Short-Range Nuclear Structure: First Experimental Results

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"Light-ion physics in the EIC era"
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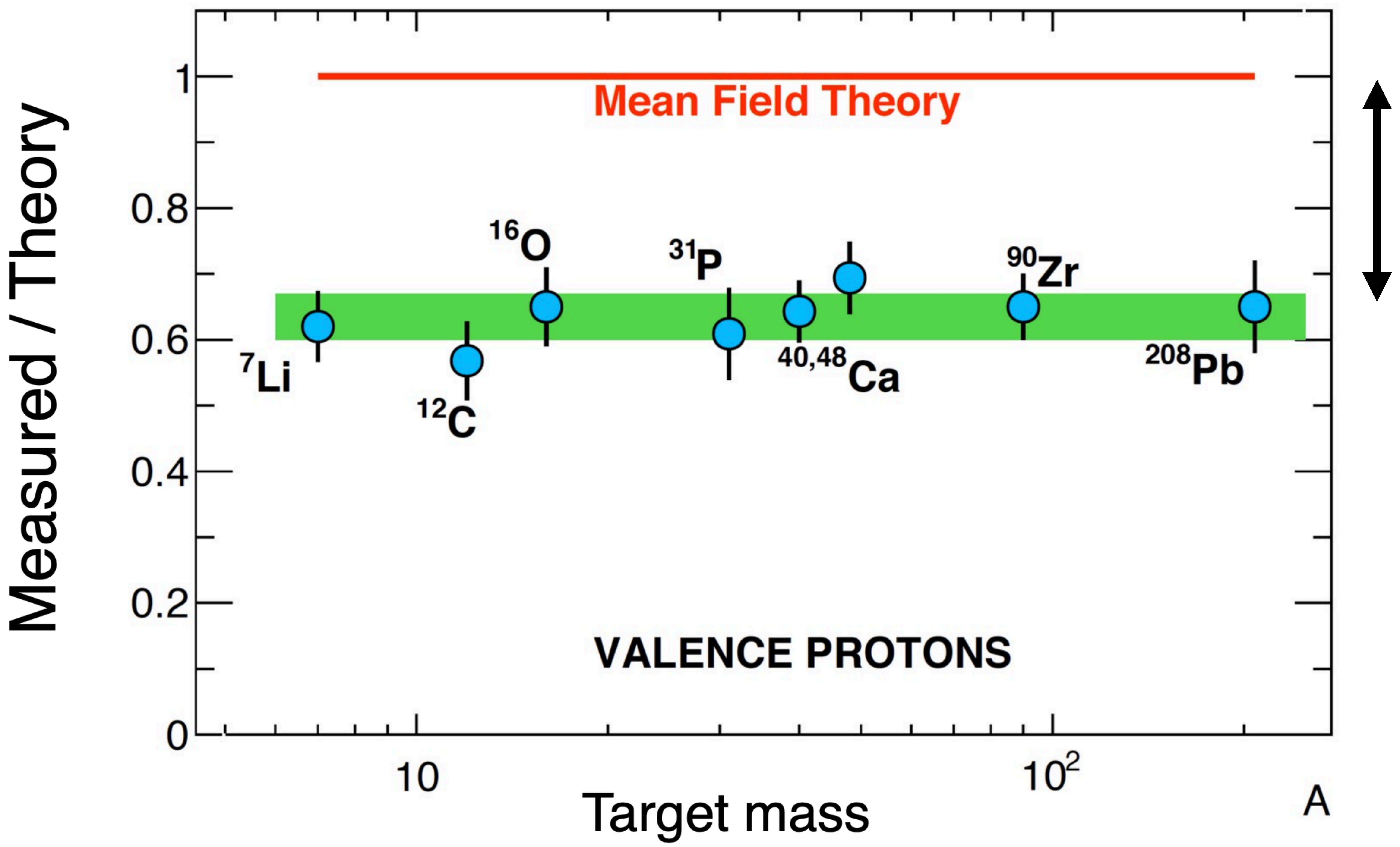
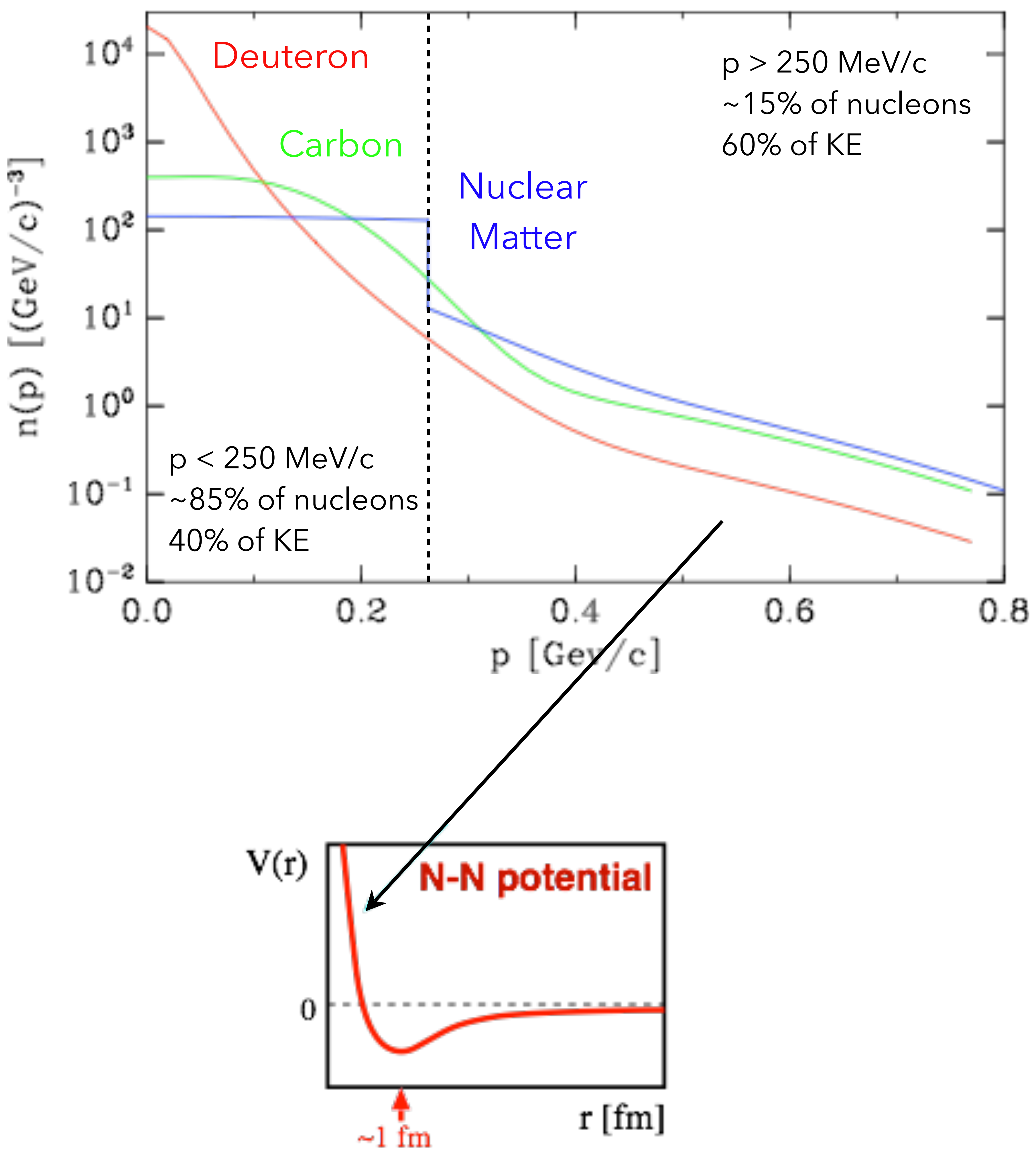
Nuclear Shell Model cannot explain the entire nucleus



Need long-range and short-range correlations to fill the gap

Short-Range Correlations

- IPSM describes $k < k_{Fermi} \approx 250$ MeV/c well, but missing strength
- Nuclear structure calculations show high-momentum tail $k > k_{Fermi}$
  - Dominated by two-nucleon "Short-Range Correlations" (SRCs)
- Small fraction (10-20%) of nucleons, but large impact on overall structure

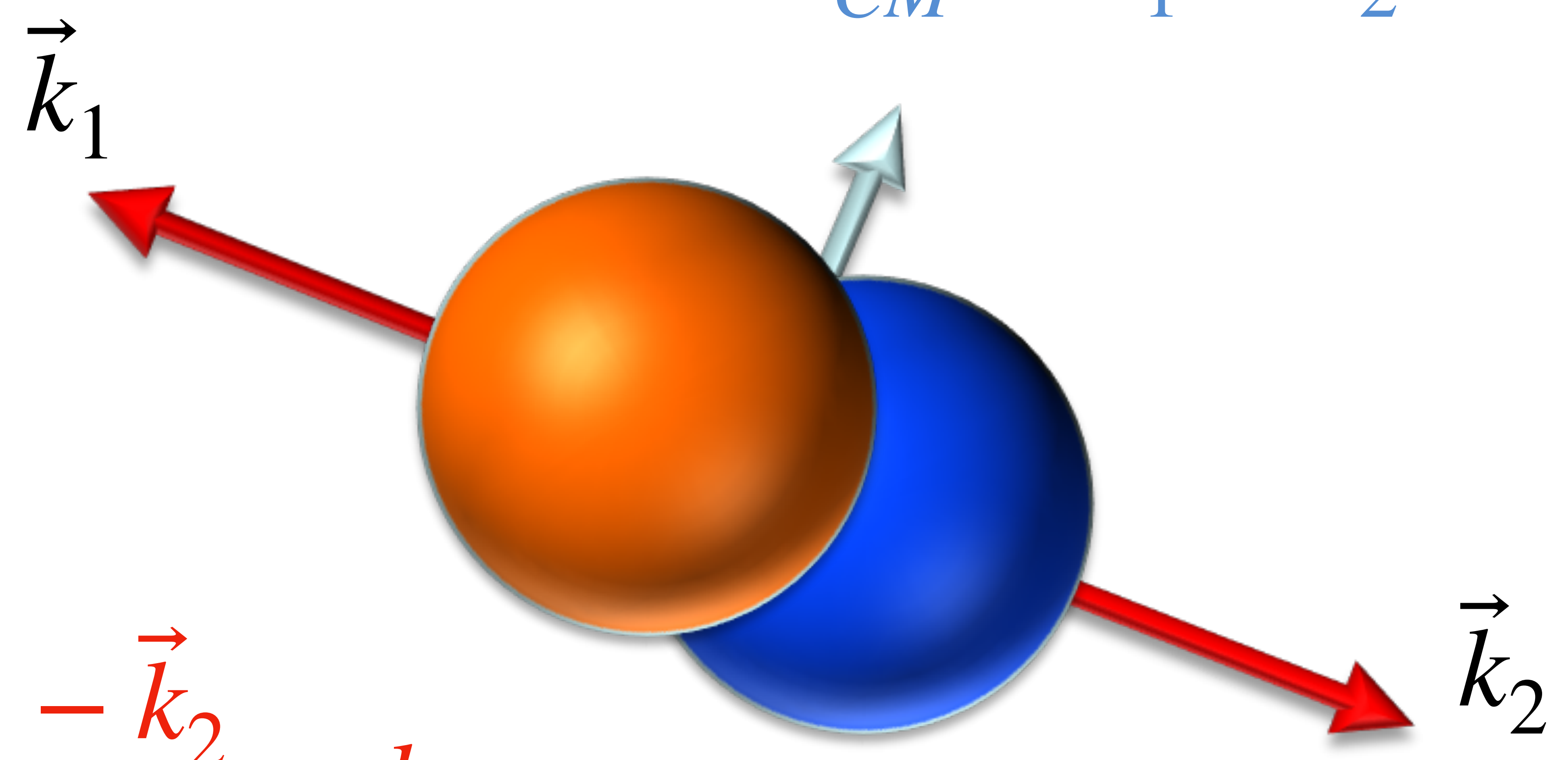


Short-Range Correlations

Nucleon pairs that are very close together in the nucleus

Momentum-space: Large relative and lower C.M. momentum

$$\vec{k}_{CM} = \vec{k}_1 + \vec{k}_2 \ll \vec{k}_{rel}$$



$$\vec{k}_{rel} = \frac{\vec{k}_1 - \vec{k}_2}{2} > k_F$$

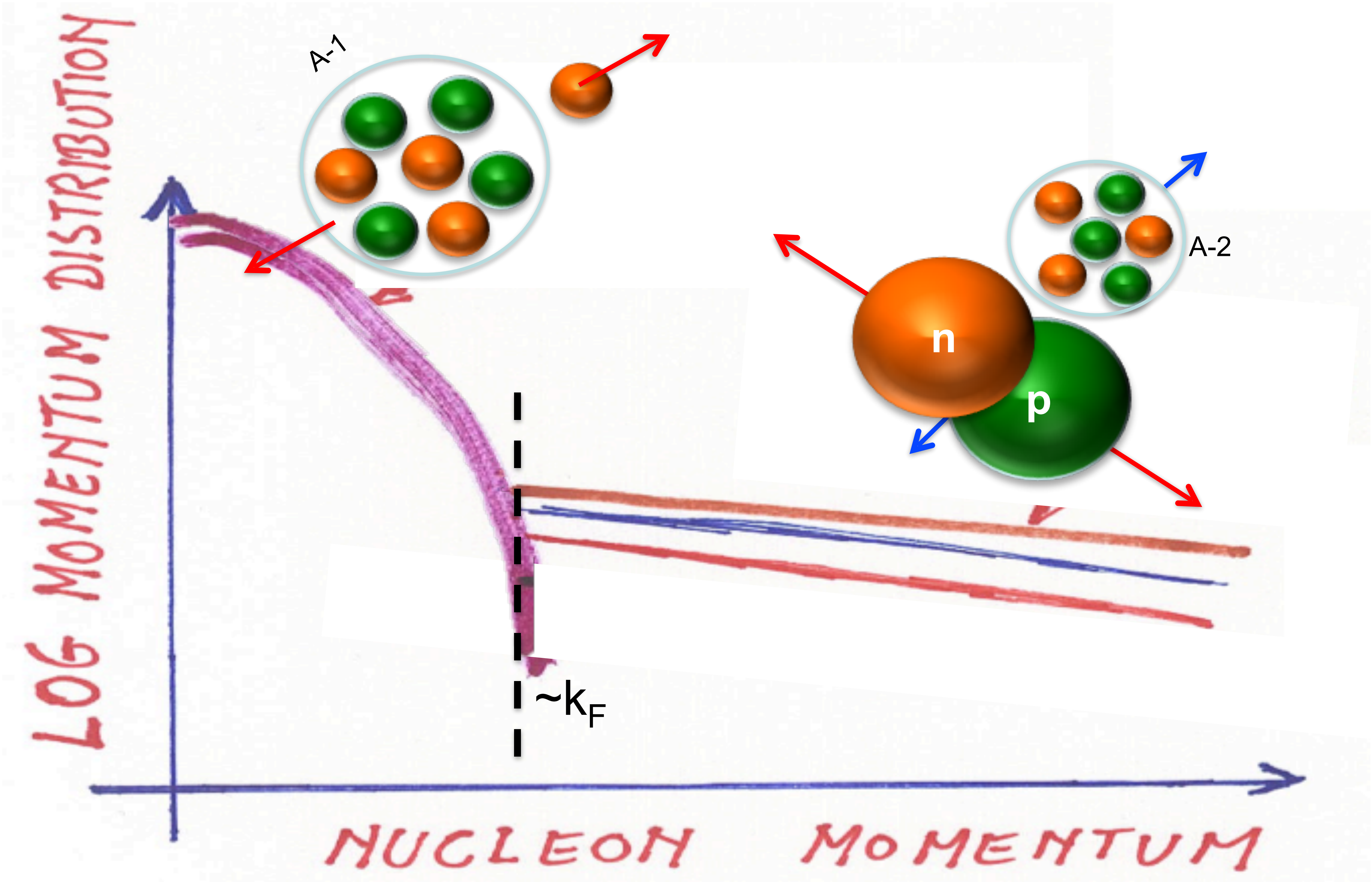
Position-space

Momentum-space

Shell model + LRCs
(Mean field)

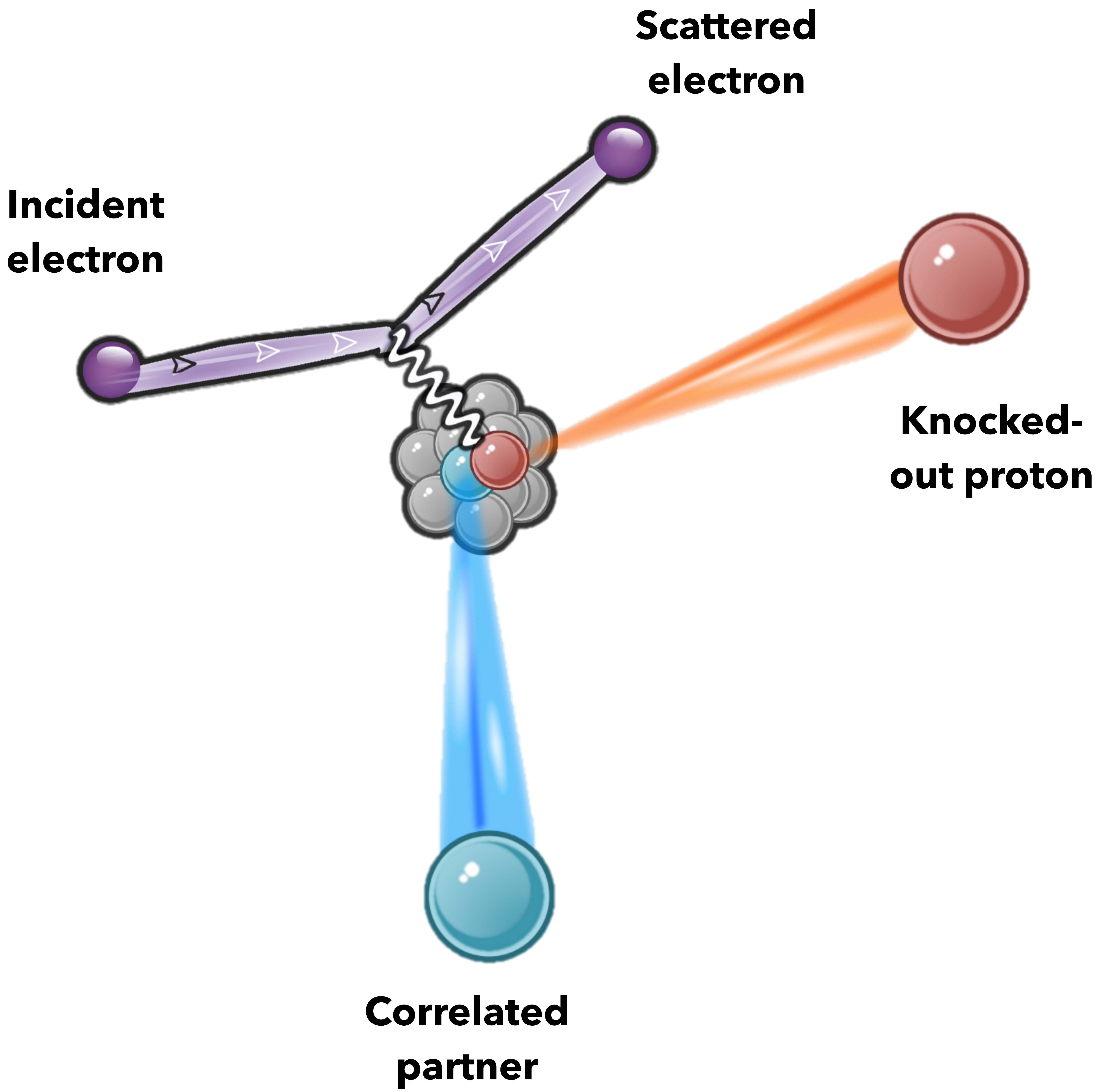
+

SRC Pairs



How do we study SRC?

- Hard knockout reactions – large momentum-transfer to a bound nucleon in the nucleus
- For SRC pairs, partner/spectator nucleon also recoils from the nucleus
- Different channels for studying SRCs:
  - Inclusive (e, e')
  - Semi-inclusive $(e, e'N)$
  - Exclusive $(e, e'NN)$



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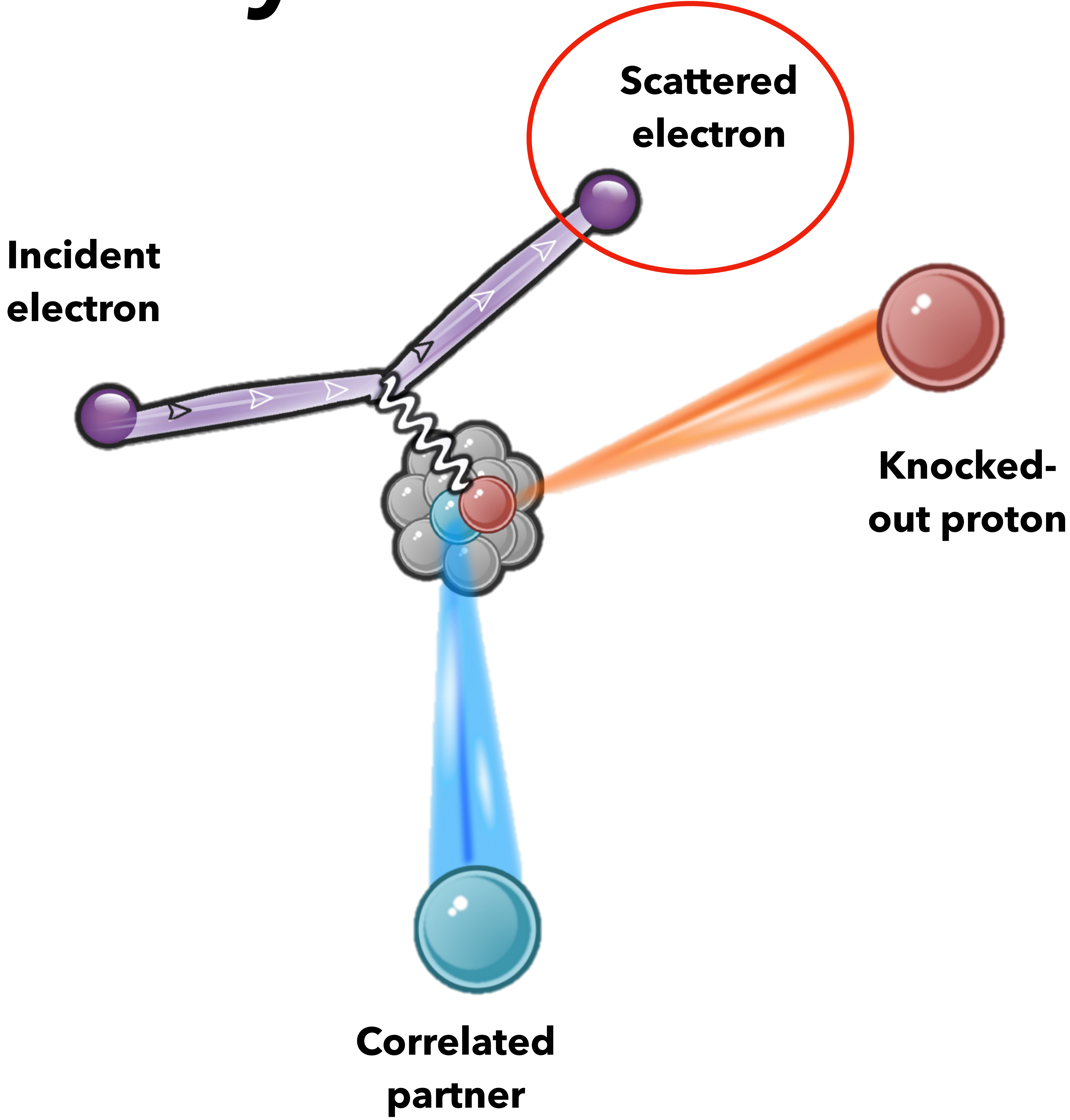

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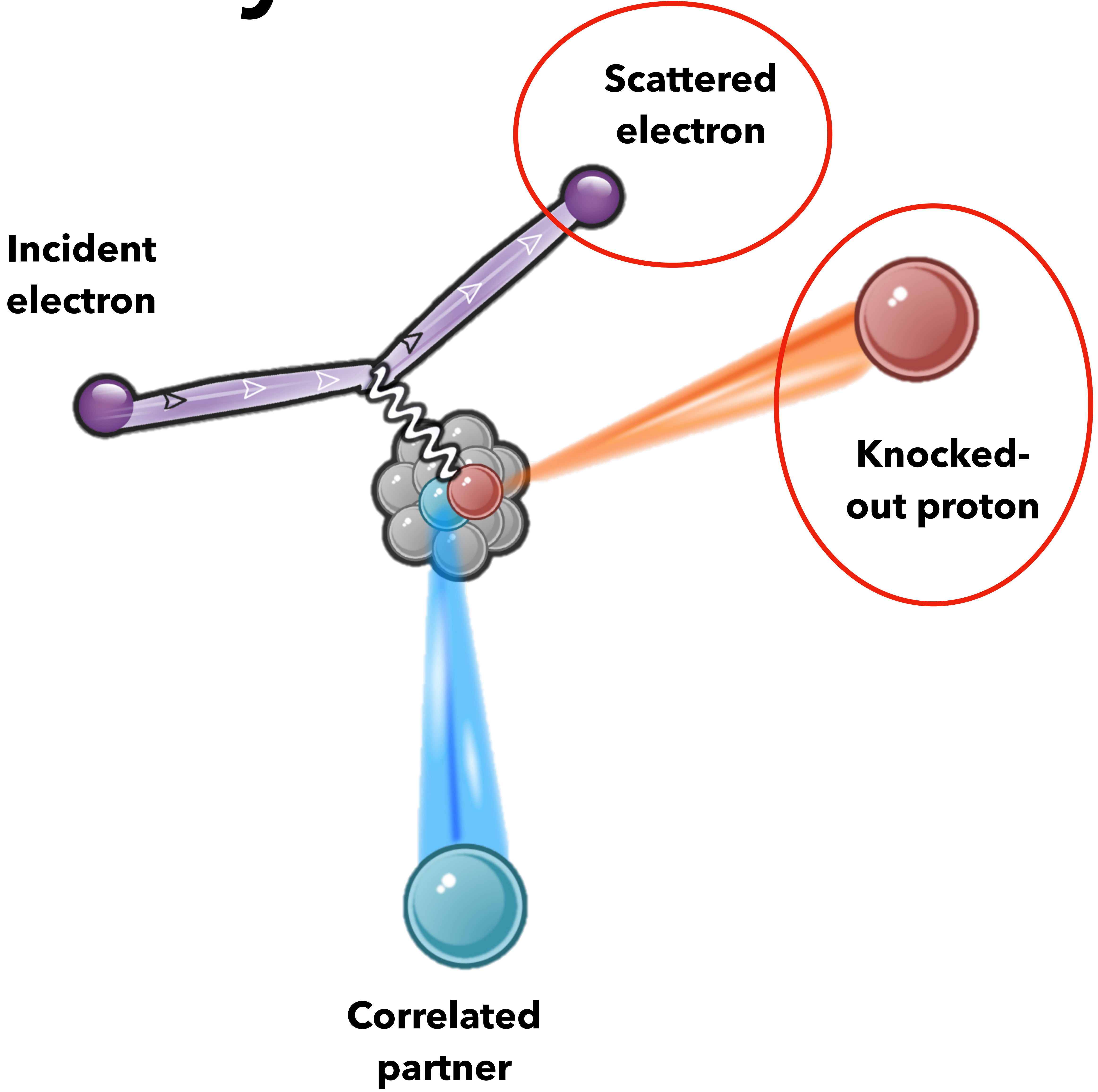

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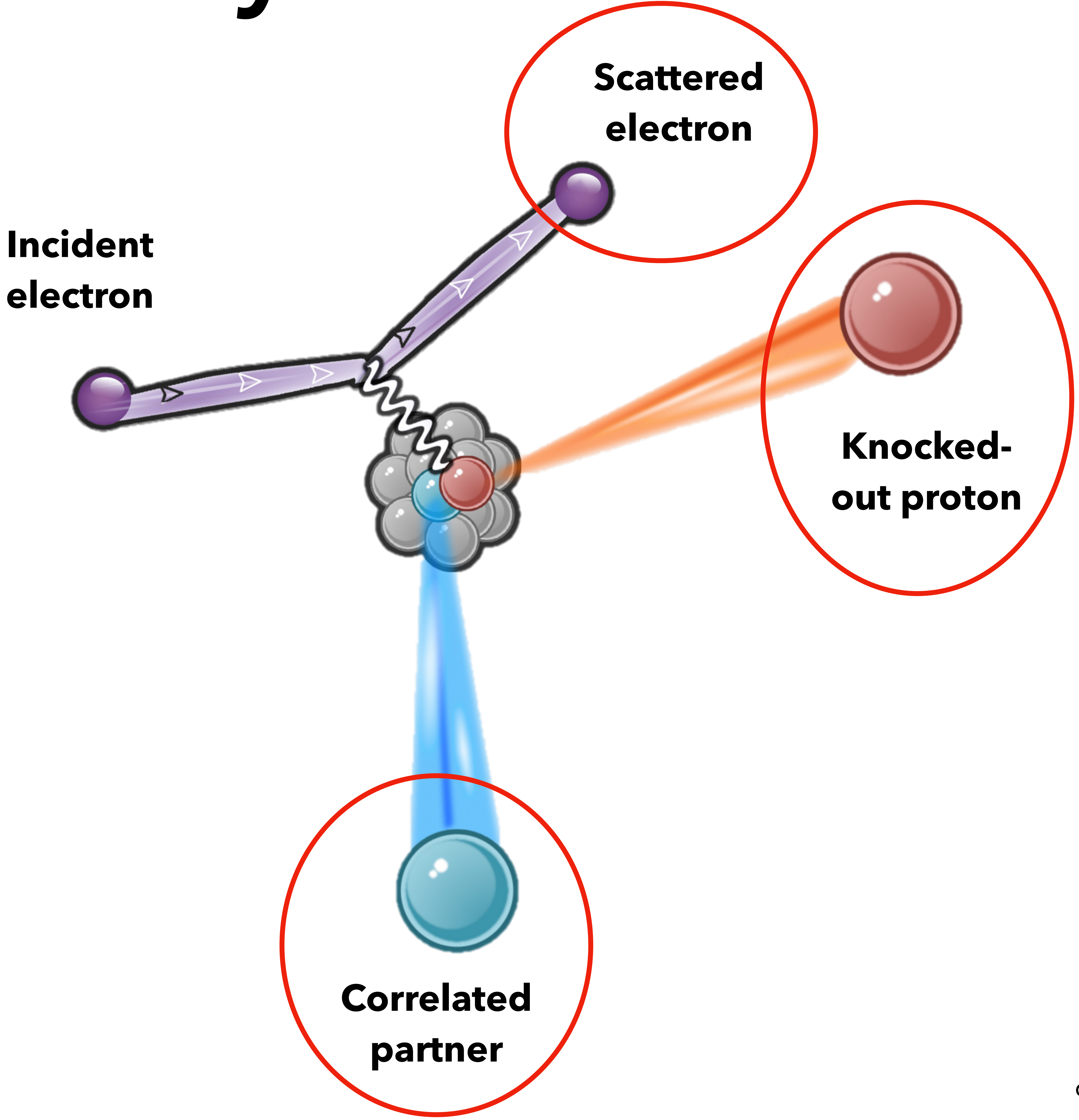
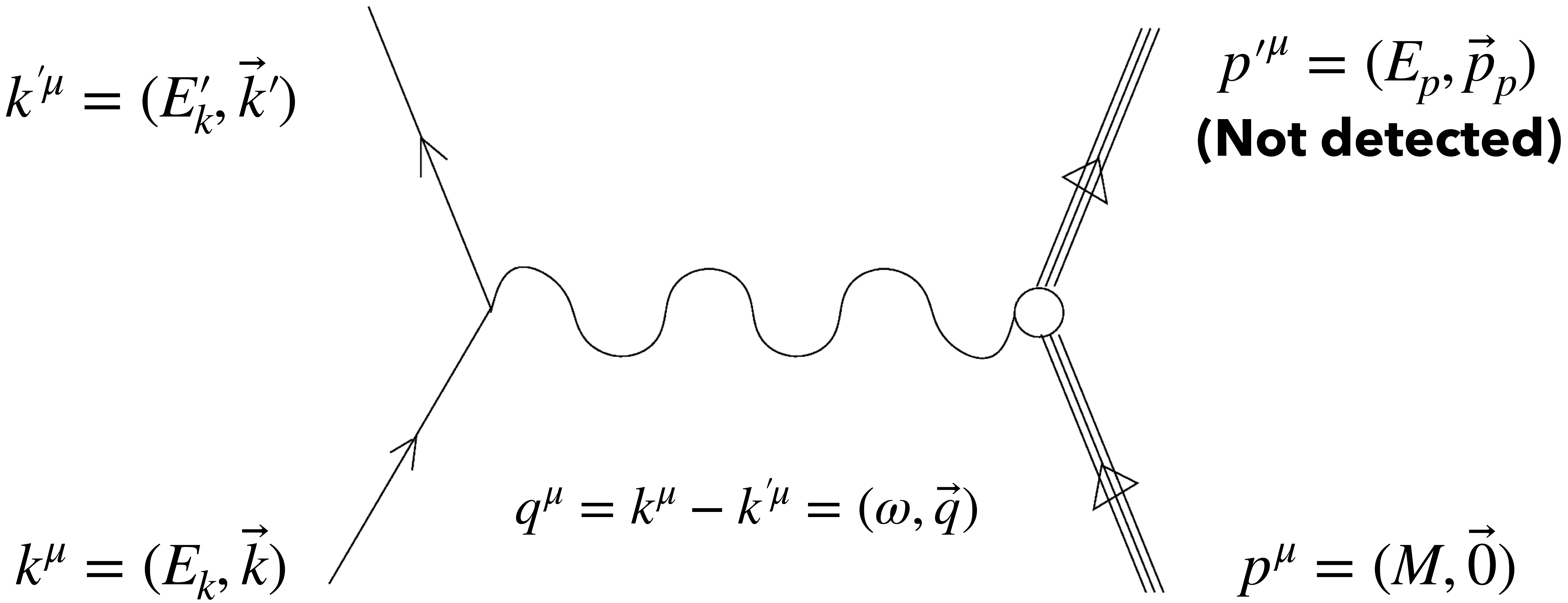


Inclusive Electron Scattering



Kinematic invariants:

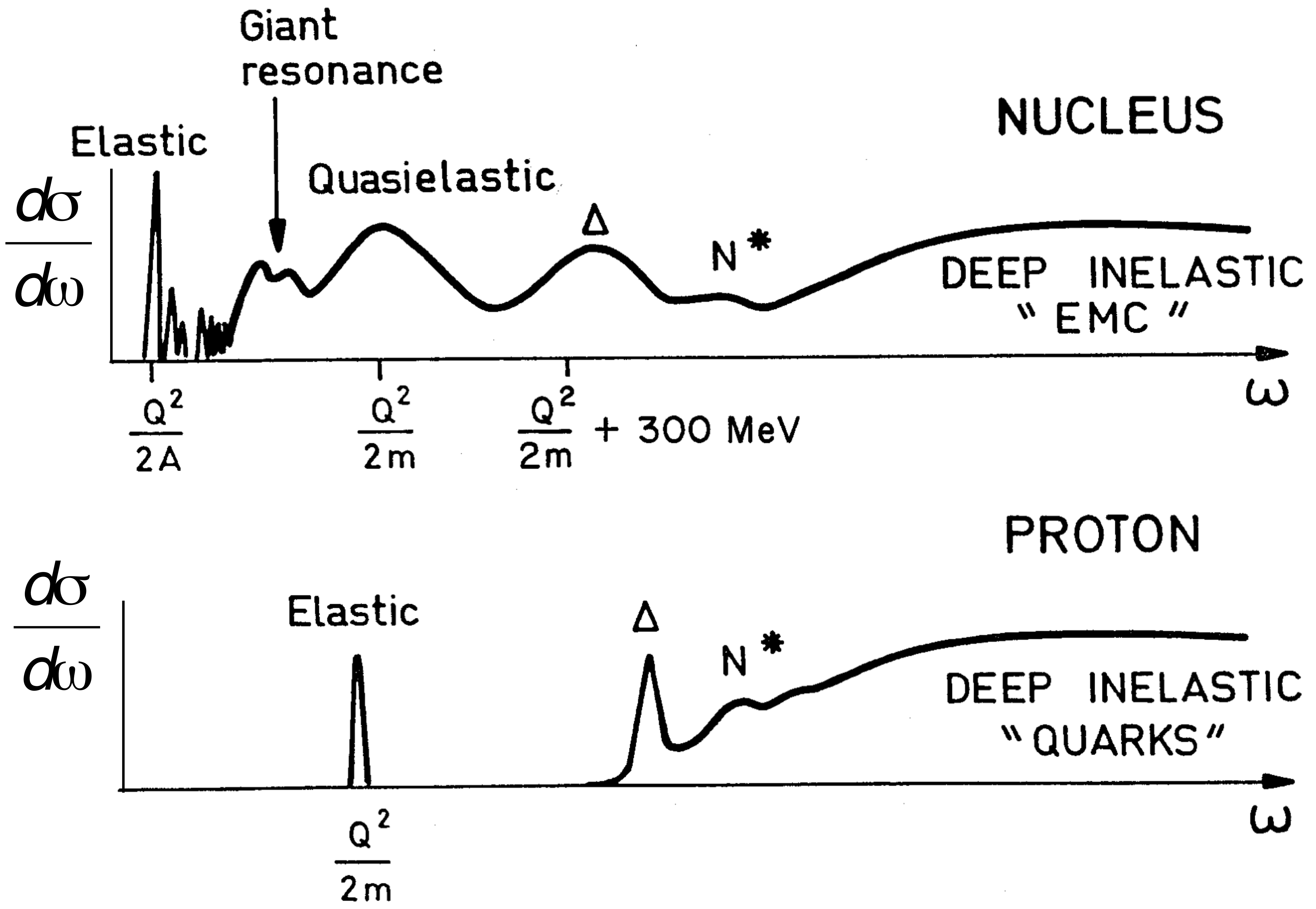
$$p^{\mu} p_{\mu} = M^2 \qquad p_{\mu} q^{\mu} = M\omega$$

$$Q^2 = -q^{\mu} q_{\mu} = |\vec{q}\,|^2 - \omega^2 \qquad W^2 = p'^{\mu} p'_{\mu} = (q^{\mu} + p^{\mu})^2$$

(e, e') Energy Spectrum

Generic electron scattering at <u>fixed momentum-transfer</u>

The energy deposited by the electron can tell us about the underlying process we're measuring



(e, e') Energy Spectrum

Generic electron scattering at
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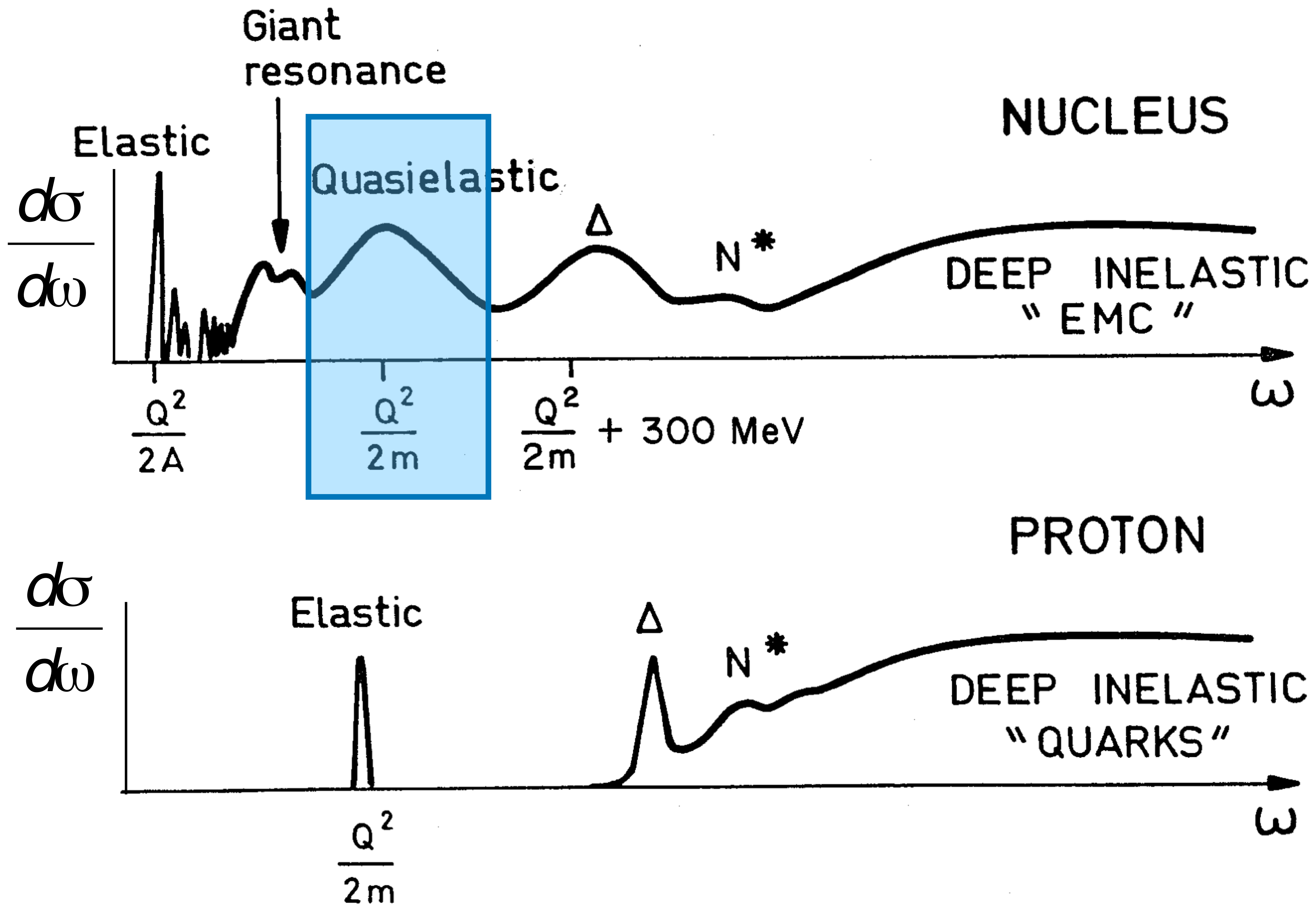
The energy deposited by the electron can tell us about the underlying process we're measuring

"Quasielastic" scattering occurs at $\frac{Q^2}{2m\omega} \equiv x_B \sim 1$



Quasielastic Electron Scattering

- Neglecting off-shell effects, we can use conservation of 4-momentum:

$$p_i + q = p_f$$

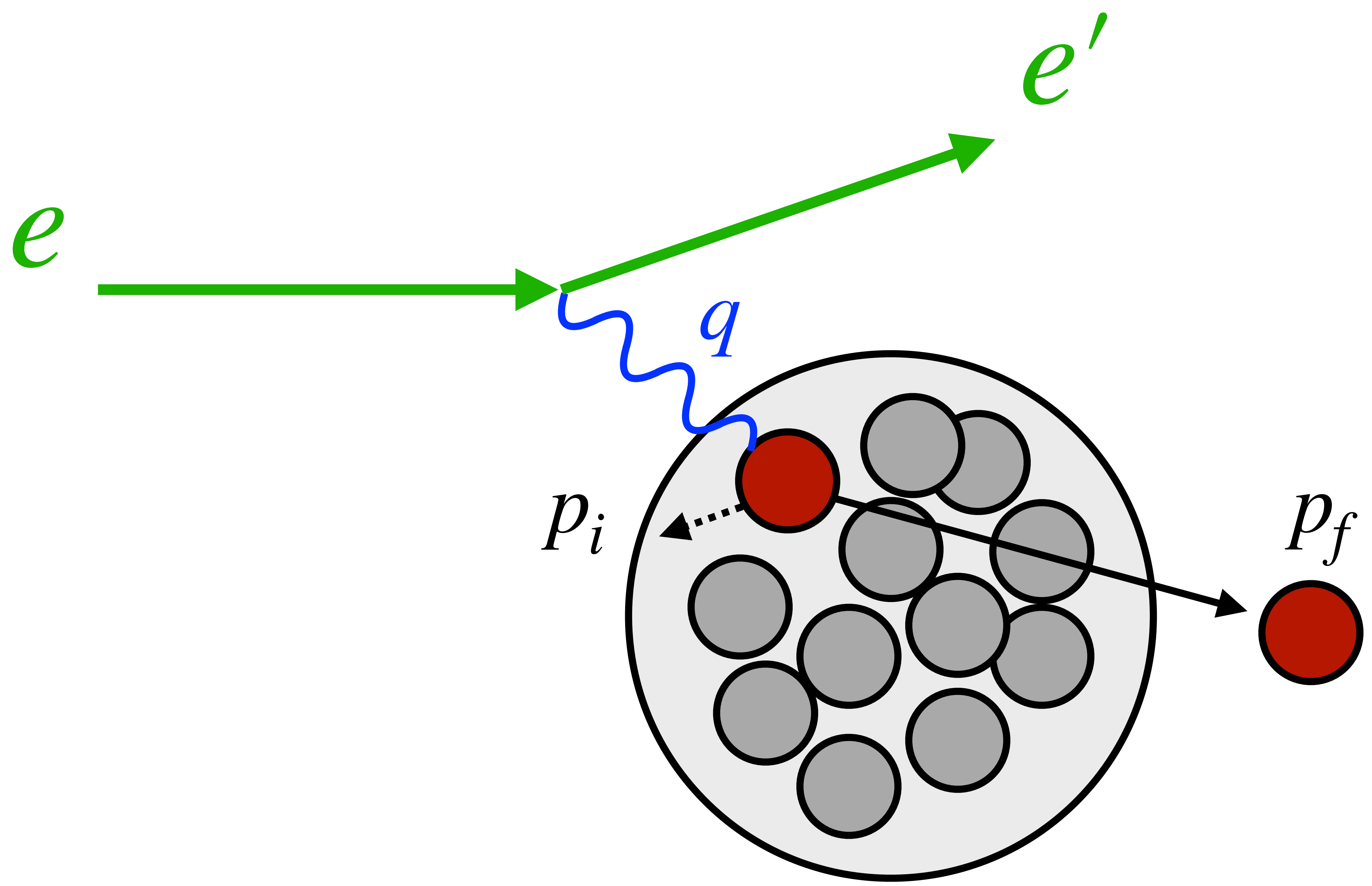
$$(p_i + q)^2 = p_i^2 + 2p_i \cdot q + q^2 = p_f^2$$

$$Q^2 = 2p_i \cdot q = 2E_i\omega - 2\vec{p}_i \cdot \vec{q}$$

$$x_B = \frac{Q^2}{2m_N\omega} = \frac{2E_i\omega - 2\vec{p}_i \cdot \vec{q}}{2m_N\omega}$$

- If we assume Q^2 is large and $|\vec{p}_i|$ is small,

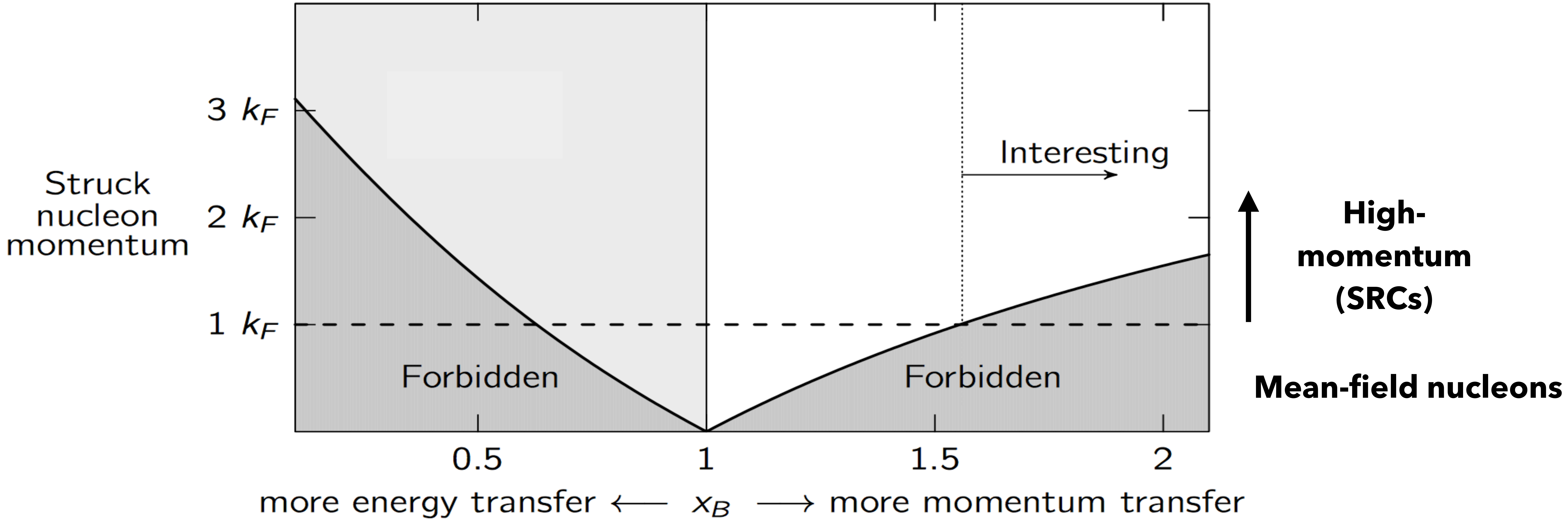
$$x_B \approx 1 - \frac{\vec{p}_i \cdot \hat{q}}{m_N}$$



Inclusive (e, e') Scattering

Inclusive (e, e') cross section at different kinematics are sensitive the nuclear momentum distribution

Minimum momentum for the struck nucleon is set by x_B



Inclusive (e, e') Scattering

- Measuring (e, e') cross section as function of x_B tells us about the nuclear momentum distribution $n(k)$ – at least in one dimension
- **Ratios** between nuclear cross sections can let us compare nuclear momentum distributions
- Areas where the ratio is constant represent **scaling**, where the cross section depends only on x_B and not on A
    - Scaling → **Universal behavior**

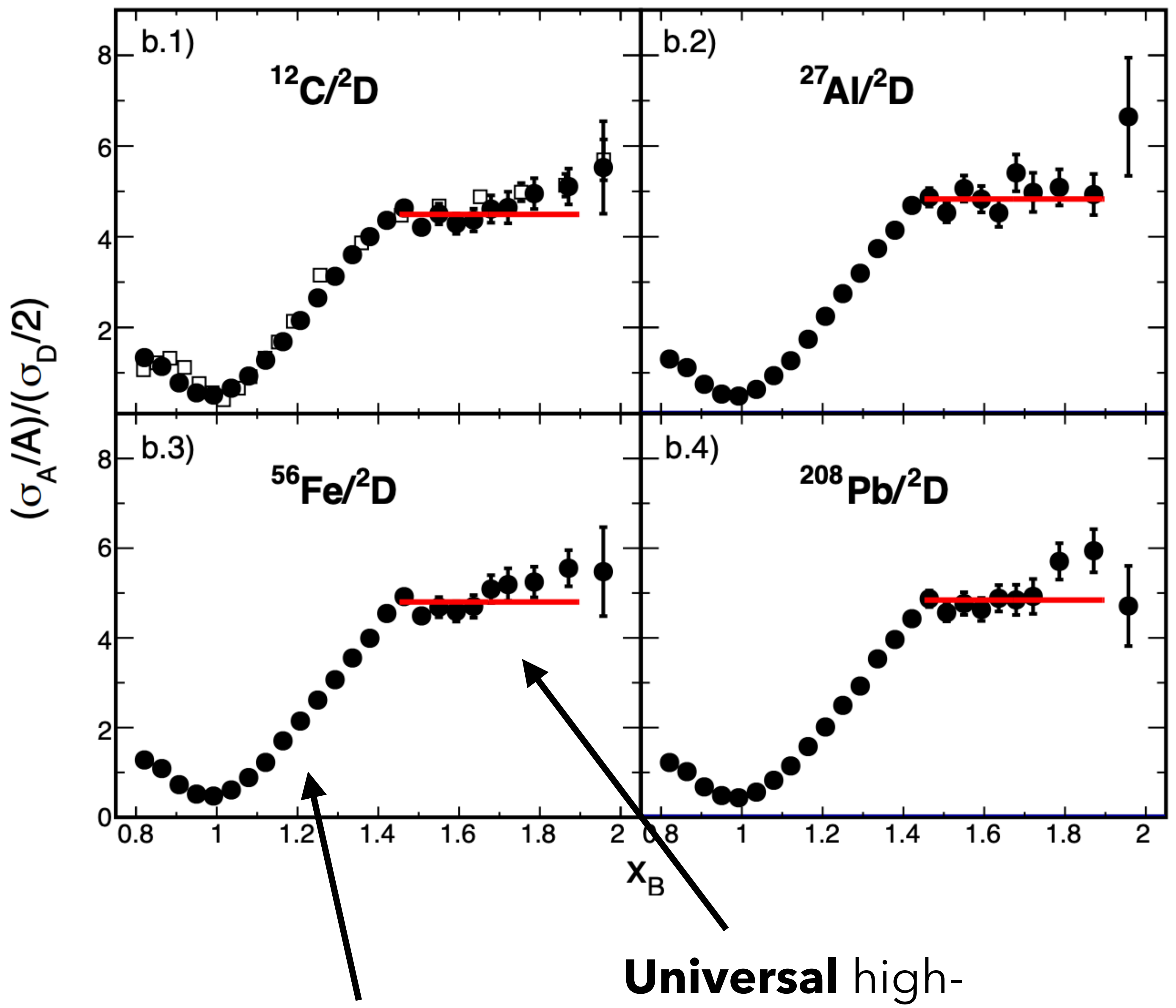
Inclusive (e, e') Scattering

- Measured σ_A/σ_d cross section for (e, e'), sensitive to $n_A(k)/n_d(k)$

- Scaling observed for $x_B > 1.5$ – above "Fermi momentum" where shell-model dominates

- Scaling down to $A = 2$ deuteron suggests **universal two-nucleon pairing behavior**

$$a_2(A) = \frac{n_A(k > k_F)}{n_d(k > k_F)} \sim \text{\# Nucleon pairs}$$

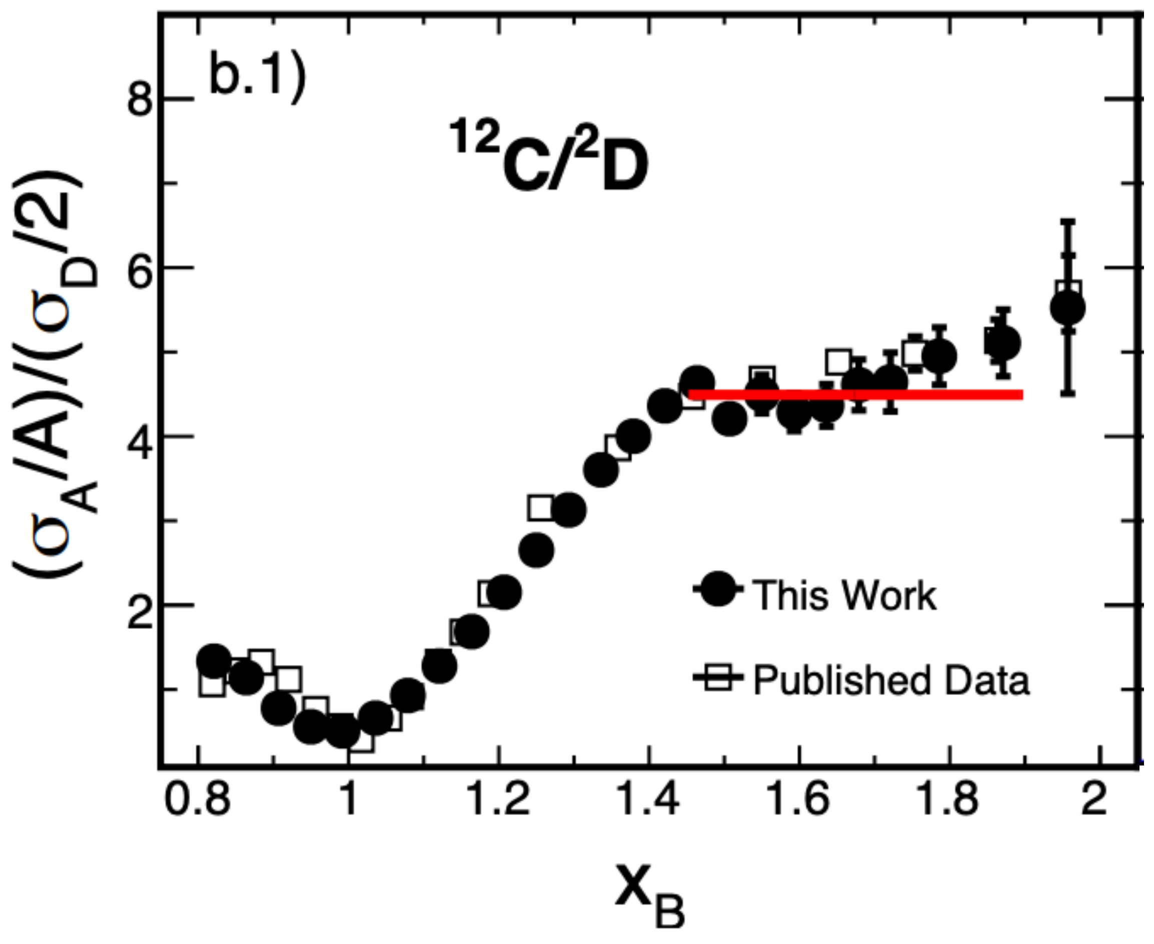


Different mean-field shell structure

Universal high-momentum 2N pairs

Day et al, PRL (1987)
Frankfurt et al, PRC (1993)
Egiyan et al, PRL (2006)
Fomin et al, PRL (2012)
Schmookler et al, Nature (2019)

First estimate of SRC fraction in nuclei



A	a_{2N}(A/d)
^{3}He	2.08±0.01
^{4}He	3.47±0.02
Be	4.03±0.04
C	4.95±0.05
Cu	5.48±0.05
Au	5.43±0.06

Measure of SRC relative to deuteron comes from a_2

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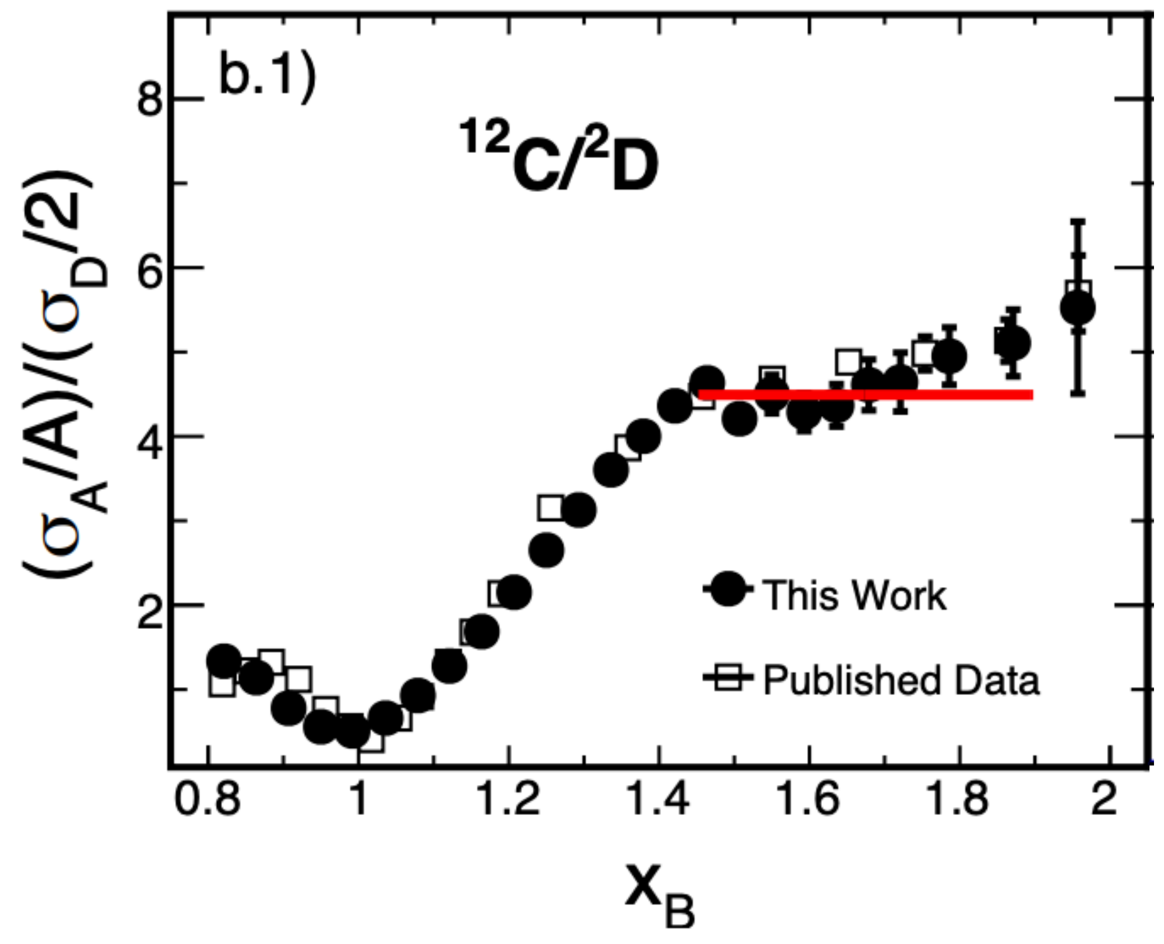

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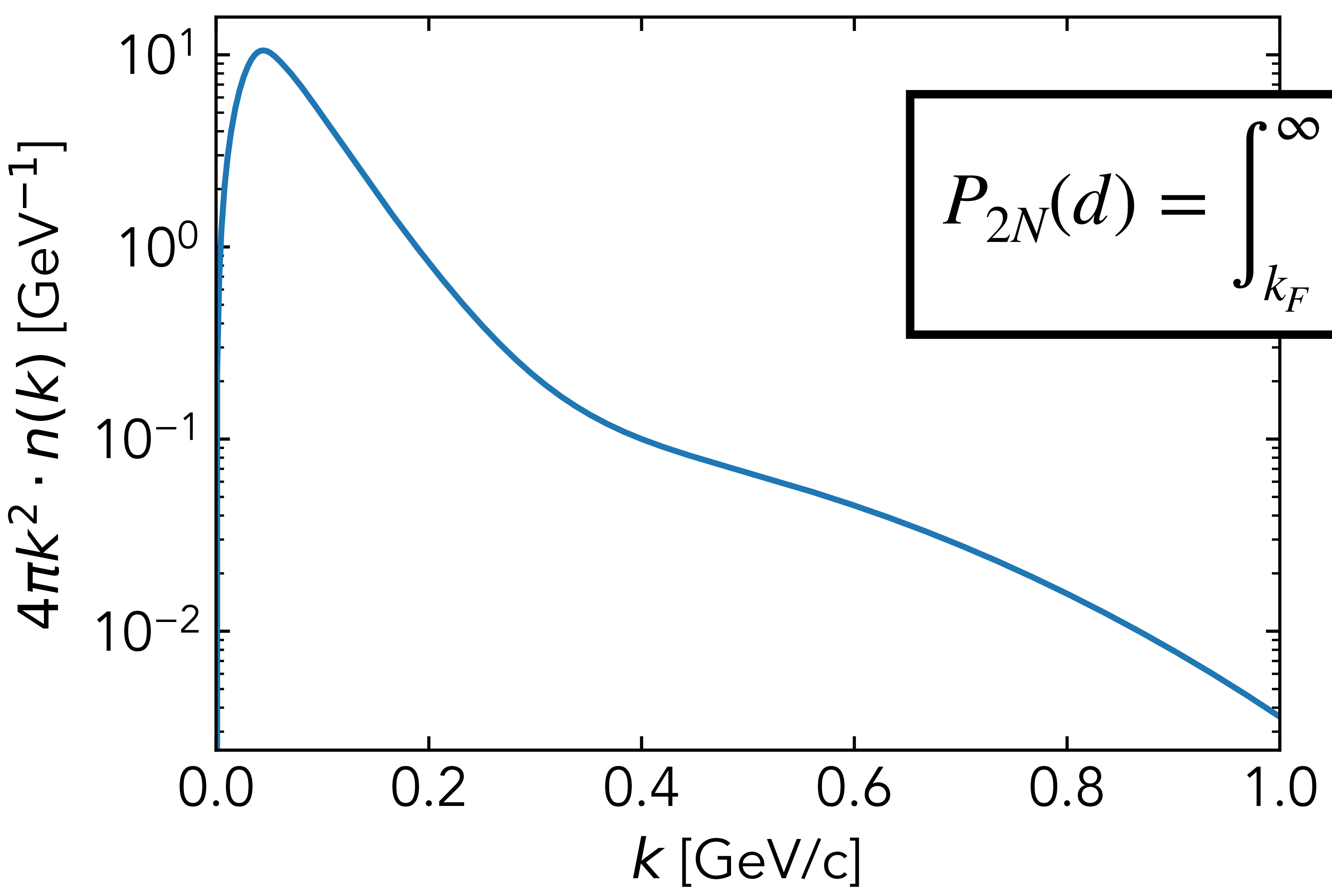
Deuteron momentum distribution



$$P_{2N}(d) = \int_{k_F}^{\infty} n_d(k)\ d^3k = 4.1 \pm 0.8\ \%$$

2-body calculations of deuteron wavefunction: About **4%** short-distance

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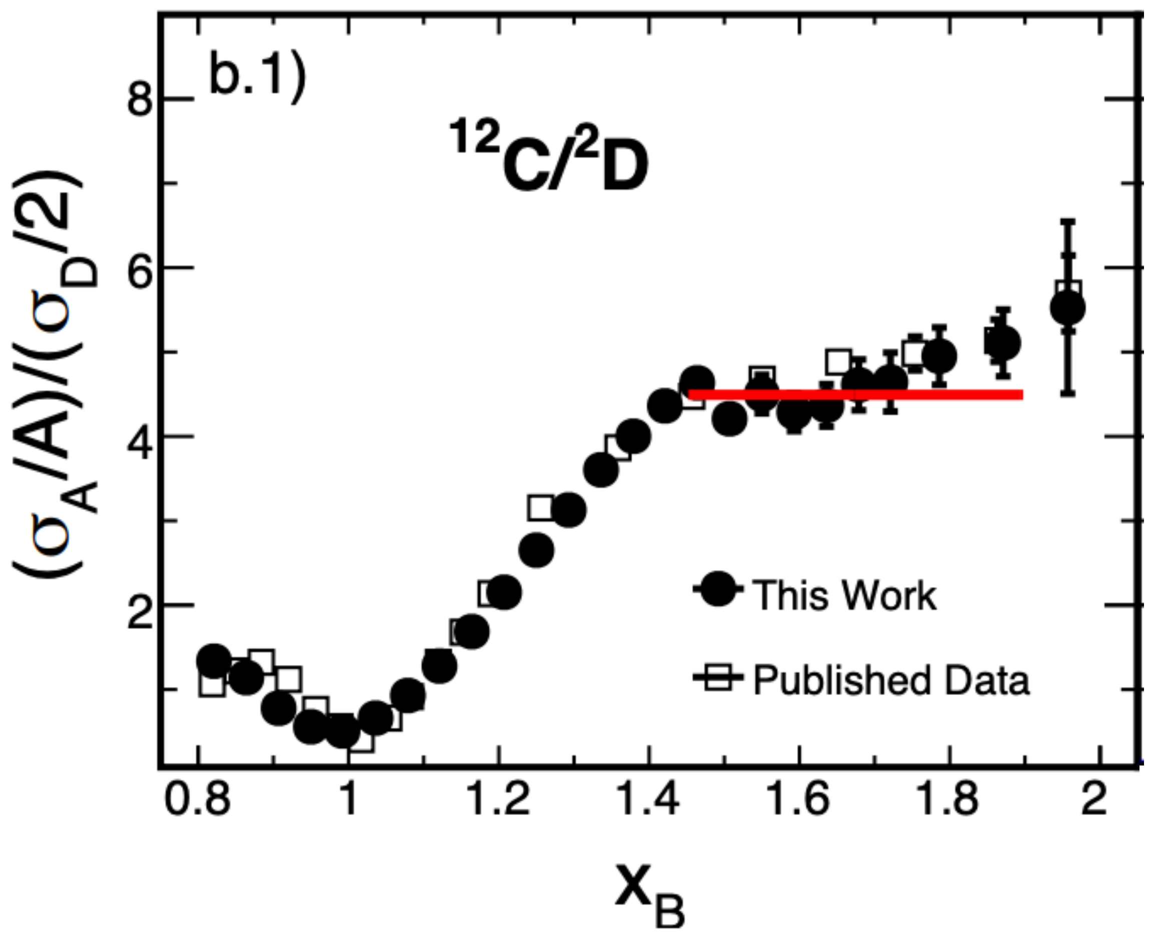

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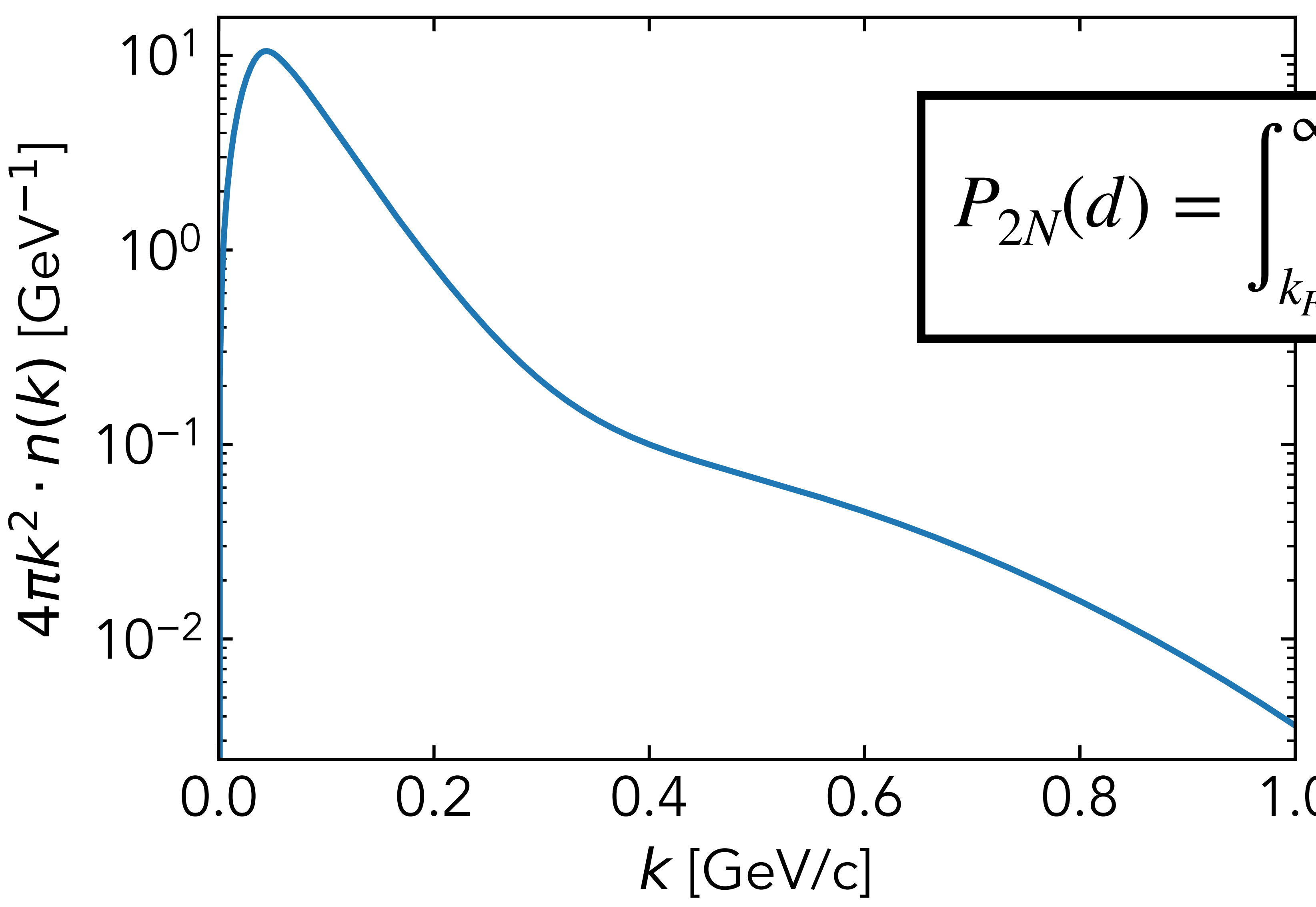

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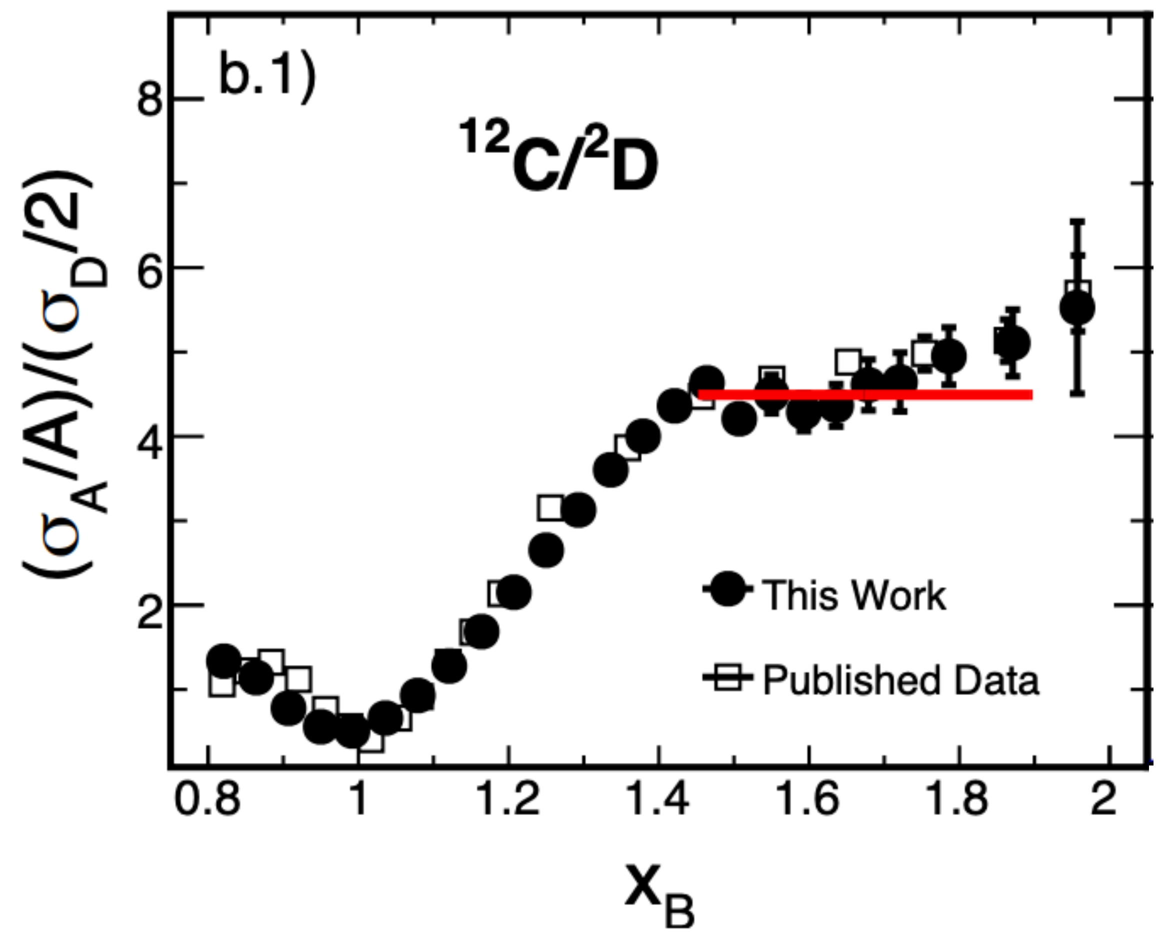
2-body calculations of deuteron wavefunction: About **4%** short-distance

Measurement

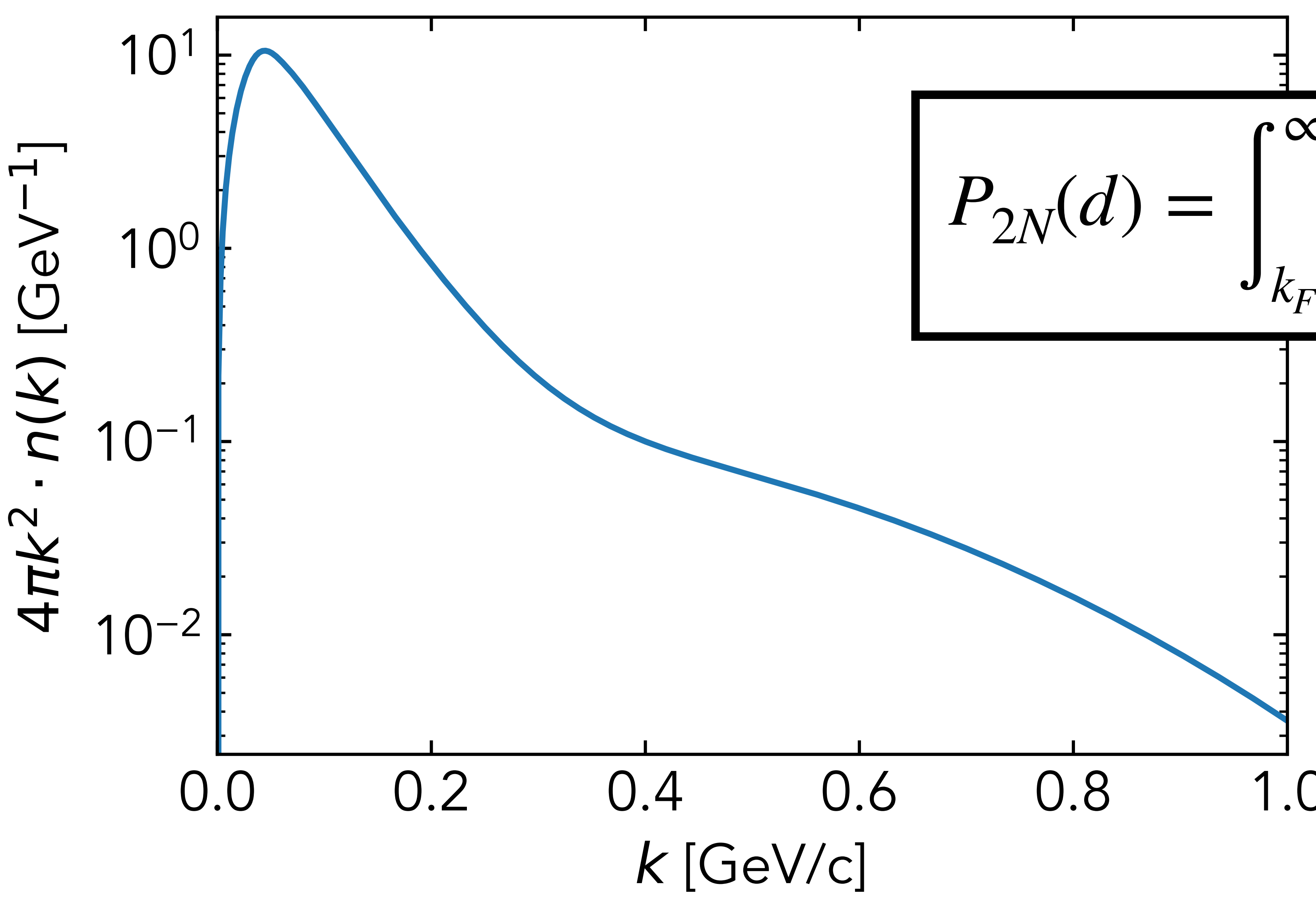
Theory

$$P_{2N}(A) \approx a_{2N}(A/d) \cdot P_{2N}(d)$$

First estimate of SRC fraction in nuclei



Deuteron momentum distribution



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Measure of SRC relative to deuteron comes from a_2

Measurement

Theory

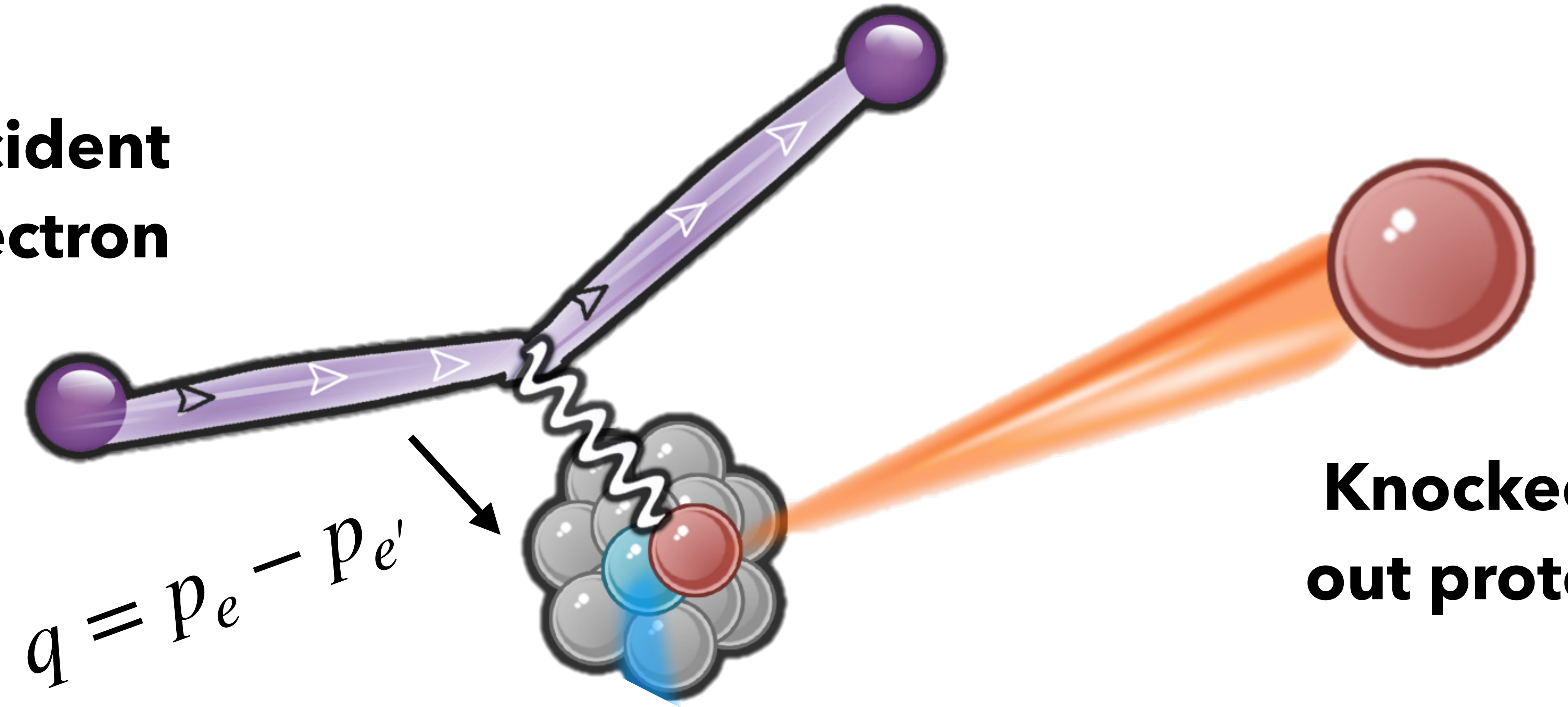
$$P_{2N}(A) \approx a_{2N}(A/d) \cdot P_{2N}(d)$$

Carbon: $P_{2N}(^{12}C) \approx 5 \cdot 4\ \% = 20\ \%$ SRC

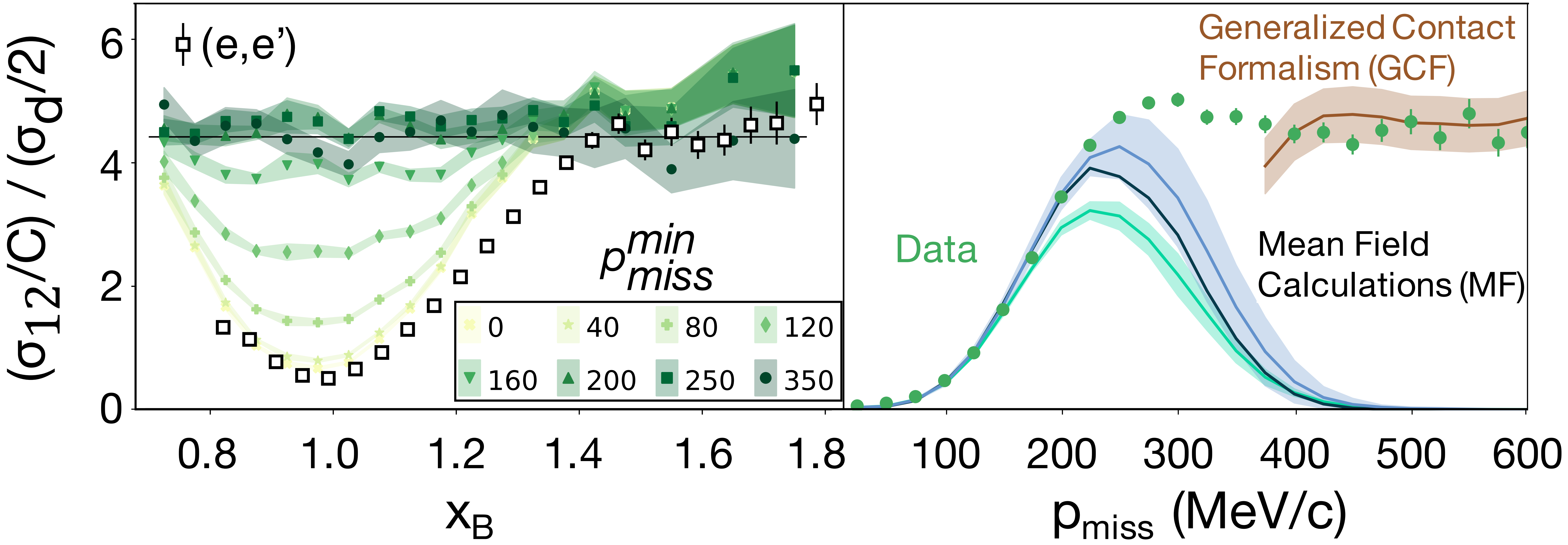
Semi-inclusive $(e, e'p)$

Detecting knocked-out nucleon – **reconstruct initial-state nucleon**:

$$p_i \approx p_{miss} = p_N - q$$



High-Momentum SRC Dominance



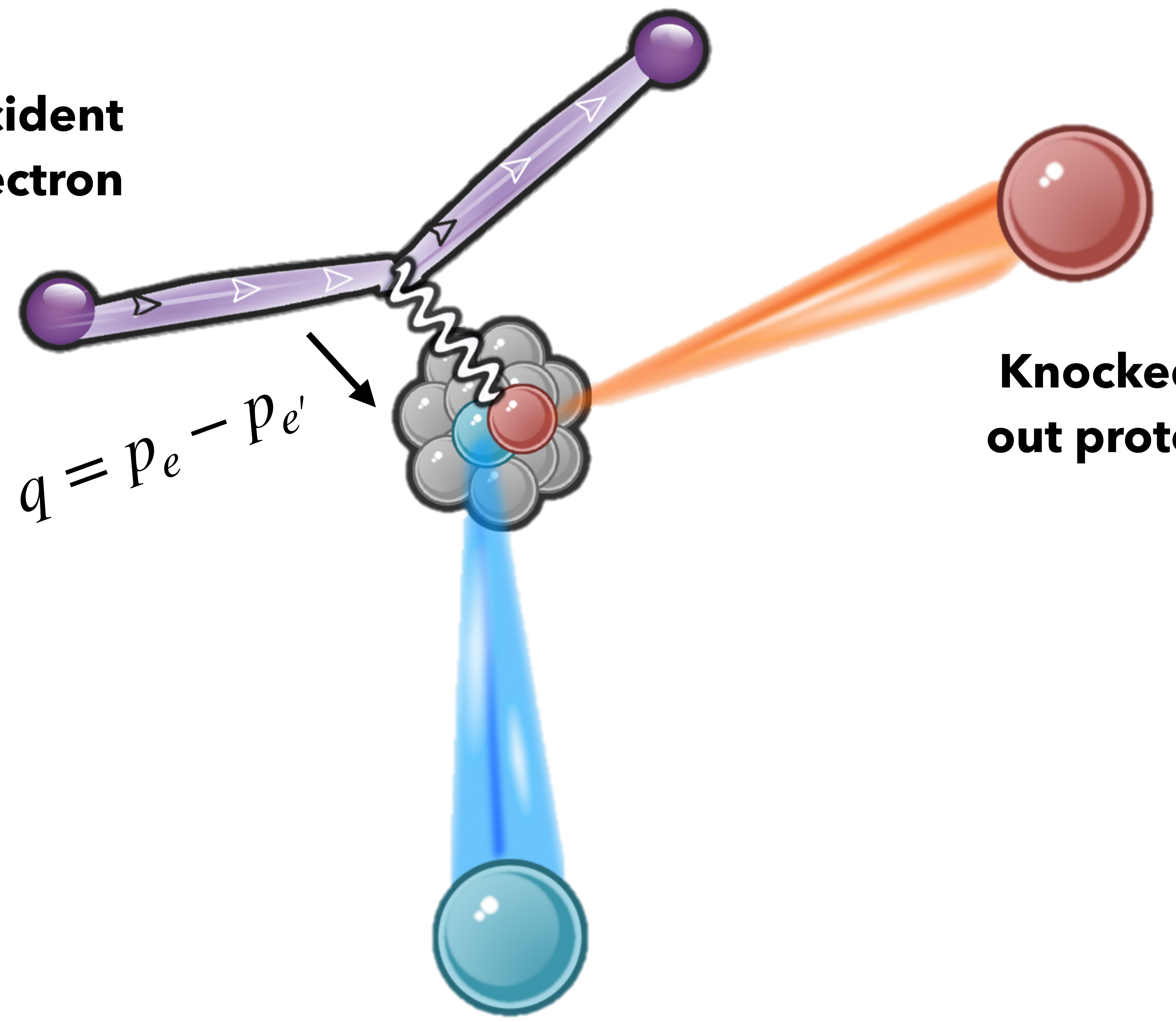
Semi-inclusive $(e, e'p)$ data extends inclusive large-x_B A/d scaling

Everything above $p_{miss} \sim 250$ MeV/c looks like a deuteron

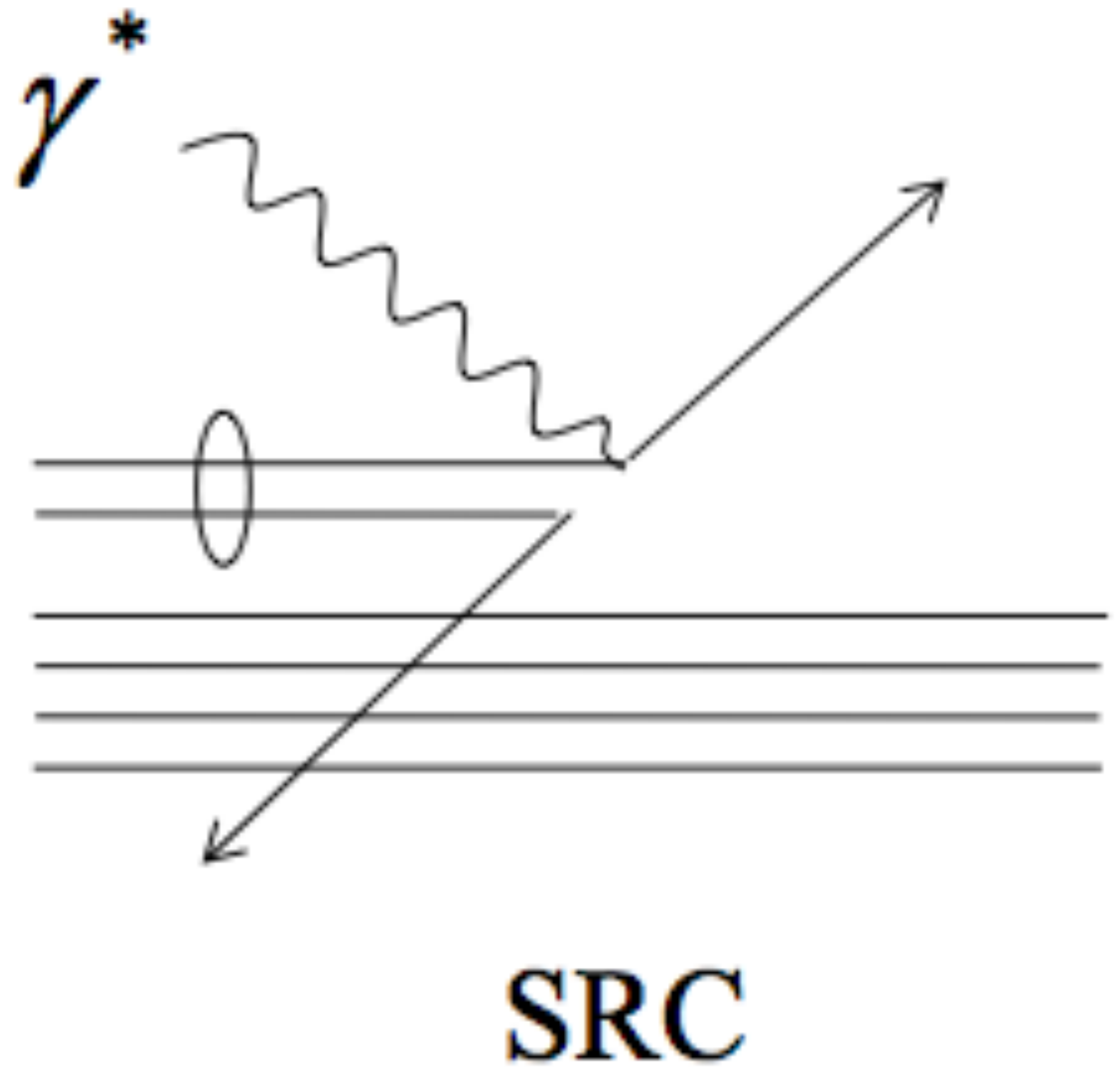
Korover et al. PRC (2023)

Exclusive $(e, e'pN)$

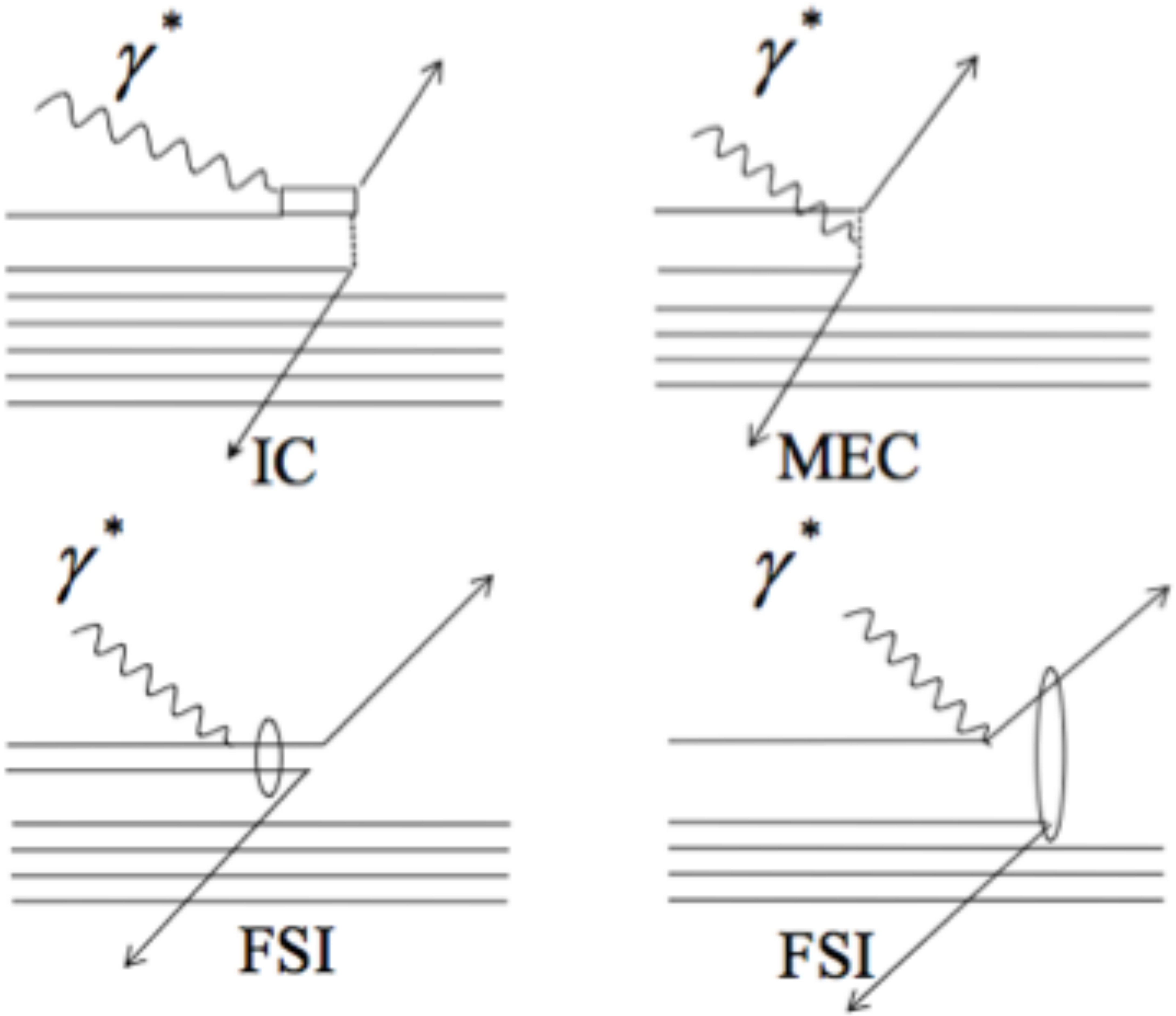
- Breakup the pair
- Detect **both** nucleons
- Reconstruct initial-state pair
- Allows direct measurement of center-of-mass and relative momentum
- Gives access to full isospin information of the pair



Two-Nucleon Knockout



Reaction Mechanisms!



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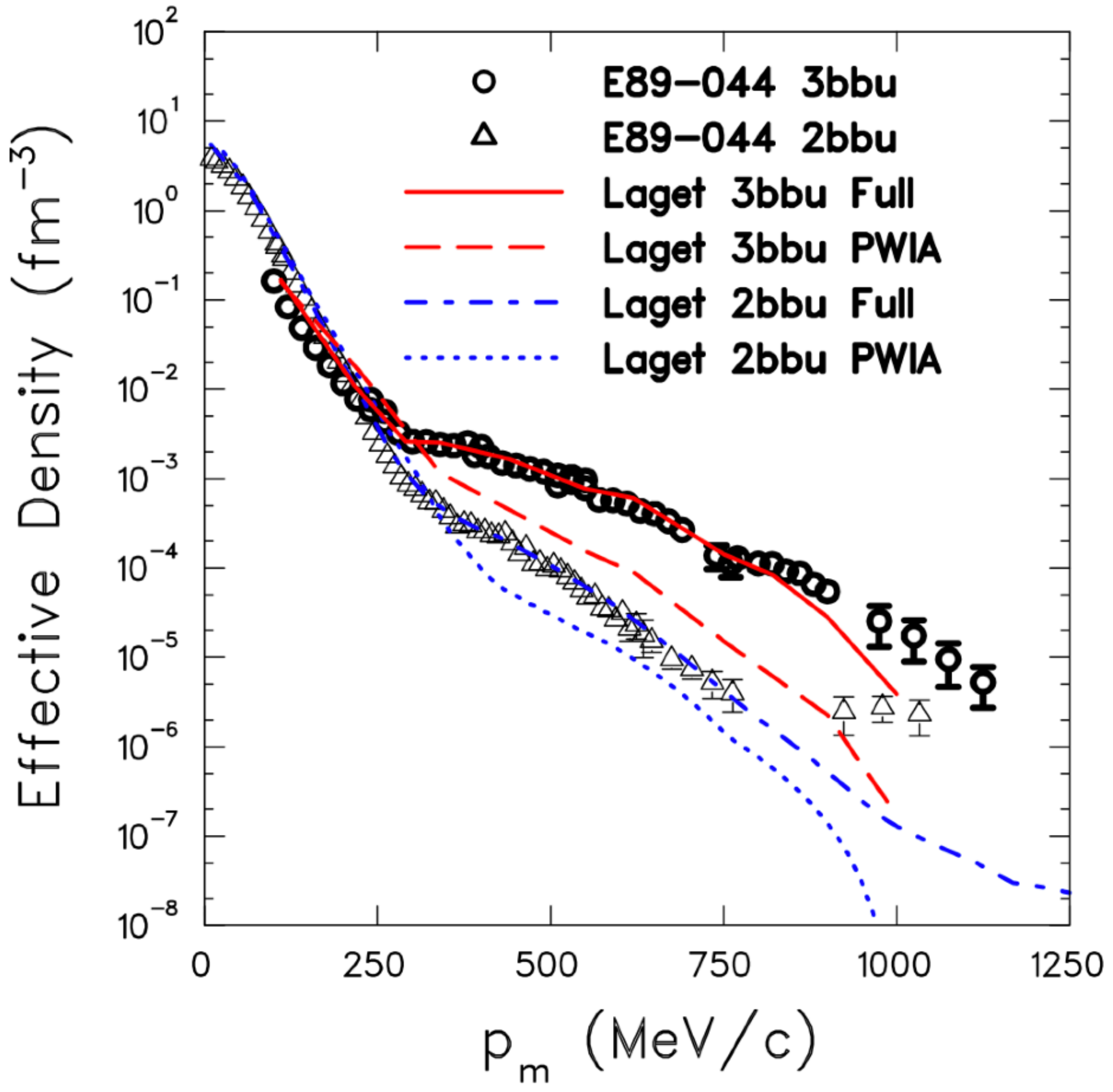

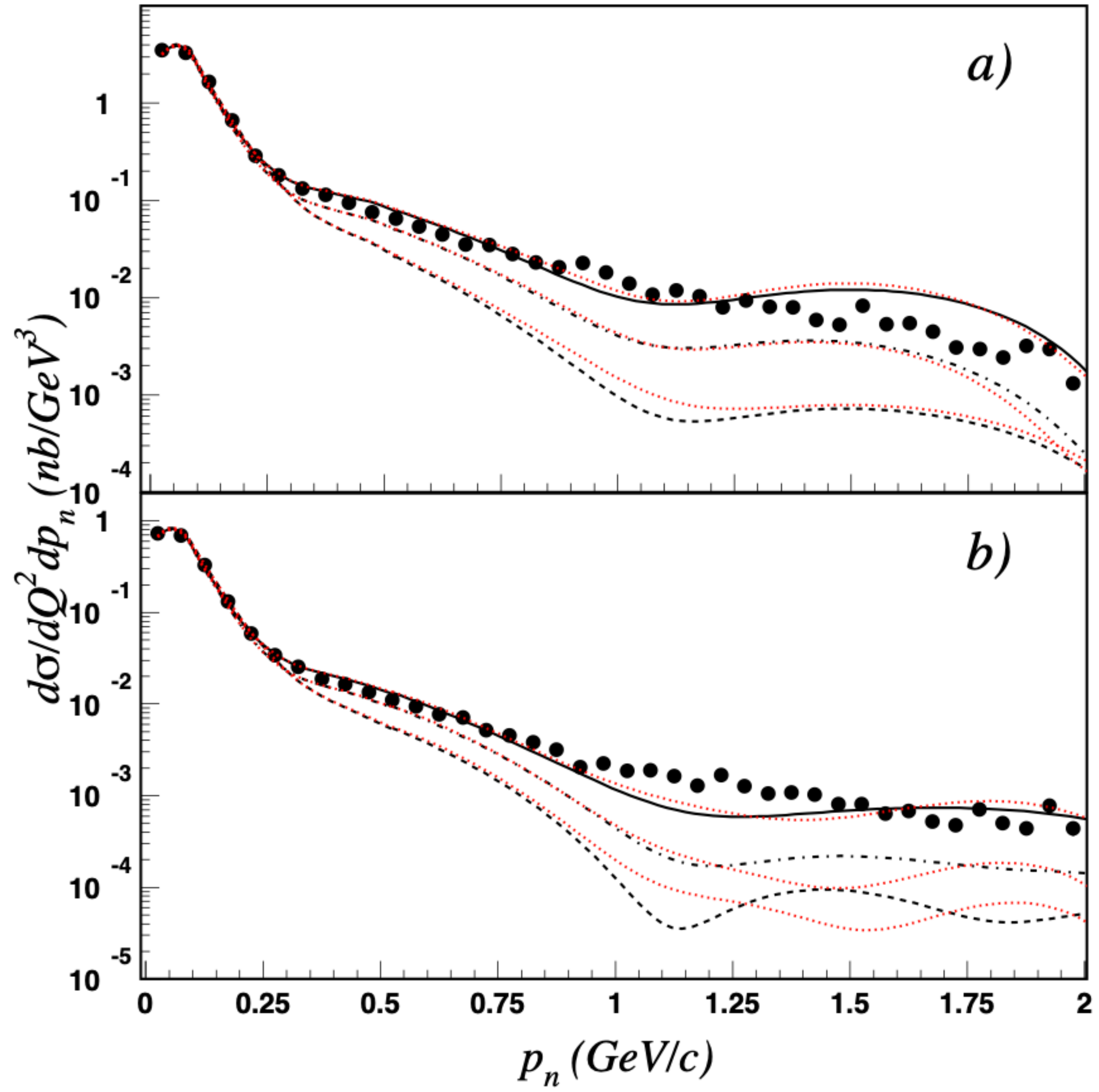

FIG. 1: Color online. The recoil neutron momentum distribution for (a) $Q^2 = 2 \pm 0.25$ GeV^2 and (b) $Q^2 = 3 \pm 0.5$ GeV^2. Dashed, dash-dotted and solid curves are calculations with the Paris potential for PWIA, PWIA+FSI and PWIA+FSI+MEC+NΔ, respectively. Dotted (red) curves are calculations with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

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Egiyan et al, PRL (2007)

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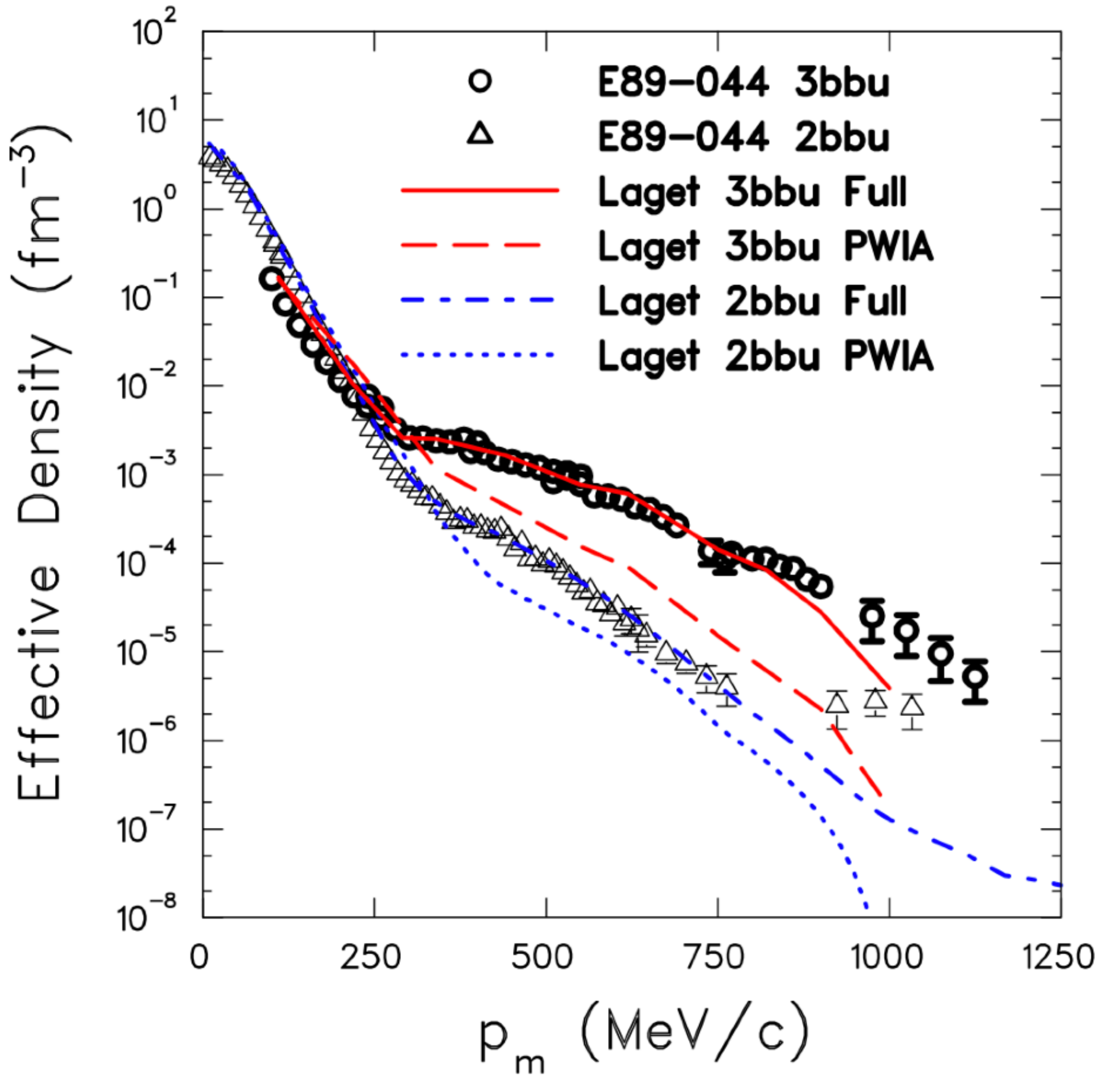

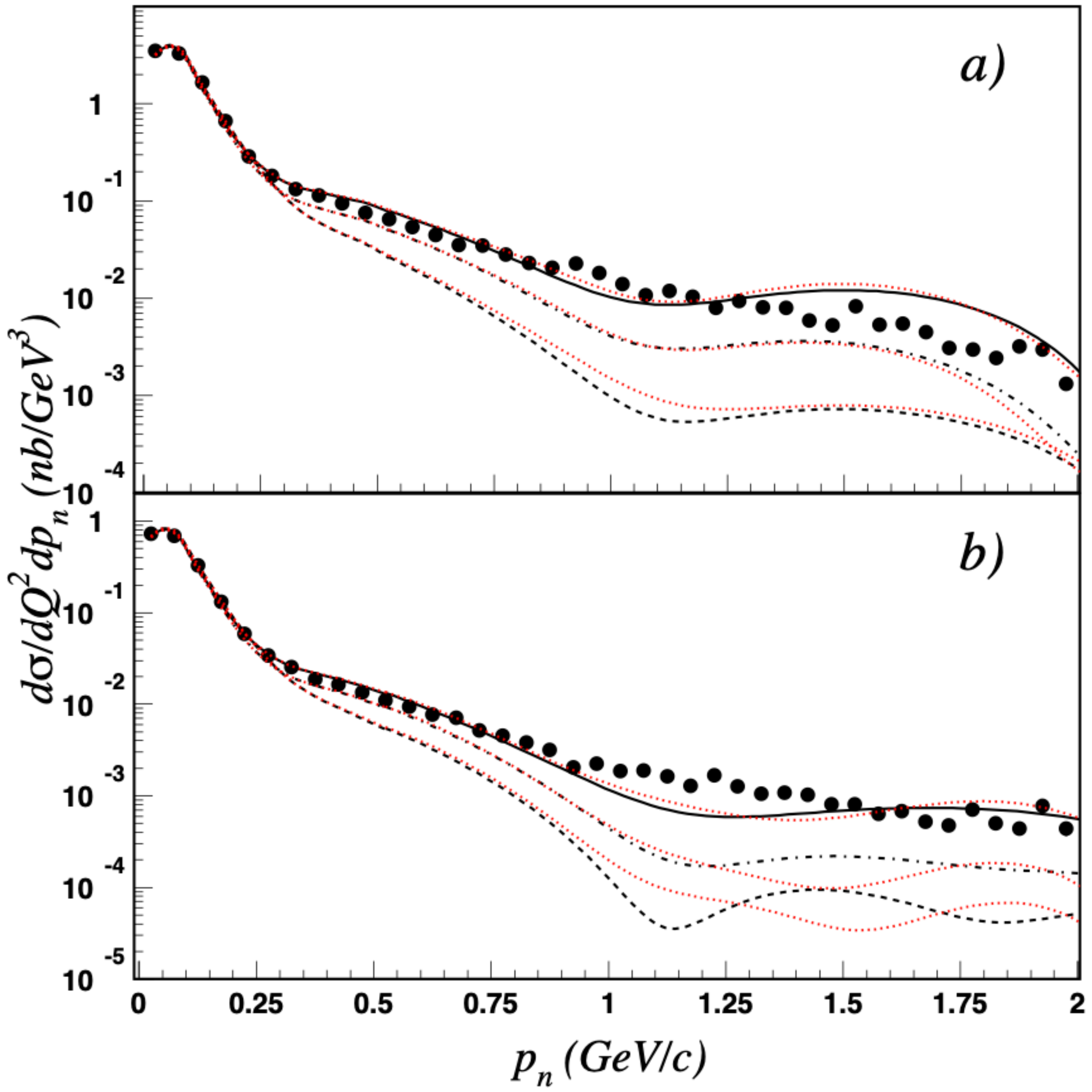

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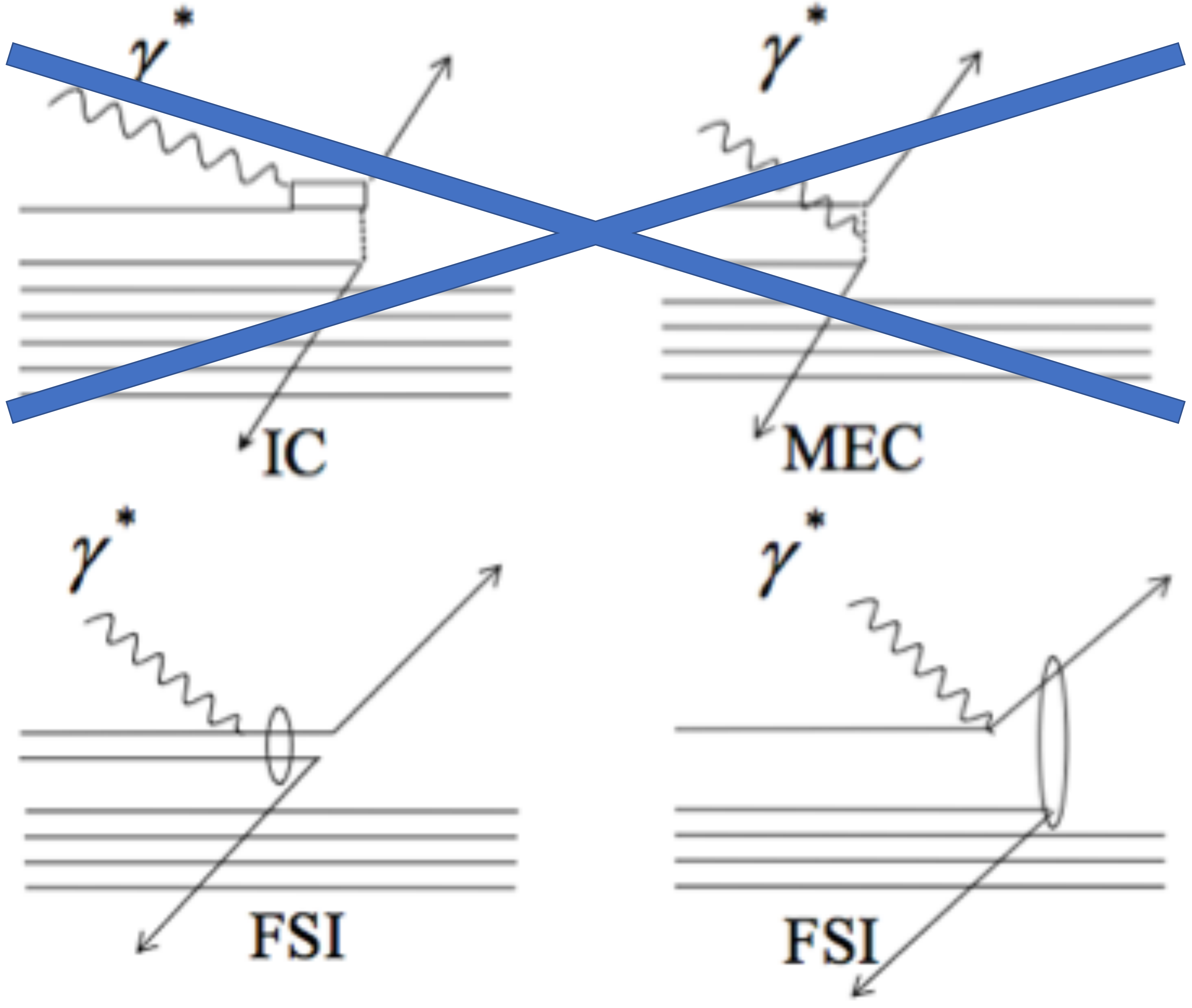
Egiyan et al. PRL 2007

Suppressing competing reaction effects



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

Frankfurt, Sargsian, and Strikman PRC 1997
Colle, Cosyn, and Ryckebusch, PRC 2016

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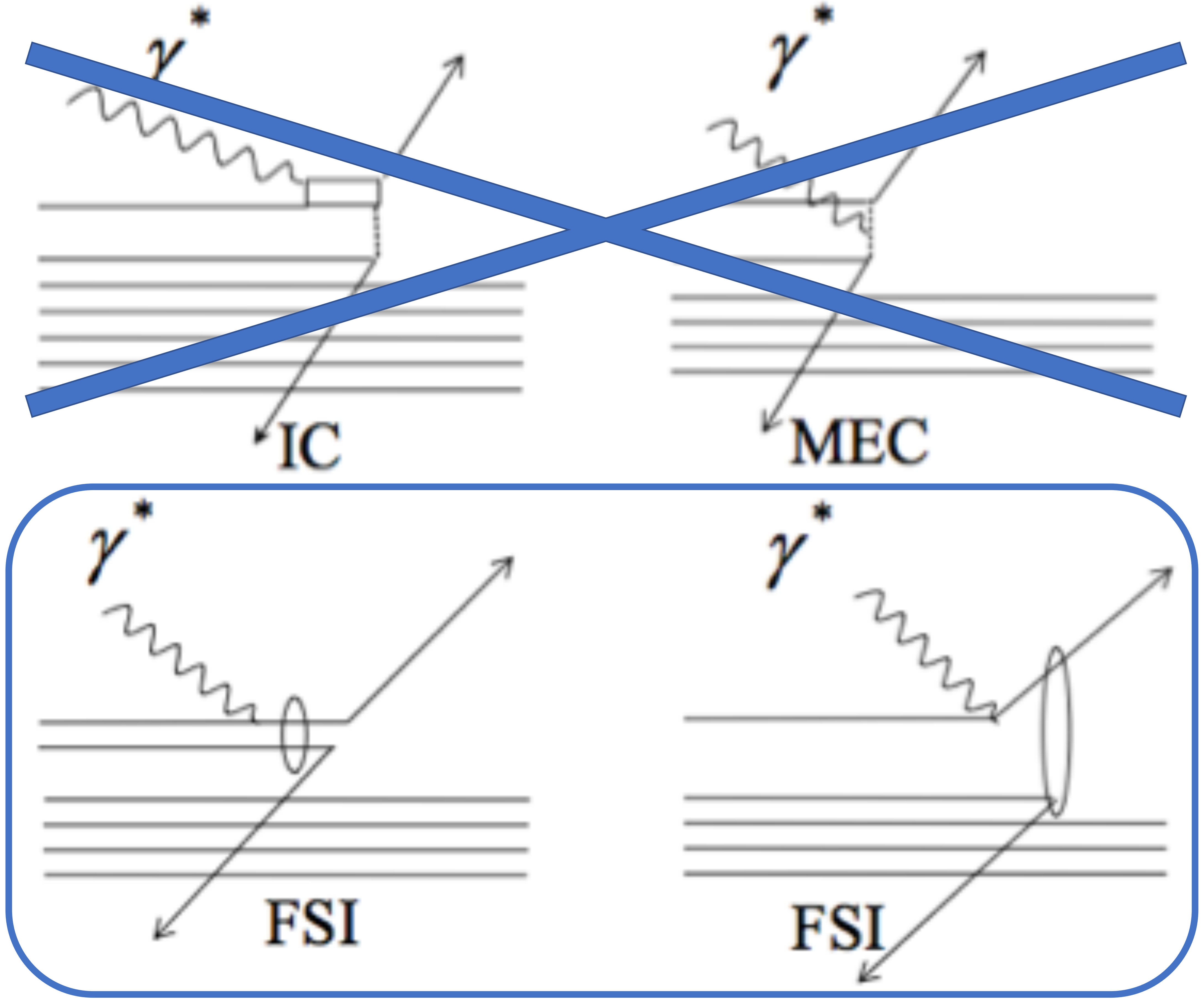
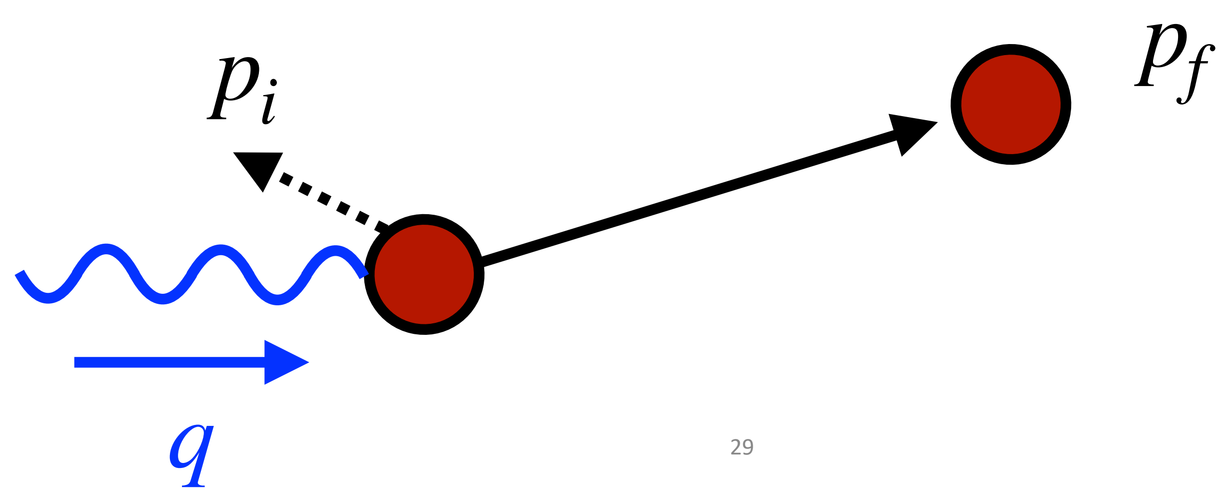


MEC suppressed @ **high-Q^2**

IC suppressed at **x_B > 1**

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



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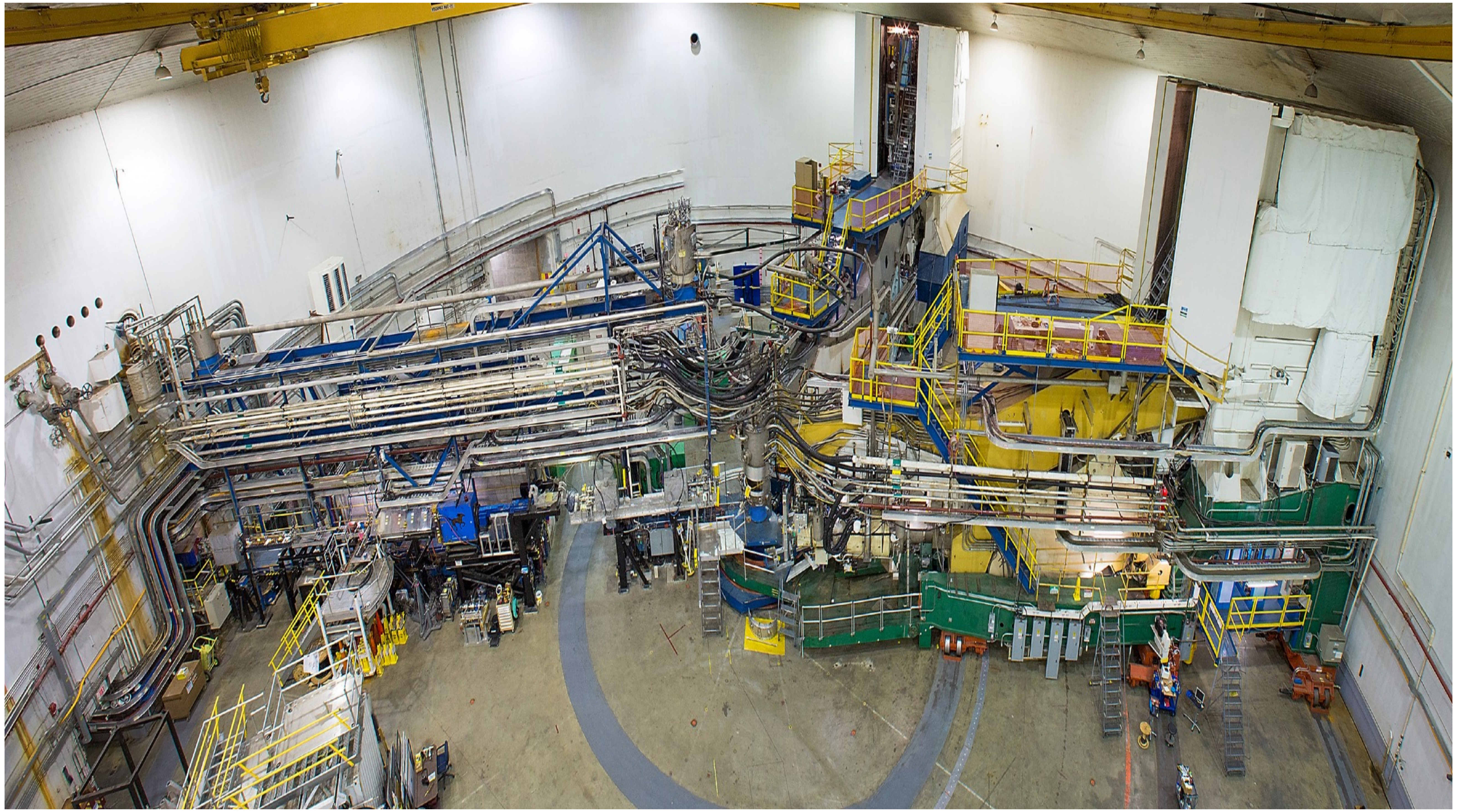
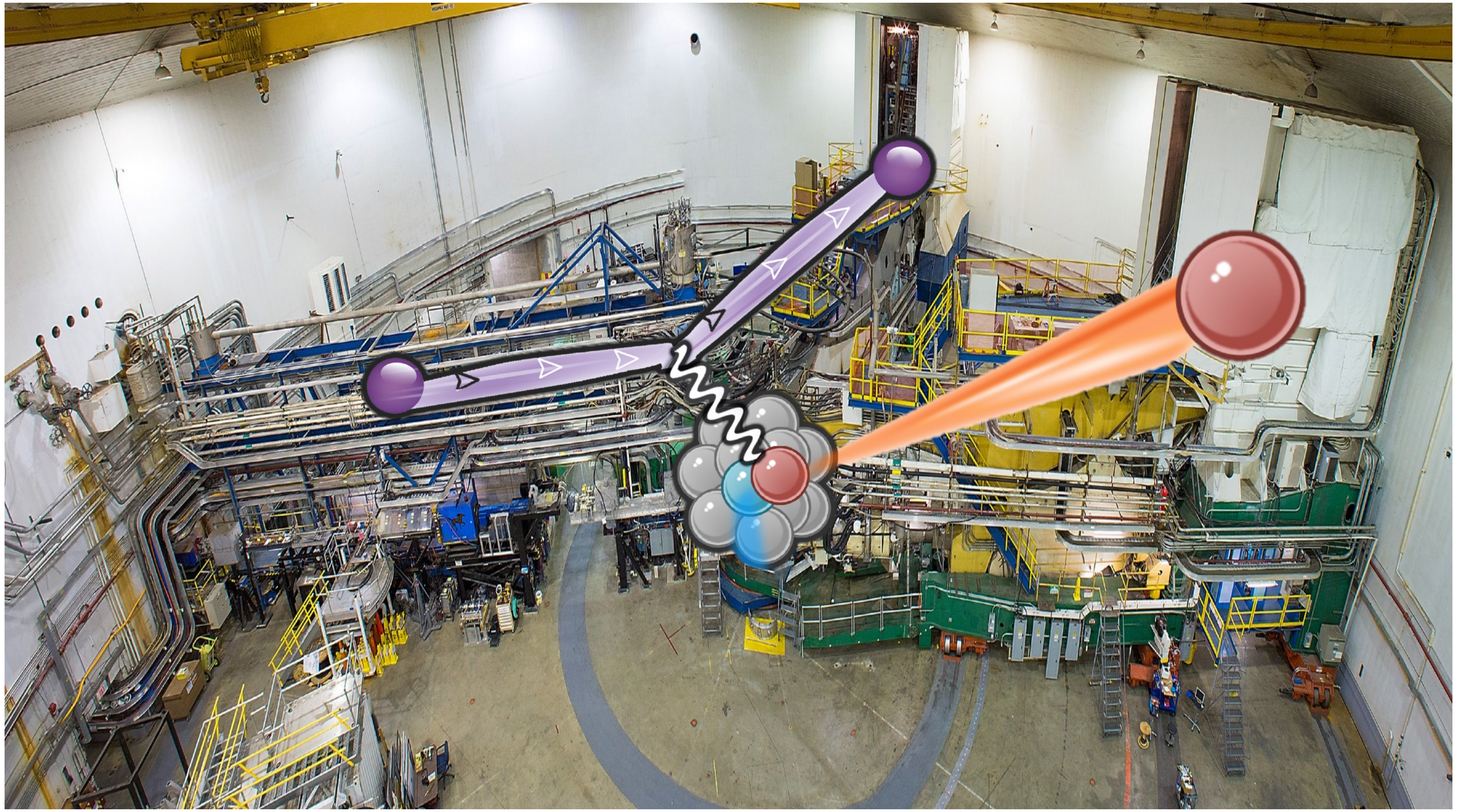
Jefferson Lab Hall A



Hall A: $A(e, e'pN)$



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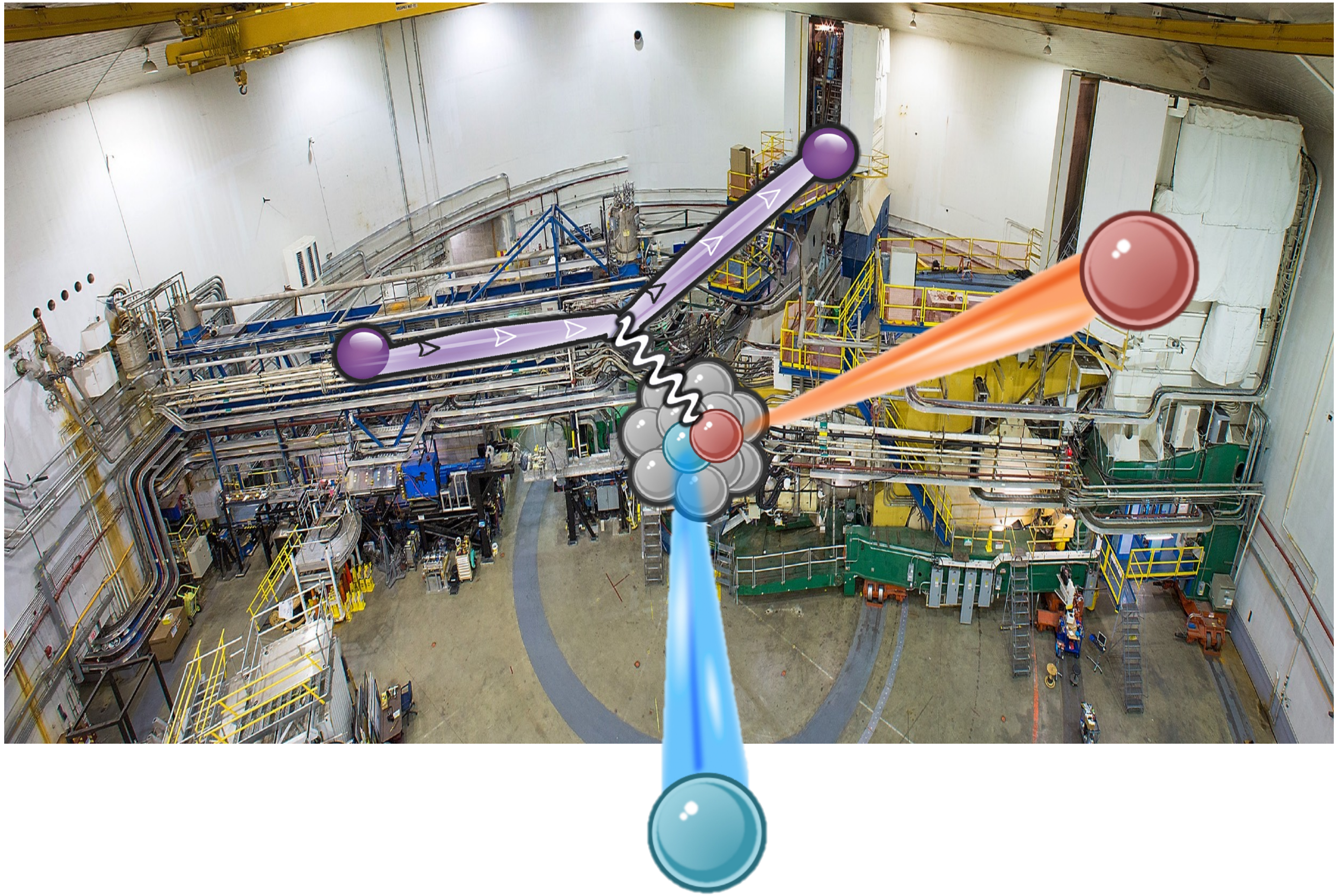
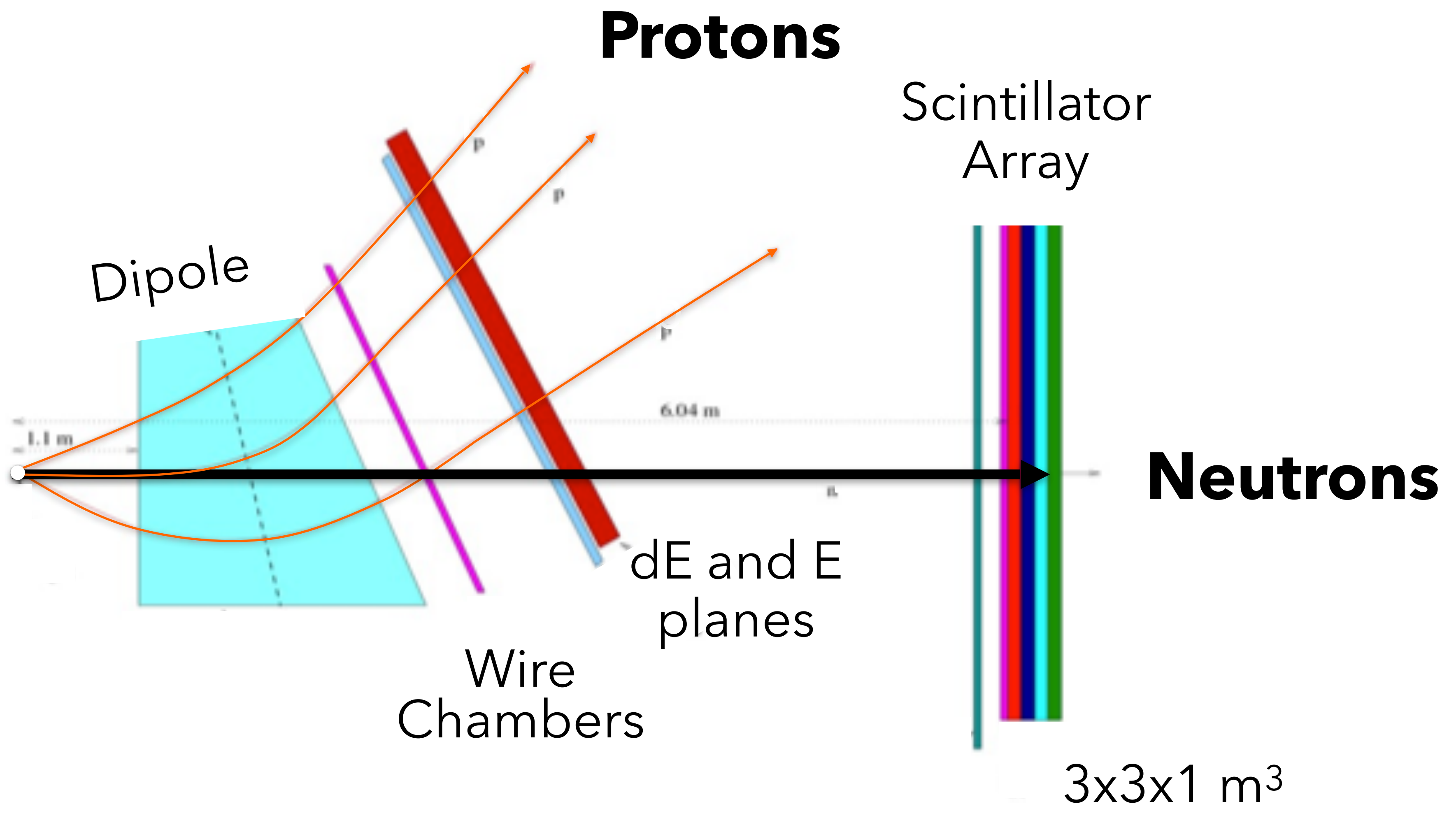
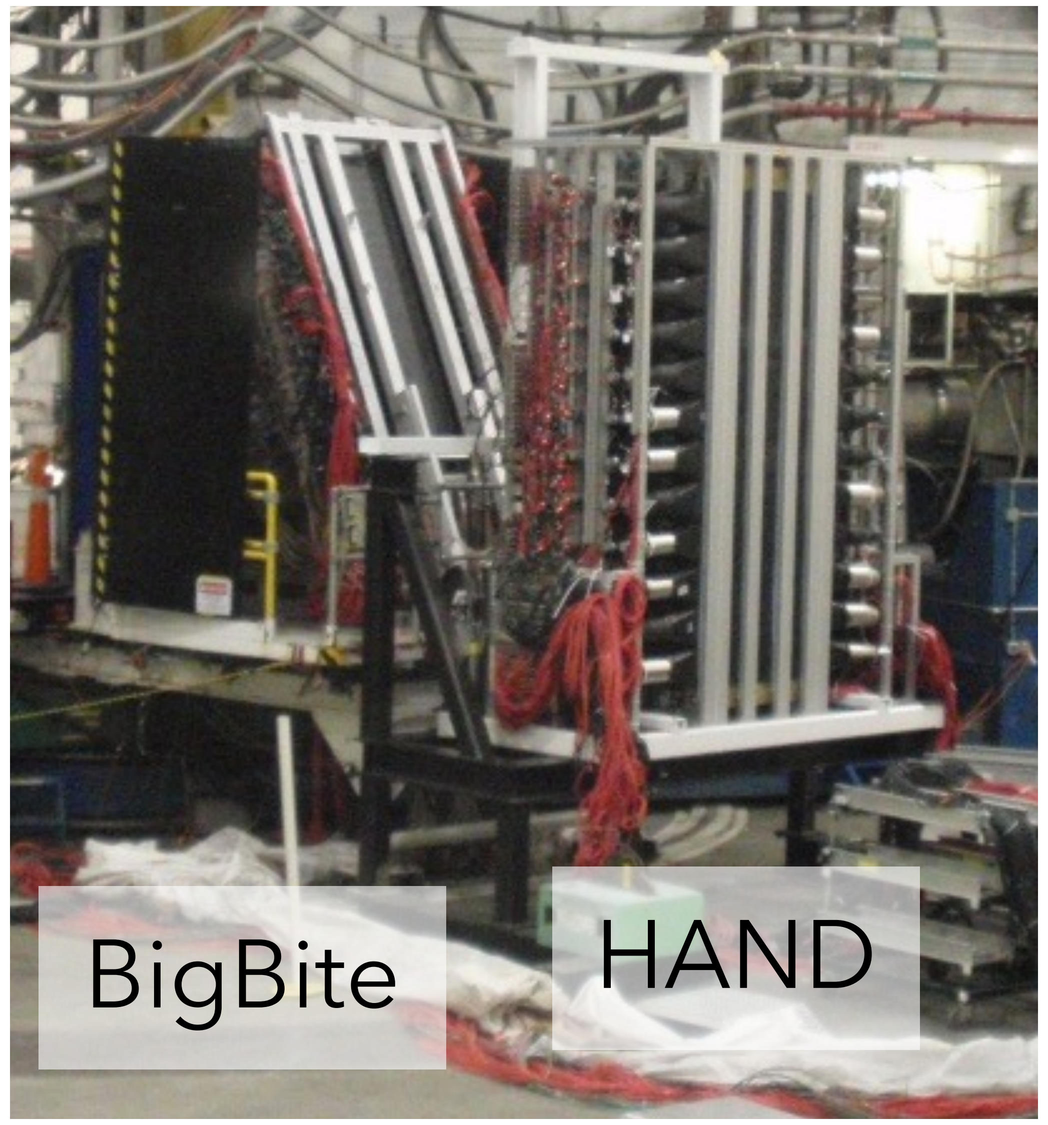


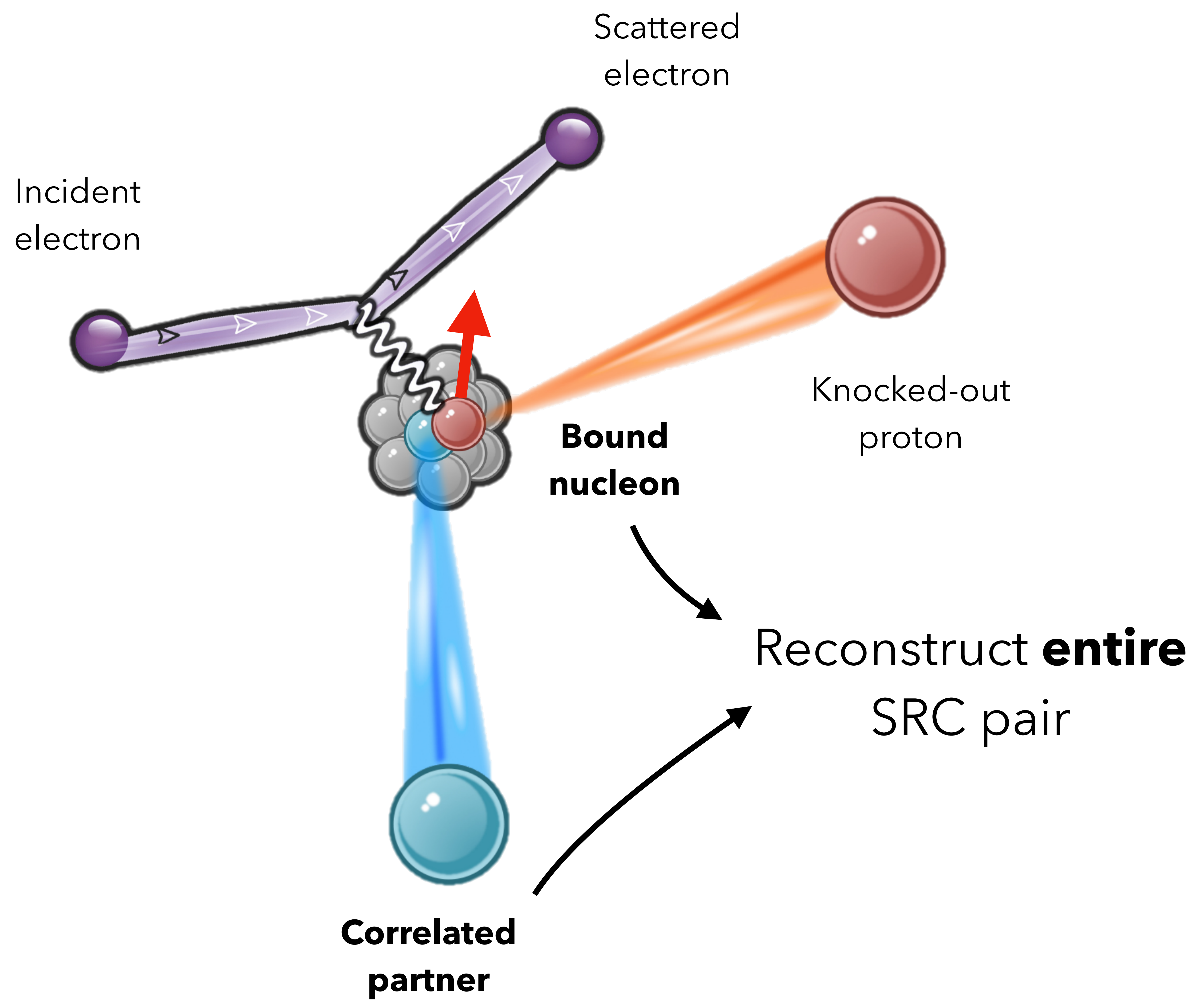
Hall A: $A(e, e'pN)$

- $E_{beam} = 4.6$ GeV
- $Q^2 \sim 2$ GeV^2
- $x_B \sim 1.2$
- $300 < p_{miss} < 800$ MeV/c
- Detect knocked-out proton, look for partner nucleon

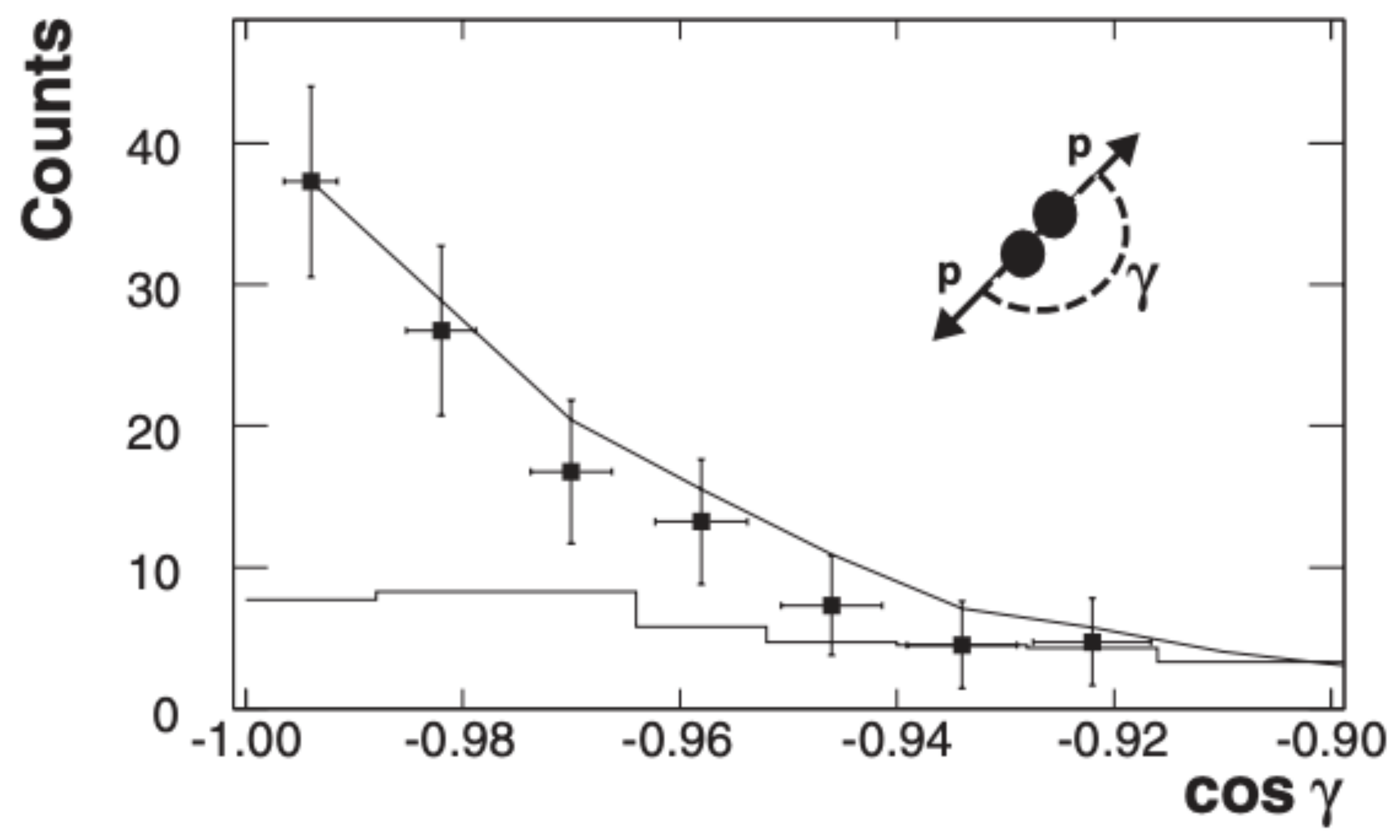




$(e, e'pp)$ – First direct observation of SRC knockout in electron-scattering

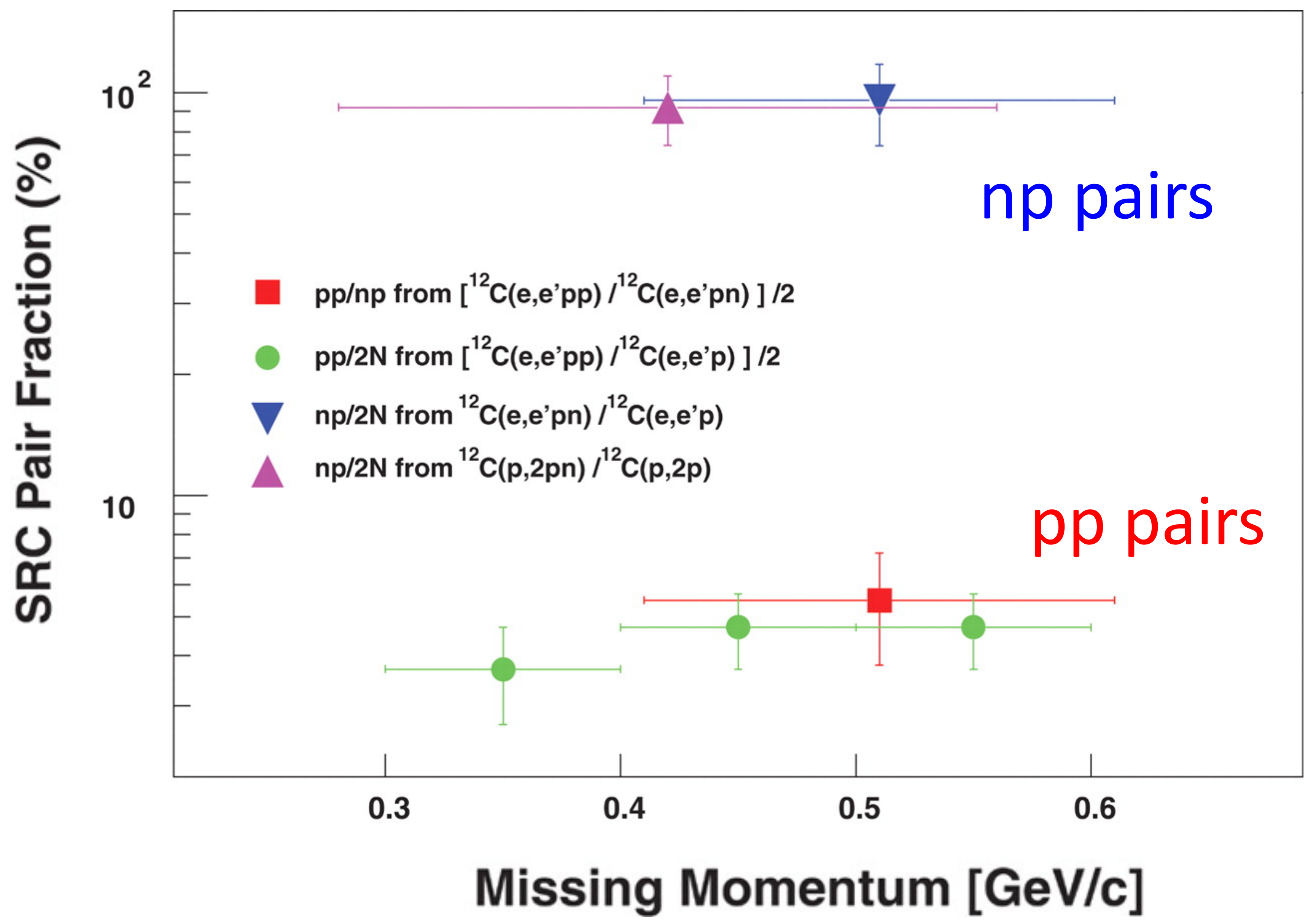


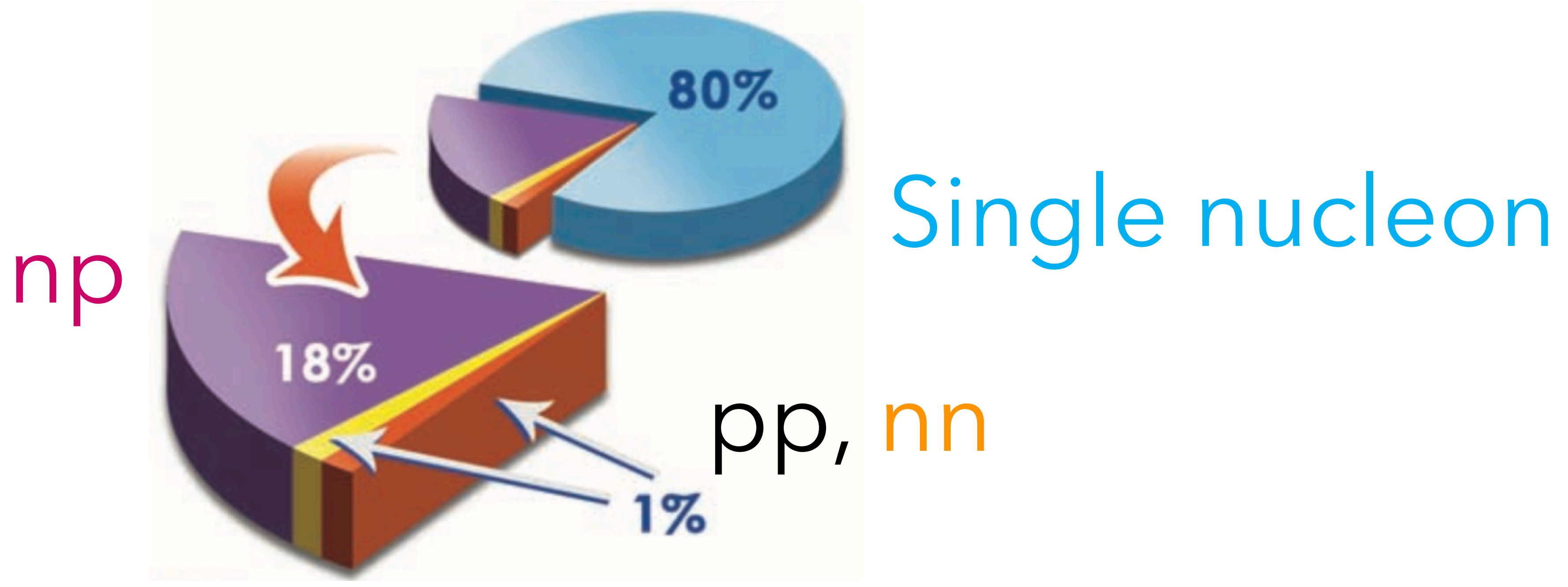
- Reconstruct struck proton, measure recoiling partner
- Protons in pair have high "back-to-back" momentum in **opposite directions**
- High momentum comes from strong, short-distance interactions **within** the pair



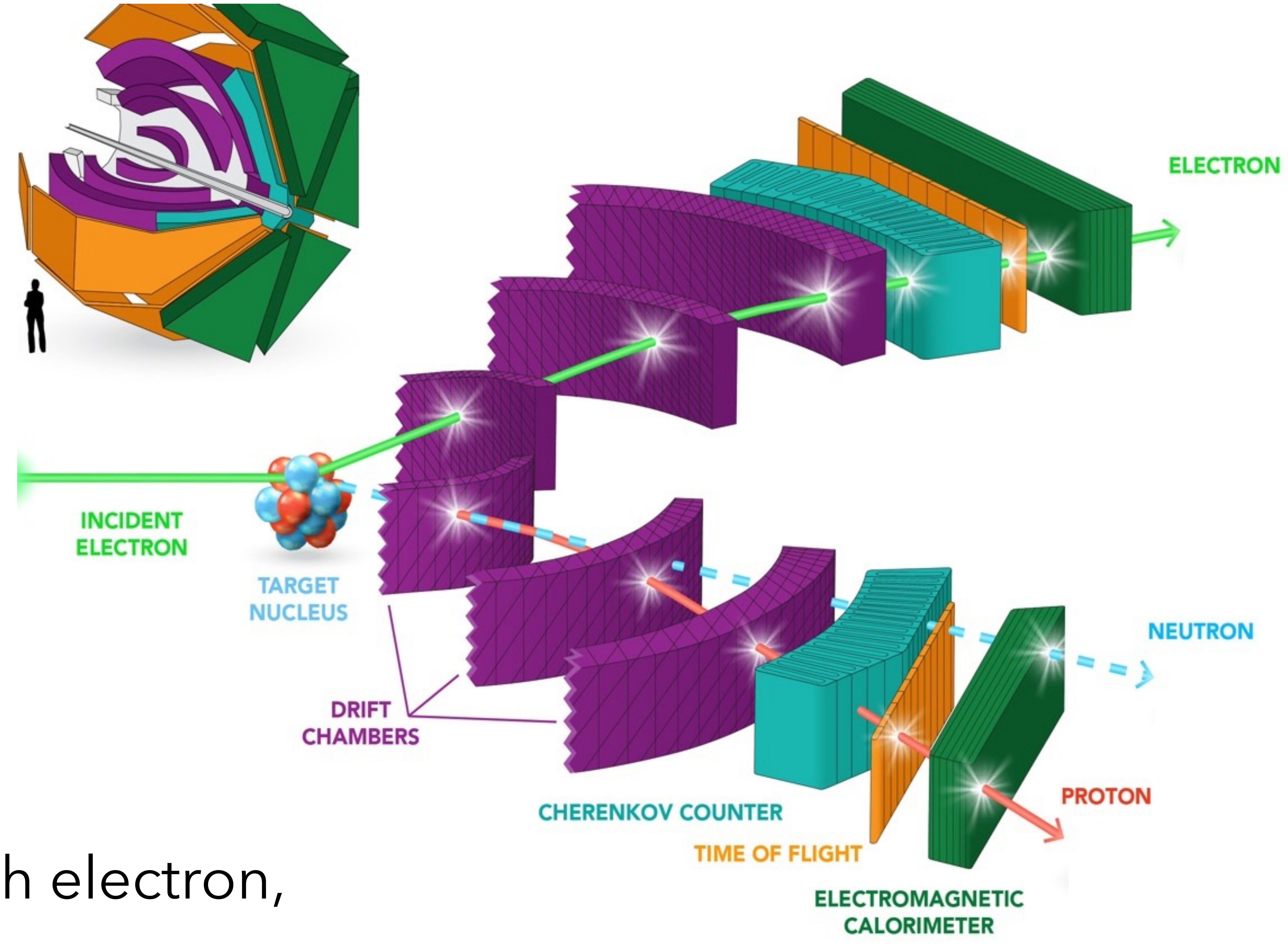
$(e, e'pp)$ vs. $(e, e'pn)$: What kind of pairs do we see?

- BigBite and HAND measure the recoil nucleon isospin
- We find about $10\times$ as many recoil neutrons for a leading proton!
- **Neutron-proton pairs** dominate at $300 < p_i < 600$ MeV/c





Jefferson Lab Hall B

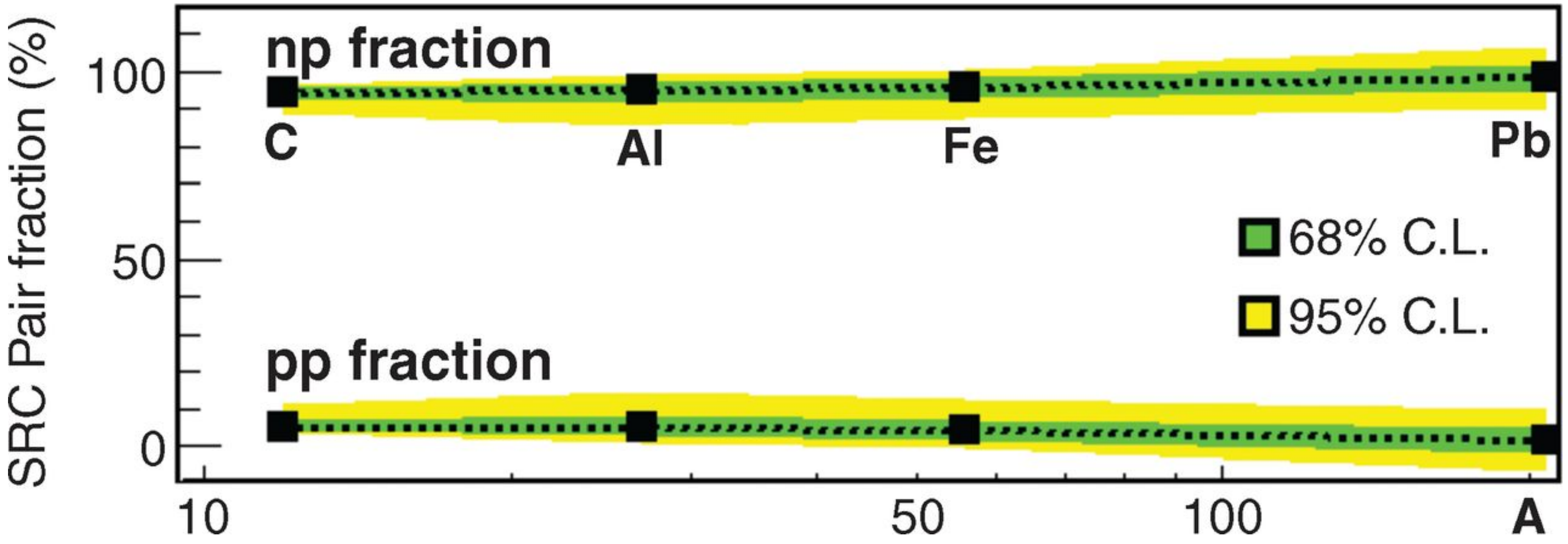


CLAS6 data-mining

- Large-acceptance detector with electron, proton and neutron detection
- Existing nuclear-target data to analyze

NP-dominance across nuclei

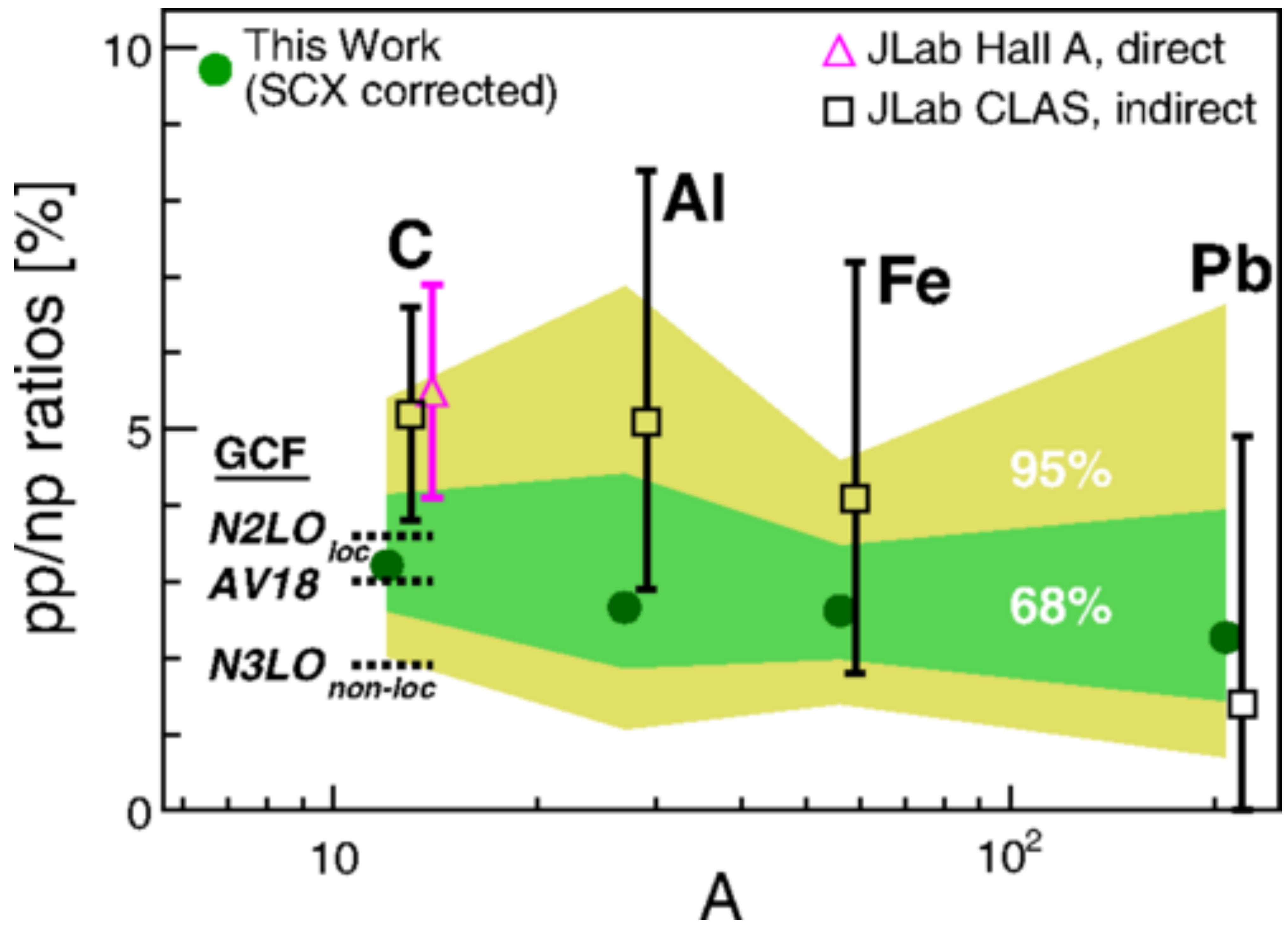
- Used $\sigma_A(e, e'pp)/\sigma_A(e, e'p)$ ratio to estimate pp fraction
  - Assume all high-p_{miss} nucleons have a correlated partner
- NP-SRC pair dominance holds across nuclei, even in highly asymmetric systems



Hen et al, Science (2014)

Direct measurement with $(e, e'pp)/(e, e'np)$

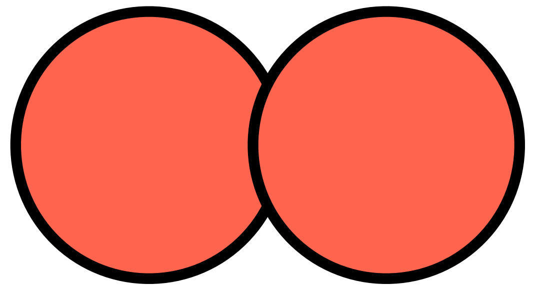
- Direct observation using $(e, e'pp)$ and $(e, e'np)$ across nuclei
- NP-SRC pairs dominate in all nuclei by more than an order of magnitude
- **This is the product of short-distance nuclear interactions that drive SRCs**



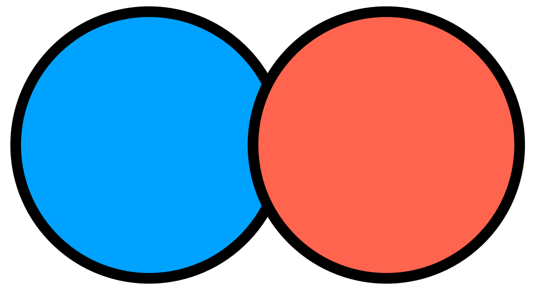
Duer et al, PRL (2019)

How can we build 2N-SRCs?

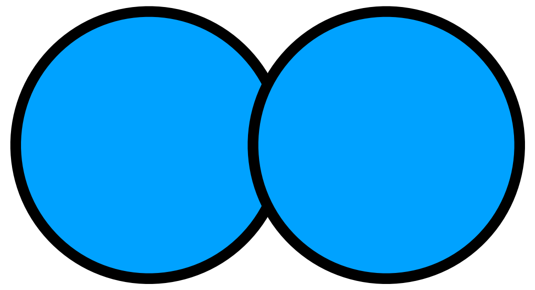
Proton-Proton Pairs:



Neutron-Proton Pairs:



Neutron-Neutron Pairs:



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Proton-Proton Pairs:

Neutron-Proton Pairs:

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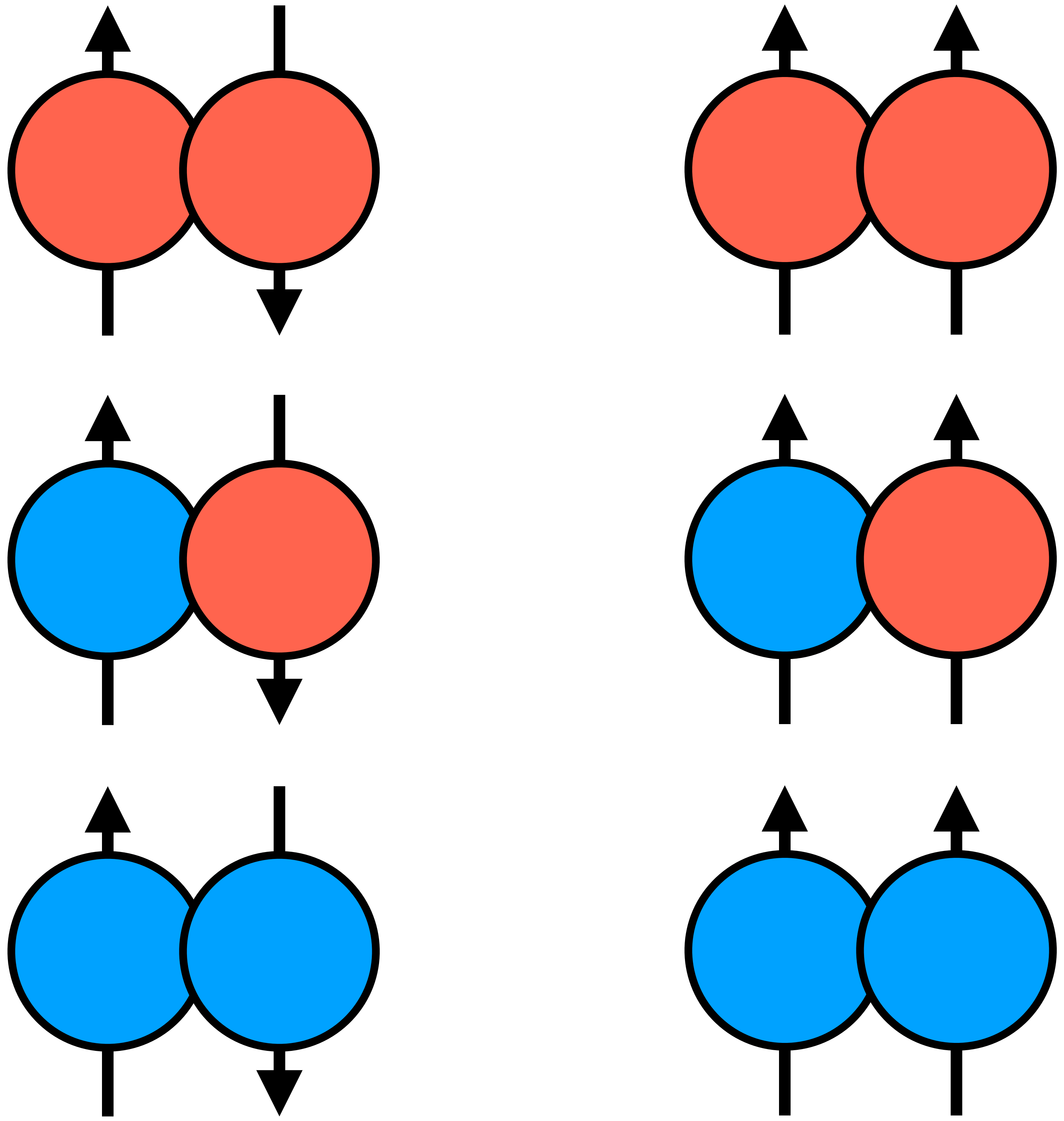

$S = 0$ $\quad$ $S = 1$

$3 \times 2 = 6$ types of pairs?

How can we build 2N-SRCs?

Proton-Proton Pairs:

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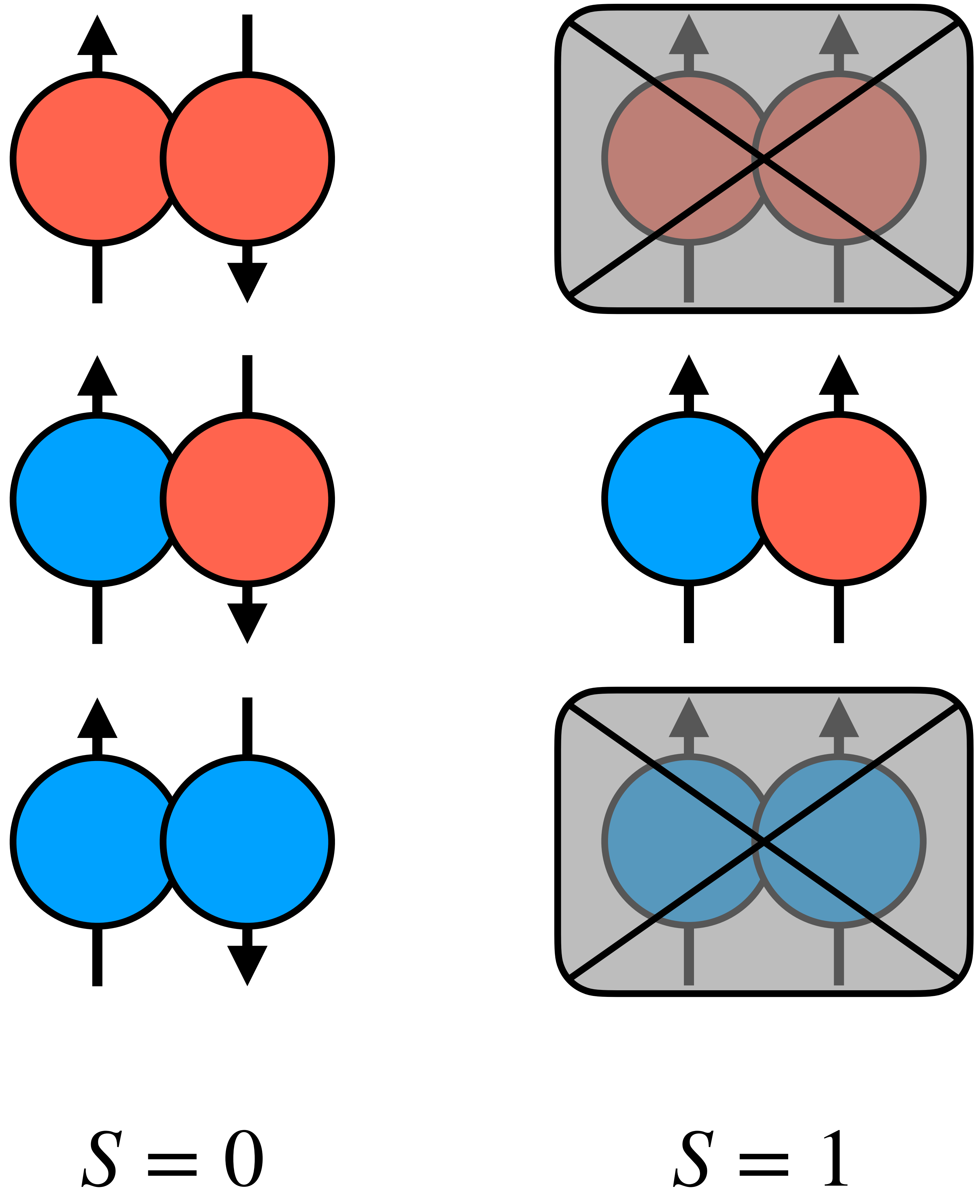


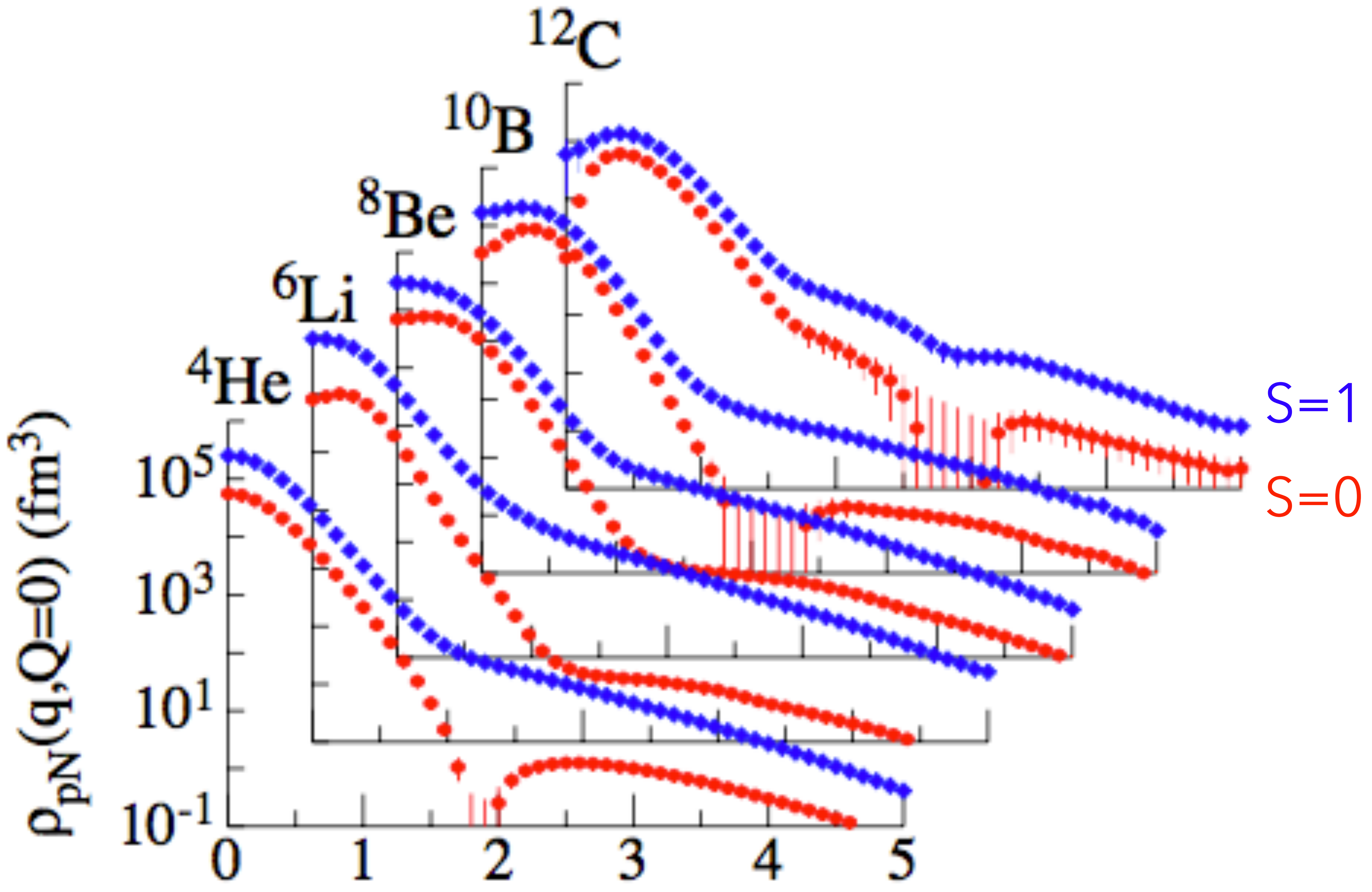
$3 \times 2 = 6$ types of pairs?

Pauli disagrees!

Only neutron-proton can have aligned spin $S = 1$

Nucleons prefer S=1 pairing

Carlson et al., RMP **87** (2015) 1067



Pair relative momentum (fm^{-1})

- At $p_{rel} = 300 - 500$ MeV/c, the s-wave momentum distribution has a minimum (node)
- Filled in by **tensor correlations** when $S = 1$:

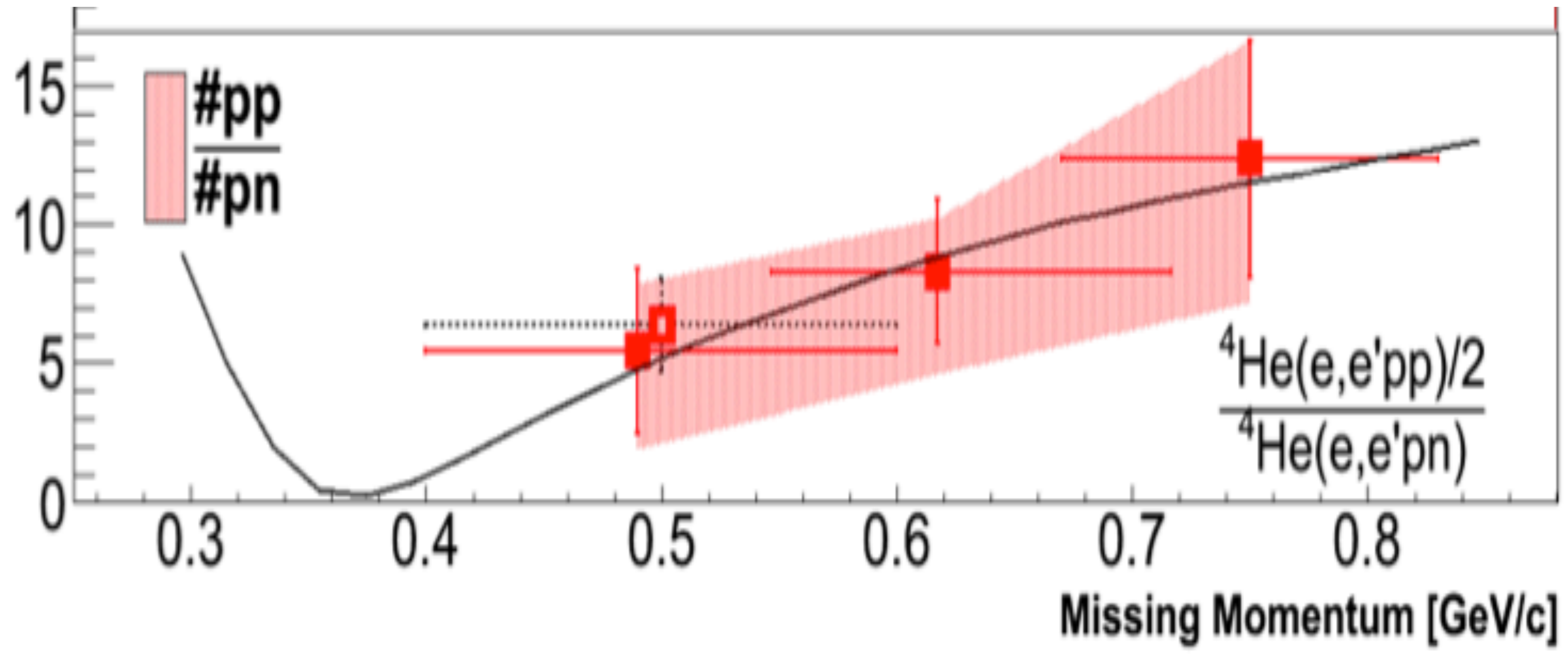
$$V_{NN}(r) = V_c(r) + V_T(r) S_{12}$$

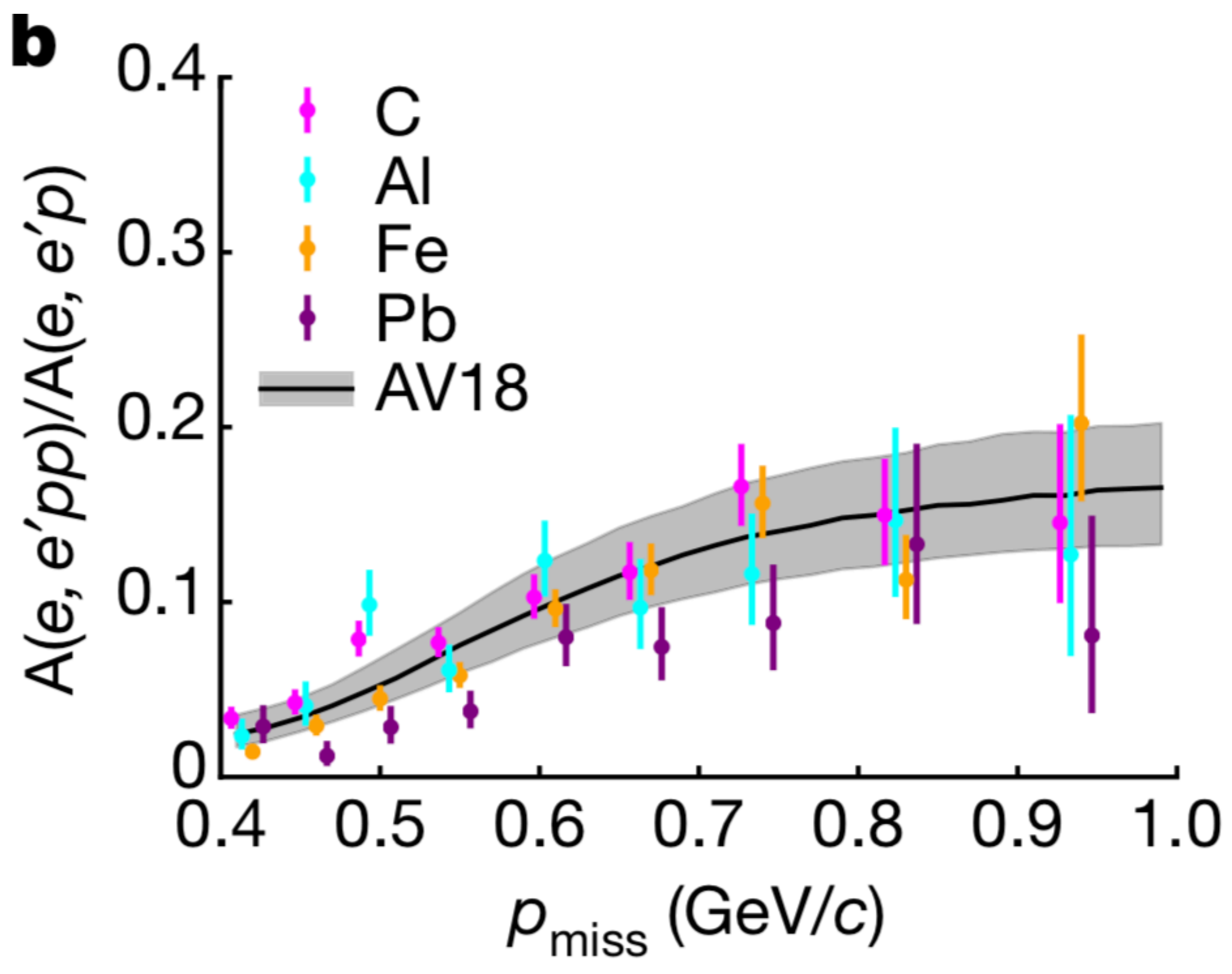
$$S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \cdot \sigma_2$$

- Think about the deuteron – np, $S = 1$ is bound, while pp and nn are not!

Ciofi and Alvioli, Gent workshop, Aug. 2007
Sargsian, Abrahamyan, Strikman, Frankfurt, PRC (2005).

But this is not constant!

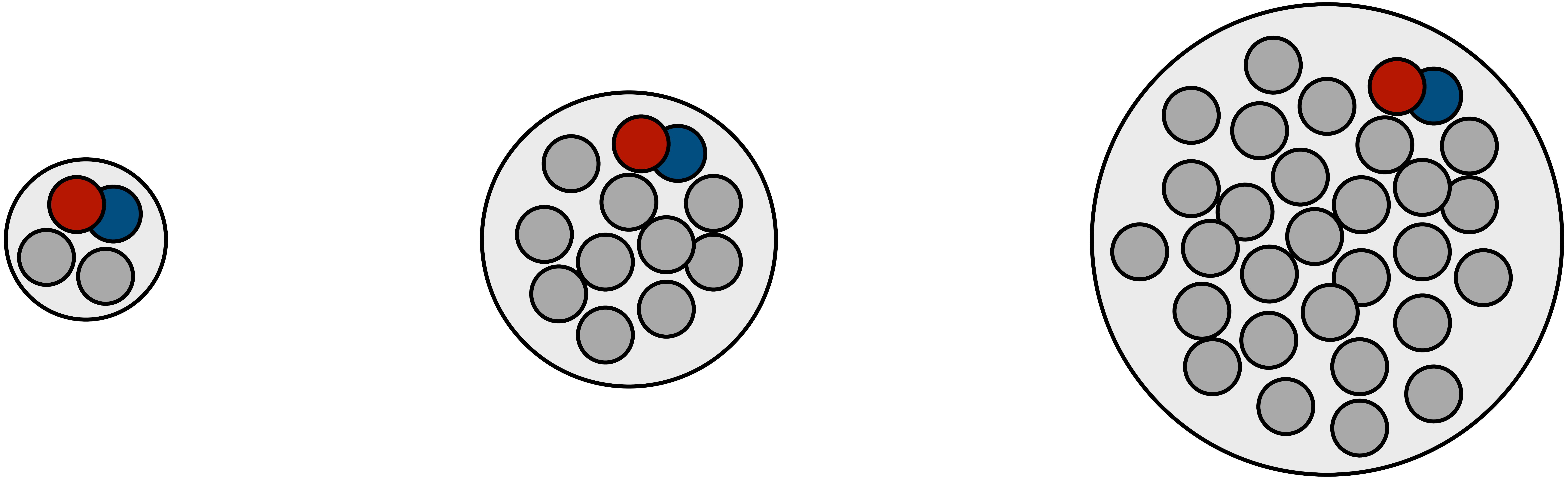




- Higher missing momentum moves us away from the S=0 node at $p_{rel} \approx 400$ MeV/c
- Tensor force does not dominate everywhere – pp-pair fraction increases with momentum
- We will see this relates to changing structure of nucleon-nucleon force at shorter distances

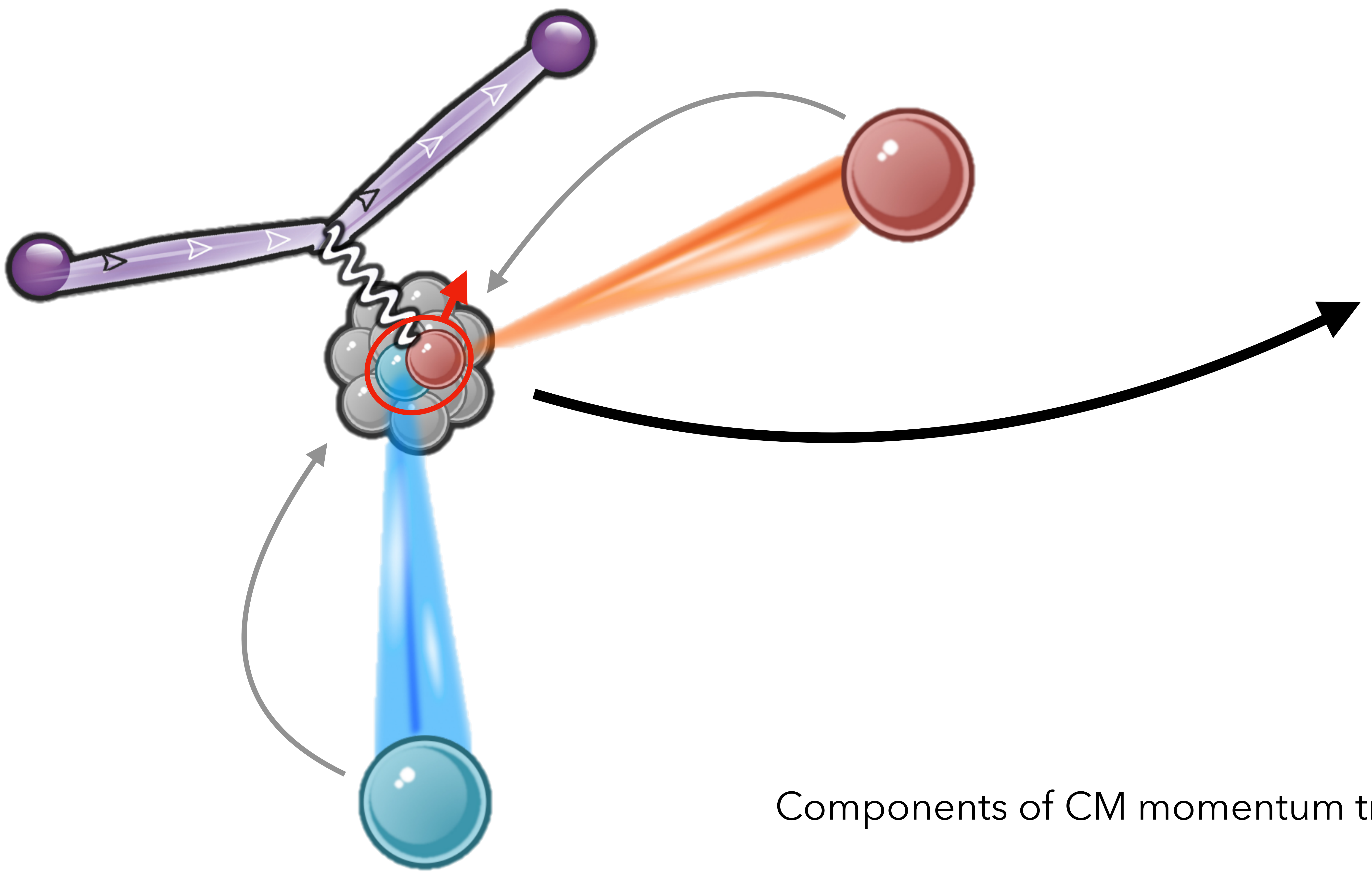
Korover et al, PRL (2014)
Schmidt et al, Nature (2020)

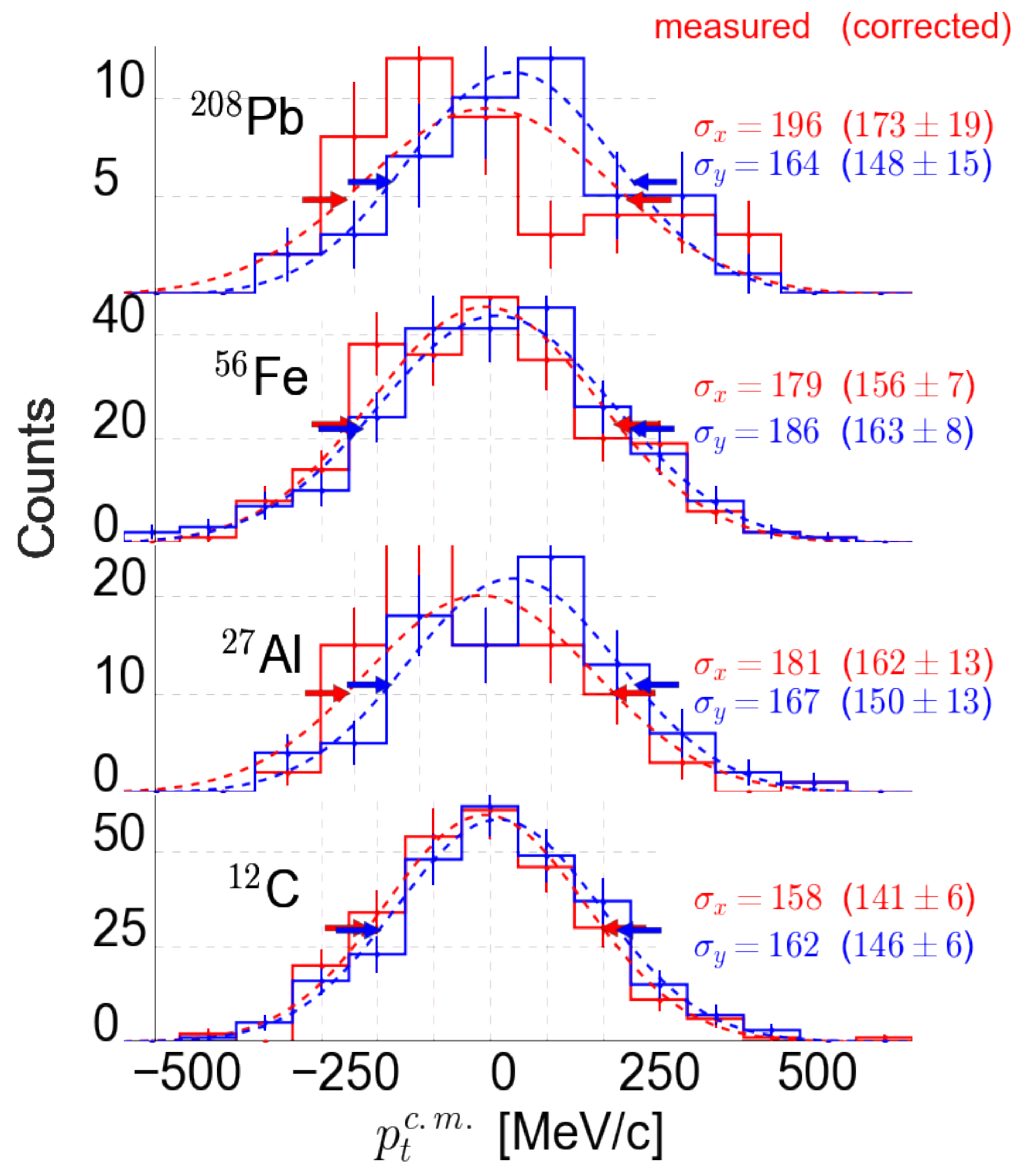
How does the nuclear medium affect SRC behavior?



- We know from a_2 that SRC **abundances** differ across nuclei, increasing with A
  - More nucleons together → greater chance of pairing up
- How else does SRC formation impact their behavior?

Exclusive $(e, e'pp)$ let us reconstruct pair center-of-mass motion



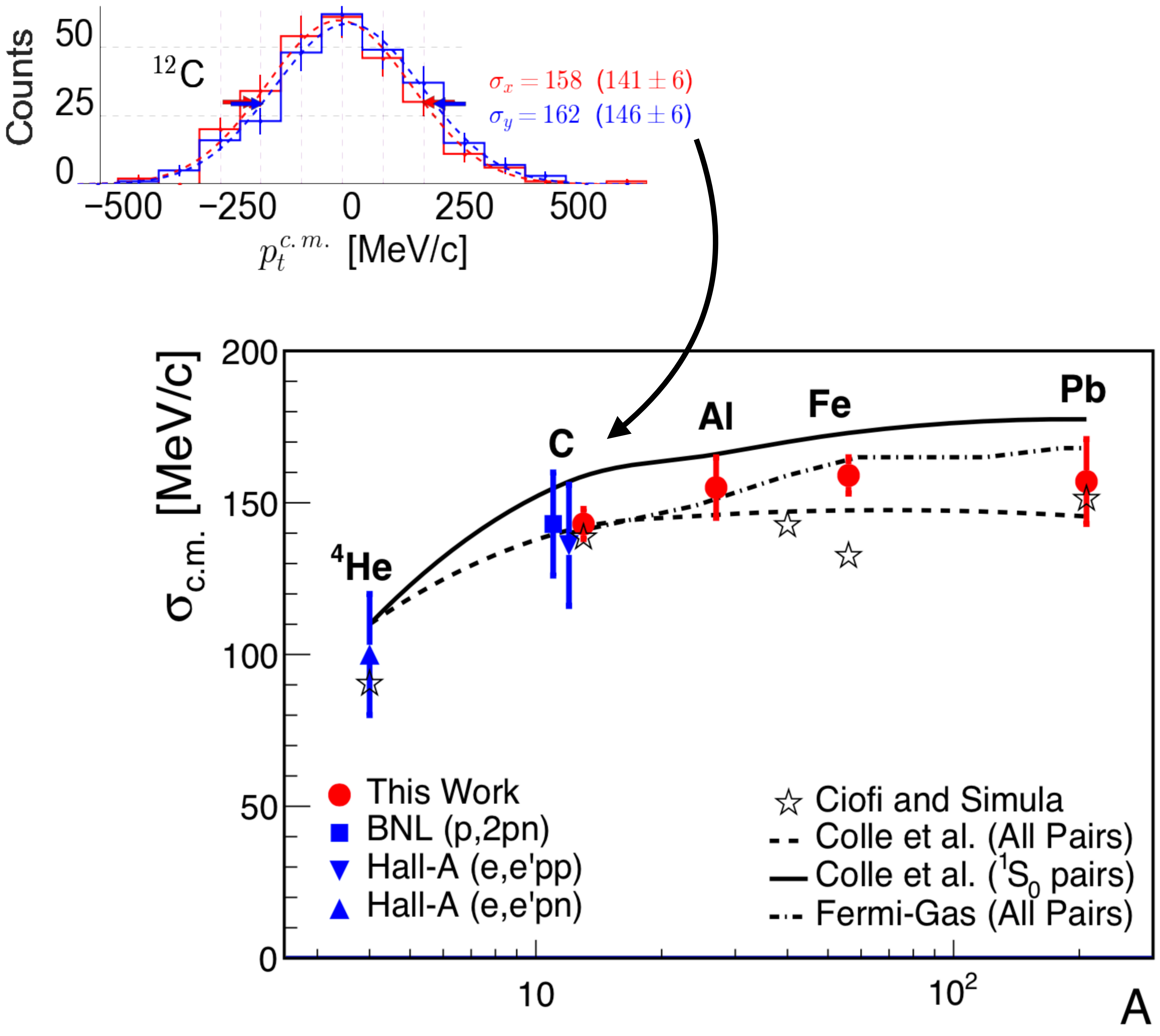


Components of CM momentum transverse to p_{miss}

→ Minimizes impact of final-state rescattering

Cohen, PRL (2018)

Extract CM across different nuclei

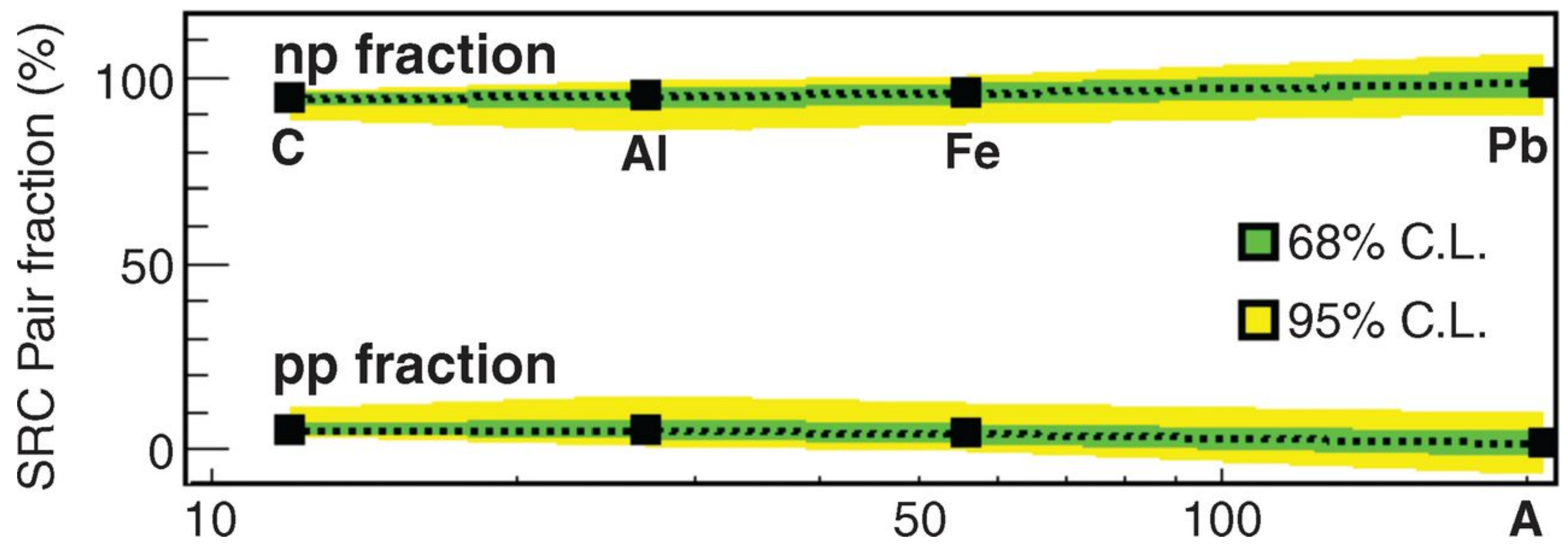


- Larger nuclei → pairs are moving more within
- Higher average momentum of pairing nucleons → higher total momentum of pairs
- **Nucleon pairing into SRCs is a mean-field phenomenon!**

Cohen, PRL (2018)

Which nucleons pair together?

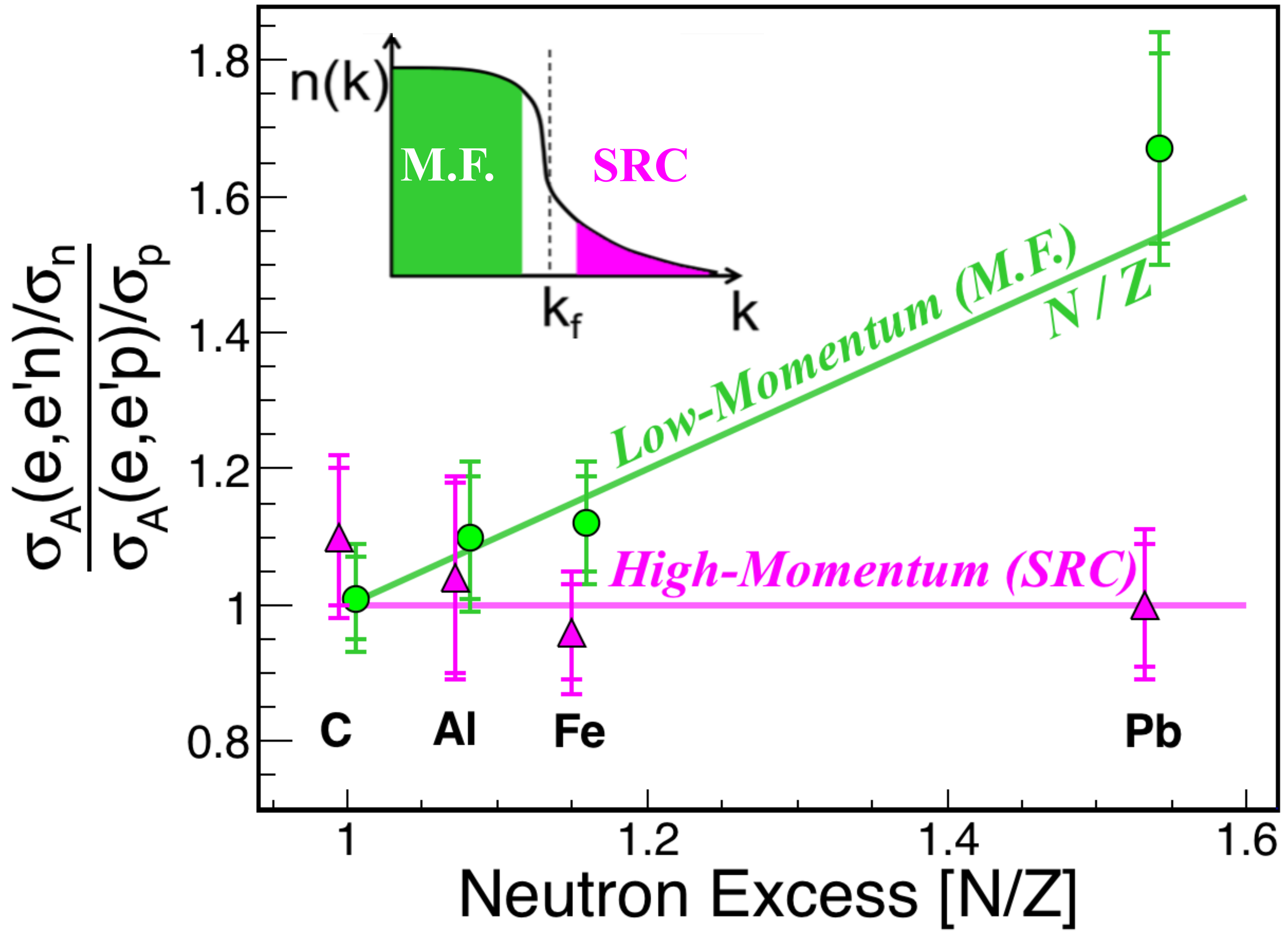
We know that NP-SRC dominance holds even for heavy nuclei



As we add neutrons:

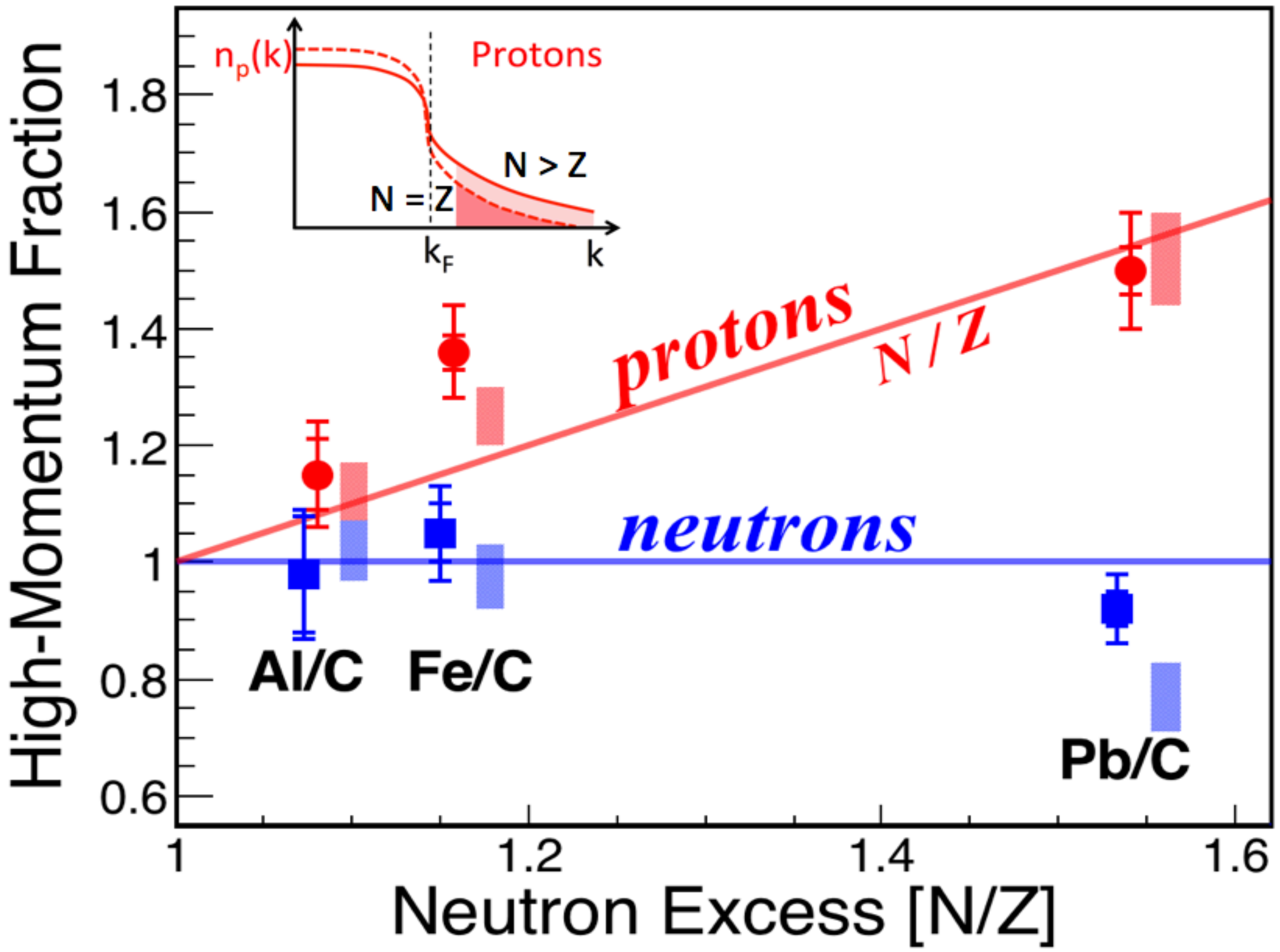
Larger neutron fraction in mean-field

SRCs remain $N \approx Z$!



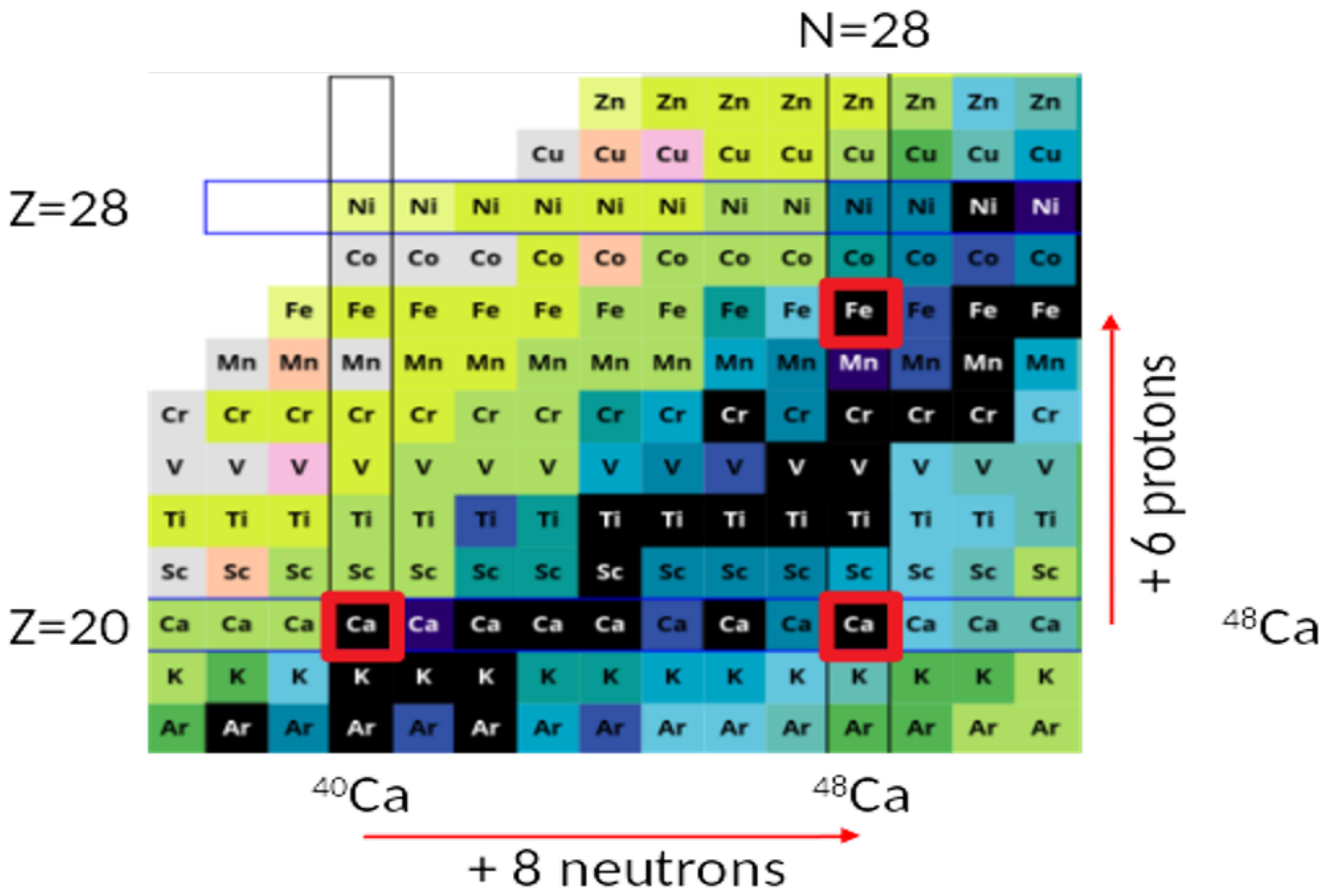
Hen et al, Science (2014)
Duer et al, Nature (2018)

In $N > Z$, Protons correlate, Neutrons saturate

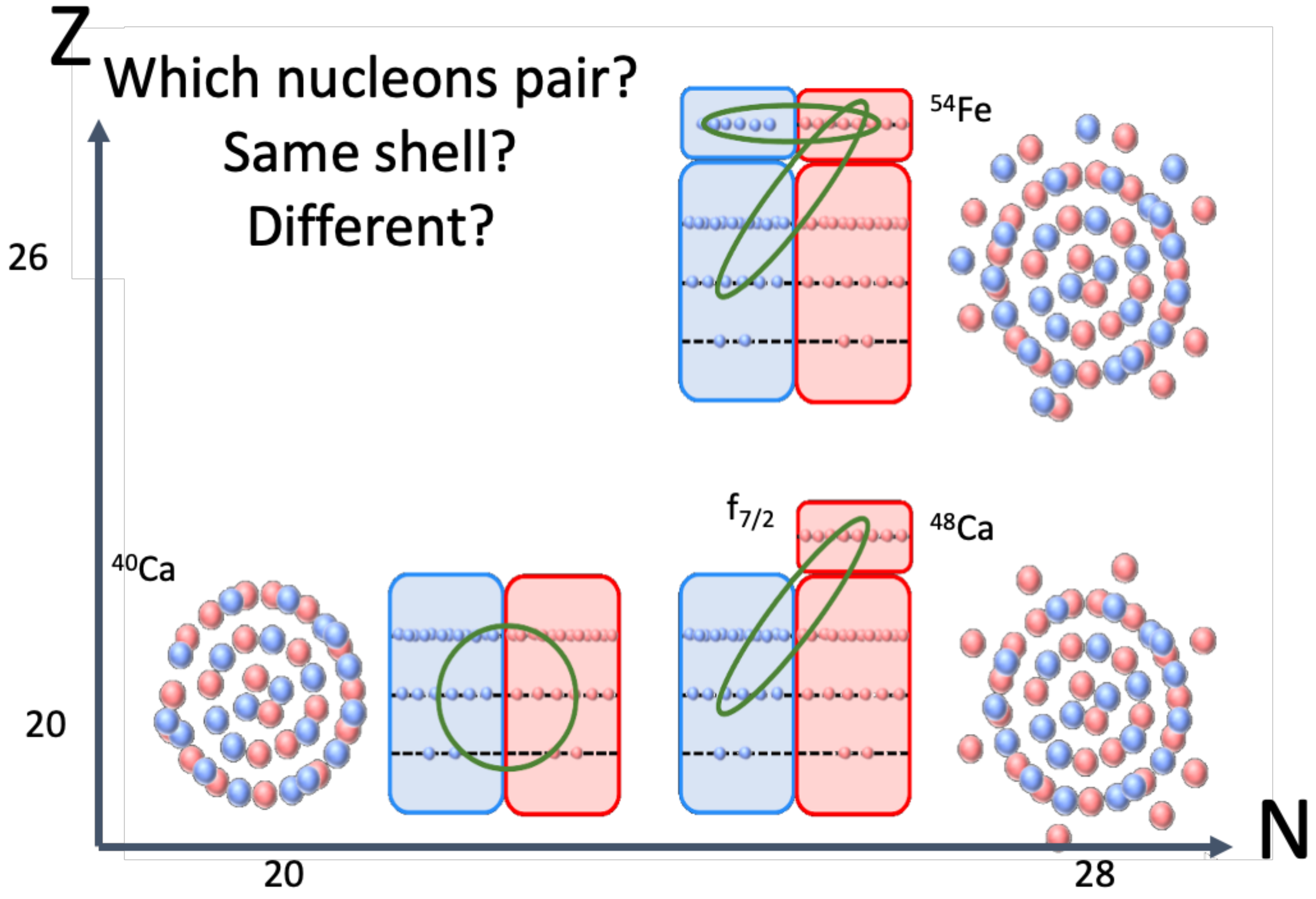


Duer et al, Nature (2018)

Does shell structure impact nucleon pairing?



^{40}Ca, ^{48}Ca, ^{54}Fe can teach us about pairing mechanisms

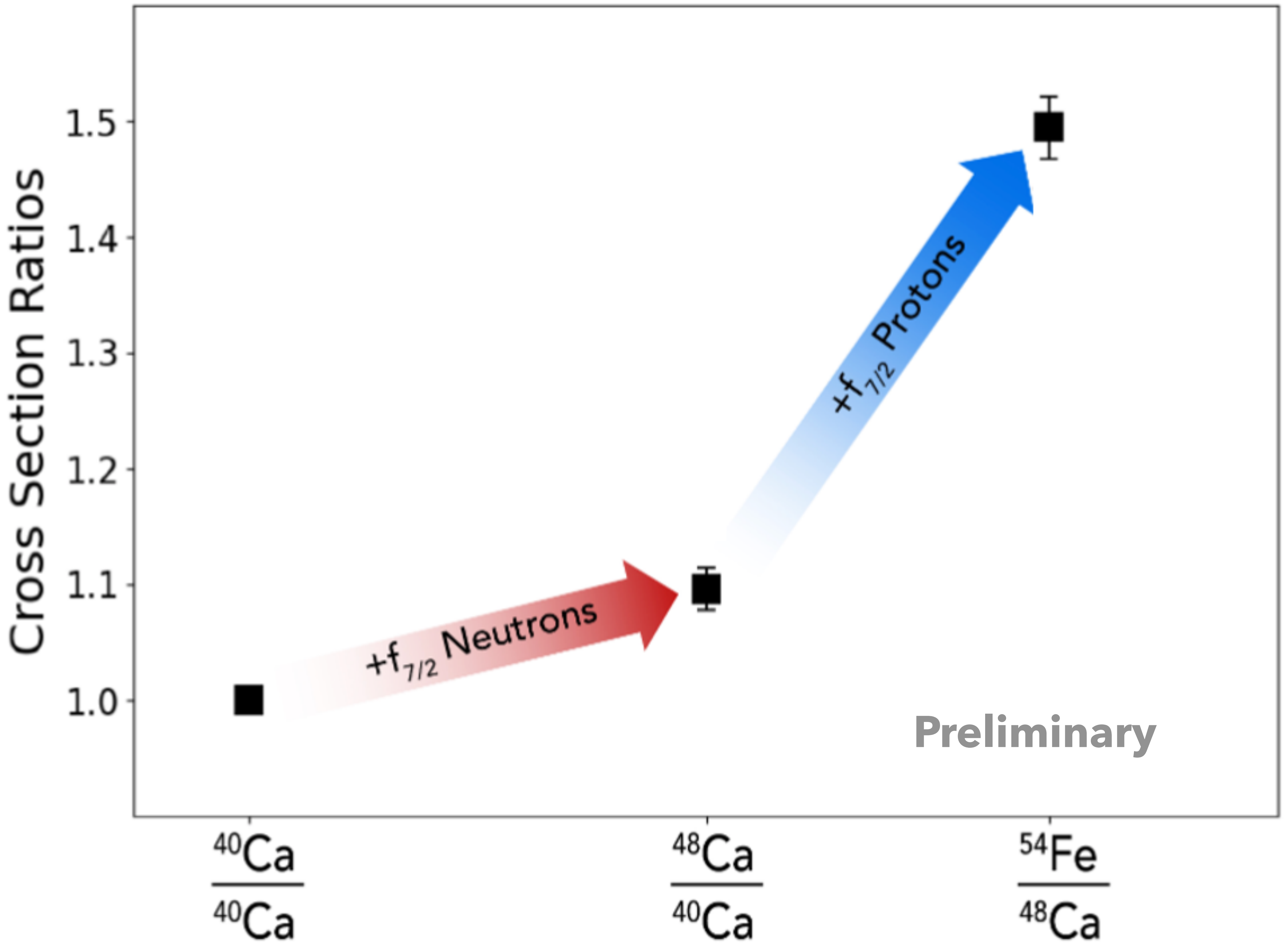


Number of protons

Number of neutrons

^{40}Ca, ^{48}Ca, ^{54}Fe can teach us about pairing mechanisms

New Hall C data: CaFe $(e, e'p)$



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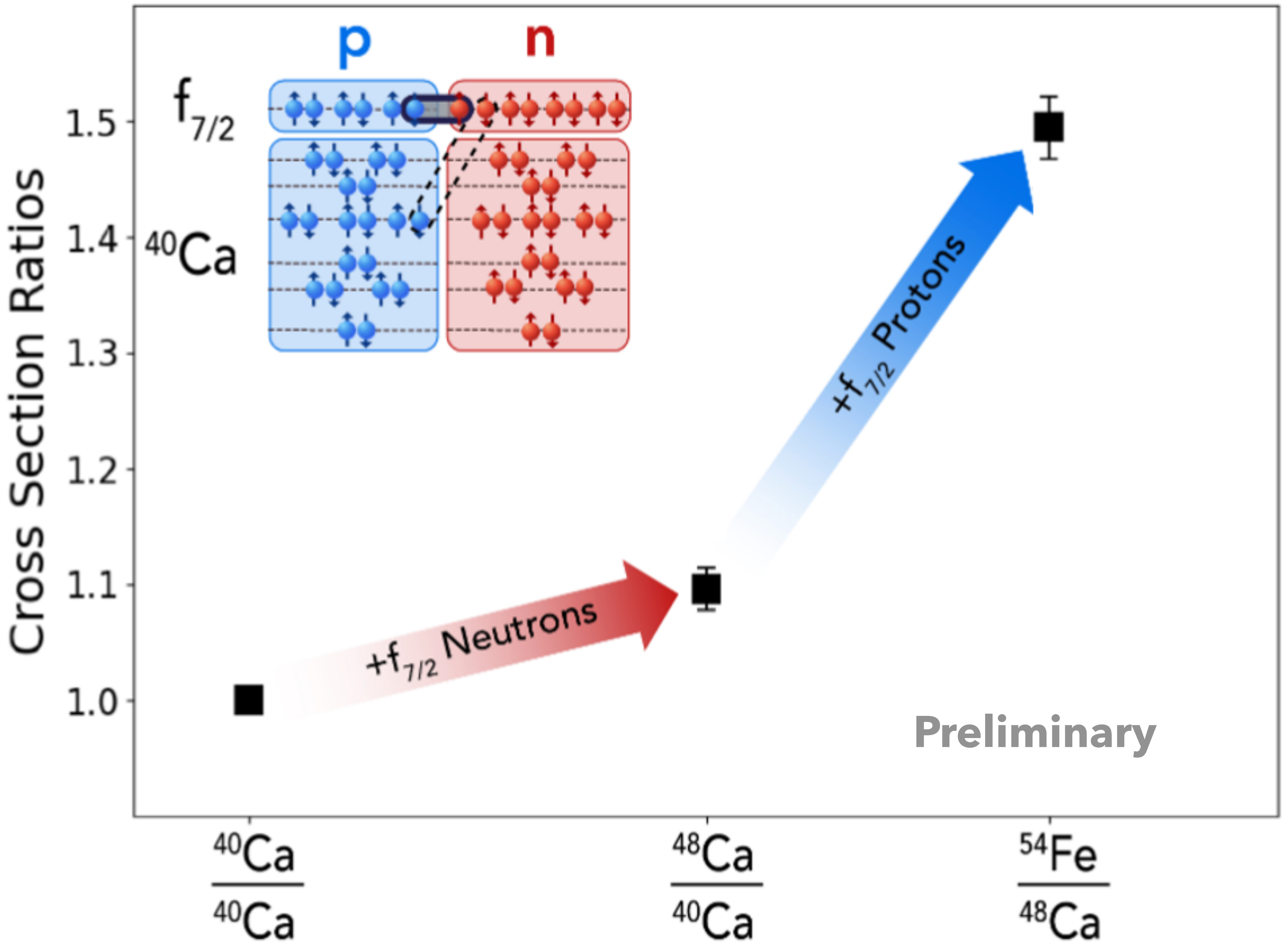

Nucleons pair within their shells

New Hall C data: CaFe $(e, e'p)$