Theoretical advancements in the study of short-range correlations

Ronen Weiss

Washington University in St. Louis

2025 JLUO Annual Meeting, June 24, 2025

SRC - Theory

- Understanding **the impact of short-range physics** on observables
- **Validate theories** against experimental data: **Structure + Reaction** (nuclear interactions, PWIA, FSI, factorization…)
- Studies of **relativistic effects**, **non-nucleonic degrees of freedom**, medium modifications, …
- …

Methods:

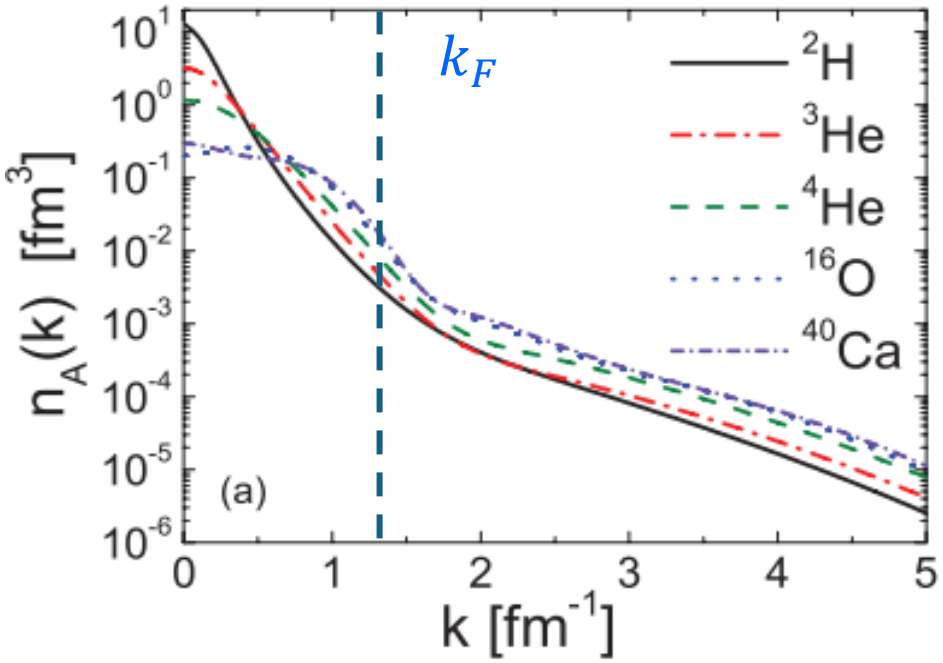
Ground-state ab-initio calculations	Approximated factorized approaches	Studies of few-body systems	QMC for reactions	• • •

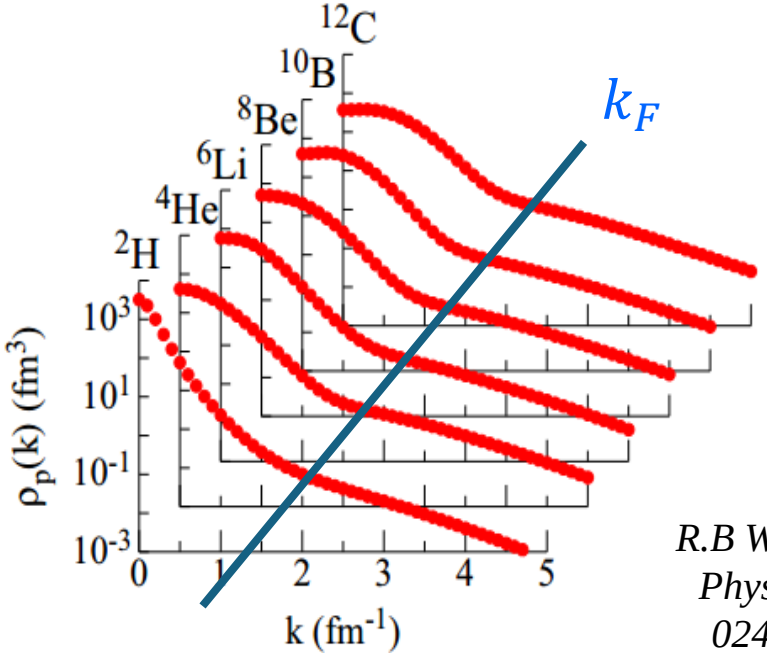
Ab-initio calculations

- Calculations based on **exact solution** of the Schrodinger equation
- Learn about **main SRC features**

- **Light-medium** nuclei ($A \leq 40$)
- **Ground-state quantities** (e.g., mom. distributions)
- **Limited comparison to data**

Ab-initio calculations



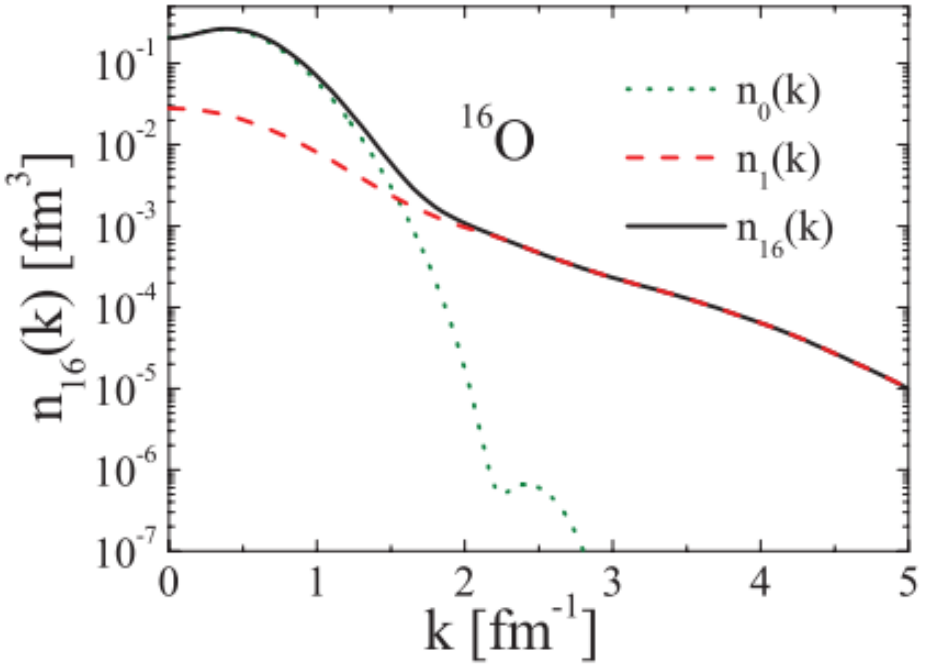


R.B Wiringa et. al., Phys. Rev. C 89, 024305 (2014)

High-momentum tails

Similar shapes

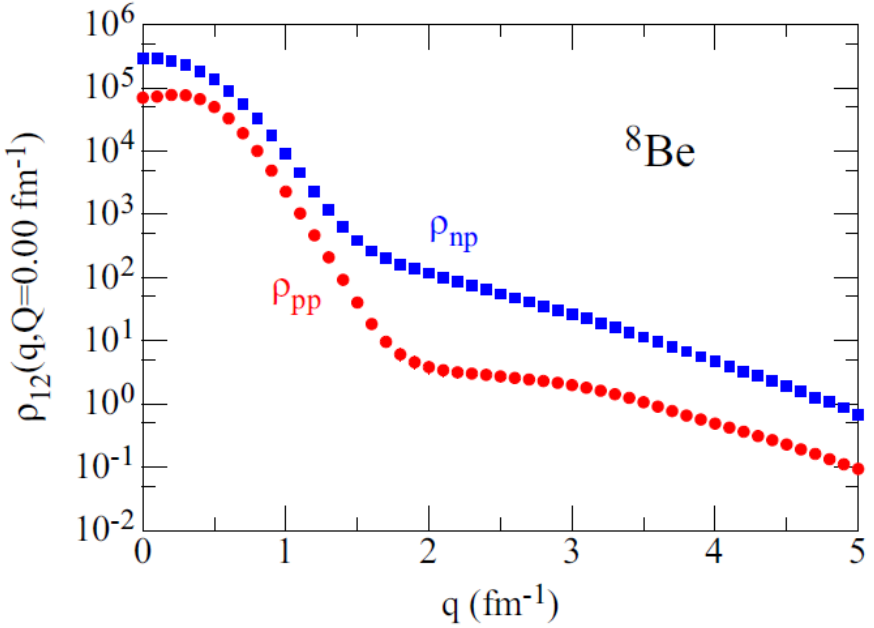
contribution from excited $A-1$ system



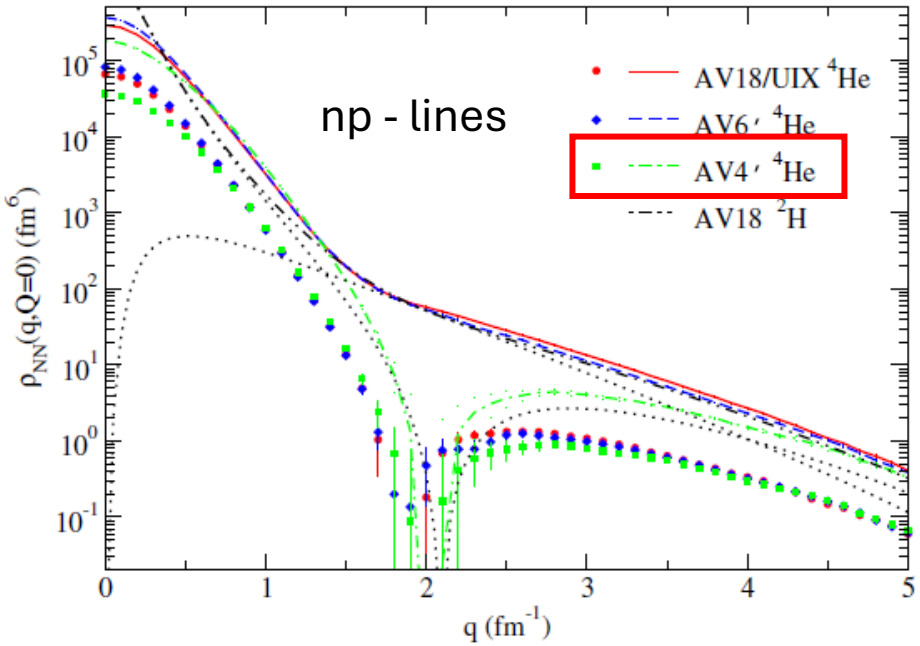
M. Alvioli et al. PRC 87, 034603 (2013)

Ab-initio calculations

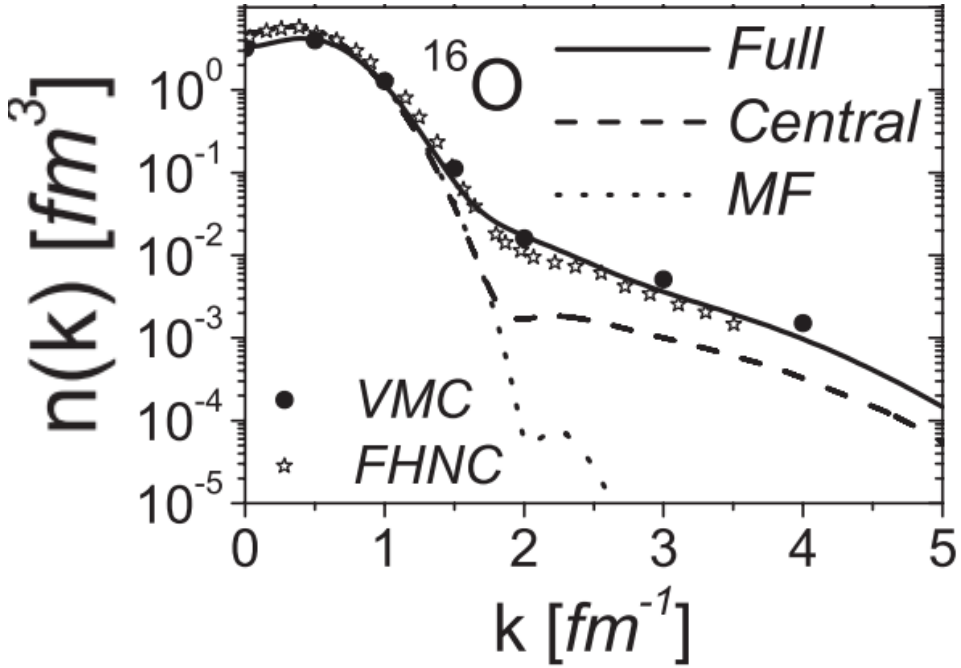
np dominance & tensor force



R.B Wiringa et. al., Phys. Rev. C 89, 024305 (2014)



R. Schiavilla et al. PRL 100, 162503 (2008)

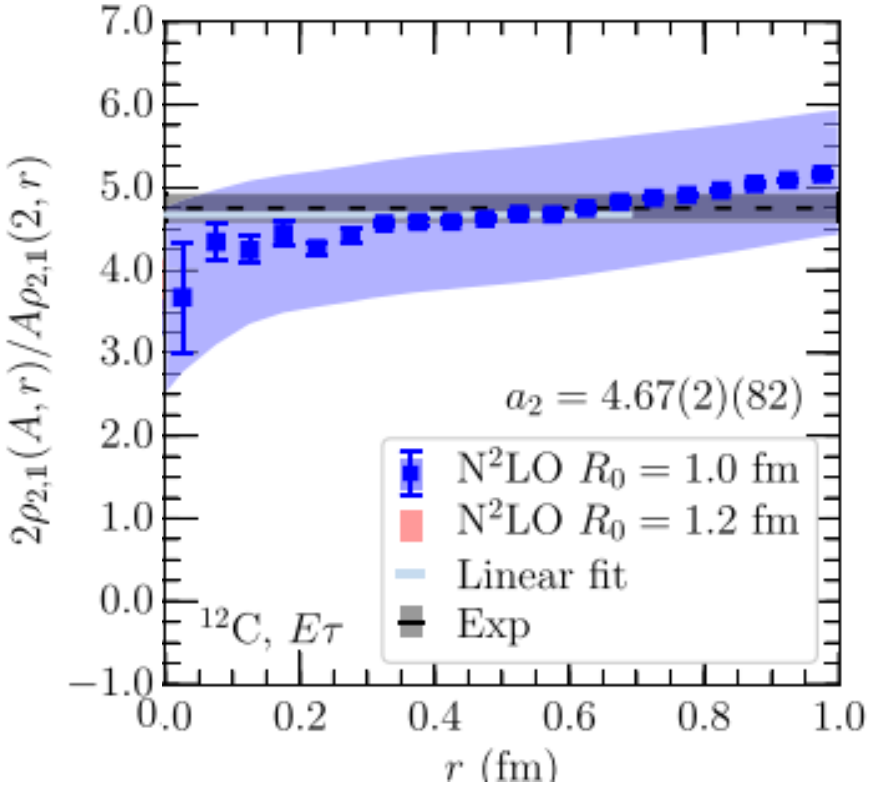


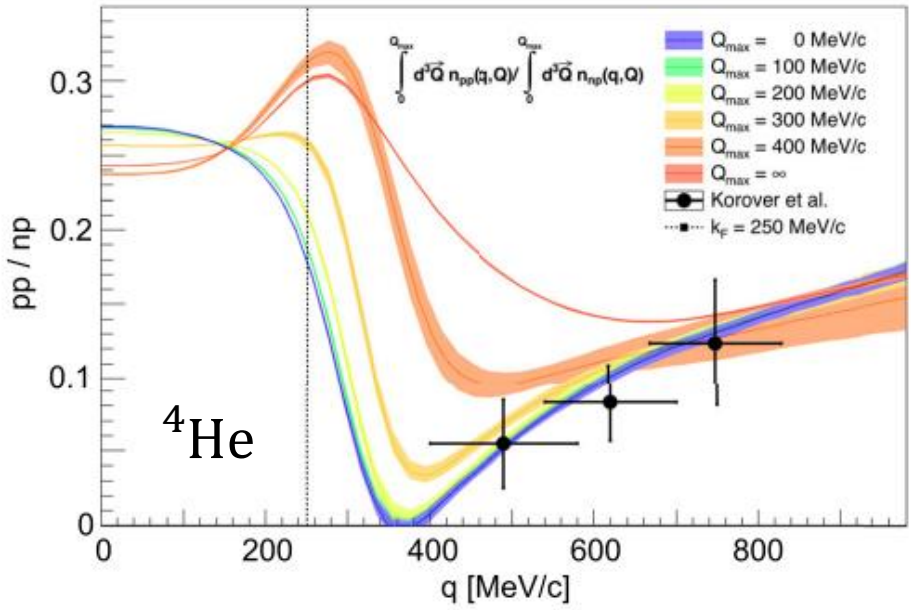
M. Alvioli et al. PRL 100, 162503 (2008)

Ab-initio calculations

Comparison to data

Lynn et al, J. Phys. G: Nucl. Part. Phys. 47 045109 (2020)



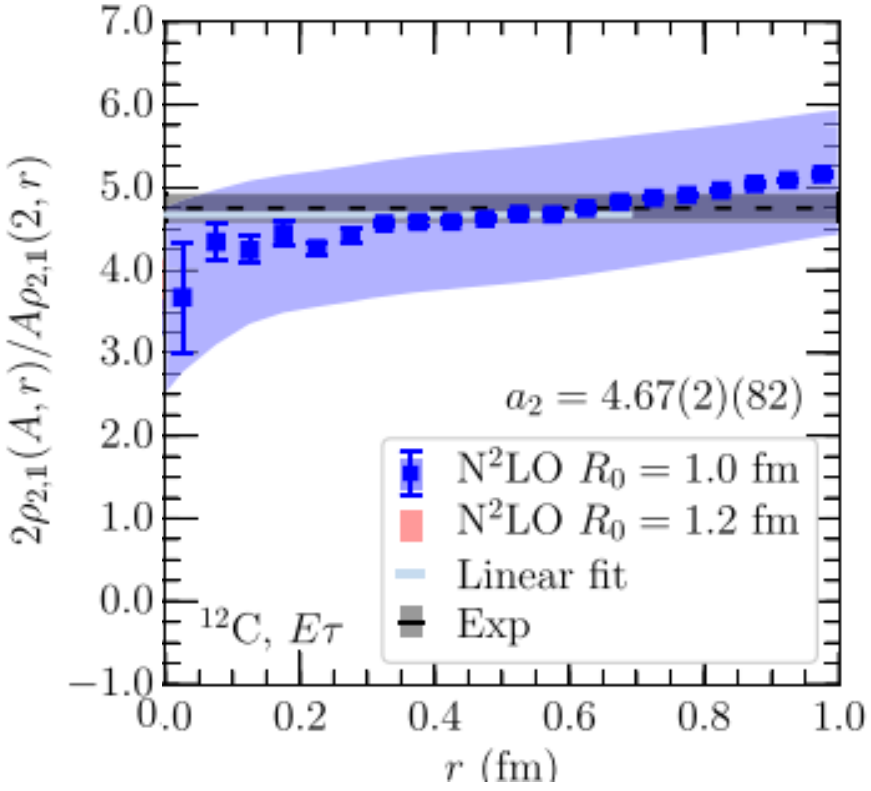


Data: Korover et al., 2014, Calculations: Wiringa et al., 2014, Figure: Hen et al., 2017

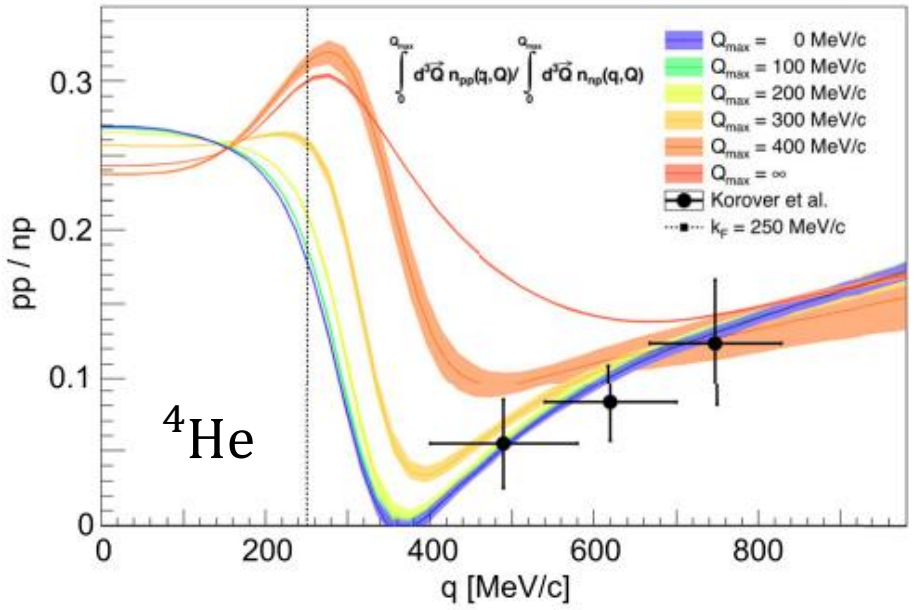
Ab-initio calculations

Comparison to data

Lynn et al, J. Phys. G: Nucl. Part. Phys. 47 045109 (2020)



- How do we describe **heavier nuclei**?
- Description of **reaction cross sections**?



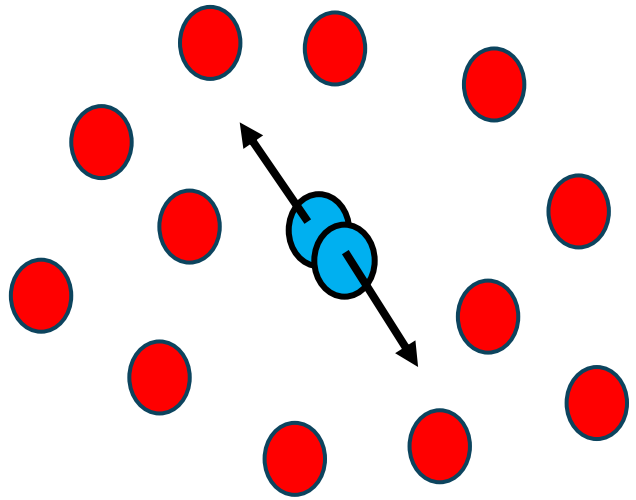
Data: Korover et al., 2014, Calculations: Wiringa et al., 2014, Figure: Hen et al., 2017

Factorized methods

SRC ground-state factorization: $\Psi \rightarrow \varphi_2 \Phi_{A-2}$

Various methods:

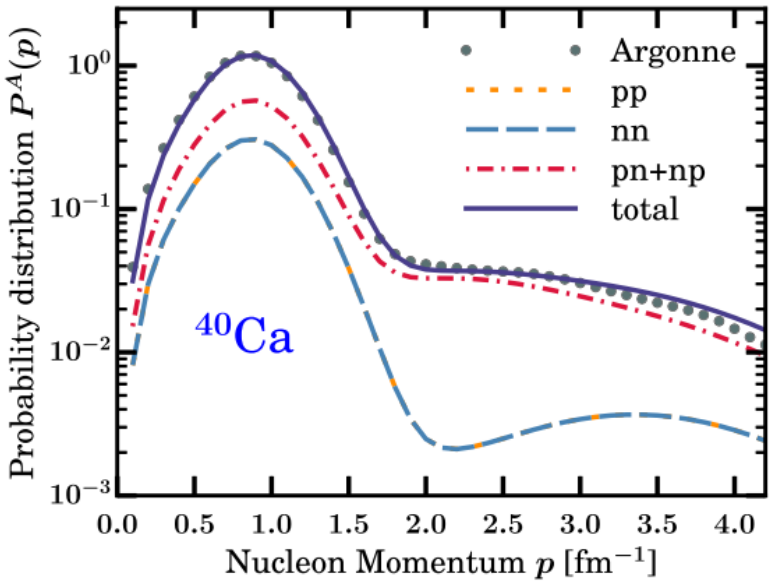
- **Spectral function models** (convolution model: degli Atti, Simula, Frankfurt, Strikman; model by Benhar; Rocco, Lovato…)
- **LCA method** (Ryckebusch, Cosyn,…)
- **RG methods** (Tropiano, Bogner, Furnstahl)
- **GCF** (Barnea, Bazak, Weiss)
- **…**

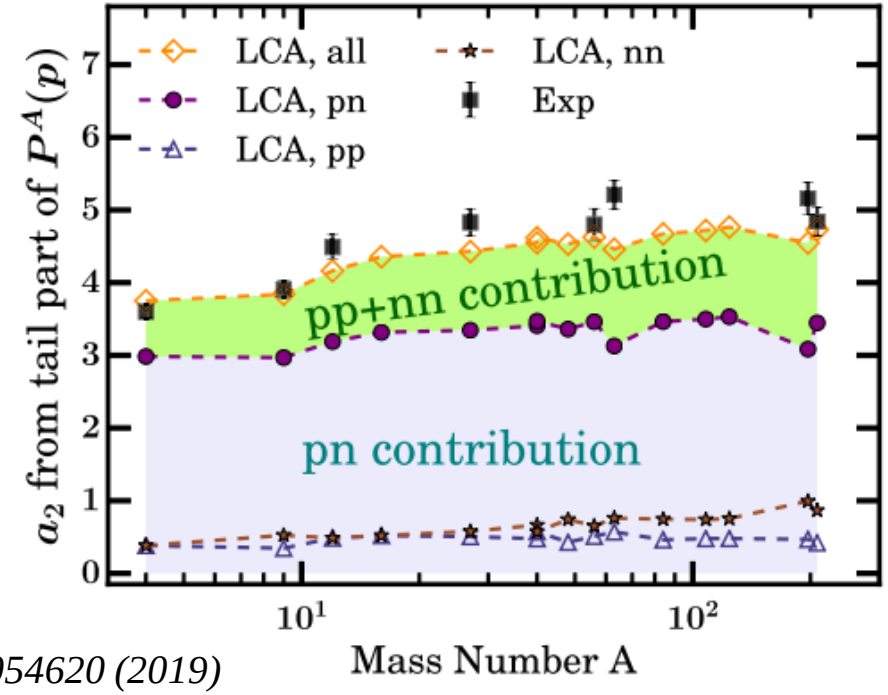


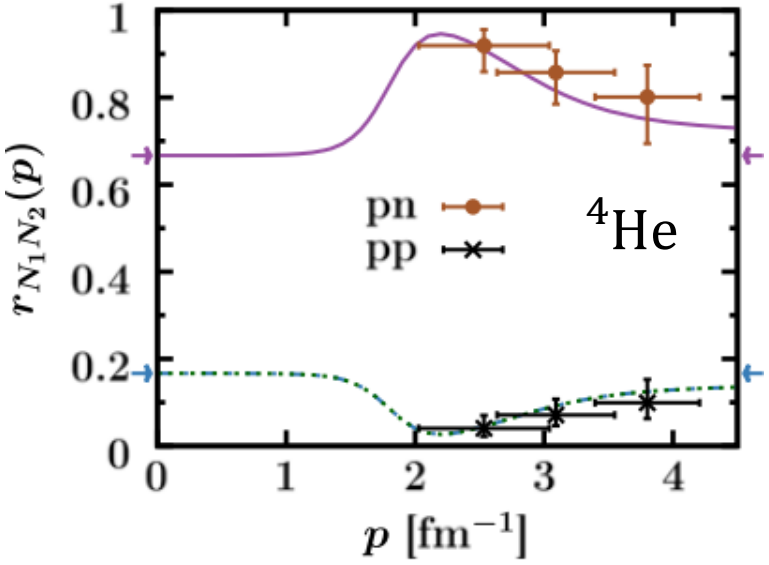
Factorized methods

Lowest-order correlation operator approximation (LCA):

Ground state = correlation operators × mean-field state $|\Psi\rangle \sim g|\Phi\rangle$







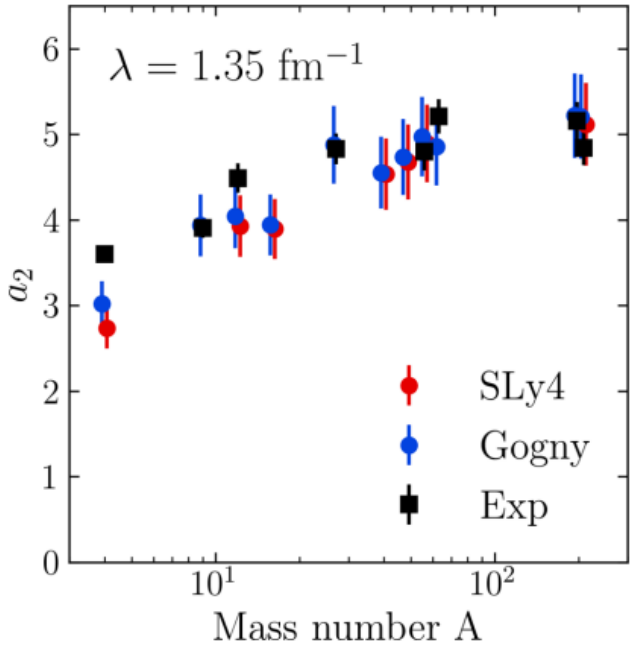
Ryckebusch, et al., *PRC 100, 054620 (2019)*

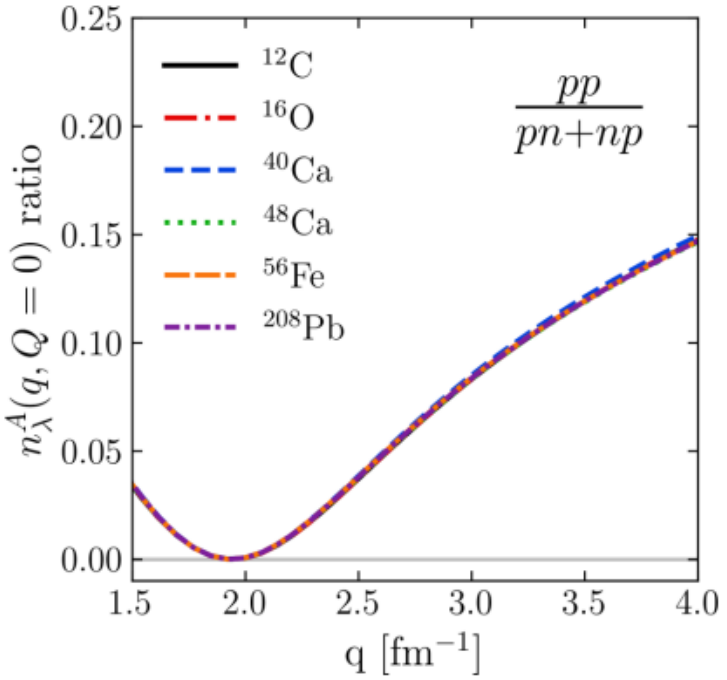
Ryckebusch et al, J. Phys. G: Nucl. Part. Phys. 42, 055104 (2015)

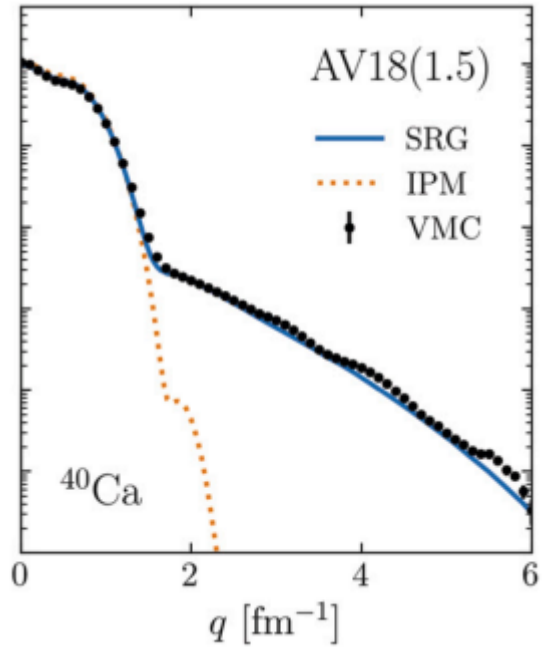
Factorized methods

Similarity renormalization group:

$$\langle \Psi | \hat{O} | \Psi \rangle = \langle \Psi | U^\dagger U \hat{O} U^\dagger U | \Psi \rangle \sim \langle \Phi | U \hat{O} U^\dagger | \Phi \rangle$$







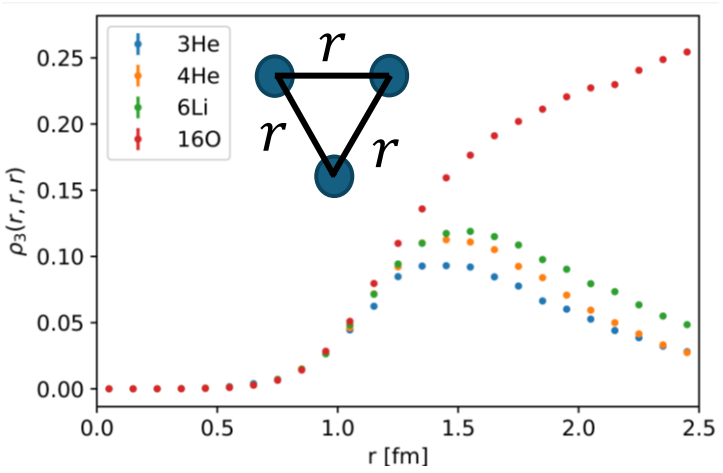
Tropiano, et al., *PRC 104, 034311 (2021)*

Tropiano, et al., *PLB 852, 138591 (2024)*

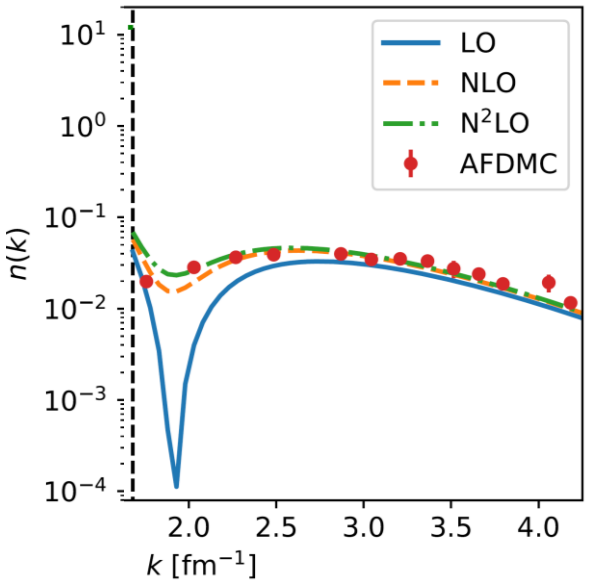
Factorized methods

Generalized contact formalism (GCF):

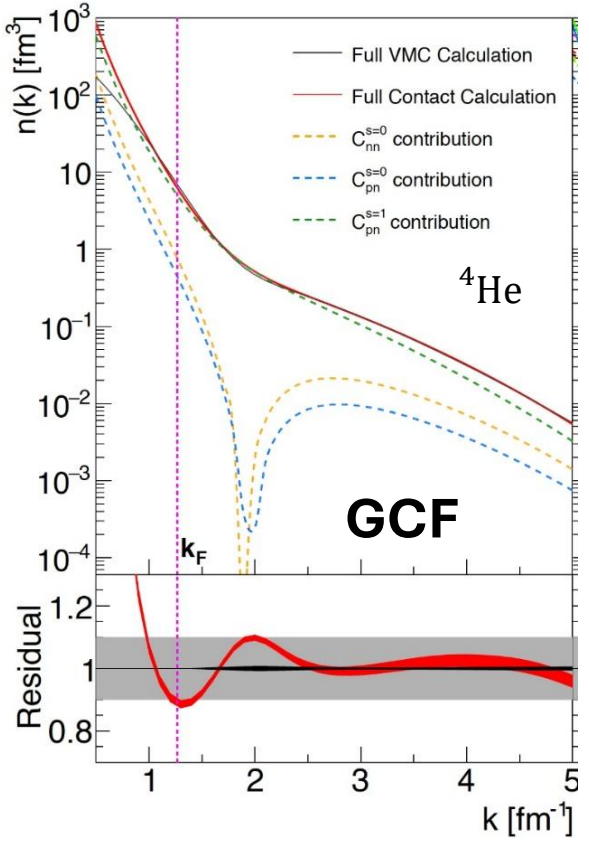
$$\langle\Psi|\hat{O}_2|\Psi\rangle = \sum_{\alpha,\beta}\left(\langle\varphi_\alpha^{E=0}(r)|\hat{O}_2|\varphi_\beta^{E=0}(r)\rangle C_{\alpha\beta}^{00} + \cdots\right)$$



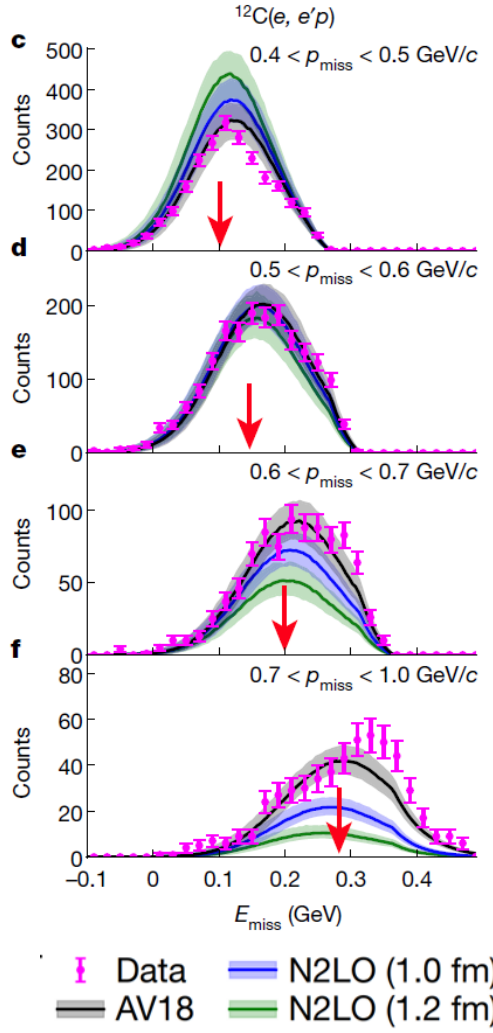
RW and S. Gandolfi, Phys. Rev. C 108, L021301 (2023)



RW, D. Lonardoni, S. Gandolfi, PLB 857, 138974 (2024)



Weiss et al.,, PLB 780, 211 (2018)



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

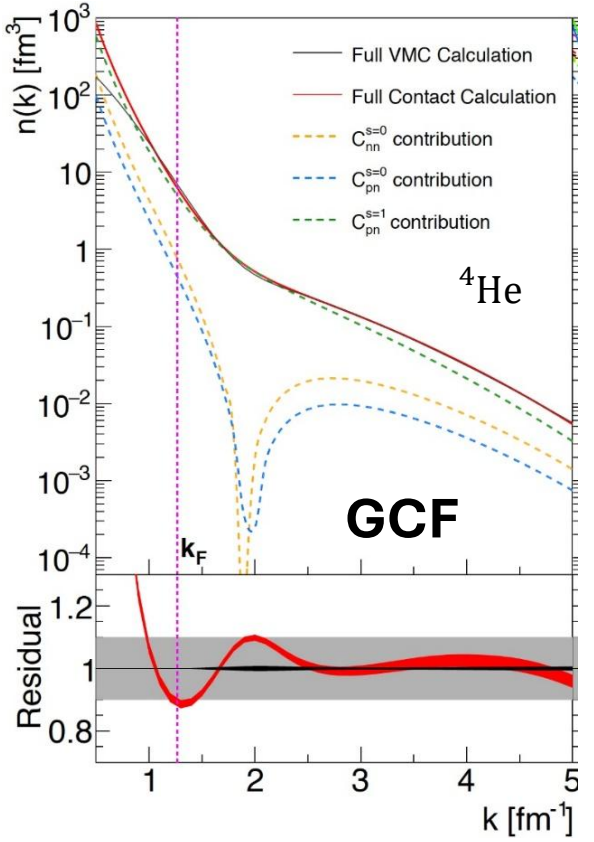
Factorized methods

Generalized contact formalism (GCF):

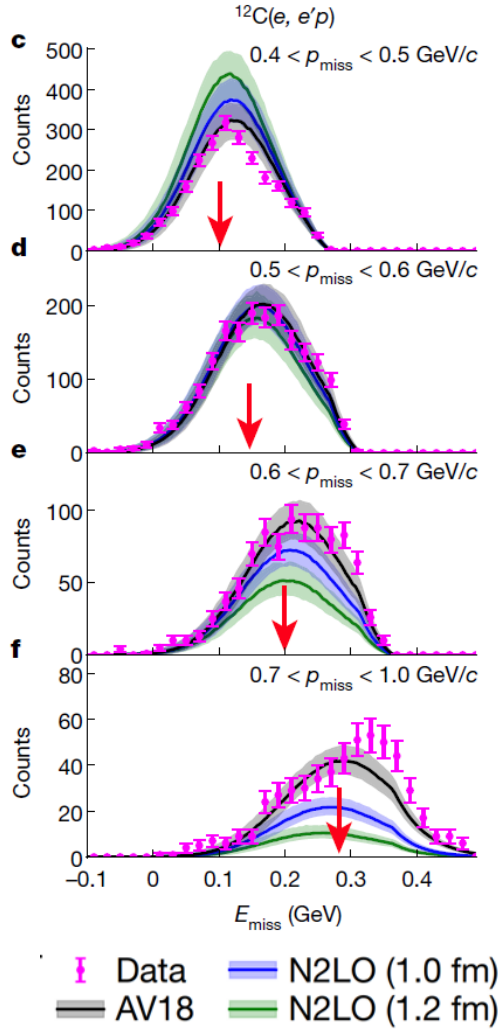
$$\langle\Psi|\hat{O}_2|\Psi\rangle = \sum_{\alpha,\beta}\left(\langle\varphi_\alpha^{E=0}(r)|\hat{O}_2|\varphi_\beta^{E=0}(r)\rangle C_{\alpha\beta}^{00} + \cdots\right)$$

How accurate are these factorization-based methods?

$$\Psi \to \varphi_2 \Phi_{A-2}$$



Weiss et al.,, PLB 780, 211 (2018)



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

Few-body systems

For $A = 2$ and $A = 3$:

- More **accurate reaction calculations**
- **No ground-state factorization is assumed**
- Including partial **final-state interaction**

Few-body systems

For $A = 3$ (e,e'p):

PWIA calculations: (FSI between spectators)

$$\sigma \sim \sigma_{eN} S_N(p_{miss}, \epsilon_{miss})$$

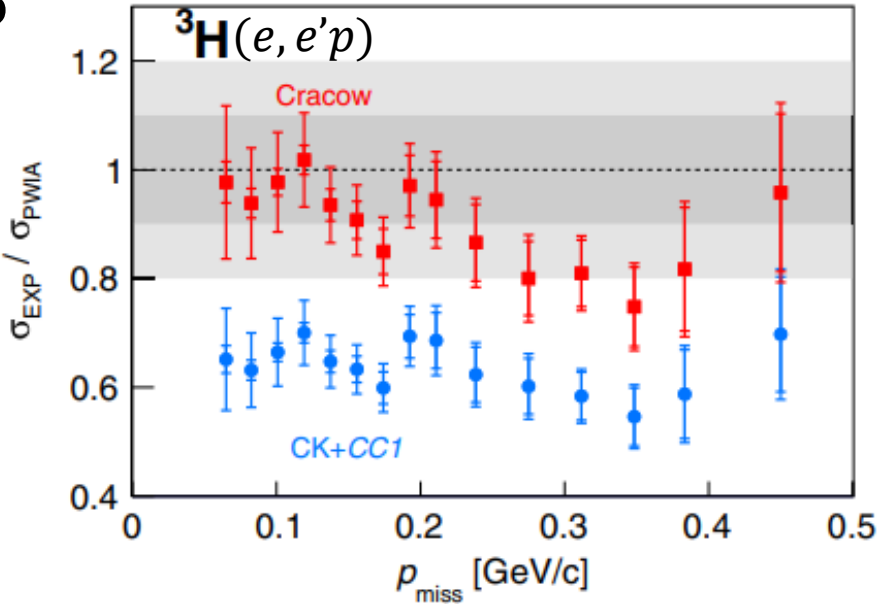
J. Golack et al.: CD-Bonn interaction

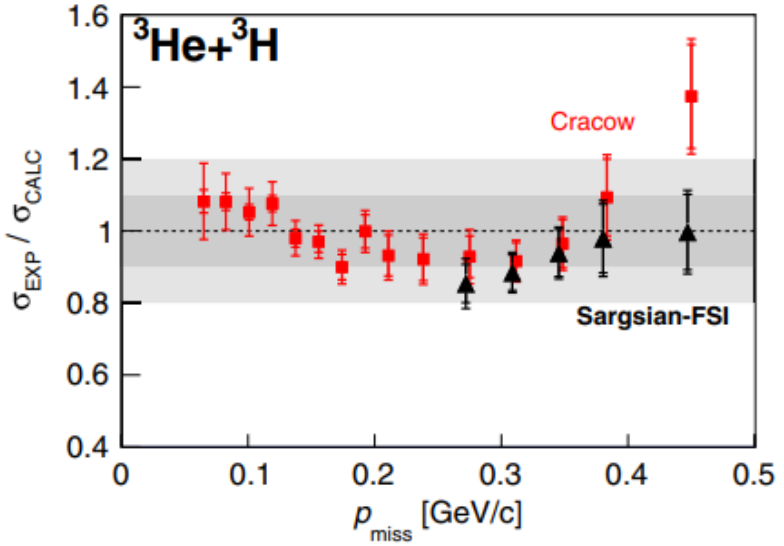
Ciofi and Kaptari: AV18 interaction

Also:

M. Sargsian: FSI of the struck nucleon

Not included: 3N force, beyond PWIA (2b currents, interference terms, full FSI)





Cruz-Torres et al., PRL 124, 212501 (2020)

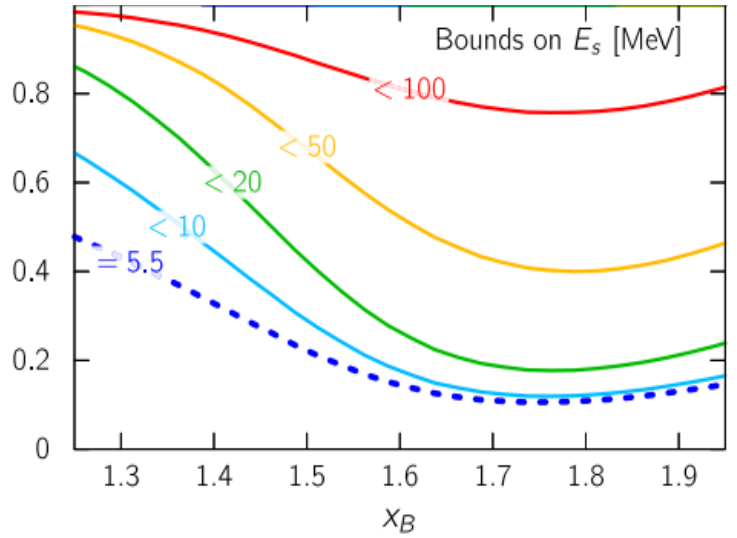
Few-body systems

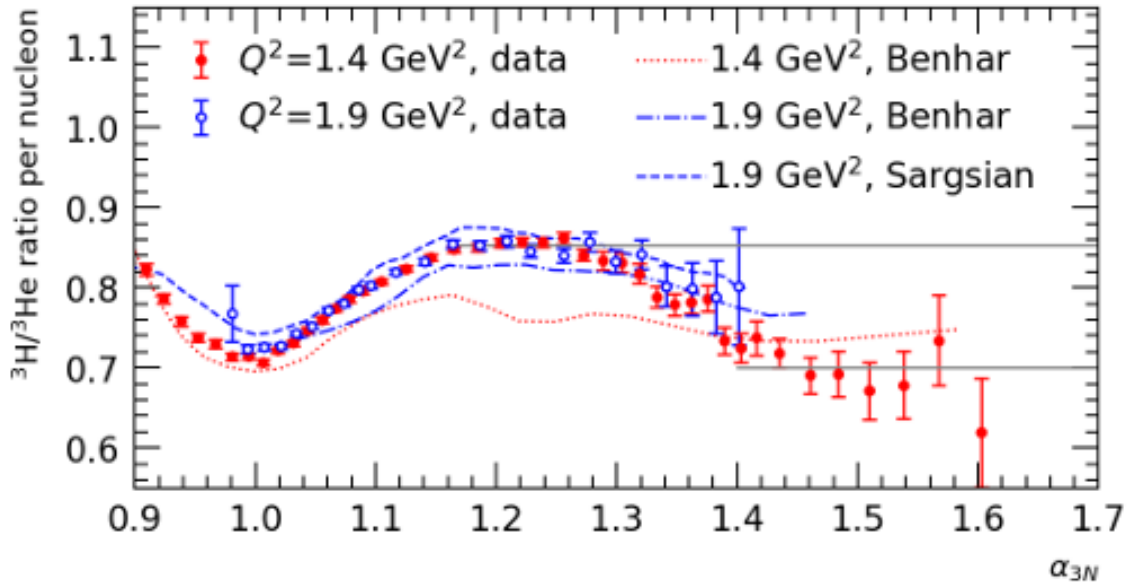
For $A = 3$ (e,e'):

PWIA calculations:

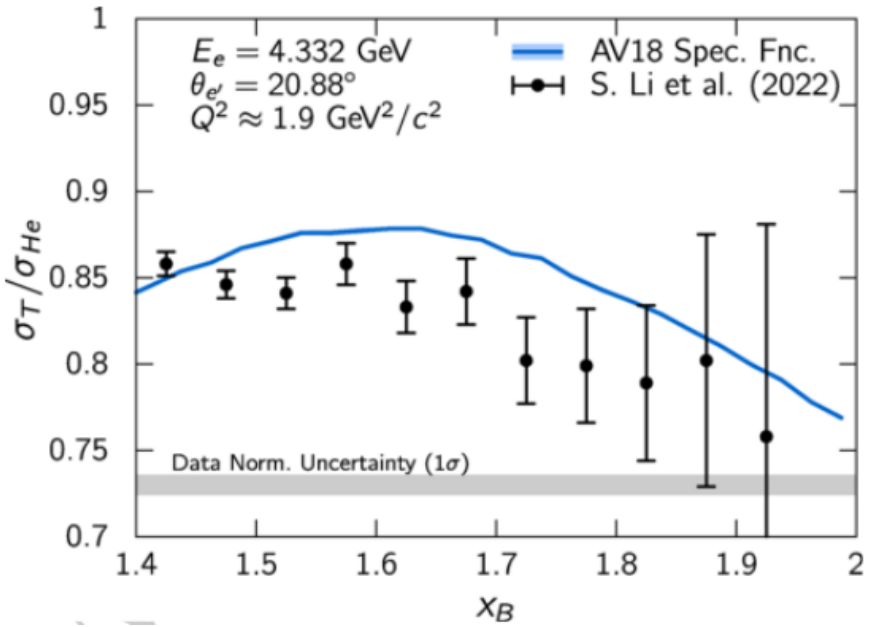
$$\sigma \sim \sigma_{eN} S_N(p_{miss}, \epsilon_{miss})$$

(non 2N SRC contributions)





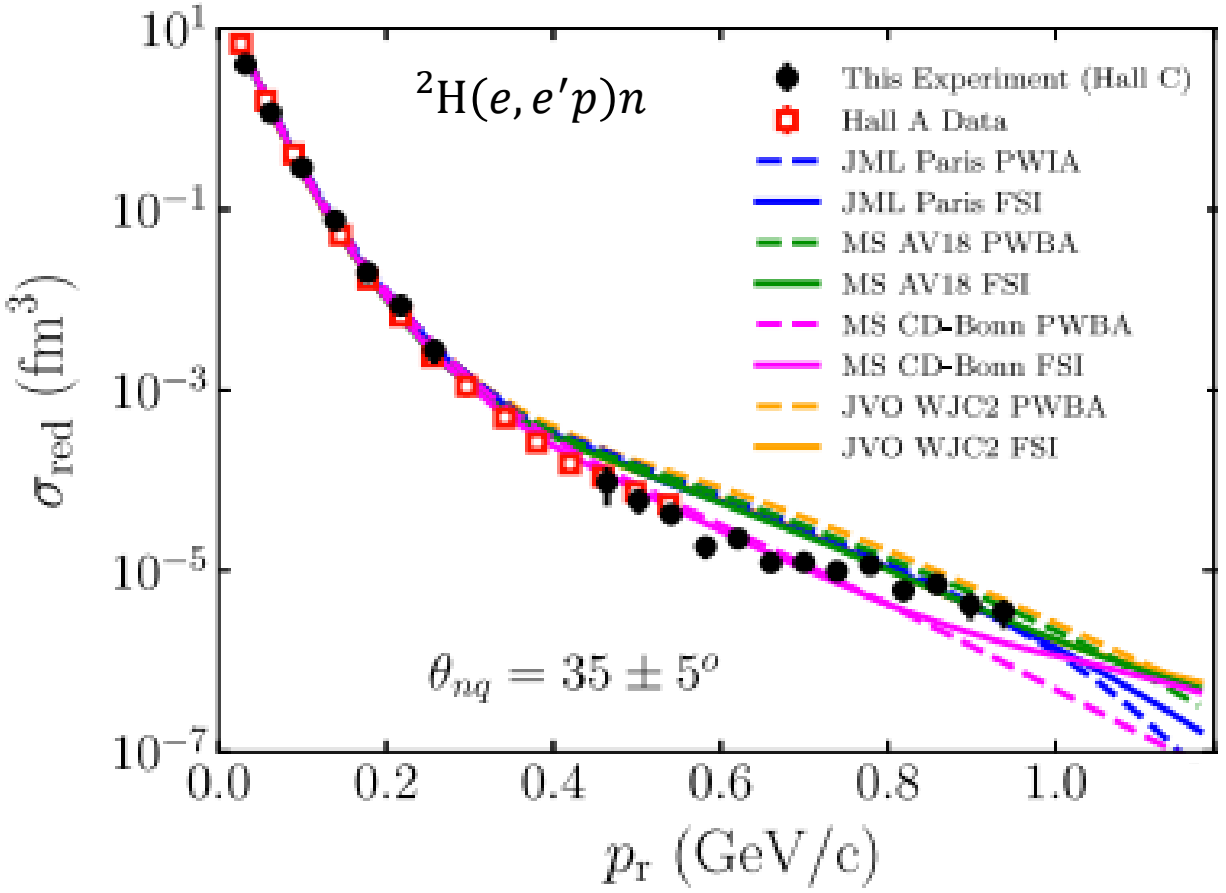
Li et al., arXiv:2404.16235 [nucl-ex] 2024



Schmidt et al., PRC 109, 054001 (2024)

Few-body systems

For $A = 2$ ^2H(e,e'p)n:



Relativistic effects for $p > 700$ MeV/c?

C. Yero et al., PRL 125, 262501 (2020)

QMC-based approaches

Quantum Monte Carlo approaches:

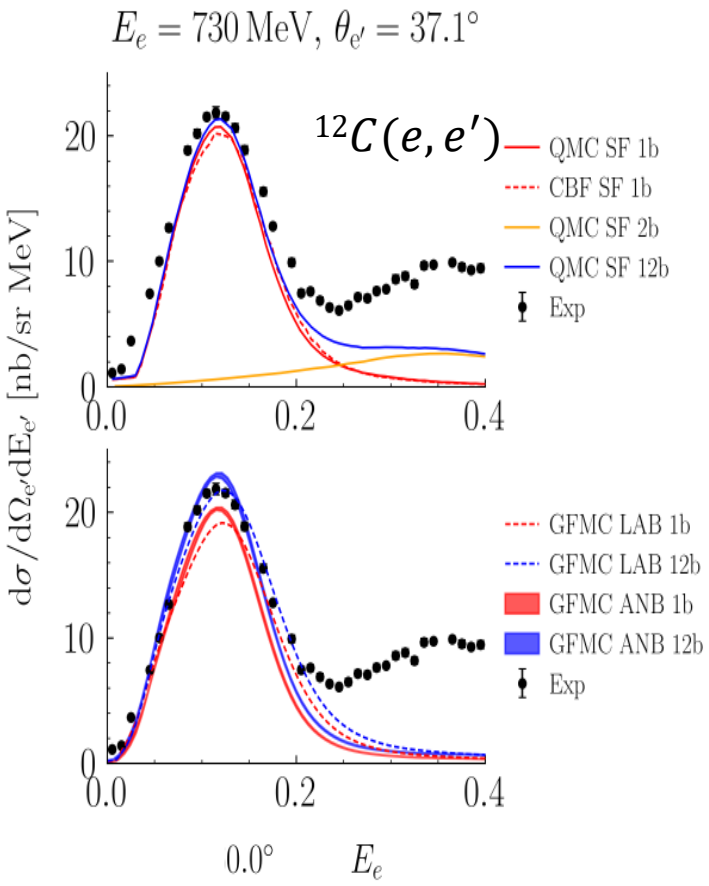
- **Heavier nuclei with accurate methods**
- **2N+3N forces**
- **Cross sections with QMC**
- **Including two-body currents**
- **Partial relativistic effects**

Methods:

- GFMC
- QMC spectral function
- QMC short-time approximation

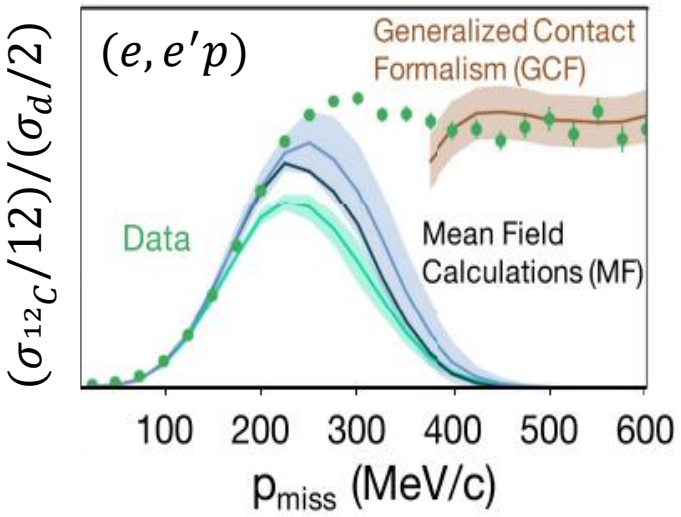
QMC-Based Approaches

SF and GFMC cross sections

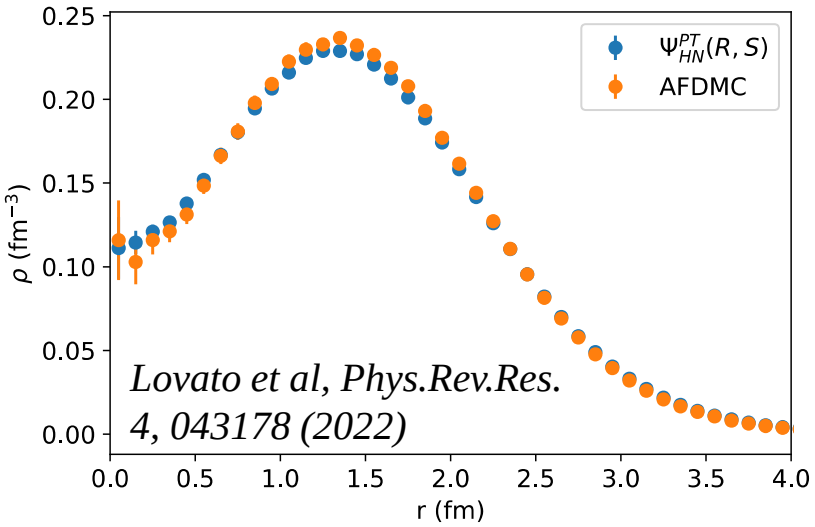


Nikolakopoulos, et al, Universe 9 (2023) 8, 367

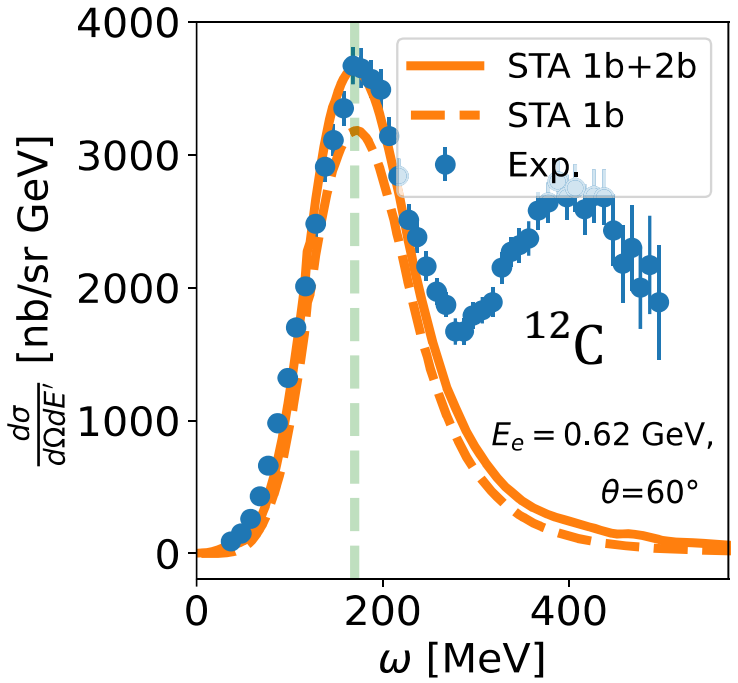
Korover et al, PRC 107, L061301 (2023)



NN Quantum States vs AFDMC ^{16}O



Short Time Approximation



Andreoli et al, PRC 110, 064004 (2024)

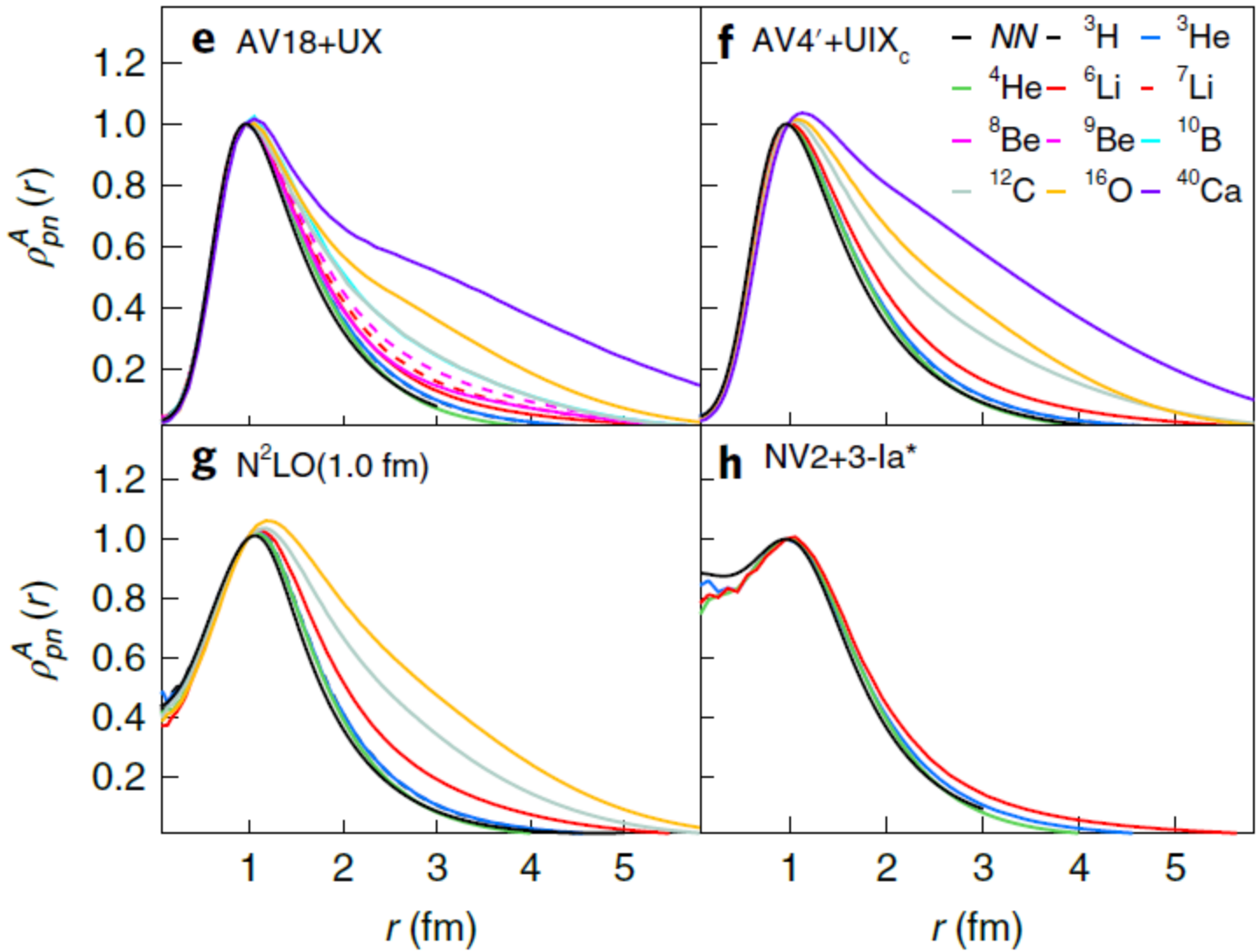
More theory aspects

- **Importance of relativistic treatment – light front** (Strikman, Frankfurt, Sargsian,…)
- **non-nucleonic degrees of freedom** (Strikman, Frankfurt, Sargsian,…)
- **Studies of FSI effects (transparency, charge exchange), suppression of meson-exchange currents…** (Sargsian, Colle, Cosyn, Ryckebusch, …)
- **…**

SRC Theory – Outlook

- **Few-body systems:**
  - Reaction calculations including two-body currents, three-body forces, relativistic effects, coherent contributions, FSI…
- **3N SRC:**
  - Impact on ground-state distributions; Identifying sensitive quantities.
  - Impact on reactions: inclusive + exclusive *[a few papers already published]*
- **Factorized methods:**
  - Sub-leading corrections to ground-state factorization; Improved spectral functions.
  - Consistent inclusion of 3N effects; predictions of different quantities impacted by SRC.
- **Reaction support** (for 3N SRC detection)
- **Probe-independence:**
  - Calculations for various probes
- **RG methods:**
  - Description of reactions
  - Spectroscopic factors
- **QMC methods:**
  - AFDMC spectral functions for (e,e'p) and (e,e'pn) reactions including relativistic effects. STA calculations.
  - Leverage NN-QS to study medium size nuclei with realistic interactions
- **Data Interpretation:**
  - Extracting "ground-state information" (cleaning impact of FSI, non-SRC contamination, CM motion…)
- **Non-nucleonic degrees of freedom…**

BACK UP


e AV18+UX
f AV4′+UIX$_c$
g N^{2}LO(1.0 fm)
h NV2+3-Ia*
$\rho^A_{pn}(r)$
r (fm)
NN
^{3}H
^{3}He
^{4}He
^{6}Li
^{7}Li
^{8}Be
^{9}Be
^{10}B
^{12}C
^{16}O
^{40}Ca