Short-Range Correlations in Nuclei

Axel Schmidt

10th Workshop of the APS Topical Group on Hadronic Physics

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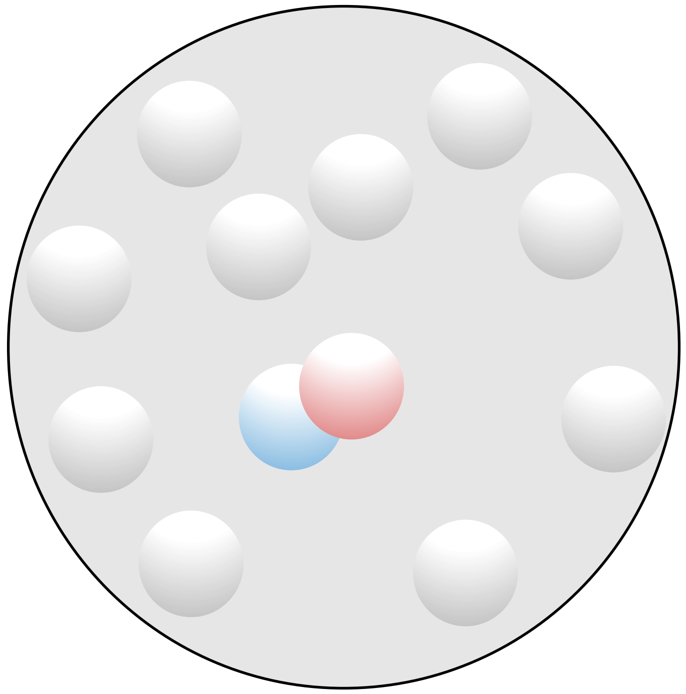
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Short-range correlations are a universal feature of nuclei.

- All nuclei have them



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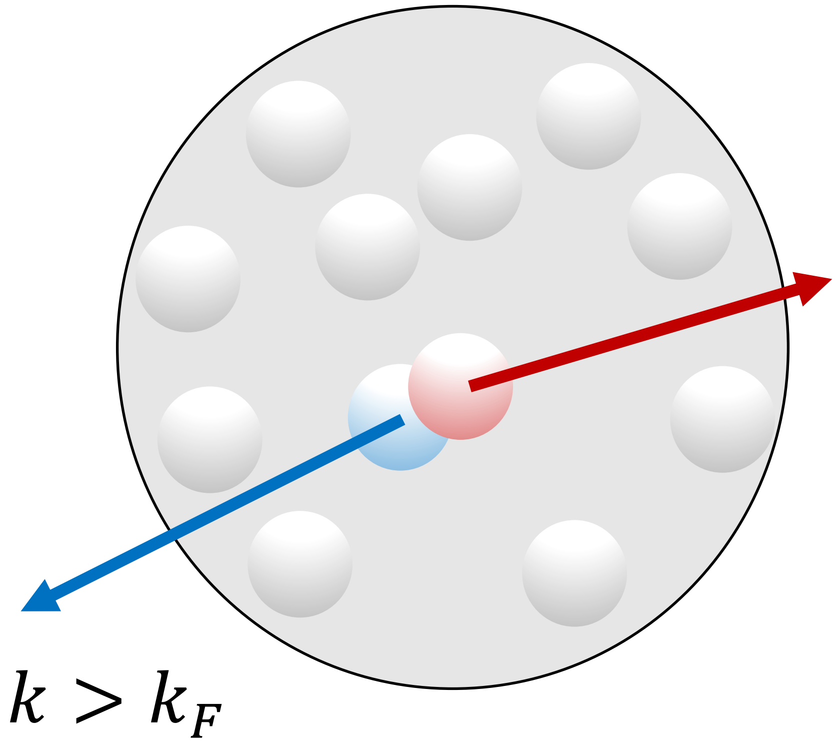

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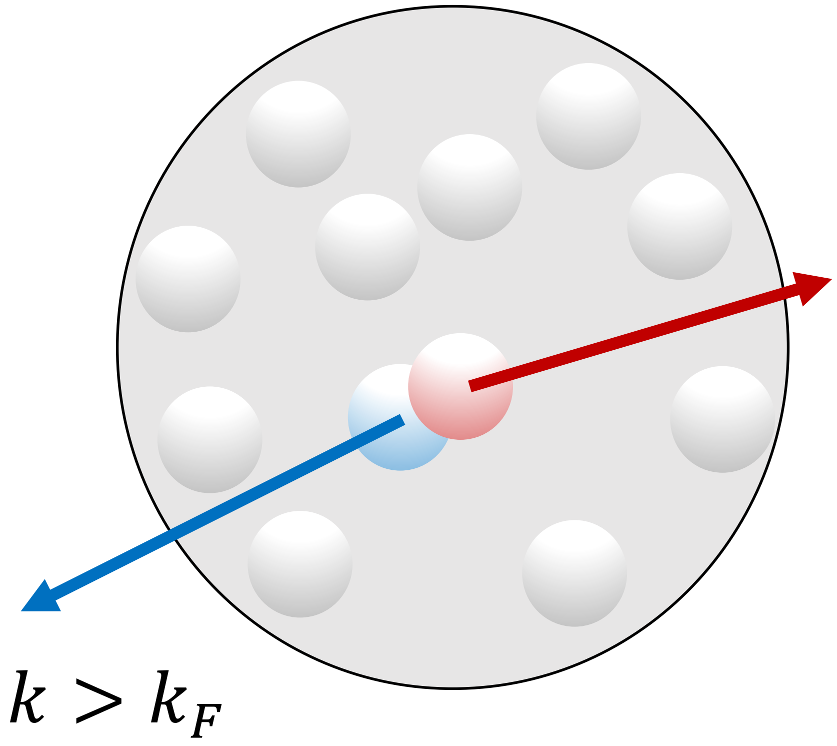

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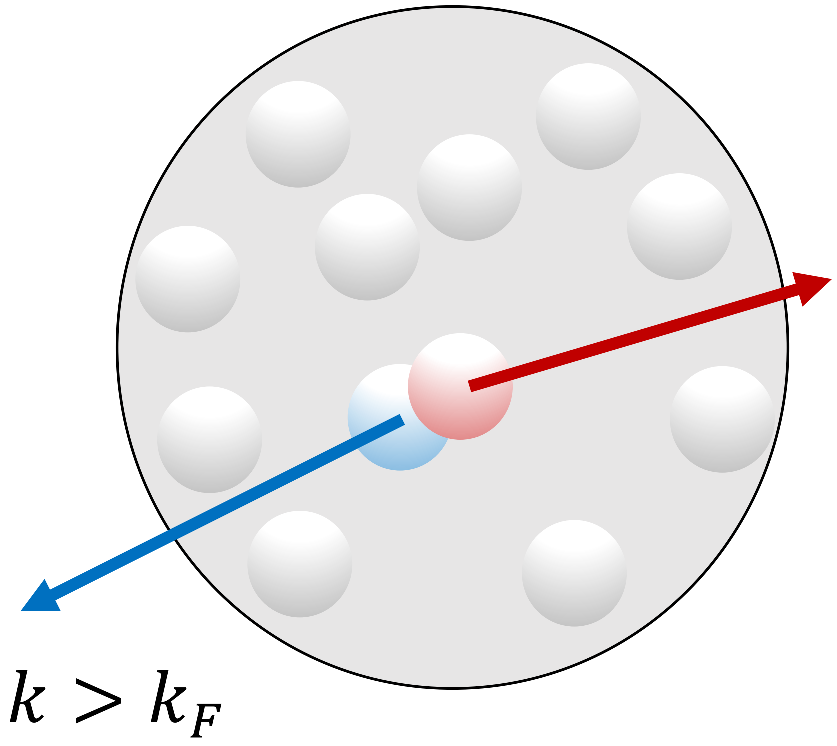
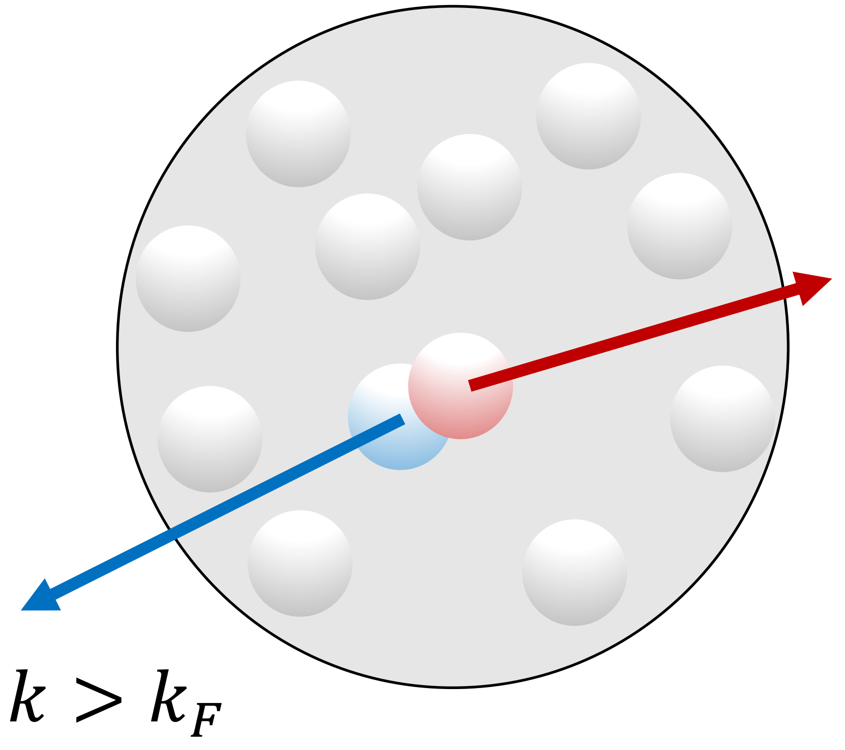
- ≈10–20% of nucleons



Short-range correlations are a universal feature of nuclei.

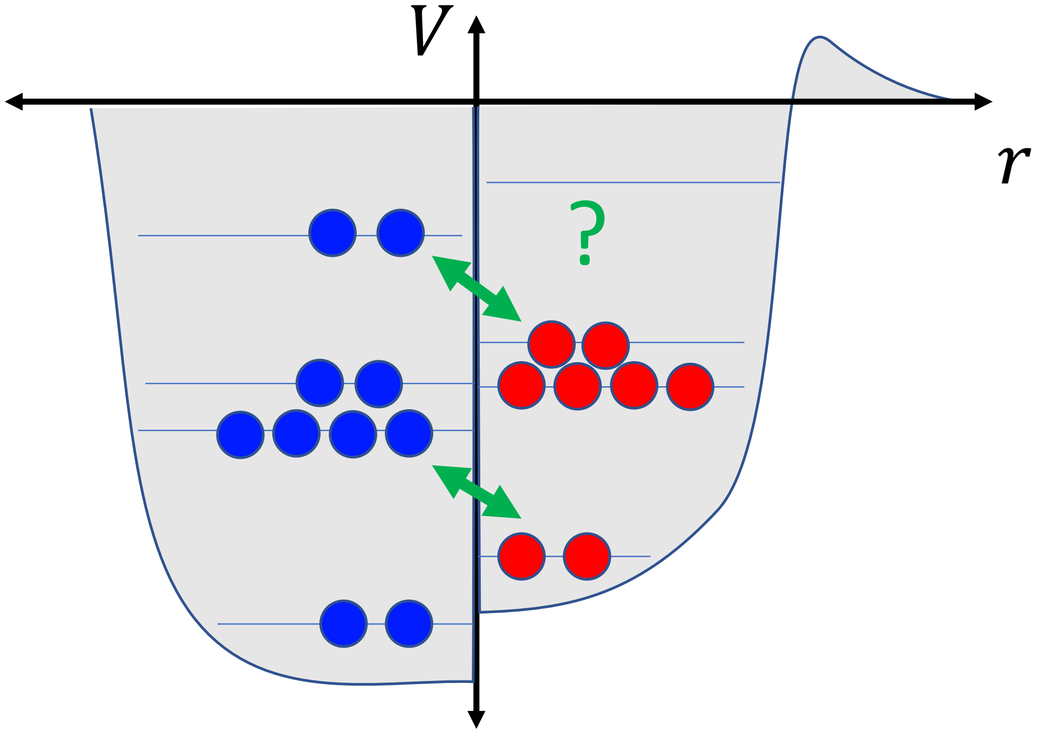
- All nuclei have them.
- High-momentum nucleons
- Back-to-back momenta
- ≈10–20% of nucleons
- Primarily np pairs, spin 1
  - Driven by tensor force
  - Persists in asymmetric nuclei
  - Changes with momentum range



Short-range correlations play a role in many open questions of nuclear, hadronic physics.

1. Nuclear structure

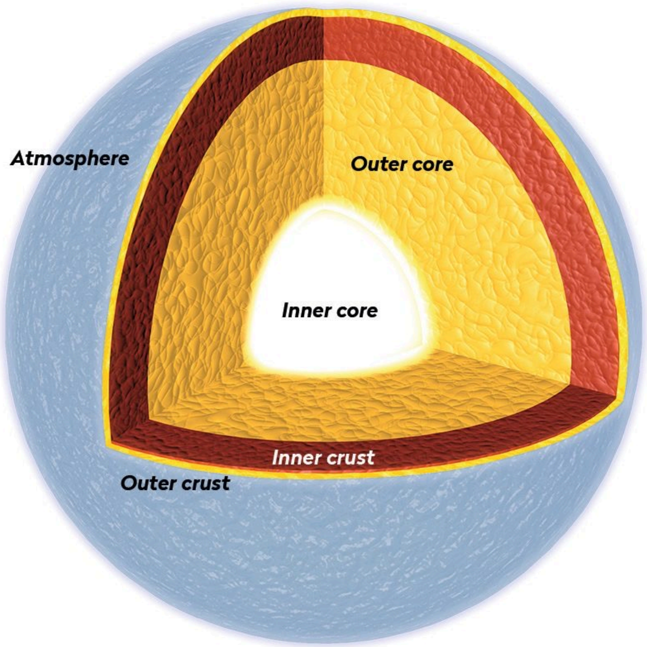
- How do correlations form?
- Are there 3N correlations?
- SRCs influence nuclear properties.
  - have the majority of kinetic energy
  - e.g. double beta decay matrix elements



Short-range correlations play a role in many open questions of nuclear, hadronic physics.

1. Nuclear structure

2. **Nuclear matter at high density**
   - High-density laboratory
   - Effective NN forces at short-distances
   - Connection to neutron star matter

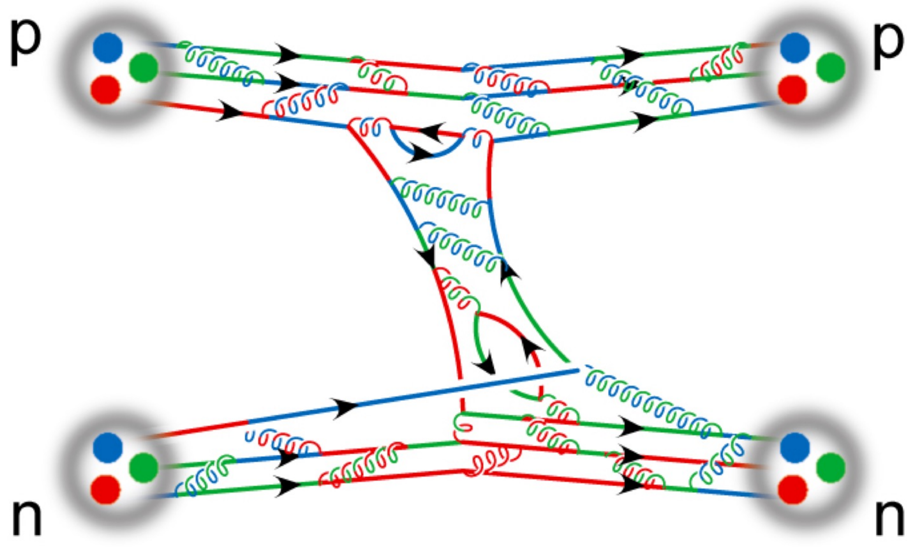


Short-range correlations play a role in many open questions of nuclear, hadronic physics.

1. Nuclear structure

2. Nuclear matter at high density

3. **Hadronic-Partonic bridge**
   - EMC Effect
   - Emergence of quark d.o.f.s



Quick announcements

Caveats:

- Other people did the impressive work.
- Experimental focus
- Opinions are solely my own.

- Check out the Short-Range Correlations Parallel Session!
    - 2 PM, Orchestra A

In my talk today:

- Short-range correlations is asymmetric nuclei
  - How does size, neutron-proton imbalance affect pairing?
  - See Dien Nguyen's, Burcu Duran's talk
- Factorization: probe- and scale-independence
  - How can we separate what we learn about pairs, from hard scattering?
  - See Tim Kolar's talk
- Short-range correlations and the EMC Effect
  - What roles to SRCs play in medium modification?
  - See Florian Hauenstein's talk

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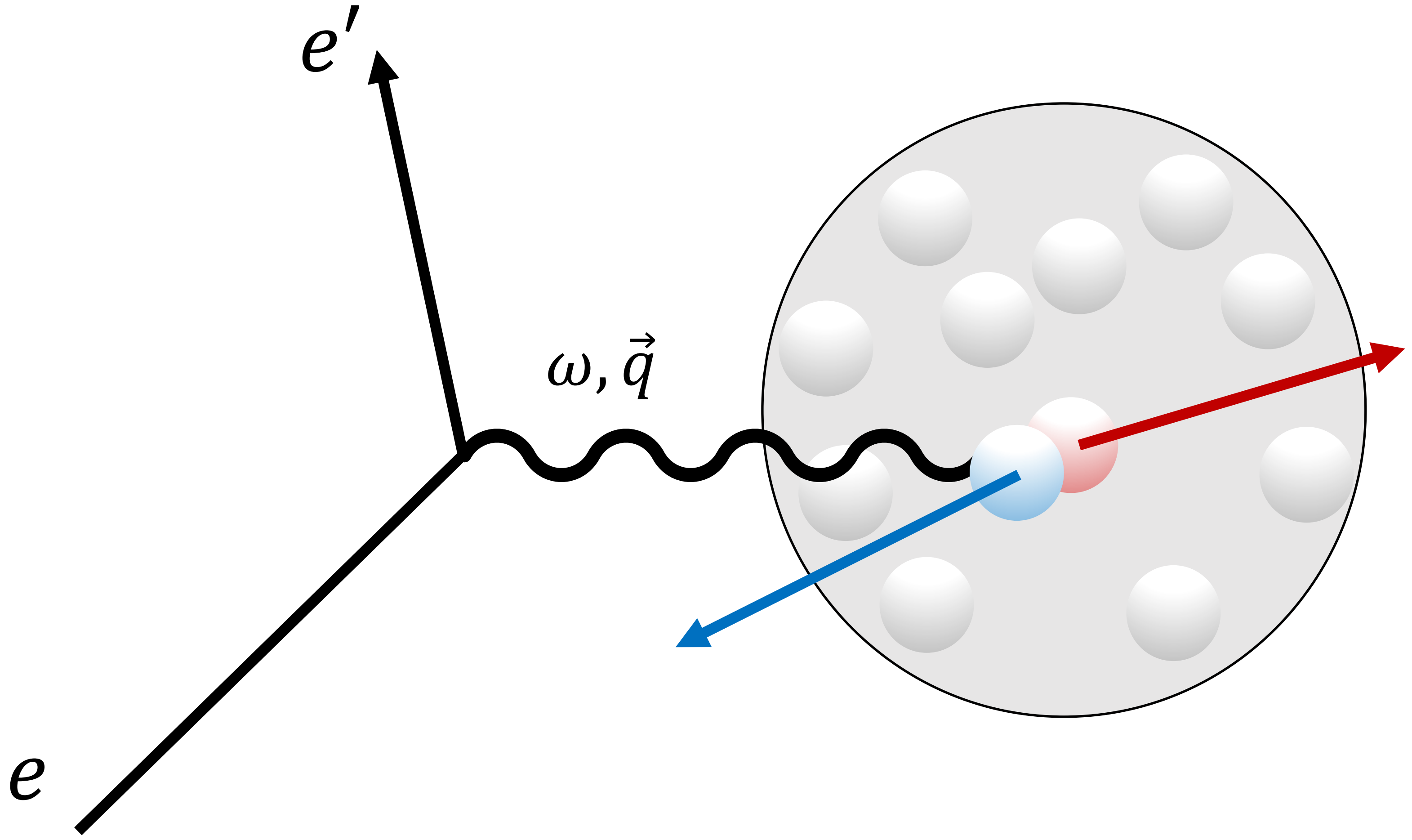

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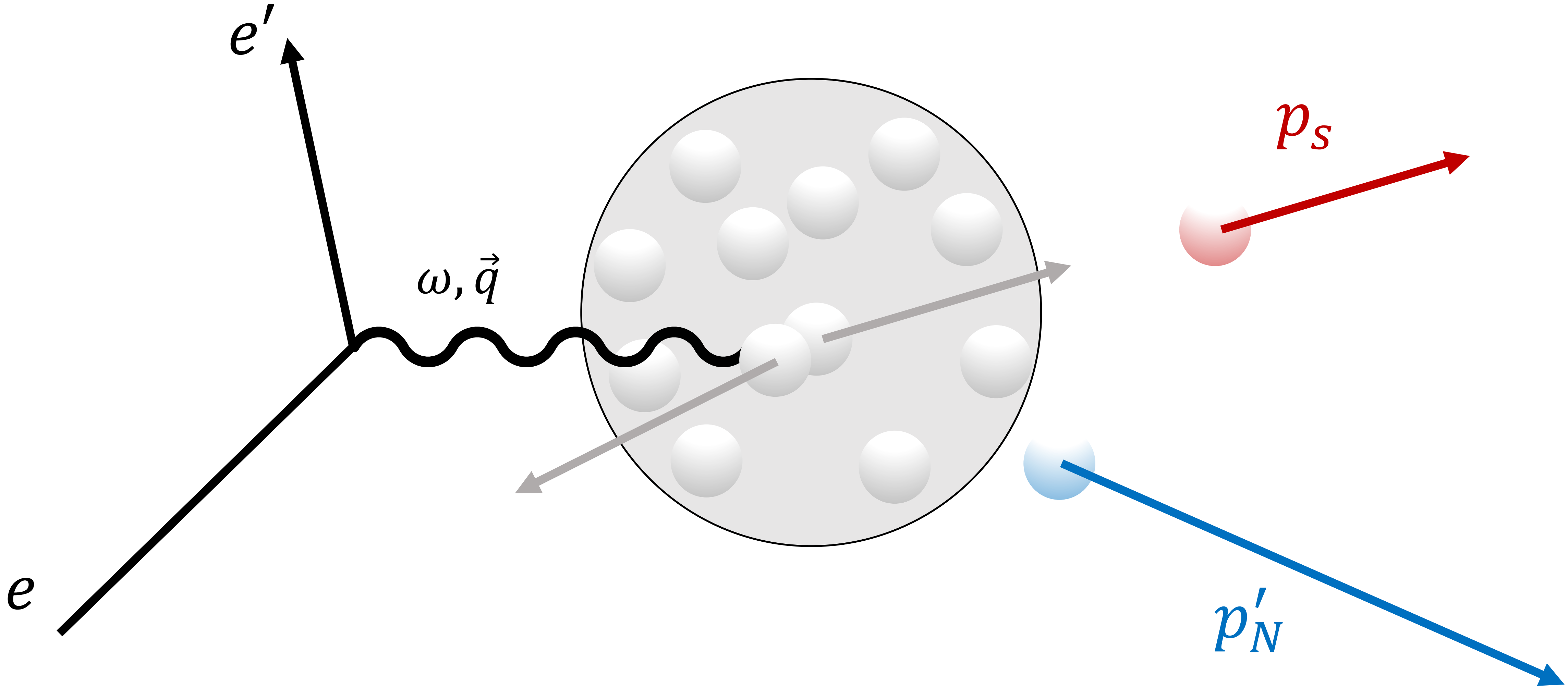

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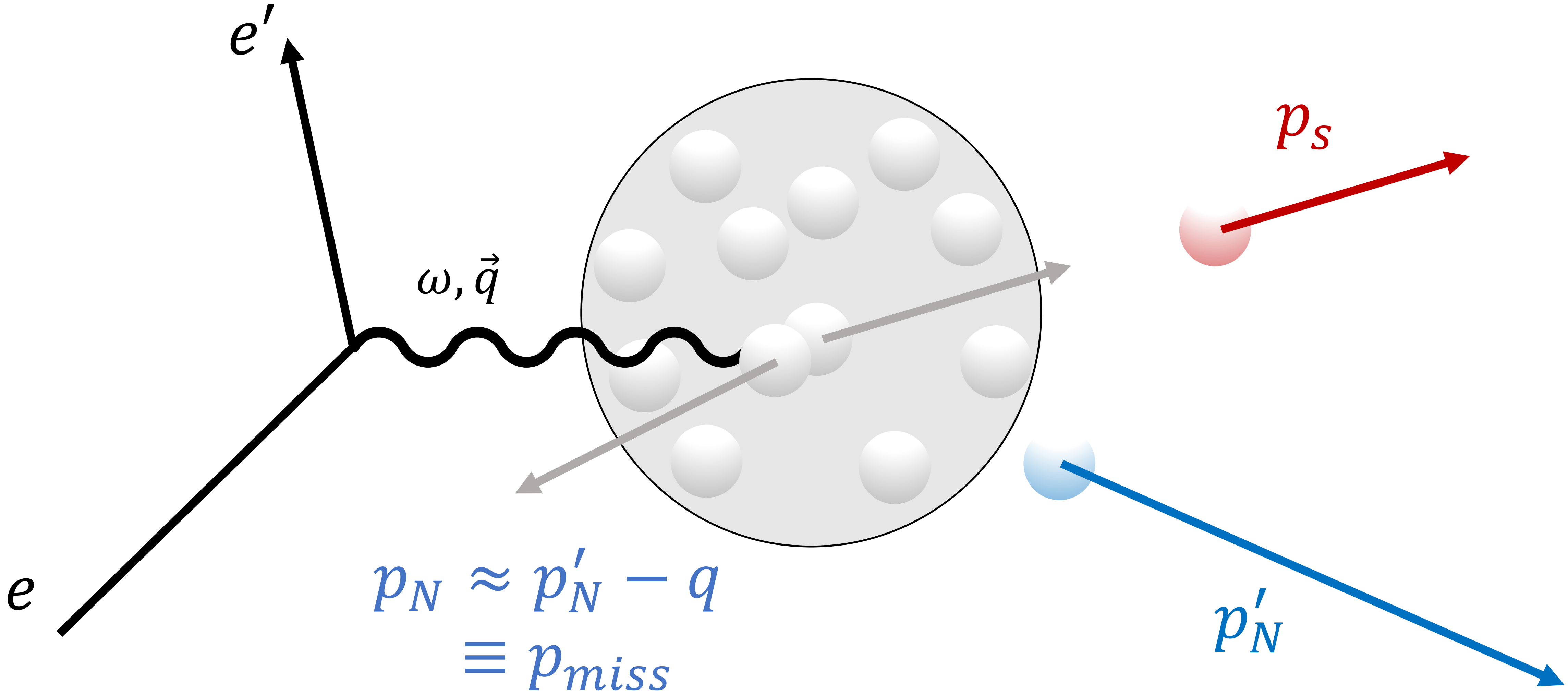
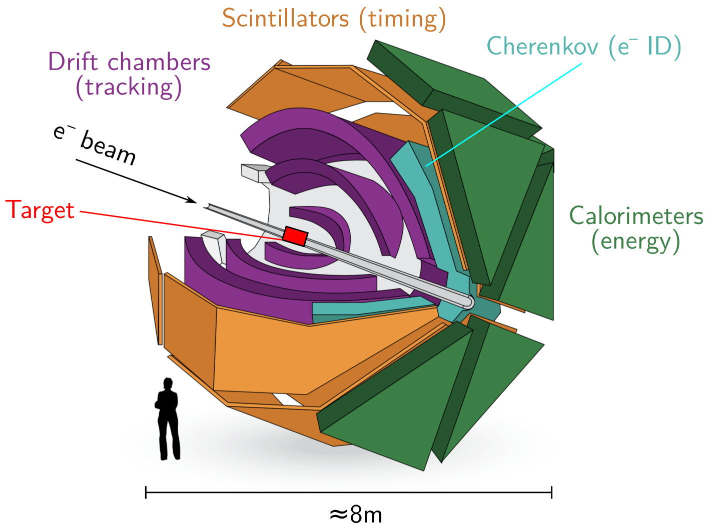
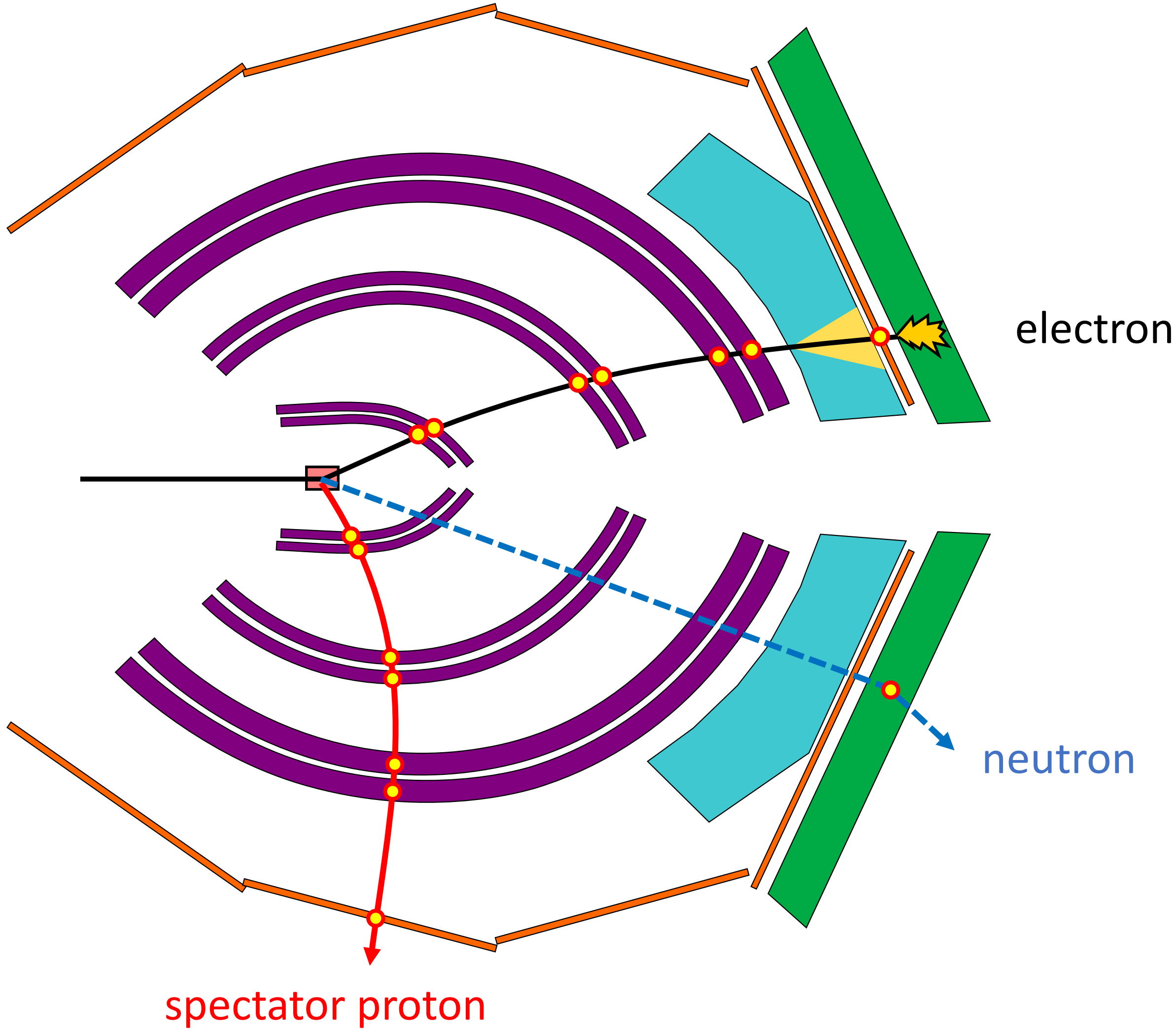


Quasi-elastic electron scattering has been the tool of choice.

CLAS, JLab Hall B

eg2 Experiment (2004)
- 5 GeV beam
- d, C, Al, Fe, Pb targets





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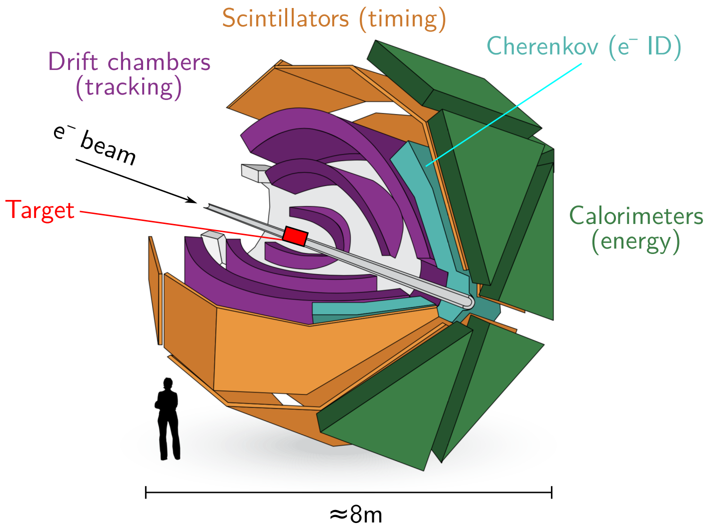

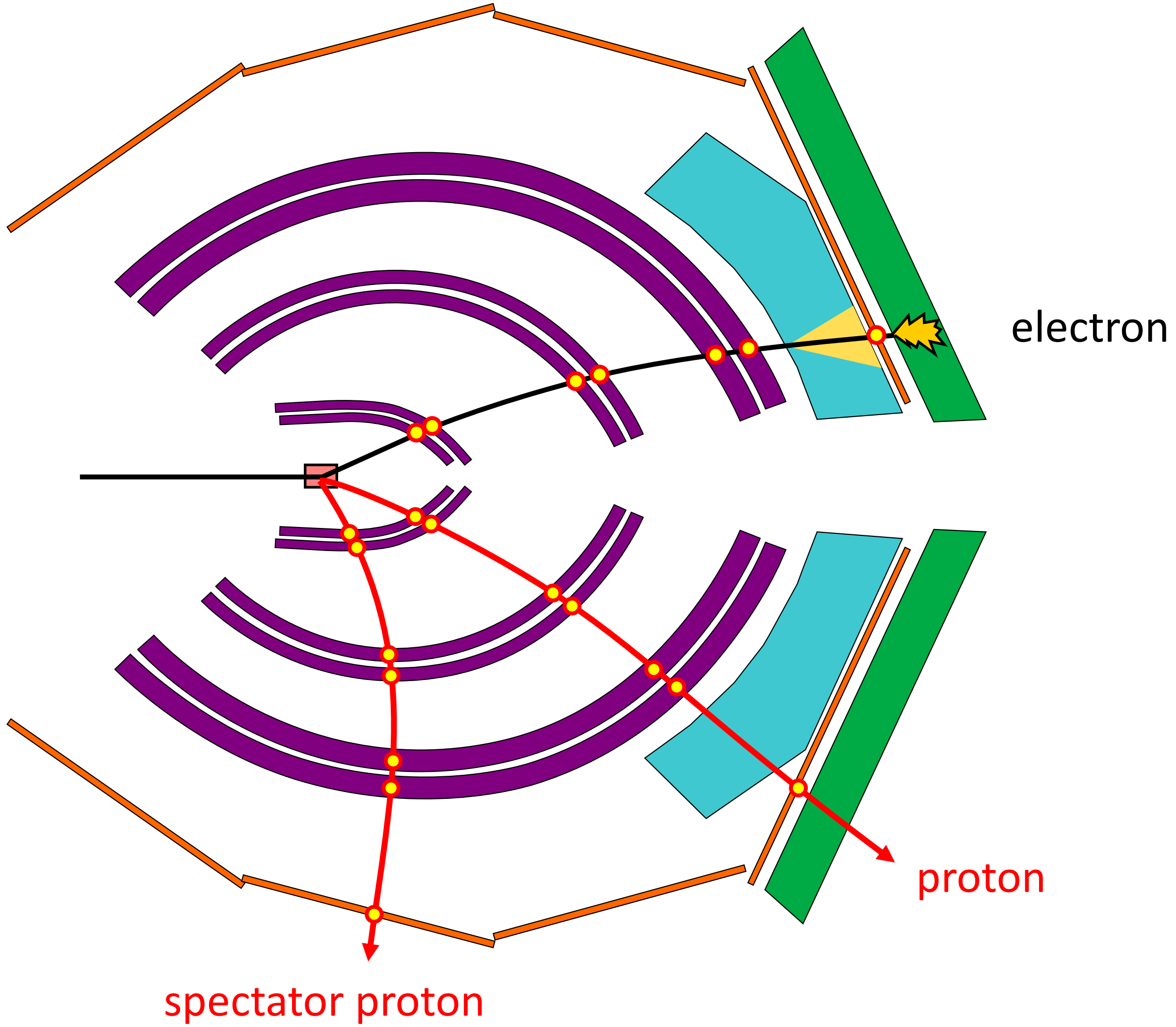

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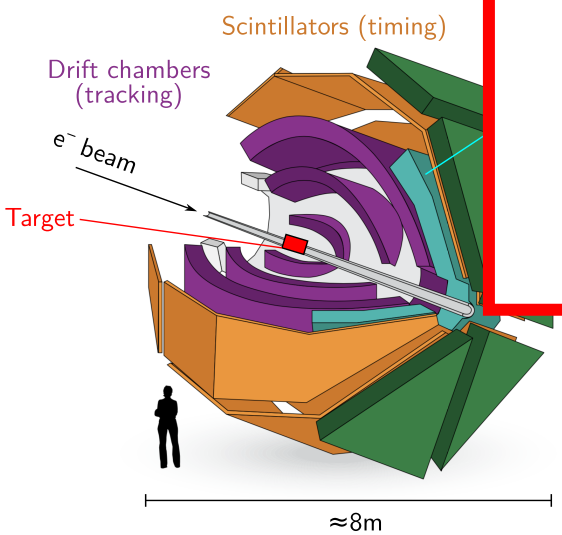
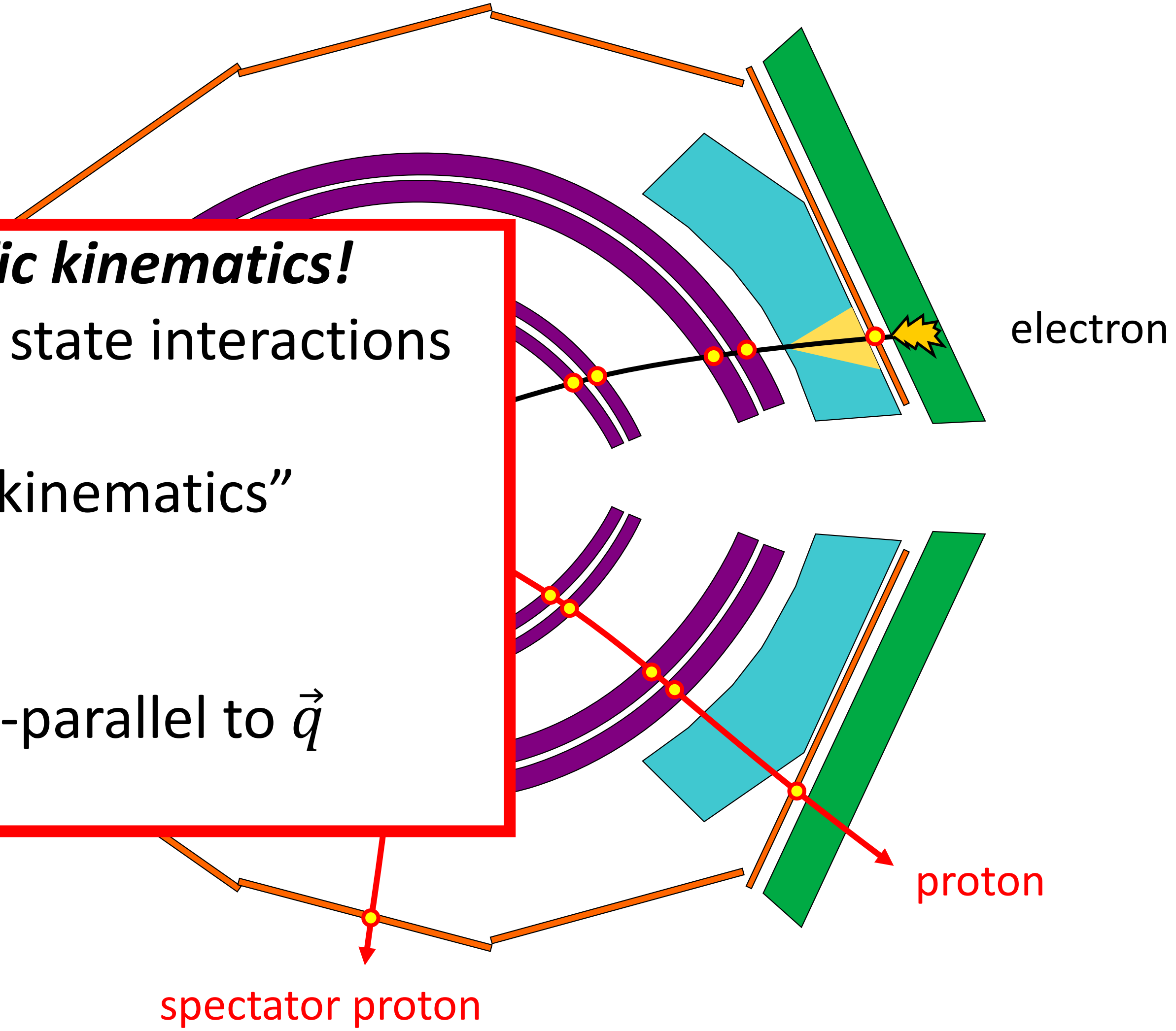


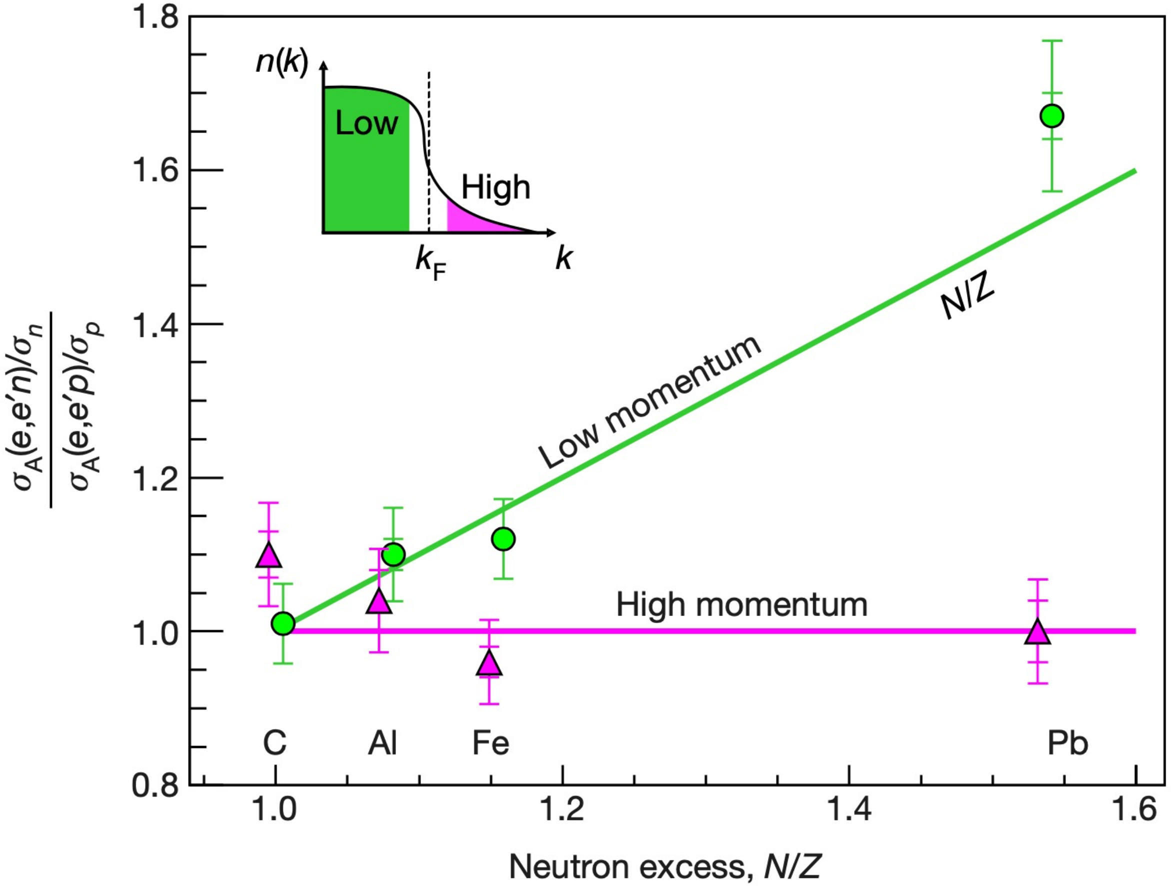
Very specific kinematics!
to suppress final state interactions

- “Anti-parallel kinematics”
  - $x_B > 1$
  - Large Q^2
  - $\vec{\boldsymbol{p}}_{miss}$ anti-parallel to $\vec{q}$



The SRC regime still has equal numbers of protons and neutrons.

Meytal Duer



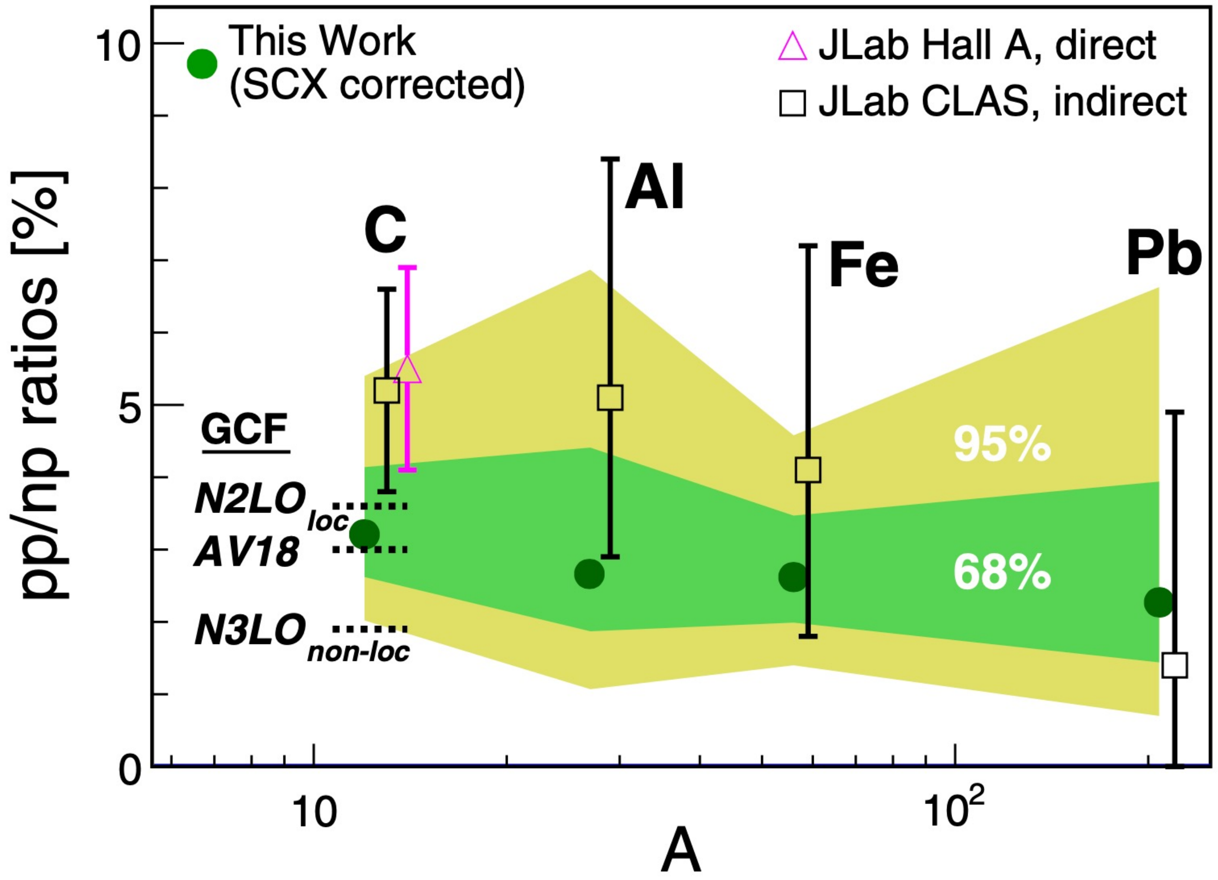
Non-correlated nucleons

SRC nucleons

M. Duer et al., Nature 560, p. 617, (2018)

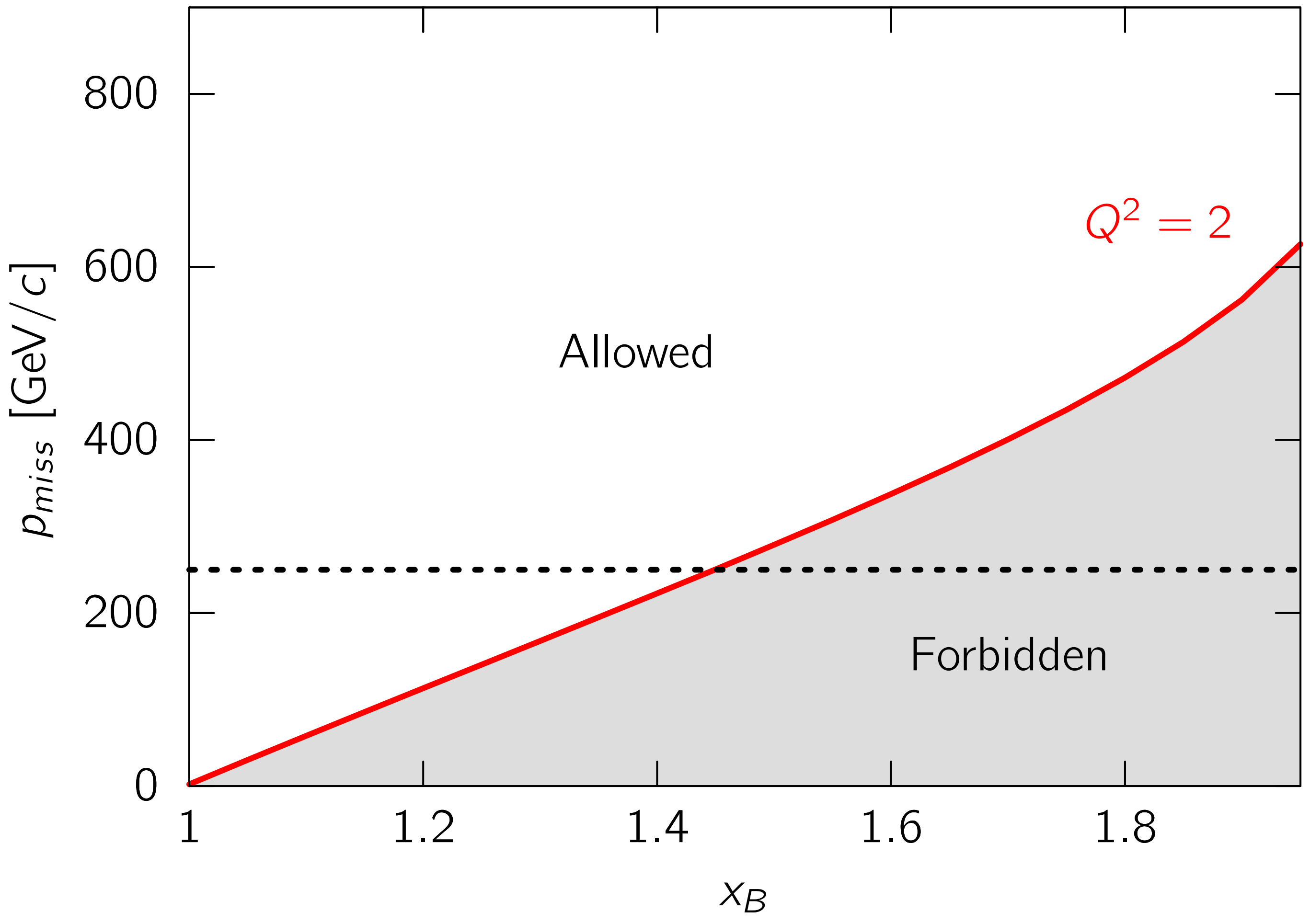
Correlated protons are predominantly in neutron-proton pairs.

Meytal Duer

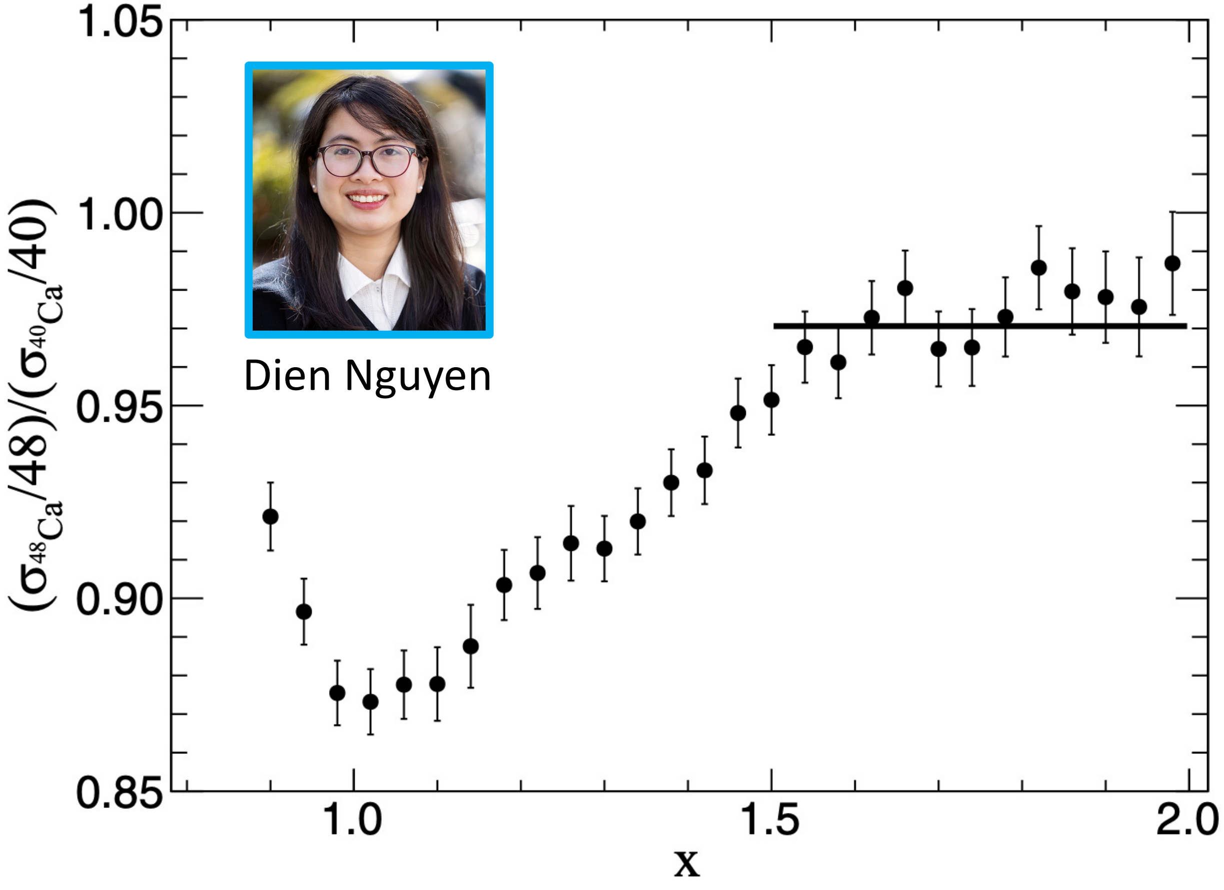


M. Duer et al., PRL 122, 172502 (2019)
O. Hen et al., Science 346, p. 614 (2014)

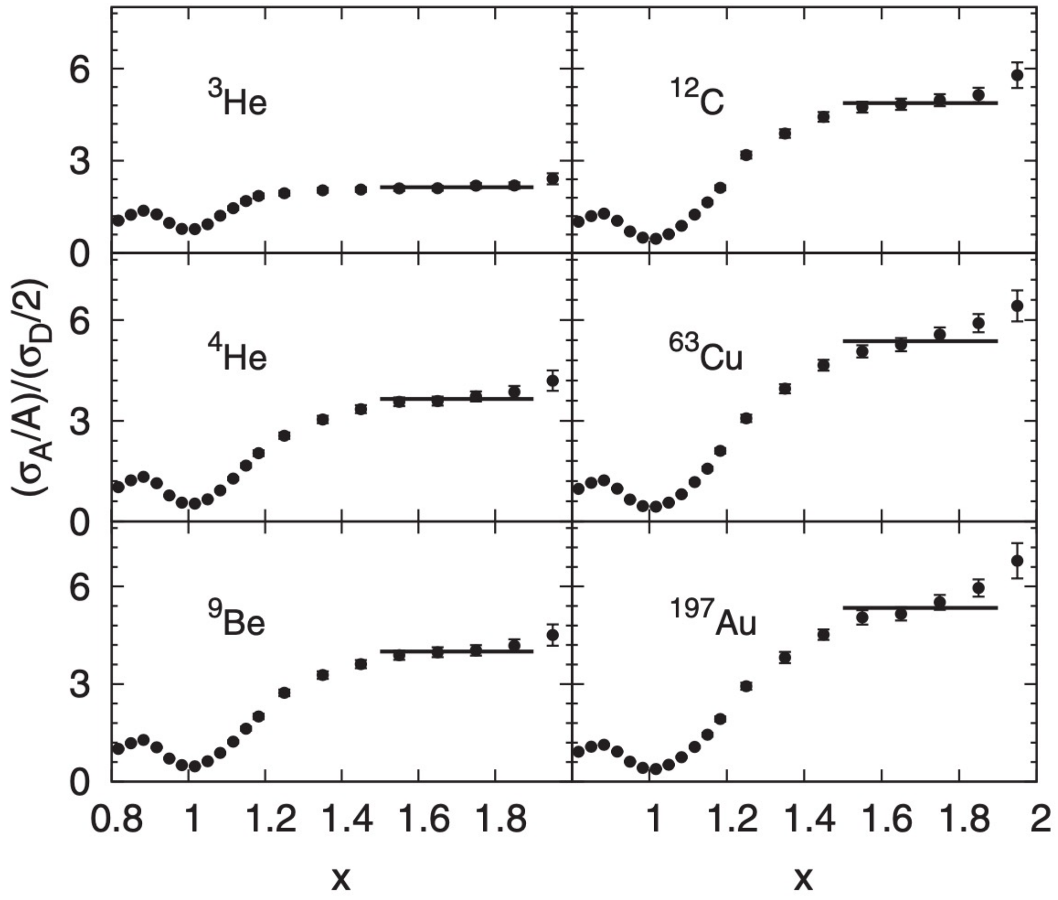
Inclusive scattering at high x_B can also tell you about short-range correlations.



At $x_B \gtrsim 1.5$, inclusive cross sections scale, indicating correlations.



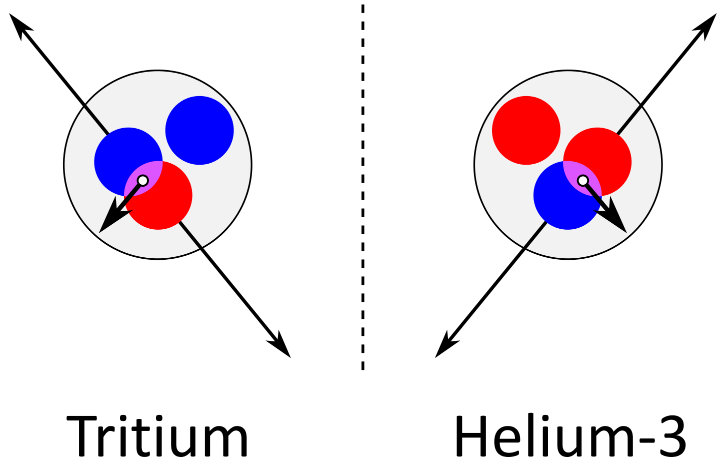
D. Nguyen et al., PRC 102, 064004 (2020)



N. Fomin et al., PRL 108, 092502 (2012)

Inclusive scattering can reveal relative pairing between pn and pp pairs.

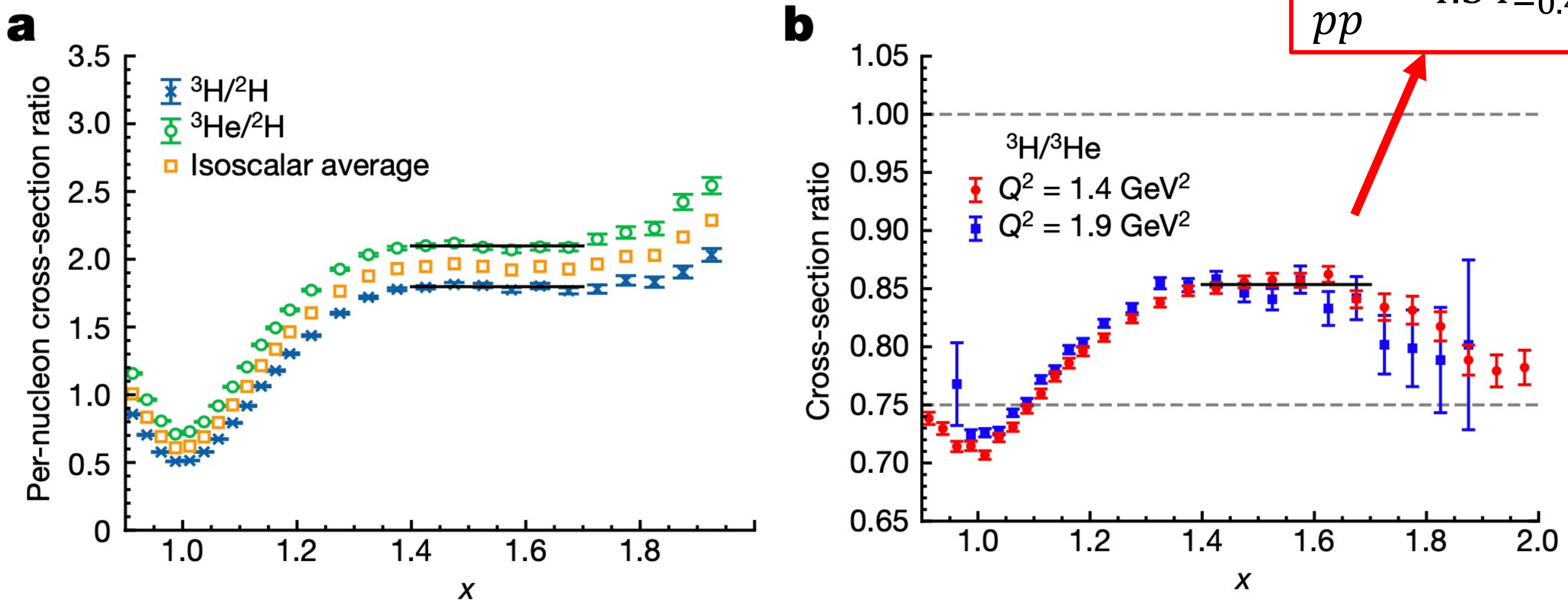
Compare isospin mirror nuclei.



$$R \equiv \frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{1 + \frac{\sigma_{ep}}{\sigma_{en}} + 2\left(\frac{pp}{np}\right)}{1 + \frac{\sigma_{ep}}{\sigma_{en}} + 2\left(\frac{pp}{np}\right)\frac{\sigma_{ep}}{\sigma_{en}}}$$

Preference for np pairs is less strong in the A=3 system.

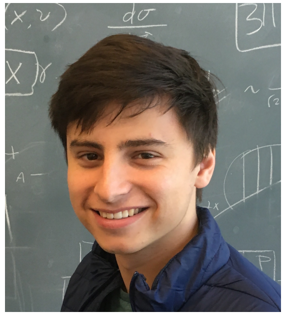
$$\frac{np}{pp} = 4.34^{+0.49}_{-0.40}$$



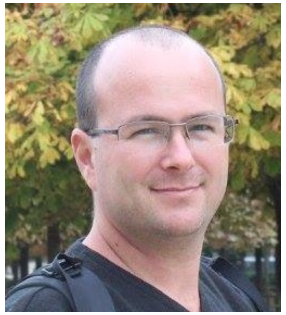
S. Li et al. (Hall A), Nature 609 p. 41 (2022)

By rejecting non-QE background, scaling can even persist down to $x_B = 1$.

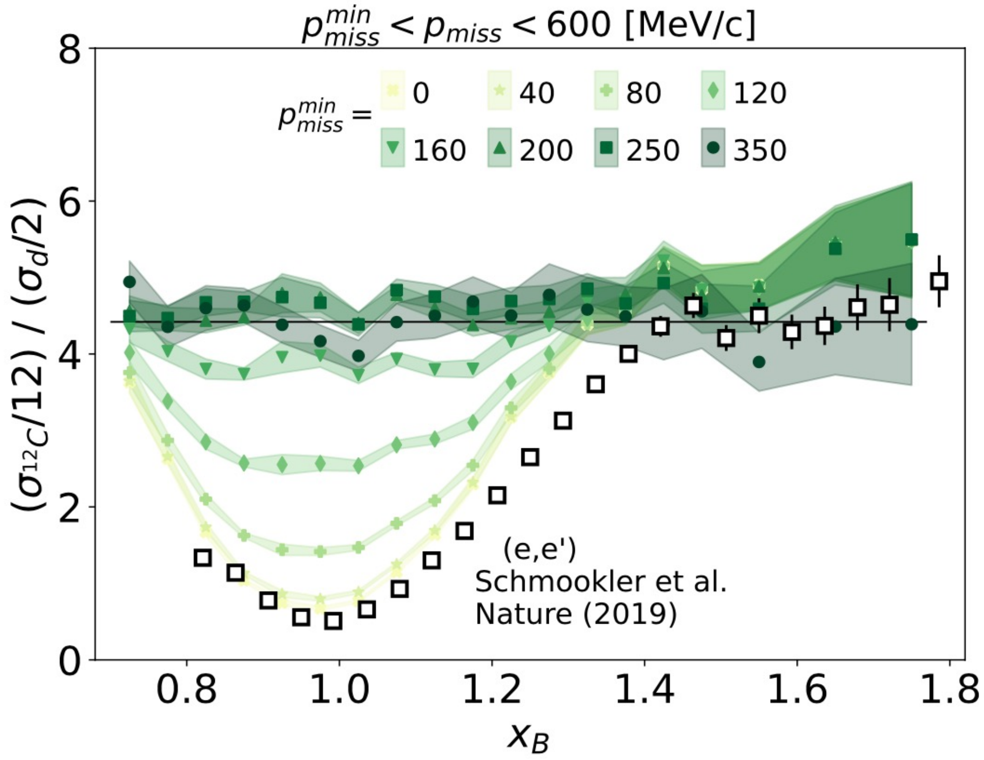
$(e, e'p)$ data from CLAS

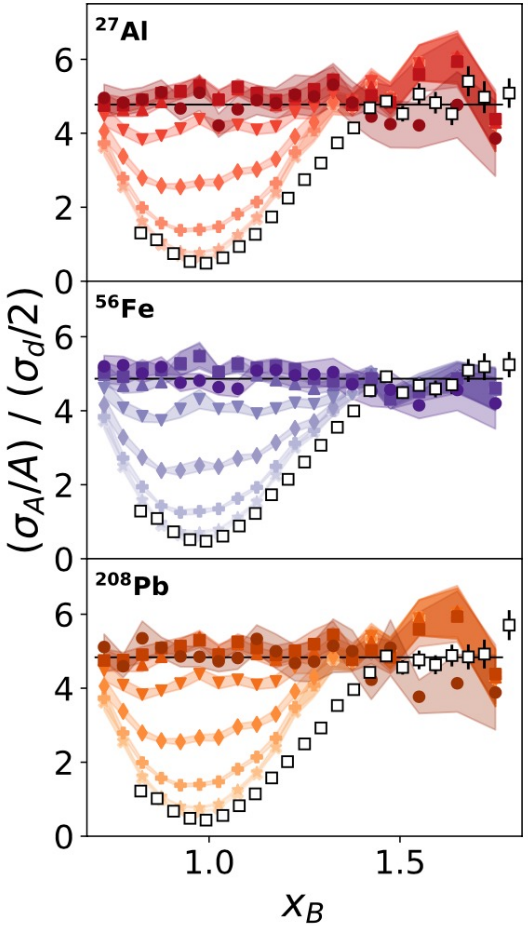


Andrew Denniston



Igor Korover





I. Korover, A. Denniston et al. (CLAS), arXiv:2209.01492 (2022)

This technique allows the study of the MF to SRC transition region.

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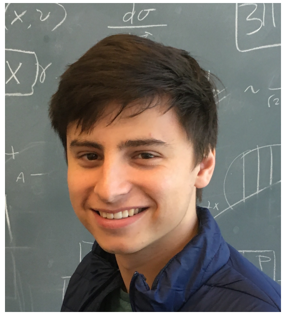

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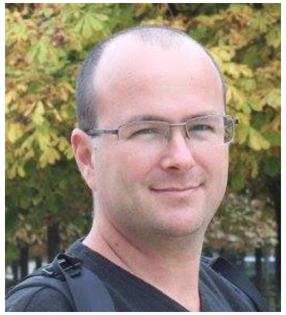

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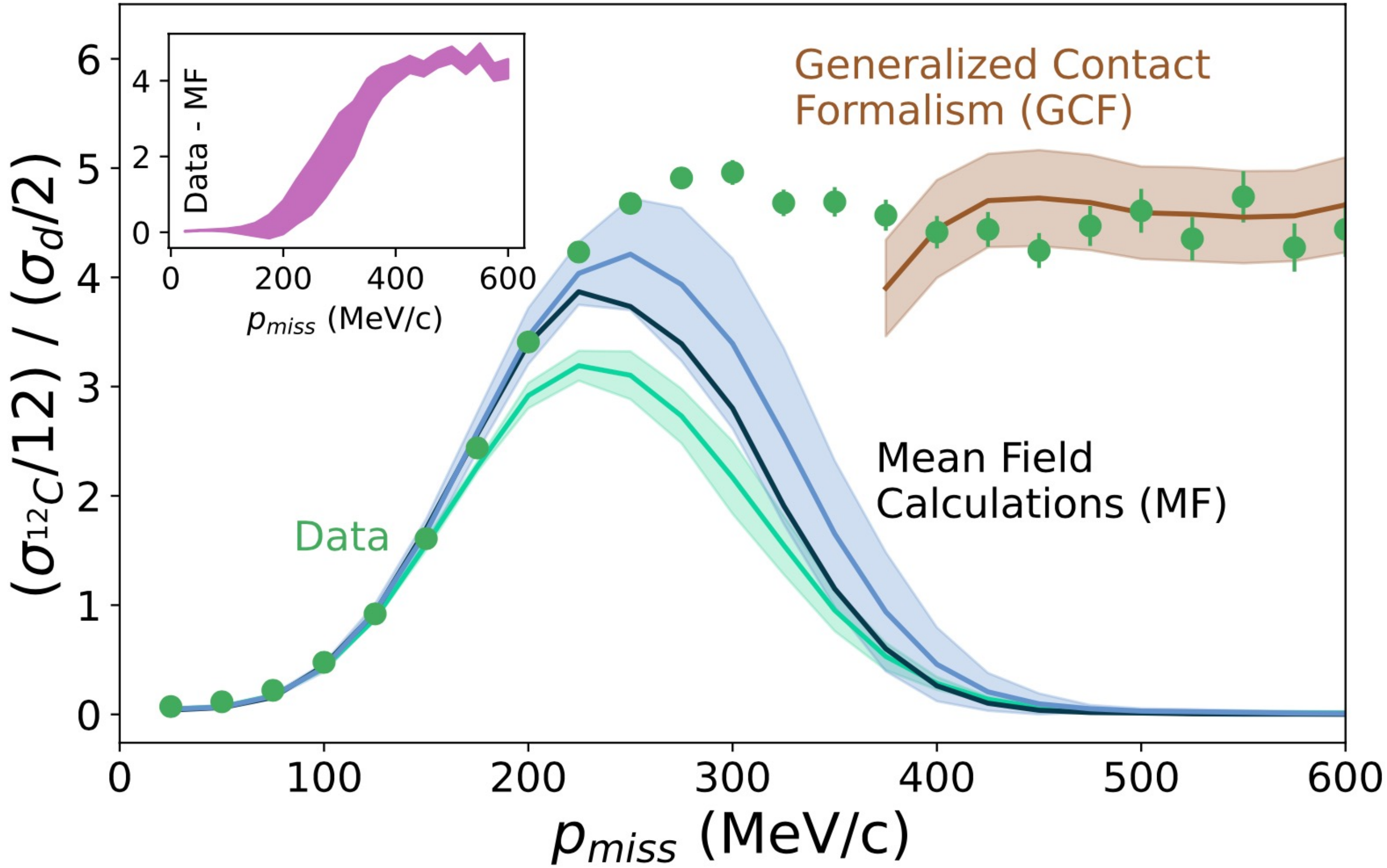

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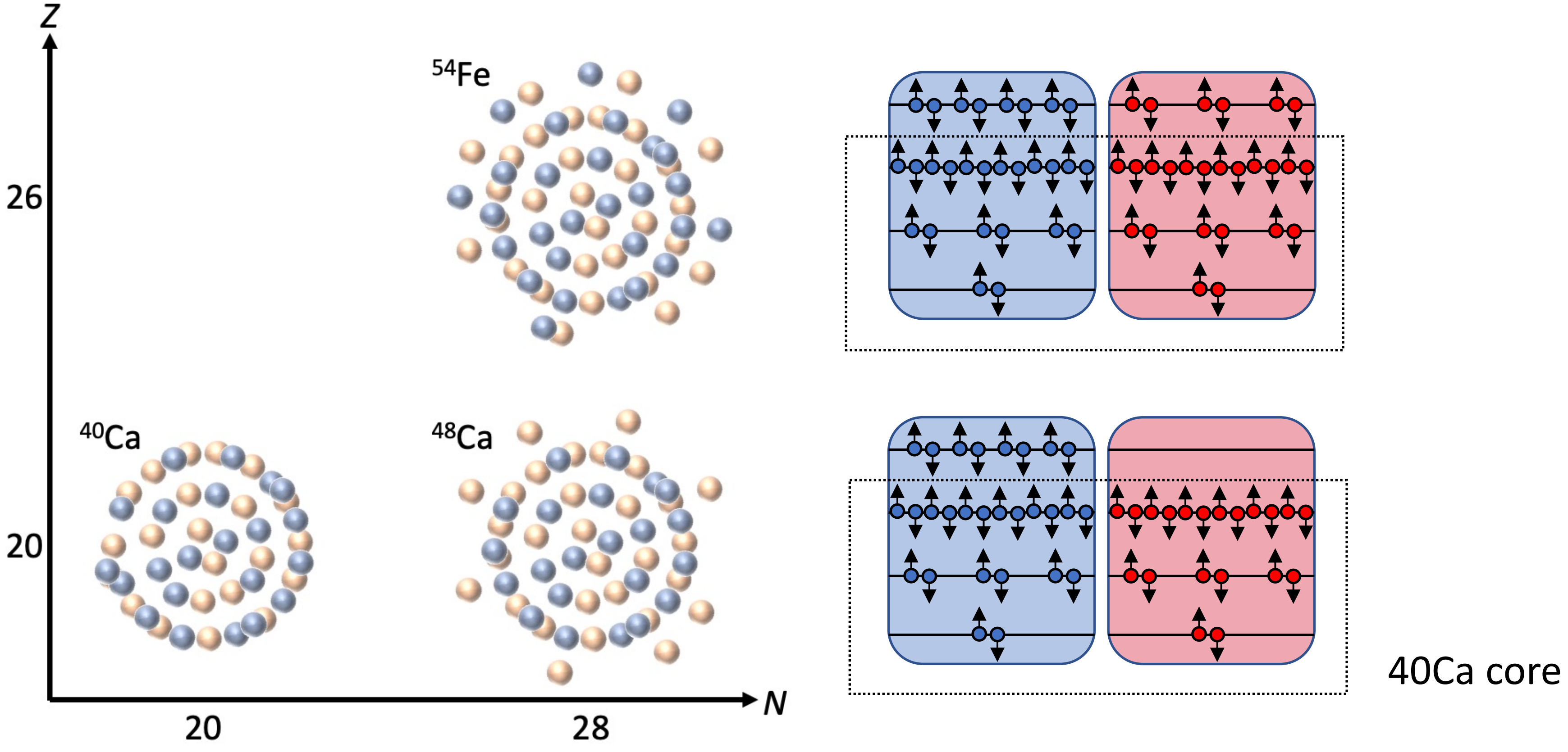
New data on asymmetric nuclei are under analysis!

- Hall C
  - Experiments *this year* covered Be, B, 40Ca, 48Ca, 54Fe
  - Inclusive x>1 experiment
  - CaFe $(e, e'p)$ experiment
  - See Dien and Burcu's talks later today

- CLAS-12
  - Nuclear targets experiment, 2021–22
  - 40Ca, 48Ca targets

The 40Ca, 48Ca, 54Fe system can teach us about pairing mechanisms.



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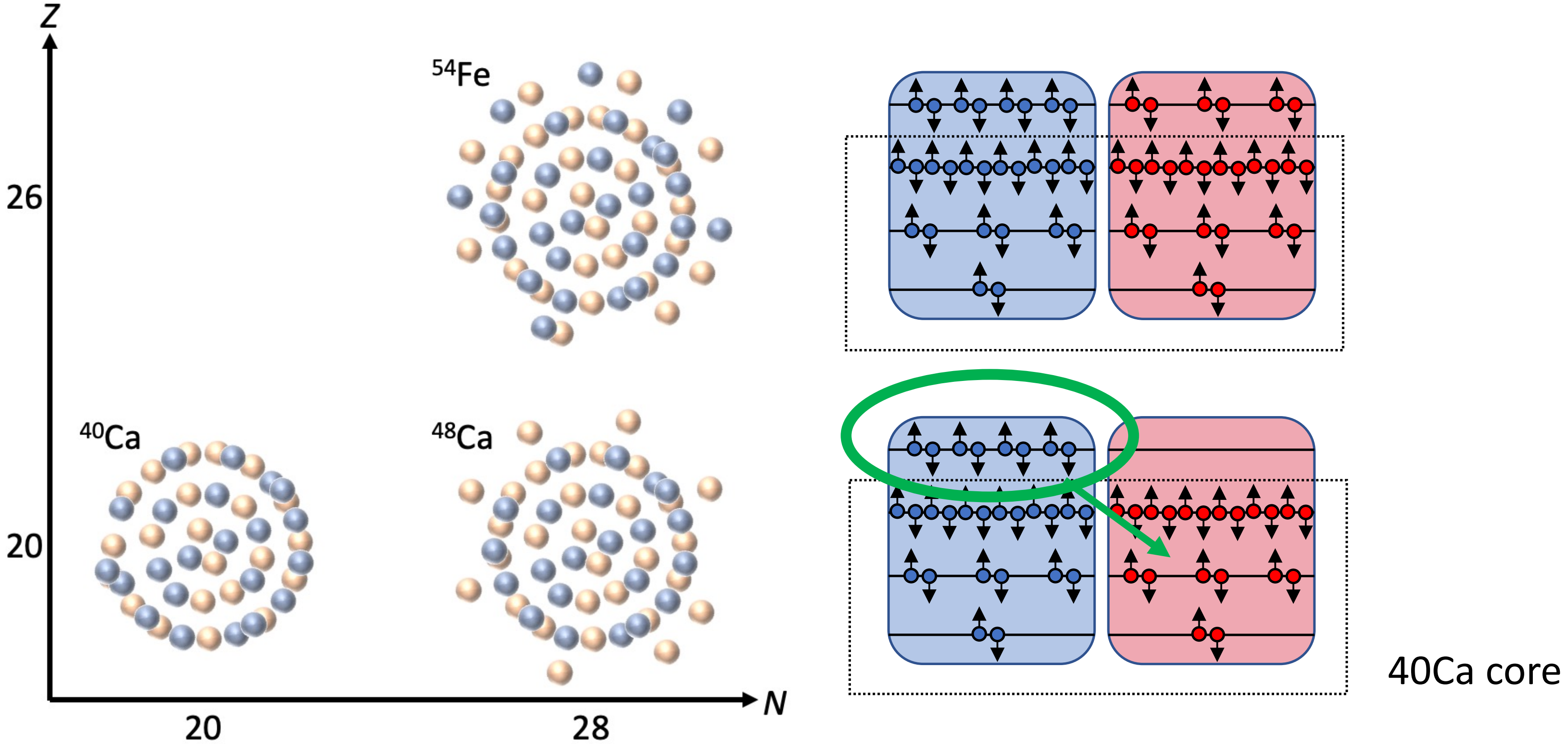

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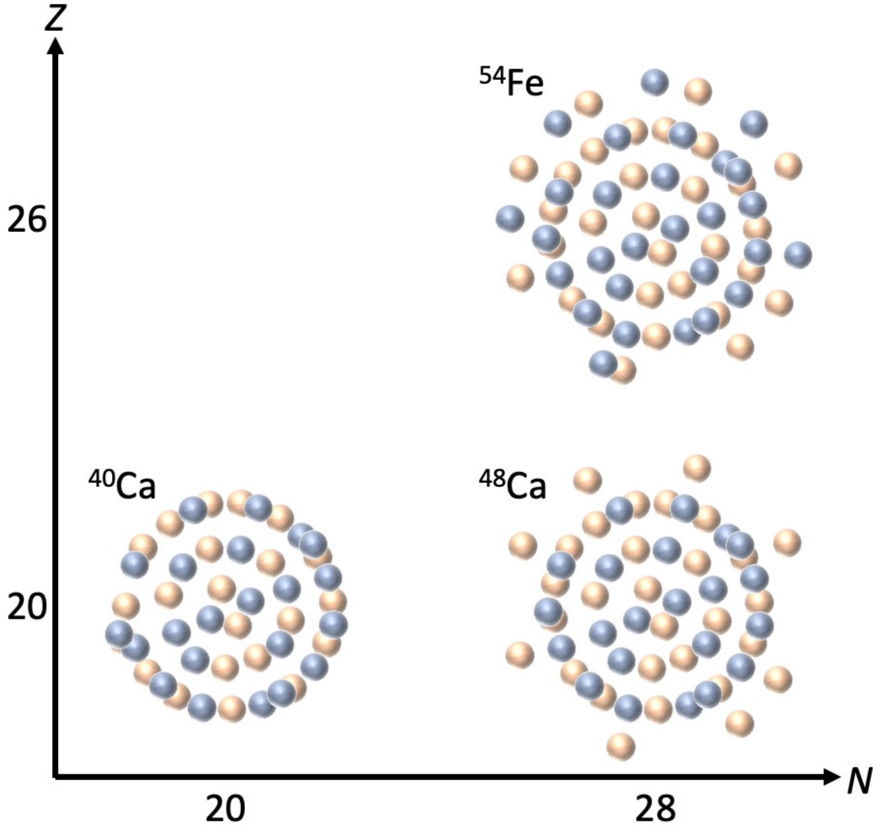

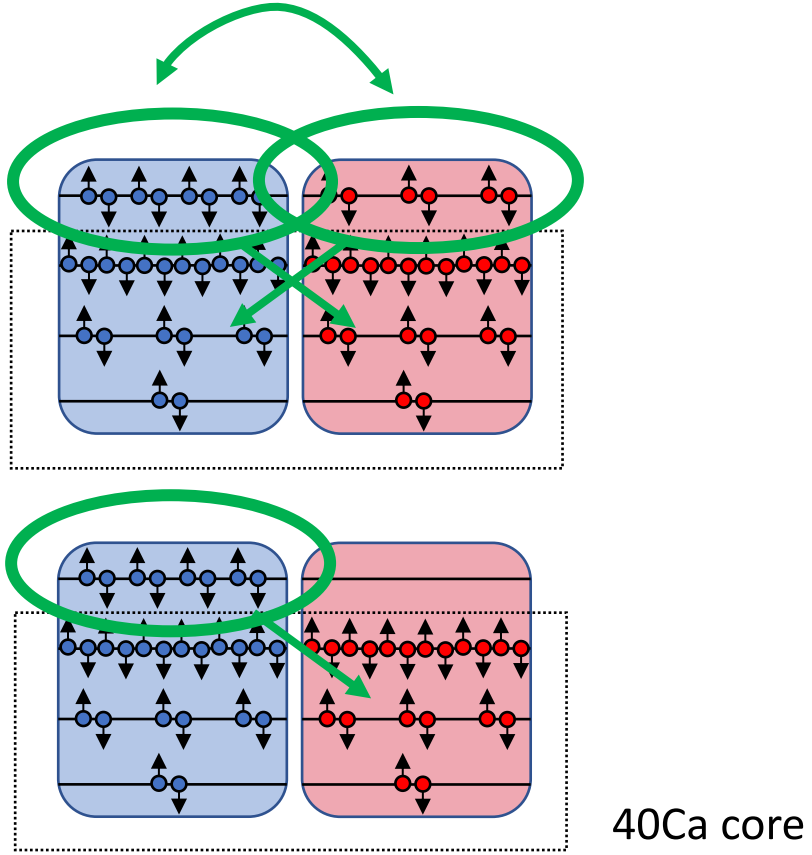

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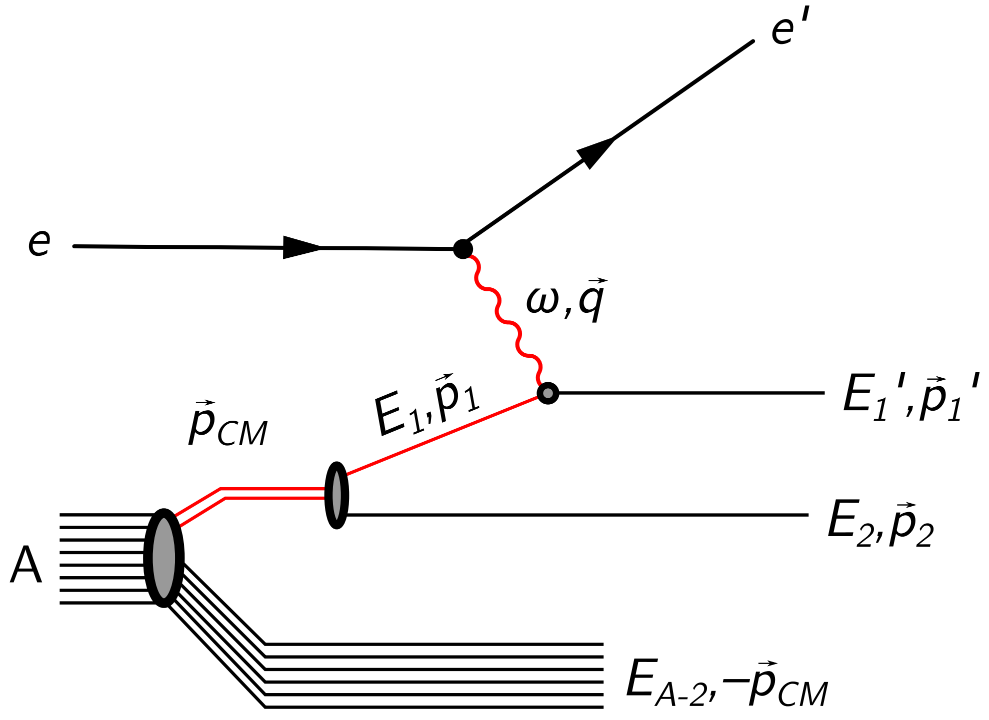
Data are well-described by a high-momentum factorized picture.

Generalized Contact Formalism

(see Ronen Weiss's talk this afternoon)



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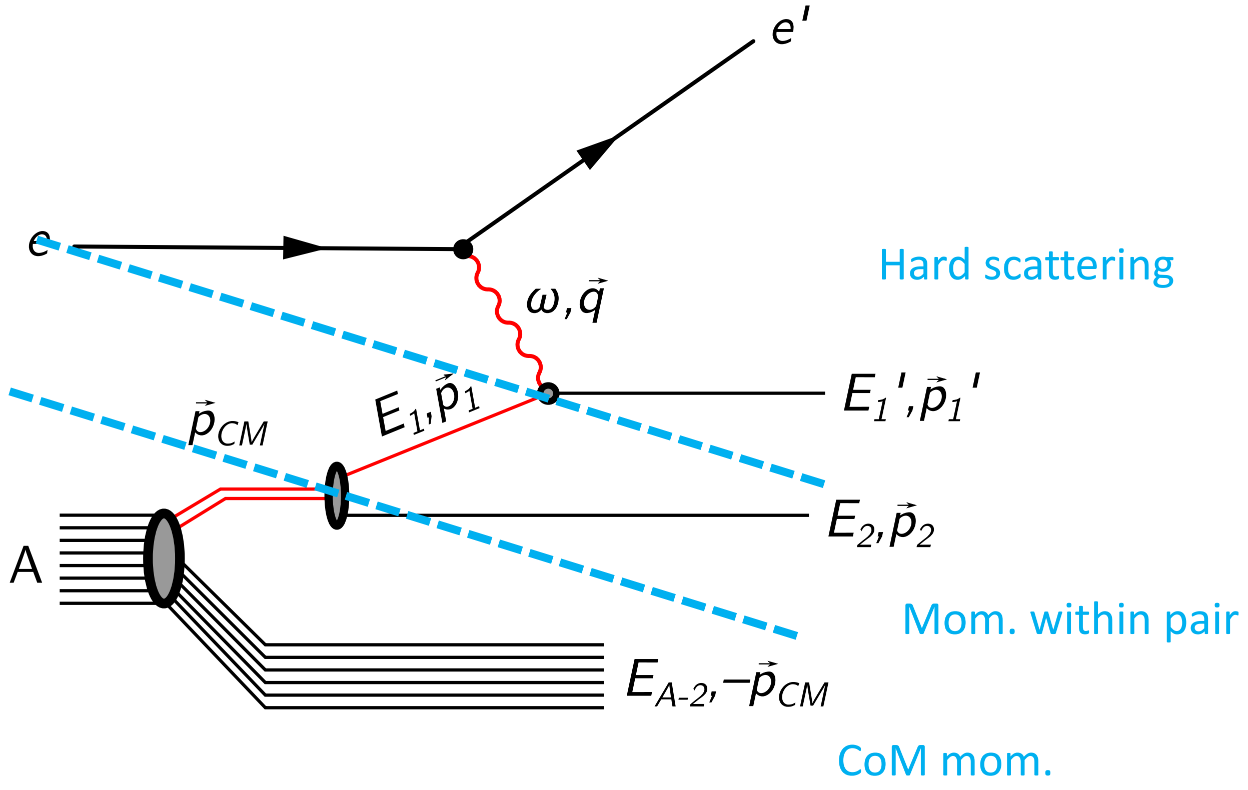

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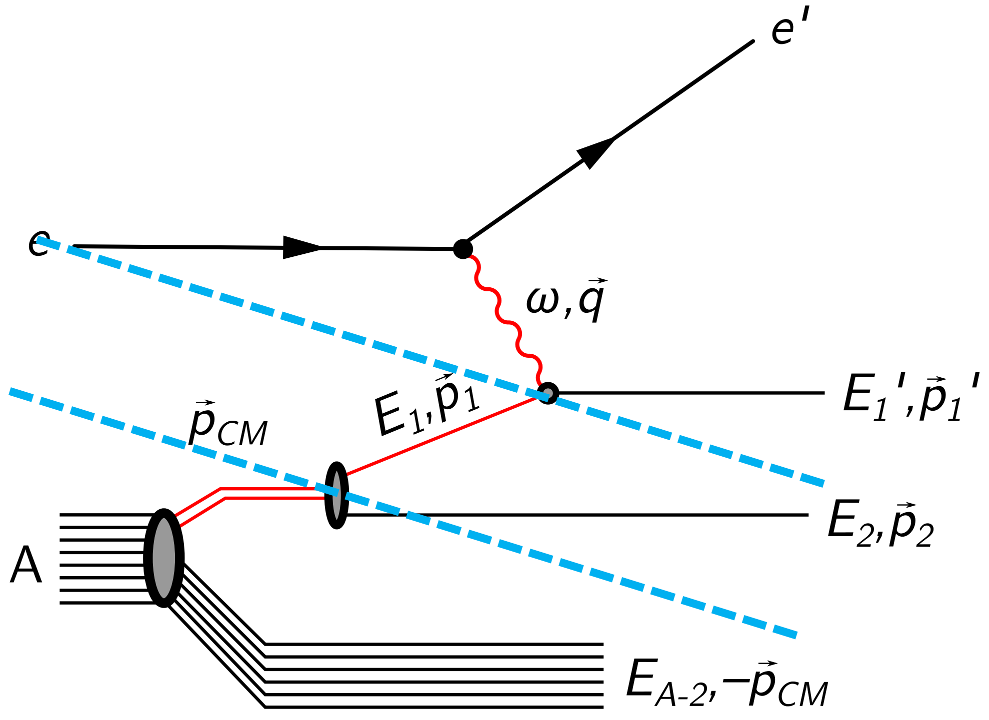

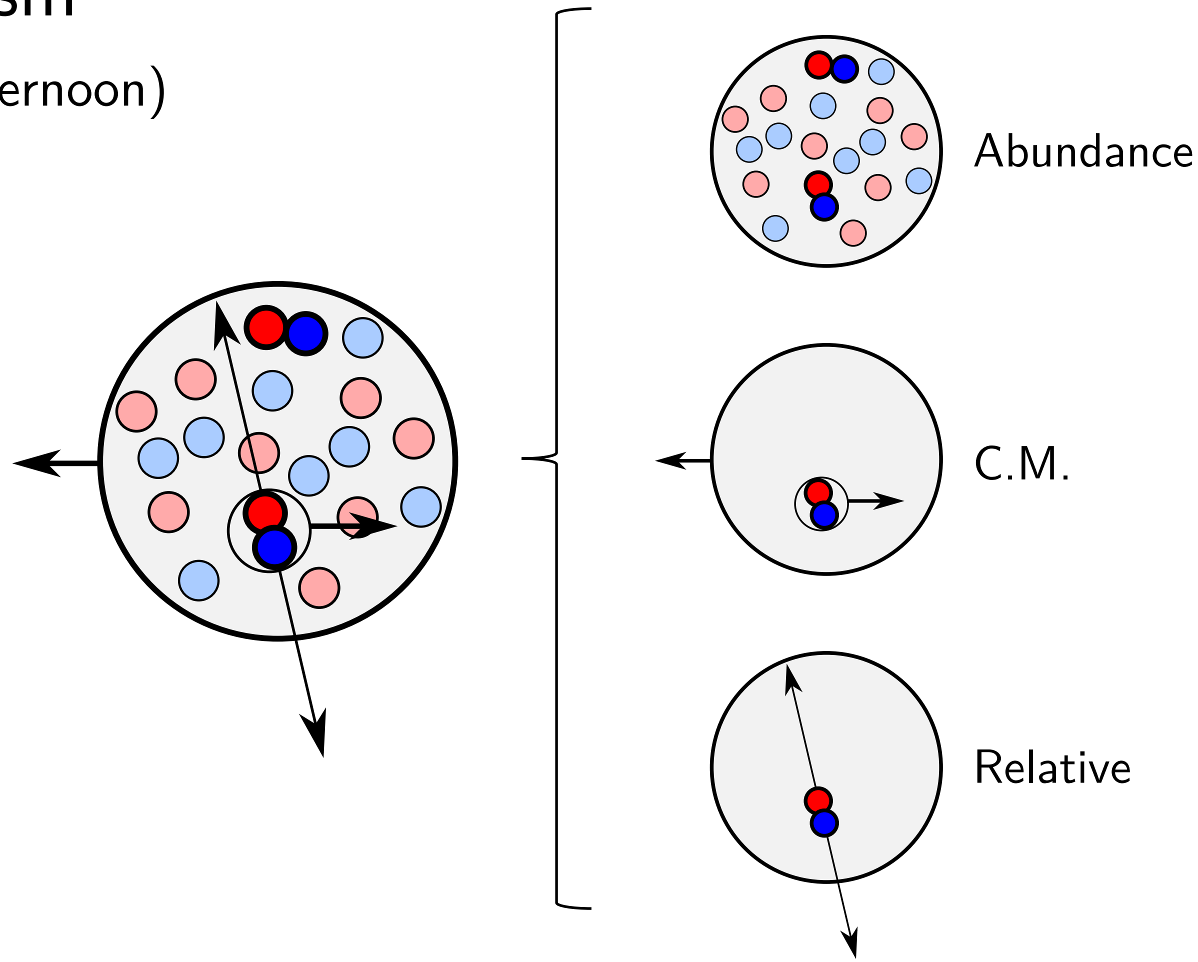

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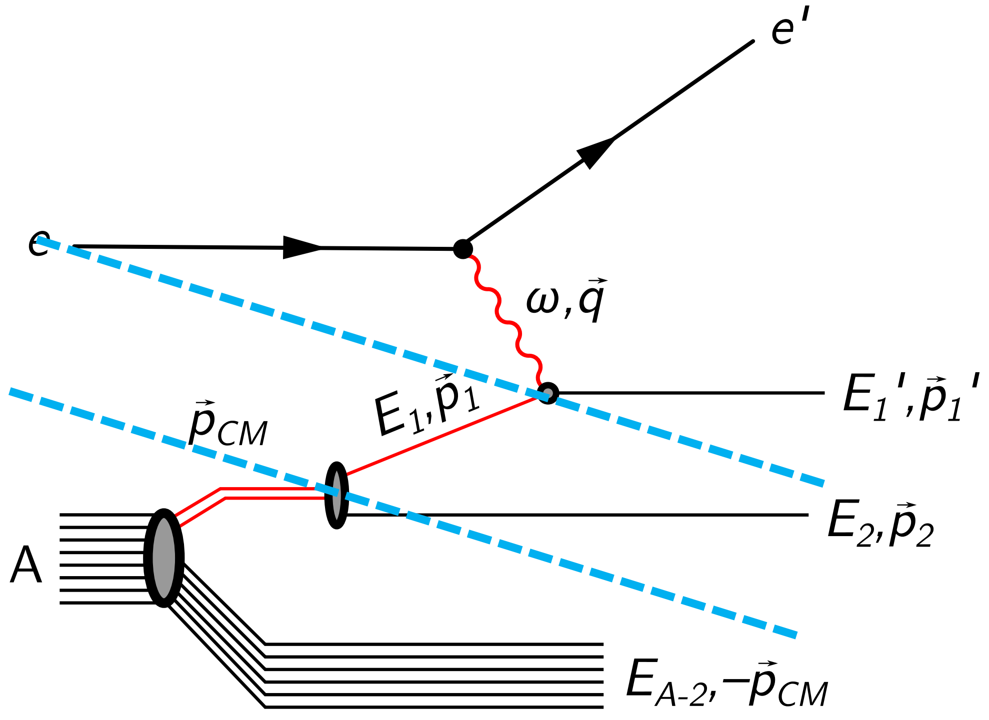
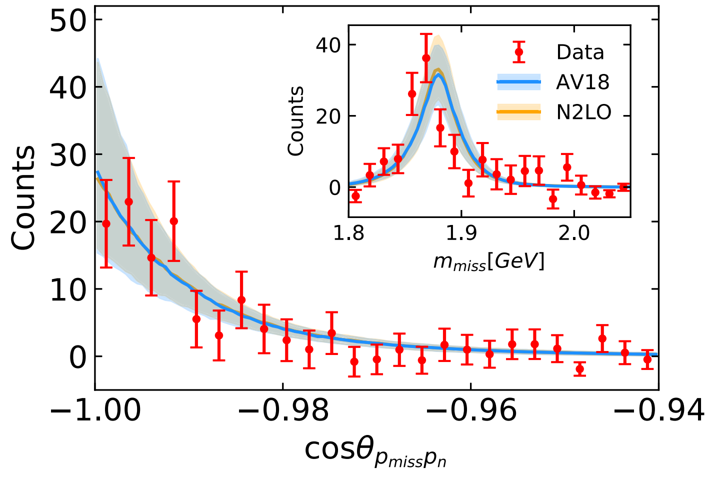
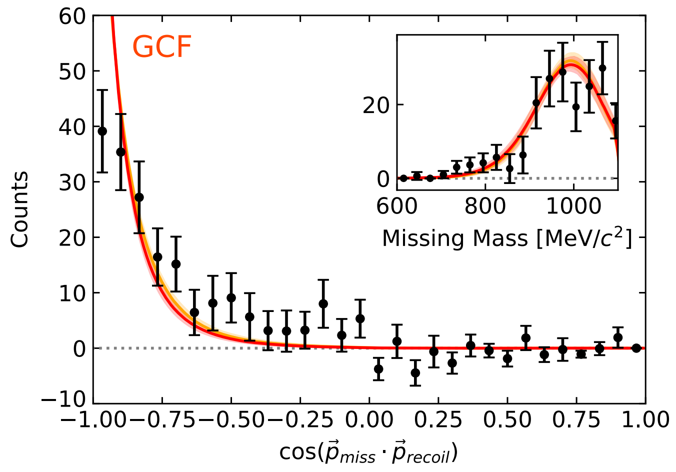




J. R. Pybus et al., Phys. Lett B 805, 135429 (2020)



I. Korover et al., Phys. Lett B 820, 136523 (2021)

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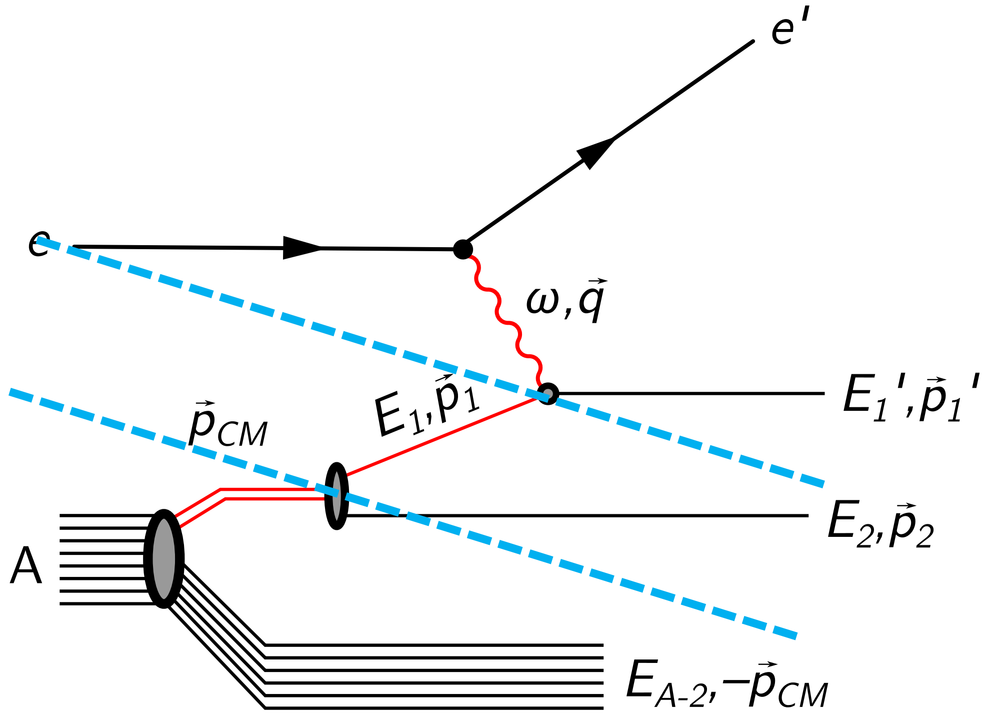
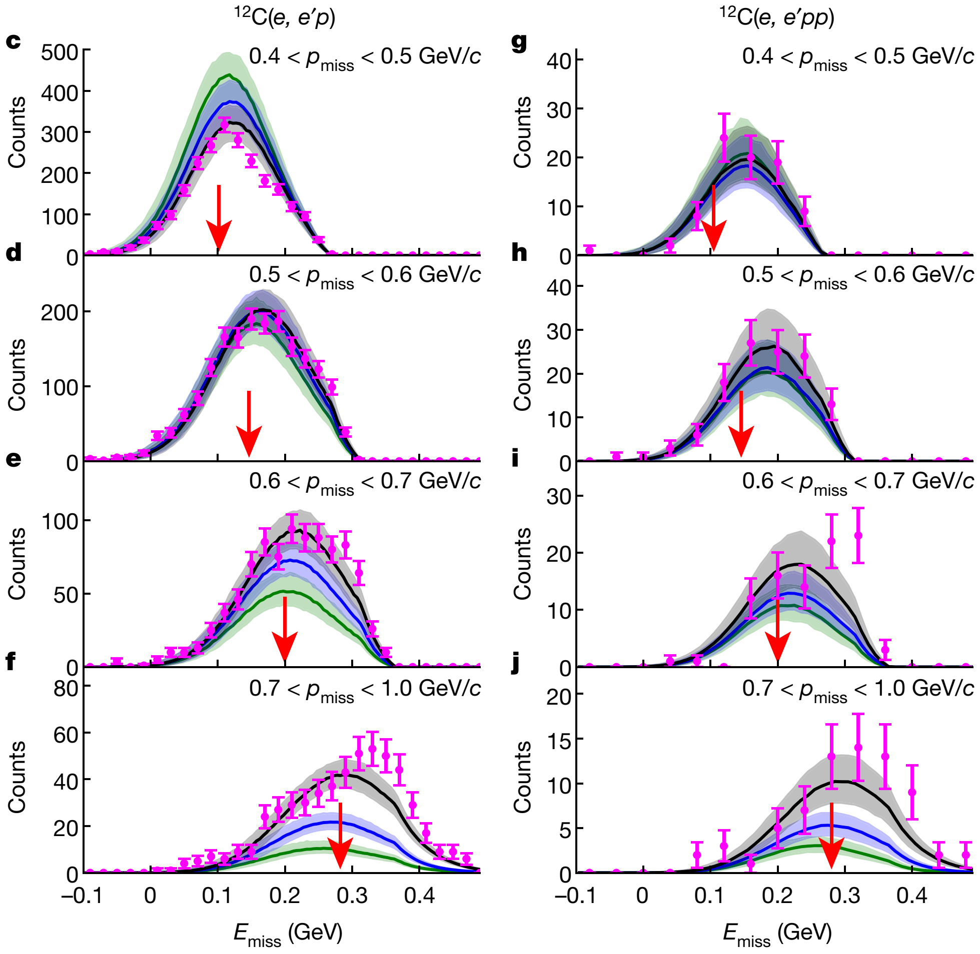
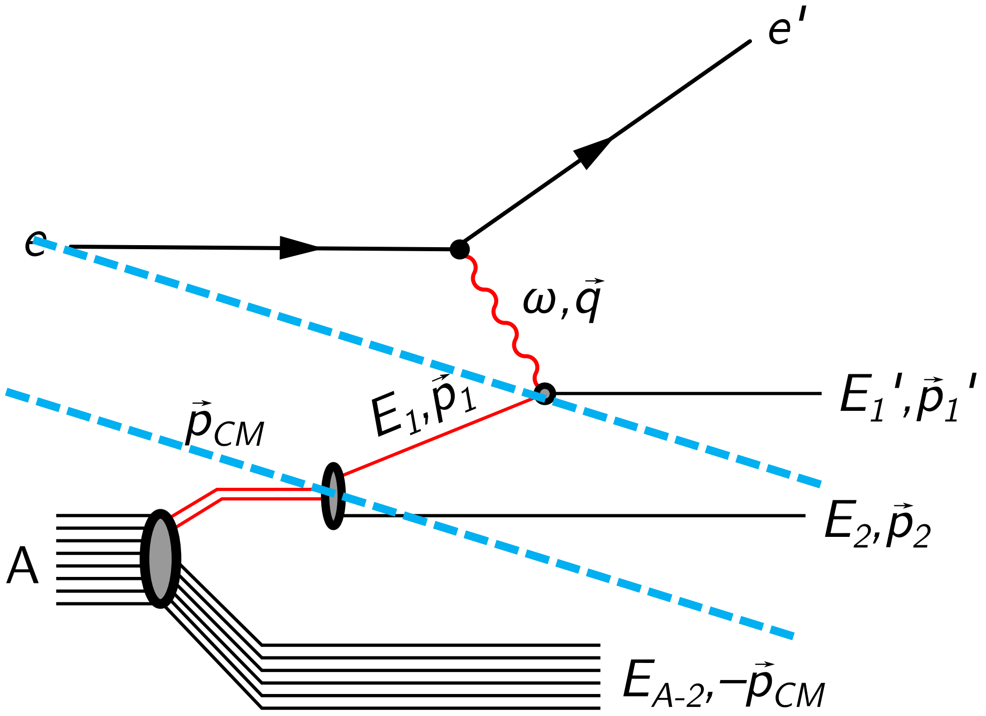


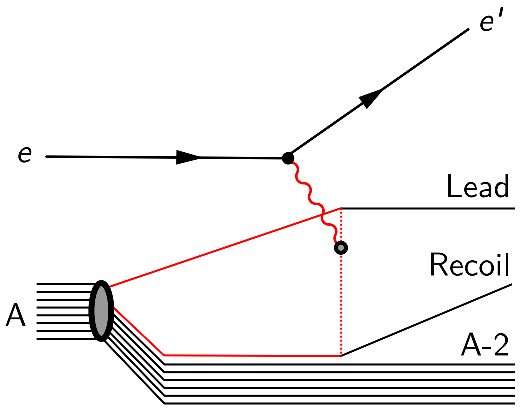


A. Schmidt et al., Nature 578, p. 540 (2020)

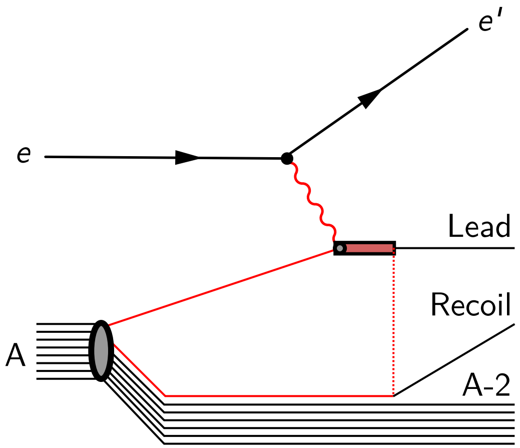
The detection of hadrons is complicated by final-state interactions.

Plane-Wave Scattering

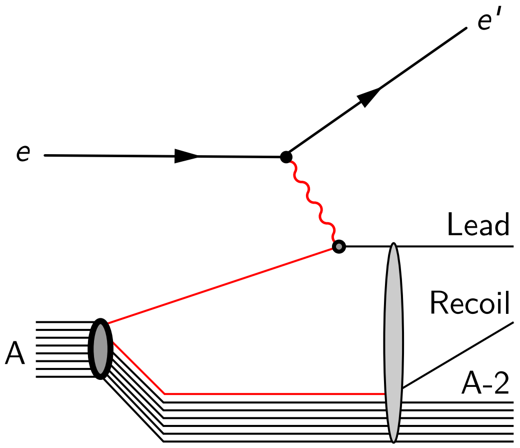




Meson-Exchange Currents



Isobar Configurations

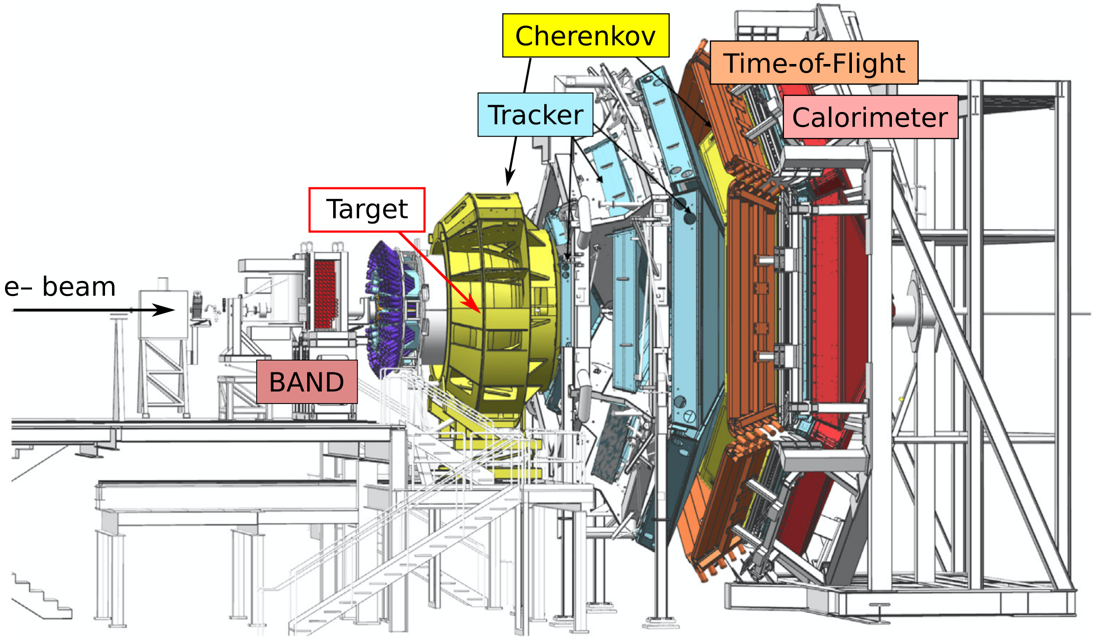


Final-State Rescattering

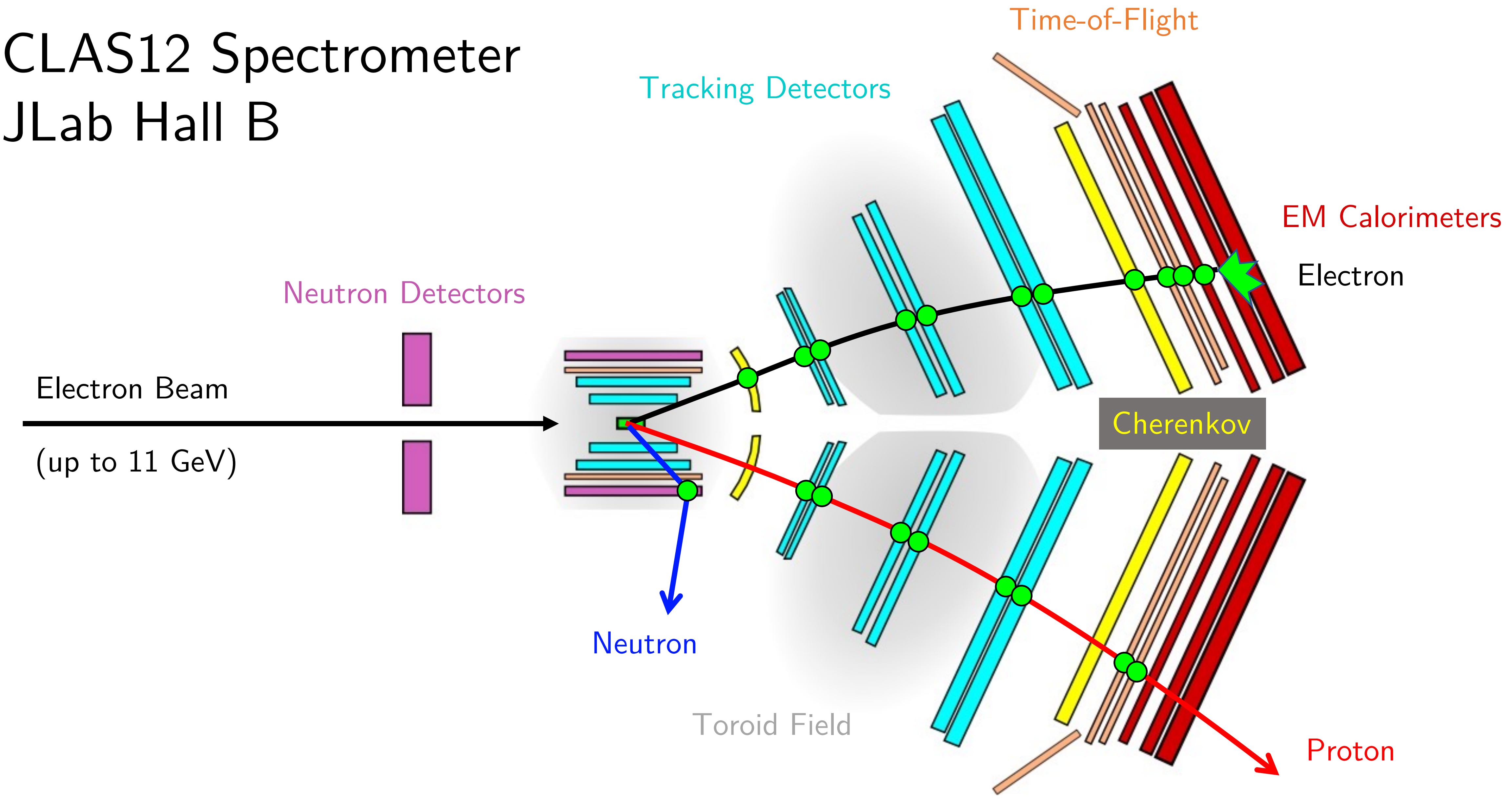
CLAS12 SRC Experiment (Run Group M)

JLab E12-17-006A

- Nov 10, 2021 – Feb 7, 2022
- > 300 fb^{-1}
  - $>$10x improvement over CLAS6
- Targets: H, d, ^{4}He, ^{12}C, ^{40,48}Ca, ^{120}Sn
- 2, 4, and 6 GeV beam
- CLAS12 Spectrometer

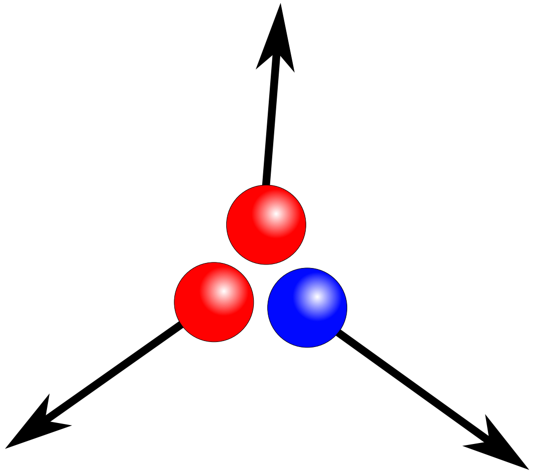


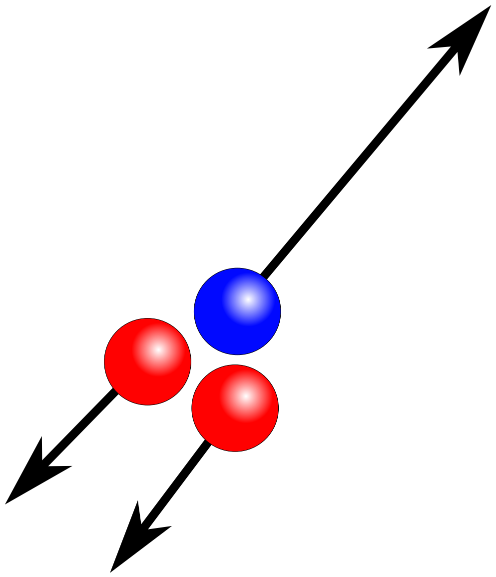
CLAS12 Spectrometer
JLab Hall B



Goal: direct detection of 3N SRCs

Formation mechanism will lead to different structures:





10,000s of 2N SRC Events, hopefully a few hundred 3N SRC events

Fomin, Higinbotham, Sargsian, Solvignon, Ann.Rev.Nucl.Part.Sci. 67 129 (2017)
Day, Frankfurt, Sargsian, Strikman, arXiv:1803.07629 (2018)

Goal: direct detection of 3N SRCs

Different 3N structures lead to very different kinematics.

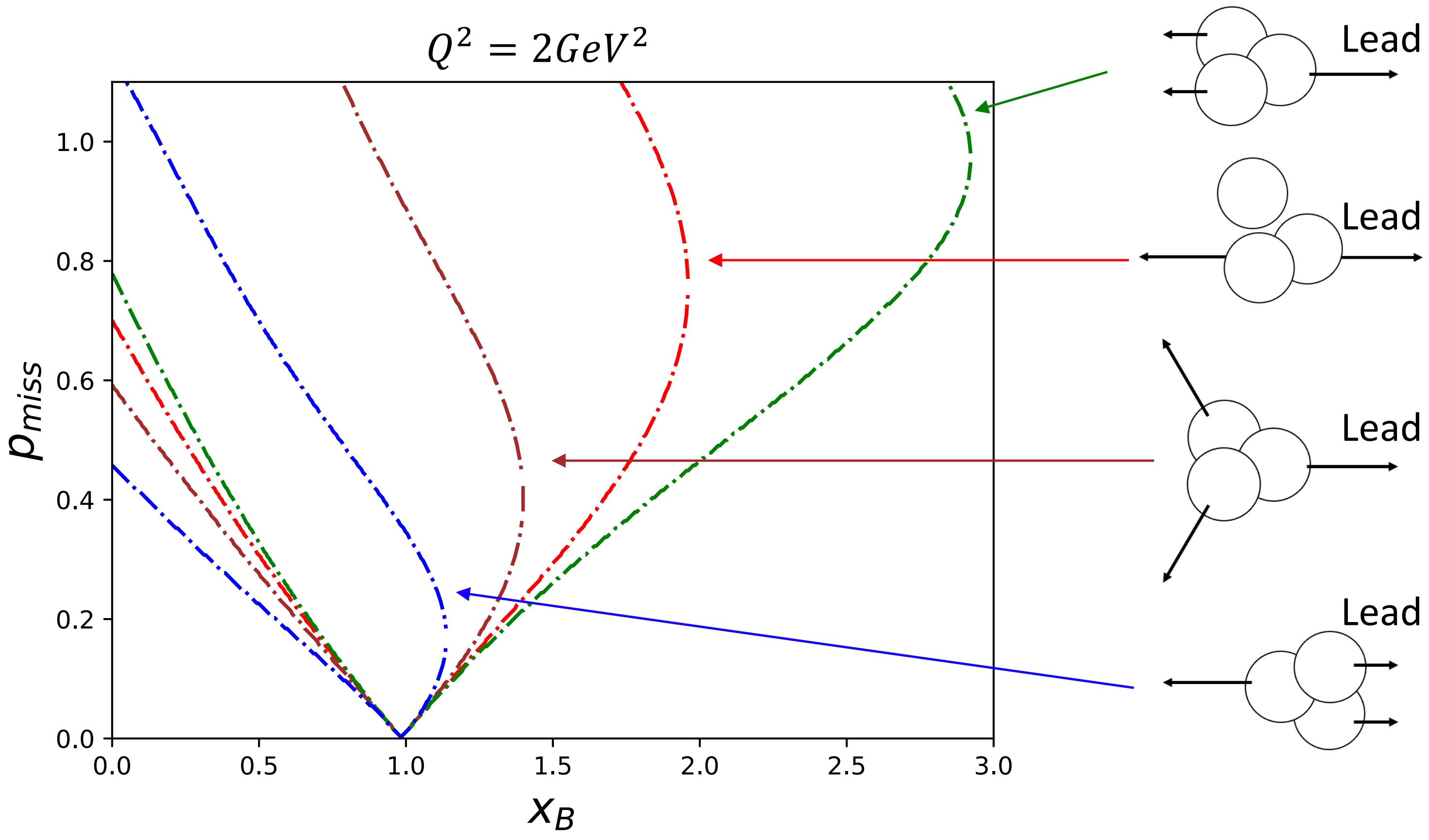
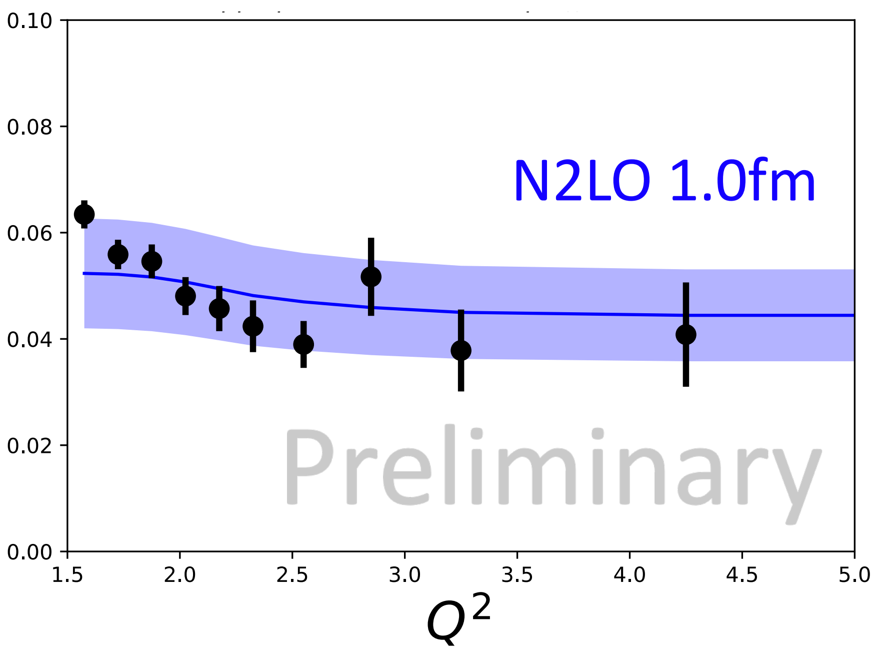


Figure credit: Andrew Denniston

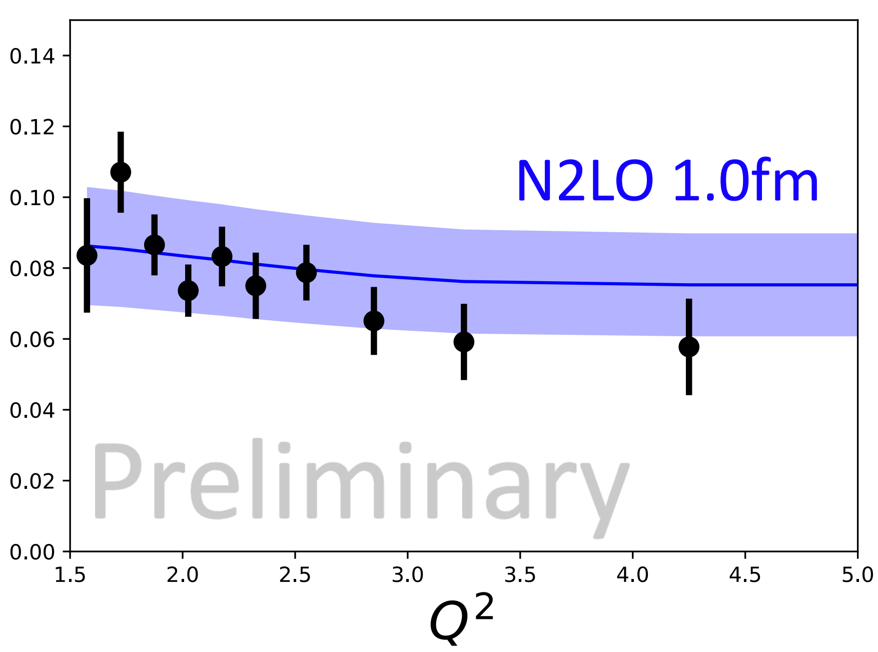
SRC properties are consistent across Q^2.

Proton-proton pairing probability

$$\frac{A(e,e'pp)}{A(e,e'p)}$$



p_{miss}: 550 – 700 MeV/c

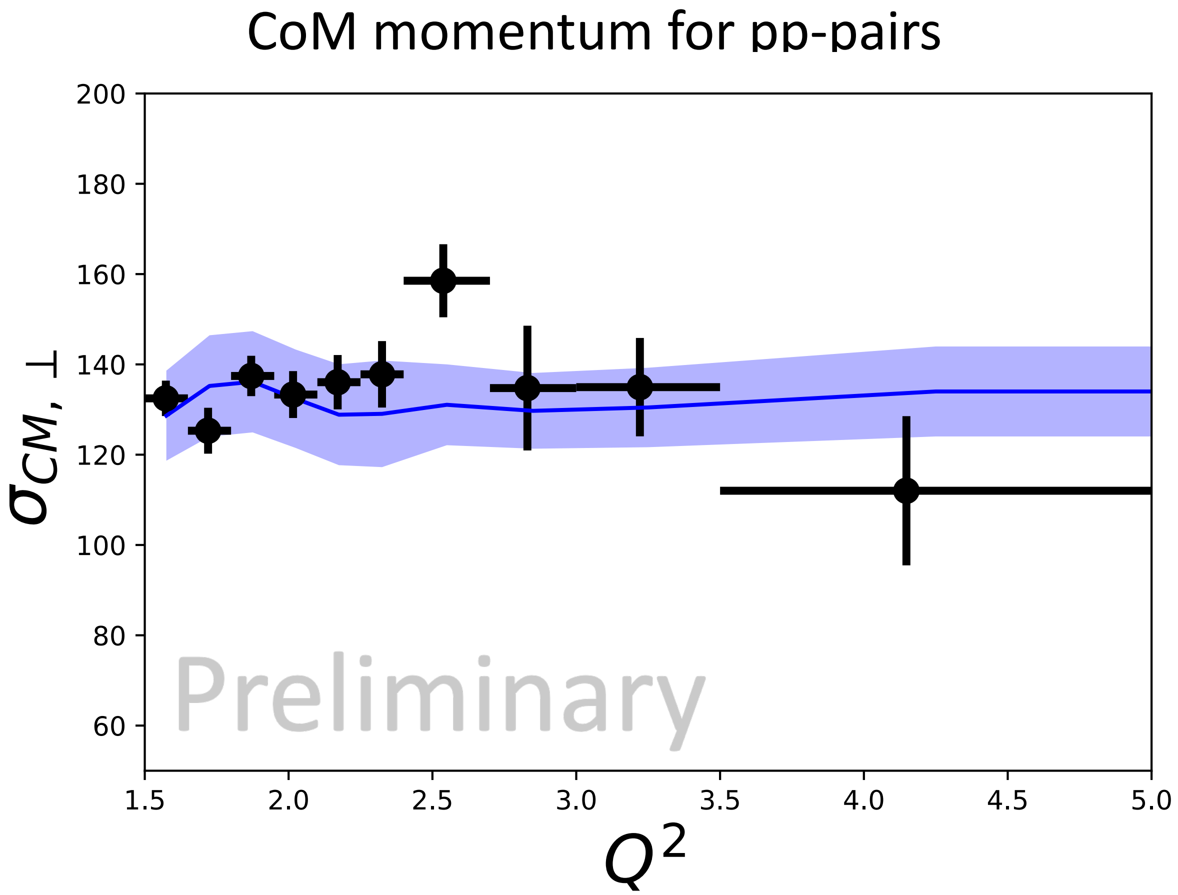


p_{miss}: 700 – 850 MeV/c

Final alignments, detector calibrations are on-going.

Figure credit: Andrew Denniston

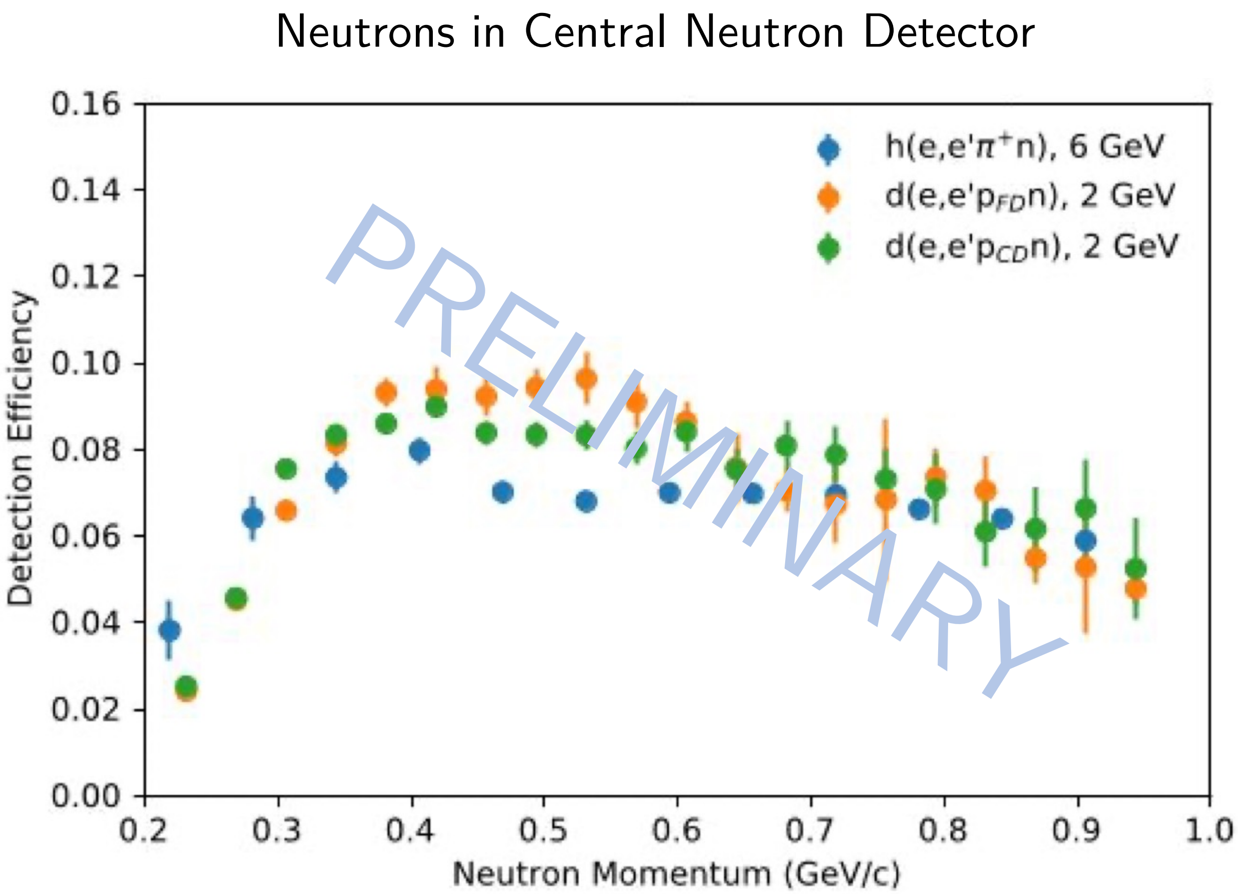
SRC properties are consistent across Q^2.



Final alignments, detector calibrations are on-going.

Figure credit: Andrew Denniston

CLAS12 has significantly improved neutron detection capabilities.



Erin Seroka
GWU

GCF assumes that the probe-nucleon interaction factorizes.

Proton-Nucleus Scattering

JINR/GSI

(in inverse kinematics)

$^{12}C(p,2p)X$

M. Patsyuk, JK et al., Nat. Phys. 17 (2021).

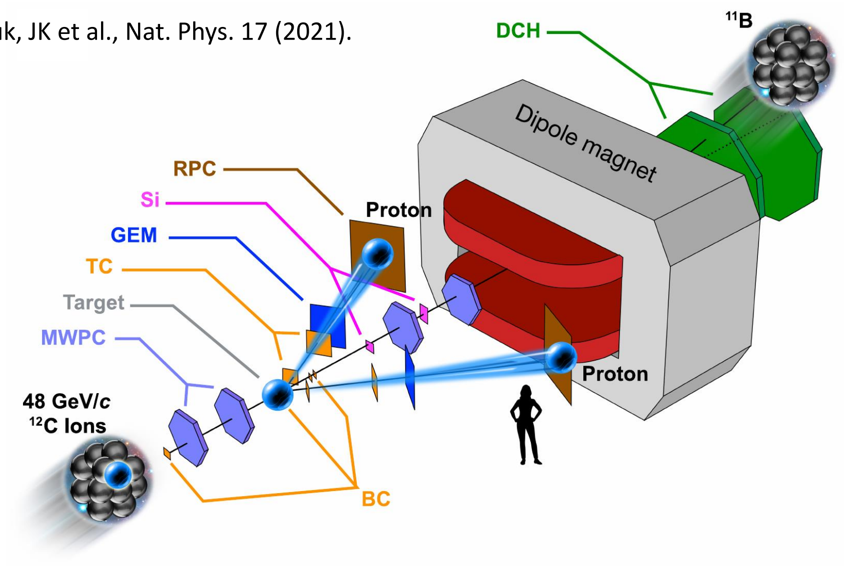
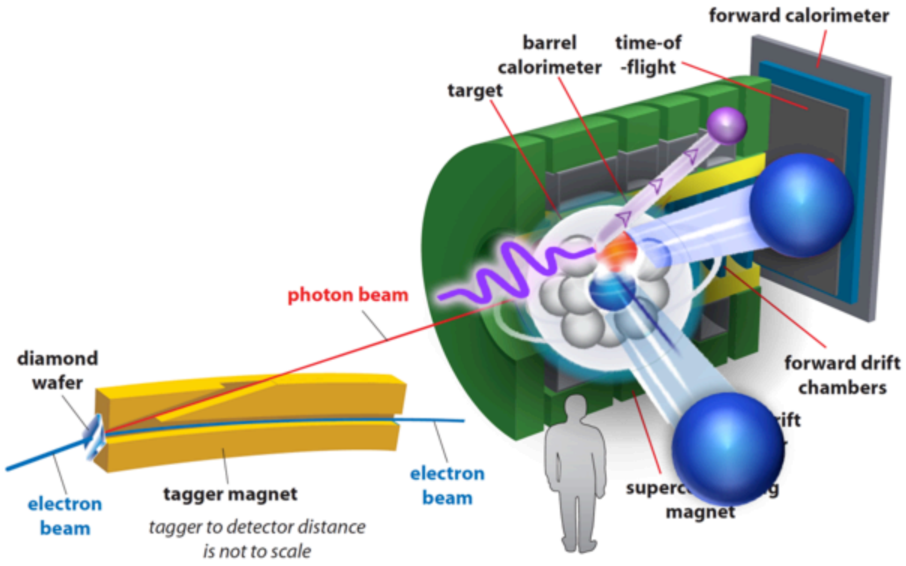


Photo-production

JLab Hall D

(GlueX spectrometer)



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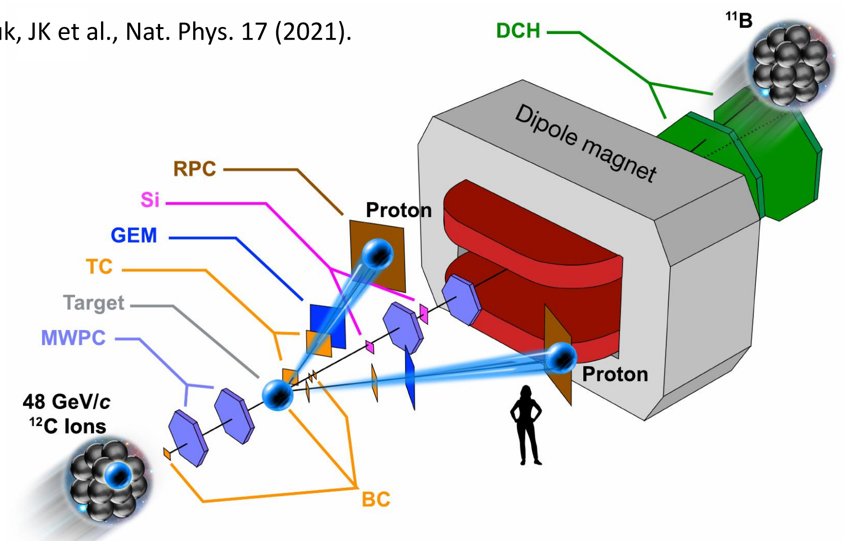

Photo-production

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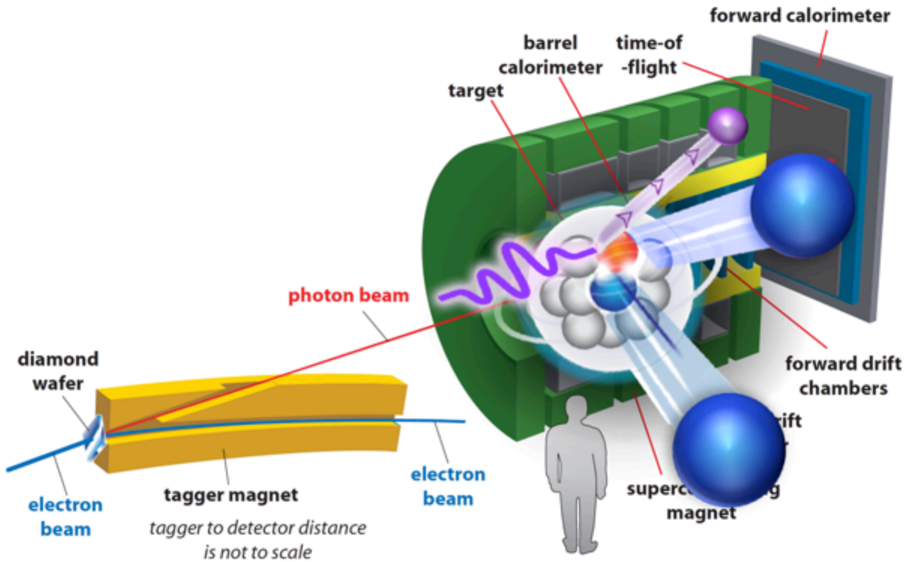
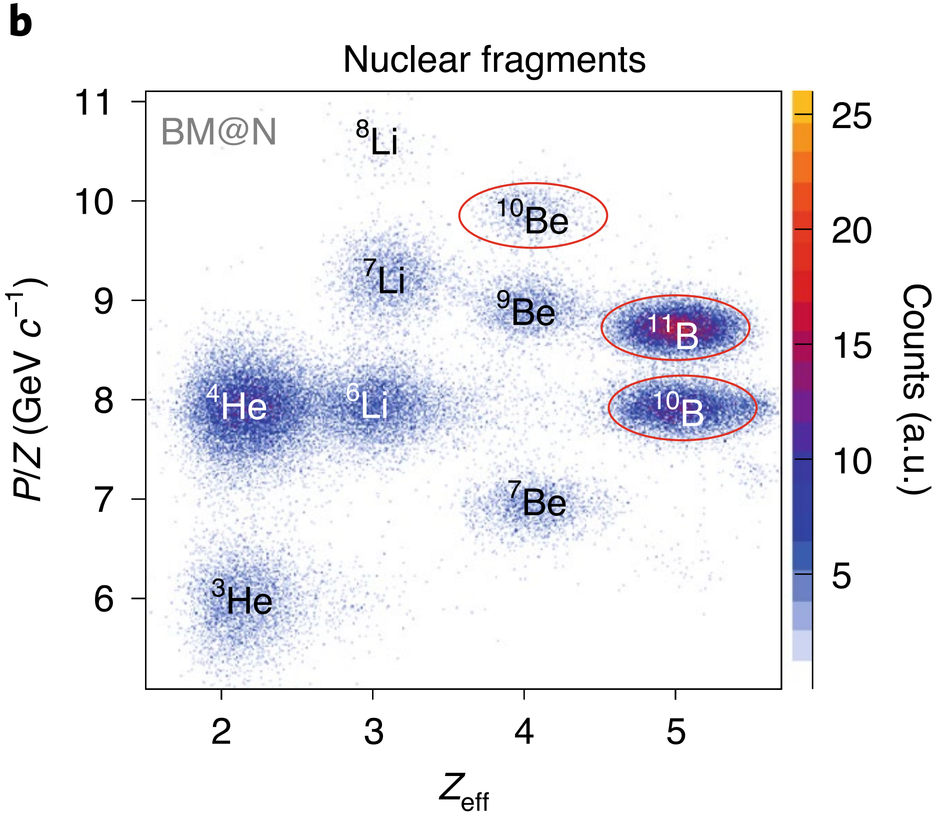
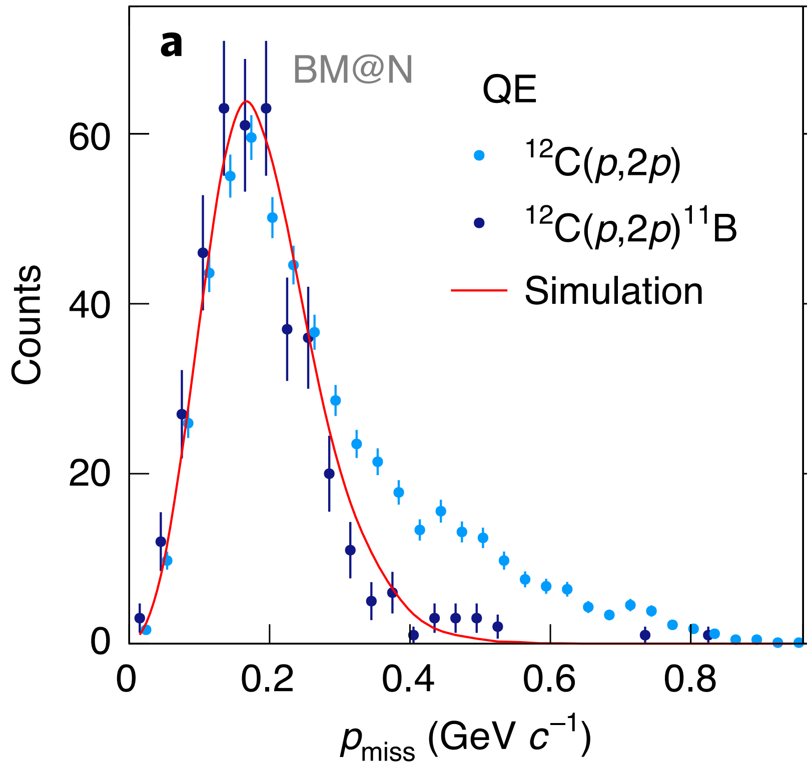


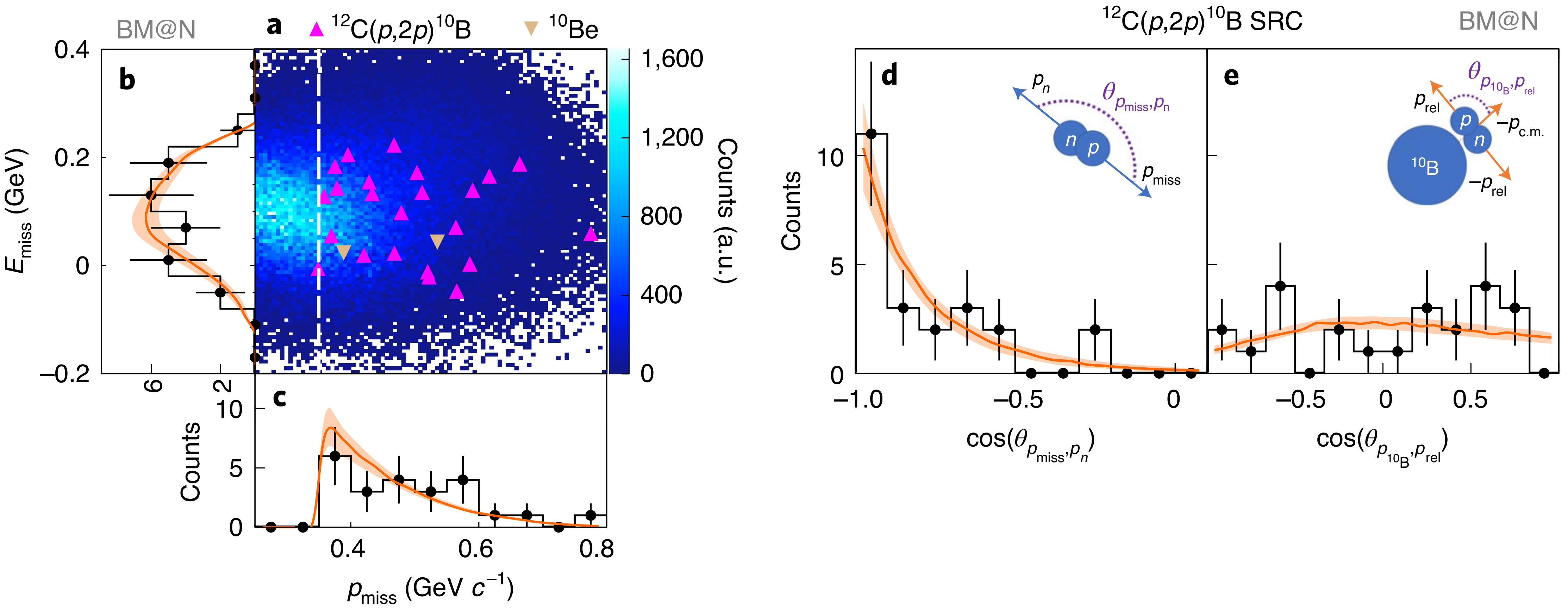
Tagging the nuclear remnant suppresses final-state interactions.





M. Patsyuk et al., Nature Physics 17, p. 693 (2021)

Vastly different reaction, but still consistent with factorized GCF picture.



M. Patsyuk et al., Nature Physics 17, p. 693 (2021)

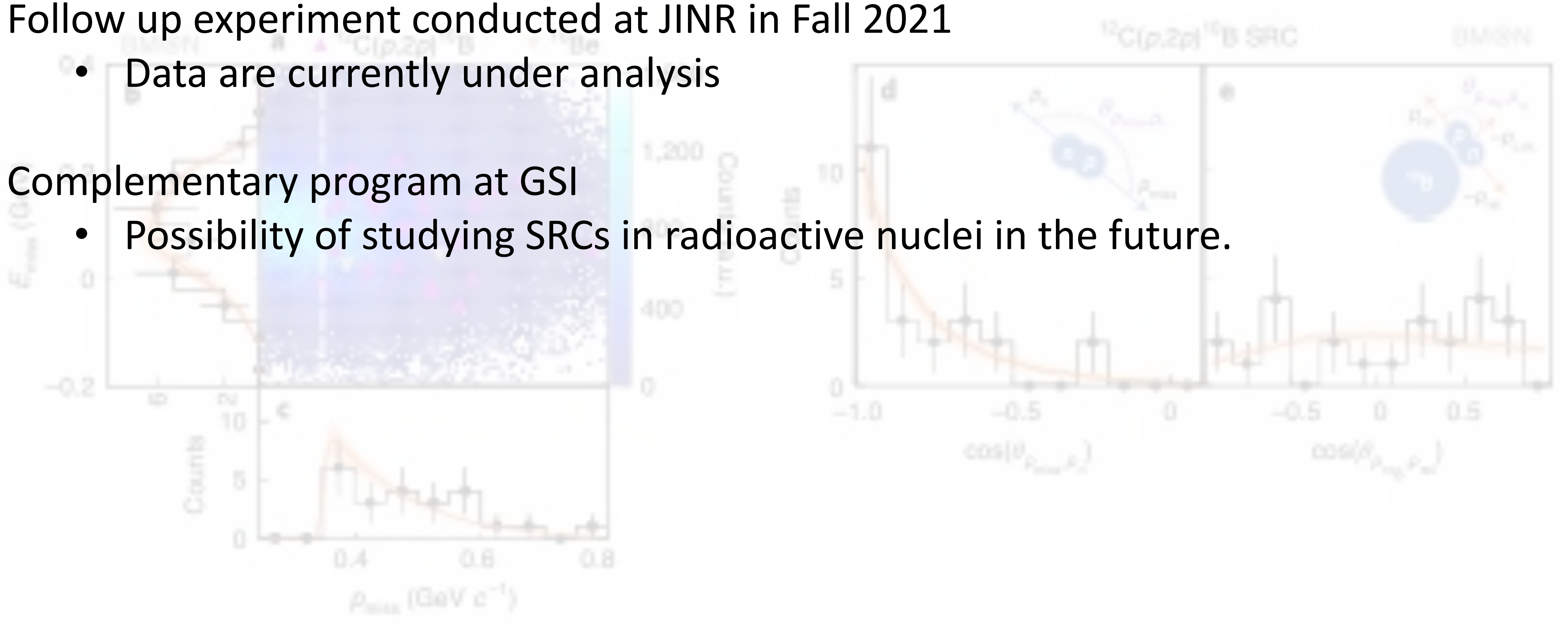
Vastly different reaction, but still consistent with factorized GCF picture.

Follow up experiment conducted at JINR in Fall 2021

- Data are currently under analysis

Complementary program at GSI

- Possibility of studying SRCs in radioactive nuclei in the future.



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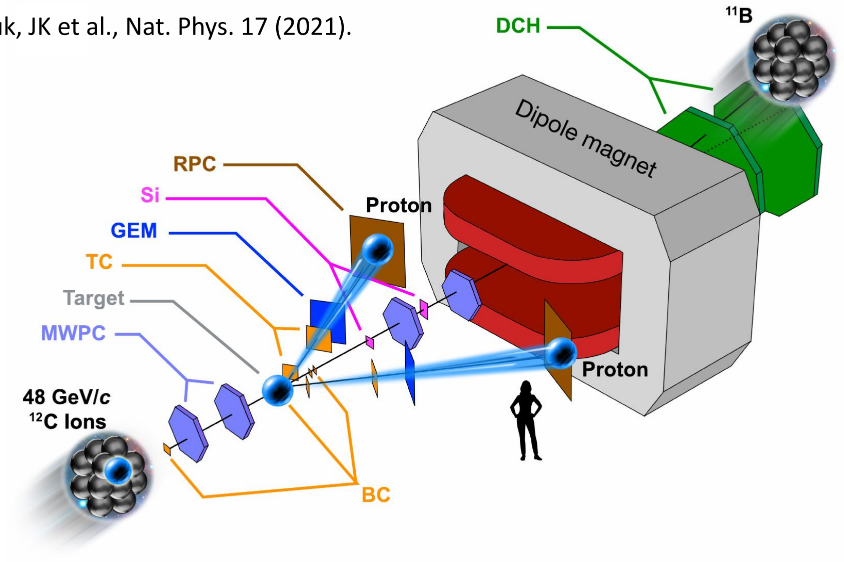
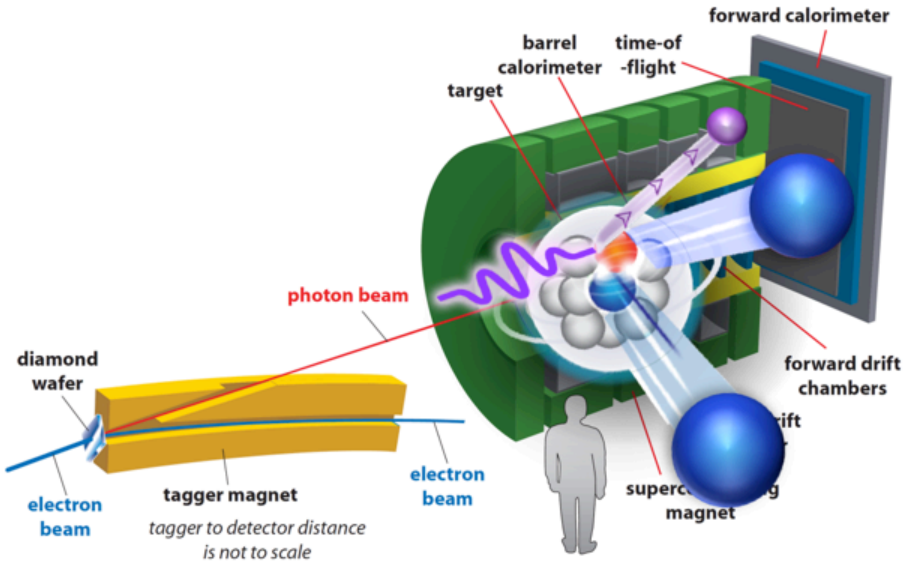


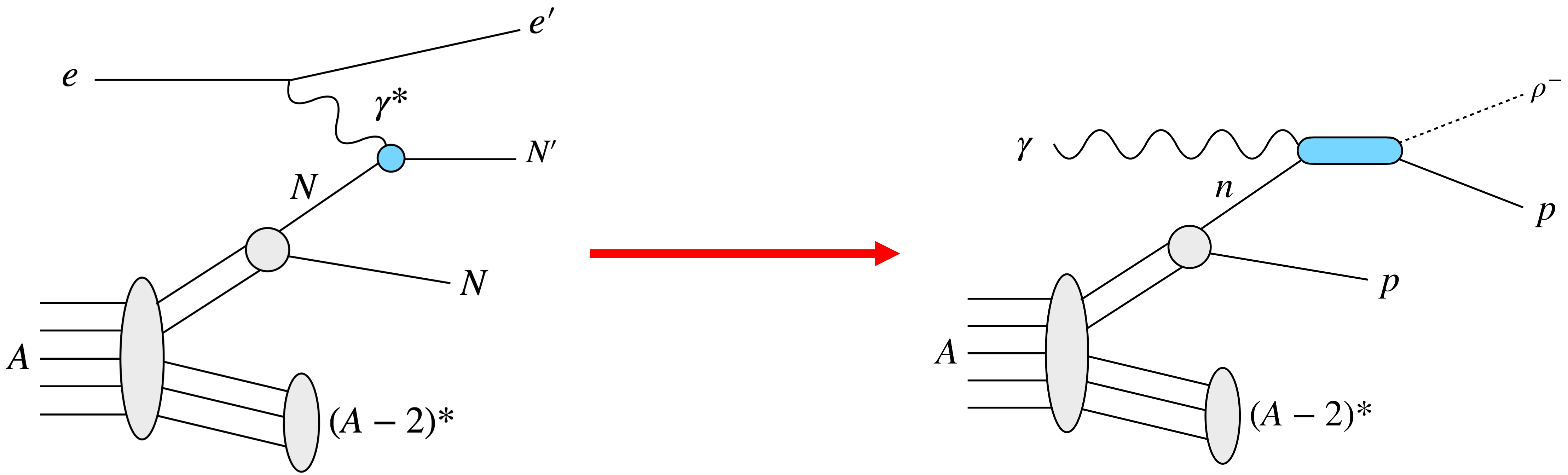
Photo-production

JLab Hall D

(GlueX spectrometer)



Can we learn about SRCs through photoproduction reactions?

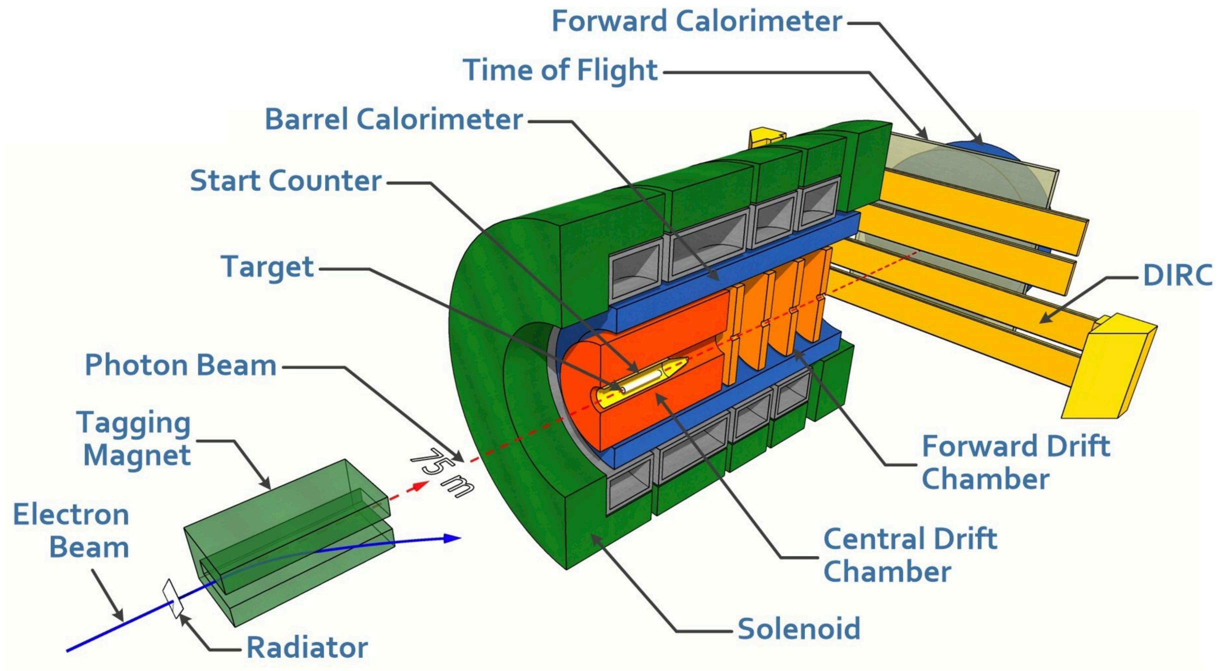


- Vastly different kinematics, sensitivity to final-state effects
- Study SRC neutrons without having to detect them

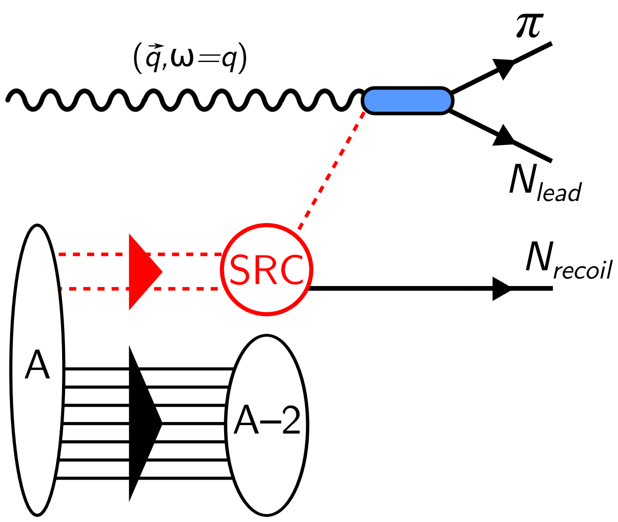
Hall D Short-Range Correlations experiment ran in Fall, 2021.

Target	Days	Luminosity [pb^{-1}] $E_\gamma > 6$ GeV
Deuterium	4	18.0
Helium-4	10	16.7
Carbon-12	14	8.6

GlueX Spectrometer

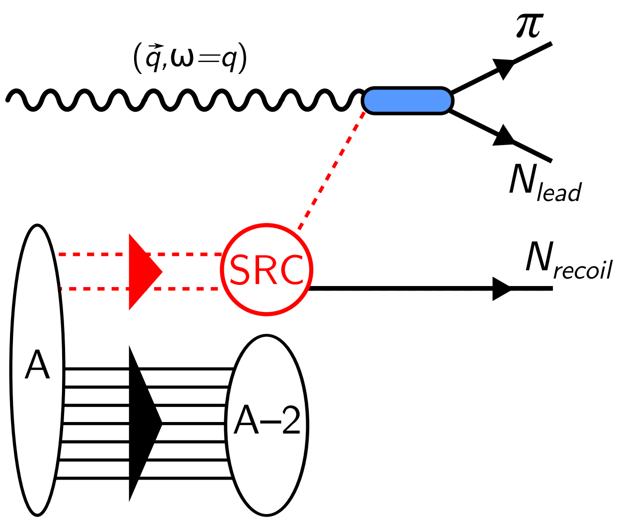


A wide range of final states are possible



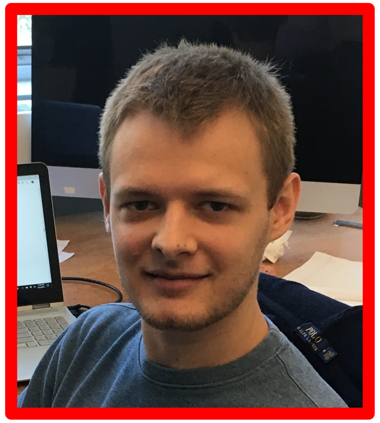
γp			γn		
$\gamma p \to \pi^0 p$	$\gamma p \to \rho^0 p$	$\gamma p \to \eta p$	$\gamma n \to \pi^0 n$	$\gamma n \to \rho^- p$	$\gamma n \to \eta n$
$\gamma p \to \pi^+ n$	$\gamma p \to \rho^+ n$	$\gamma p \to \omega p$	$\gamma n \to \pi^- p$		$\gamma n \to \omega n$
$\gamma p \to \pi^- \Delta^{++}$	$\gamma p \to K^+ \Lambda^0$	$\gamma p \to \phi p$		$\gamma n \to K^0 \Lambda^0$	$\gamma n \to \phi n$
$\gamma p \to \pi^0 \Delta^+$	$\gamma p \to K^+ \Sigma^0$	$\gamma p \to J/\psi p$	$\gamma n \to \pi^- \Delta^+$	$\gamma n \to K^0 \Sigma^0$	$\gamma n \to J/\psi n$
$\gamma p \to \pi^+ \Delta^0$	$\gamma p \to K^0 \Sigma^+$			$\gamma n \to K^+ \Sigma^-$	

A wide range of final states are possible



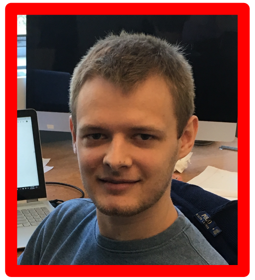
γp			γn		
$\gamma p \to \pi^0 p$	$\gamma p \to \rho^0 p$	$\gamma p \to \eta p$	$\gamma n \to \pi^0 n$	$\gamma n \to \rho^- p$	$\gamma n \to \eta n$
$\gamma p \to \pi^+ n$	$\gamma p \to \rho^+ n$	$\gamma p \to \omega p$	$\gamma n \to \pi^- p$		$\gamma n \to \omega n$
$\gamma p \to \pi^- \Delta^{++}$	$\gamma p \to K^+ \Lambda^0$	$\gamma p \to \phi p$		$\gamma n \to K^0 \Lambda^0$	$\gamma n \to \phi n$
$\gamma p \to \pi^0 \Delta^+$	$\gamma p \to K^+ \Sigma^0$	$\gamma p \to J/\psi p$	$\gamma n \to \pi^- \Delta^+$	$\gamma n \to K^0 \Sigma^0$	$\gamma n \to J/\psi n$
$\gamma p \to \pi^+ \Delta^0$	$\gamma p \to K^0 \Sigma^+$			$\gamma n \to K^+ \Sigma^-$	

Phoebe Sharp
GWU

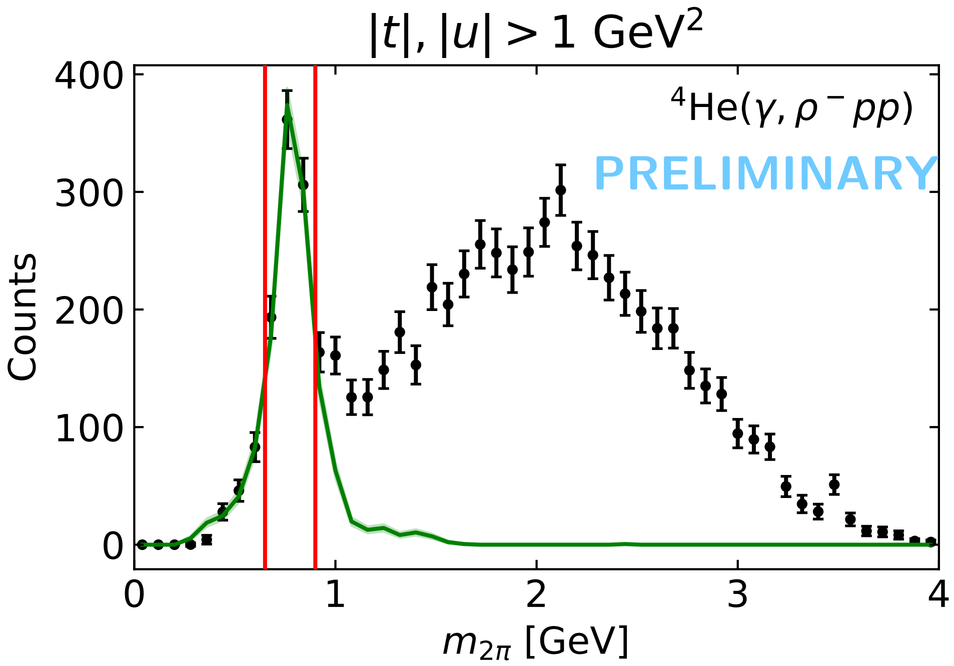


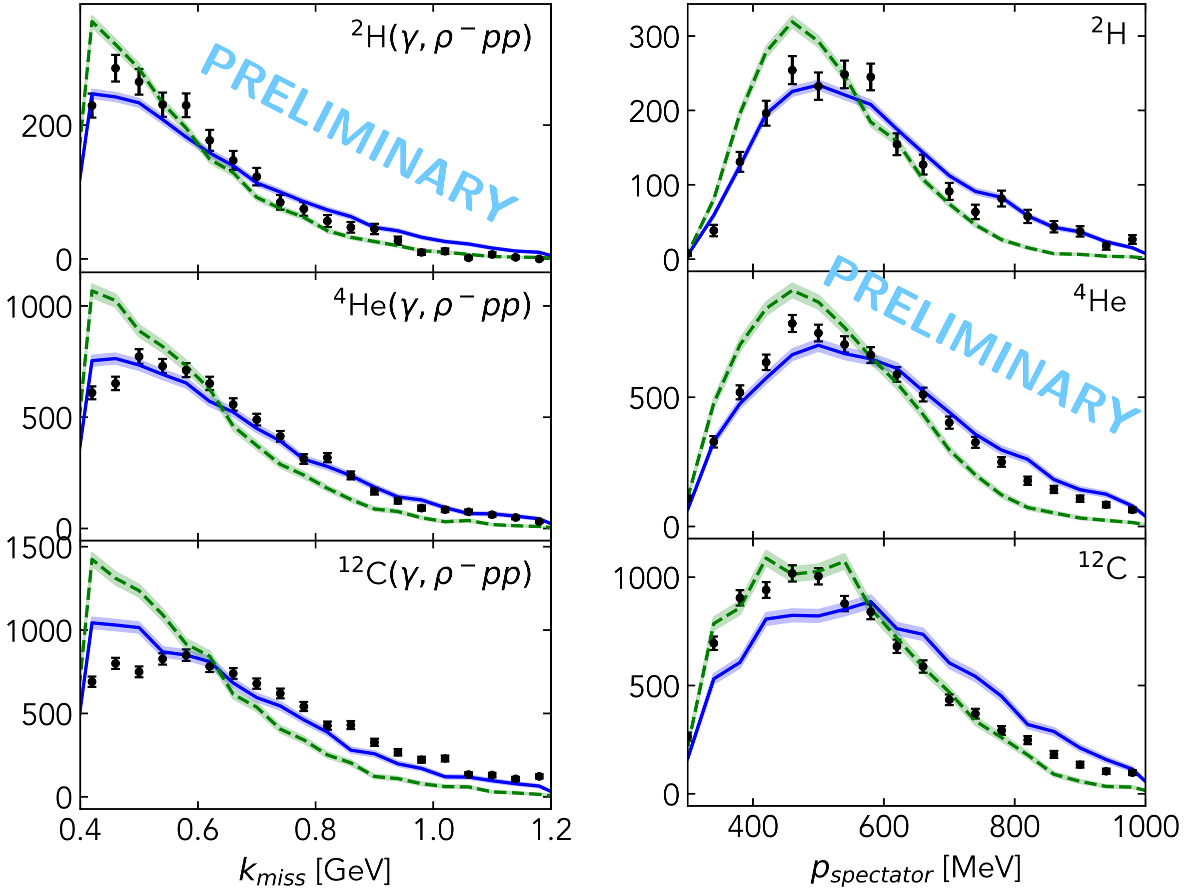
Jackson Pybus
MIT

Preliminary analysis shows GCF working for high-energy photoproduction.



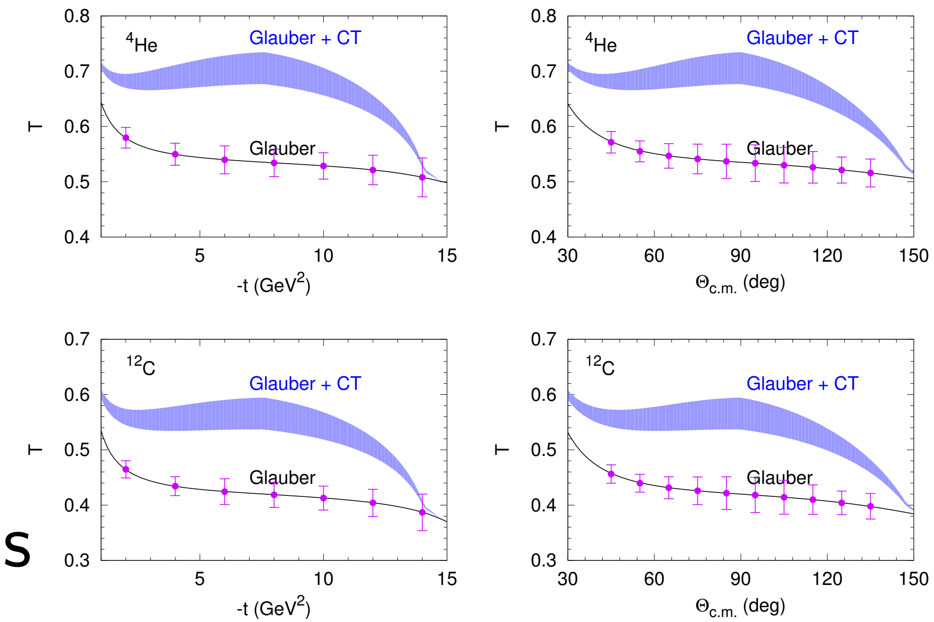
Jackson Pybus
MIT

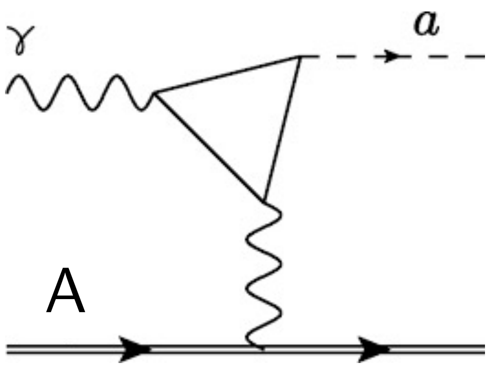




Other topics that we'll address

- Color transparency in photo-production
- Photon structure
- Tests of Regge theory on bound neutrons
- Branching ratio modification
- Axion-like dark matter search





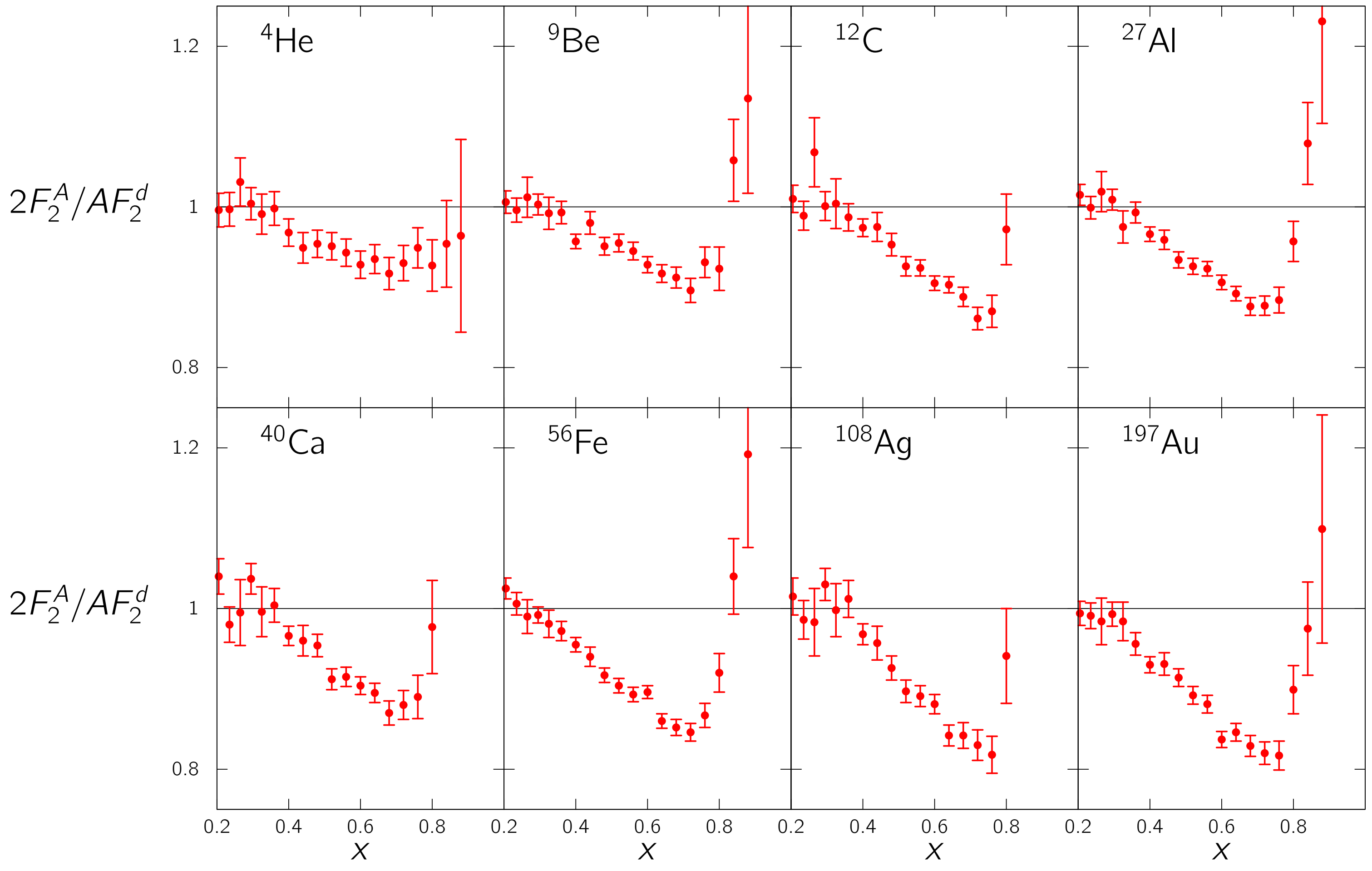
In my talk today:

- Short-range correlations is asymmetric nuclei
  - How does size, neutron-proton imbalance affect pairing?
  - See Dien Nguyen's, Burcu Duran's talk

- Factorization: probe- and scale-independence
  - How can we separate what we learn about pairs, from hard scattering?
  - See Tim Kolar's talk

- **Short-range correlations and the EMC Effect**
  - What roles to SRCs play in medium modification?
  - See Florian Hauenstein's talk

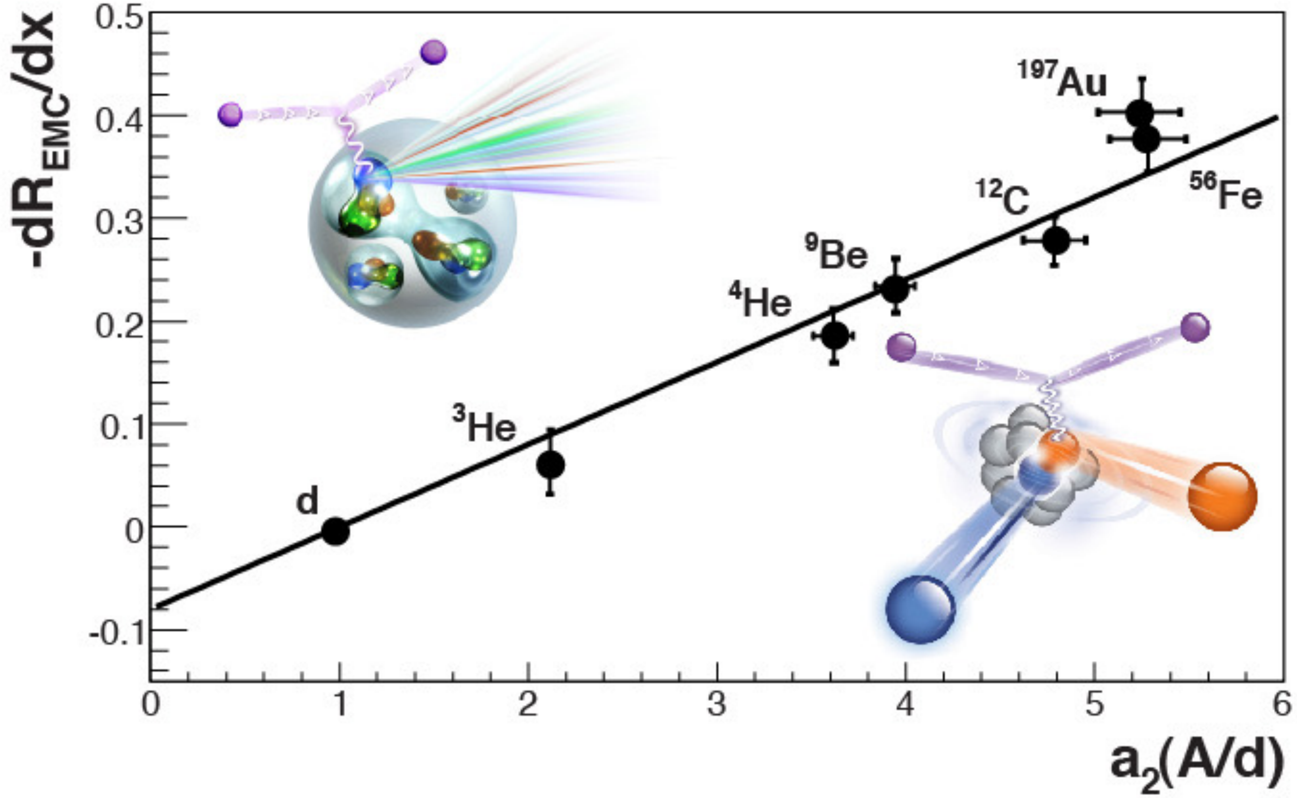
The EMC Effect shows the modification of quark distributions in bound nucleon.



Data from J. Gomez et al. (SLAC), PRD 49 (1994)

The frequency of SRC pairs correlates with the strength of the EMC Effect.

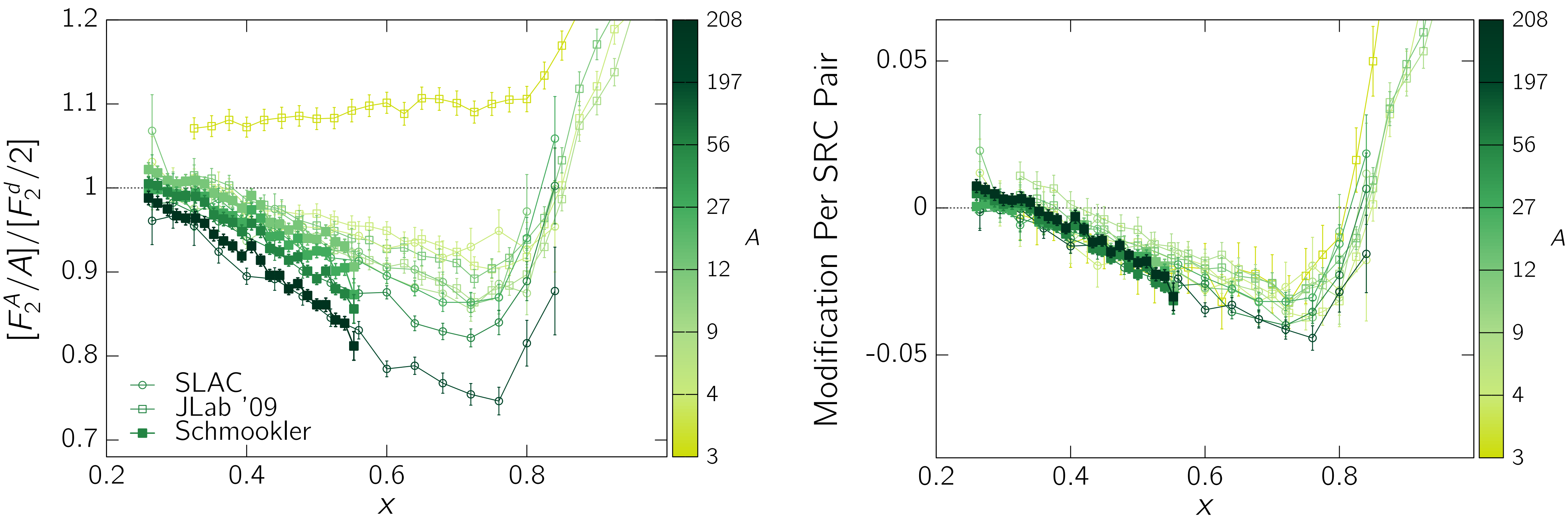
Magnitude of
the EMC Effect



Relative density of SRC pairs

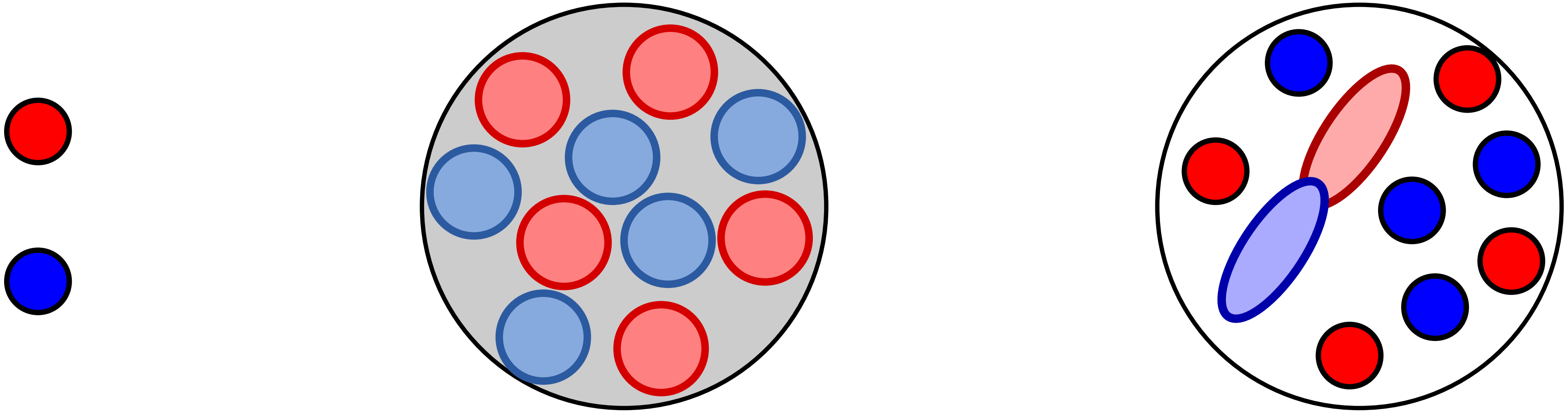
Weinstein et al., PRL 106, 052301 (2011)
Hen et al., PRC 85, 047301 (2012)
Arrington et al., PRC 68, 065204 (2012)

The modification per SRC pair appears to be universal.



B. Schmookler et al., Nature 566, p. 354, (2019)

Models of the EMC Effect

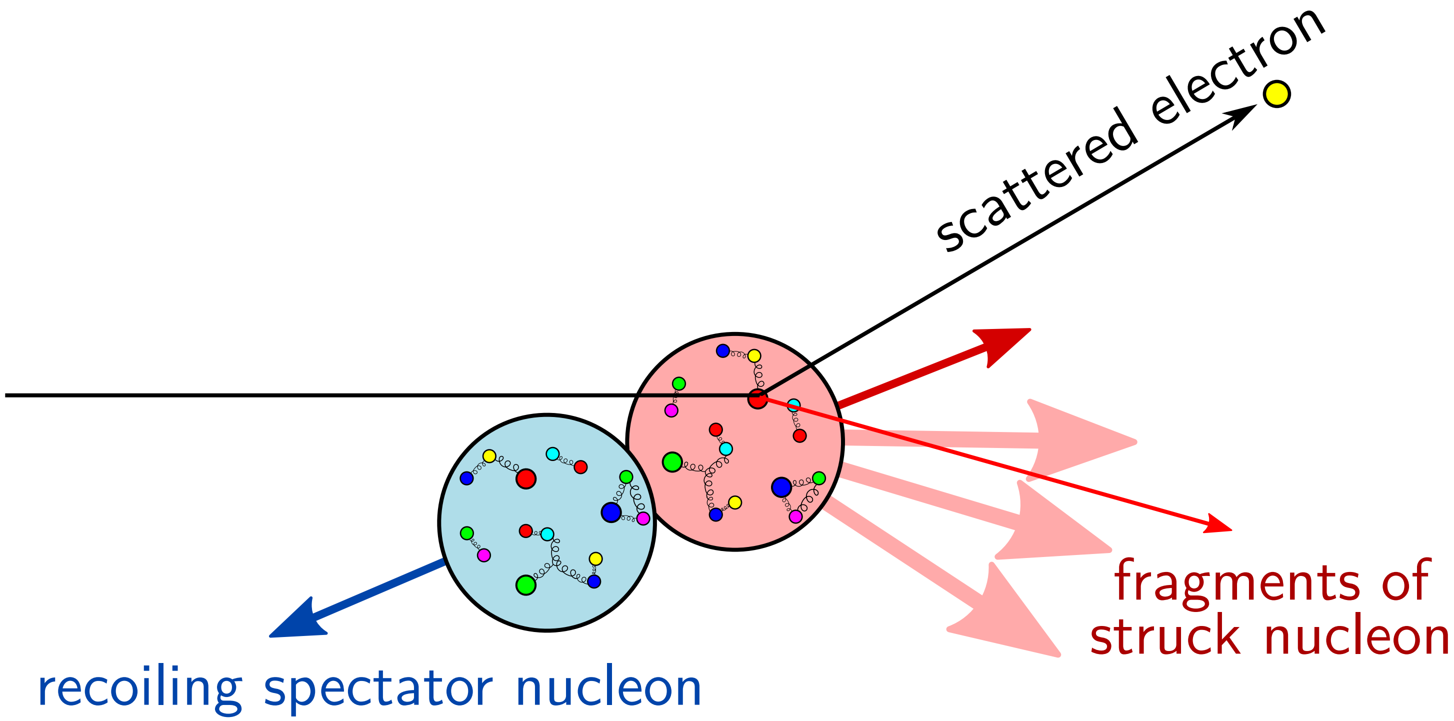


Free

Medium Modification Hypothesis

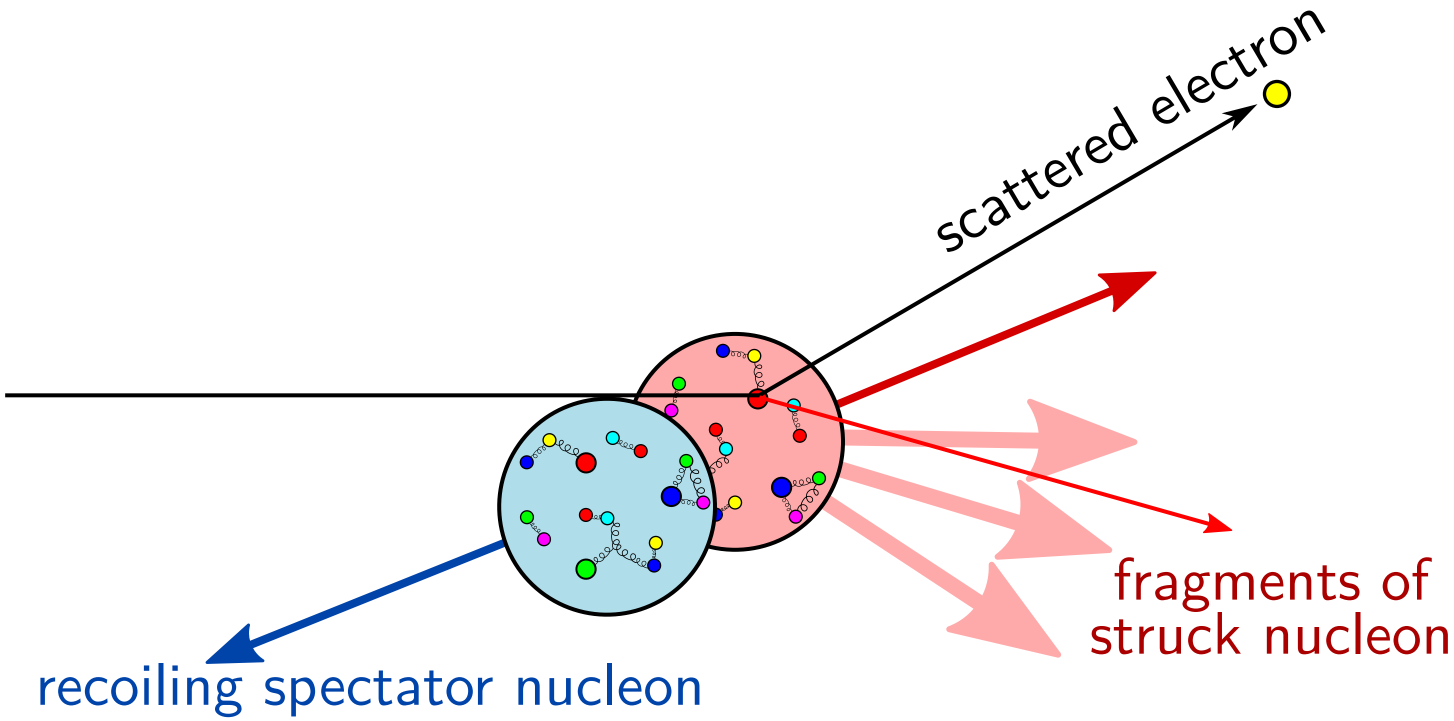
Short-Range Correlation Hypothesis

We can isolate SRC nucleons by “tagging” the correlated spectator.



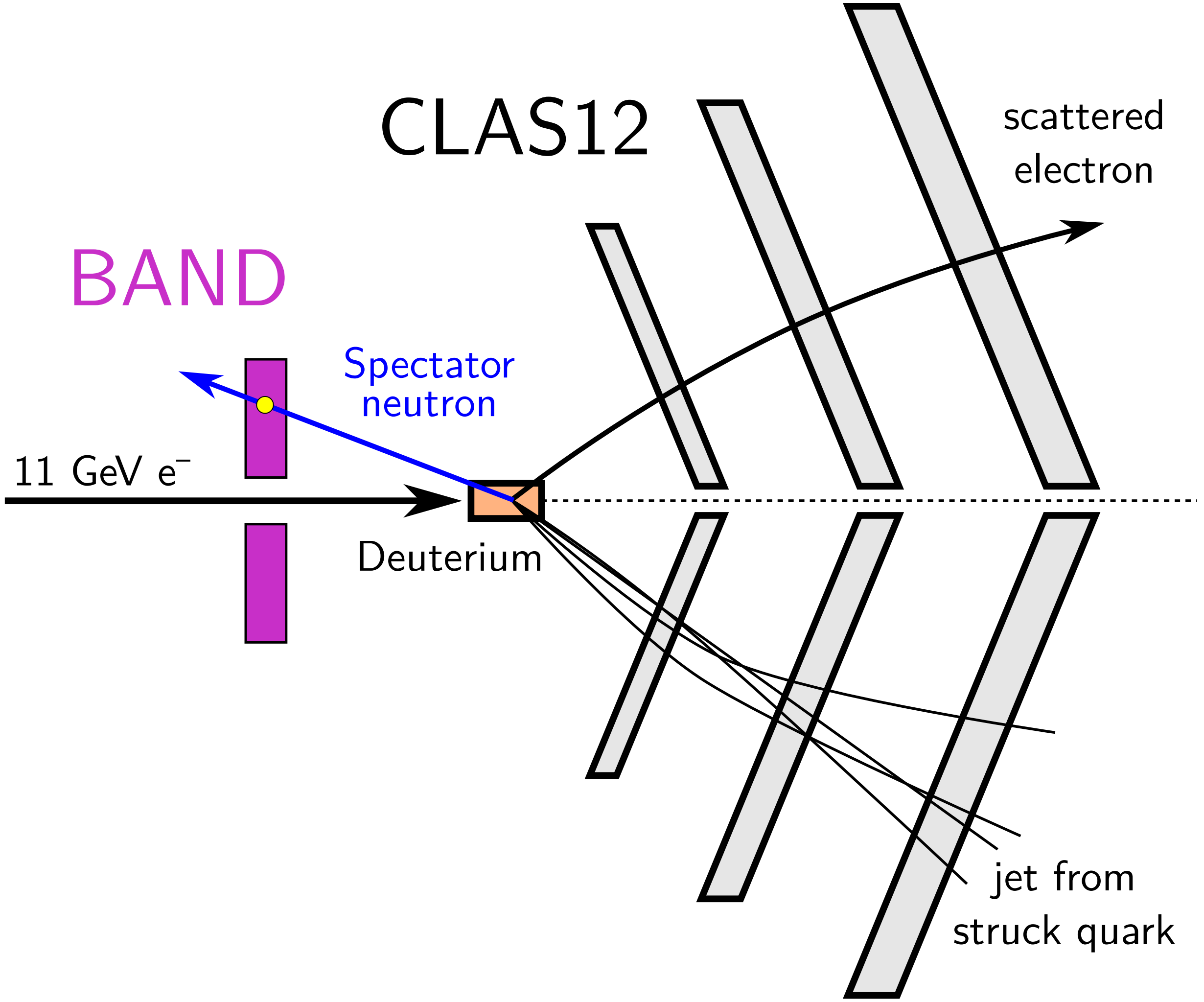
- Detecting the electron ----> momentum of the struck quark
- Detecting the recoil nucleon ----> initial state of the struck nucleon

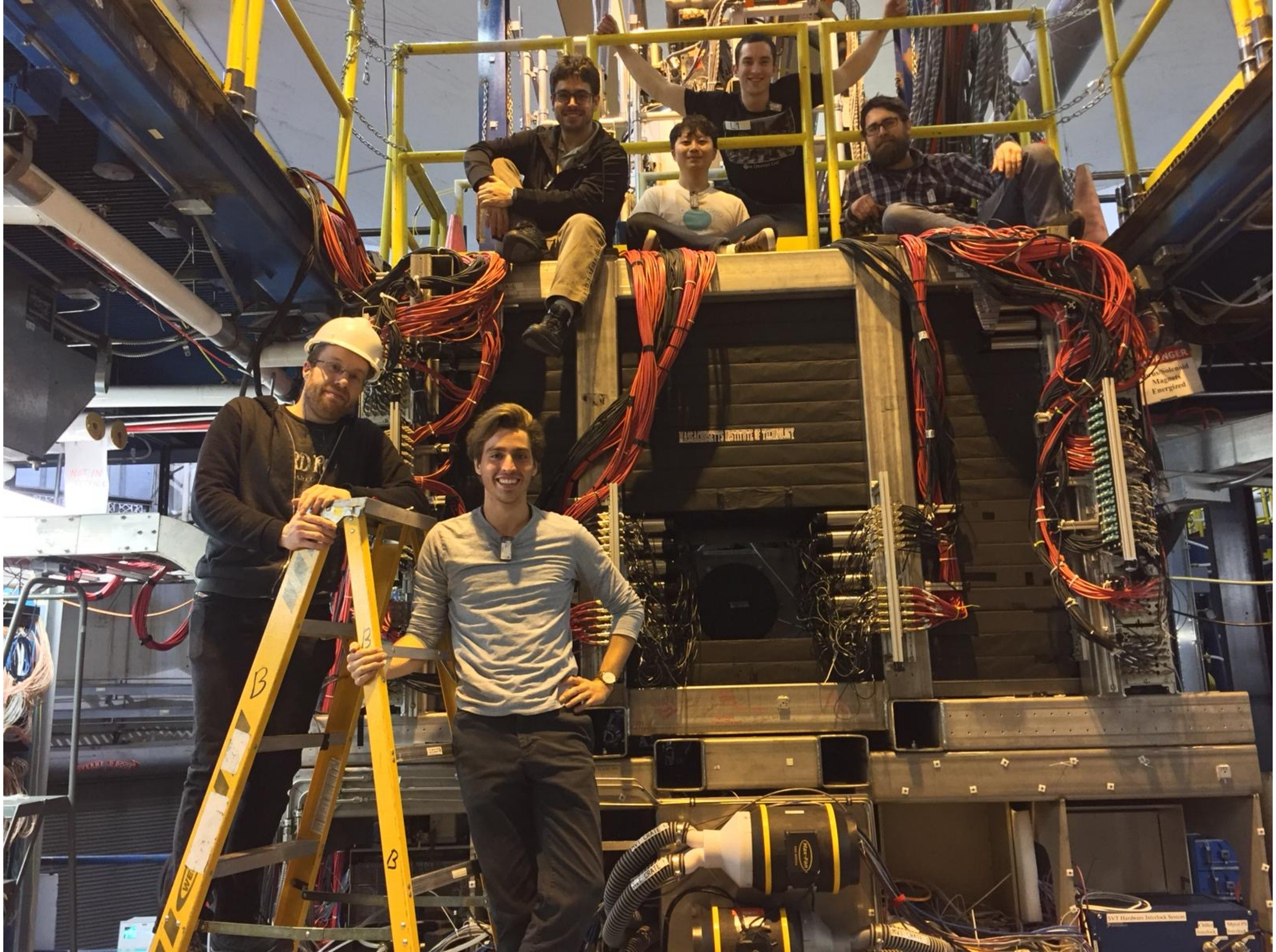
We can isolate SRC nucleons by “tagging” the correlated spectator.



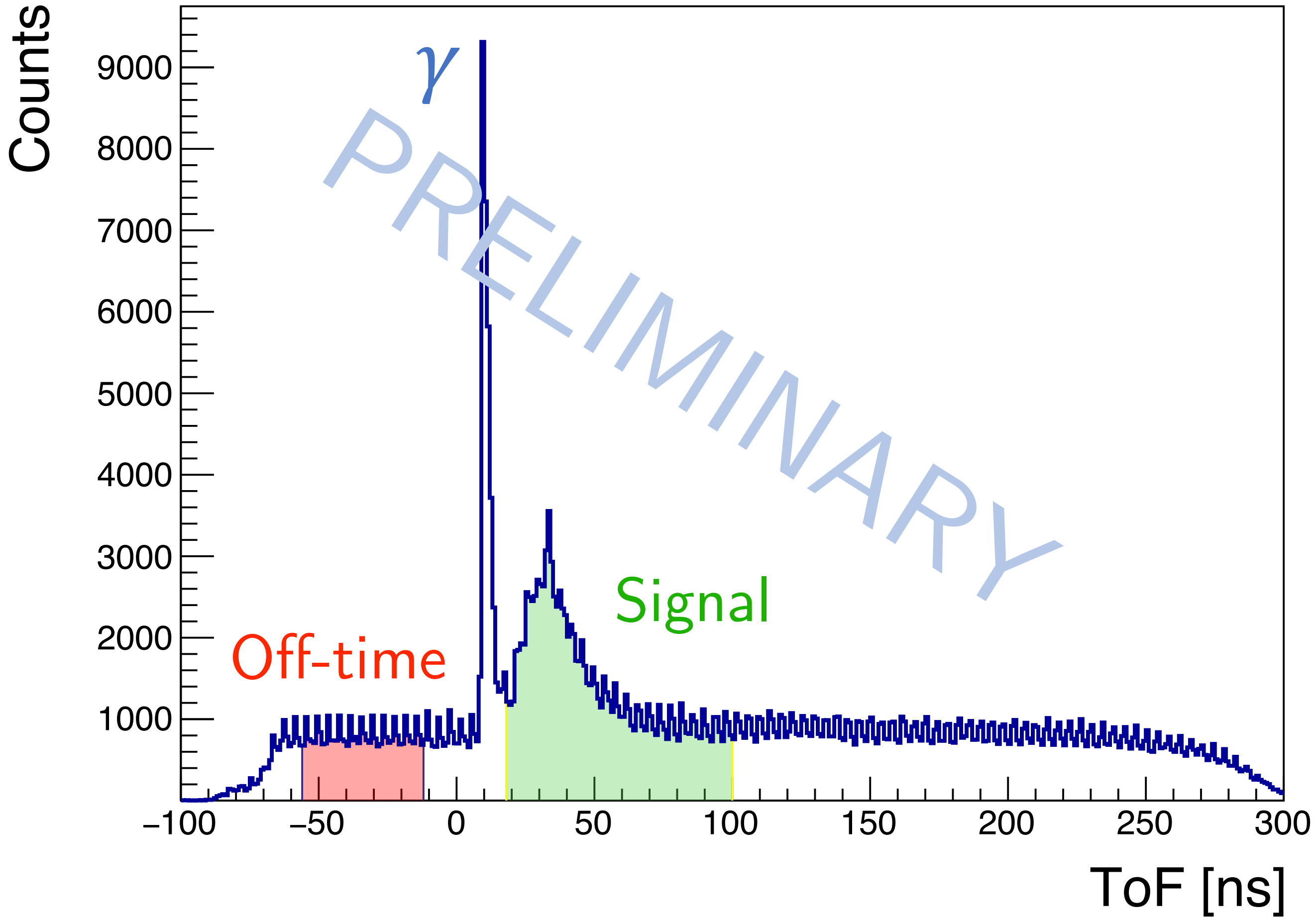
- Detecting the electron ----> momentum of the struck quark
- Detecting the recoil nucleon ----> initial state of the struck nucleon

The Backward Angle Neutron Detector (BAND) was built to detect recoiling neutrons.

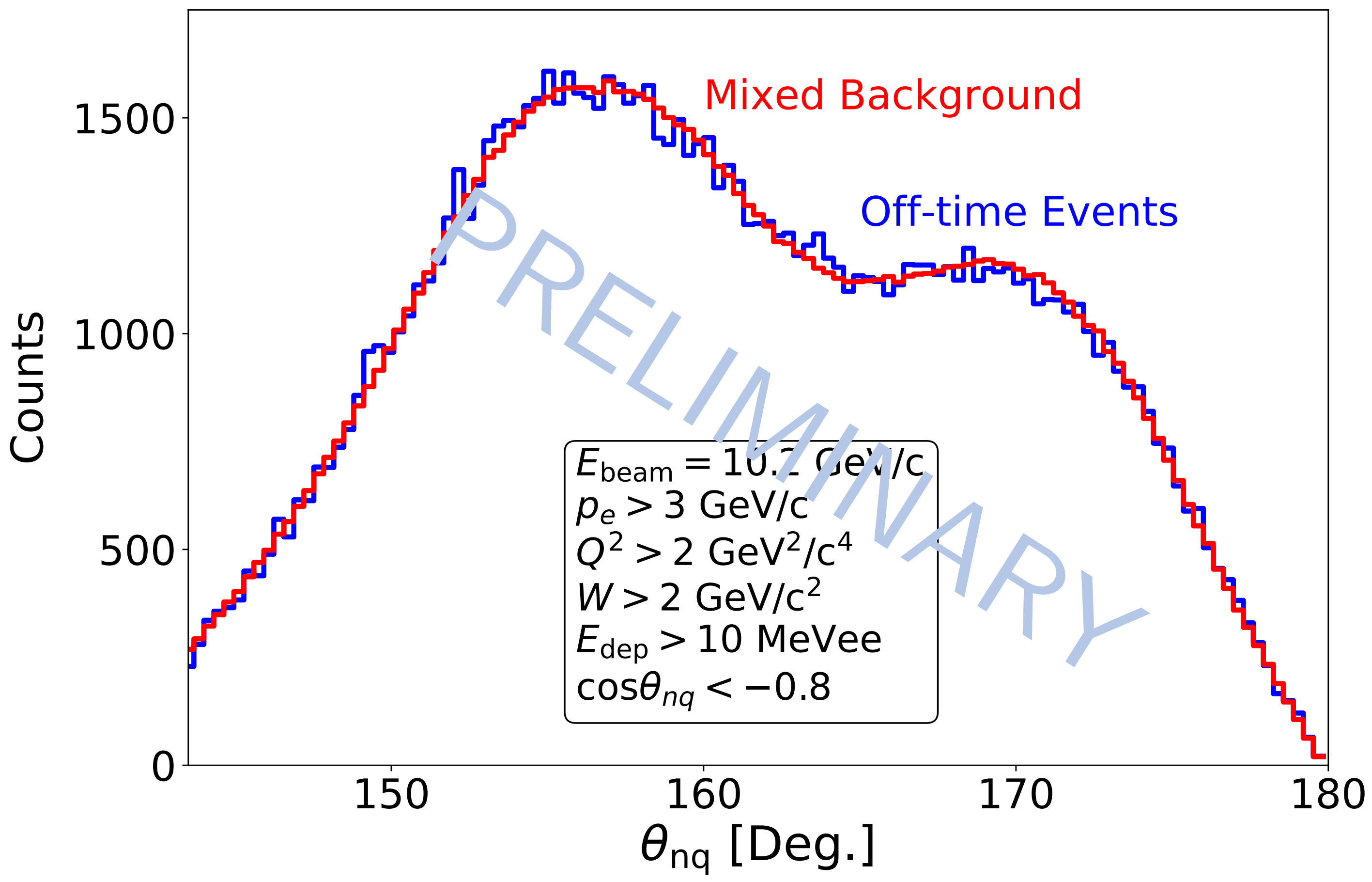



MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SVT Hardware Interlock System

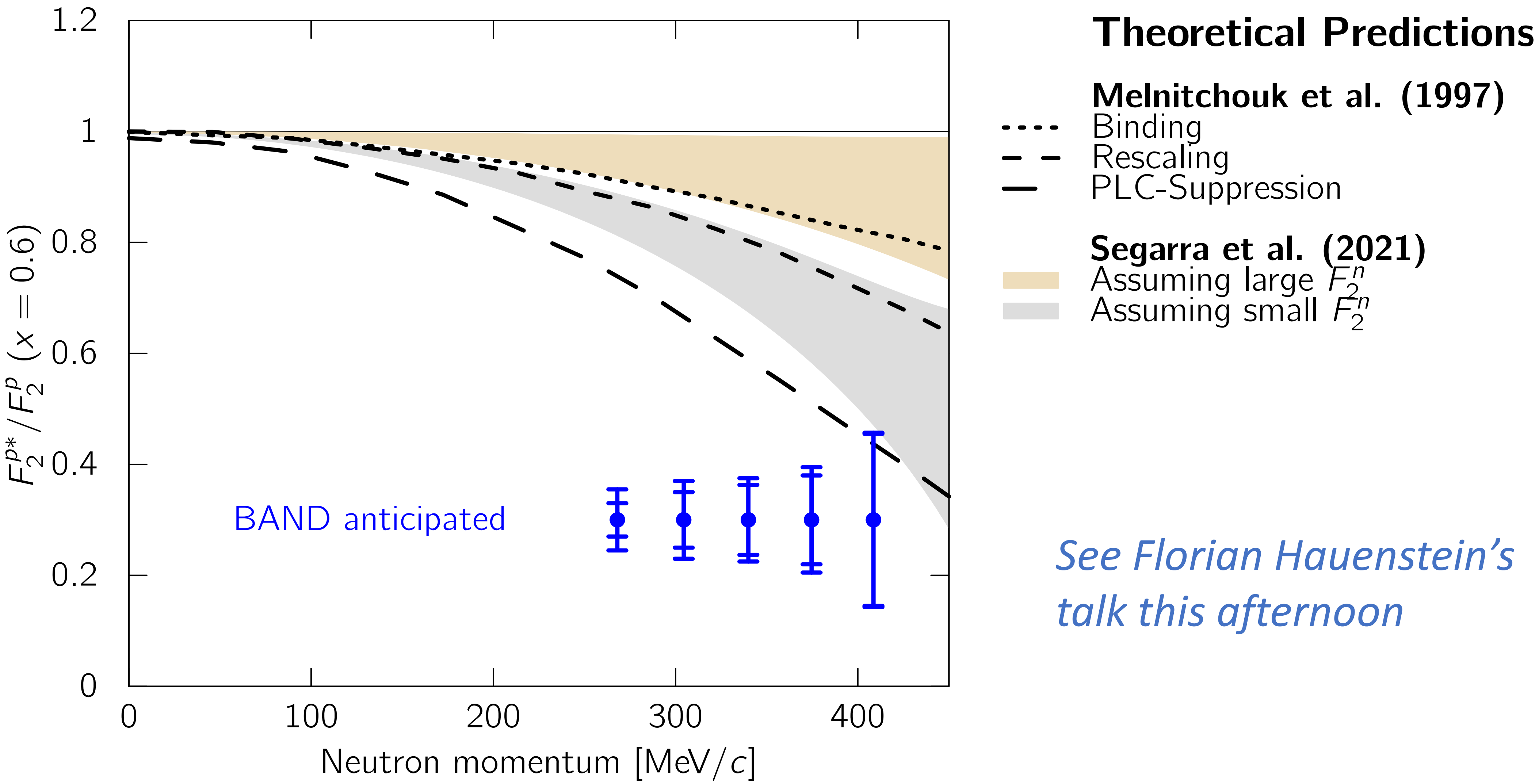
Our neutron signal sits on top of random background.



We use event-mixing to estimate and subtract it.



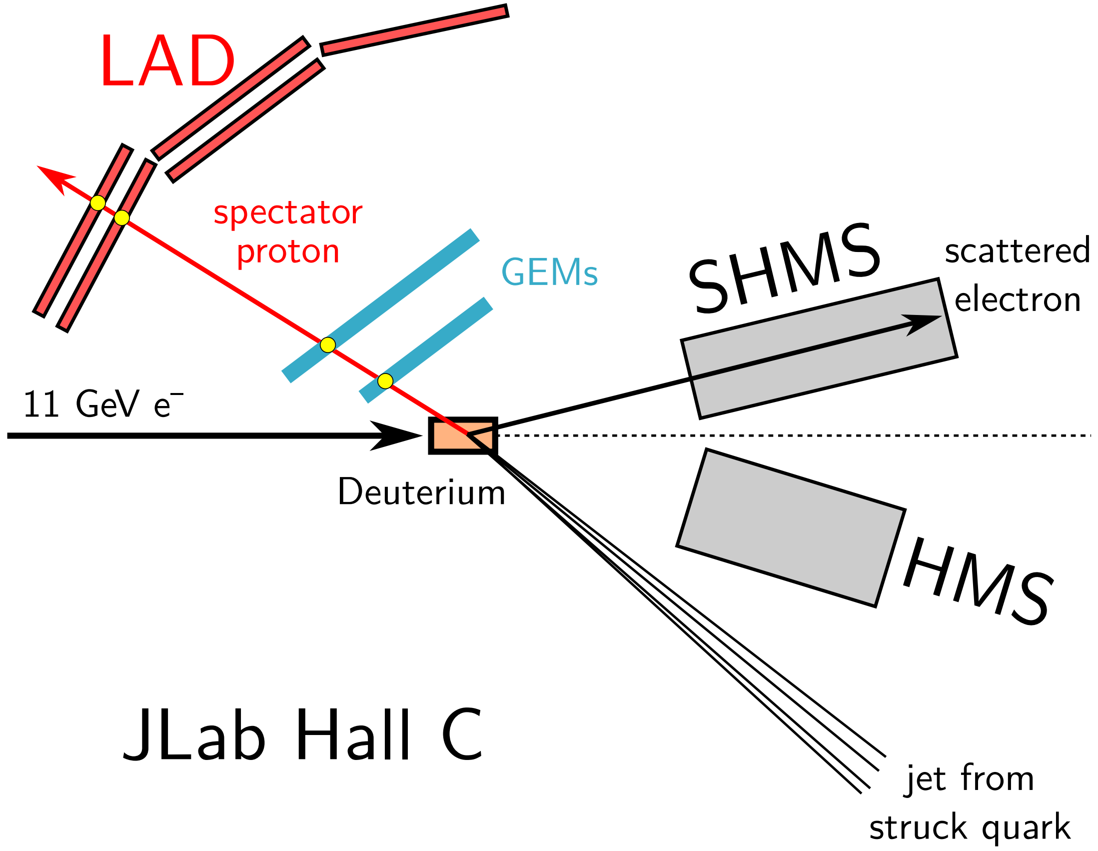
Expected precision

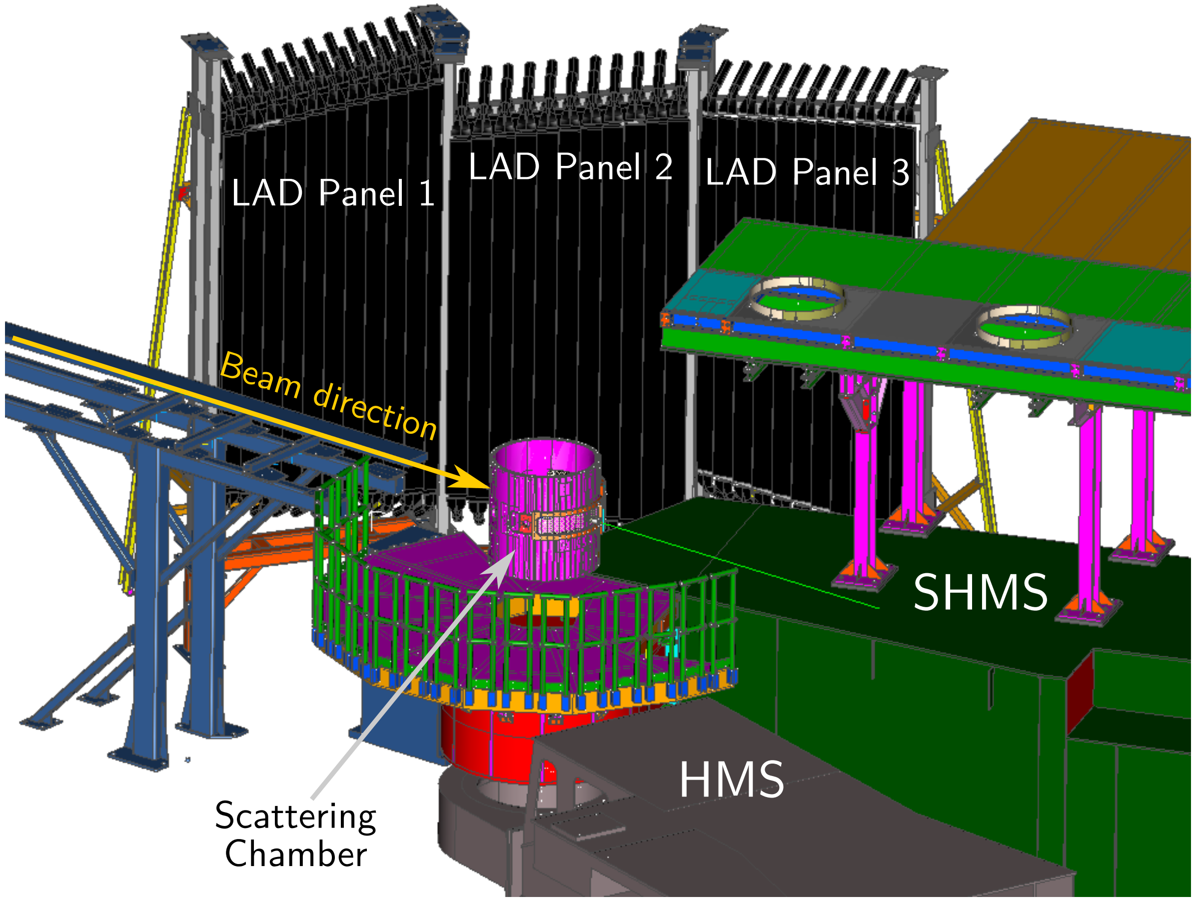


See Florian Hauenstein's talk this afternoon

The complementary LAD experiment will tag spectator protons.

With BAND, pin-down flavor dependence of EMC Effect.





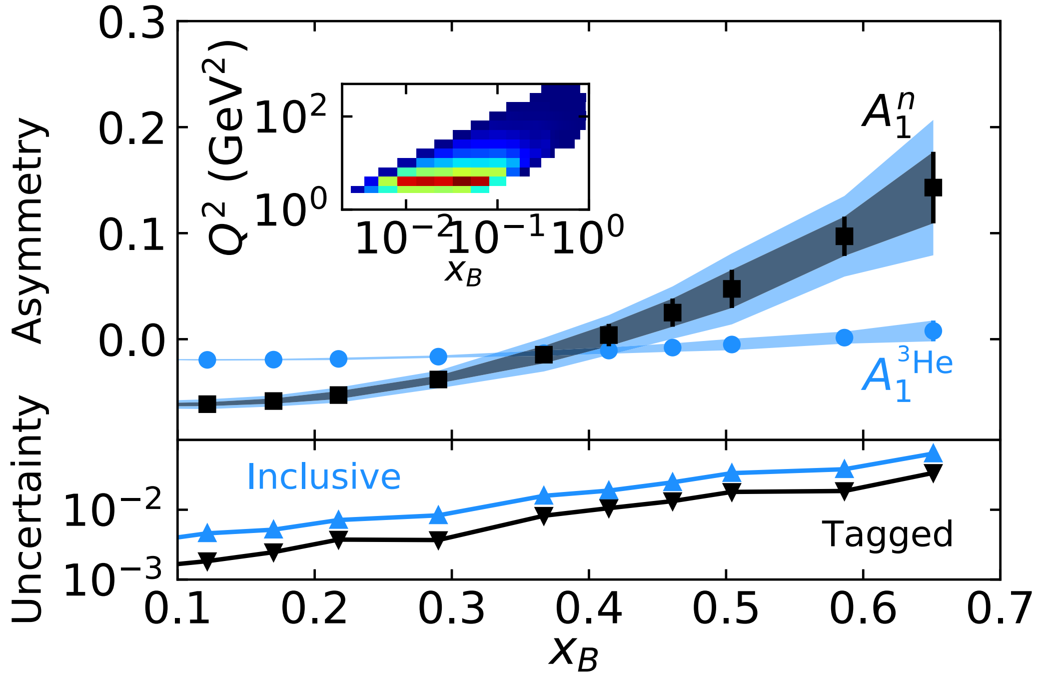
Tagging is growing in importance and will be a big part of physics at the EIC.

Fixed-target tagging experiments

- BoNUS12
- ALERT
- TDIS @ SBS
- BAND/LAD

Example EIC tagging concept:

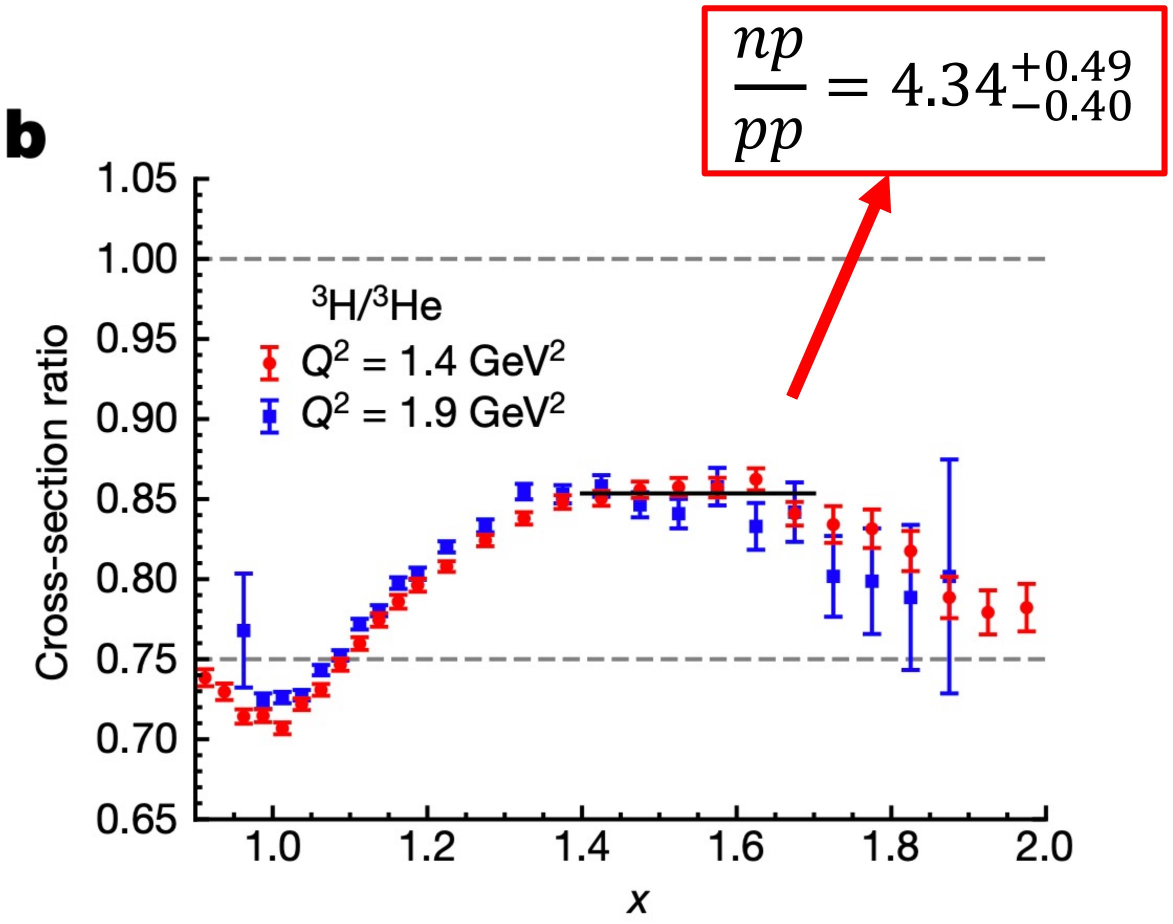
$$^3\overrightarrow{He}(e, e' p_s p_s)X$$



I. Friscic, D. Nguyen, J.R. Pybus et al., PLB 823, 136726 (2021)

To Recap:

- Asymmetric nuclei teach us about which nucleons correlate.



S. Li et al. (Hall A), Nature 609 p. 41 (2022)

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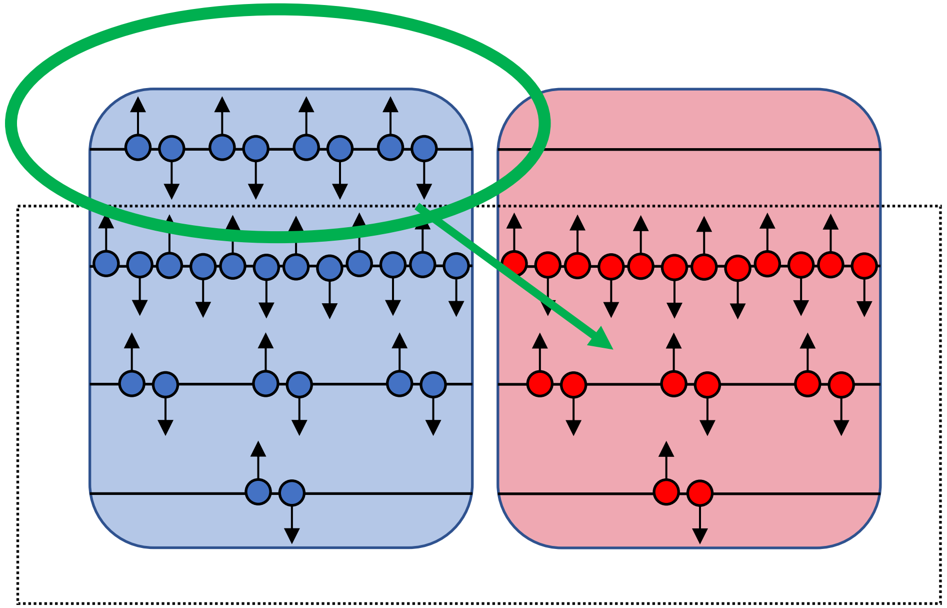
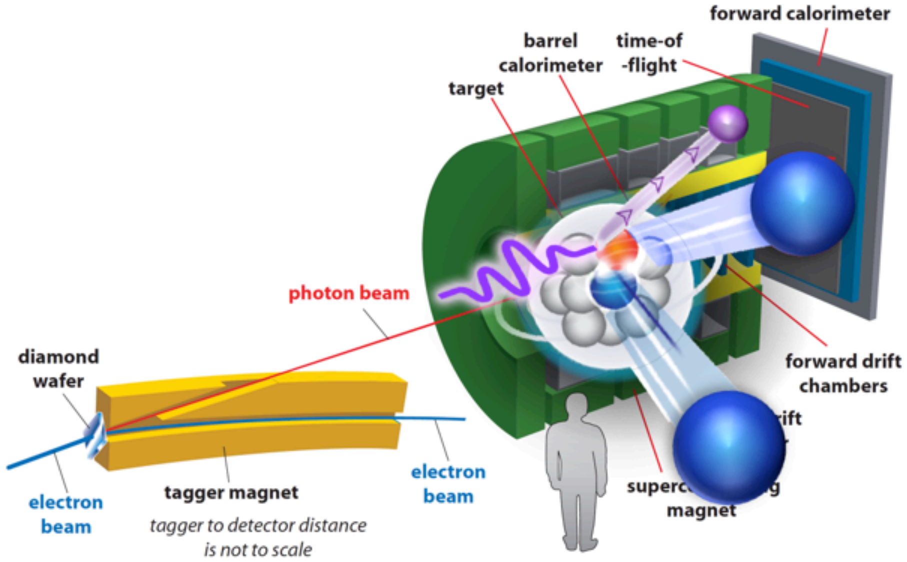


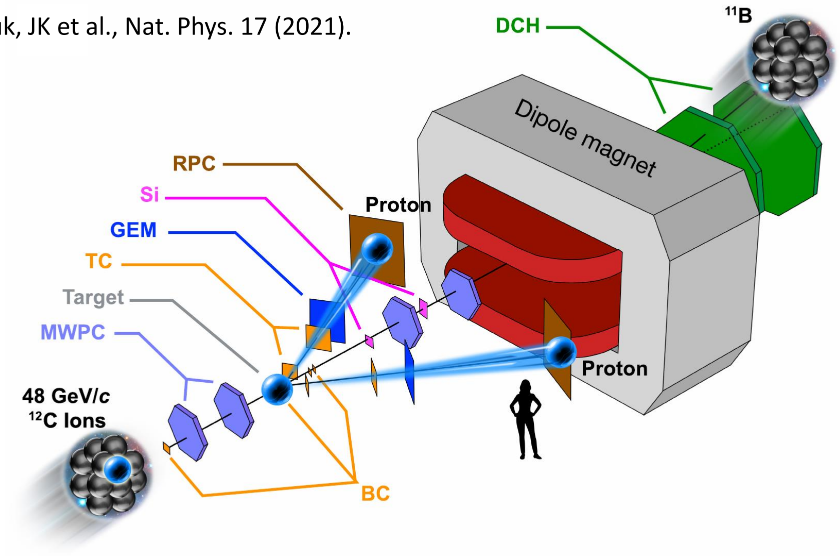
To Recap:

- Asymmetric nuclei teach us about which nucleons correlate.
- New probes can teach us about factorization.



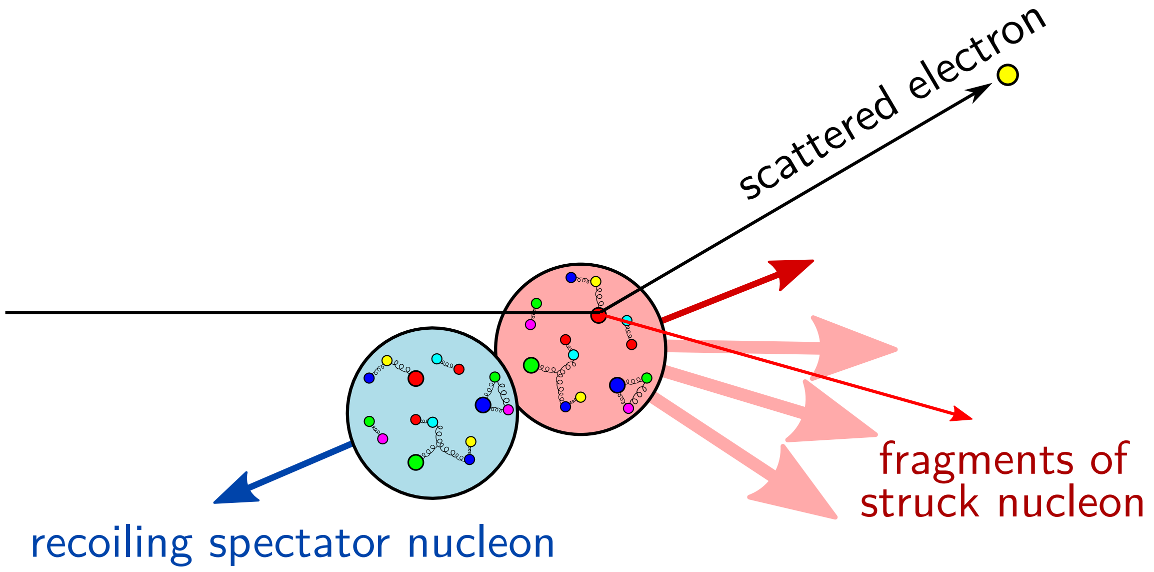
$^{12}C(p,2p)X$

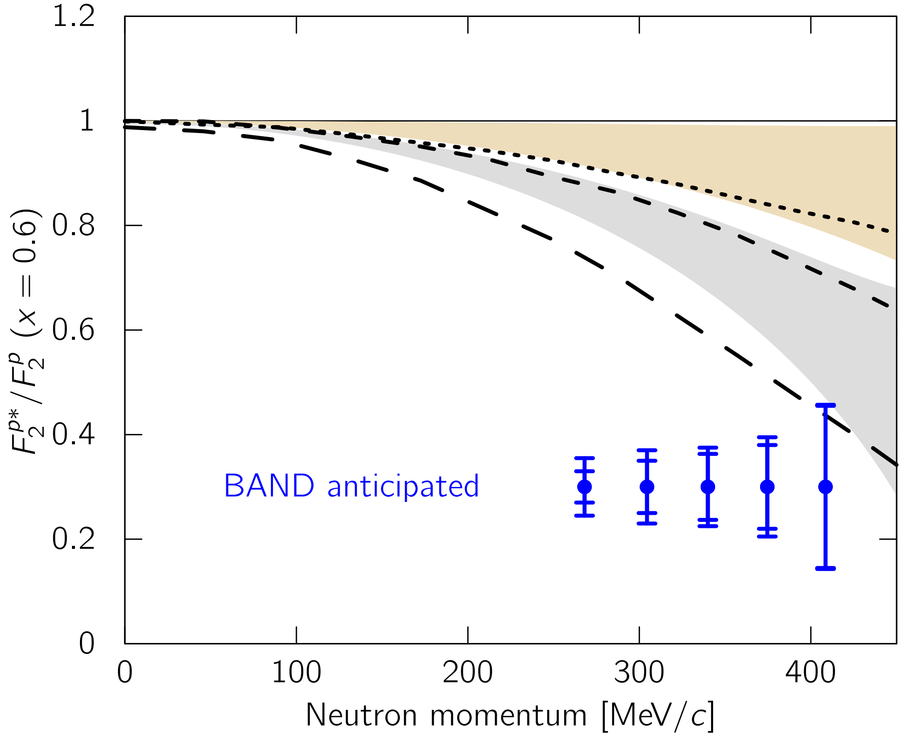
M. Patsyuk, JK et al., Nat. Phys. 17 (2021).



To Recap:

- Asymmetric nuclei teach us about which nucleons correlate.
- New probes can teach us about factorization.
- Spectator tagging will tell us the role SRCs play in the EMC Effect.



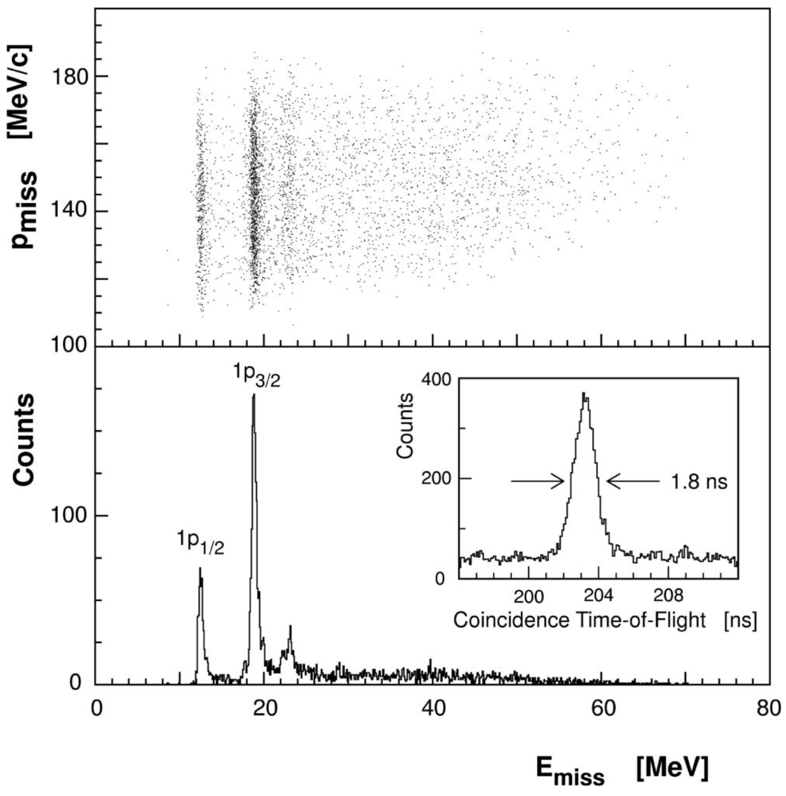


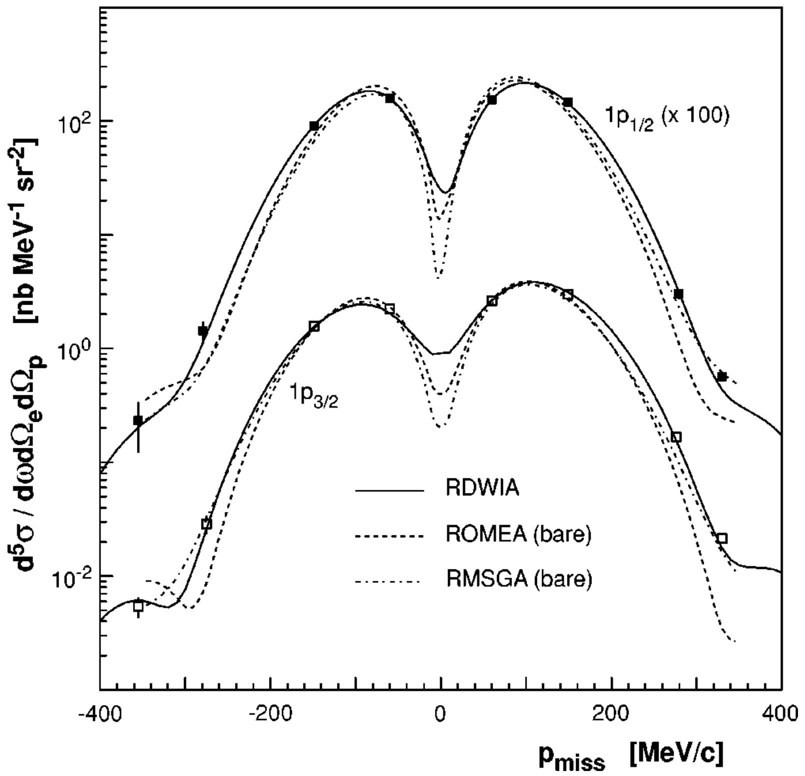
Conclusions

- Balance between “inclusive” and “exclusive” approaches.
  - Inclusive: clean observables, difficulty in interpretation
  - Exclusive: messy observables, direct interpretation
- I’m excited for new data:
  - Hall C campaign on Be, B, Ca, Fe
  - CLAS12 Run Group M
  - Hall D Short-Range Correlations Experiment
- Spectator-tagging is the way to make progress on the EMC Effect.
  - BAND, LAD, and others, building to the EIC!

BACK-UP

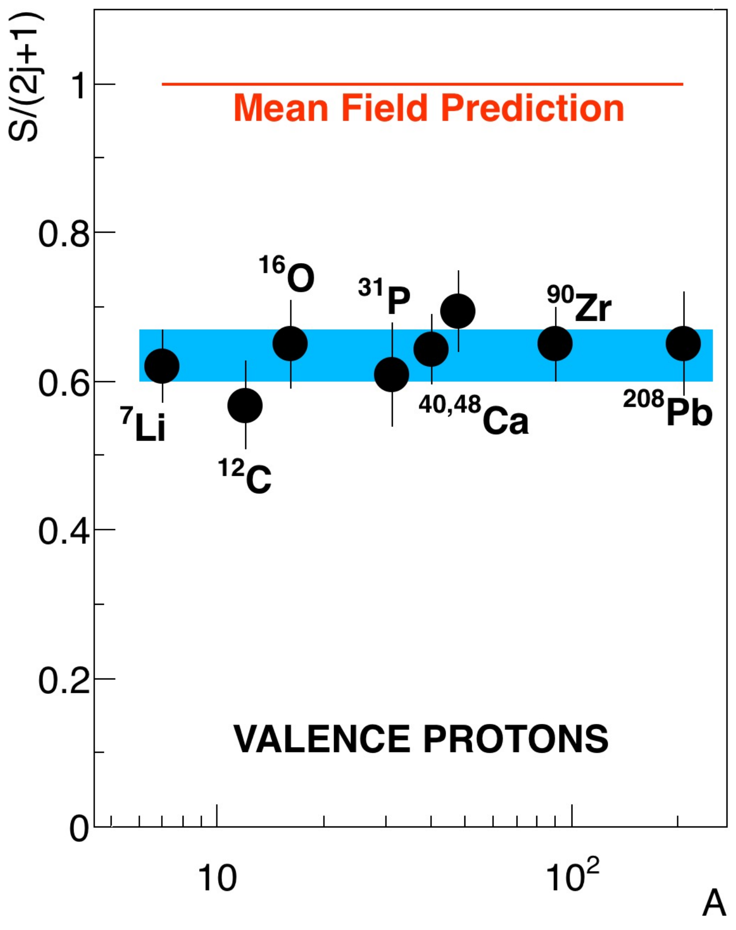
Shell-model orbitals are not fully occupied.



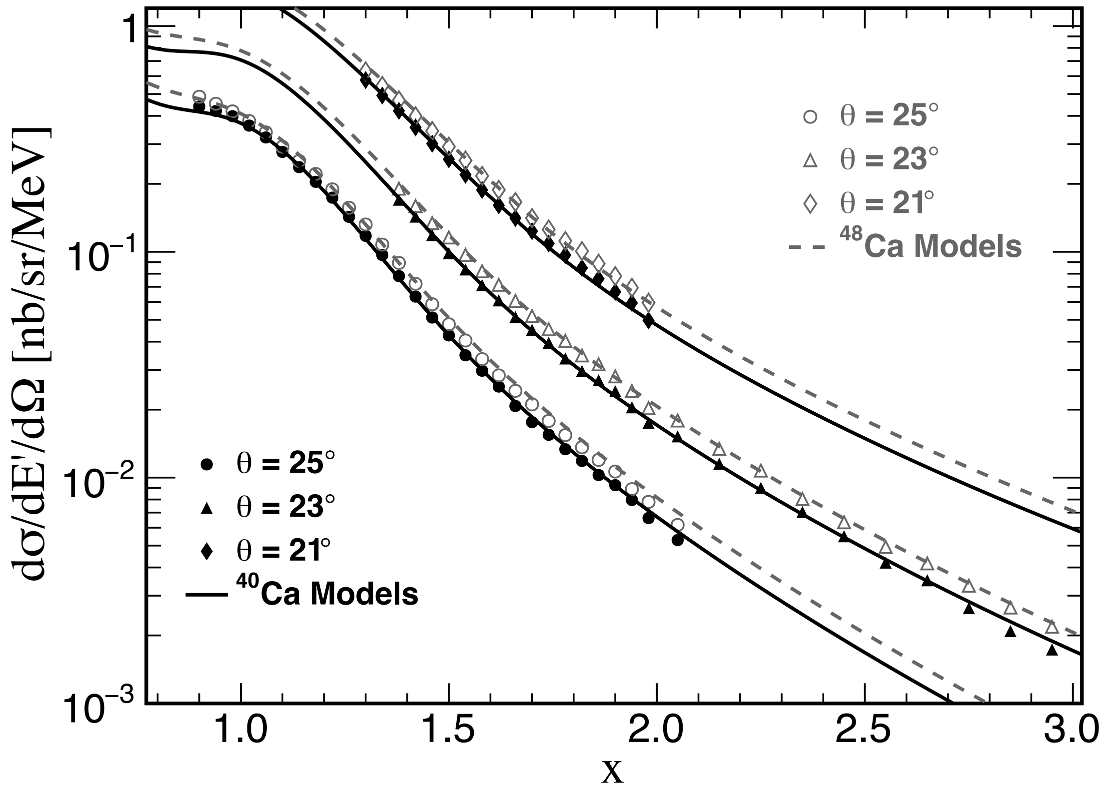


Fissum et al., PRC 70, 034606 (2004)

Reproduced based on (Lapikas, 1993)



The nucleon momentum distribution has a long tail above the Fermi momentum.



Hitting a fast-moving nucleon

Hitting a fast-moving nucleon

Nguyen et al., PRC 102, 064004 (2020)

Ab initio VMC calculations
R. Wiringa, ANL