Nuclear structure and the formation of short-range nucleon-nucleon correlations

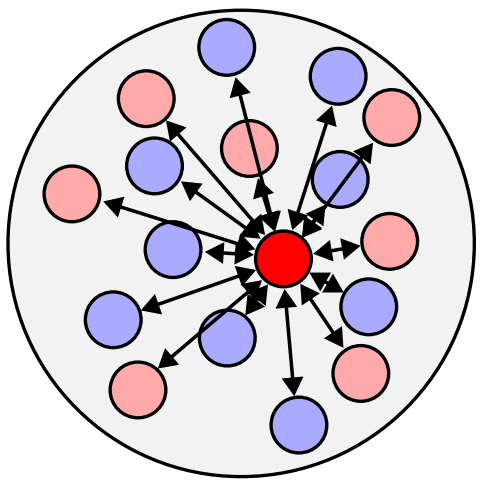
Axel Schmidt

62nd International Winter Meeting on Nuclear Physics

January 23, 2026

Simple patterns emerge in nuclear structure.

Calculating all pair-wise interactions is hard.



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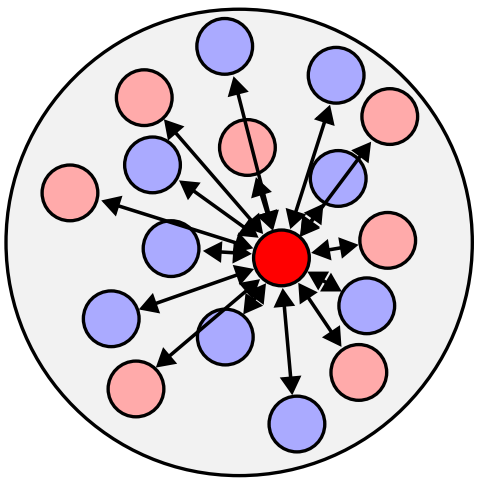
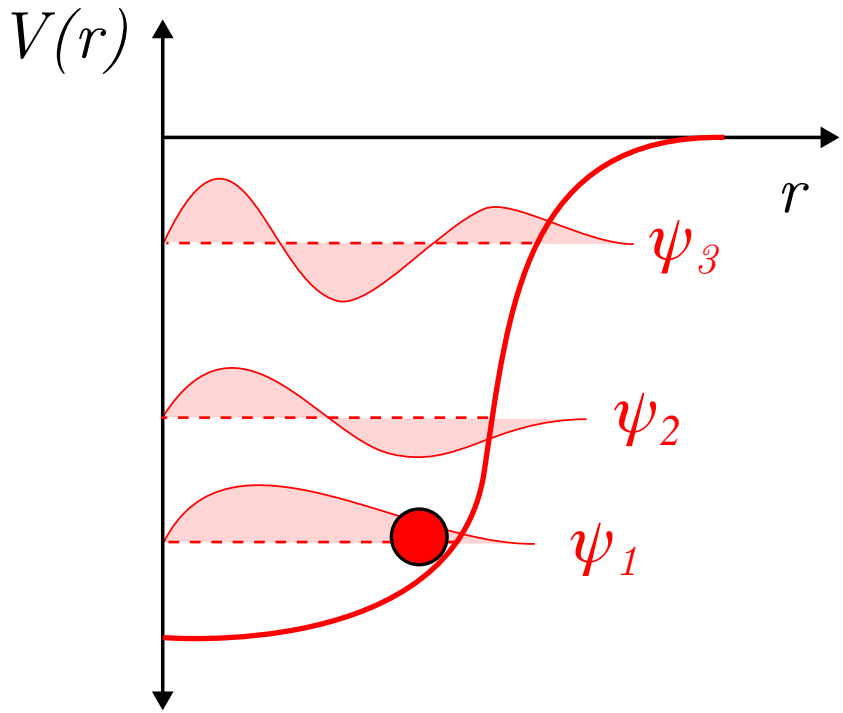


Approximate with non-interacting nucleons in a mean-field..



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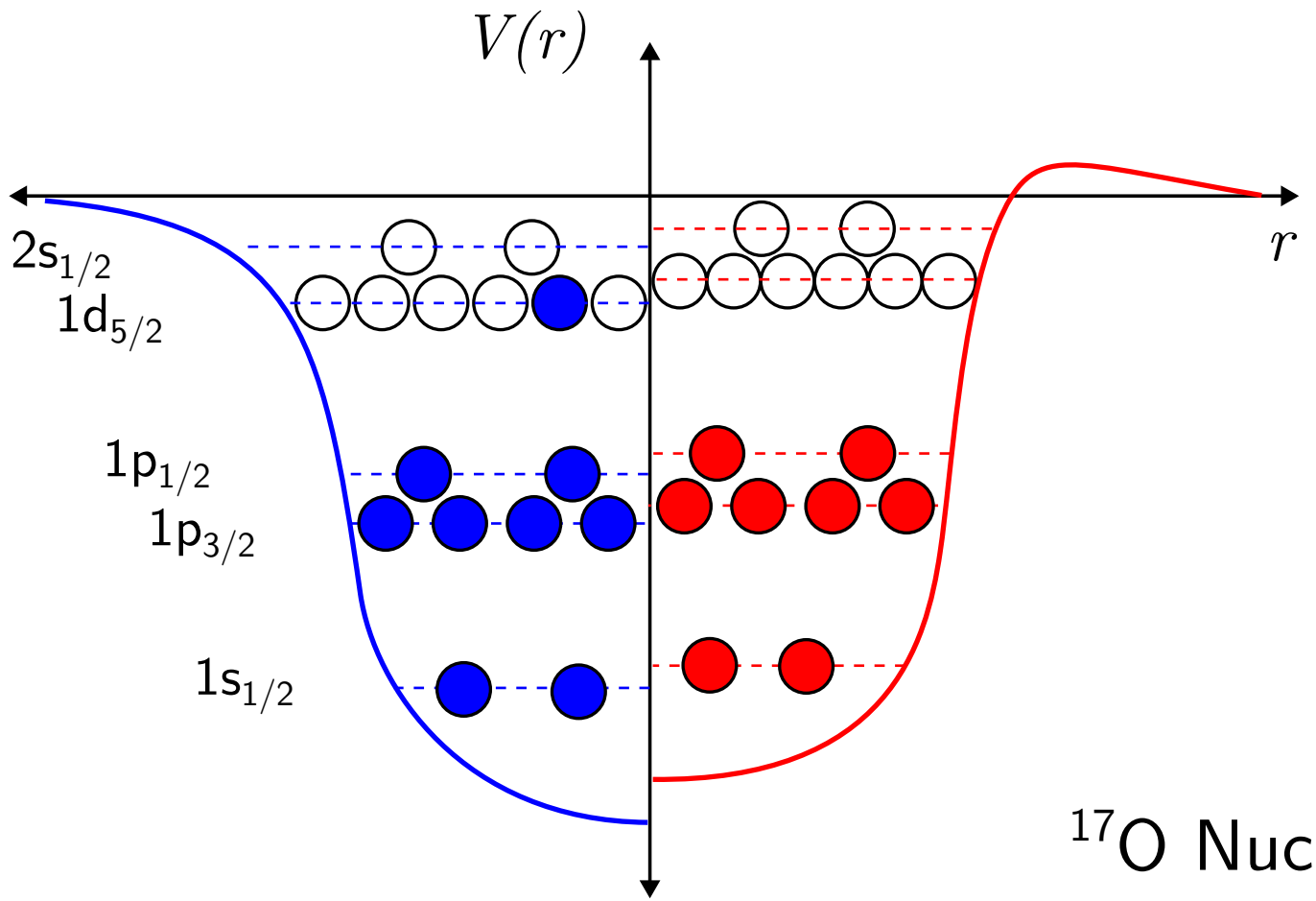
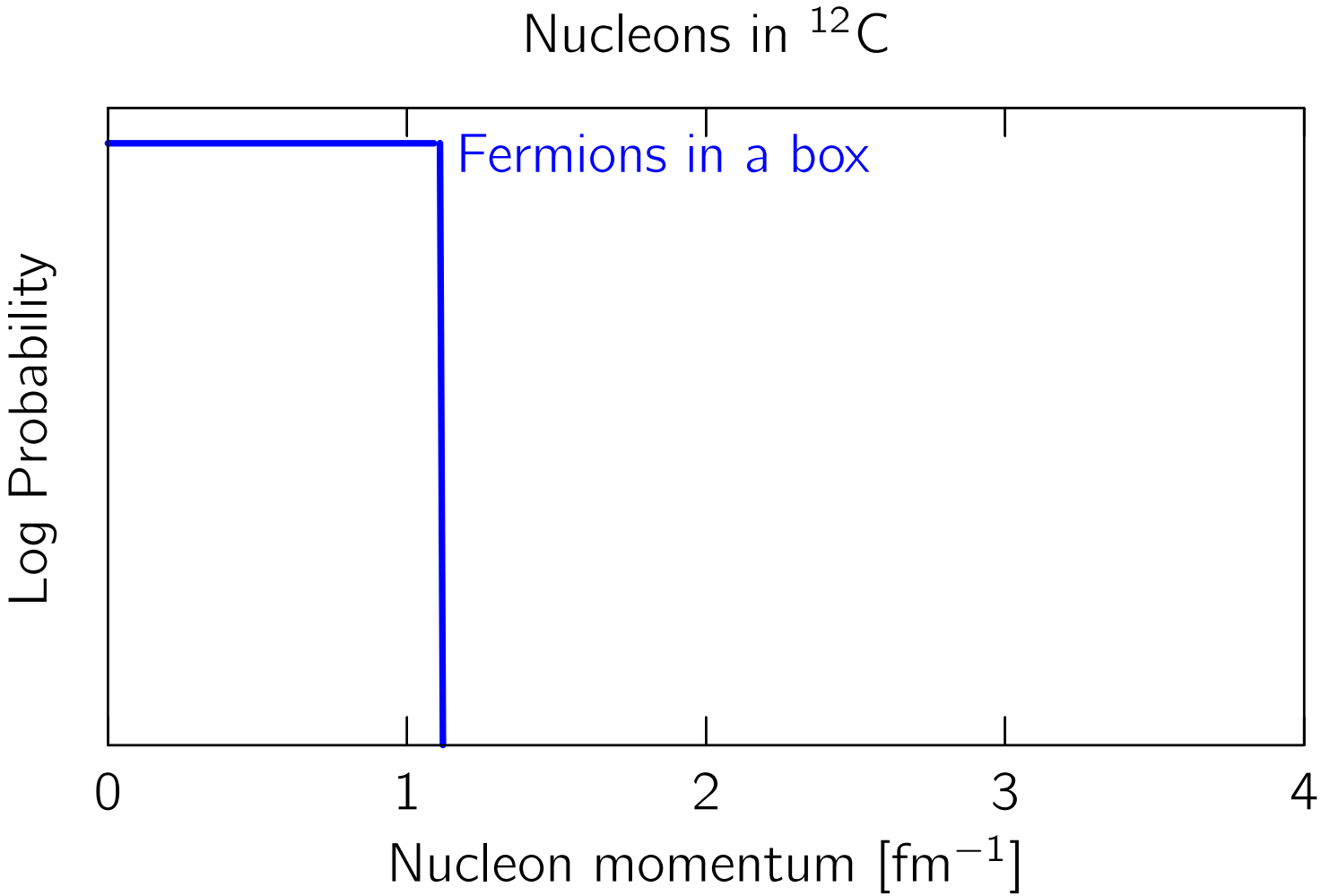


^{17}O Nucleus

Pauli-exclusion leads to "Fermi momentum."



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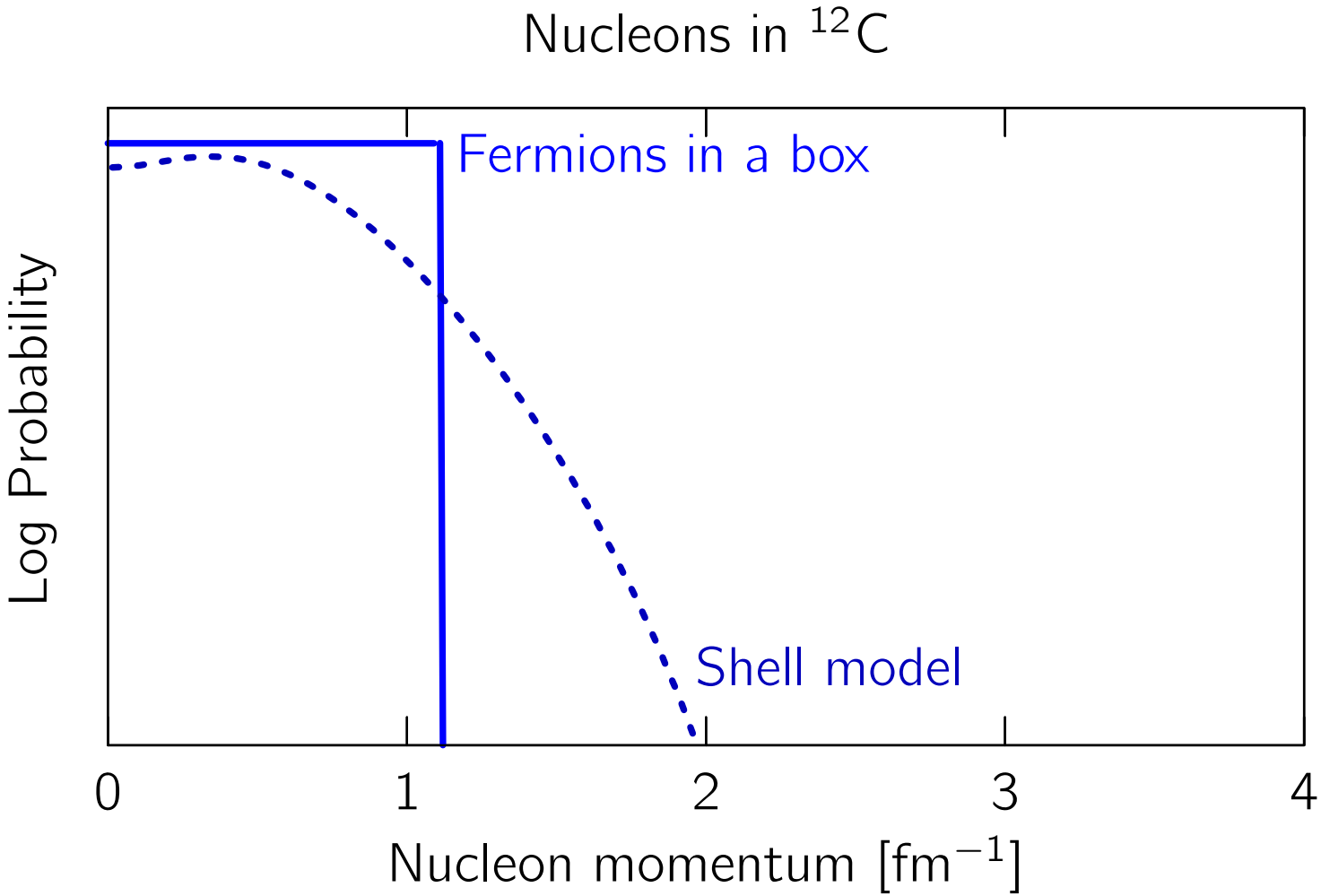

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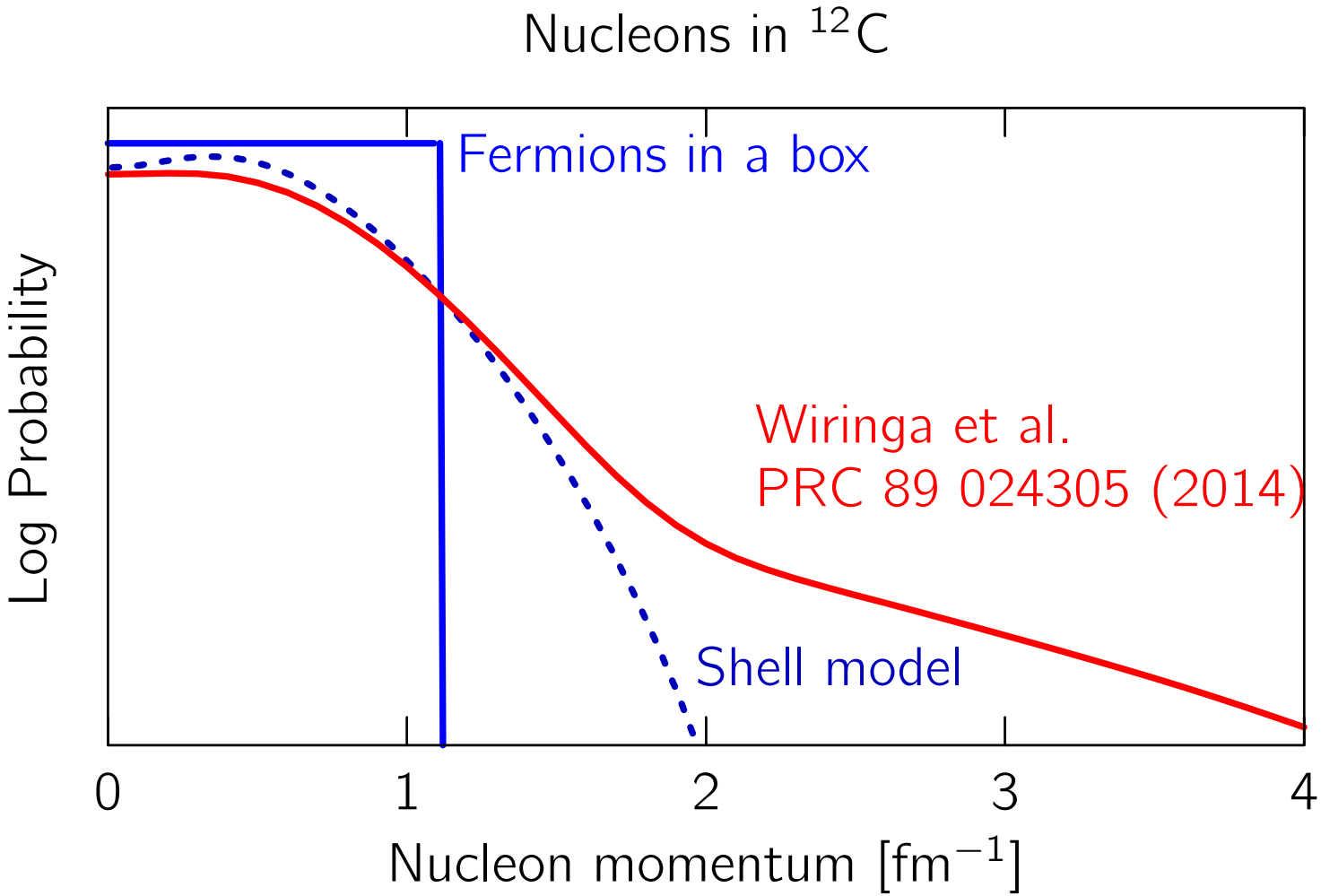

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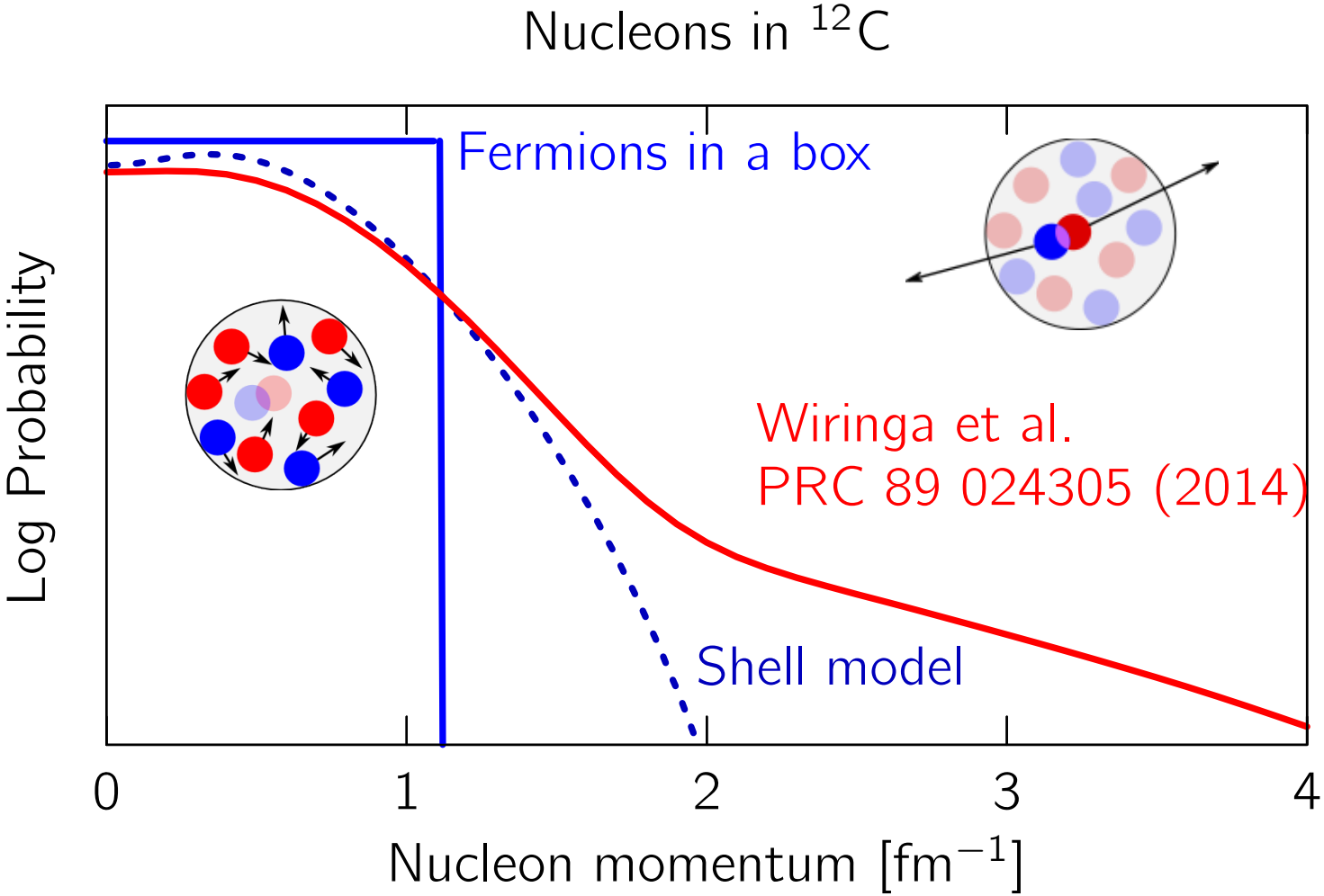
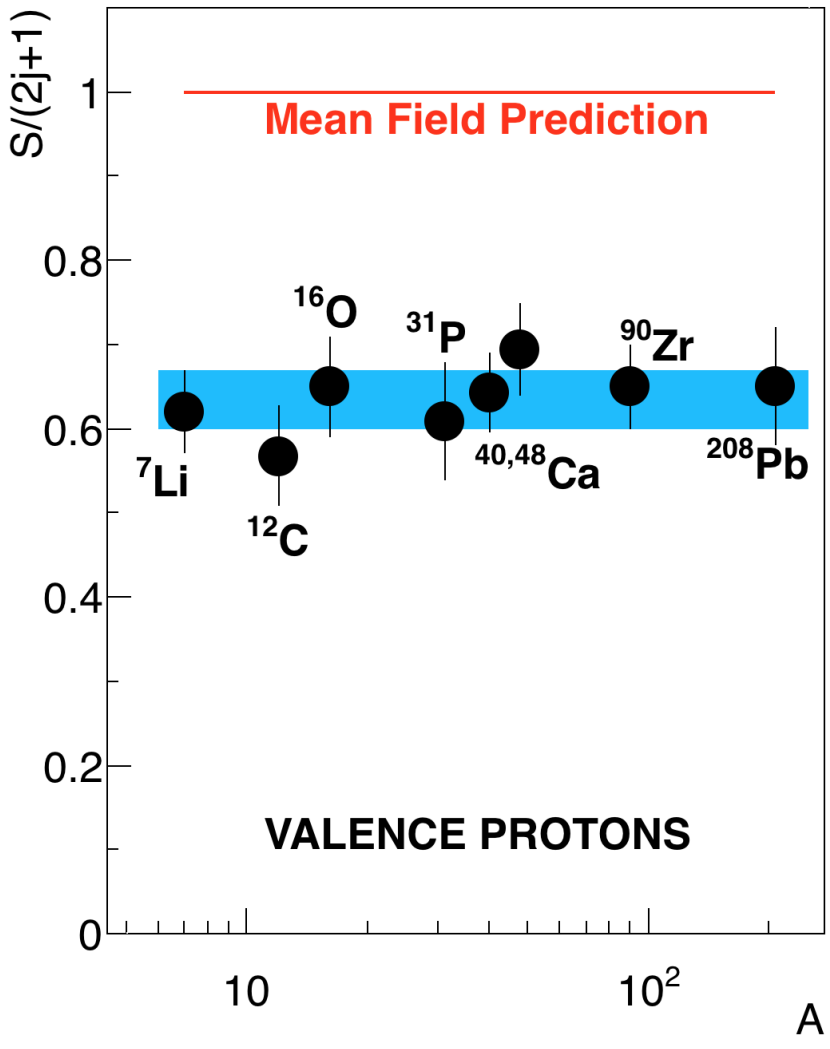


Evidence for short-range correlations (SRCs)

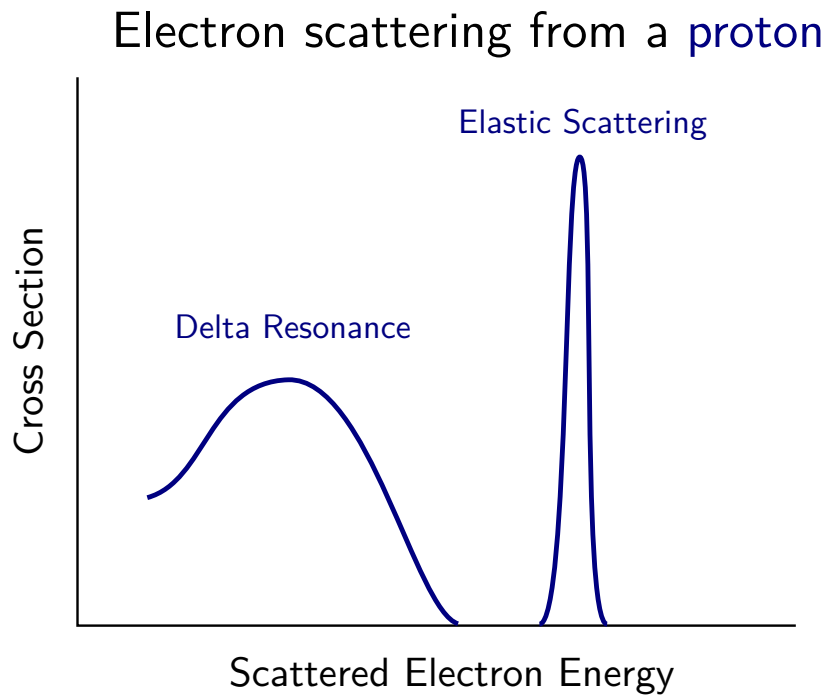
- Depletion of shell-model orbitals

Reproduced based on (Lapikas, 1993)



Evidence for short-range correlations (SRCs)

- Depletion of shell-model orbitals
- Quasi-elastic electron scattering



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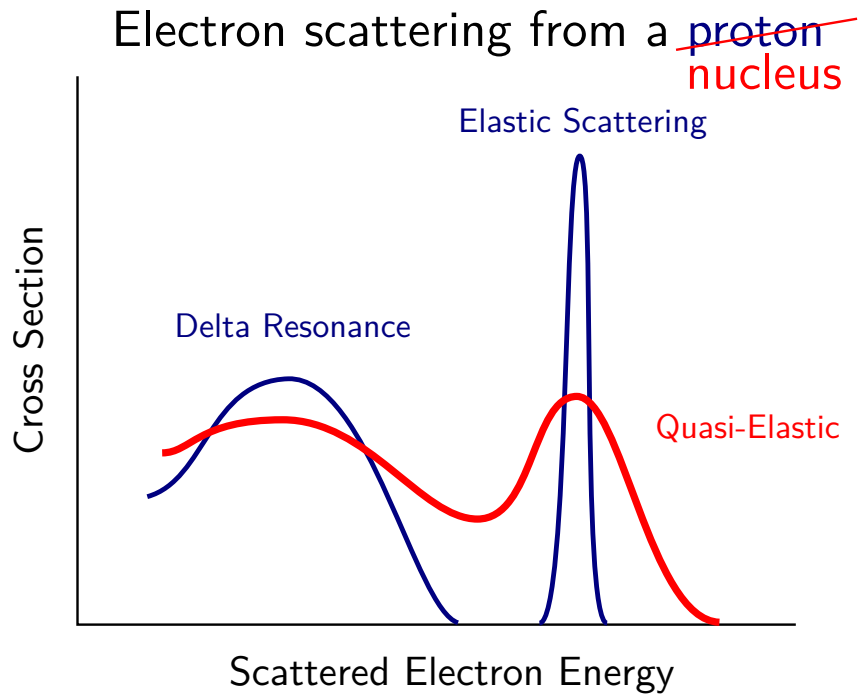

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- Depletion of shell-model orbitals
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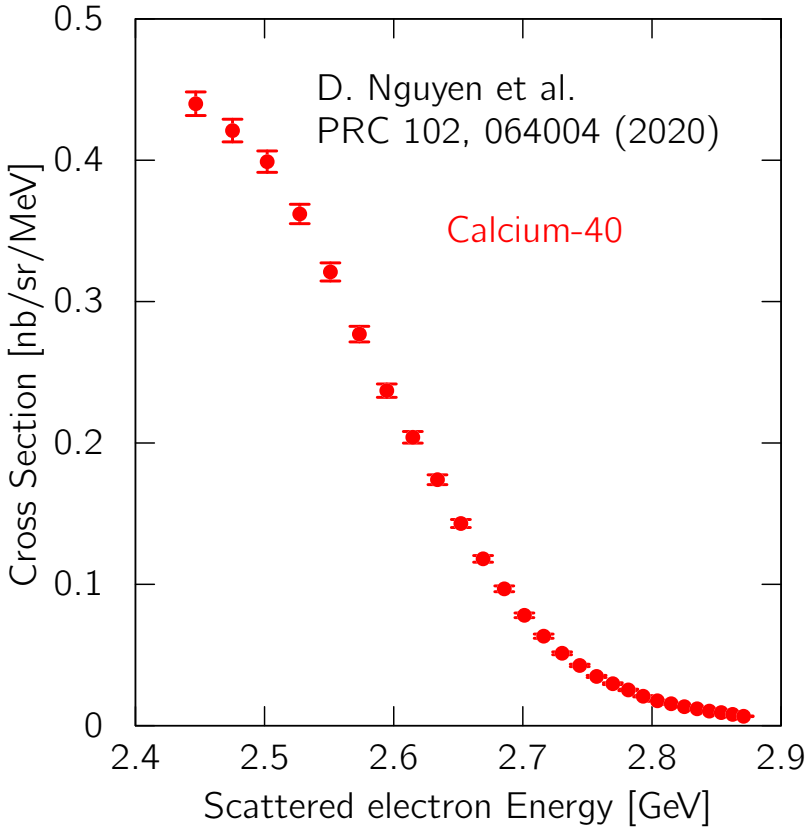
  - High-momentum tails



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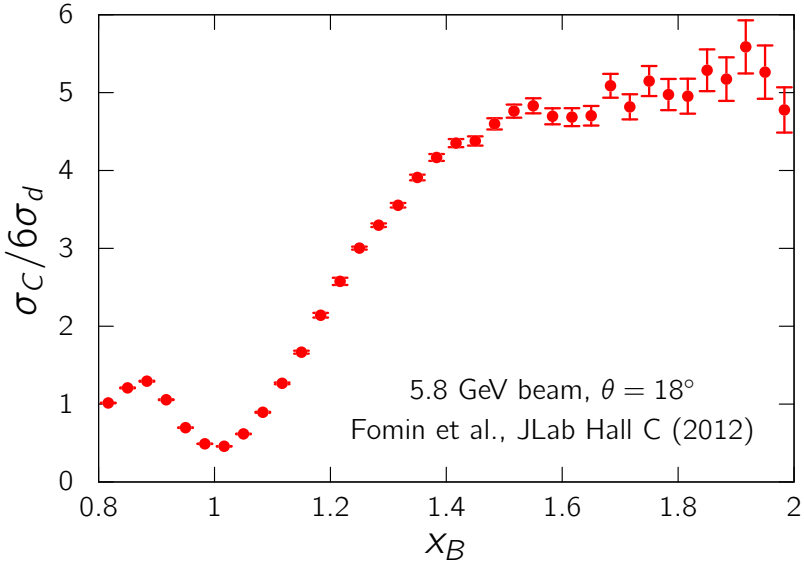

Evidence for short-range correlations (SRCs)

- Depletion of shell-model orbitals
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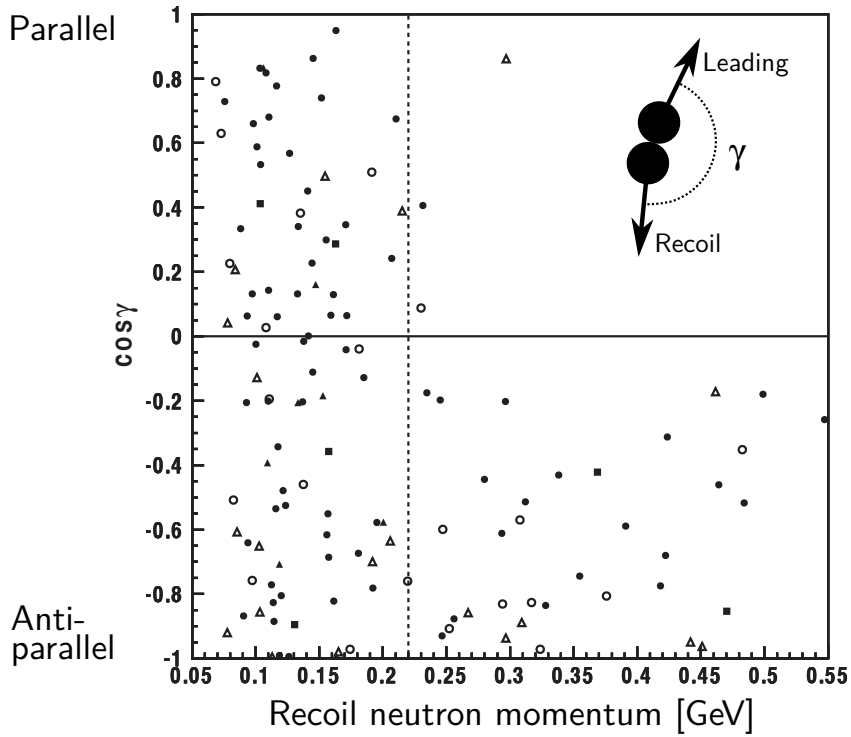
- Correlated emission



Piasetzky et al., PRL (2006)

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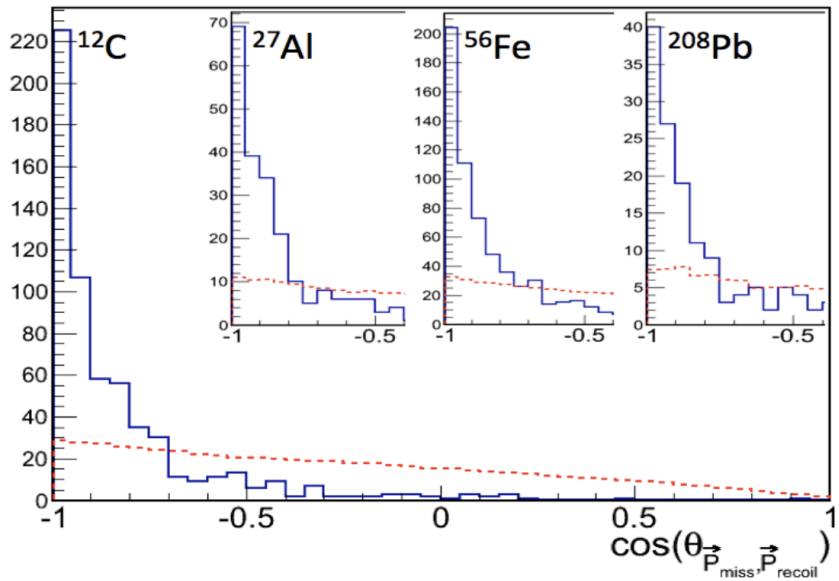

Hen et al., Science (2014)

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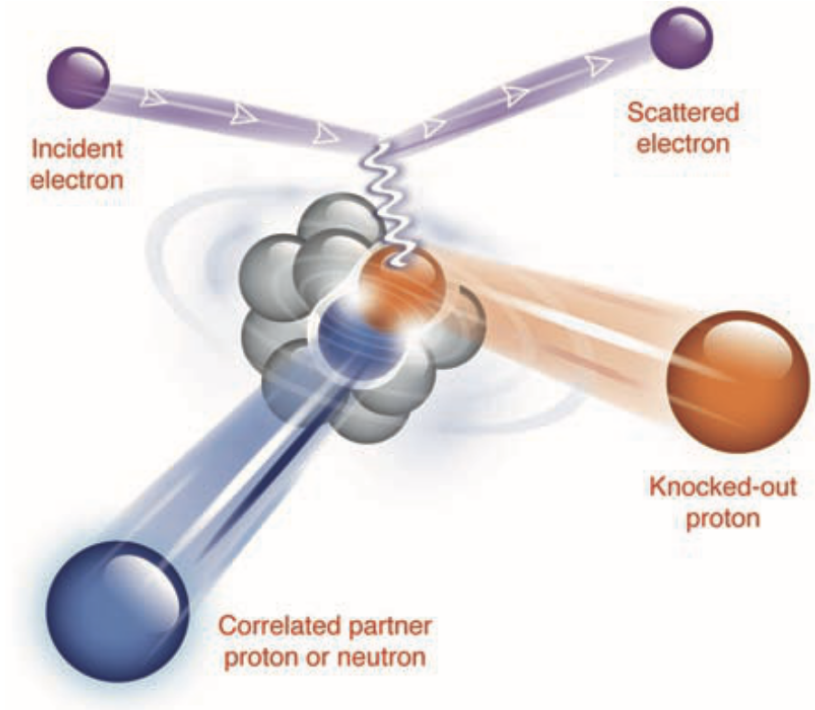
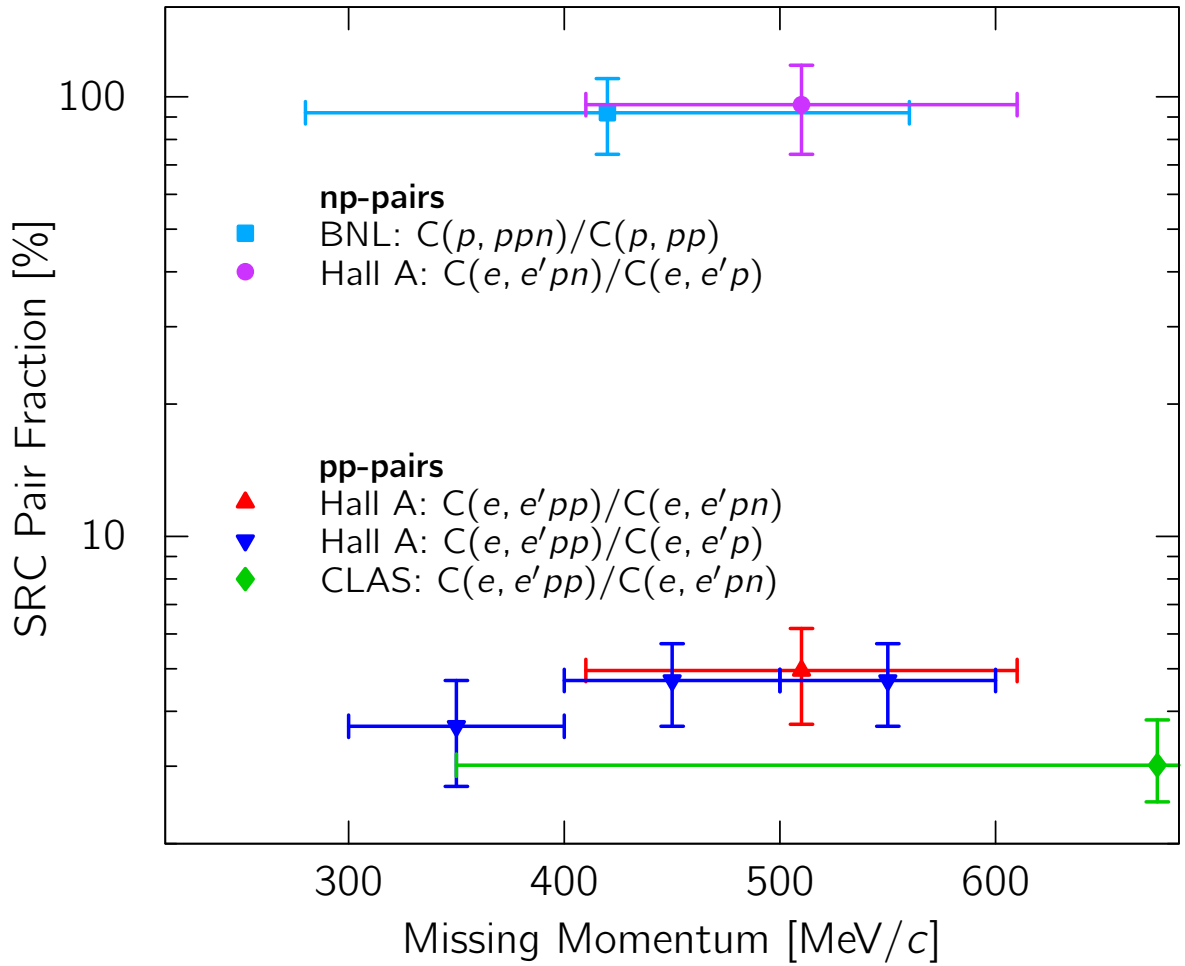


Subedi et al., Science (2008)

SRC pairs are predominantly $T = 0, S = 1$, i.e., *np*-dominance



Arrington, Fomin, **Schmidt**, Ann.Rev.Nucl.Part.Sci. (2022)

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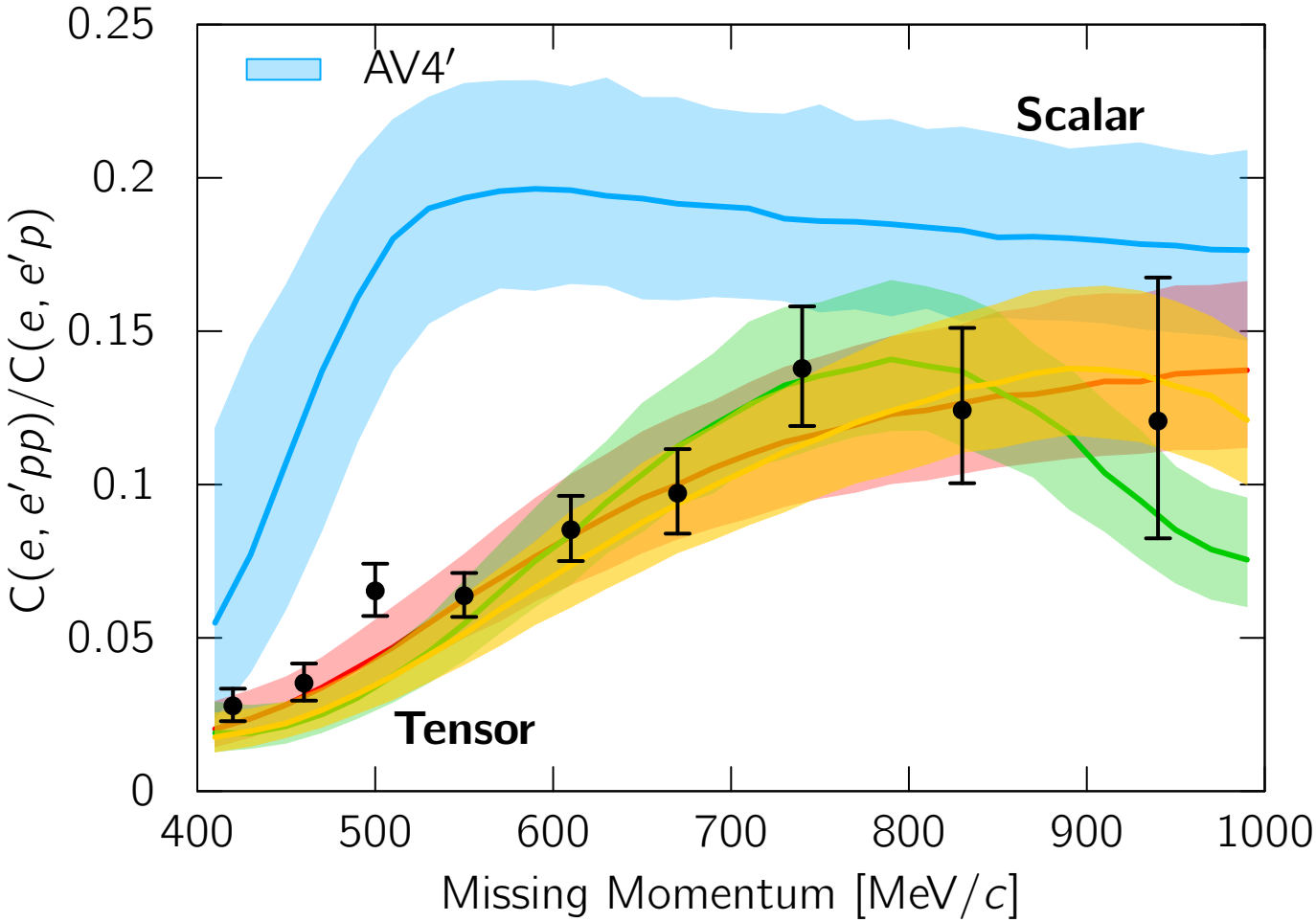
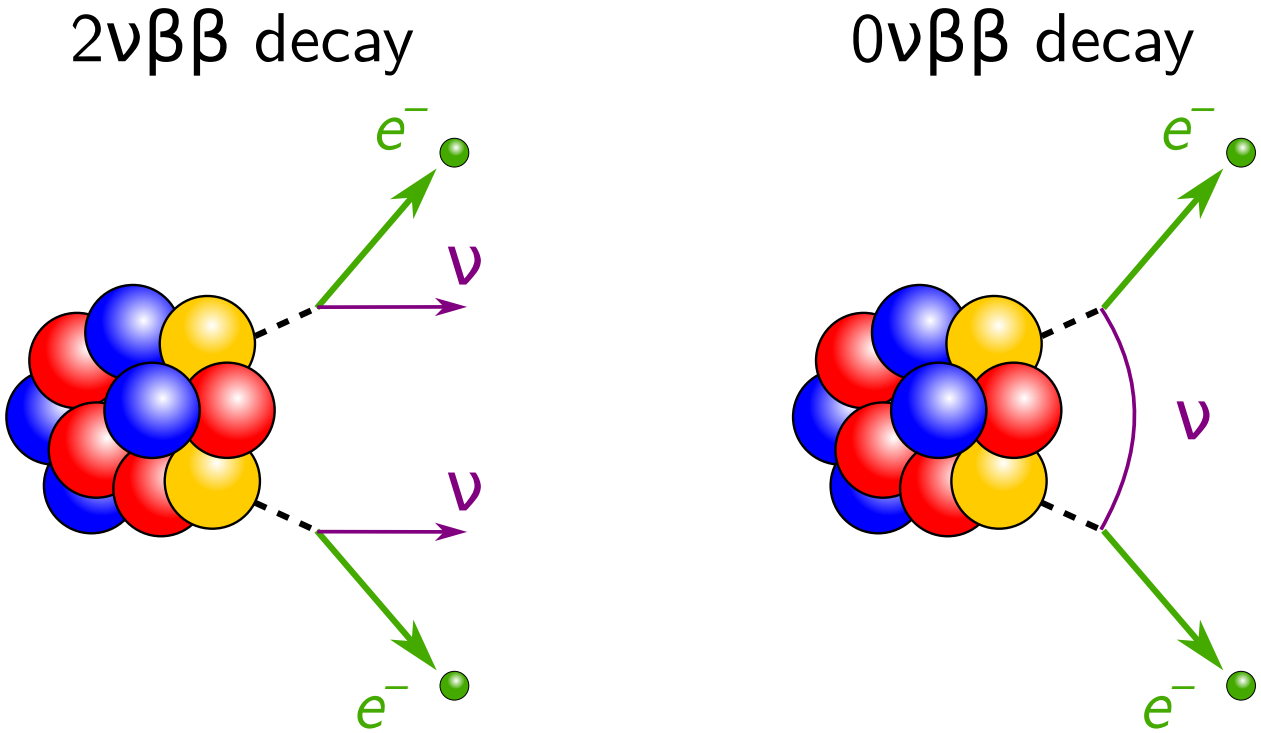


Schmidt et al., Nature (2020)

There is still much we do not know about SRCs

1. What are the mechanisms by which correlations form?
   - Which nucleons are correlating?
2. How do correlations depend on nuclear mass, p/n asymmetry?
   - Do *np* pairs still predominate in very neutron-rich nuclei?
3. What about 3N correlations?
   - Or 4N?
4. *How universal are our findings?*
   - Can they be corroborated in other scattering reactions?

SRCs affect double beta decay matrix elements.



See e.g. M. Agostini et al., RMP 95, 025002 (2023)

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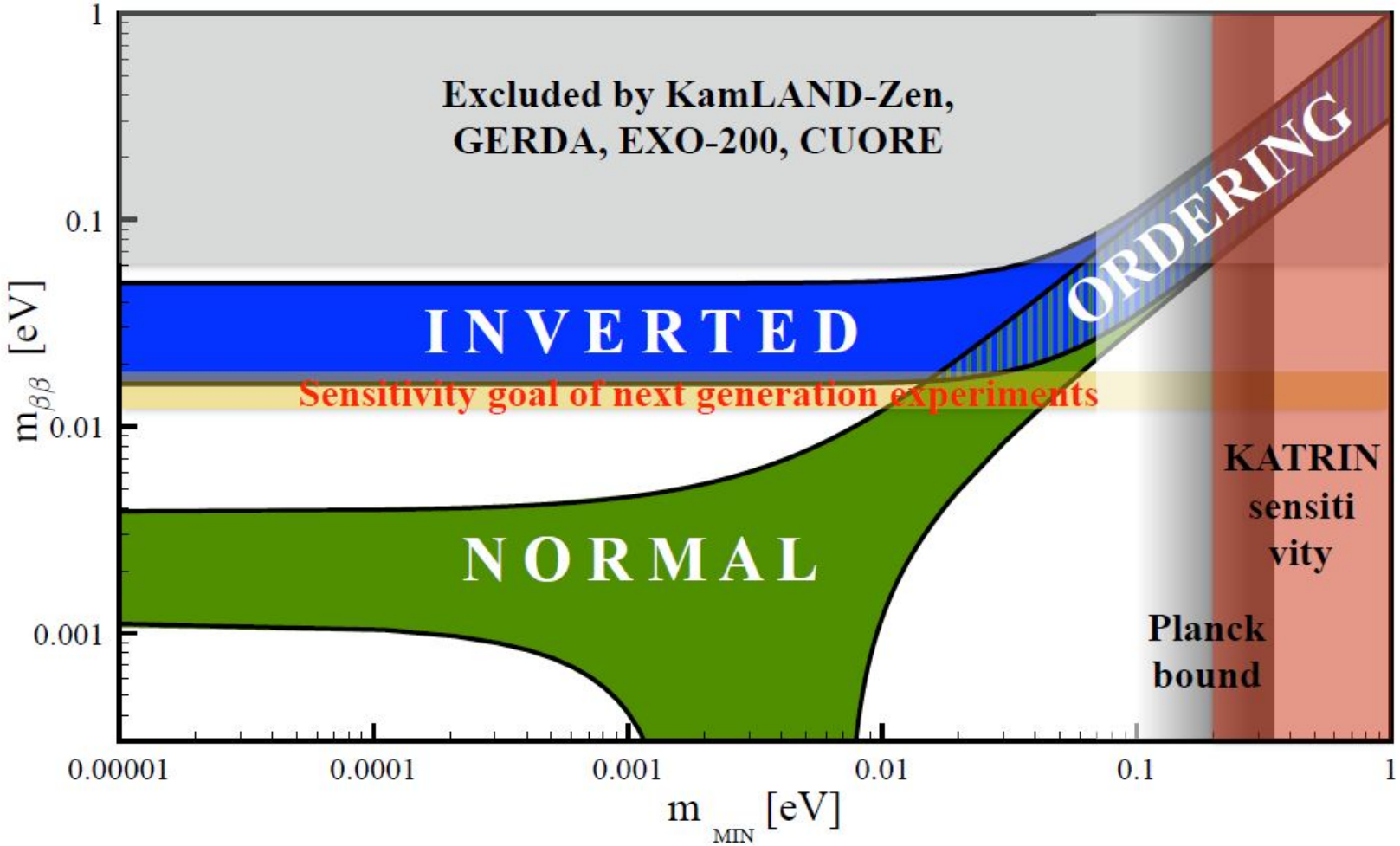
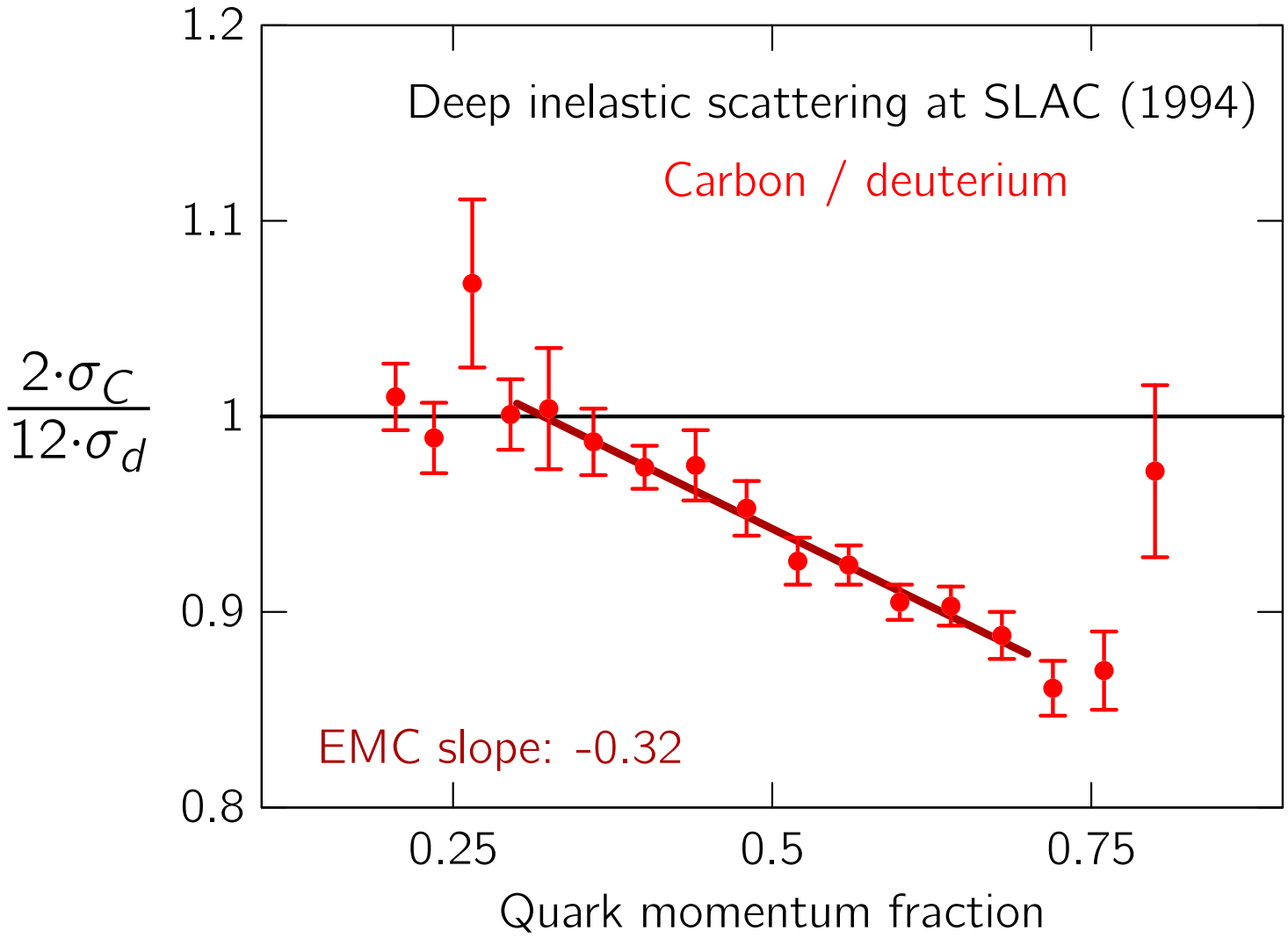


2020 Double Beta Decay APPEC Committee Report

SRCs may be driving the EMC Effect.



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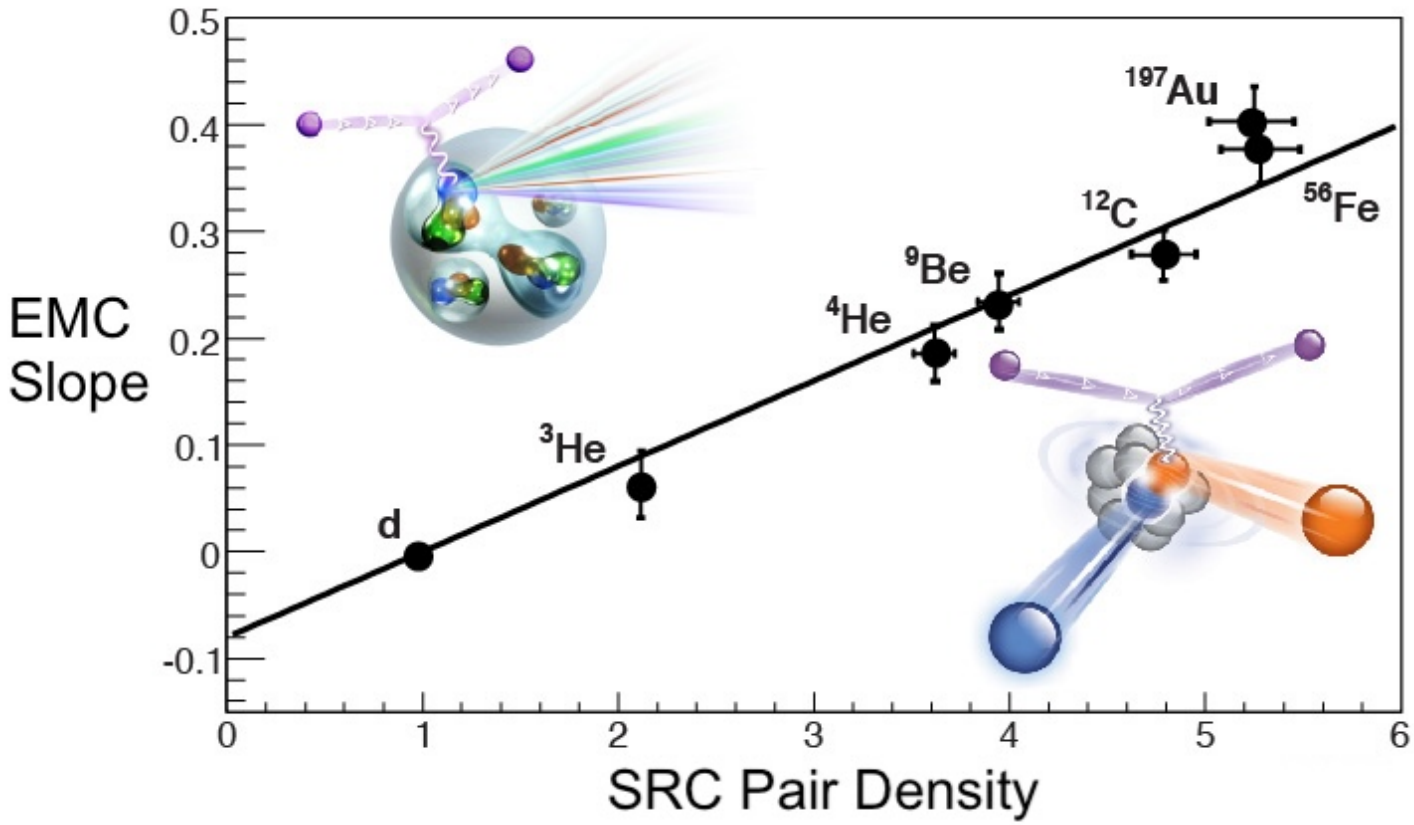

L. B. Weinstein et al., PRL 106, 052301 (2011)

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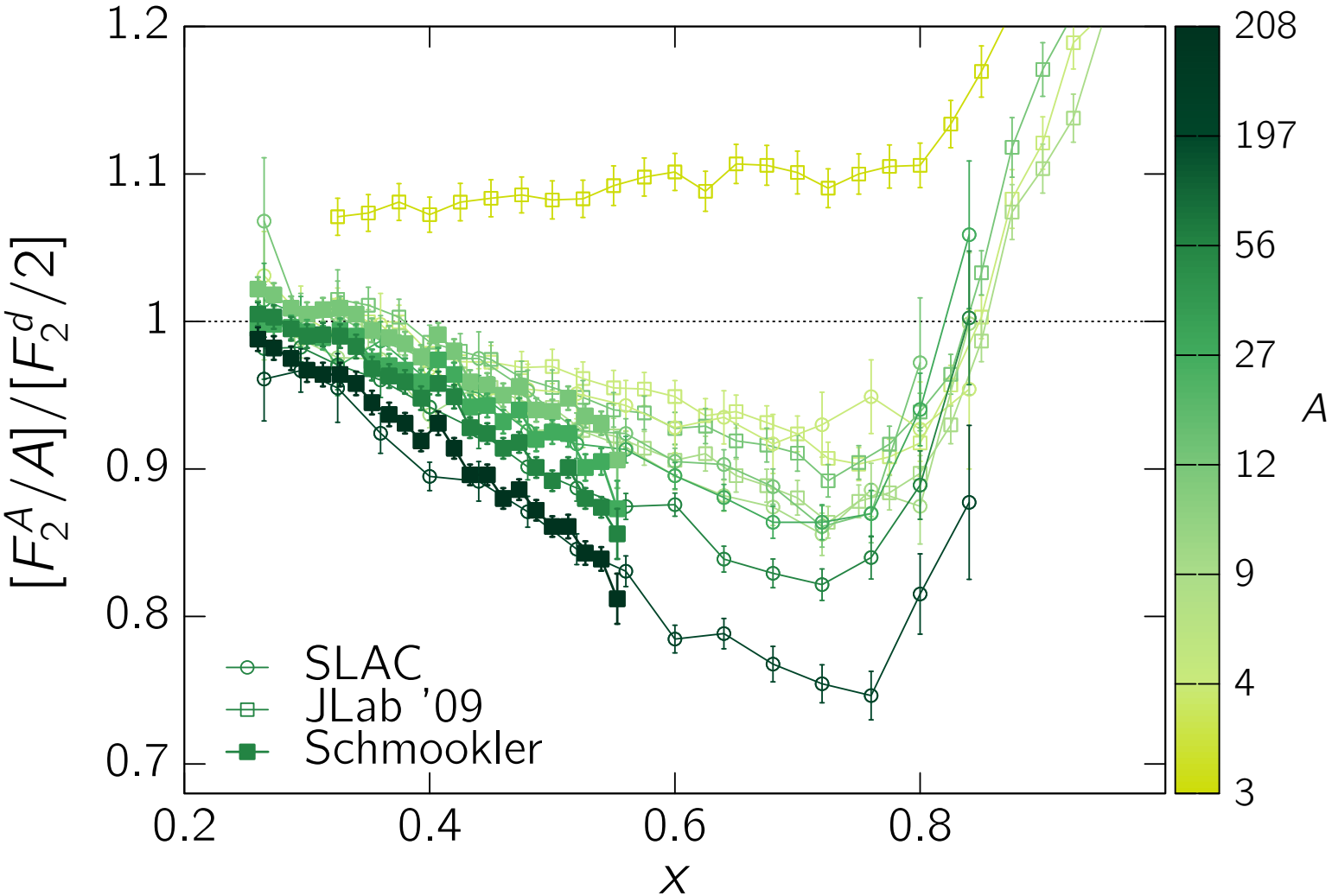

B. Schmookler, M. Duer, A. Schmidt et al., Nature (2019)

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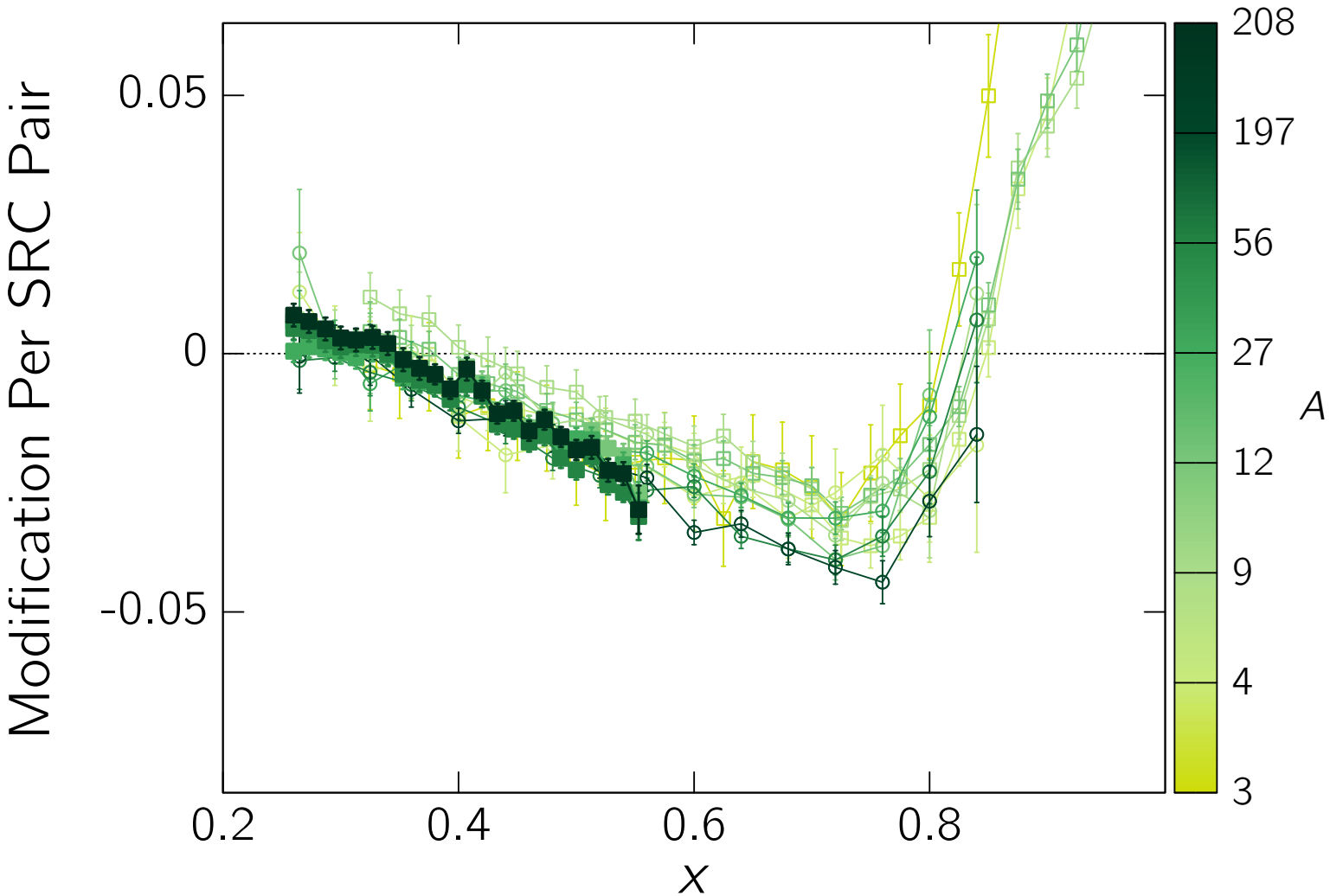
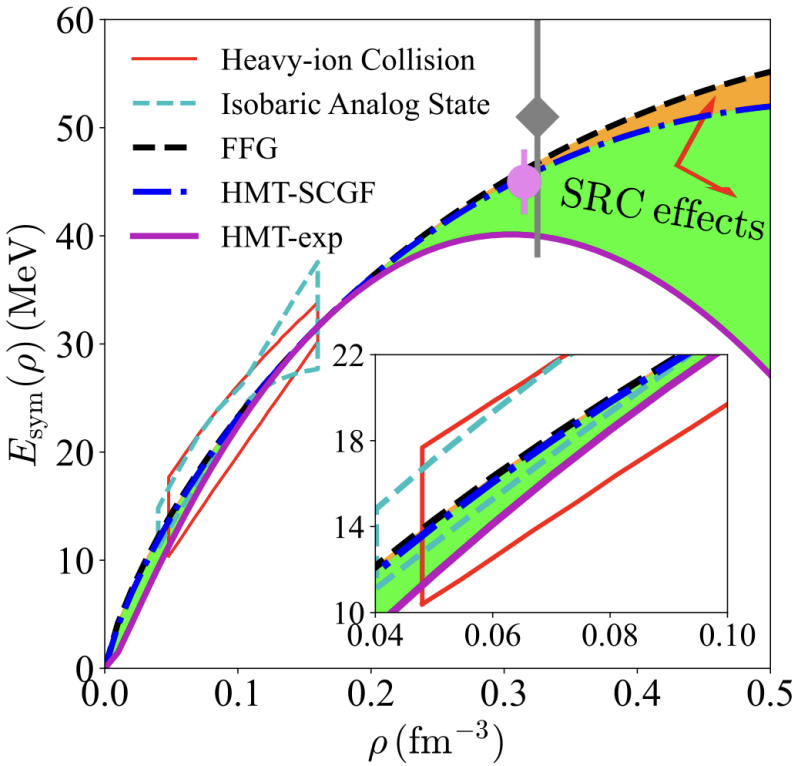
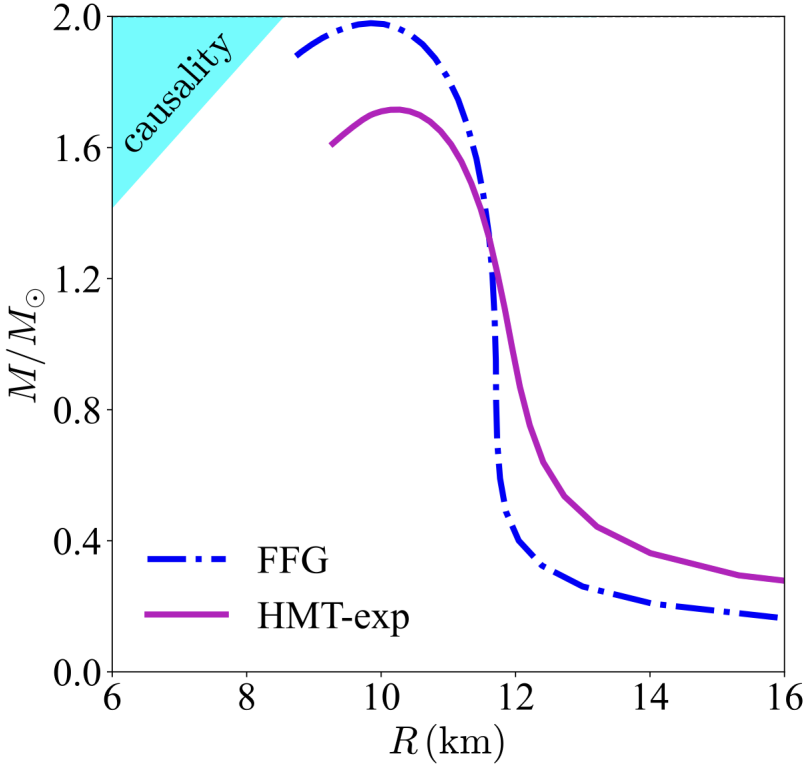


B. Schmookler, M. Duer, A. Schmidt et al., Nature (2019)

SRCs affect nuclear matter equation of state.





B.-J. Cai, B.-A. Li, Y.-G. Ma, arXiv:2512.04206

Answering these questions requires a team effort.

Some of my collaborators

- Or Hen, MIT
- Tyler Kutz, Mainz
- Dien Nguyen, Tennessee
- Eli Piasetzky, Tel Aviv
- Holly Szumila-Vance, Florida Intl.
- Larry Weinstein, Old Dominion
- Jefferson Lab
  - Dave Gaskell
  - Florian Hauenstein
  - Doug Higinbotham
  - Sasha Somov

Additional JLab experiments led by:

- John Arrington, LBL
- Nadia Fomin, Tennessee
- Burcu Duran, New Mexico State

Experiments around the world

- Tom Aumann, GSI
- Maria Patsyuk, JINR
- Zhihong Ye, Tsinghua/HIAF
- Satoru Terashima, RCNP

My group at George Washington University

Prof. Axel Schmidt

Dr. Marshall Scott

Phoebe Sharp

Sara Ratliff

Olivia Nippe-Jeakins

Prof. Bill Briscoe

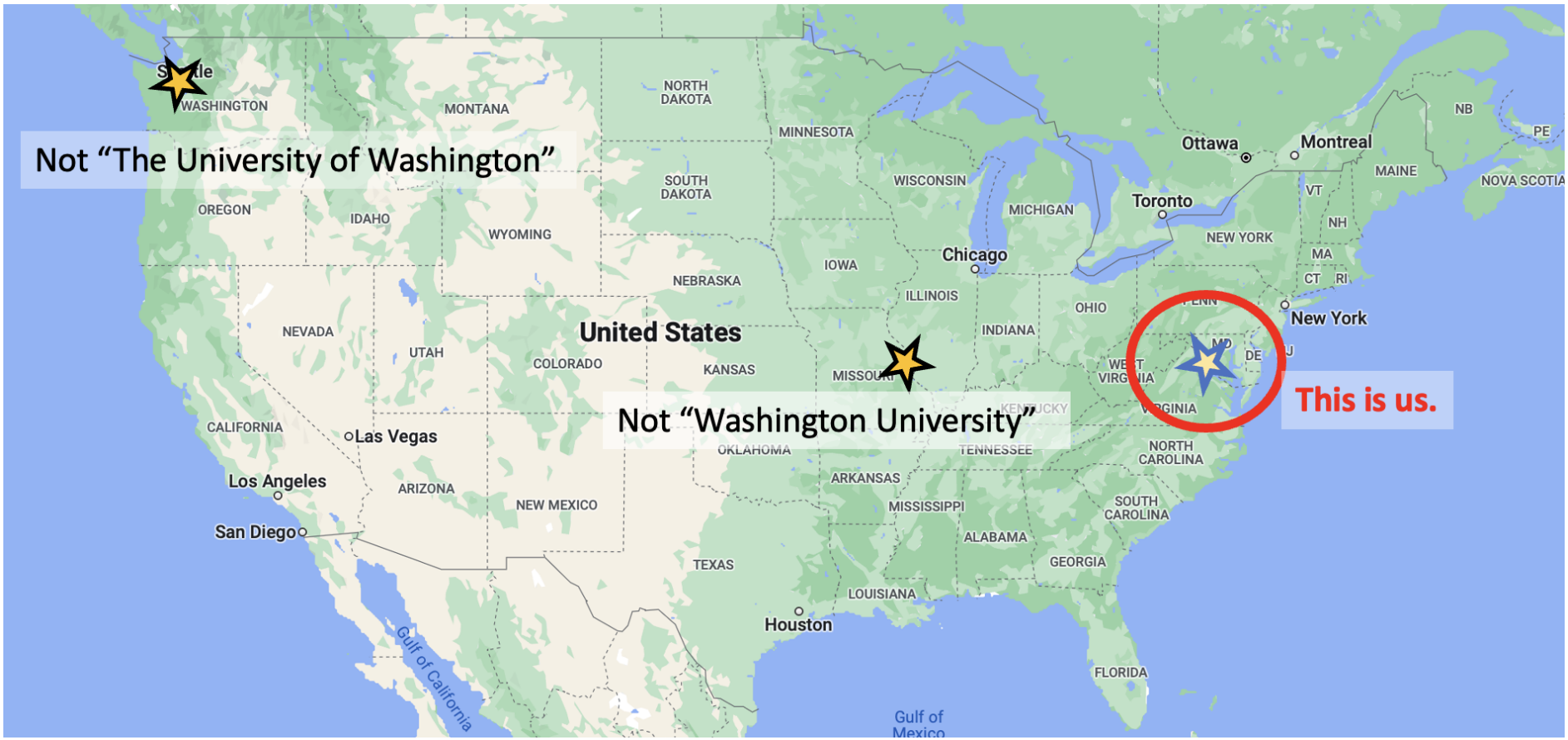
Prof. Igor Strakovsky

Payton Arber

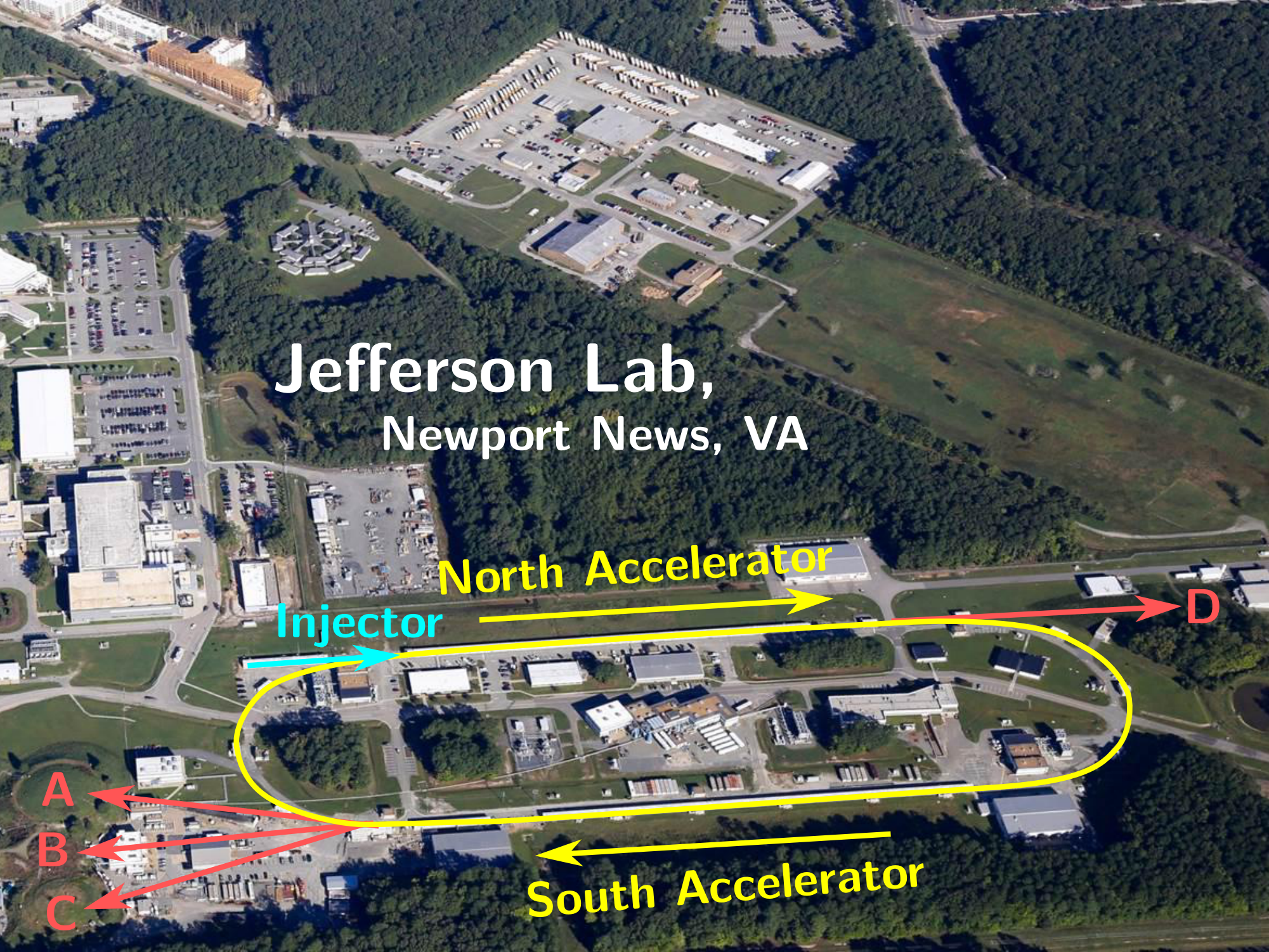
August Friebolin

Marlena Pegolo

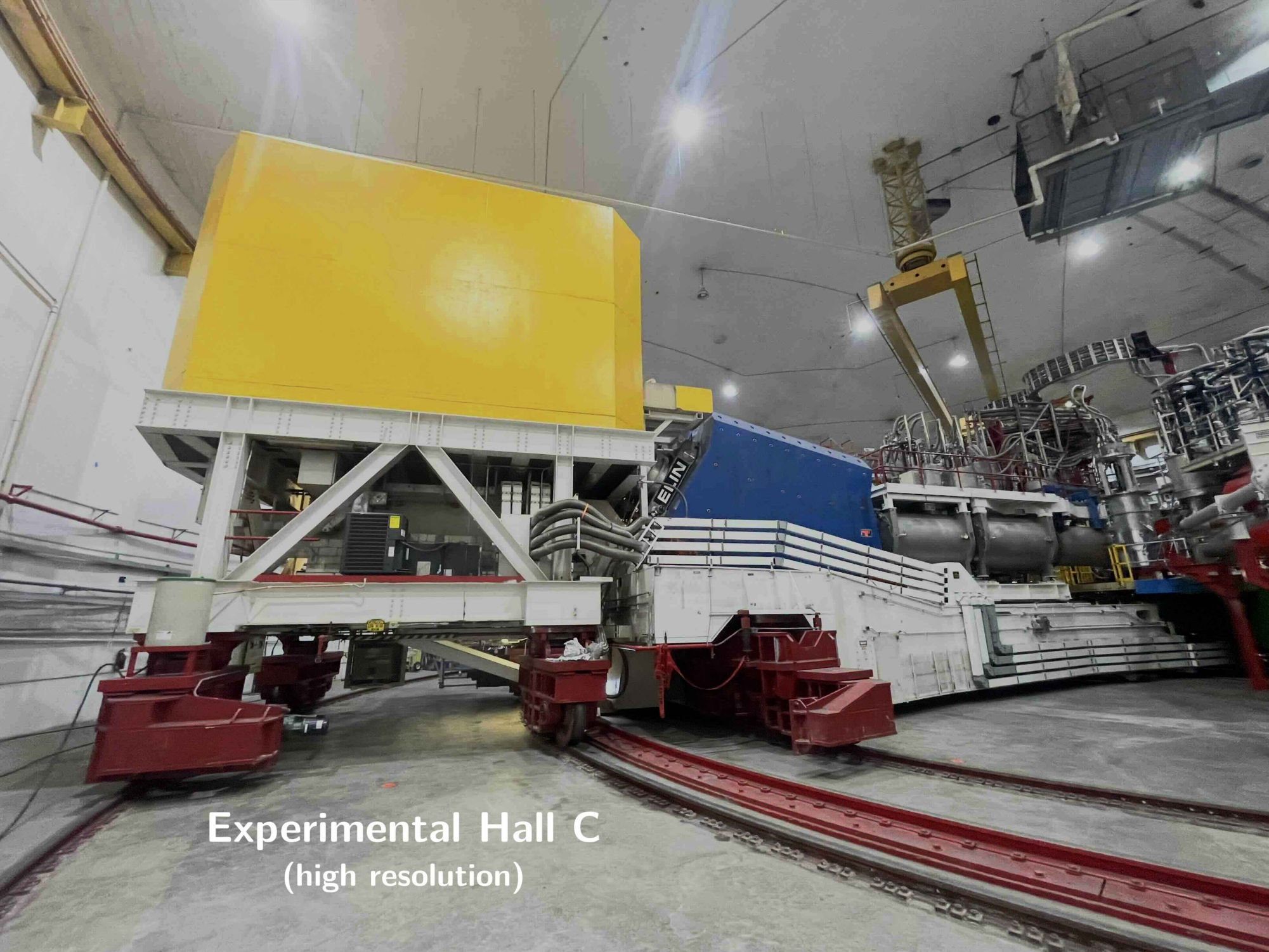
George Washington University in Washington, DC



George Washington University in Washington, DC


Jefferson Lab,
Newport News, VA
North Accelerator
Injector
D
A
B
C
South Accelerator


Experimental Hall B
(large acceptance)



Experimental Hall C

(high resolution)

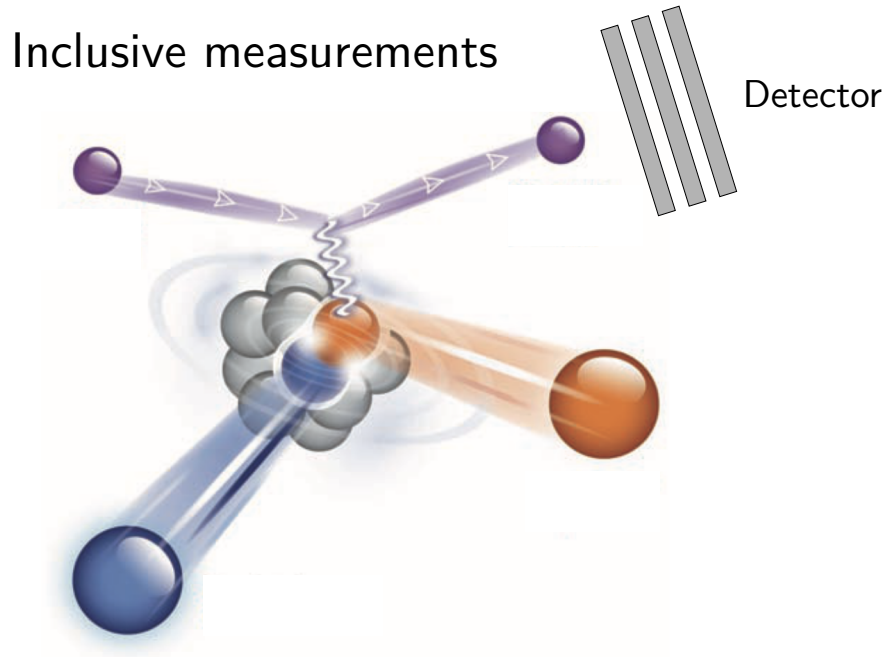

Experimental Hall D
(photo-production)

In my talk today:

1. Preliminary Results from the CaFe Experiment
   - Cross-shell pairing appears suppressed.
   - Evidence for quantum number selectivity.

2. Recently conducted experiments
   - Hall D SRC/CT Experiment tests universality
   - CLAS12 Run Group M expands available nuclei and stats.
   - BAND/LAD test the SRC-EMC connection

There are two general approaches for studying SRCs in e^- scattering.



Pros:

- Higher rates
- Minimal FSIs

Cons:

- Little information about struck nucleon.
- Interpretation is not 100% straightforward.

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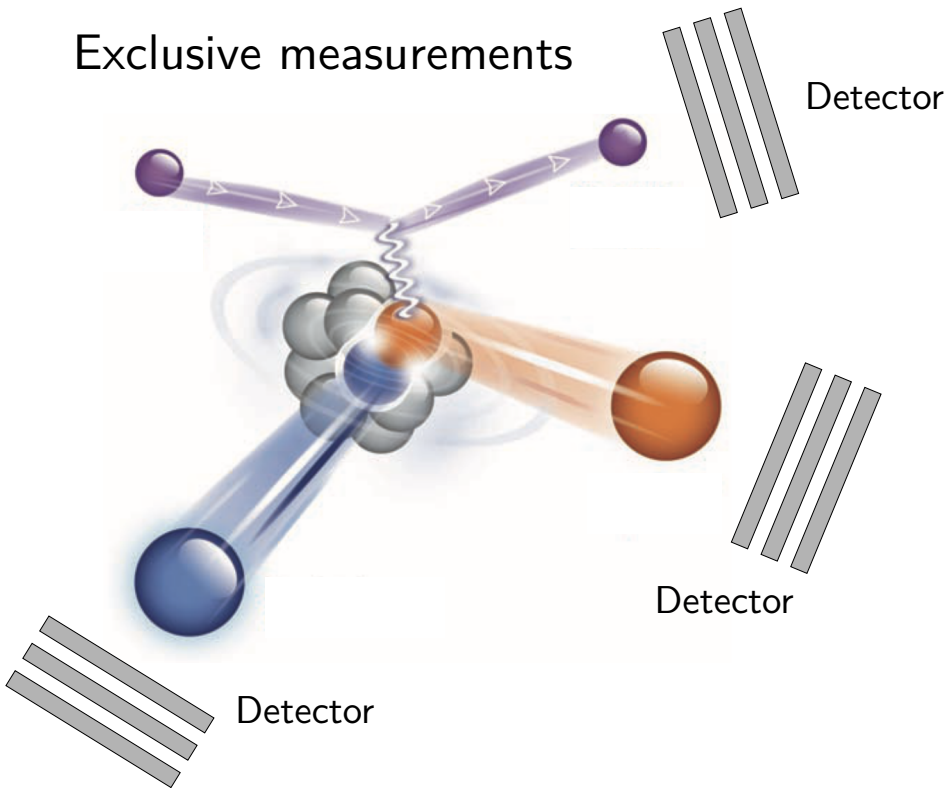


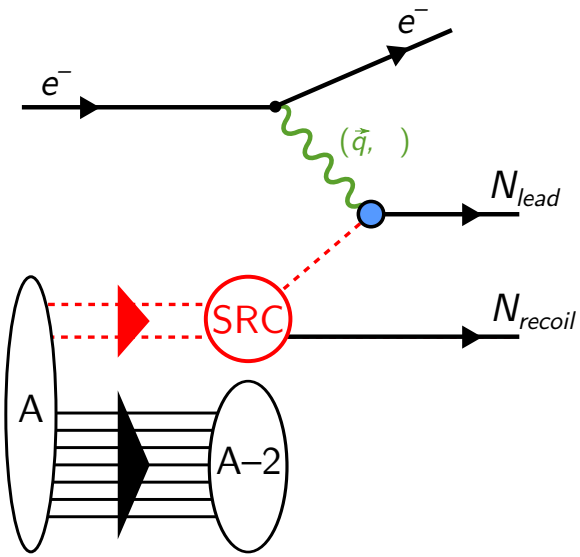
Pros:

- Isospin information
- More info about momentum

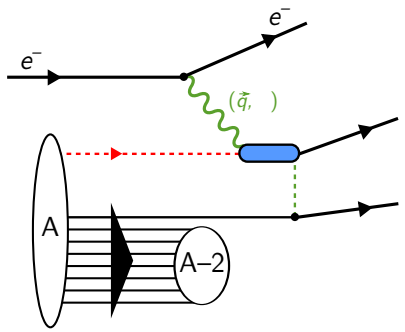
Cons:

- Need large acceptance
- **Final-state interactions.**

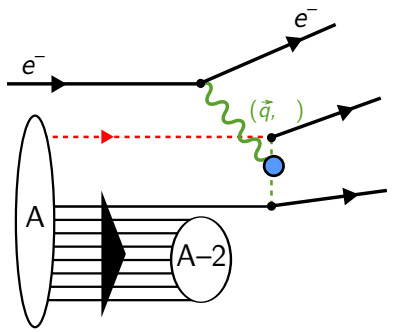
Exclusive measurements are always affected by final state interactions.



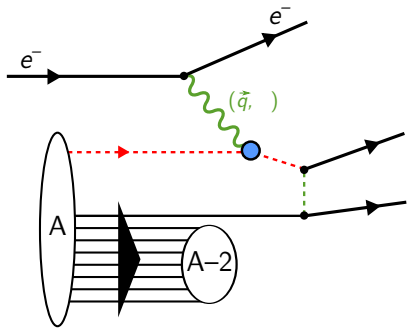
Plane-Wave



Isobar Configurations

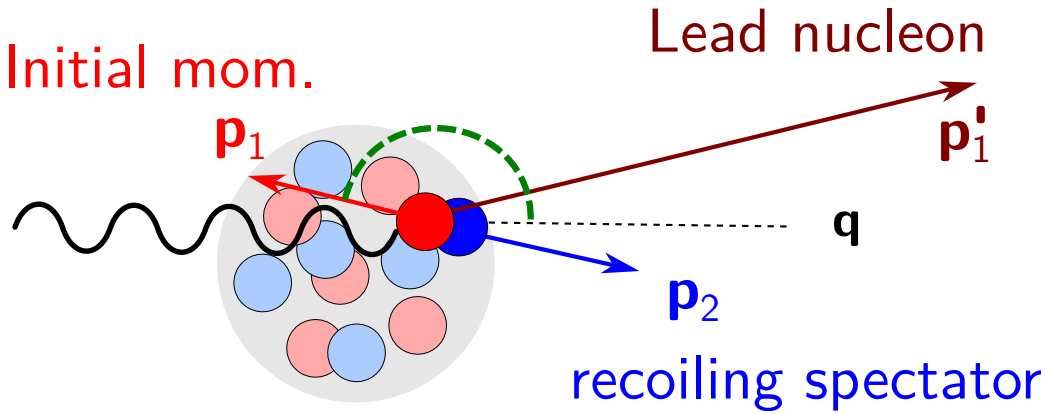


Meson-Exchange Currents



Final State interactions

To reduce the impact of FSIs, measure in anti-parallel kinematics.



Missing momentum

$$\vec{p}_{\text{miss}} \equiv \vec{p}_1' - \vec{q}$$

is a proxy for the initial momentum.

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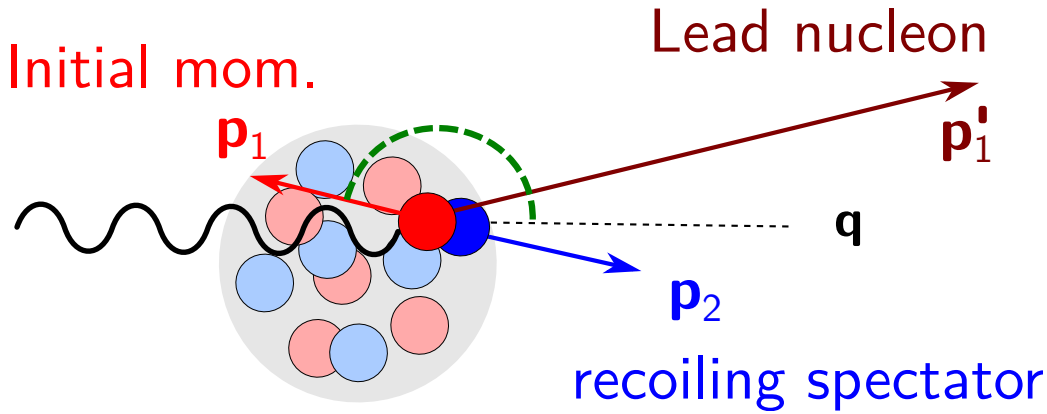

Missing momentum

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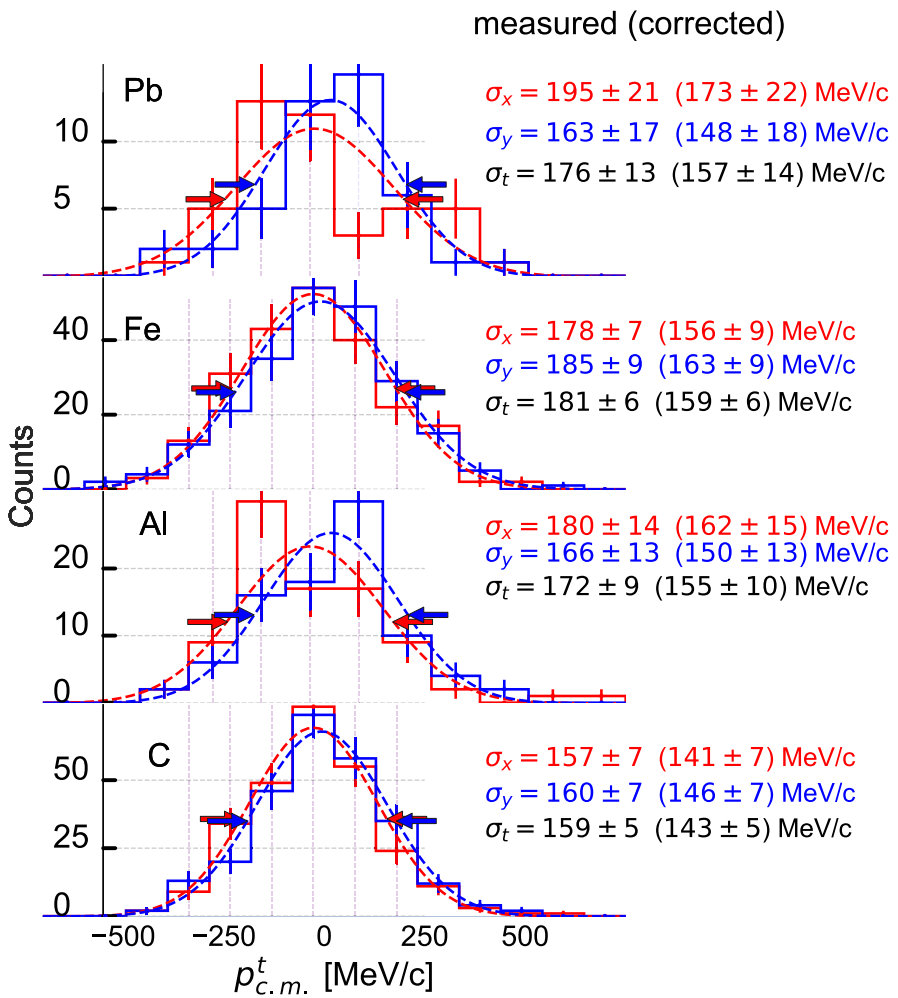
is a proxy for the initial momentum.

In practice:

- $p_{\text{miss}} > k_F$
- $x_B \gg 1$
- Large Q^2
- $\vec{p}_{\text{miss}} \,\uparrow\!\downarrow\, \vec{q}$

Which nucleons are forming pairs?
Can we tell from C.o.M. momentum?



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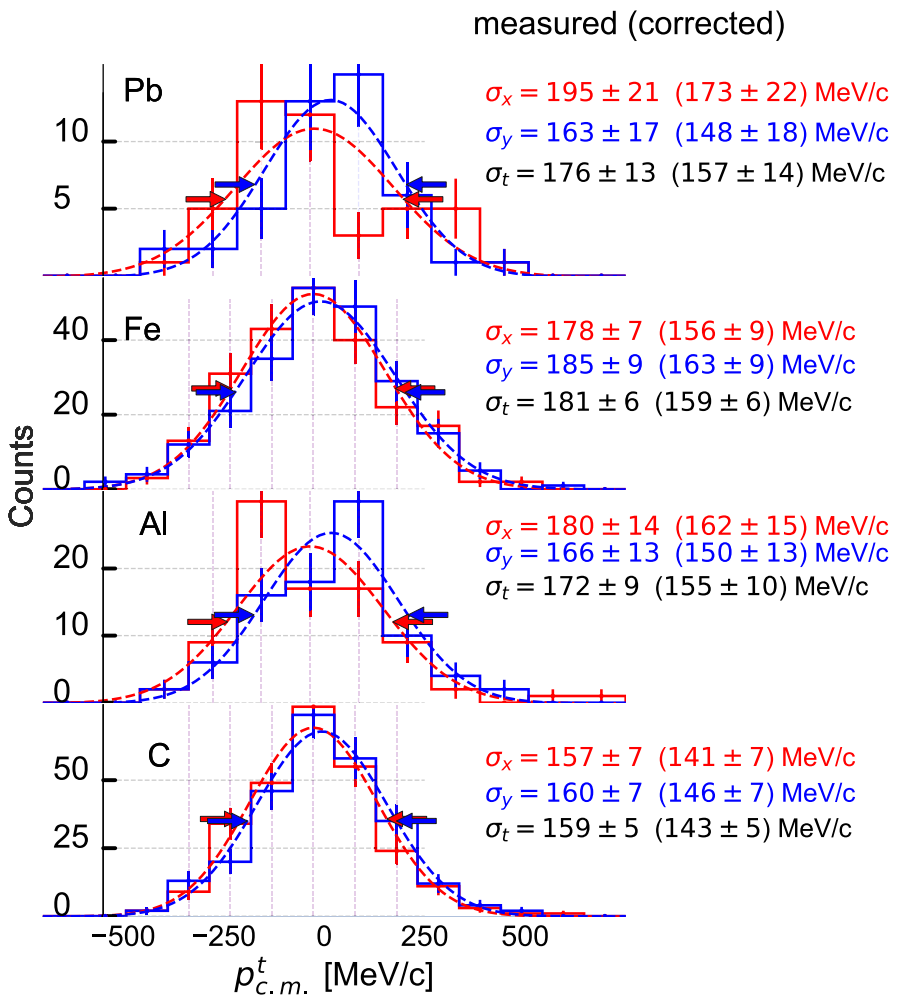
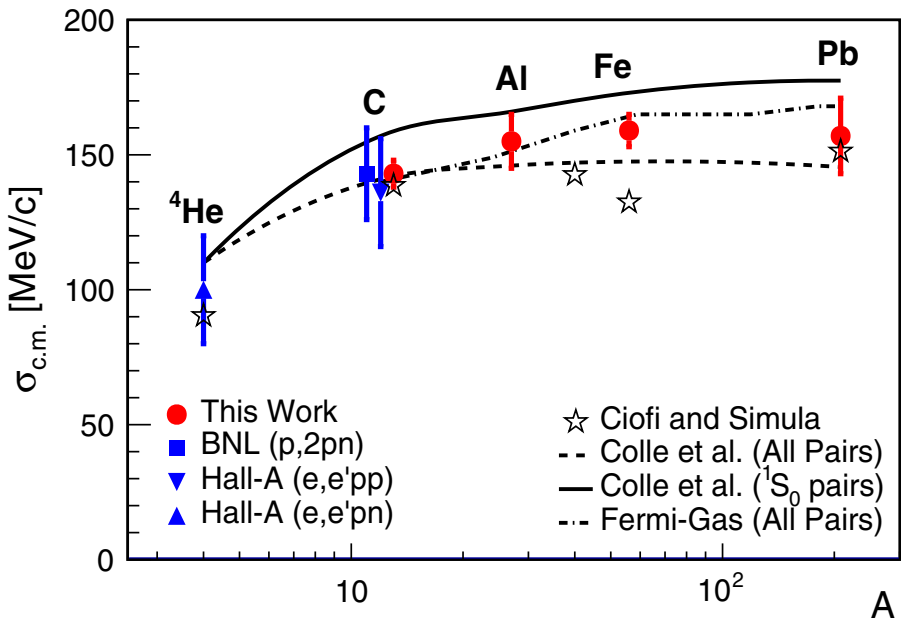
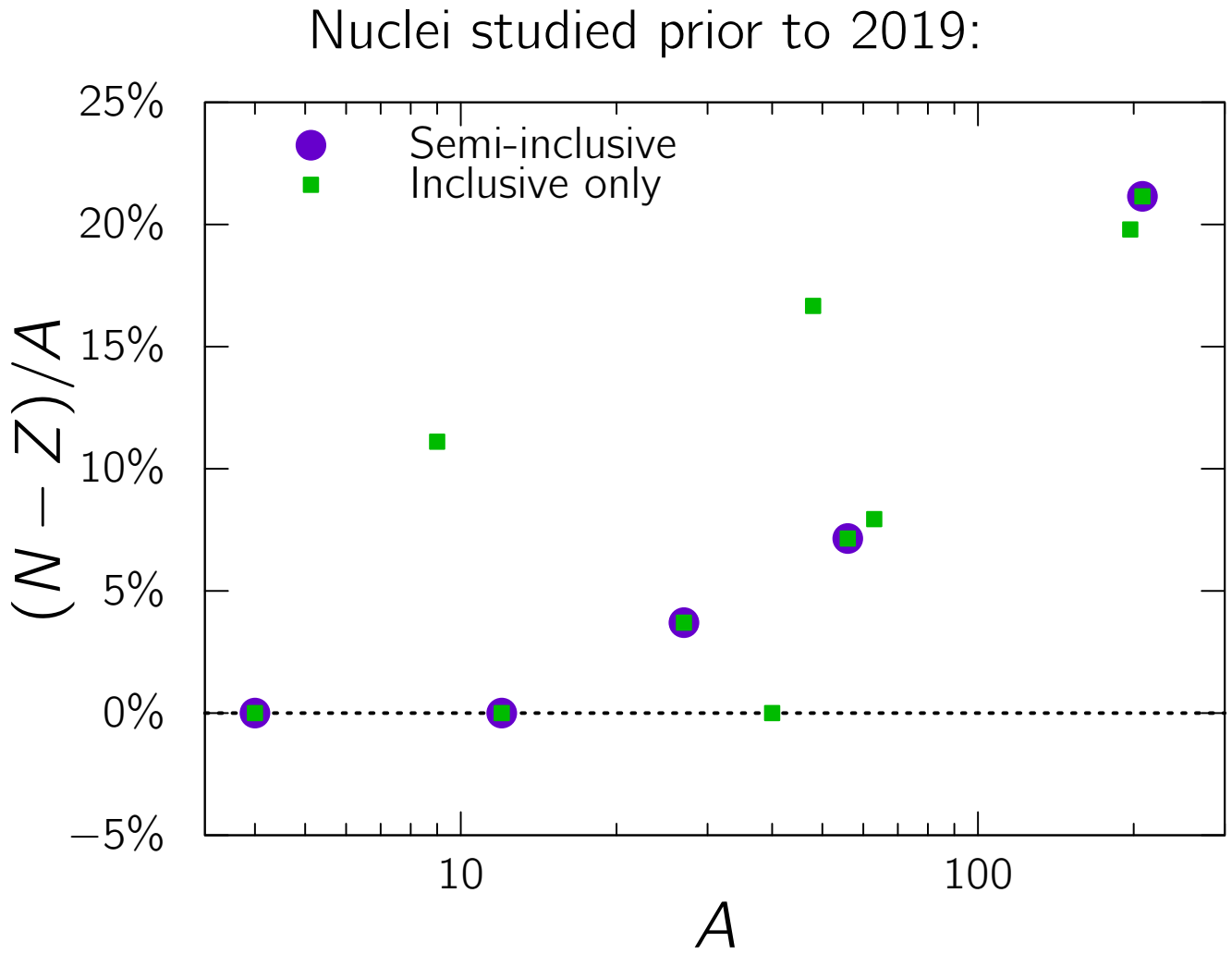




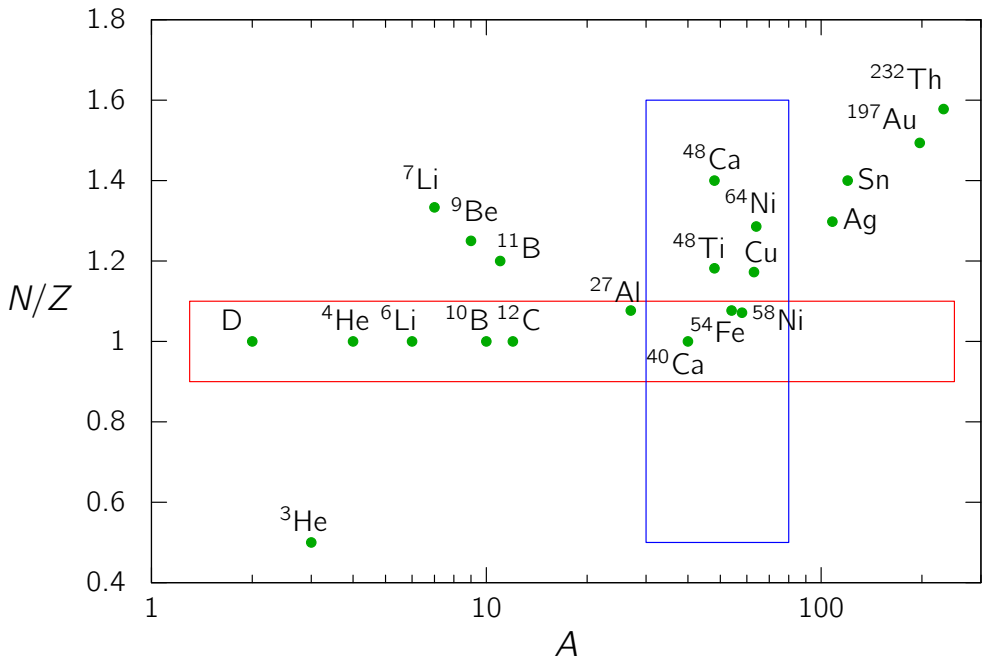
E. O. Cohen et al. (CLAS), PRL 2018

We have lacked a way to disentangle size and asymmetry effects.

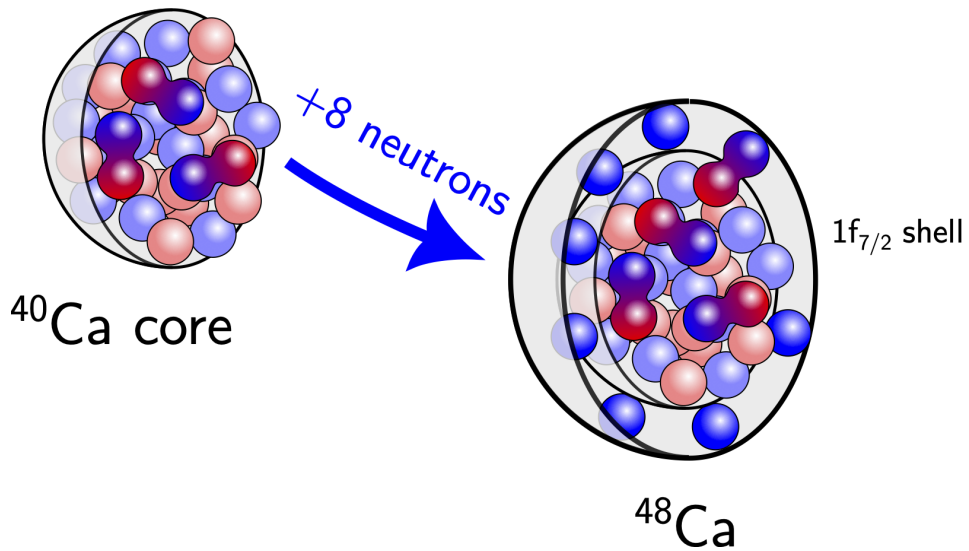


The XEM2 experiment has measured a swath of light and heavy targets.

- Spokespeople: J. Arrington, N. Fomin, D. Gaskell
- 2018, 2019, 2022–23
- JLab Hall C
- Also covering $x_B > 2$



The CaFe Experiment studied ^{40}Ca, ^{48}Ca, ^{54}Fe, to test *pn* pairing across the 1d/1f gap.



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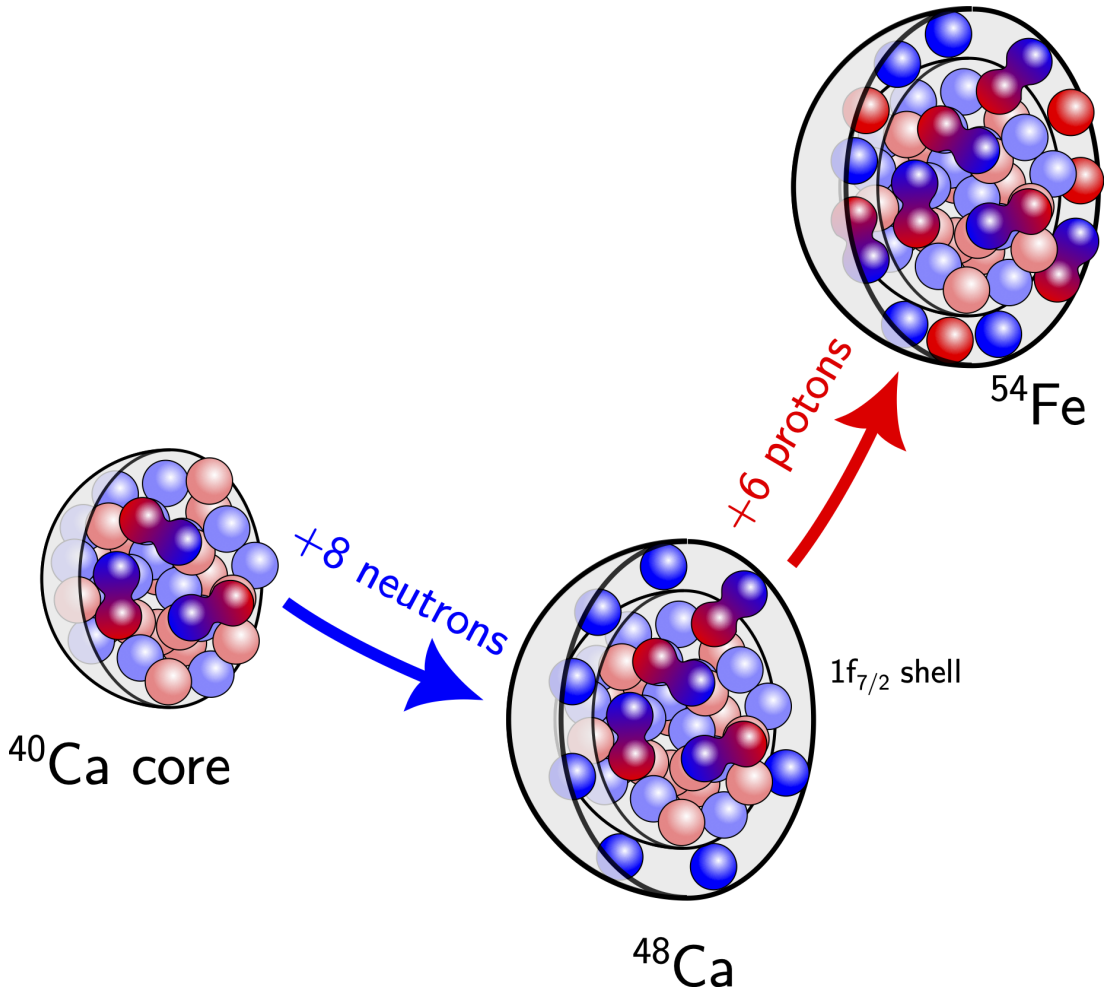

The CaFe Experiment

Jefferson Lab E12-17-005

- Spokespeople: O. Hen,
  L. B. Weinstein,
  D. Higinbotham, F. Hauenstein
- Collected data in 2022–23
- Experimental Hall C
- 10.5 GeV e^- beam
- ^{40}Ca, ^{48}Ca, ^{54}Fe targets
  - +others for calibration
- $(e, e'p)$ coincidence

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Electron detector

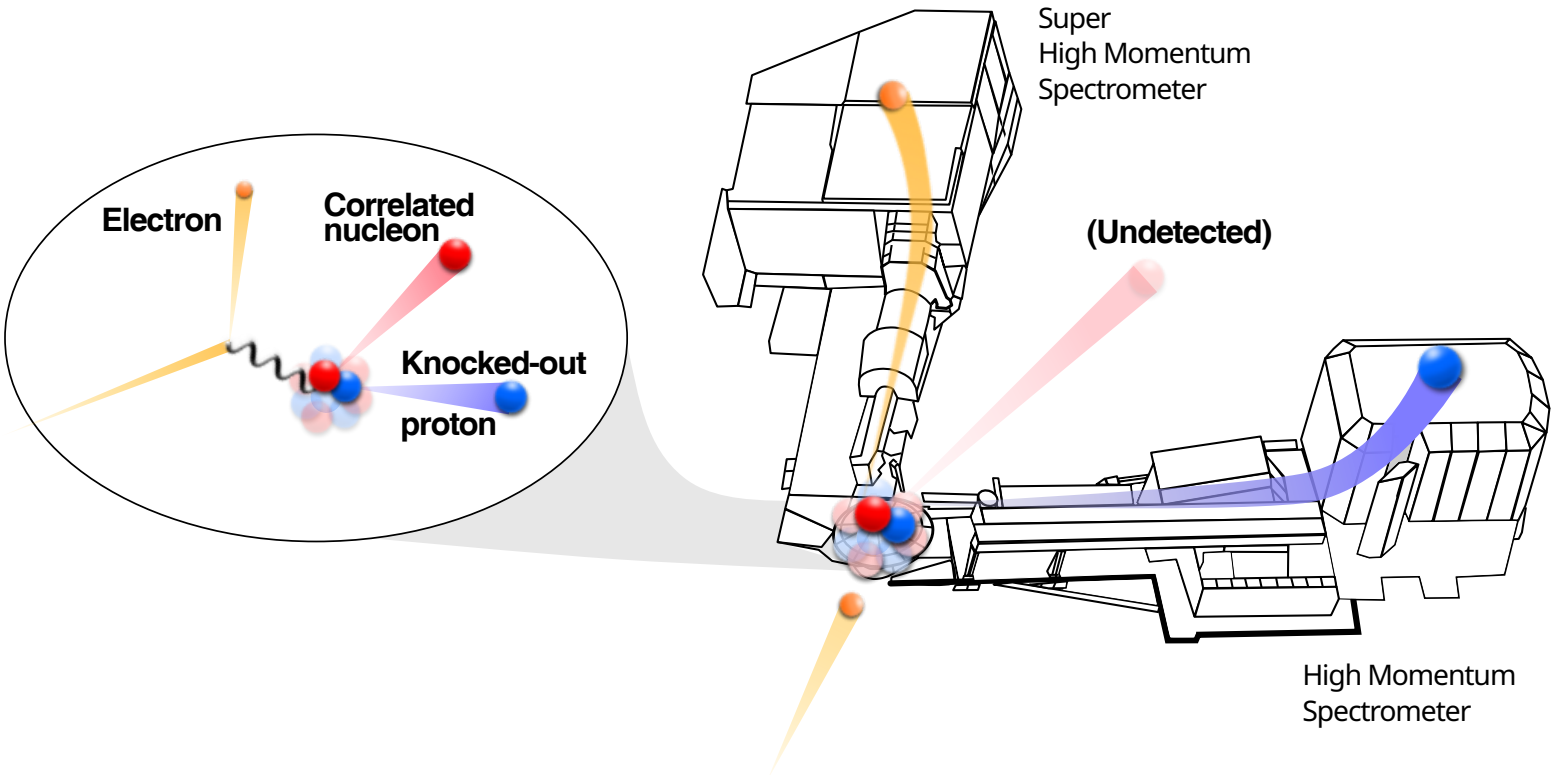
- Super High-Momentum Spectrometer
- $\theta_c = 8.3°$
- $p_c = 8.55$ GeV$/c$
- $Q_c^2 = 1.88$ GeV$^2/c^2$
- $\theta_q \approx 31°$

Proton detector

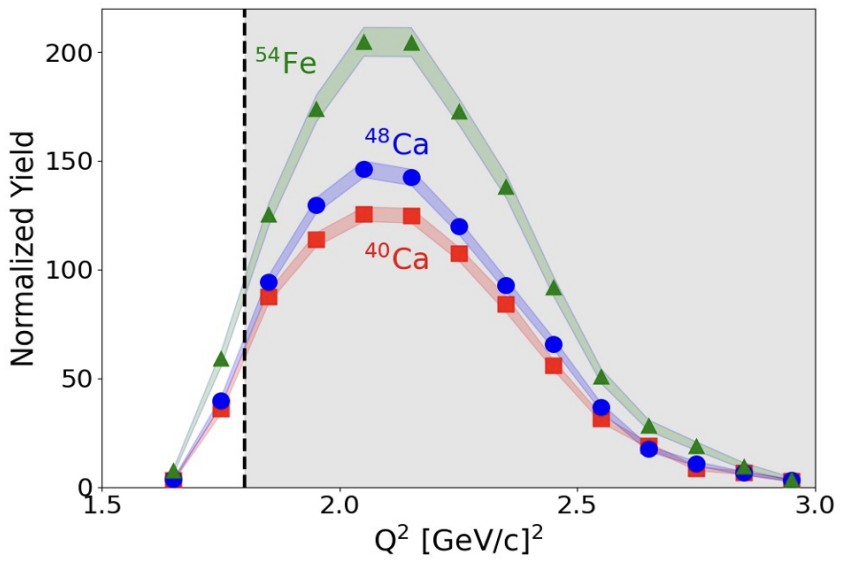
- High-Momentum Spectrometer
- $\theta_c = 66.4°$
- $p_c = 1.325$ GeV$/c$

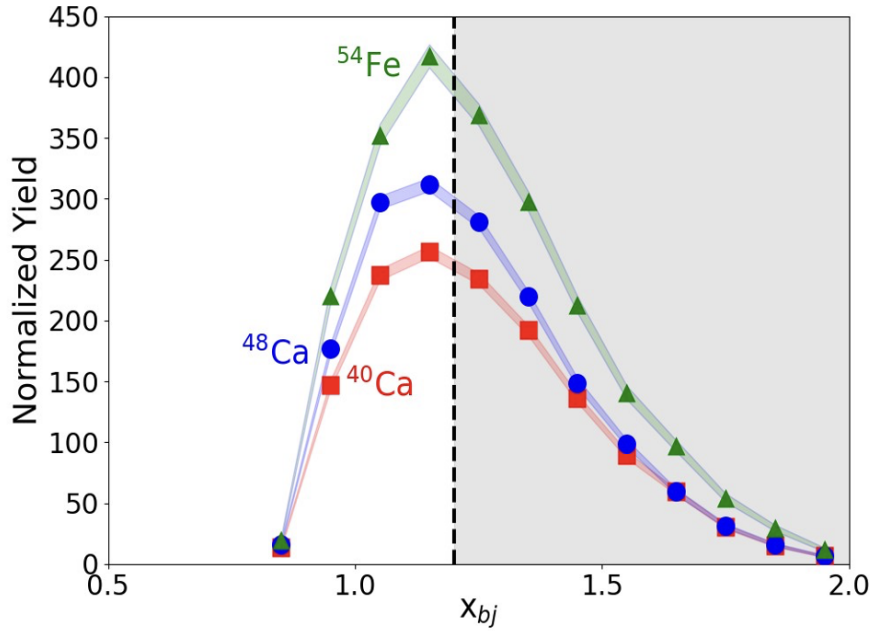

ELIN

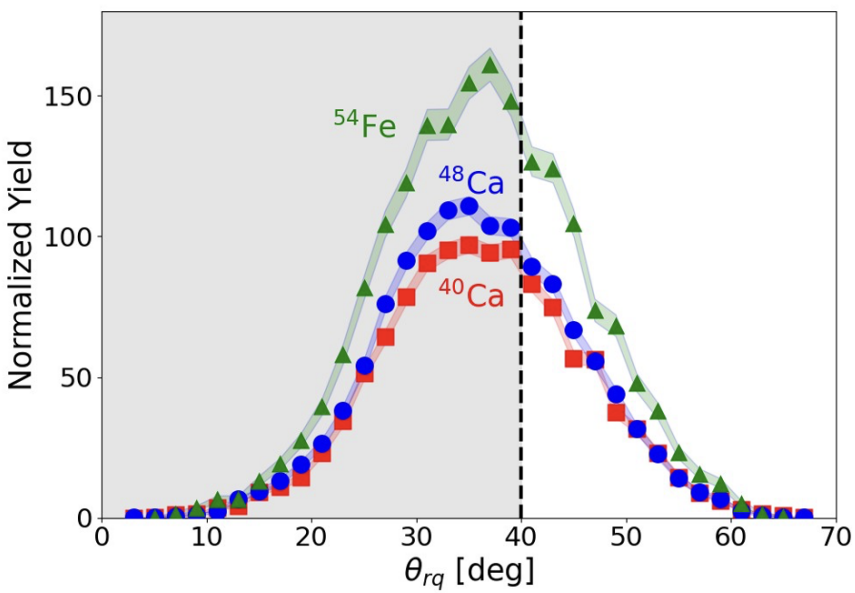
By detecting the proton, Ca-Fe is sensitive specifically to proton pairing.

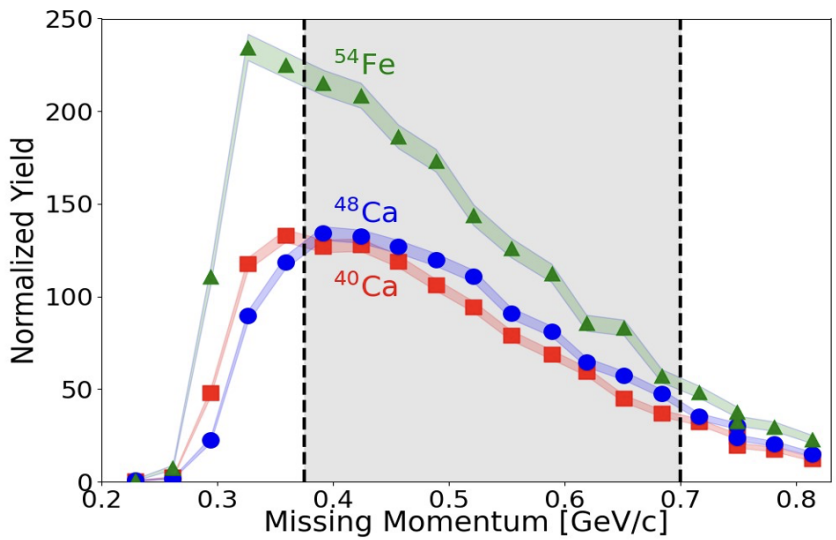


CaFe Kinematics

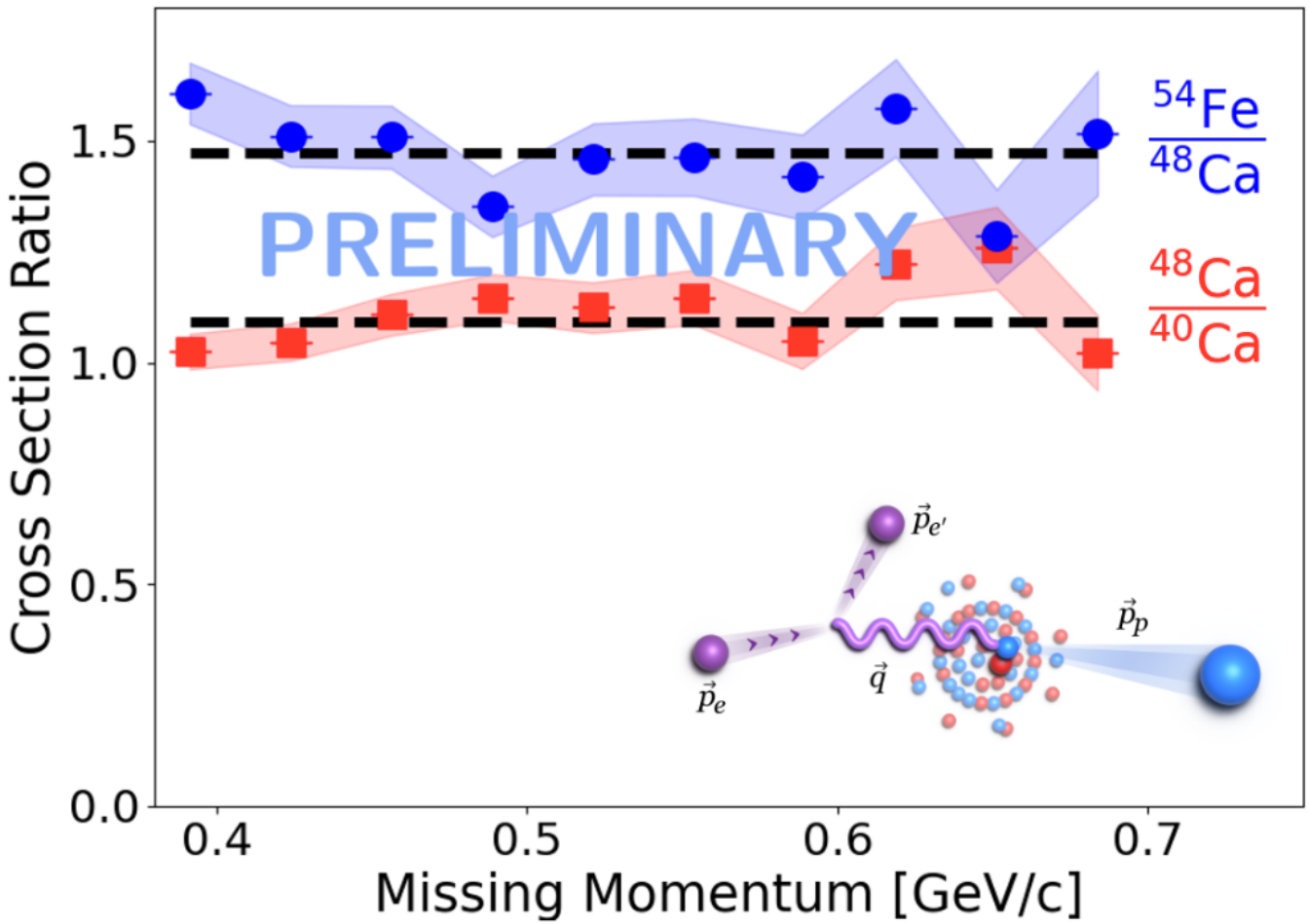




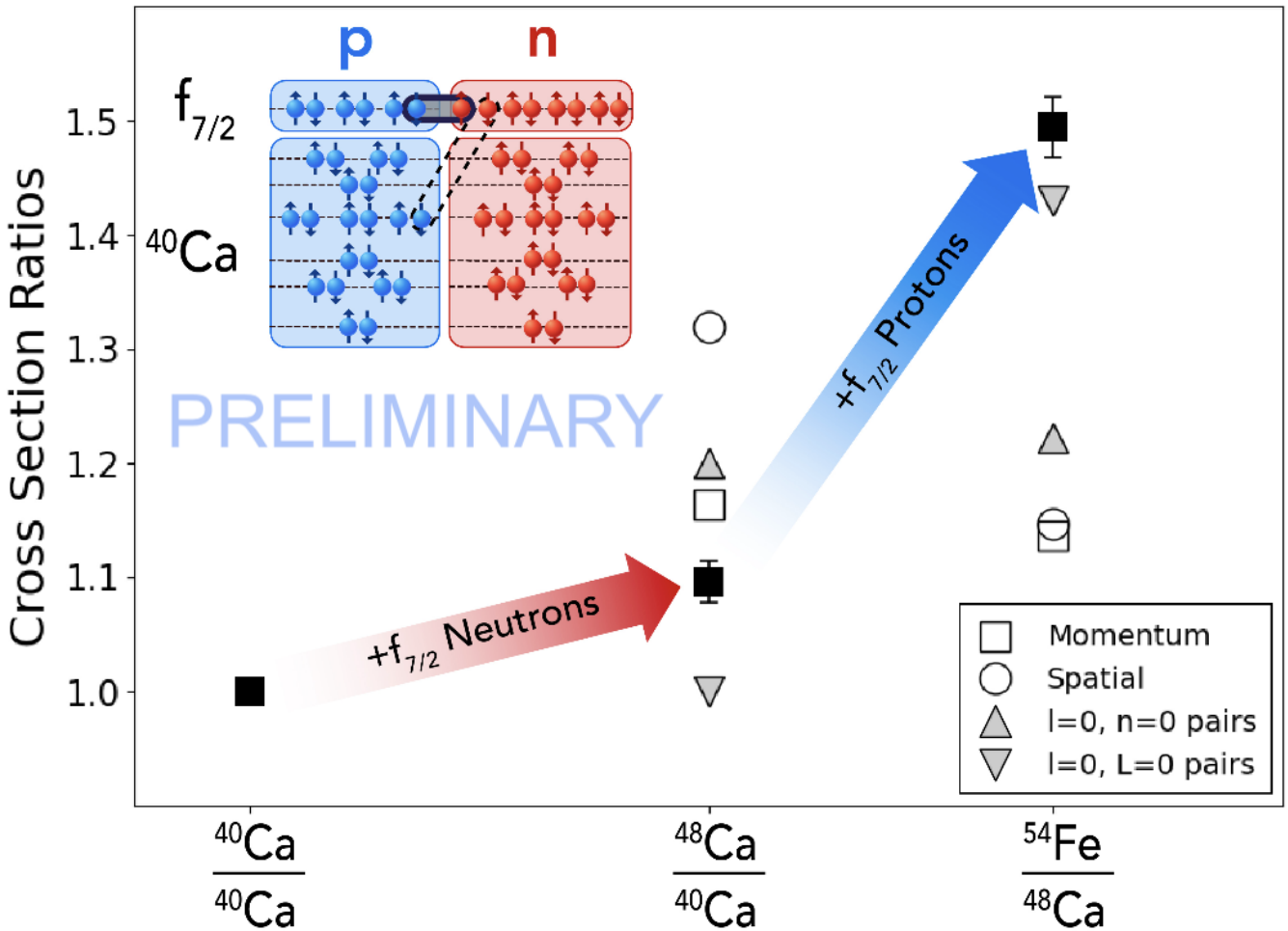




Cross-section ratios scale, indicating SRC-dominated sample



We see very little cross-shell pairing.



Currently under peer review!

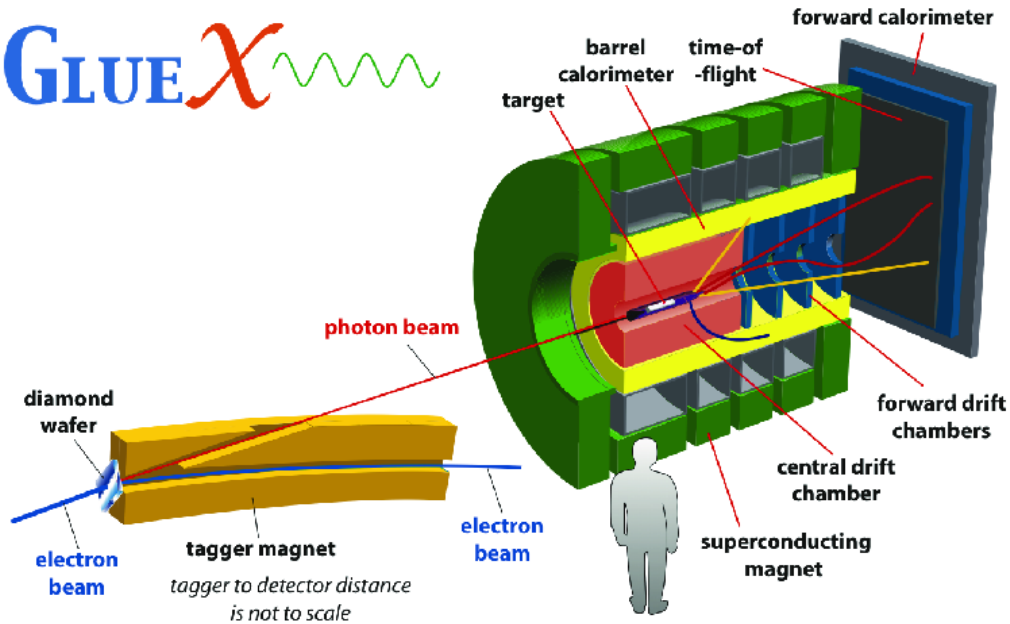
In my talk today:

1. Preliminary Results from the CaFe Experiment
   - Cross-shell pairing appears suppressed.
   - Evidence for quantum number selectivity.

2. **Recently conducted experiments**
   - Hall D SRC/CT Experiment tests universality
   - CLAS12 Run Group M expands available nuclei and stats.
   - BAND/LAD test the SRC-EMC connection

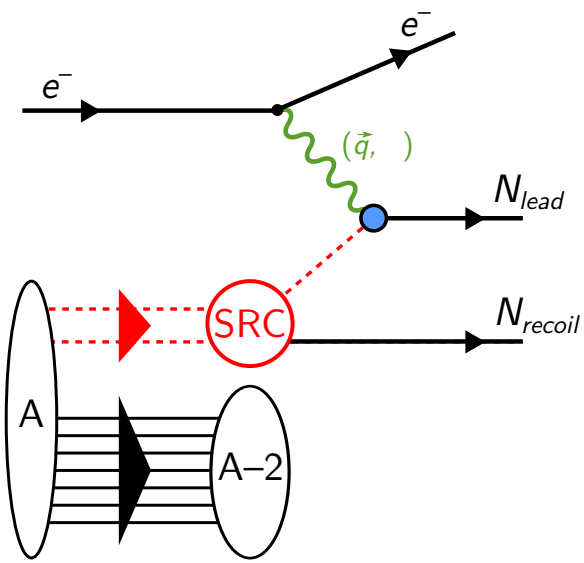
Hall D SRC/Color-Transparency Experiment: probing SRCs with photoproduction reactions

- Nov.–Dec., 2021
- $>$ 90 billion triggers
- Targets: D, ^{4}He, ^{12}C
- Peak flux at 8.5 GeV
- GlueX Spectrometer

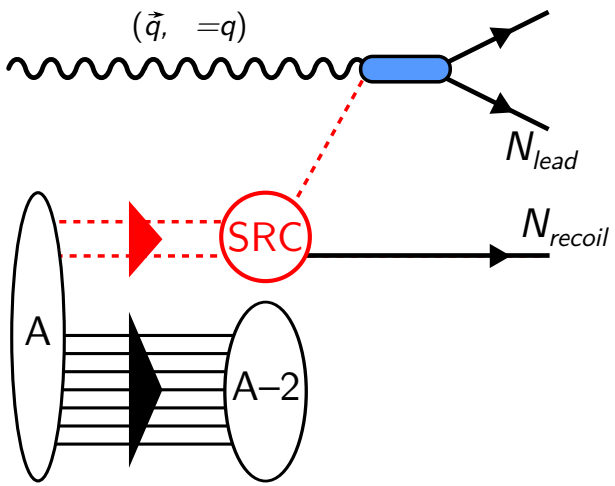


- Axion-like particle search: J. R. Pybus et al., Phys. Lett. B 855, 138790 (2024)
- Subthreshold J/ψ production: J. R. Pybus et al., Phys. Rev. Lett. 134, 201903 (2025)

Does the probe-nucleon interaction factorize from the nuclear ground state?



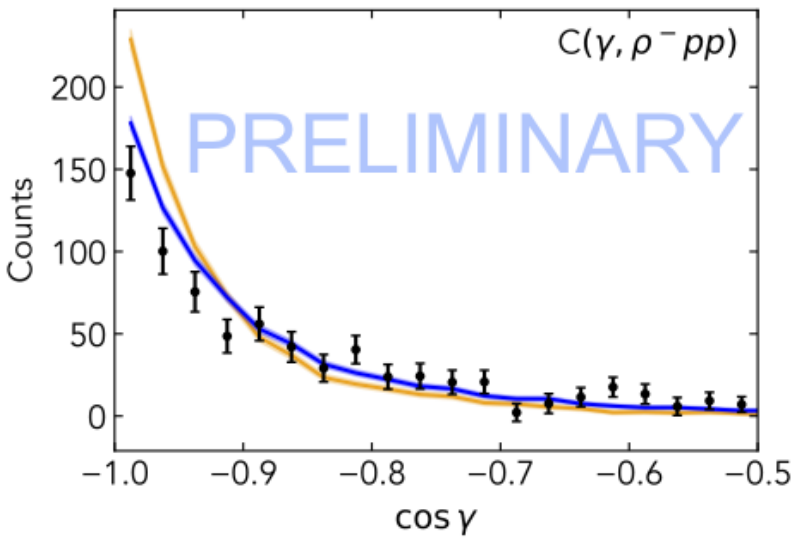
Plane wave QE scattering



Plane-wave photo-production

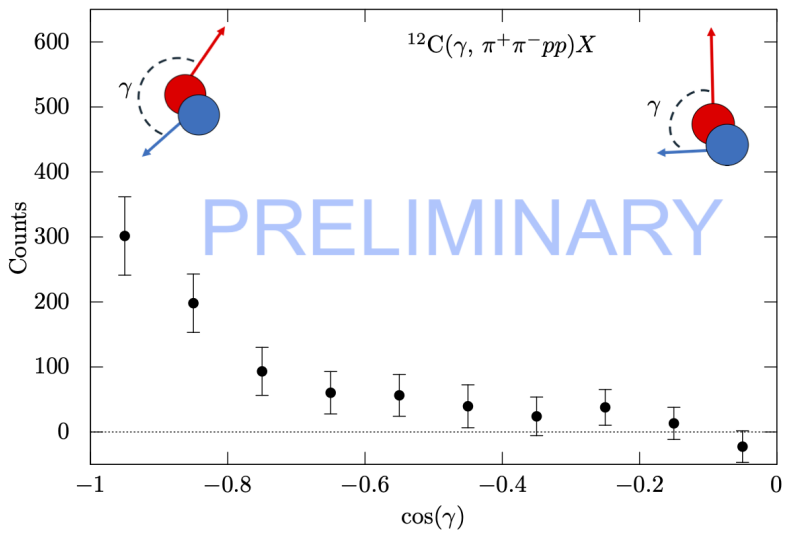
We see angular correlations in multiple reaction channels.

$\gamma n(p) \to \rho^- pp$



Credit: Jackson Pybus, MIT

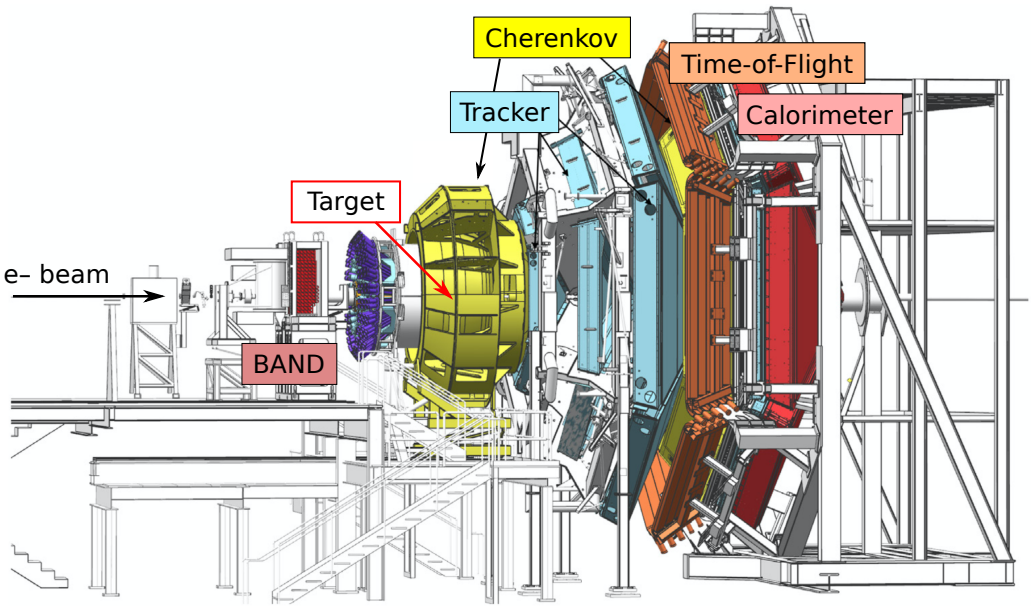
$\gamma p(p) \to \rho^0 pp$



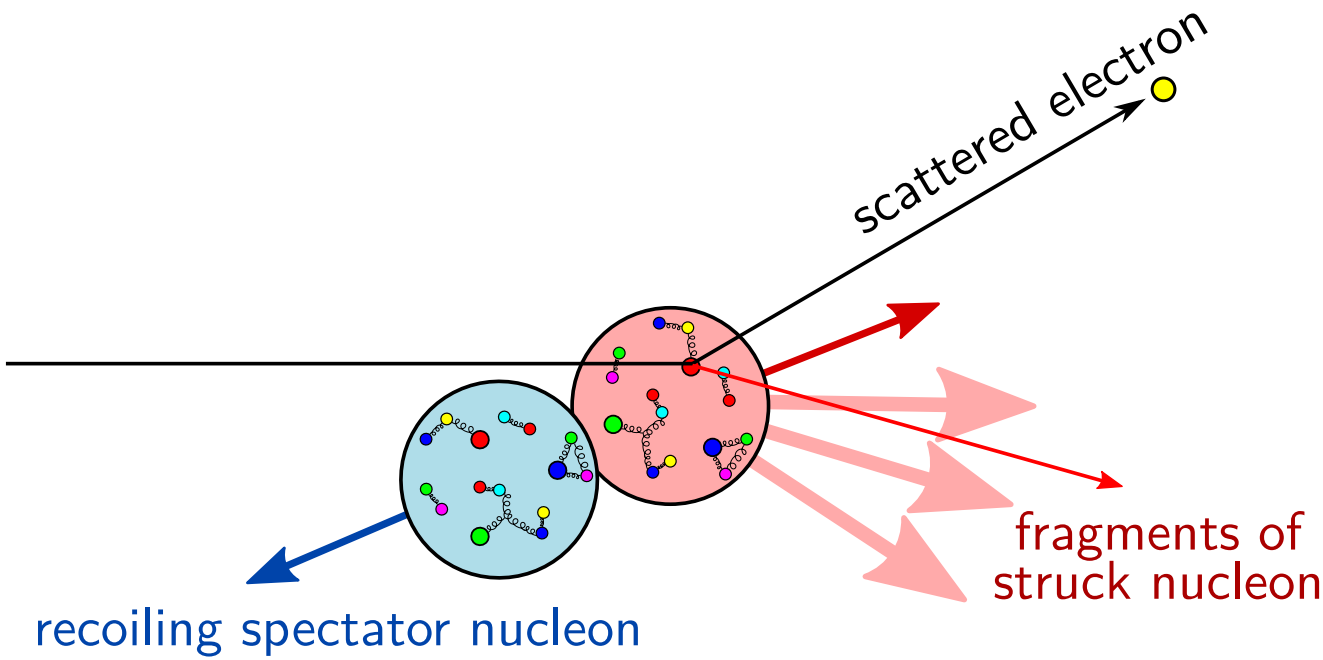
Credit: Phoebe Sharp, GW

CLAS12 Run Group M is a dedicated high-statistics SRC experiment.

- Nov. 2021–Feb. 2022
- 300 fb^{-1}
  - 10× more than CLAS
- Targets: H, D, ^{4}He, ^{12}C, ^{40,48}Ca, ^{120}Sn
- 2, 4, 6, GeV beams
- CLAS12 Spectrometer

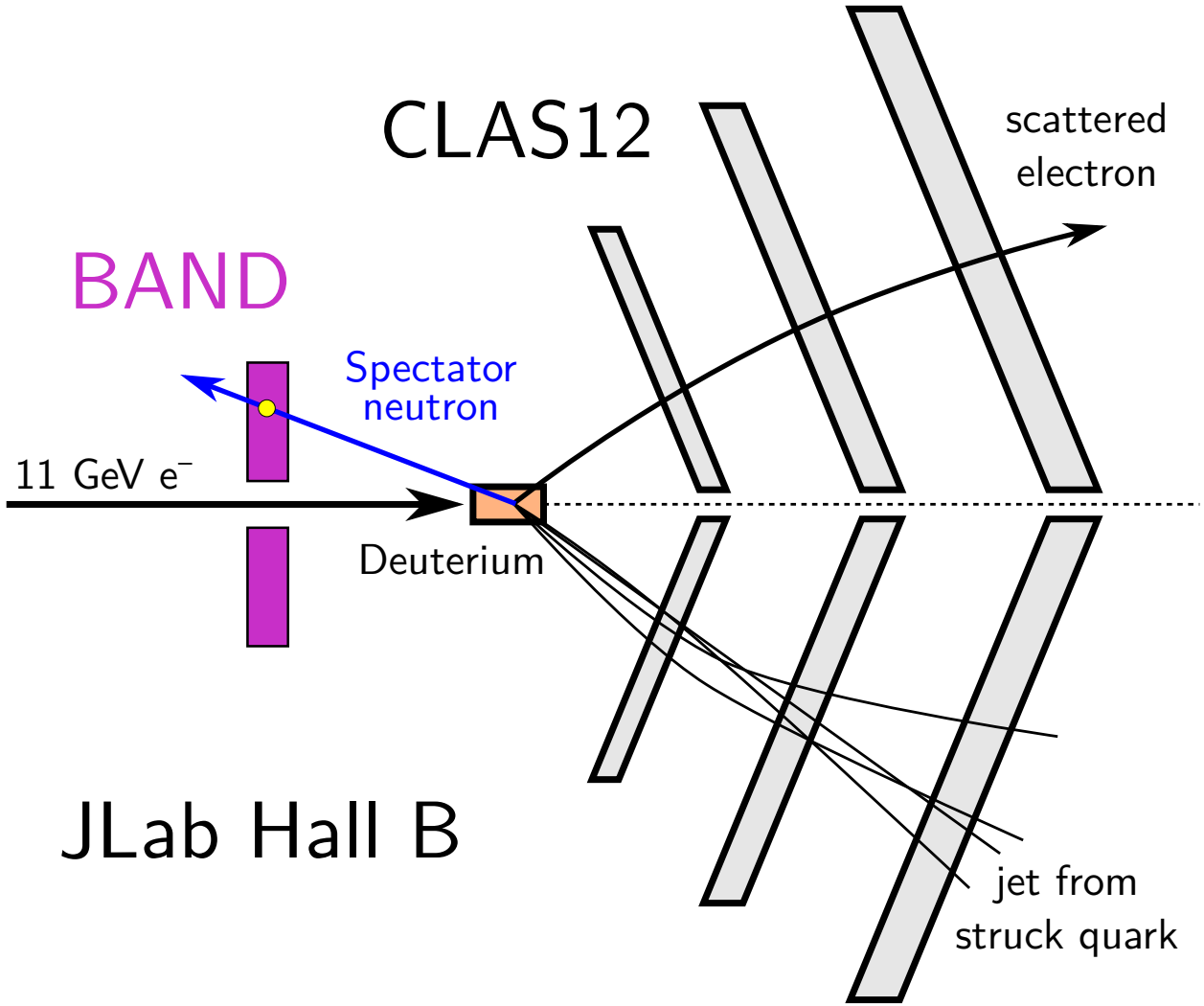


We can isolate SRC nucleons by "tagging" a correlated partner.

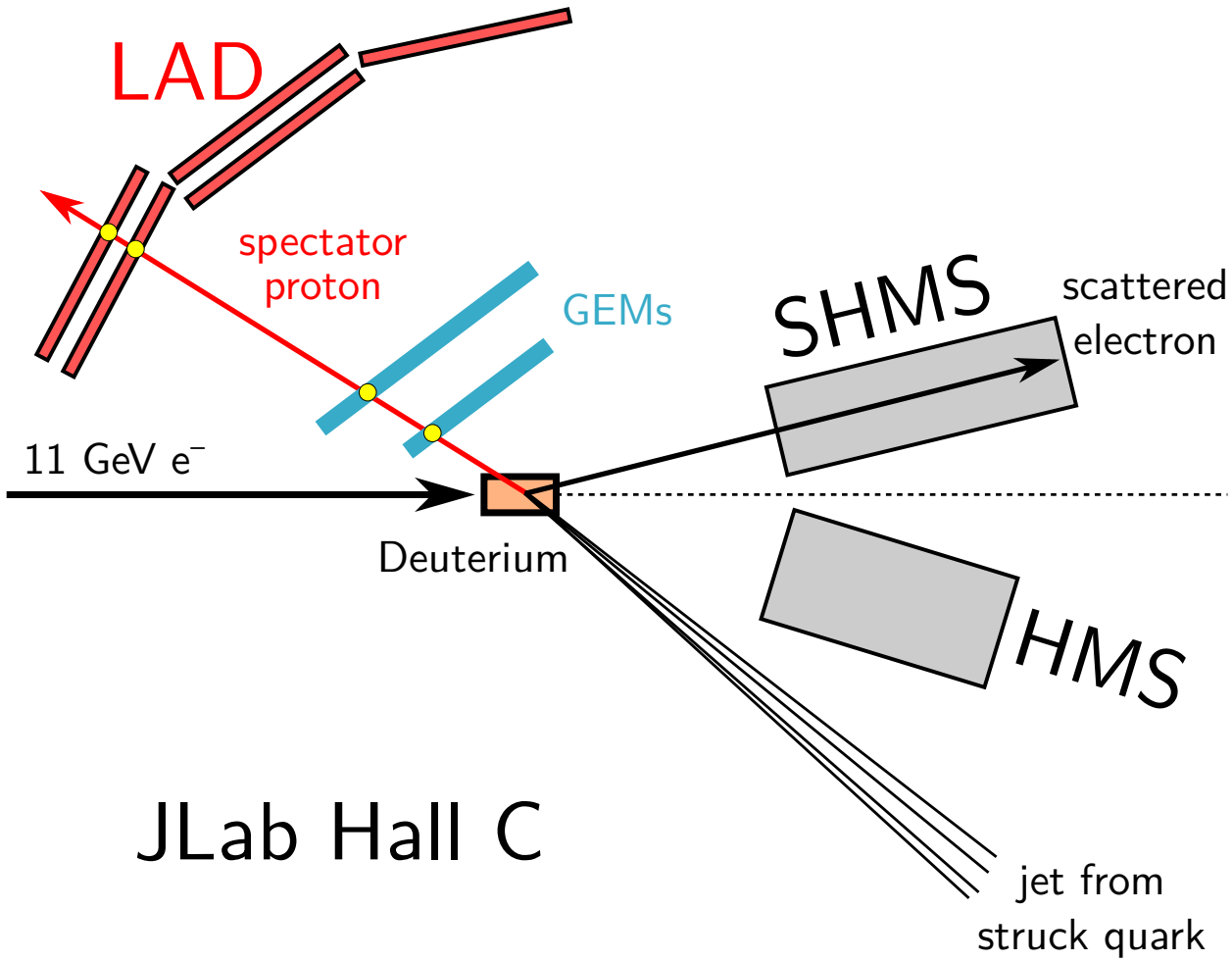


1. Mom. of the scattered e^- $\longrightarrow$ determine quark momentum
2. Mom. of the spectator $\longrightarrow$ determine if correlated

"Backward Angle Neutron Detector"
was built to detect recoiling spectator neutrons.

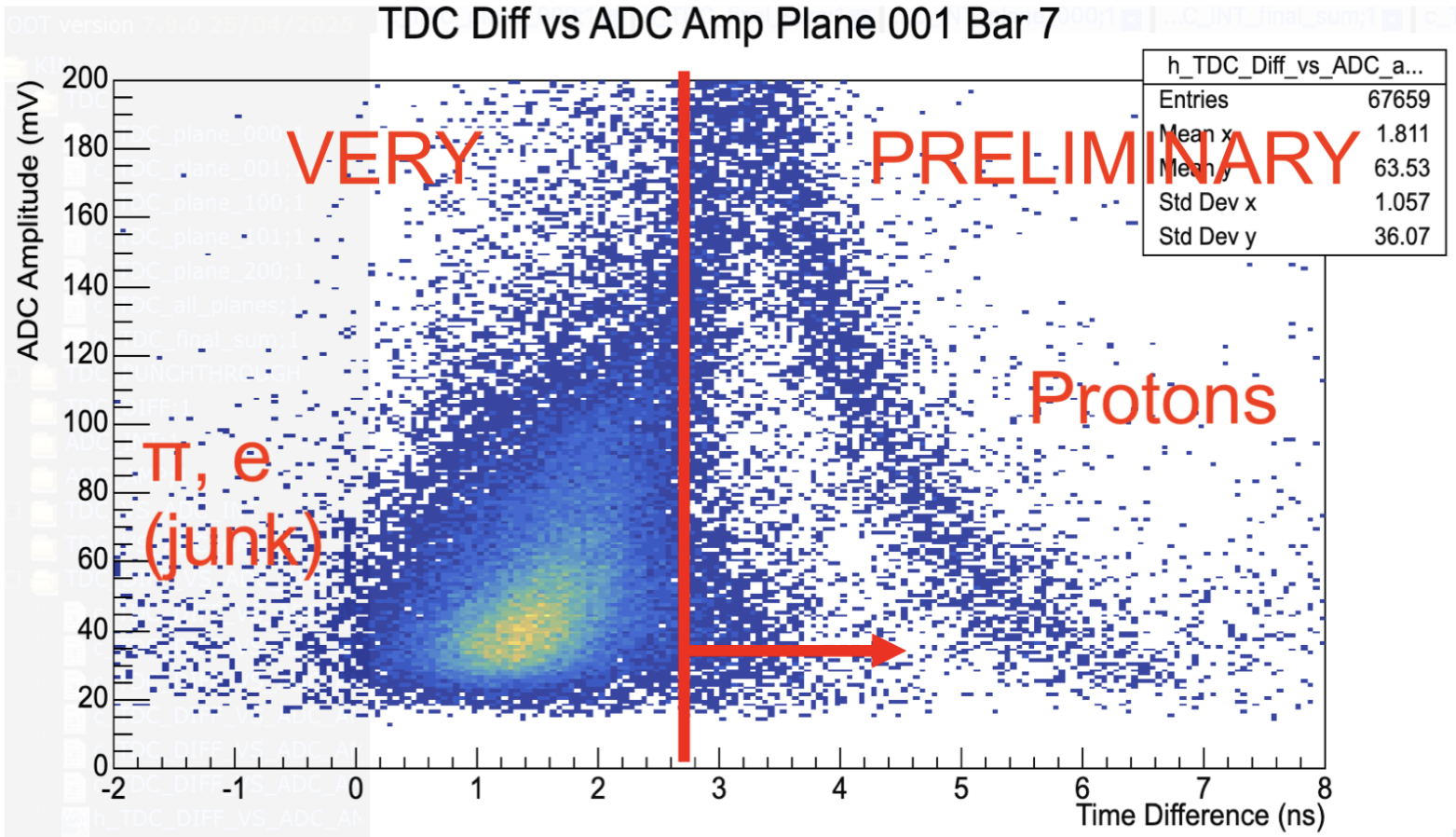


LAD collected data this past summer tagging spectator protons.




CAUTION DO NOT ENTER
CUIDADO NO ENTRE

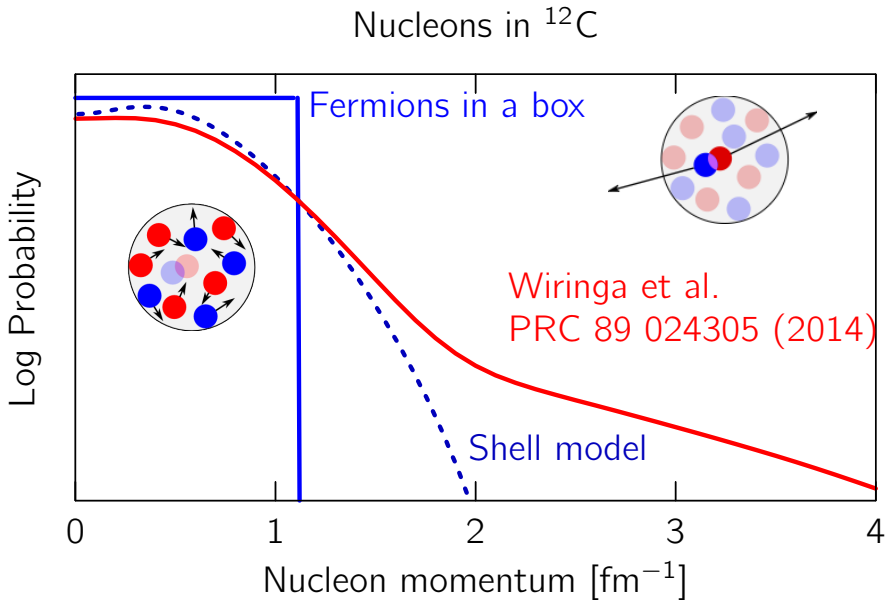
We see coincident protons in LAD!



Credit: Lucas Ehinger, MIT

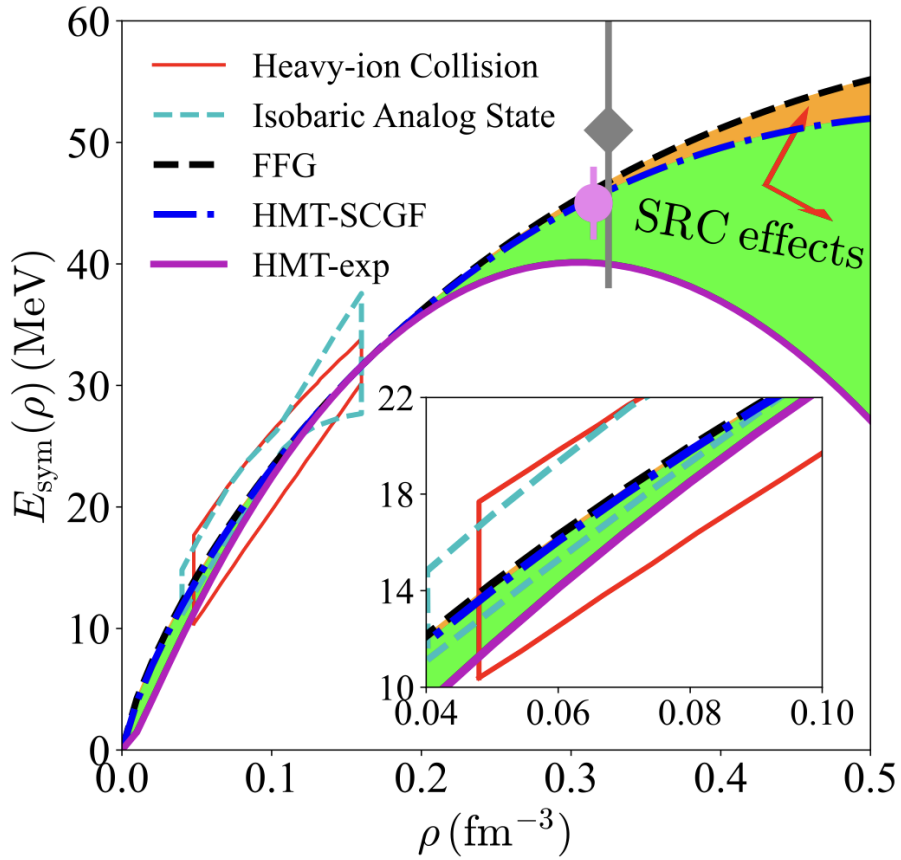
To recap:

- SRCs are pairs of high-momentum strongly interacting nucleons.



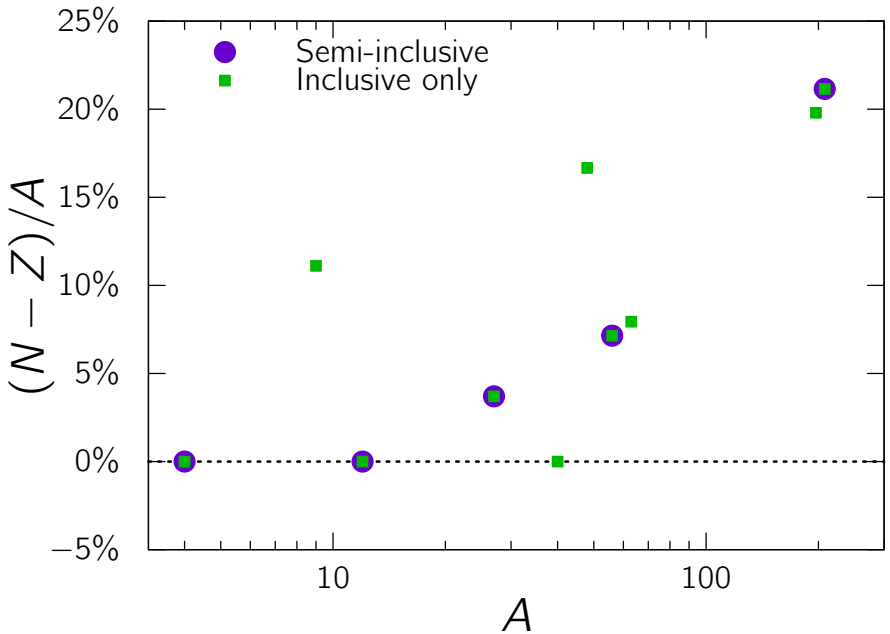
To recap:

- SRCs are pairs of high-momentum strongly interacting nucleons.
- Relevant for key problems in nuclear physics



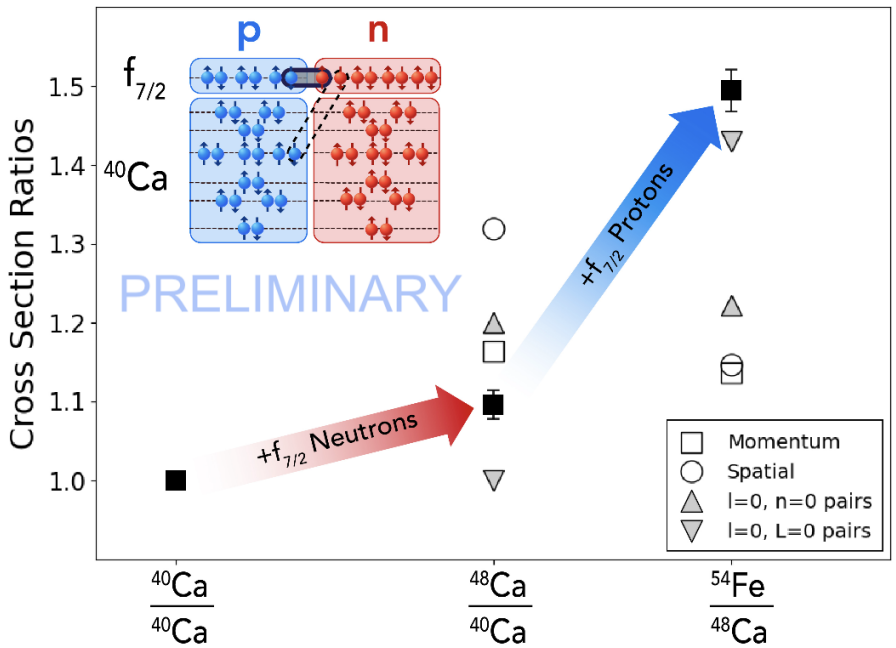
To recap:

- SRCs are pairs of high-momentum strongly interacting nucleons.
- Relevant for key problems in nuclear physics
- Disentangling size/asymmetry has been a challenge



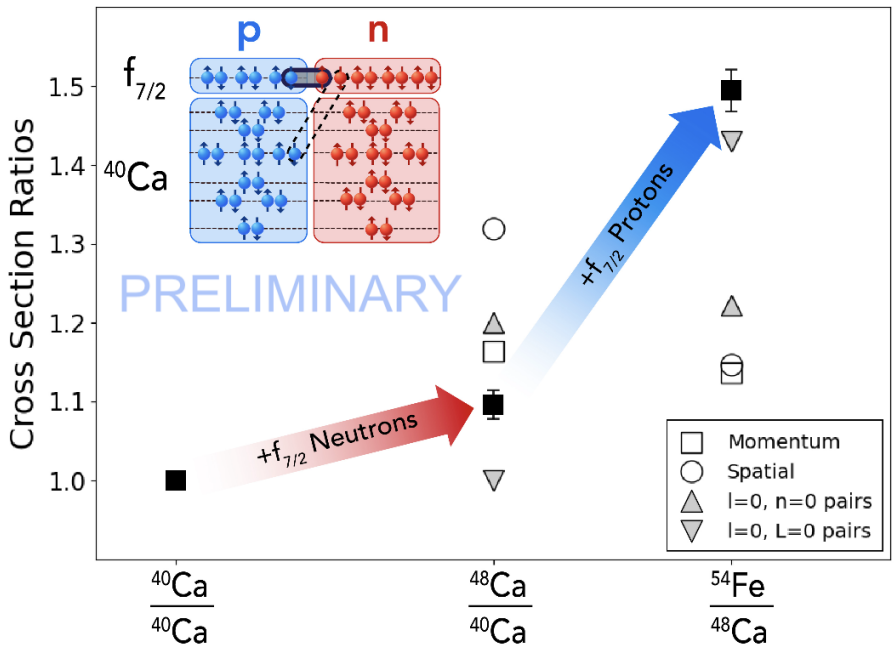
To recap:

- SRCs are pairs of high-momentum strongly interacting nucleons.
- Relevant for key problems in nuclear physics
- Disentangling size/asymmetry has been a challenge
- CaFe shows minimal cross-shell pairing



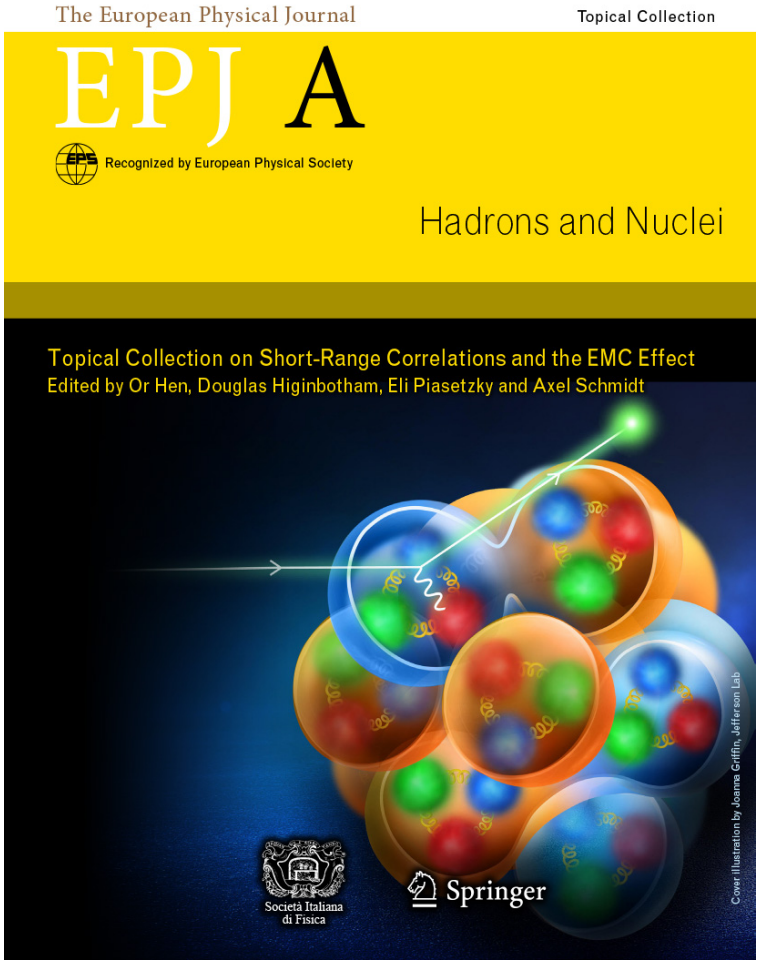
To recap:

- SRCs are pairs of high-momentum strongly interacting nucleons.
- Relevant for key problems in nuclear physics
- Disentangling size/asymmetry has been a challenge
- CaFe shows minimal cross-shell pairing
- Lots of new data being analyzed!




Thank you!
especially for the intellectual
short-range correlations!

Recent Documents by the SRC Community



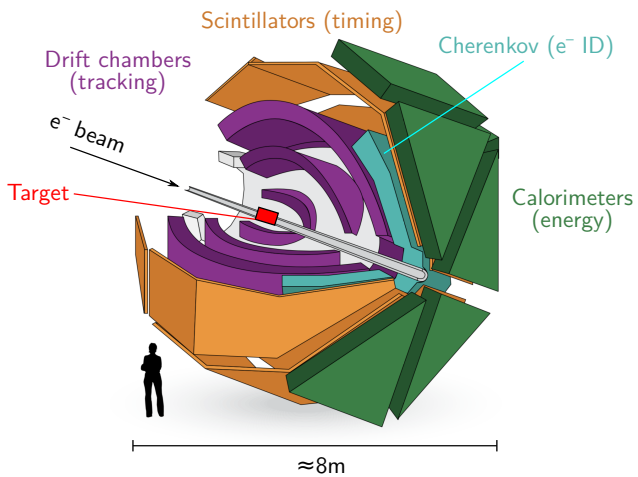
- EPJA Topical Issue on SRCs
  - May 21, 2025
  - Guest editors: Or Hen, Douglas Higinbotham, Eli Piasetzky, Axel Schmidt
- Long-range outlook for short-range correlations
  - January 14, 2026
  - arXiv:2601.09568

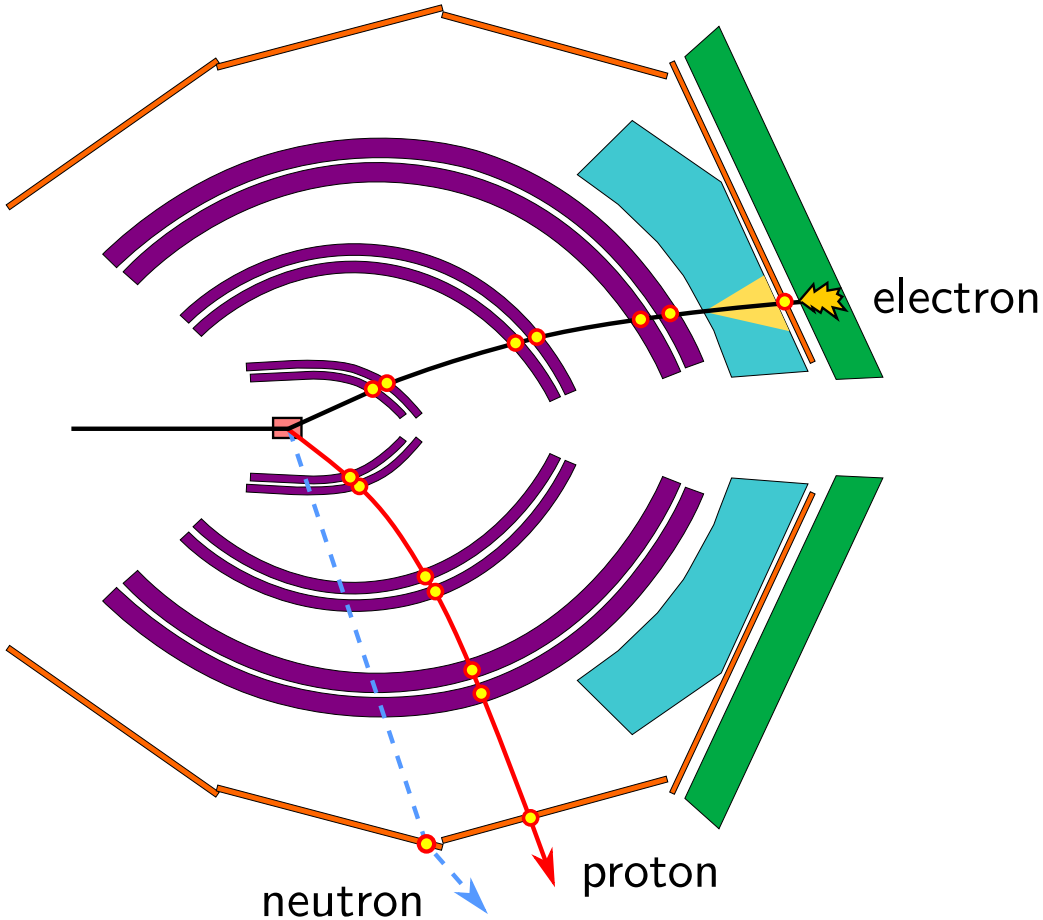
Back-Up

Mining CLAS data

CLAS eg2 Experiment (2004)

- 5 GeV beam
- d, C, Al, Fe, Pb targets
- large acceptance spectrometer

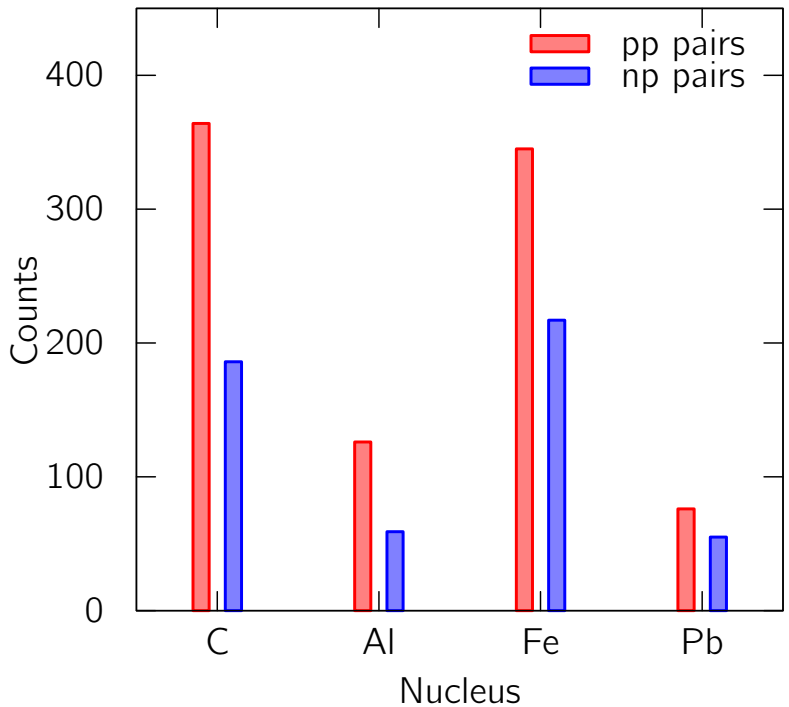




Until 2020, most SRC studies were conducted by data mining.

Publications:

- Hen et al., PLB 722, p. 63 (2013)
- Hen et al., Science 346 p. 614 (2014)
- Duer et al., Nature 560, p. 617 (2018)
- Cohen et al., PRL 121, 092501 (2018)
- Duer et al., PLB 797, 134792 (2019)
- Schmookler et al., Nature 566, p. 354 (2019)
- Duer et al., PRL 122, 172502 (2019)
- Schmidt et al., Nature 578, p. 540 (2020)
- Korover et al., PLB 820, 136523 (2021)
- Korover et al., PRC 107, L061301 (2023)



Sub-threshold J/ψ photoproduction on nuclei

J. R. Pybus et al., PRL 134, 201903 (2025)