

THEORETICAL STUDIES OF SHORT-RANGE CORRELATIONS IN NUCLEI AND NUCLEAR MATTER

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MOTIVATIONS

Known since a long time:

Nuclear force: short-range repulsion, medium-range attraction.

Therefore, mean-field picture has limitations.

**Nuclear wave functions overlap strongly:
correlations**

**Short-range correlations (SRC)
= nucleon dynamics at short distances**



Responsible for the high-momentum components in the wave function

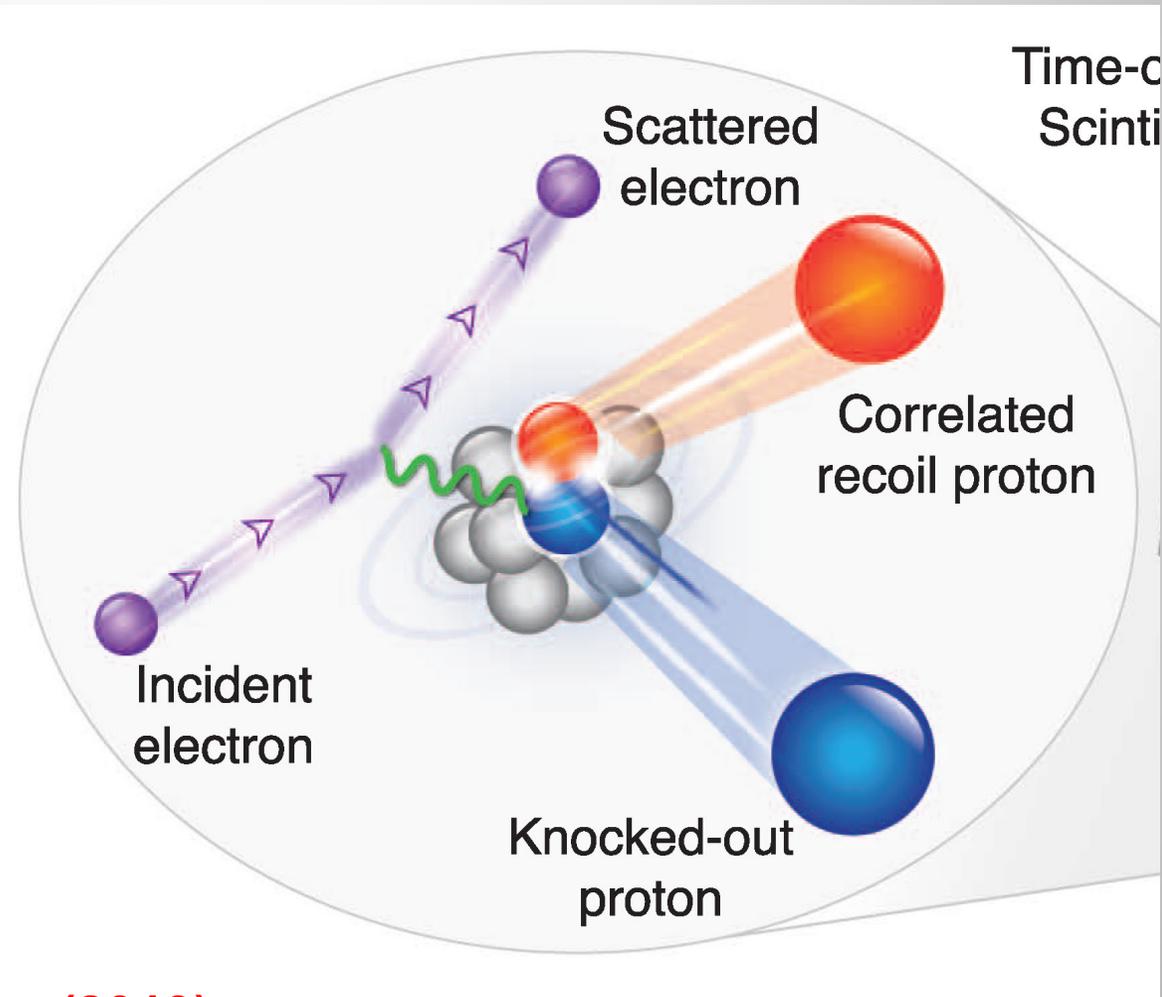
Additional driving force from the experimental program at Jlab with $A(e,e')X$ (and other) measurements at high momentum-transfer (CLAS Coll., Jefferson Lab Hall A, B, C Coll., etc..)

$A(e,e')X$ inclusive

$A(e,e'p)$ exclusive

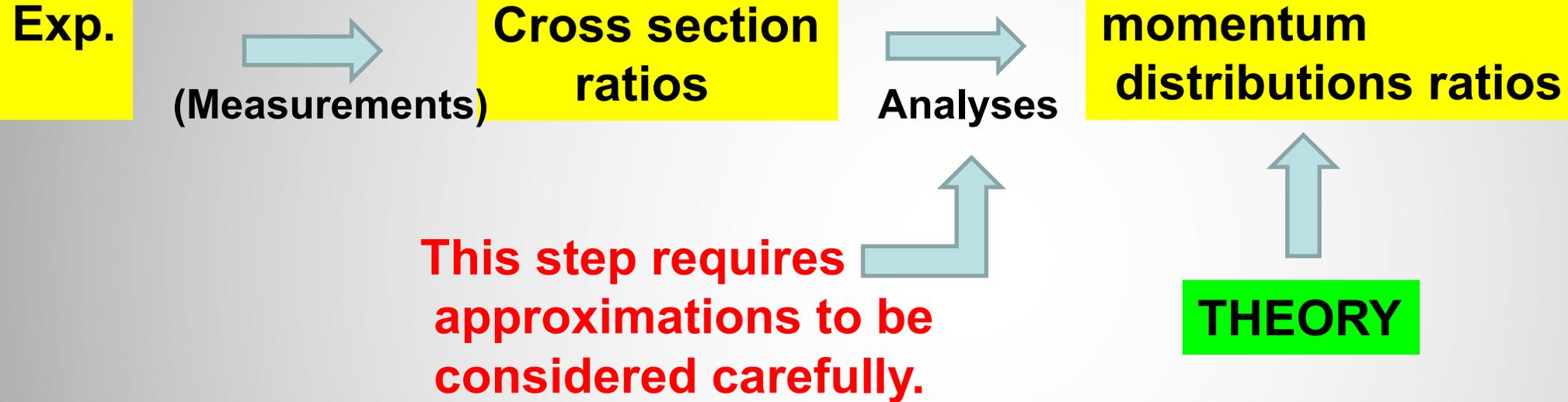
$A(e,e'pN)$ exclusive

Frankfurt&Strikman (1981),
Egiyan et al. (2003,2006),
Fomin et al. (2012),
Tang et al. (2003),
Piassetzky et al. (2006),
Shneor et al. (2007),
Subedi et al. (2008),
Baghdasaryan et al. (2010)
Hen et al. (2014),
Korover et al. (2014),
Monaghan et al. (2014),
Makek et al. (2016)



Jlab Hall A Tritium Collaboration (2019)

In summary, SRC is an important and timely issue



Intriguing question:

What does a nucleon “do” in a nucleus?

Can we “see” a high-momentum proton in a nucleus?

1980's:

The bremsstrahlung reaction



was proposed as a way to determine off-shell aspects of the NN interactions.

1998-2000:

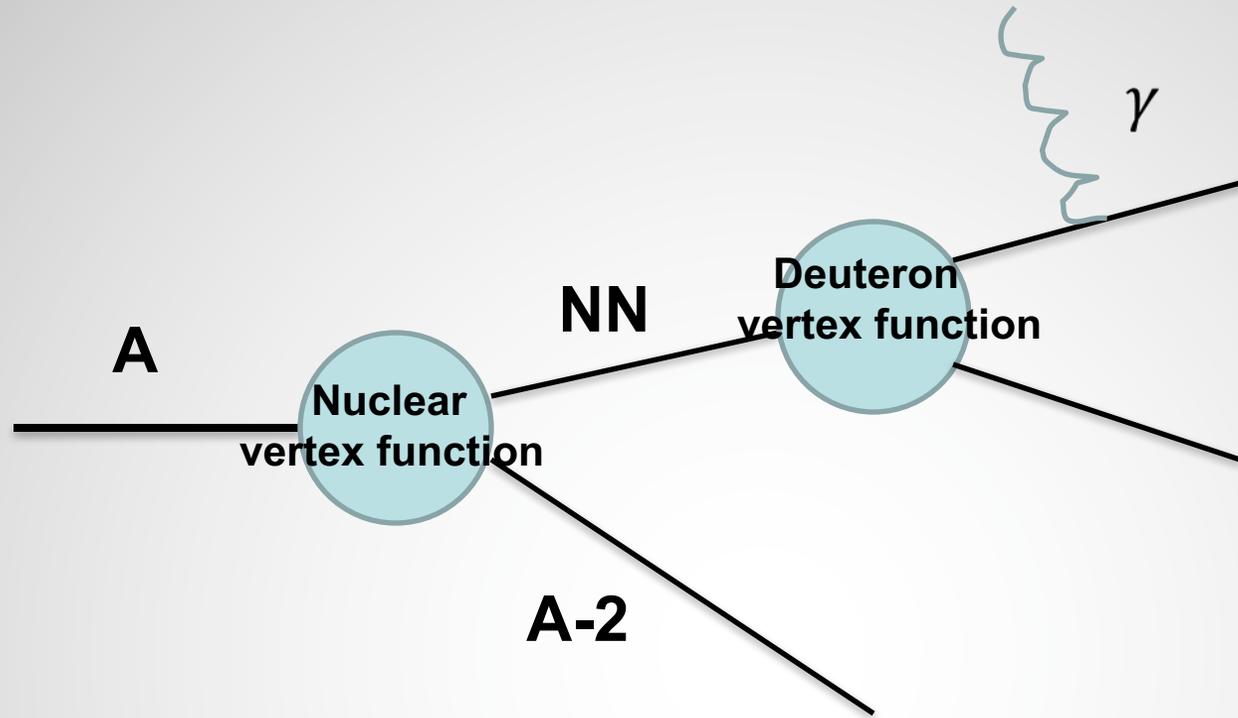
Fearing & Scherer show the

“*Impossibility of Measuring Off-Shell Amplitudes*”

PRC62, 034003 (2000)

2019:

F.S. et al.: Should we carefully revisit similar issues as those raised by Fearing *et al.* with regard to constraining the off-shell nature of the NN interaction? (In progress.)



Electron QE scattering from a nucleon in a SRC pair in a nucleus.

**Is invariance of the S-matrix under a field transformation preserved?
May require, in addition, $NNN\gamma$ contact term.**

Until recently, **momentum distributions (MD)** in nuclei studied mostly with phenomenological (AV18) or meson-theoretic NN potentials (CD-Bonn), w/without 3NF (UIX or TM).

Our concept of nuclear forces has evolved.

Recently, we have taken a broader look at MD and SRC including state-of-the-art chiral forces.

(Marcucci et al., PRC99, 034003 (2019)).

For low energies, nuclear chiral EFT has become the authoritative approach to construct nuclear two- and few-body forces in a systematic and essentially model-independent way.

Based upon the symmetries of low-energy QCD, while using degrees of freedom relevant for low-energy nuclear physics. Predictions can be improved systematically.

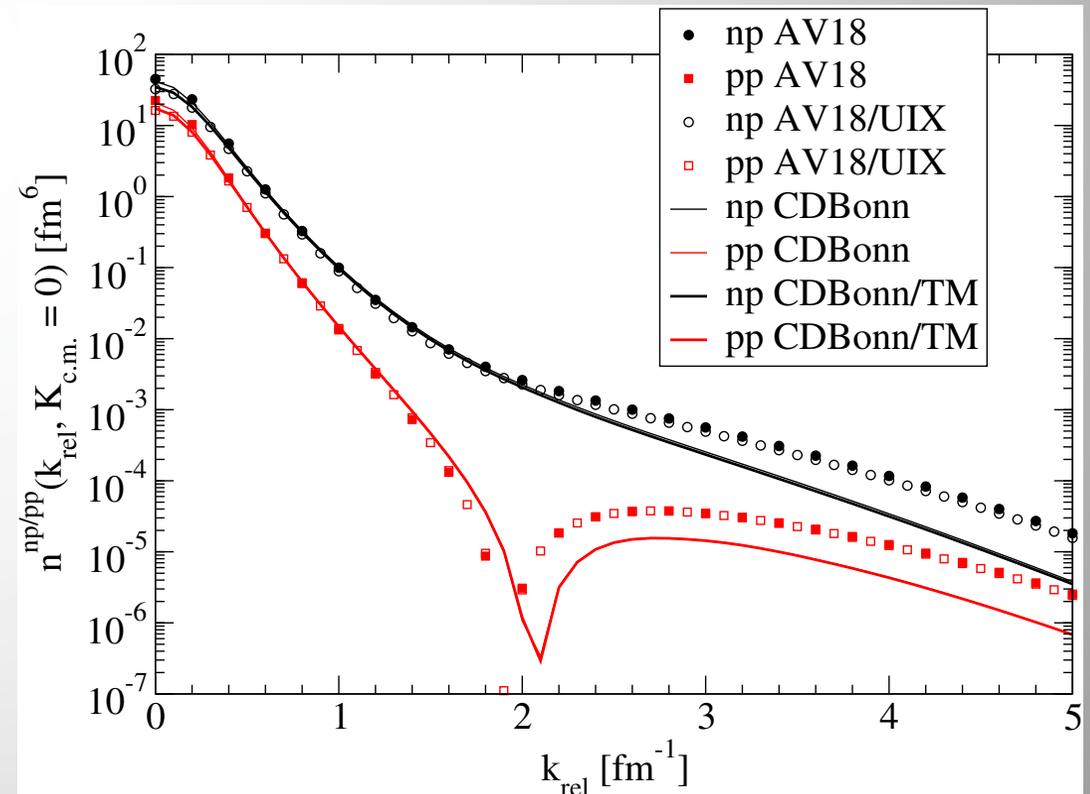
**Together with an organizational scheme to rank-order the various diagrams (power counting),
nuclear two- and few-body forces can be developed
in a controlled hierarchy.**

A brief survey of current results for A=3:

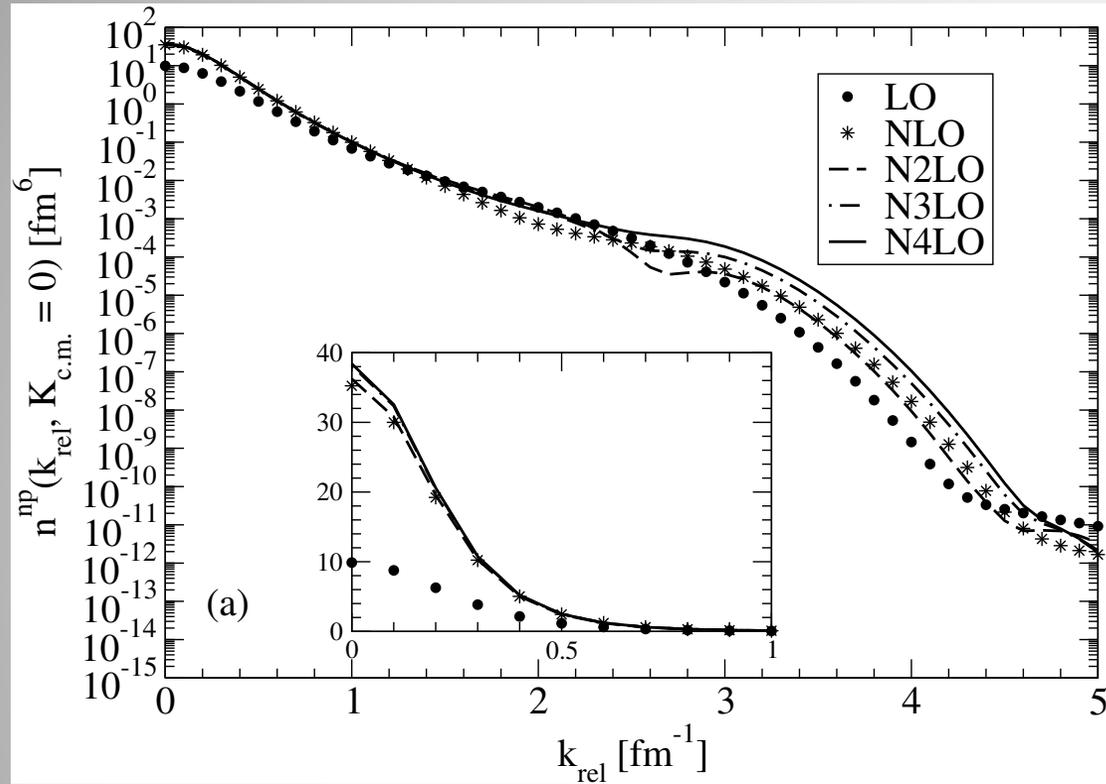
MD in ^3He calculated by L. Marcucci with the Hyperspherical Harmonics method;

No restrictions on the choice of local or non-local potentials,
or coordinate vs. momentum space.

2N momentum distributions obtained
with AV18 w/o the UIX 3NF and with
CDBonn w/o the TM 3NF.

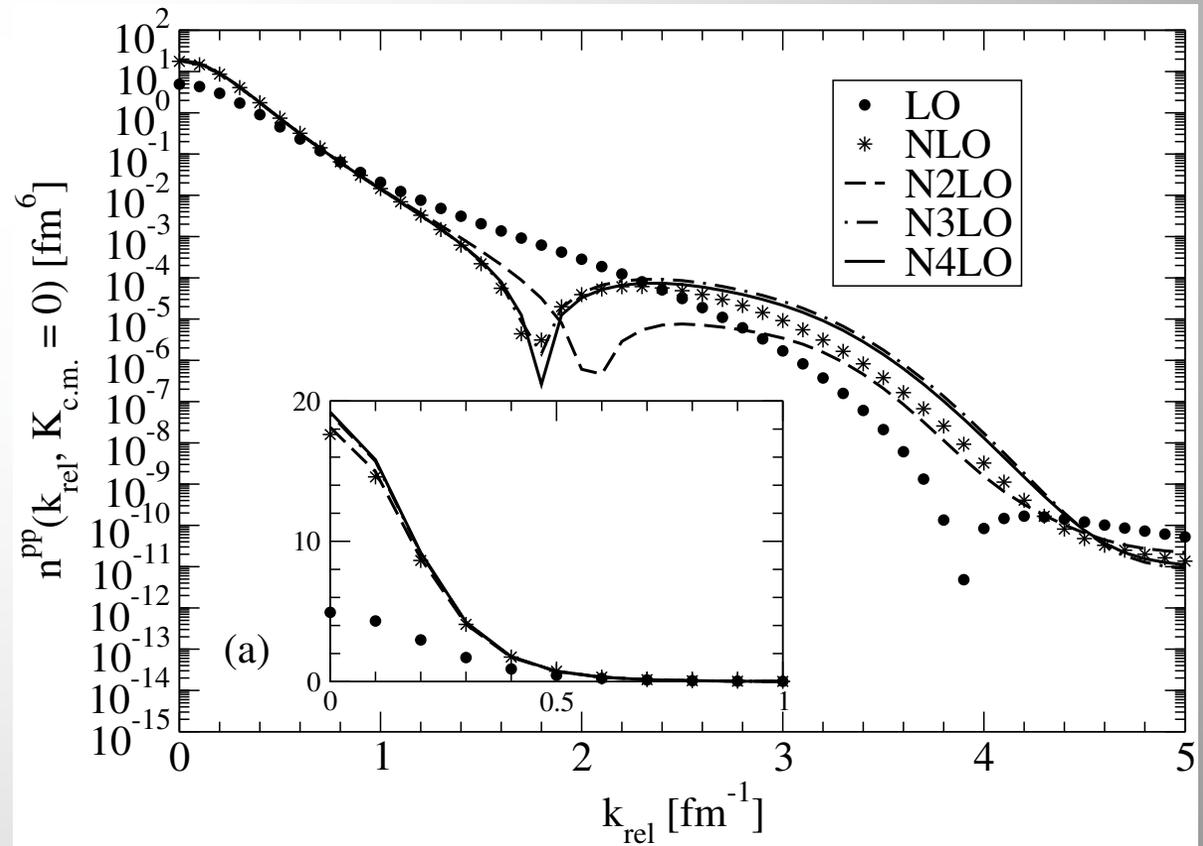


Overview of order-by-order pattern

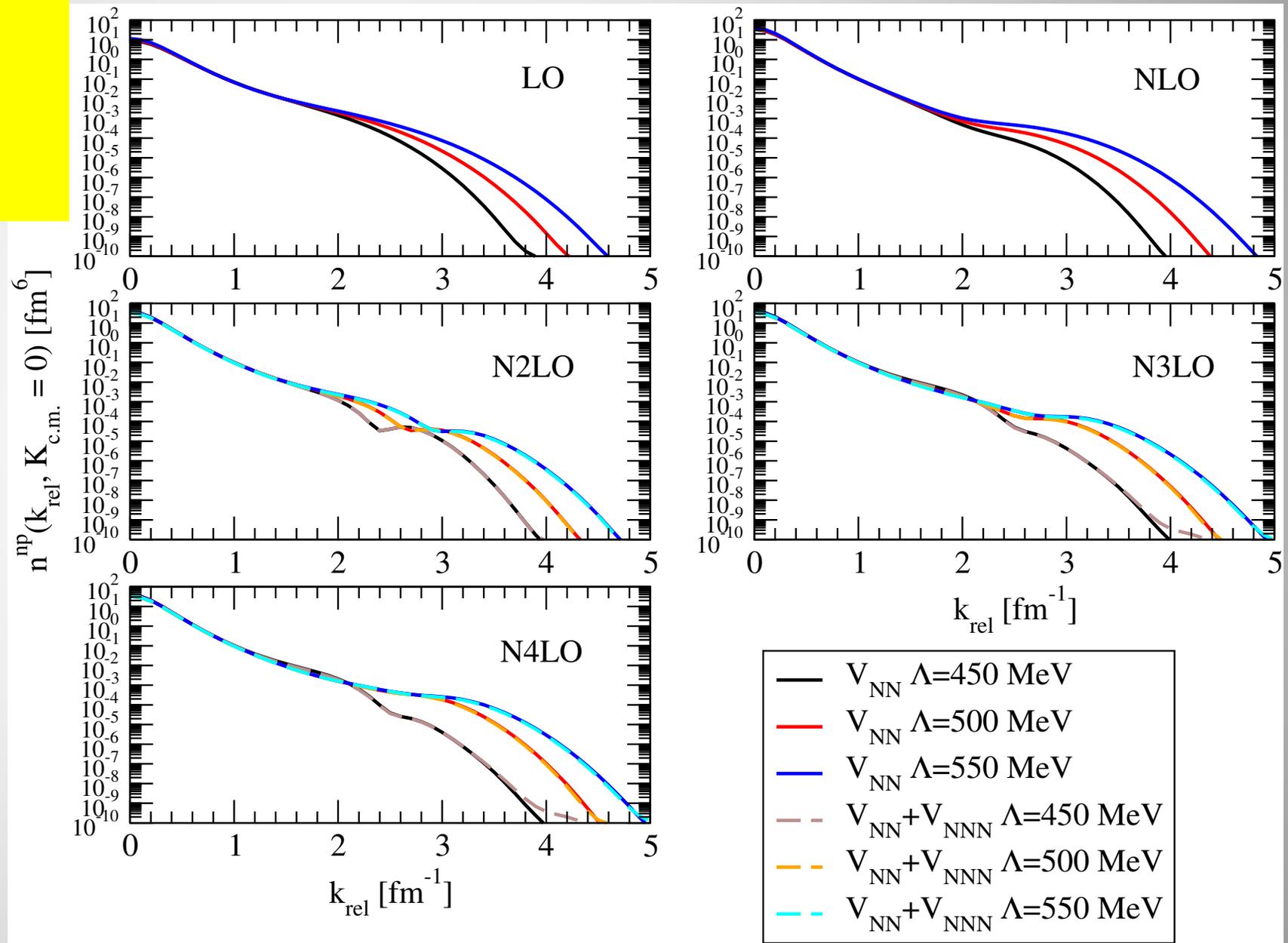


np momentum distributions obtained with only 2N chiral forces from leading to fifth order.

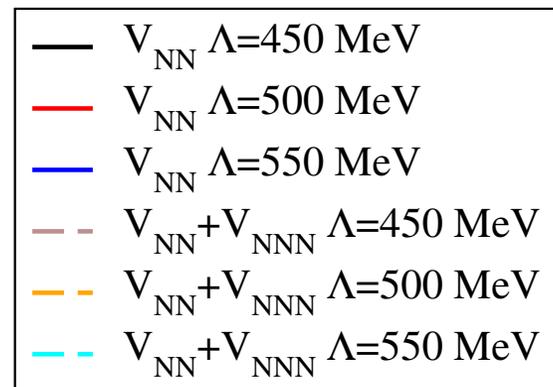
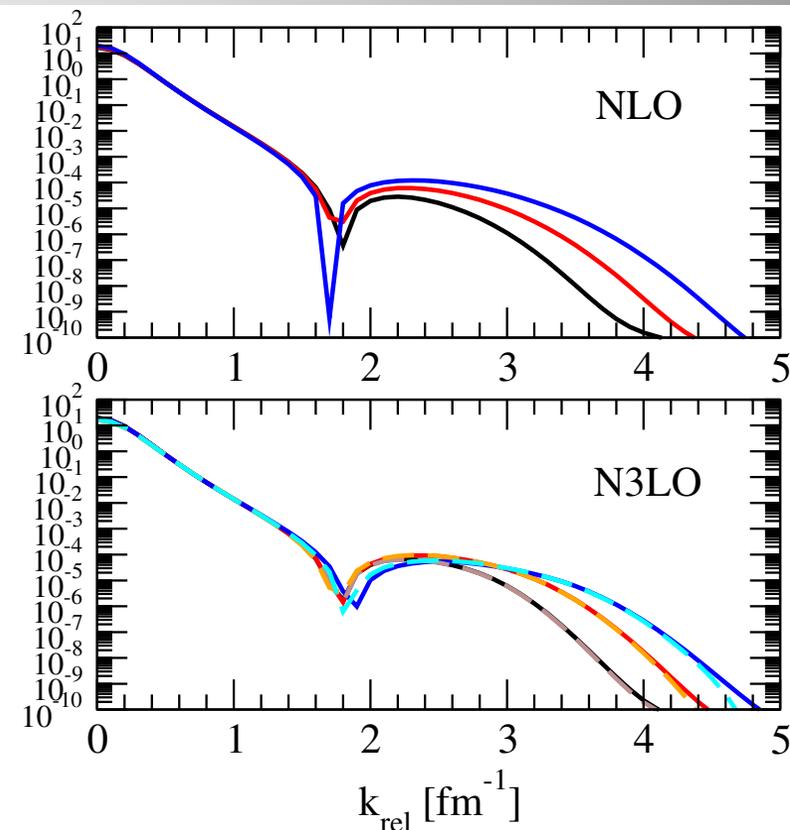
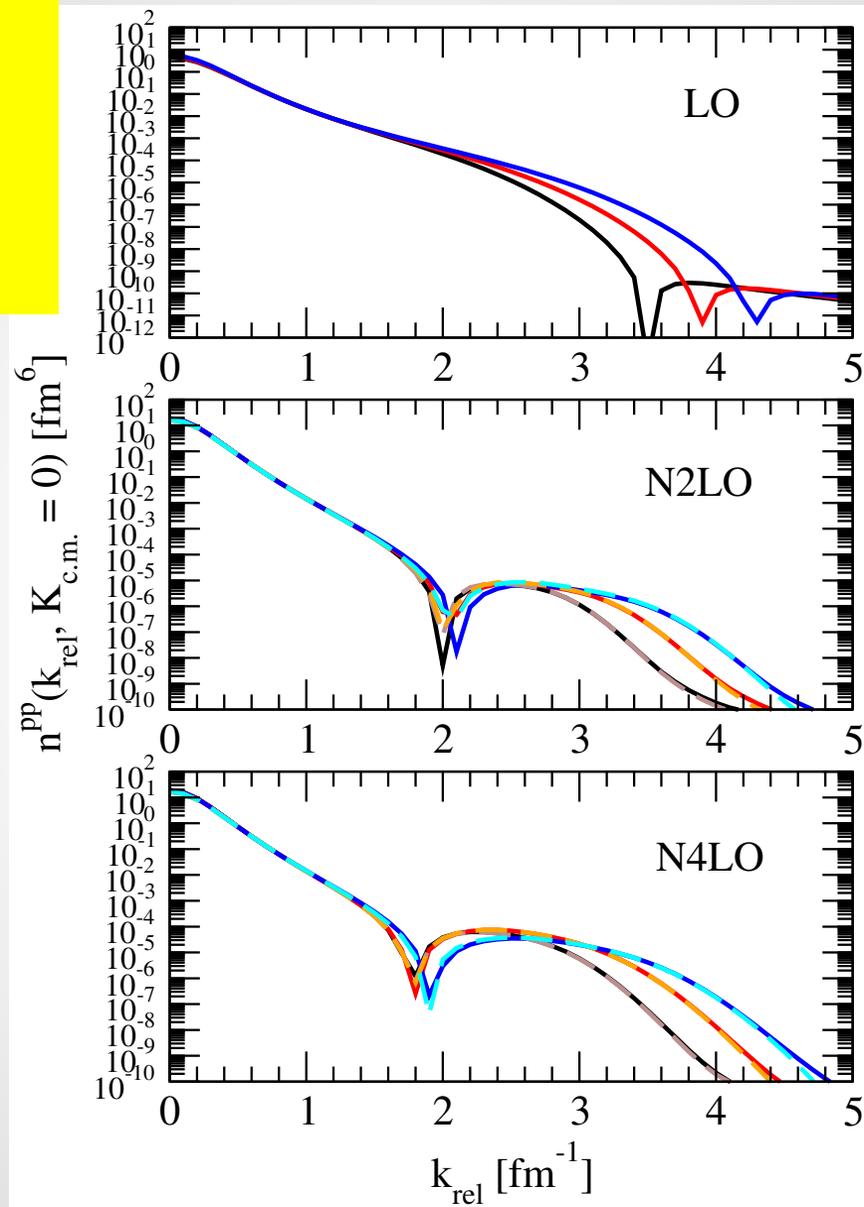
pp momentum distributions



**np momentum distributions.
Impact of cutoff
variations and inclusion
of 3NF across 5 orders
of the chiral expansion.**

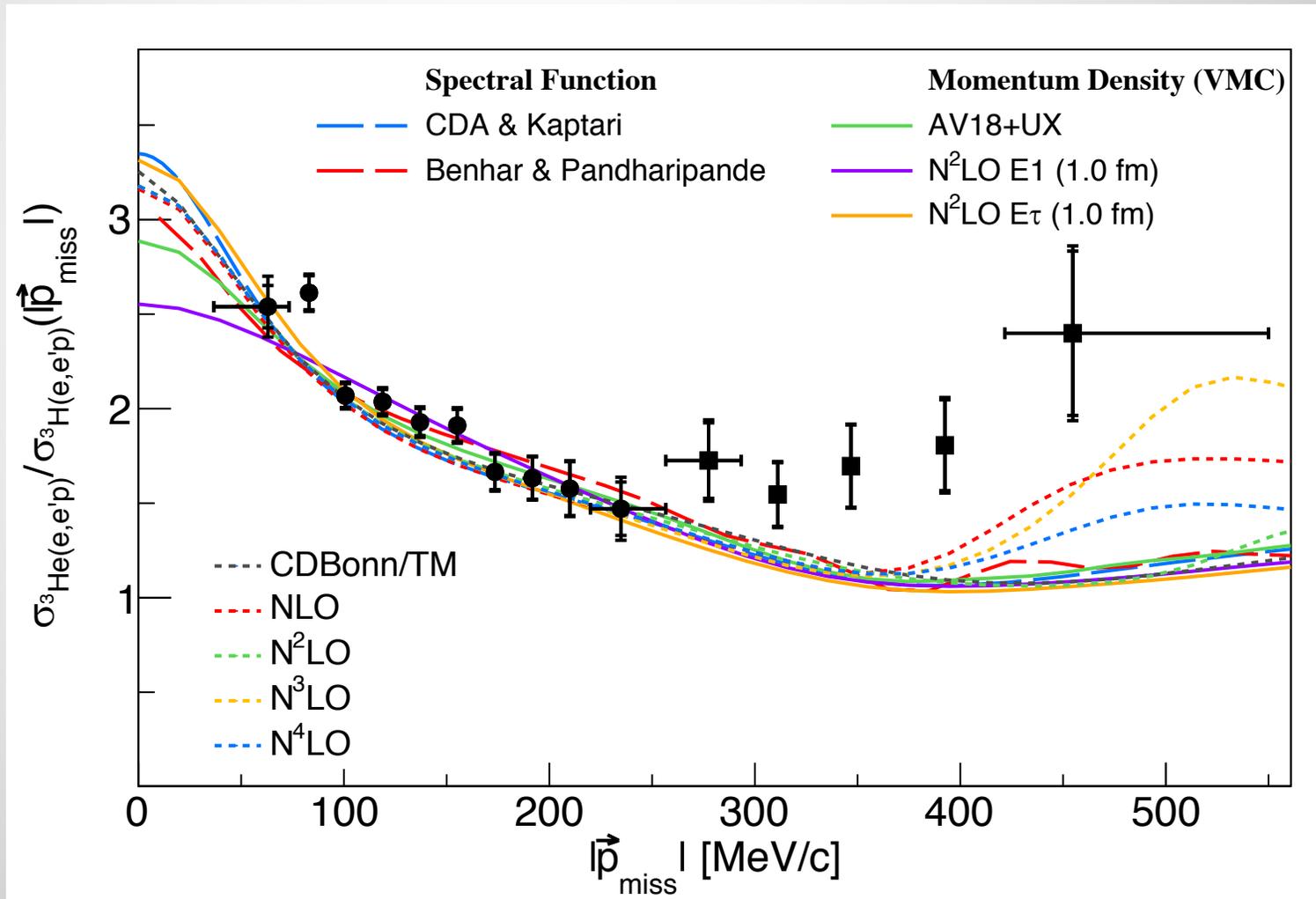


pp momentum distributions.
Impact of cutoff
variations and inclusion
of 3NF across 5 orders
of the chiral expansion.



More recently, we calculated the ratio of momentum distributions in ${}^3\text{He}$ and ${}^3\text{H}$ with both traditional and most recent chiral interactions and compared with the ratio of cross sections for quasi-elastic ${}^3\text{He}(e,e'p)$ and ${}^3\text{H}(e,e'p)$.

(Jlab Hall A Tritium Collaboration, arXiv:1902.06358 [nucl-ex].)

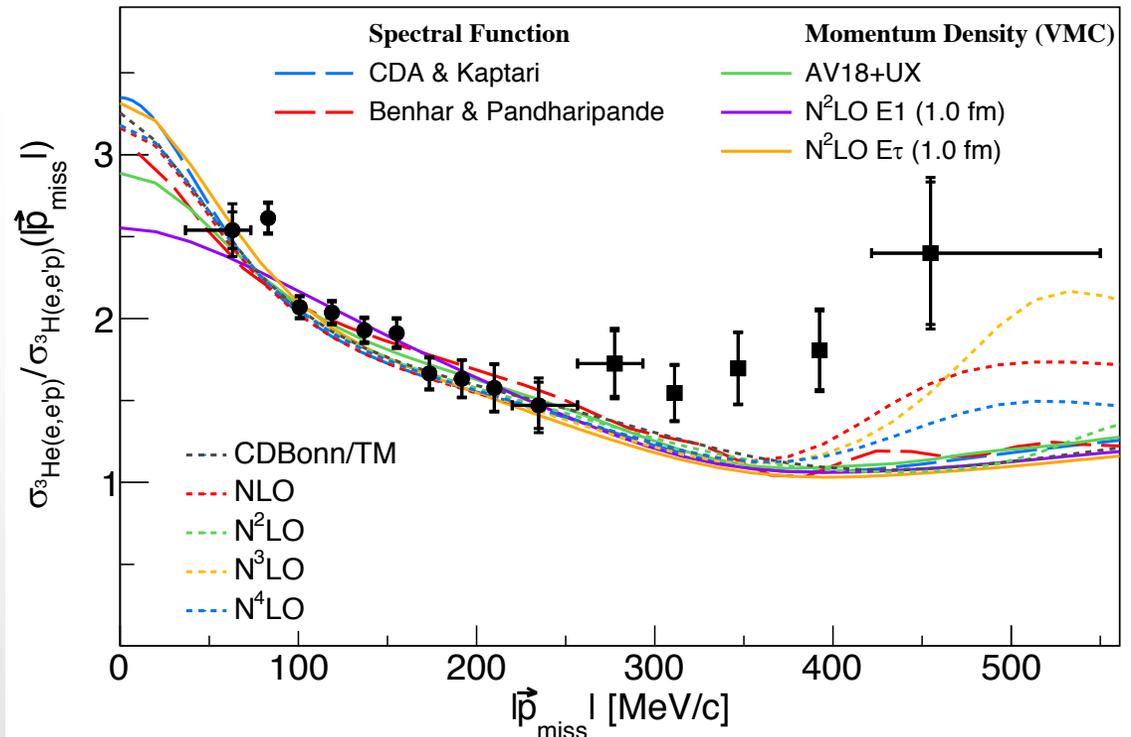


Observations:

Up to about $p_{\text{miss}} = 250 \text{ MeV/c}$, all calculations are in good agreement with the data.

Above that: both significant discrepancy and model dependence.

A systematic study from our group is underway.
(Need to better understand the application of soft, non-local potentials in these reaction calculations involving current operators.)



The interior of a heavy nucleus resembles nuclear matter around saturation density

Thus the nucleon momentum distribution, $n(k)$, in **nuclear matter** can be insightful (in progress).

Schematically:

Nucleon self-energy
(complex)



Spectral function



$n(k)$

Nuclear matter can provide important information about the underlying nuclear forces and short-range dynamics also through:

Correlated wave function obtained from the infinite ladder sum in the BG equation.

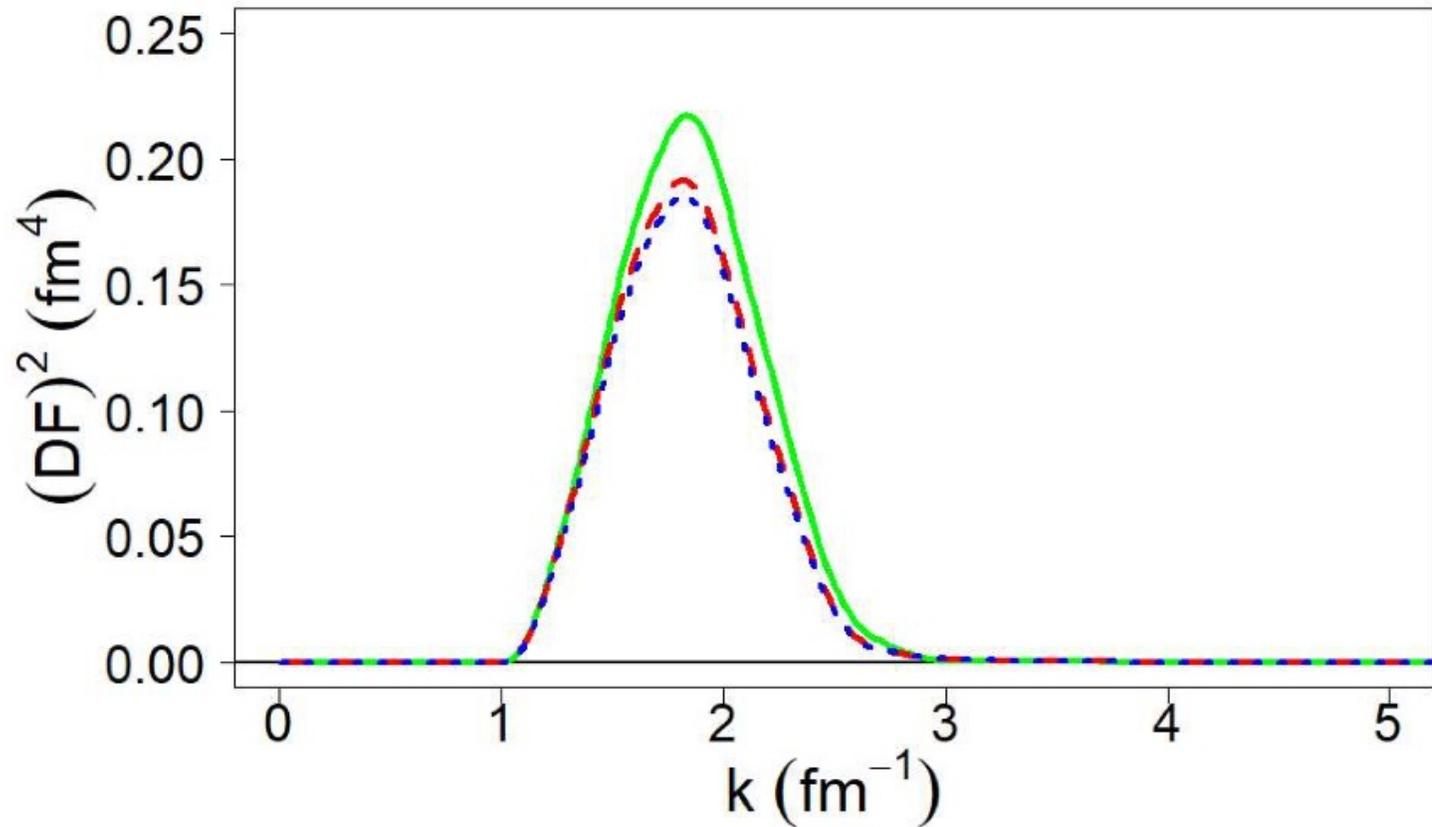
The defect function is the difference between the correlated and the uncorrelated wave functions,

$$\mathbf{f} = \psi - \varphi$$

and provides a measure of SRC in the wave function and the G-matrix.

Historically, such correlations have been found to depend strongly on the nature of the nuclear potential, particularly the tensor component (coupled S-waves).

Magnitude squared of the defect function for the 3S_1 - 3D_1 transition (normal density):



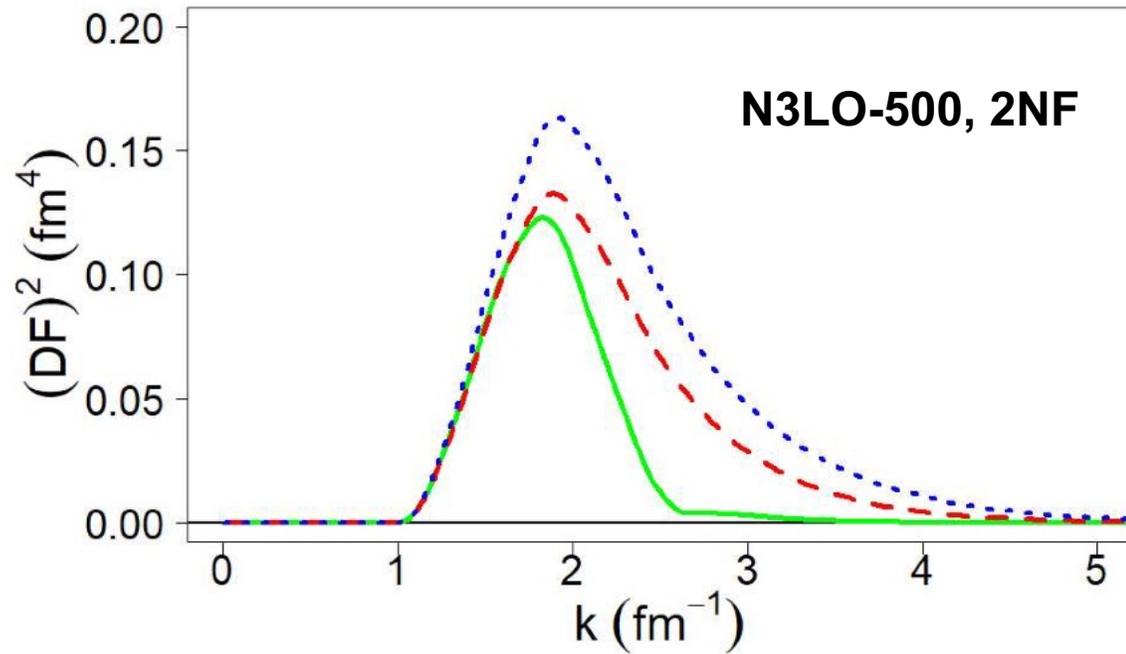
N2LO

N3LO

N4LO

(cutoff = 500 MeV)

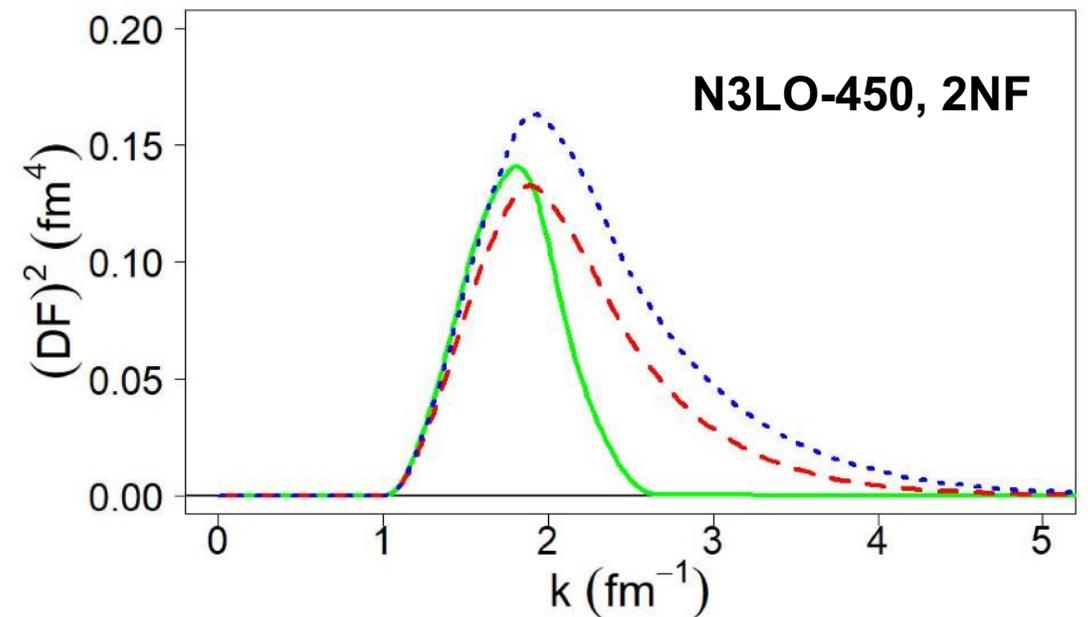
Comparison with traditional potentials:



N3LO

CD-Bonn

AV18



The integral of the (momentum-dependent) defect amplitude squared at some density is known as the “**wound integral**”:

$$W = \rho \int_0^{\infty} |f_{LL'}^{JST}|^2 dk$$

“Wound integral” at normal density in symmetric nuclear matter (2NF only):

INTERACT.	w(j=0,1)	w(all j_s)
N2LO	0.053	0.059
N3LO	0.079	0.085
N4LO	0.080	0.080
CDBonn	0.104	0.114
AV18	0.147	0.157

Correlations in neutron matter are an order of magnitude smaller:



INTERACT.	w(j=0,1)	w(all j_s)
N2LO	0.004	0.005
N3LO	0.006	0.008
N4LO	0.005	0.006

Conclusions, future plans

SRC depend strongly on the nature of the underlying nuclear force.

Impact of 3NF on the MDs in for $A=3$ is weak.

SRC in nuclear/neutron matter:

SRC in nuclear matter are mostly due to the coupled S waves; negligible in NM.

Density dependence of the symmetry energy is very sensitive to tensor SRC.

In progress/near future:

Continuing and extending systematic predictions in $A=3,4$ with the Pisa group.

Extending study of MD in nuclear matter.

Thank you