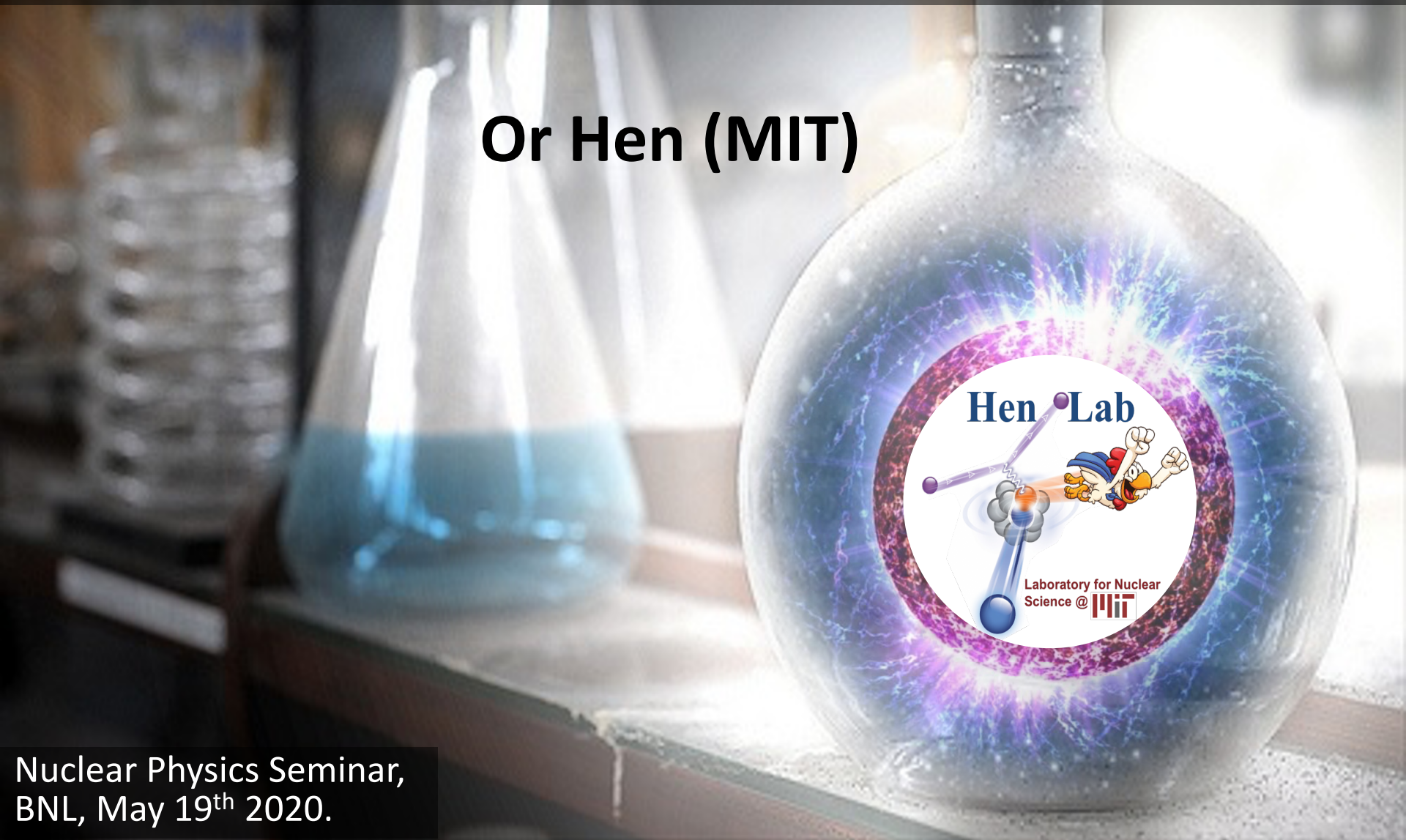
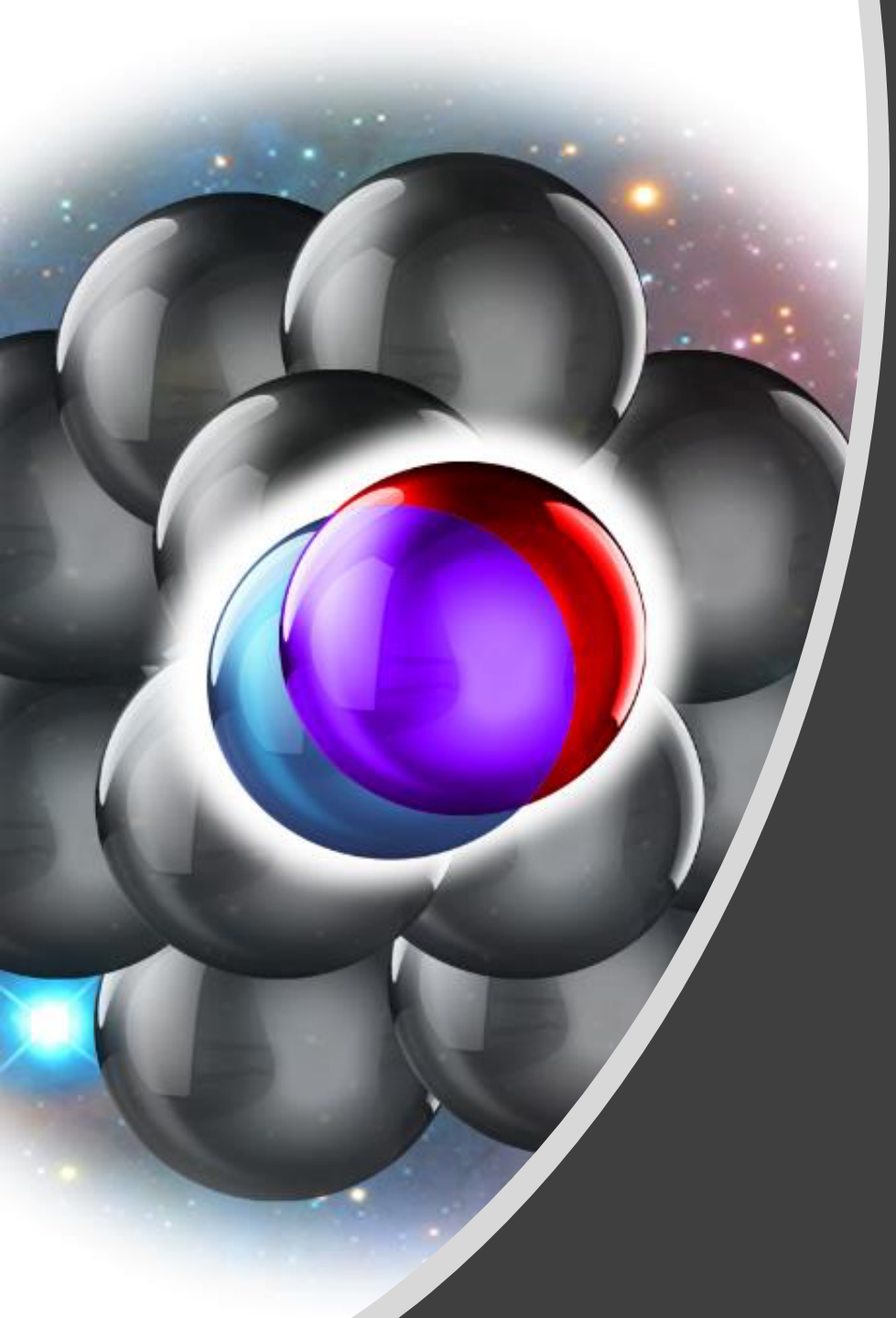
short-range correlations in nuclei: from the Nuclotron to FAIR & EIC

Or Hen (MIT)



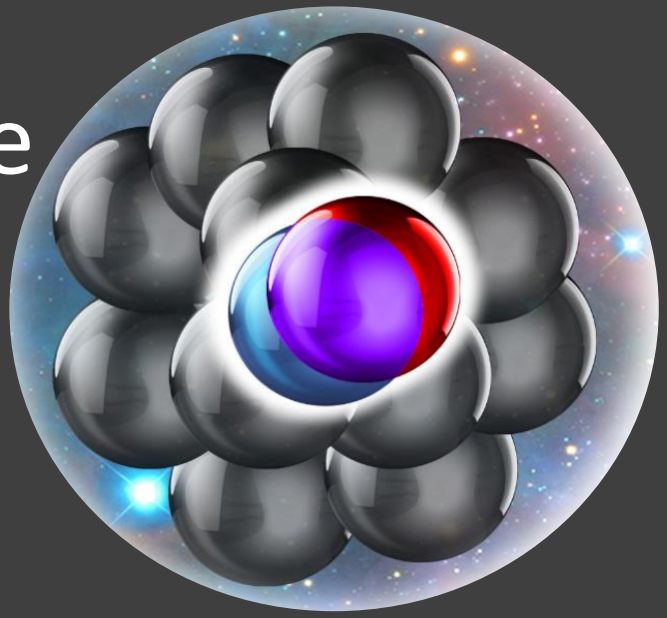
Nuclear Physics Seminar, BNL, May 19th 2020.



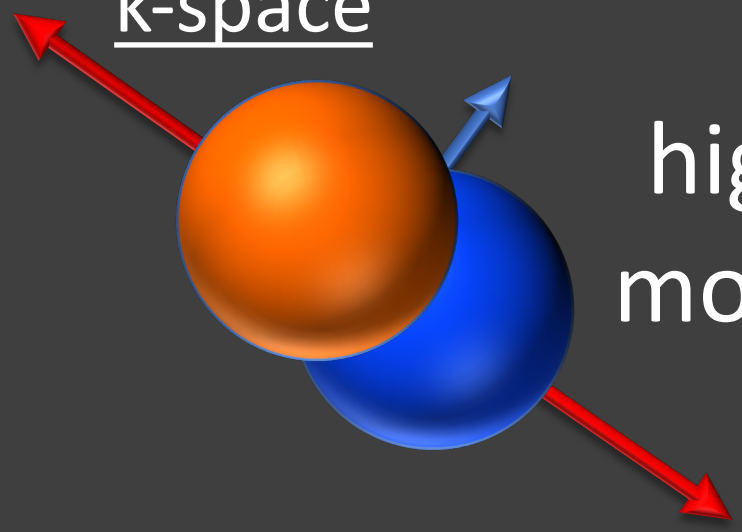
Short-Range Correlations (SRC)

Nucleon pairs that are close together in the nucleus

r-space

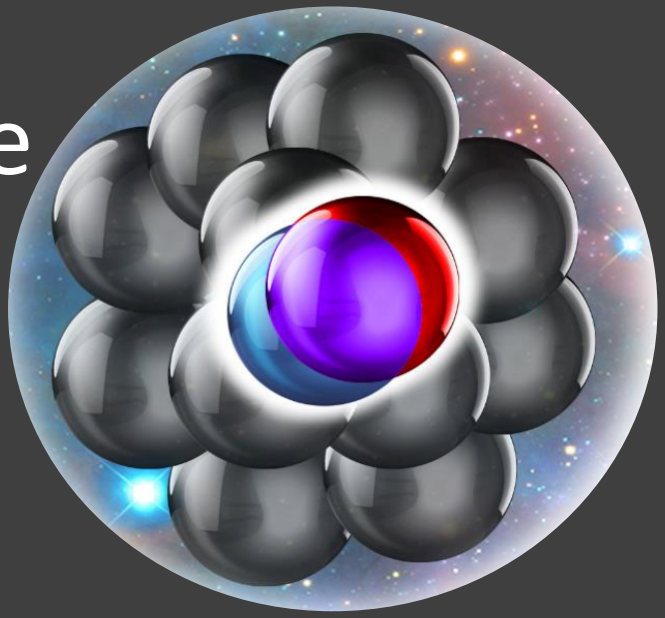


k-space



high ***relative*** and low ***c.m.*** momentum compared to k_F

r-space



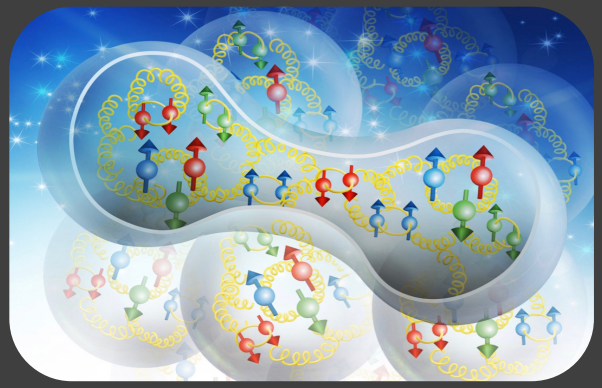
Nucleon pairs that are close together in the nucleus

Why SRC?

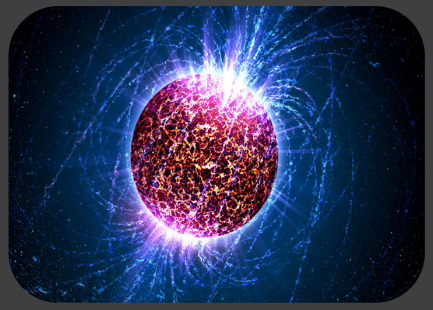
Why SRC?

Required for a high-resolution, first principle, description of nuclear systems & processes.

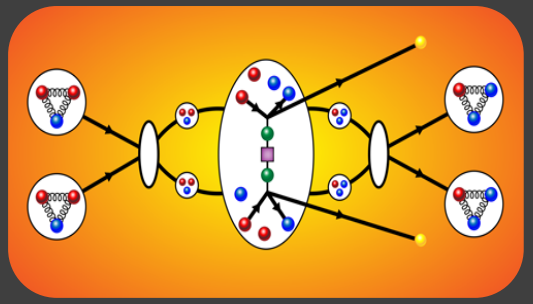
NN interaction from QCD & QCD in nuclei



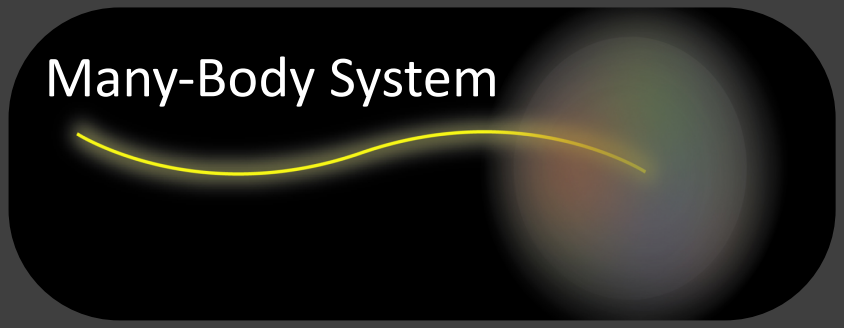
High-density systems

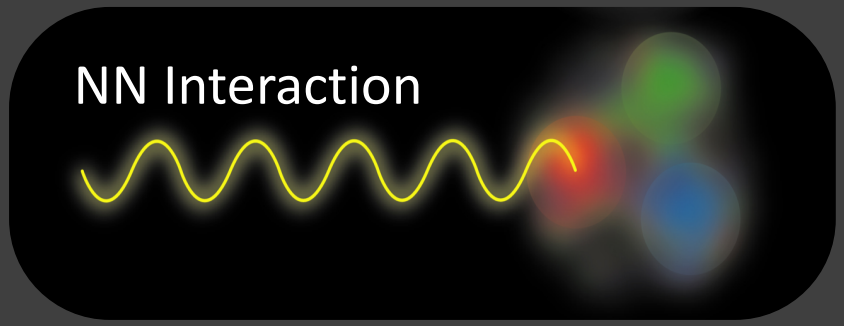


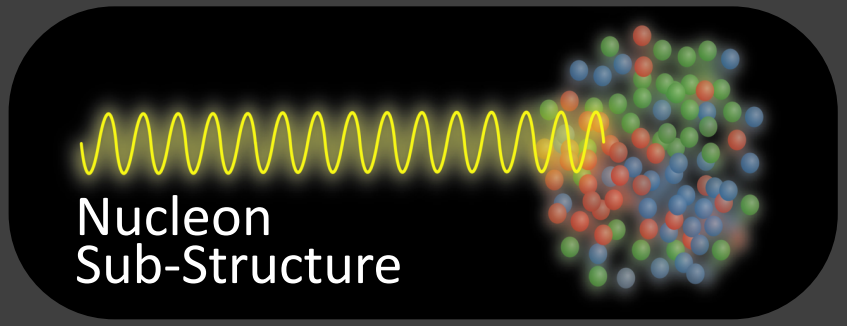
High-q processes (e.g. $0\nu\beta\beta$ decay)

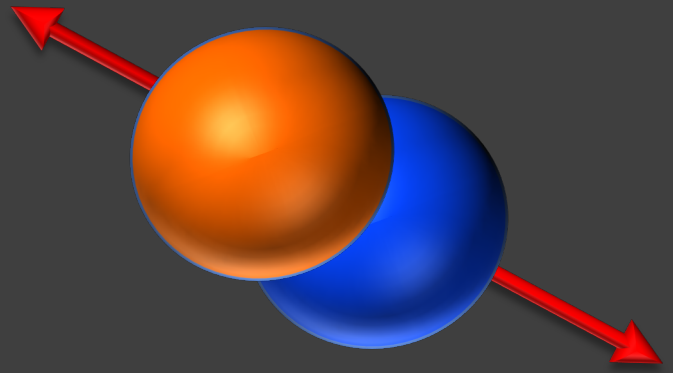


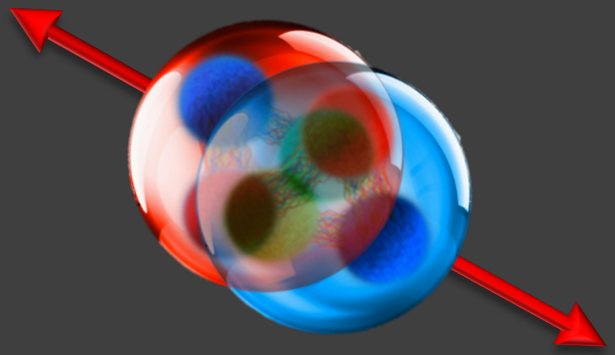
SRCs Across Scales



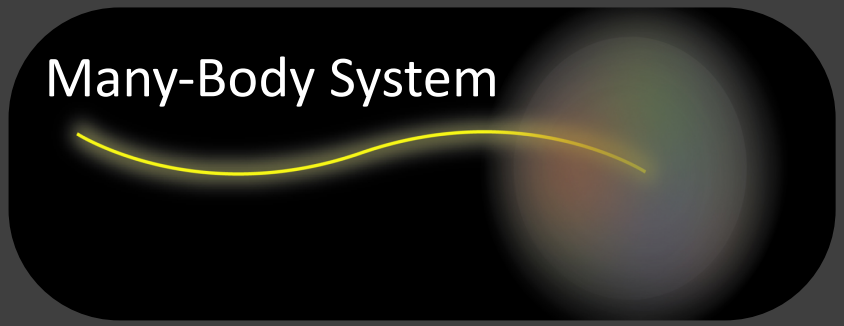


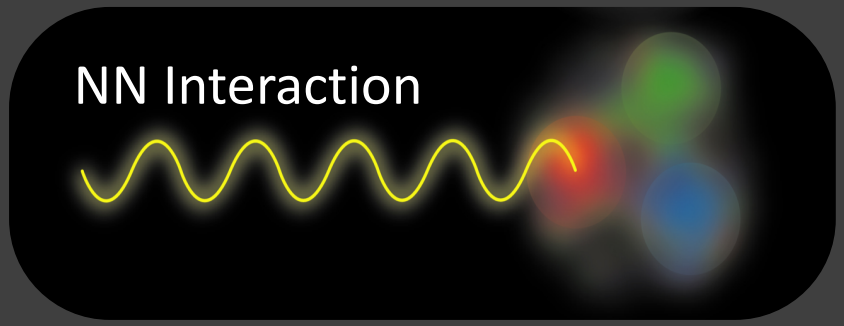


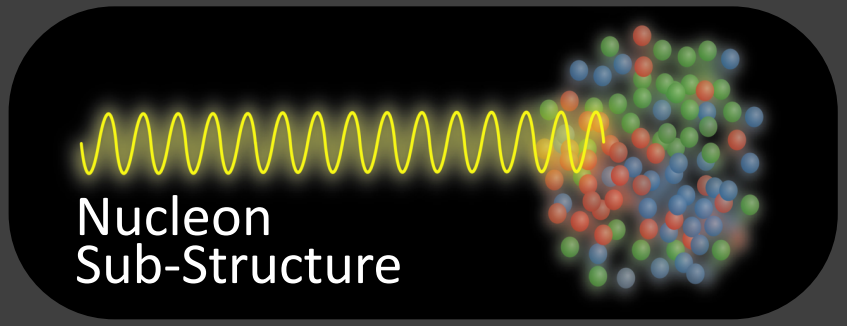




SRCs Across Scales



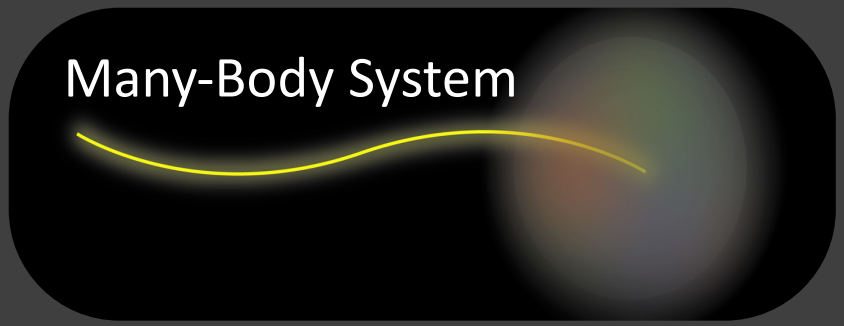


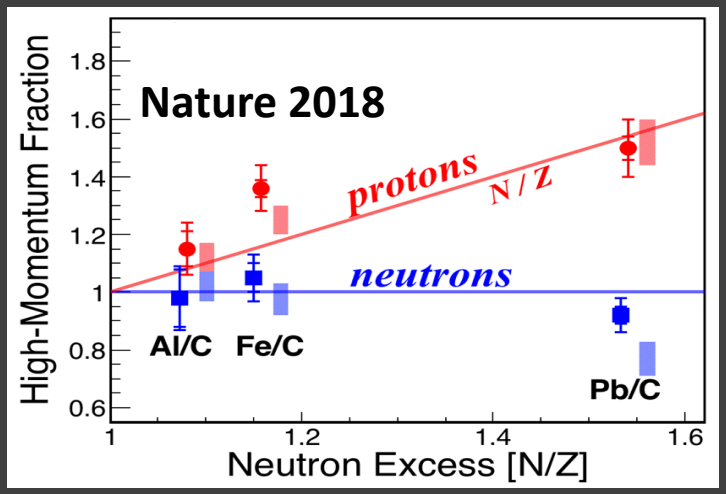


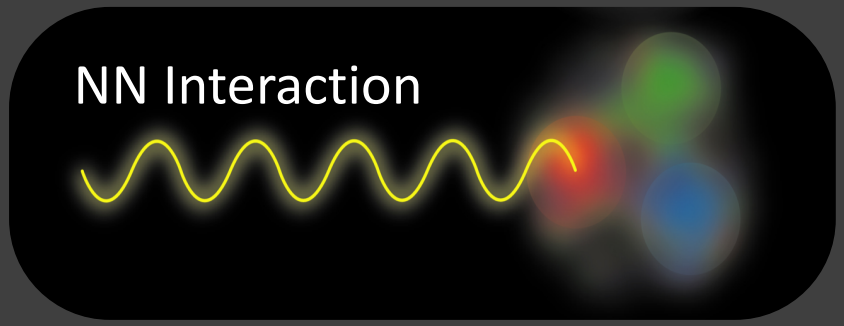
<u>2018-20 SRC Publications:</u>

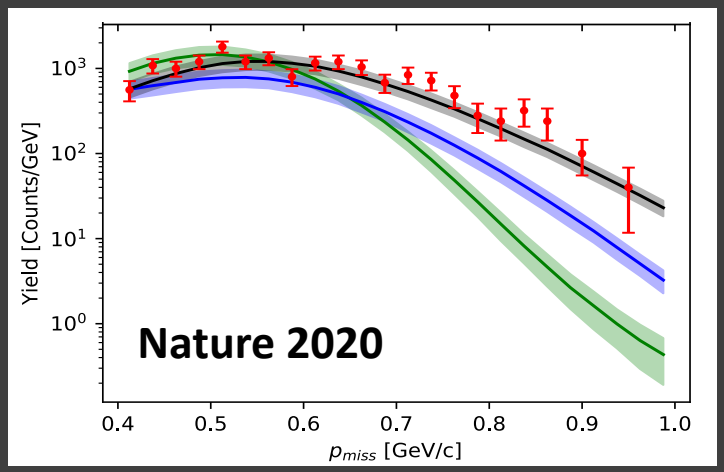
- Nature 578, 540 (2020)
- Nature 566, 354 (2019)
- Nature 560, 617 (2018)
- PRL, In-Print (2020)
- PRL 124, 092002 (2020)
- PRL 122, 172502 (2019)
- PRL 121, 092501 (2018)
- Phys. Lett. B 805, 135429 (2020)
- Phys. Lett. B 800, 135110 (2019)
- Phys. Lett. B 797, 134890 (2019)
- Phys. Lett. B 797, 134792 (2019)
- Phys. Lett. B 791, 242 (2019)
- Phys. Lett. B 793, 360 (2019)
- Phys. Lett. B 785, 304 (2018)
- Phys. Lett. B 780, 211 (2018)

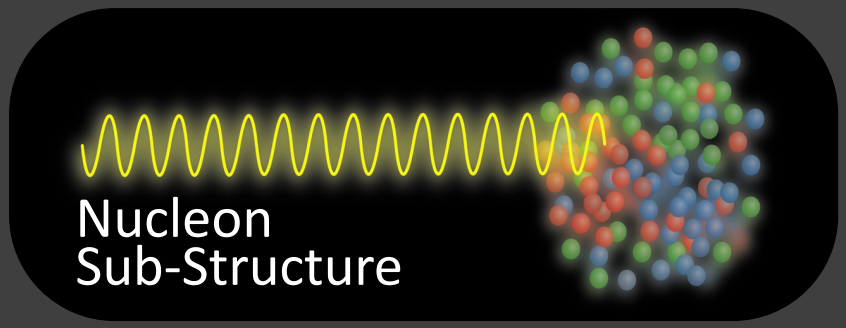
arXiv: 1907.03658;
2004.07304;
2005.01621.

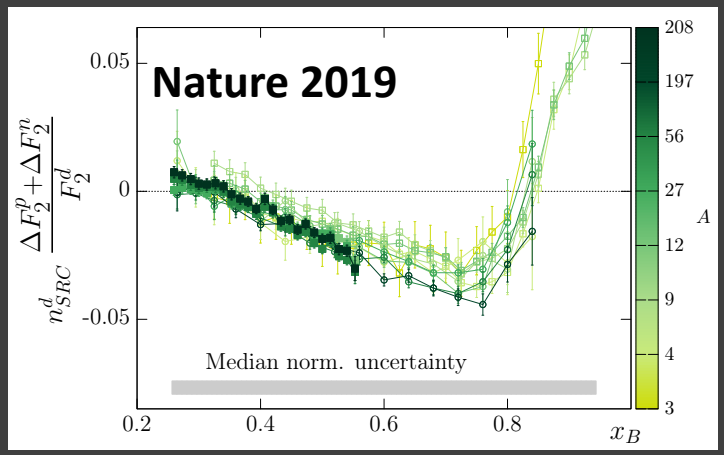

Many-Body System

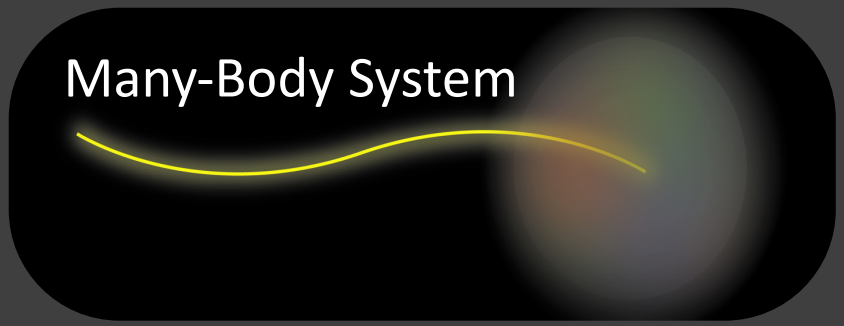

Nature 2018
High-Momentum Fraction
Neutron Excess [N/Z]
protons
N / Z
neutrons
Al/C
Fe/C
Pb/C
1.8
1.6
1.4
1.2
1
0.8
0.6
1
1.2
1.4
1.6

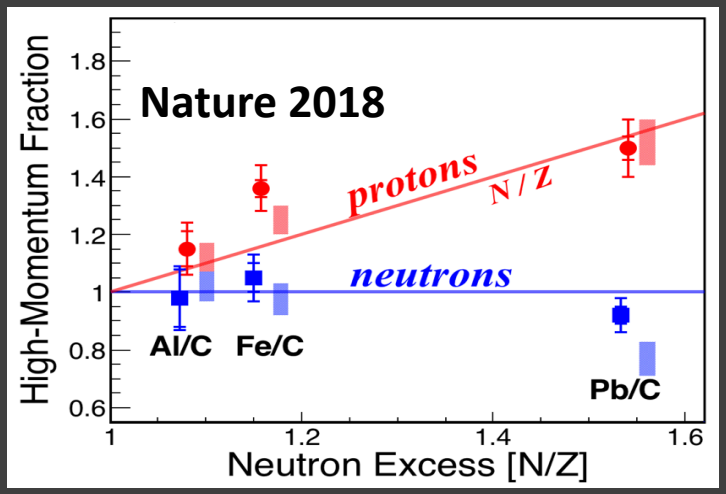

NN Interaction

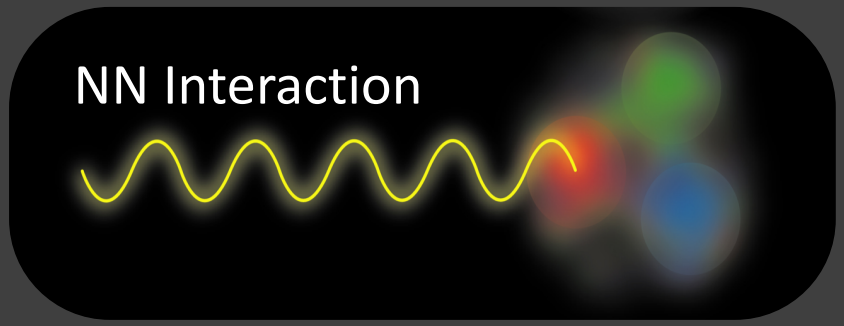

Nature 2020
Yield [Counts/GeV]
p_{miss} [GeV/c]
10^3
10^2
10^1
10^0
0.4
0.5
0.6
0.7
0.8
0.9
1.0

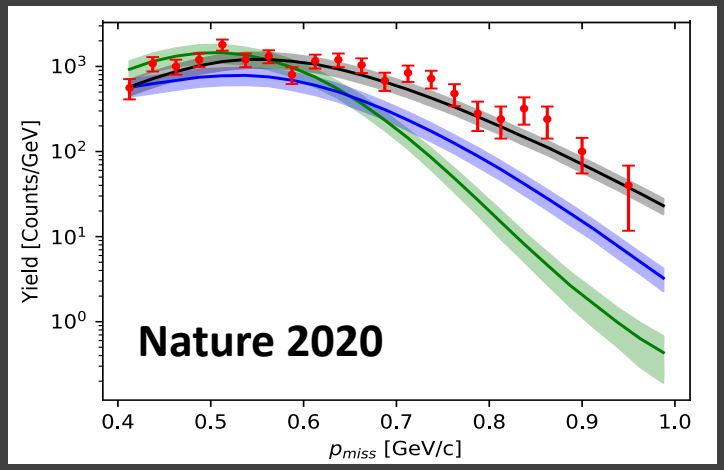

Nucleon
Sub-Structure

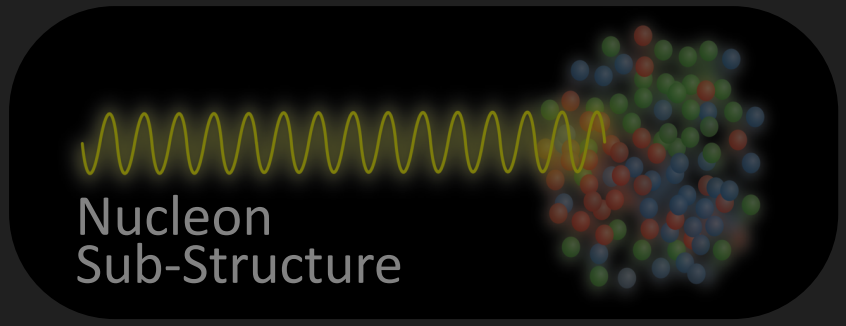

Nature 2019
$\frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} / n_{SRC}^d$
0.05
0
-0.05
Median norm. uncertainty
0.2
0.4
0.6
0.8
x_B
208
197
56
27
12
9
4
3
A

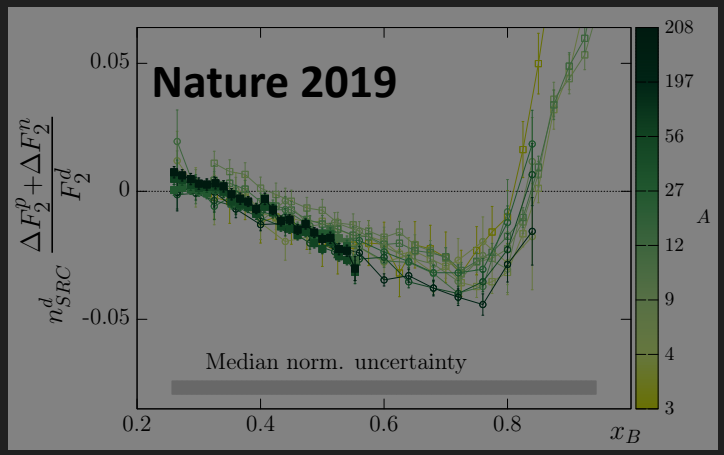

Many-Body System


Nature 2018
High-Momentum Fraction
Neutron Excess [N/Z]
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

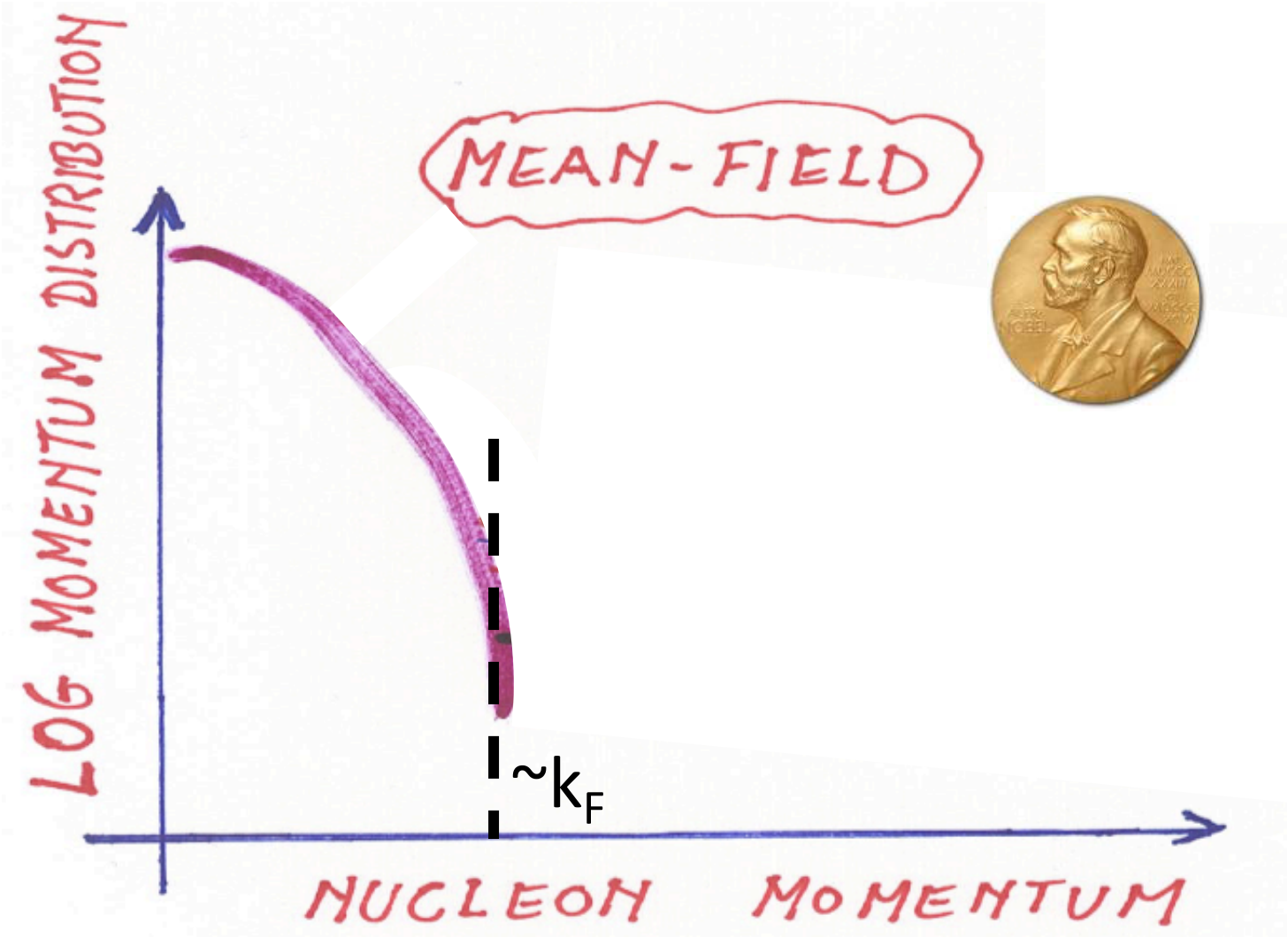

NN Interaction

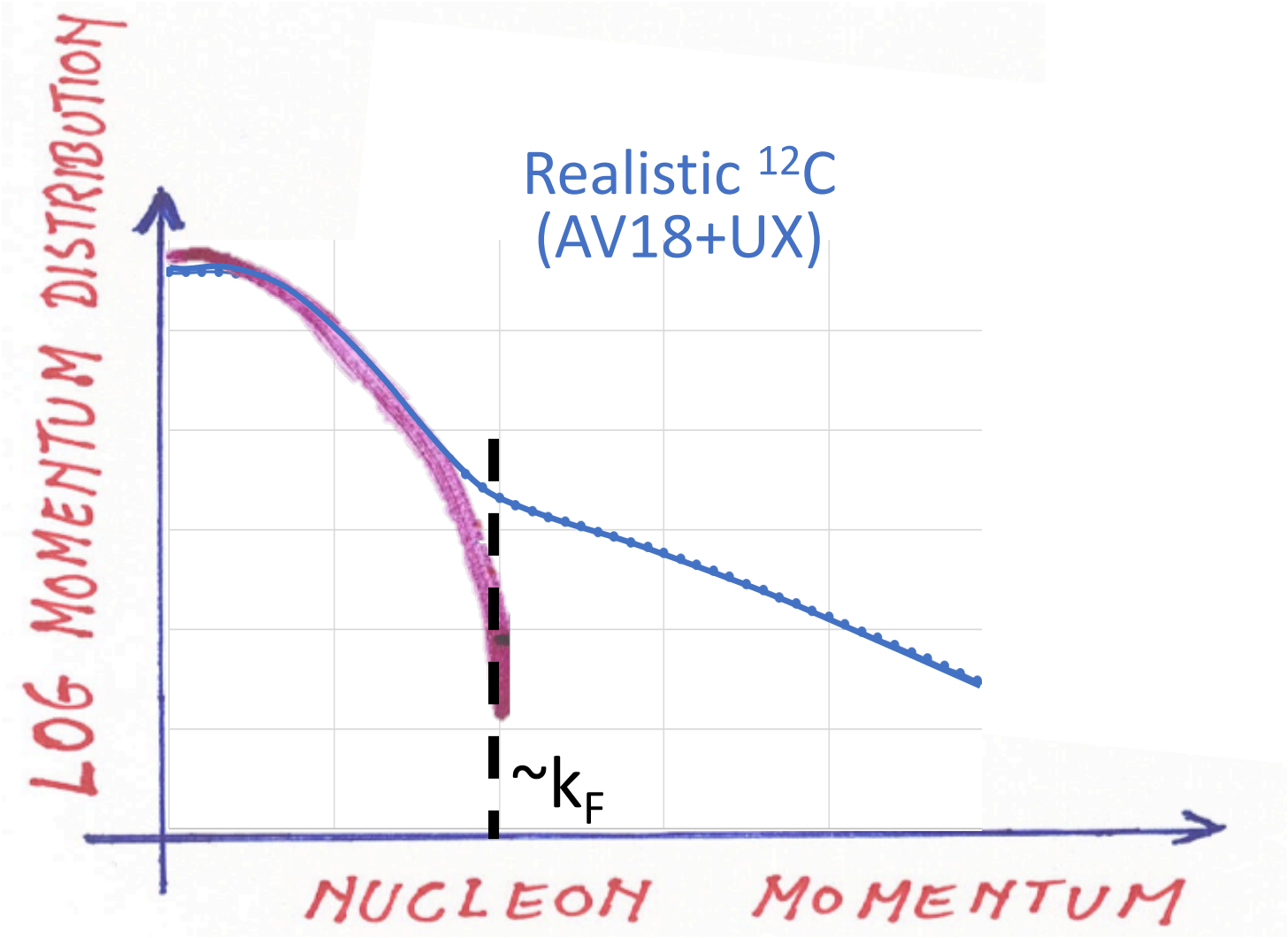

Nature 2020
Yield [Counts/GeV]
p_{miss} [GeV/c]
10^3
10^2
10^1
10^0
0.4
0.5
0.6
0.7
0.8
0.9
1.0


Nucleon
Sub-Structure

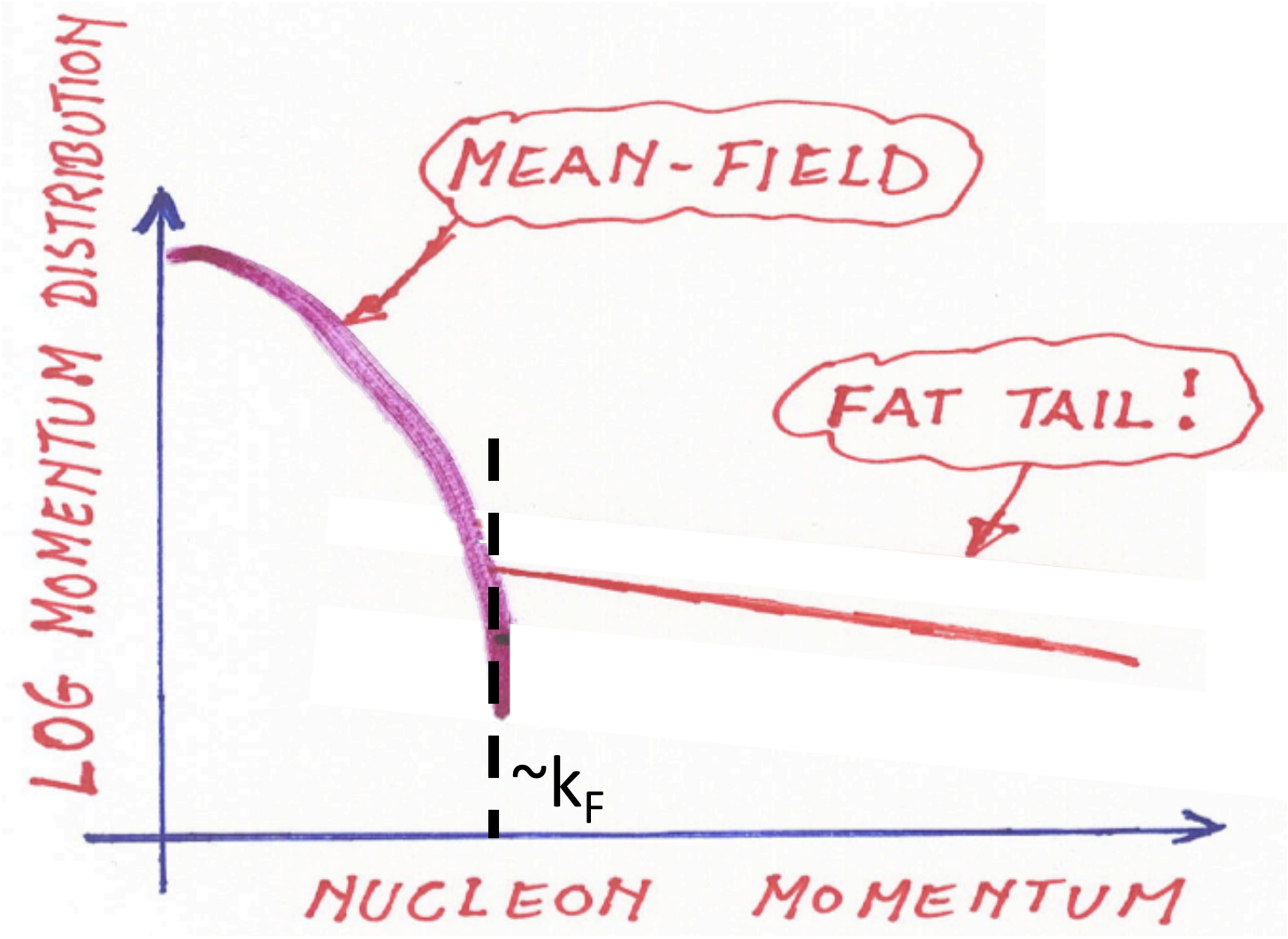

Nature 2019
$\frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} / n_{SRC}^d$
x_B
Median norm. uncertainty
0.05
0
-0.05
0.2
0.4
0.6
0.8
208
197
56
27
12
9
4
3
A

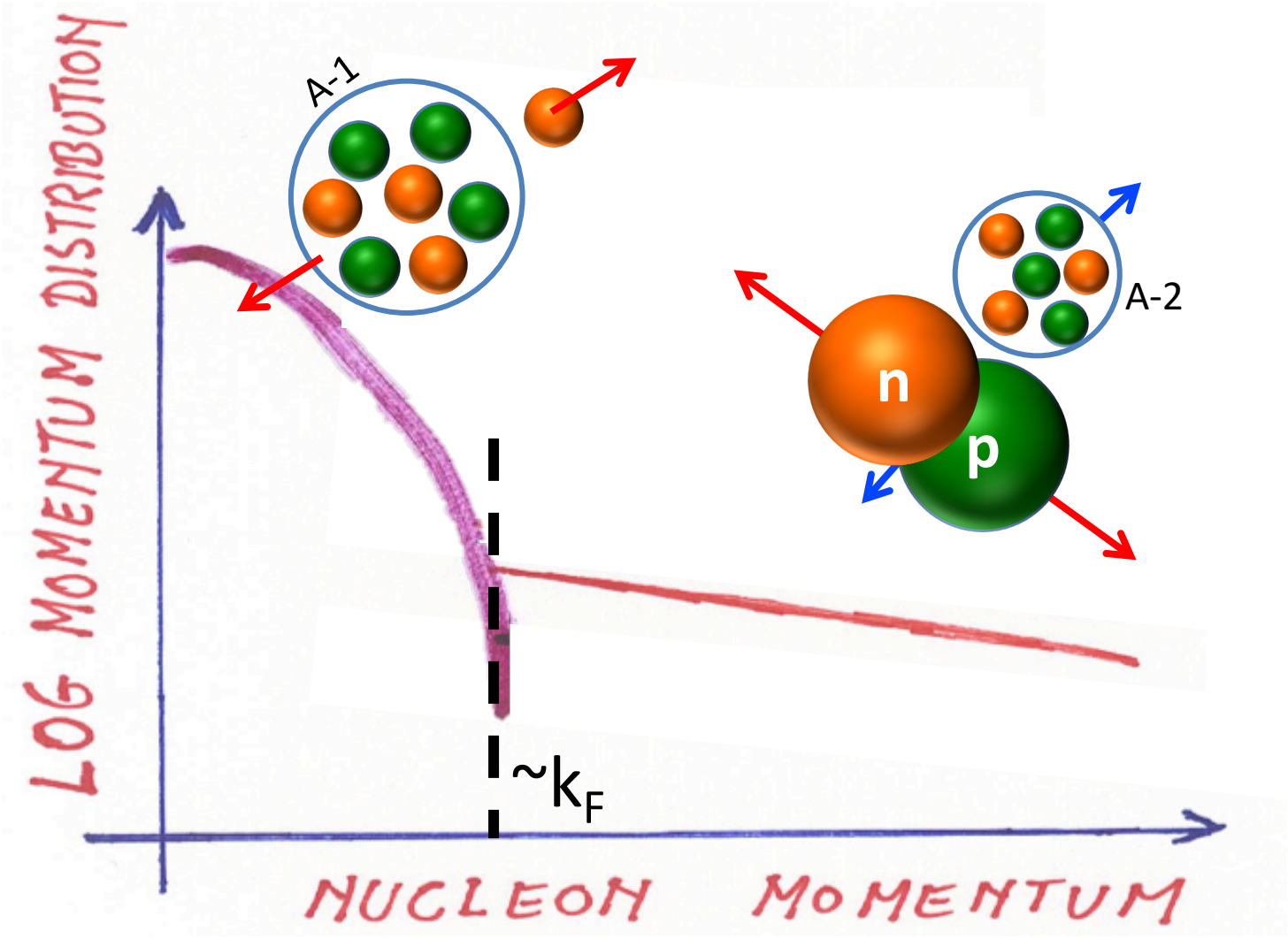
Looking For Correlations



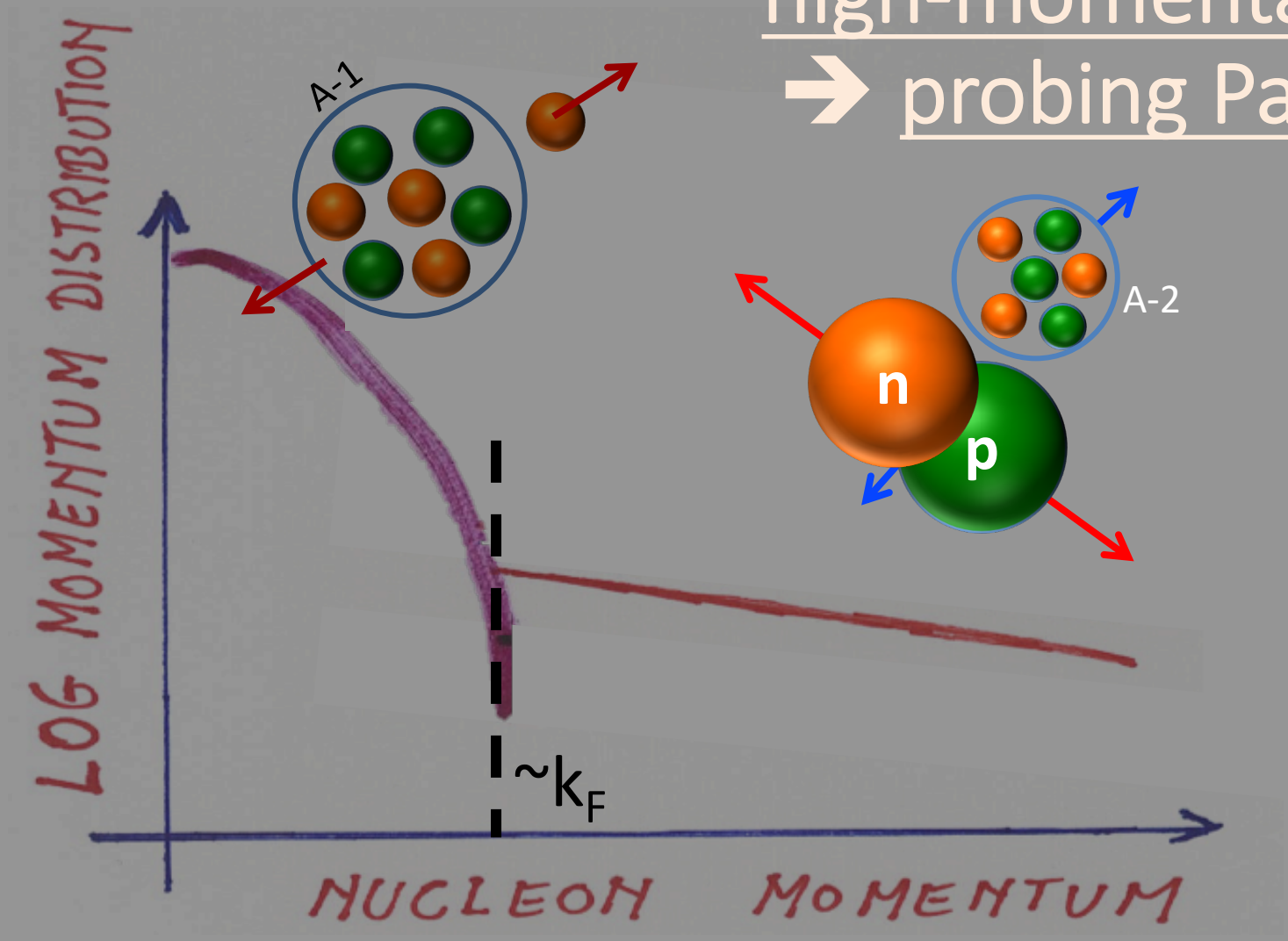


Wiringa, PRC (2014); Carlson, RMP (2015); …

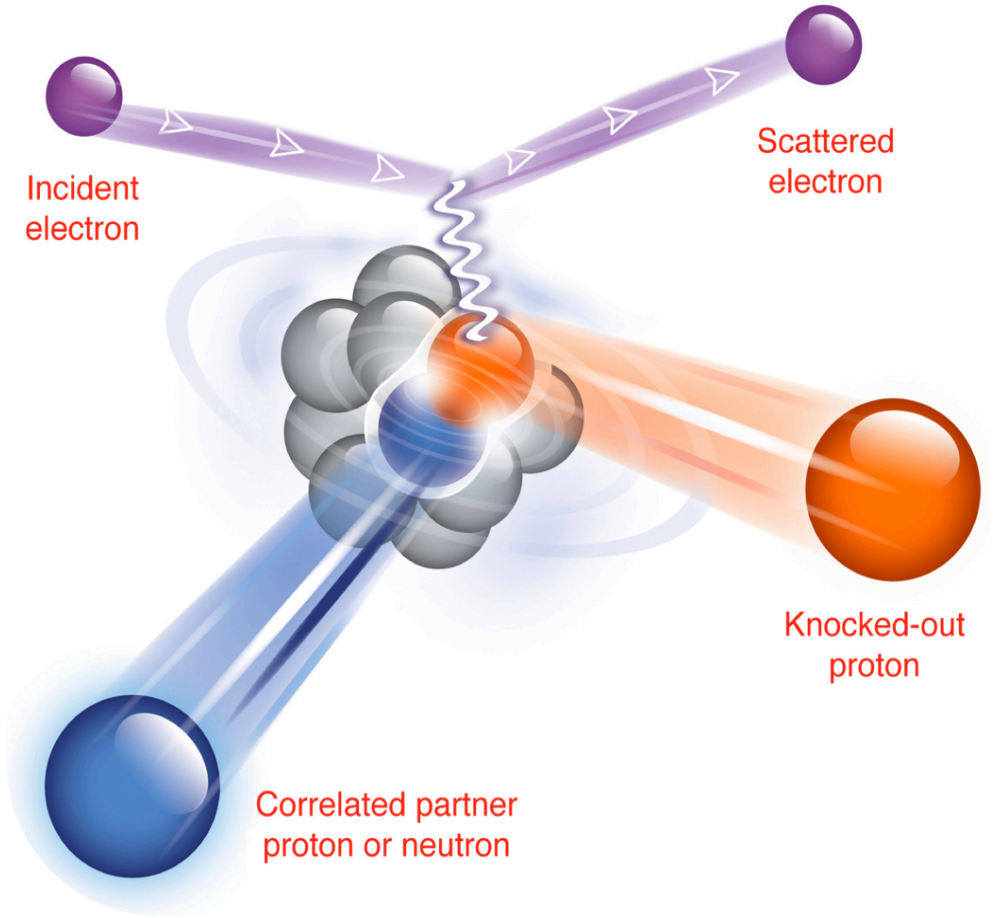

LOG MOMENTUM DISTRIBUTION
MEAN-FIELD
FAT TAIL!
~k_F
NUCLEON MOMENTUM


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

high-momenta
➔ probing Pairs

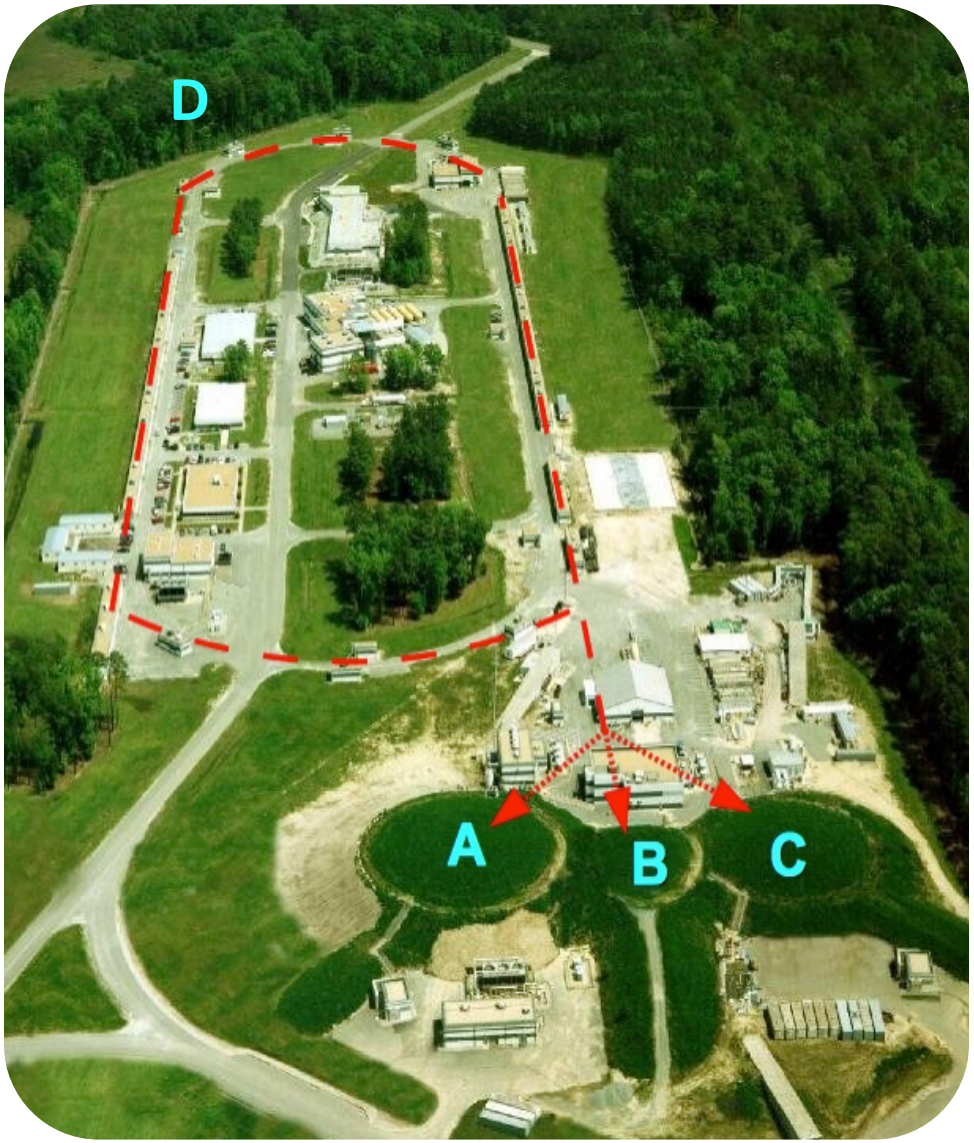


Breakup the pair =>
Detect ***both*** nucleons =>
Reconstruct 'initial' state

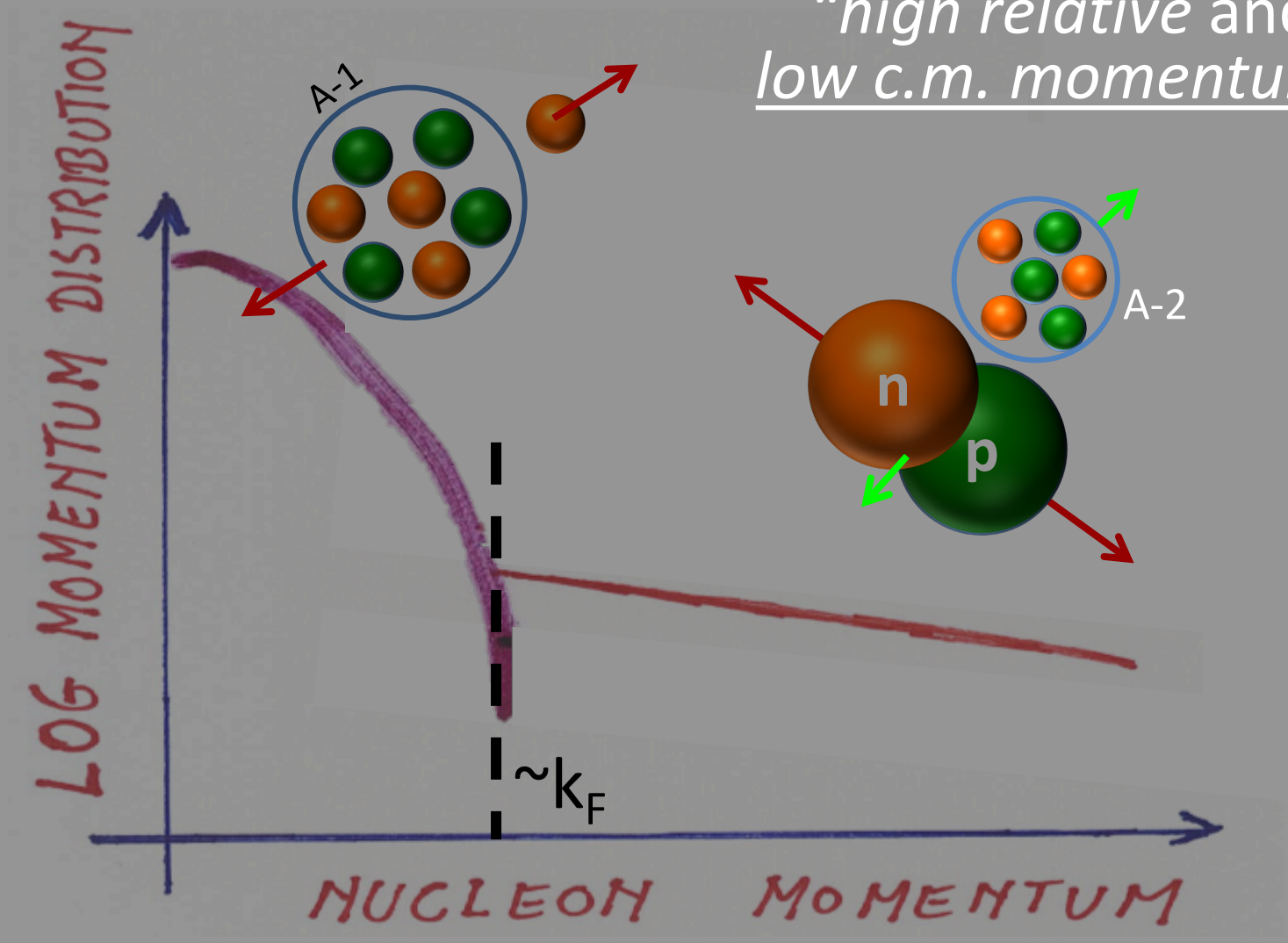


Jefferson-Lab National Accelerator Facility

- Virginia, USA.
- Electron beam.
  [12 GeV; ~80 uA; polarized]
- 4 experimental halls.
- Approved program for coming decade; Leading to the EIC.

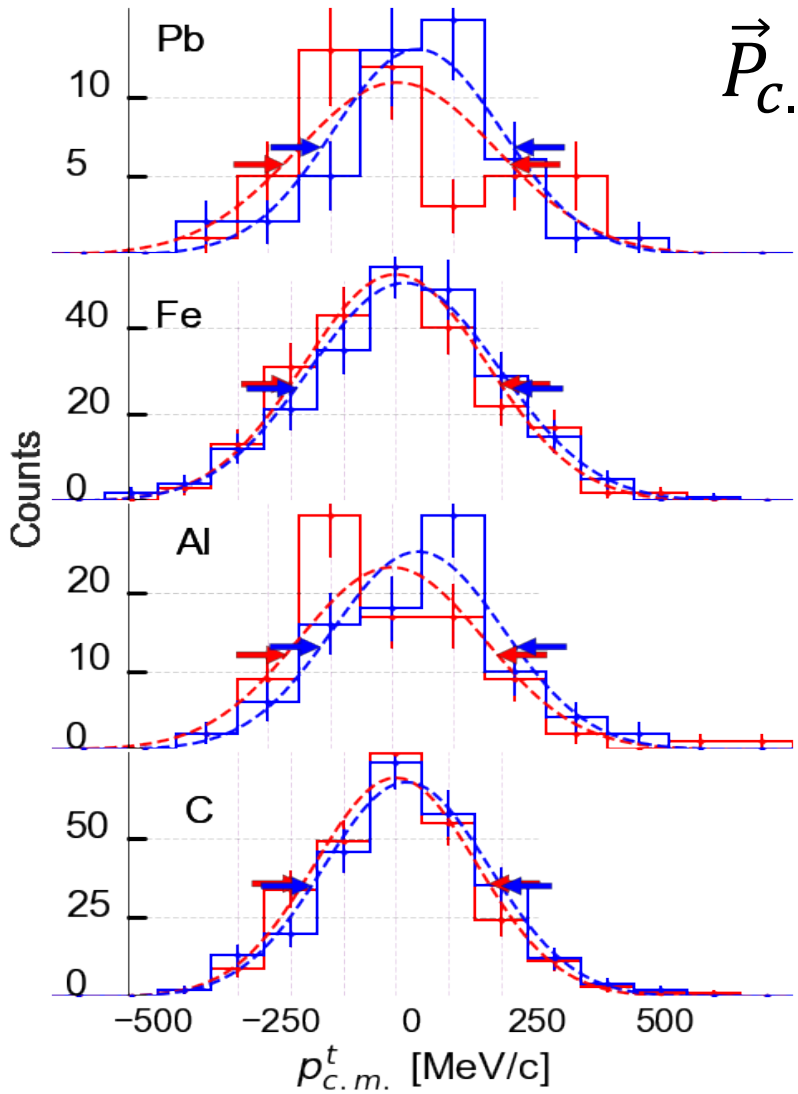


"high relative and
low c.m. momentum"



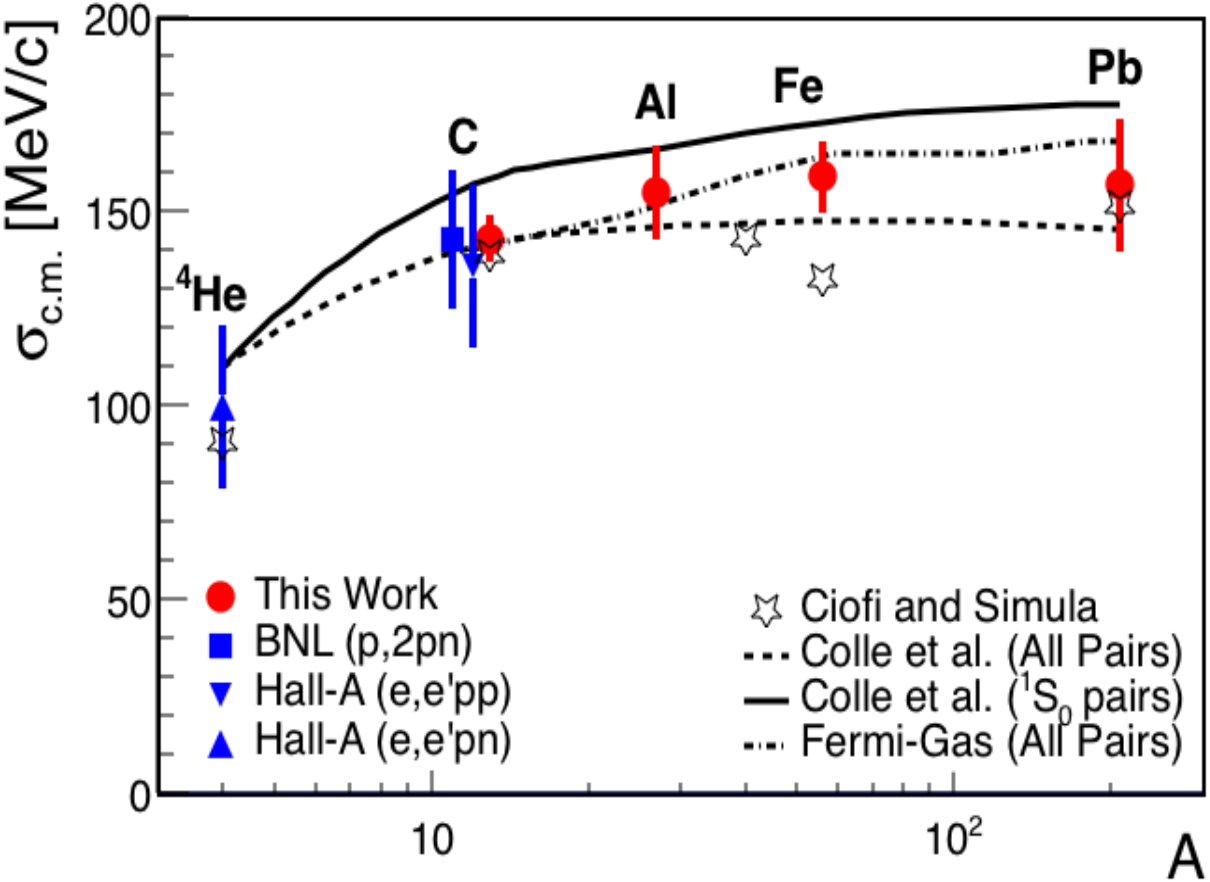
Low Pair C.M. Motion

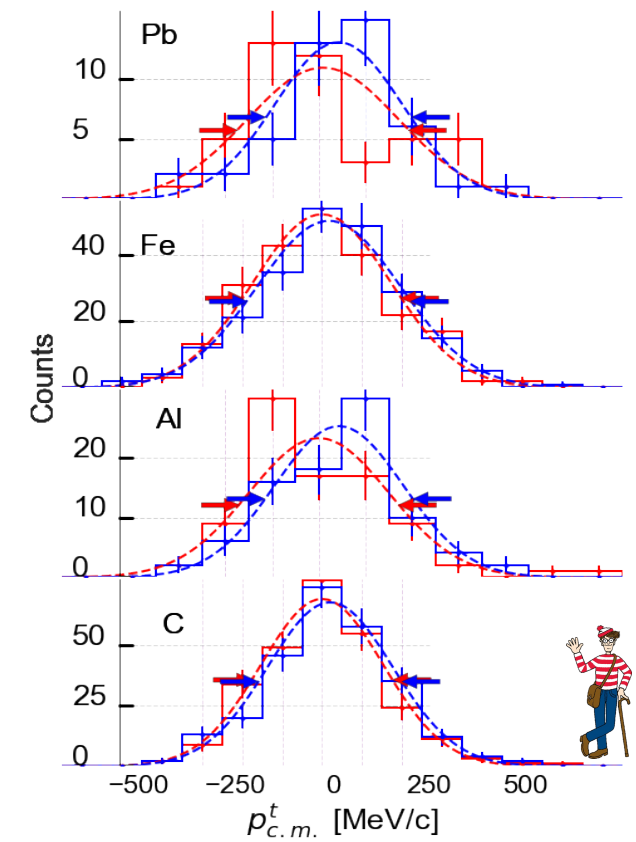
$$\vec{P}_{c.m.} = \vec{P}_{N1} + \vec{P}_{N2}$$



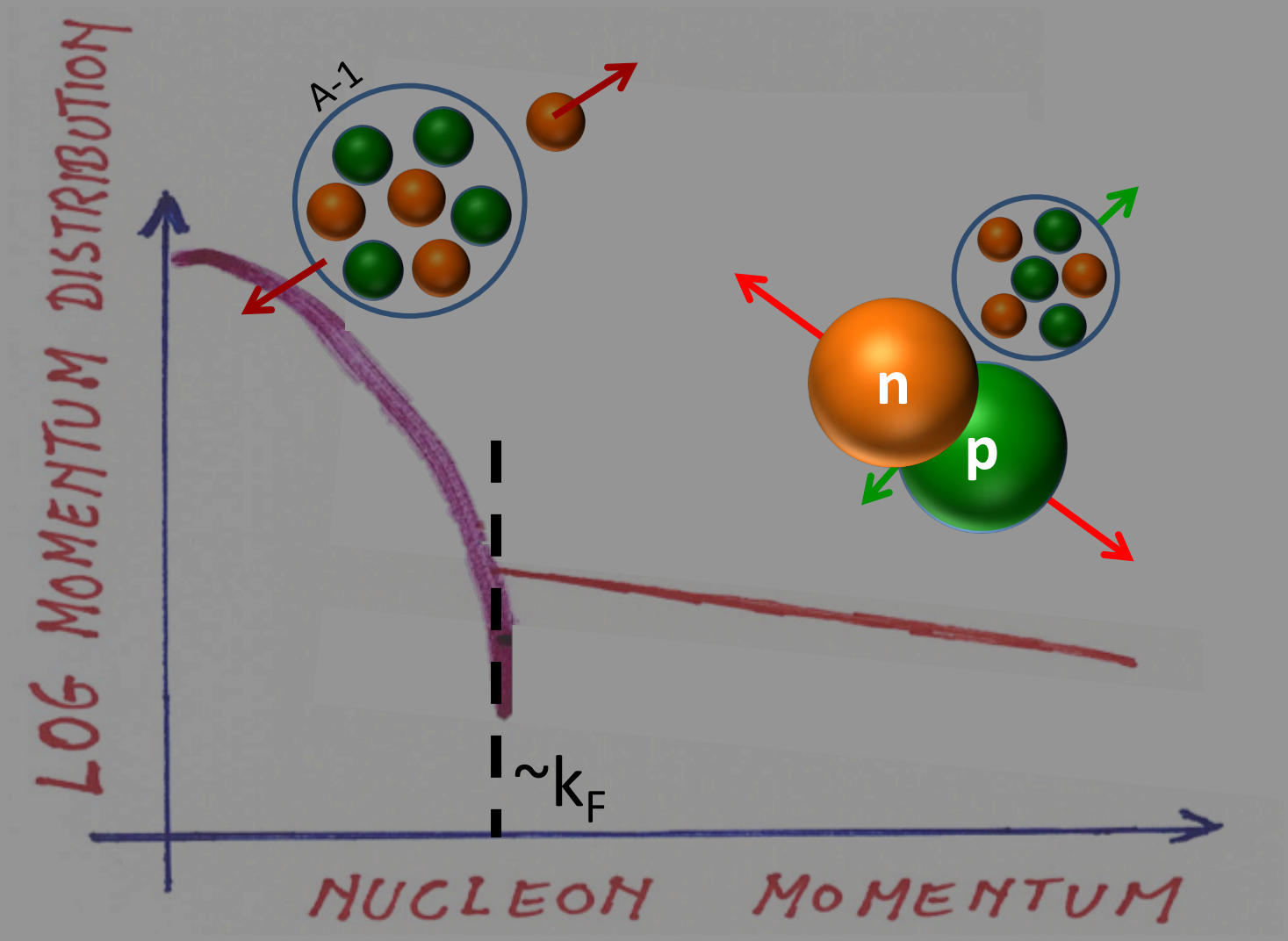
Cohen, PRL (2018).

Consistent \w combining two mean-field nucleons

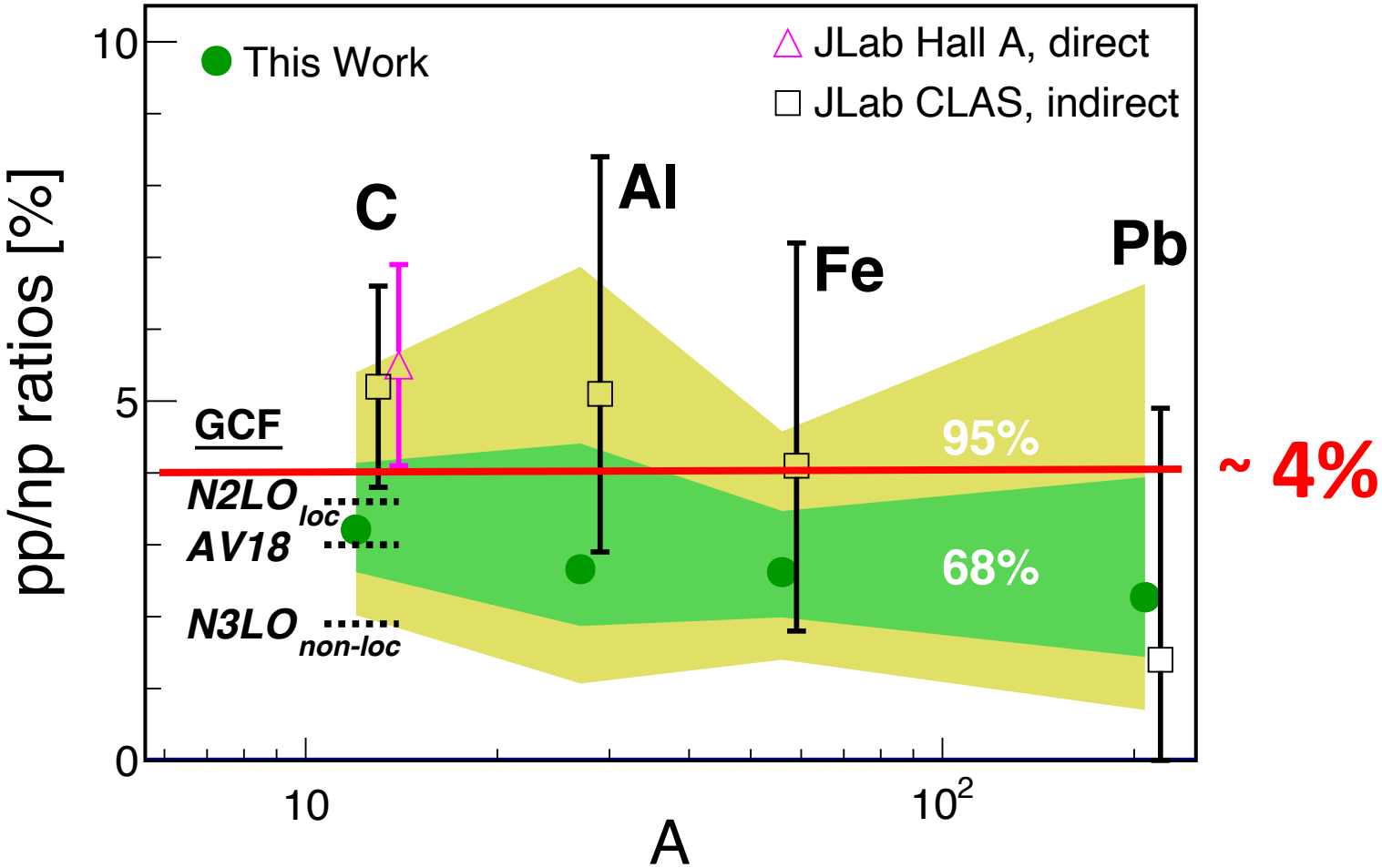




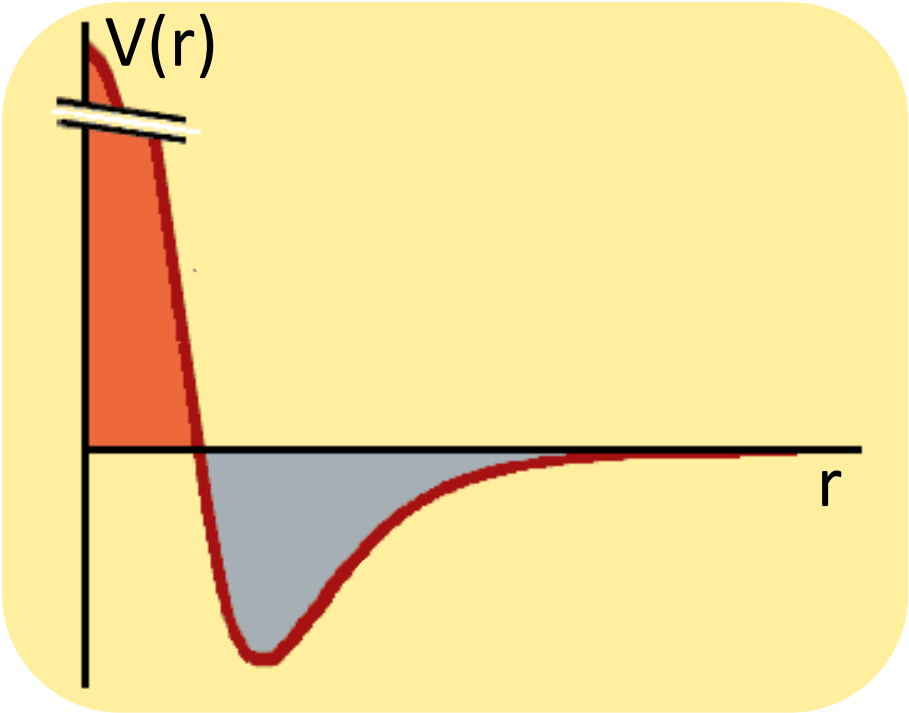
Cohen, PRL (2018),
Korover, PRL (2014),
Shneor, PRL (2007),
Tang, PRL (2003).

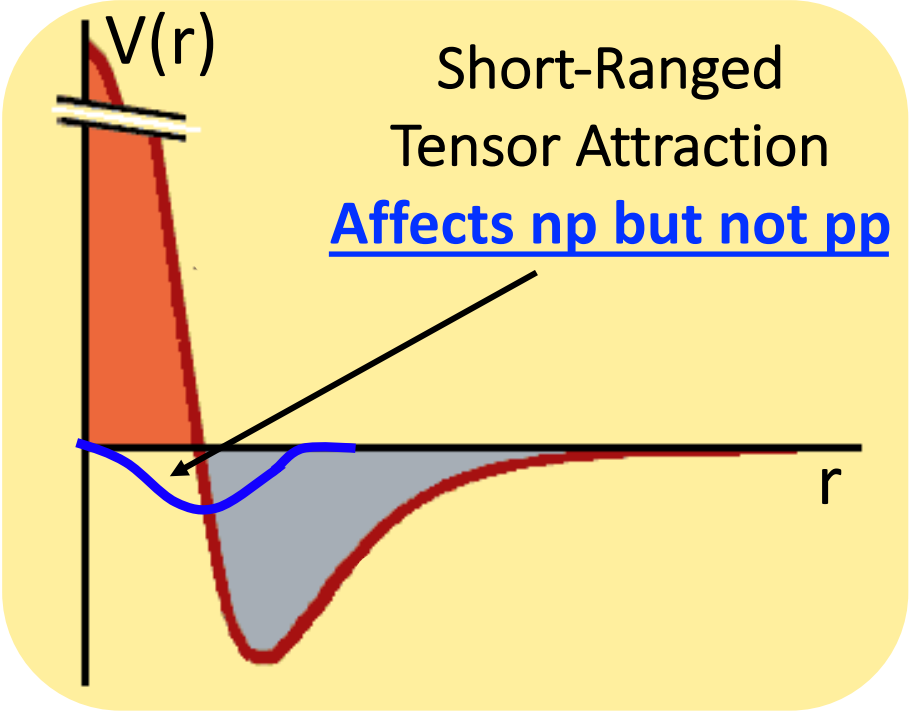

LOG MOMENTUM DISTRIBUTION
A-1
n
p
~k_F
NUCLEON MOMENTUM

np pairs predominate



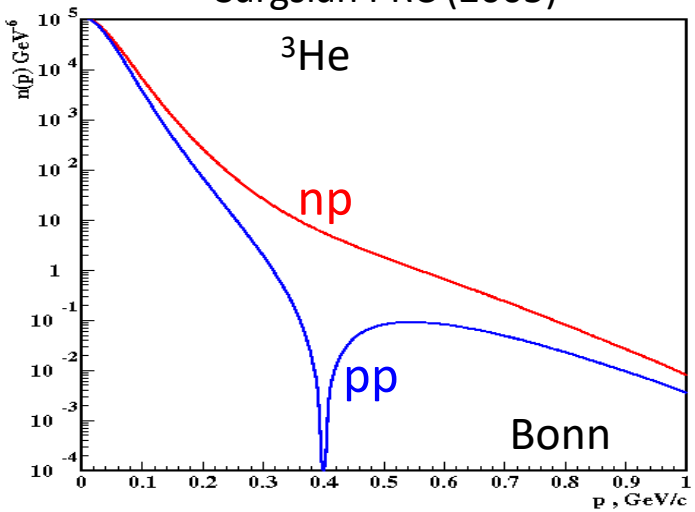
Duer, PRL (2019); Duer, Nature (2018); Hen, Science (2014); Korover, PRL (2014); Subedi, Science (2008); Shneor, PRL (2007); Piasetzky, PRL (2006); Tang, PRL (2003); Review: Hen RMP (2017);


V(r)
r

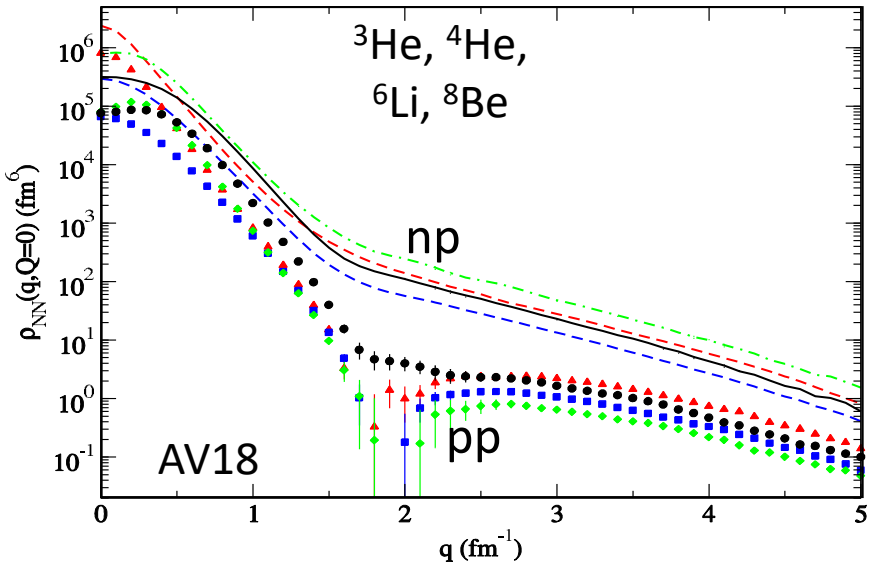

V(r)
Short-Ranged
Tensor Attraction
Affects np but not pp
r

Also seen in ab-initio pair distributions

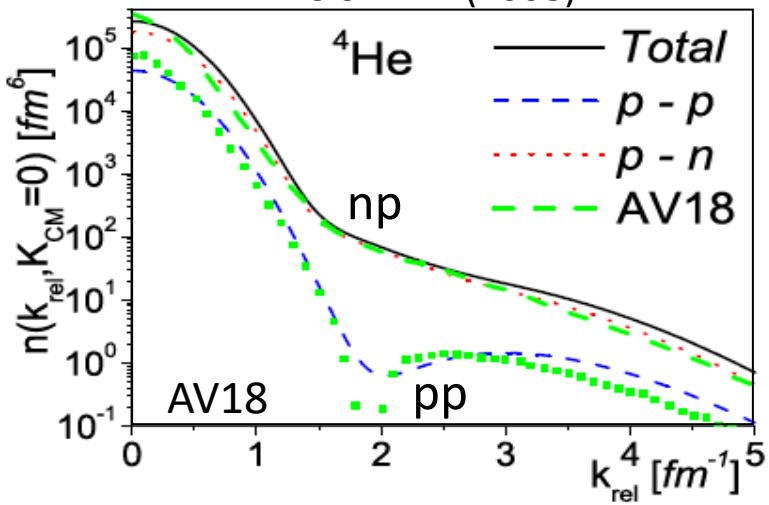
Sargsian PRC (2005)



Schiavilla PRL (2007)



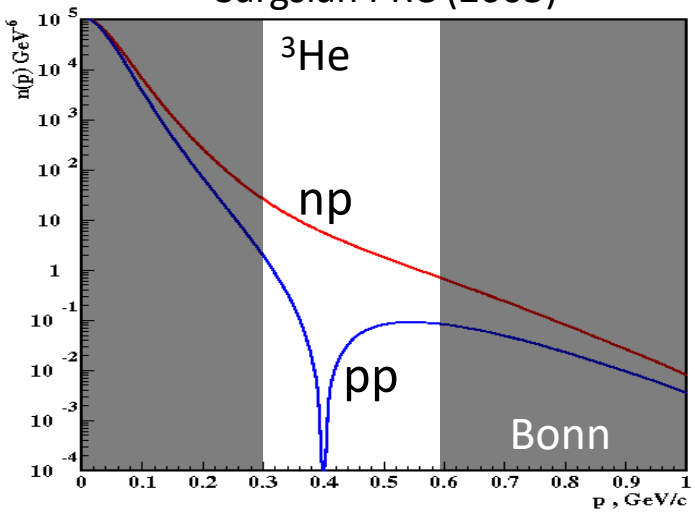
Ciofi PRL (2008)



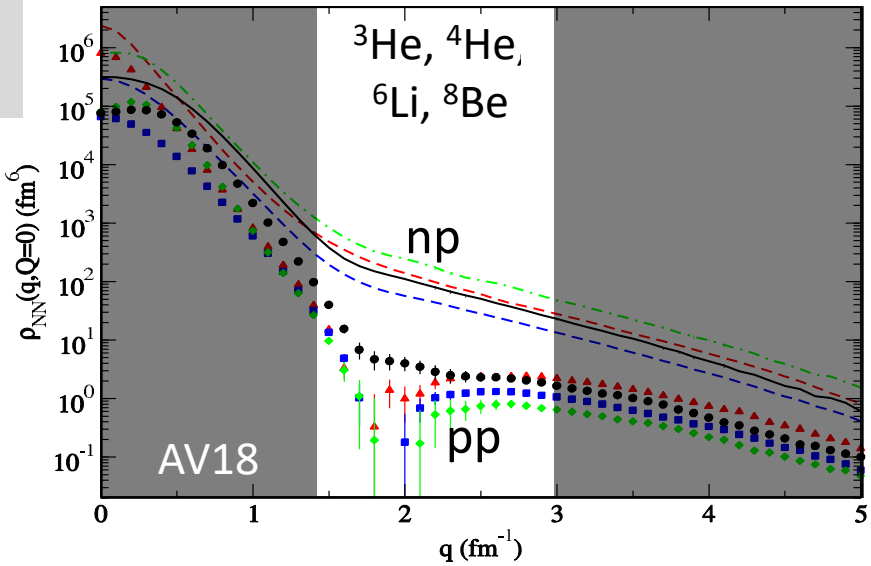
Also seen in ab-initio pair distributions

300 – 600 MeV/c Window

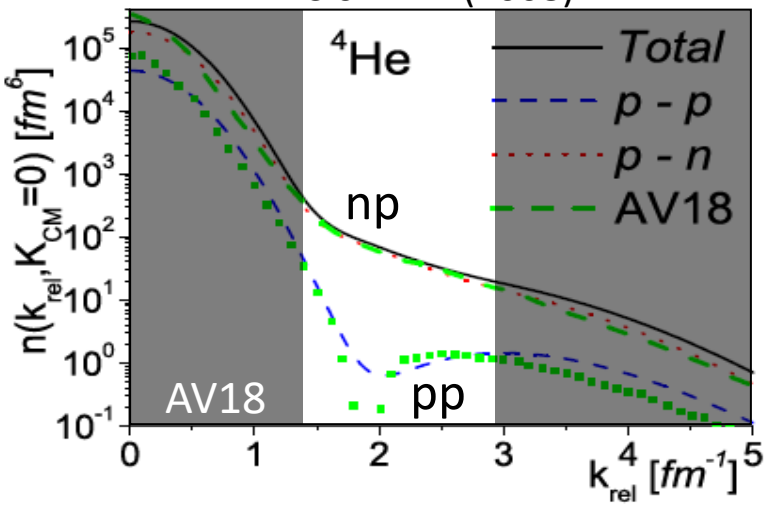
Sargsian PRC (2005)

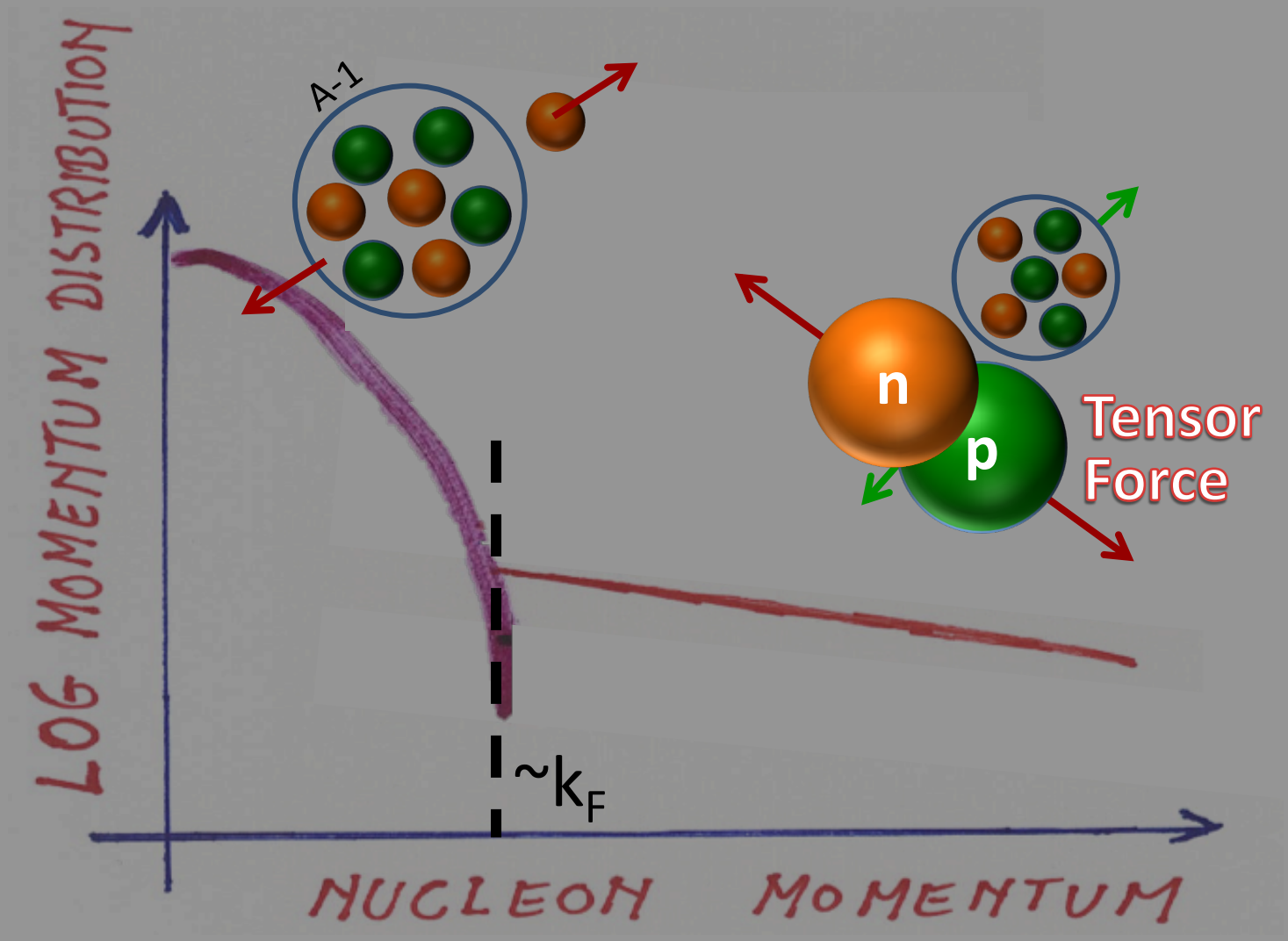


Schiavilla PRL (2007)



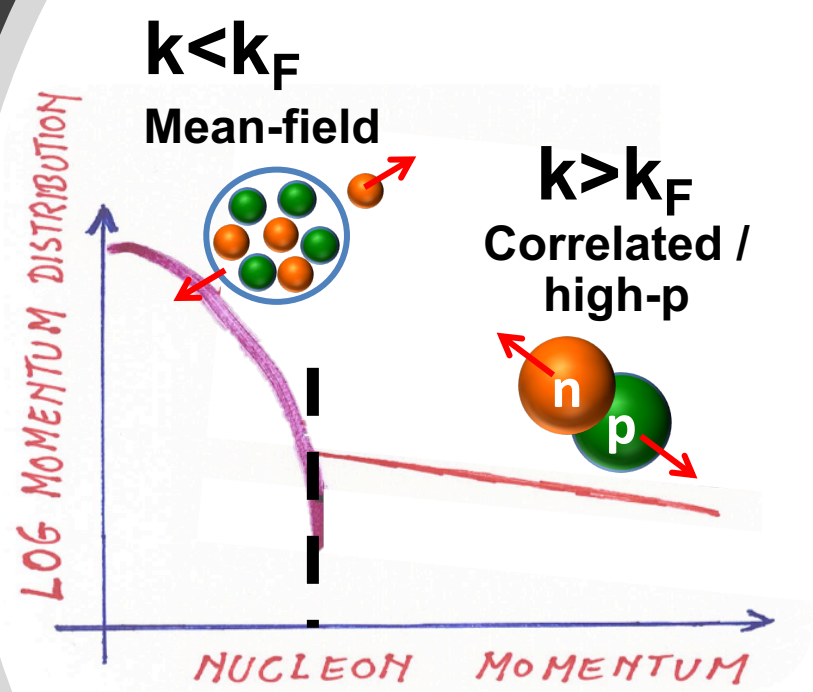
Ciofi PRL (2008)




LOG MOMENTUM DISTRIBUTION
A-1
n
p
Tensor
Force
~k_F
NUCLEON MOMENTUM

Interim Summary

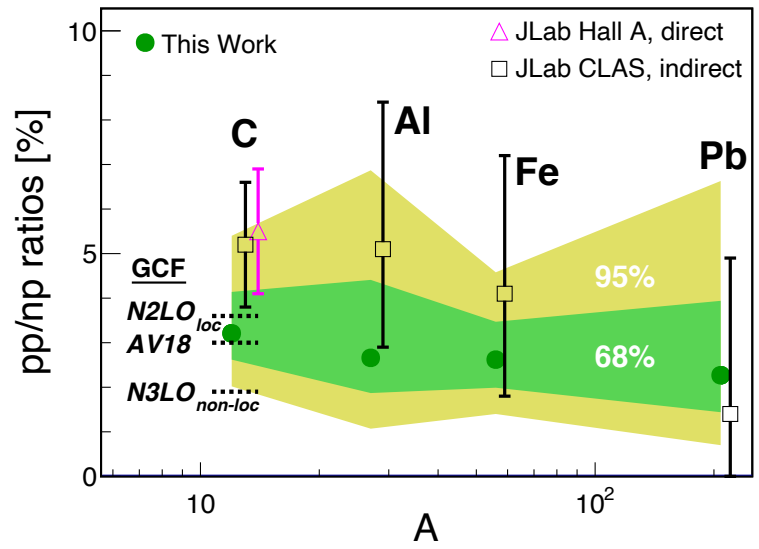
- Nuclear momentum distribution has two distinct regions.



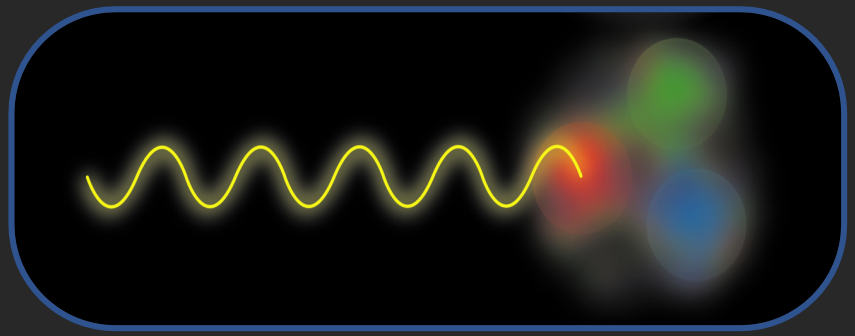
Interim Summary

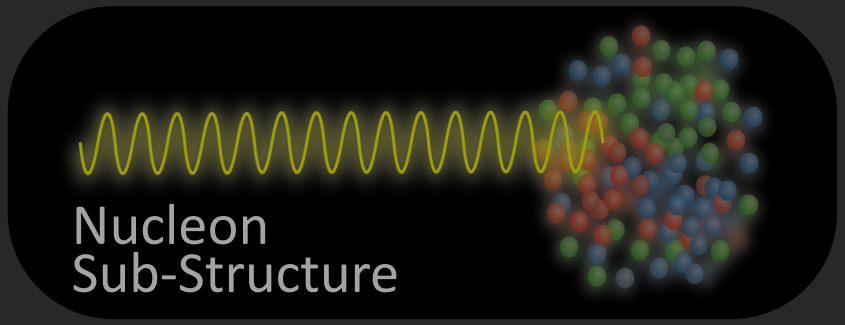
- Nuclear momentum distribution has two distinct regions.
- np-SRC dominate between ~ k_F – 2.5 k_F

  (Tensor Force)



Short-Ranged Interaction





Probing the NN Interaction

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

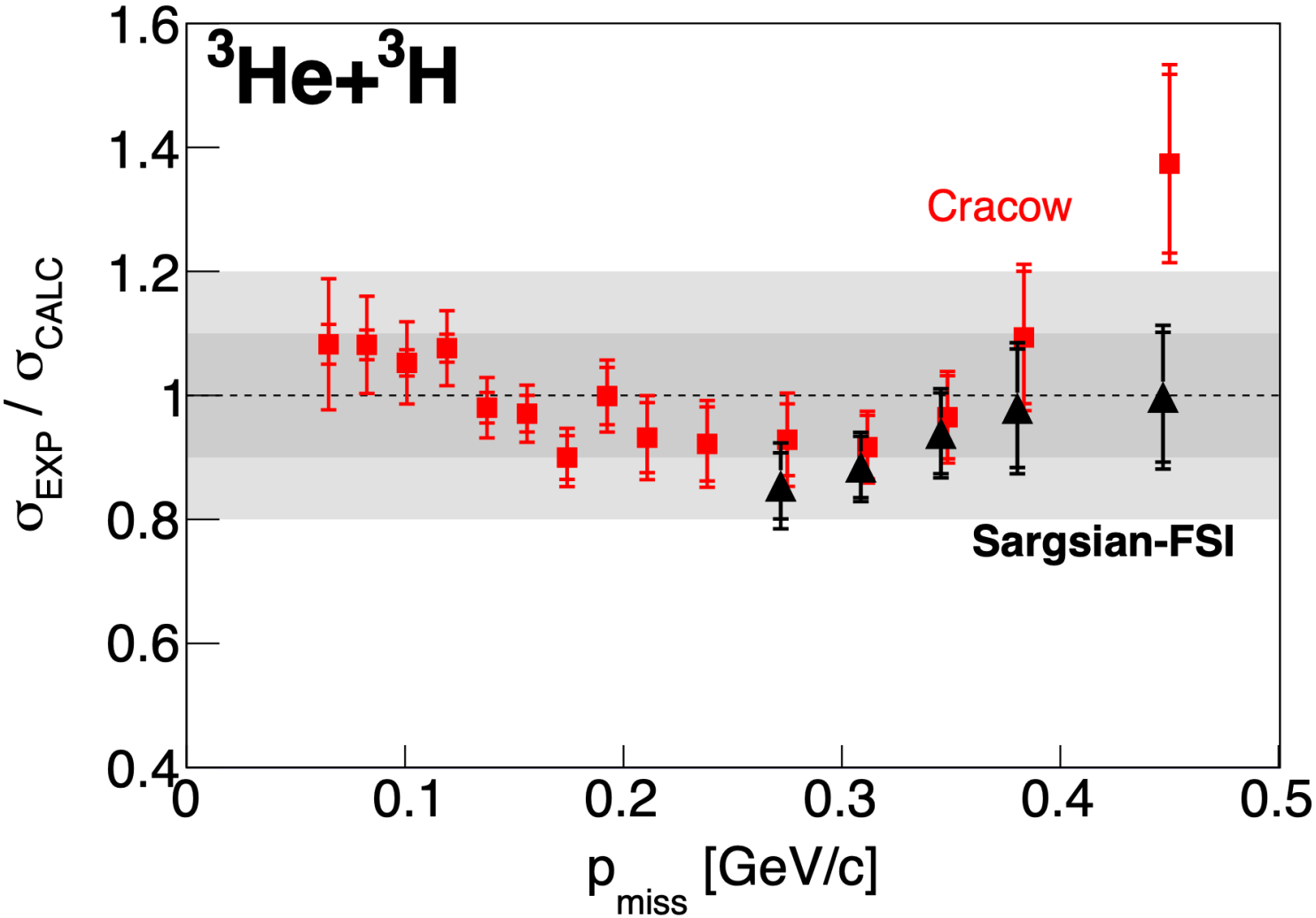
Probing the NN Interaction

<u>What's needed?</u>

- Data

- Ab-initio cross-section calculations

Works Well for A=3! \w limited stat



Cruz Torres and Nguyen et al., PRL (2020)

Probing the NN Interaction

<u>What's needed?</u>

✓ Data

- ~~Ab-initio cross-section calculations~~

✓ Factorization \w spectral functions from NN interaction

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

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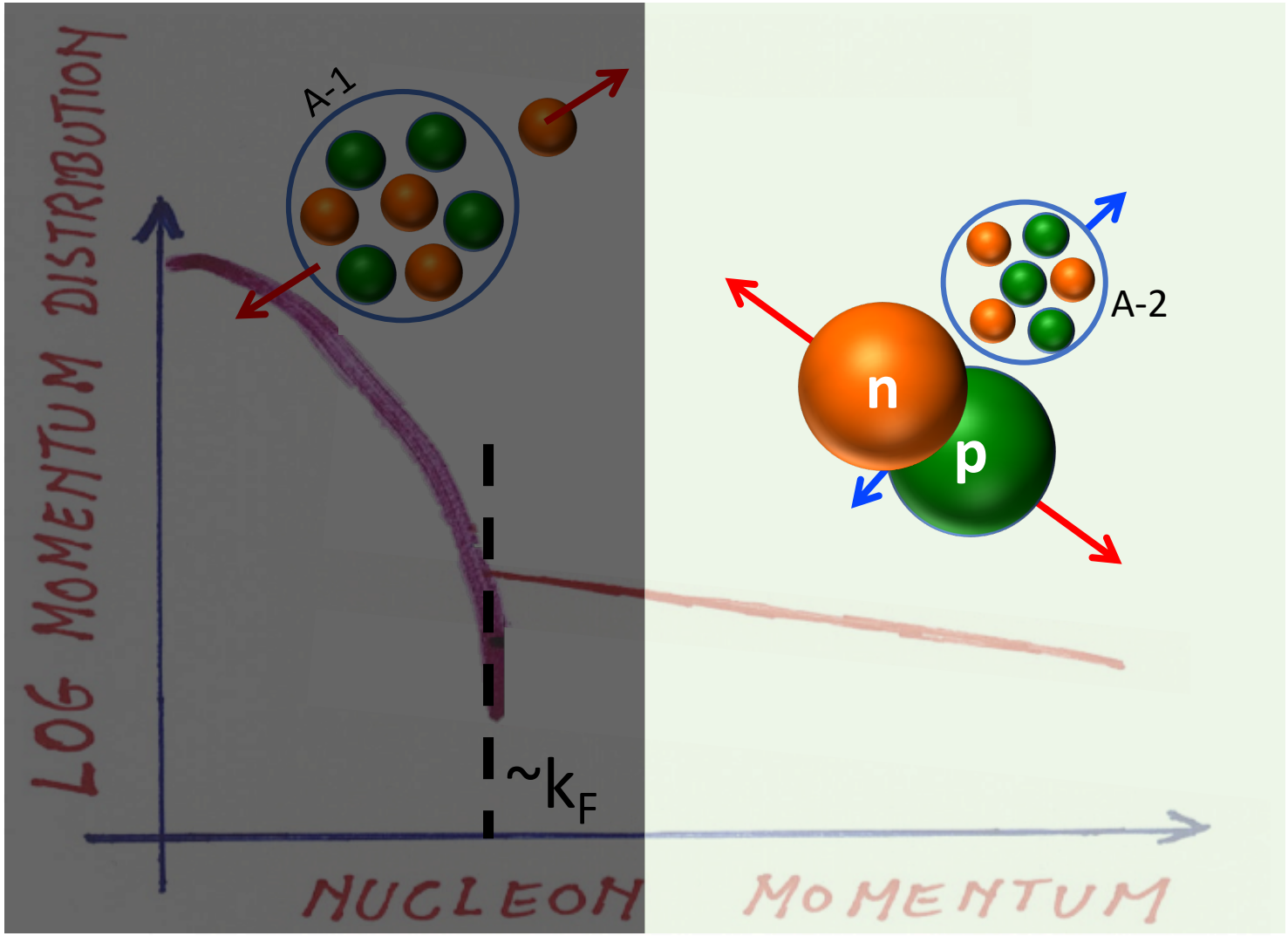
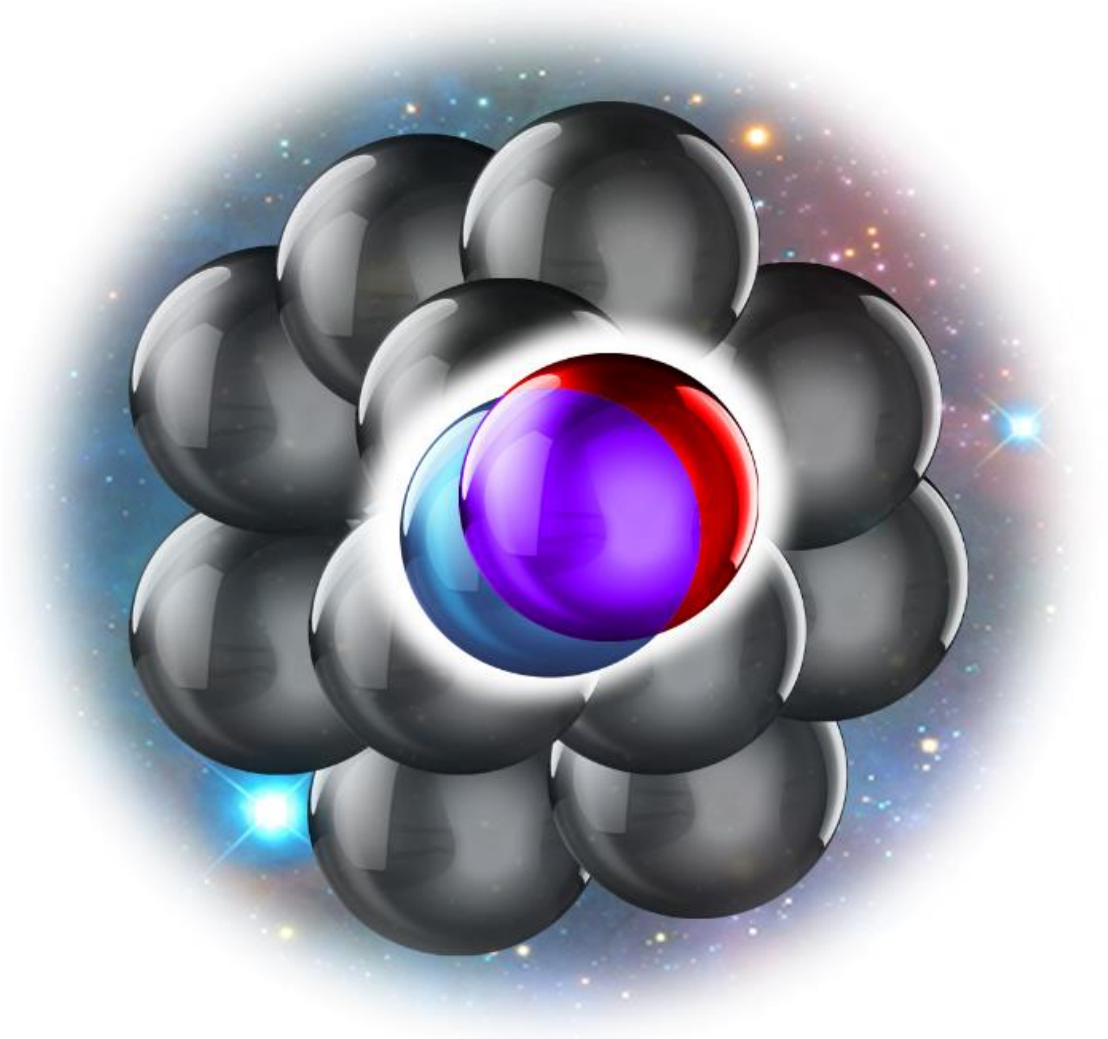
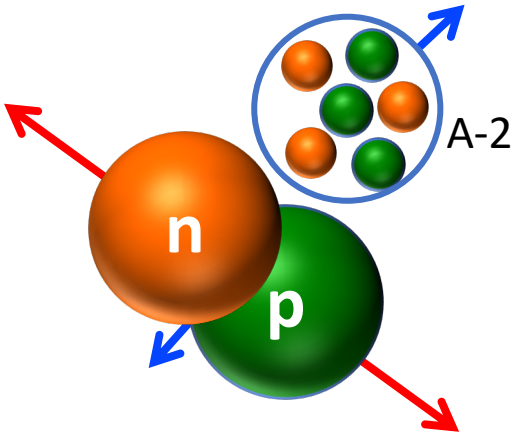
High-Momenta => Pairs Spectral Functions



Pairs ⇔ Scale Separation





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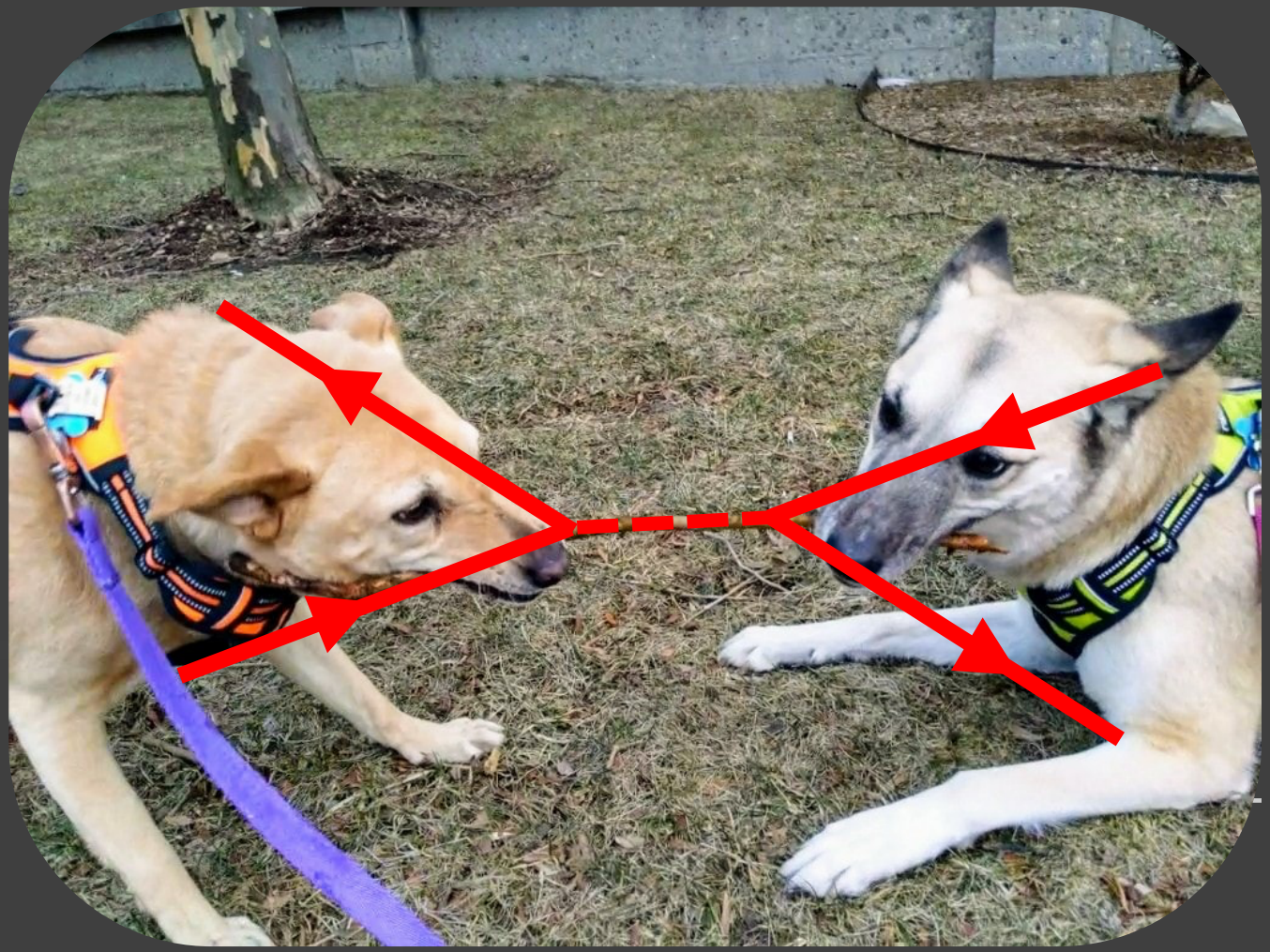
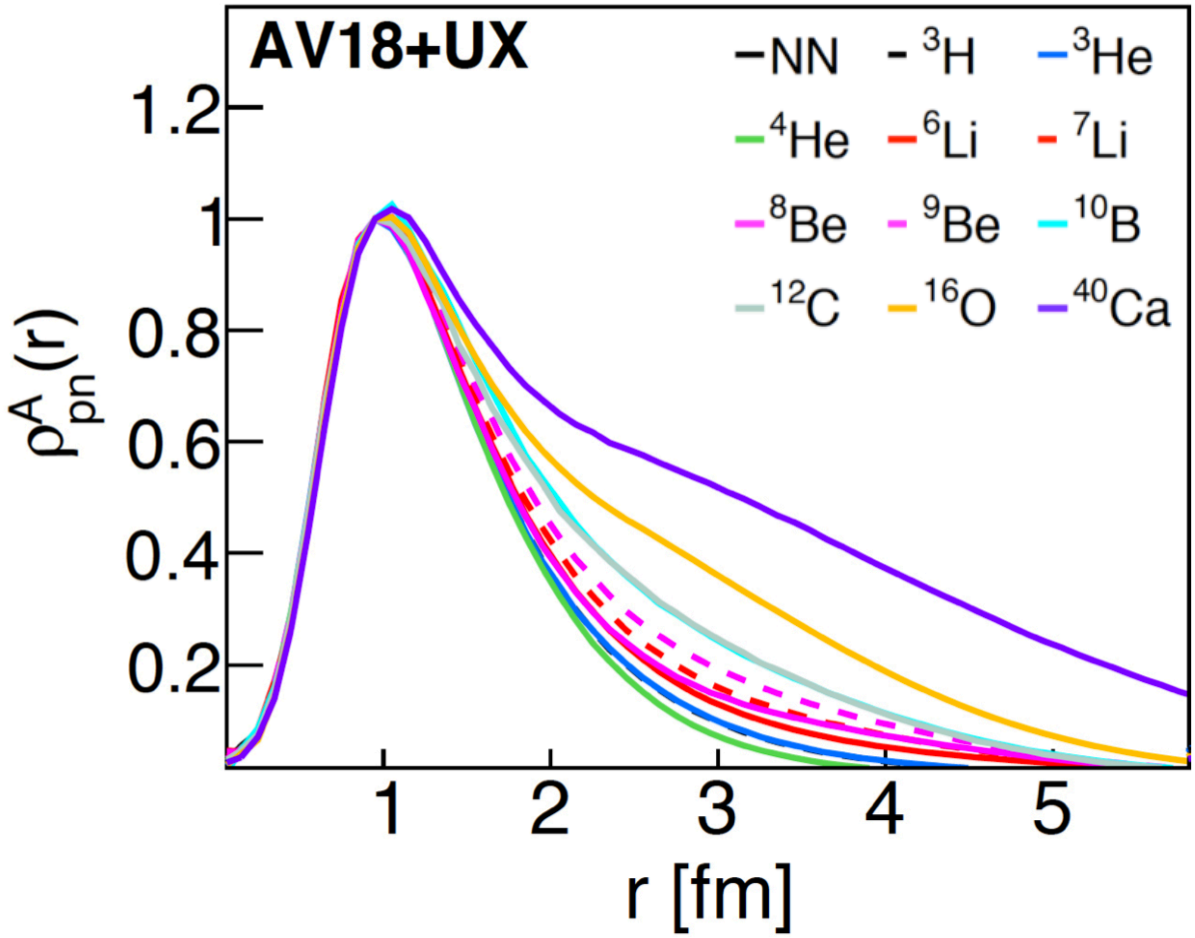
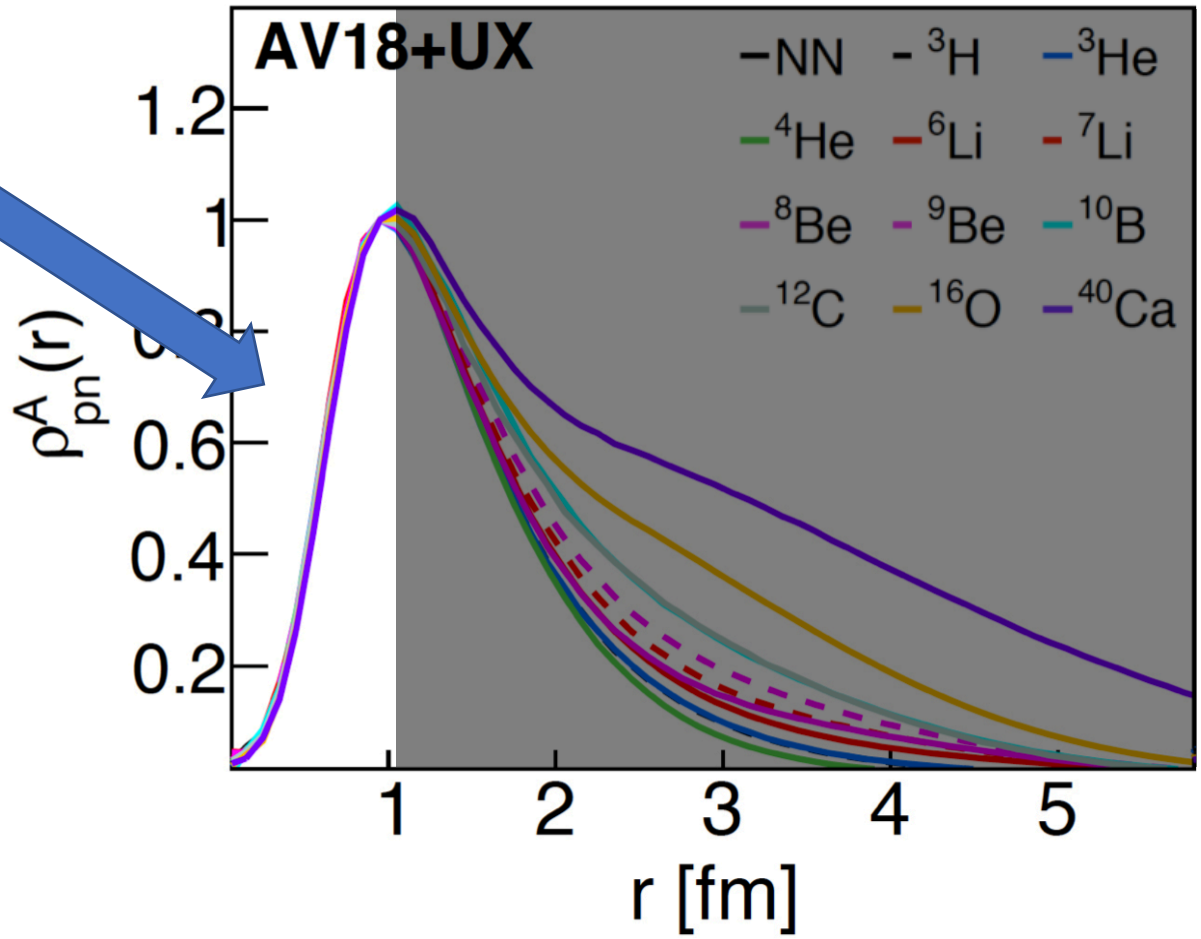


SRCs from Quantum Monte-Carlo (QMC): Pair Distance Distributions



Cruz Torres and Lonardoni et al., arXiv: 1907.03658 (2019)

Many Body = Constant x Two-Body



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

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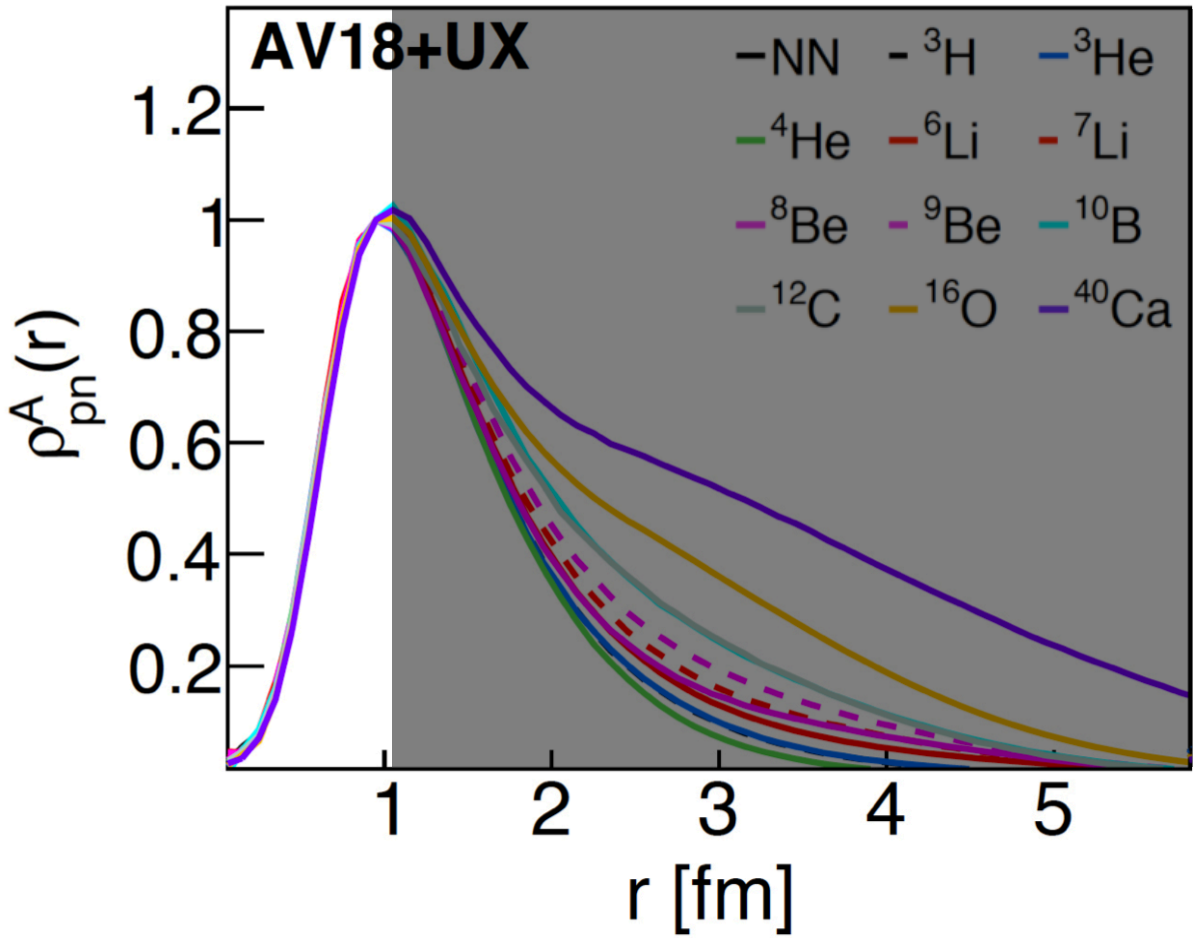
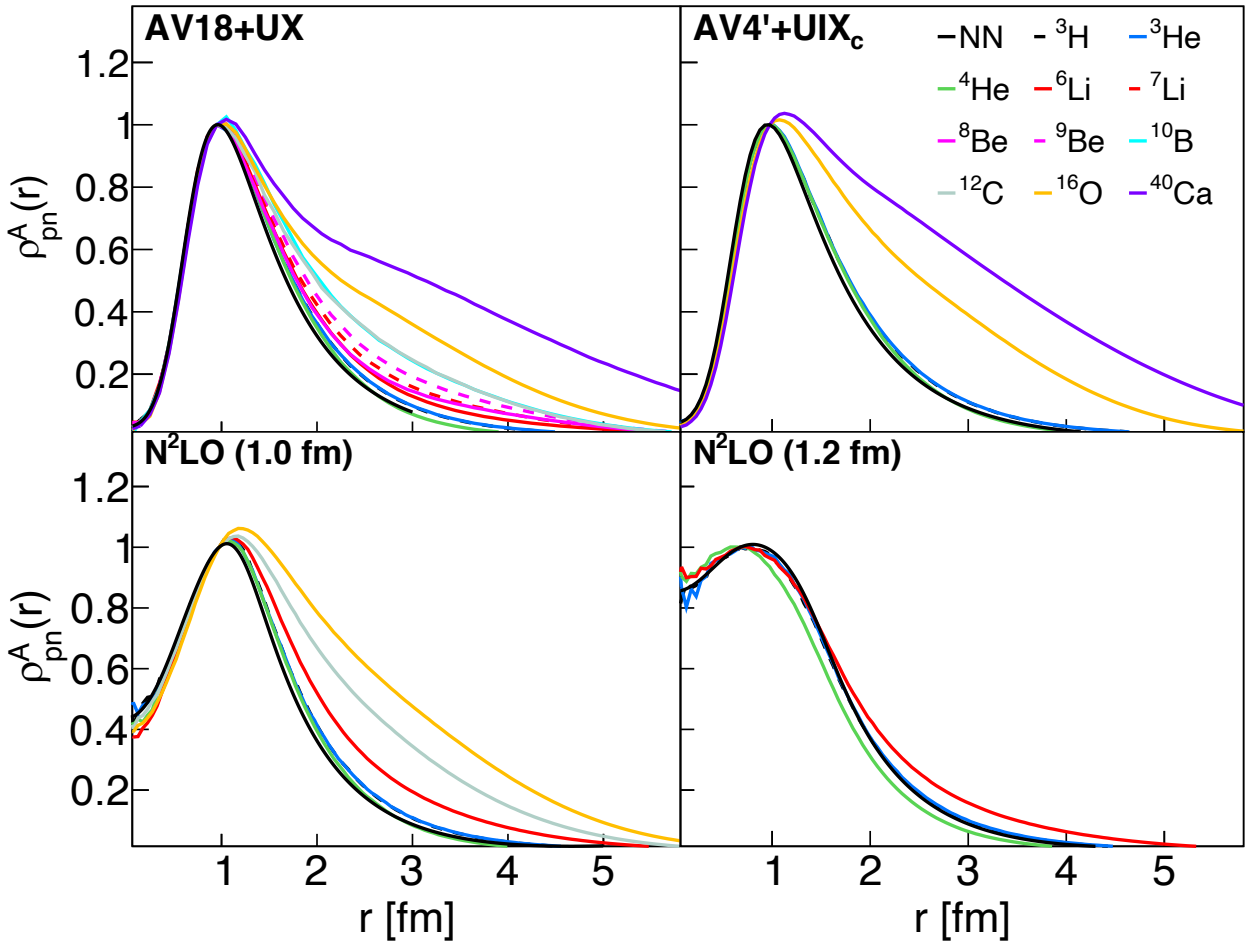


Cruz Torres and Lonardoni et al., arXiv: 1907.03658 (2019)

Factorization is Scheme Independent



Cruz Torres and Lonardoni et al., arXiv: 1907.03658 (2019)

Scale Separation

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

Total Dist. = Constant (Low-Energy) x Two-body (High-Energy)

Generalized Contact Formalism (GCF):

Pairs Spectral Functions

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

Weiss, Phys. Lett. B (2018); Cruz Torres, Phys. Lett B (2018); Weiss Phys. Lett B (2019).
+ many works by Claudio Ciofi; Jan Ryckebusch; Frankfurt Strikman; …

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Each pair is convoluted with c.m. motion:

$$
s_{ab}^{\alpha} = \frac{1}{4\pi} \int \frac{dp_2}{(2\pi)^3}\, \delta[f(p_2)]\, \underbrace{|\varphi_{ab}^{\alpha}(p_1 - p_2)/2|^2}_{\text{Relative}}\, \underbrace{n_{ab}^{\alpha}(p_1 + p_2)}_{\text{c.m.}}
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Weiss, Phys. Lett. B (2018); Cruz Torres, Phys. Lett B (2018); Weiss Phys. Lett B (2019).

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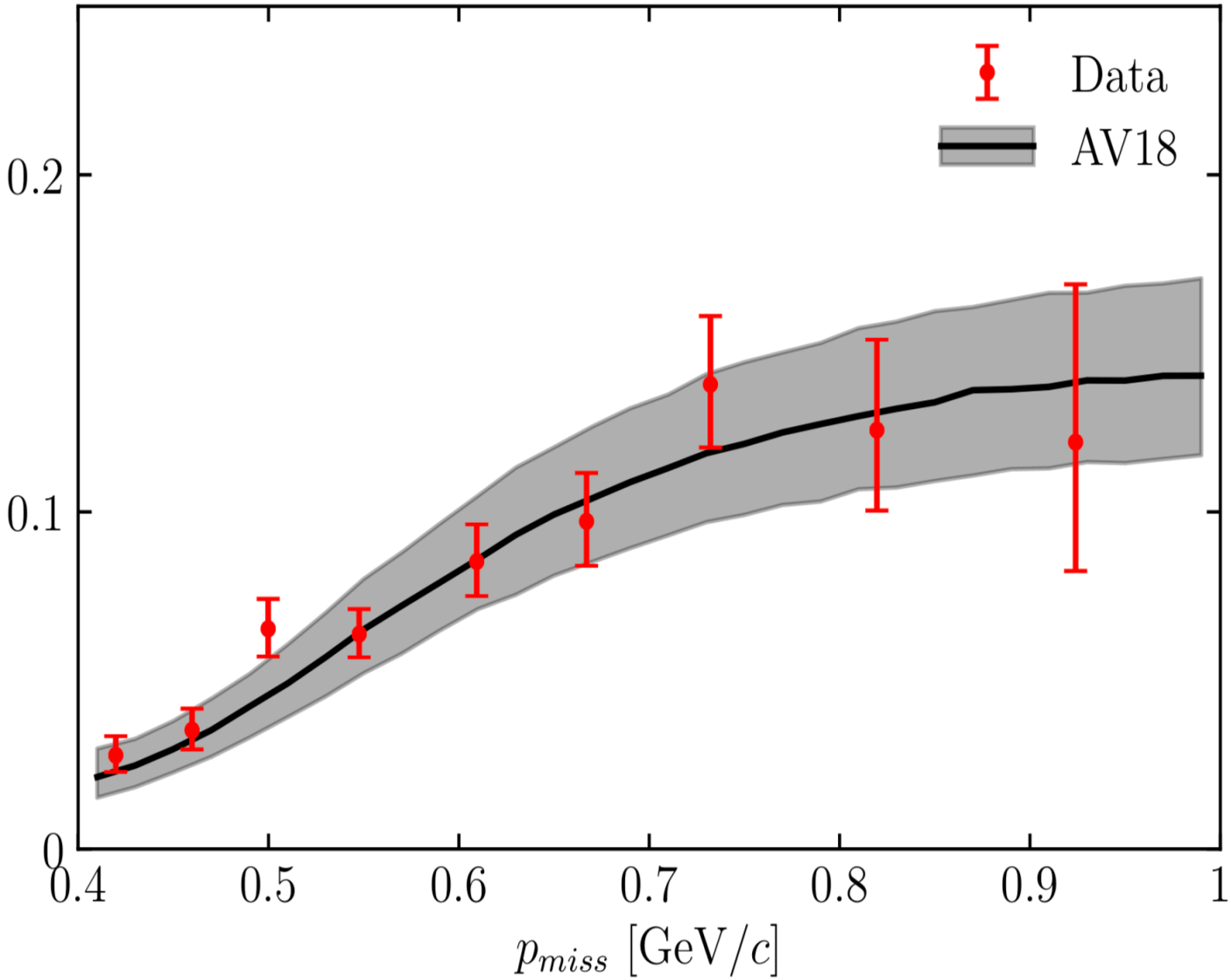
$$

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

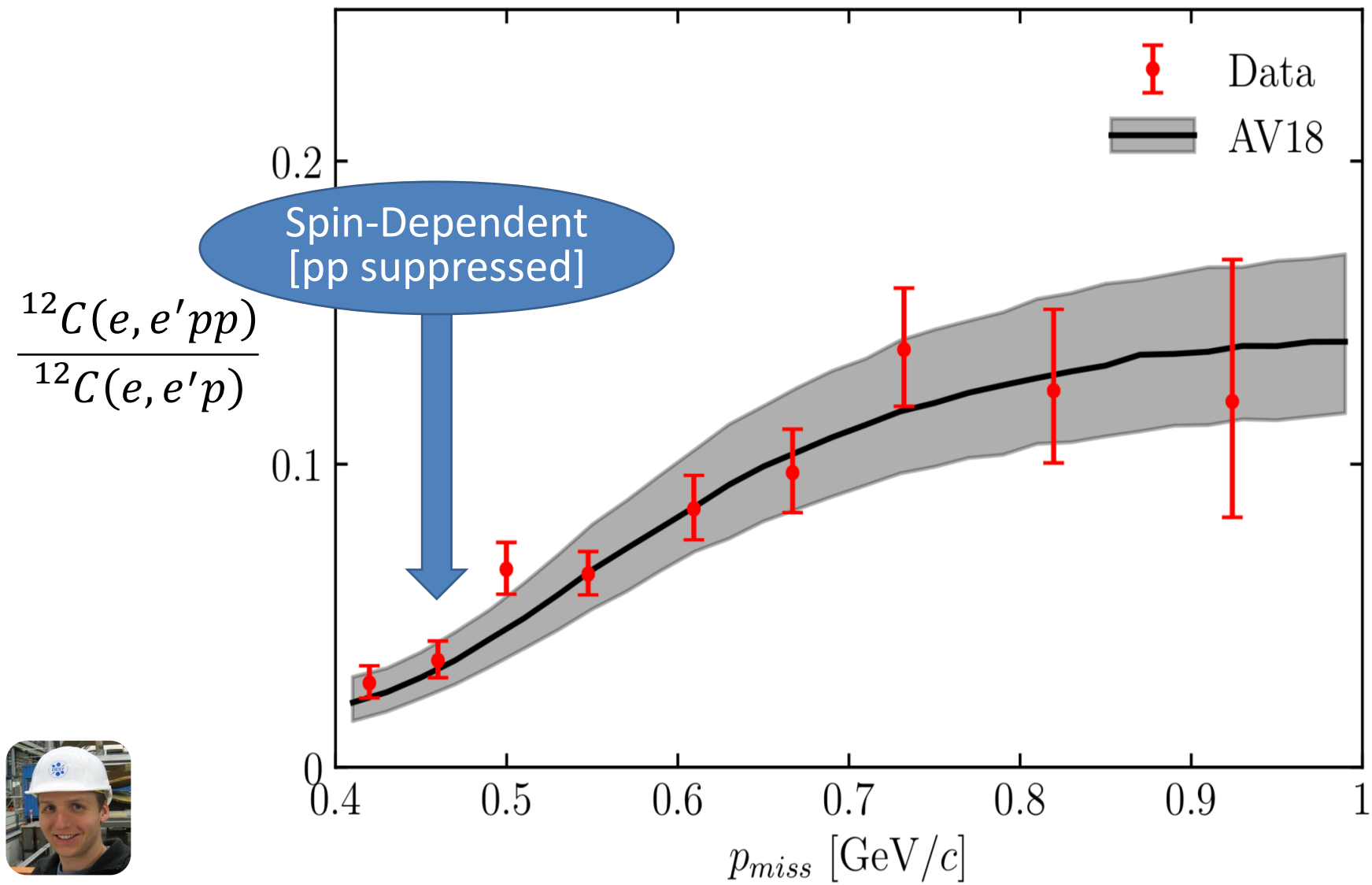
Reaching the Repulsive Core

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



Schmidt et al., Nature (2020)

Reaching the Repulsive Core



Schmidt et al., Nature (2020)

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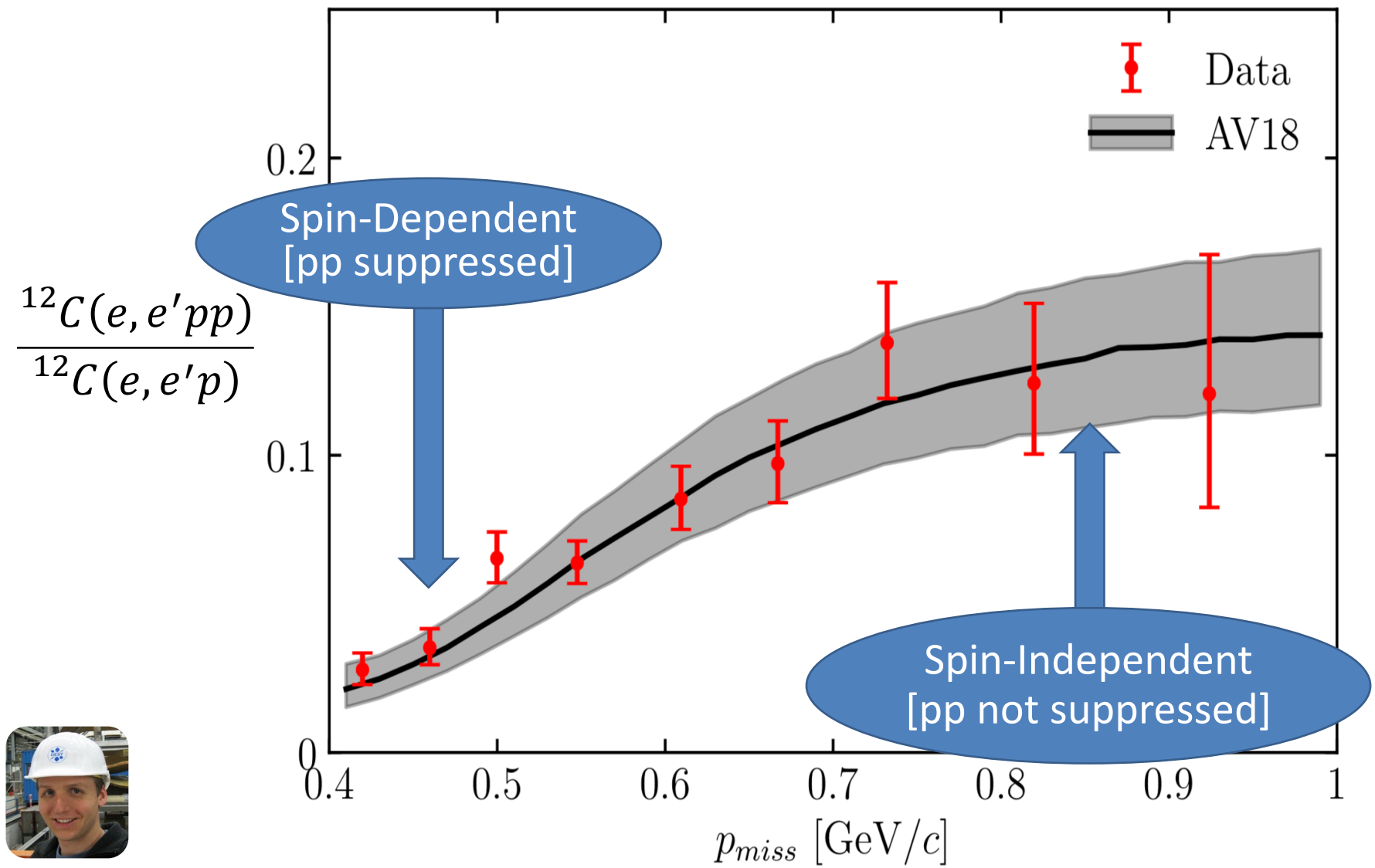

Schmidt et al., Nature (2020)

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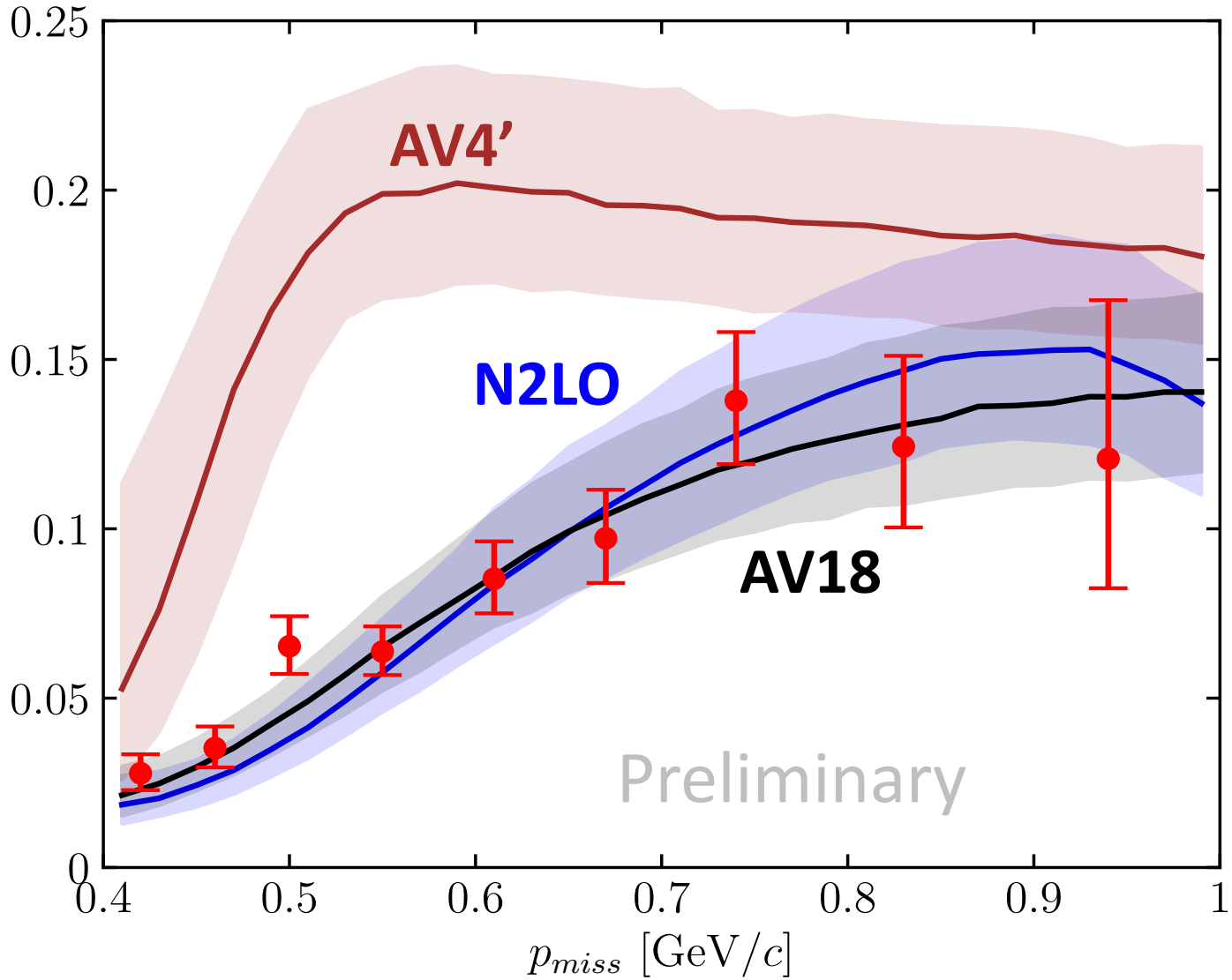
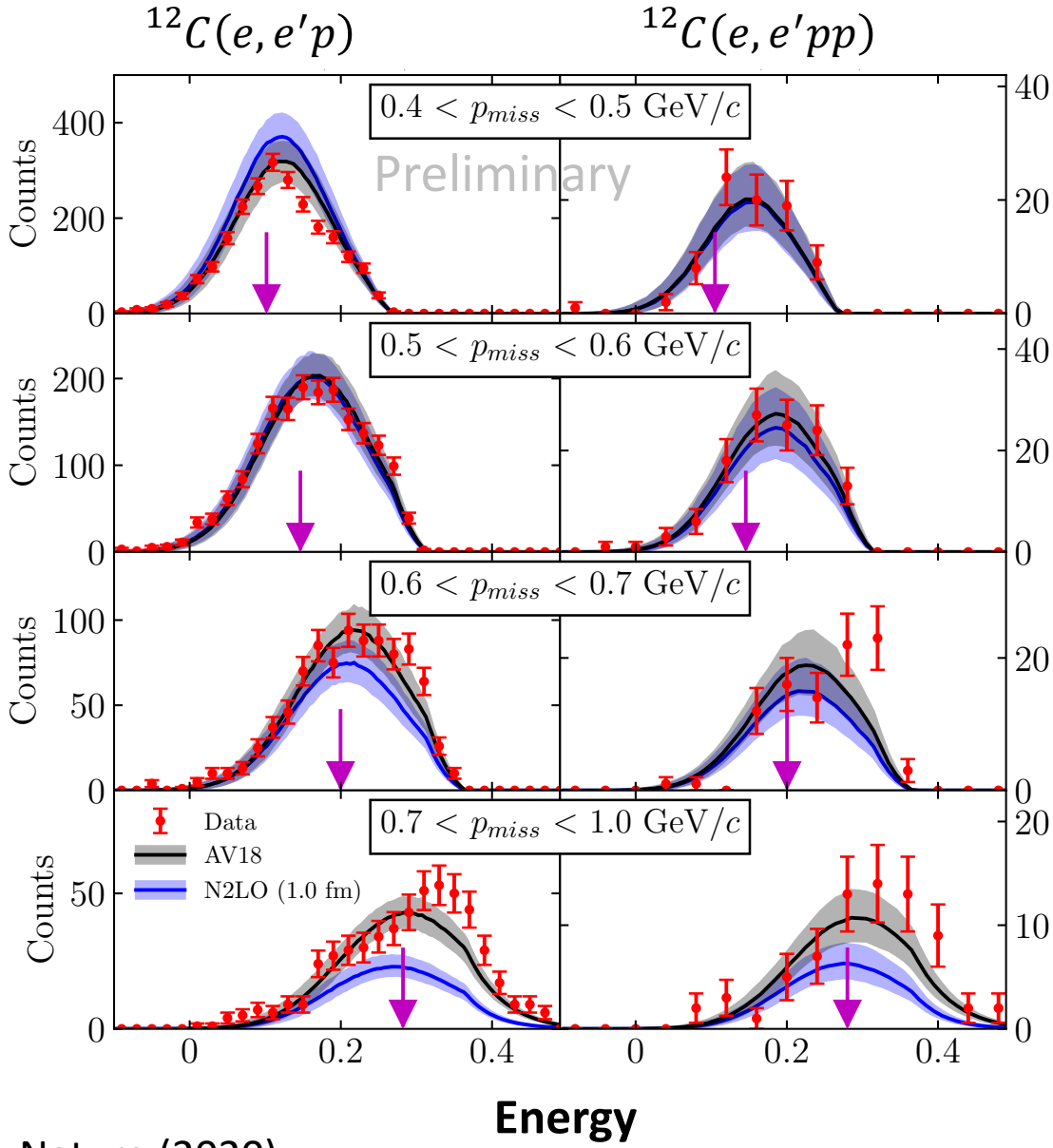


Schmidt et al., Nature (2020)

Spectral function Sensitivity



Momentum

400 – 500 MeV/c

500 – 600 MeV/c

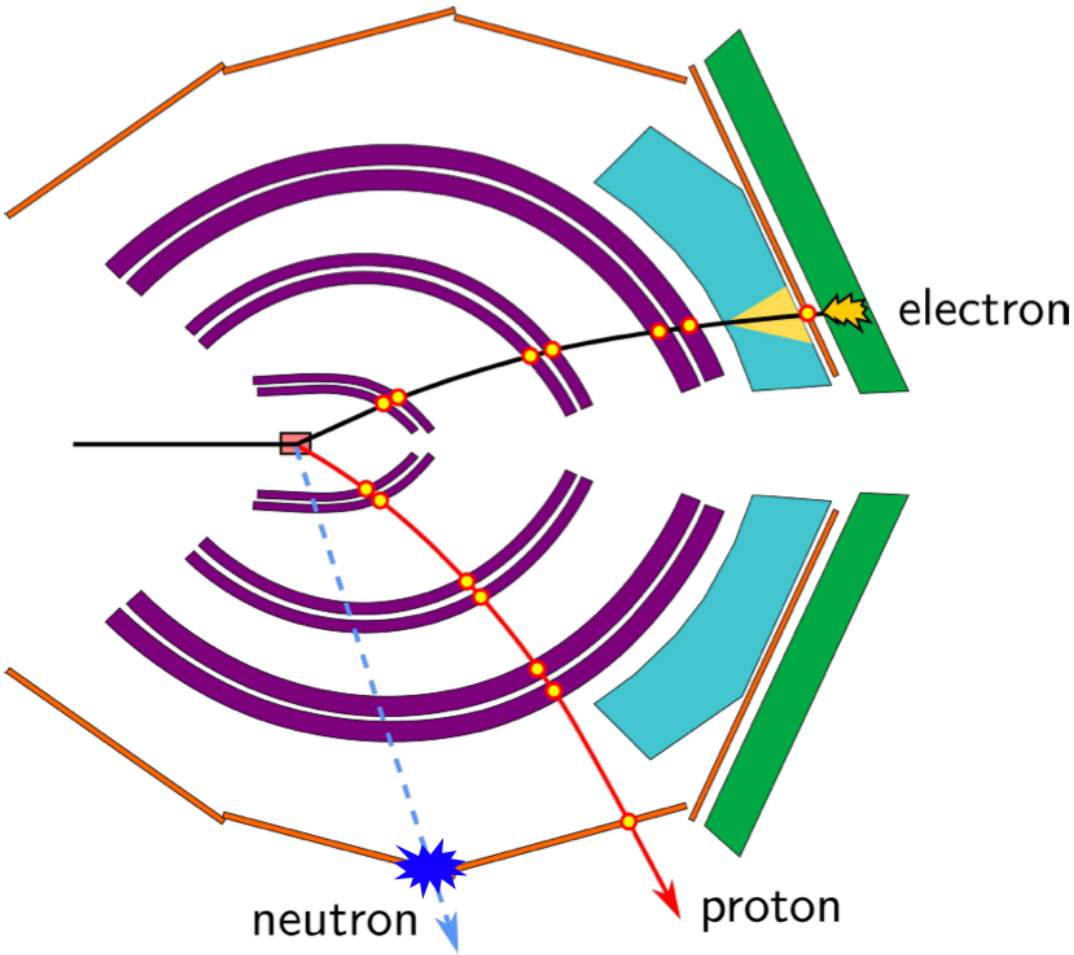
600 – 700 MeV/c

700 – 1000 MeV/c

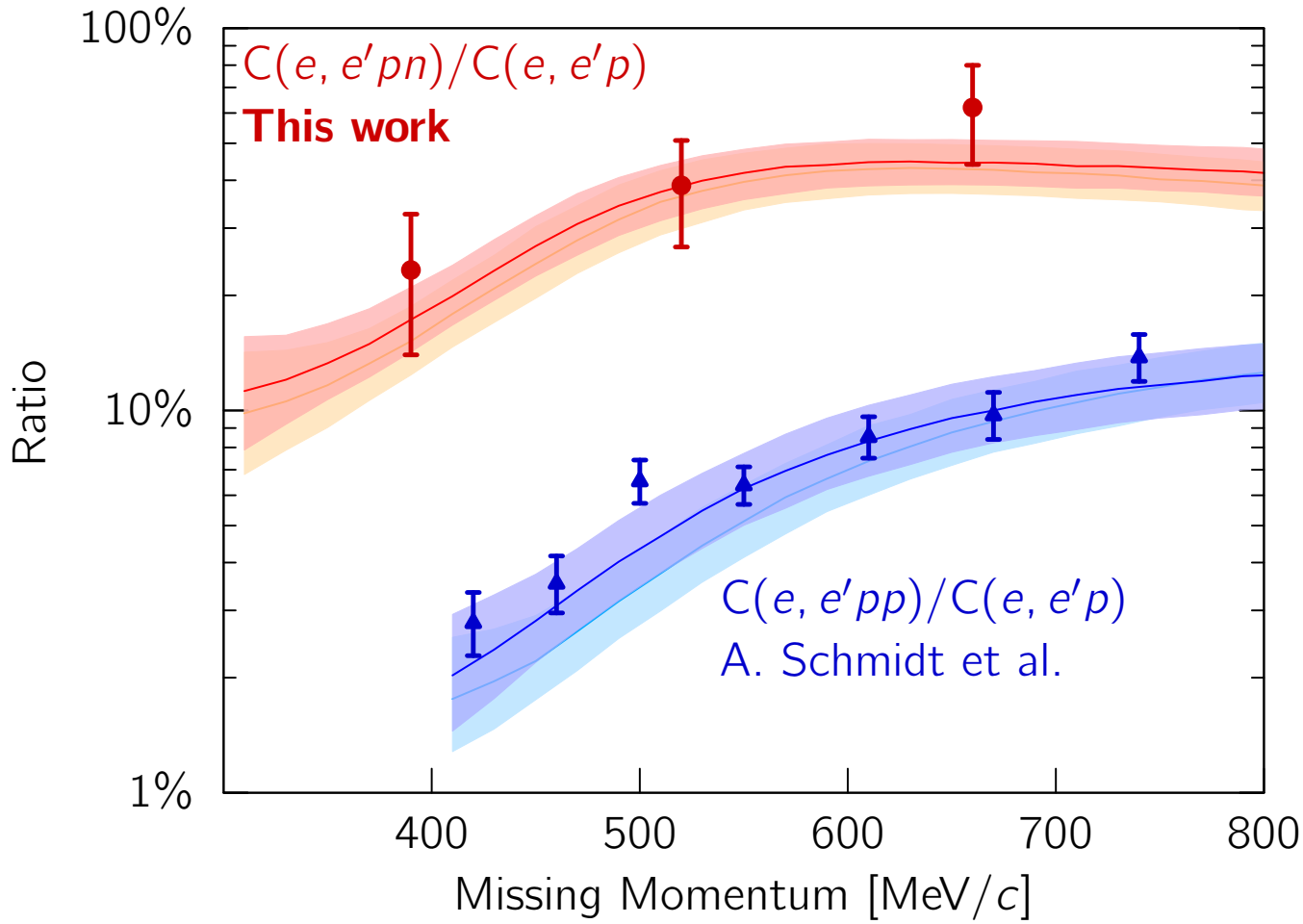
Schmidt et al., Nature (2020)

pn data completes the picture!

Korover et al. (2020)



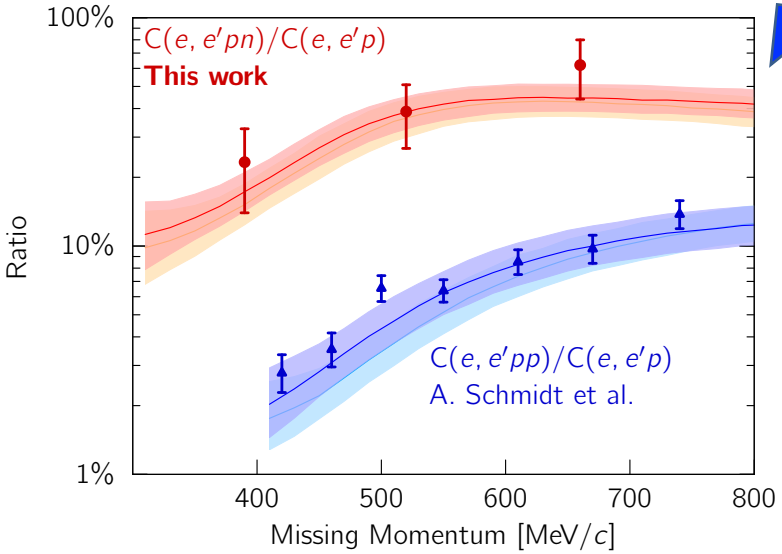
pn consistent with theory!



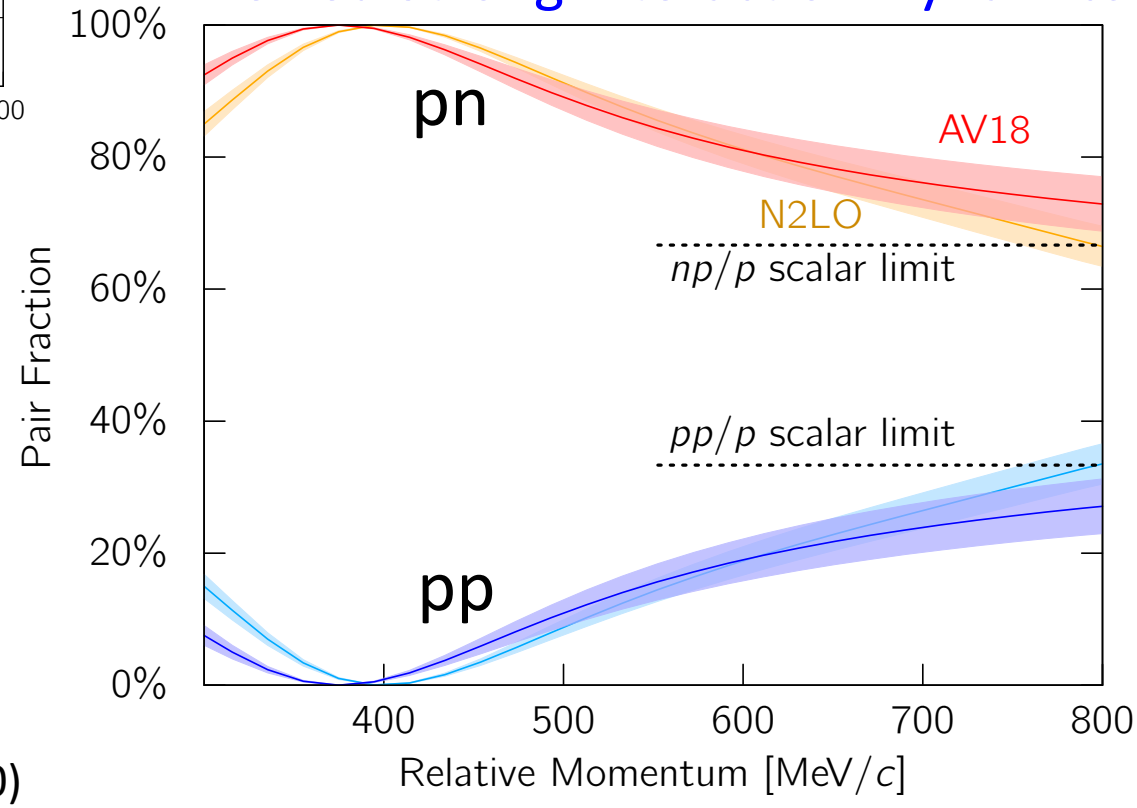
Korover et al. arXiv: 2004.07304 (2020)

Observation of scalar core

Measured cross-sections



Inferred Strong Interaction Dynamics

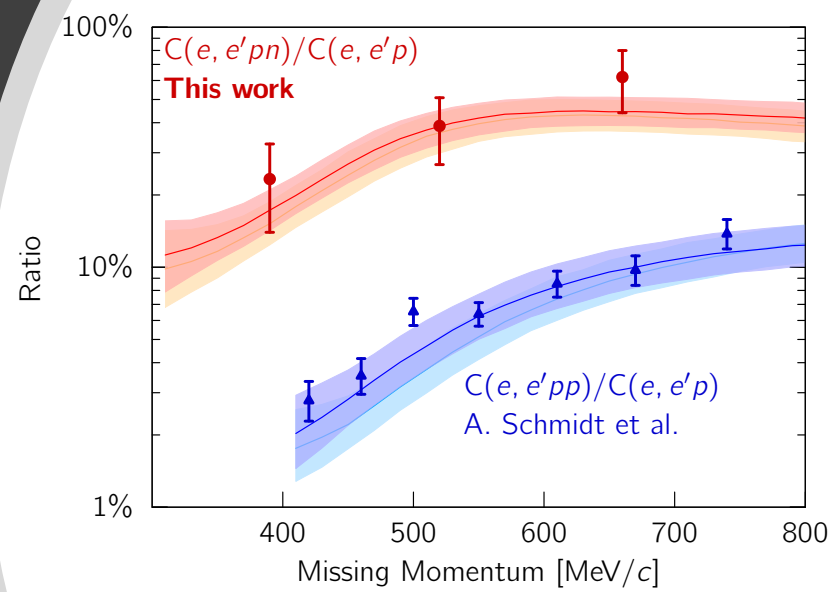


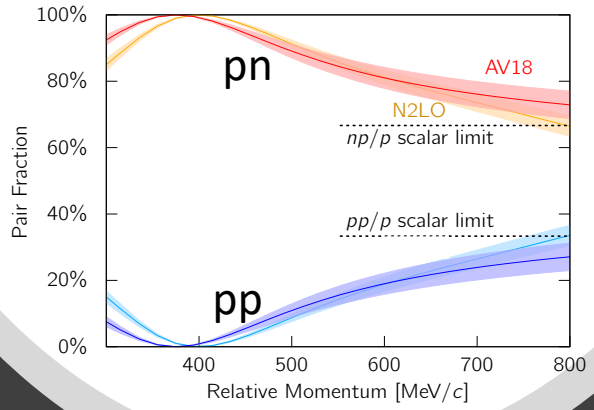
Korover et al. arXiv: 2004.07304 (2020)

Interim Summary

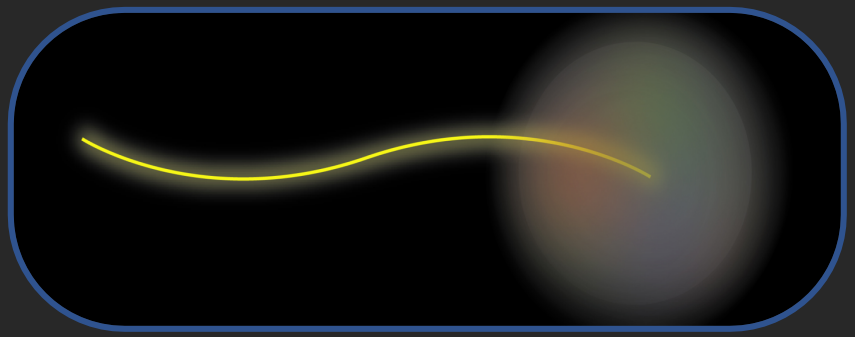
- Nuclear momentum distribution has two distinct regions.

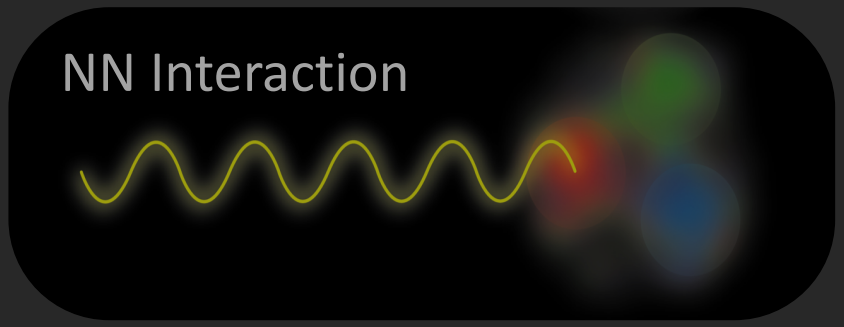
Allow probing NN interaction up to 1 GeV/c.

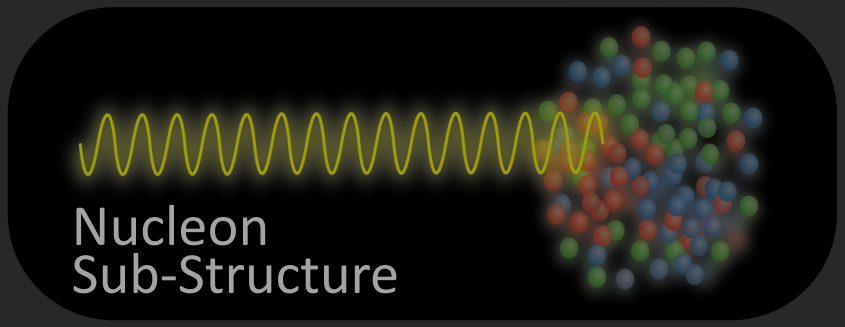




Many-Body System







Going neutron rich:

What do excess neutrons do?

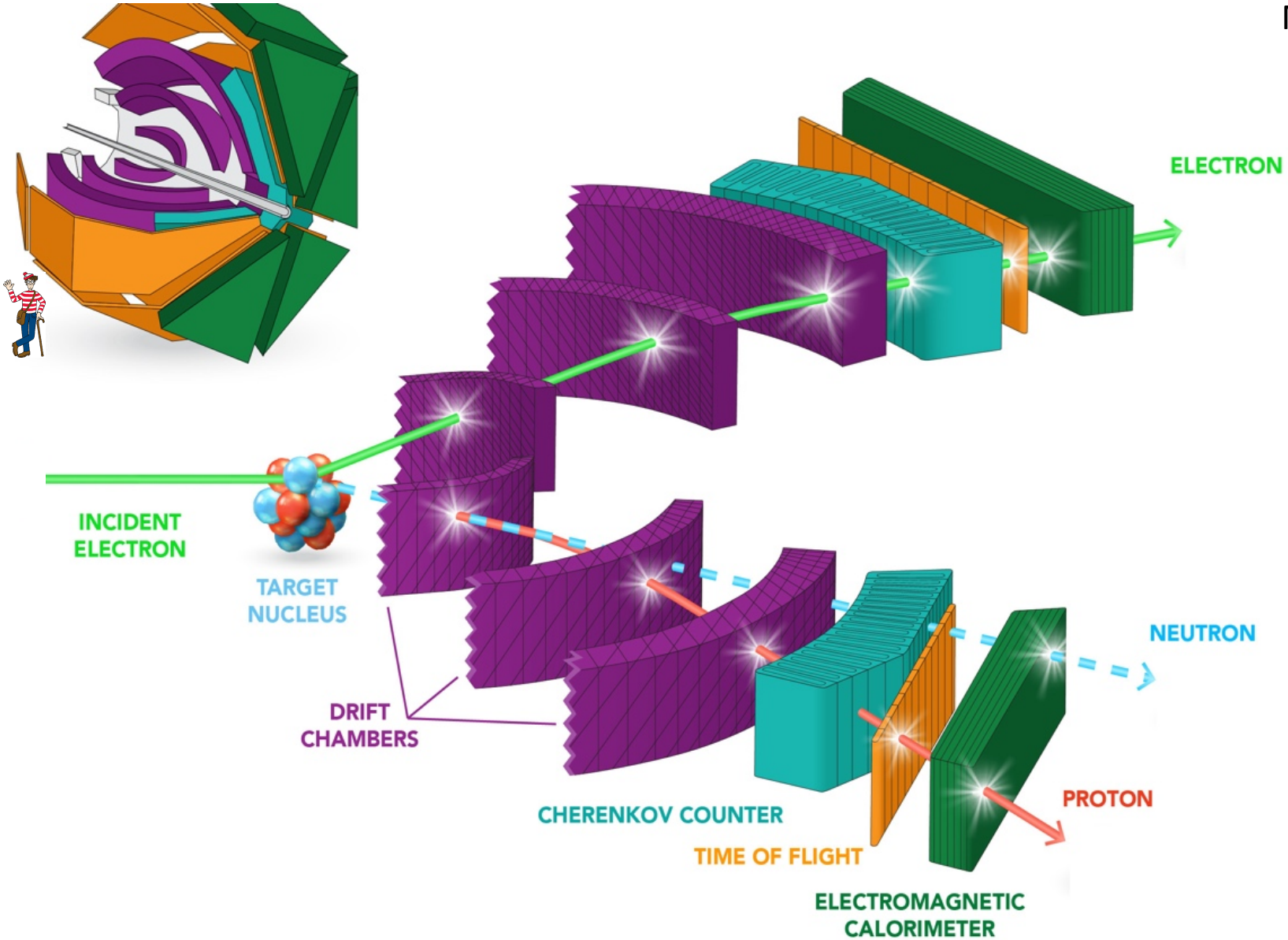
don't correlate?

correlate with each other?

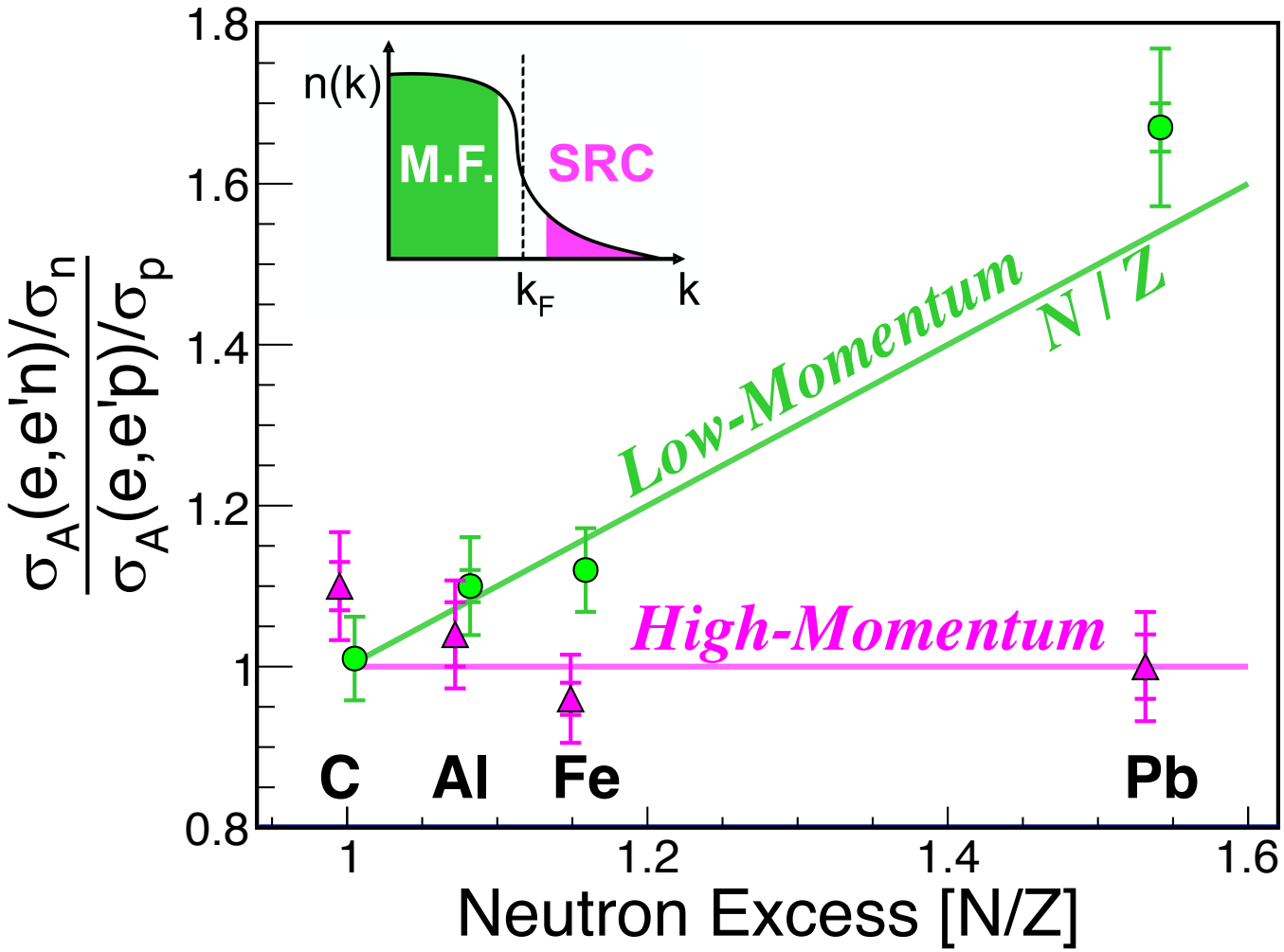
correlate with core protons?

Proton vs. Neutron Knockout

M. Duer



Same # of high-momentum p & n



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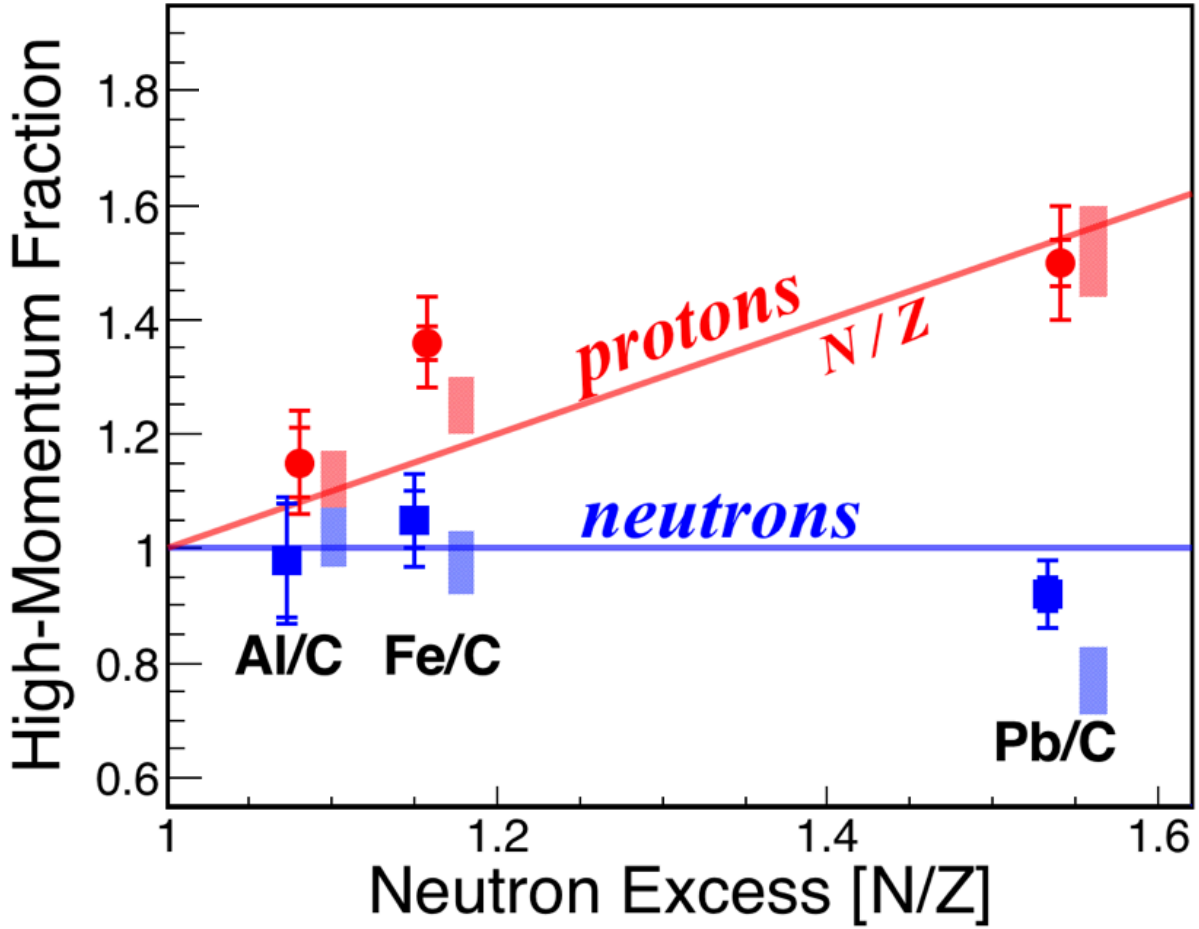
~~correlate with each other?~~

Correlation Probability:
Neutrons saturate Protons grow



Duer Nature (2018)

Going neutron rich:

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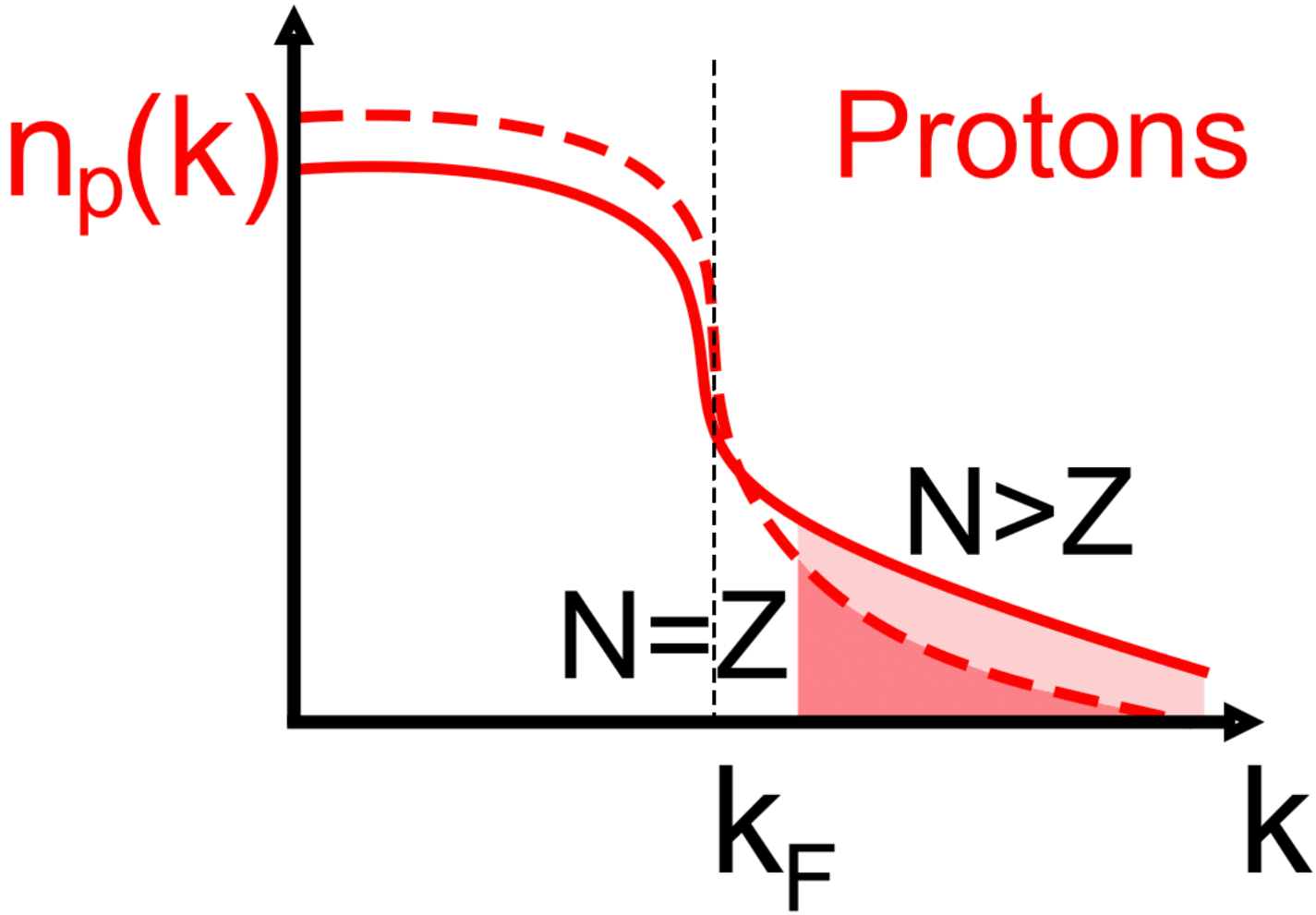
✓ correlate with core protons?

Protons 'Speed-Up' In Neutron-Rich Nuclei



Duer Nature (2018)

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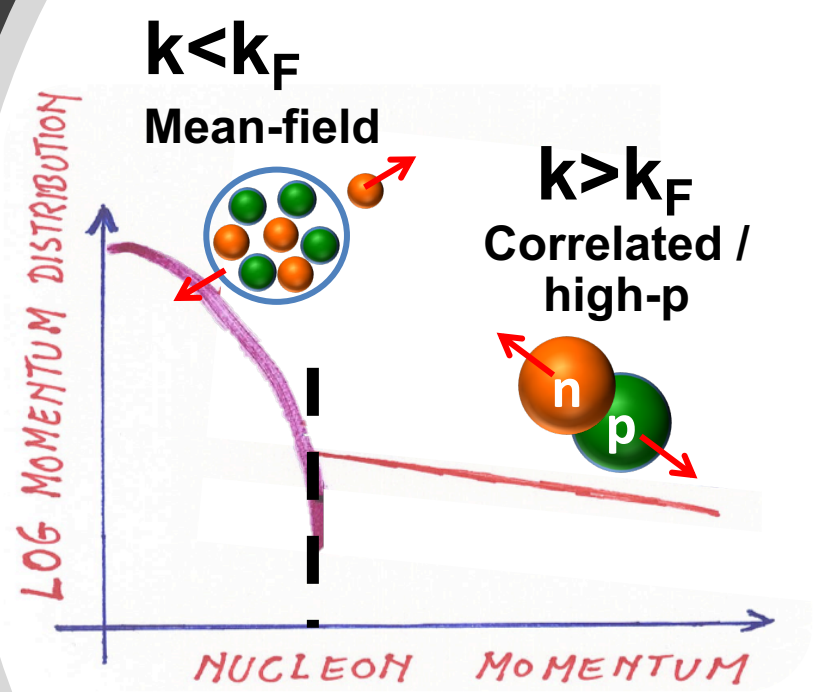
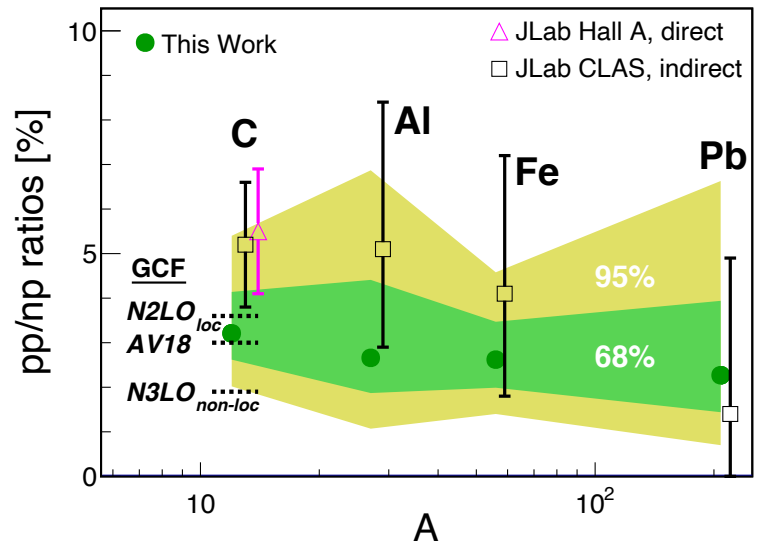


Interim Summary

- Nuclear momentum distribution has two distinct regions.
- #SRC-protons = #SRC-neutrons, independent of neutron excess.



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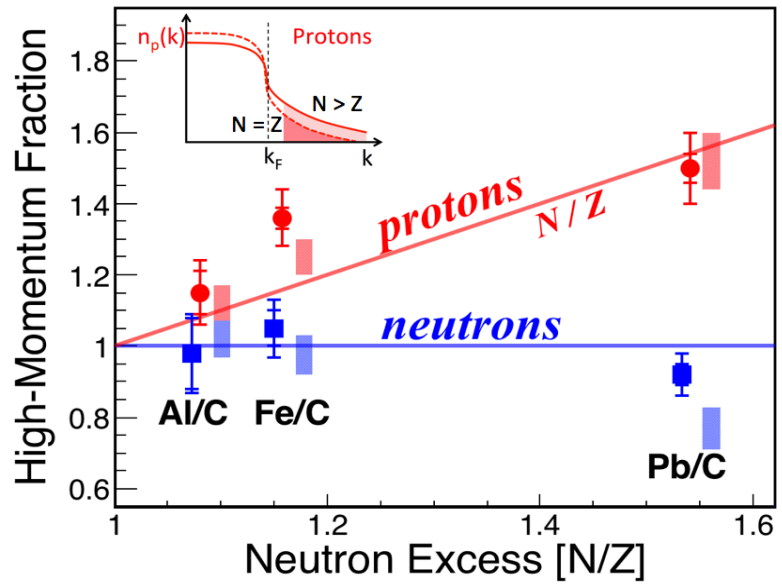

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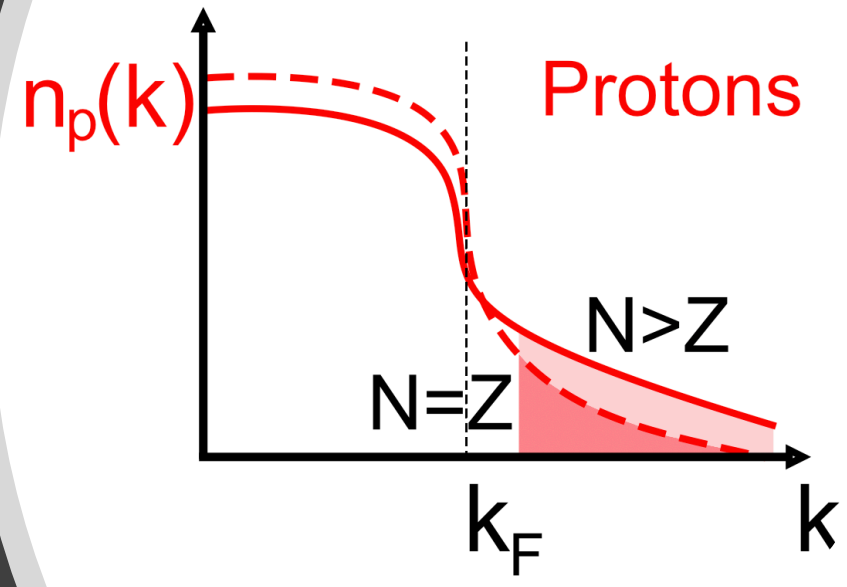
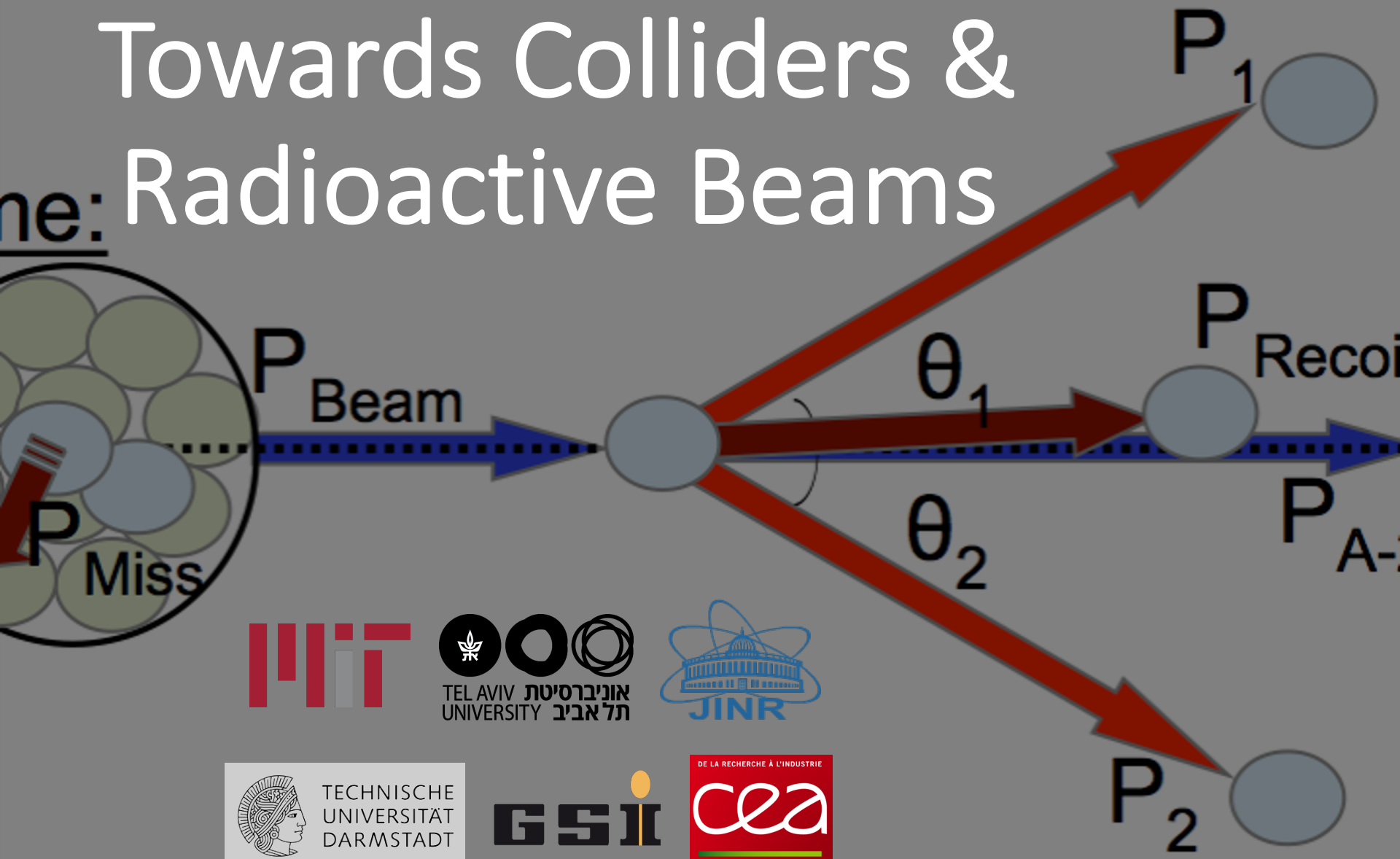


Going Inverse:

Towards Colliders & Radioactive Beams



TEL AVIV UNIVERSITY אוניברסיטת תל אביב

JINR

TECHNISCHE UNIVERSITÄT DARMSTADT

GSI

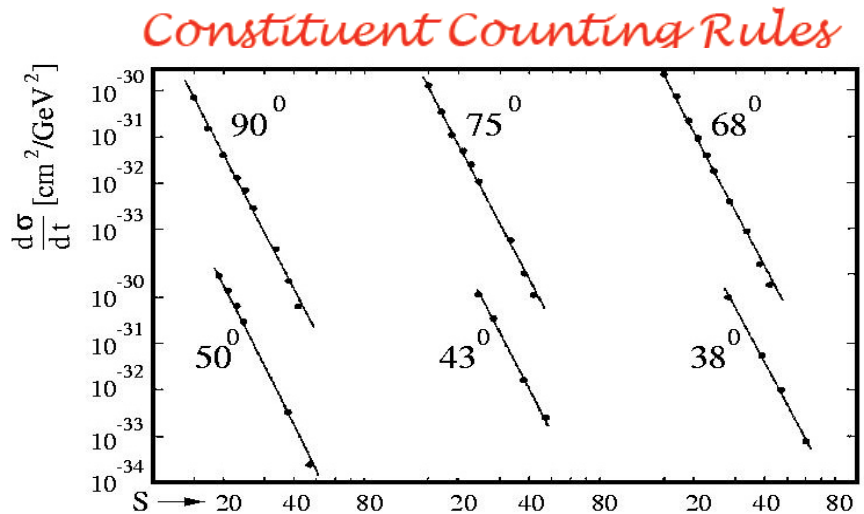
DE LA RECHERCHE À L'INDUSTRIE cea

Proton beams:

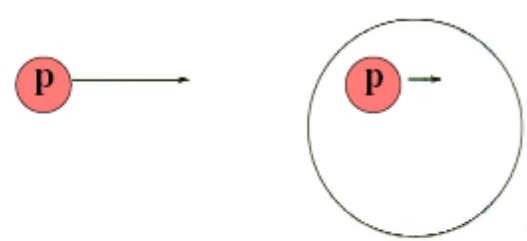
Selective Attention!

pp → pp elastic scattering near 90^0 c.m:

$$\frac{d\sigma}{dt} \propto s^{-10}$$



Incident proton prefers to interact with forward going high momentum nuclear protons



Fixed Target

Proton beams:

Selective Attention!

pp → pp elastic scattering near 90^0 c.m:

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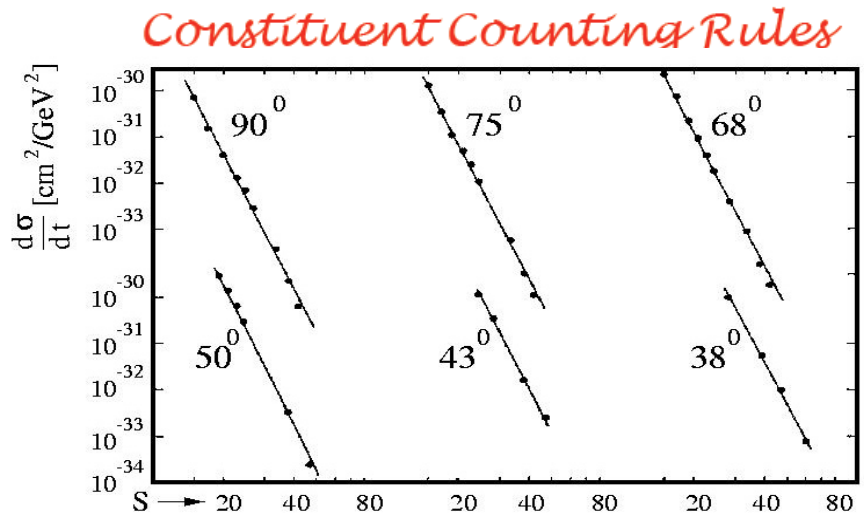
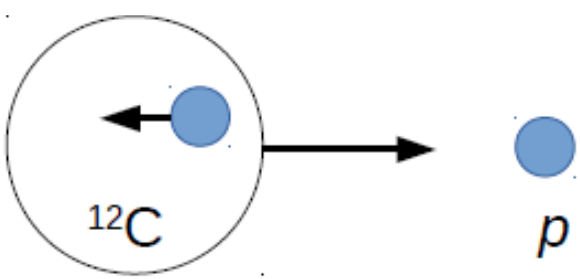
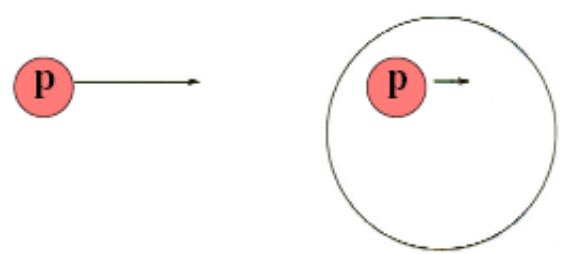




Nuclear beam



Fixed Target

Hadron Advantages

- Small deBroglie wavelength:

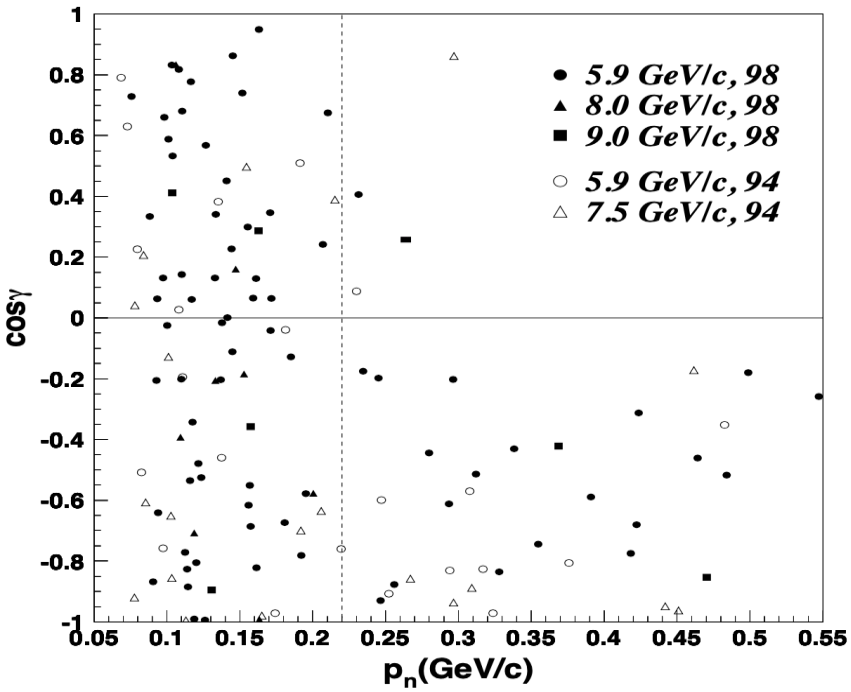
  $\lambda = h/p = hc/pc = 2\pi \bullet 0.197$ GeV-fm/(6 GeV) ≈ 0.2 fm.

- Large momentum transfer possible with wide angle scattering

- **<u>Large Cross section</u>**

n-p Short-Range Correlations from (p, $2p + n$) Measurements

A. Tang,[1] J.W. Watson,[1] J. Aclander,[2] J. Alster,[2] G. Asryan,[4,3] Y. Averichev,[8] D. Barton,[4] V. Baturin,[6,5] N. Bukhtoyarova,[4,5] A. Carroll,[4] S. Gushue,[4] S. Heppelmann,[6] A. Leksanov,[6] Y. Makdisi,[4] A. Malki,[2] E. Minina,[6] I. Navon,[2] H. Nicholson,[7] A. Ogawa,[6] Yu. Panebratsev,[8] E. Piasetzky,[2] A. Schetkovsky,[6,5] S. Shimanskiy,[8] and D. Zhalov[6]



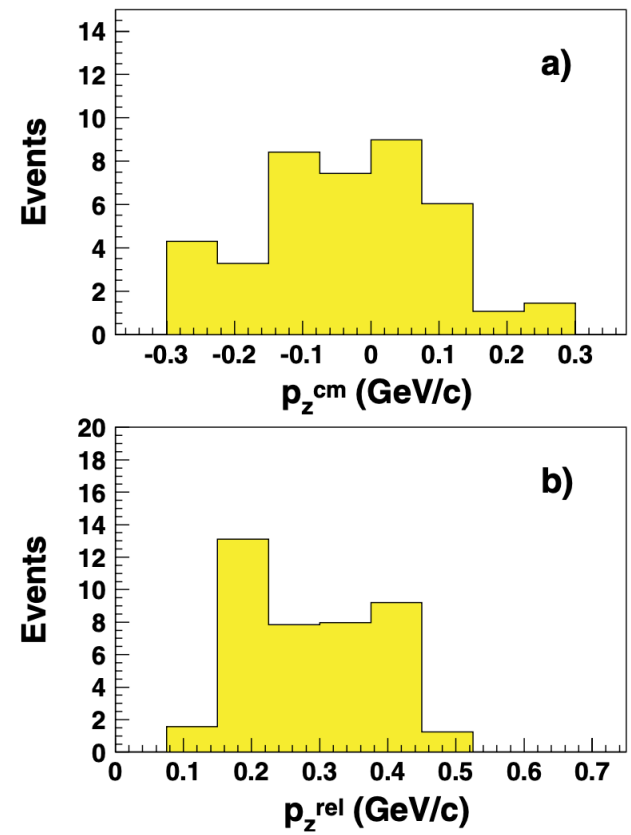
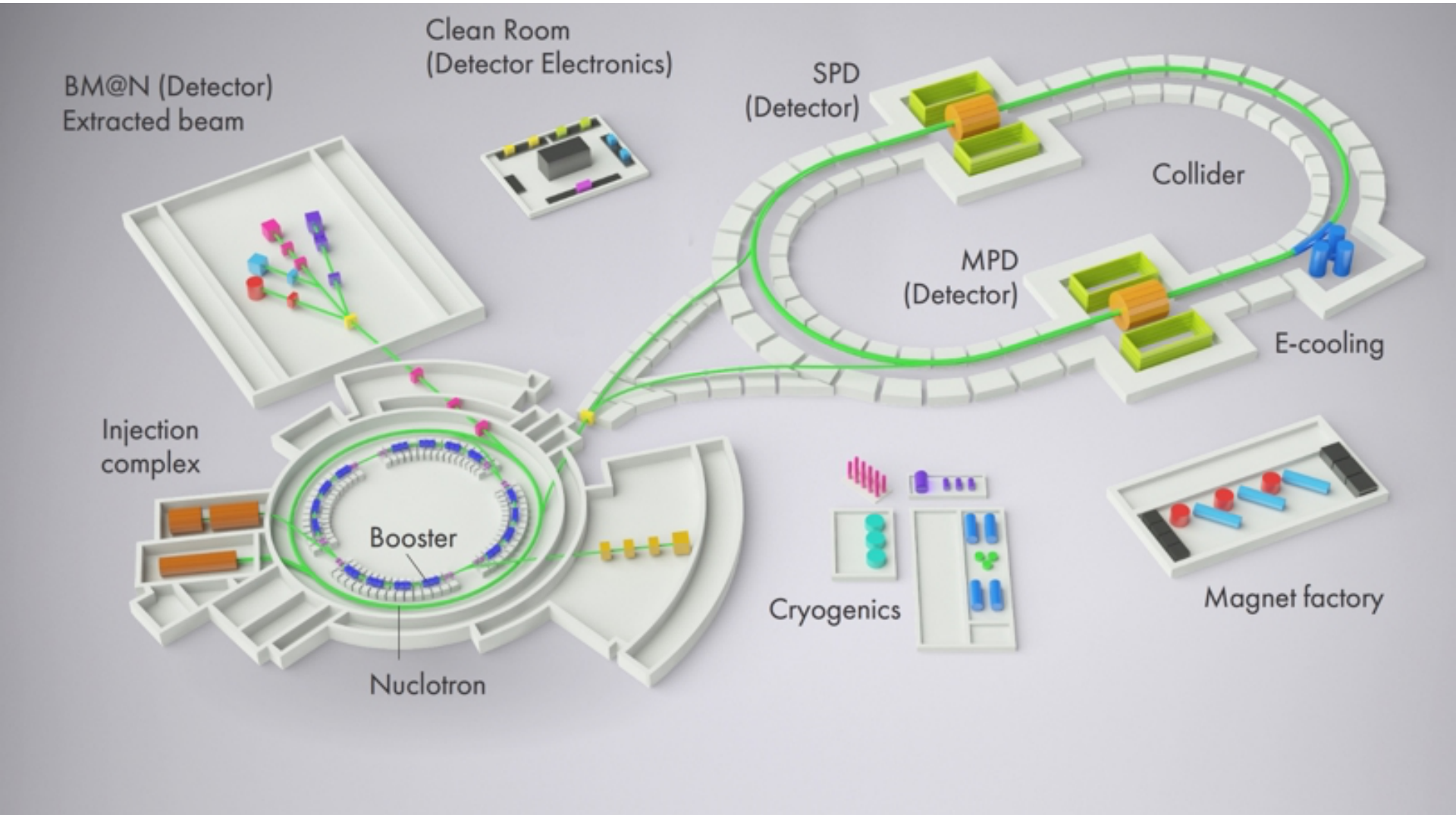
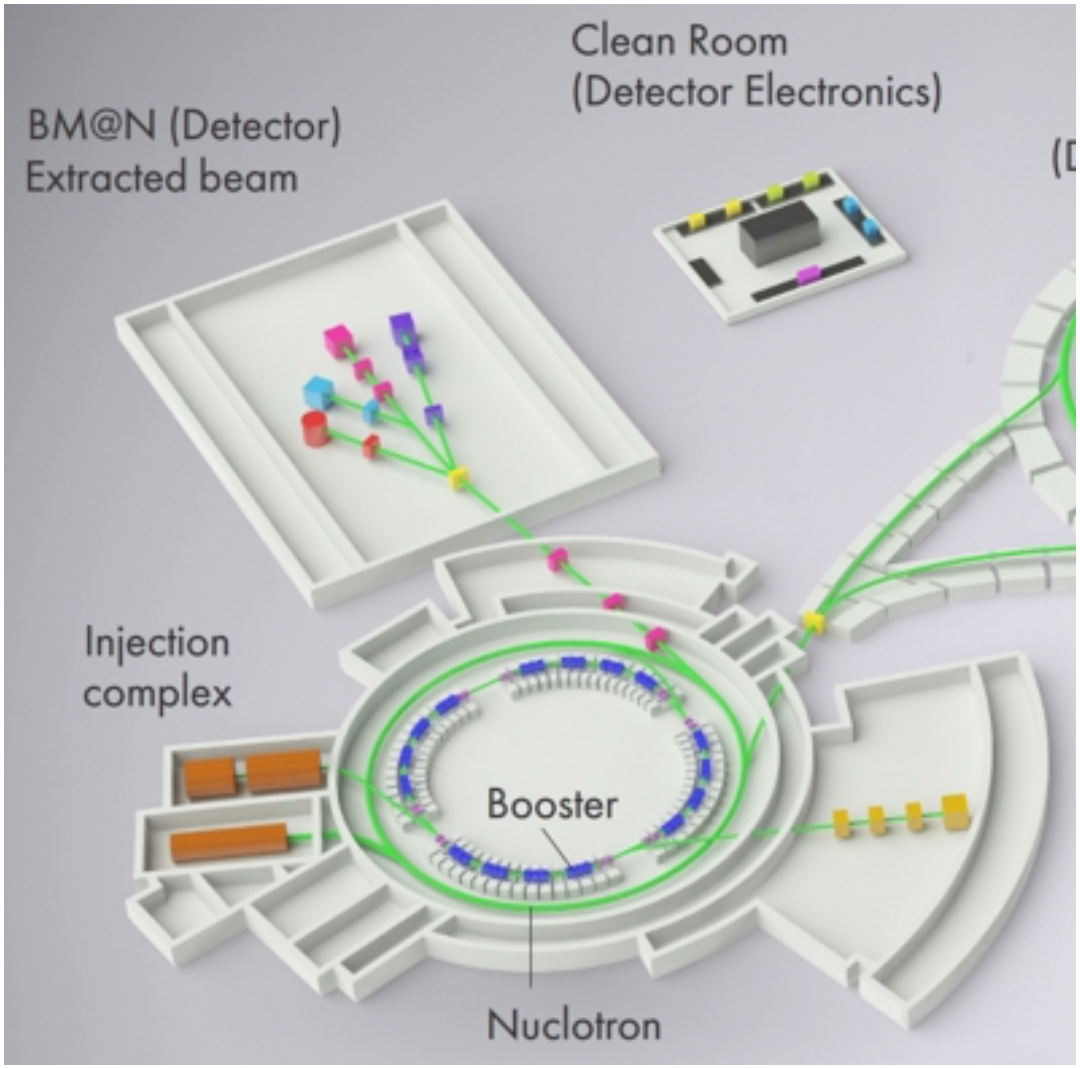


FIG. 4 (color online). Plots of (a) p_z^{cm} and (b) p_z^{rel} for correlated n-p pairs in ^{12}C, for $^{12}C(p, 2p + n)$ events. Each event has been s-weighted, as described in the text.

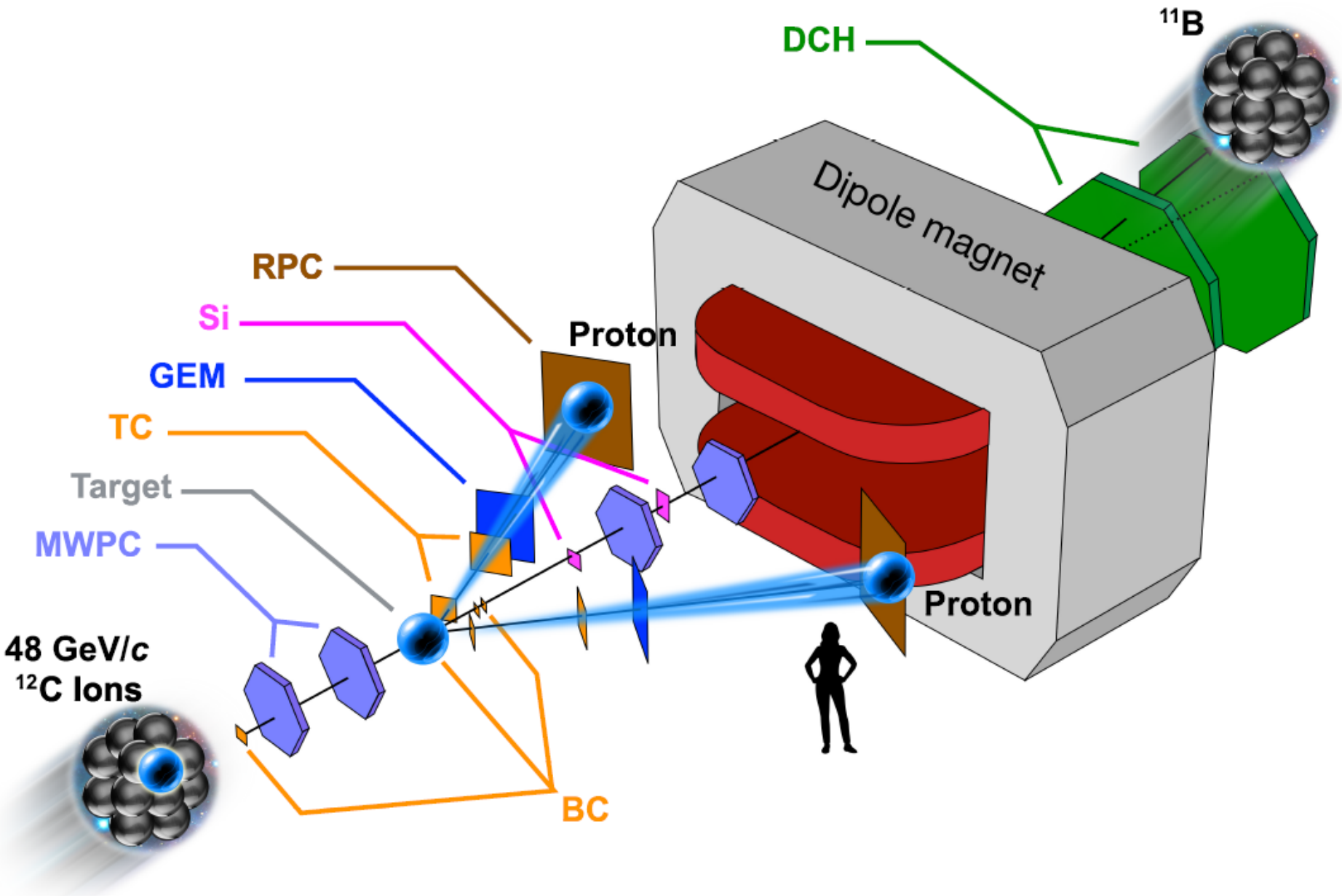
High-Energy Ion Beam @ JINR Nuclotron

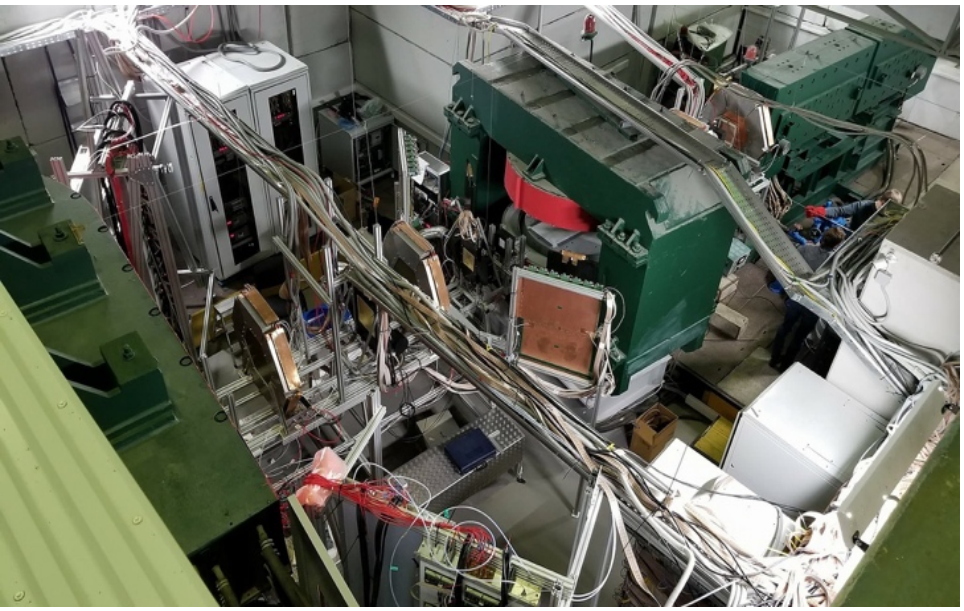


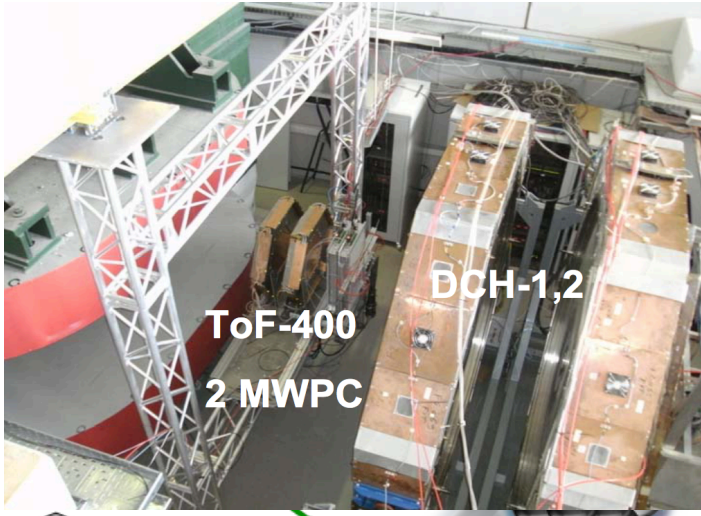
High-Energy Ion Beam @ JINR Nuclotron

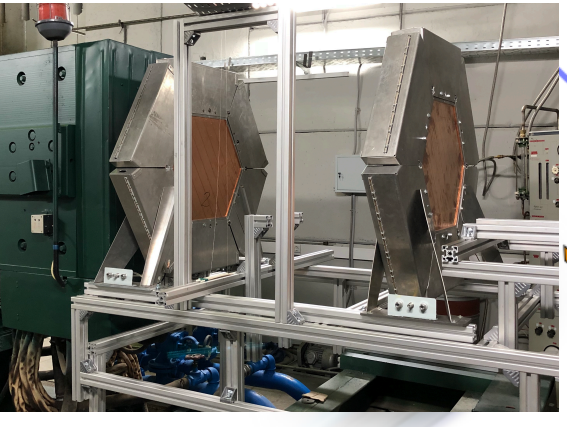


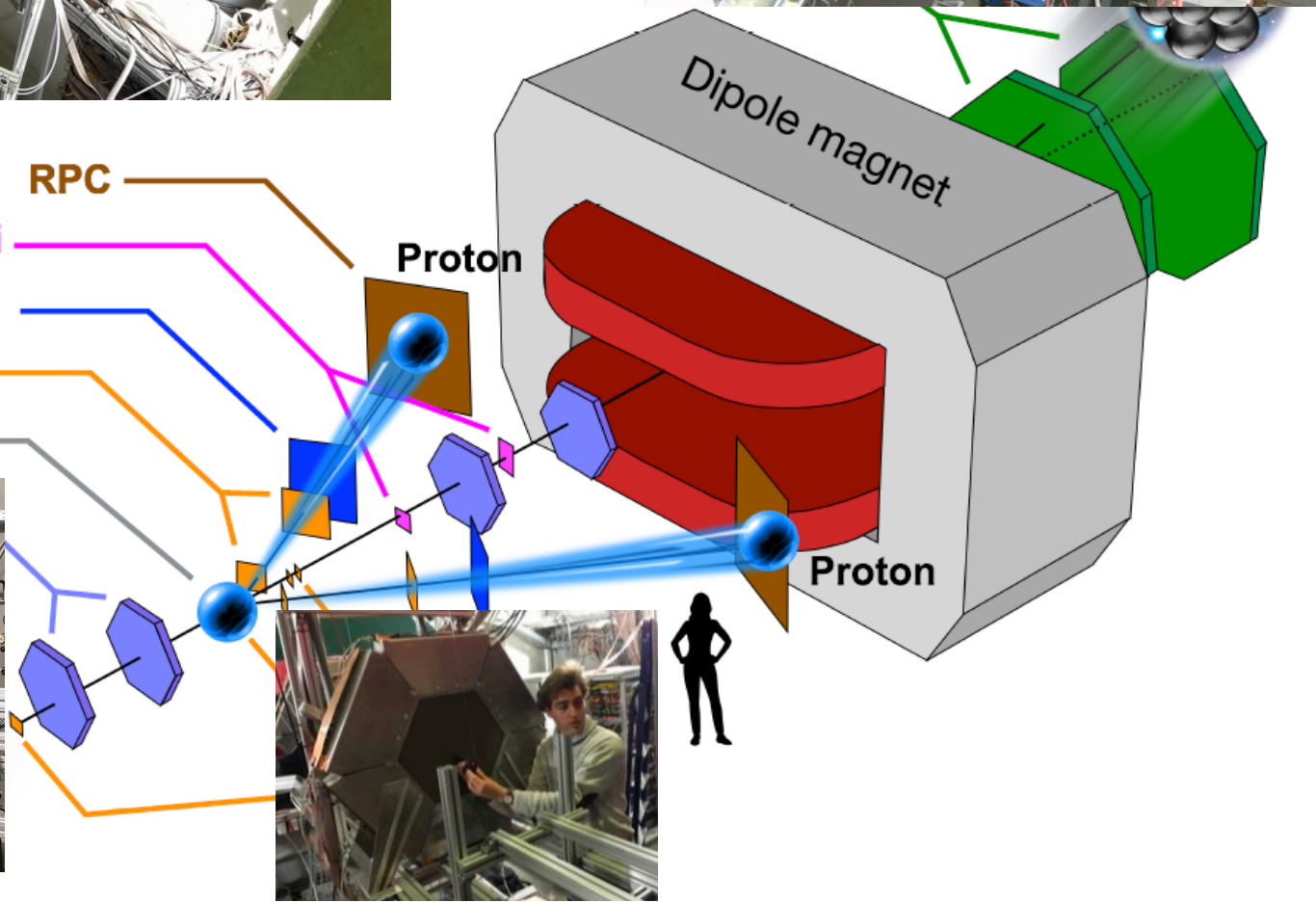
SRC @ BM@N


DCH
^{11}B
Dipole magnet
RPC
Si
GEM
TC
Target
MWPC
Proton
Proton
48 GeV/c
^{12}C Ions
BC



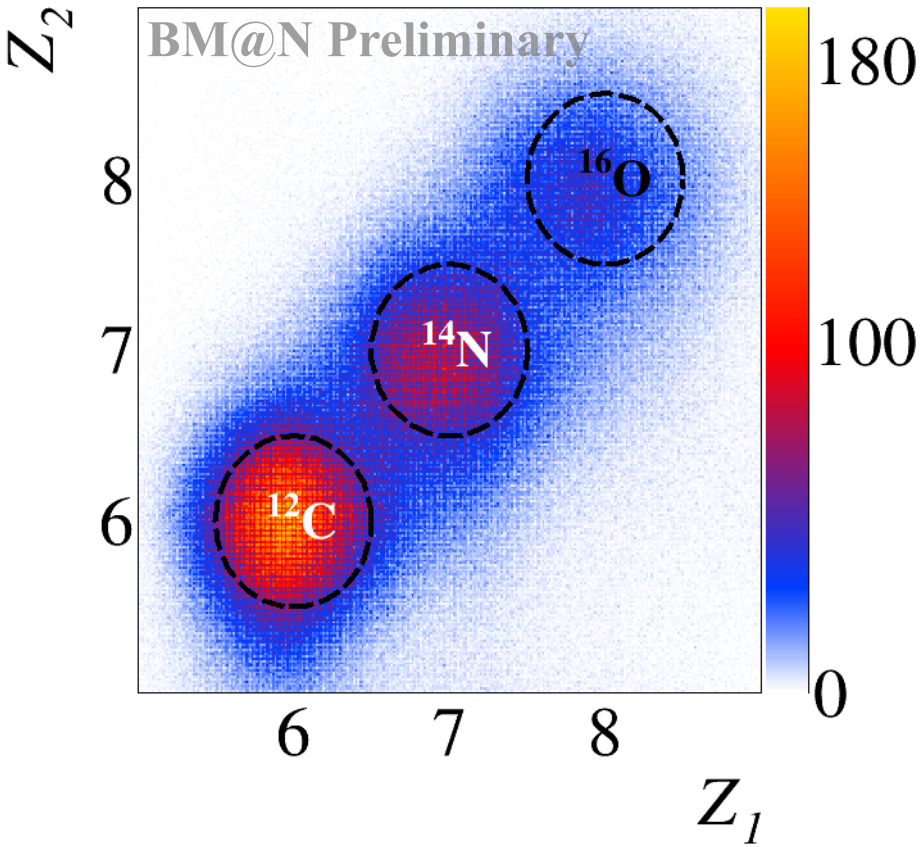

ToF-400
2 MWPC
DCH-1,2



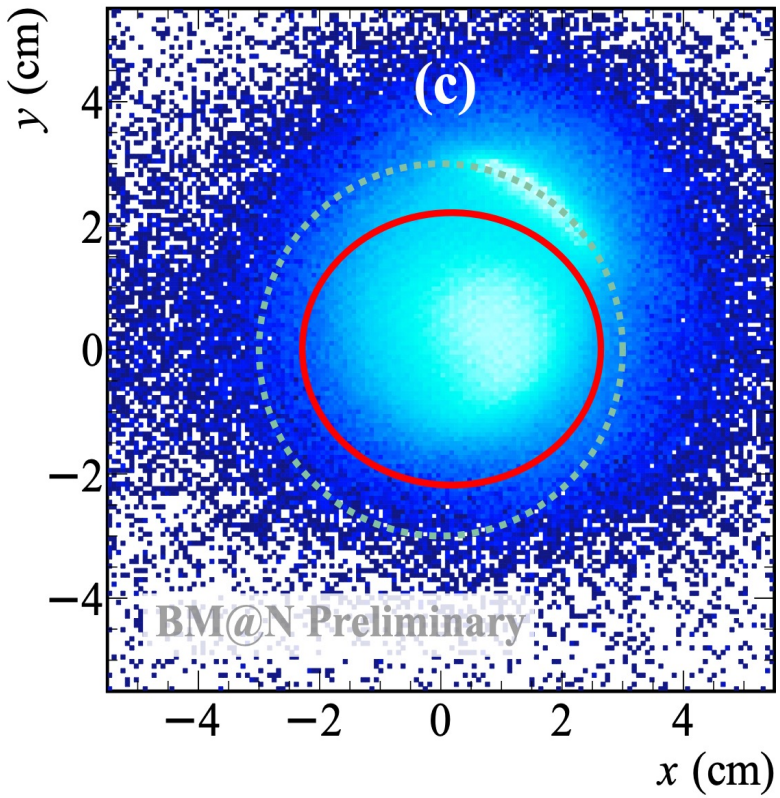

RPC
Si
GEM
TC
Target
Proton
Dipole magnet
Proton

SRC @ BM@N: Beam

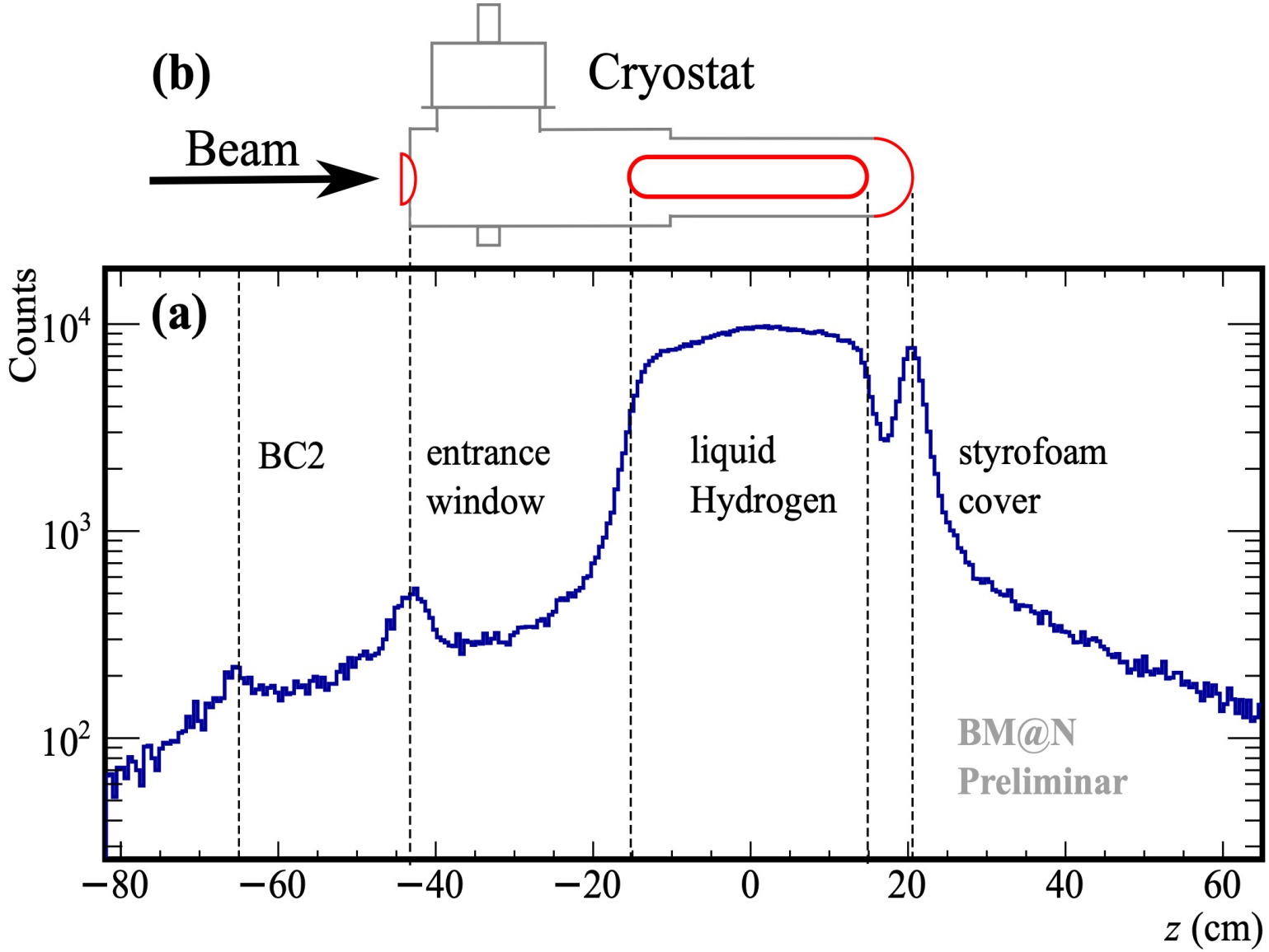
Beam Ions



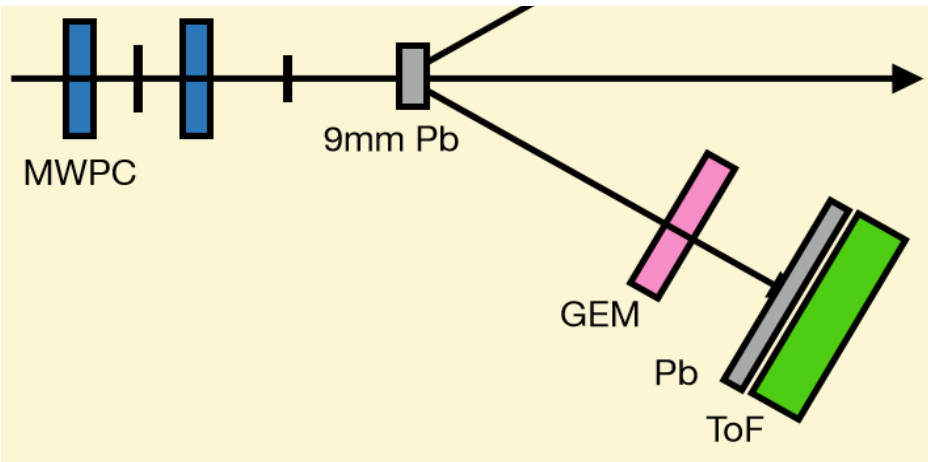
Beam Profile



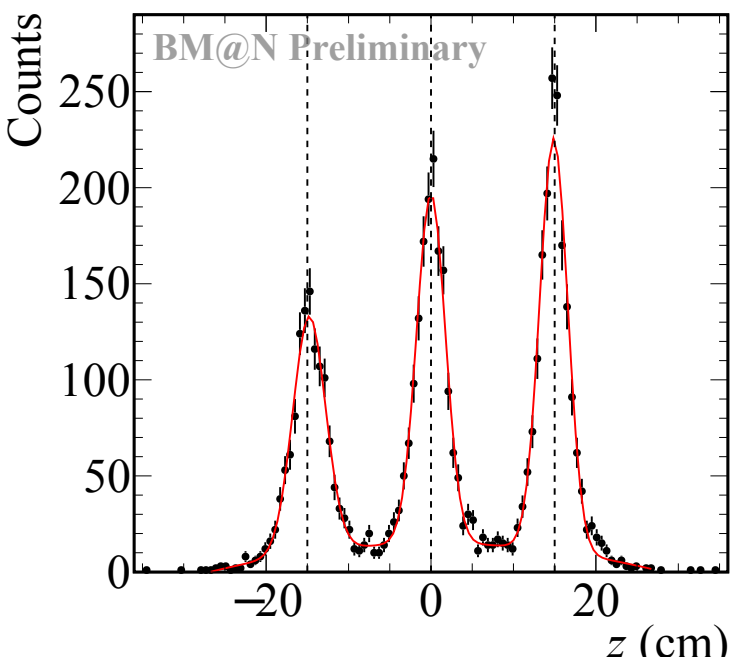
SRC @ BM@N: Target

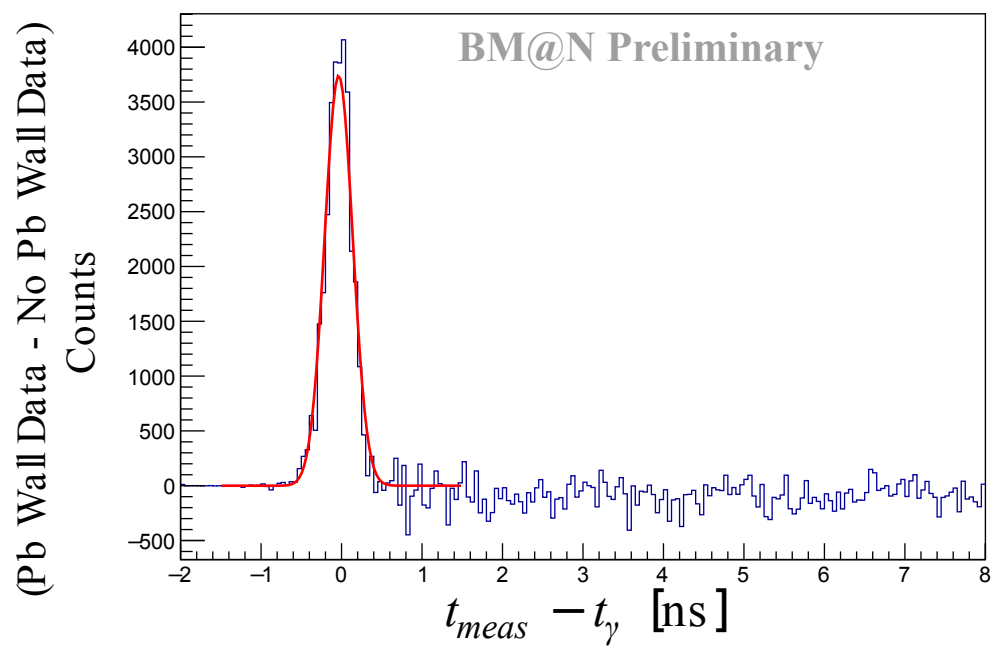


SRC @ BM@N: (p,2p)

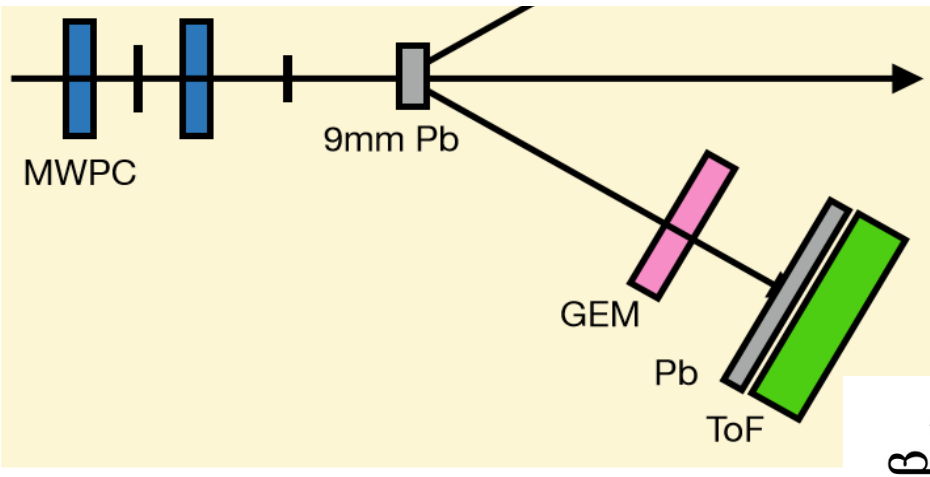


Calibrated using single- & multi-foil Lead target

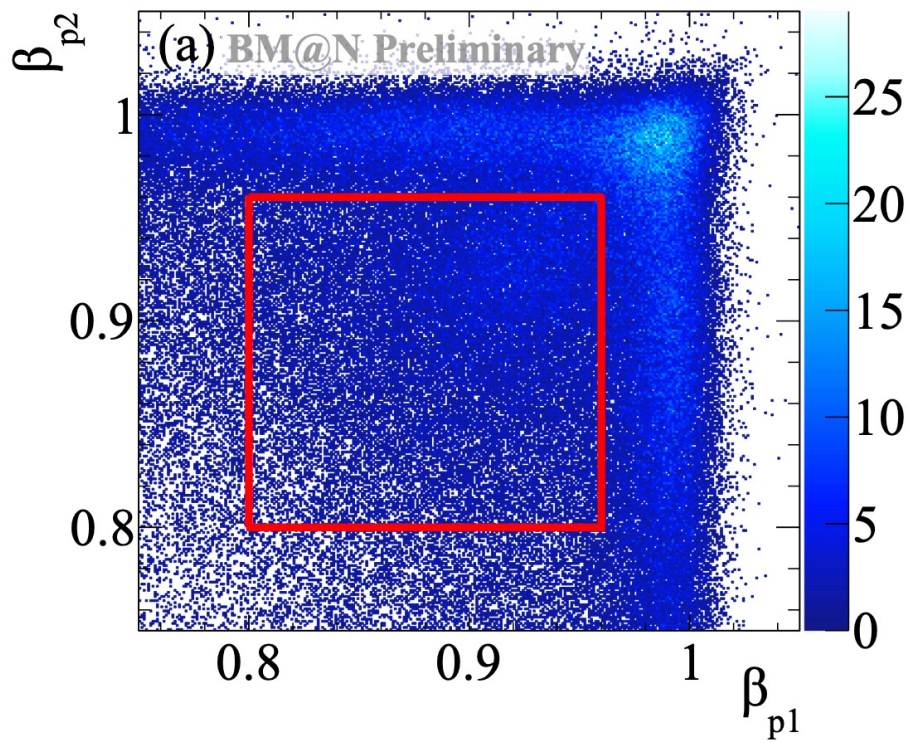




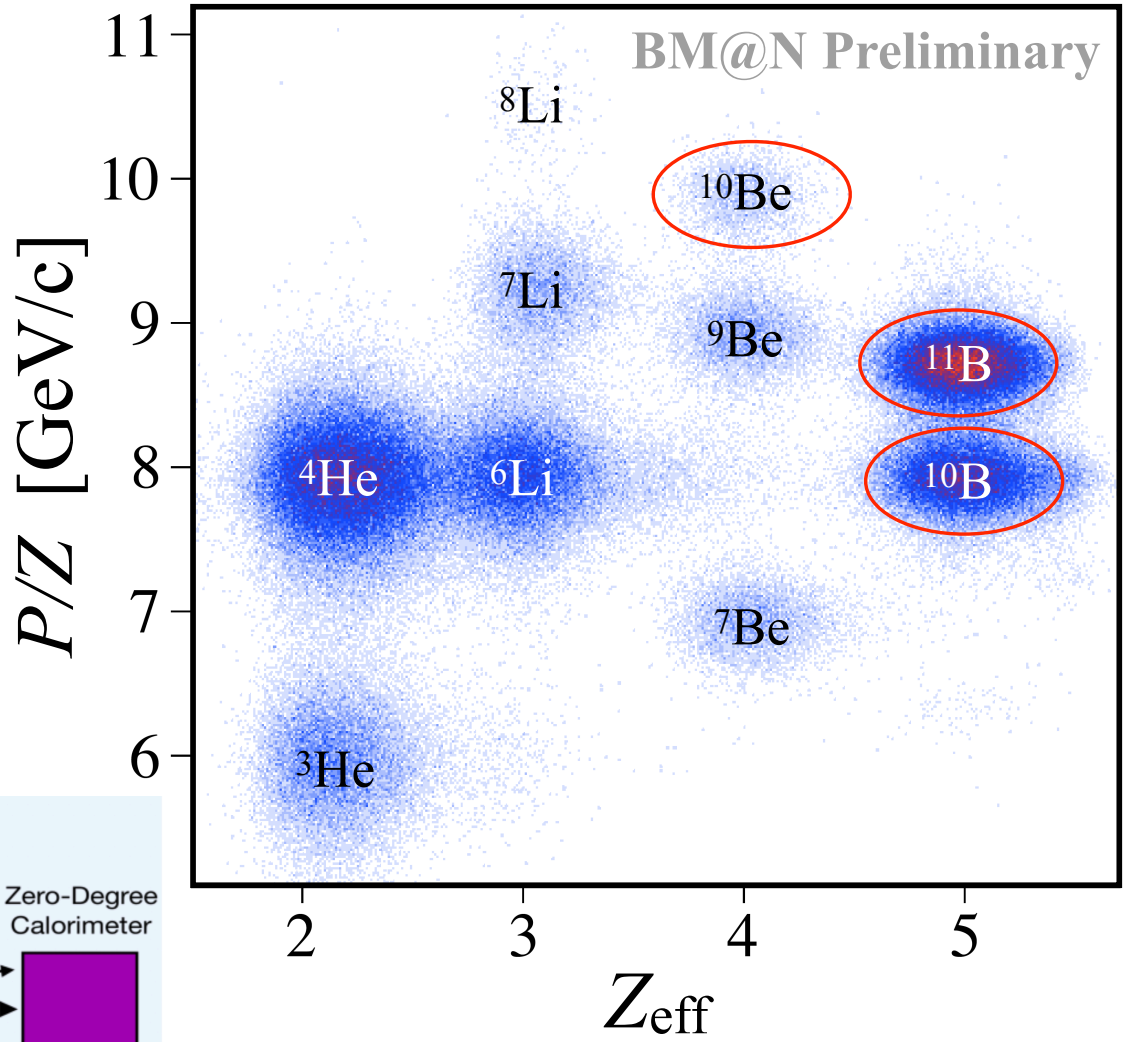
SRC @ BM@N: (p,2p)

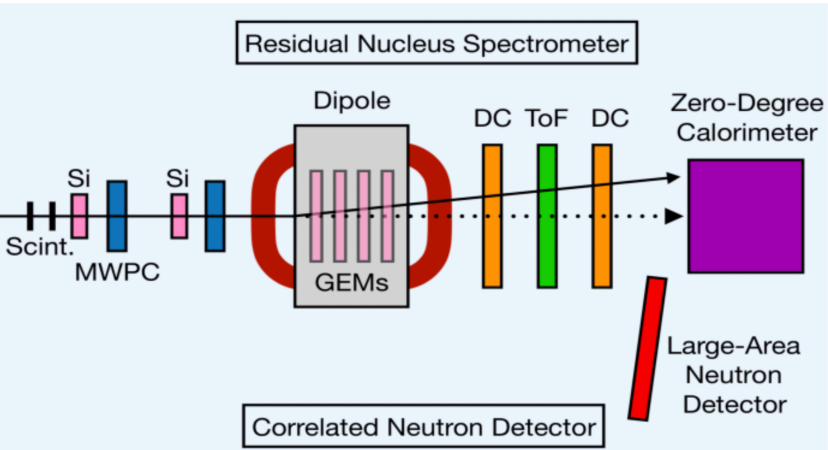


Remove fast pions

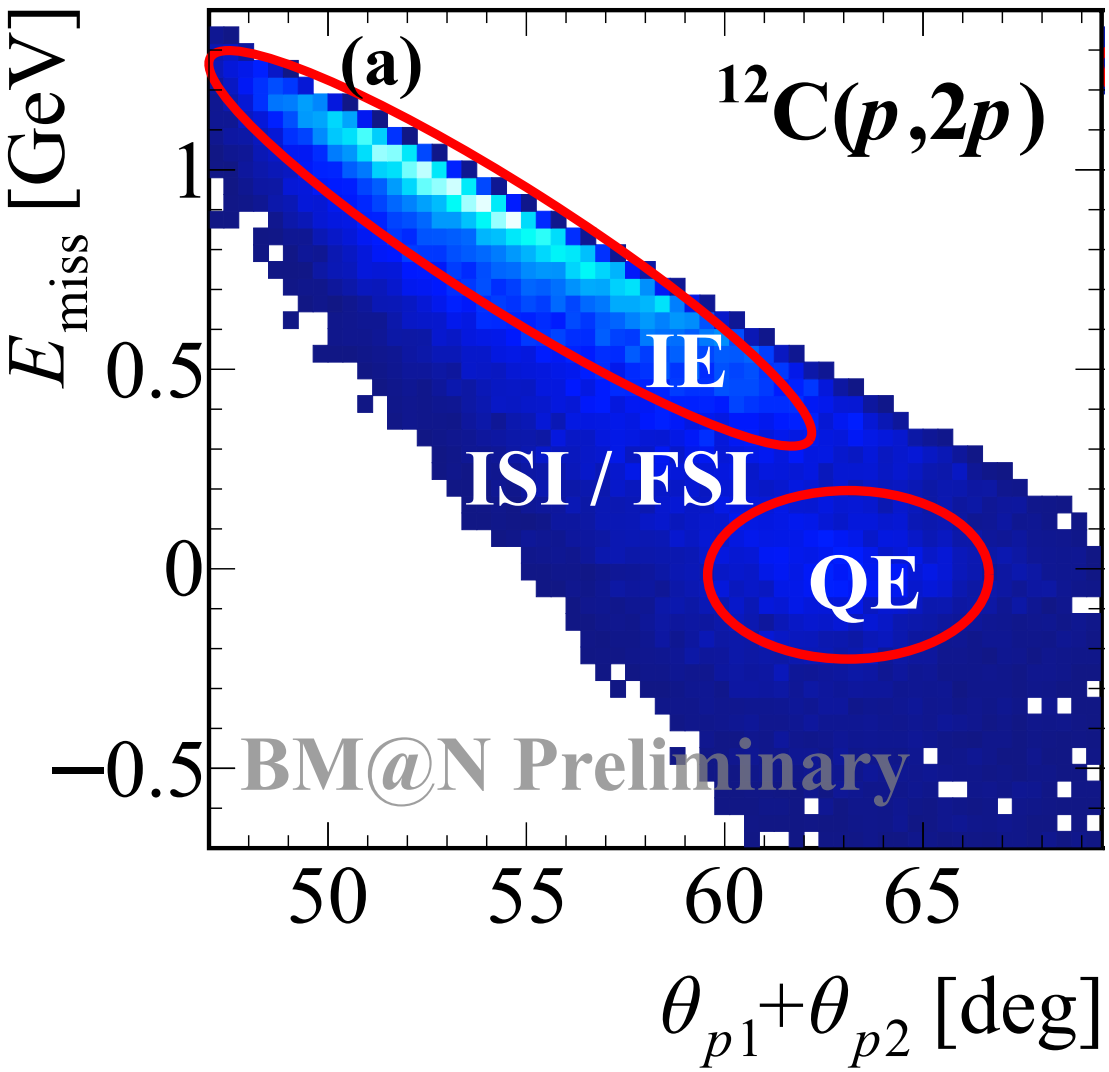


SRC @ BM@N: Fragment

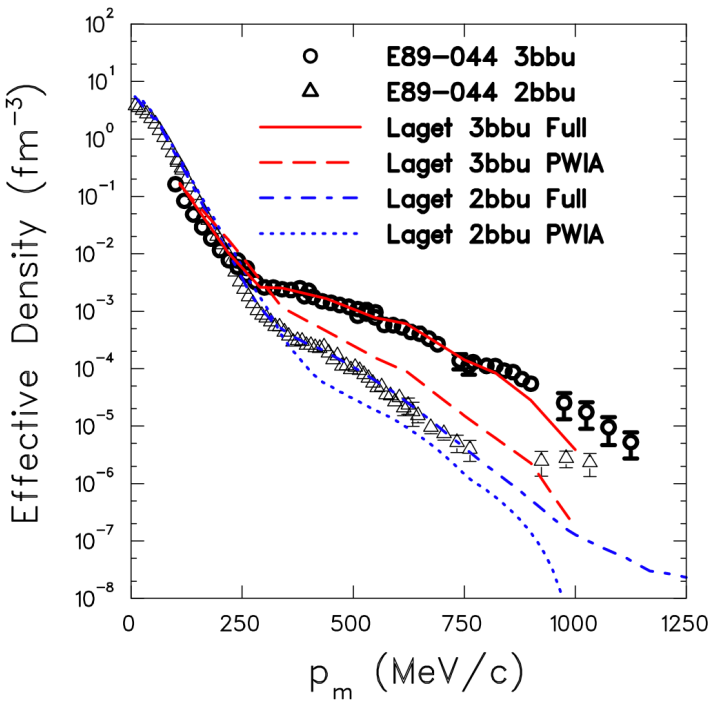




(p,2p): Quasi-Free Scattering



FSI Complications!



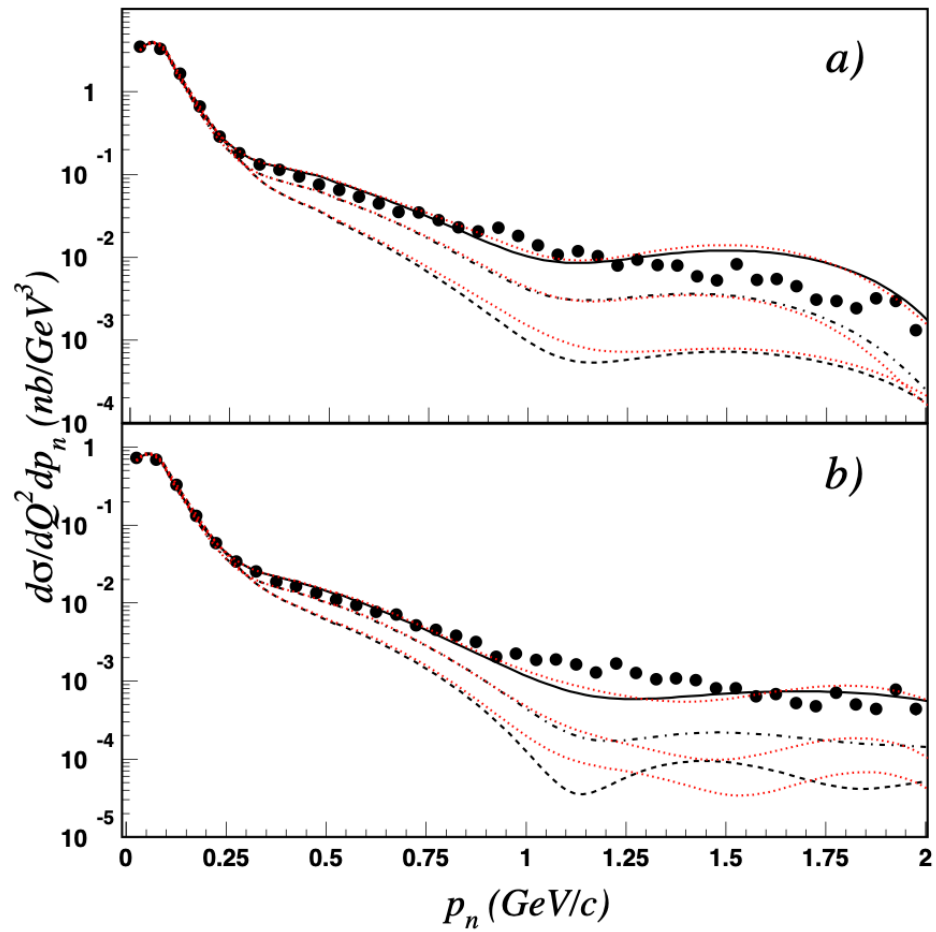
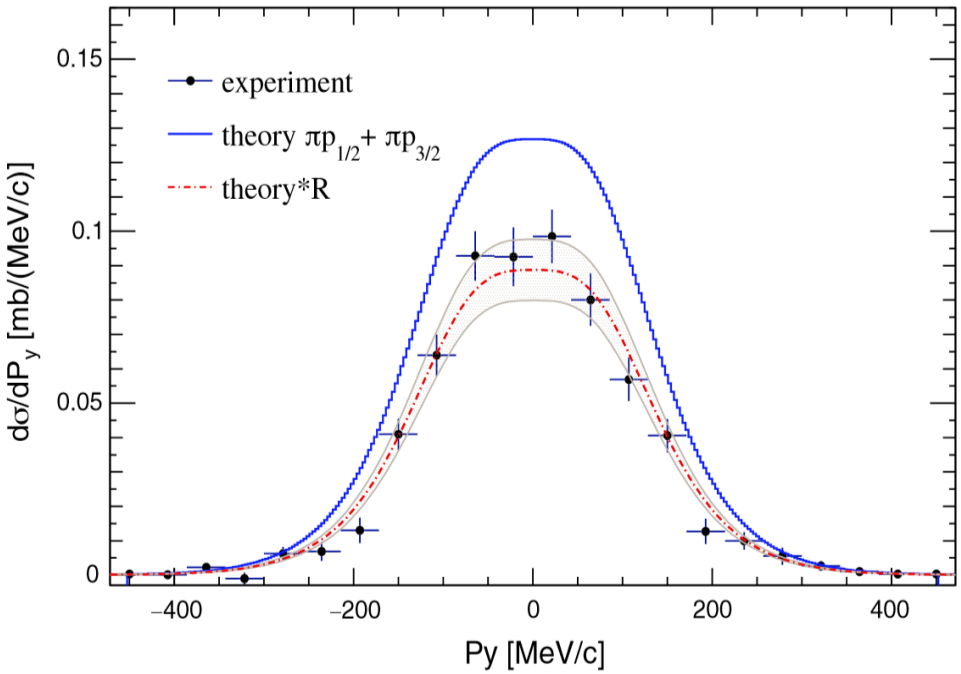


FIG. 1: Color online. The recoil neutron momentum distribution for (a) $Q^2 = 2 \pm 0.25$ GeV^2 and (b) $Q^2 = 3 \pm 0.5$ GeV^2. Dashed, dash-dotted and solid curves are calculations with the Paris potential for PWIA, PWIA+FSI and PWIA+FSI+MEC+NΔ, respectively. Dotted (red) curves are calculations with the AV18 potential.

Questions arise also in mean-field (p,2p)

^{16}O(*p,2p*) at 450MeV/u

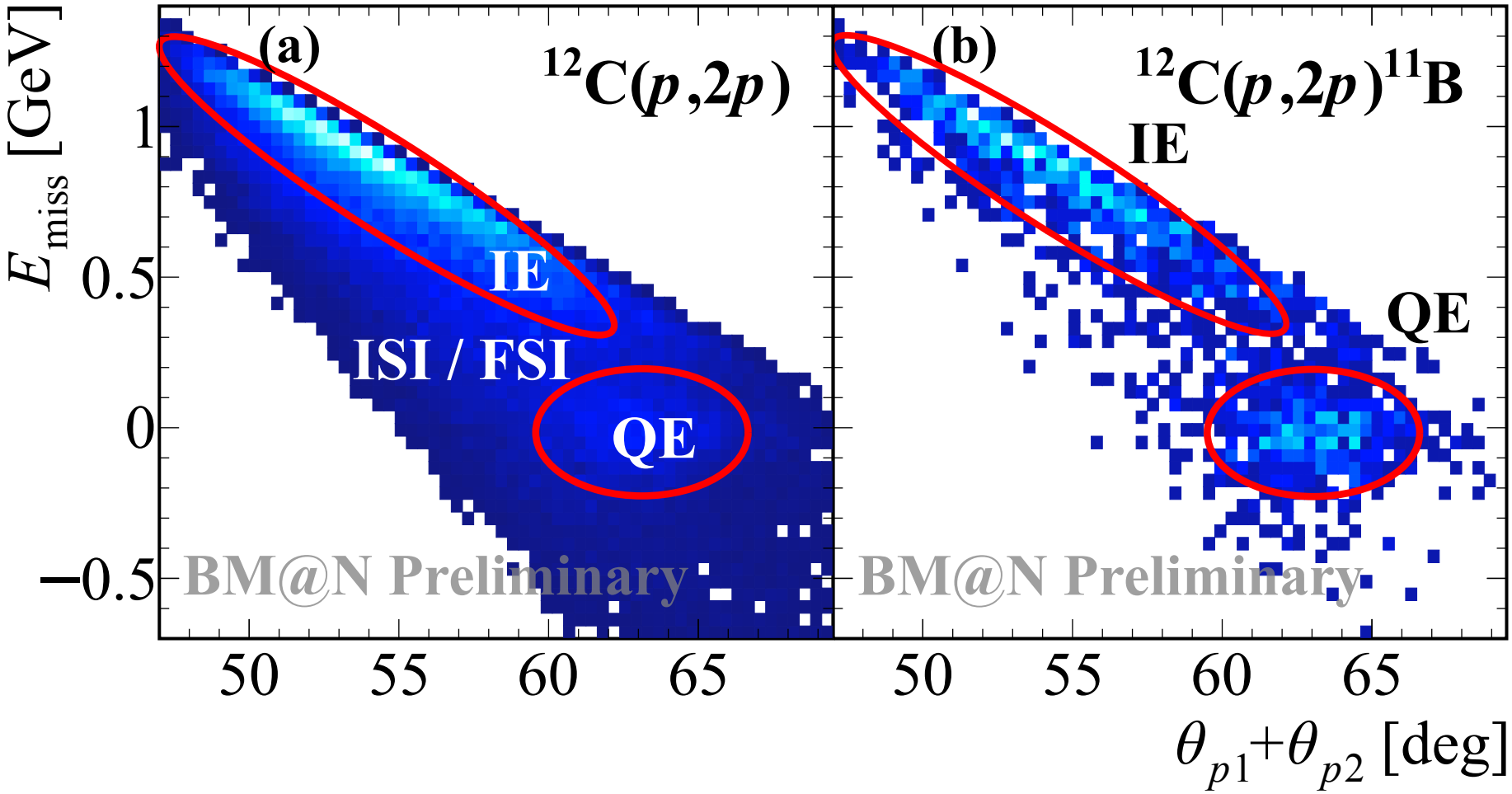


L. Atar et al. (R3B Collab.), Phys. Rev. Lett 120 (2018)

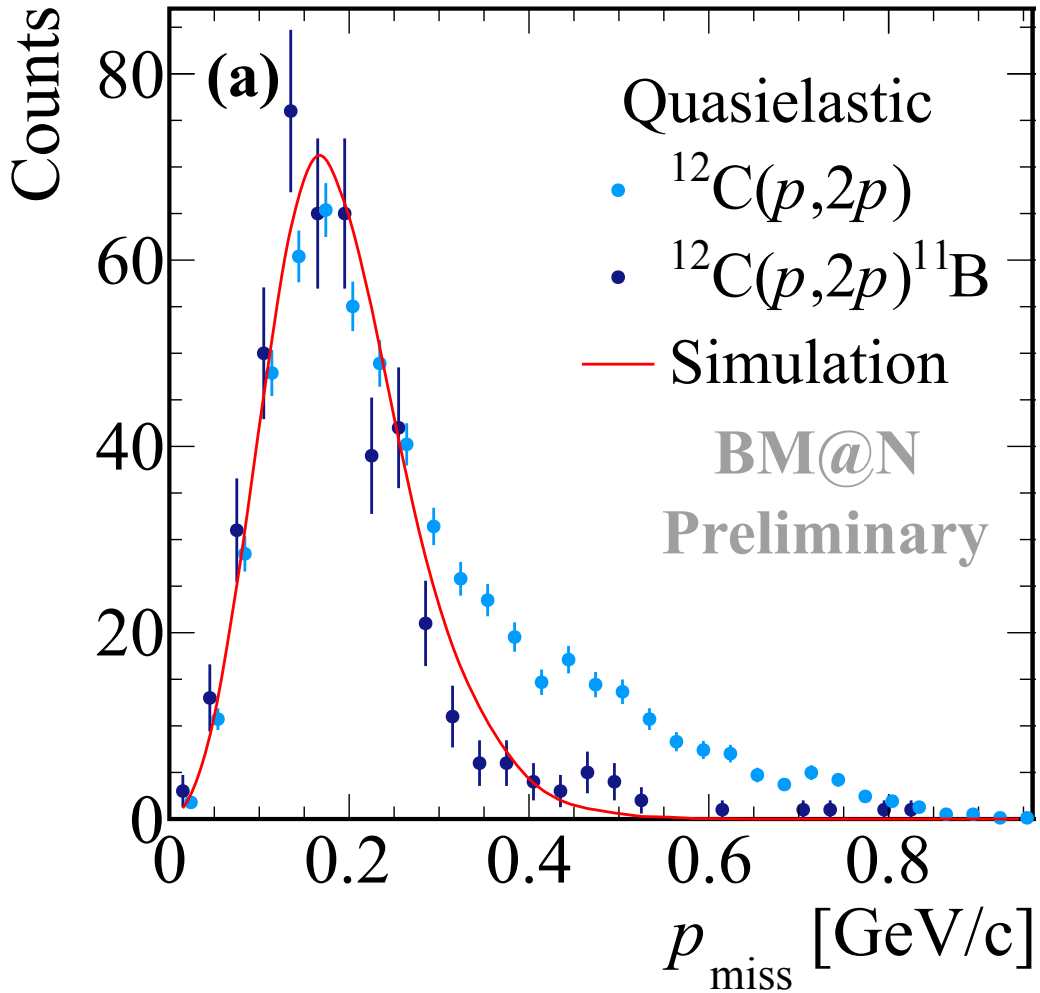
selected fragment final state, but could not distinguish inelastic contributions

→ introduce model-dependence

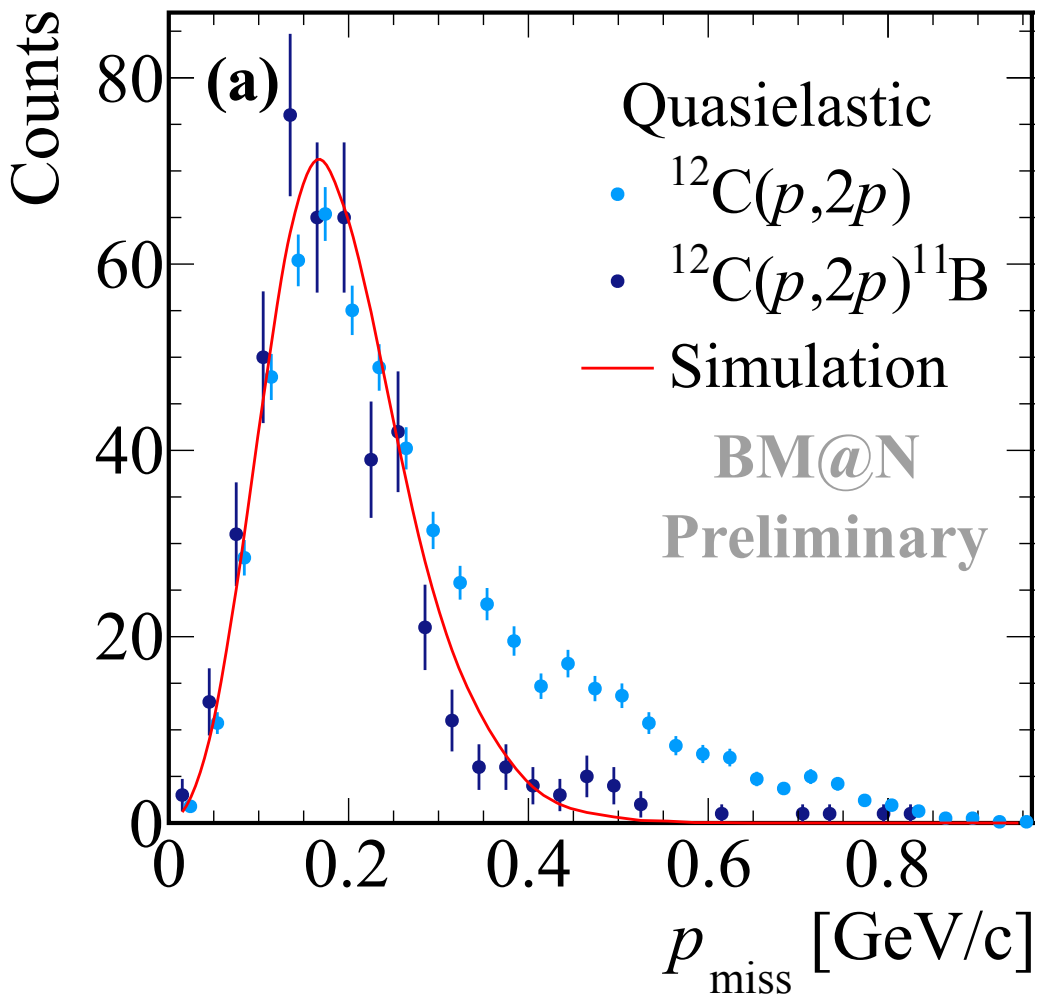
(p,2p)X vs. (p,2p)^{11}B



Quasi-elastic: (p,2p)X vs. (p,2p)^{11}B

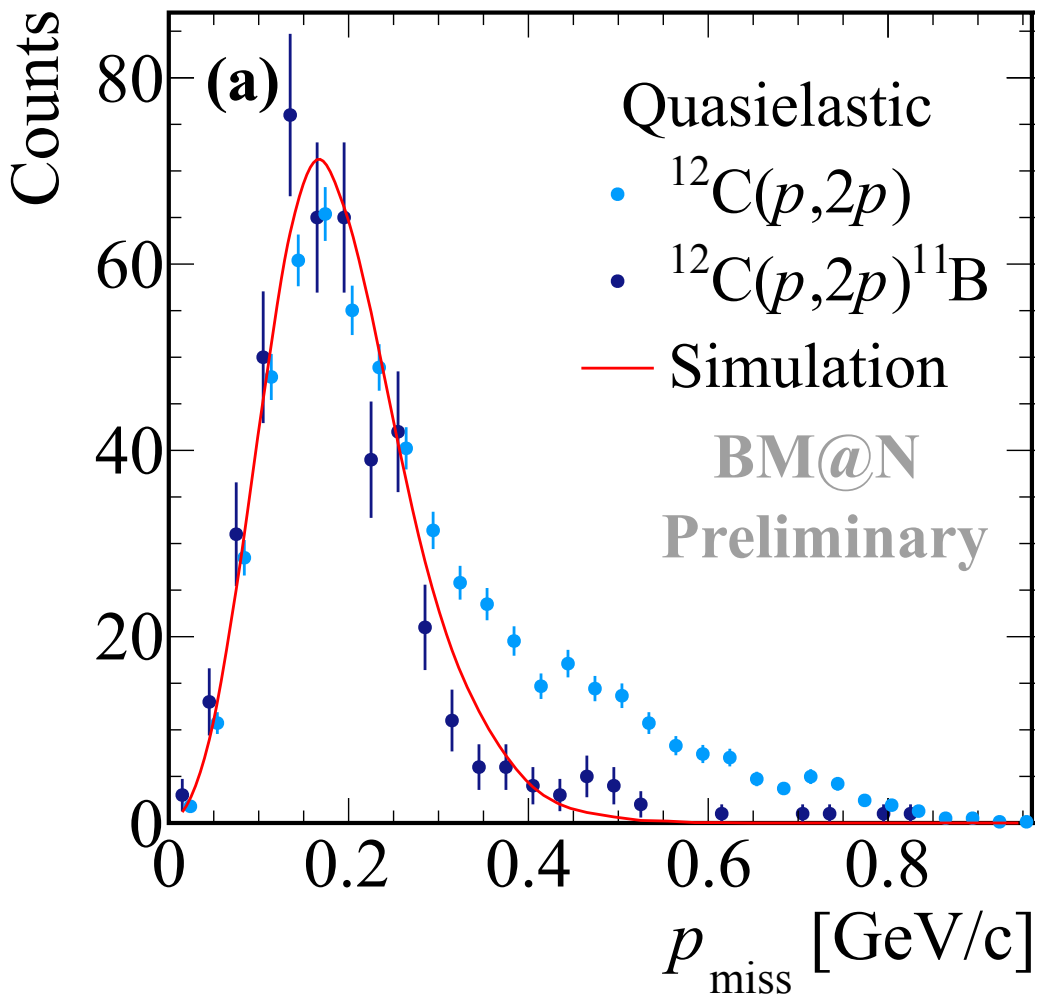


Quasi-elastic: (p,2p)X vs. (p,2p)^{11}B



Only ~40% of (p,2p) quasielastic events have ^{11}B fragment

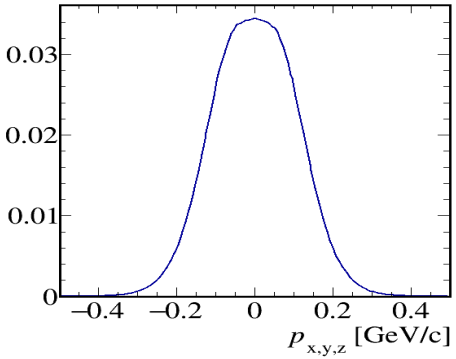
Quasi-elastic: (p,2p)X vs. (p,2p)^{11}B



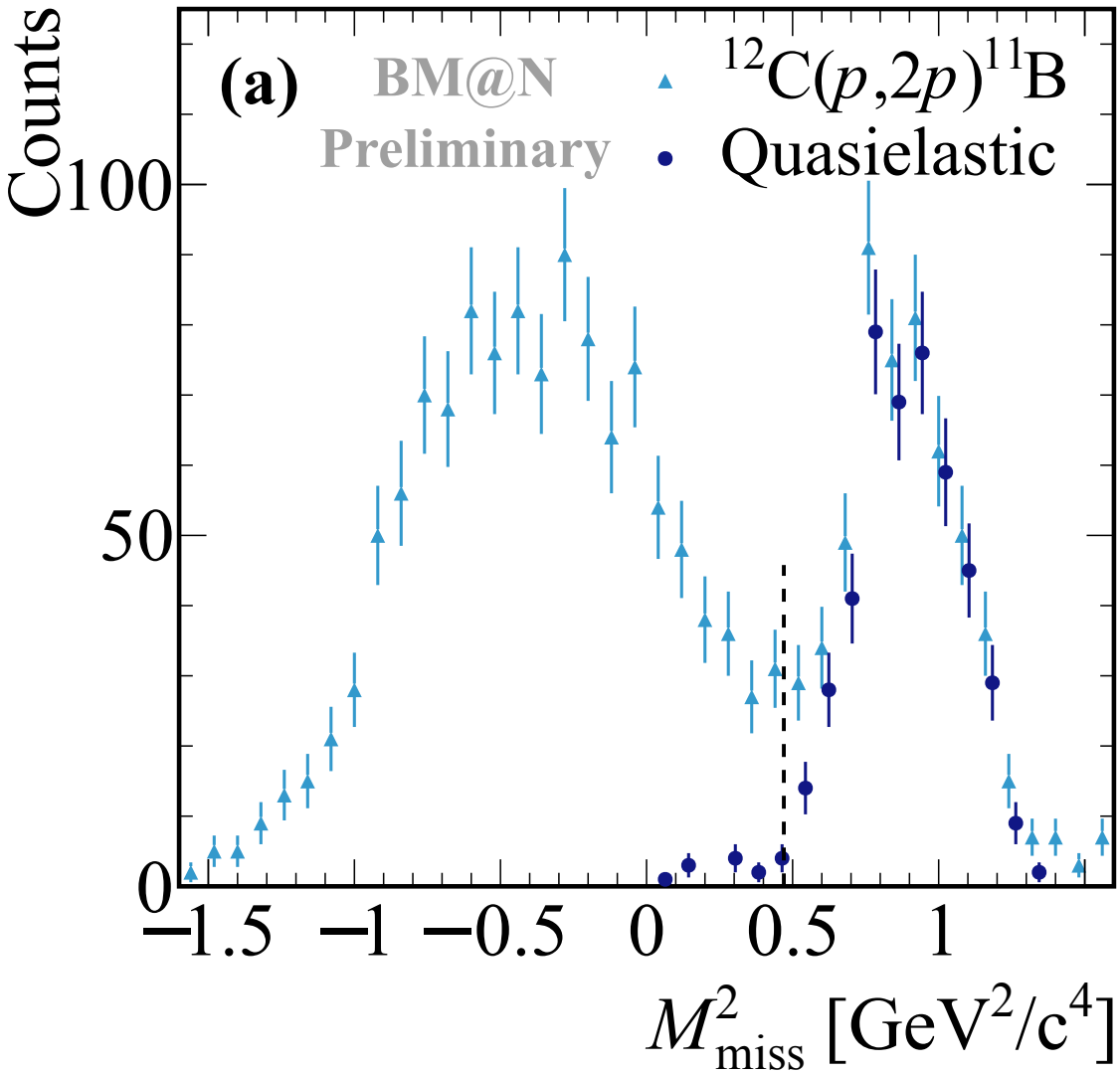
Only ~40% of (p,2p) quasielastic events have ^{11}B fragment

Simulation: ^{12}C $p_{3/2}$ shell

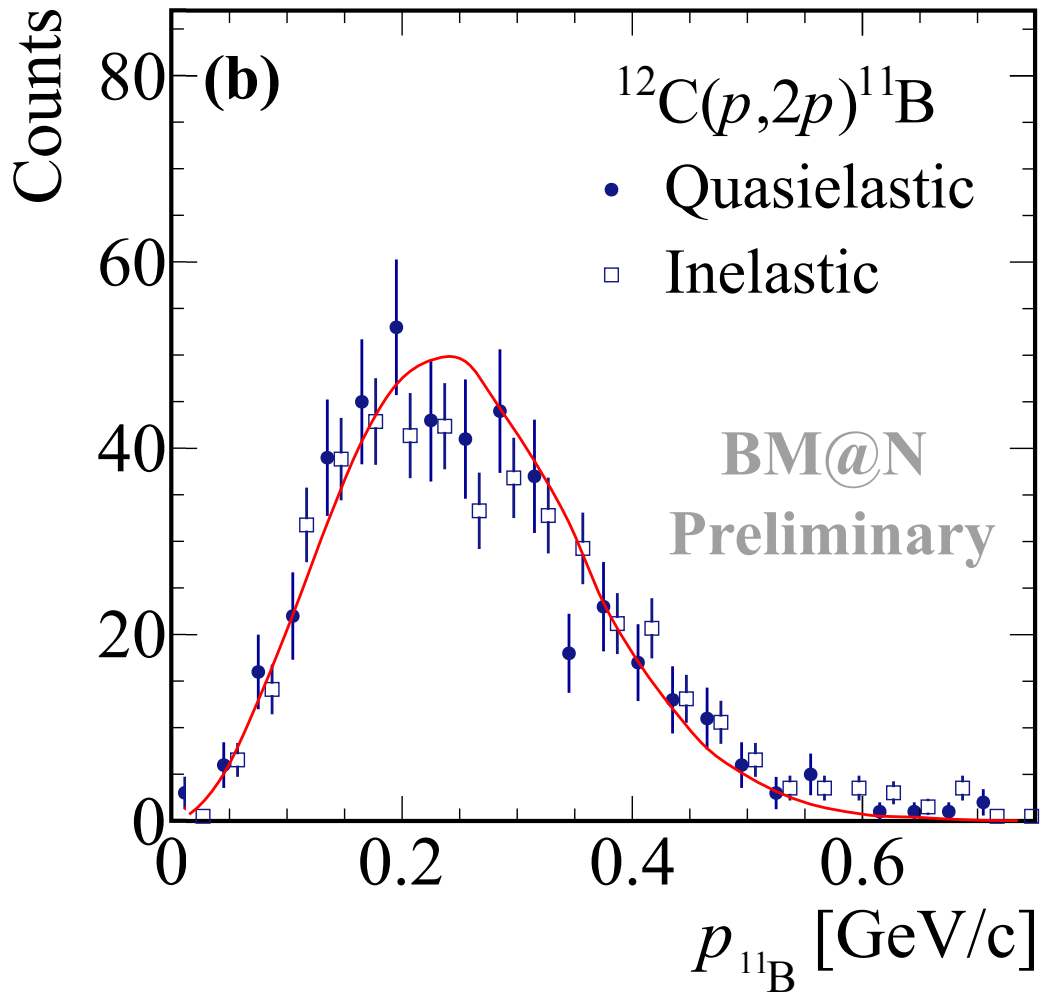
(accounts for acceptance, resolution, etc.)

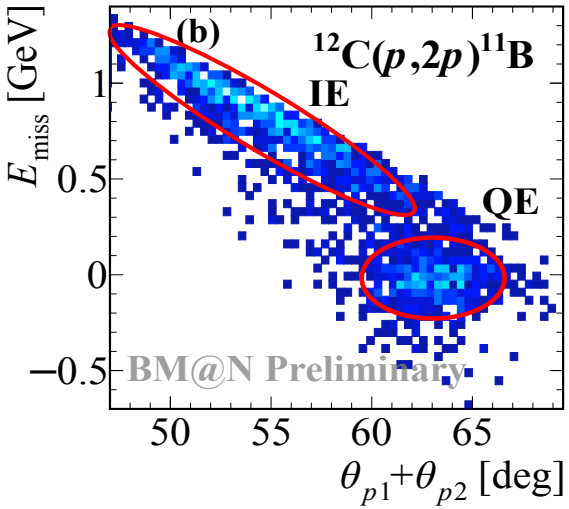


$(p,2p)^{11}B$: Inelastic Vs. Quasielastic

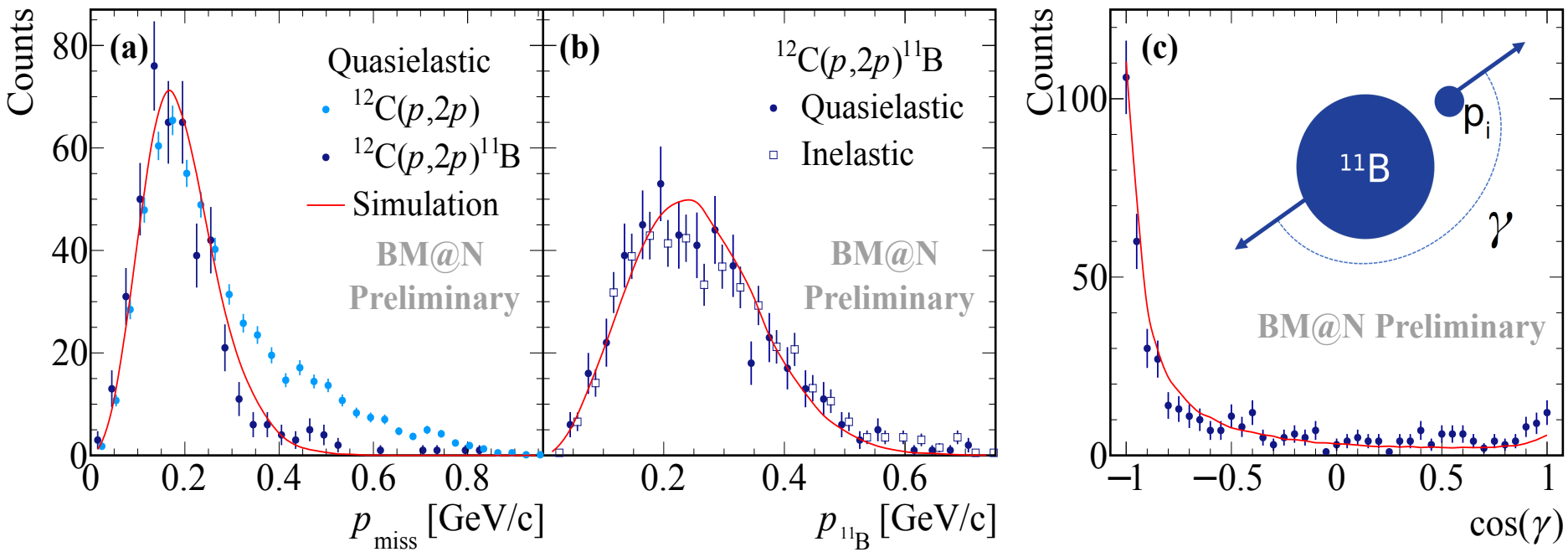


(p,2p)^{11}B: Inelastic Vs. Quasielastic

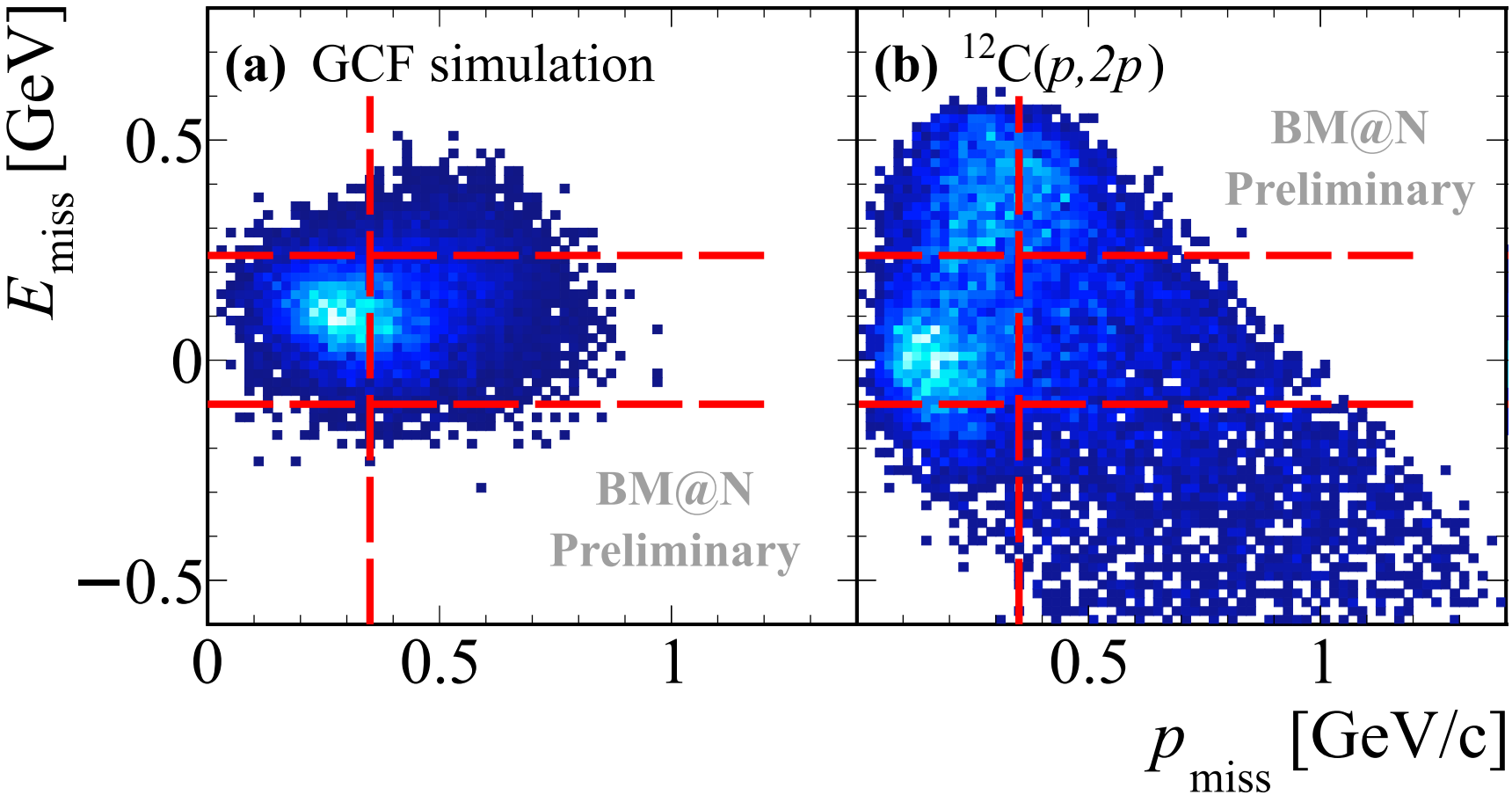




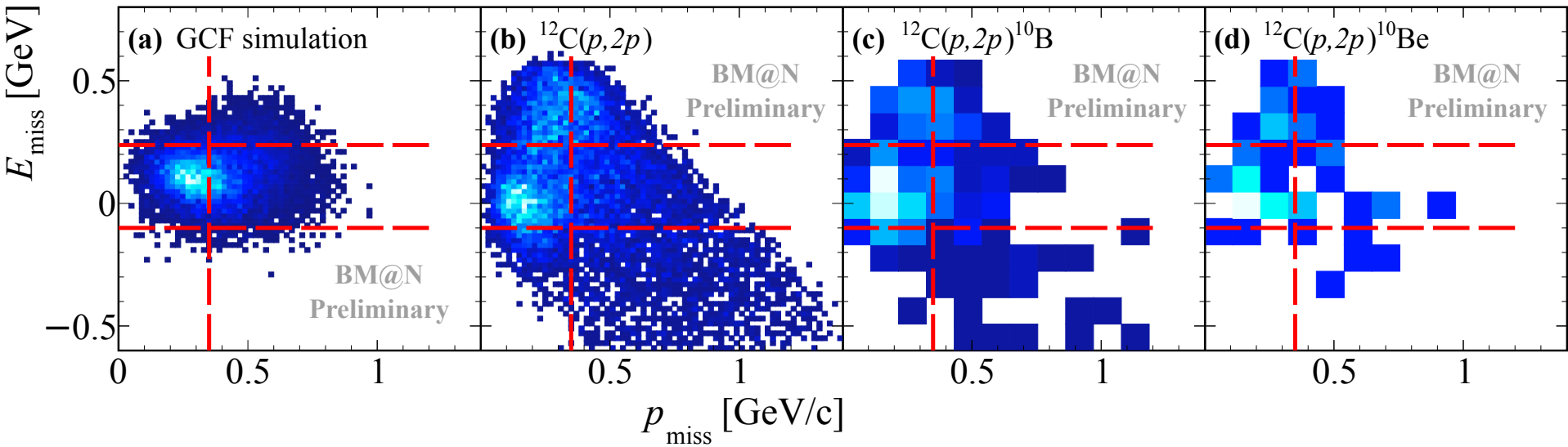
Single-nucleon knockout: ^{11}B tagging suppress ISI/FSI !



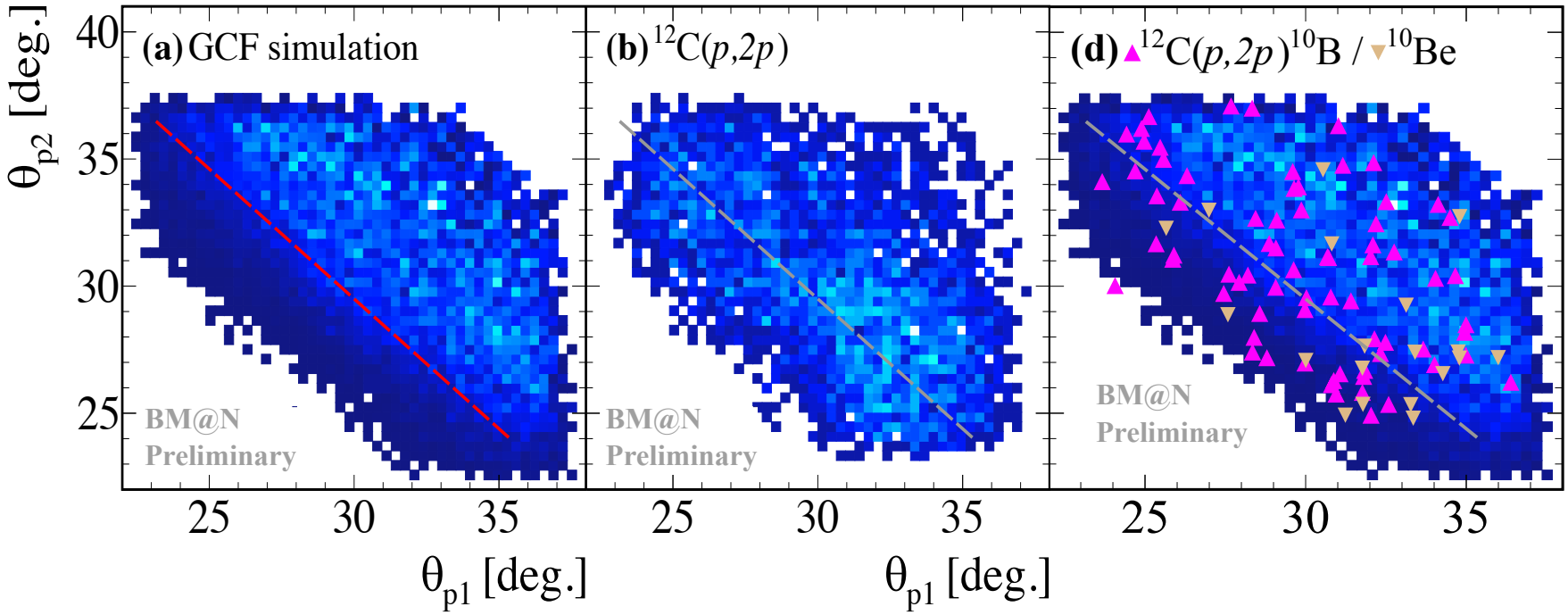
Looking for SRCs



Looking for SRCs



Looking for SRCs

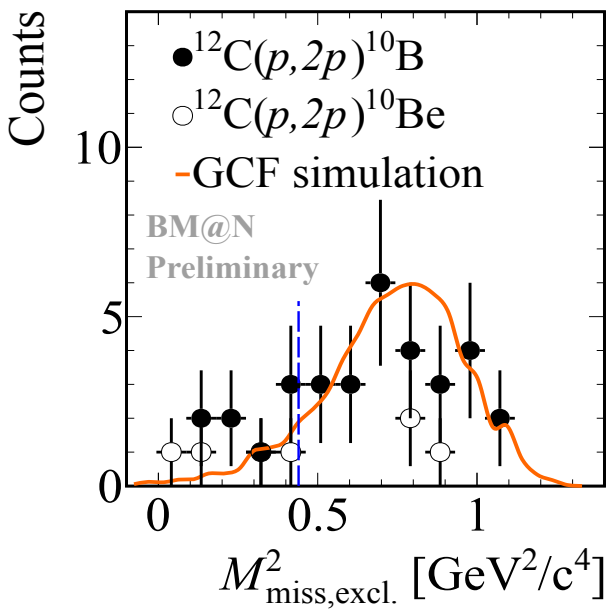


Looking for SRCs

<u>Selection Cuts:</u>

- inclusive (p,2p) + ^{10}B or ^{10}Be
- p_{miss} > 350 MeV/c
- -110 < E_{miss} < 240 MeV
- In-plane opening angle > 63°
- M_{miss} > 420 MeV²/c⁴

Missing mass consistent with a nucleon



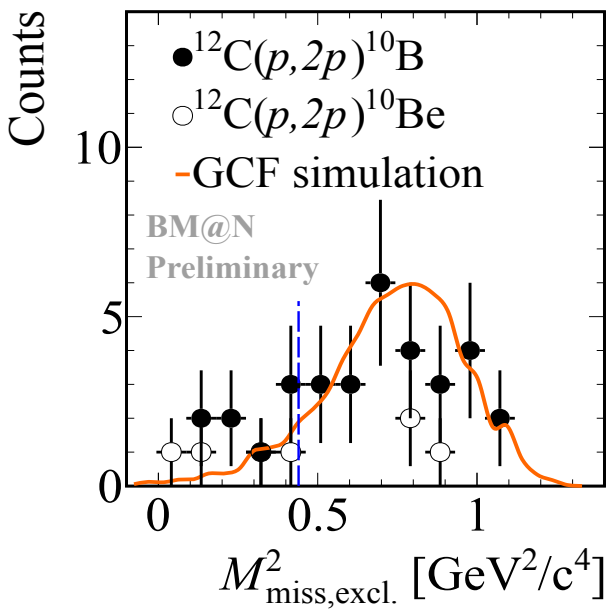
Looking for SRCs

<u>Selection Cuts:</u>

- inclusive (p,2p) + ^{10}B or ^{10}Be
- p_{miss} > 350 MeV/c
- -110 < E_{miss} < 240 MeV
- In-plane opening angle > 63°
- M_{miss} > 420 MeV²/c⁴

Only few % of relevant (p,2p) events have ^{10}B or ^{10}Be fragments.

Missing mass consistent with a nucleon

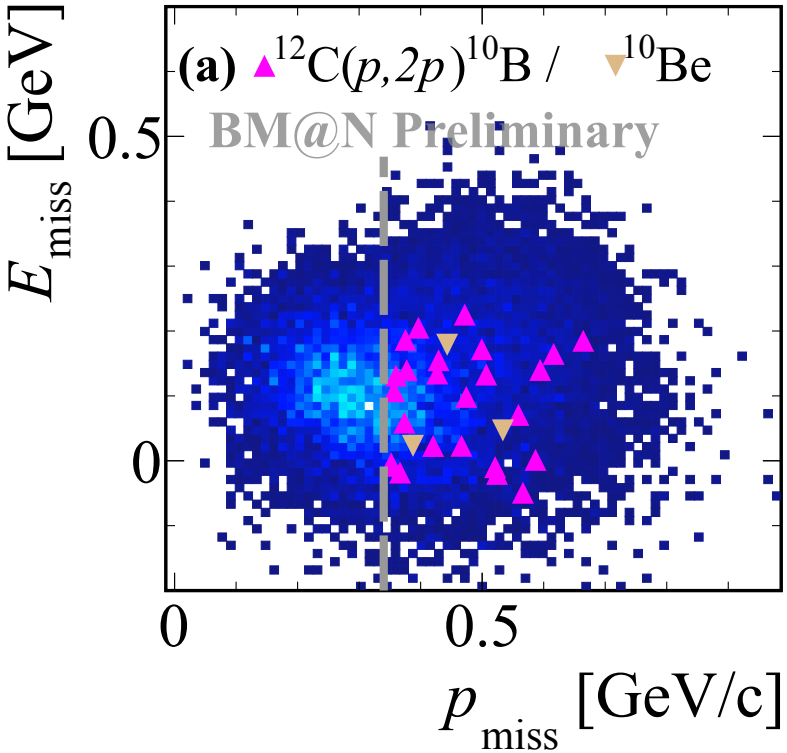


np-SRC Dominance

26 ^{10}B events

3 ^{10}Be events

→ *np* pair dominance



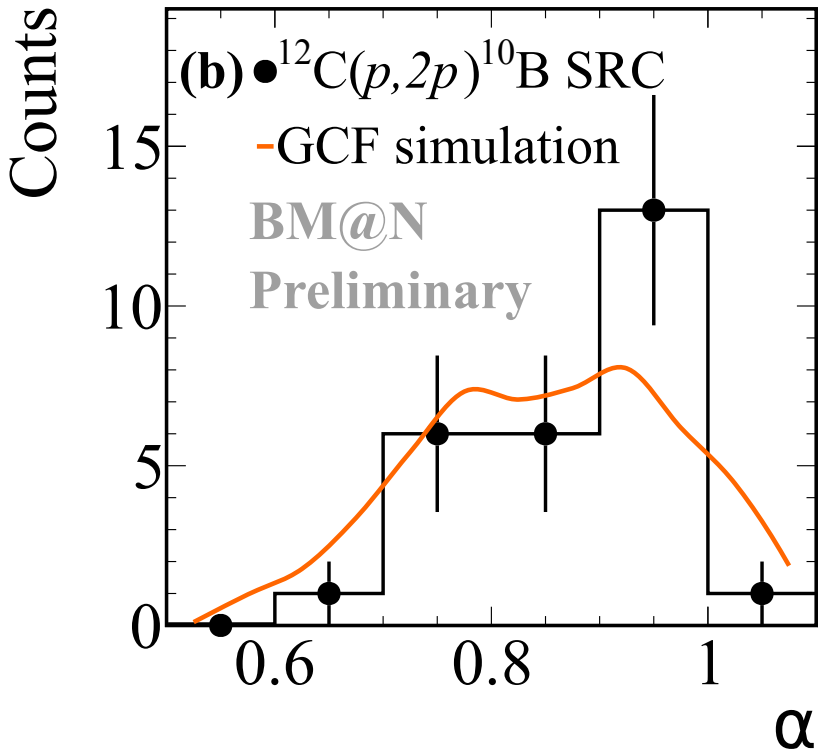
<u>Possible contamination:</u>

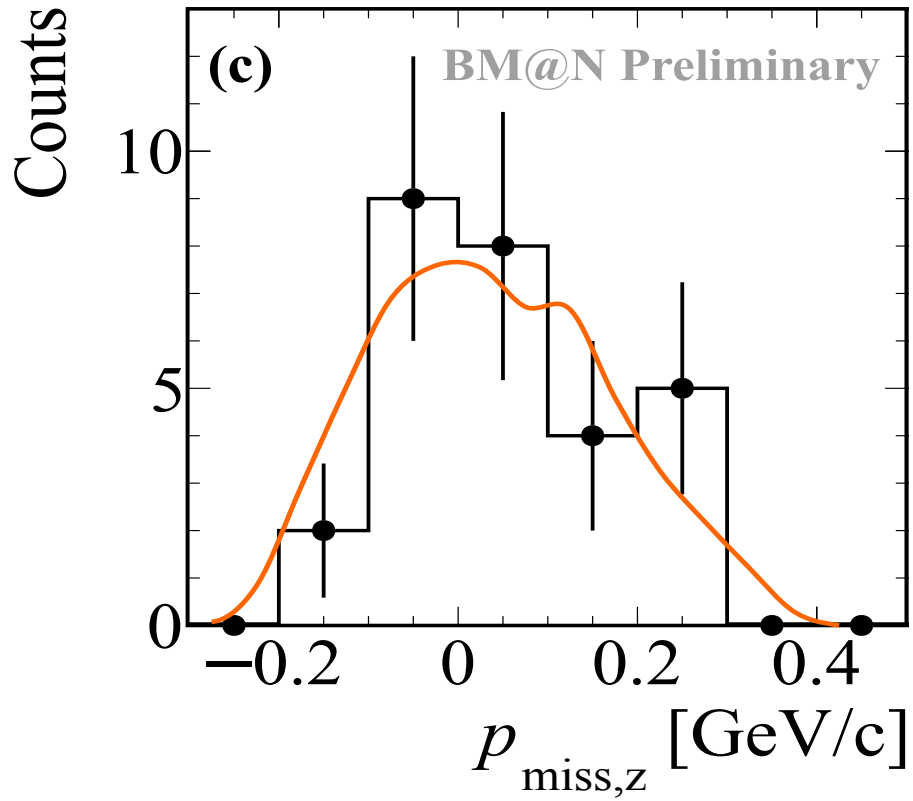
1. **^{11}B + FSI nucleon knockout?**
   Result in #^{10}B ~ ^{10}Be due to similar np / pp cross section.

2. **QE mean-field events with excited ^{11}B?**
   Estimated maximal contribution of 5 (^{10}B) and 2 (^{10}Be) events.

Momentum Distribution

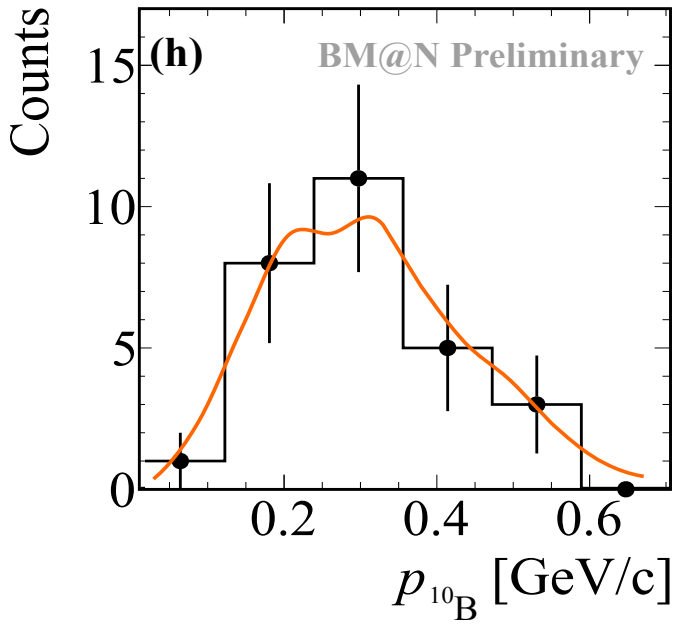
Shifted in beam direction to minimize s as expected!

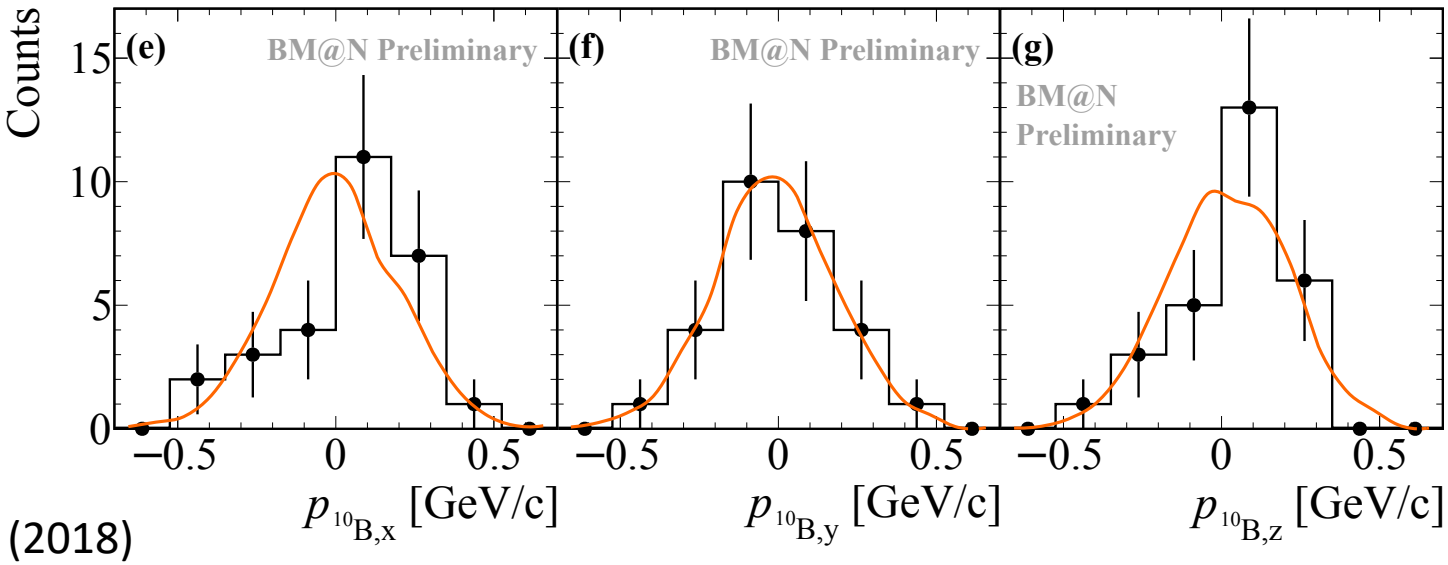




$$\alpha = (E_{\mathrm{miss}} - p^{z}_{\mathrm{miss}})/m_{p}$$

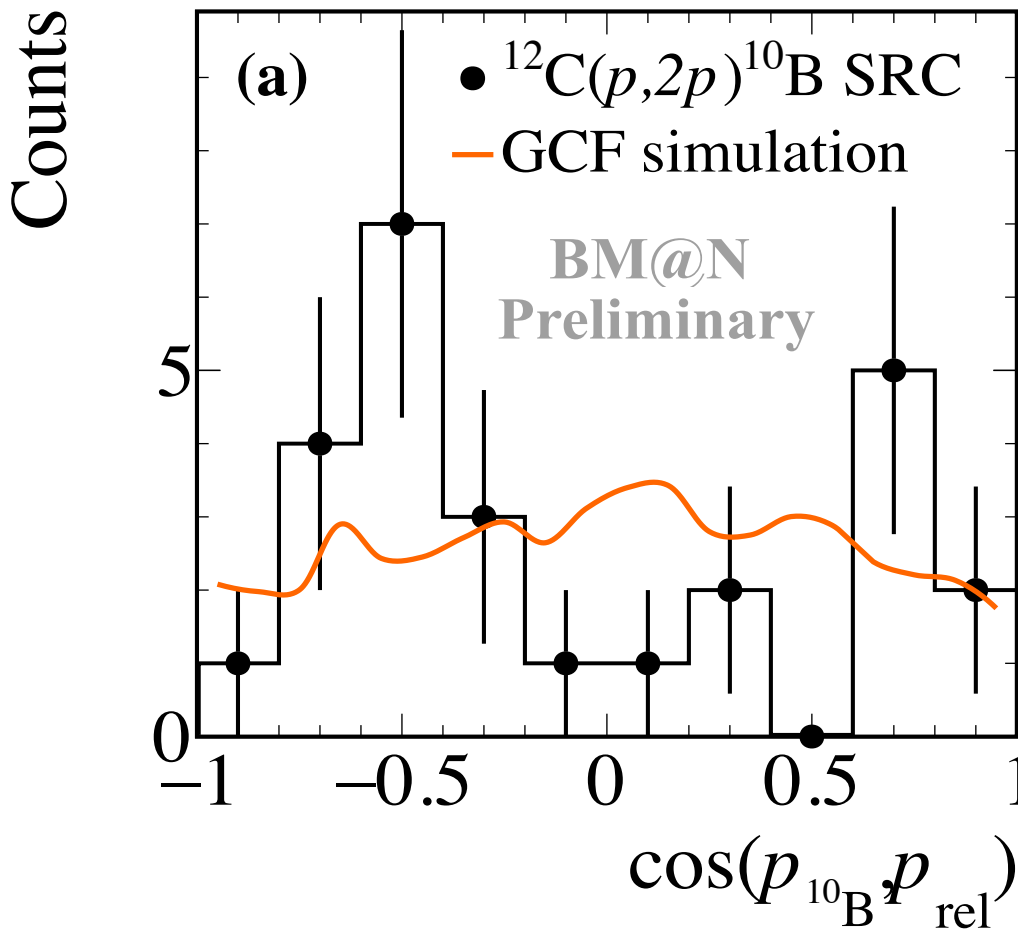
Fragment Momenta: Pair c.m. Motion

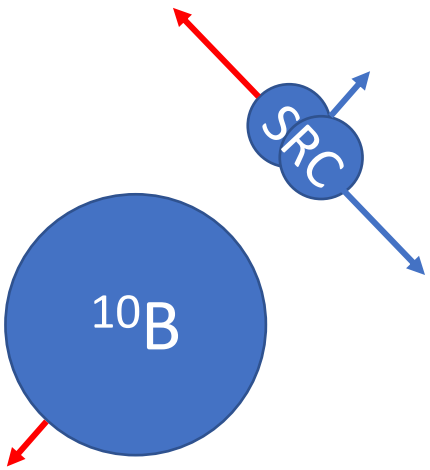




Cohen PRL (2018)

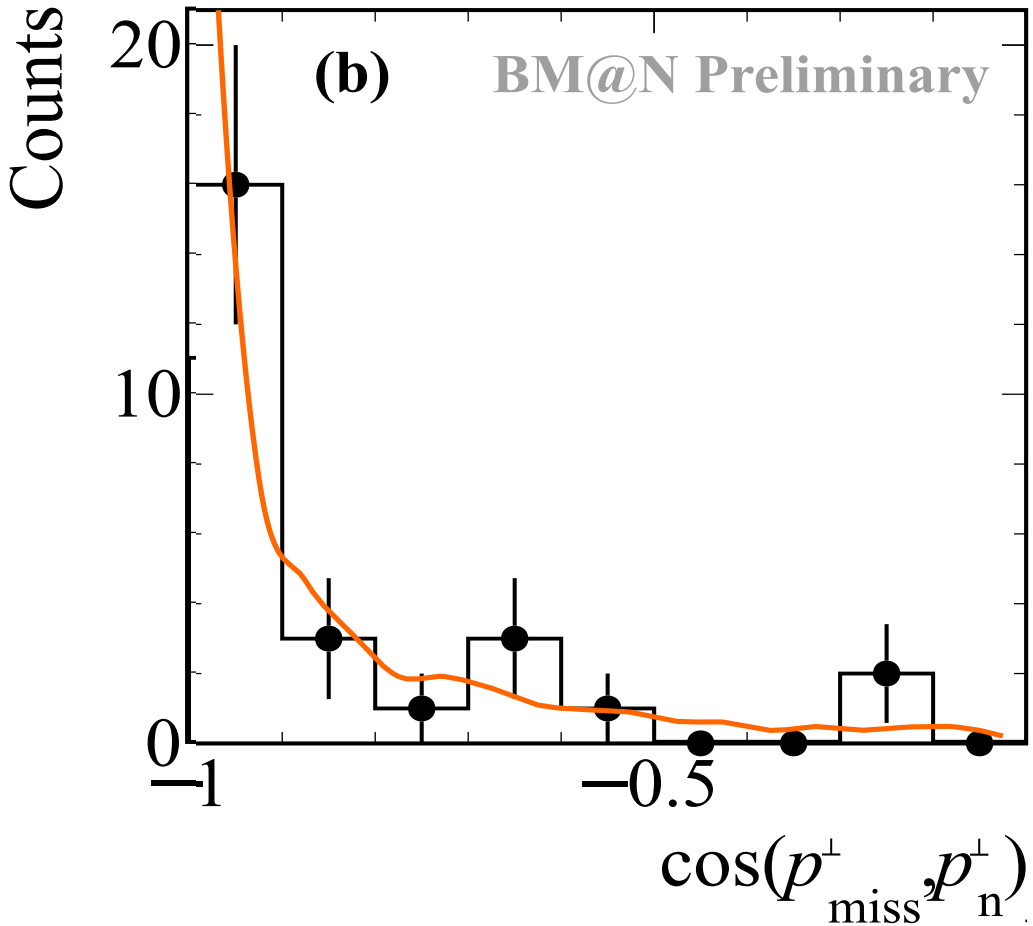
SRC:A-2 Angular de-Correlation

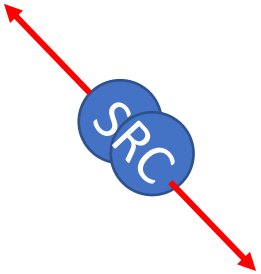




Cohen PRL (2018)

SRC Pair: Angular Correlation





Cohen PRL (2018)

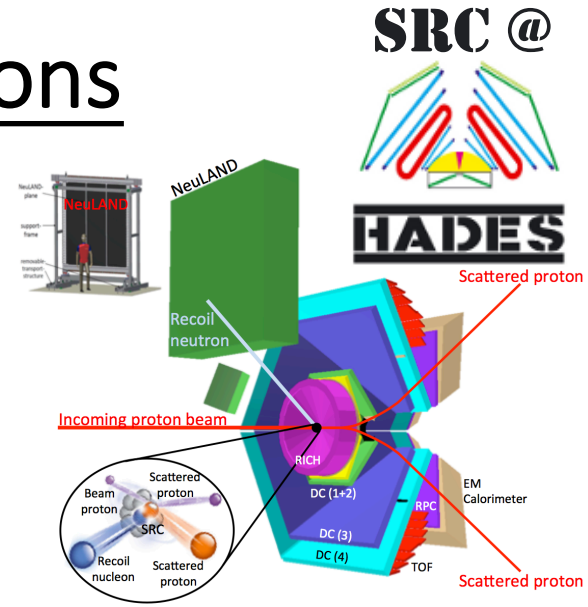
JINR Results

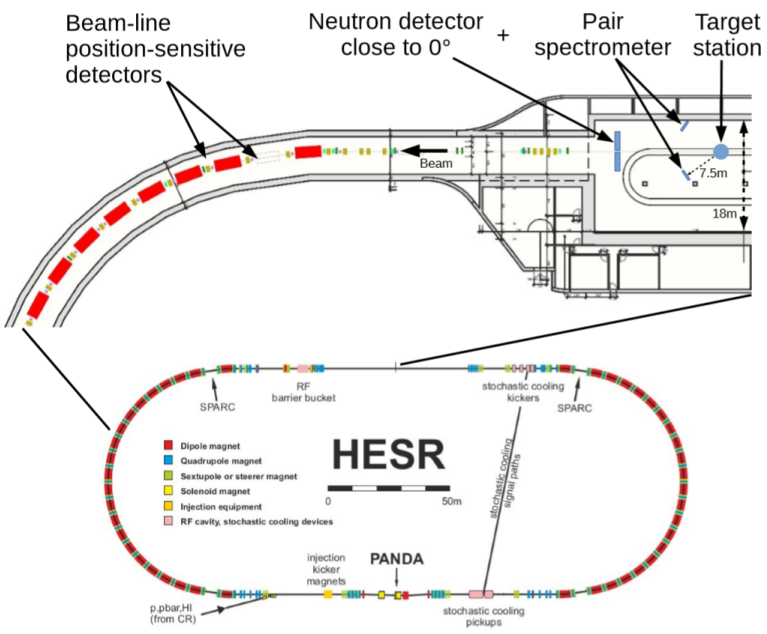
- First observation of ISI/FSI suppression and single-step nucleon knockout selection using fragment detection.

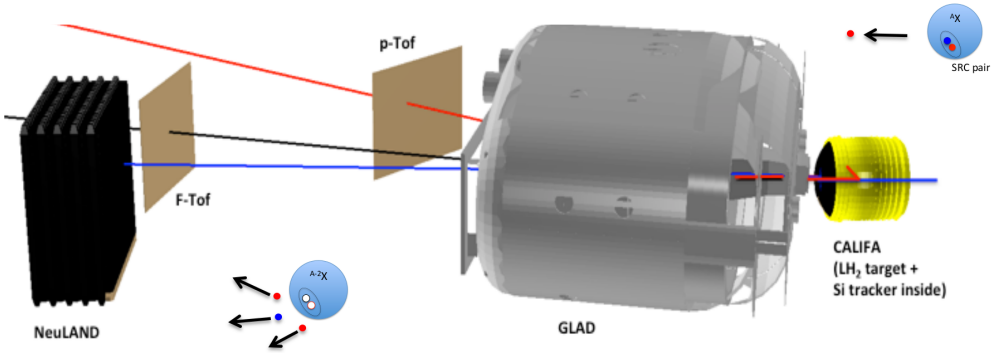
- First observation of SRCs with bound residual A-2 system:
  - Direct measurement of pair c.m. motion
  - Establishment of factorization!

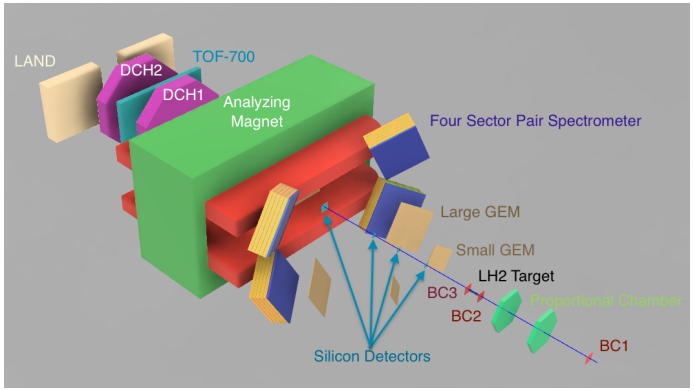
Next Steps in SRC studies \w Hadrons

- **JINR**
- **R3B**
- **HADES**
- **HESR**





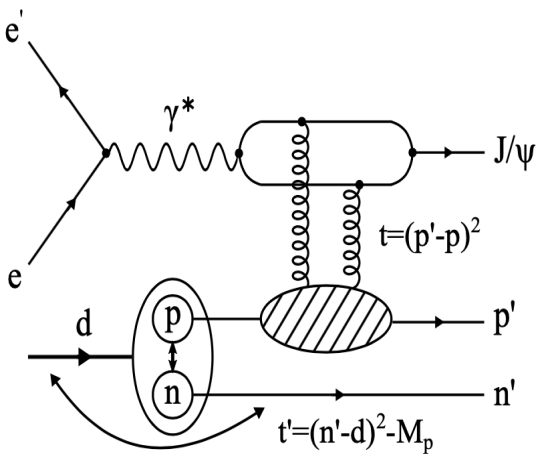


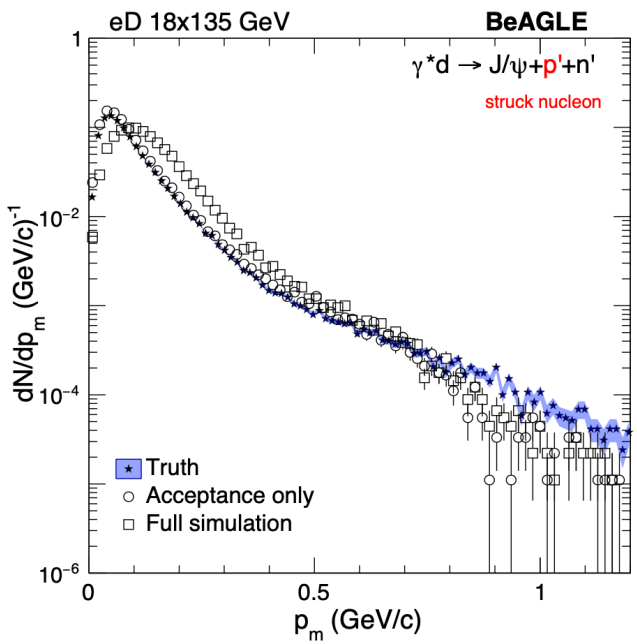


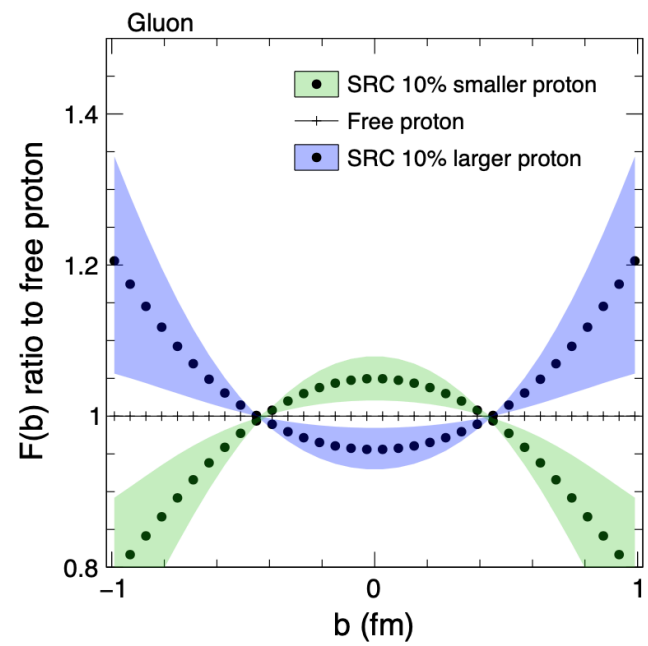
Next Steps in SRC studies @ EIC

Probing the short-range correlations in deuteron via incoherent diffractive J/ψ production at the EIC with spectator tagging

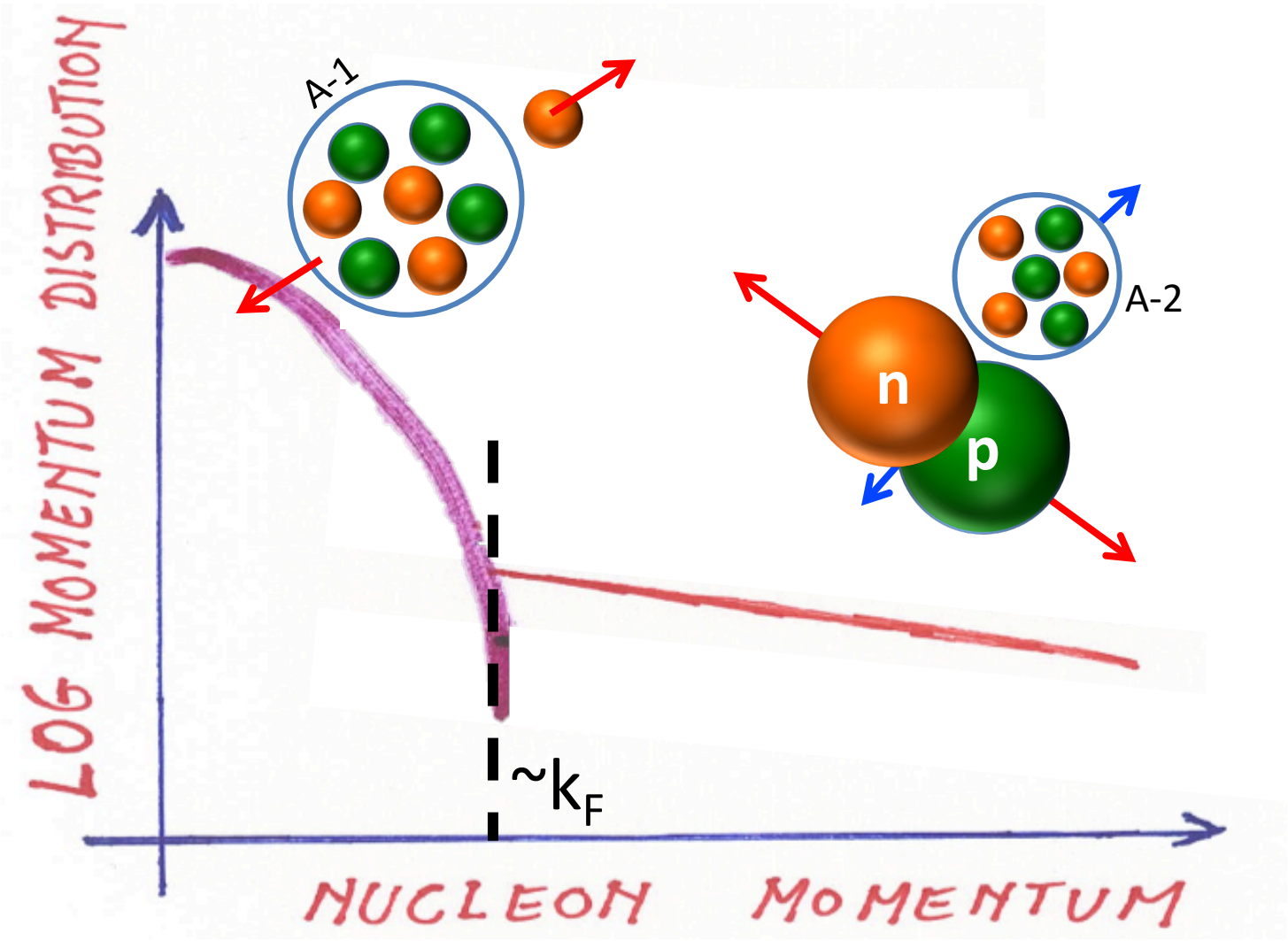
Zhoudunming Tu,[1,*] Alexander Jentsch,[1] Mark Baker,[2] Or Hen,[3]
Douglas Higinbotham,[4] Elke-Caroline Aschenauer,[1] and Thomas Ullrich[1]



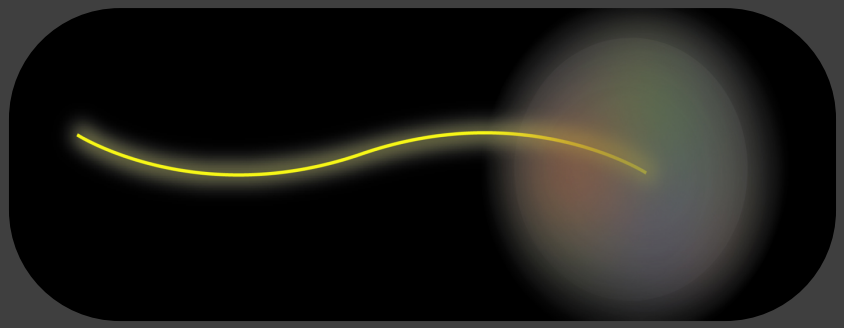


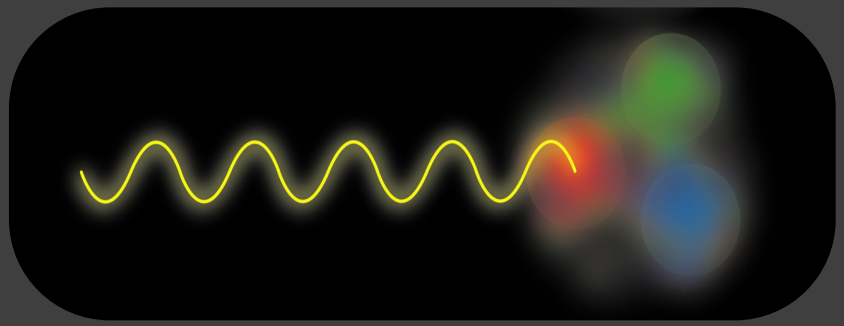


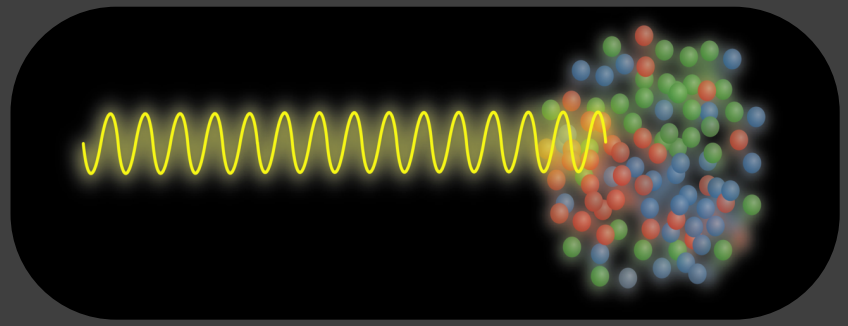
(1) Atomic nuclei have 2 'phases'

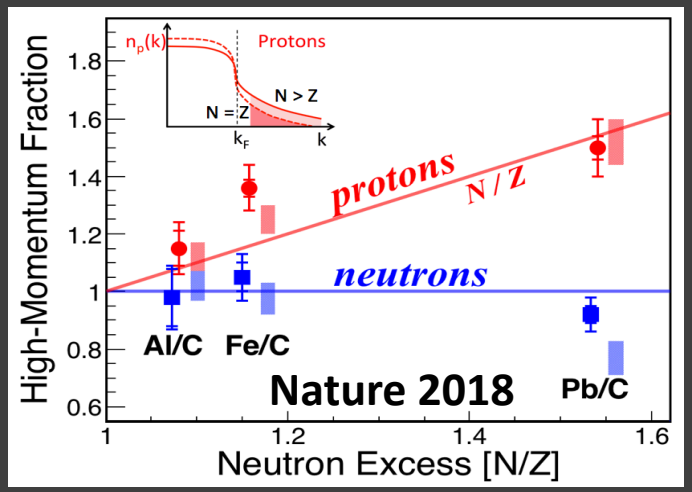


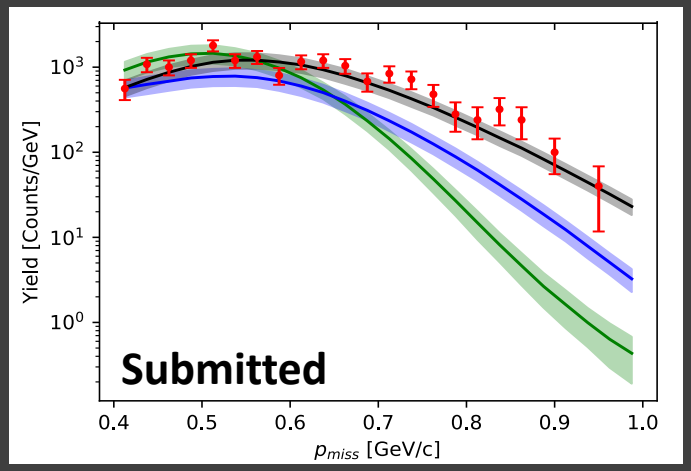
(2) Correlated phase significant across scales

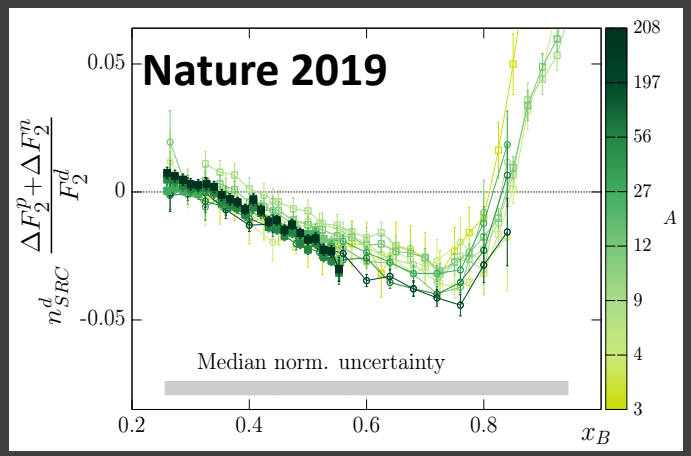












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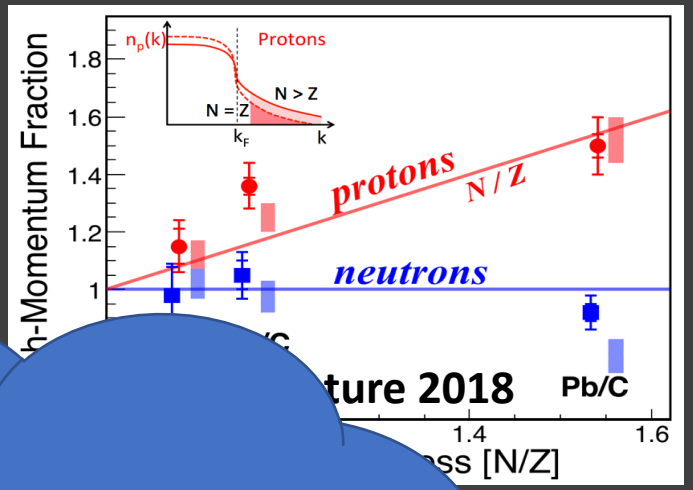
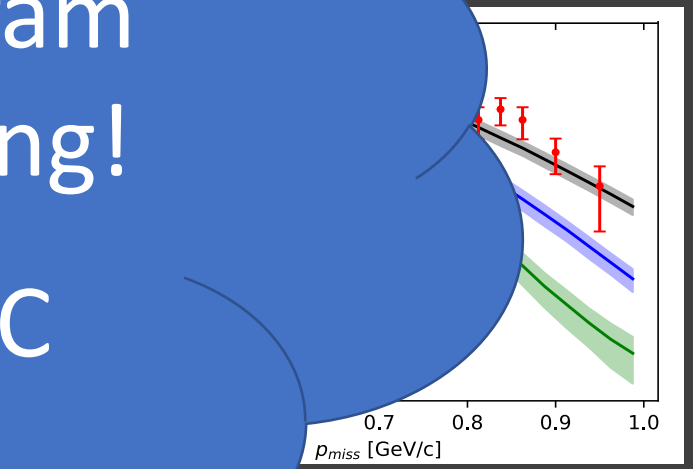
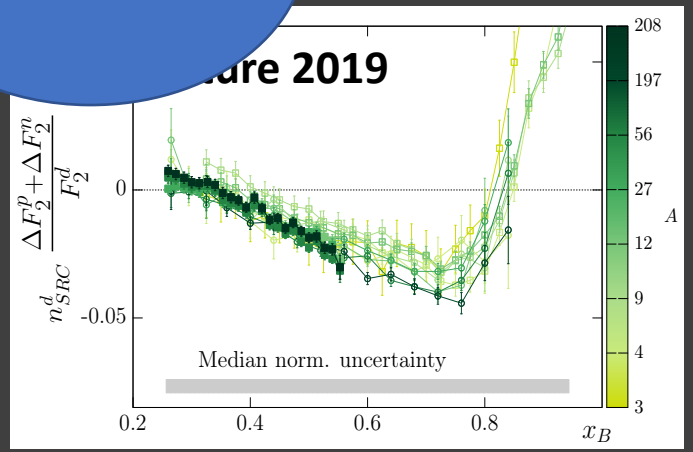
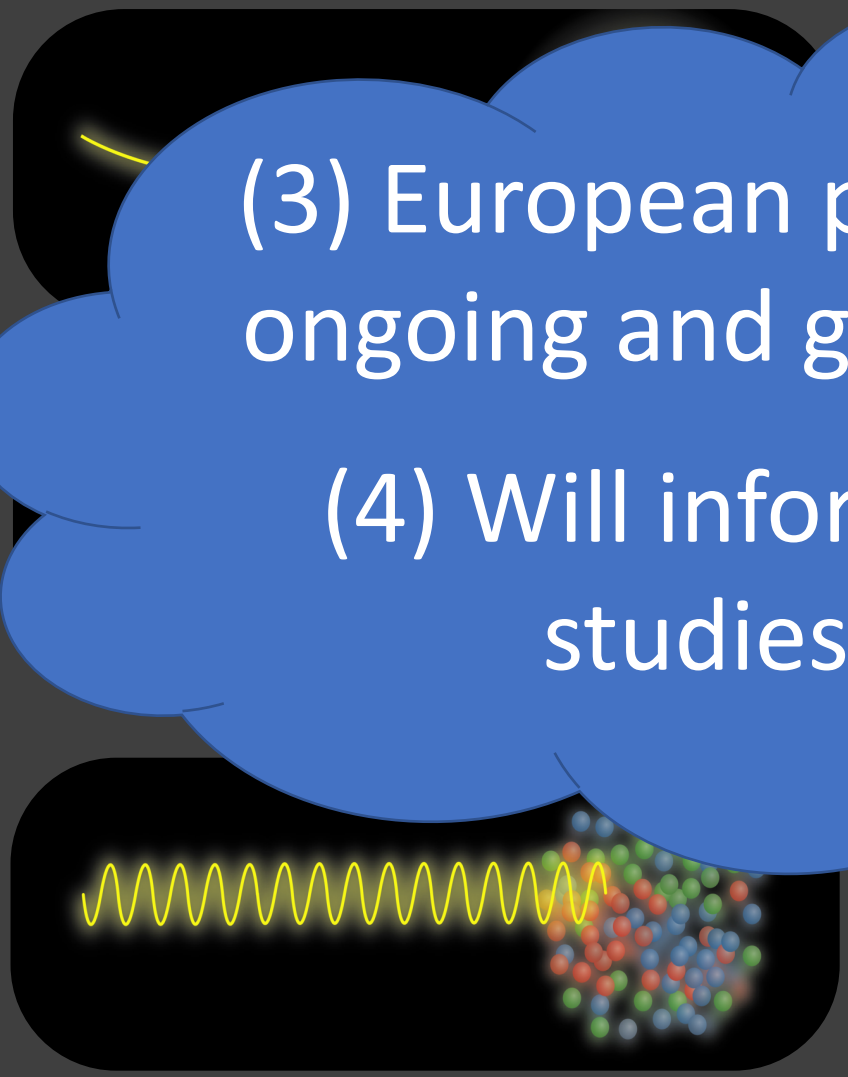




(3) European program ongoing and growing!

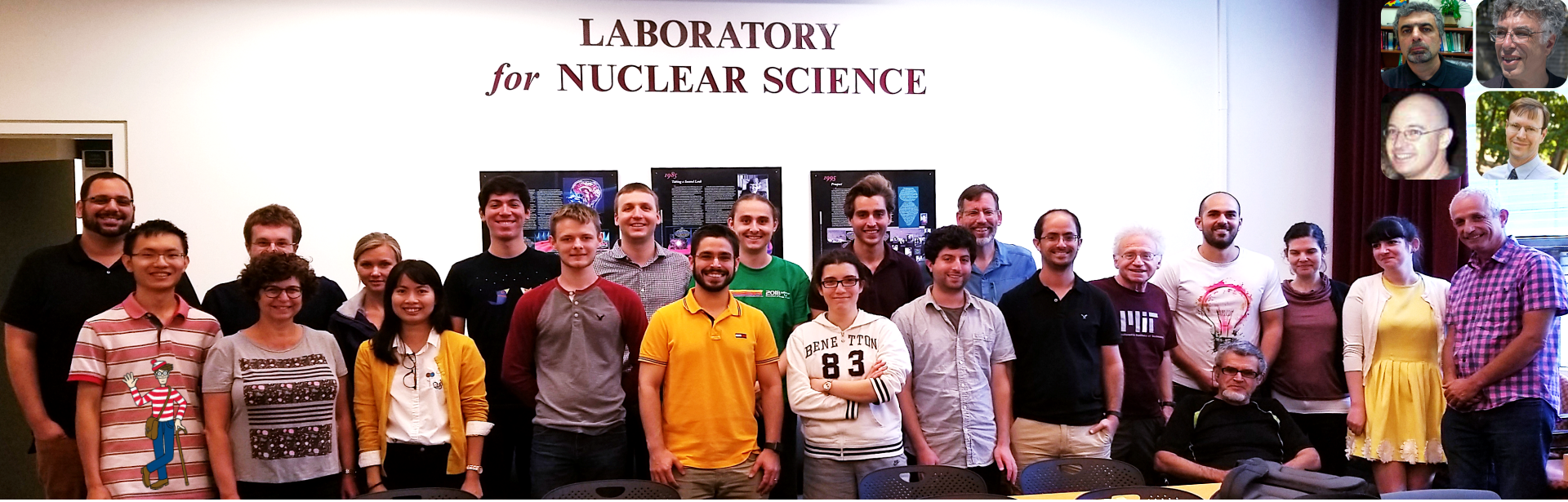
(4) Will inform EIC studies!





‘Our’ SRC World

+ Many Theory Collaborators: UW, PSU, HUJI, LANL, ANL, Gent, FIU, Perugia, Pisa, …



Afroditi Papadopoulou

Efrain Segarra

Jackson Pybus

Andrew Denniston

Dr. Adi Ashkenazy

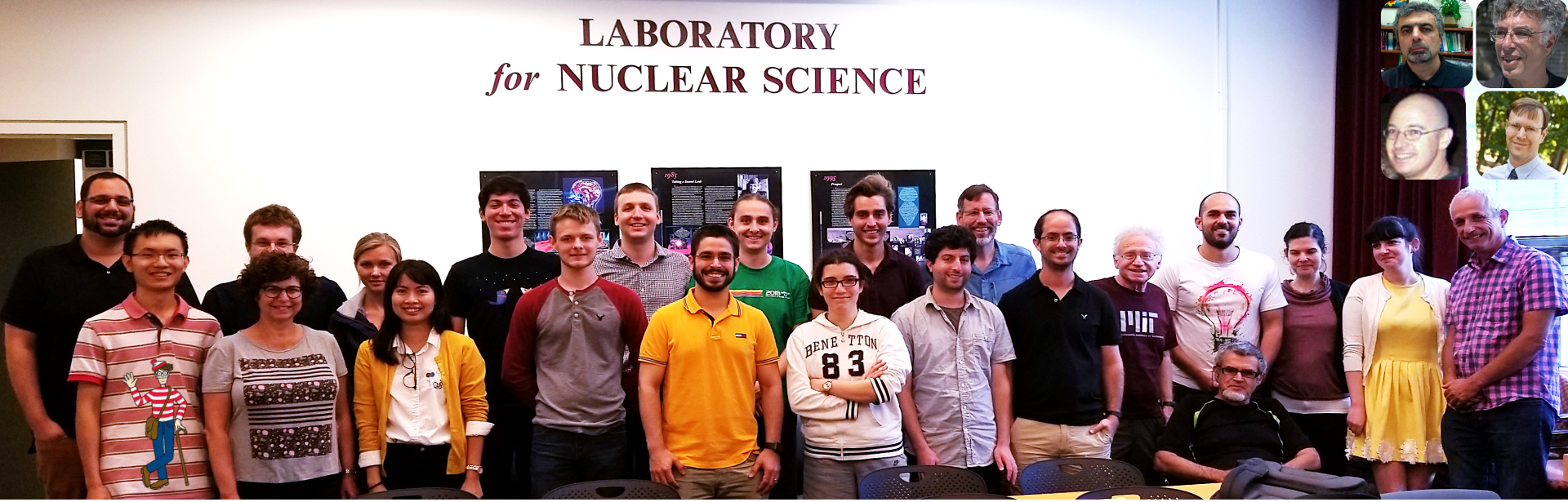
Dr. Dien Nguyen

Dr. Holly Vanse

Dr. Florian Hauenstein

Dr. Julian Kahlbow

Dr. Tyler Kutz

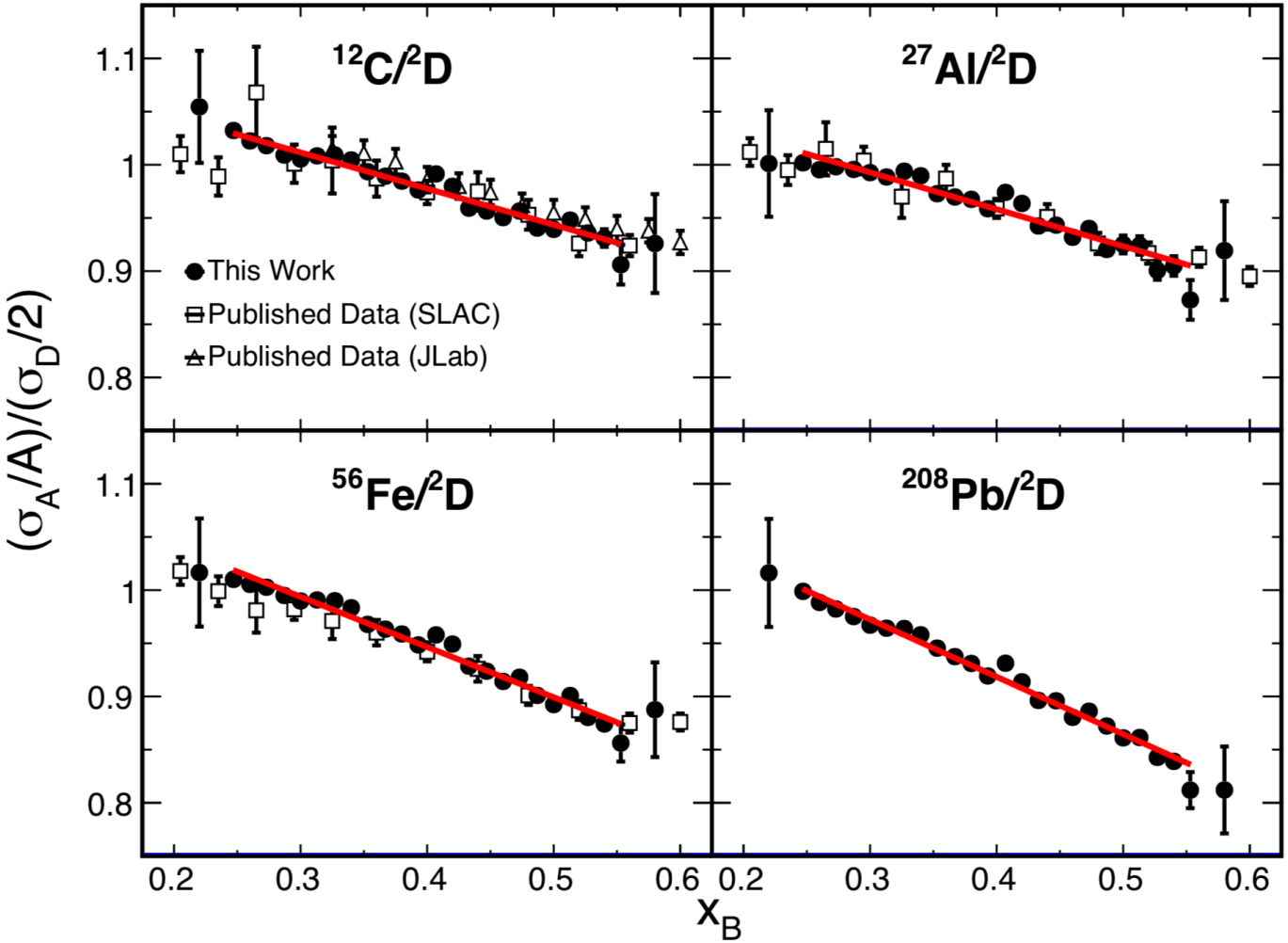


2018-20 SRC Publications:

- Nature, 578, 540 (2020)
- Nature 566, 354 (2019)
- Nature 560, 617 (2018)
- Phys. Lett. B 805, 135429 (2020)
- Phys. Lett. B 800, 135110 (2019)
- Phys. Lett. B 797, 134890 (2019)
- Phys. Lett. B 797, 134792 (2019)
- Phys. Lett. B 791, 242 (2019)
- Phys. Lett. B 793, 360 (2019)
- Phys. Lett. B 785, 304 (2018)
- Phys. Lett. B 780, 211 (2018)

- PRL, In-Print (2020)
- PRL 124, 092002 (2020)
- PRL 122, 172502 (2019)
- PRL 121, 092501 (2018)
- arXiv: 1907.03658;
  2004.07304;
  2005.01621.

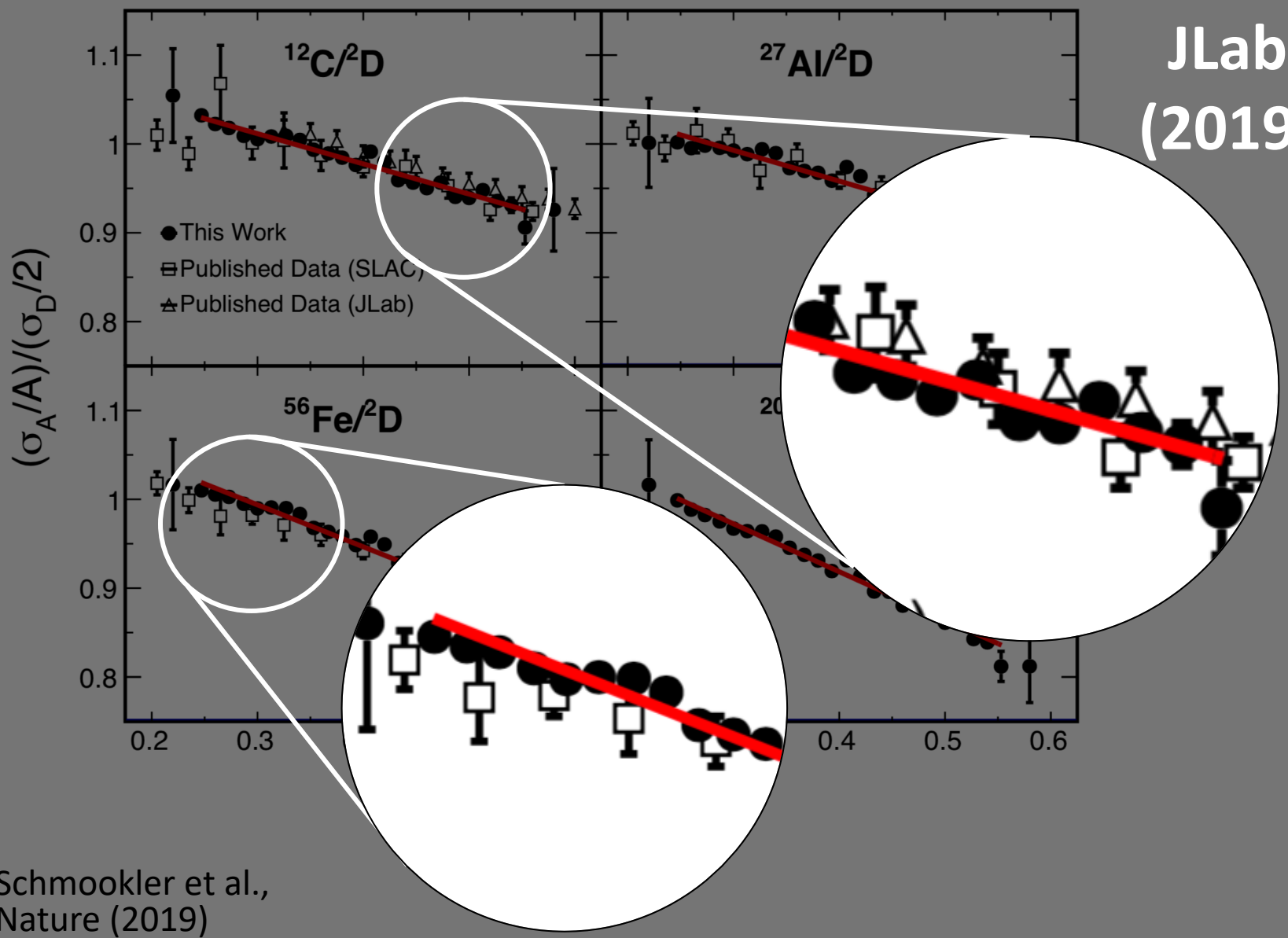
High Precision data!



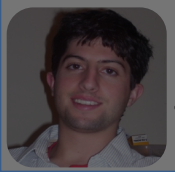
JLab (2019)

Schmookler et al., Nature (2019)

High Precision data!



JLab (2019)



Schmookler et al., Nature (2019)

$$\sigma^{GCF}_{A(e,e'pp)} =$$

$$\frac{\sigma_{eN}}{32\pi^4} n_{CM}(\boldsymbol{P}_{12}) \frac{\epsilon_1' \epsilon_2 \boldsymbol{p}_2^2 \ \Theta\left(\boldsymbol{p}_{12} - p_{rel}^{min}\right)}{\left|\epsilon_2\left(\boldsymbol{p}_2 - \boldsymbol{Z} cos\theta_{z,2}\right) + \epsilon_1' \boldsymbol{p}_2\right|} \frac{\omega}{2E_{beam}E_e x_B} \sum_\alpha C_\alpha |\tilde{\varphi}^\alpha_{NN}(\boldsymbol{p}_{12})|^2$$

$$\sigma^{Exp}_{A(e,e'pp)} = \sigma^{GCF}_{A(e,e'pp)} \cdot P_A^{pp} \cdot T_A^{NN} + \sigma^{GCF}_{A(e,e'np)} \cdot P_A^{[n]p} \cdot T_A^{NN} + \sigma^{GCF}_{A(e,e'pn)} \cdot P_A^{p[n]} \cdot T_A^{NN},$$

Relativistic Effects:

Light-Cone Formalism (Frankfurt & Strikman)

$$|\tilde{\varphi}^{\alpha}_{NN}(\boldsymbol{p}_{12})|^2 \rightarrow \rho^{\alpha}_{NN}(\alpha, p_{\perp})$$

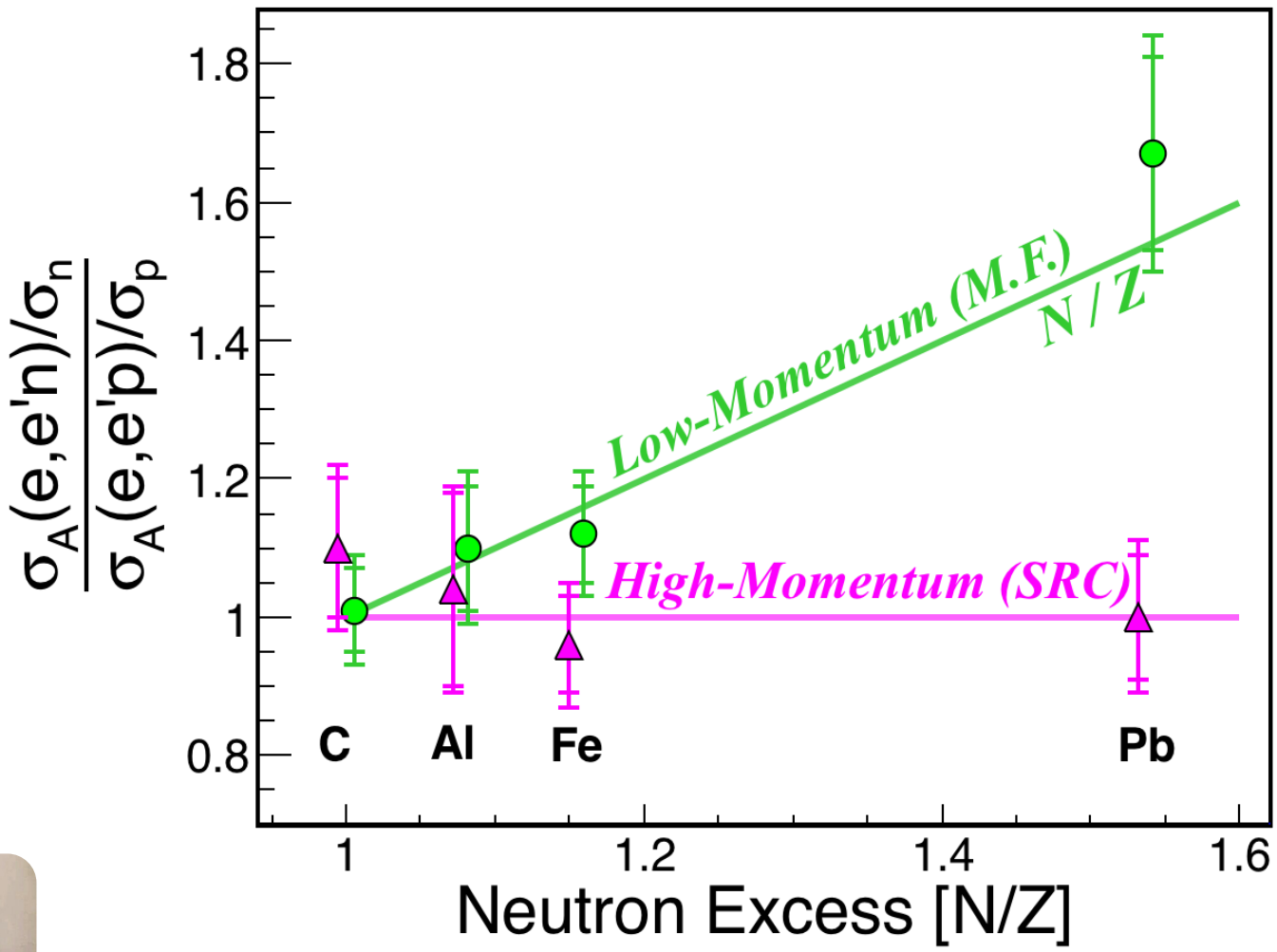
$$n_{CM}(\boldsymbol{P}_{12}) \rightarrow \rho_{cm}\left(\alpha_{cm}, p_{cm,\perp}\right)$$

$$\rho^{\alpha}_{NN}(\alpha, p_{\perp}) = \frac{|\tilde{\varphi}^{\alpha}_{NN}(k)|^2}{2-\alpha}\sqrt{m_N^2 + k^2},$$

$$\rho_{cm}\left(\alpha_{cm}, p_{cm,\perp}\right) = \frac{(m_A/A)\alpha_{cm}}{(2\pi\sigma_{cm})^{3/2}} e^{-\frac{\left(\frac{m_A}{A}\right)^2(2-\alpha_{cm})^2 + p^2_{cm,\perp}}{2\sigma^2_{cm}}}$$

FS Physics Reports 1981; 1988.

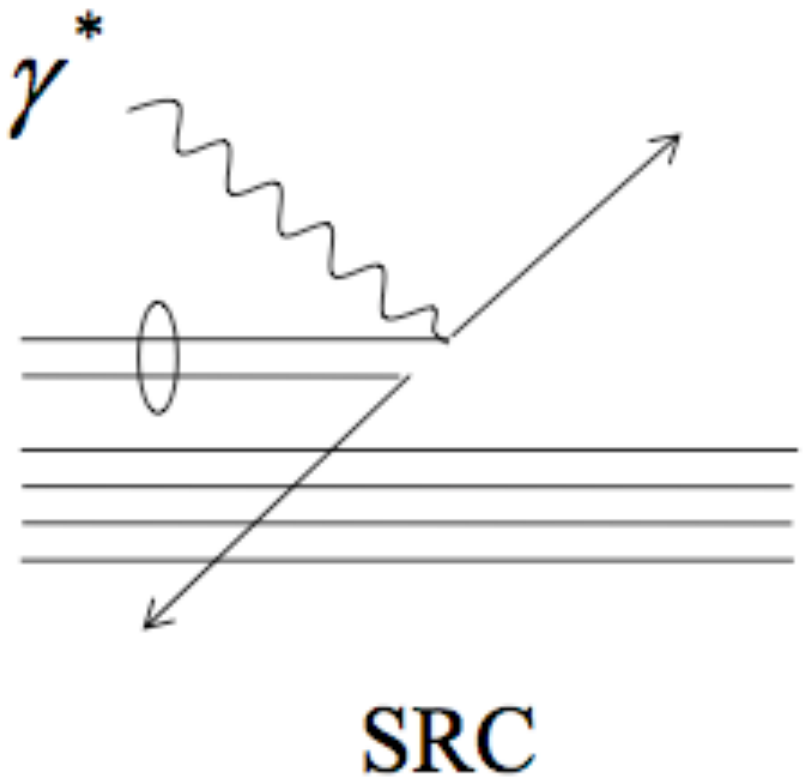
Neutron-Proton Equivalence



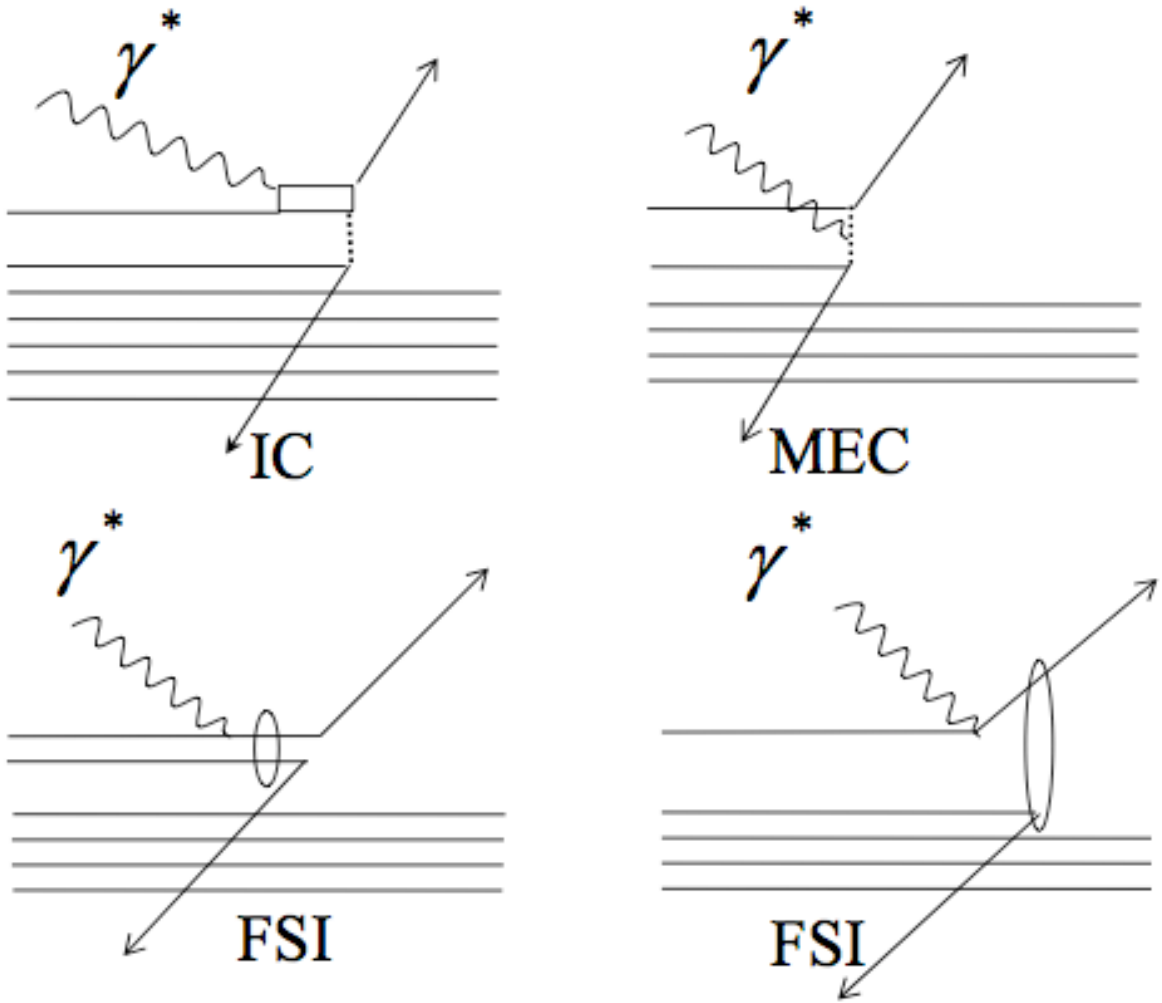
Duer et al., Nature (2018)

Backup: FSI and Reaction Theory

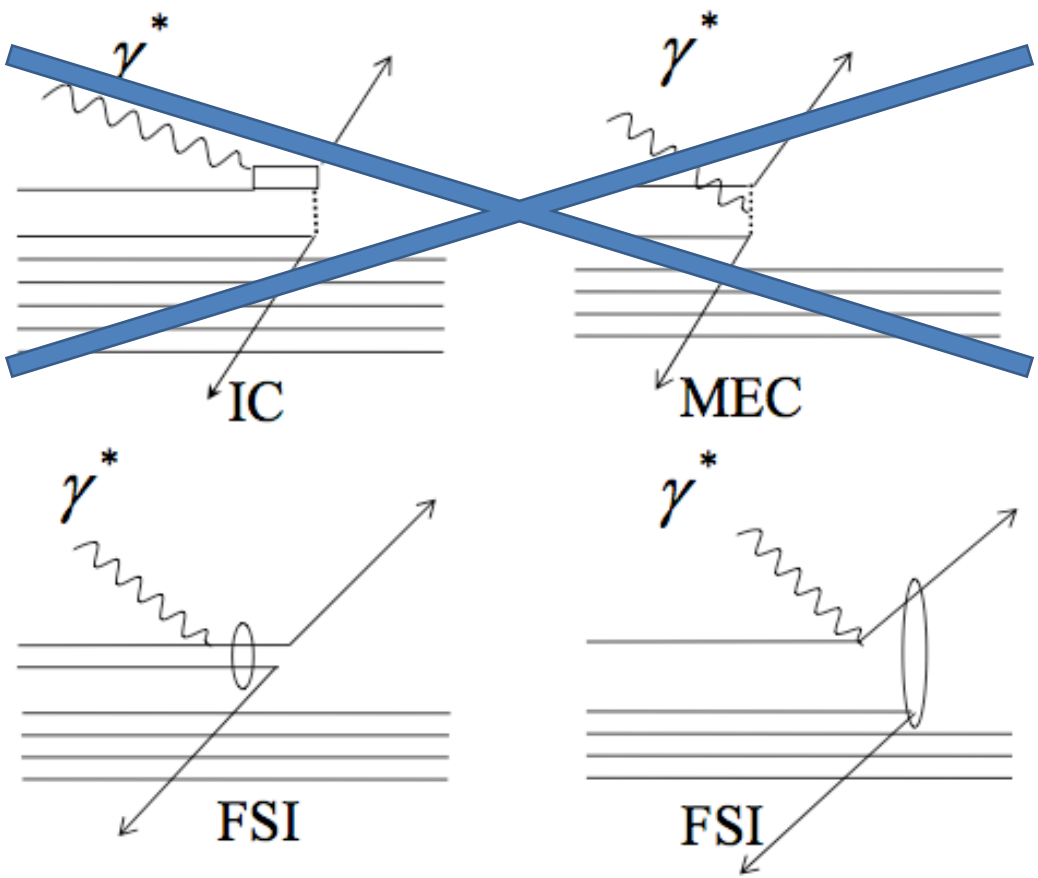
Two-Nucleon Knockout



Two-Nucleon Knockout



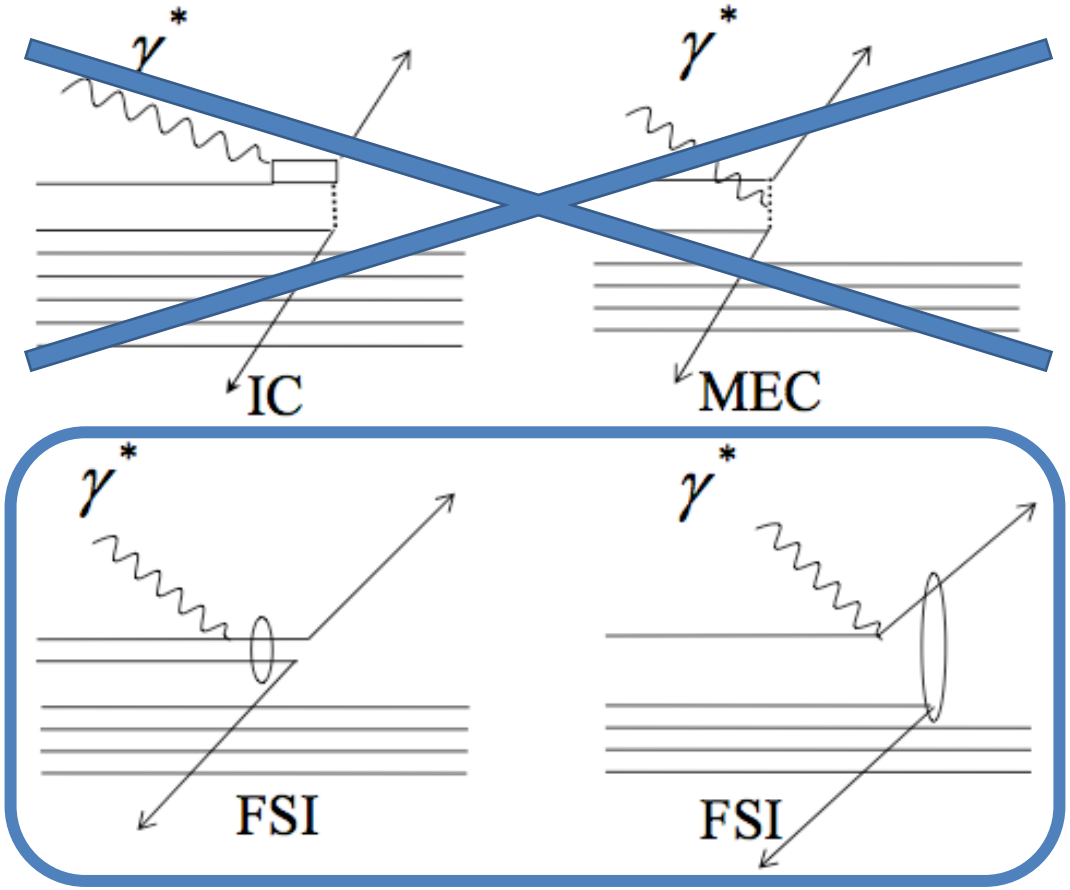
Two-Nucleon Knockout



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).

Two-Nucleon Knockout



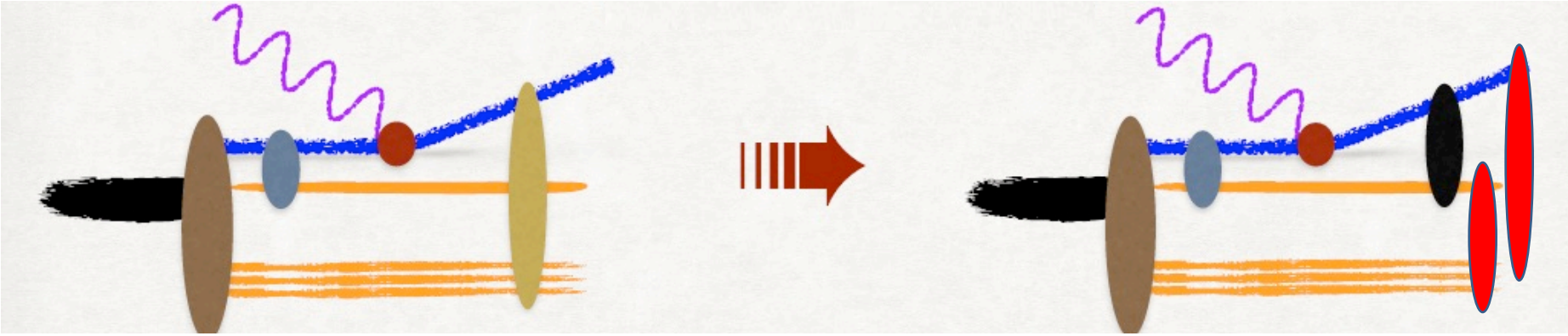
MEC suppressed @ **high-Q^2**, IC suppressed at **$x_B > 1$.**

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



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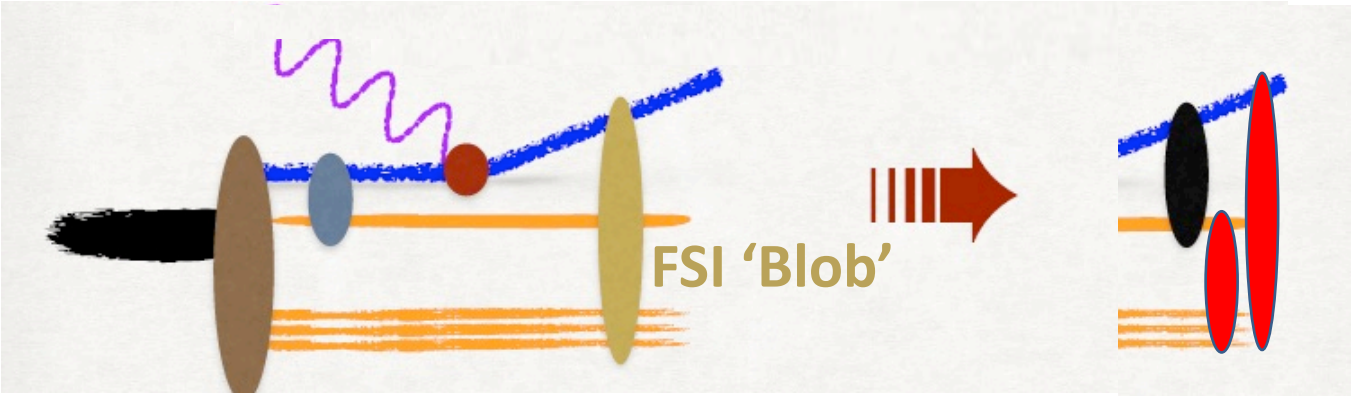
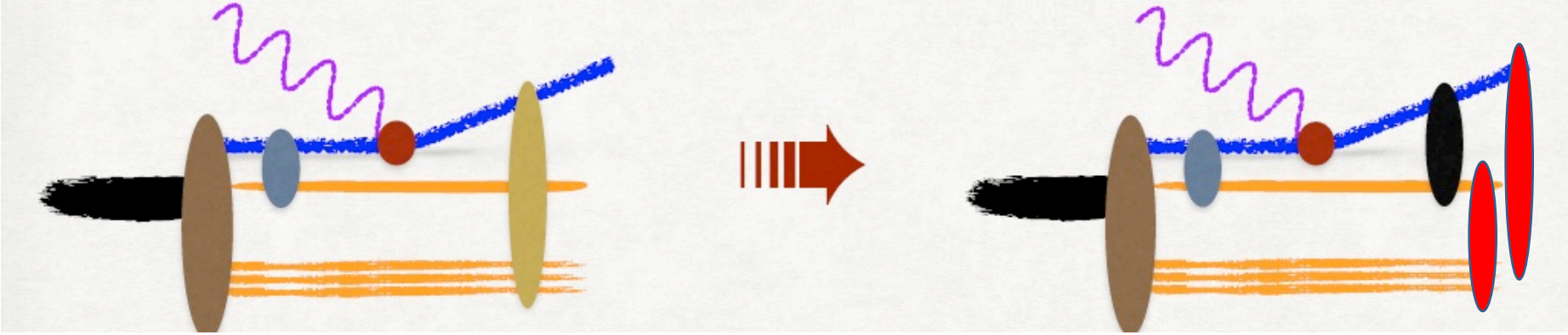


Pair rescattering:
Minimize by choosing correct kinematics

Attenuation:
Calculate using Glauber.

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 (<u>transparency</u>)

Large but confined within the SRC pair

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

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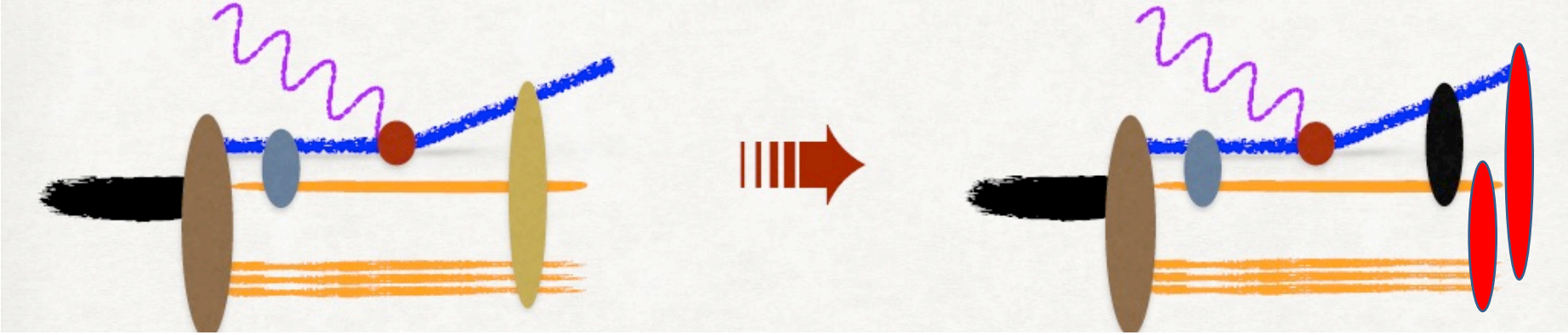

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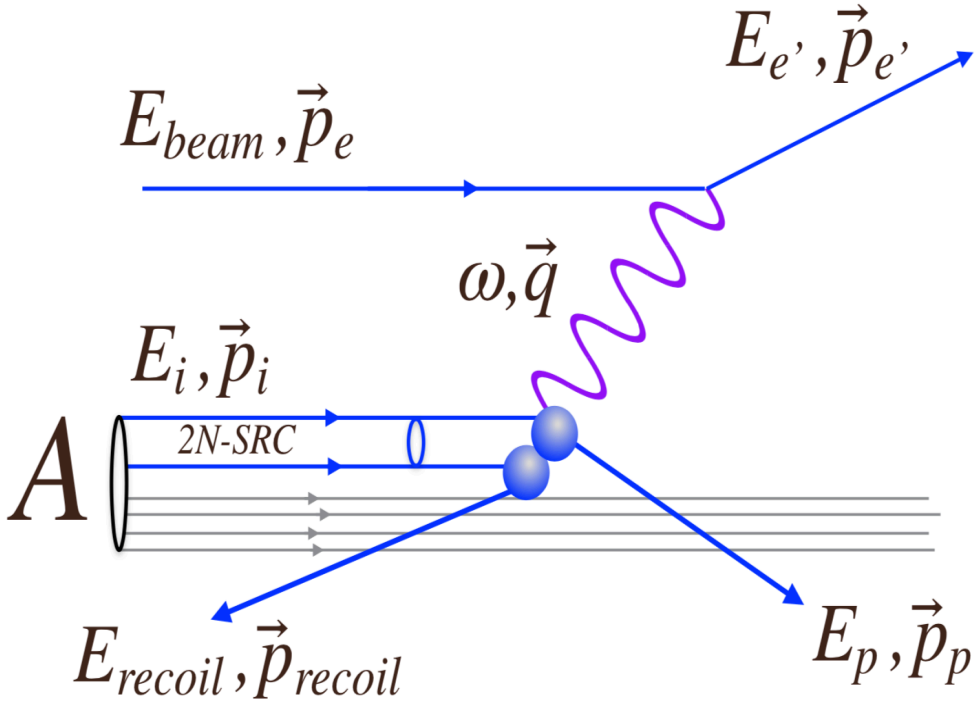
Large but confined within the SRC pair

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

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



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

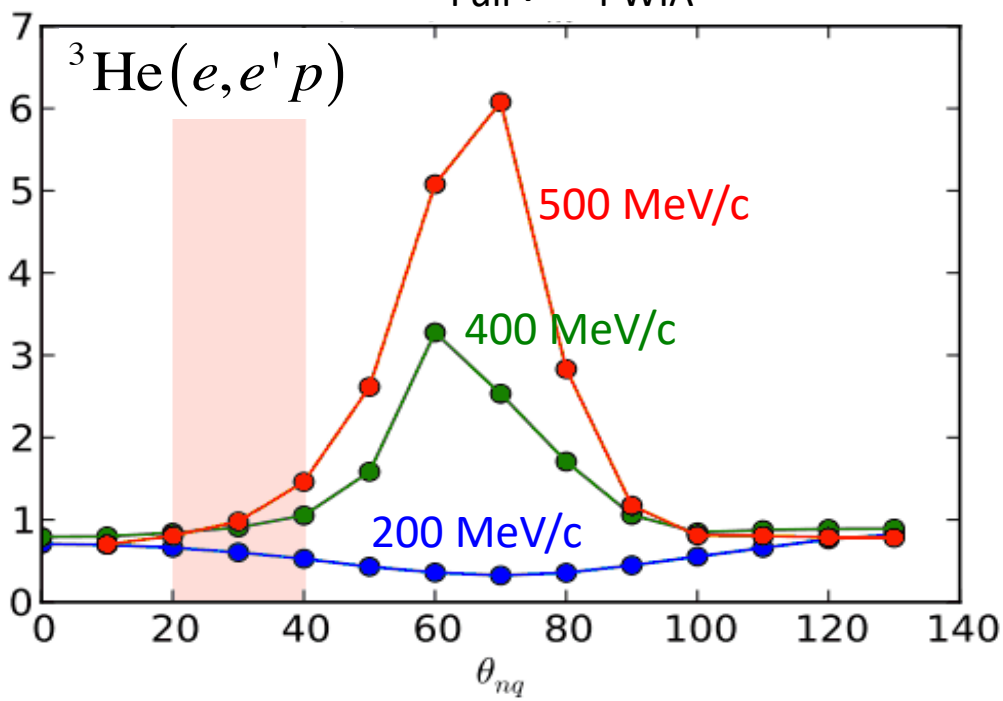
FSI Between nucleons in the pair:

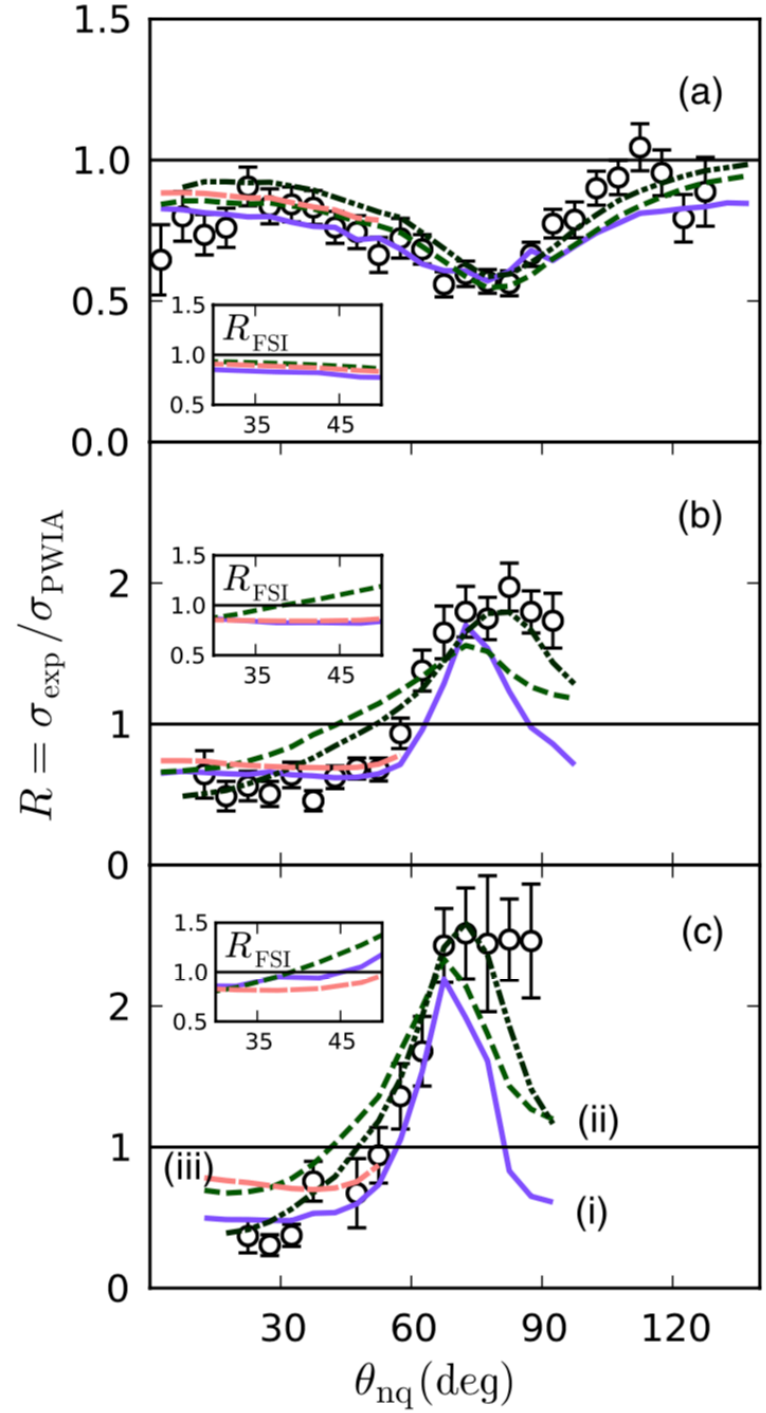
$$\vec{P}_p \rightarrow \vec{P}_p + \vec{\Delta}$$
$$\vec{P}_{recoil} \rightarrow \vec{P}_{recoil} - \vec{\Delta}$$

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

Pair Rescattering

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

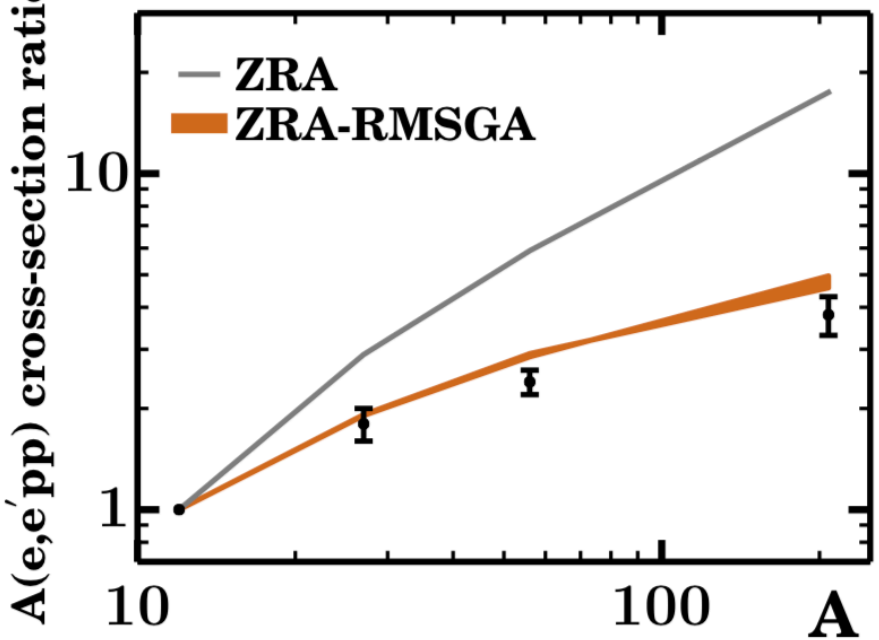


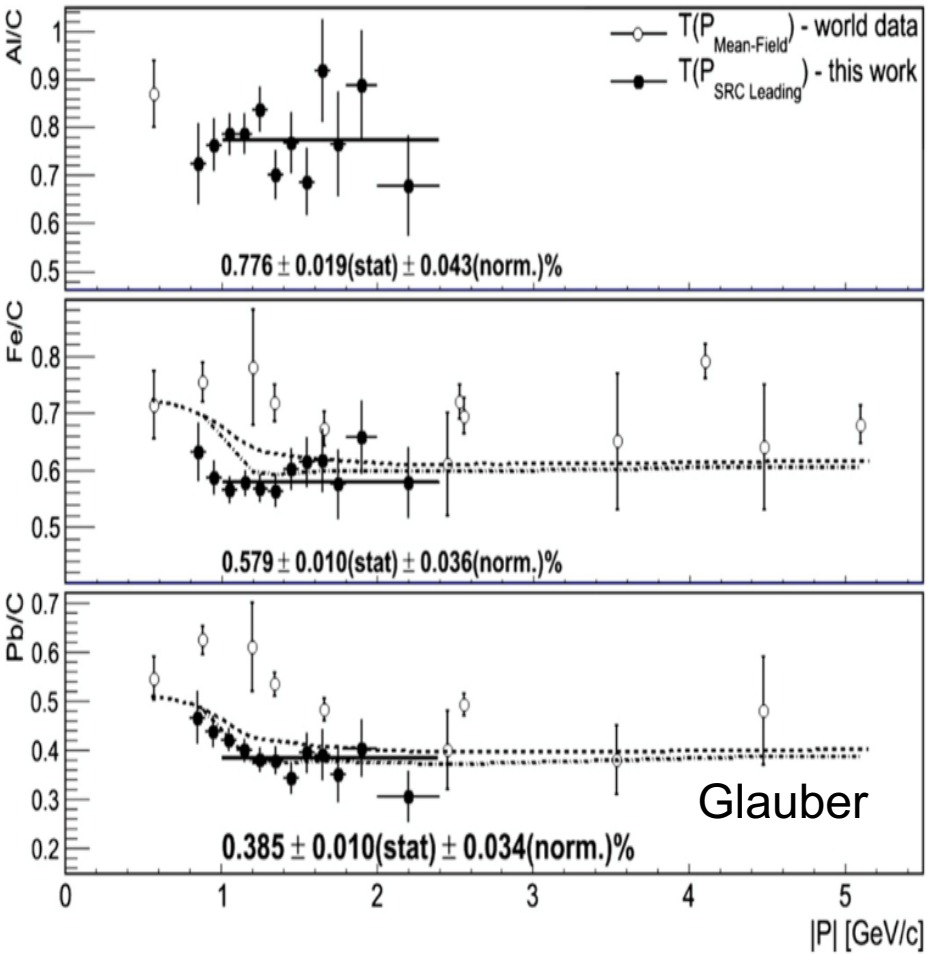


M. Sargsian; Boeglin PRL (2011).

FSI: Glauber Works!

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





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

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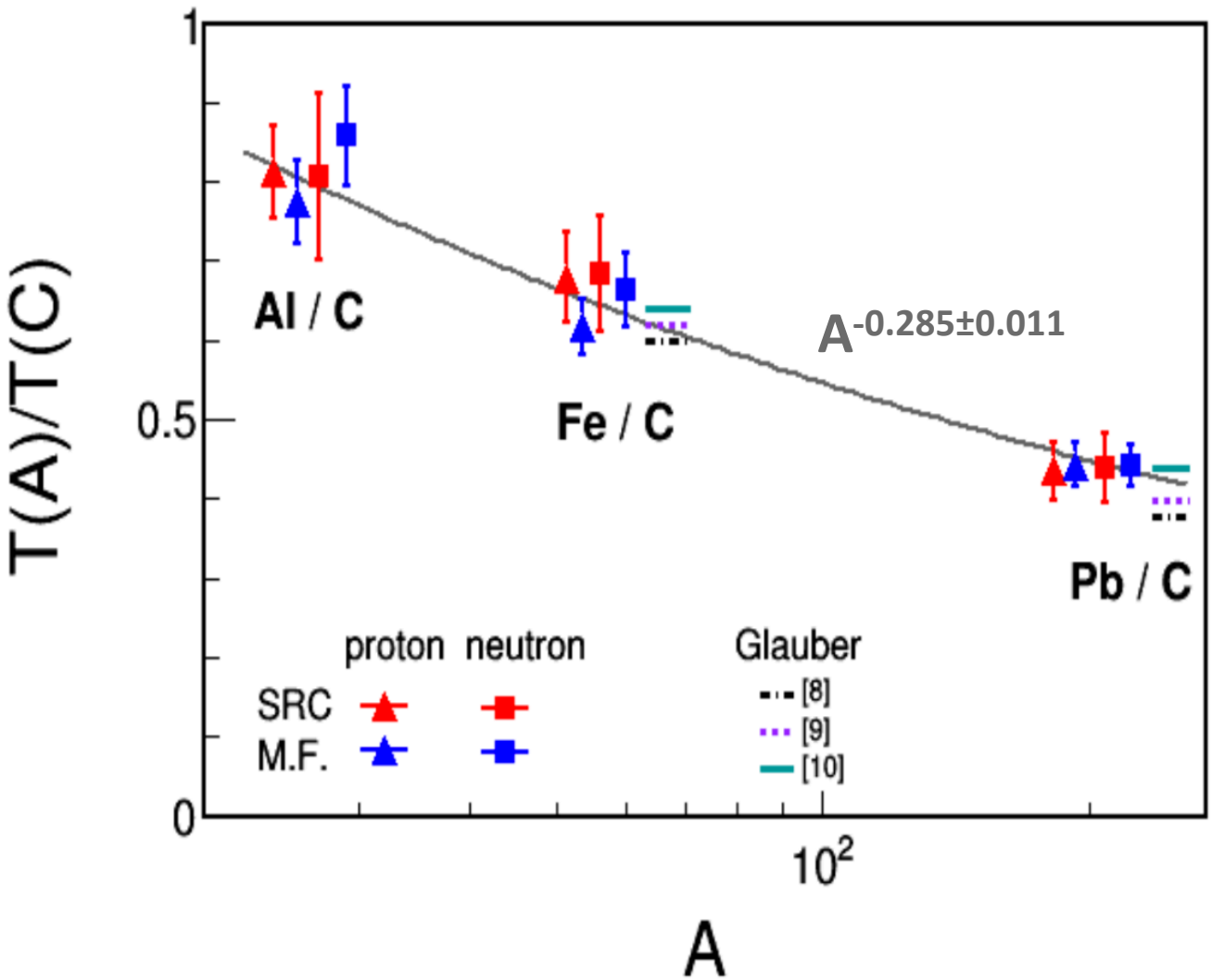
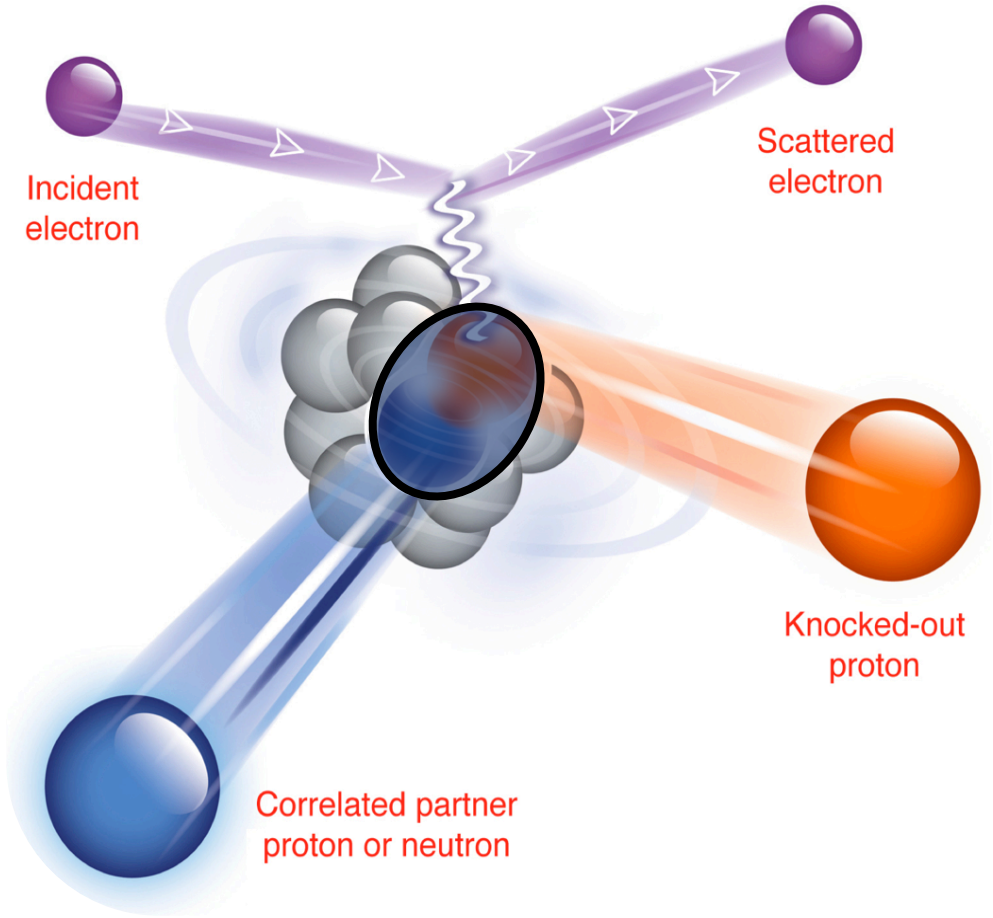


M. Duer et al., Phys. Lett. B, In-Print (2019)

Breakup the pair =>

Detect ***both*** nucleons =>

Reconstruct 'initial' state



Unitary Interlude

- "high momentum" interpretation relies on *single nucleon* interaction operators.
  - Well established formalism for exp data analysis.
  - Results compatible \w hard potential (e.g., AV18) calculation.
  - Difficult to go much beyond than C / Ca.

- Unitary transforms simplifies calculations but form many-body operators.
  - Transforms "high momentum" to "short range"
    Win: Simpler wave functions
    Lose: Complicated interaction operators
    Trick: Transform wave-function but not the operators
  - No e-scattering calculations for heavier nuclei, yet.

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

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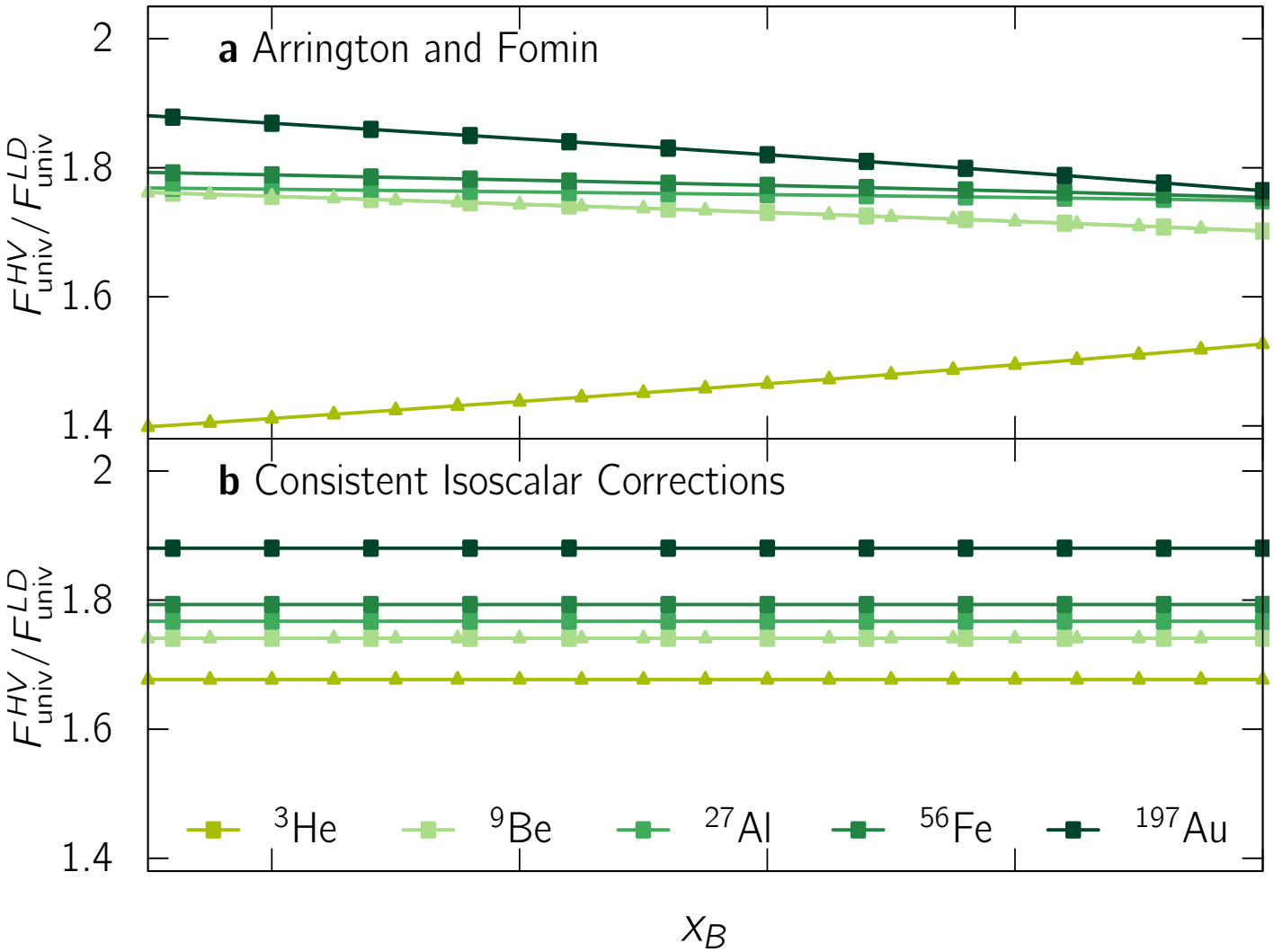
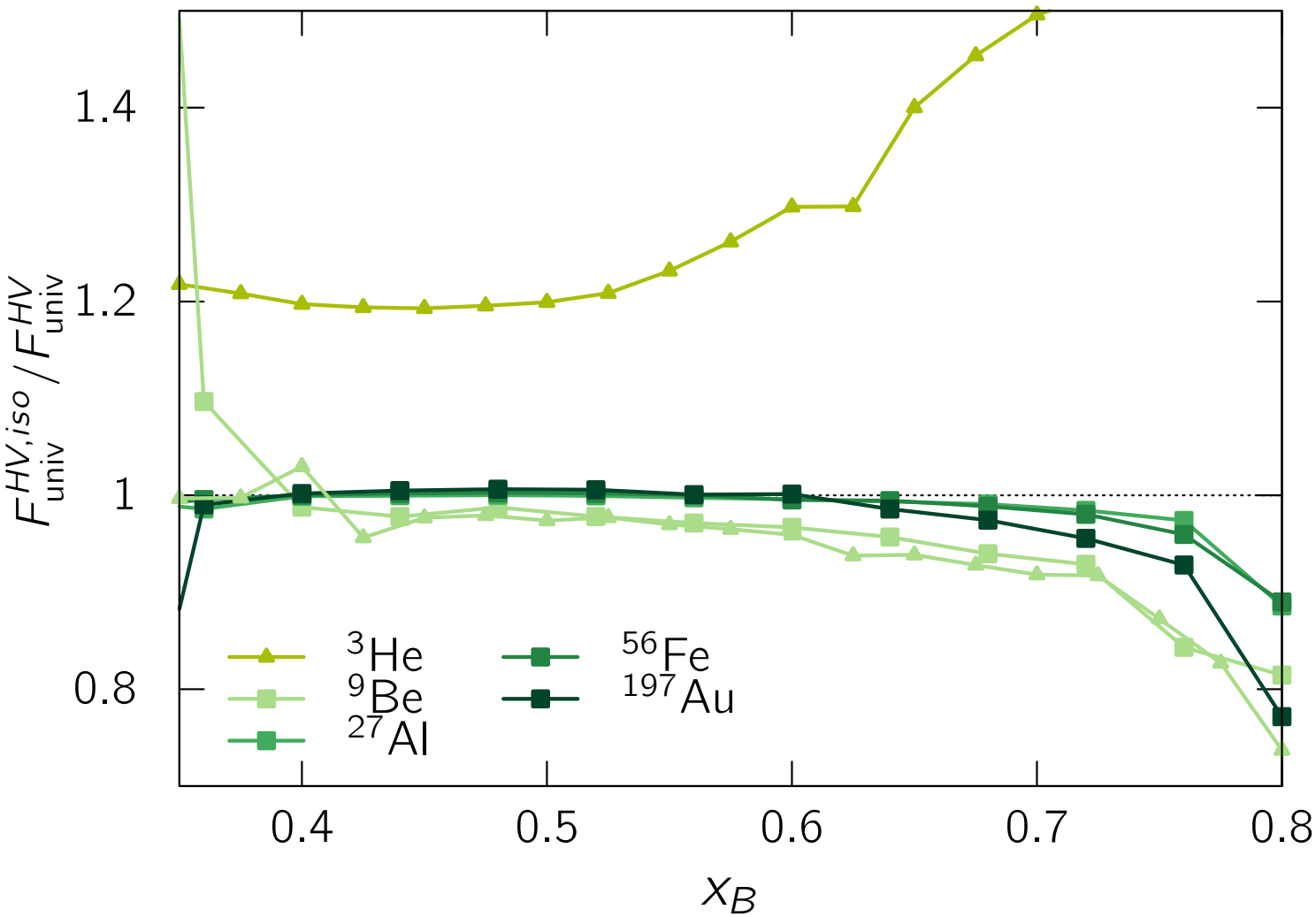
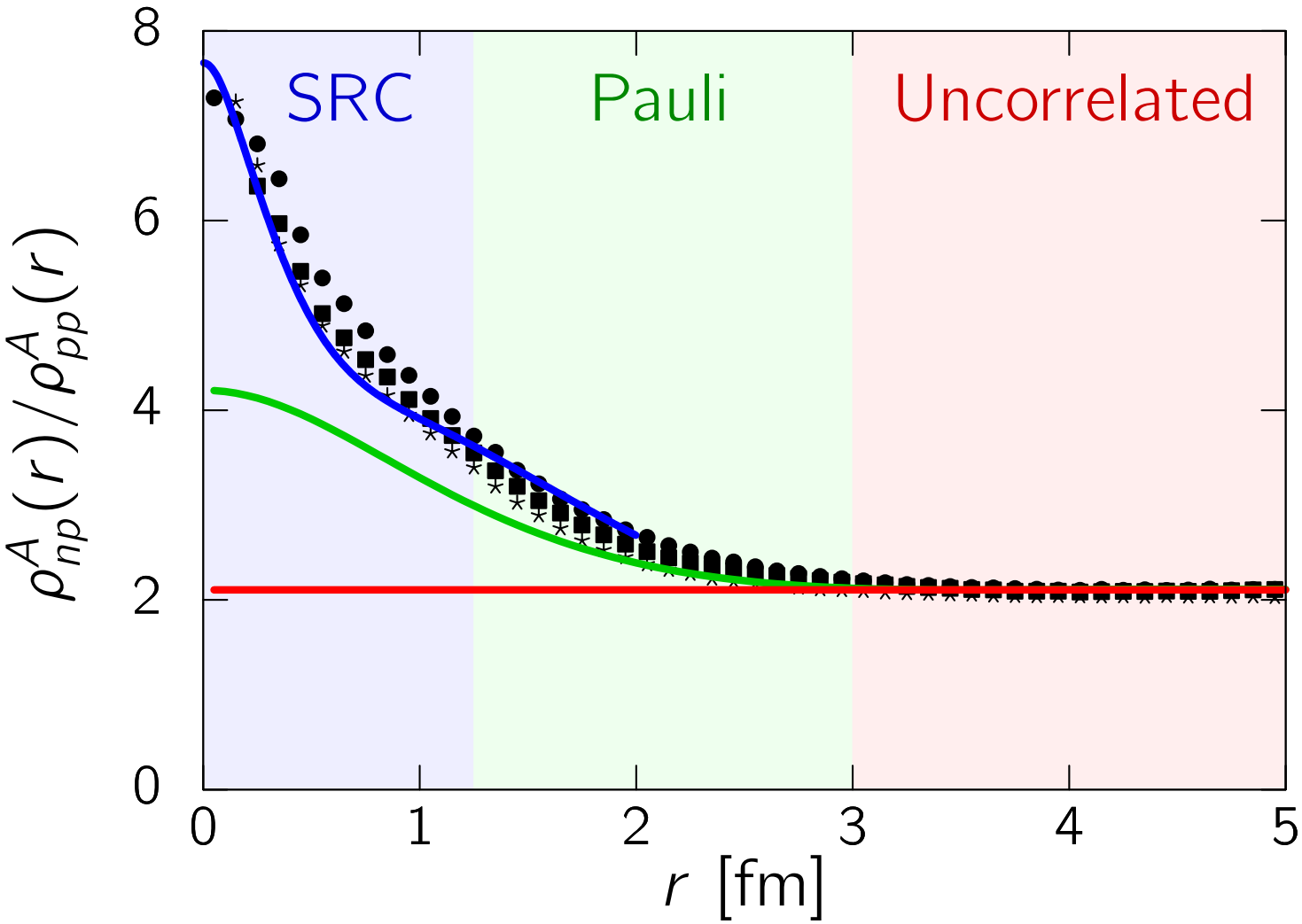
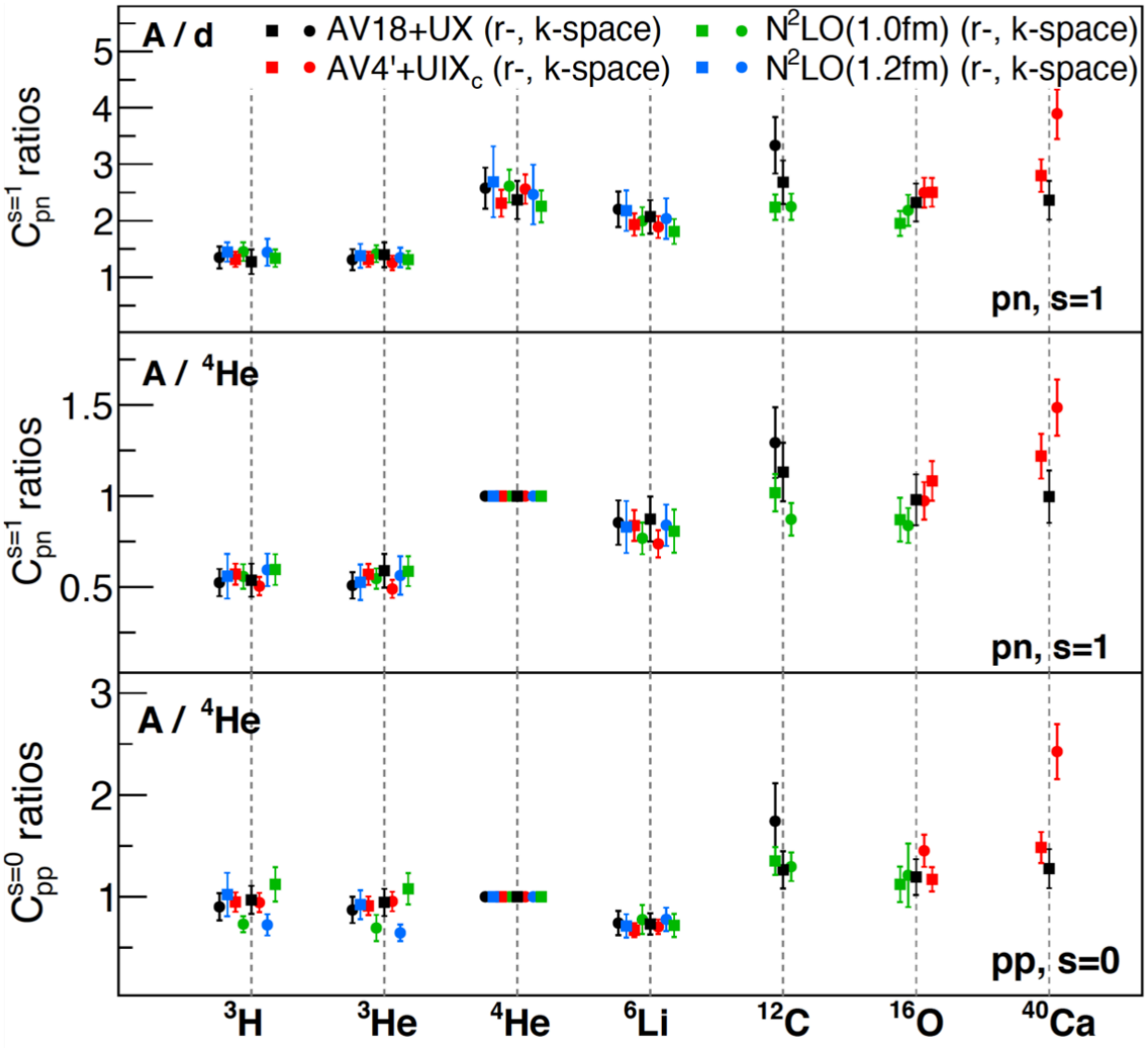
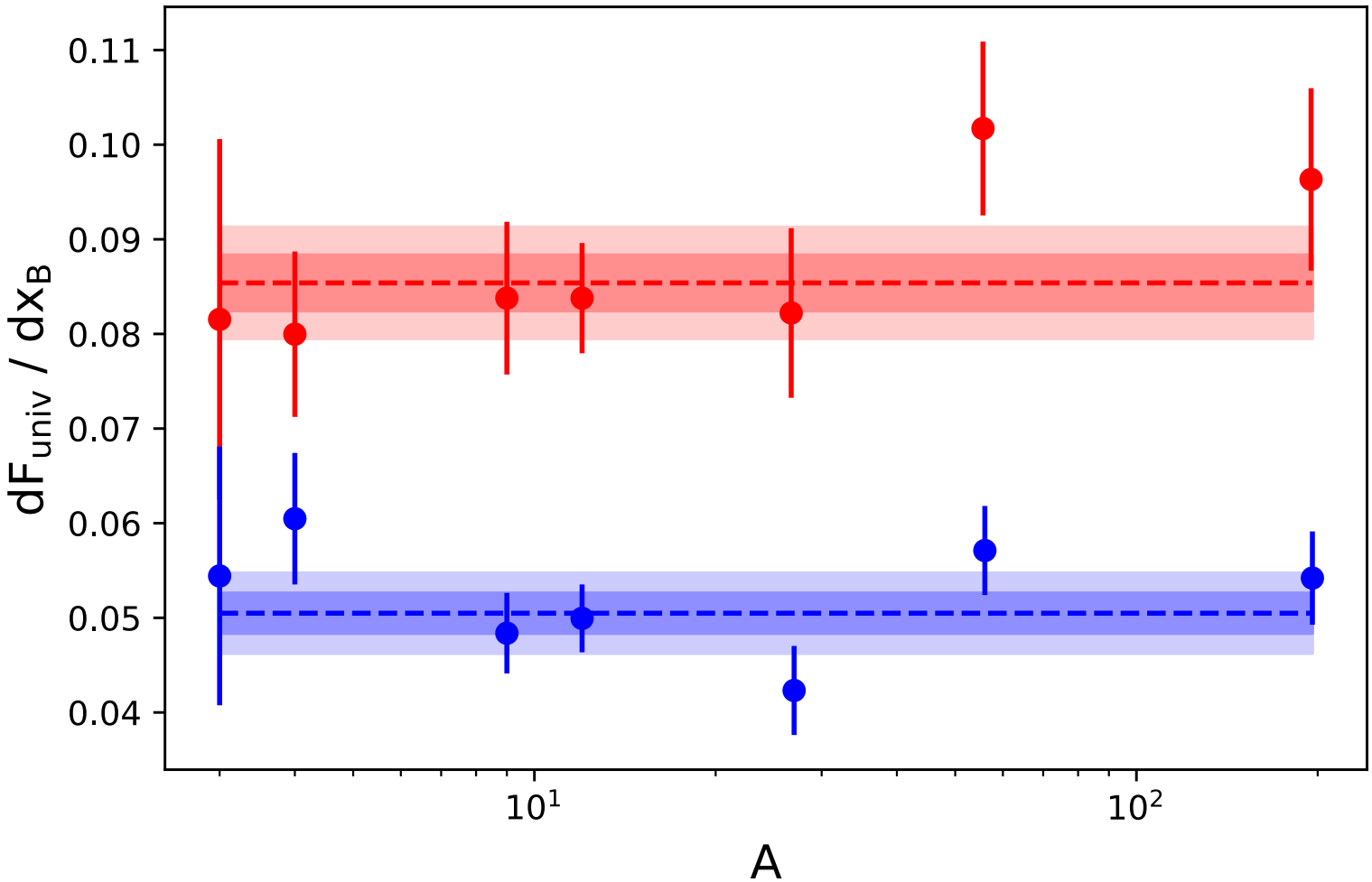

a Arrington and Fomin
b Consistent Isoscalar Corrections
$F^{HV}_{univ}/F^{LD}_{univ}$
2
1.8
1.6
1.4
^{3}He
^{9}Be
^{27}Al
^{56}Fe
^{197}Au
x_B


1.4
1.2
1
0.8
0.4
0.5
0.6
0.7
0.8
x_B
$F^{HV,iso}_{\text{univ}} / F^{HV}_{\text{univ}}$
^{3}He
^{9}Be
^{27}Al
^{56}Fe
^{197}Au


SRC
Pauli
Uncorrelated
$\rho^A_{np}(r)/\rho^A_{pp}(r)$
r [fm]
0
2
4
6
8
0
1
2
3
4
5

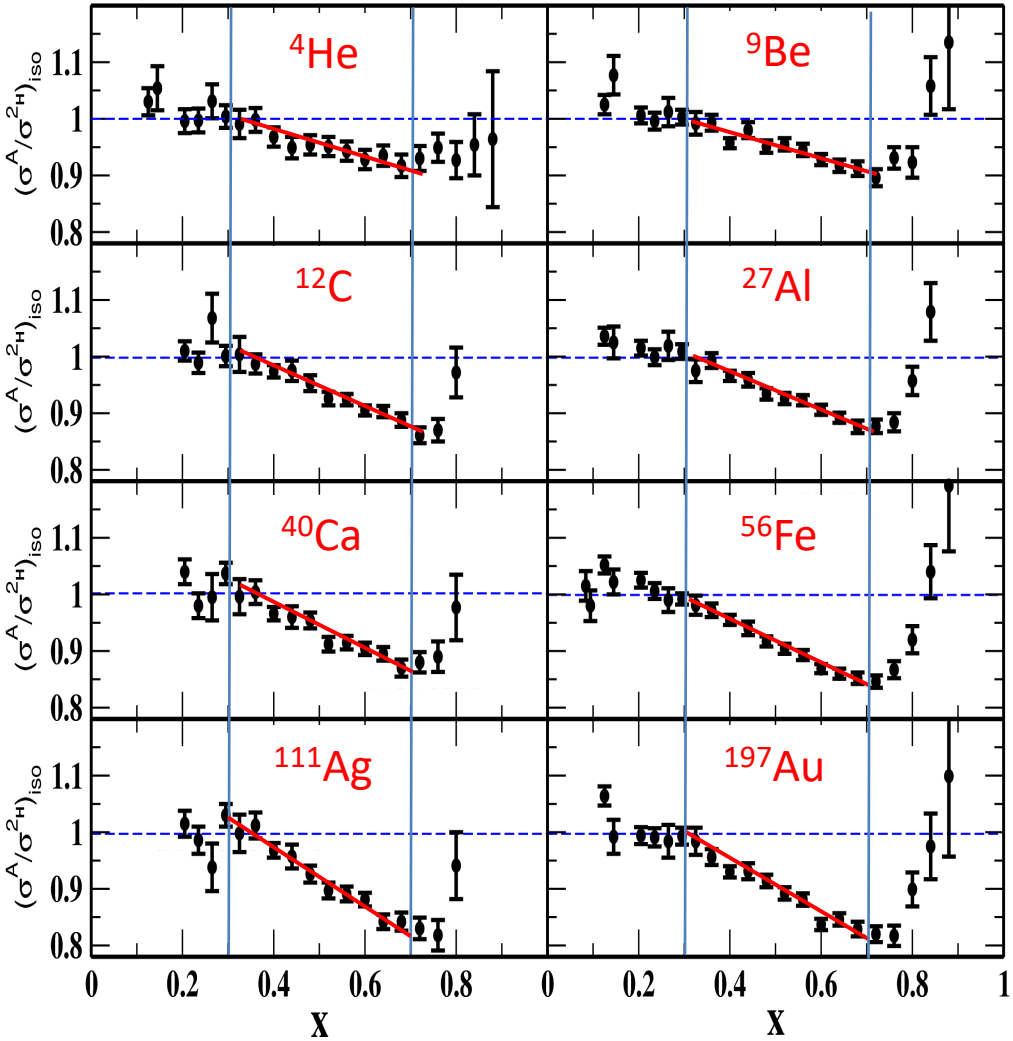


Cruz Torres and Lonardoni et al., arXiv: 1907.03658 (2019)


0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
dF_{univ} / dx_B
10^1
10^2
A

Backup: More on EMC

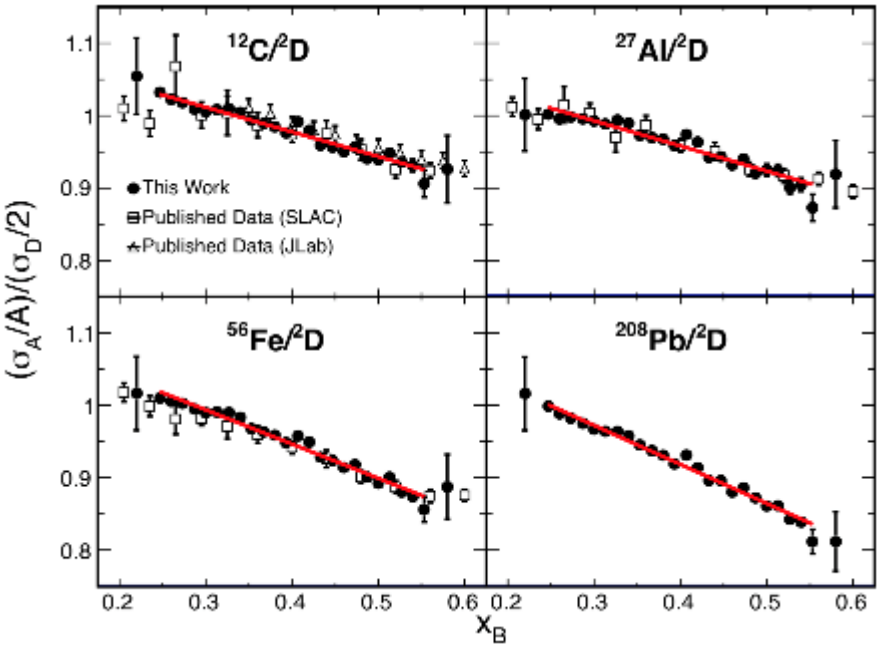
EMC Effect: Nuclear Effect



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

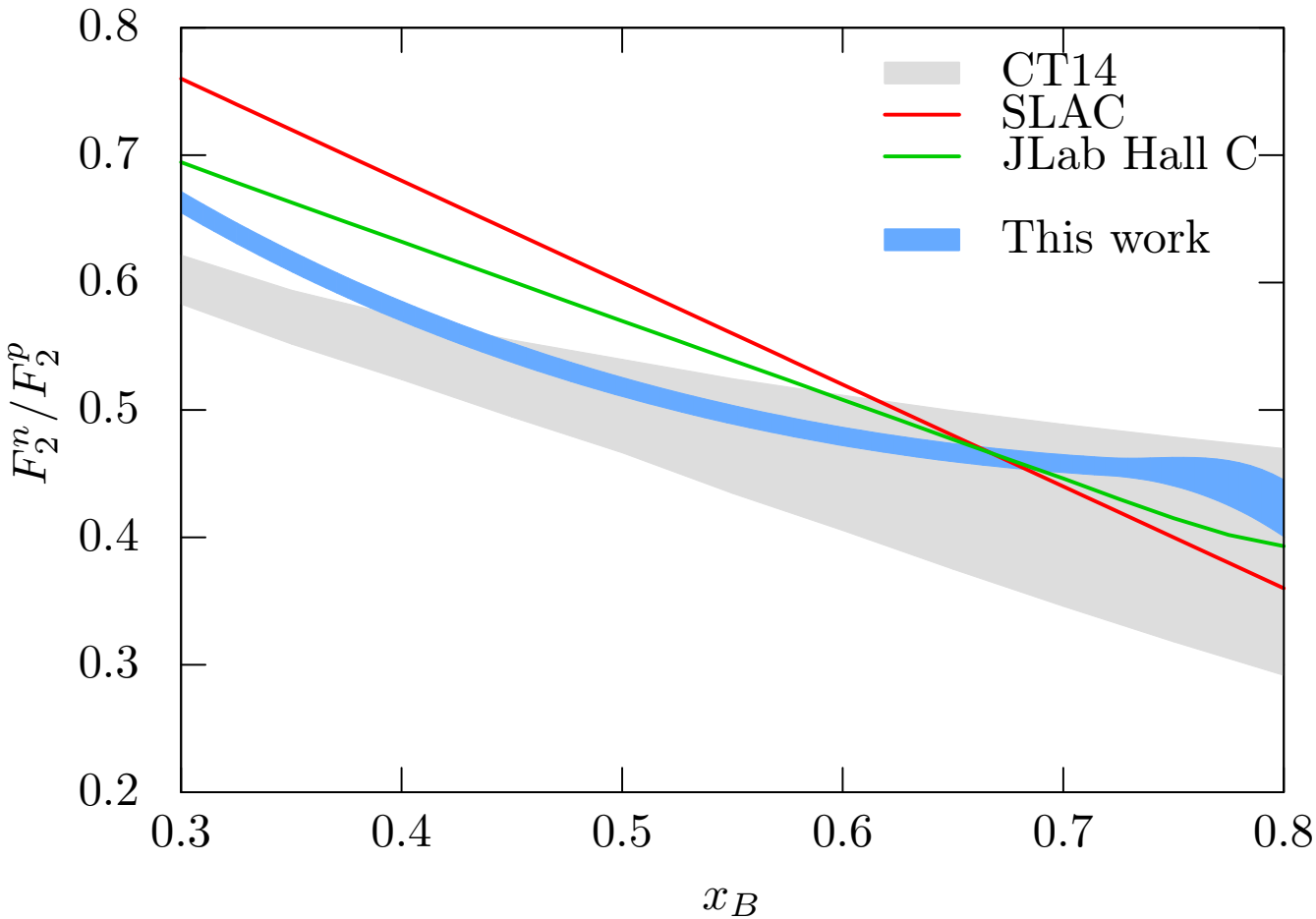
SLAC (1994)

JLab (2018)



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

Free Neutron Extraction

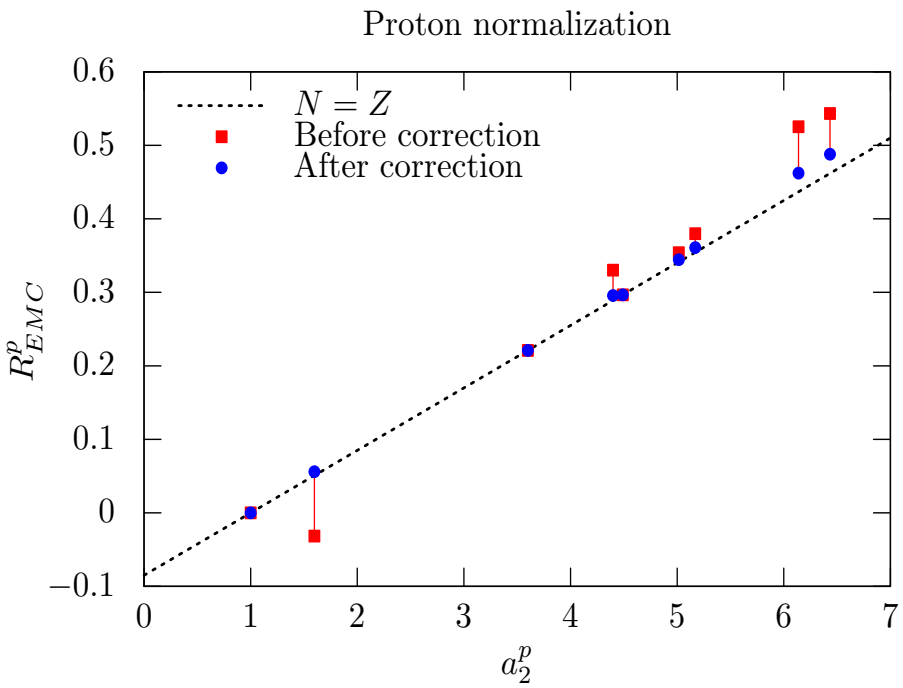


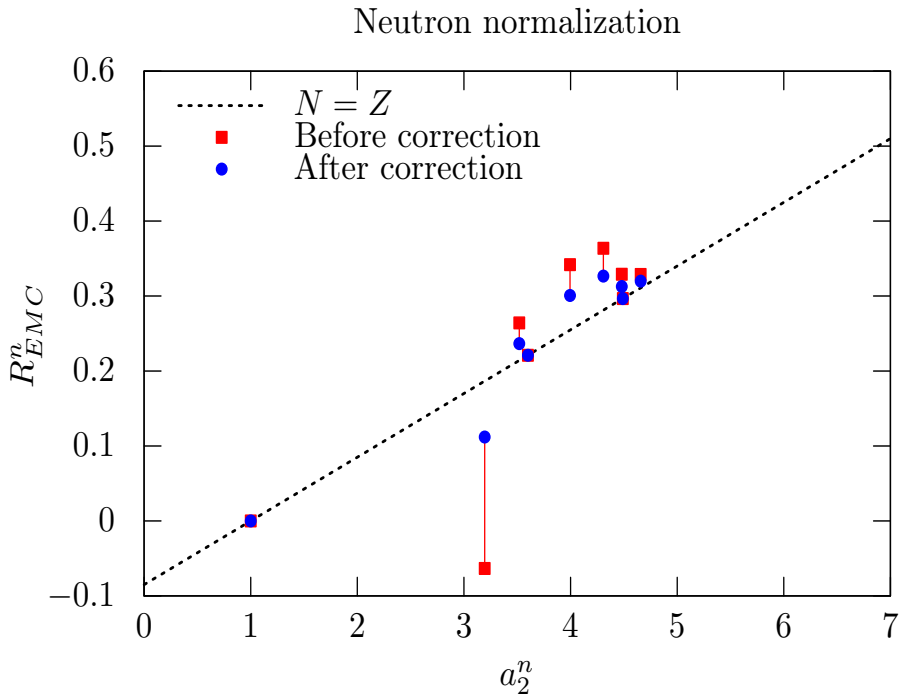
Self-consistent Isoscalar corrections

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

Model Prediction before & after isoscalar corrections

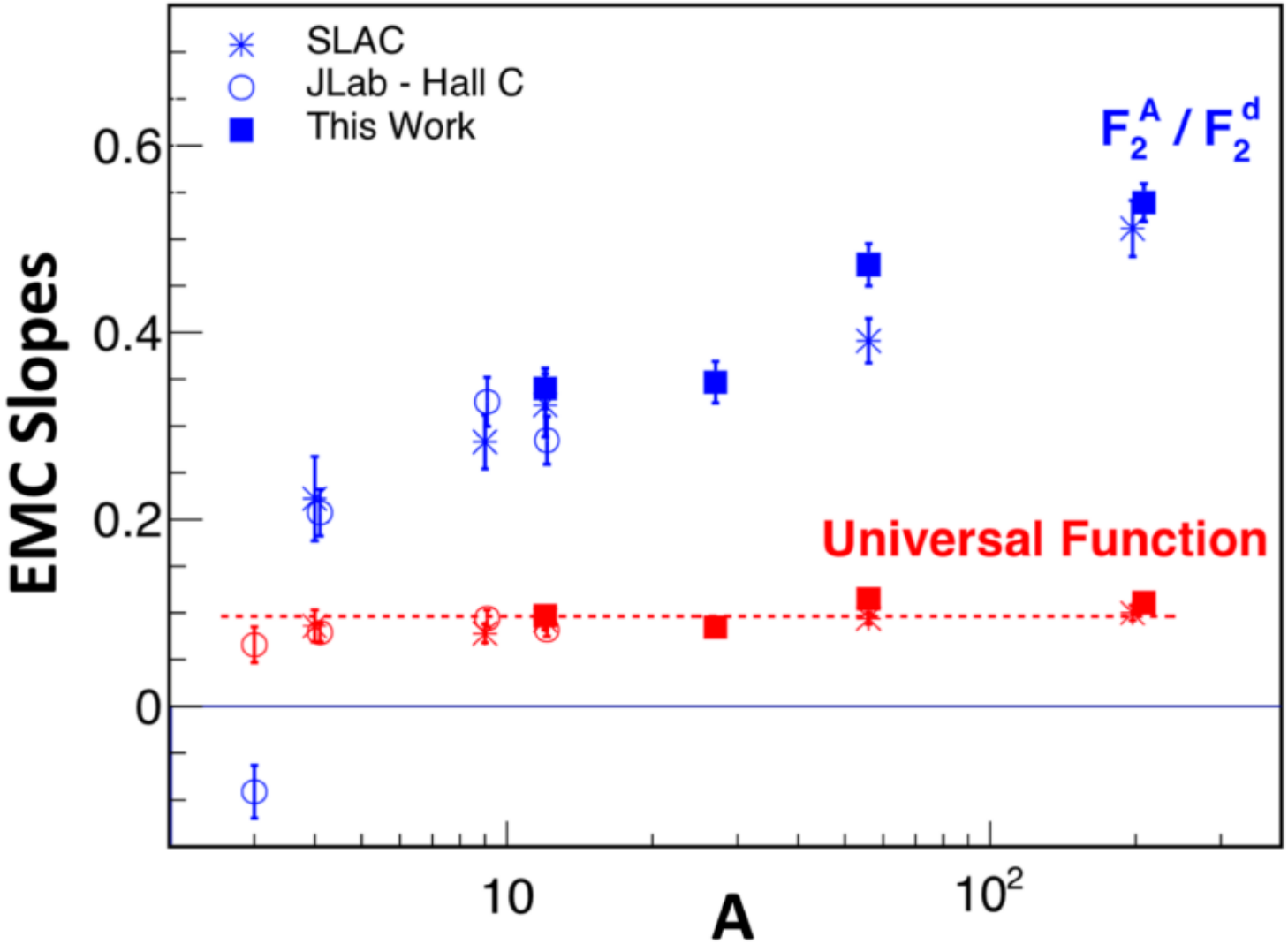
Closer to the N=Z prediction but not exactly…





Predicting the EMC-SRC Correlation

B. Schmookler



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

Bound nucleons in EFT and QCD

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

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

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

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

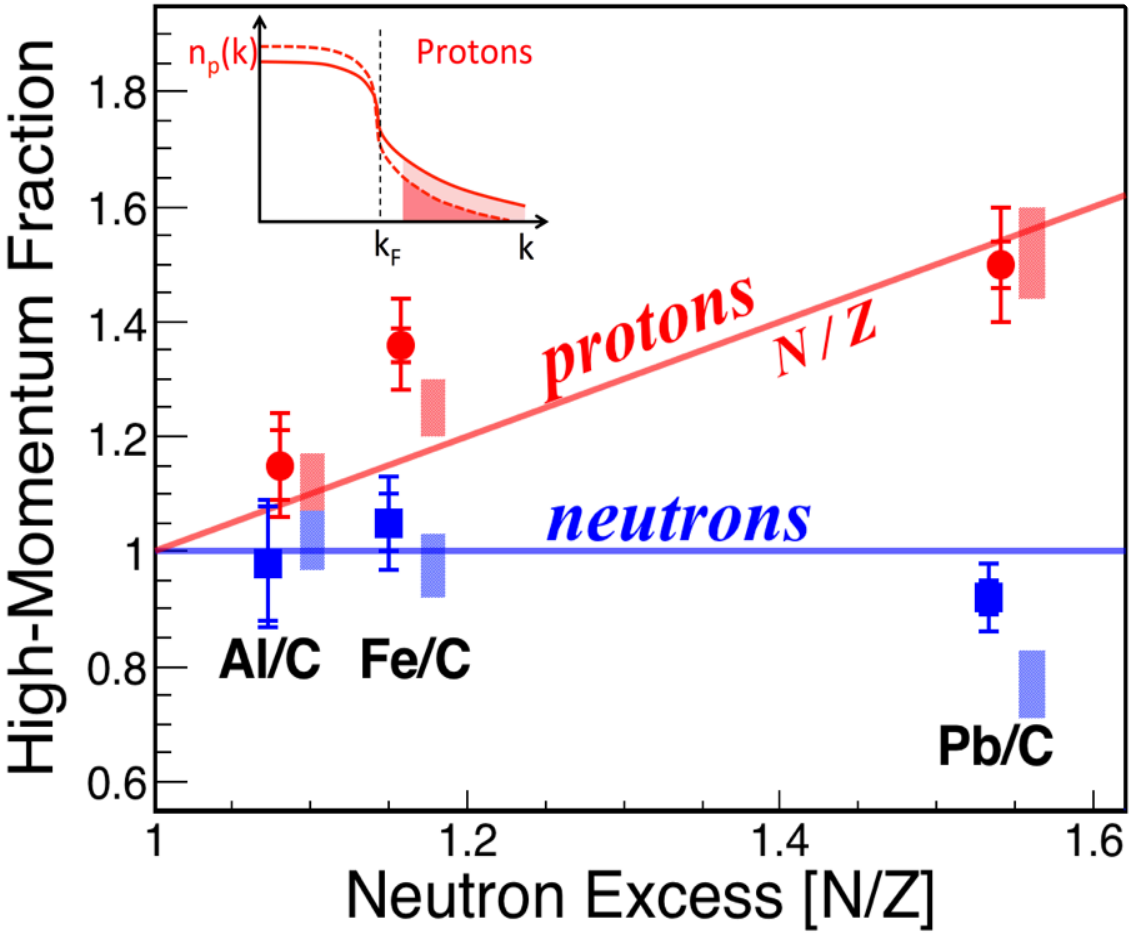
Hen, Miller, Piasetzky and Weinstein, Reviews of Modern Physics (2017).

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

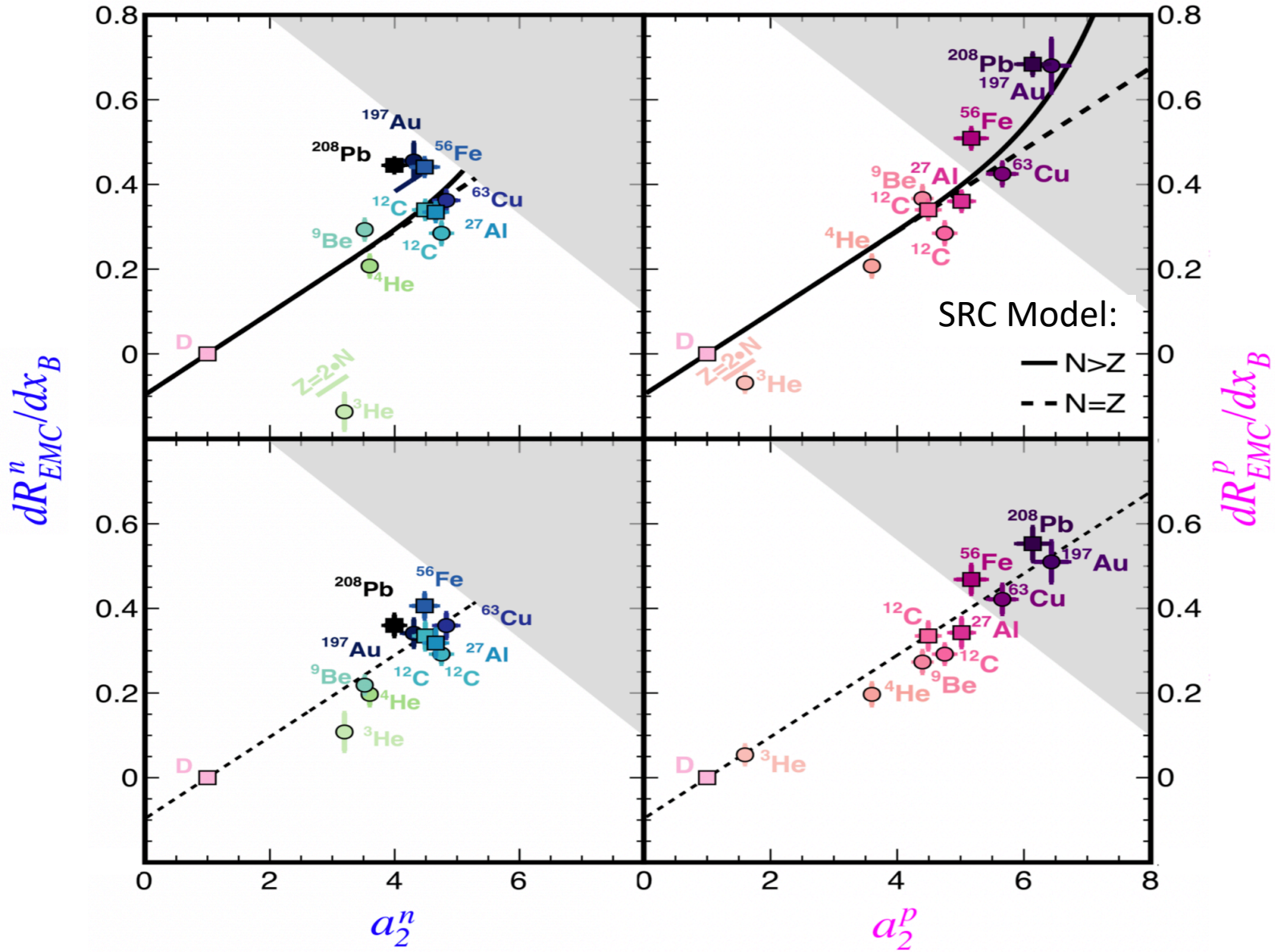
Weiss and Cruz-Torres et al., Phys. Lett B 780, 211 (2018)

Back to QE

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

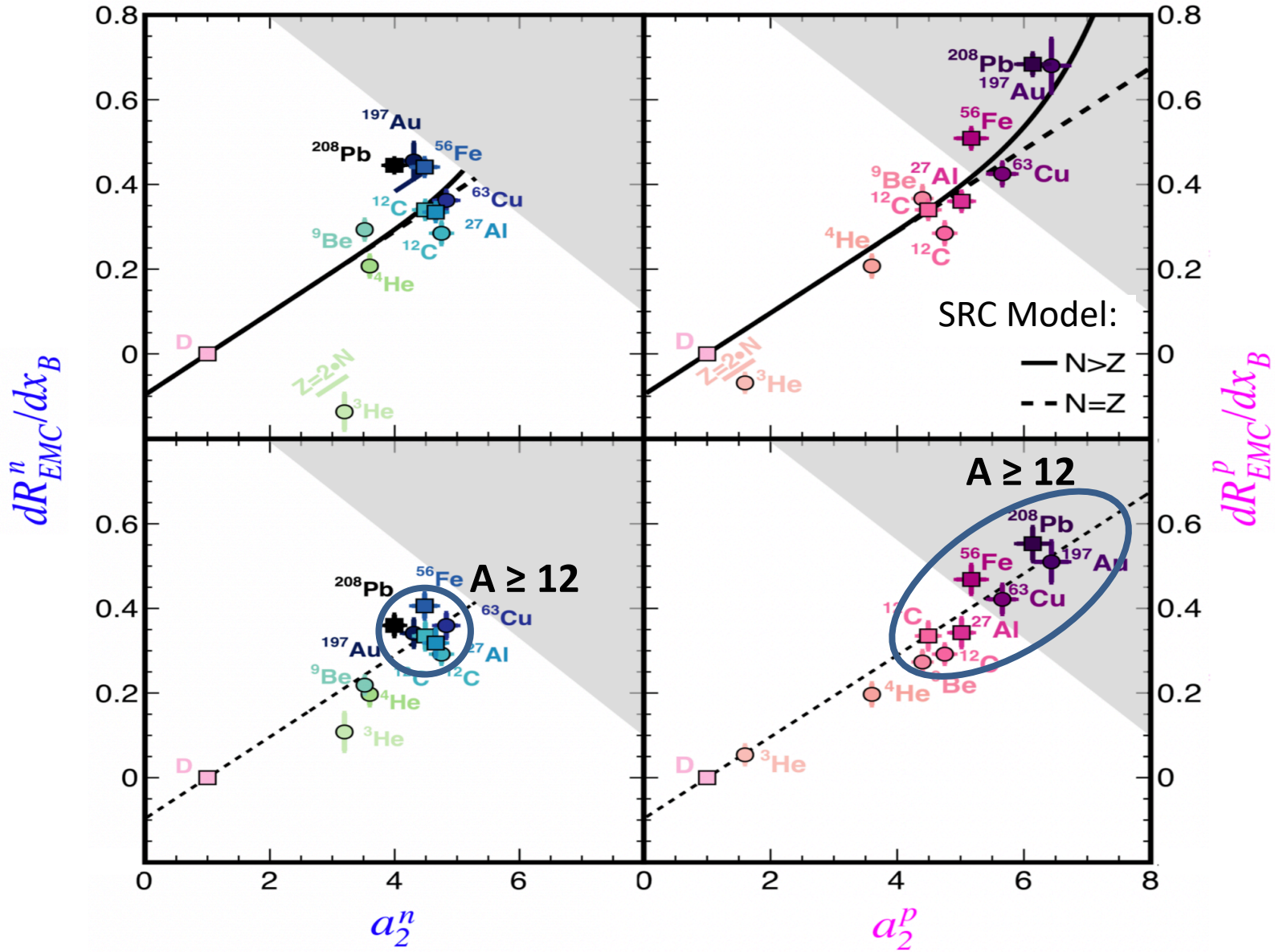


Neutrons Saturate; Protons Grow



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

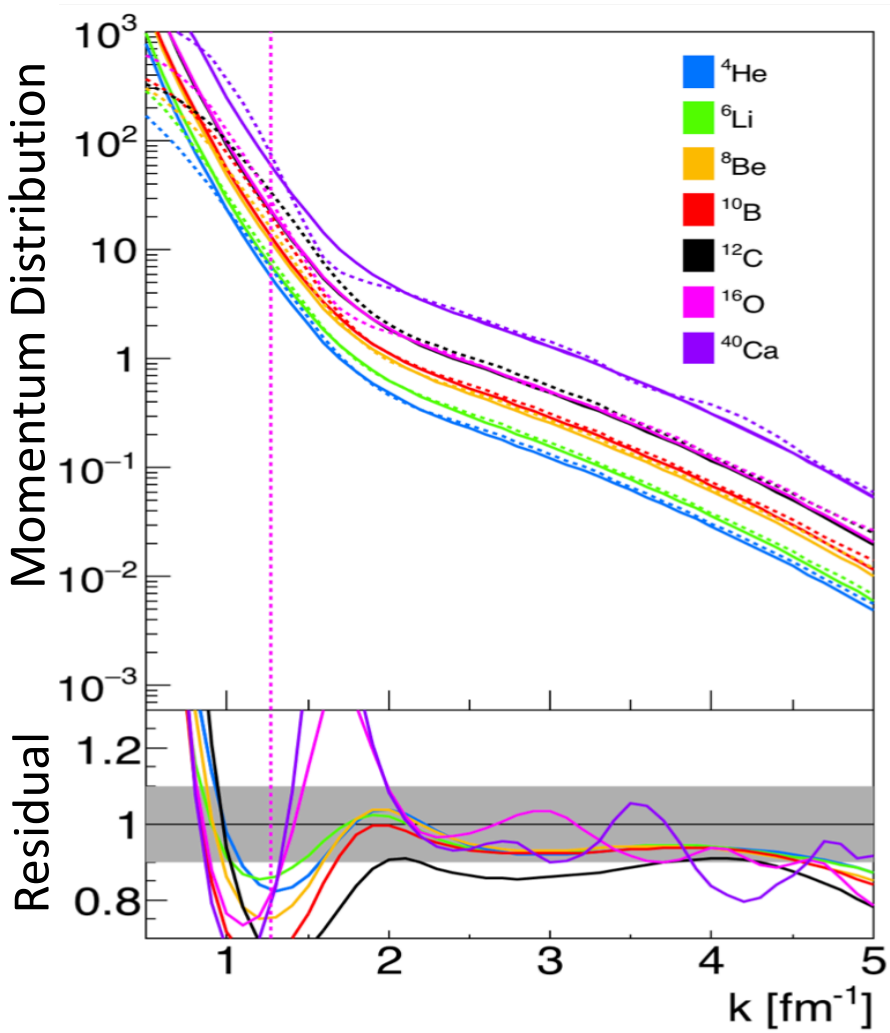
N/Z dependence of nuclear PDFs!

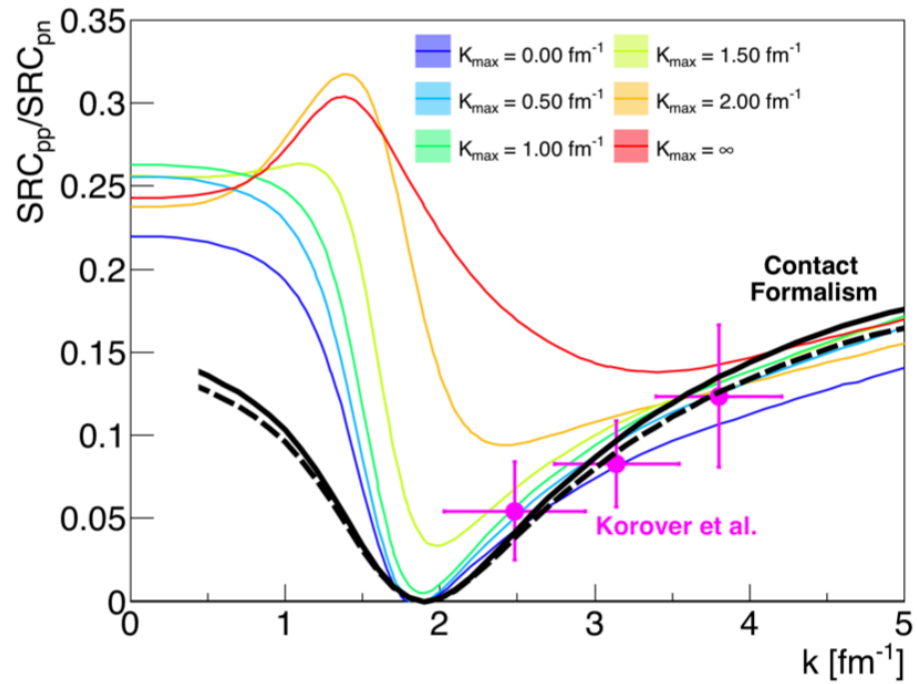


Schmookler et al., Nature In-processing (2018)

Backup: Contact & Correlation Function

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





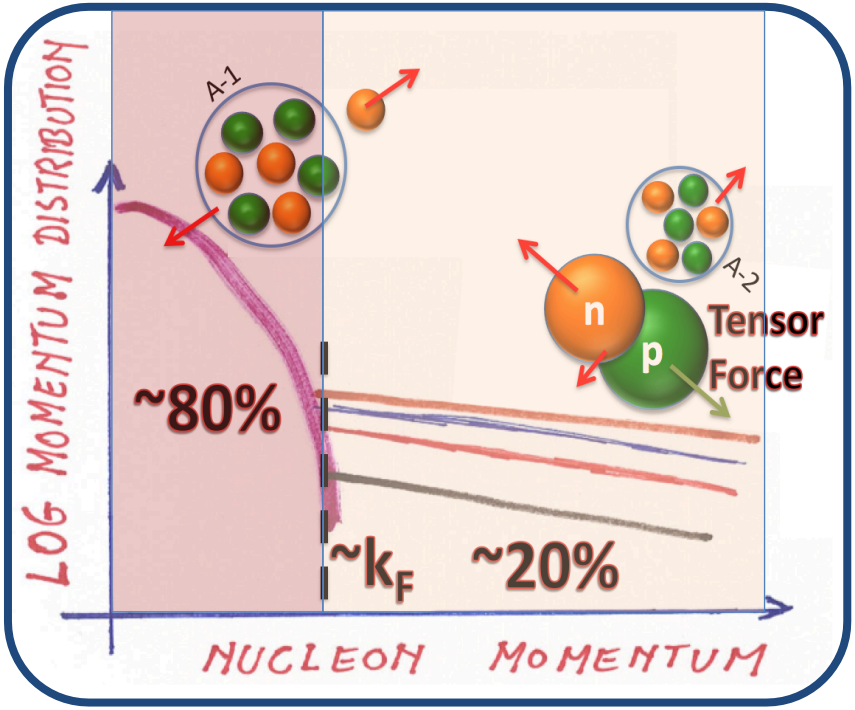
Nuclear contacts can also be extracted from experiment!

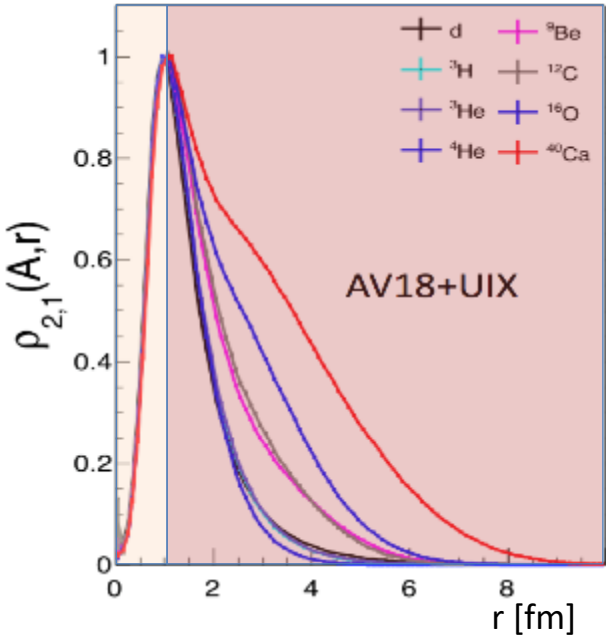
Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, Phys. Lett. B **780**, 211 (2018)

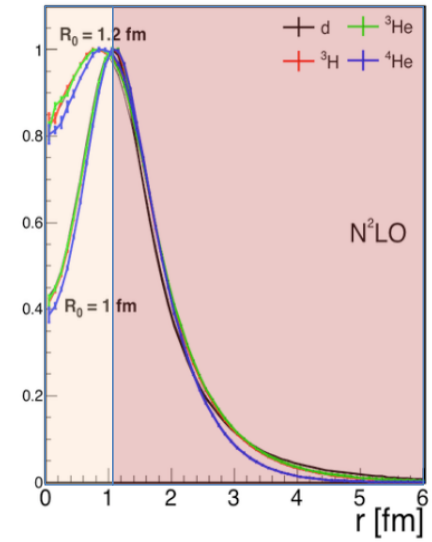
SRCs in Momentum Densities

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:

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

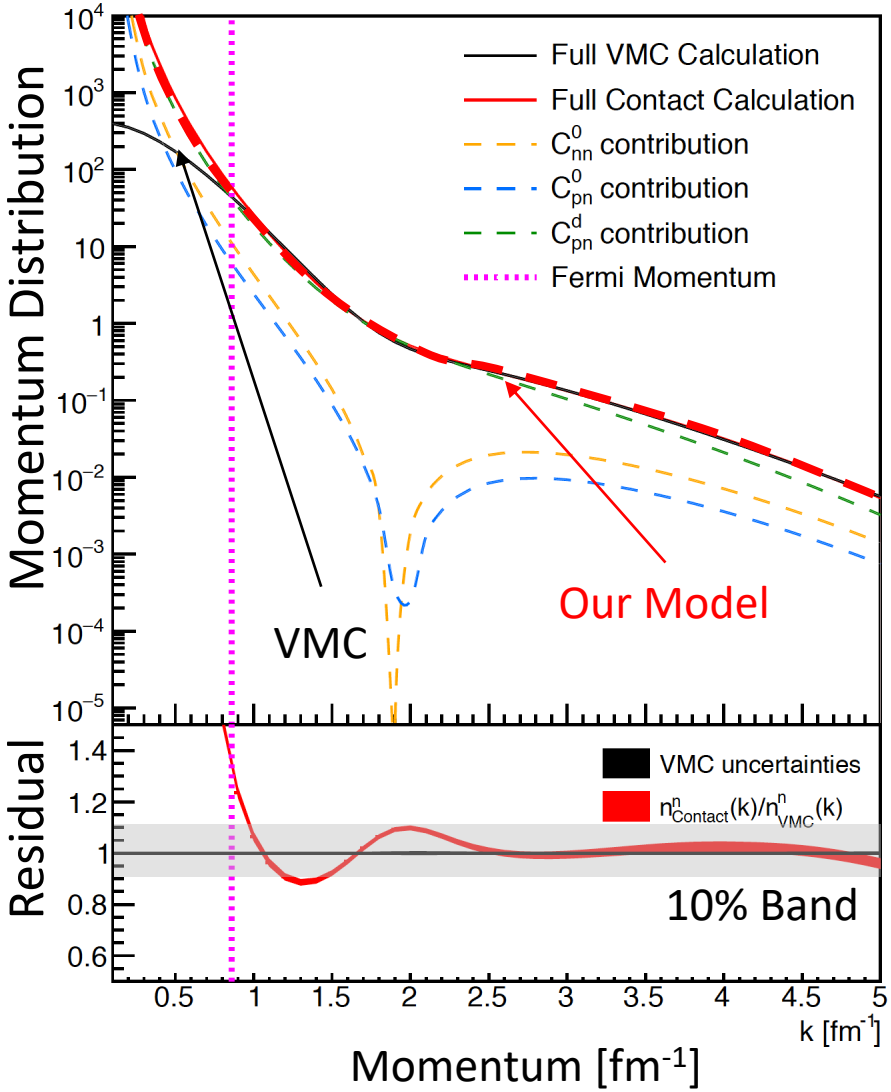
- Universal function of the NN interaction.
- Taken as the zero energy solution to the 2 body problem

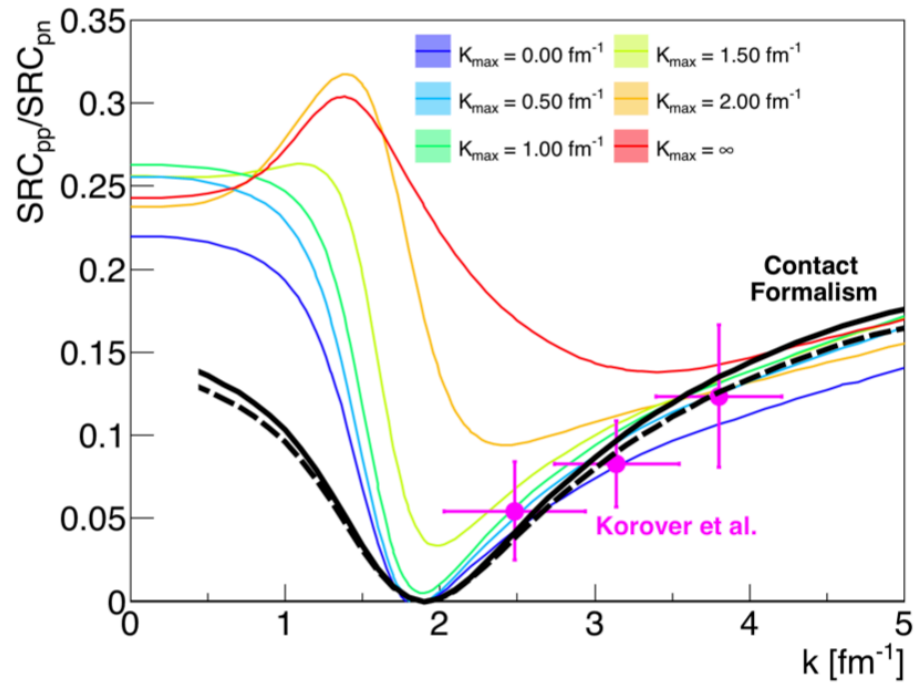
- Nucleus (/ system) specific function
- Depends on all nucleons except the SRC pair (primarily mean-field)

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)

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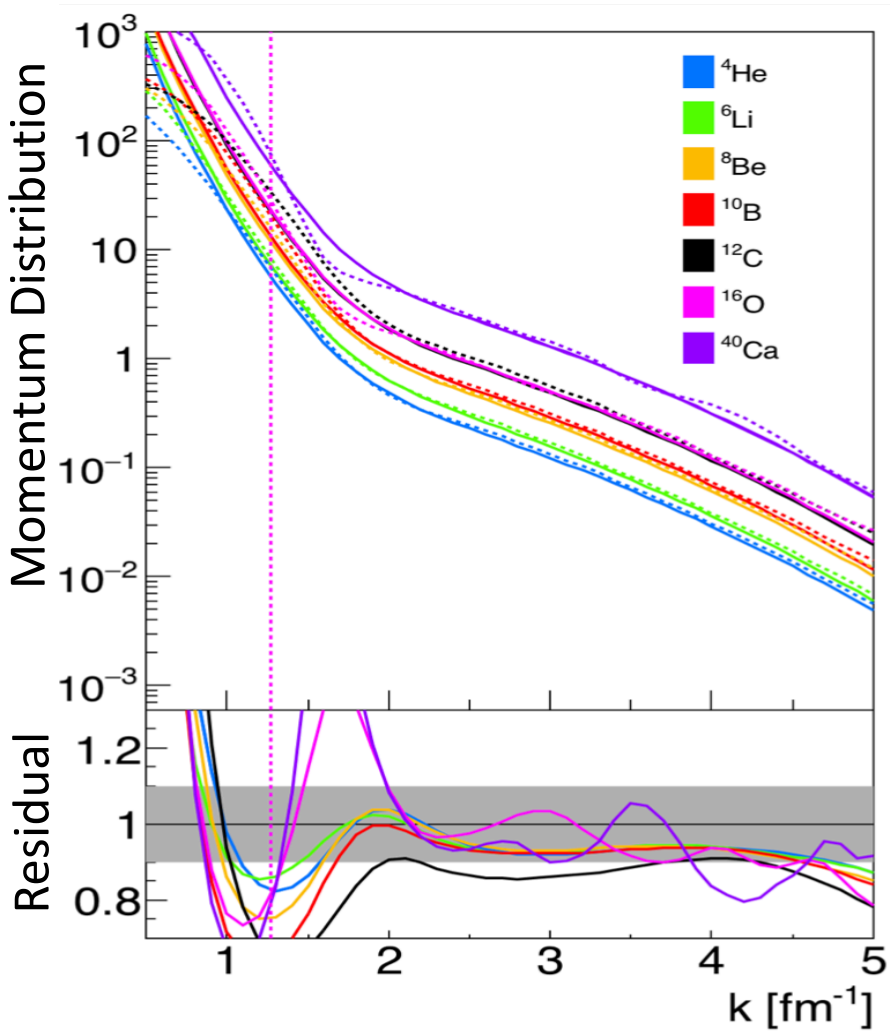
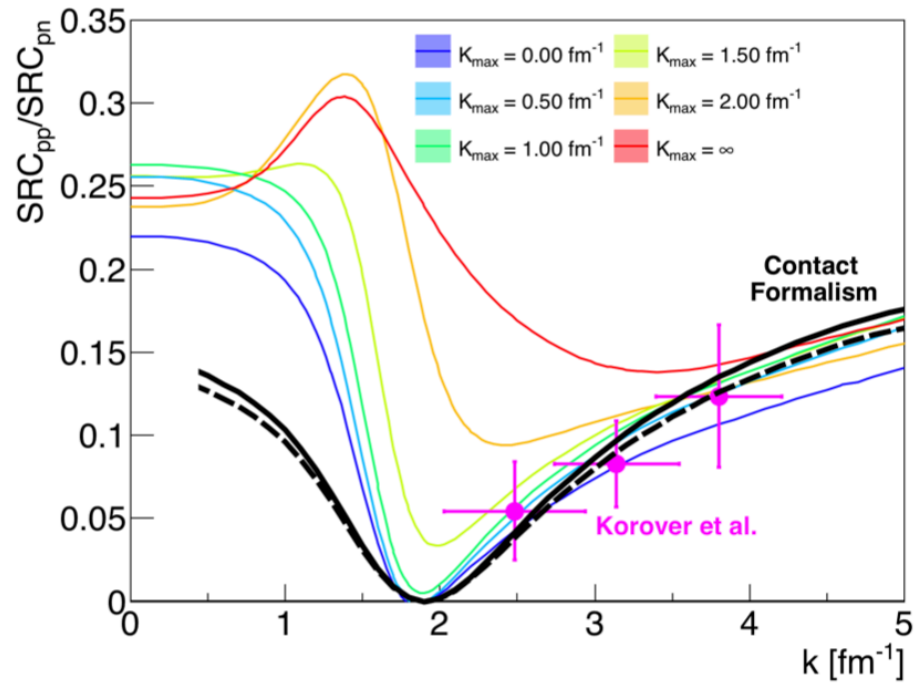




Nuclear contacts can also be extracted from experiment!

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

Spectral Function

Define pair spectral function as:

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

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

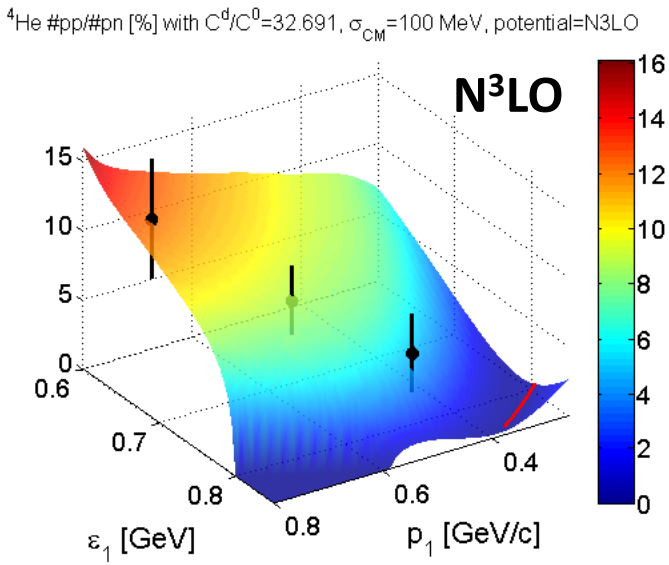
Factorize the continuum states of the spectral function:

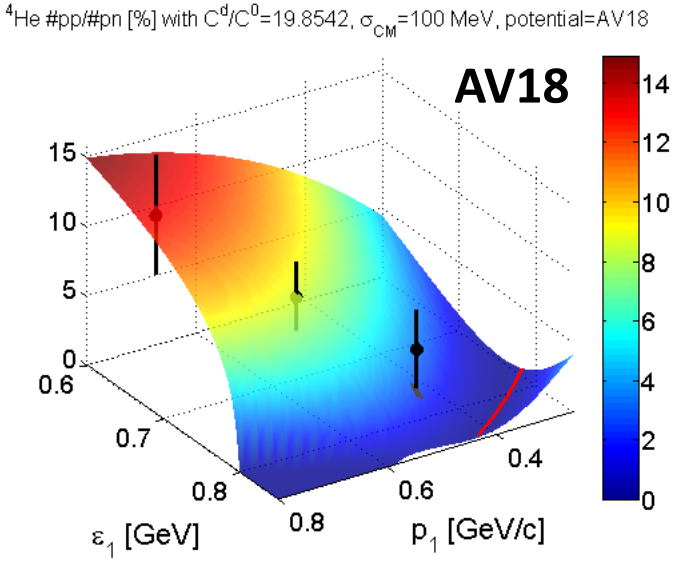
$$S^p(p_1,\epsilon_1) = C^1_{pn}S^1_{pn}(p_1,\epsilon_1)+C^0_{pn}S^0_{pn}(p_1,\epsilon_1) + 2C^0_{pp}S^0_{pp}(p_1,\epsilon_1).$$

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

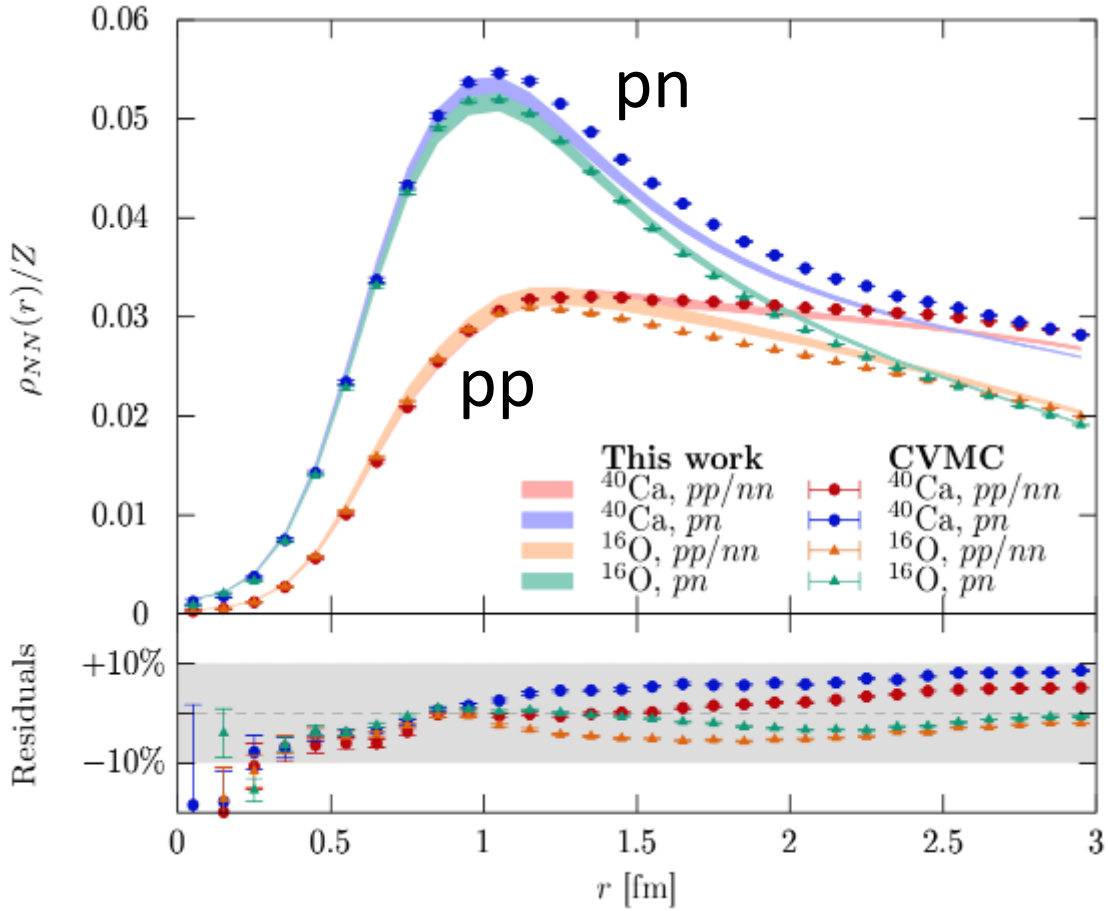
A	k-space				r-space			
	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$	$C_{pn}^{s=1}$	$C_{pn}^{s=0}$	$C_{nn}^{s=0}$	$C_{pp}^{s=0}$
^{4}He	12.3±0.1	0.69±0.03	0.65±0.03		11.61±0.03	0.567±0.004		
	14.9±0.7 (exp)	0.8±0.2 (exp)						
^{6}Li	10.5±0.1	0.53±0.05	0.49±0.03		10.14±0.04	0.415±0.004		
^{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

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

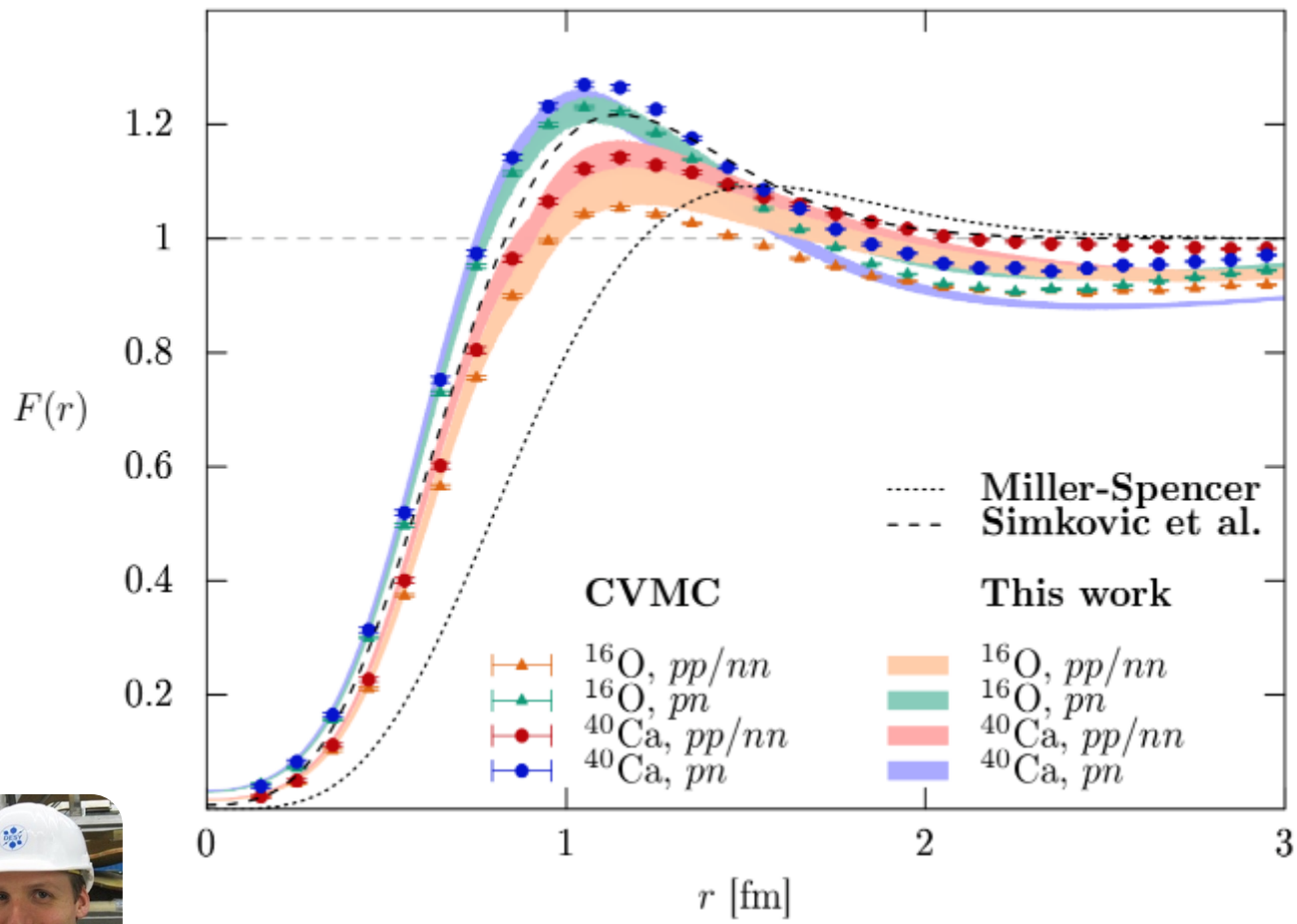
$$\rho_{NN}^{(0)}(\vec{r}) \equiv S_{NN} \int \mathrm{d}^3\vec{R}\rho_N(\vec{R} + \vec{r}/2)\rho_N(\vec{R} - \vec{r}/2)$$

[Un-correlated 2B density]

Correlation Function

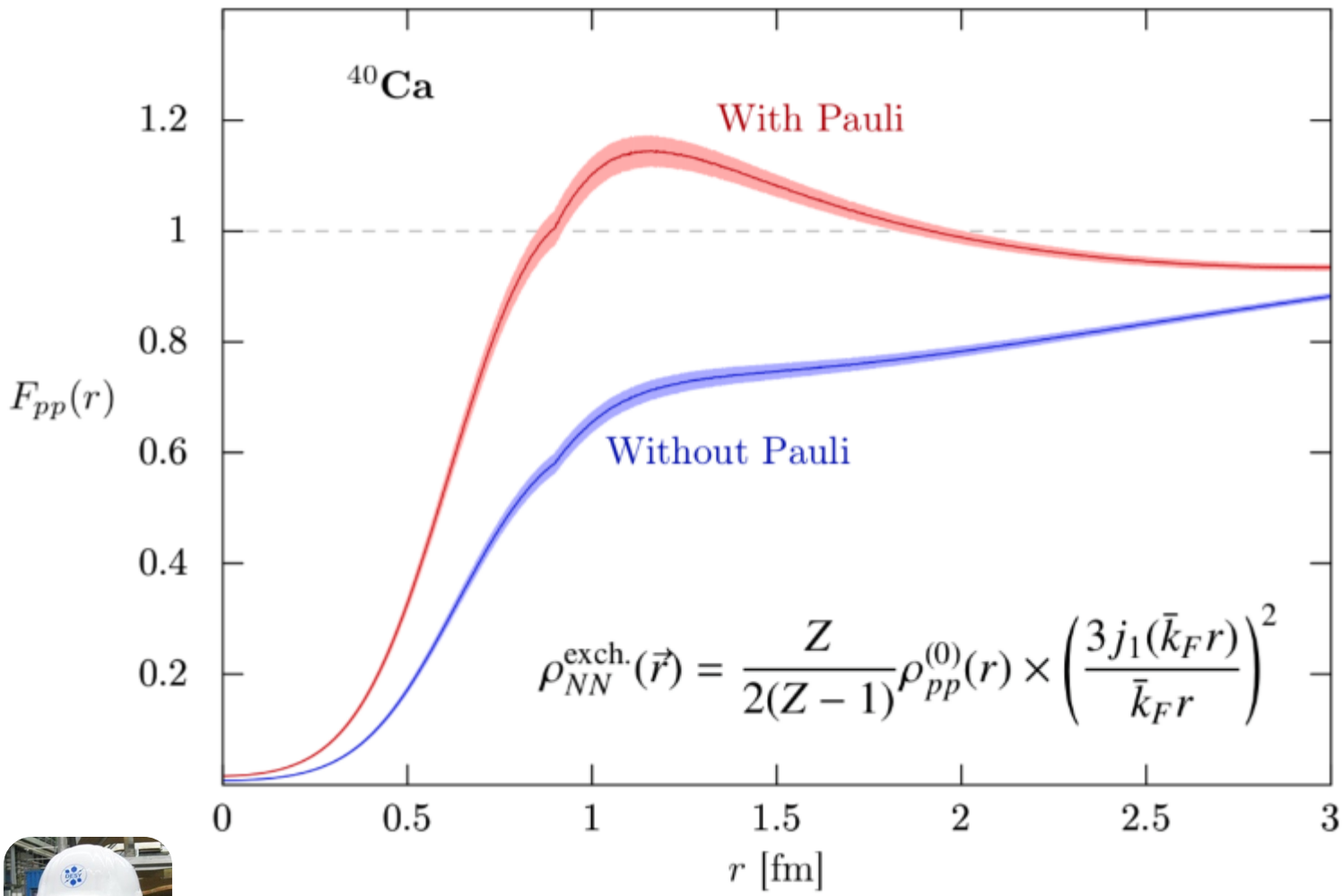
Derive Correlation function:

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

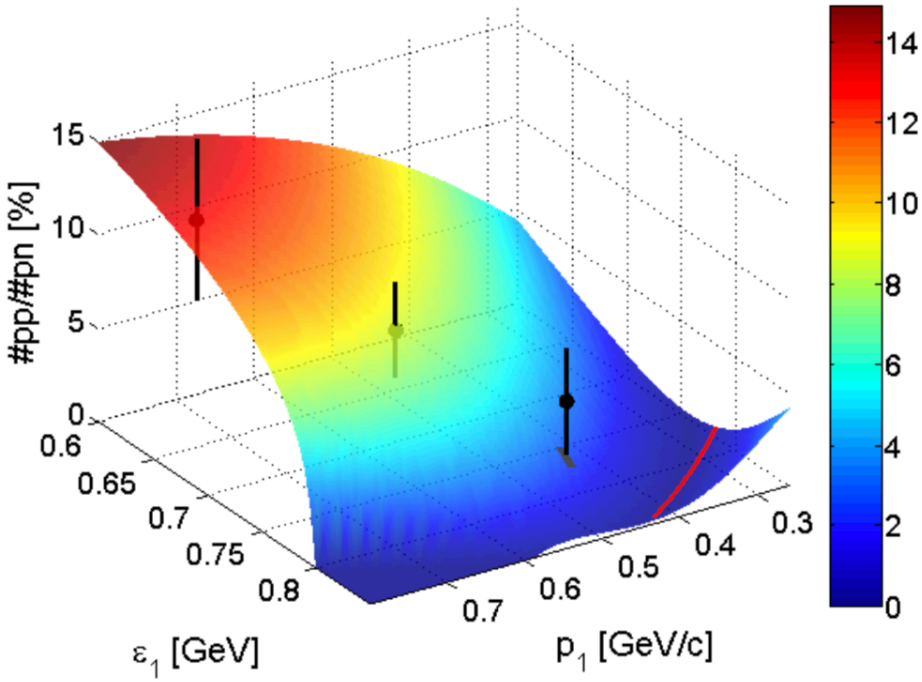
Future Direction:
Better connection \w theory using Contact Formalism

New spectral function model:

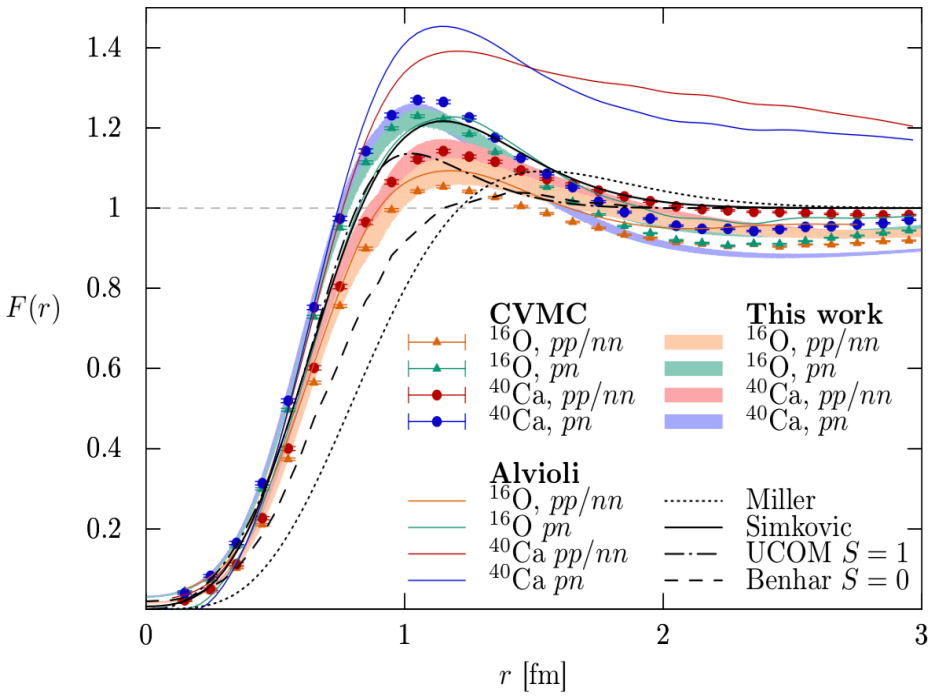
- Used to analyze (e,e'pN) data including scheme dependence
- Forthcoming calculations of (e,e')
- event generators available

Correlation function model:

- Consistent with VMC
- Grounded in experiment
- Extendible to heavy nuclei



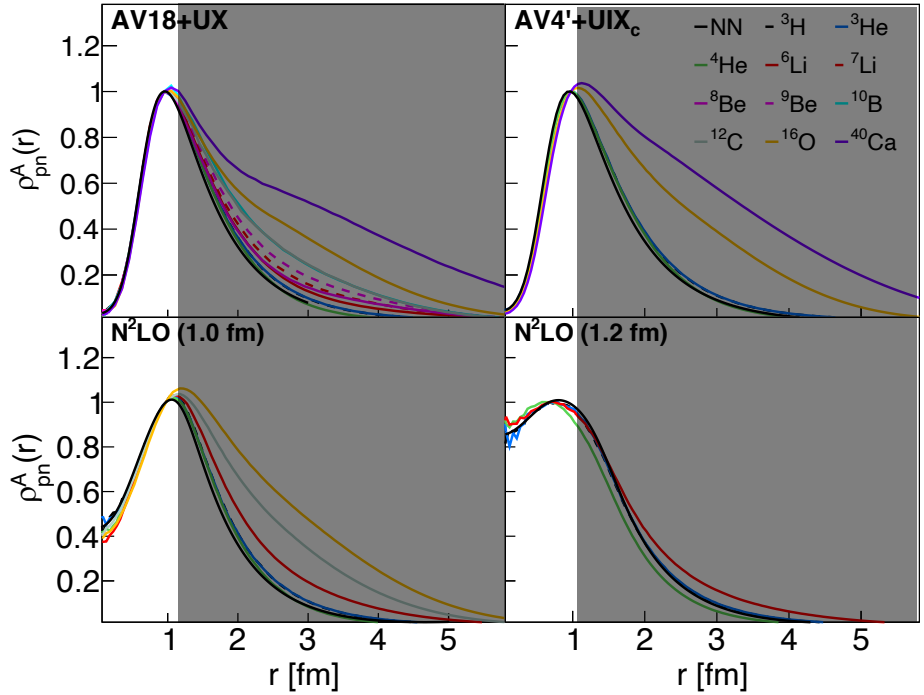
R. Weiss et al., Submitted (2018)



R. Cruz-Torres et al., Phys. Lett B, In-Print (2018)

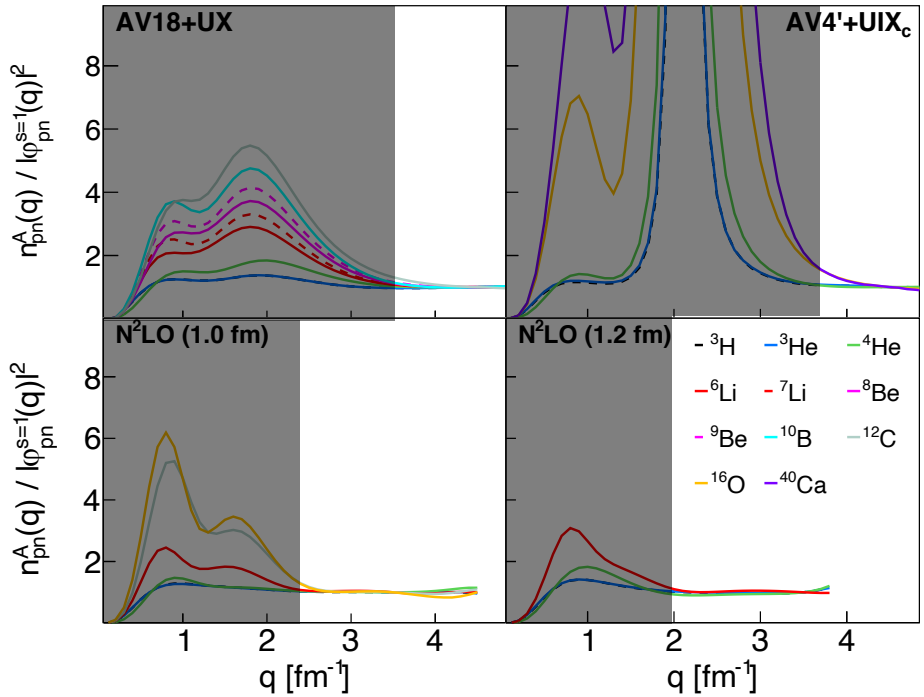
Position, < 1 fm:

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



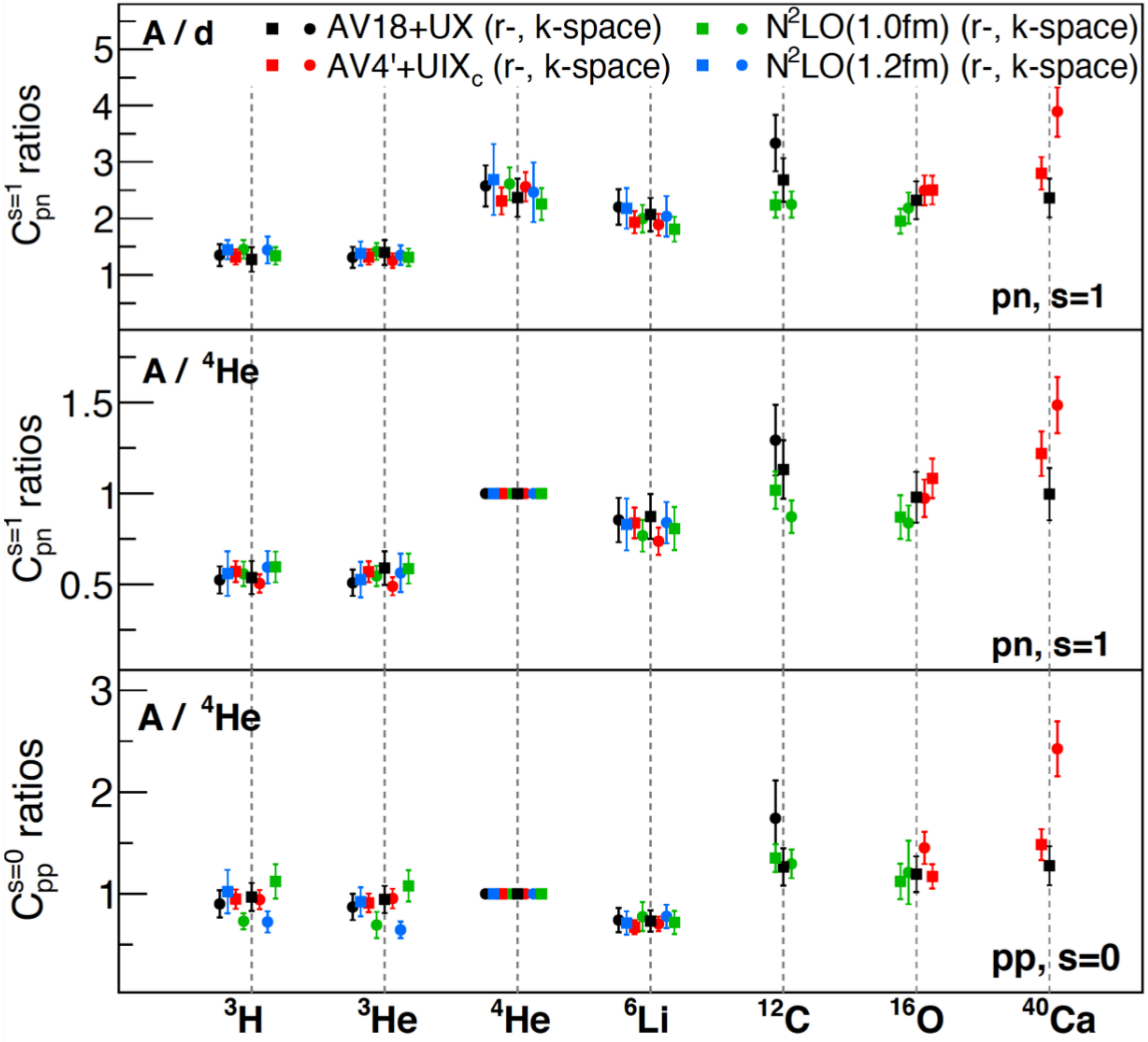
Momentum, > k_F:

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



Weiss et al., Phys. Lett. B (2018);
Cruz Torres et al., Phys. Lett B (2018);
Weiss et al., Phys. Lett B (2019);
Cruz Torres et al., arXiv: 1907.03658 (2019).

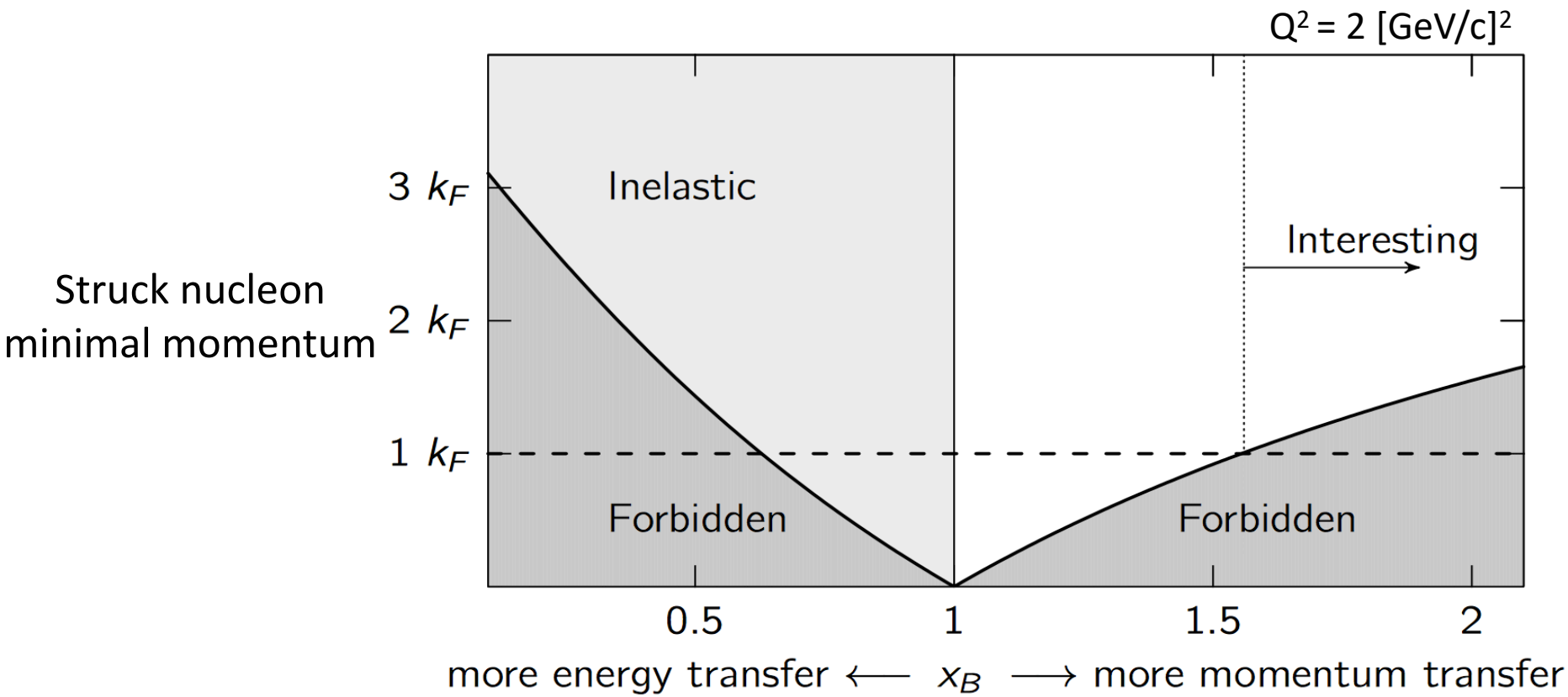
Scale & Scheme Independence
Momentum–Position Equivalence



Cruz Torres and Lonardoni et al., arXiv: 1907.03658 (2019)

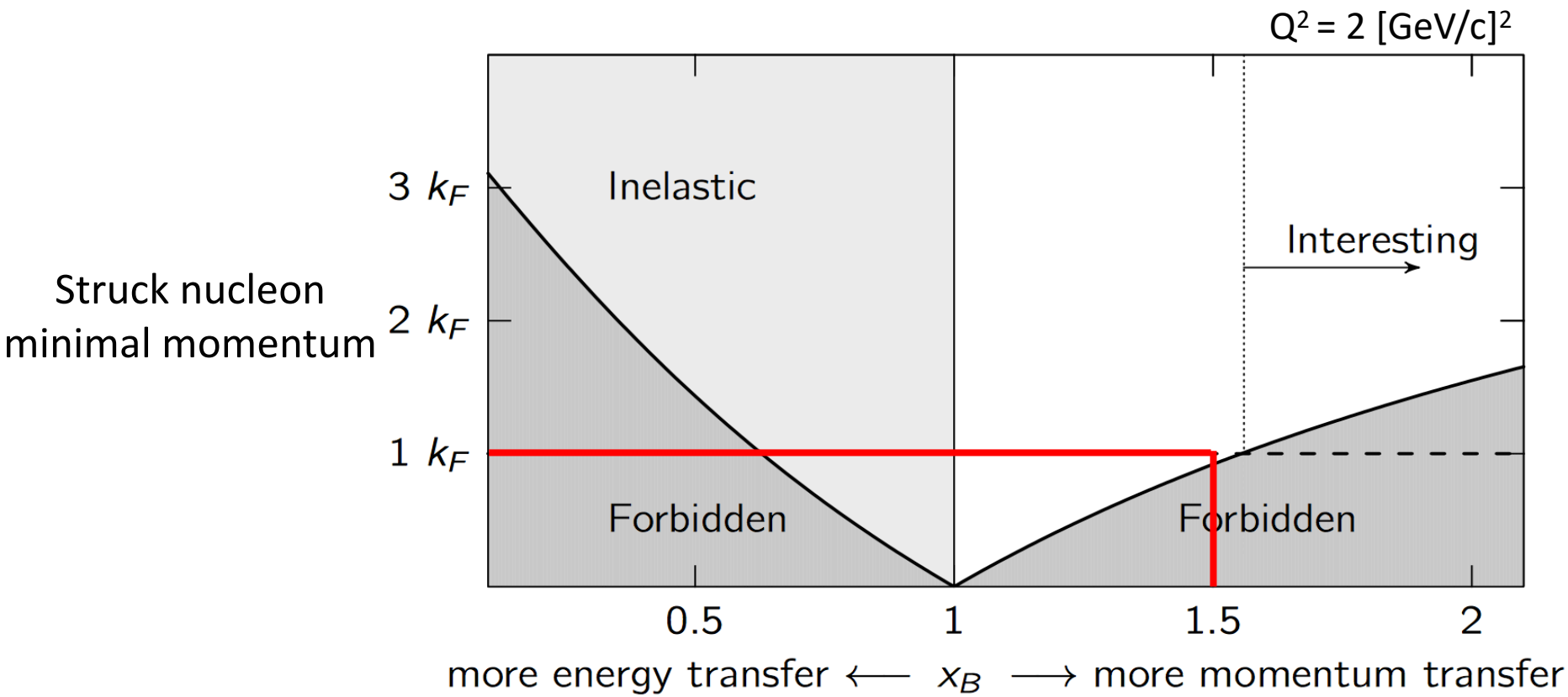
Backup: (e,e’) and SRC fractions

(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



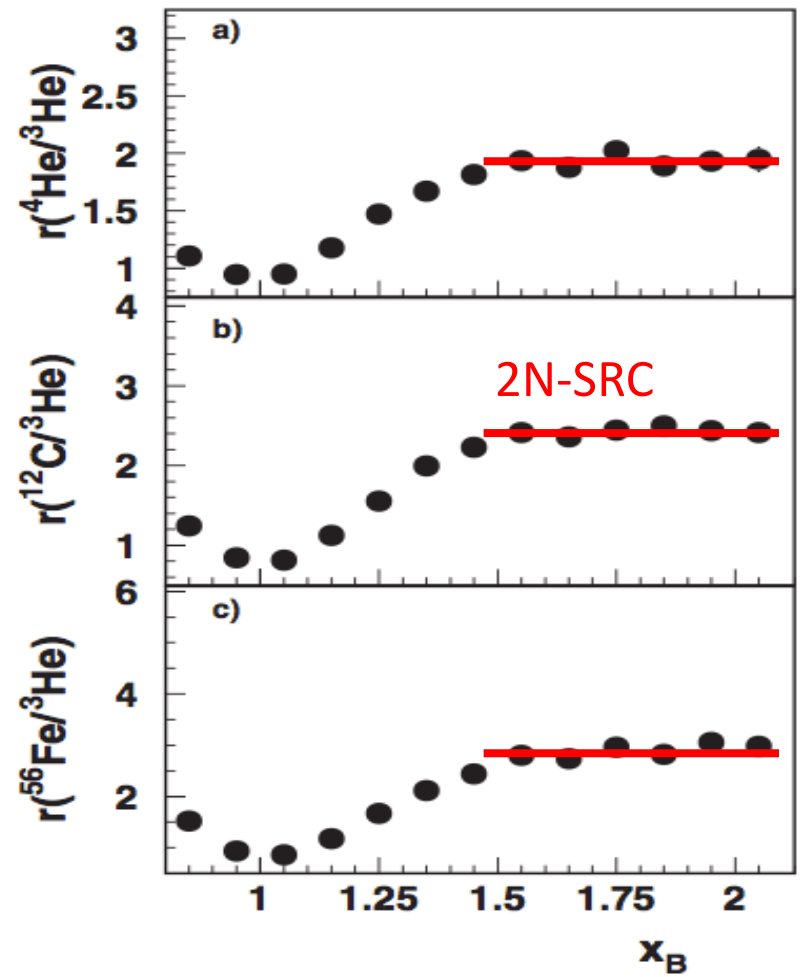
$$(q+p_A-p_{A-1})^2=p_f^2=m_N^2$$

High-Momentum Scaling

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

- Observed scaling for $x_B \geq 1.5$.

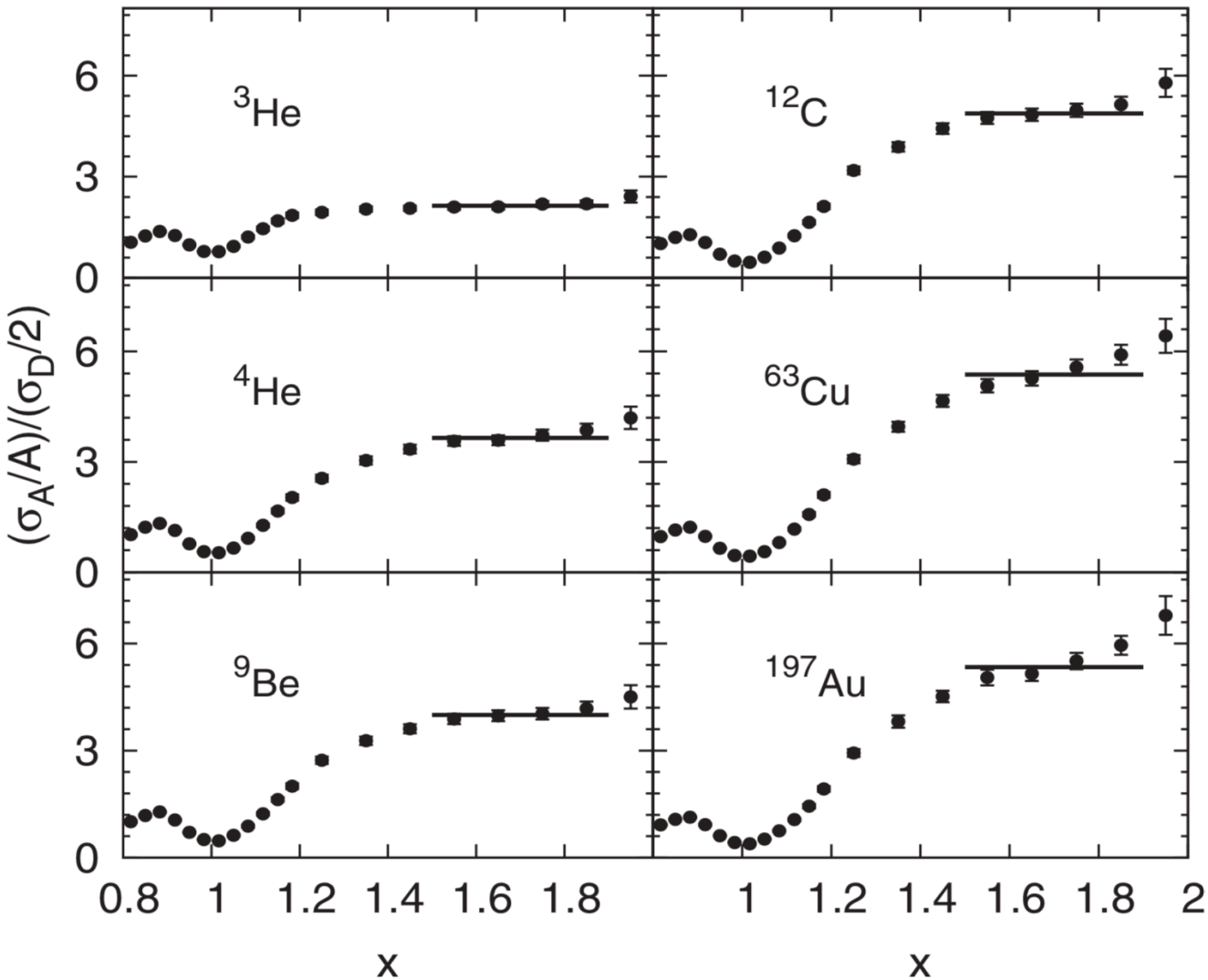
=> $n_A(k>k_F) = a_2(A) \times n_d(k)$



Egiyan et al., PRL (2006)

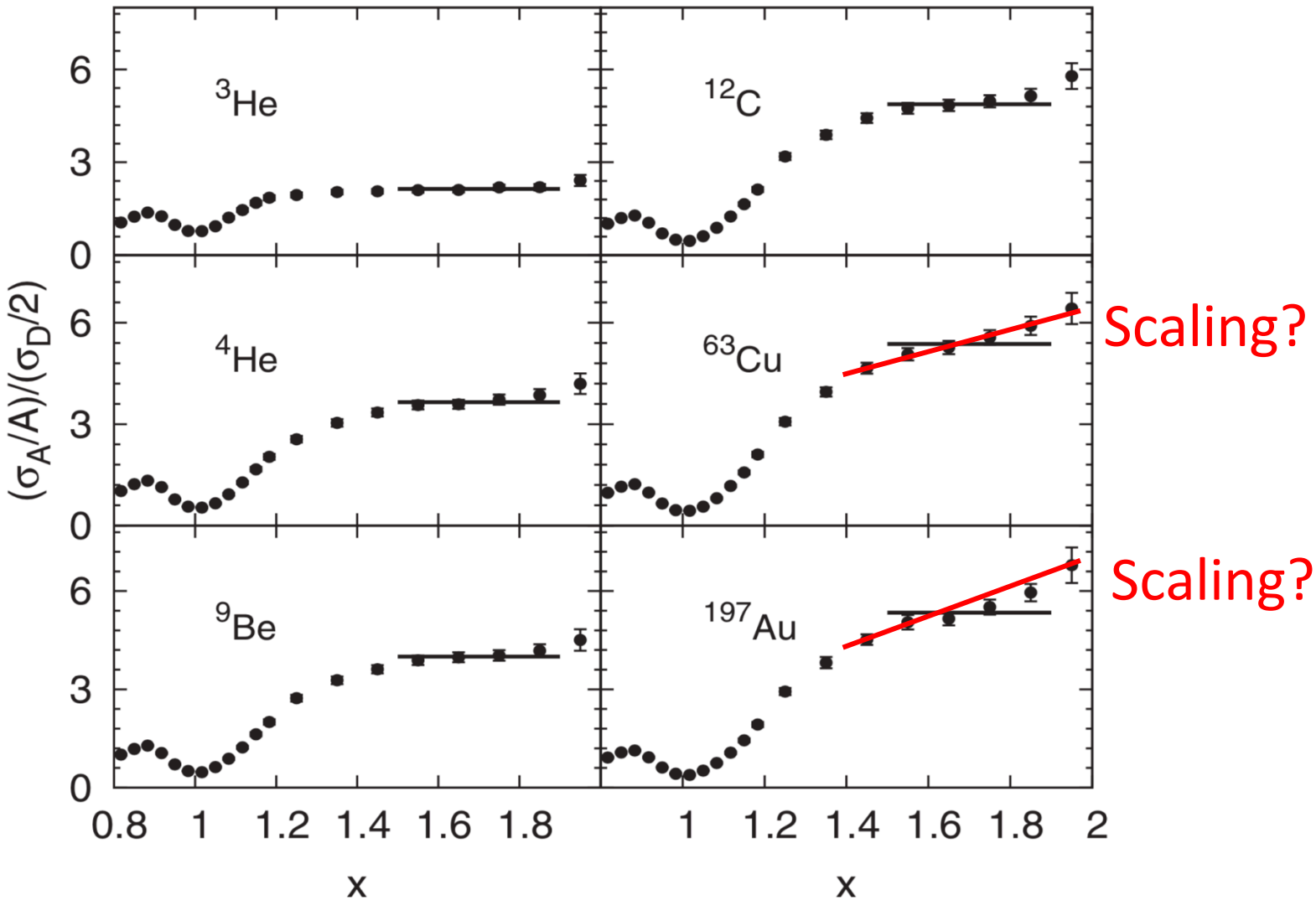
Frankfurt et al., PRC (1993); Egiyan et al., PRC (2003); Fomin et al., PRL (2012).

2012 High-Momentum [almost] Scaling



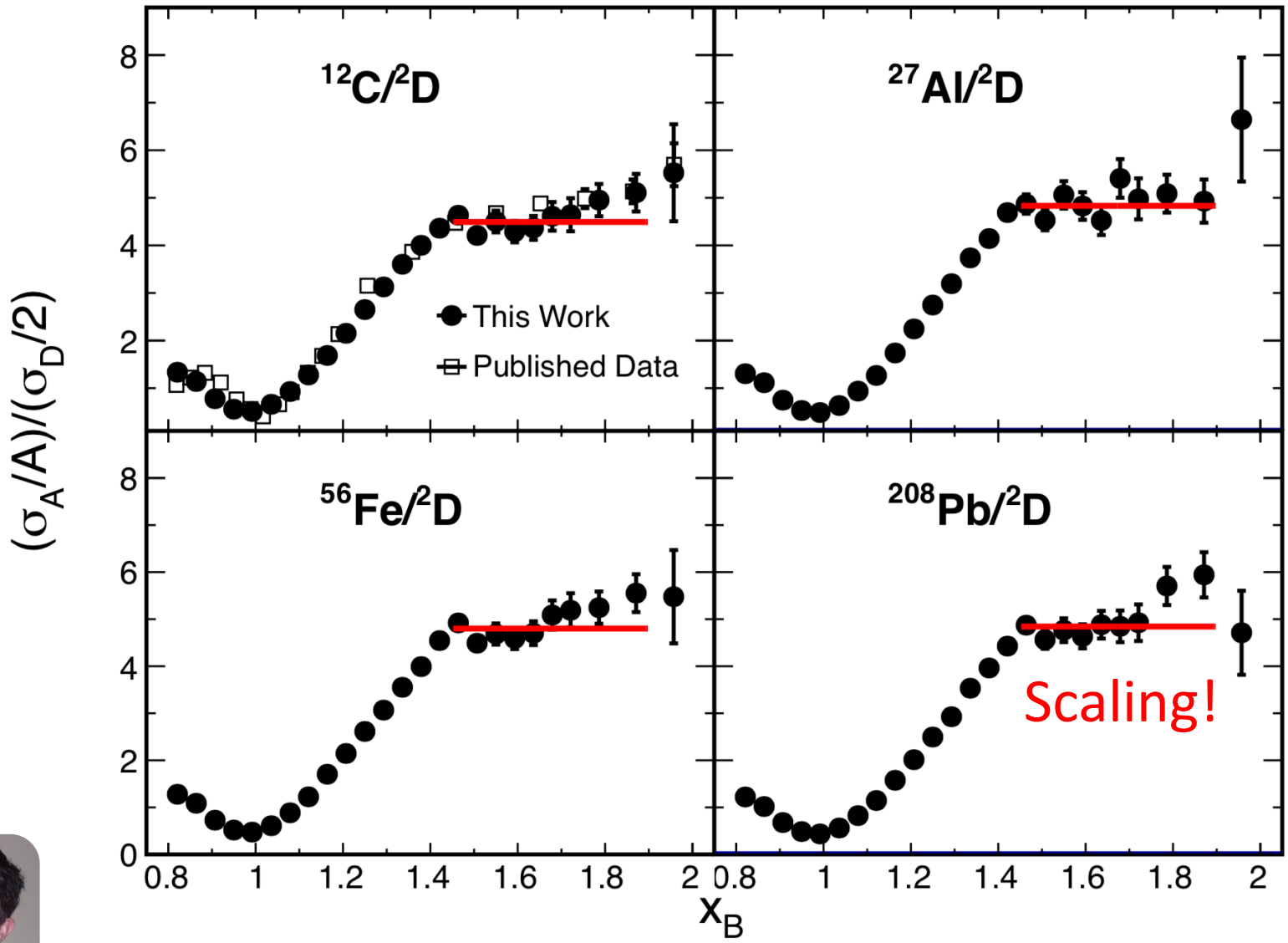
Fomin, PRL (2012)

2012 High-Momentum [almost] Scaling



Fomin, PRL (2012)

2018 High-Momentum Scaling



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

20% high-p?

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

➔ <u>5 x 4% ~ 20%</u>

20% high-p?

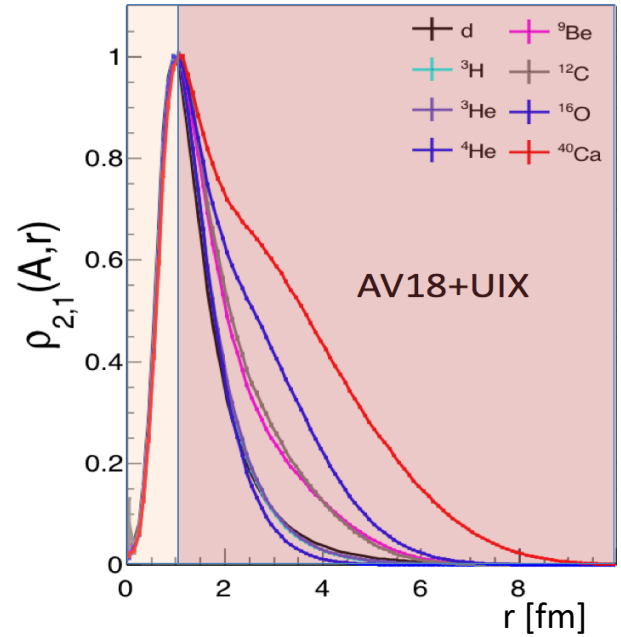
- A/d (e,e') ratio @ $x_B > 1.5$: ~5
- AV18 deuteron density above 275 MeV/c: ~4 - 5%

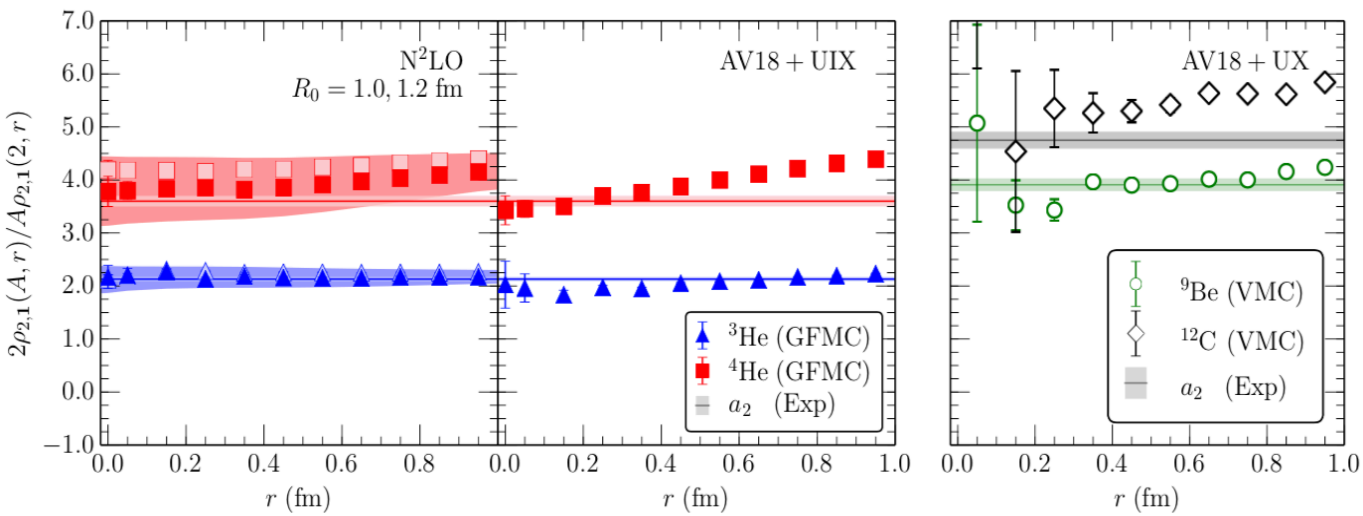
➔ 5 x 4% ~ 20%

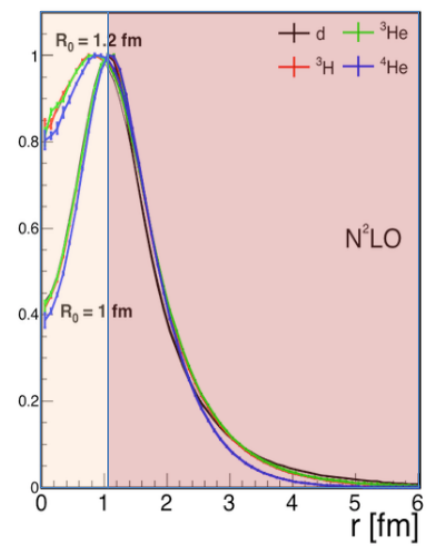
<u>~ 20% is consistent with VMC using AV18+UIX</u>

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%







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

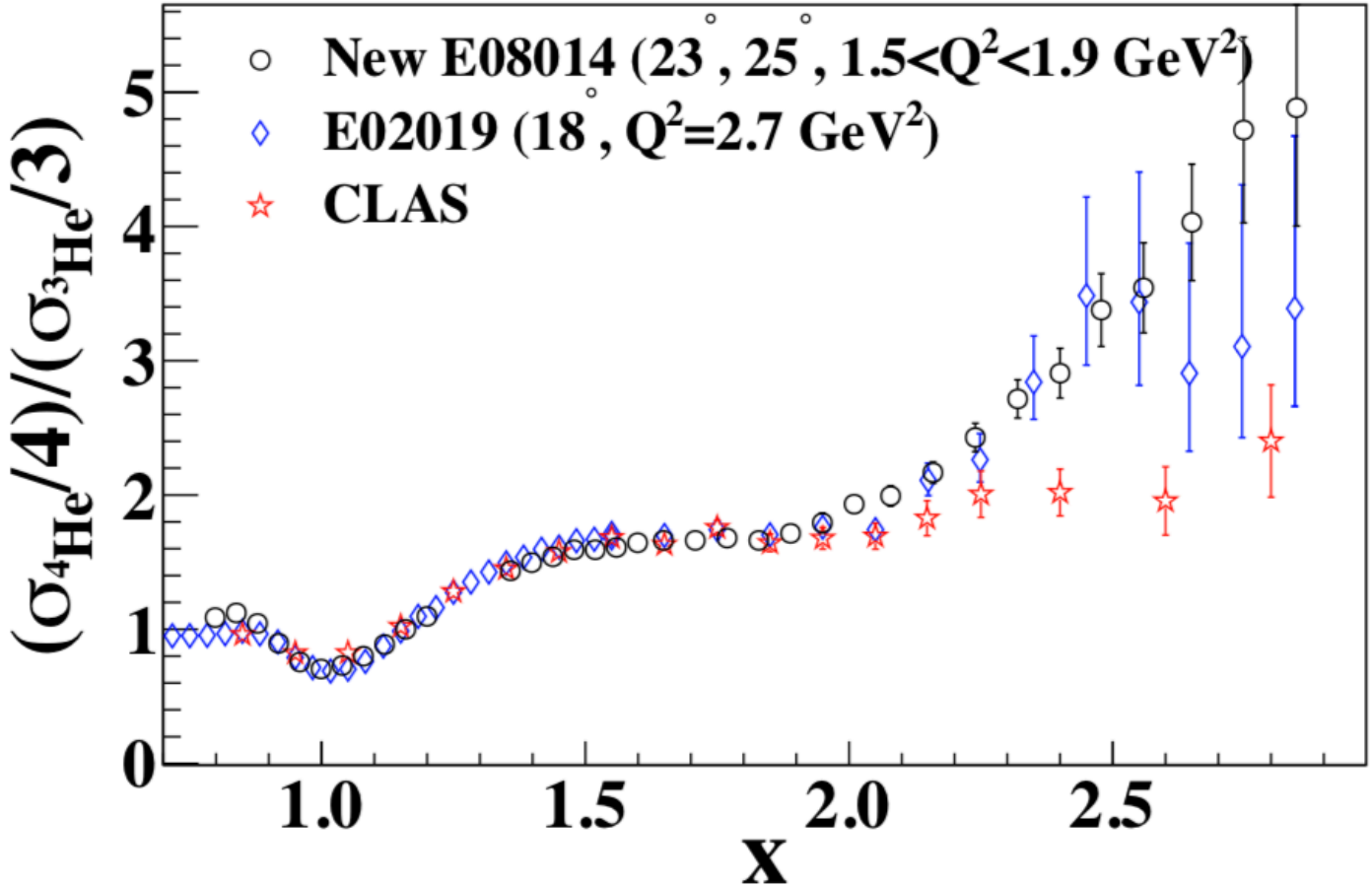
20% high-p?

<u>Open questions:</u>

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

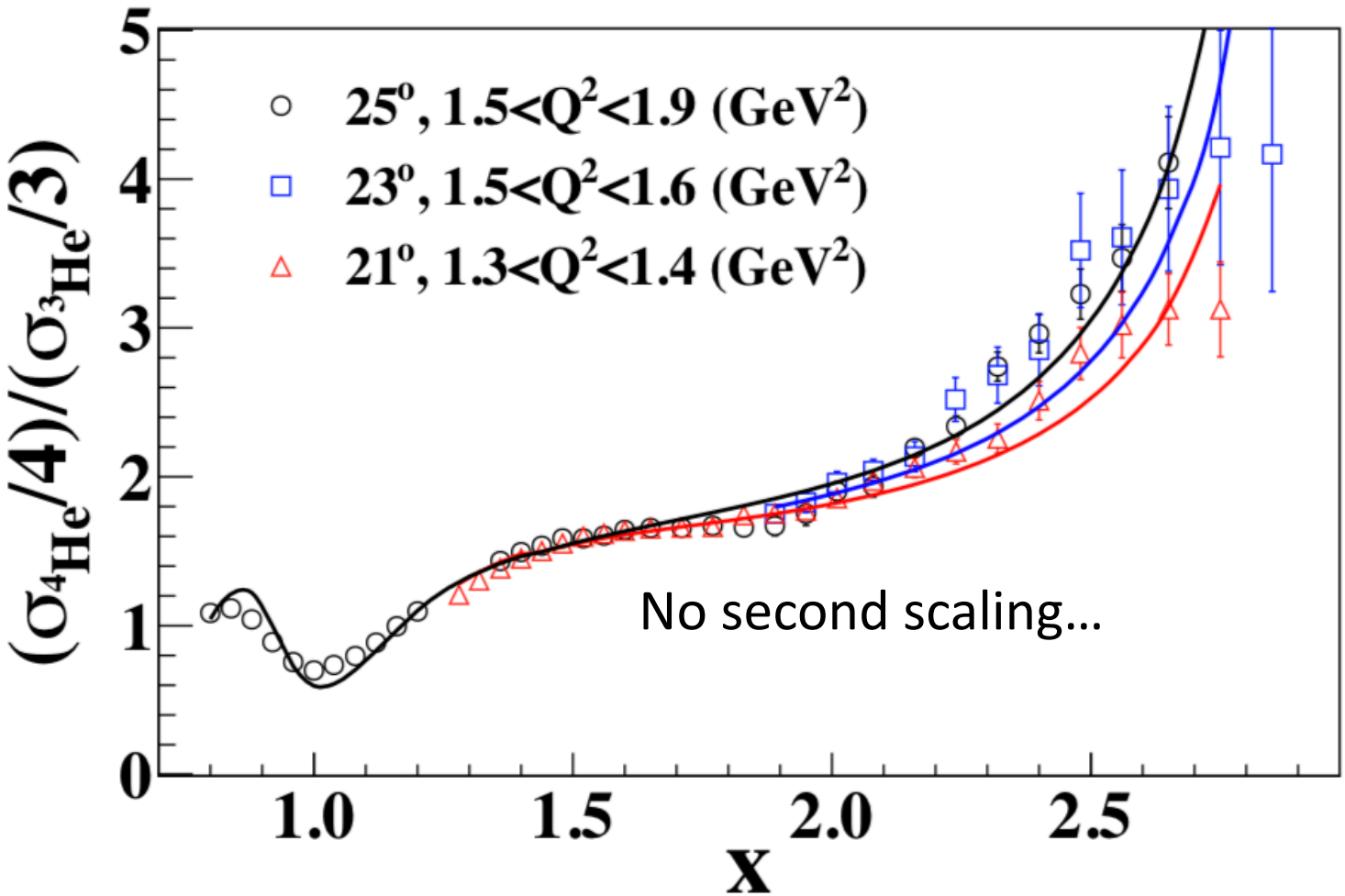
- Experiments sensitive to light-cone densities, NOT momentum densities. No light-cone calc yet…

Looking for 3N-SRC



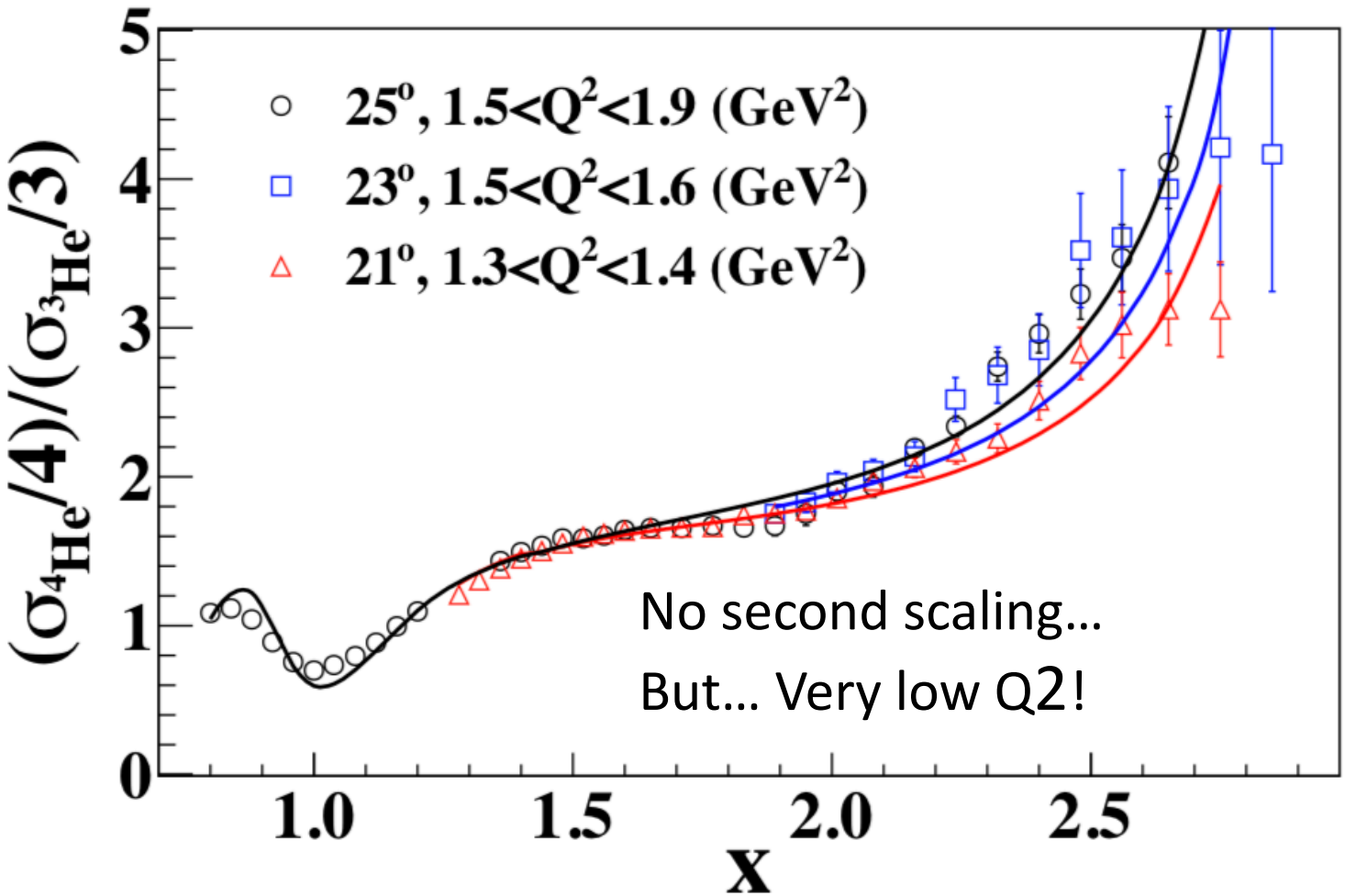
Ye et al., PRC (2018)

Looking for 3N-SRC



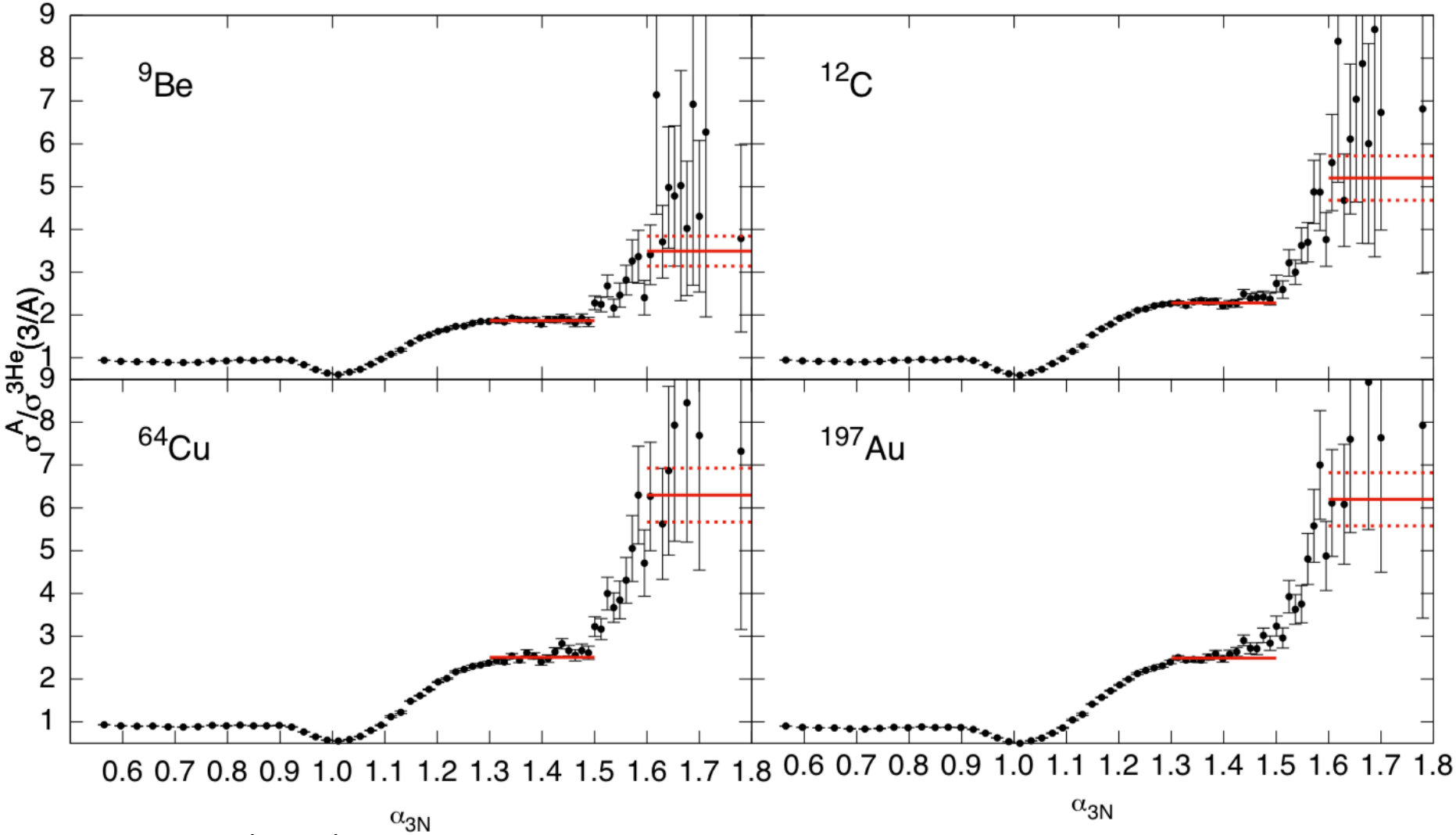
Ye et al., PRC (2018)

Looking for 3N-SRC



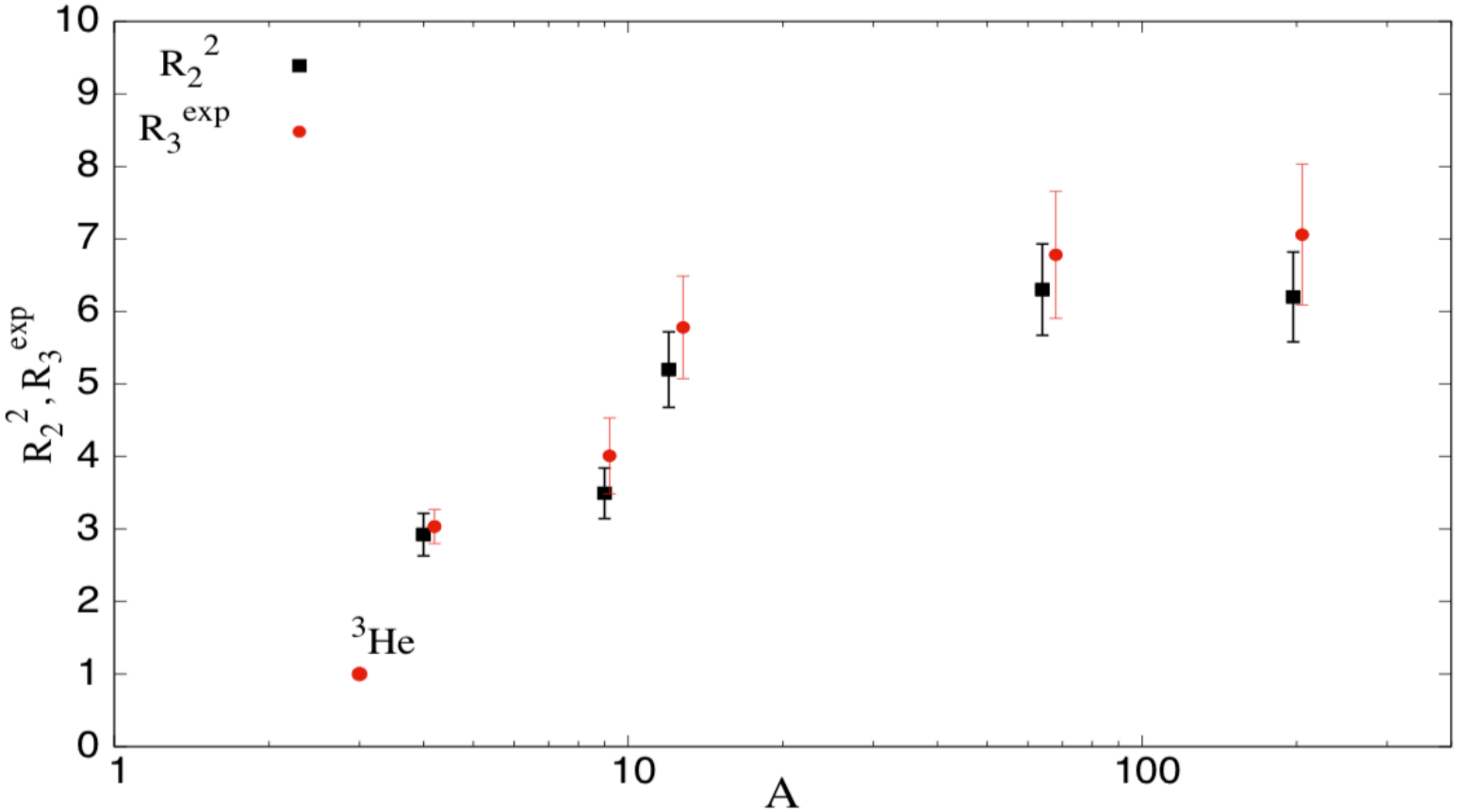
Ye et al., PRC (2018)

Looking for 3N-SRC @ higher Q^2



Day, Sargsian, FS (2018)

3N vs. $(2N)^2$



Day, Sargsian, FS (2018)

Nuclei: A 60+ year old challenge

"What holds the nucleus of the atom together? In the past quarter century physicists have devoted a huge amount of experimentation and mental labor to this problem - probably more man-hours than have been given to any other scientific question in the history of mankind." – Hans Bethe, Scientific American 1953.

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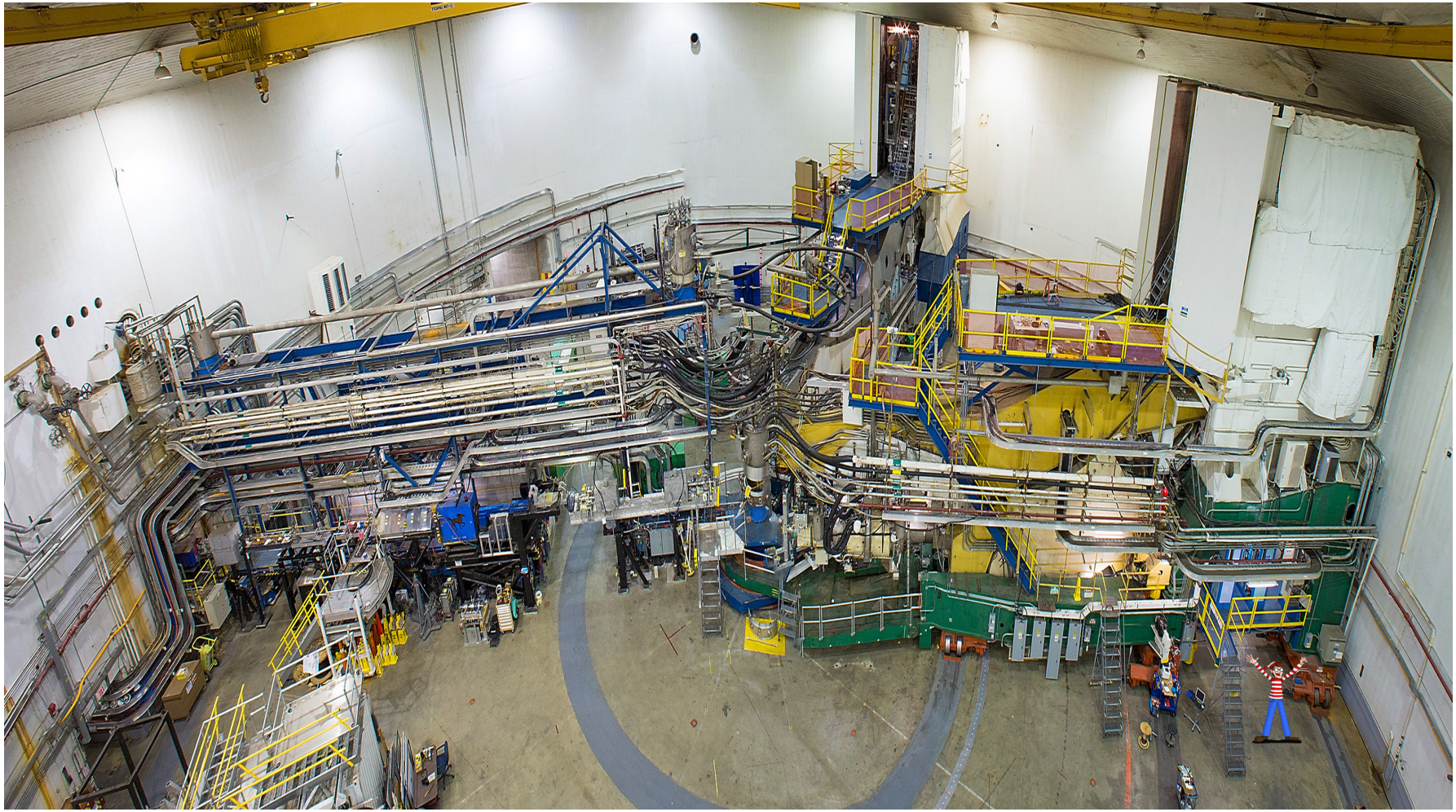
Hall-A: High-Resolution Spectrometers



Hall-A: High-Resolution Spectrometers

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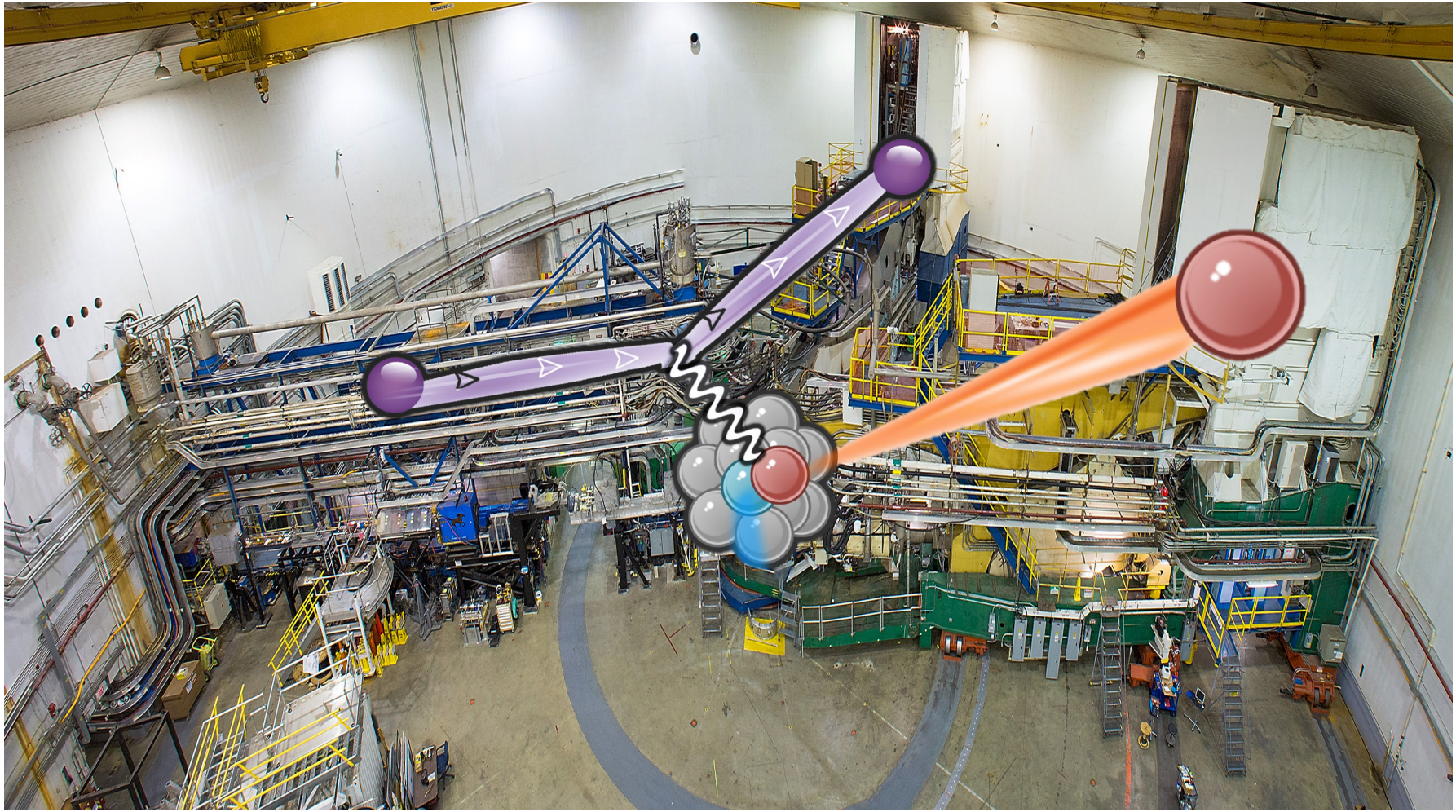
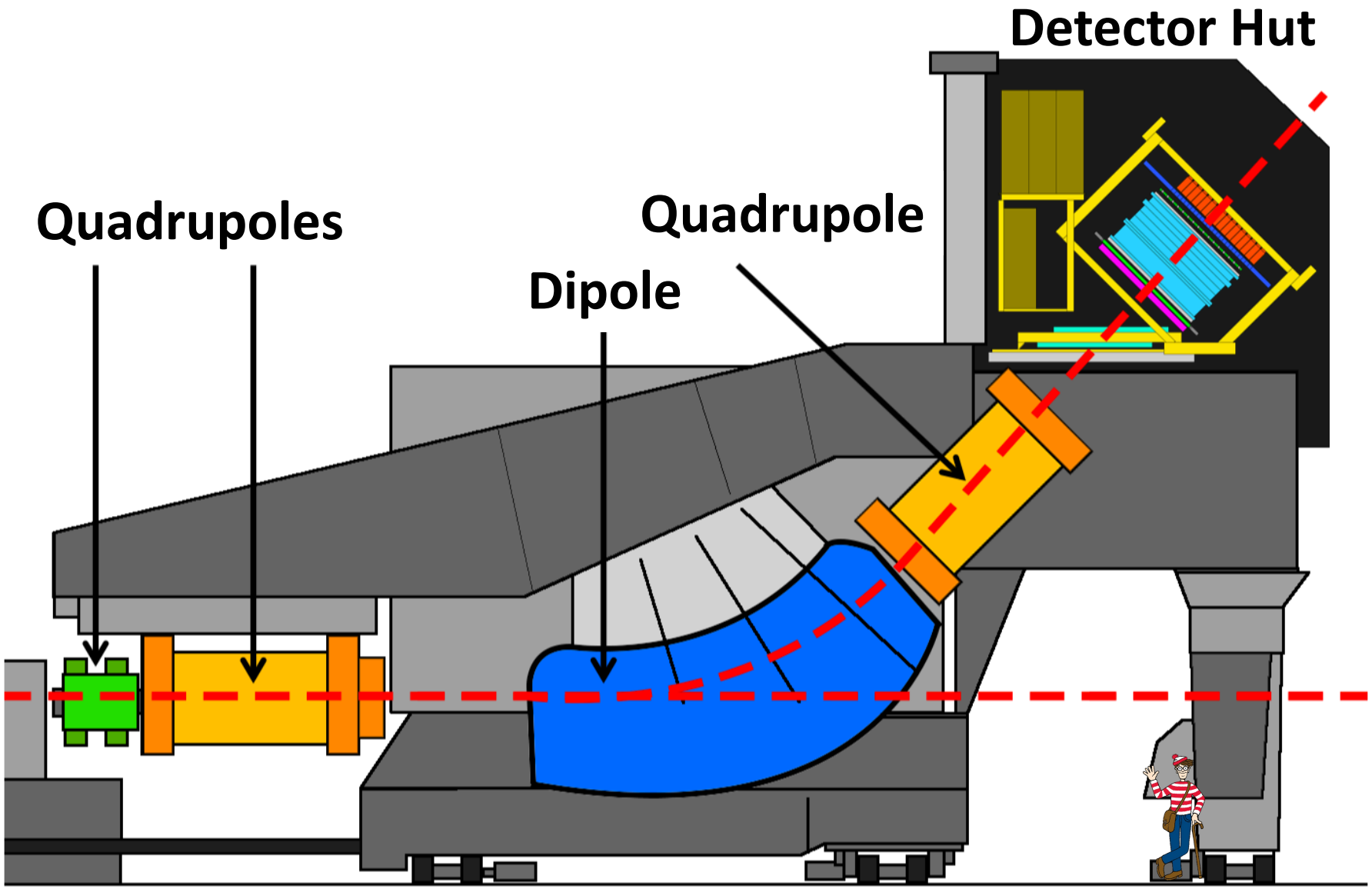
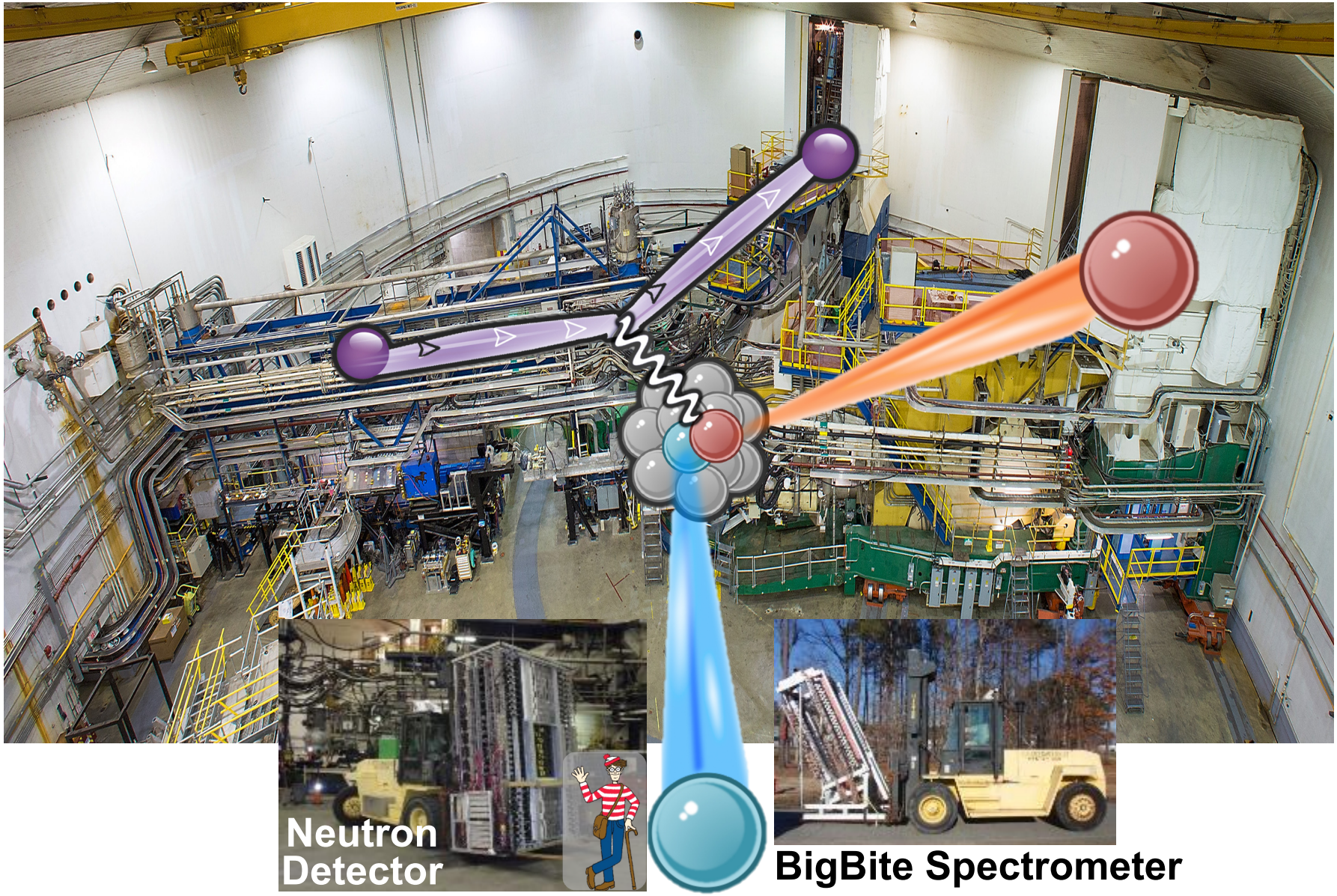
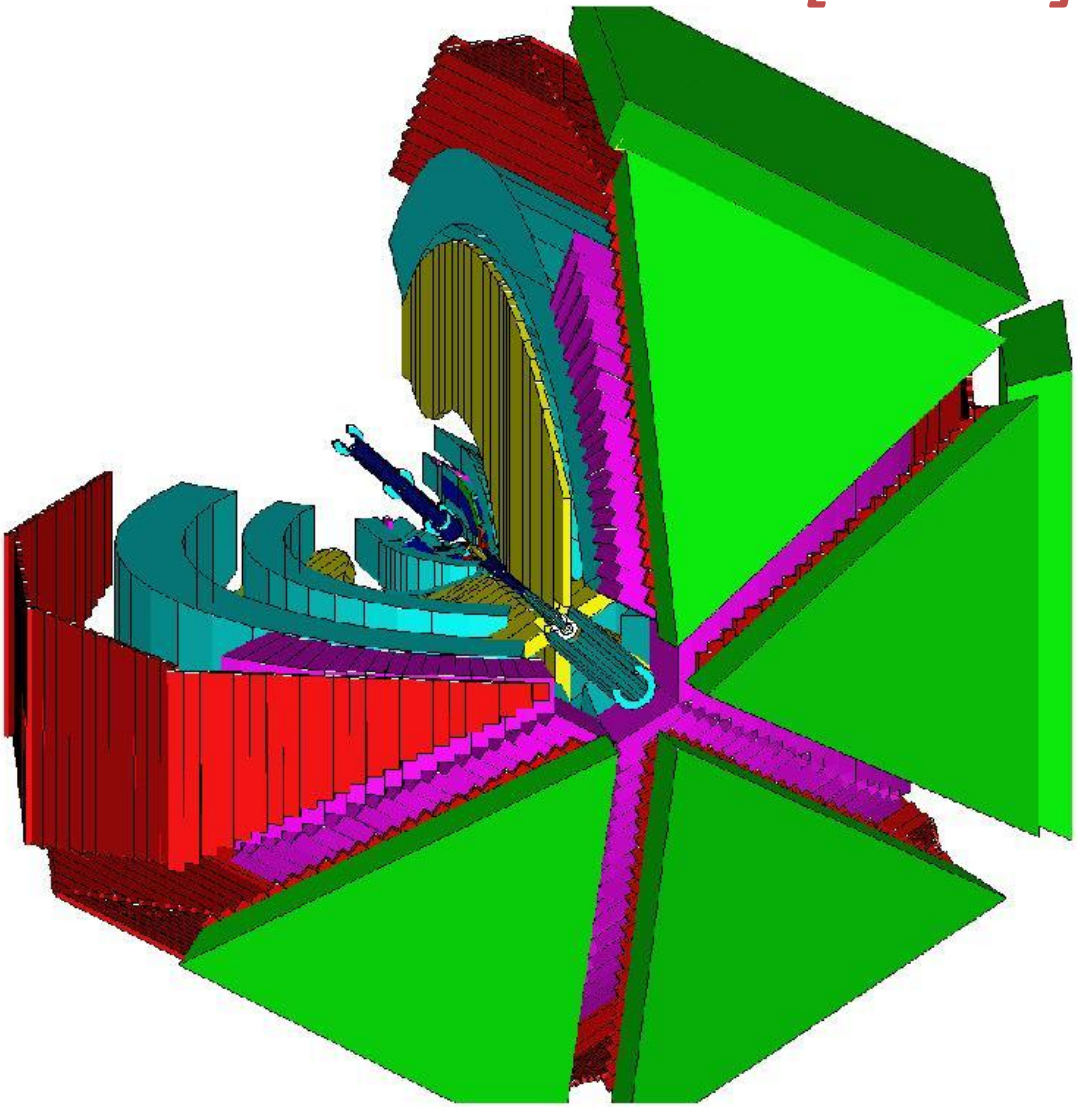


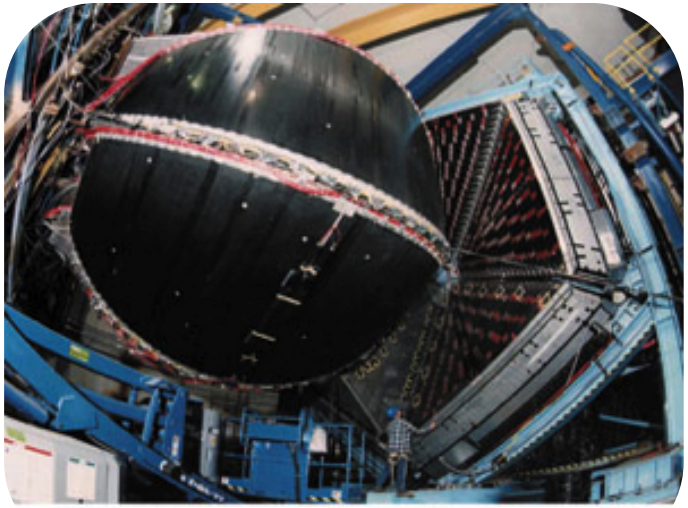

Detector Hut
Quadrupoles
Quadrupole
Dipole

Hall-A: High-Resolution Spectrometers

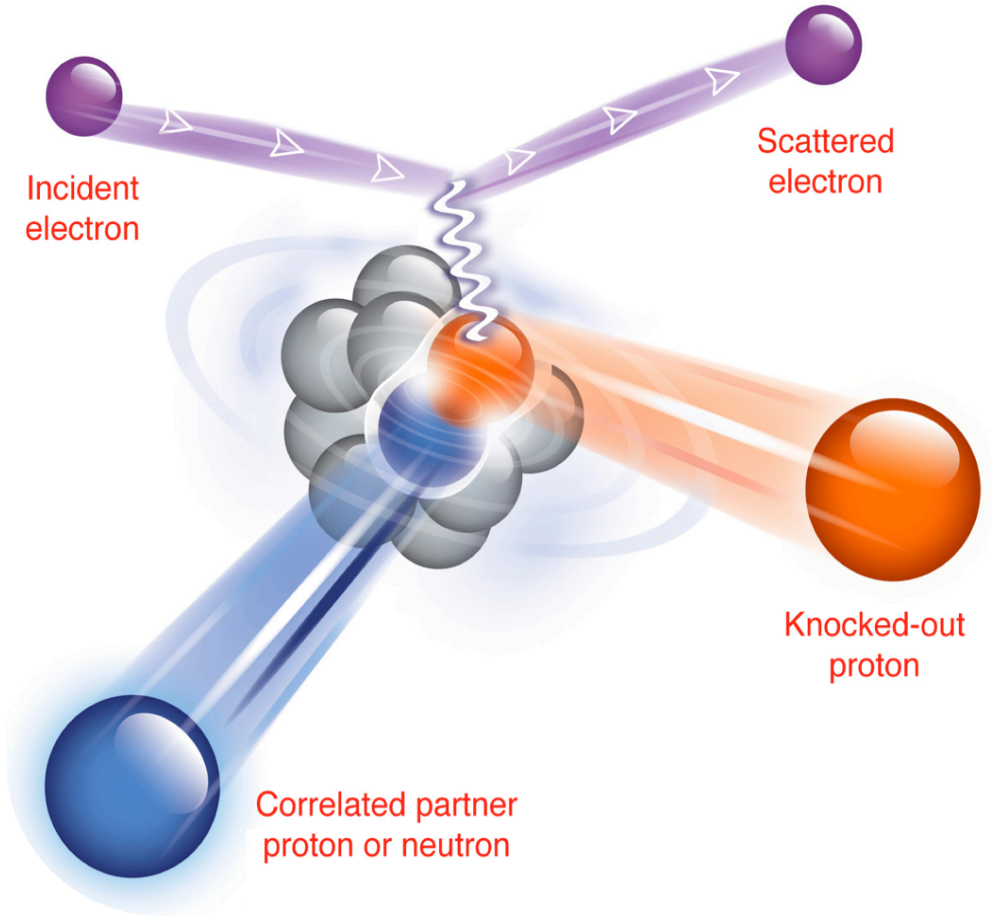


CEBAF Large Acceptance Spectrometer *[CLAS]*





Hall B Large Acceptance Spectrometer

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

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