Probing the core of the strong nuclear interaction

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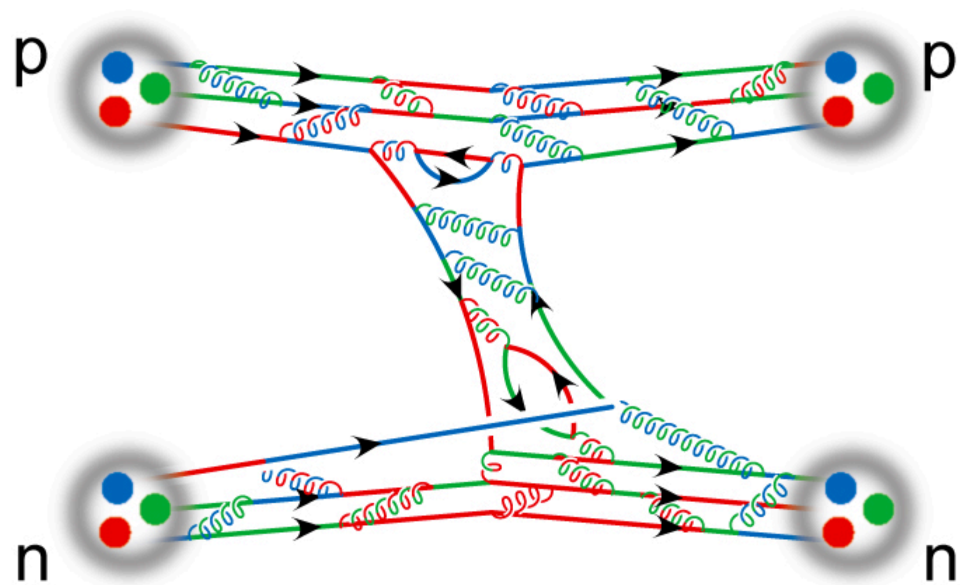
- The Nuclear Challenge
- Correlated Nucleons (SRC)
- The Generalized Contact Formalism
- High-momentum tests of the NN interaction
- Summary

The Nuclear Challenge

1. Many-body problem

$$\sum_i \left\{-\frac{\hbar^2}{2m_i}\nabla_i^2\Psi(\vec{r}_1,\ldots,\vec{r}_N,t)\right\} + U(\vec{r}_1,\ldots,\vec{r}_N)\Psi(\vec{r}_1,\ldots,\vec{r}_N,t) = i\hbar\frac{\partial}{\partial t}\Psi(\vec{r}_1,\ldots,\vec{r}_N,t)$$

2. Complex QCD interaction

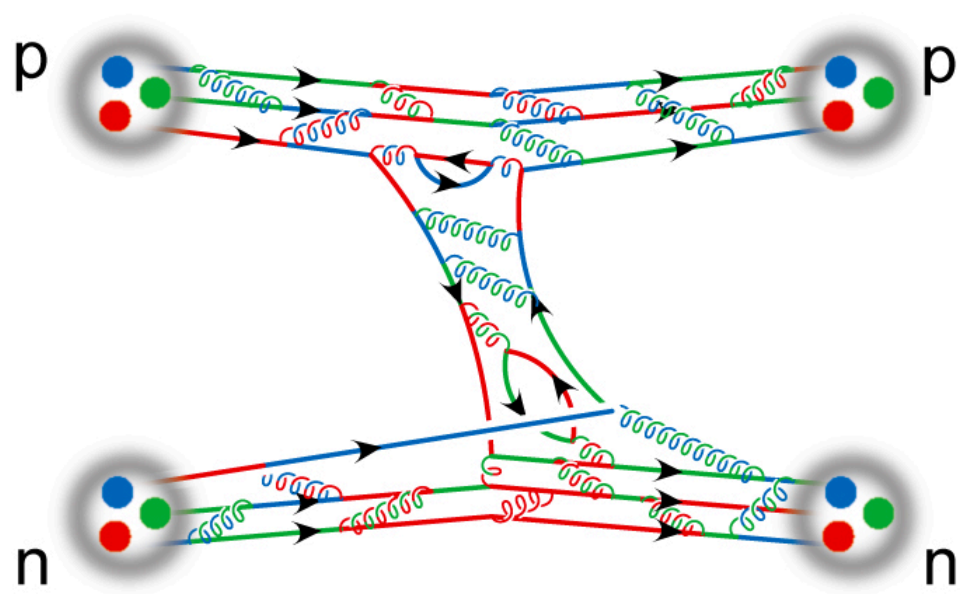


The Nuclear Challenge

1. Many-body problem

   ➔ Quantum Monte Carlo

2. Complex QCD interaction

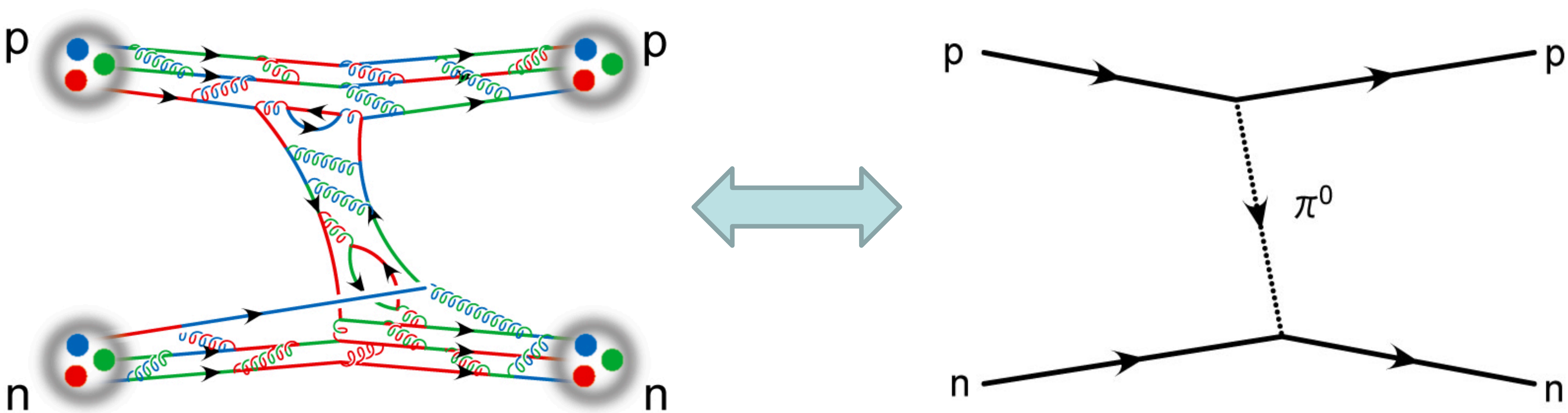


The Nuclear Challenge

1. Many-body problem

   ➔ Quantum Monte Carlo

2. Complex ~~QCD~~ Effective interaction



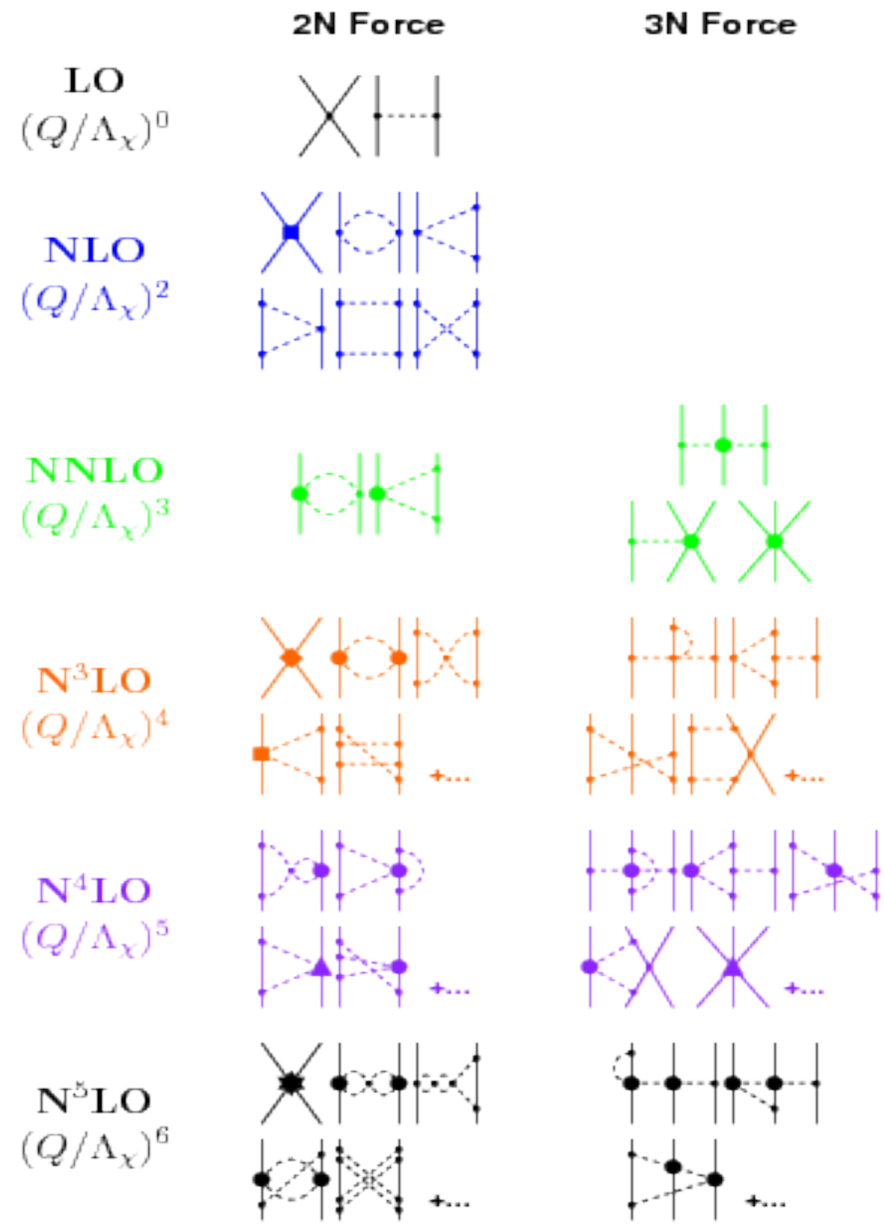
The Nuclear Interaction

Many ways to derive the effective interaction.

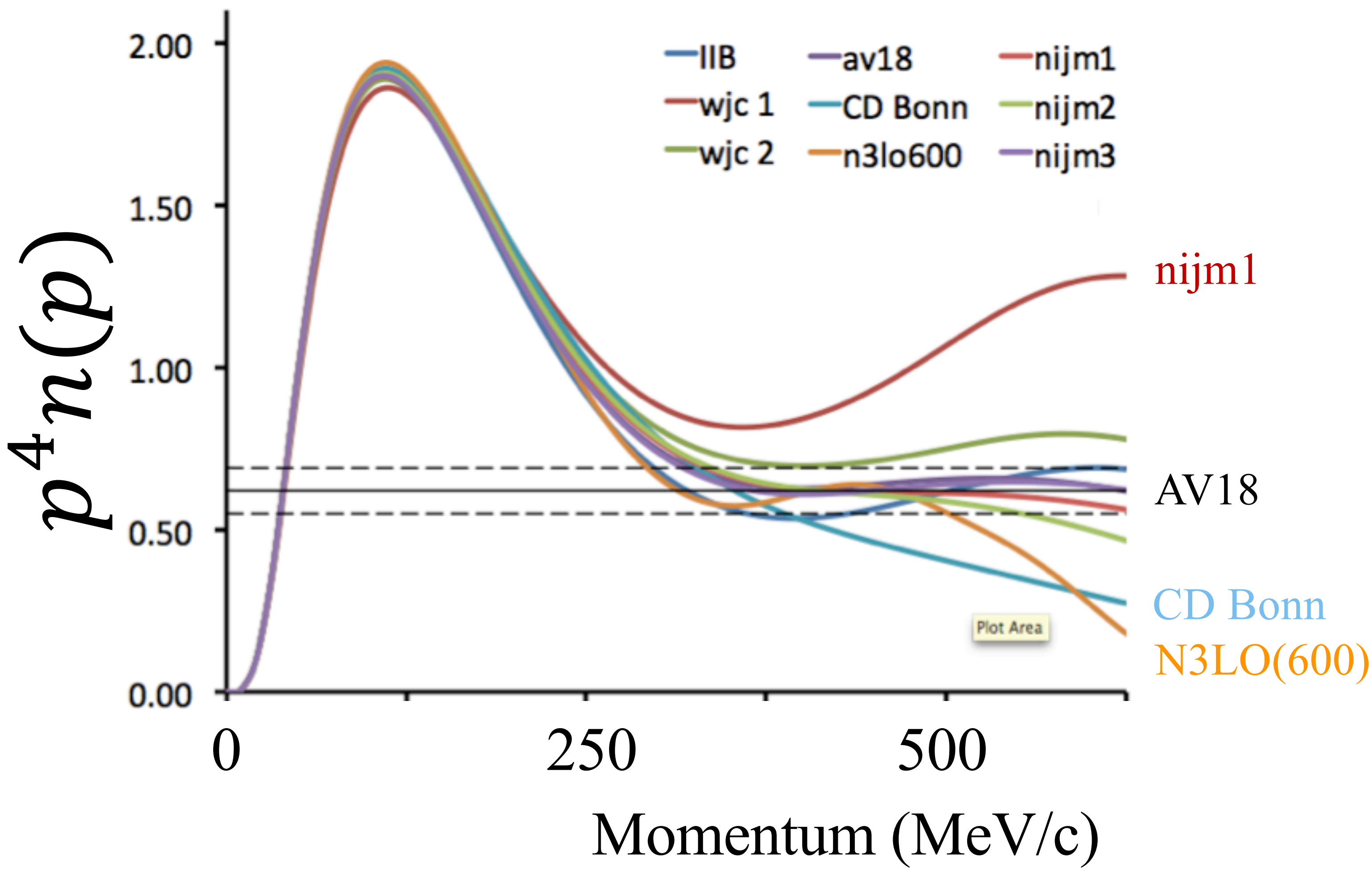
- Chiral Effective Field Theory - χEFT
- Pion exchange plus phenomenological short distance terms (AV18, etc)

All models contain effective parameters that need to be determined experimentally

Typically fit to *NN* scattering up to 350 MeV/c (pion threshold)



The Deuteron



Poorly constrained for $p > 400$ MeV/c

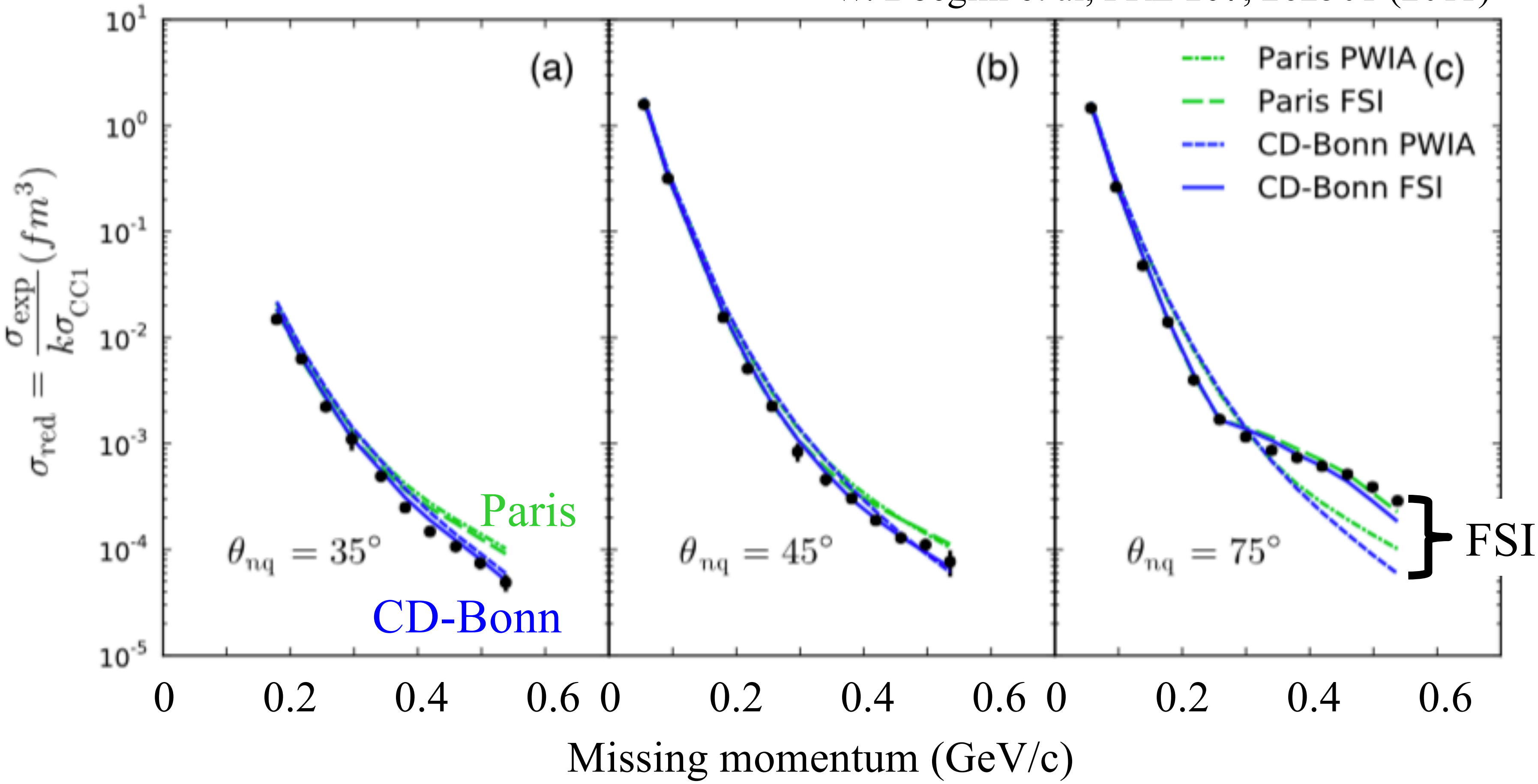
Where to test these models

NN systems at high relative momentum

- The deuteron
- Short range correlated NN pairs

The Deuteron

W. Boeglin et al, PRL **107**, 262501 (2011)

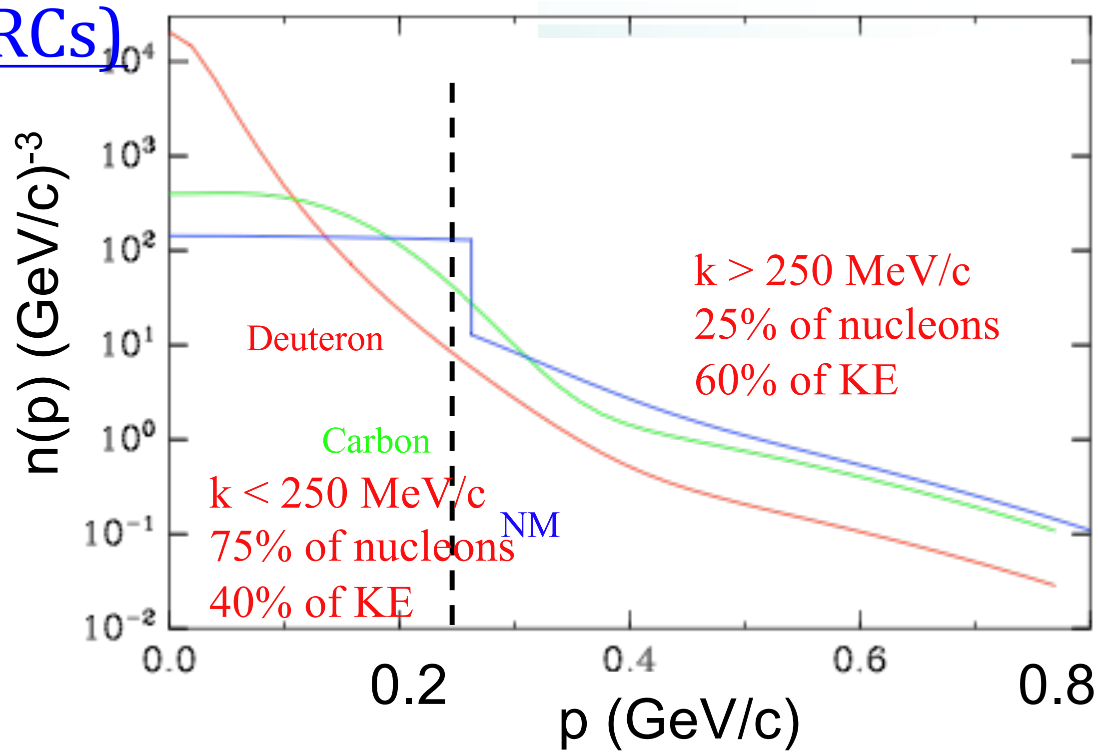


Difficulties:

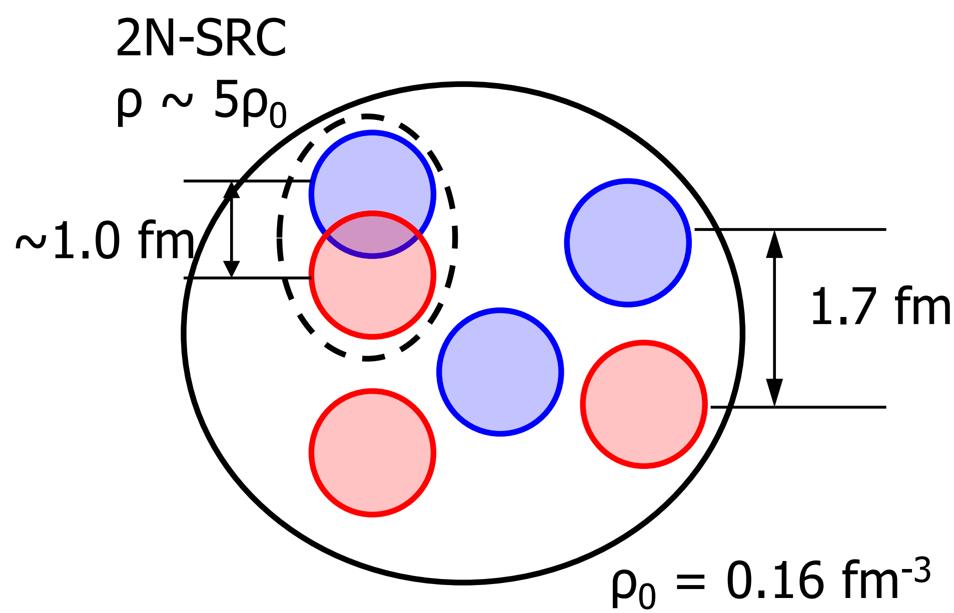
- Small cross sections
- Competing effects (Final State Interactions)

Short Range Correlations (SRCs)

➔High momentum tails:
$p > p_{\text{Fermi}}$
Calculable for $A \leq 40$ and nuclear matter.
Not well constrained at large p

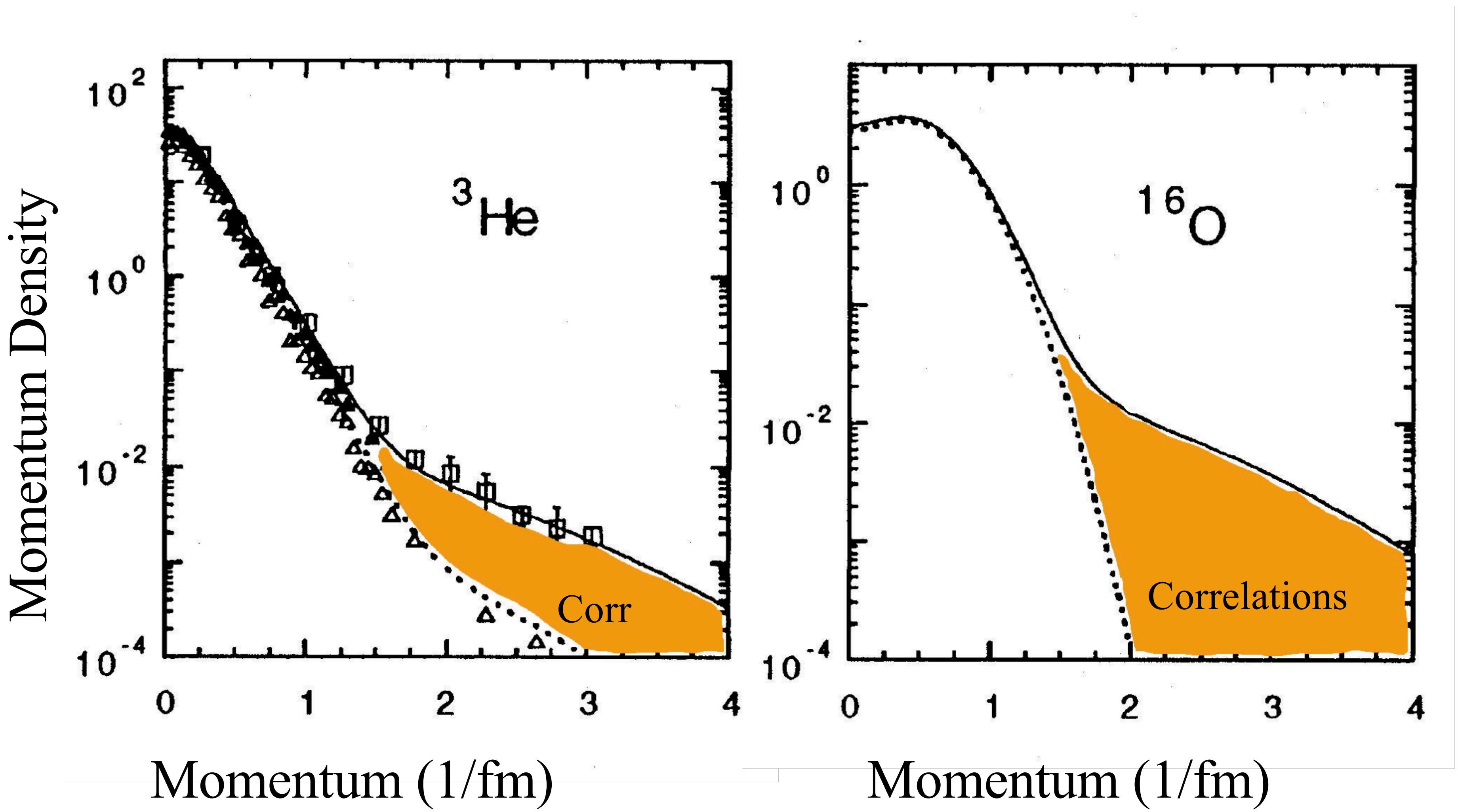


Effects:
- High momentum part of the nuclear wave function
- Short distance behavior of nucleons - modification??
- Cold dense nuclear matter
- Neutron Stars



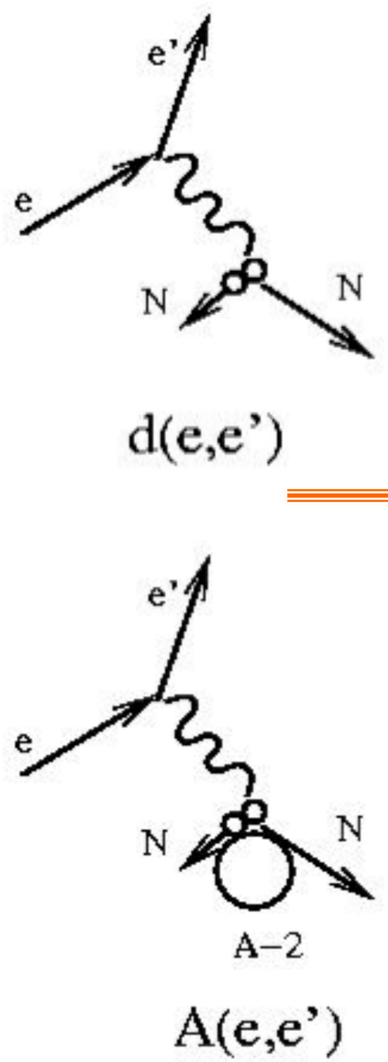
Nucleons are like people …

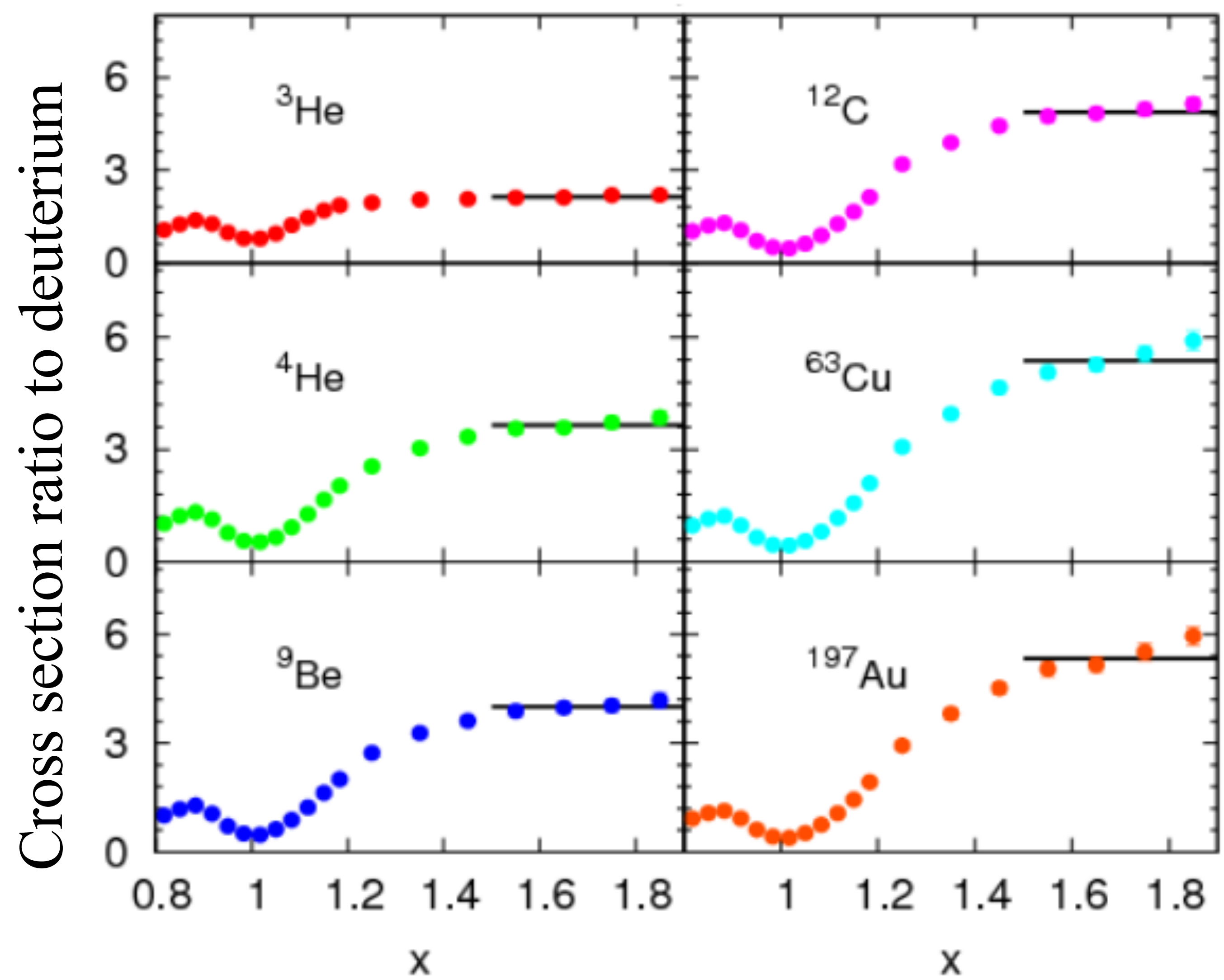
Correlations and High Momentum



Ciofi degli Atti, PRC 53 (1996) 1689

Correlations are Universal: *A*(e,e') / *d*(e,e')





Scaling (flat ratios) indicates a common momentum distribution.

1 < x < 1.5: dominated by different mean field n(k)

1.5 < x < 2: dominated by 2N SRC

$\alpha_{2N} \approx 20\%$

$x = Q^2 / 2m\nu$

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

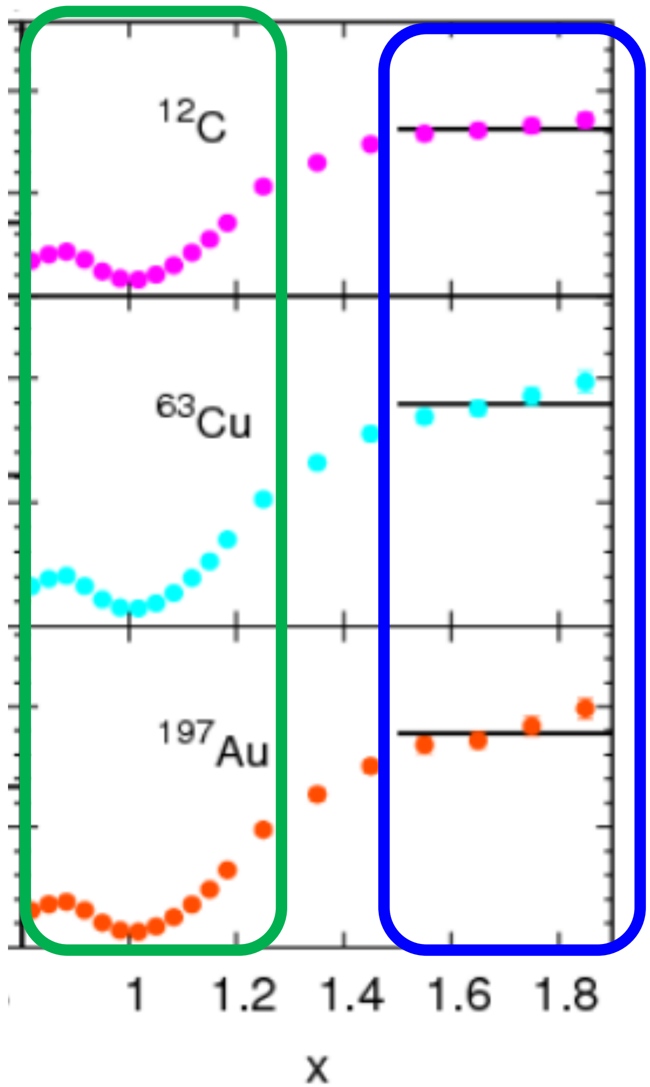
B. Schmookler + CLAS, Nature **566**, 354 (2019)

L. Weinstein, CLAS 2019

Scale separation

Long range / low momentum scale region

Nucleus dependent



Short distance / high momentum scale region

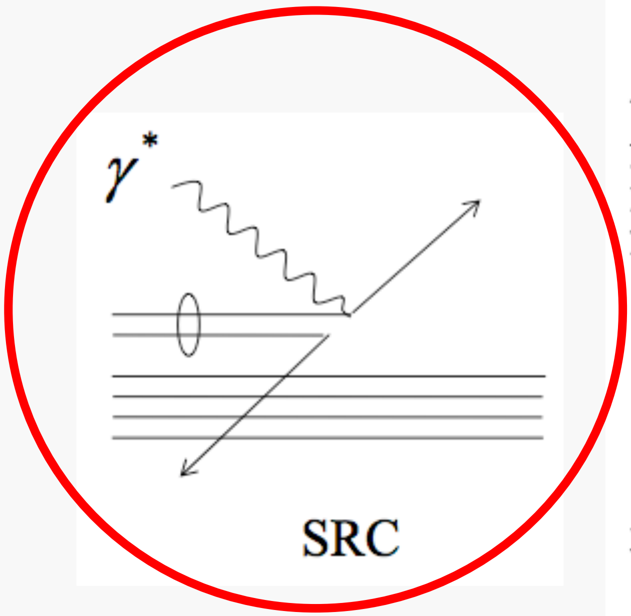
Nucleus independent

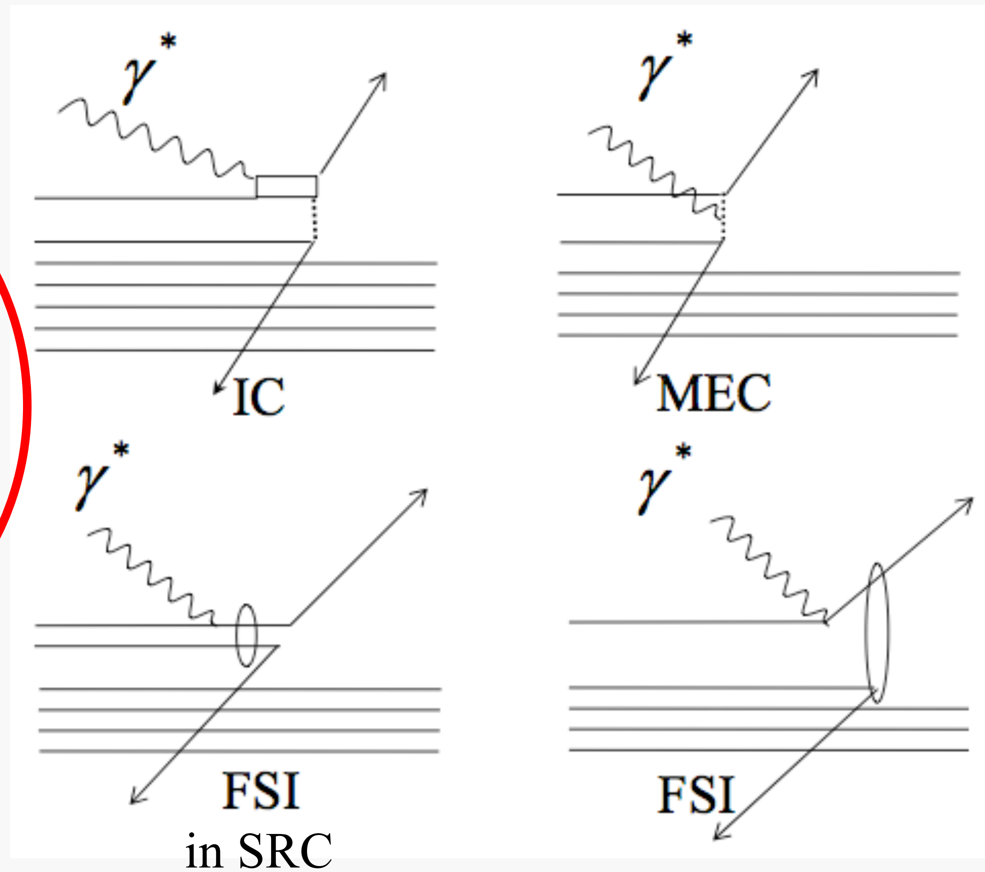
"Short Range Correlations"

What are correlations?

Average Two-Nucleon Properties in the Nuclear Ground State

Two-body currents are not Correlations
(but add coherently)

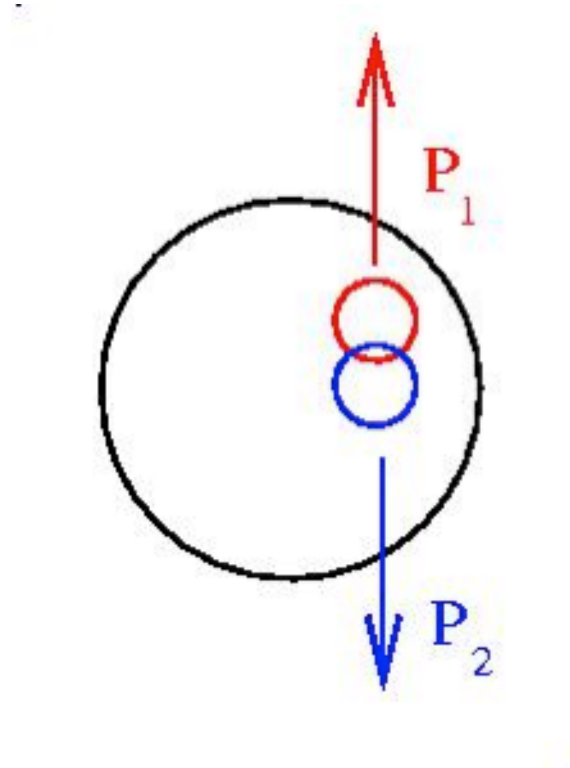




Signatures for Correlations

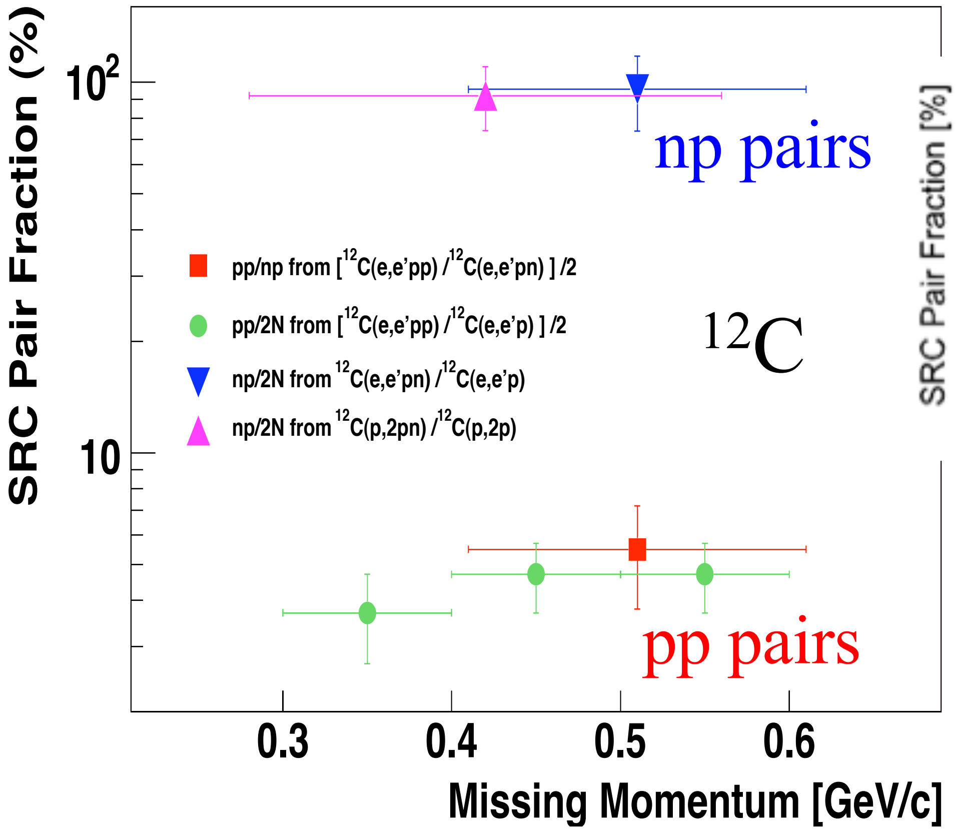
An Experimentalist's Definition:

- A high momentum nucleon whose momentum is balanced by **one** other nucleon
  - *NN* Pair with
    - Large Relative Momentum
    - Smaller Total Momentum



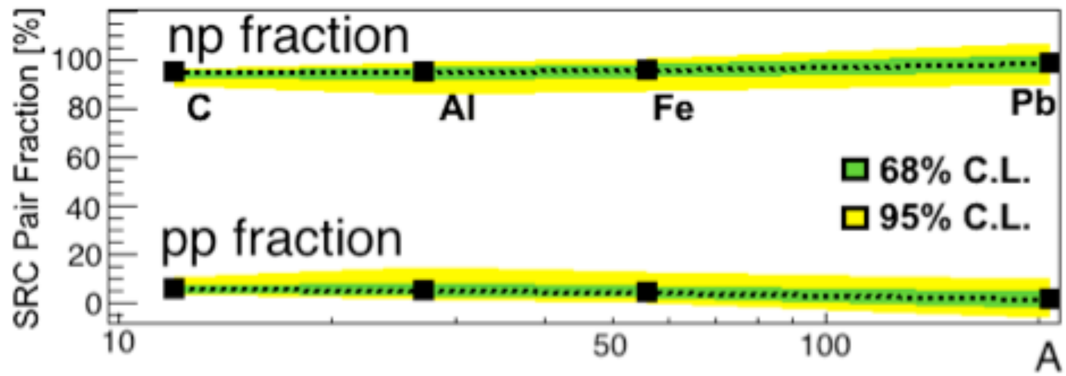
Select experimental kinematics to minimize effect of other reaction mechanisms and emphasize SRC

High momentum protons have neutron partners

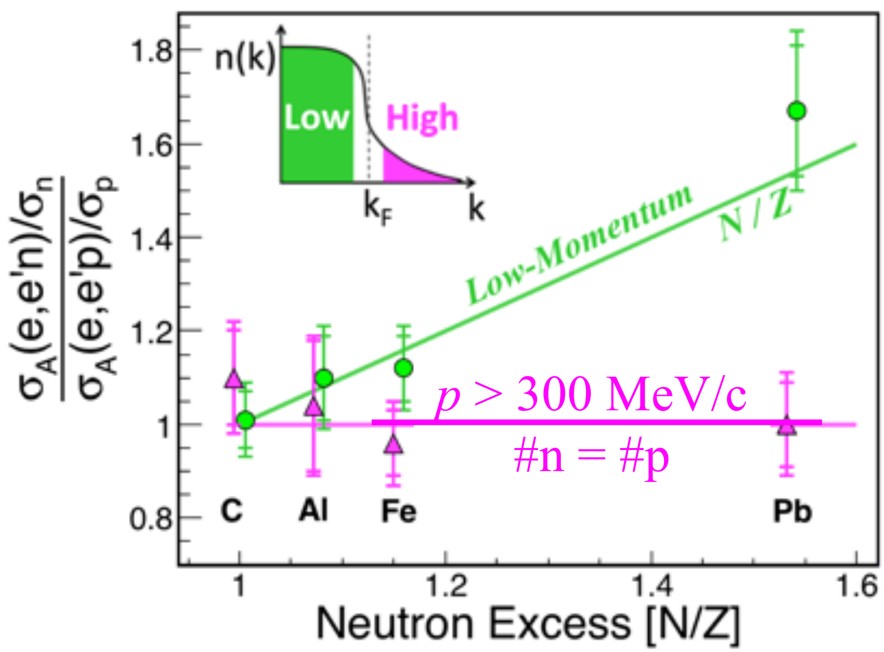


R. Subedi et al., Science **320**, 1476 (2008)

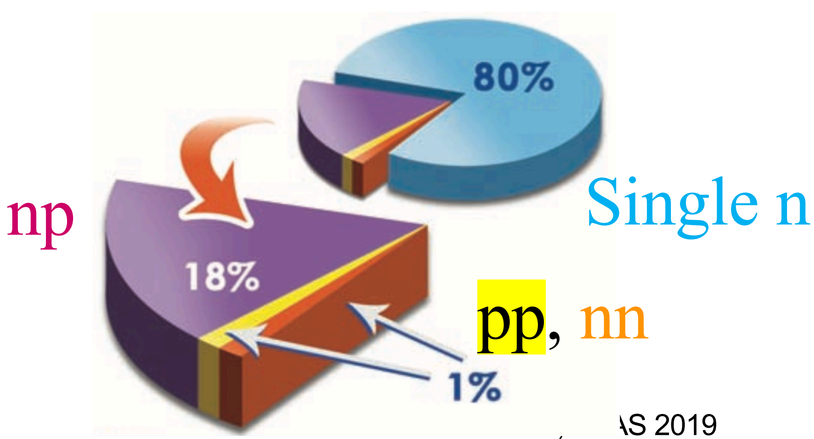
Heavier nuclei



O. Hen *et al*, Science **346** 614 (2014)



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



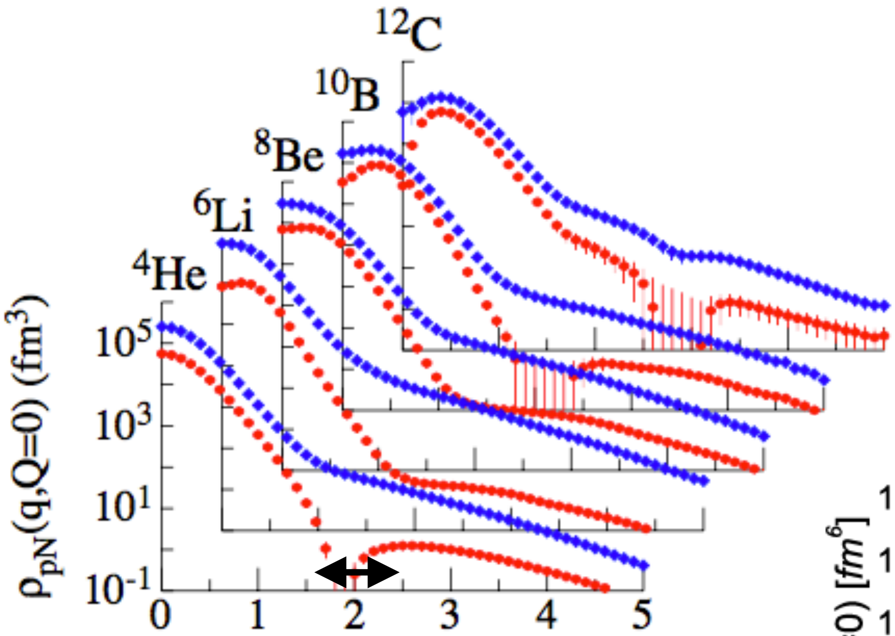
There are ~20 times more np-SRC than pp-SRC pairs in nuclei.

Why ?

pp pairs are spin-0 and must be *s*-wave

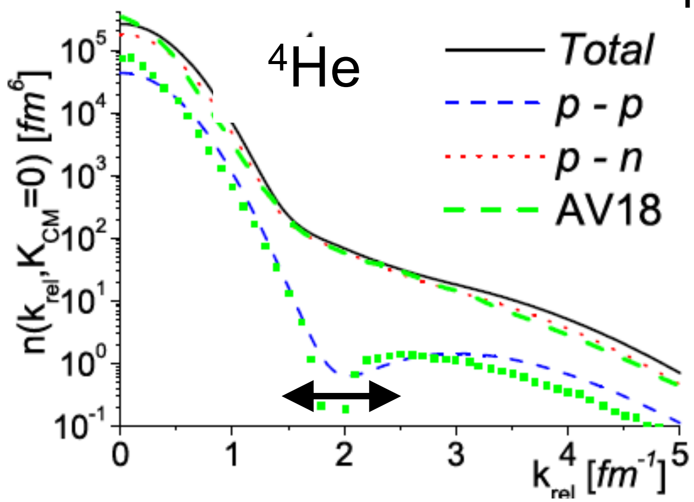
- the *s*-wave minimum at $p_{rel} \approx 400$ MeV/c

The *np* minimum is filled in by strong tensor (*l*=2) correlations

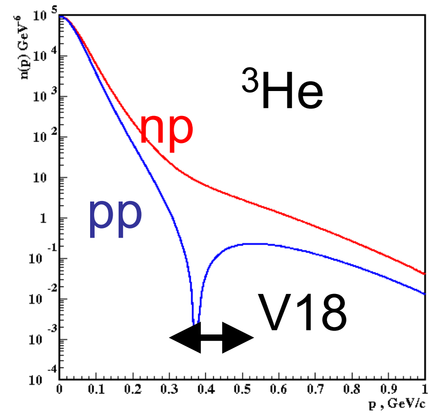


Pair relative momentum (fm^{-1})

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



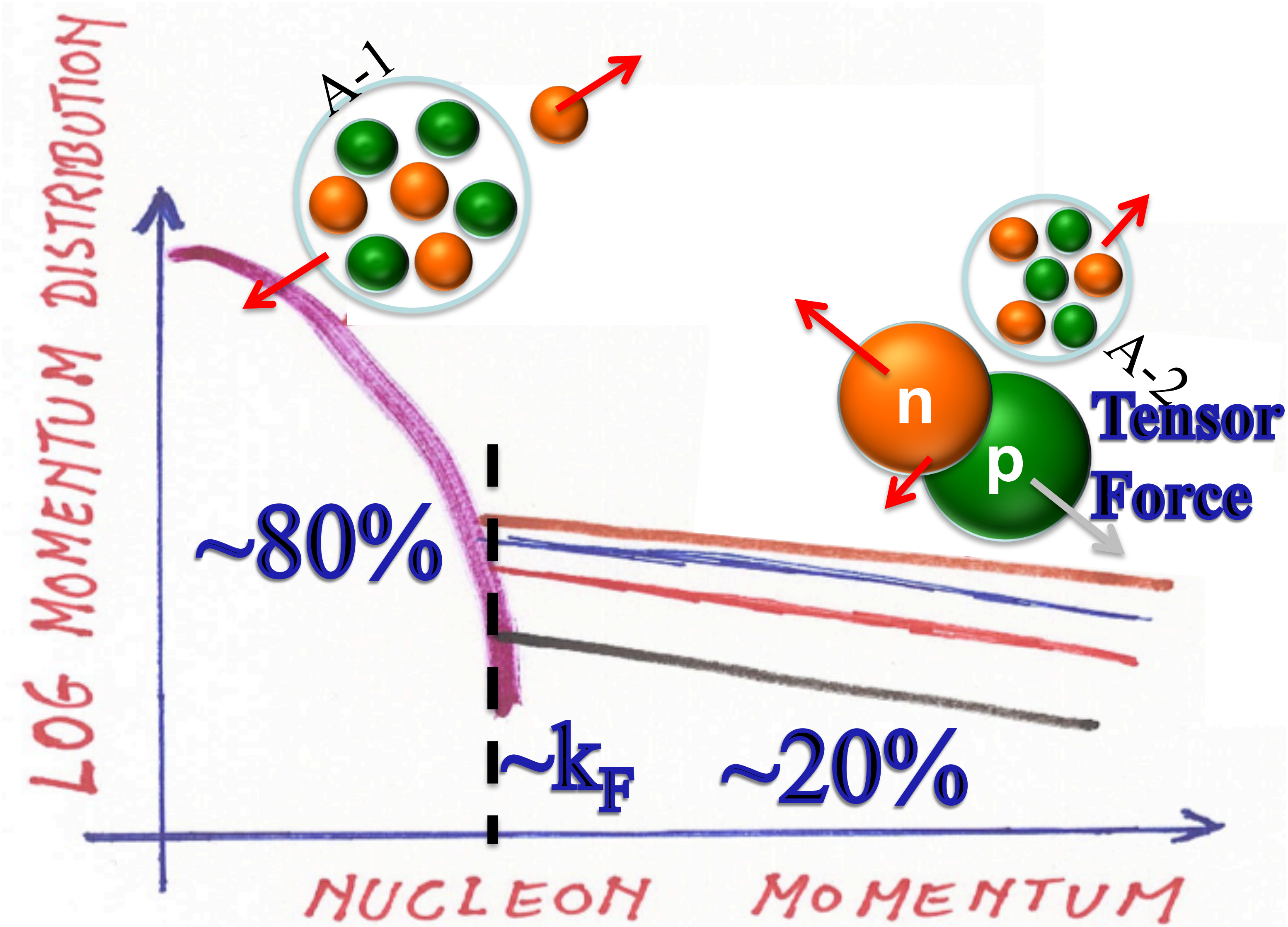
Pair relative momentum



Pair relative momentum

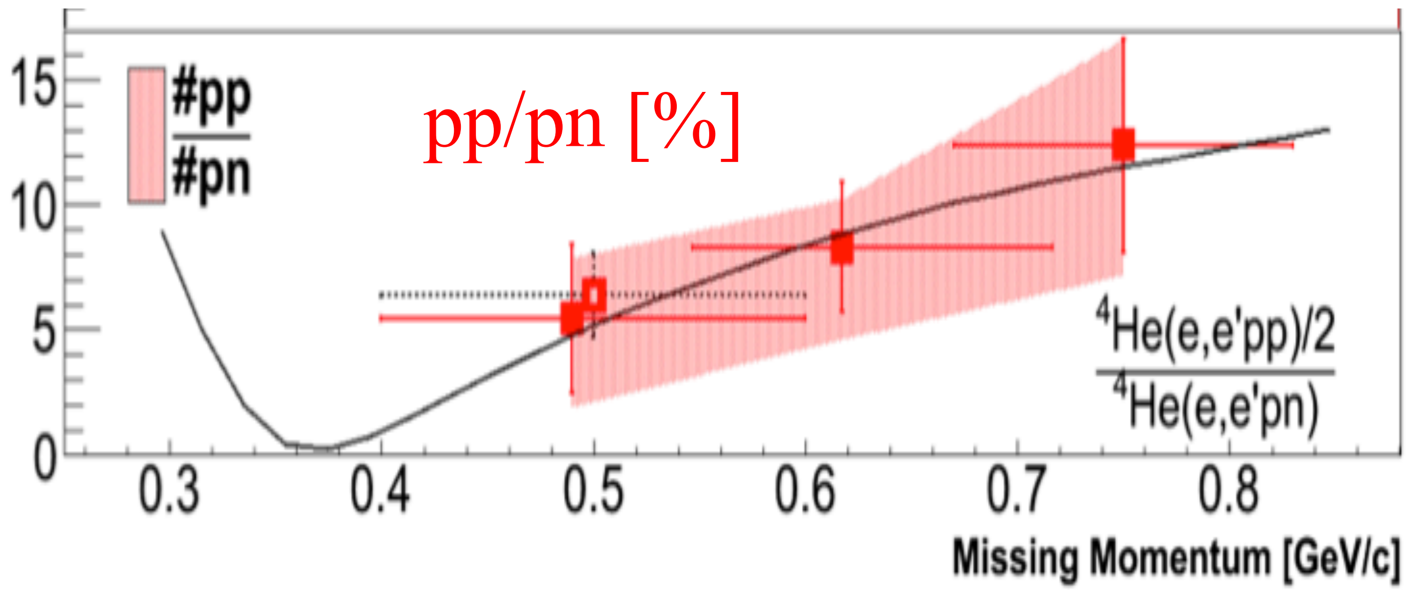
Ciofi and Alvioli
Gent workshop, Aug. 2007

Sargsian, Abrahamyan, Strikman, Frankfurt
PRC **71,** 044615 (2005).



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

Higher momentum protons?
^{4}He(e,e'pN)



- pp/np ratio increases with missing momentum
- Central correlations?

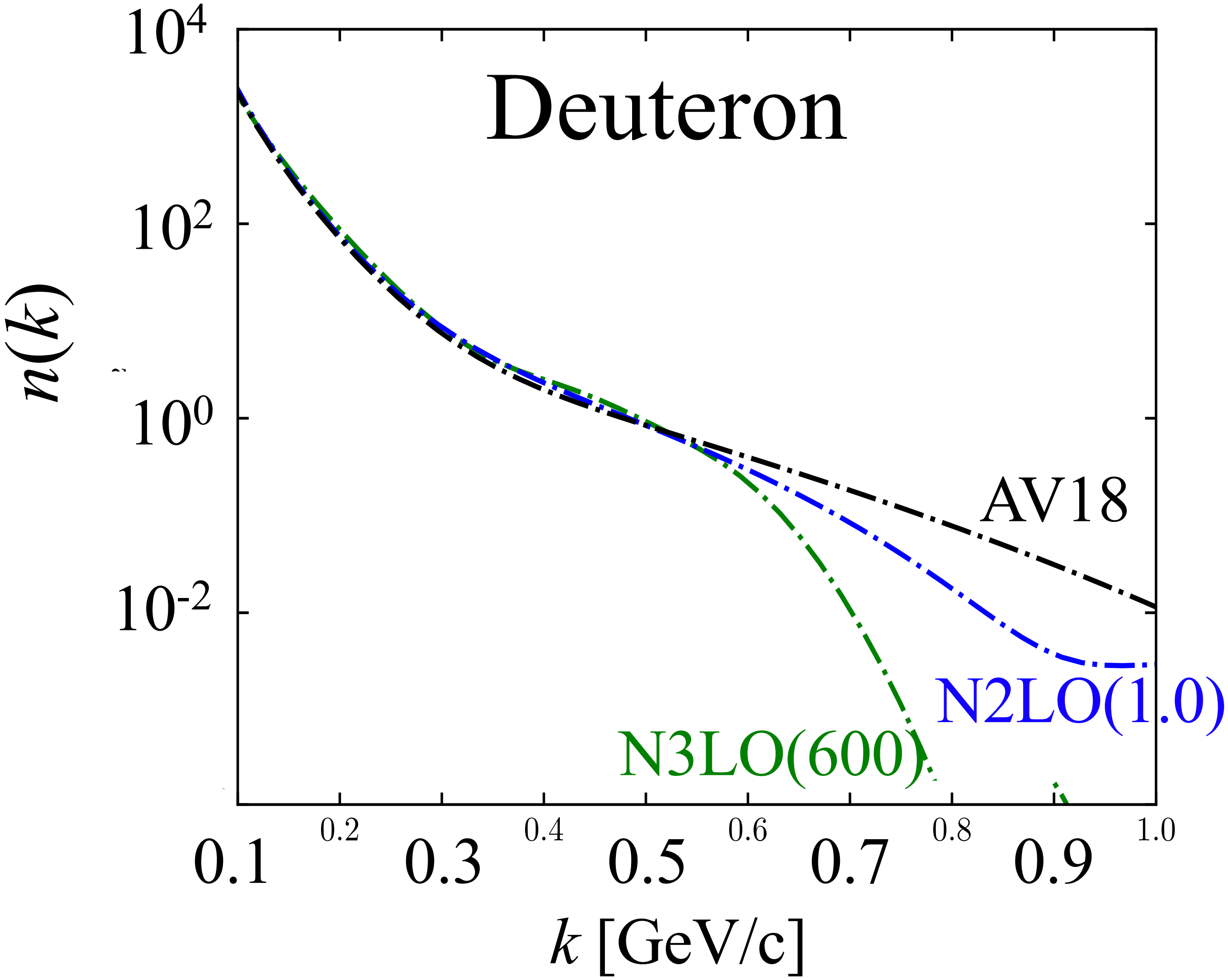
I. Korover et al., PRL 113, 022501 (2014)

SRC Summary

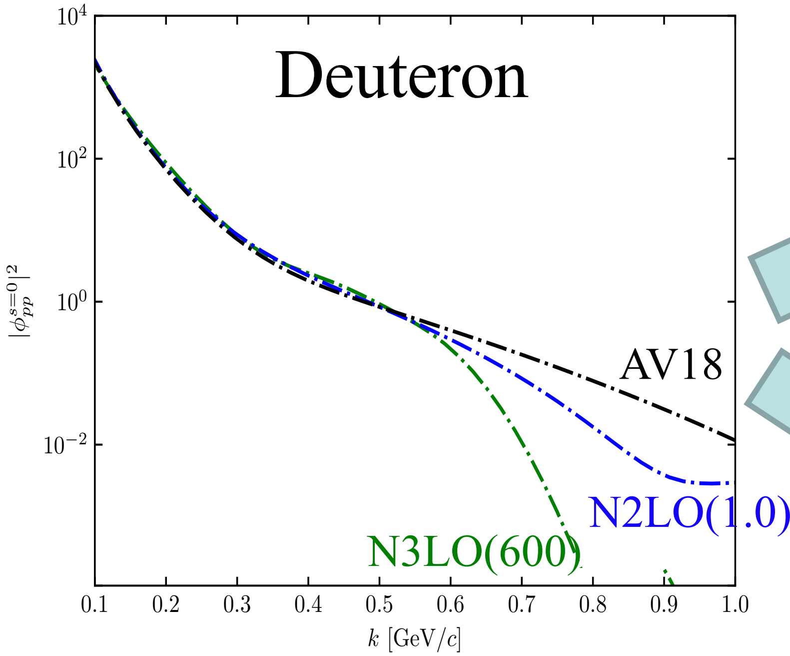
- Almost all high momentum nucleons (p > 300 MeV/c) in nuclei belong to an *NN* correlated pair
  - 20% of all nucleons for $A \geq 12$
  - Dominated by *pn* pairs, even in heavy asymmetric nuclei
  - Higher probability for minority to be at high p
  - Momentum distributions proportional to deuterium
  - Scale separation between high-momentum/short-distance phenomena and low-momentum/longer-distance

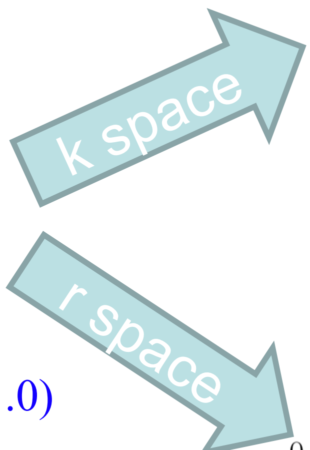
Next: use the scale separation to describe SRC in nuclei

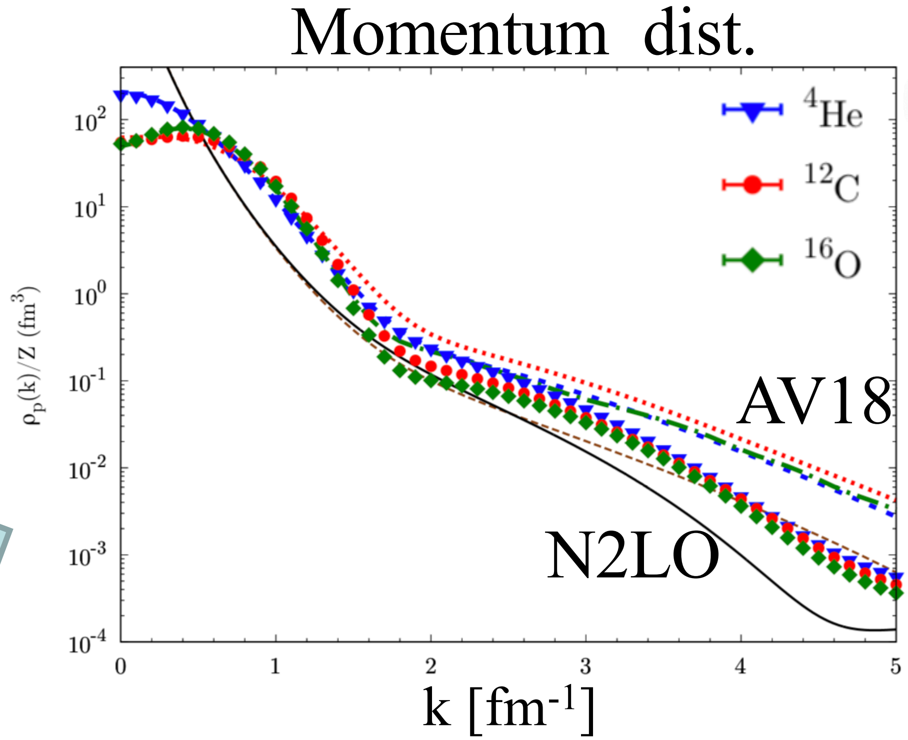
Can SRC data probe ab-initio Calculations?

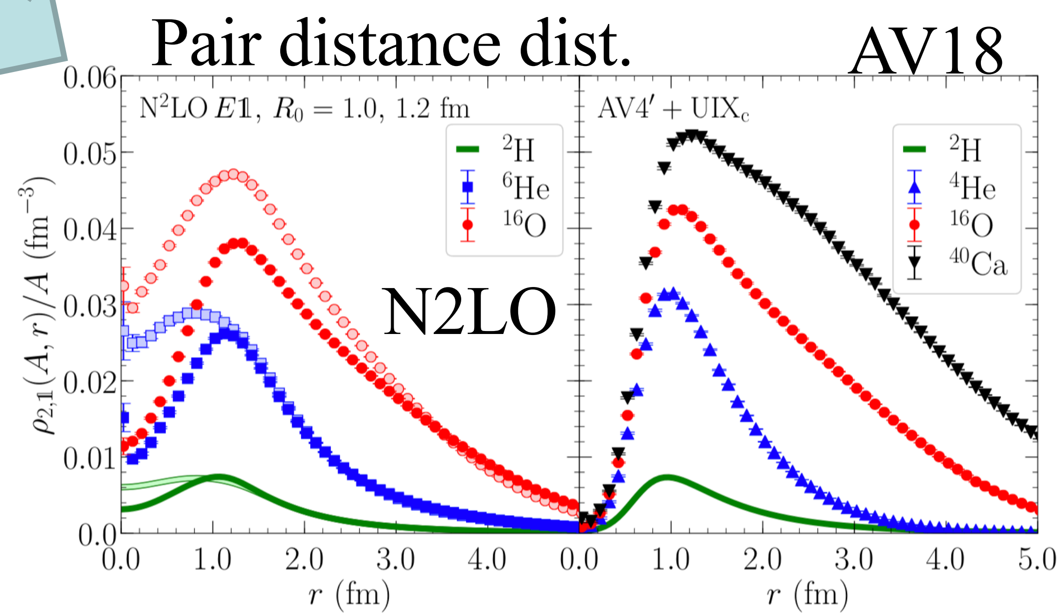

Deuteron
10^4
10^2
10^0
10^{-2}
n(k)
AV18
N2LO(1.0)
N3LO(600)
0.2
0.4
0.6
0.8
1.0
0.1
0.3
0.5
0.7
0.9
k [GeV/c]

Different Nuclei



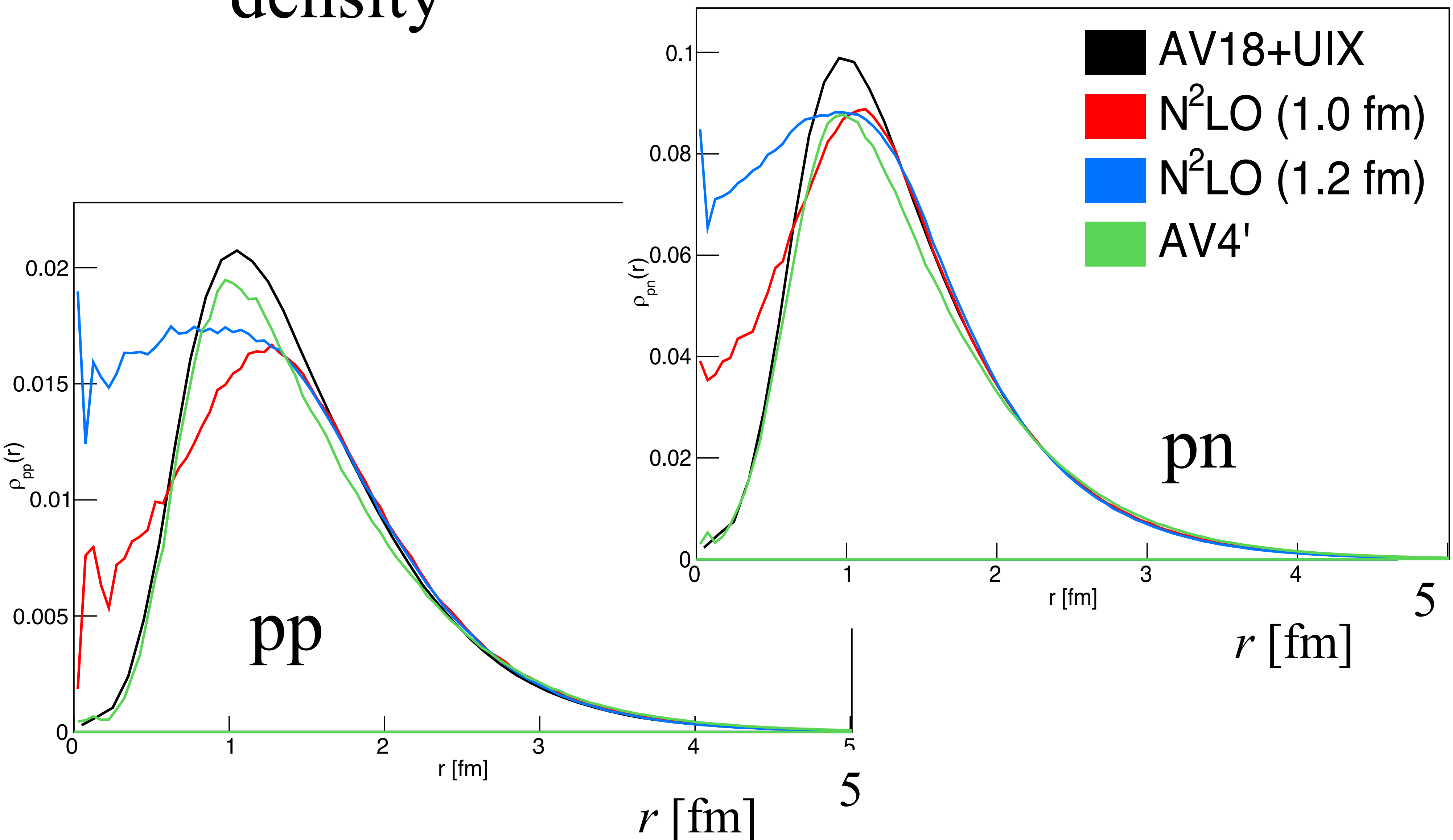






Lonardoni et al., PRC (2018)
Lynn and Lonardoni et al. arXiv 1903.12587

^{4}He two-nucleon density



Lonardoni et al., PRC (2018)
Lynn and Lonardoni et al. arXiv 1903.12587

Probing the NN Interaction

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

Probing the NN Interaction

What's needed?

- Ab-initio cross-section calculations

- Data

Probing the NN Interaction

What's needed?

- ~~Ab-initio cross-section calculations~~
  => Plane-wave \w spectral fns from *NN* interaction
- Data $$\frac{d^4\sigma}{d\Omega_{k'}\, d\epsilon'_k\, d\Omega_{p'_1}\, d\epsilon'_1} = p'_1 \epsilon'_1 \sigma_{eN} S^N(\boldsymbol{p}_1, \epsilon_1)$$

Probing the NN Interaction

What's needed?

- ~~Ab-initio cross-section calculations~~
  => Plane-wave \w spectral fns from *NN* interaction

- Data in kinematics where plane-wave works

Probing the NN Interaction

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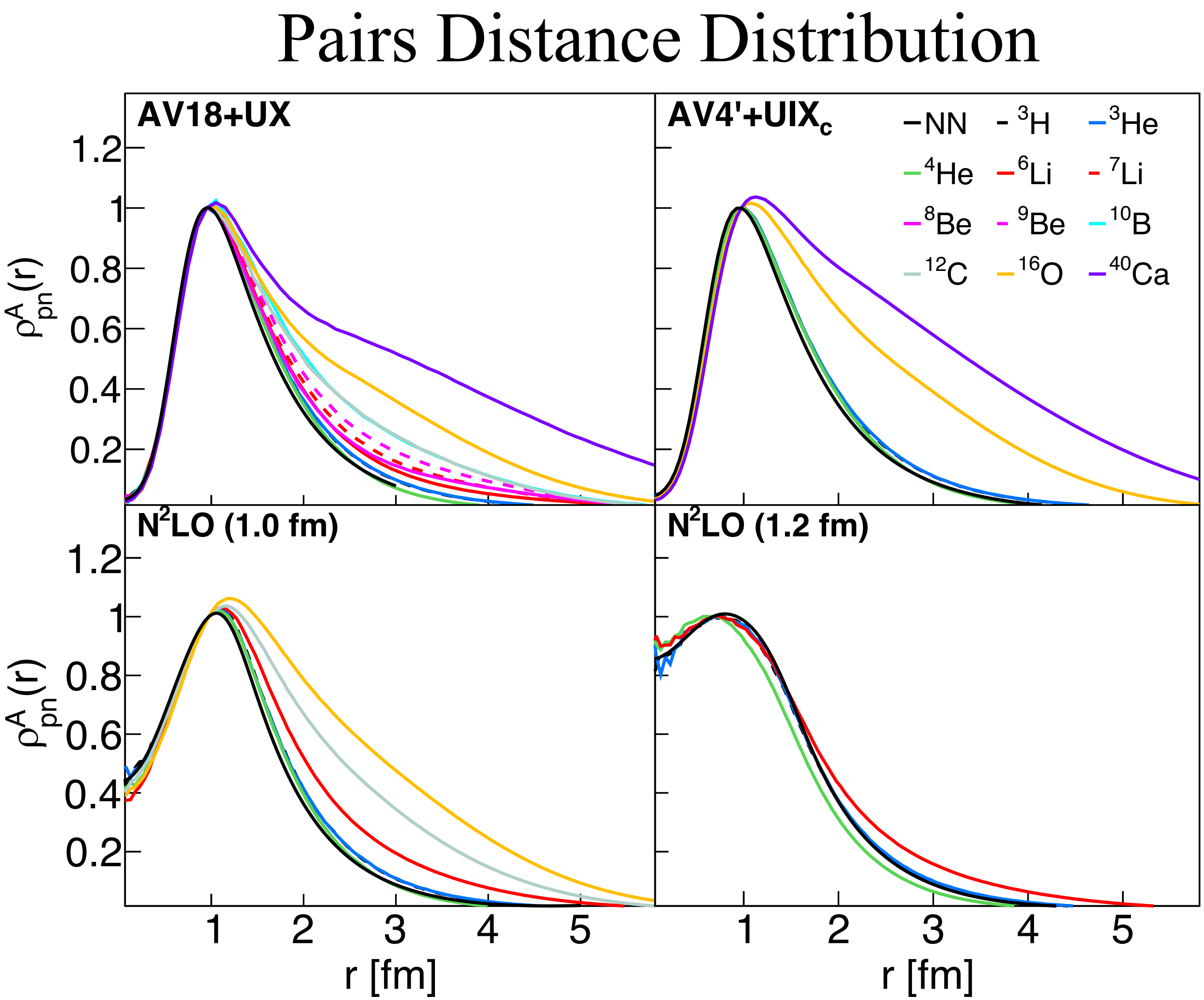
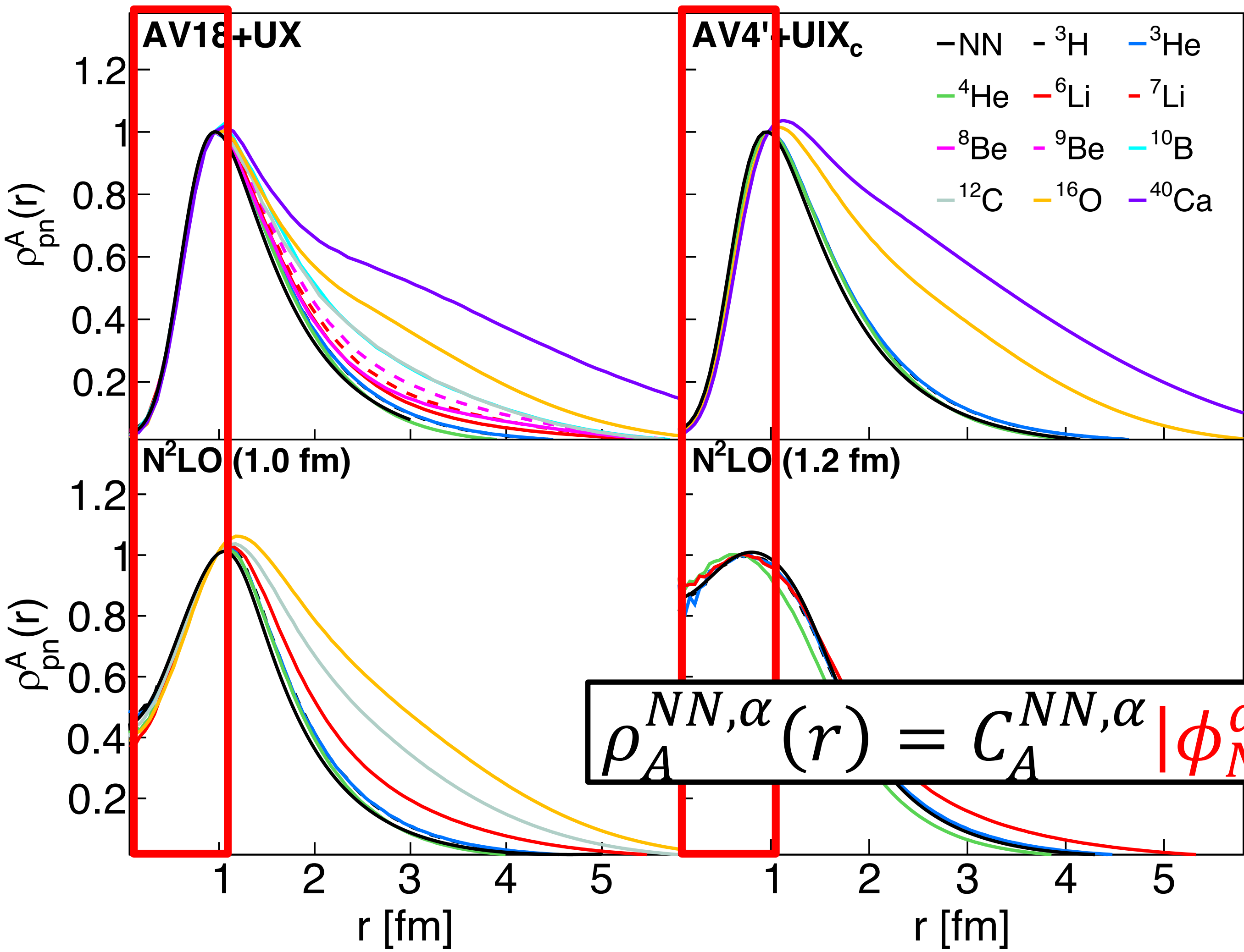
Quantum MC: **small-r** / high-k is all pairs!



Cruz Torres and Lonardoni et al. (2019)

GCF Factorization

Pairs Distance Distribution



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

Weiss et al., Phys. Lett. B (2018); Cruz Torres et al., Phys. Lett B (2018);
Weiss et al., Phys. Lett B (2019); Cruz Torres and Lonardoni et al. (2019).

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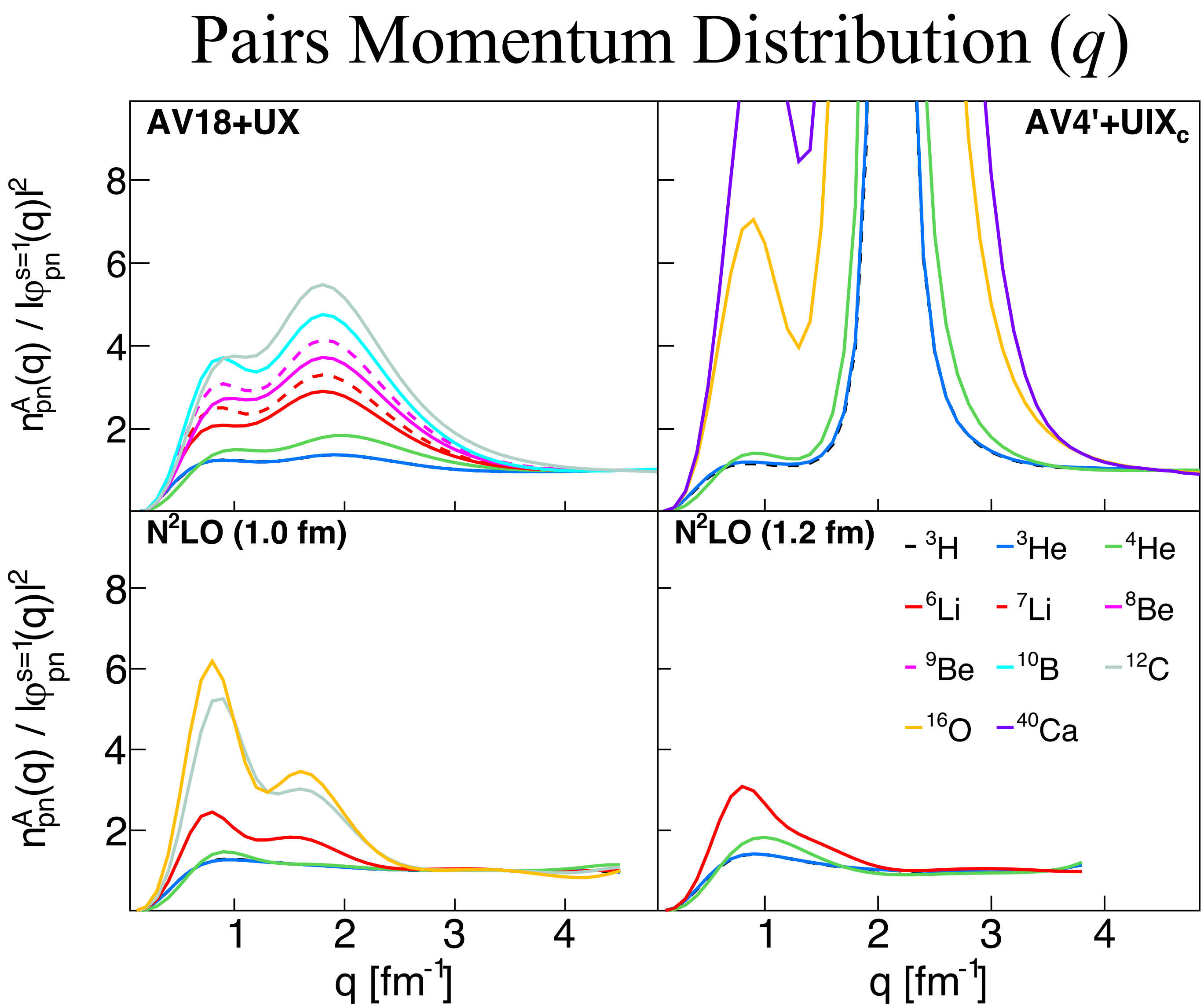
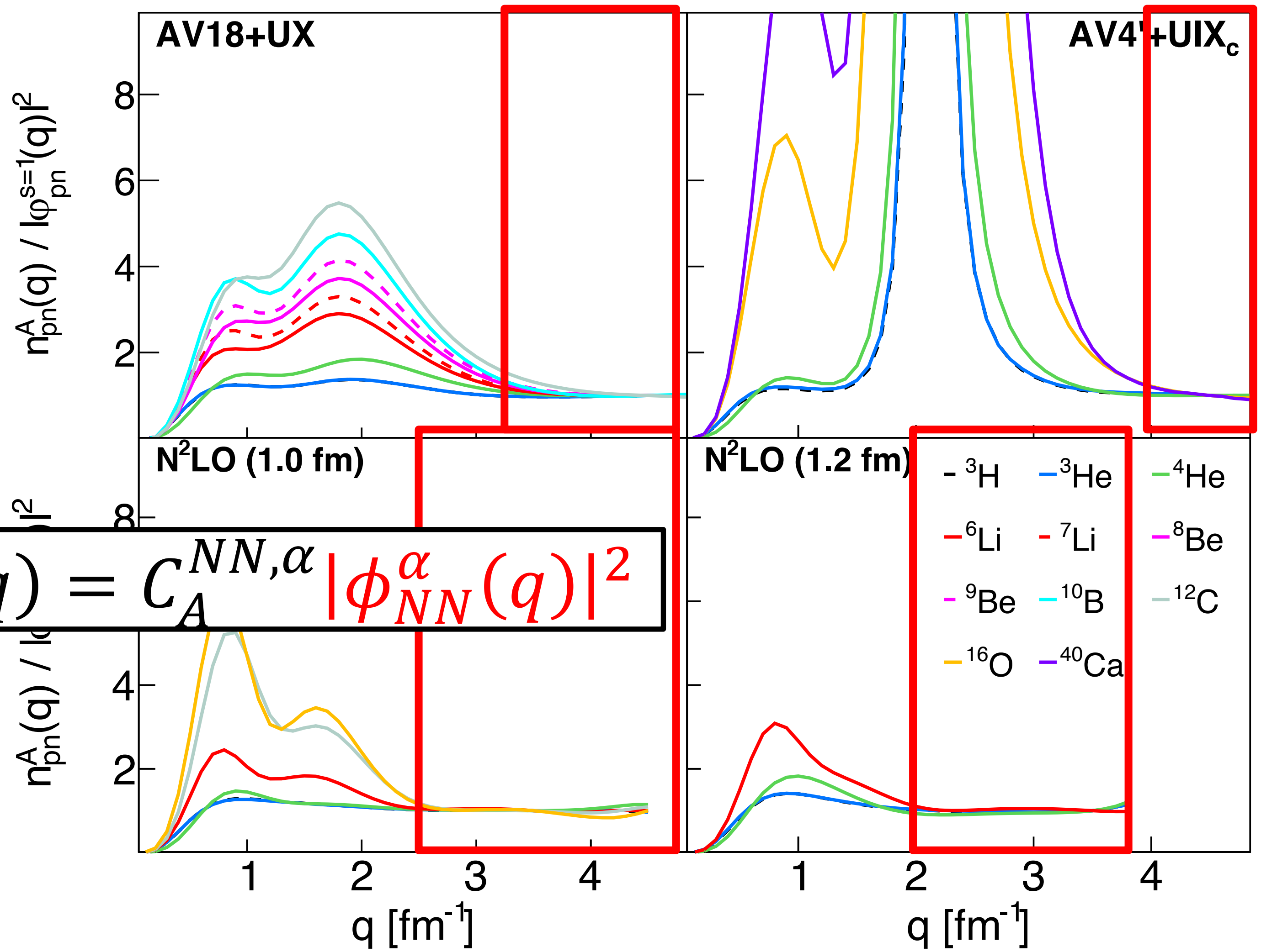


Cruz Torres and Lonardoni et al. (2019)

GCF Factorization

Pairs Momentum Distribution (q)



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

Weiss et al., Phys. Lett. B (2018); Cruz Torres et al., Phys. Lett B (2018);
Weiss et al., Phys. Lett B (2019); Cruz Torres and Lonardoni et al. (2019).

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

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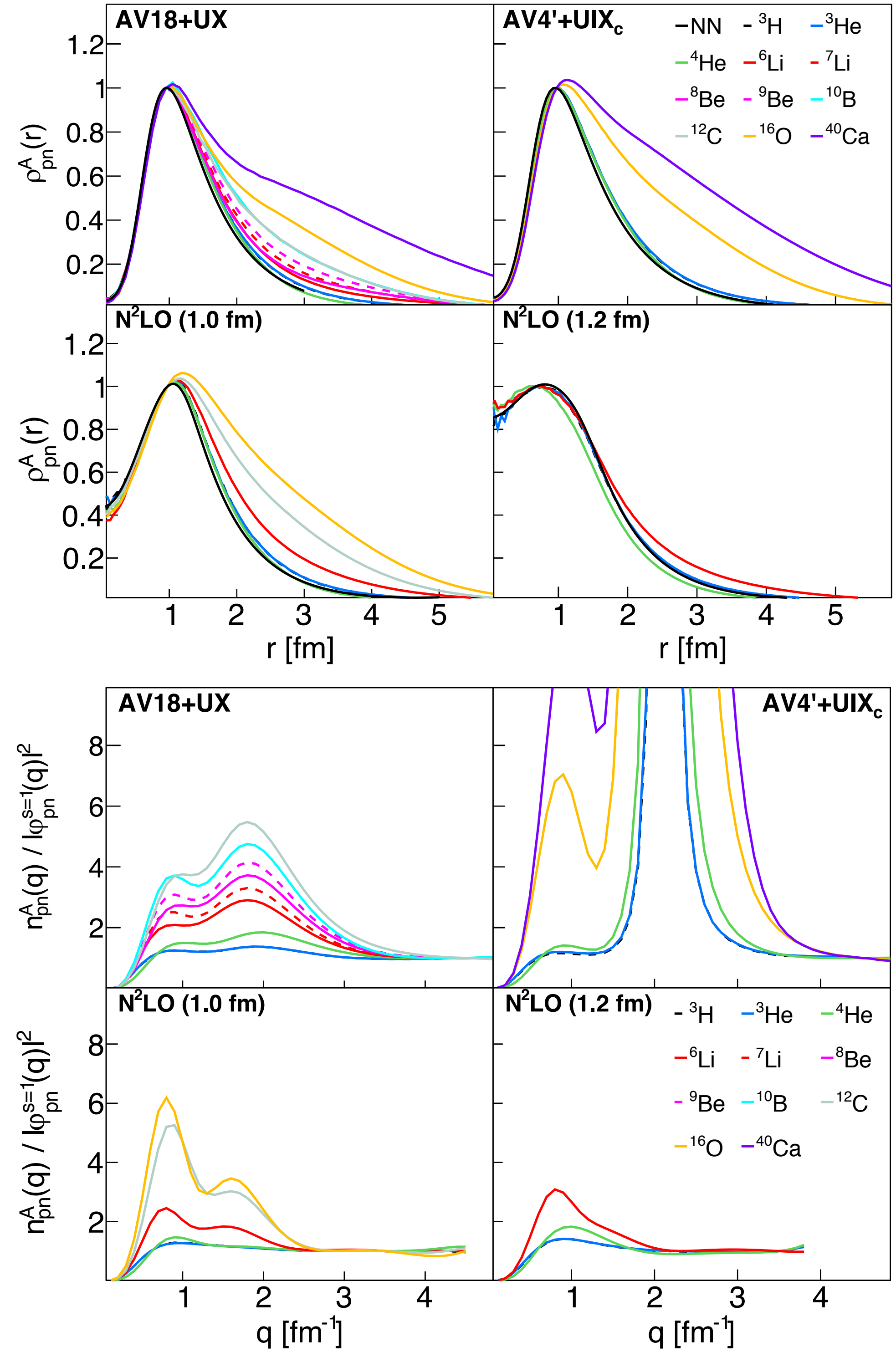
Same $C_A^{NN,\alpha}$



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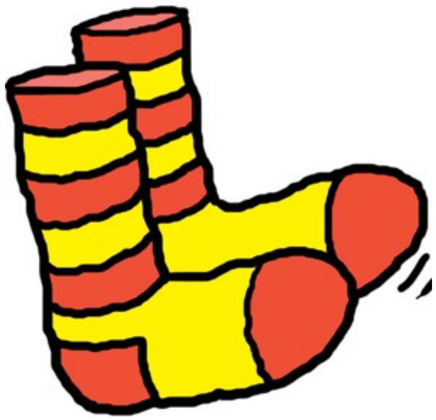
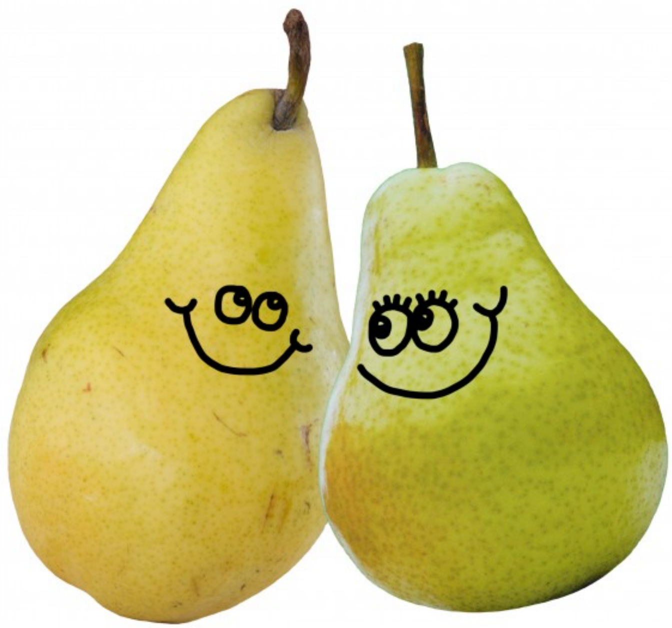


P-A-I-R-S



GCF: Pairs Spectral Functions

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

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

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\end{aligned}
$$

Each pair is convoluted with c.m. motion:

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

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

GCF: Pair Spectral Functions

$$S^p(p,\varepsilon) = C_A^{pn,\,s=1} \cdot S_{pn}^{s=1}(p,\varepsilon) + C_A^{np,\,s=0} \cdot S_{pn}^{s=0}(p,\varepsilon) + 2C_A^{pp,\,s=0} \cdot S_{pp}^{s=0}(p,\varepsilon)$$

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

GCF: Pair Spectral Functions

$$S^p(p,\varepsilon) = C_A^{pn,\,s=1} \cdot S_{pn}^{s=1}(p,\varepsilon) + C_A^{np,\,s=0} \cdot S_{pn}^{s=0}(p,\varepsilon) + 2C_A^{pp,\,s=0} \cdot S_{pp}^{s=0}(p,\varepsilon)$$

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AV18 / N2LO / … Measured

Available for Carbon

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

Probing the NN Interaction

What's needed?

✓ Plane-wave \w spectral fns from *NN* interaction

- Data in kinematics where plane-wave works

The Data

2004 5.016 GeV EG2 data

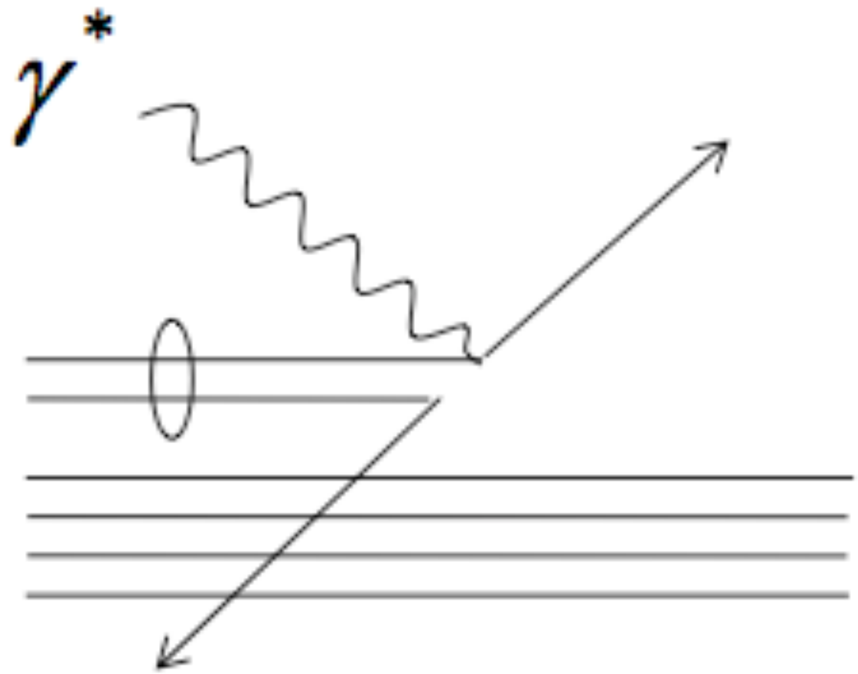
d, **C**, Al, Fe, Pb targets

- $Q^2 > 1.5$ GeV^2
- $x_B > 1.2$
- Leading proton:
  - $\theta_{pq} < 25°$,
  - $\frac{p_N}{q} > 0.6$,
  - $400 \leq p_{miss} \leq 1000$ MeV/c
- Recoil proton:
  - $p_R > 350$ MeV/c

Identical data used in

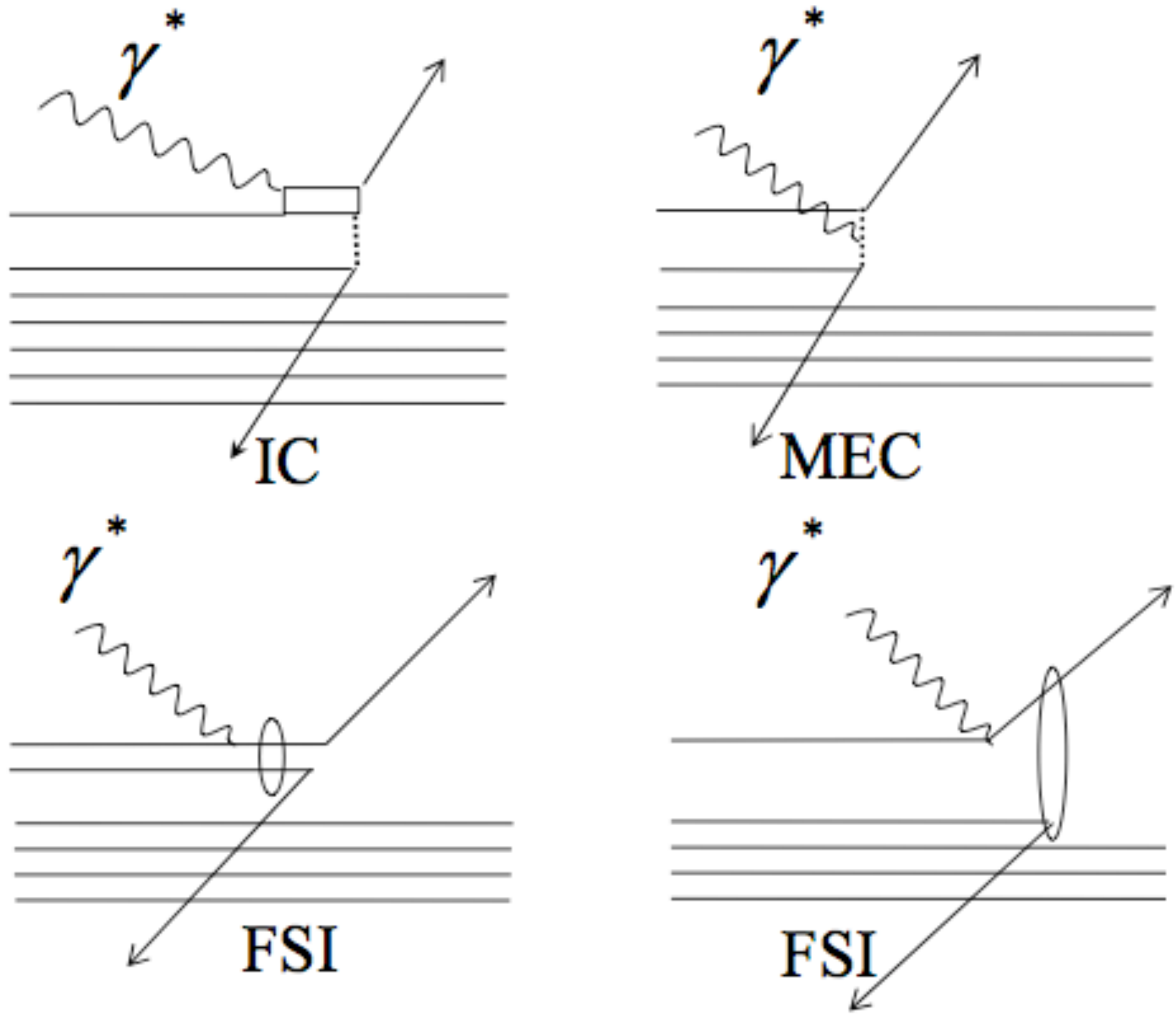
- O. Hen (CLAS), Science **346,** 614 (2014)
- M. Duer (CLAS), Nature **560**, 617 (2018)
- E. Cohen (CLAS), PRL **121**, 092501 (2018)
- M. Duer (CLAS), PRL **122**, 172502 (2019)

Two-Nucleon Knockout (Plane Wave)

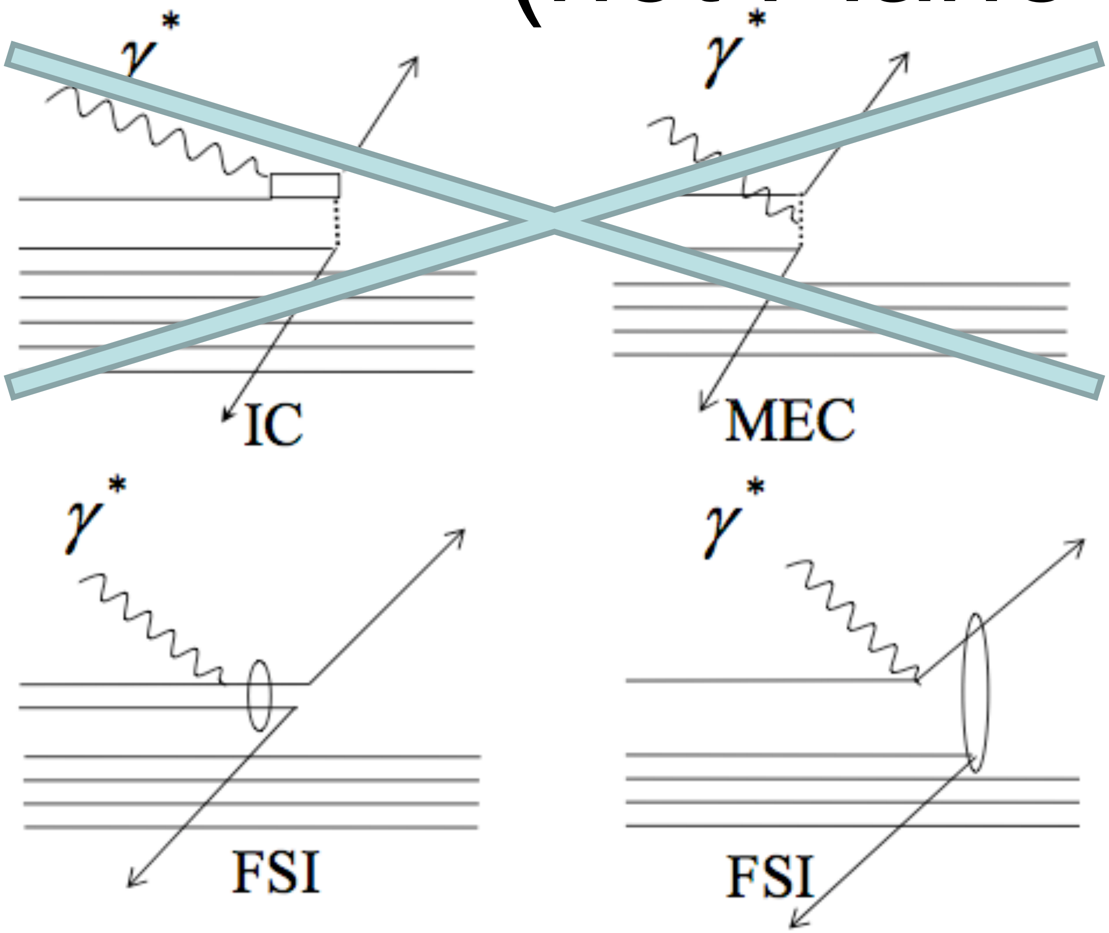


SRC

Two-Nucleon Knockout (not Plane Wave)



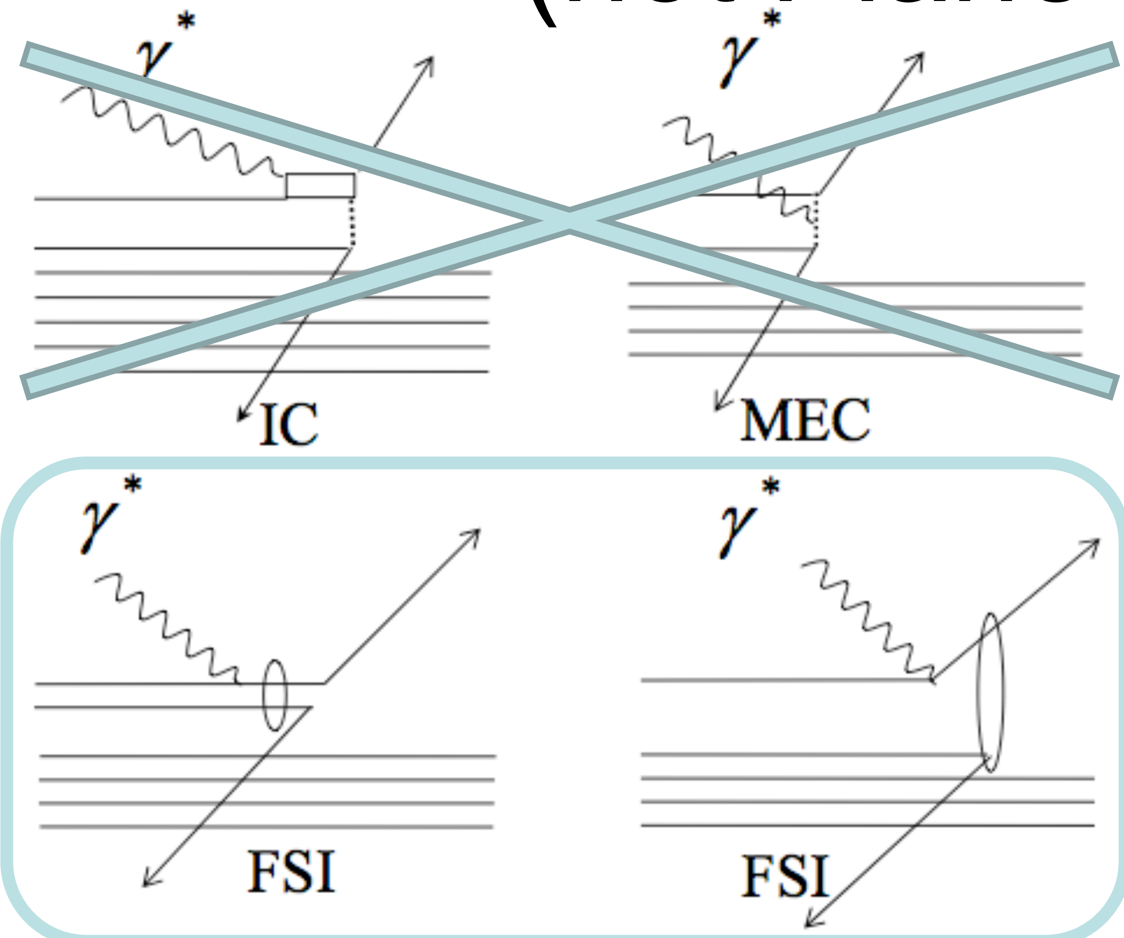
Two-Nucleon Knockout (not Plane Wave)



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 (not Plane Wave)



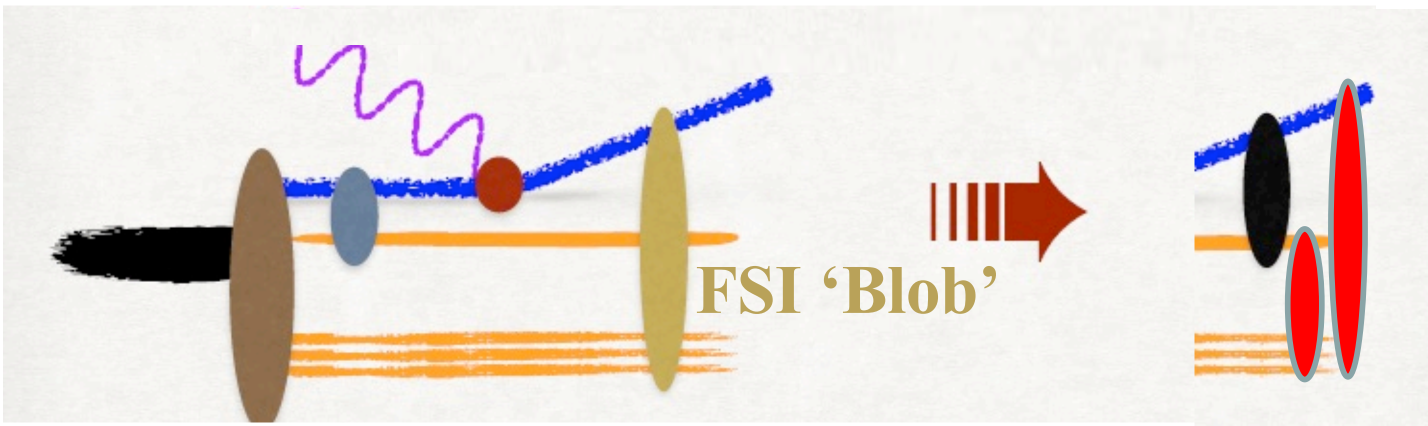
MEC suppressed @ **high-Q^2**, IC suppressed at **$x_B > 1$.**

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

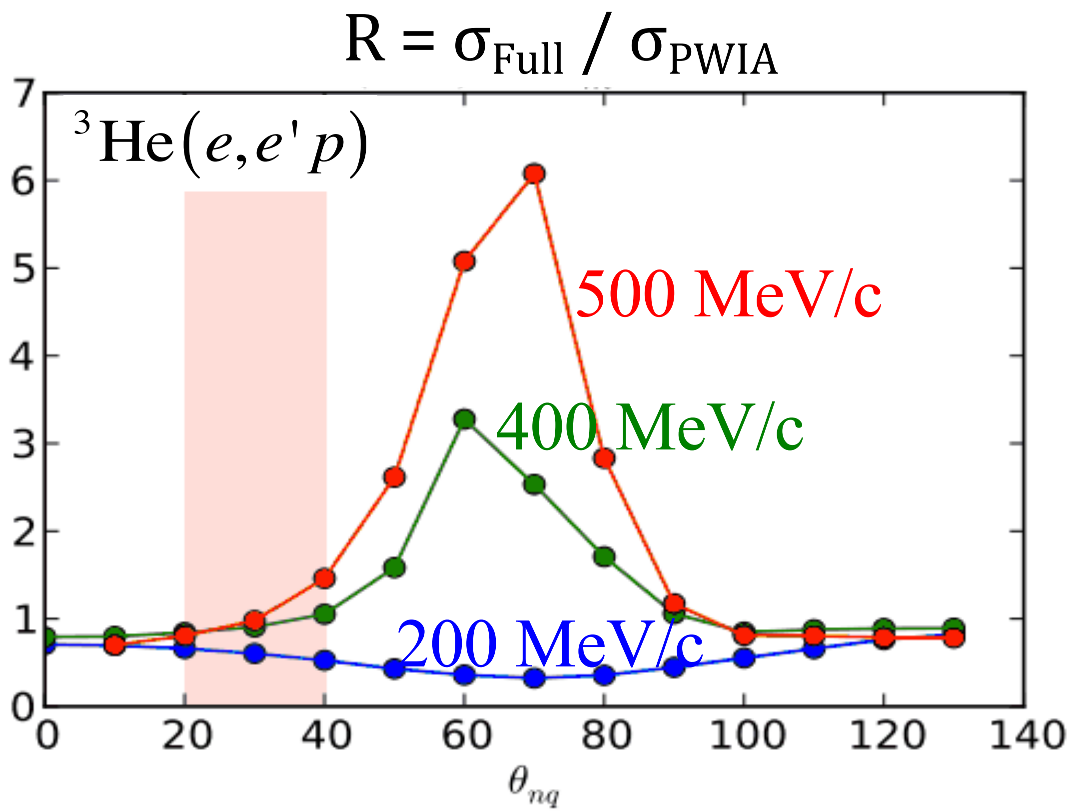
For large Q^2, x>1

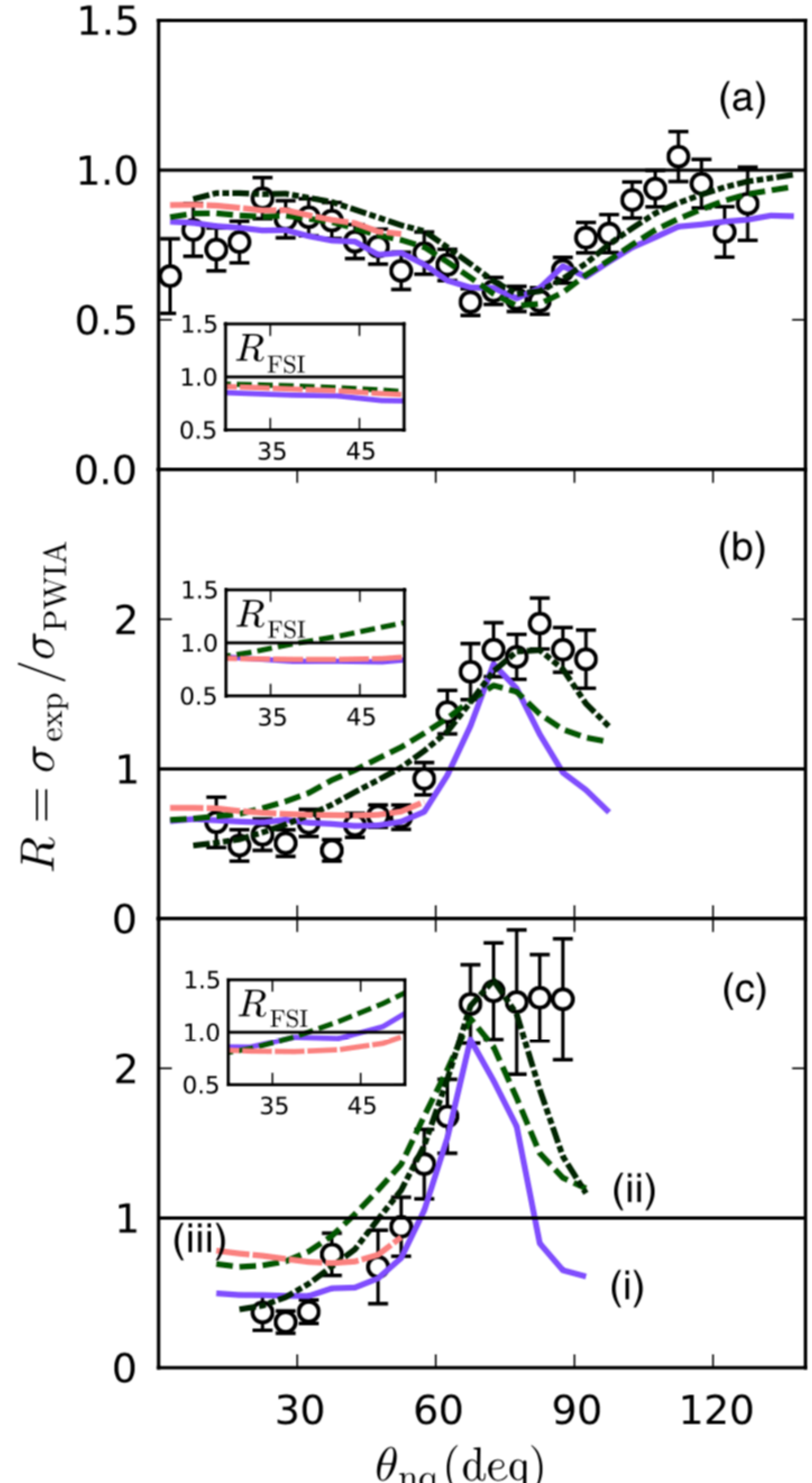


Pair rescattering:
Minimize by choosing correct kinematics

Attenuation:
Calculate using Glauber.

Pair Rescattering

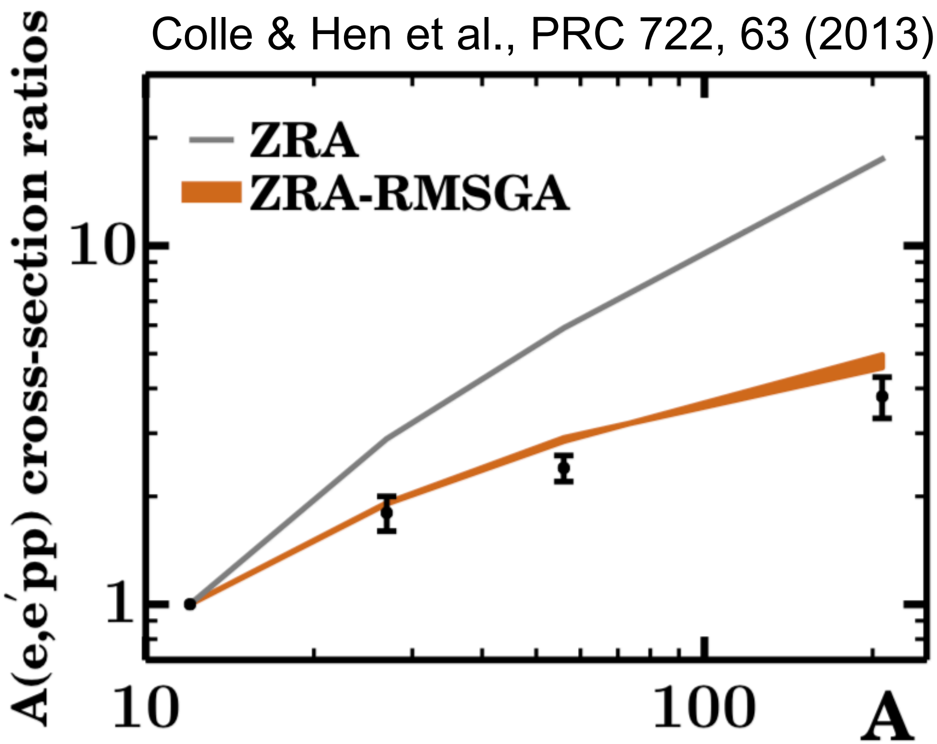


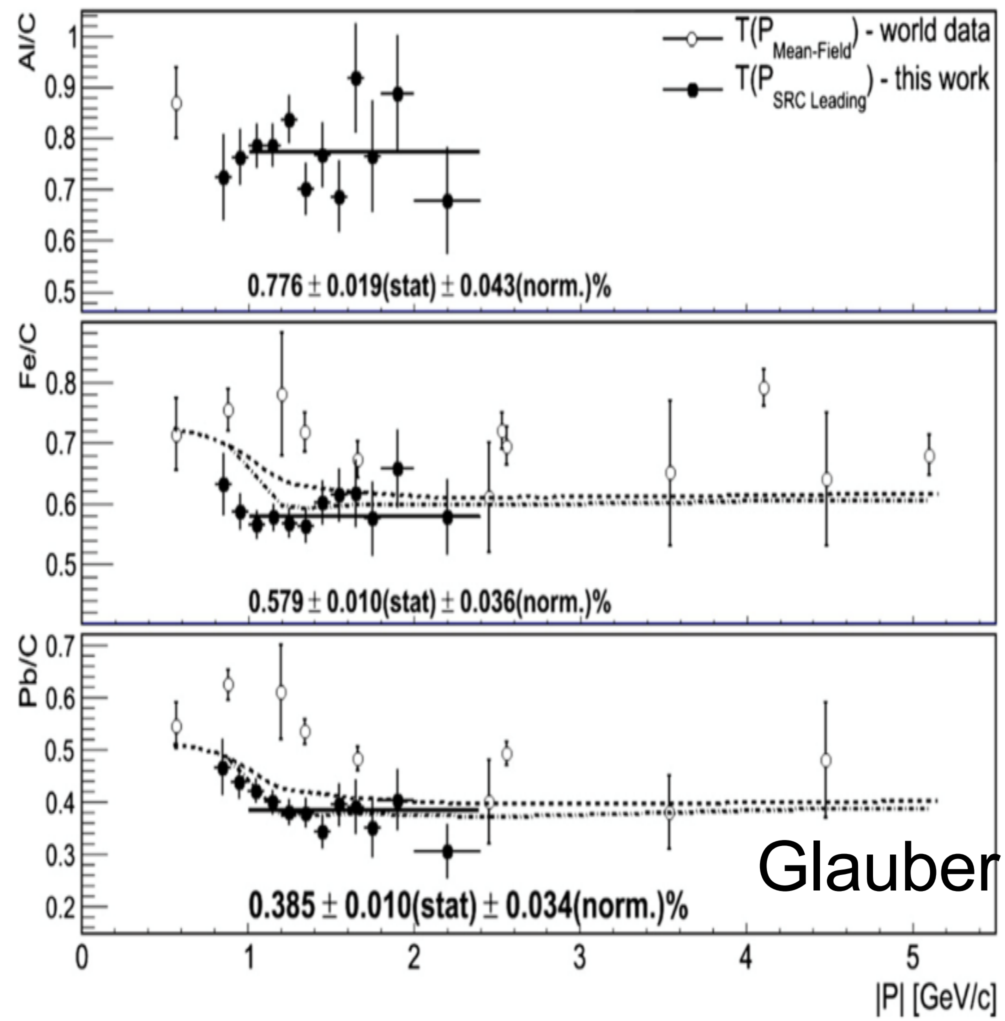


M. Sargsian; Boeglin PRL (2011).

Attenuation: Glauber

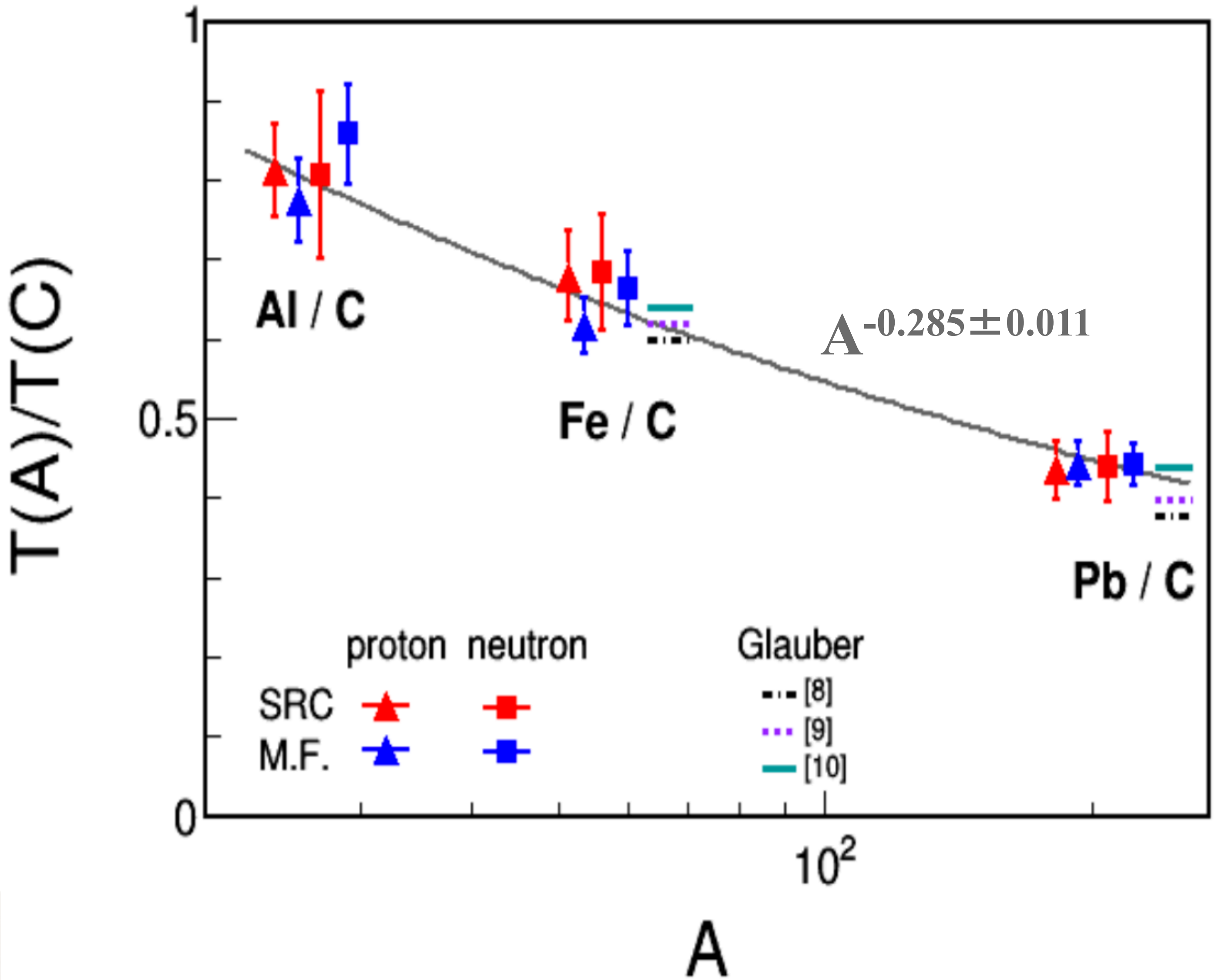
Colle & Hen et al., PRC 722, 63 (2013)





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

Attenuation: Glauber



M. Duer et al., submitted (2018)

Probing the NN Interaction

What's needed?

✓ Plain-wave \w spectral fns from NN interaction

✓ Data in kinematics where plane-wave works

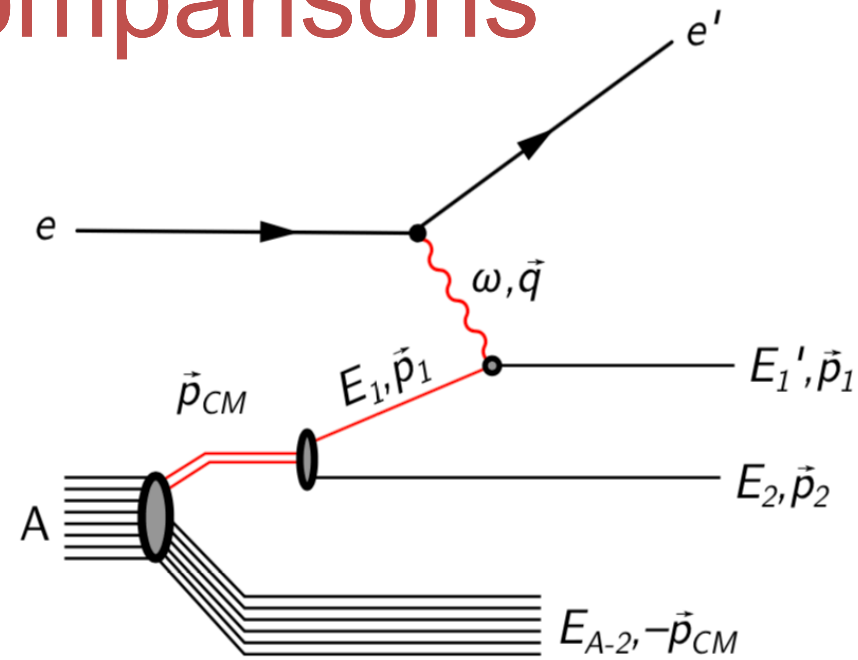
Theory-Data Comparisons

Usually correct data for detector acceptance and reaction mechanism effects and then compare to theory.

Corrected data is model dependent.

We instead will correct the theory.

Theory-Data Comparisons



- Generate PWIA A(e,e'NN) events.
- Run through detector simulation.
- Weigh by GCF cross-sections + reaction effects (transparency & single charge exchange)
- Apply event selection cuts

& overlay on data.

Theory-Data Comparisons

- Generate PWIA A(e,e'NN) events.
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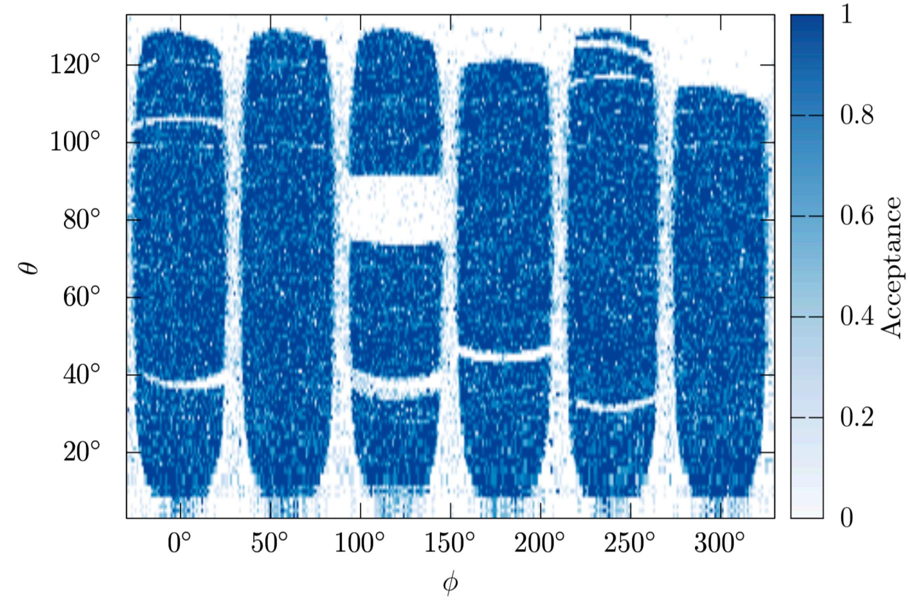


Single particle acceptance maps and resolution smearing

Theory-Data Comparisons

- Generate PWIA A(e,e'NN) events.
- Run through detector simulation.
- Weigh by GCF cross-sections + reaction effects (transparency & single charge exchange)

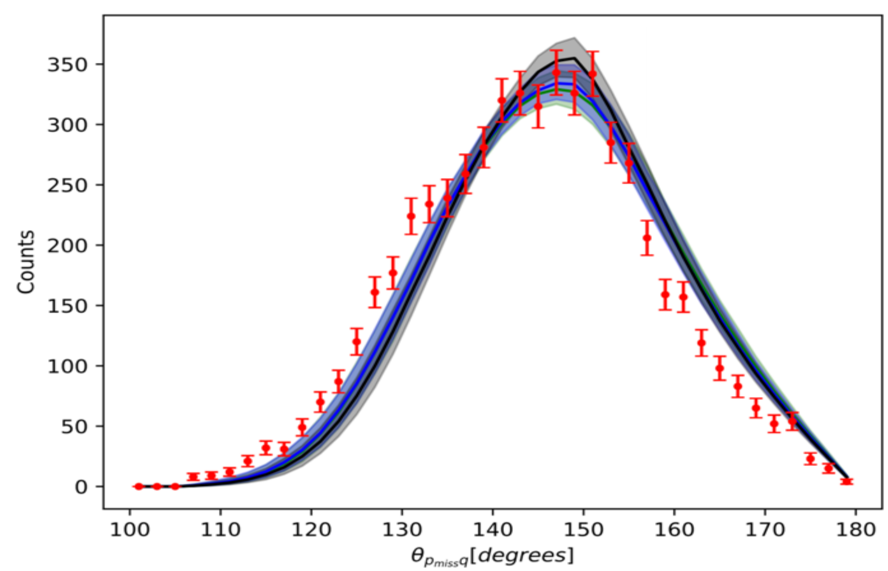
$$\frac{d^4\sigma}{d\Omega_{k'} d\epsilon'_k d\Omega_{p'_1} d\epsilon'_1} = p'_1 \epsilon'_1 \sigma_{eN} S^N(\boldsymbol{p}_1, \epsilon_1)$$

- Apply event selection cuts & overlay on data.

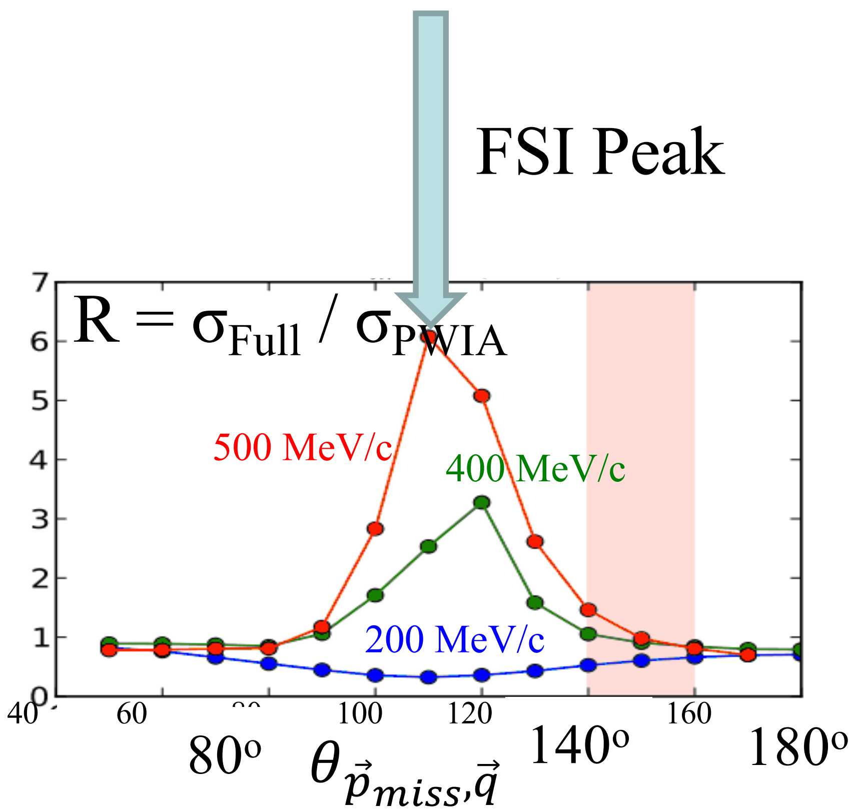
Theory-Data Comparisons

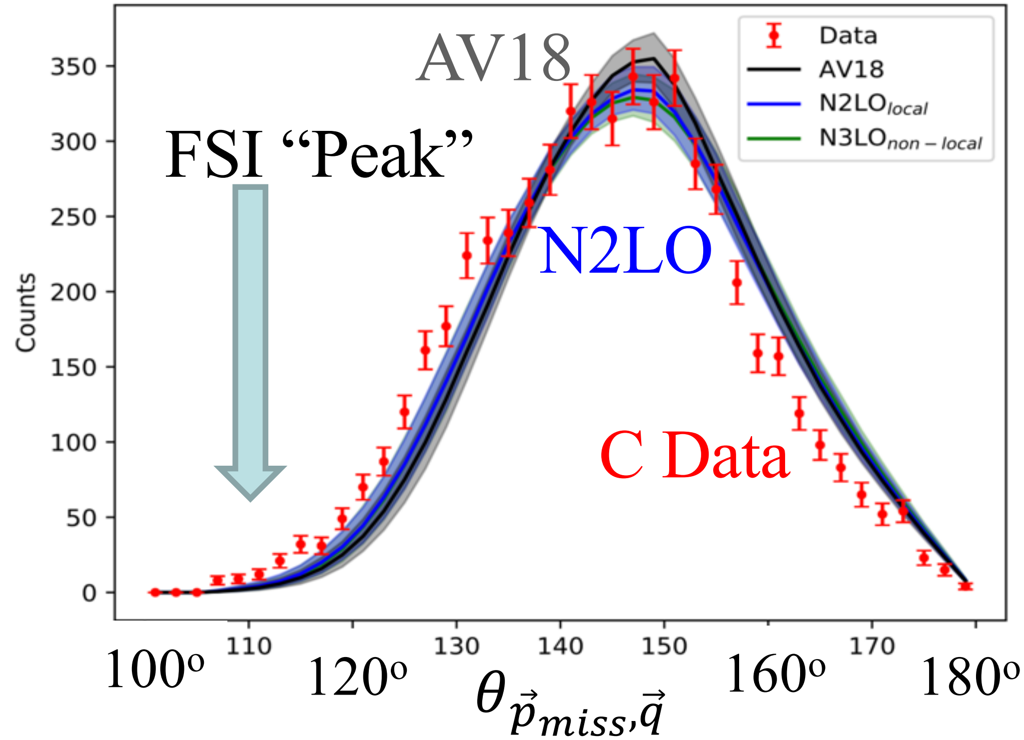
- Generate PWIA A(e,e'NN) events.
- Run through detector simulation.
- Weigh by GCF cross-sections + reaction effects (transparency & single charge exchange)
- Apply event selection cuts

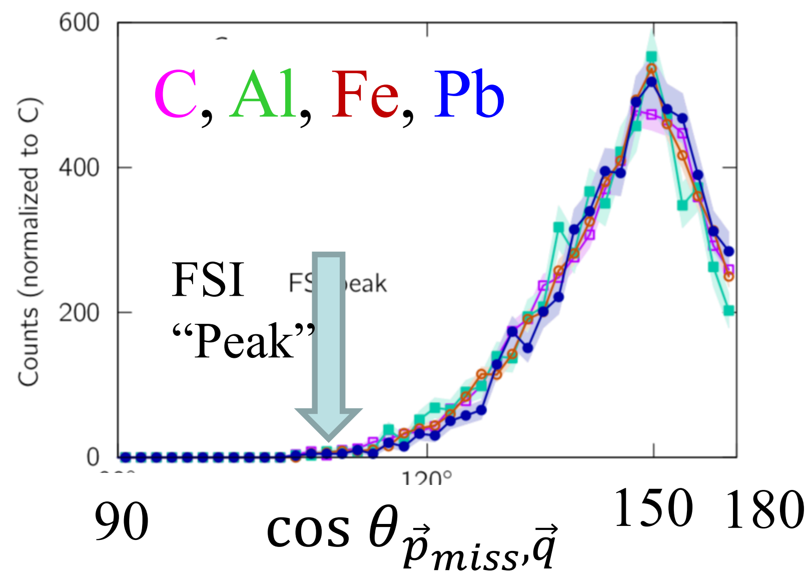
& overlay on data.



No evidence of FSI enhancements

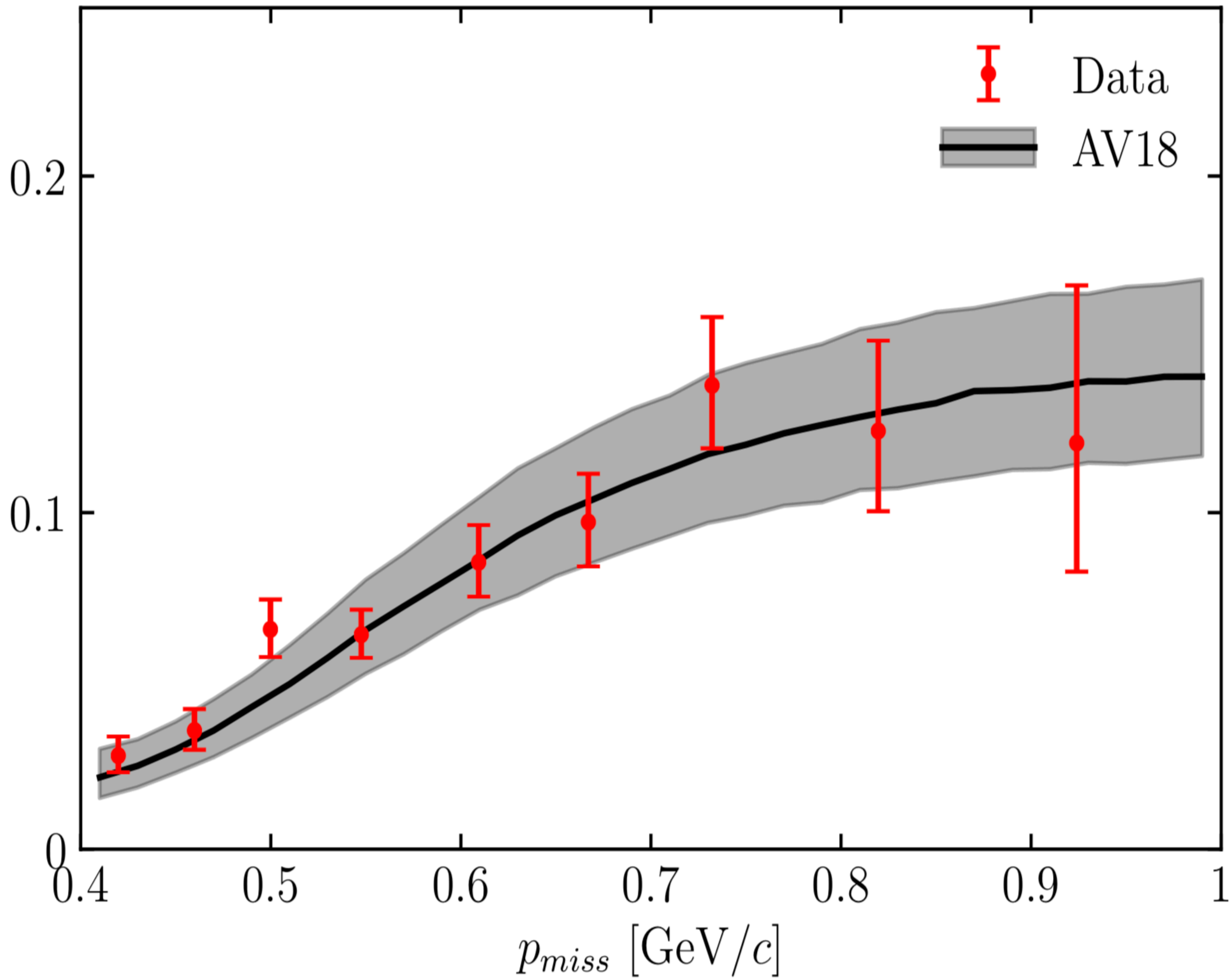






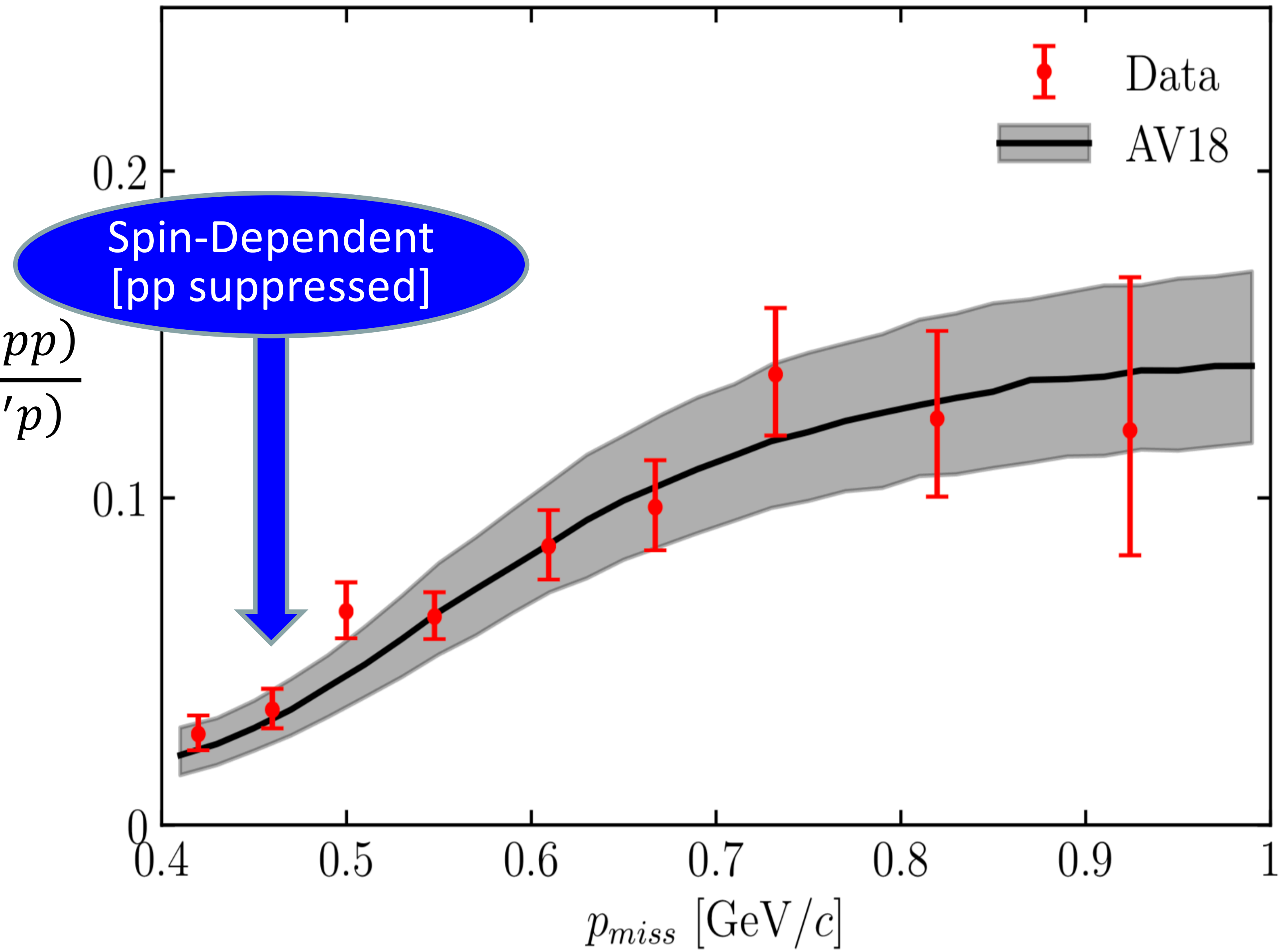
Reaching the Repulsive Core

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



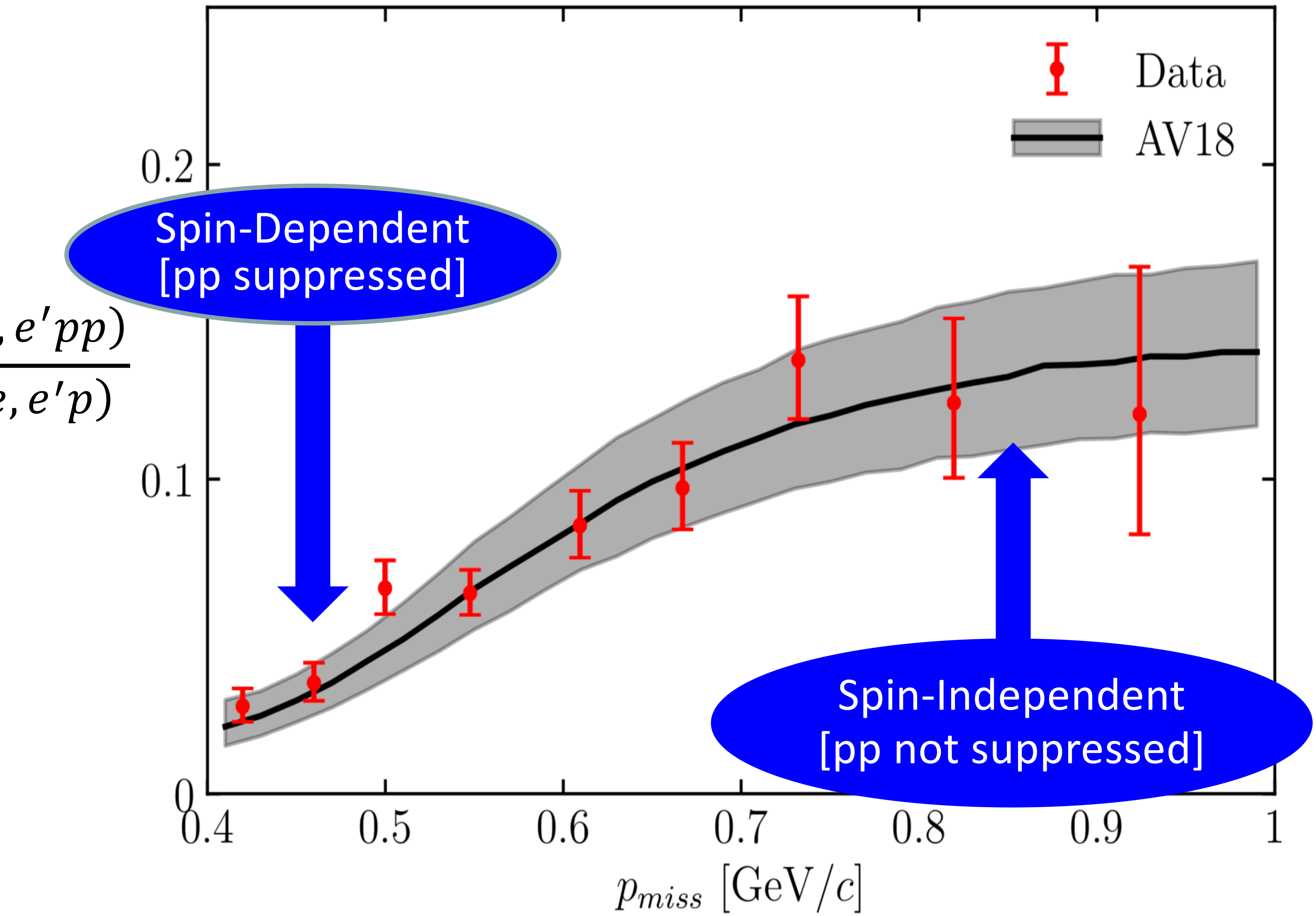
A. Schmidt

Reaching the Repulsive Core



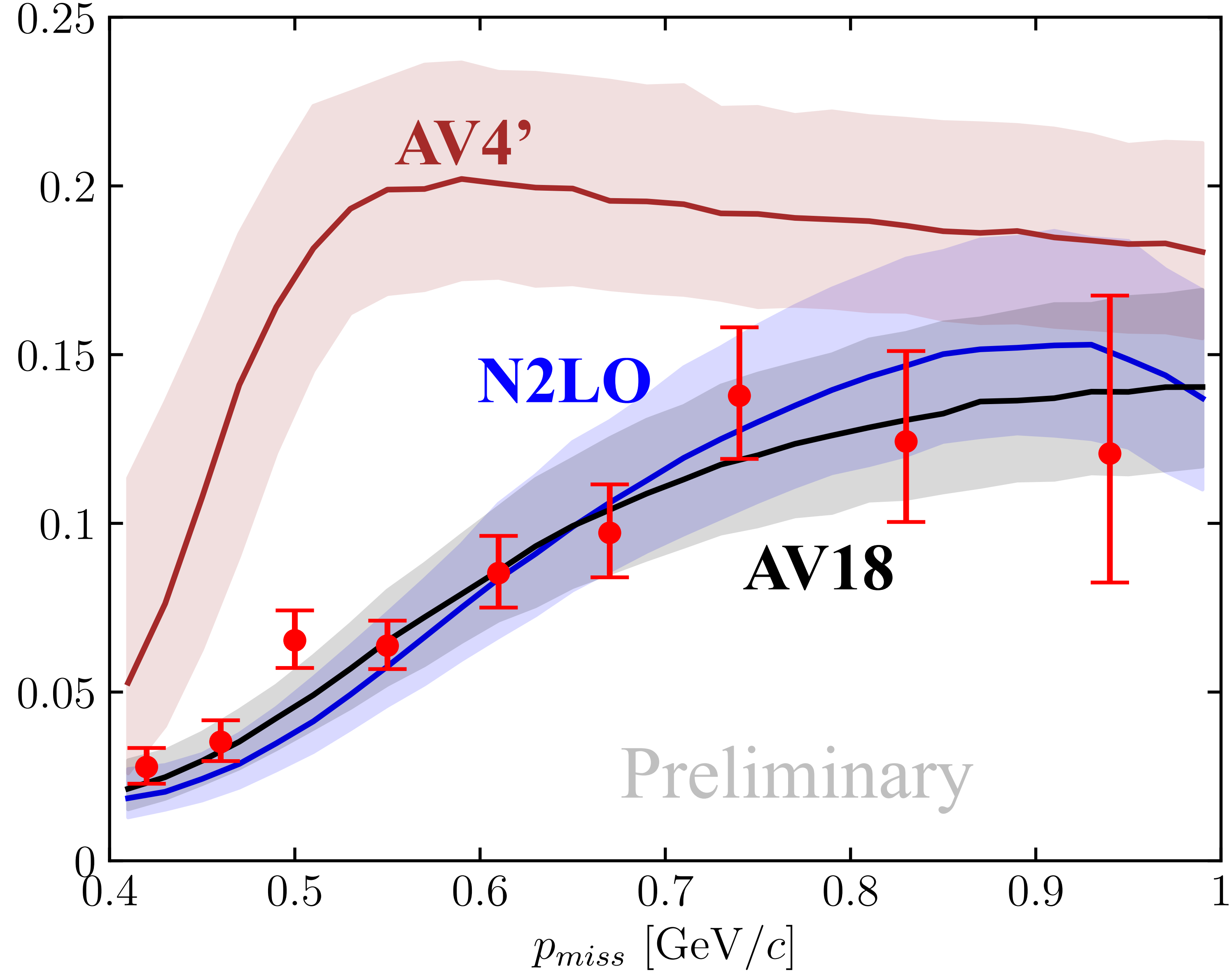
A. Schmidt

Reaching the Repulsive Core



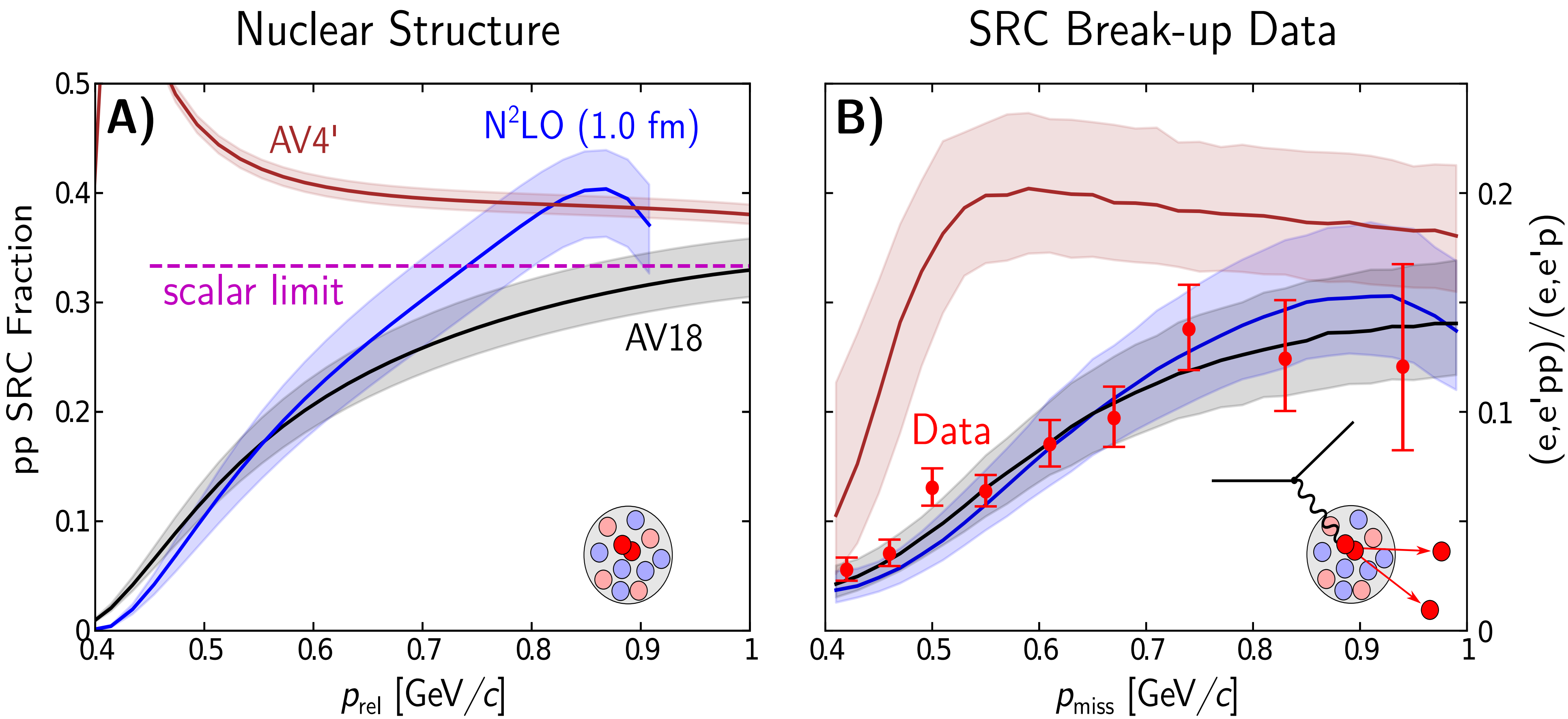
A. Schmidt

Reaching the Repulsive Core



A. Schmidt

Reaching the Repulsive Core

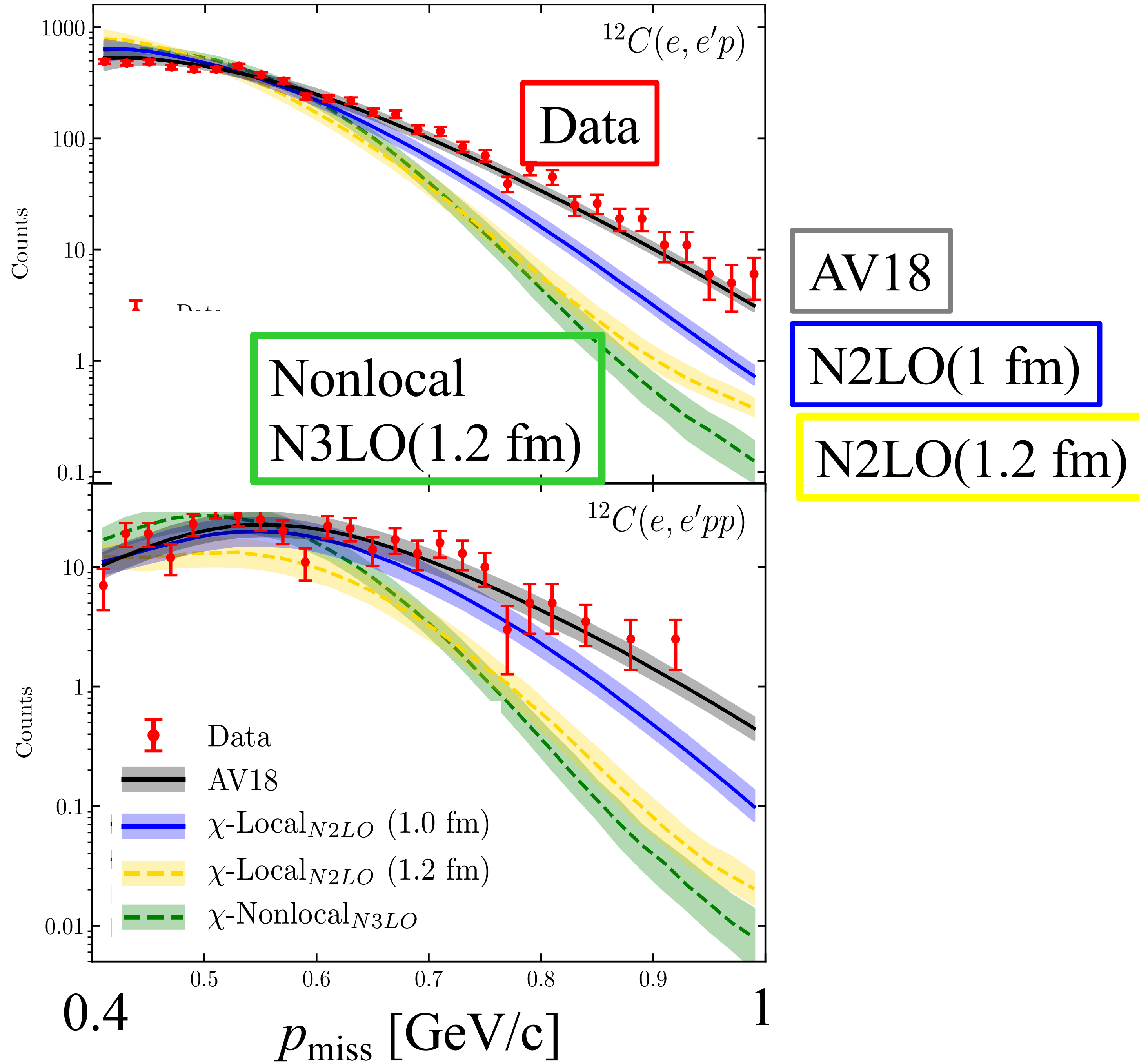


A. Schmidt

Reaching the Repulsive Core

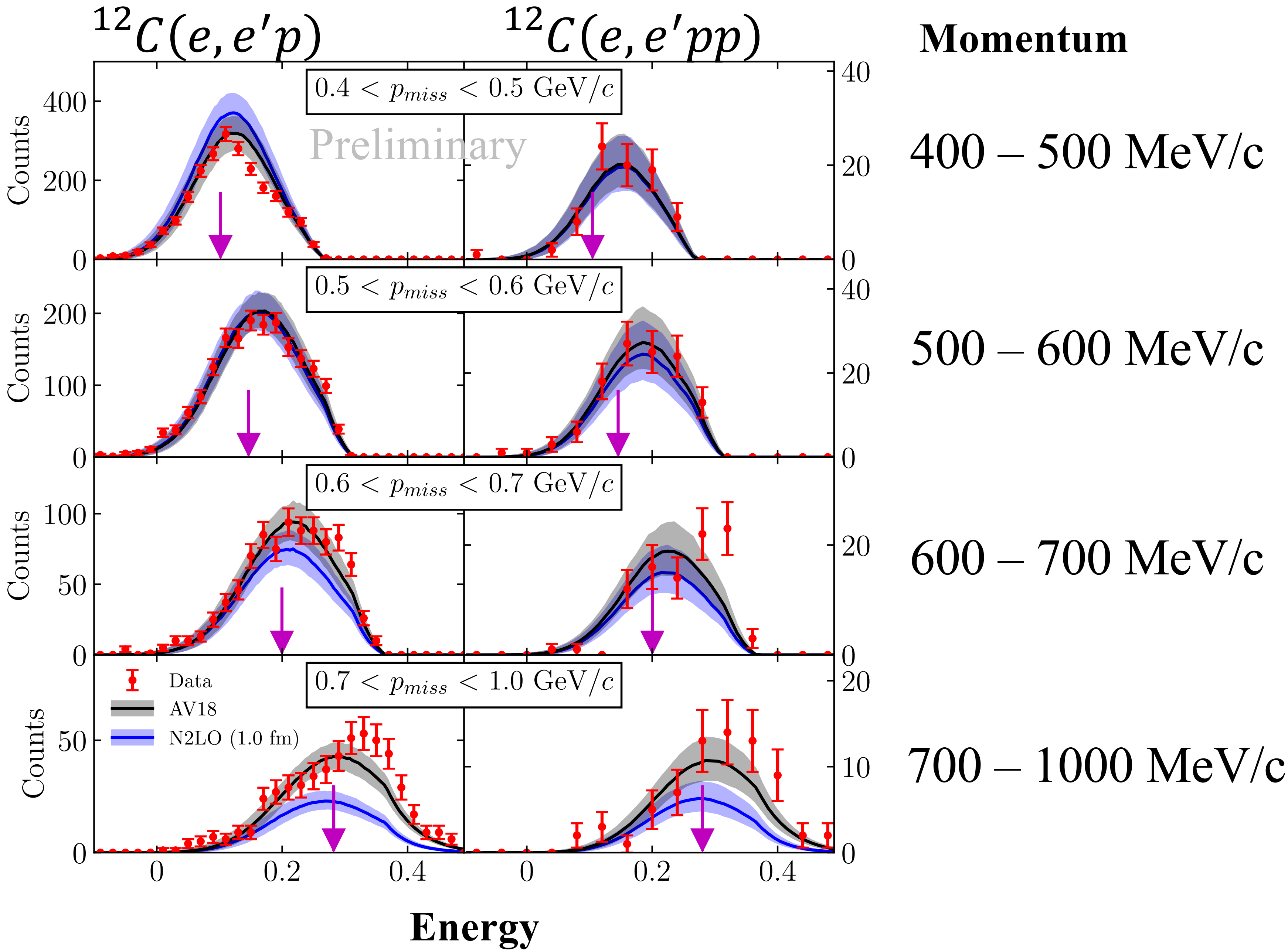
^{12}C(e,e'p)

^{12}C(e,e'pp)



A. Schmidt

GCF Spectral Function Works!



Summary

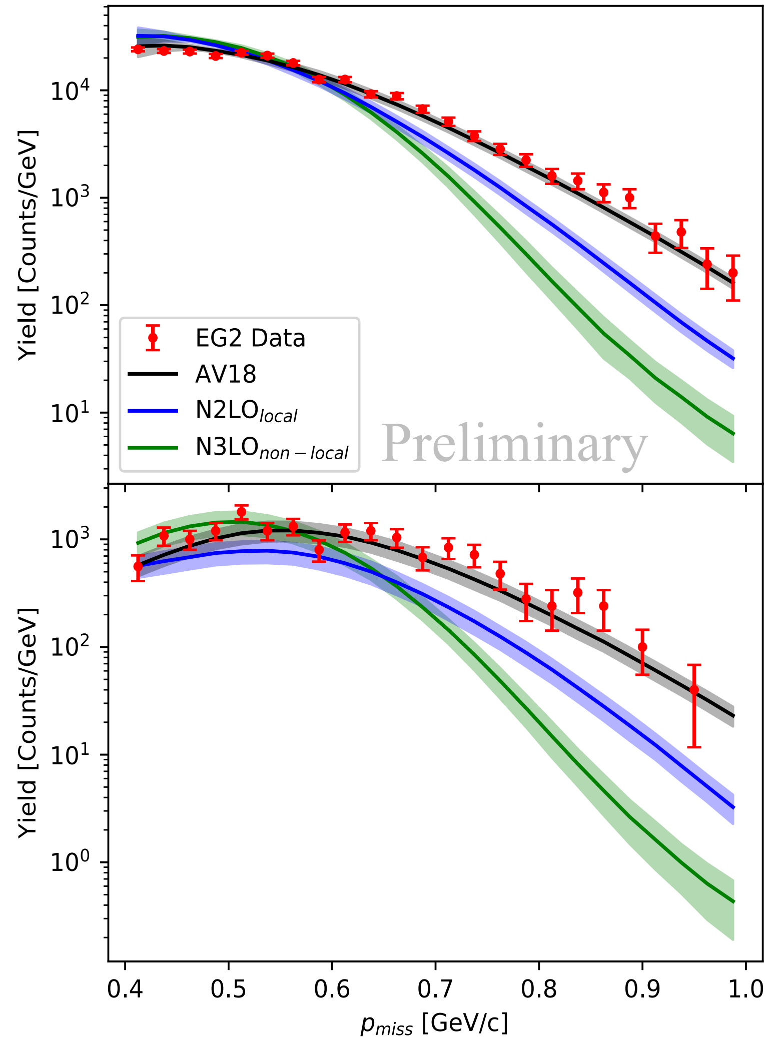
Nuclear momentum distribution has two distinct regions

- ➢ Scale separation

Describe the high momentum region with the Generalized Contact Formalism

- ➢ GCF describes (e,e'p) and (e,e'pp) data remarkably well up to 1000 MeV/c
- ➢ transition from tensor to scalar part of NN interaction
- ➢ Tests of NN interactions

Paper approved for CLAS Review 6/20



See Axel Schmidt's NPPWG talk for more details