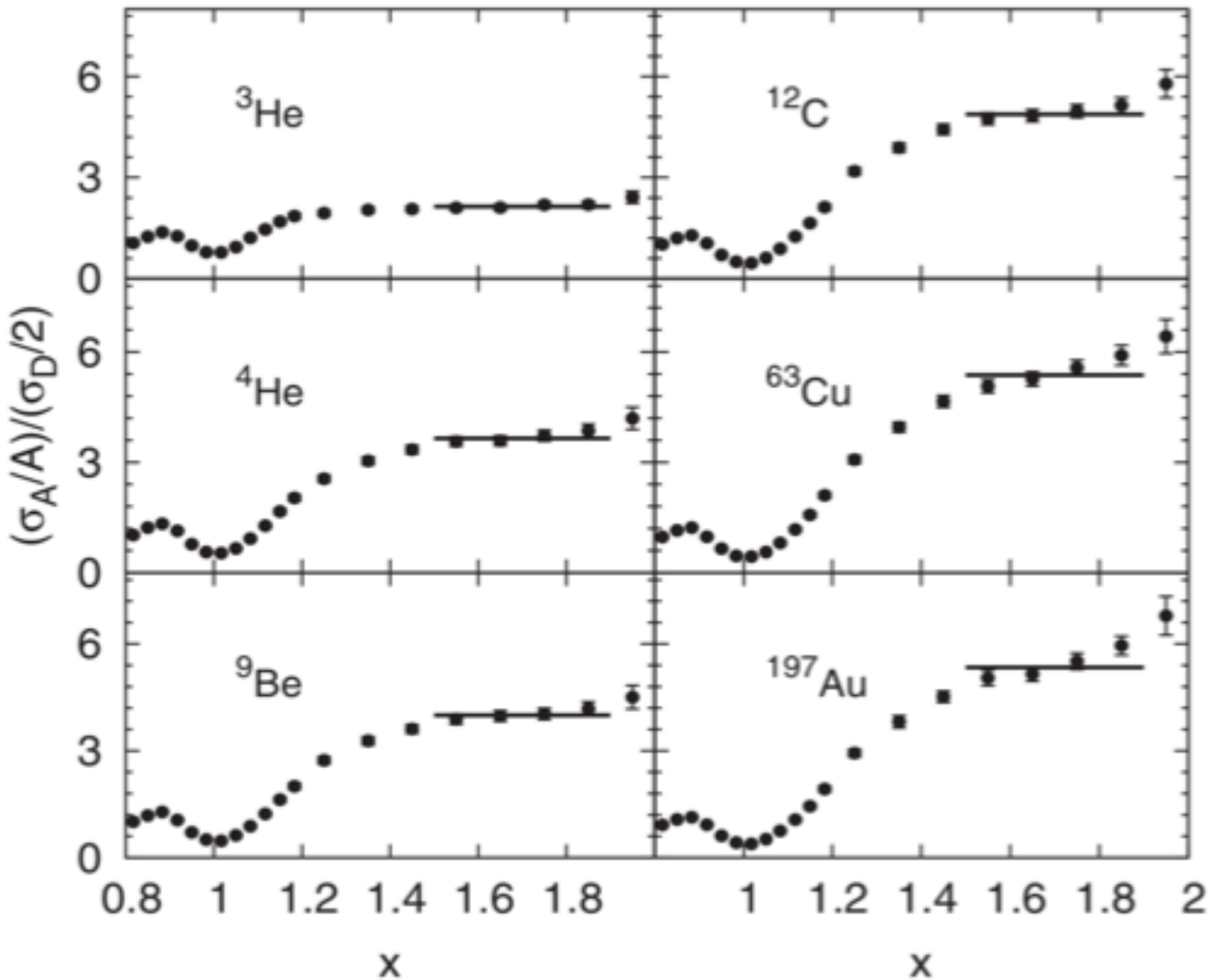
=> $n_A(k>k_F) = a_2(A) \times n_d(k)$



Egiyan et al., PRL (2006)

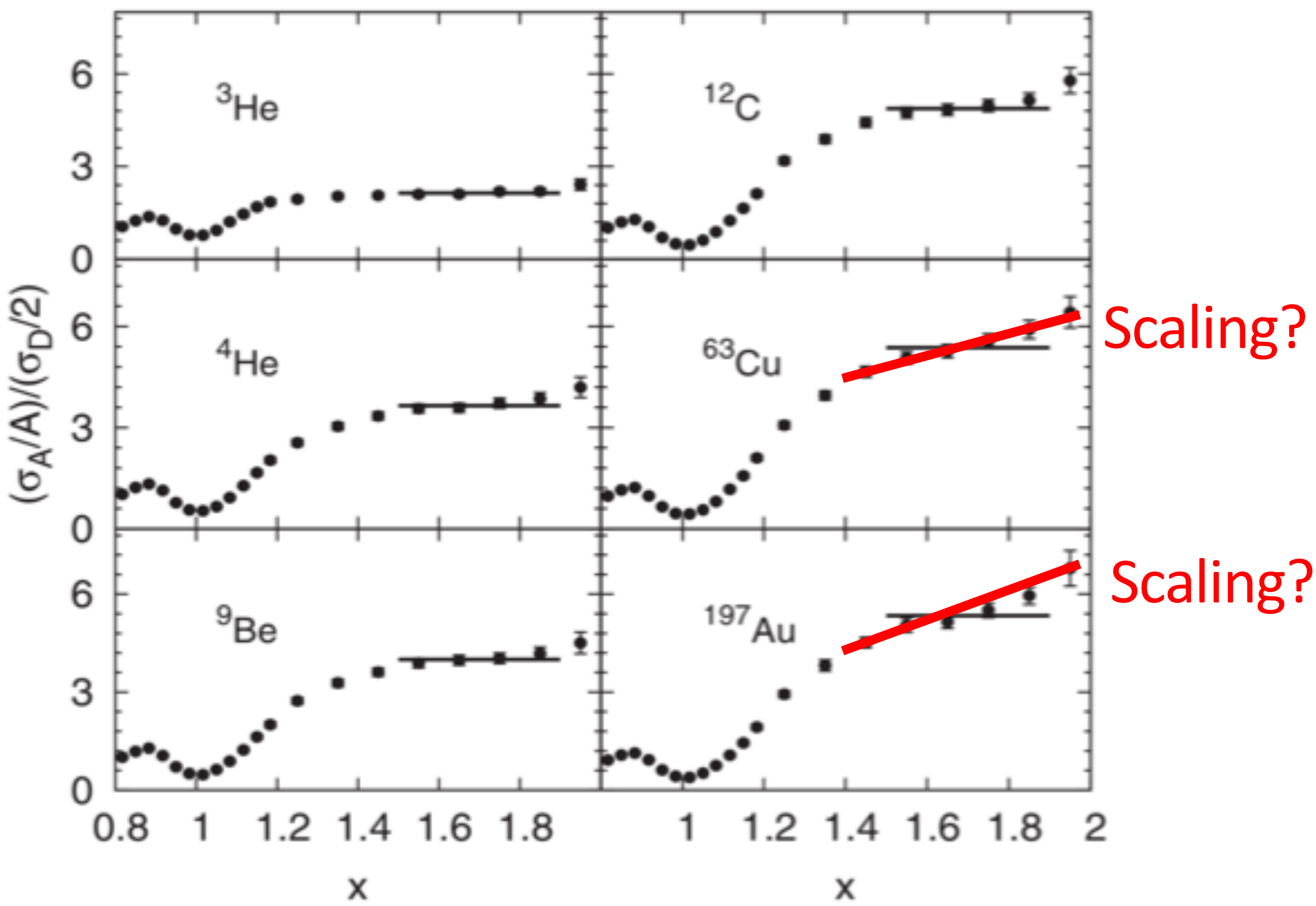
Frankfurt et al., PRC (1993); Egiyan et al., PRC (2003); Fomin et al., PRL (2012).

2012 High-Momentum [almost] Scaling



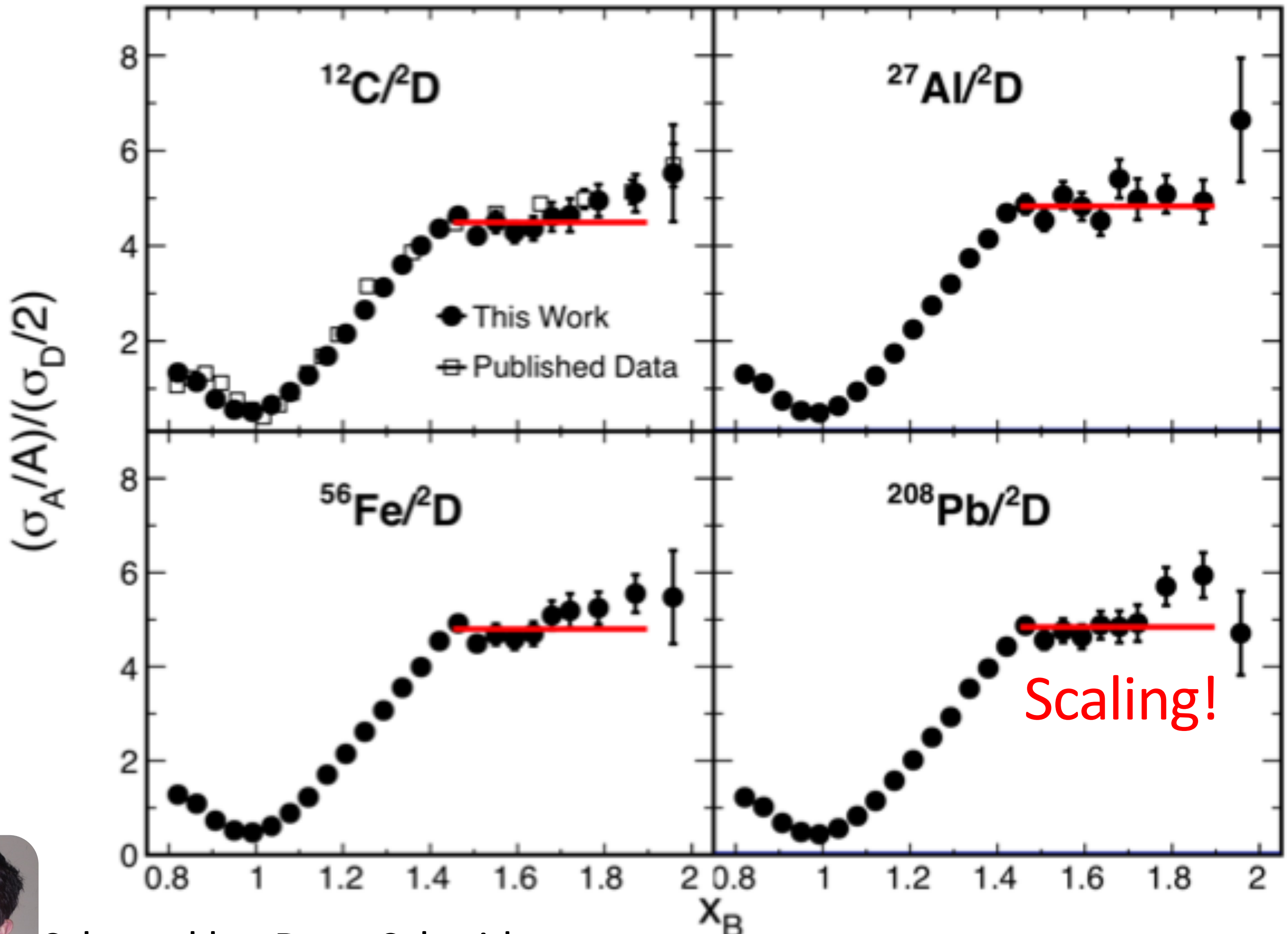
Fomin, PRL (2012)

2012 High-Momentum [almost] Scaling



Fomin, PRL (2012)

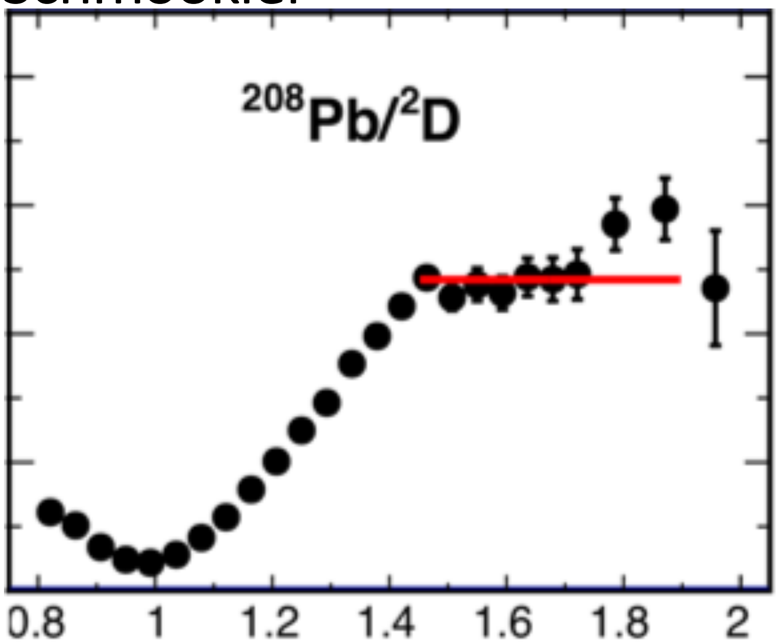
2018 High-Momentum Scaling (!)



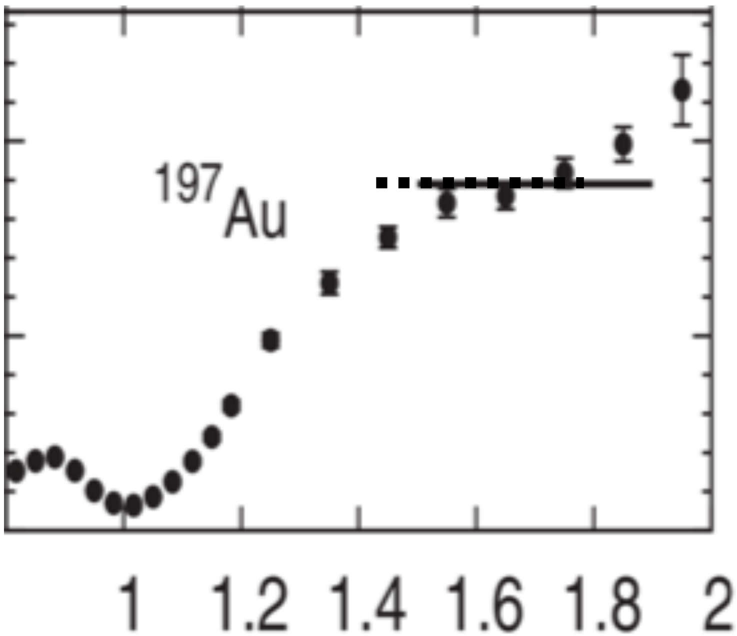
Schmookler, Duer, Schmidt et al., submitted (2018)

2018 High-Momentum Scaling

Schmookler



Fomin



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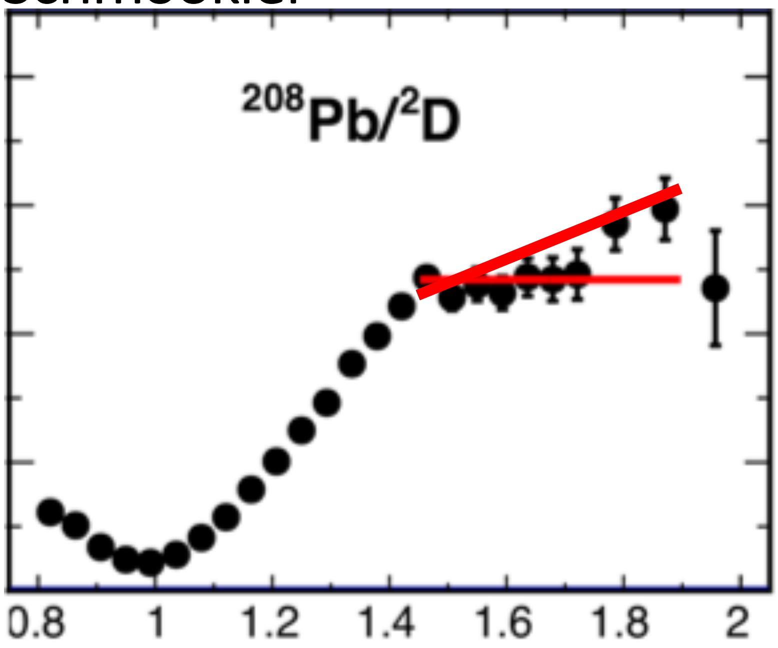

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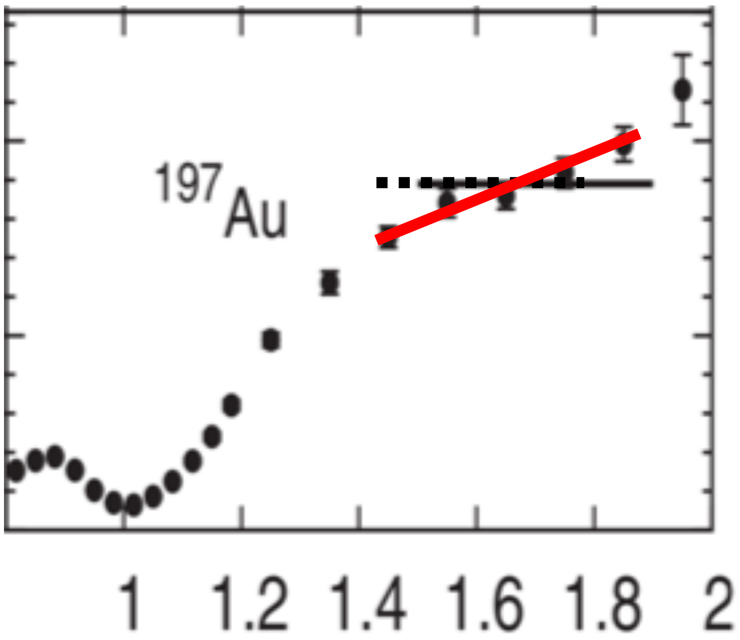
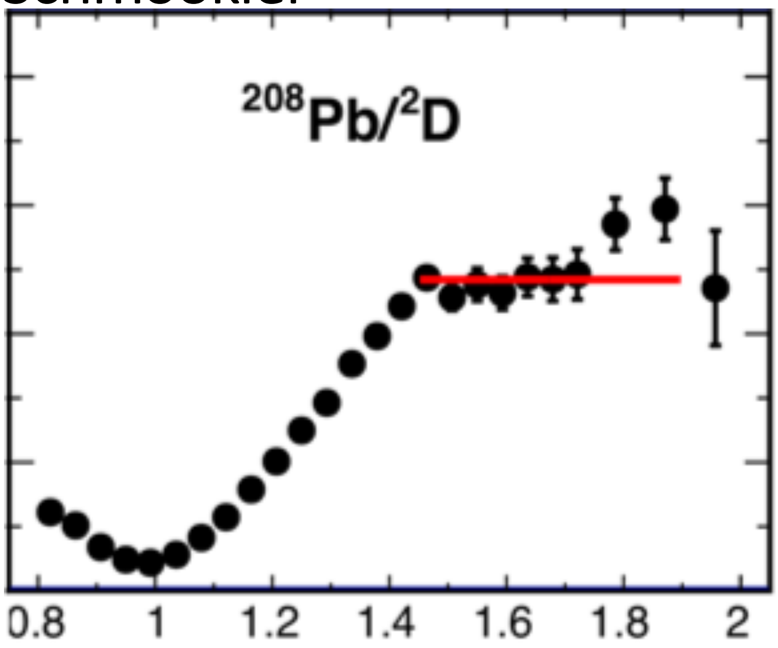


2018 High-Momentum Scaling

Schmookler



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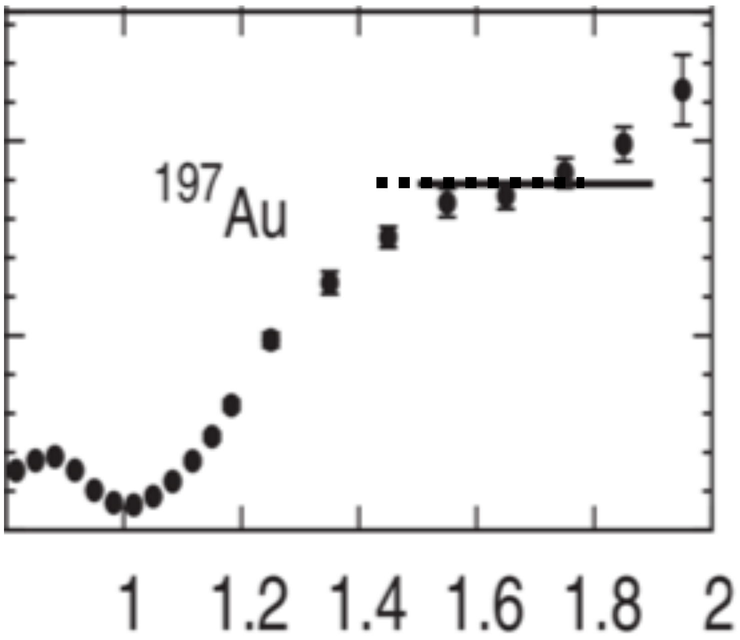


20% high-p?

- A/d (e,e') ratio @ $x_B > 1.5$: ~5
- AV18 deuteron density above 275 MeV/c: ~4 - 5%

➔ 5 x 4% ~ 20%

20% high-p?

- A/d (e,e') ratio @ $x_B > 1.5$: ~5
- AV18 deuteron density above 275 MeV/c: ~4 - 5%

➔ 5 x 4% ~ 20%

~ 20% is consistent with VMC using AV18+UIX

20% high-p?

Open questions:

- Similar (?) A/d high-p scaling observed for soft chiral interactions [Lonardoni 2018; Weiss 2018], where Deuteron density above 275 MeV/c << 4-5 %

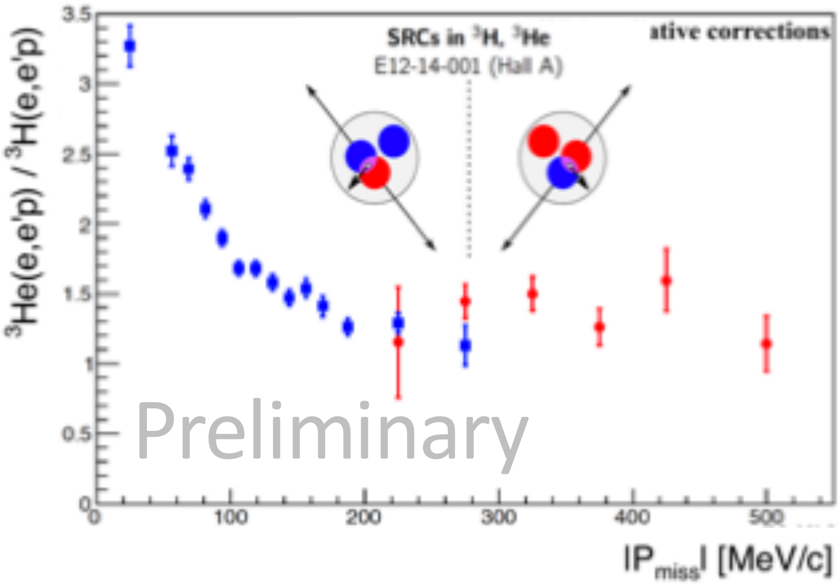
- Experiments sensitive to light-cone densities, NOT momentum densities. No light-cone calc yet…

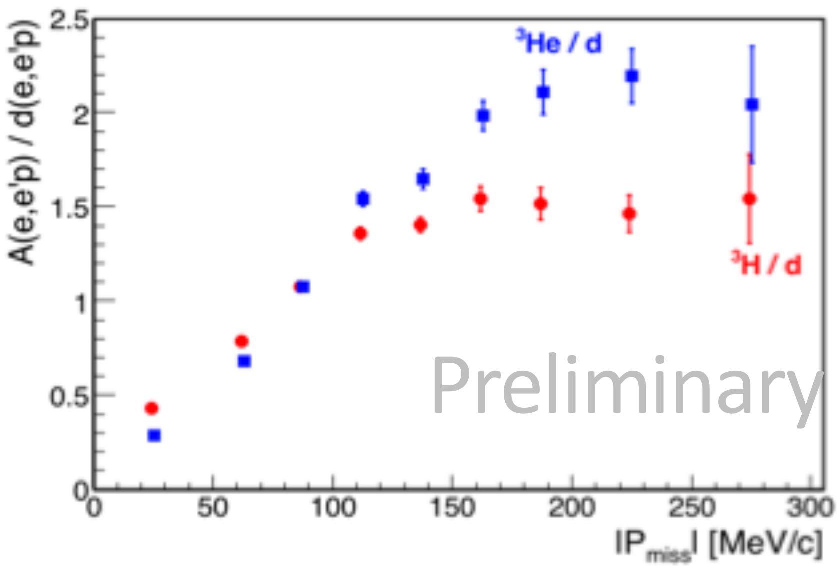
So… It’s all about the NN


BRACE YOURSELF
DATA
~~WINTER~~ IS COMING
Troll.me

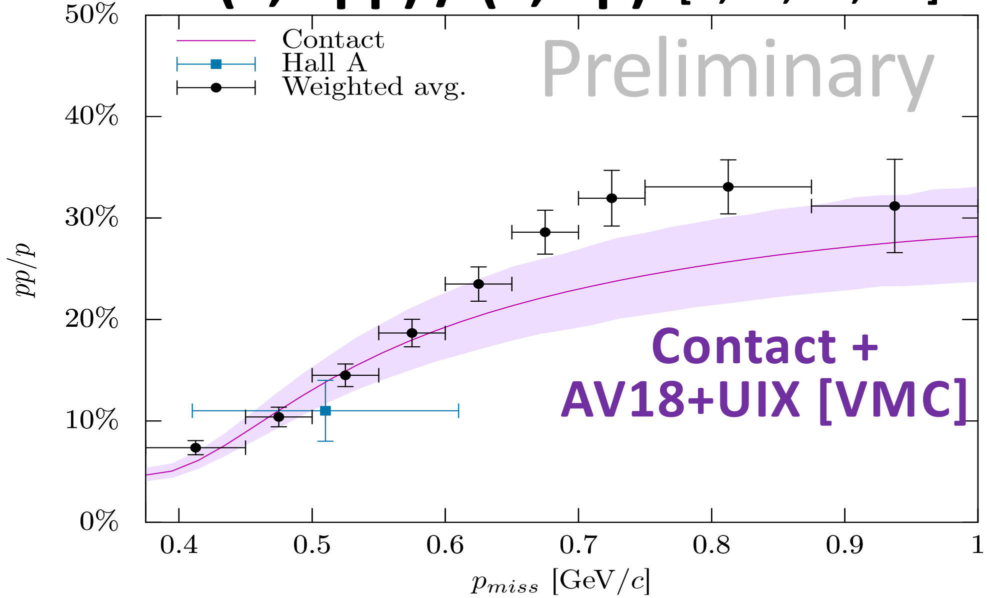
Initial work on observables sensitive to NN

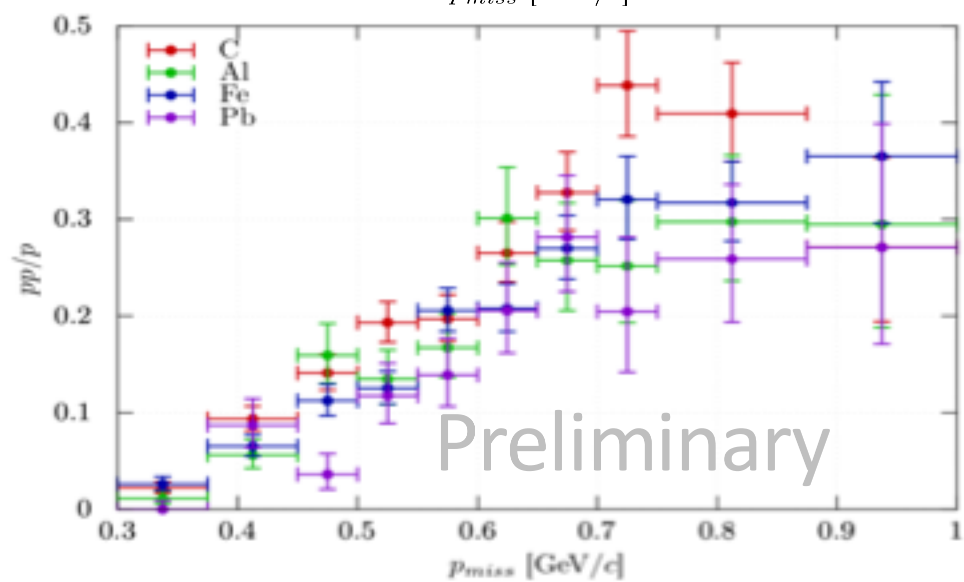
^{3}He / ^{3}H (e,e'p)

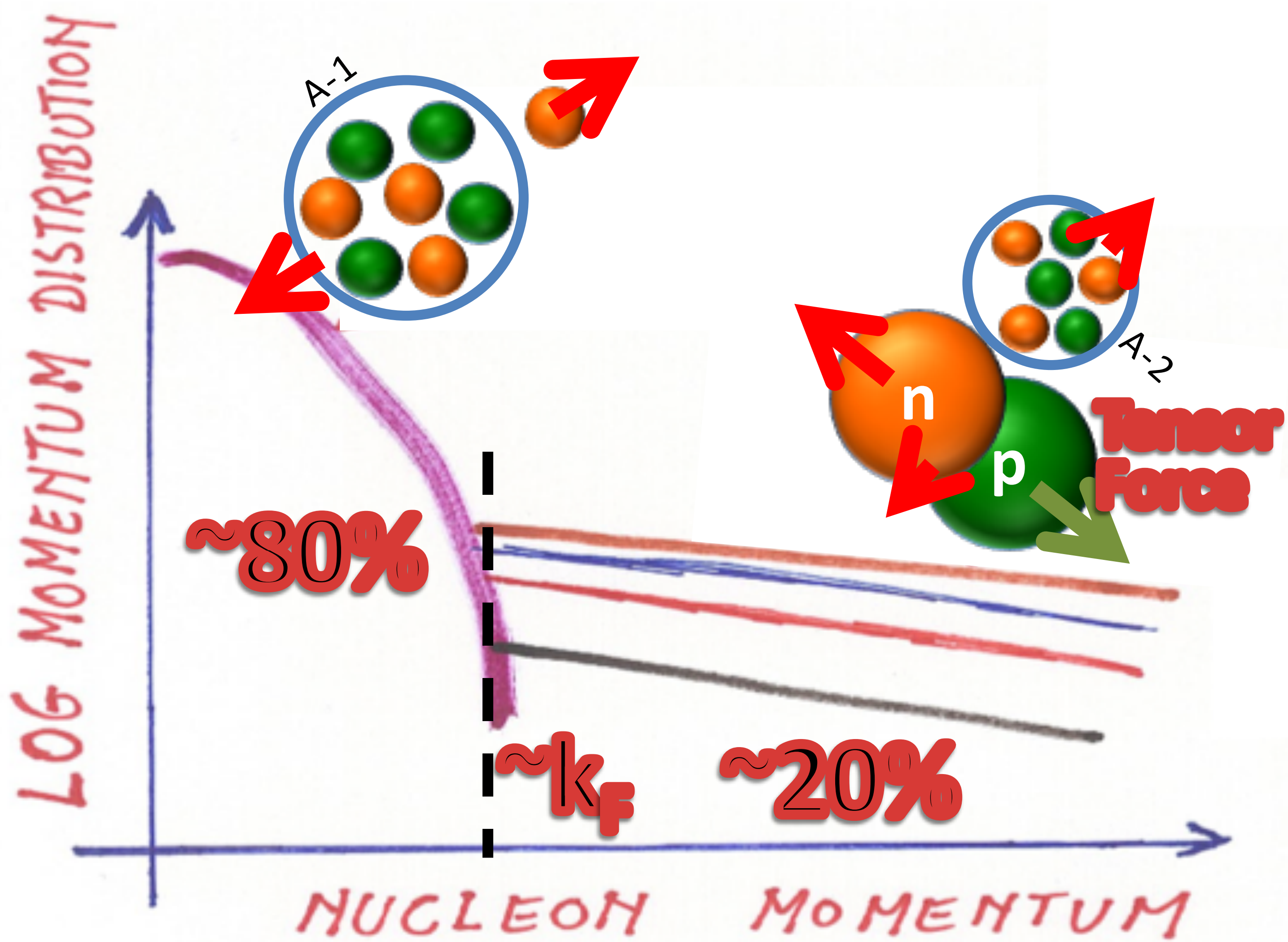




A (e,e'pp) / (e,e'p) [C, Al, Fe, Pb]

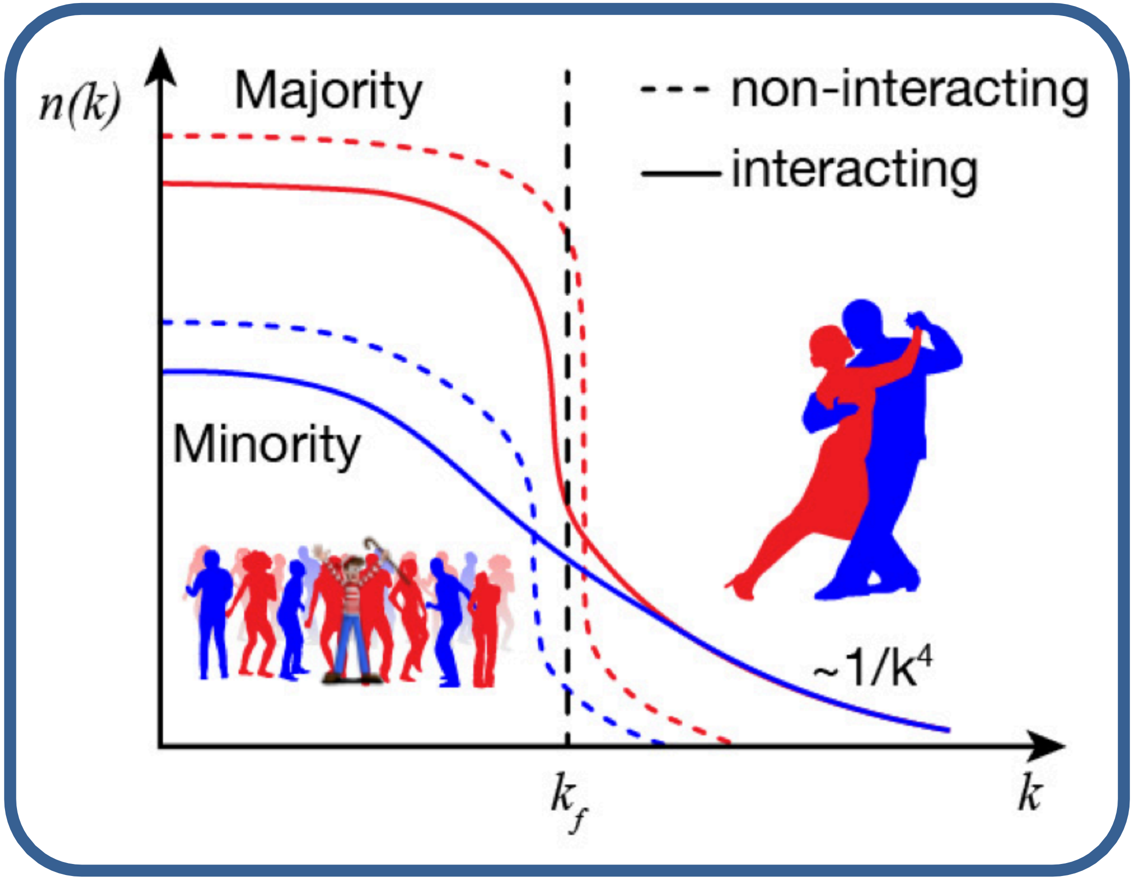


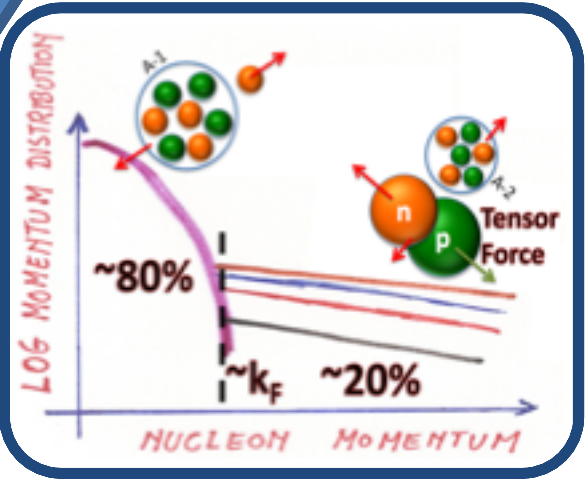




LOG MOMENTUM DISTRIBUTION
A-1
A-2
n
p
Tensor Force
~80%
~k_F
~20%
NUCLEON MOMENTUM

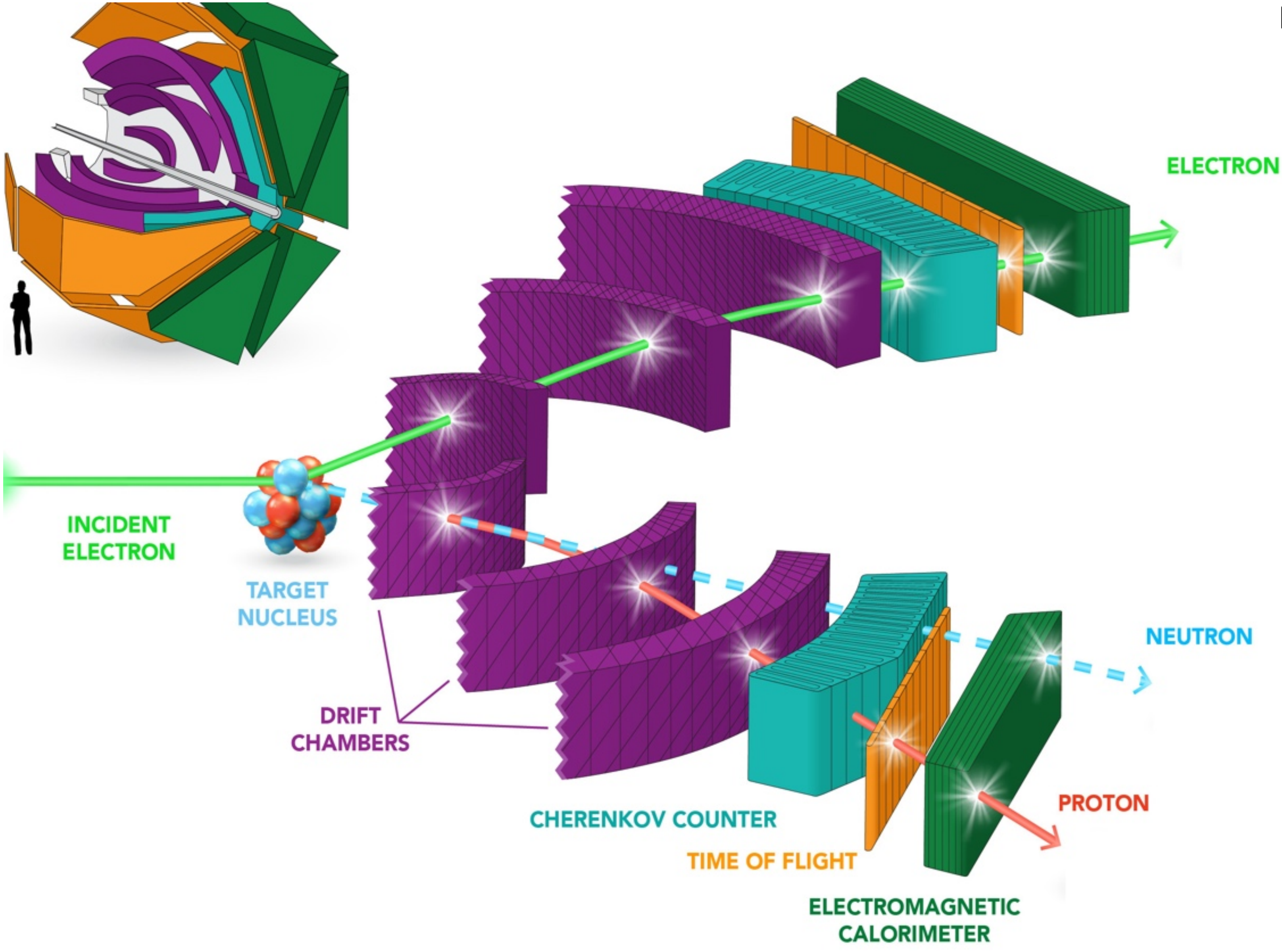
Asymmetric Nuclei?



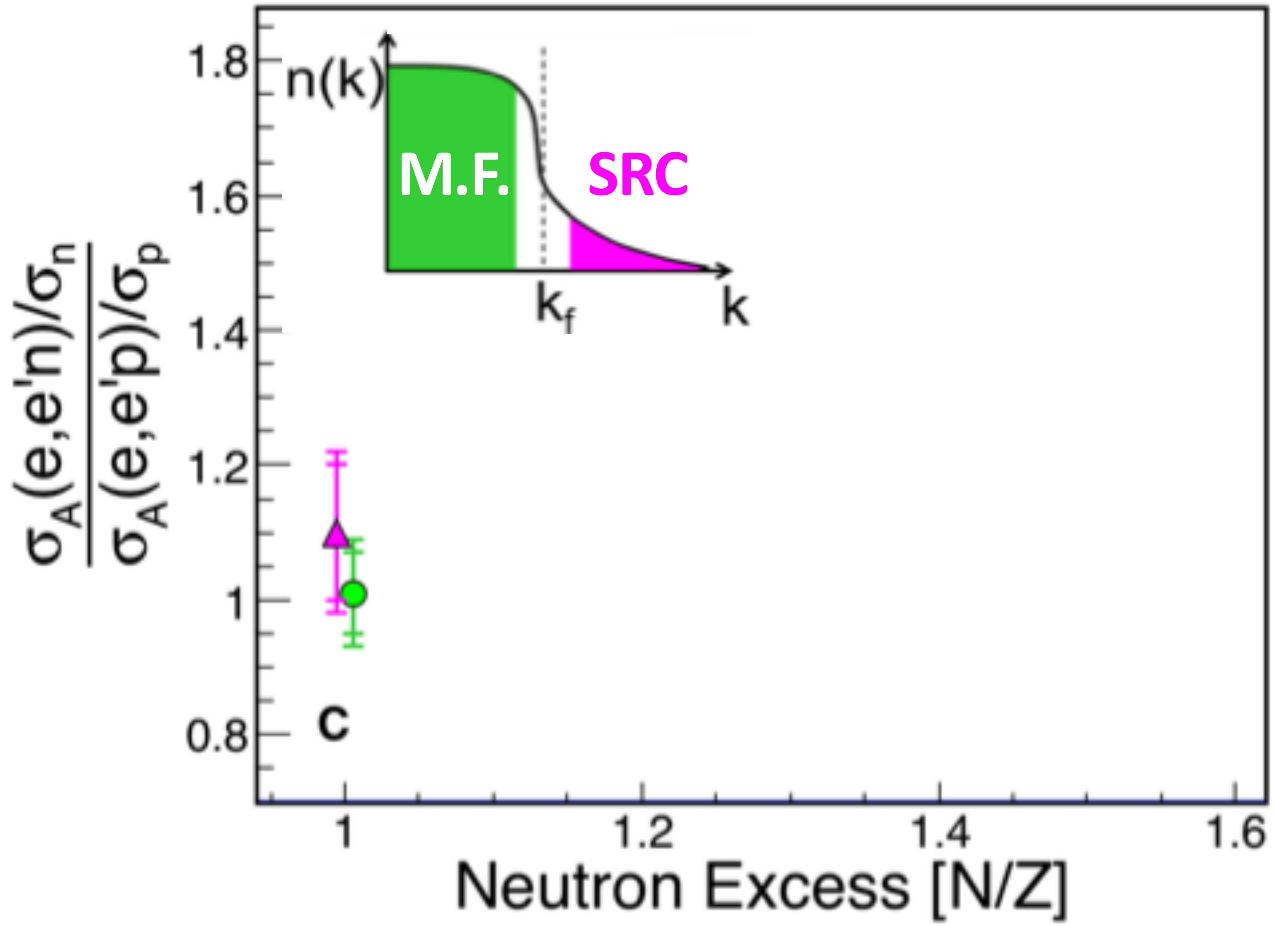


Proton vs. Neutron Knockout

M. Duer

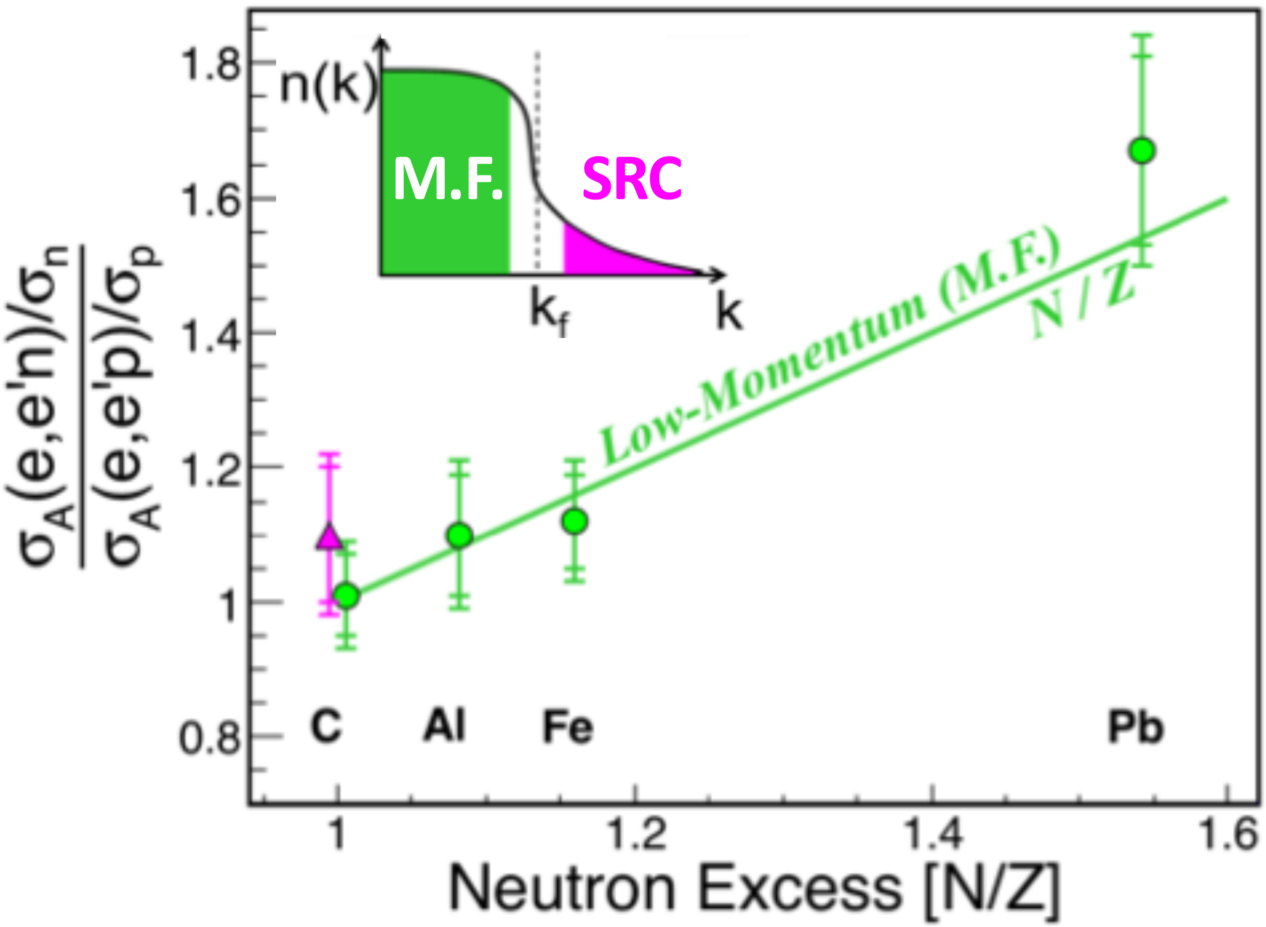


Proton / Neutron Populations



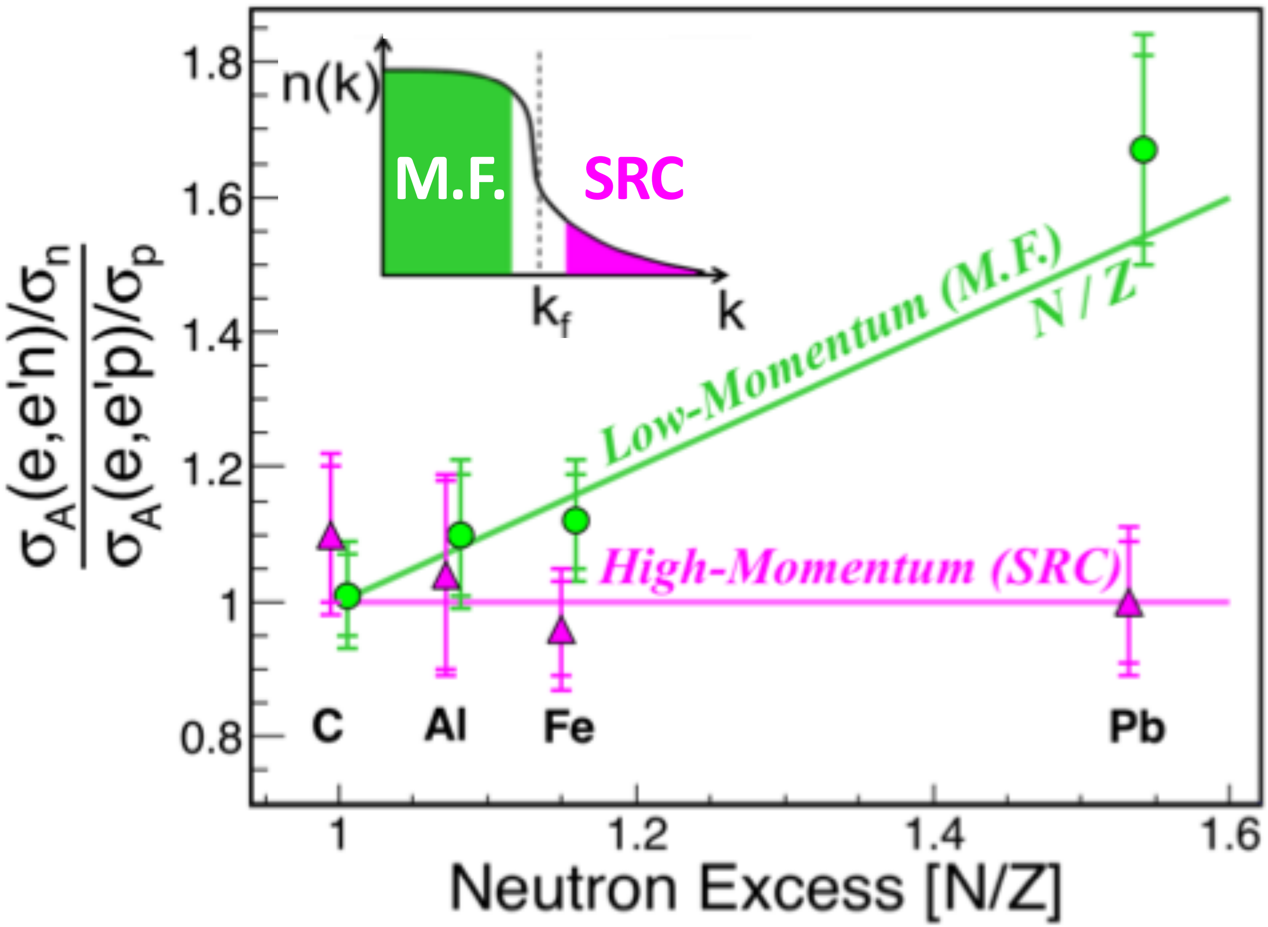
M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)

Mean-Field: n/p ~ N/Z



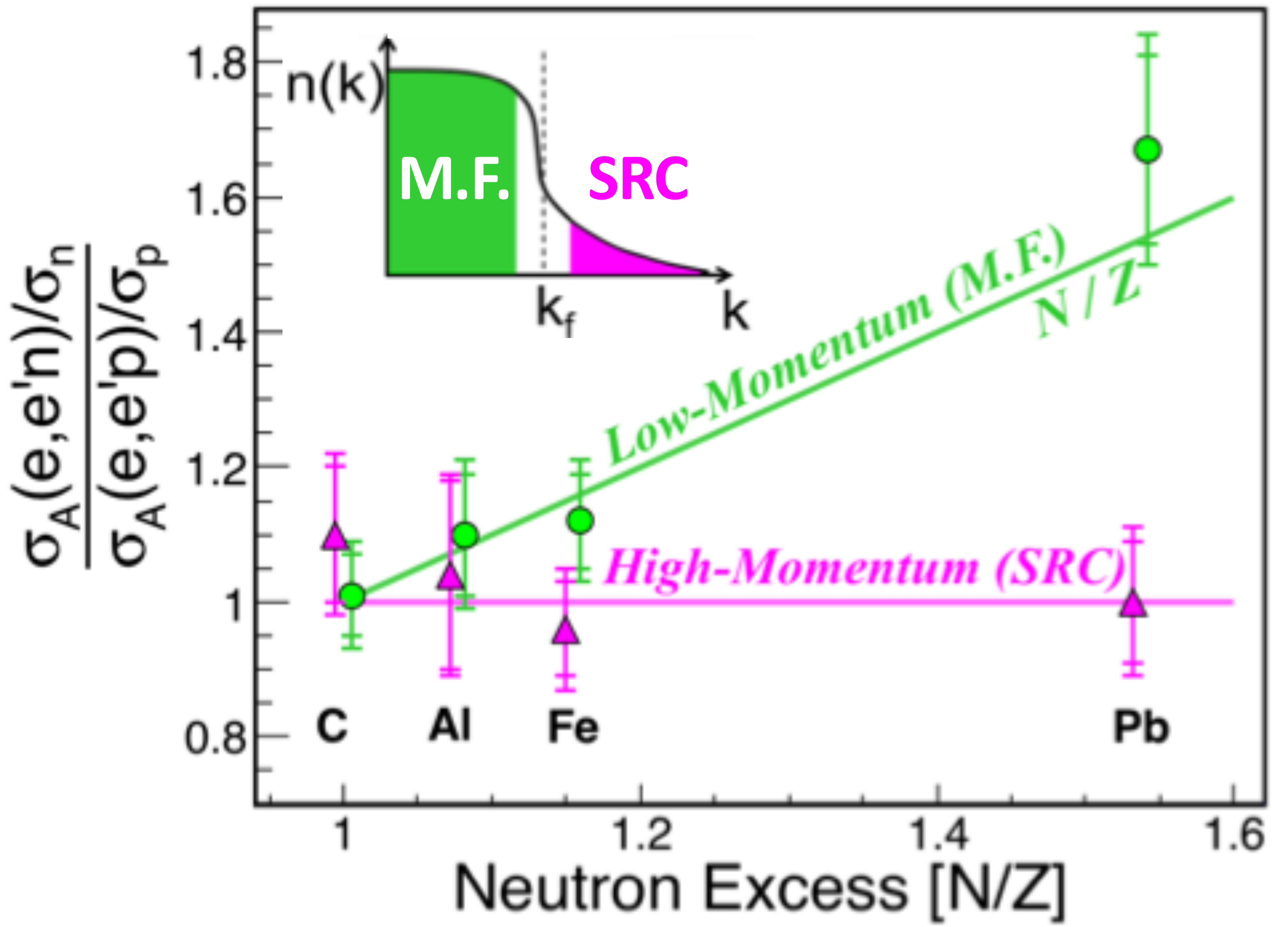
M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)

SRC: n/p ~ 1



M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)

➔ Same # of high-momentum protons and neutrons



M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)

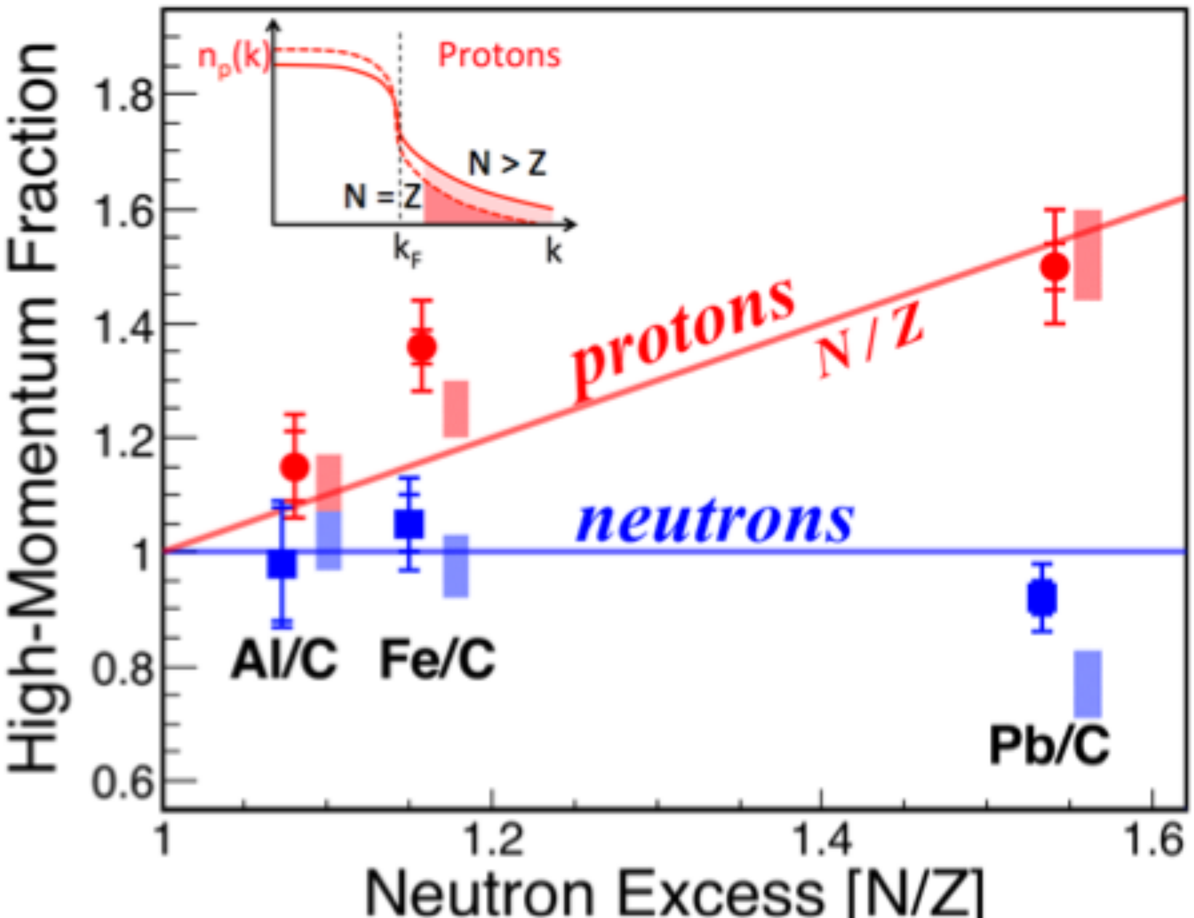
What do the outer neutrons do?

don't correlate?

correlate with core protons?

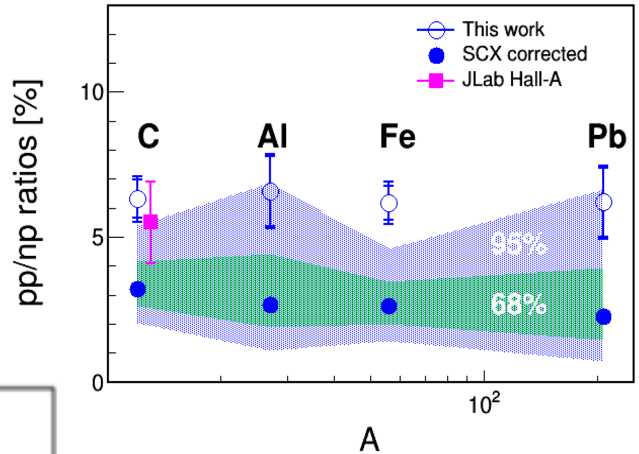
M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)

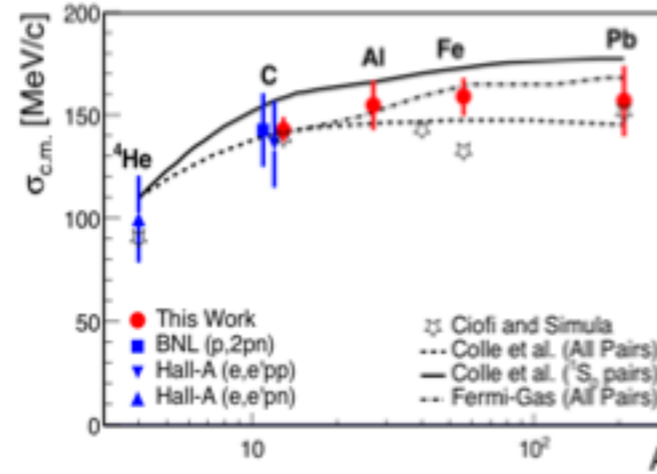
Correlation Probability:
Neutrons saturate Protons grow

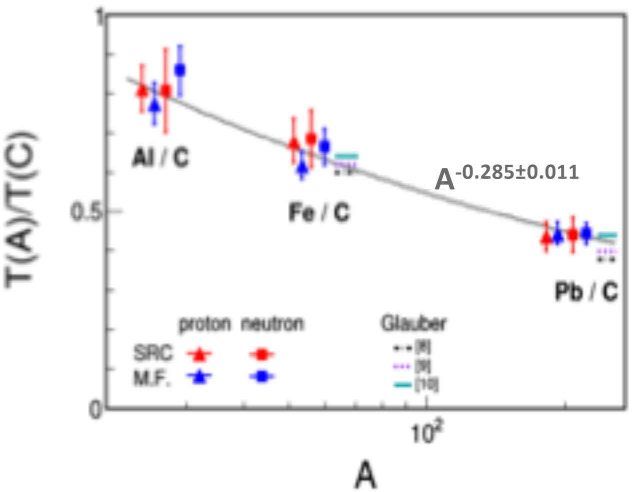


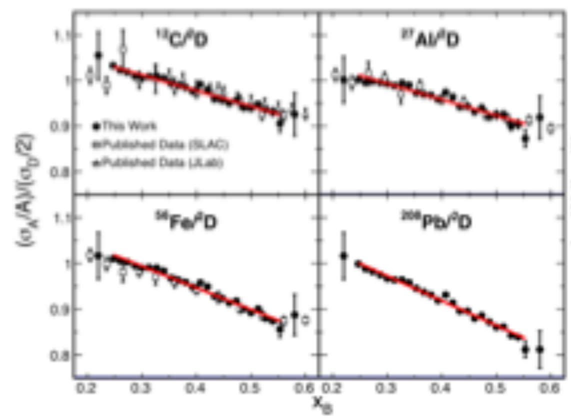
M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)

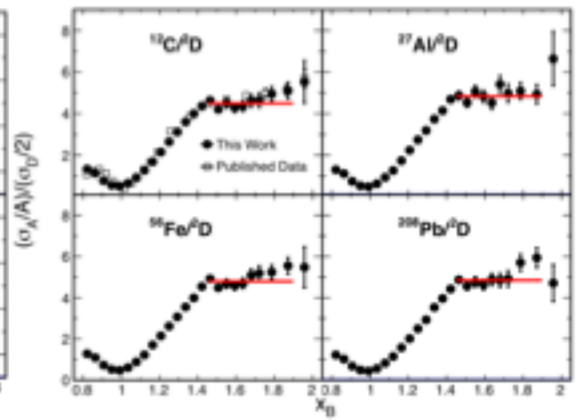
New Exp. Results!

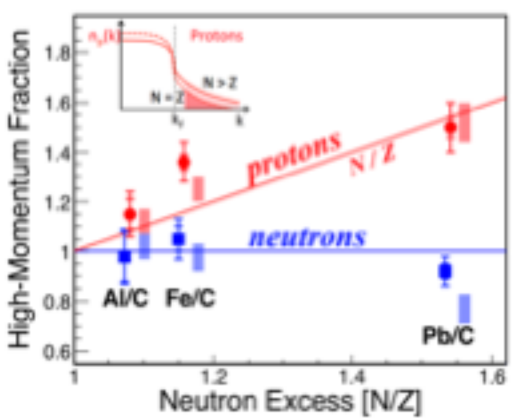


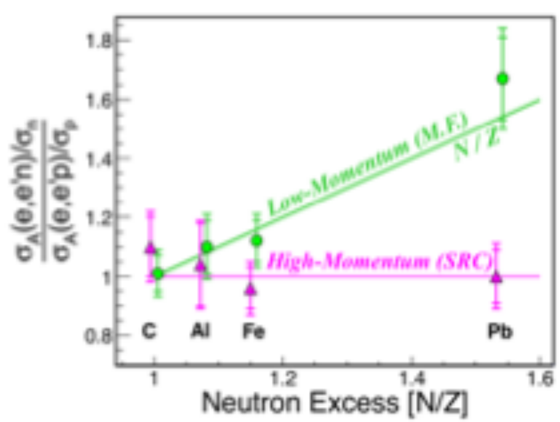


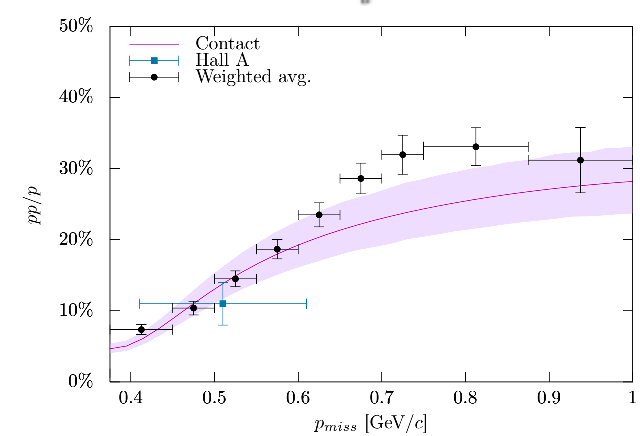












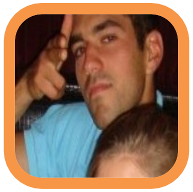
There’s more to come…

- Constraining the <u>repulsive core</u> of the NN interaction via A(e,e’pp)/A(e,e’p)
- <u>Tagged</u> EMC and SRC measurements via A(e,e’p_{recoil})
- SRC dynamics in <u>few-body systems</u> via ^{3,4}He(e,e’N) & ^{3,4}He(e,e’Np)
- <u>3N-SRC</u> searches in exclusive channels via A(e,e’ppp); A(e,e’npp) and A(e,e’ppn)
- Electrons 4 Neutrinos <u>**[See talk by Adi]**</u>

A. Achmidt

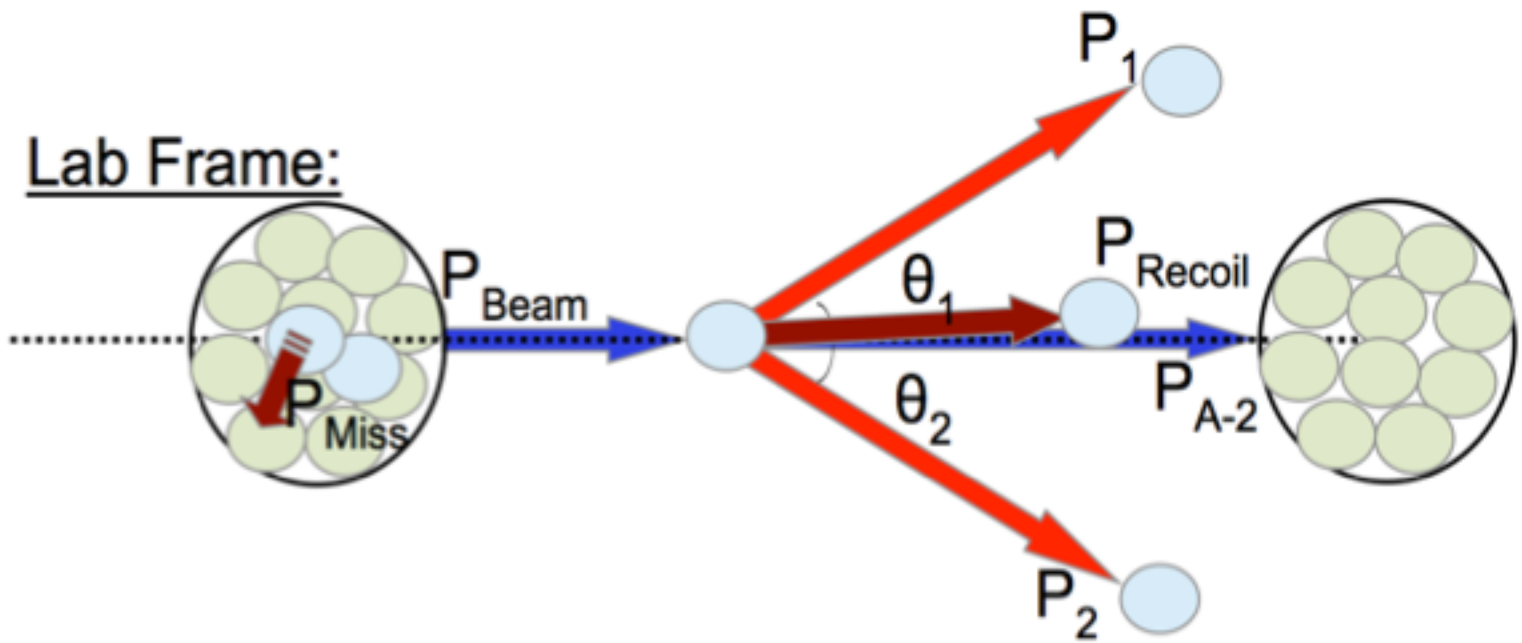


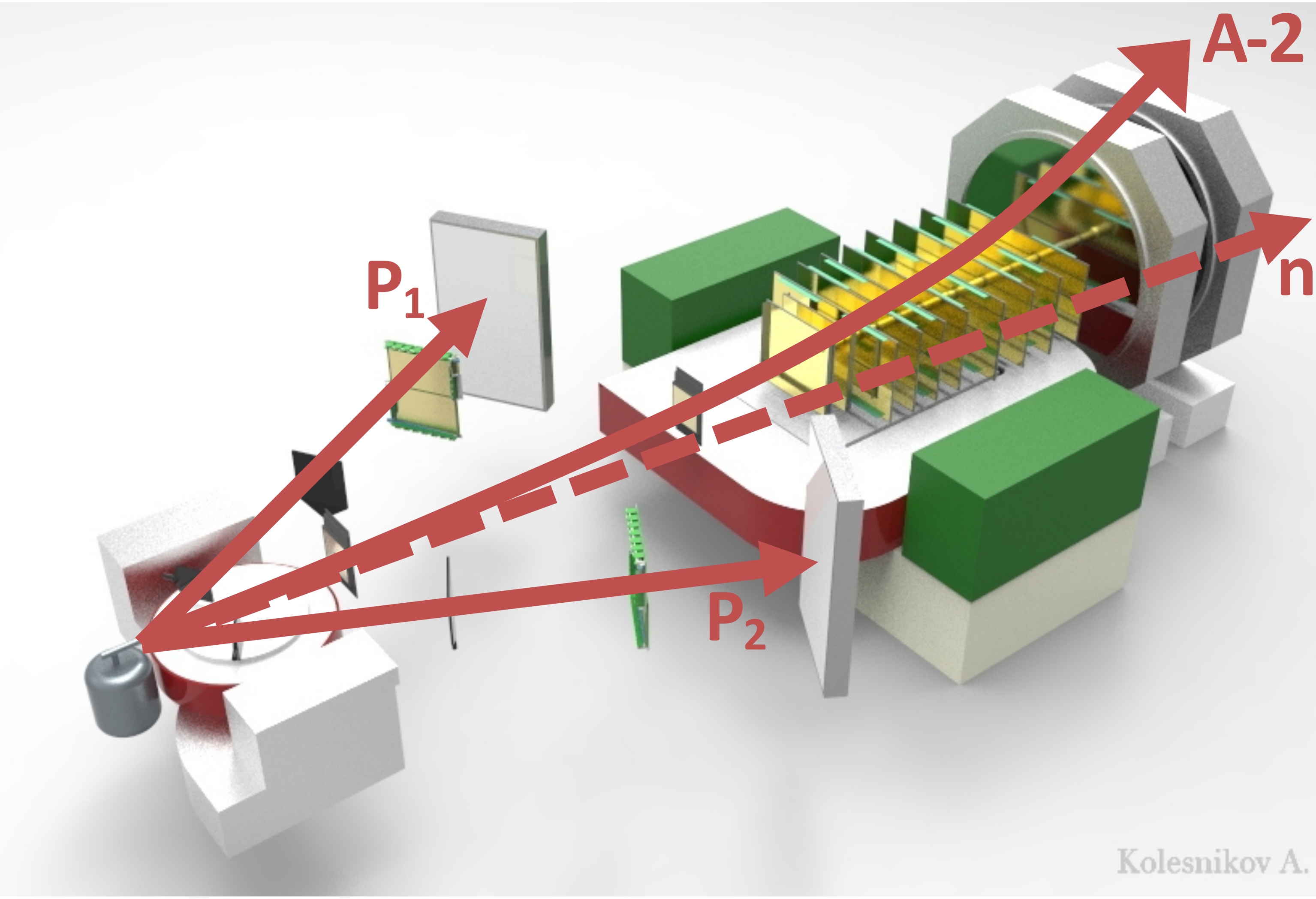





Going Fully Exclusive @ JINR

1st measurement in inverse kinematics; probing the residual A-2 nuclear system!

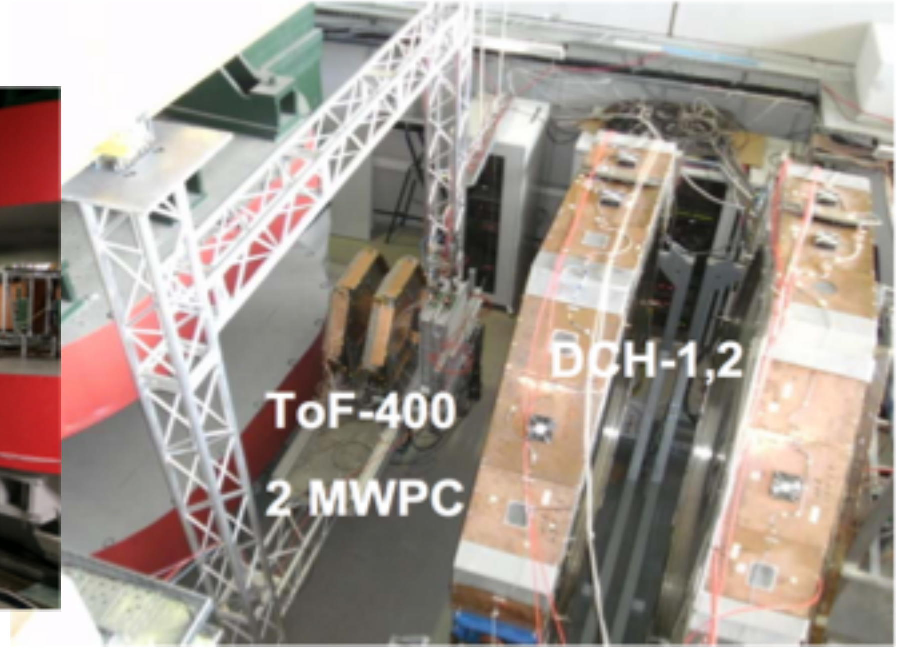





G. Laskaris


M. Patsyuk


E. Segarra

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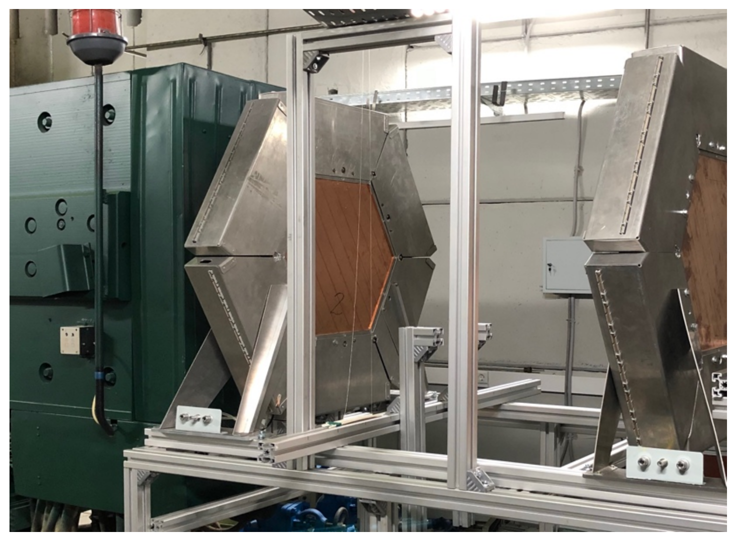
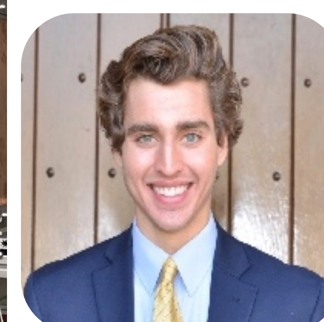
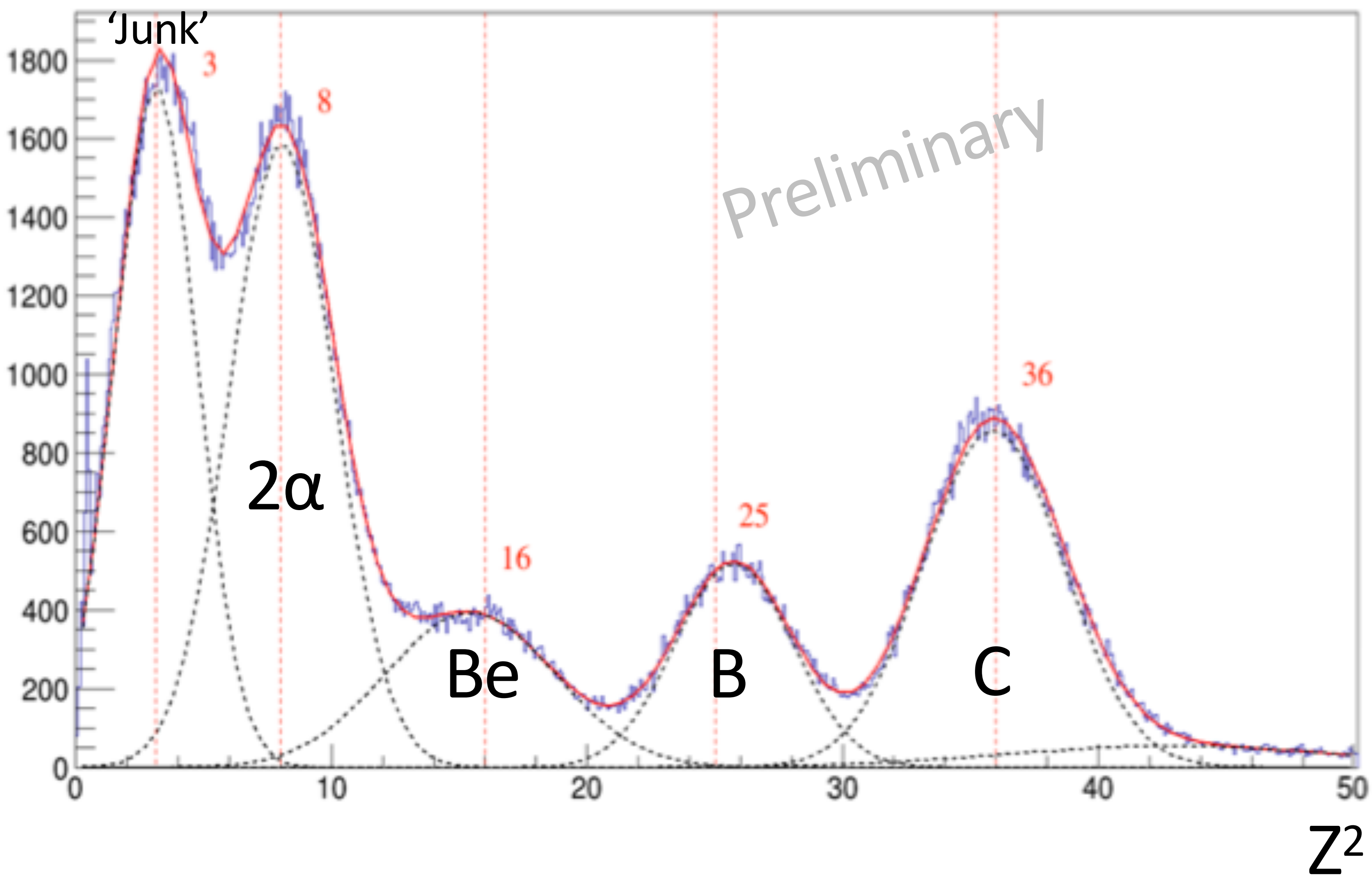



E. Segarra

'A-2' System



'Junk'
3
8
16
25
36
2α
Be
B
C
Preliminary
0
200
400
600
800
1000
1200
1400
1600
1800
0
10
20
30
40
50
Z²


ASK ME
IF I CARE

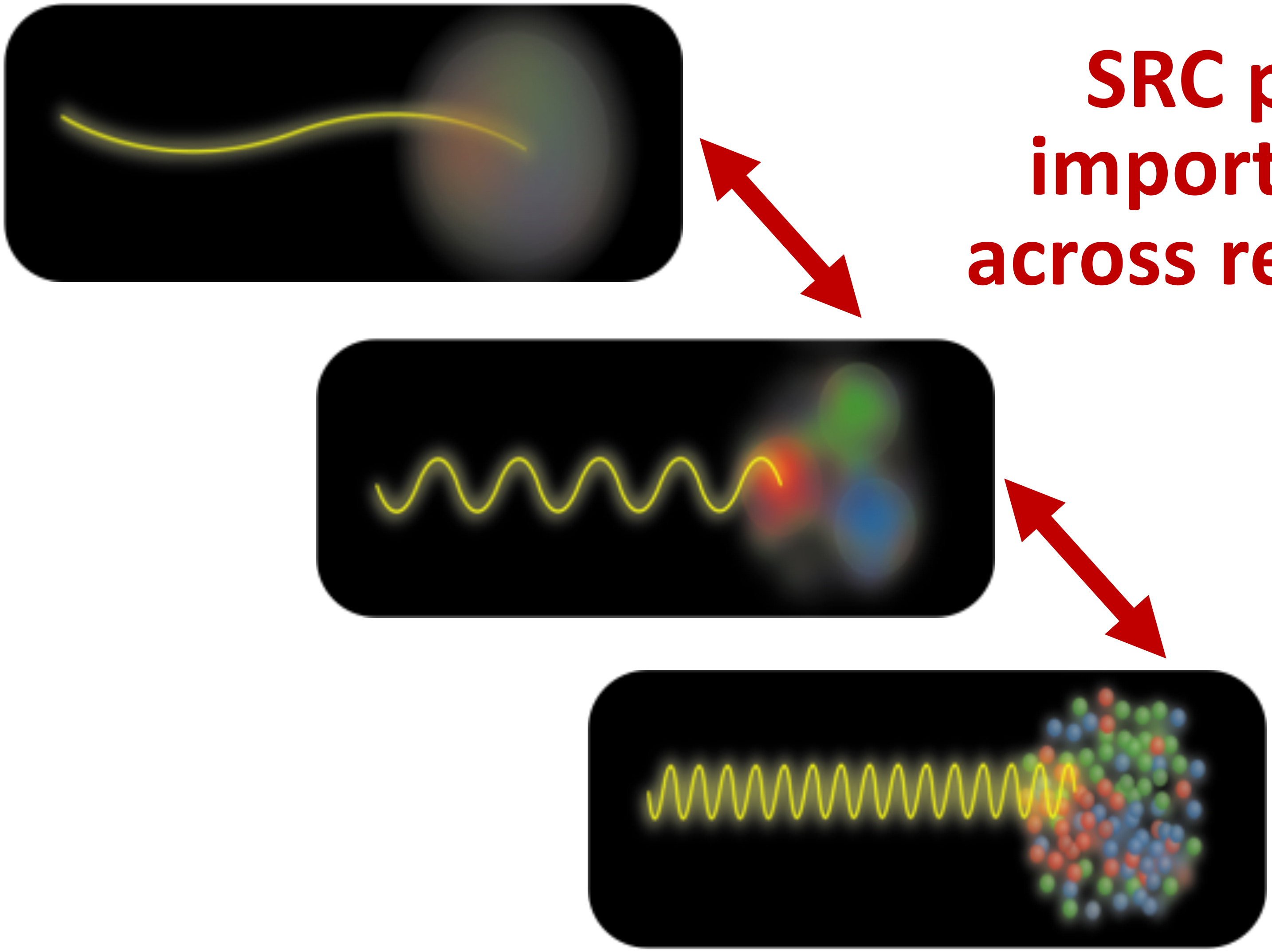
Short-Range Correlations

Or Hen (MIT)

- (new) Exp. results
- **(new) Implications**
- (new) Theory results

INT Workshop on Fundamental Physics with Electroweak Probes of Light Nuclei, July 2nd 2018.

Physics is resolution dependent



SRC play an important role across resolutions

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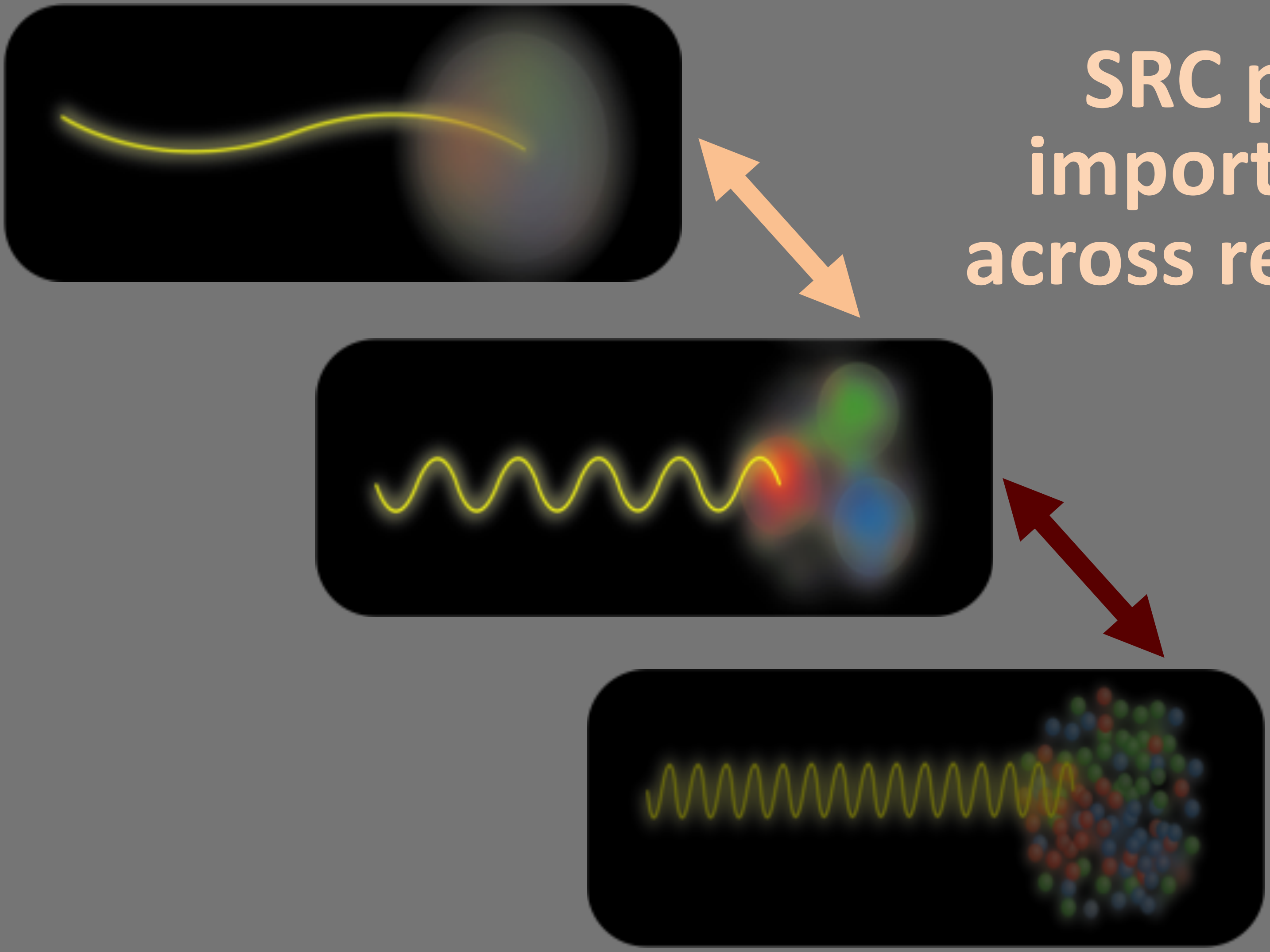
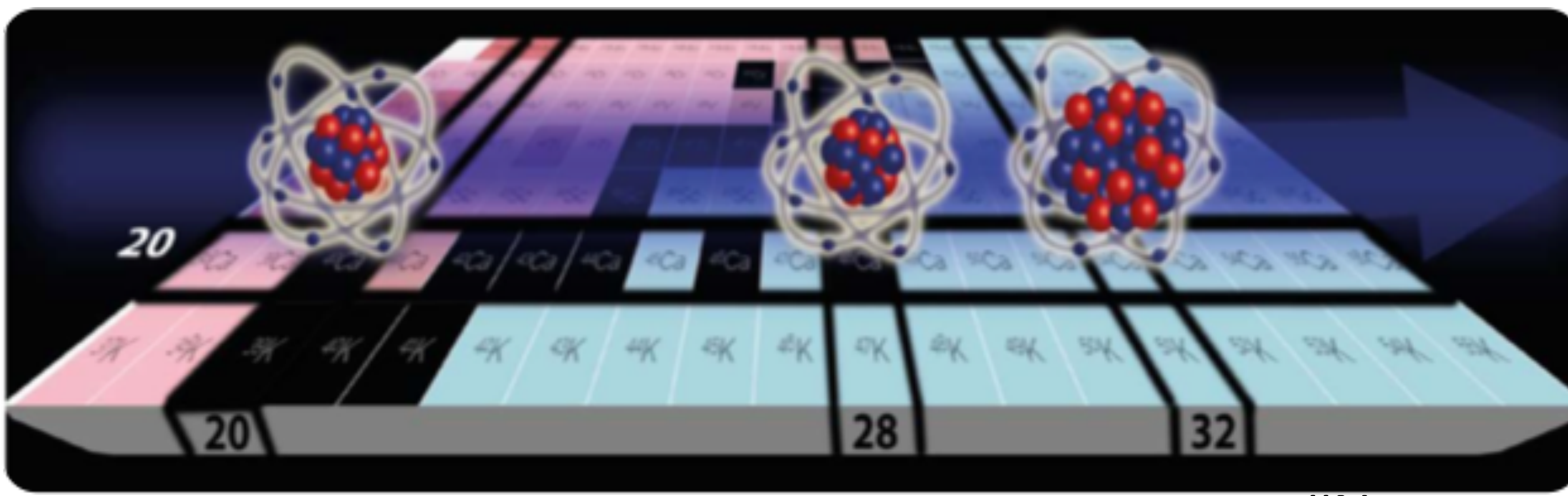


SRC play an important role across resolutions

Proton Charge Radii of neutron rich nuclei

Add *neutrons* => Measure impact on *protons*
=> Learn about proton-neutron pairing

#Protons



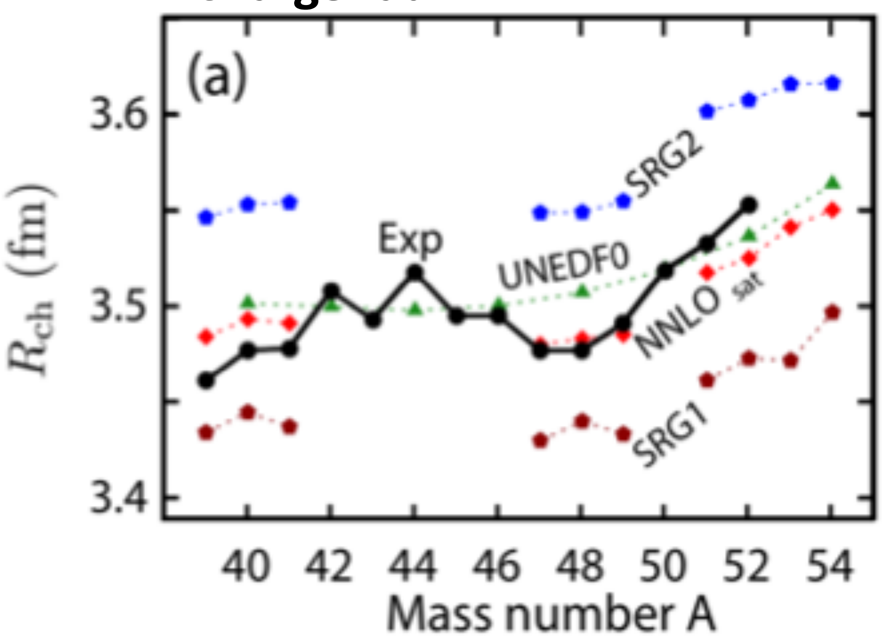
#Neutrons

Ab-Initio Under Predict….

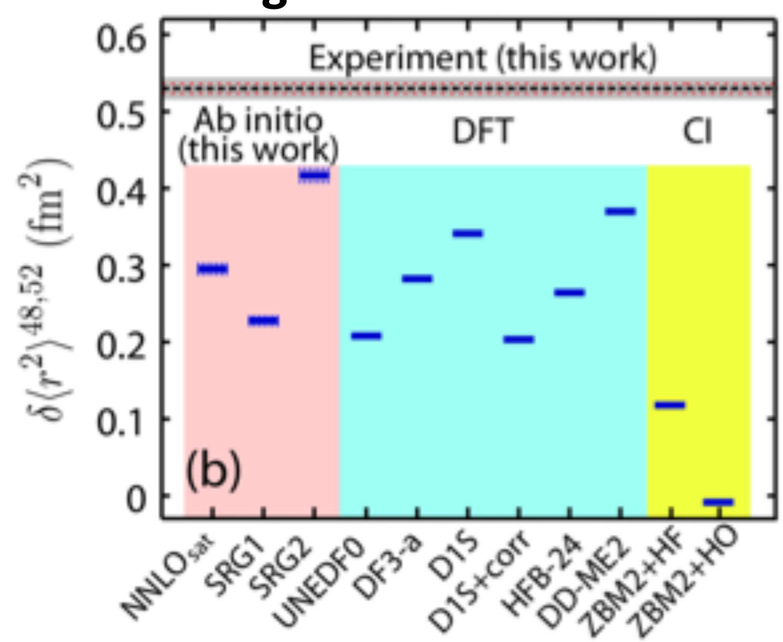
Specifically under predict the measured charge radius increase from ^{48}Ca to ^{52}Ca

These calculations truncate SRCs by evolving the wave function but not the radius operator

Charge radii



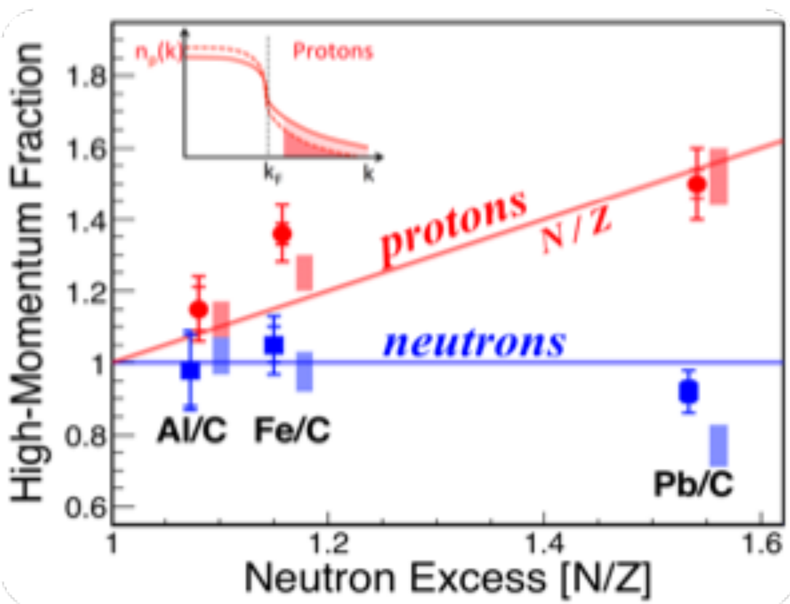
Charge radii diff: ^{52}Ca – ^{48}Ca



R.F. Garcia Ruiz et al., Nature Physics **12**, 594 (2016)

SRCs not Included in the Calculations

np-SRCs of core protons & outer neutrons:
pull out protons, increasing their radius?



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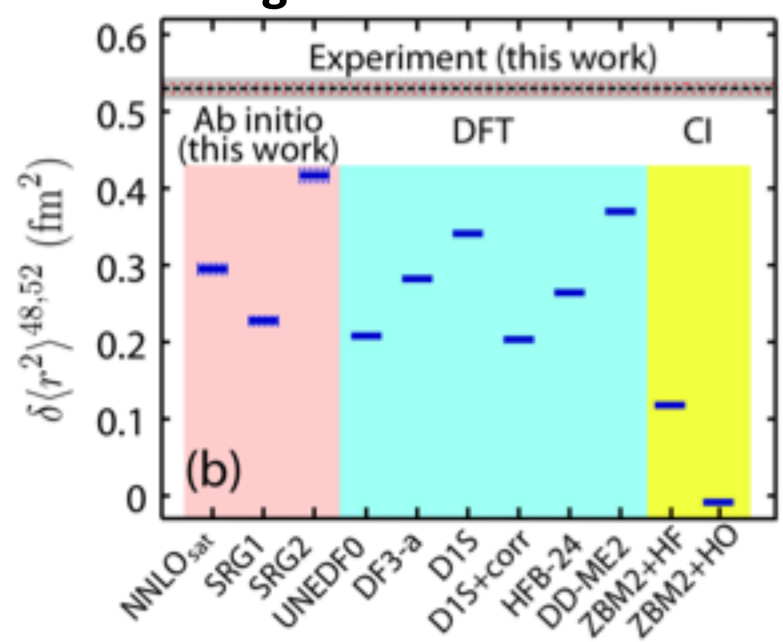
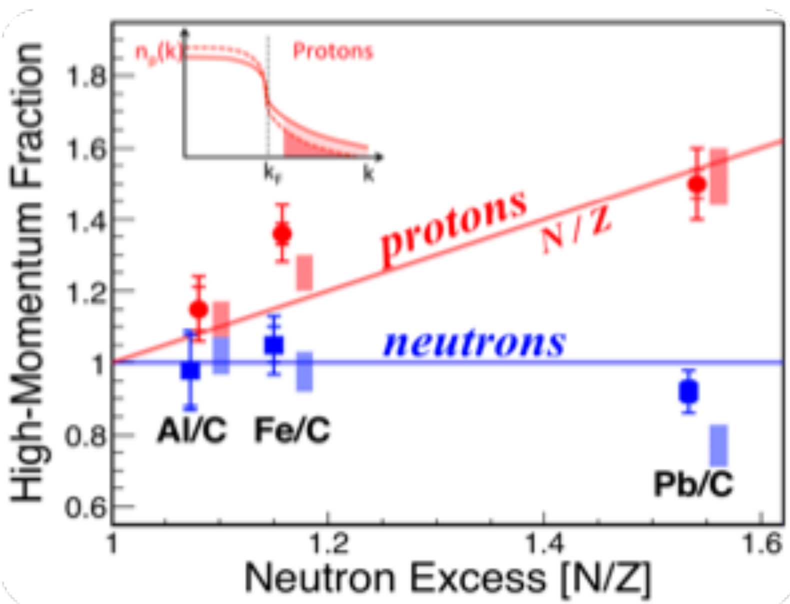


Miller, Beck, May-Tal Beck, Piasetzky, Weinstein and Hen, arXiv: 1805.12099 (2018)

SRCs Can Account for the Difference!

Our estimation for the impact of np-SRCs:

^{49}Ca - ^{48}Ca: $\delta_{SRC}\langle r^2 \rangle = 0.15$ fm^2



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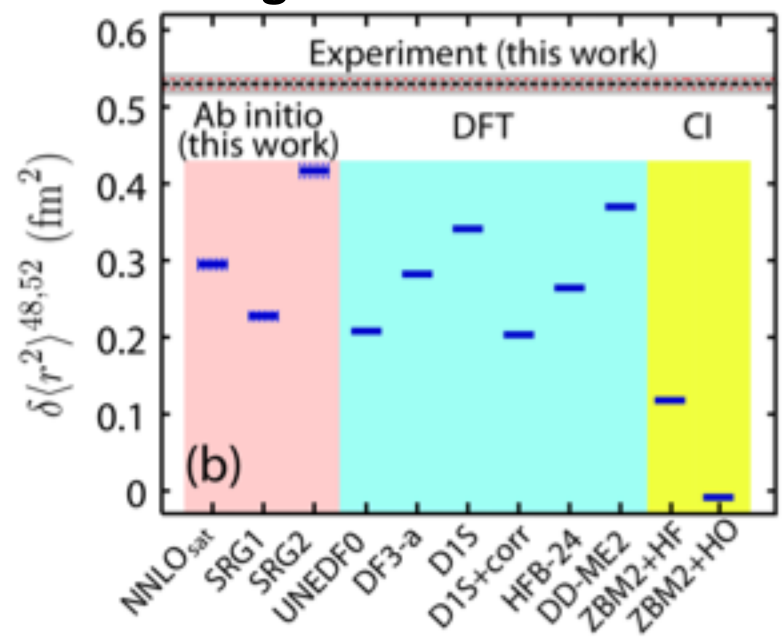

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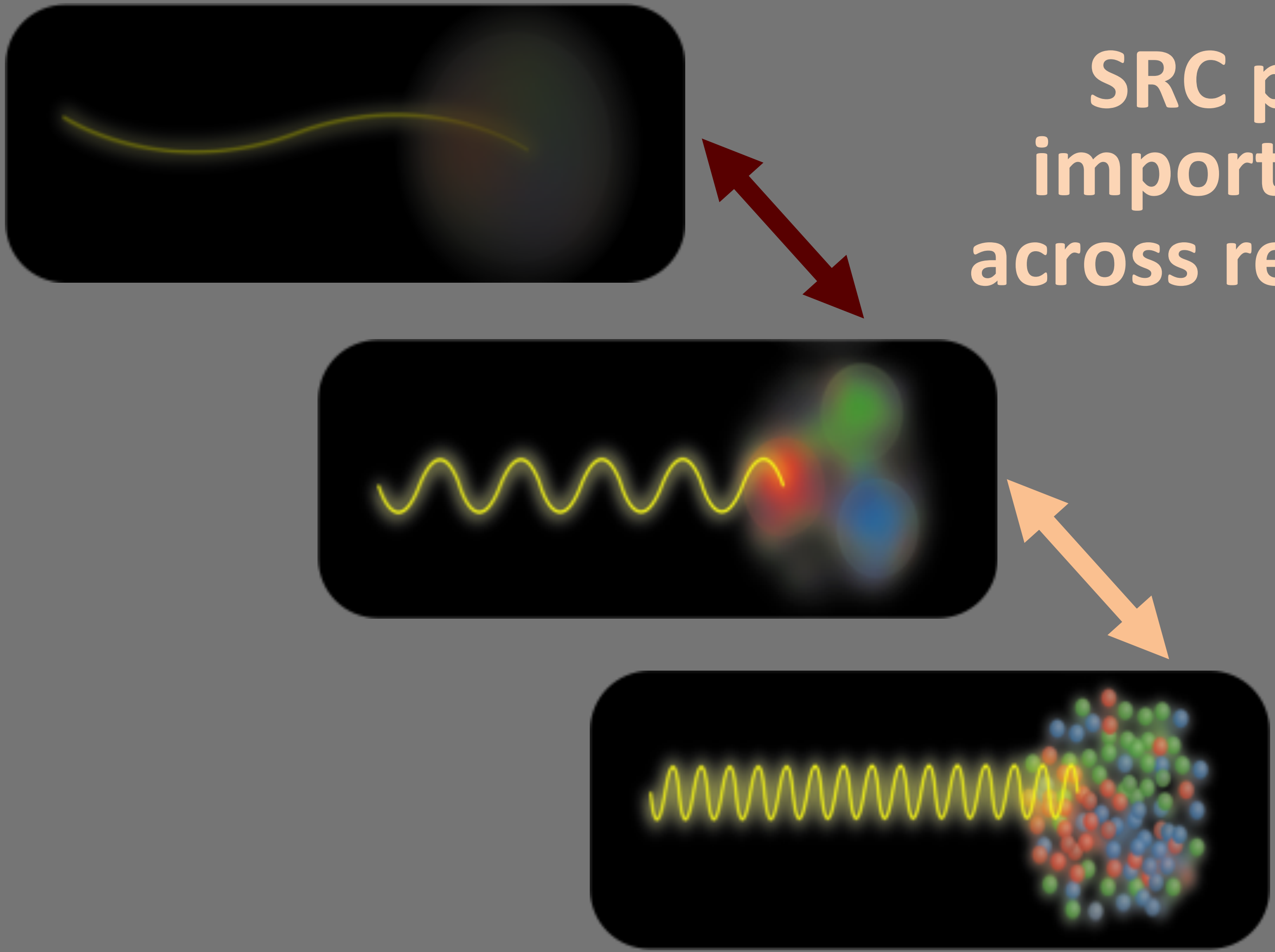
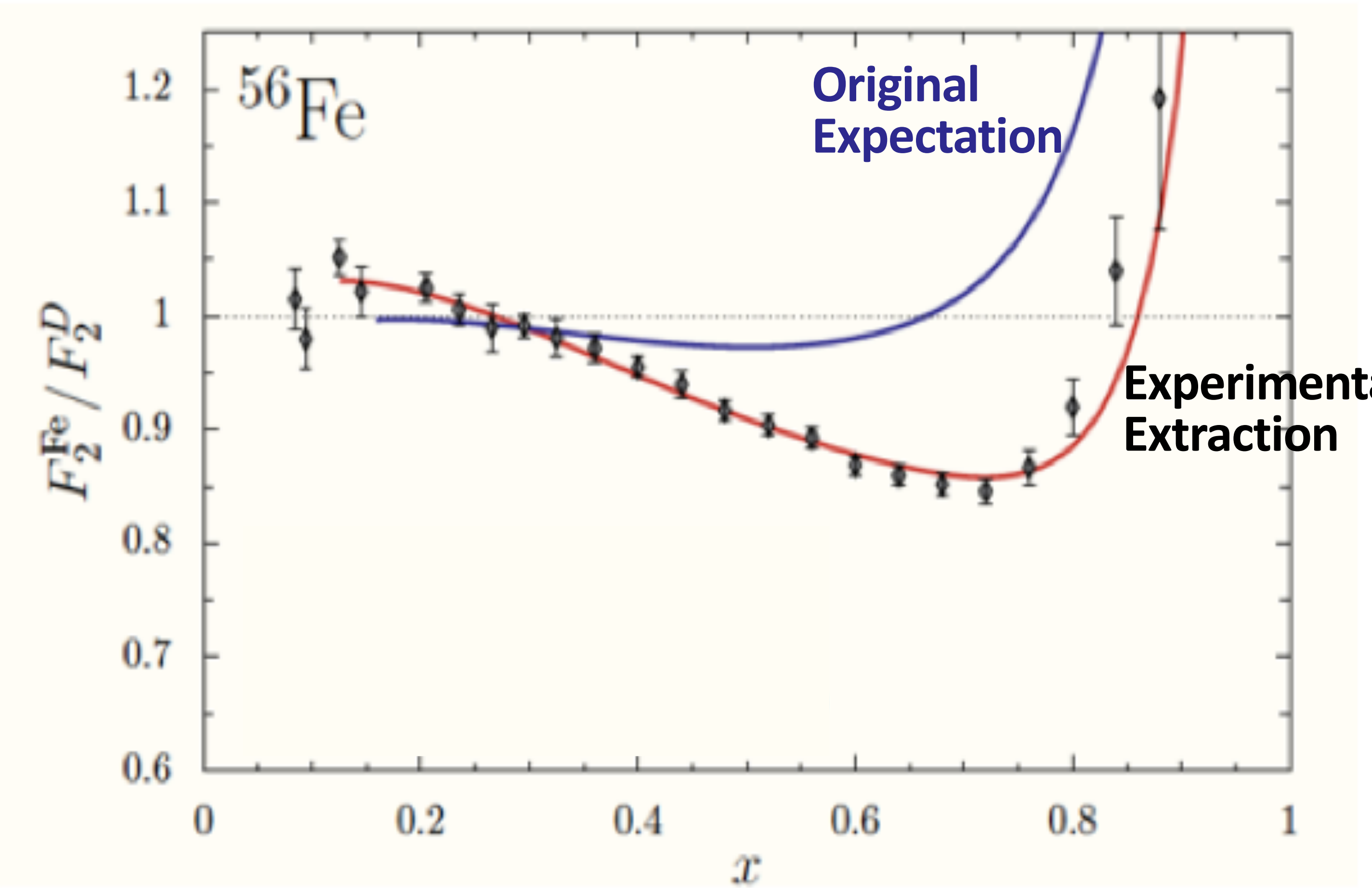


SRC play an important role across resolutions

EMC Effect: Quarks move "slower" in nuclei



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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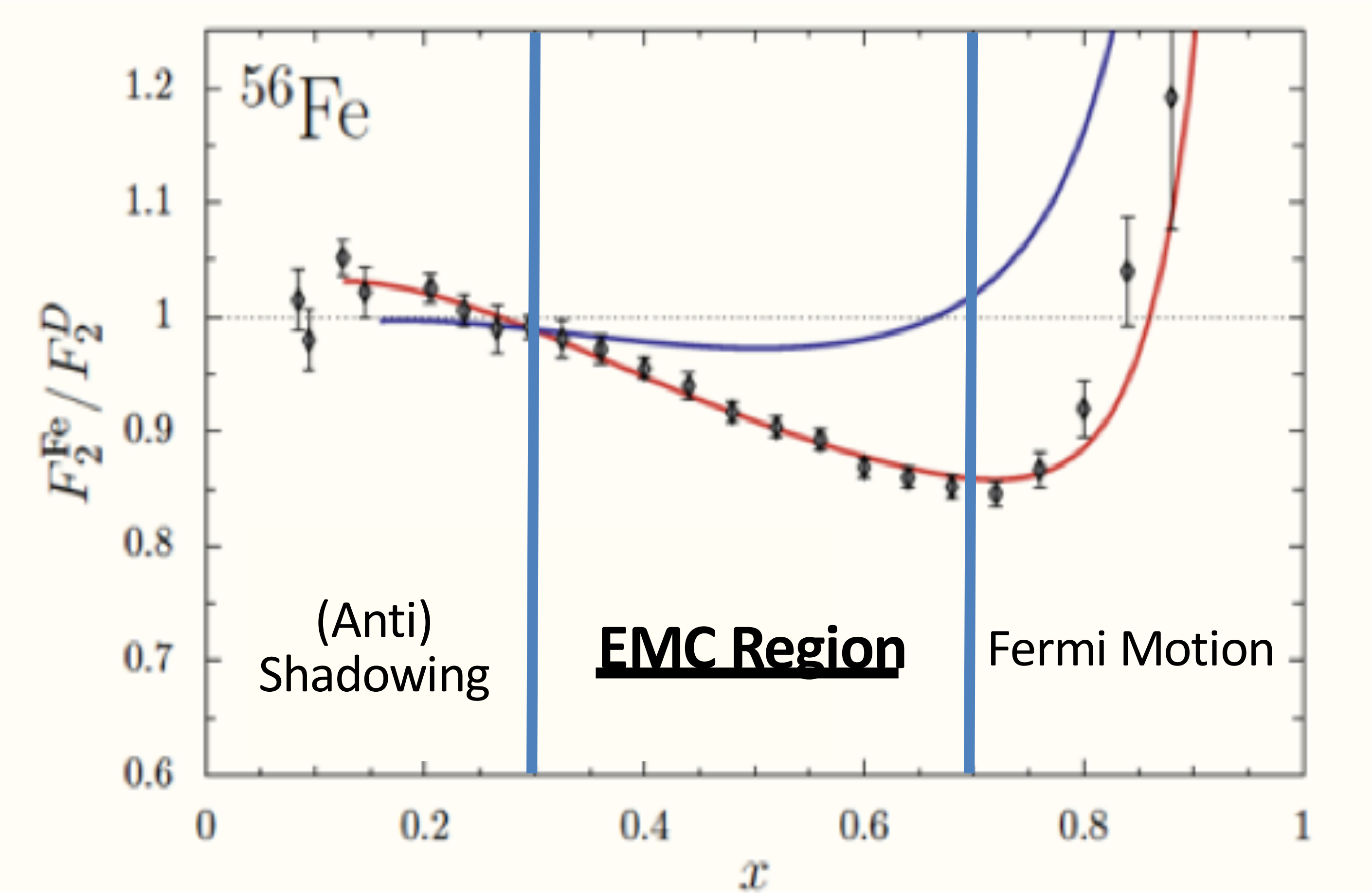

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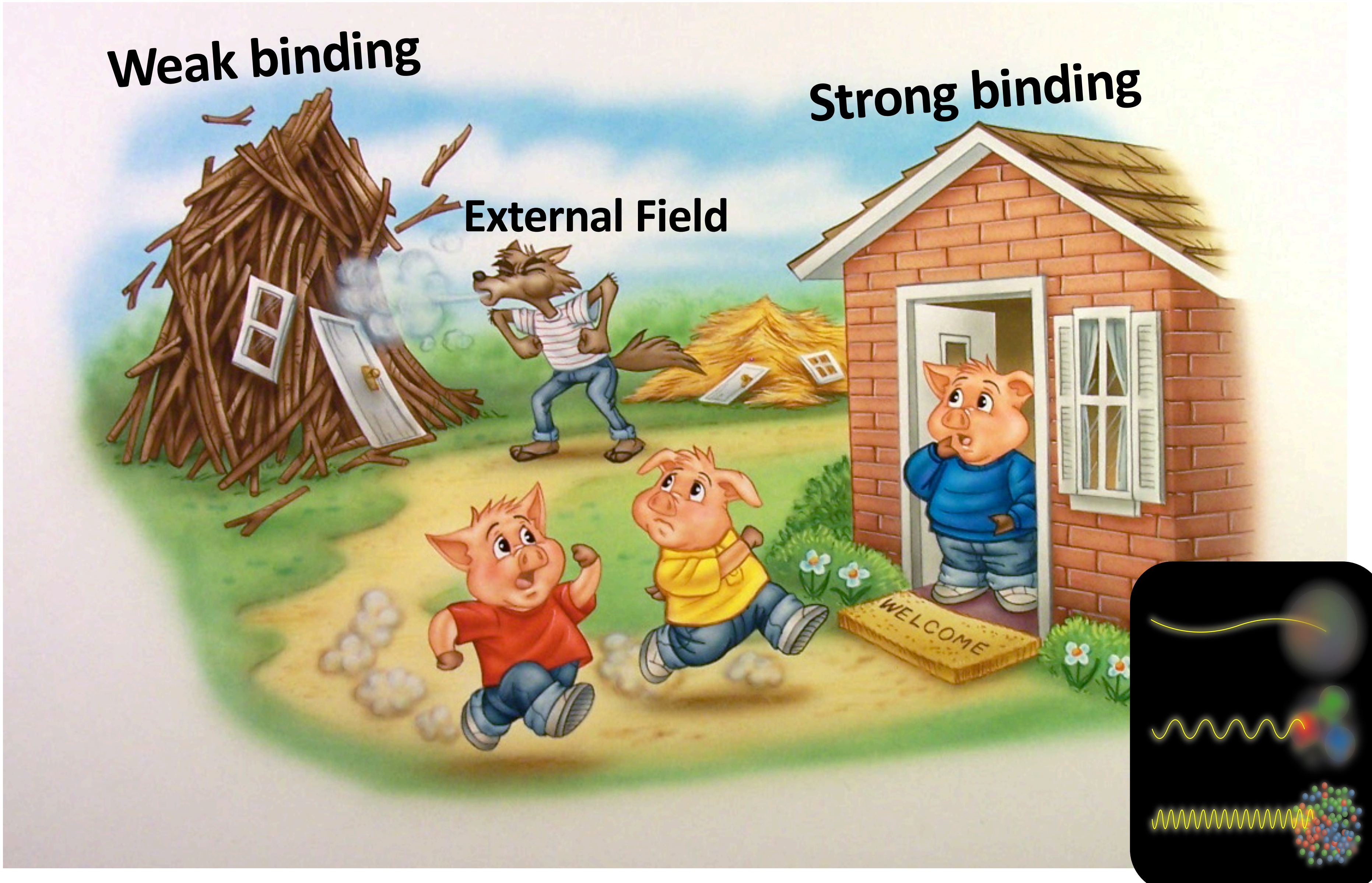
Nuclear / Parton Scale Separation



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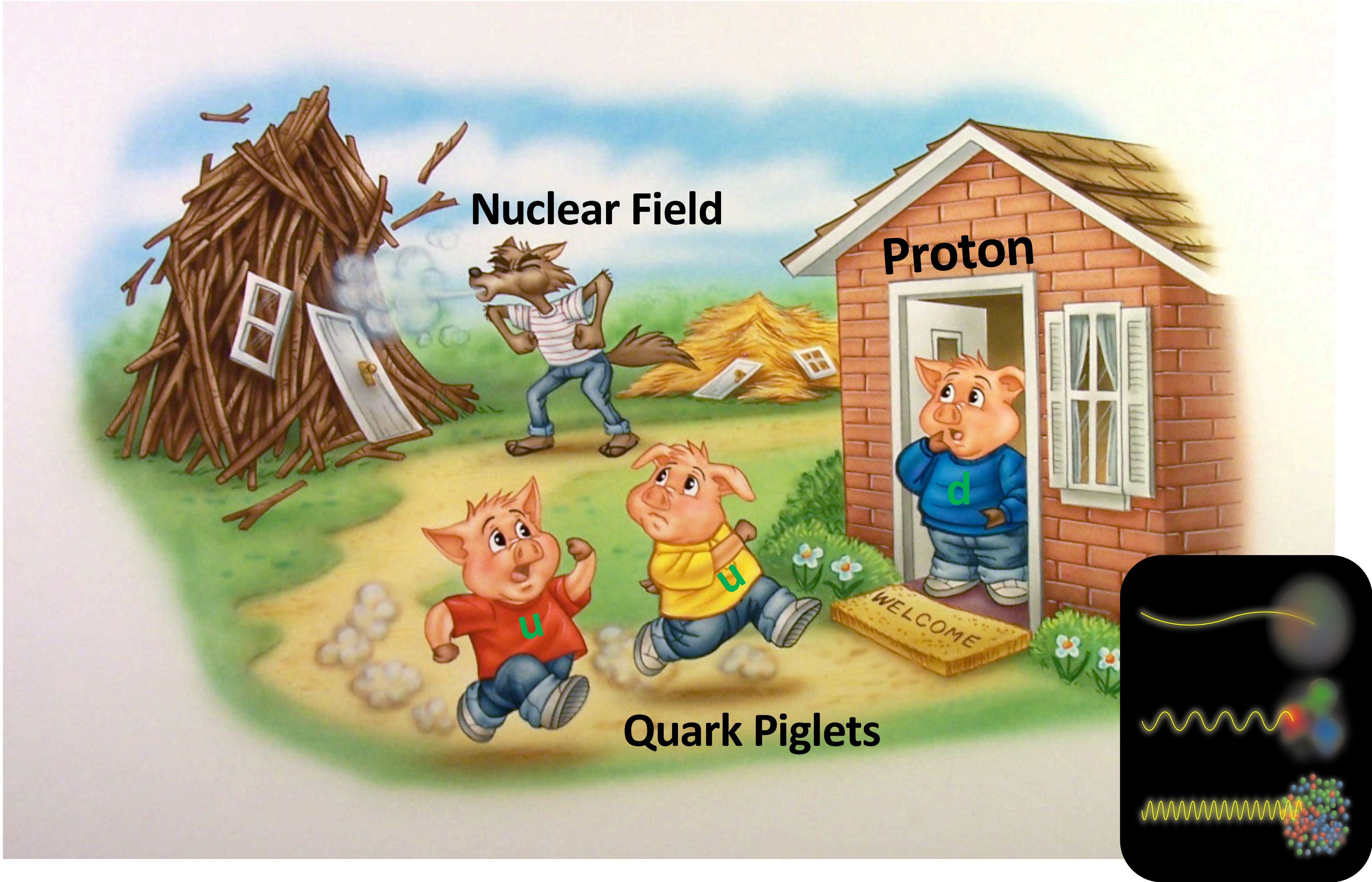
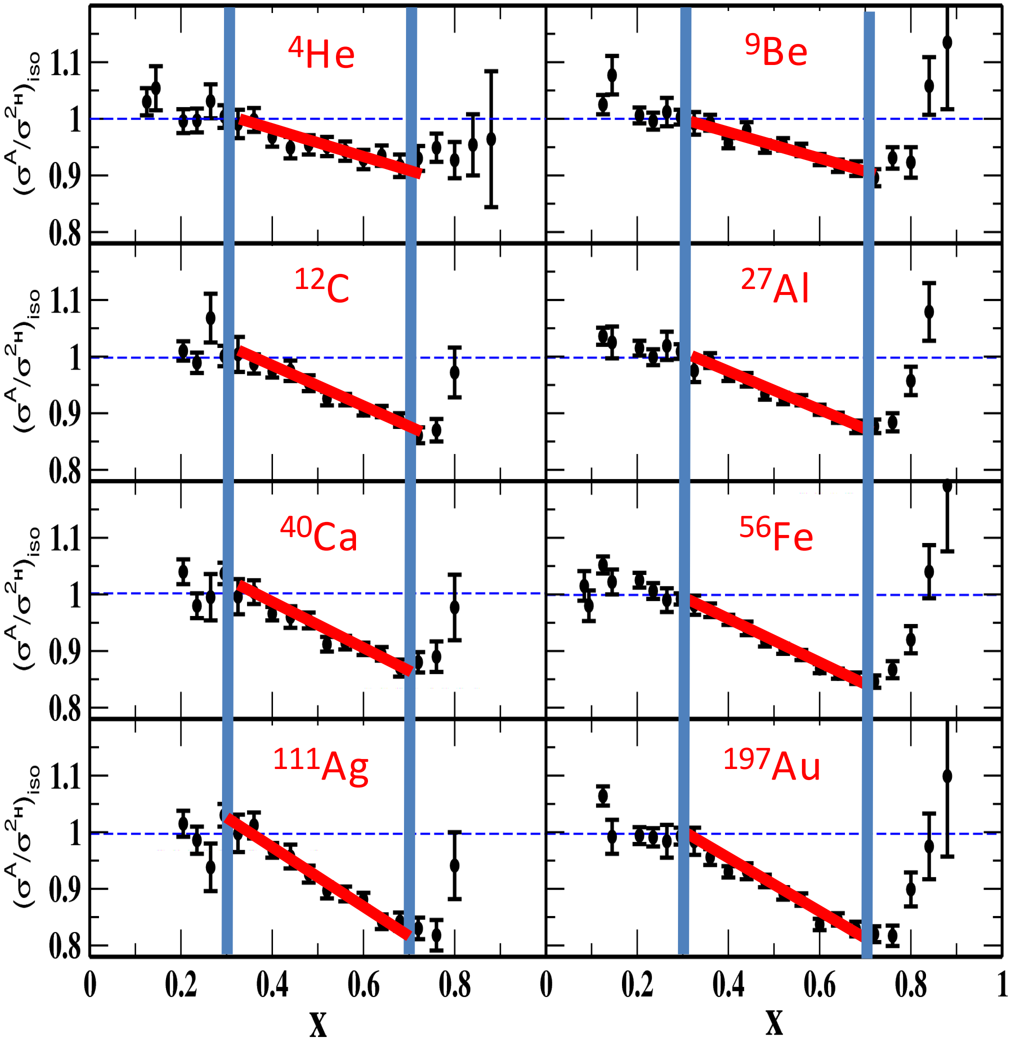


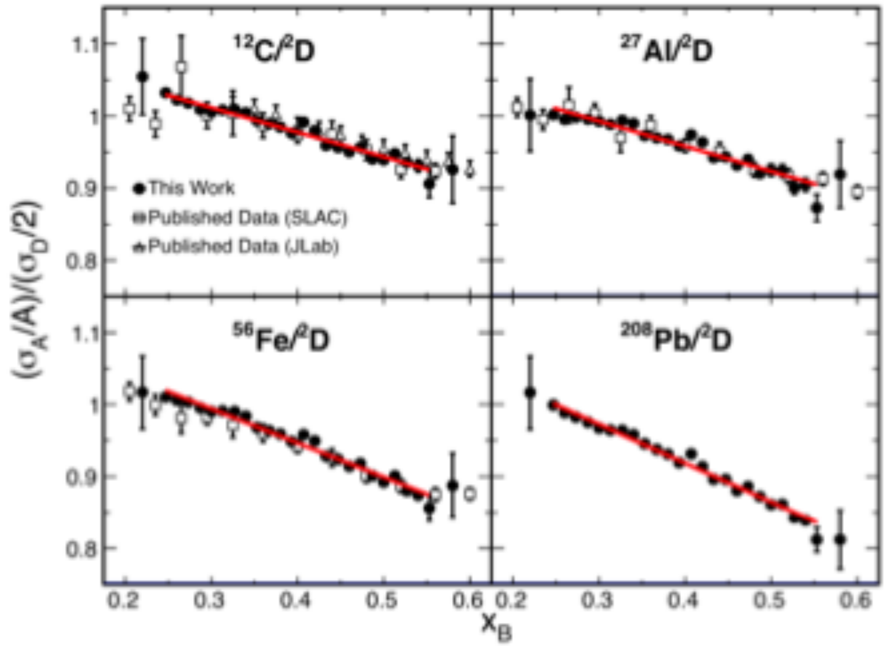
EMC Effect: Nuclear Effect



J. Gomez et al., Phys. Rev. D **49**, 4348 (1994).

SLAC (1994)

JLab (2018)



Schmookler, Duer, Schmidt, and Hen et al., submitted (2018)

EMC Effect: Nuclear Effect

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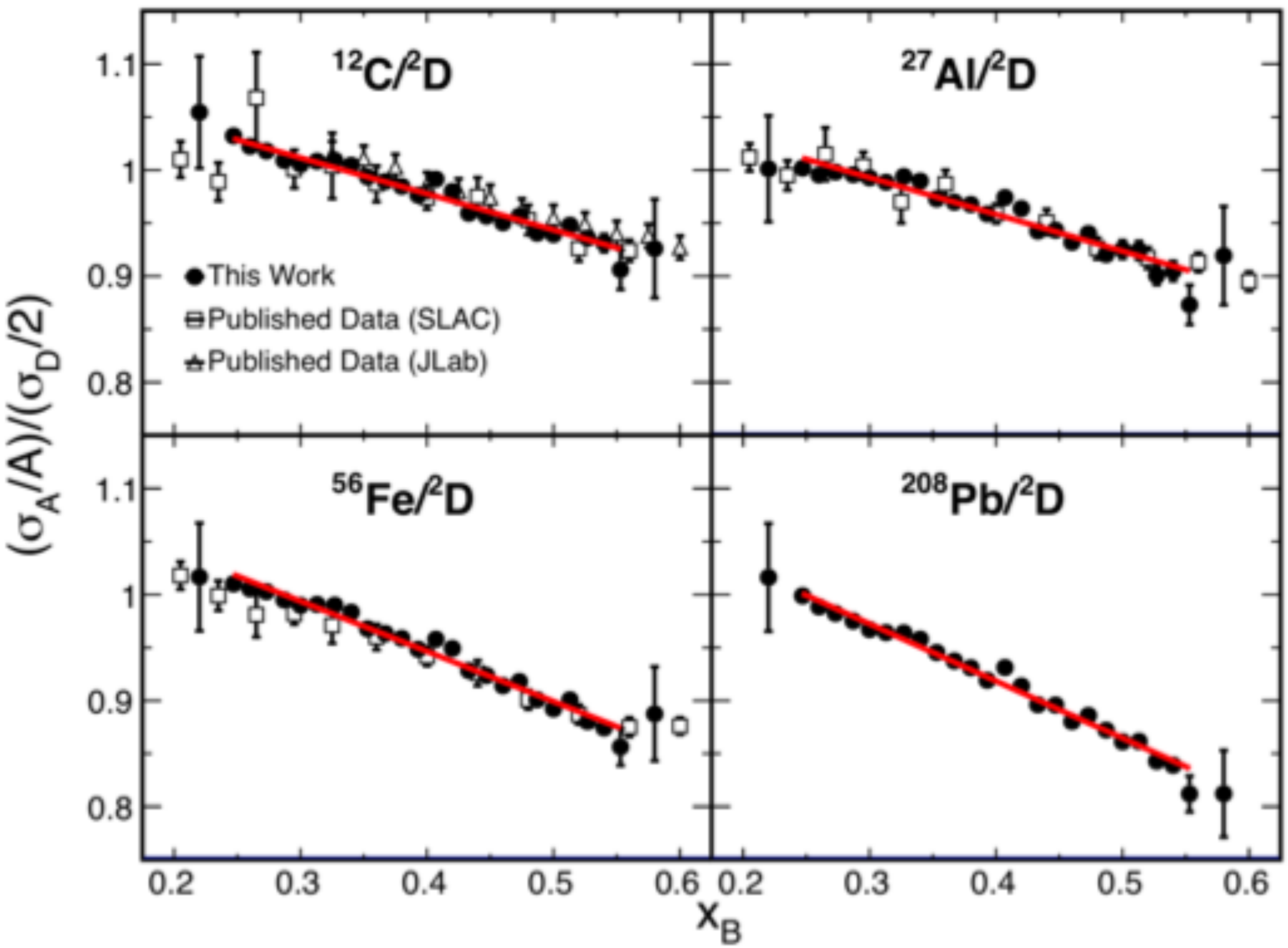

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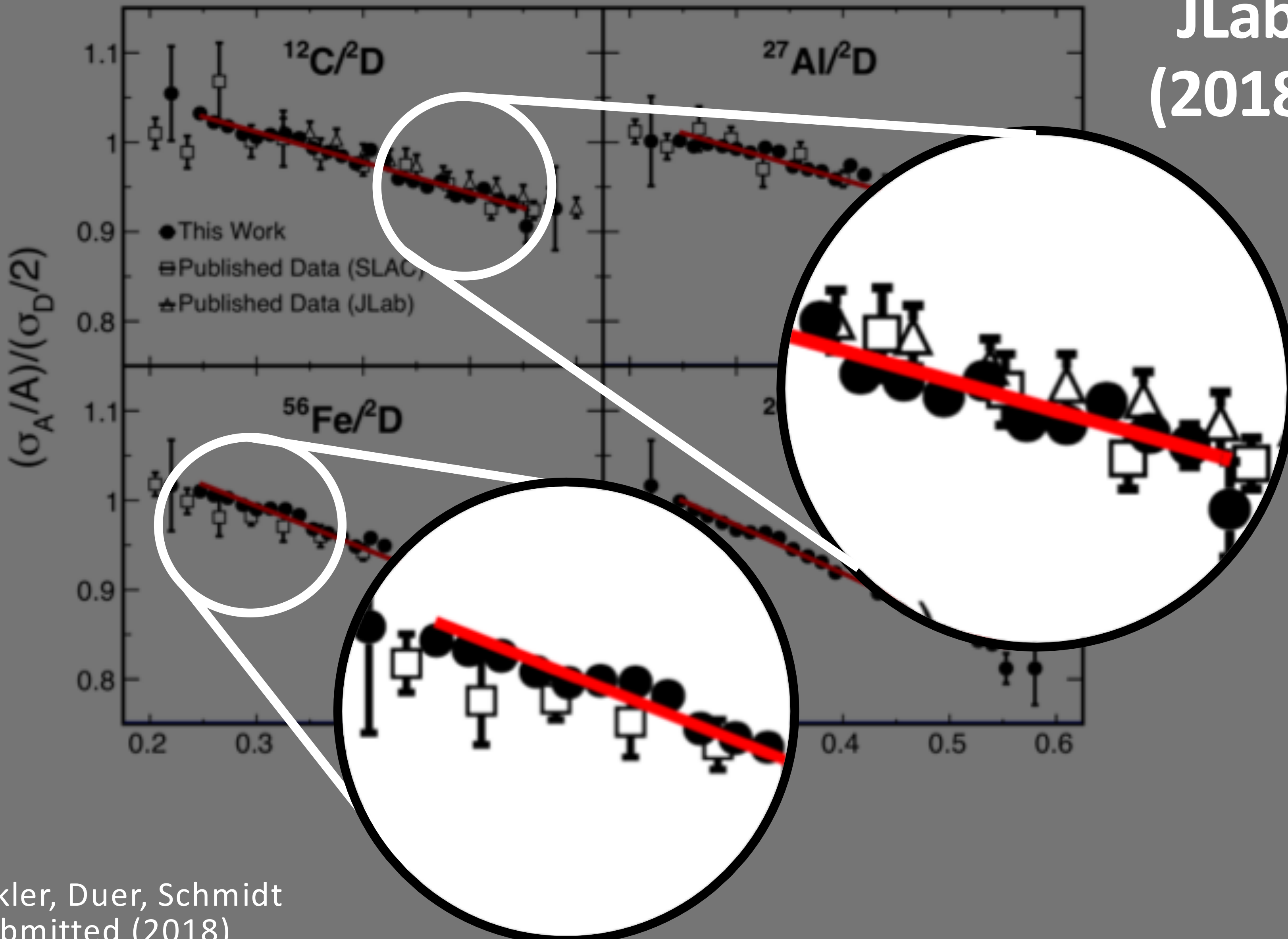

JLab (2018)

Schmookler, Duer, Schmidt et al., submitted (2018)

35 years, 1000 papers, 3 Ideas

1. Proper treatment of 'known' nuclear effects
   [explain some of the effect, up to $x \approx 0.5$]
   - 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.
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O. Hen et al., Rev. Mod. Phys. 89, 045002 (2017)

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

35 years, 1000 papers, 3 Ideas

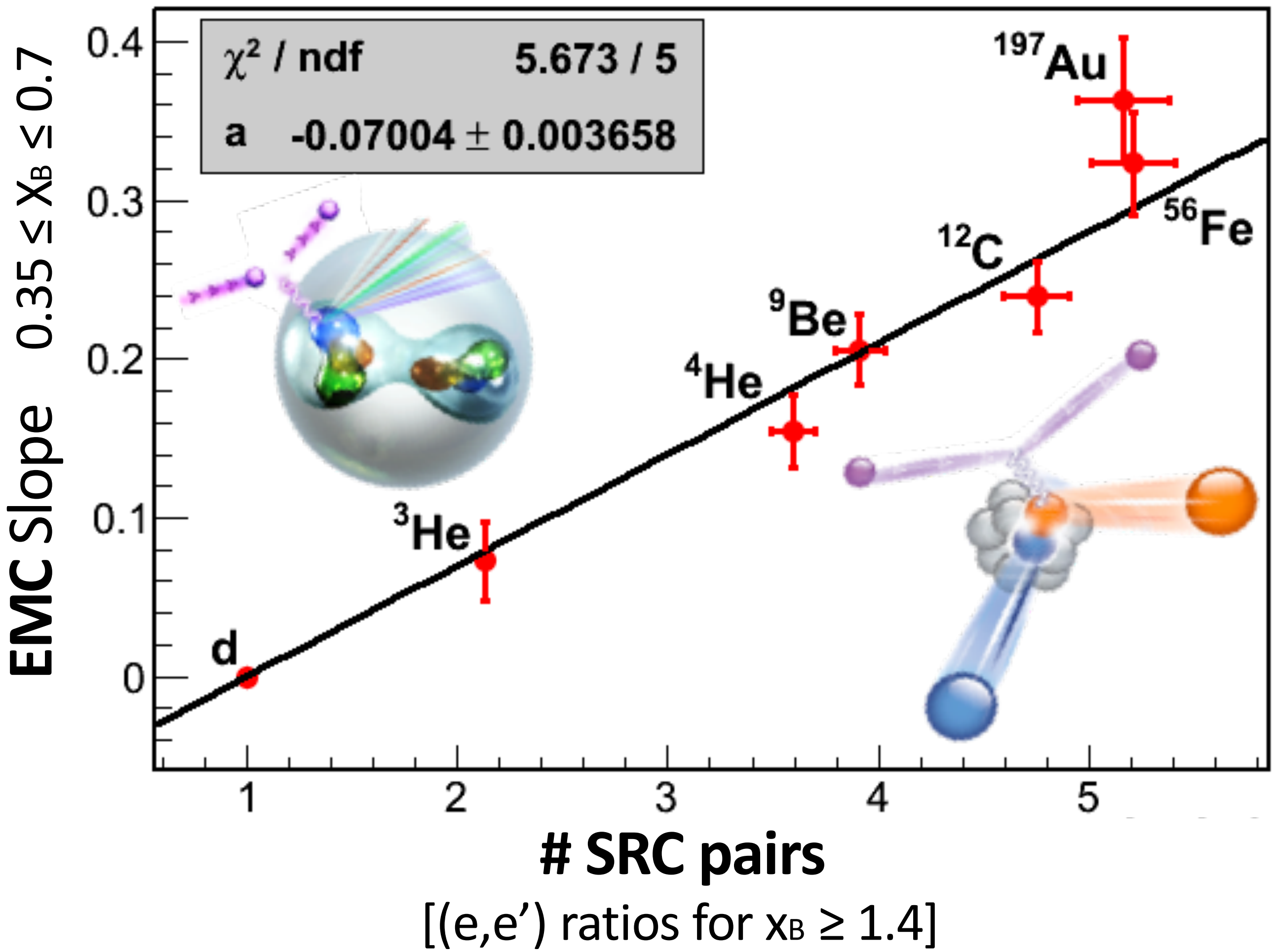
1. ~~Proper treatment of 'known' nuclear effects~~
   ~~[explain some of the effect, up to x≈0.5]~~
   - ~~Nuclear Binding and Fermi motion, Pions, Coulomb Field.~~
   - ~~**No modification of bound nucleon structure.**~~

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

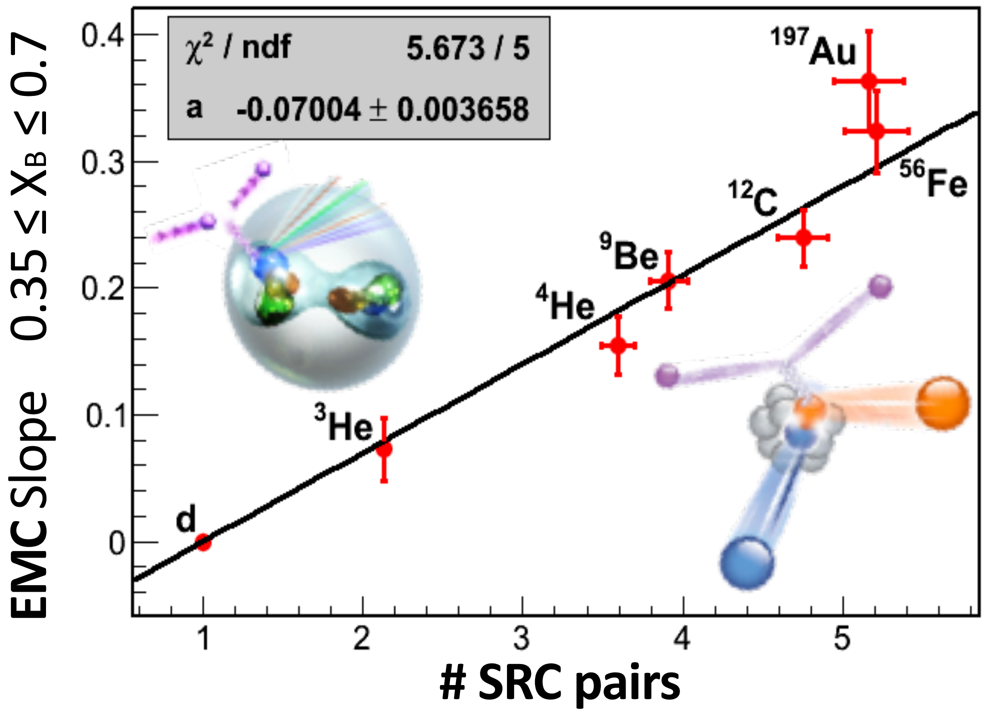
3. Bound Nucleons are 'larger' than free nucleons.
   - Larger confinement volume => slower quarks.
   - Mean-Field effect.
   - Momentum Independent.
   - **Static Modification.**

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

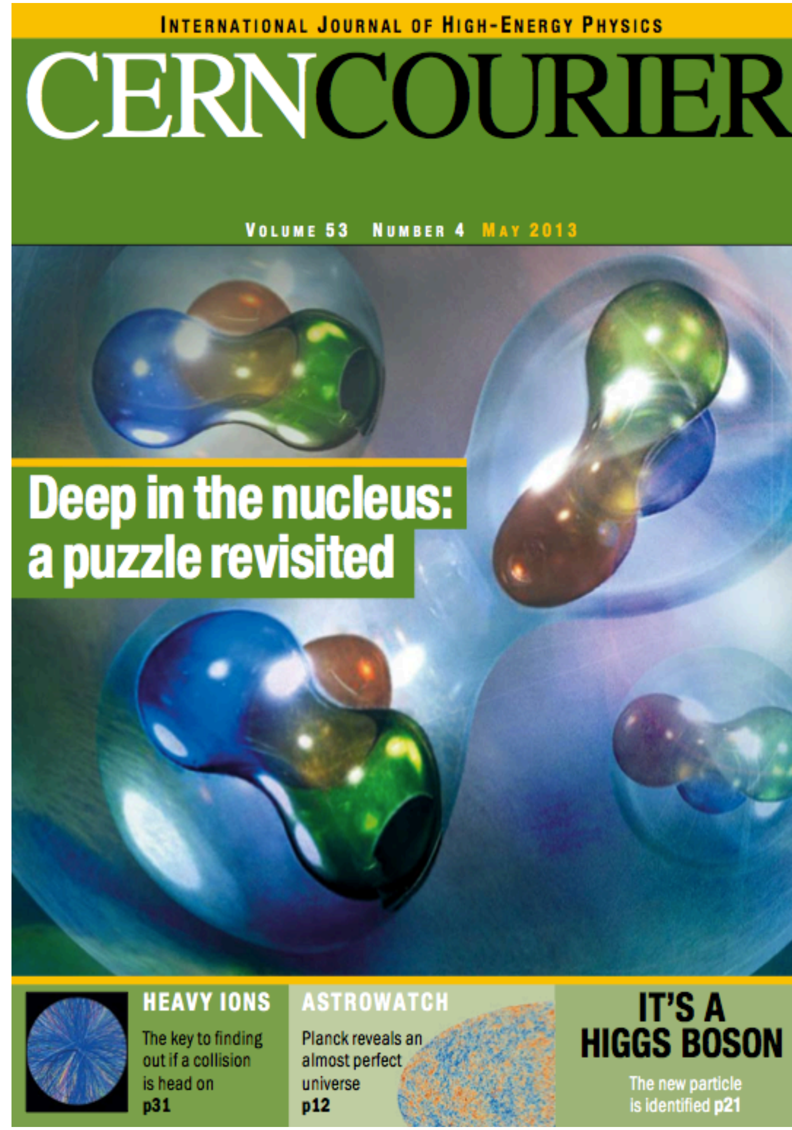
EMC - SRC Correlation



Hen et al., RMP (2017); Hen et al., IJMPE (2013); Hen et al., PRC (2012); Weinstein, Piasetzky, Higinbotham, Gomez, Hen, and Shneor, PRL (2011).

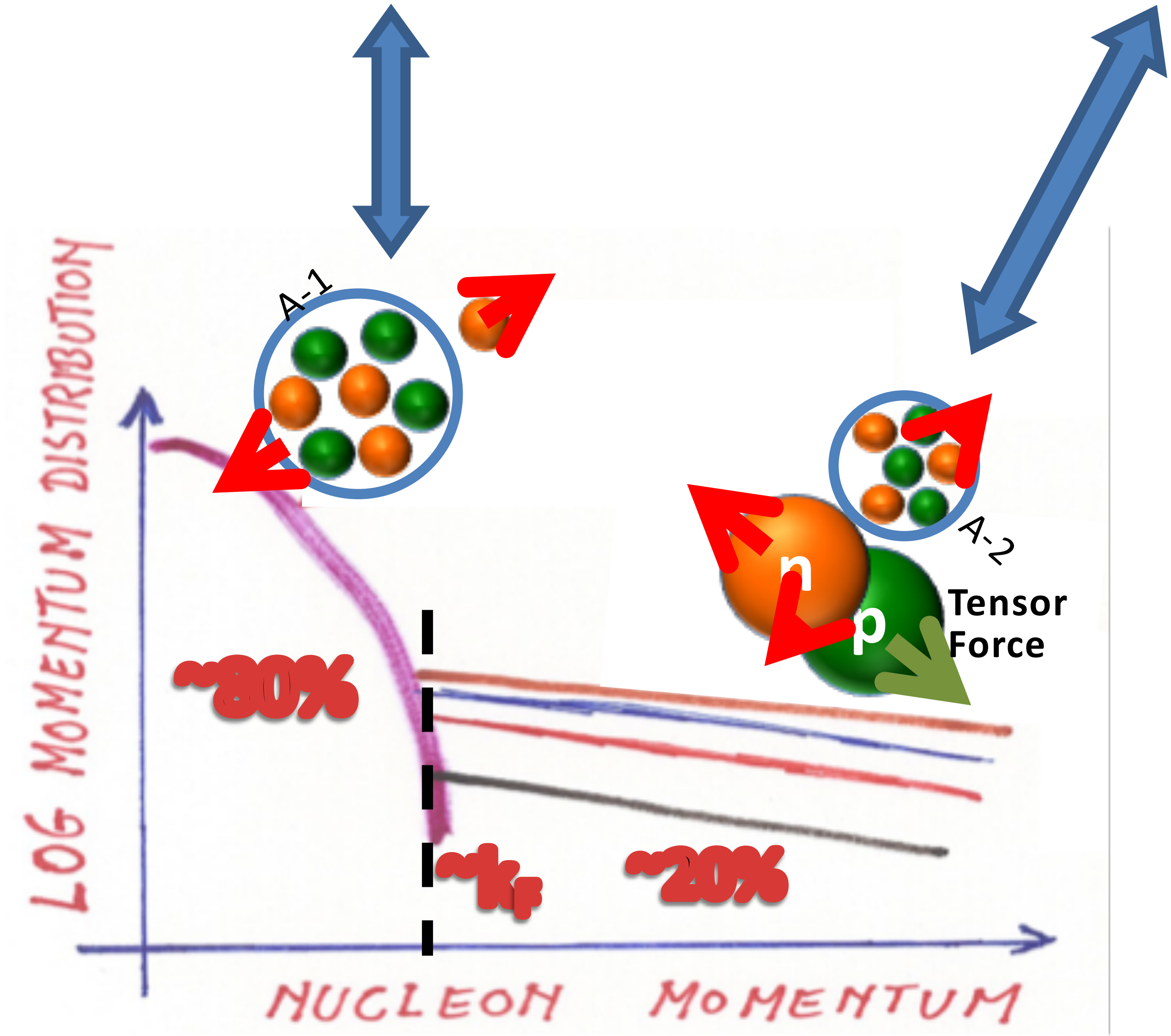


[(e,e') ratios for $x_B \geq 1.4$]



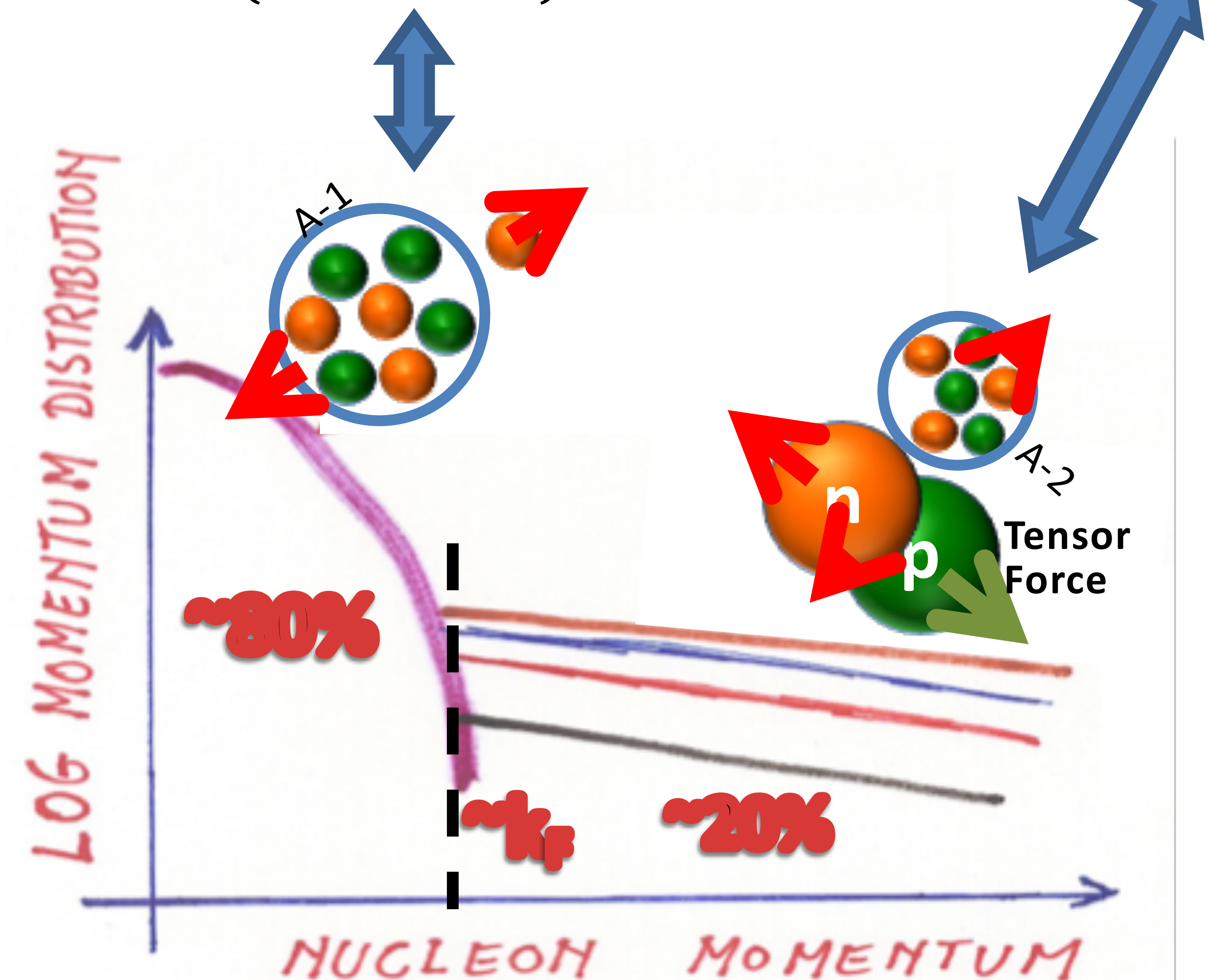
Higinbotham, Miller, **Hen**, and Rith. CERN Cour. 53N4, 35 (2013)

Bound = 'quasi Free' + Modified SRCs



Bound = 'quasi Free' + Modified SRCs

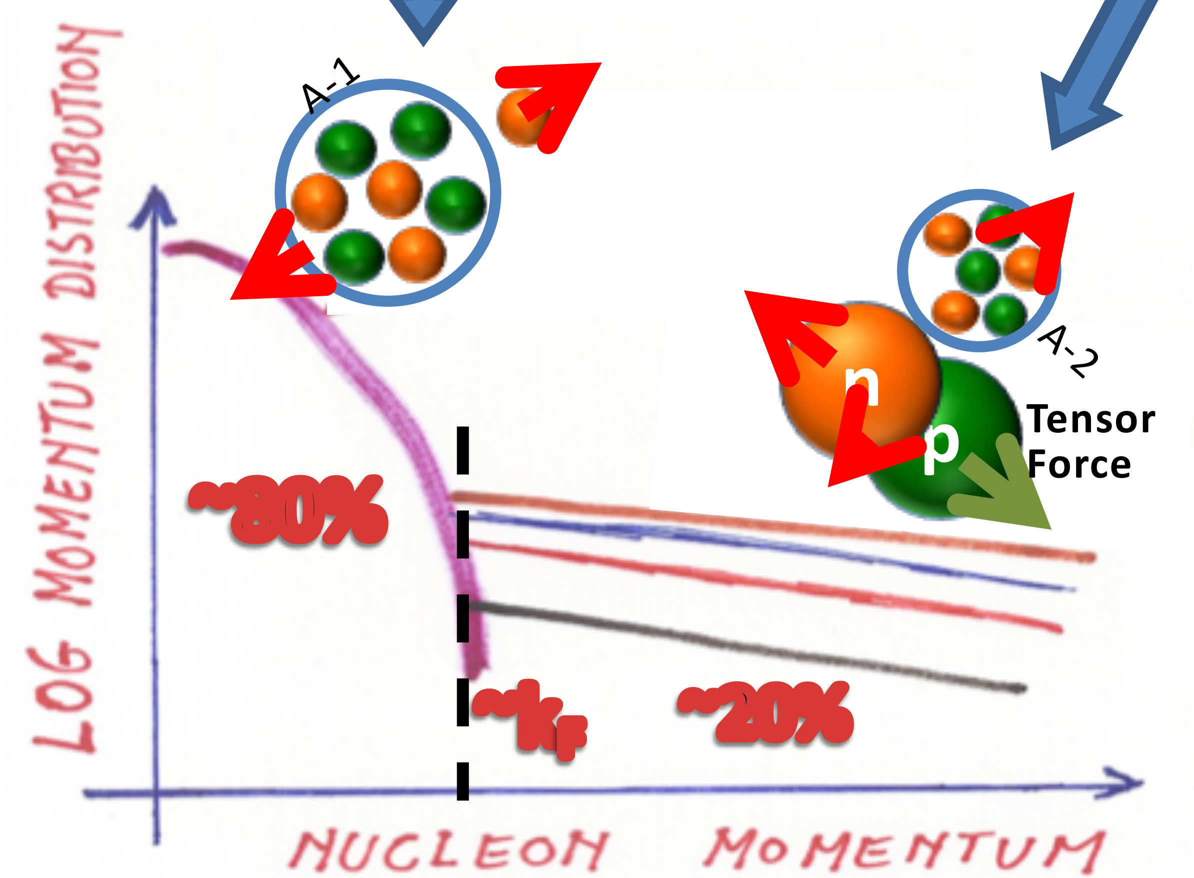
$$F_2^A = \begin{matrix}(Z - n_{SRC}^A)F_2^p \\ +(N - n_{SRC}^A)F_2^n\end{matrix} + n_{SRC}^A\left(F_2^{p*} + F_2^{n*}\right)$$



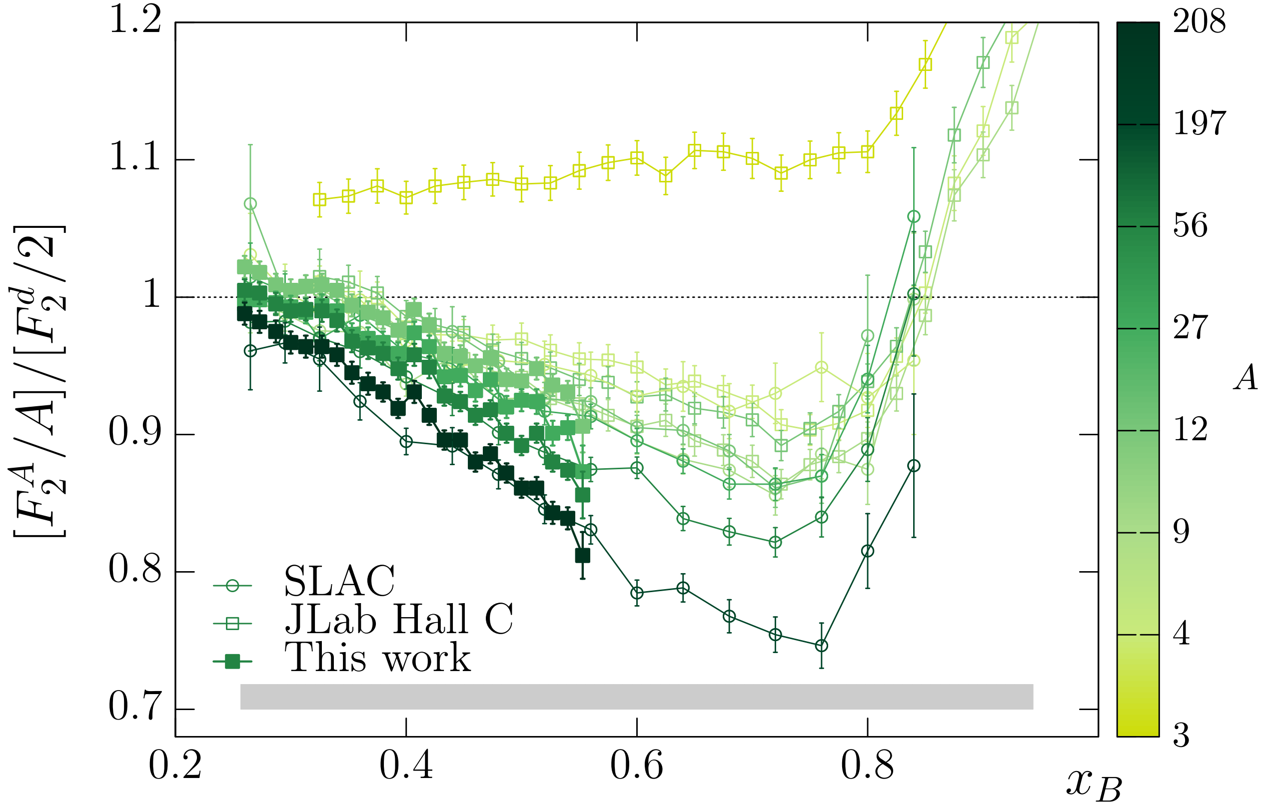
Bound = 'quasi Free' + Modified SRCs

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

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



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

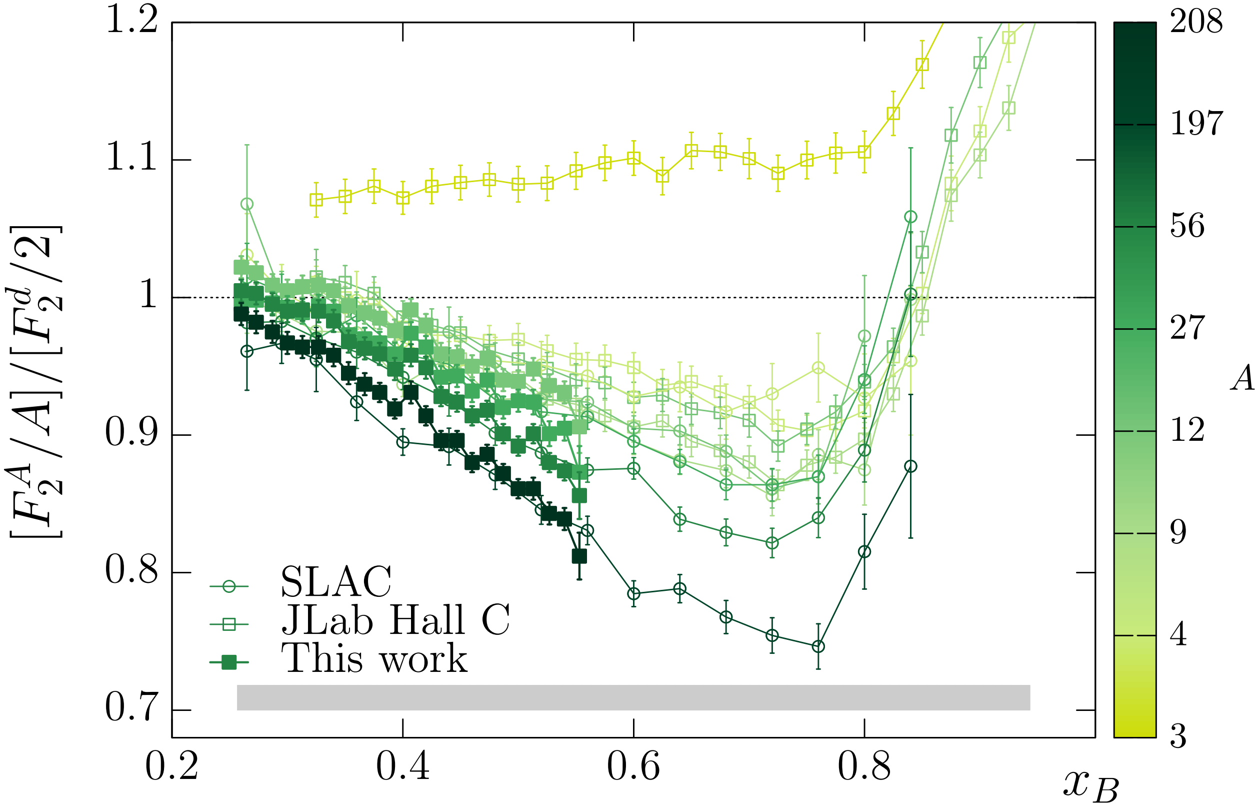


Schmookler, Duer, and Schmidt et al., submitted (2018)

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

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

A Dependent **Universal?** **A Dependent**



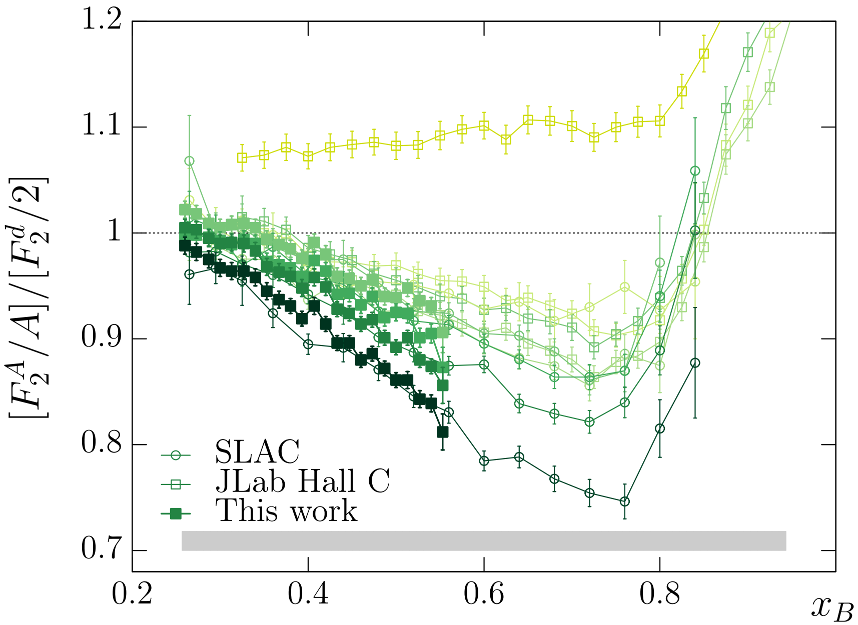
Schmookler, Duer, and Schmidt et al., submitted (2018)

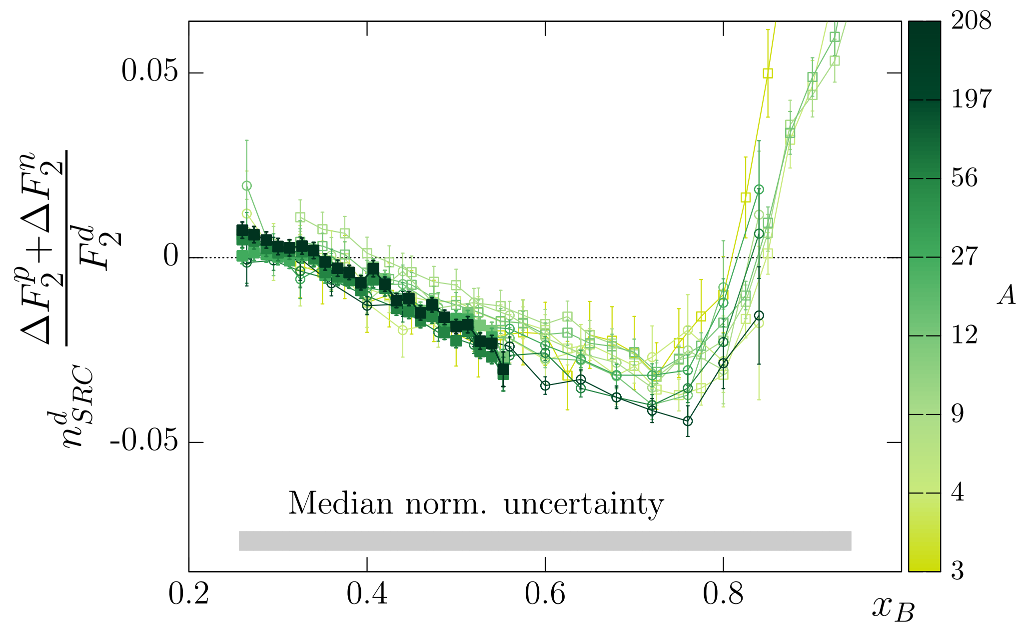
$\Delta F_2^N = F_2^{N*} - F_2^N$

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

A Dependent **A Dependent**

Universal!

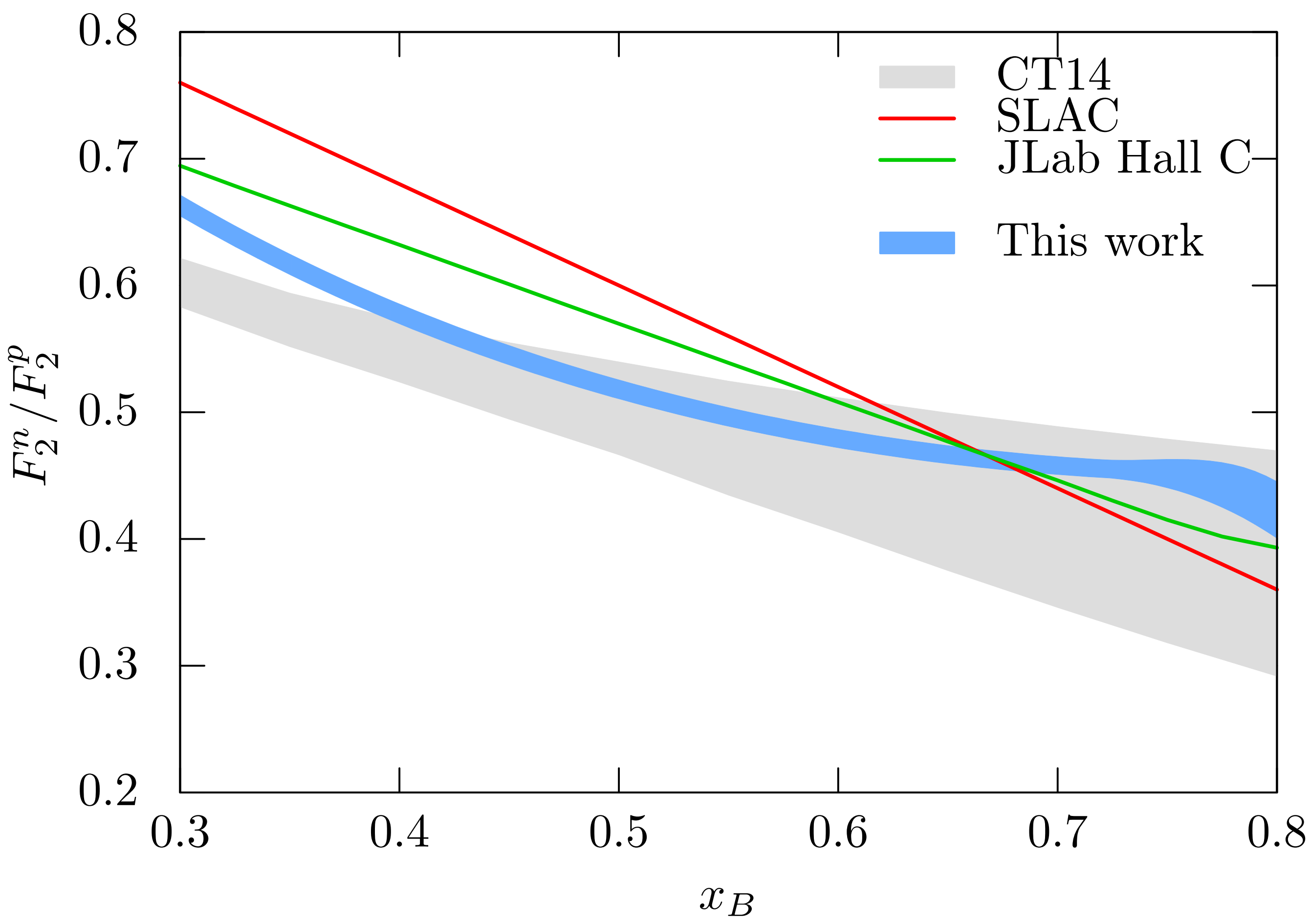




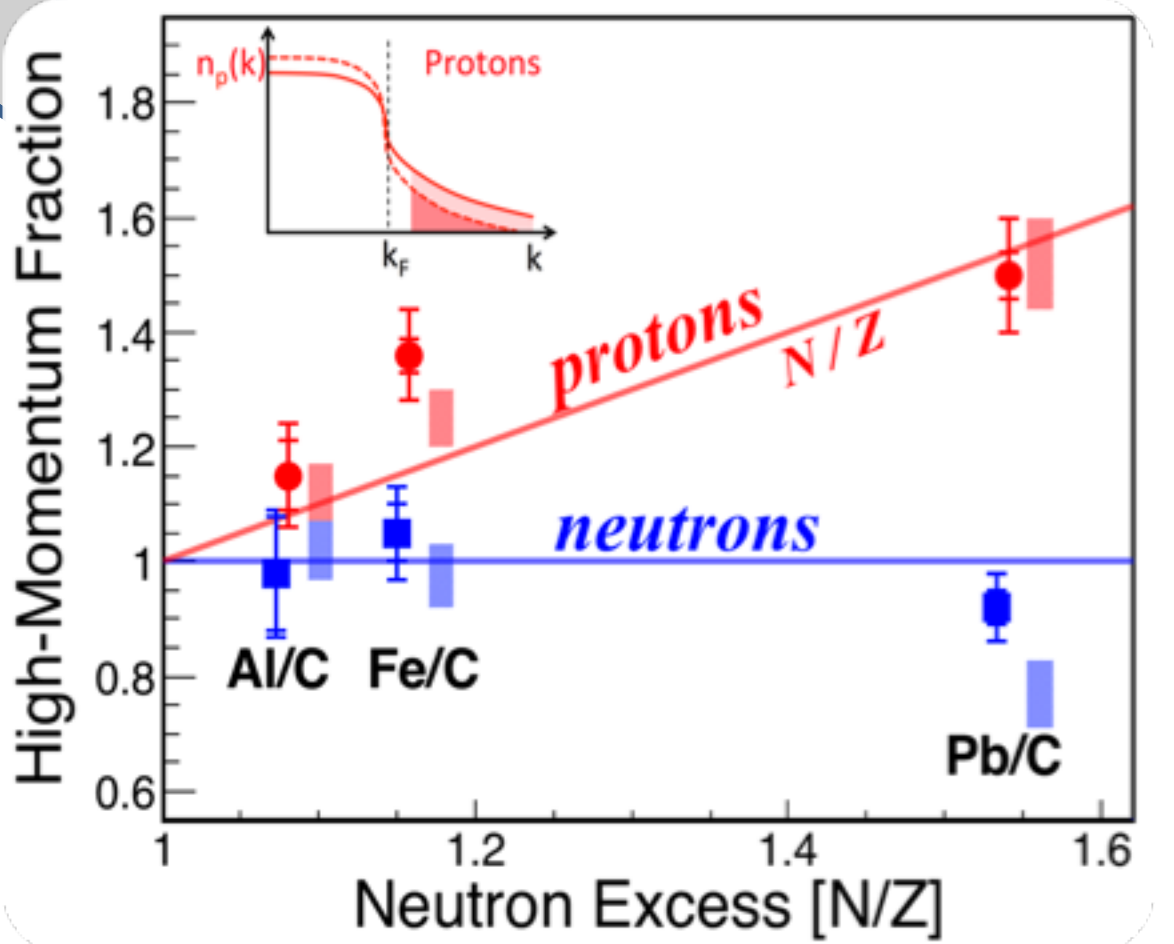
Schmookler, Duer, and Schmidt et al., submitted (2018)

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

Free Neutron Extraction

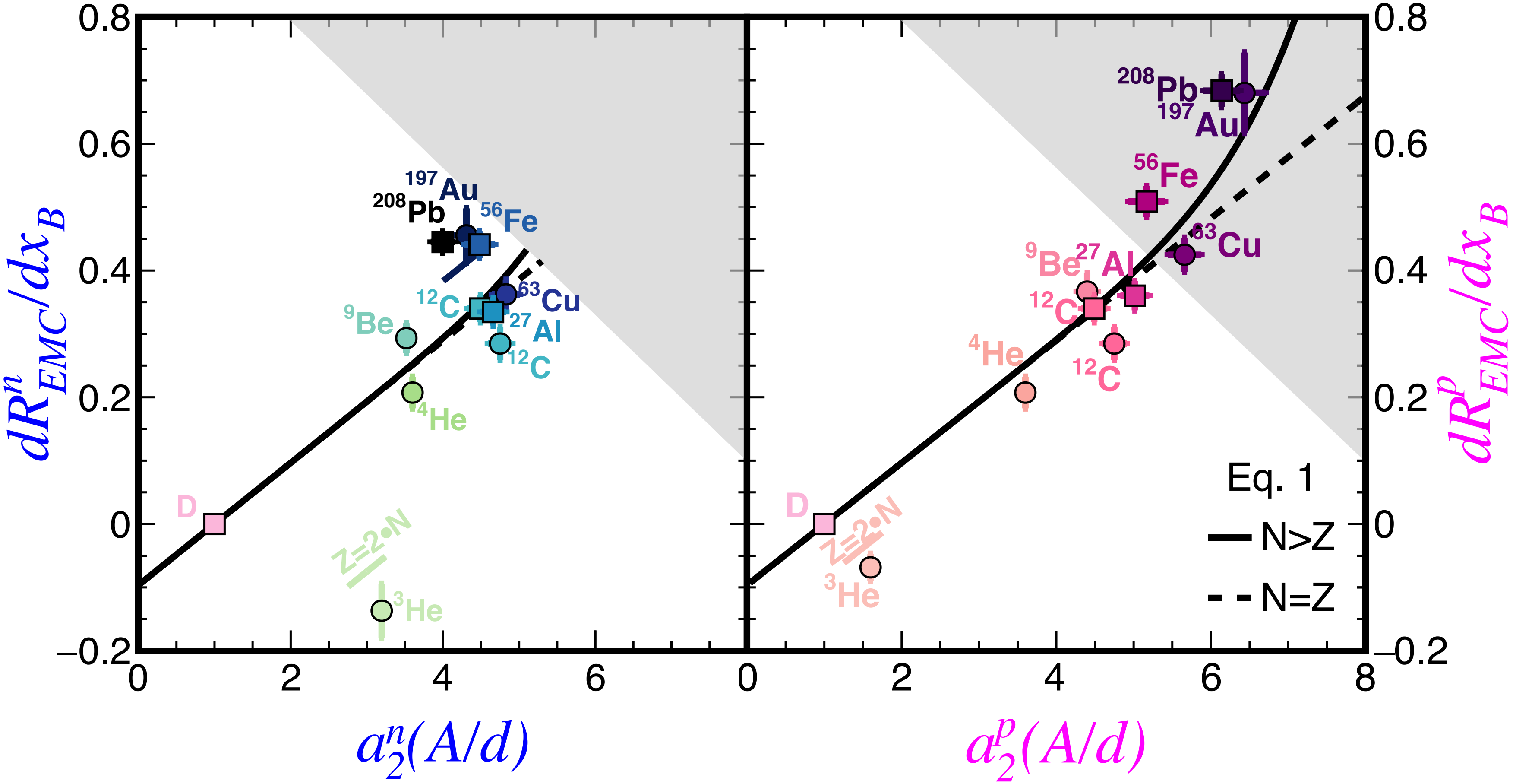


’Prediction’:
EMC effect should
saturate for neutrons
and grow for protons



Predicting the EMC-SRC Correlation

B. Schmookler



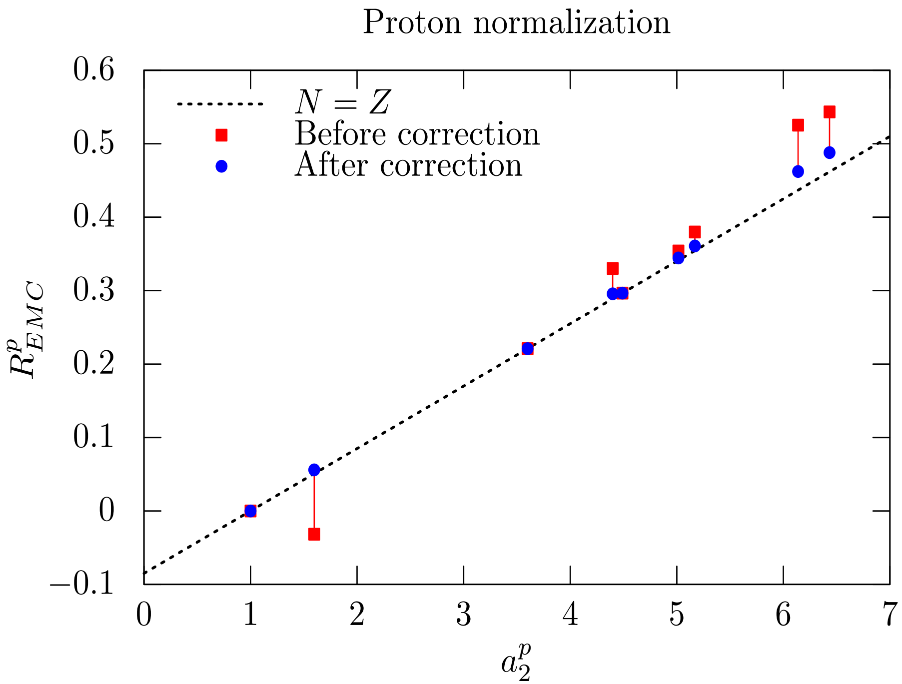
Schmookler, Duer, and Schmidt et al., submitted (2018)

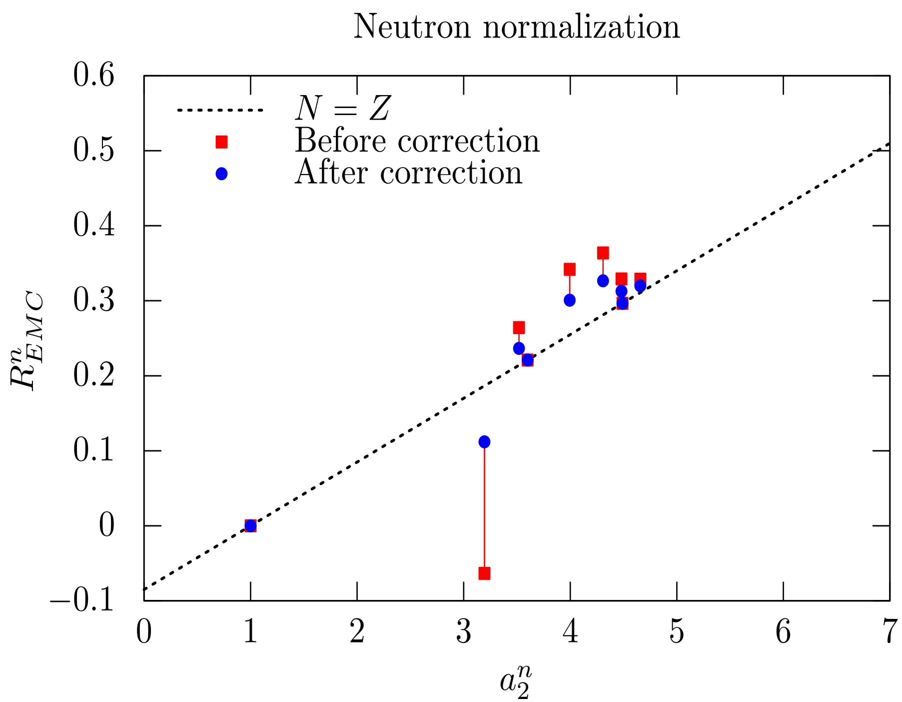
Self-consistent Isoscalar corrections

$$ISO = \frac{F_2^n + F_2^p}{Z \cdot F_2^n + N \cdot F_2^p}$$

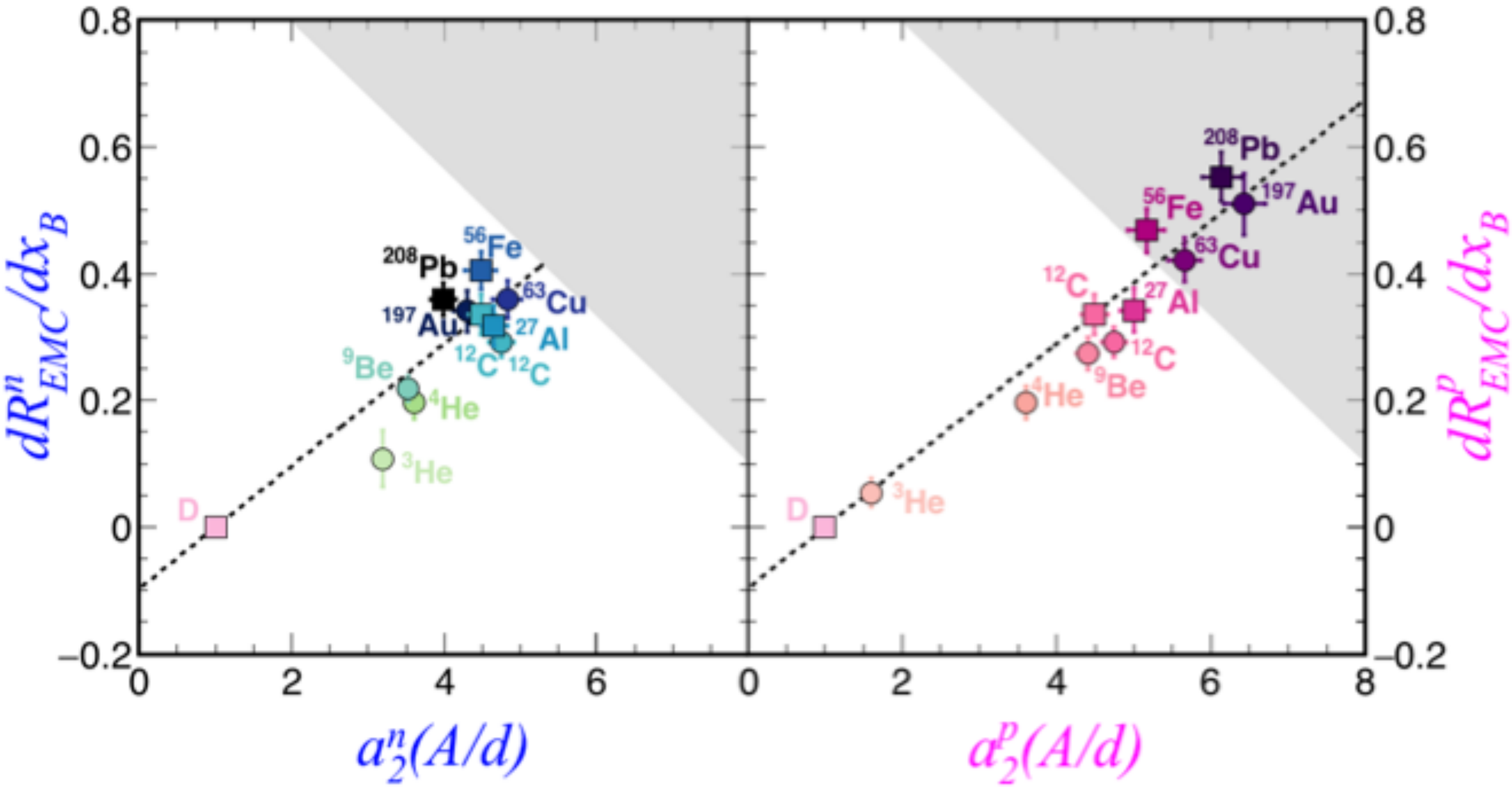
Model Prediction before & after isoscalar corrections

Closer to the N=Z prediction but not exactly…



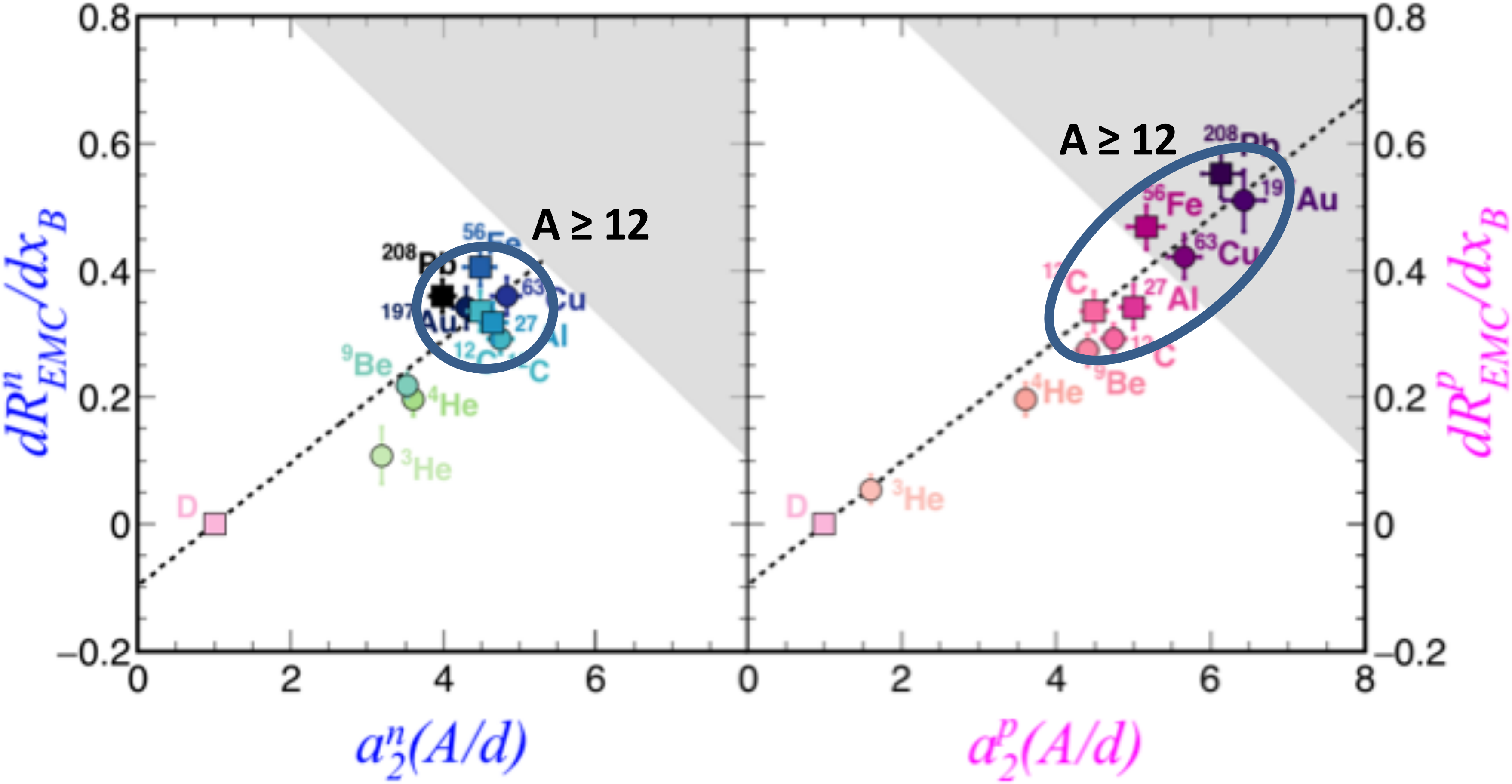


Neutrons Saturate, Protons Grow



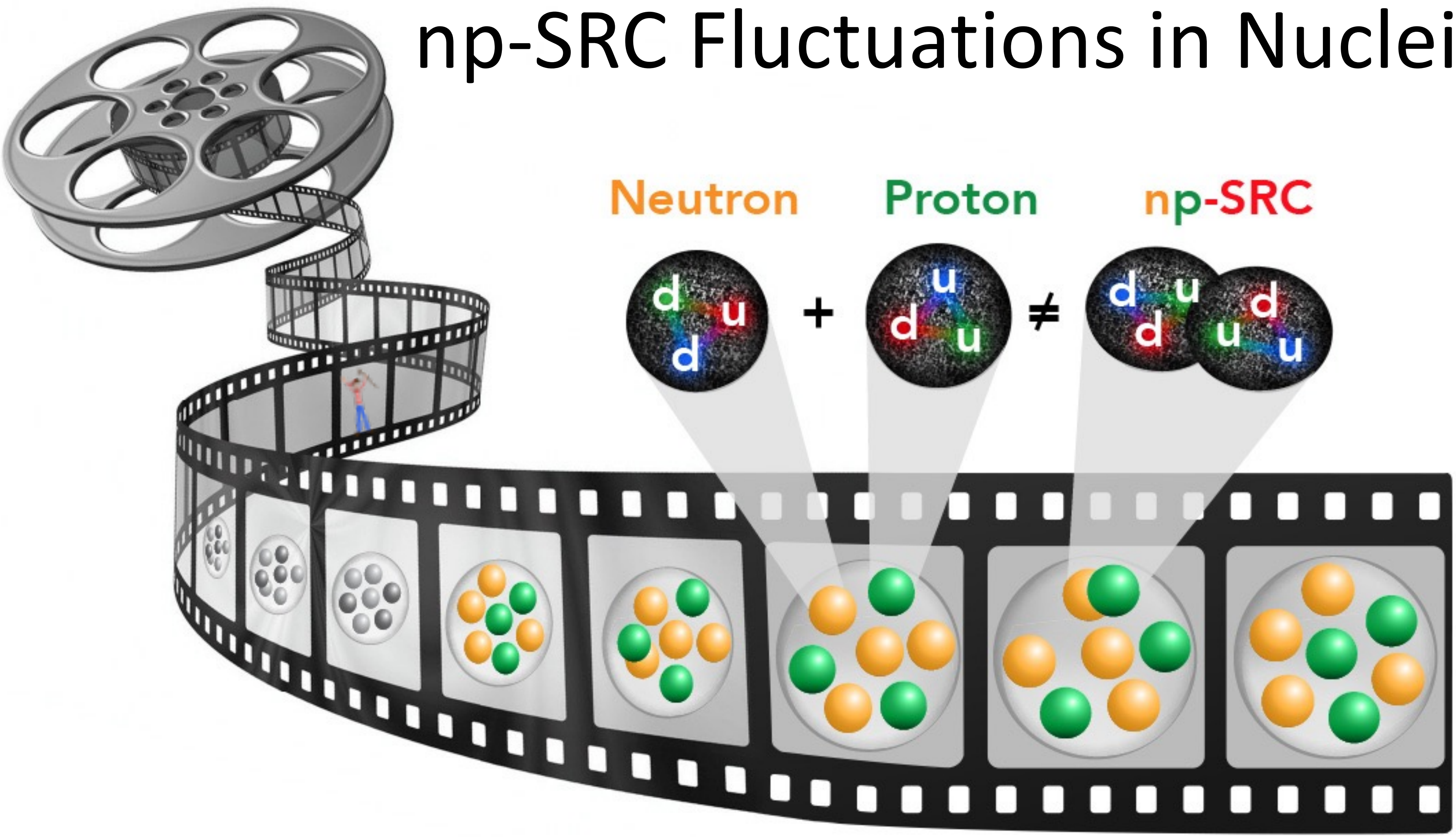
Schmookler, Duer, and Schmidt et al., submitted (2018)

Neutrons Saturate, Protons Grow



Schmookler, Duer, and Schmidt et al., submitted (2018)

np-SRC Fluctuations in Nuclei



Short-Range Correlations

Or Hen (MIT)

- (new) Exp. results
- (new) Implications
- **(new) Theory results**

INT Workshop on Fundamental Physics with Electroweak Probes of Light Nuclei, July 2nd 2018.

Requirements from theories of SRCs

Requirements from theories of SRCs

Reproduce the data.

Requirements from theories of SRCs

Reproduce *all features* of the data:

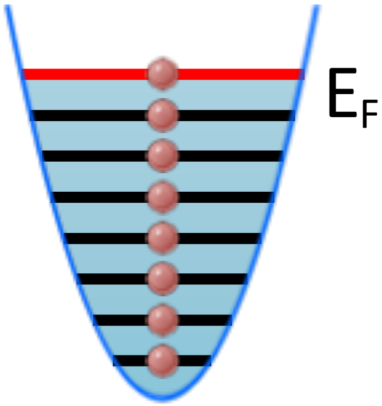
- A-Independence of gross SRC features
- Asymmetry dependence of p/n correlations

- Q^2 independence of observables
- P_{miss} dependence of observables

Factorized Theory Advances

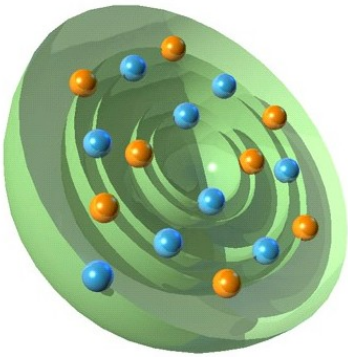
Scale Separation in Effective Theories

Fermi Gas Model

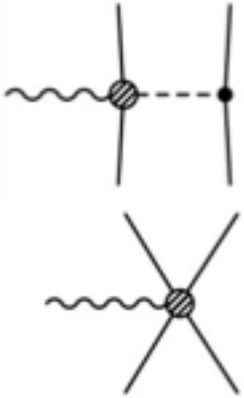


Liquid Drop Model

Shell Model



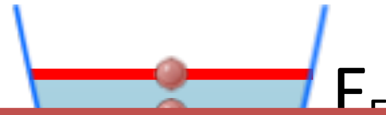
Chiral Perturbation Theory*



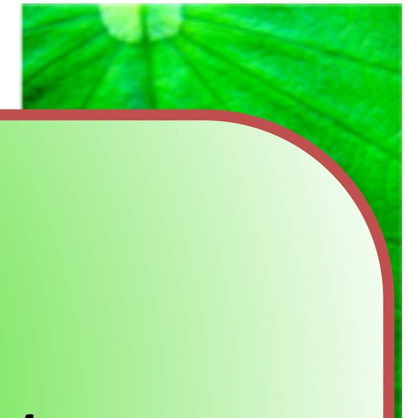
* Should converge to exact solution

Scale Separation in Effective Theories

Fermi



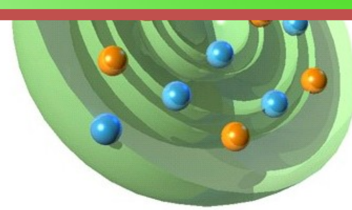
Liquid



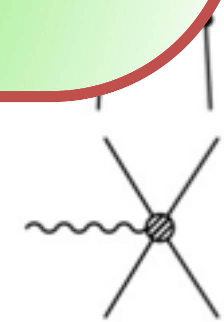
Common idea:

Scale separation of *long* and *short* range dynamics

Model



Perturbation Theory*

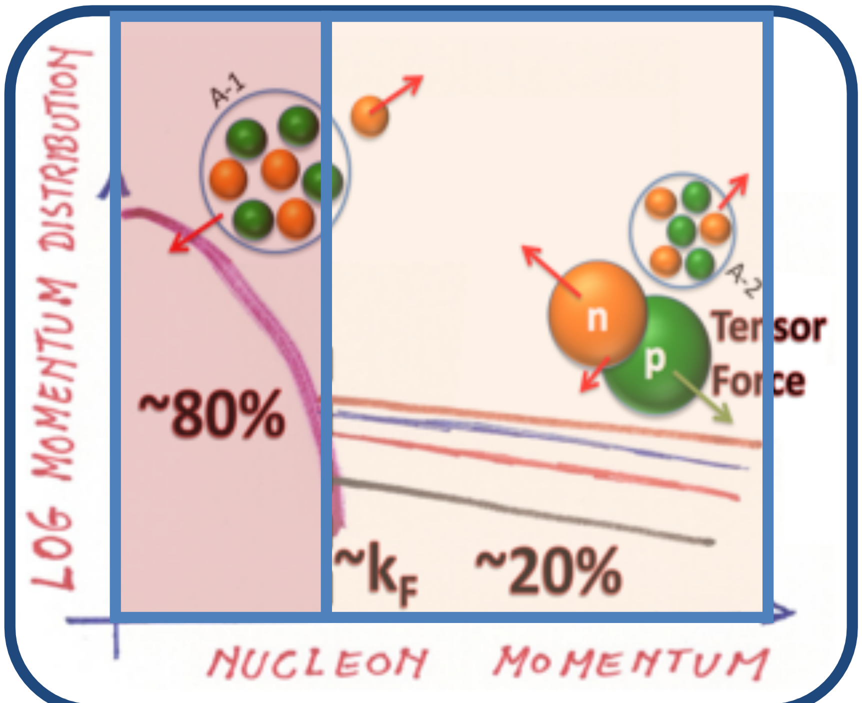


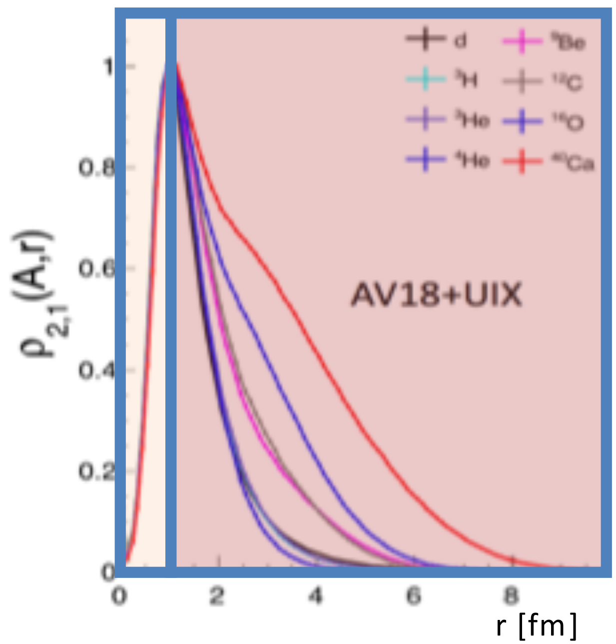
* Should converge to exact solution

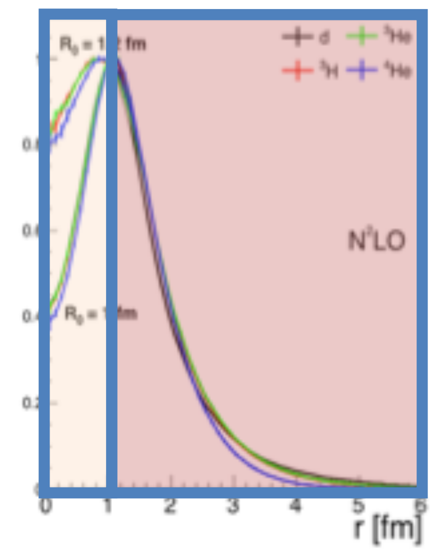
SRCs in Momentum Densities

Can we formulate a universal description of SRC (both coordinate and momentum space) without relying on many-body calculations? (YES)

Can we use it to confront theory and experiments? (YES)







Short-Distance Factorization

1. Factorized ansatz for the short-distance (high-momentum) part of the many-body wave function:

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_{\alpha} \varphi_{\alpha}(\boldsymbol{r}_{ij}) A^{\alpha}_{ij}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}\}_{k\neq ij})$$

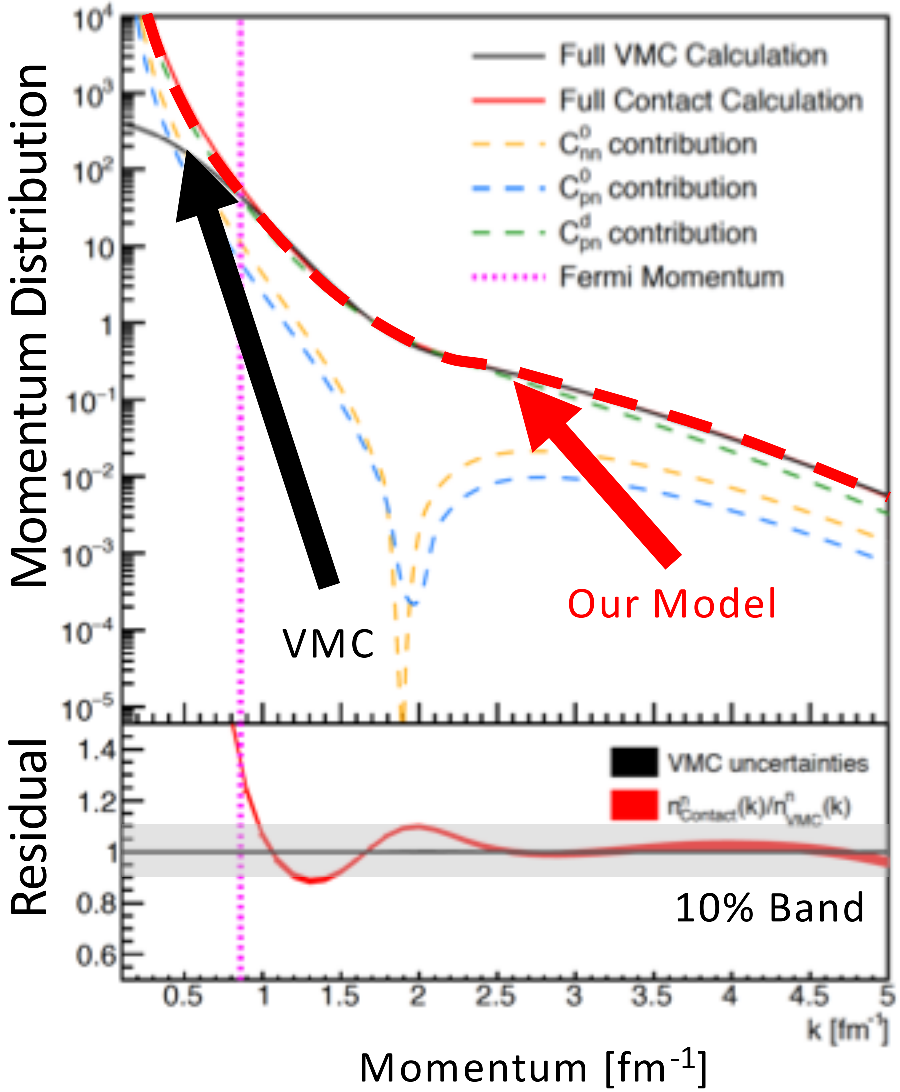
- Universal function of the NN interaction.
- Taken as the zero energy solution to the 2 body problem

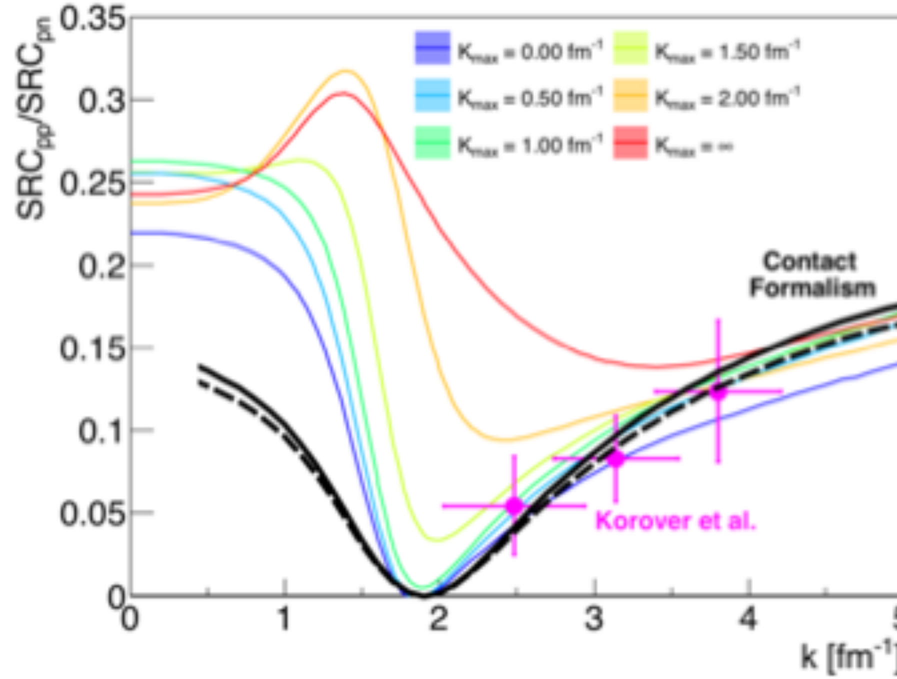
- Nucleus (/ system) specific function
- Depends on all nucleons except the SRC pair (primarily mean-field)

2. Test by comparing to many-body calculations *and* data from hard knockout measurements

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, Phys. Lett. B **780**, 211 (2018)

$$n_p(k) = \sum_\alpha \left|\tilde{\varphi}^\alpha_{pp}(k)\right|^2 2C^\alpha_{pp} + \sum_\alpha \left|\tilde{\varphi}^\alpha_{pn}(k)\right|^2 C^\alpha_{pn}$$

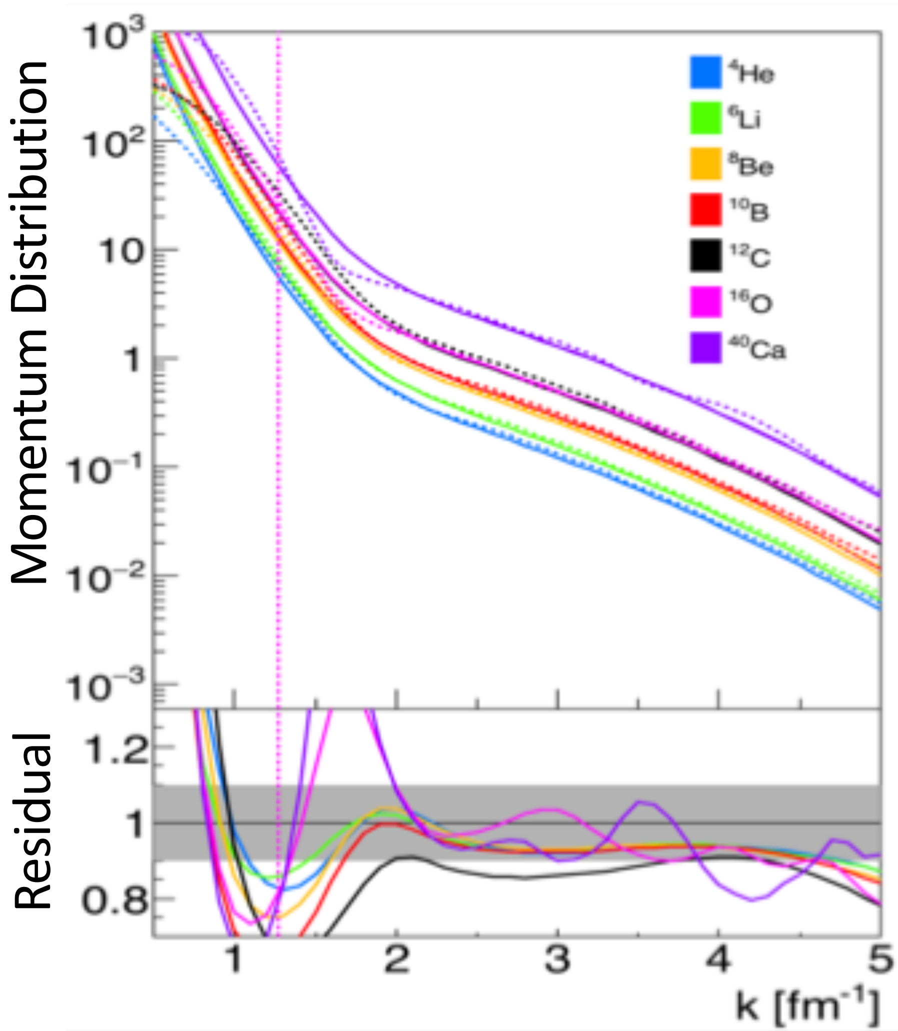


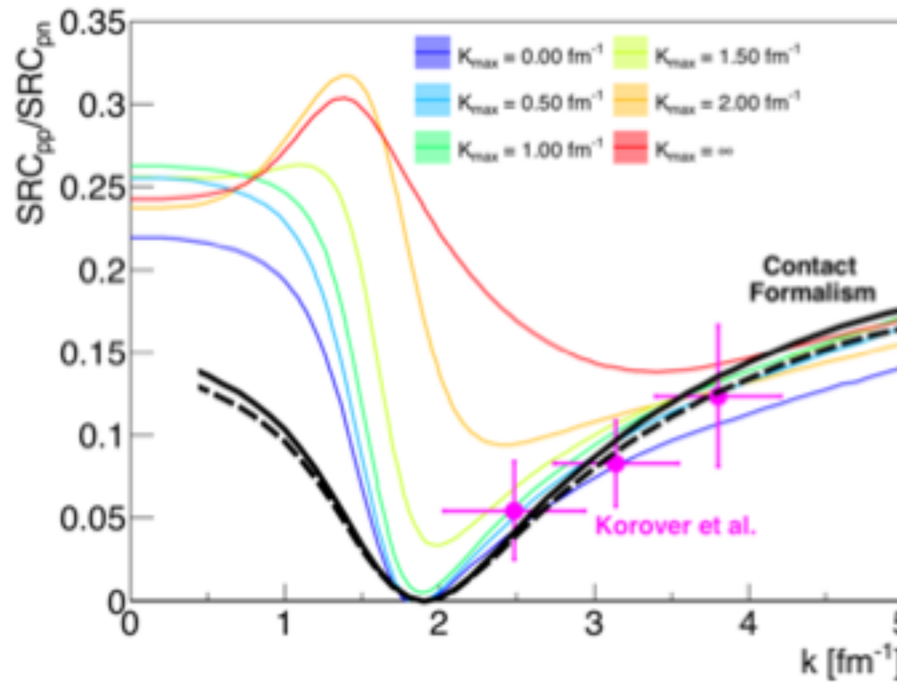


Nuclear contacts can also be extracted from experiment!

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, Phys. Lett. B **780**, 211 (2018)

$$n_p(k) = \sum_{\alpha} \left|\tilde{\varphi}^{\alpha}_{pp}(k)\right|^2 2C^{\alpha}_{pp} + \sum_{\alpha} \left|\tilde{\varphi}^{\alpha}_{pn}(k)\right|^2 C^{\alpha}_{pn}$$





Nuclear contacts can also be extracted from experiment!

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, Phys. Lett. B **780**, 211 (2018)

Spectral Function

Define pair spectral function as:

$$S_{ab}^{\alpha} = \frac{1}{4\pi}\int \frac{d\boldsymbol{p}_2}{(2\pi)^3}\delta(f(p_2))\,|\tilde{\varphi}_{ab}^{\alpha}(|(\boldsymbol{p}_1-\boldsymbol{p}_2)/2|)|^2\, n_{ab}^{\alpha}(\boldsymbol{p}_1+\boldsymbol{p}_2)$$

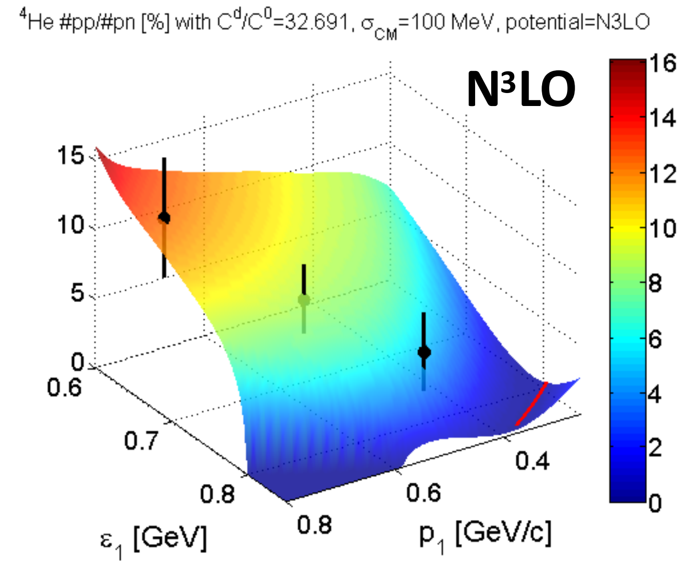
$$f(p_2) = \epsilon_1+\epsilon_2-2m+(B_i^A-\bar{B}_f^{A-2})+\frac{(\boldsymbol{p}_1+\boldsymbol{p}_2)^2}{2m(A-2)}$$

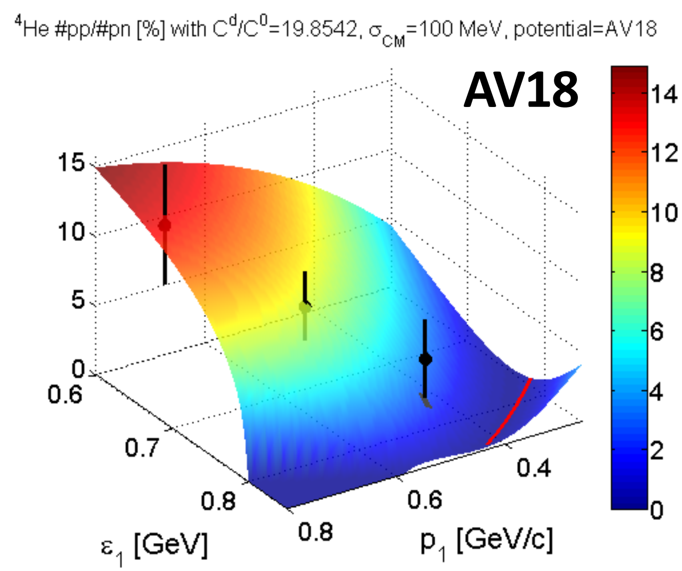
Factorize the continuum states of the spectral function:

$$S^p(p_1,\epsilon_1) = C_{pn}^1 S_{pn}^1(p_1,\epsilon_1) + C_{pn}^0 S_{pn}^0(p_1,\epsilon_1) + 2C_{pp}^0 S_{pp}^0(p_1,\epsilon_1).$$

Compare with (e,e’pN) data!

First studies of combined missing energy and momentum!





Weiss, Korover, Piasetzky, Hen, and Barnea, arXiv: 1806.10217 (2018)

Consistent k- & r-Space Contacts

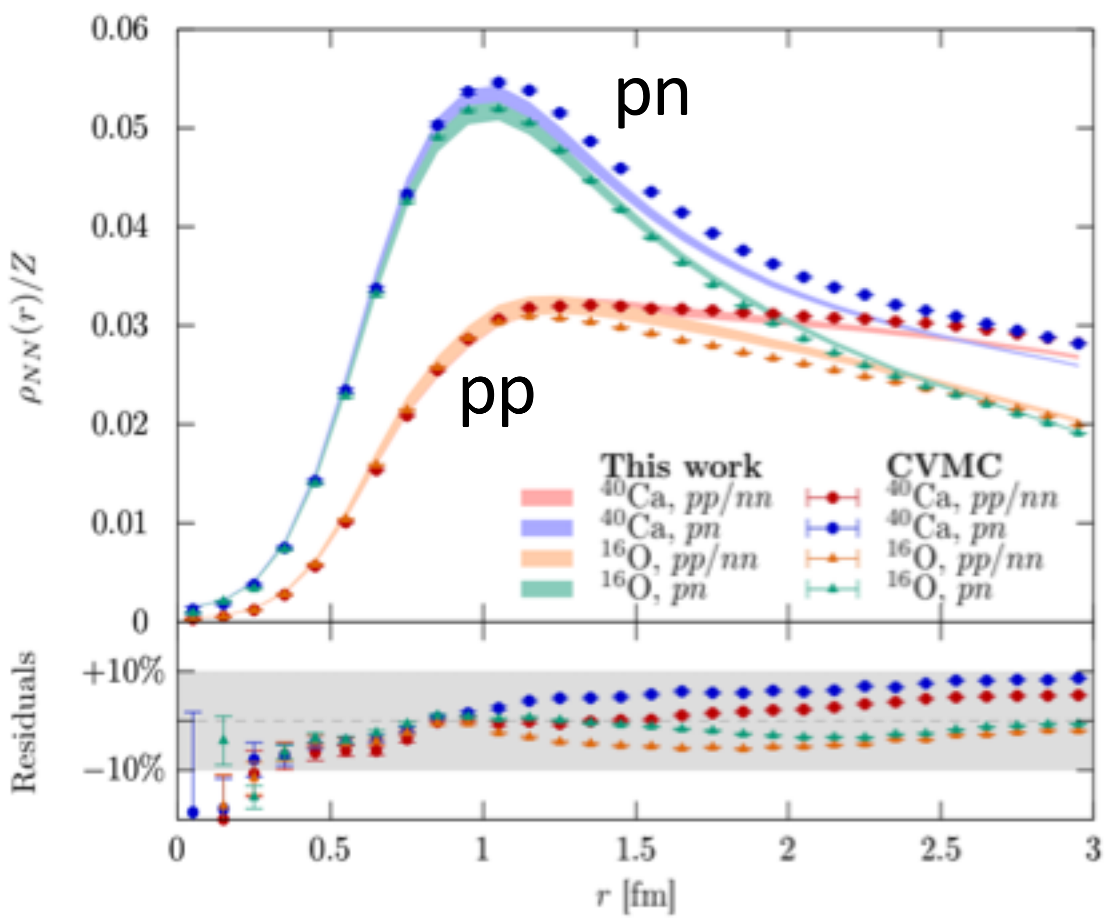
A	k-space				r-space			
	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$
^{4}**He**	12.3±0.1	0.69±0.03	0.65±0.03		11.61±0.03	0.567±0.004		
	14.9±0.7 (exp)	0.8±0.2 (exp)						
^{6}**Li**	10.5±0.1	0.53±0.05	0.49±0.03		10.14±0.04	0.415±0.004		
^{7}**Li**	10.6 ± 0.1	0.71 ± 0.06	0.78 ± 0.04	0.44 ± 0.03	9.0 ± 2.0	0.6 ± 0.4	0.647 ± 0.004	0.350 ± 0.004
^{8}**Be**	13.2±0.2	0.86±0.09	0.79±0.07		12.0±0.1	0.603±0.003		
^{9}**Be**	12.3±0.2	0.90±0.10	0.84±0.07	0.69±0.06	10.0±3.0	0.7±0.7	0.65±0.02	0.524±0.005
^{10}**B**	11.7±0.2	0.89±0.09	0.79±0.06		10.7±0.2	0.57±0.02		
^{12}**C**	16.8±0.8	1.4±0.2	1.3±0.2		14.9±0.1	0.83±0.01		
	18±2 (exp)	1.5±0.5 (exp)						

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, Phys. Lett. B **780**, 211 (2018)

Understanding two-body densities

$$\rho_{NN,s}(\vec{r}) \equiv \sum_{\substack{i,j\in NN \\ i<j}} \langle\psi|\delta(\vec{r}-\vec{r}_{ij})P_s|\psi\rangle$$

Significant isospin dependence



Factorized Model

$$\rho_{NN}(r) = g_{NN}(r)\rho_{NN}^{\text{contact}}(r) + \kappa(1 - g_{NN}(r))\rho_{NN}^{(0)}(r)$$

Universal SRC
Blending Function

$$\rho_{NN,s}^{\text{contact}}(r) = C_A^{NN,s} \times |\varphi_{NN,s}(r)|^2$$

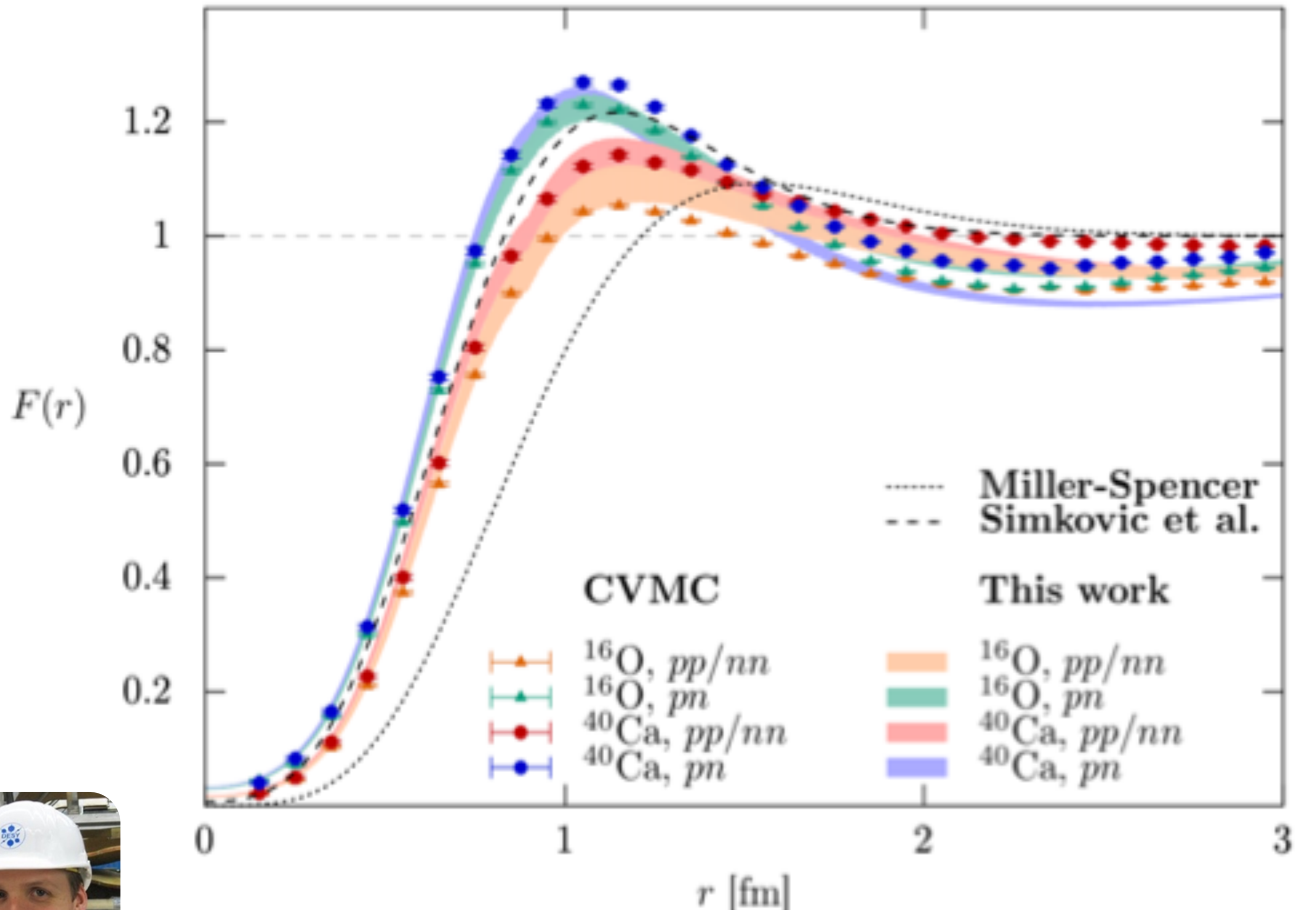
$$\rho_{NN}^{(0)}(\vec{r}) \equiv S_{NN} \int \mathrm{d}^3\vec{R}\,\rho_N(\vec{R}+\vec{r}/2)\rho_N(\vec{R}-\vec{r}/2)$$

[Un-correlated 2B density]

Correlation Function

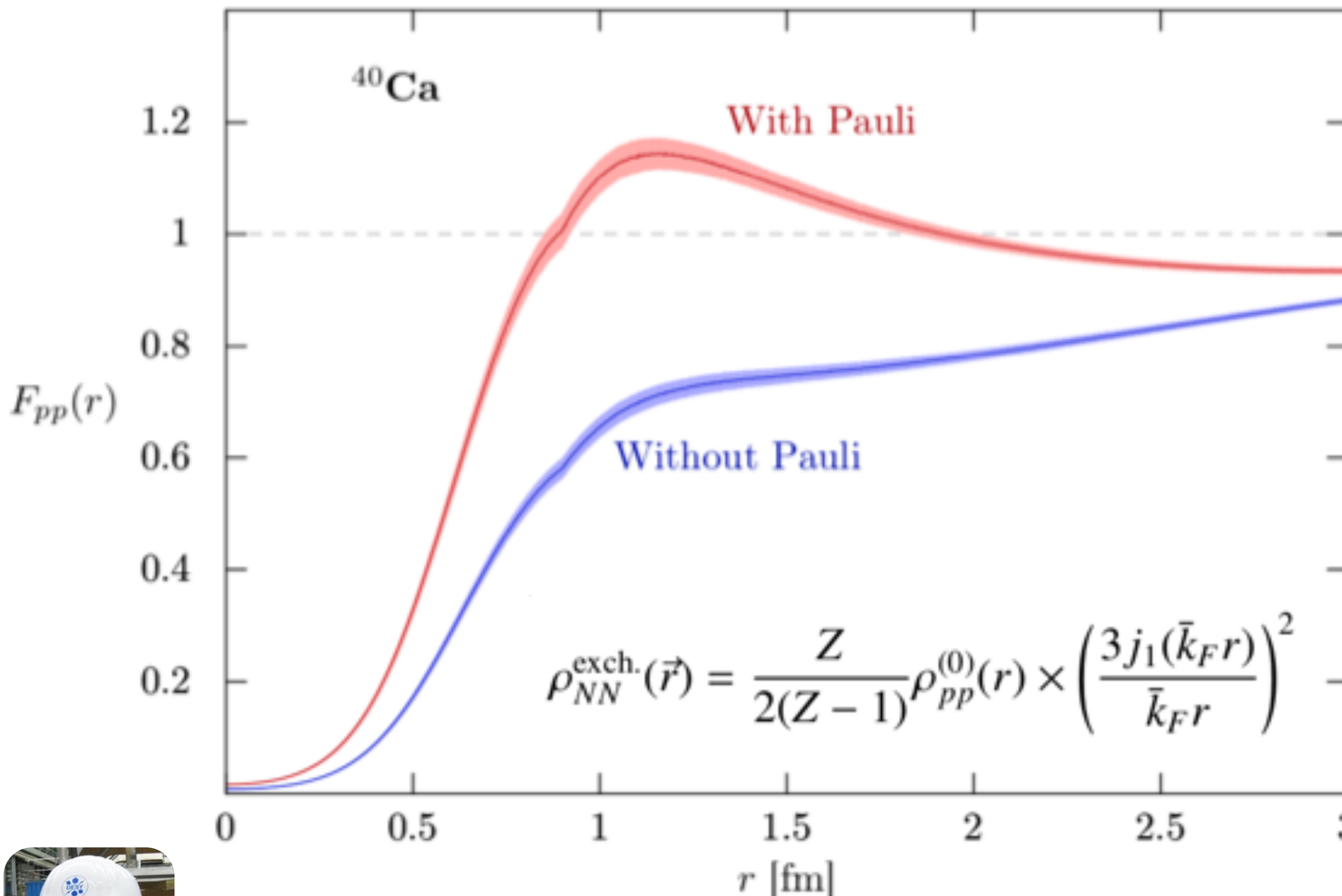
Derive Correlation function:

$$F_{NN,s}(r) \equiv \frac{\rho_{NN,s}(r)}{\rho_{NN}^{\text{uncorr.}}(r)}$$ +Pauli Exchange



Cruz-Torres and Schmidt et al., arXiv: 1710.07966 (2018)

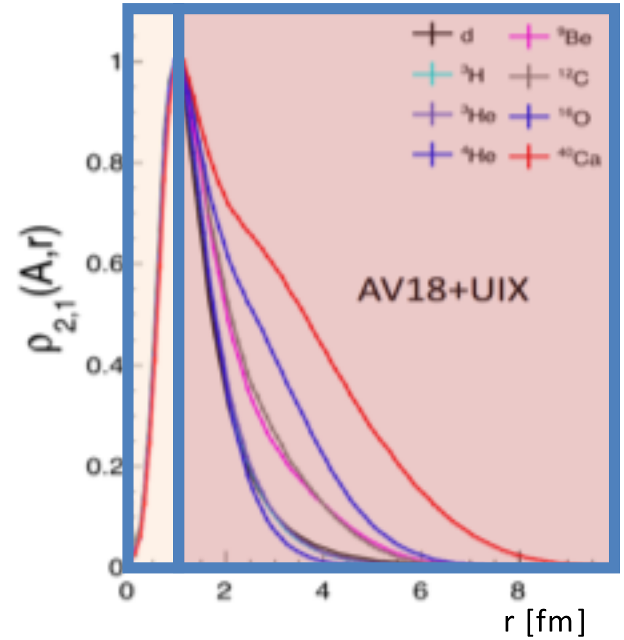
Pauli Exchange remediates the isospin dependence

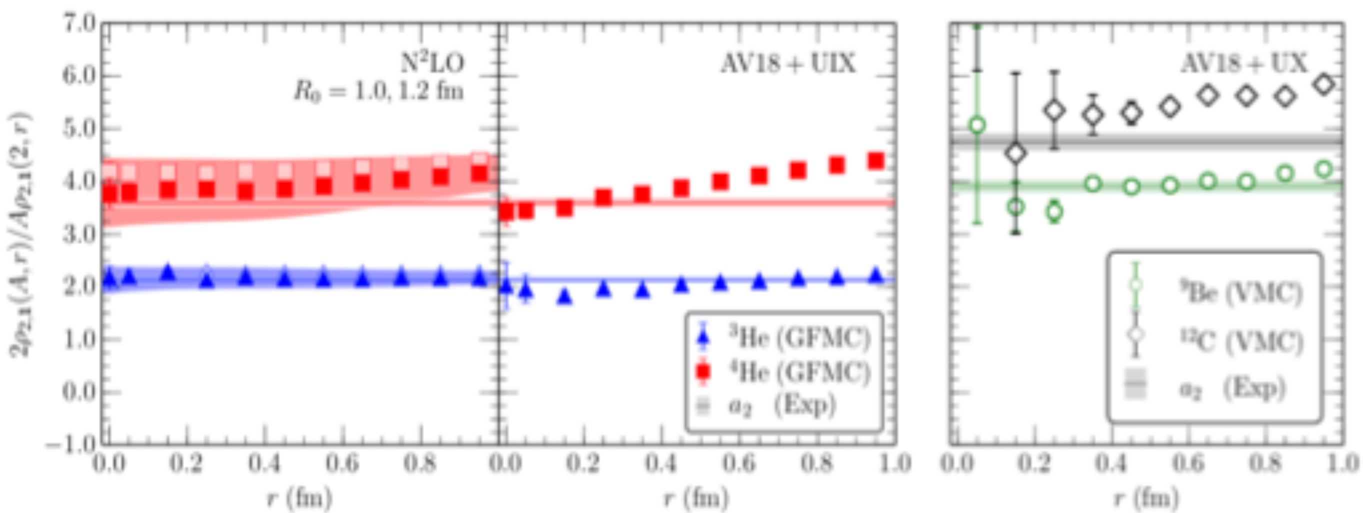


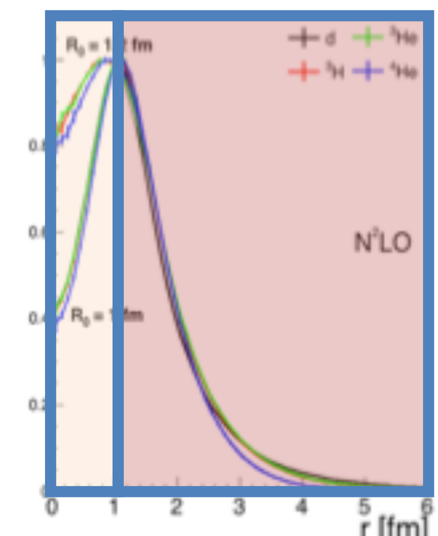
Cruz-Torres and Schmidt et al., arXiv: 1710.07966 (2018)

Coordinate Space Scaling

- Two-body densities scale at short distance for all interaction.
- A/d scaling coefficient matches k-space and (e,e') scaling data.
- Deuteron density (AV-18):
  k-space > 1.3 fm^{-1}: ~5%
  r-space < 1.0 fm : ~5%

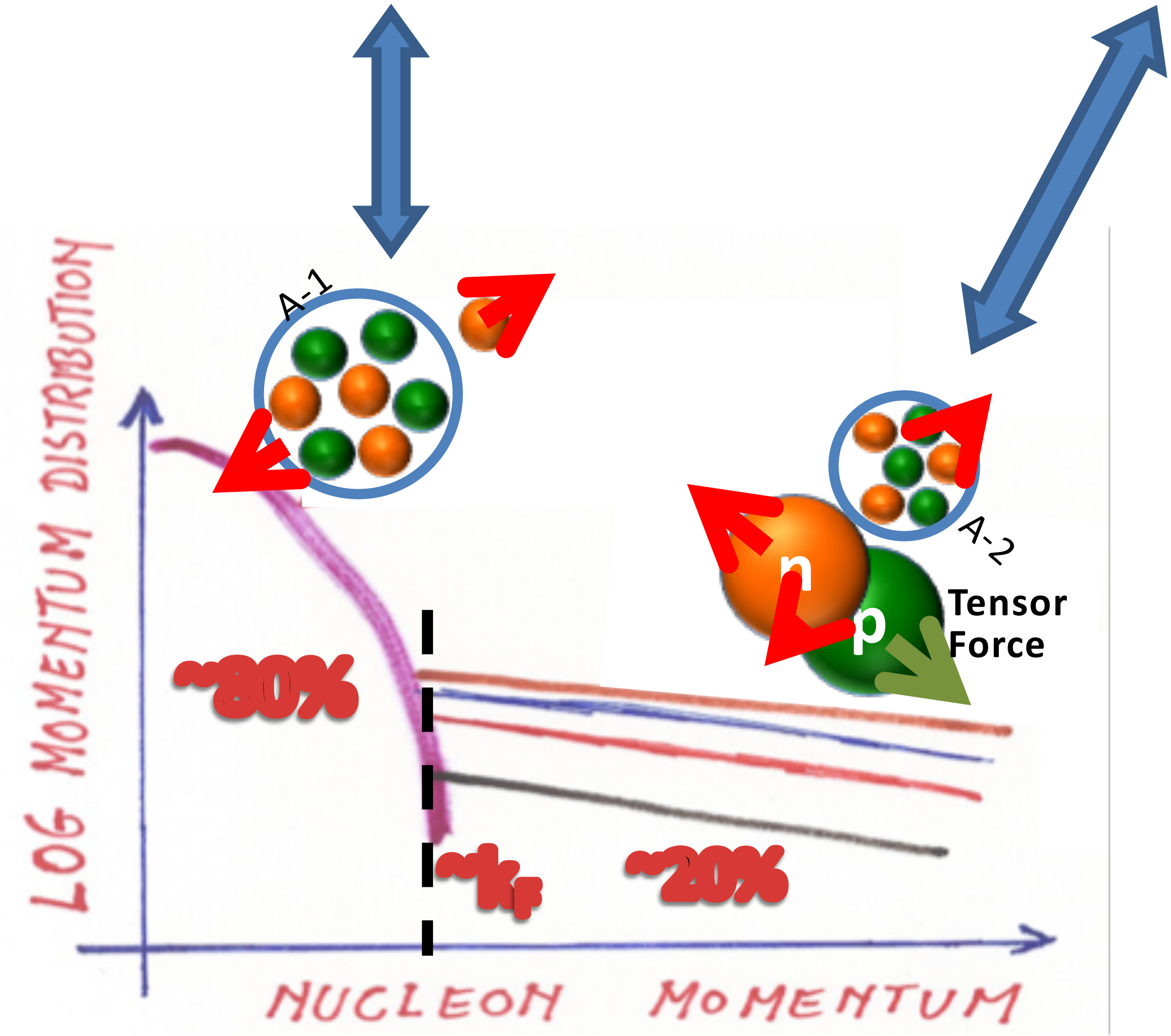






Hen, Miller, Piasetzky and Weinstein, RMP (2017)
Chen, Detmold, Lynnm, and Schwenk, PRL (2018)

Bound = 'quasi Free' + Modified SRCs



Bound nucleons in EFT and QCD

1) Factorization:

Bound Nucleon = Free Nucleon + Universal Modification x Nucleus Amplitude

Hen, Miller, Piasetzky and Weinstein, Reviews of Modern Physics (2017).

Bound nucleons in EFT and QCD

1) Factorization:

Bound Nucleon = Free Nucleon + Universal Modification x Nucleus Amplitude

2) SRC Dominance:

Nucleus Amplitude <=> Abundance of SRC pairs

Hen, Miller, Piasetzky and Weinstein, Reviews of Modern Physics (2017).

Bound nucleons in EFT and QCD

1. EFT: $F_2^A(x,Q^2) = F_2^N(x,Q^2) + g_2(A,\Lambda)\cdot f_2(x,Q^2,\Lambda)$

2. QCD: $|N\rangle_{bound} = |N\rangle + (\varepsilon_{bound} - \varepsilon)|N^*\rangle$

Hen, Miller, Piasetzky and Weinstein, Reviews of Modern Physics (2017).

Chen, Detmold, Lynnm, and Schwenk, PRL (2018).

Bound nucleons in EFT and QCD

<u>1. EFT:</u> $F_2^A(x,Q^2) = F_2^N(x,Q^2) + g_2(A,\Lambda)\cdot f_2(x,Q^2,\Lambda)$

Bound = Free

<u>2. QCD:</u> $|N\rangle_{bound} = |N\rangle + (\varepsilon_{bound} - \varepsilon)|N^*\rangle$

Hen, Miller, Piasetzky and Weinstein, Reviews of Modern Physics (2017).

Chen, Detmold, Lynnm, and Schwenk, PRL (2018).

Bound nucleons in EFT and QCD

1. EFT: $F_2^A(x,Q^2) = F_2^N(x,Q^2) + g_2(A,\Lambda)\cdot f_2(x,Q^2,\Lambda)$

Bound = Free + Factorized Modification

2. QCD: $|N\rangle_{bound} = |N\rangle + (\varepsilon_{bound} - \varepsilon)|N^*\rangle$

Hen, Miller, Piasetzky and Weinstein,
Reviews of Modern Physics (2017).

Chen, Detmold, Lynnm, and
Schwenk, PRL (2018).

Bound nucleons in EFT and QCD

<u>1. EFT:</u> $F_2^A(x, Q^2) = F_2^N(x, Q^2) + g_2(A, \Lambda) \cdot f_2(x, Q^2, \Lambda)$

Bound = Free + <u>Factorized Modification</u>

<u>2. QCD:</u> $|N\rangle_{bound} = |N\rangle + (\varepsilon_{bound} - \varepsilon)|N^*\rangle$

Hen, Miller, Piasetzky and Weinstein, Reviews of Modern Physics (2017).

Chen, Detmold, Lynnm, and Schwenk, PRL (2018).

Bound nucleons in EFT and QCD

1. EFT: $F_2^A(x,Q^2) = F_2^N(x,Q^2) + g_2(A,\Lambda)\cdot f_2(x,Q^2,\Lambda)$

$$g_2(A,\Lambda) = \frac{1}{A}\underbrace{\langle A|\left(N^\dagger N\right)^2|A\rangle_\Lambda}_{\text{SRC contact**}}$$

2. QCD: $|N\rangle_{bound} = |N\rangle + (\varepsilon_{bound} - \varepsilon)|N^*\rangle$

$$(\varepsilon_{bound} - \varepsilon) \propto \underbrace{\frac{p^2 - m^2}{2M}}_{\text{SRC dominated}}$$

Hen, Miller, Piasetzky and Weinstein, Reviews of Modern Physics (2017).

Chen, Detmold, Lynnm, and Schwenk, PRL (2018).

Weiss and Cruz-Torres et al., Phys. Lett B 780, 211 (2018)

Short-Range Correlations

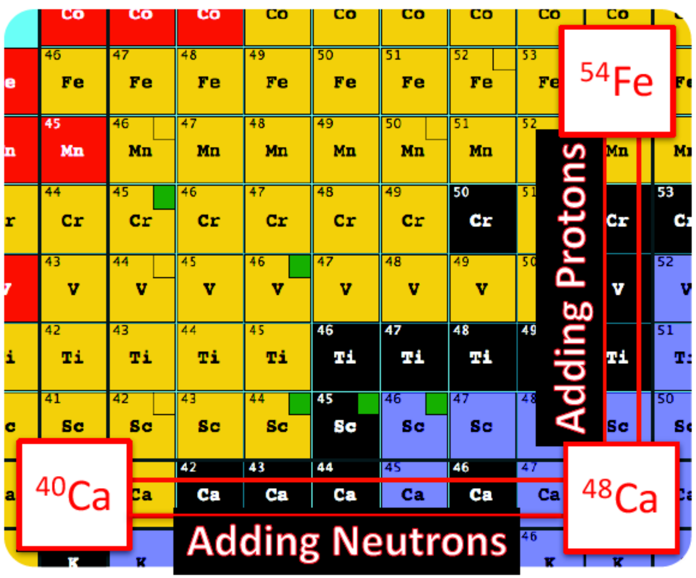
Or Hen (MIT)

- **Future Directions**

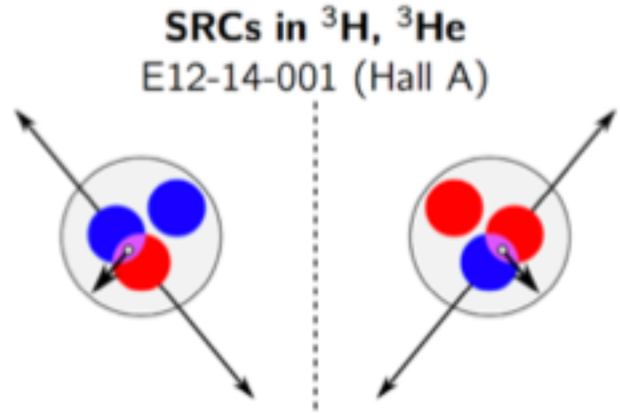
INT Workshop on Fundamental Physics with Electroweak Probes of Light Nuclei, July 2nd 2018.

Future Avenues @ JLab

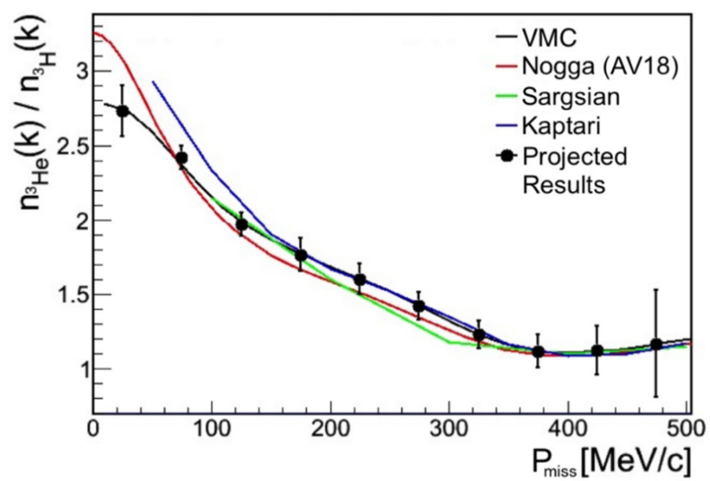
SRC Dynamics in asymmetric nuclei



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

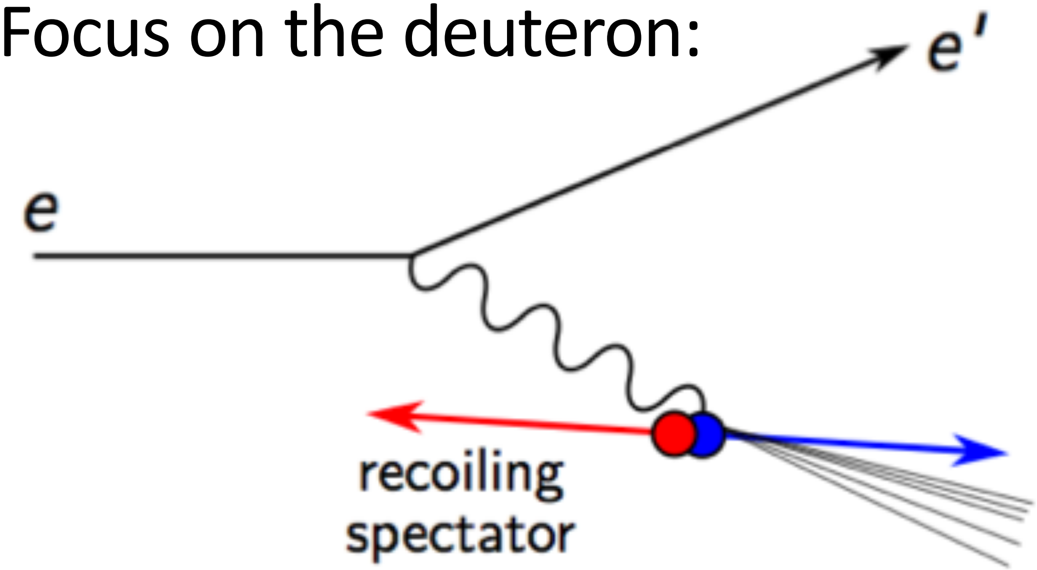


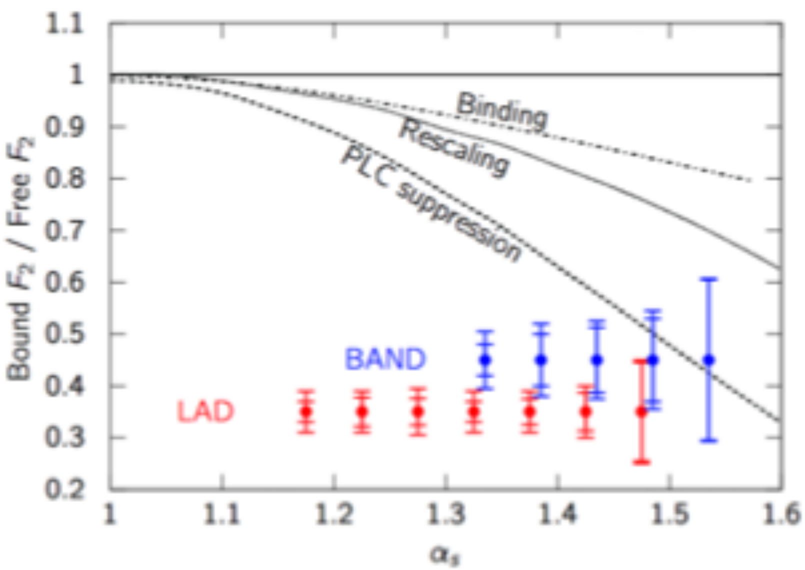
- Hall A Tritium target
- Exploit isospin asymmetry
- 3H and 3He are extremely asymmetric!
- Constrain and test ab-initio calculations!



Internal Structure of Bound Nucleons

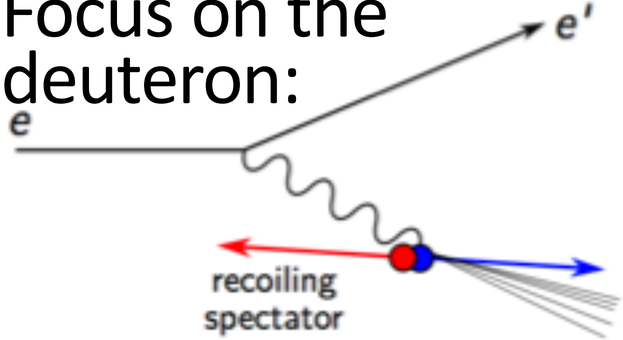
Focus on the deuteron:

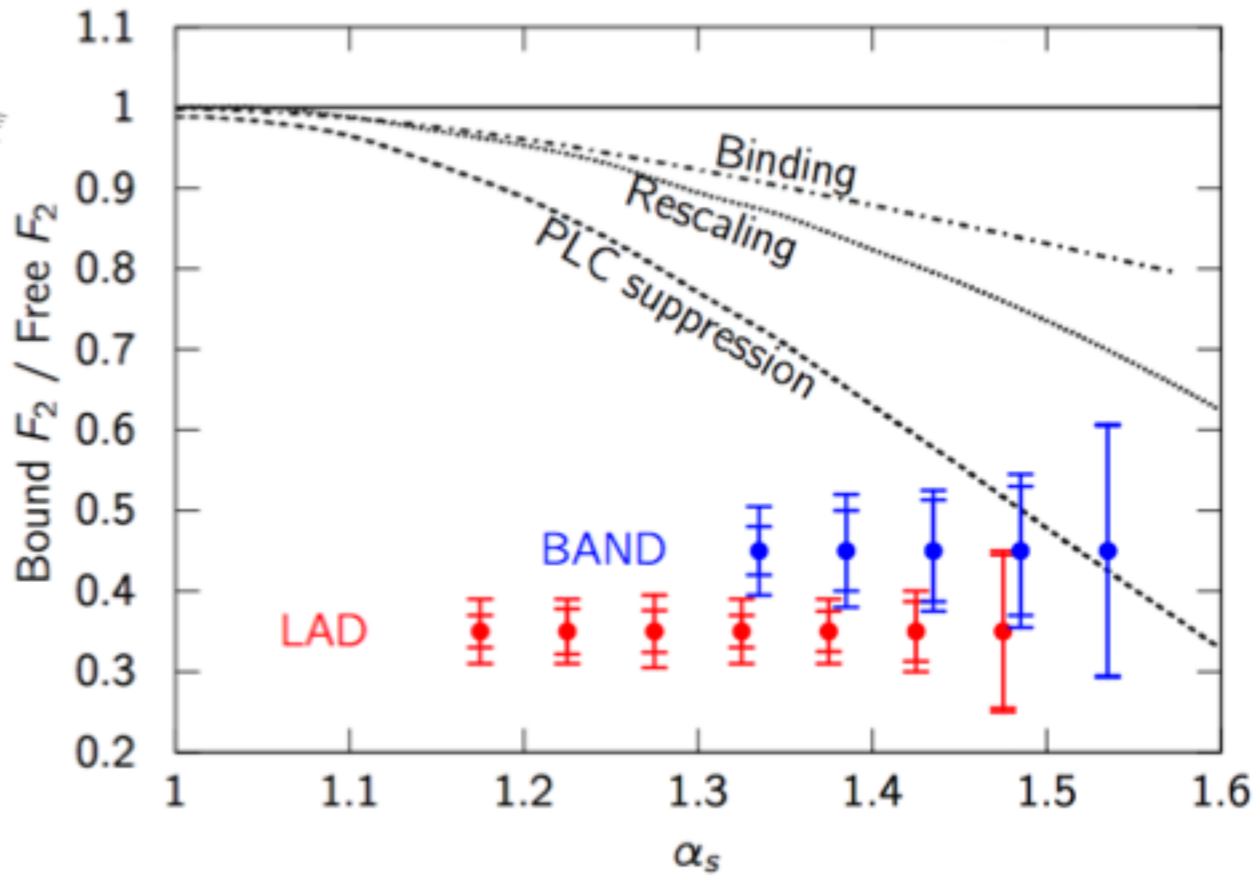




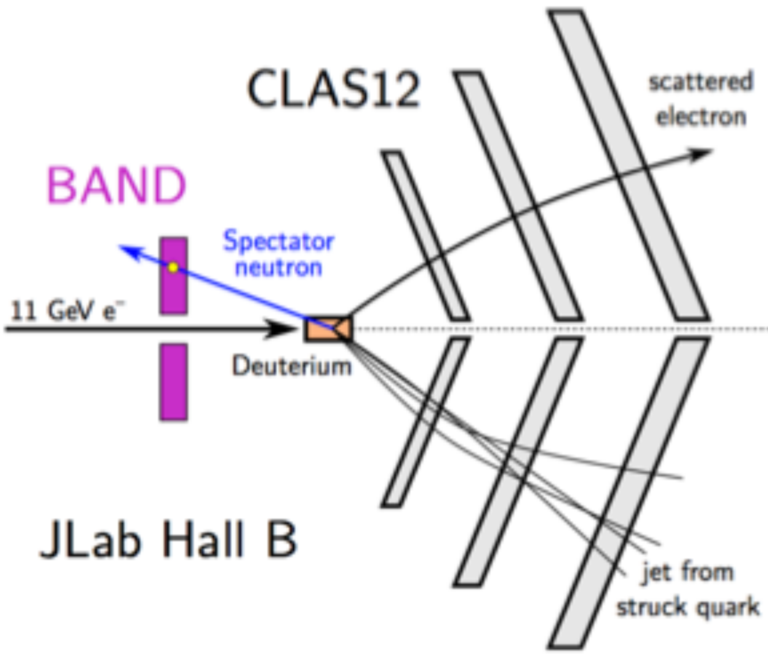
Internal Structure of Bound Nucleons

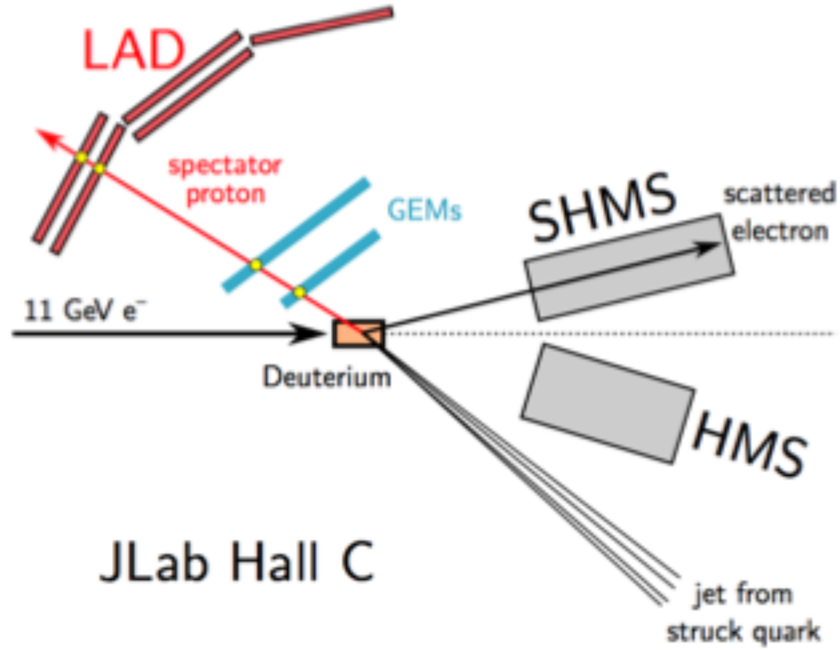
Focus on the deuteron:

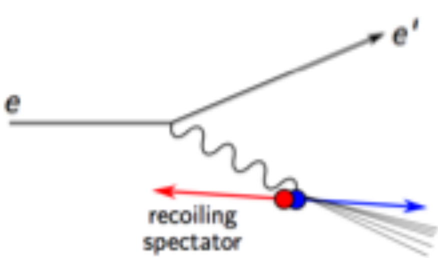


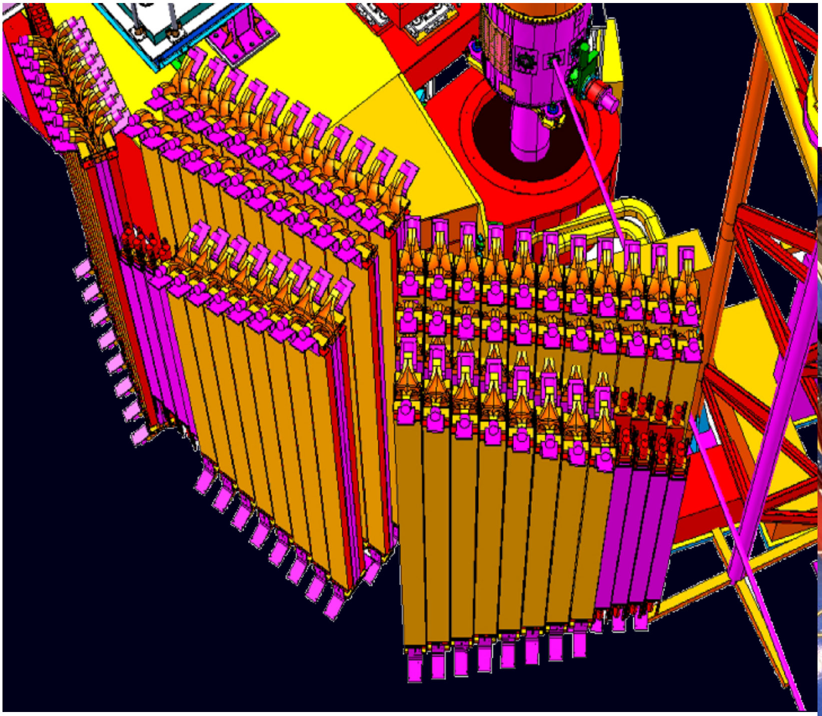


Internal Structure of Bound Nucleons

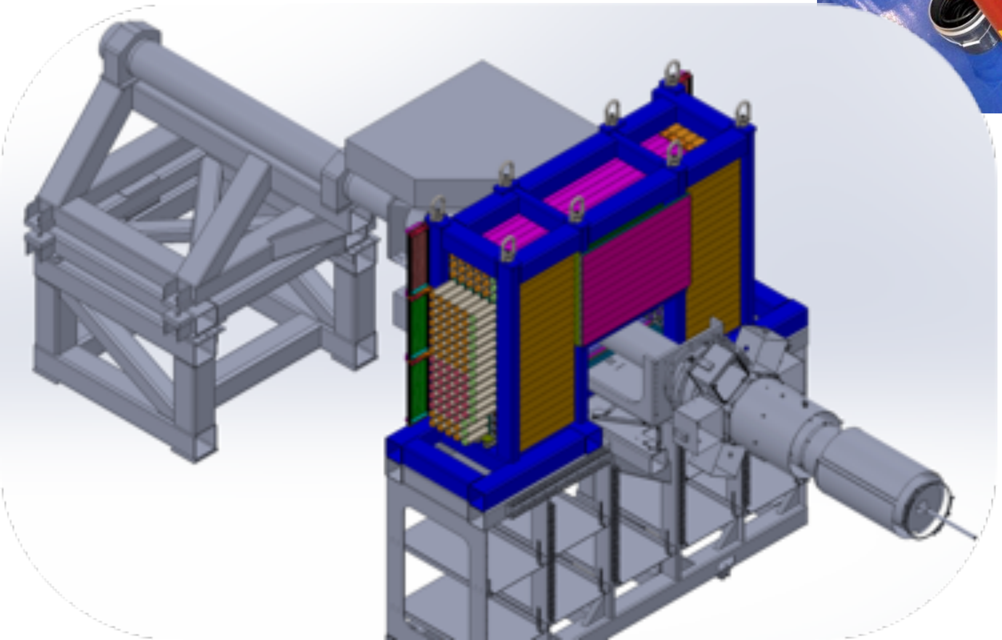








Large Acceptance
Detector (LAD@Hall-C)

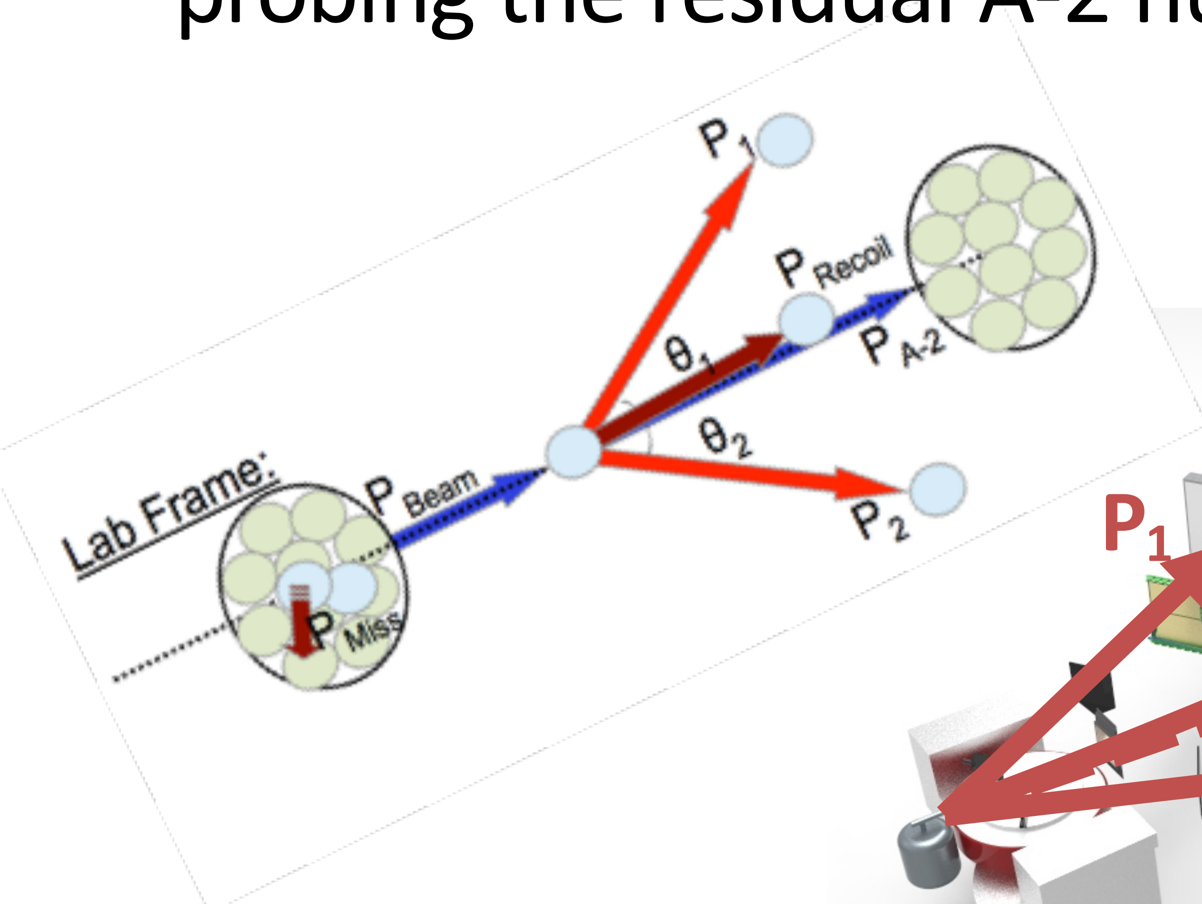


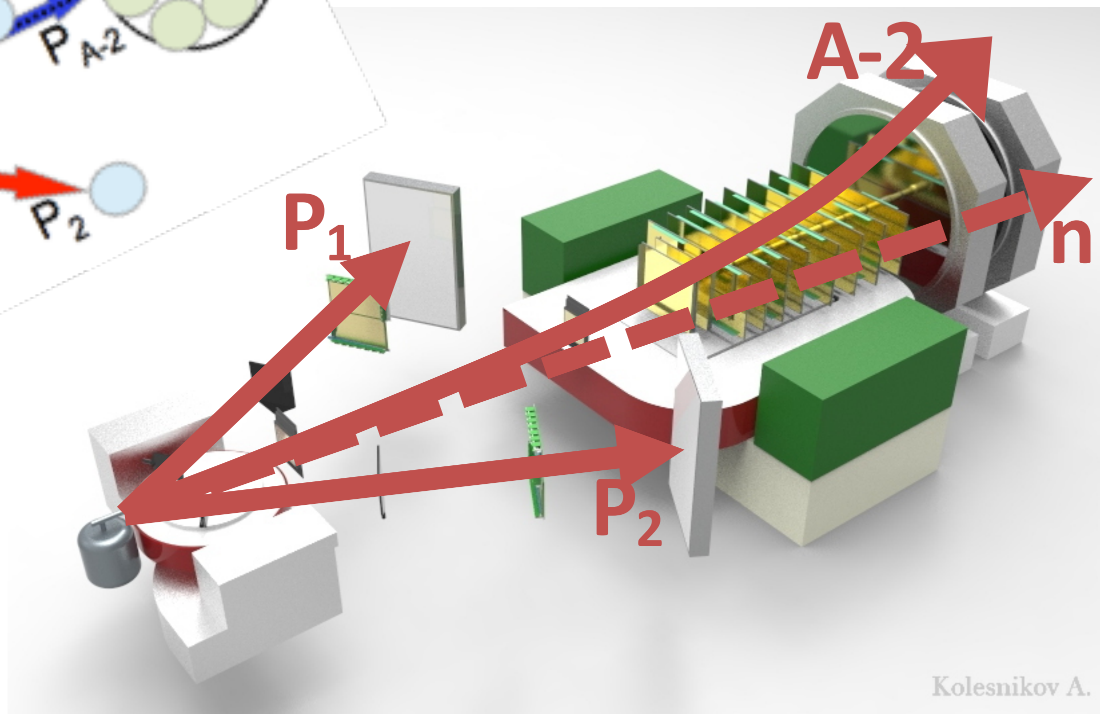
Backward Angle Neutron
Detector (BAND@Hall-B)

MIT-BATES / TAU / ODU
/ UTSM

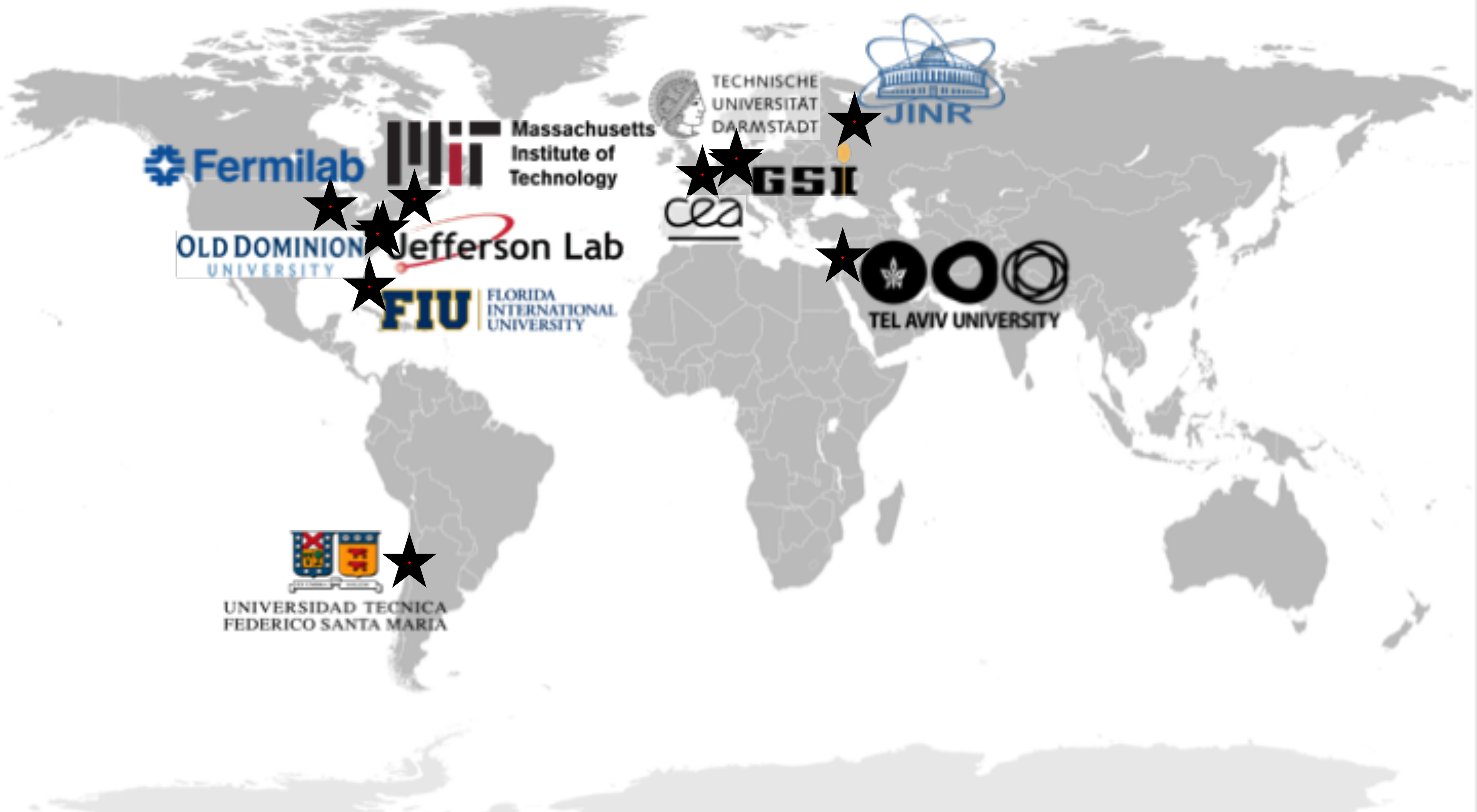
Going Fully Exclusive @ JINR

1st measurement in inverse kinematics;
probing the residual A-2 nuclear system!





The SRC World



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

The MIT Correlations group


Barak Schmookler


Reynier Torres


Afroditi Papadopoulou


Efrain Segarra


Dr. Axel Schmidt


Dr. Adi Ashkenazy


Dr. Maria Patsyuk


Dr. George Laskaris


BRACE YOURSELF
DATA
~~WINTER~~ IS COMING
Troll.me

Requirements from theories of SRCs

Reproduce the data.

Requirements from theories of SRCs

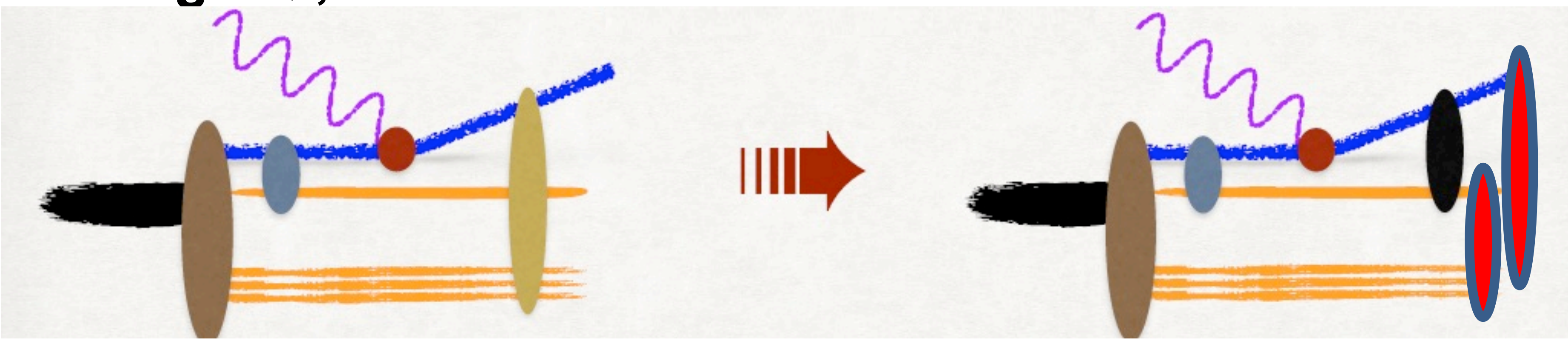
Reproduce *all features* of the data:

- A-Independence of gross SRC features
- Asymmetry dependence of p/n correlations

- Q^2 independence of observables
- P_{miss} dependence of observables

FSI: Theory Guidance

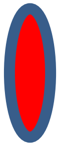
For large Q^2, x>1



$$r_{FSI} \sim \frac{1}{\Delta E v} \lesssim 1 \text{ fm}$$

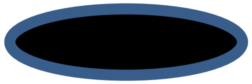
[PRC 56 1124-1137 (1997), arXiv: 0806.4412]

$$\Delta E = -q_0 - M_A + \sqrt{m^2 + (p_i + q)^2} + \sqrt{M_{A-1}^2 + p_i^2}$$

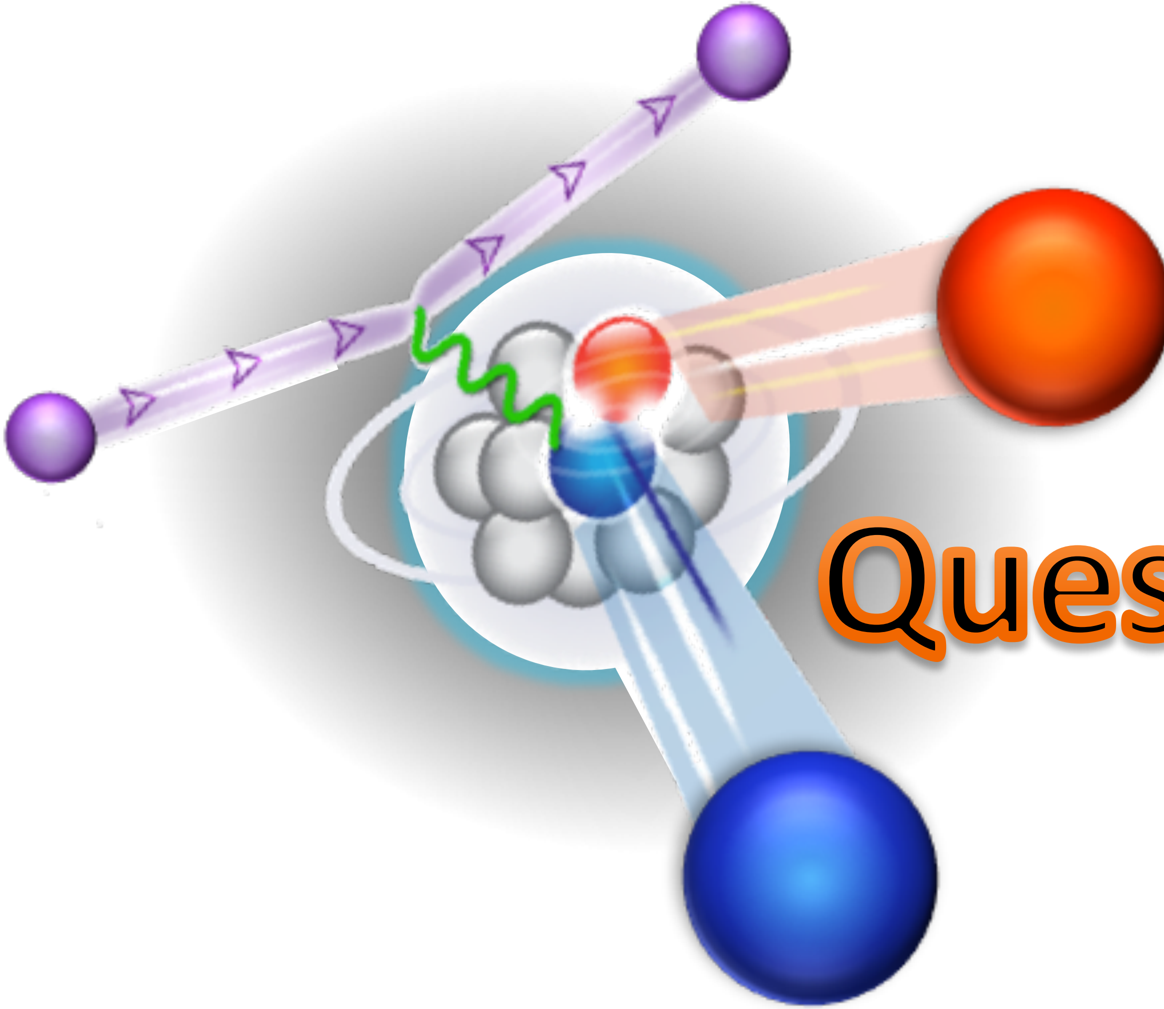
 Can be approximated by Glauber (transparency)

 Large but confined within the SRC pair

Rescattering do not produce 2N–SRC candidates due to high pt

- **Choose kinematics to min FSI**
- **Choose observables not sensitive to** 

Thank You!



Questions?