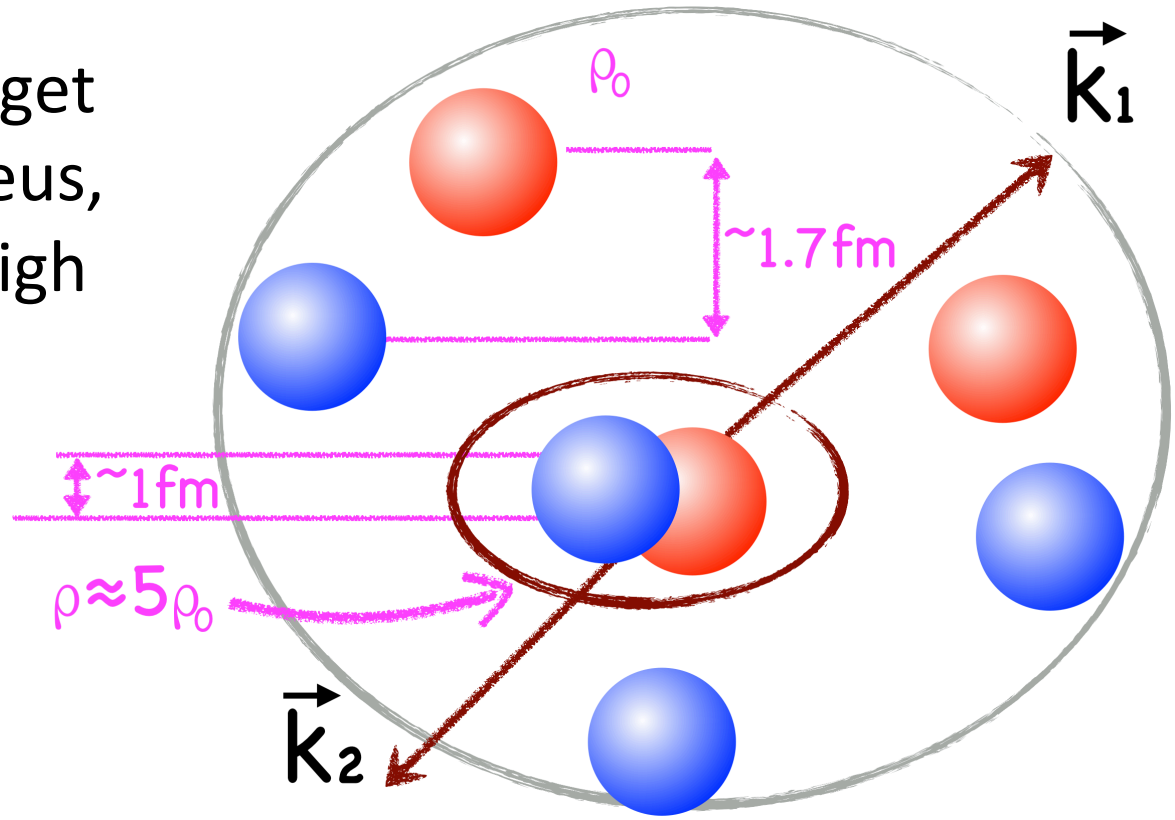
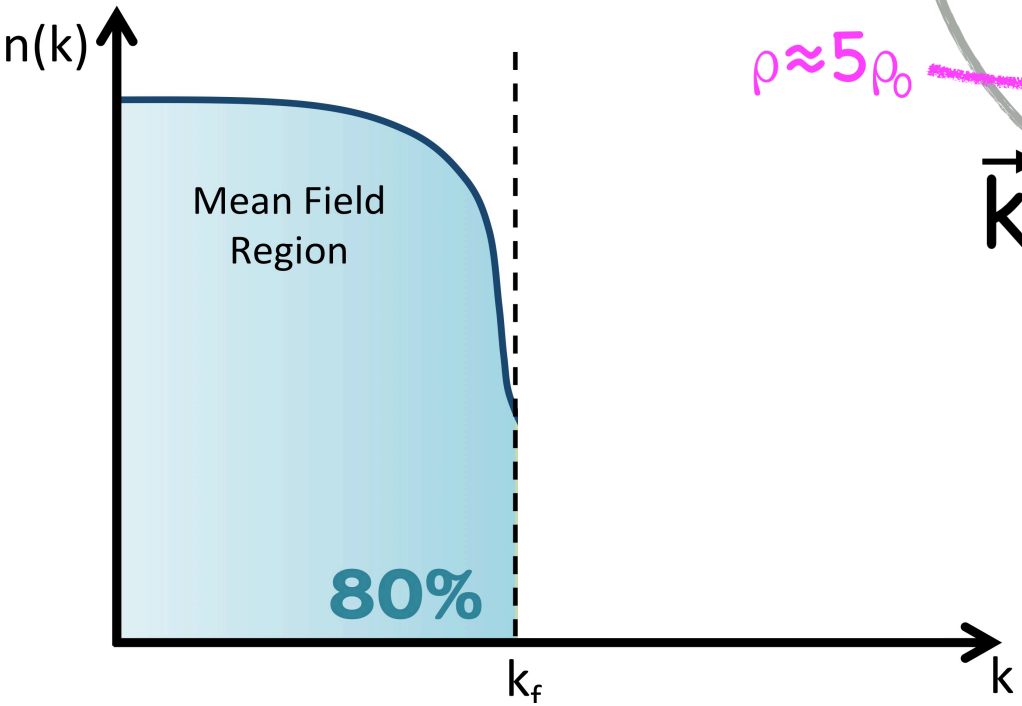
Short-Range Correlations (SRC)

When two nucleons get close inside the nucleus, they fly apart with high momentum





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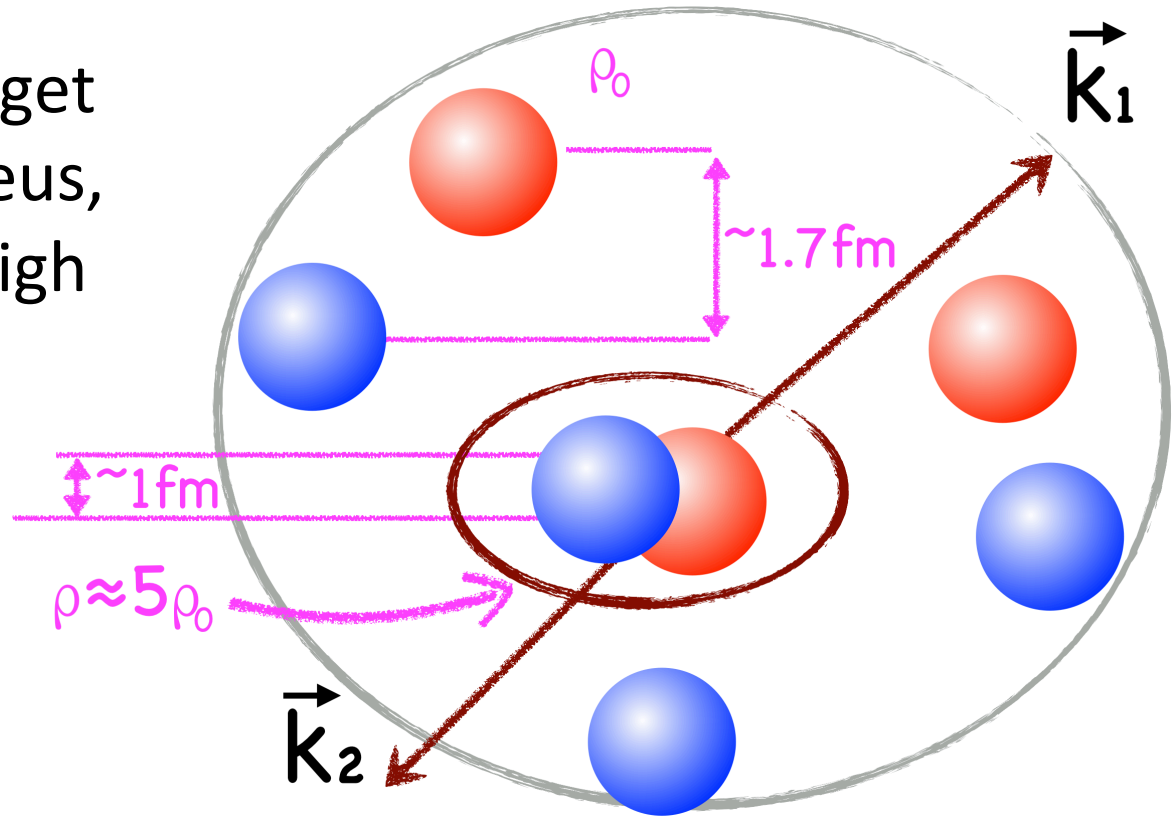

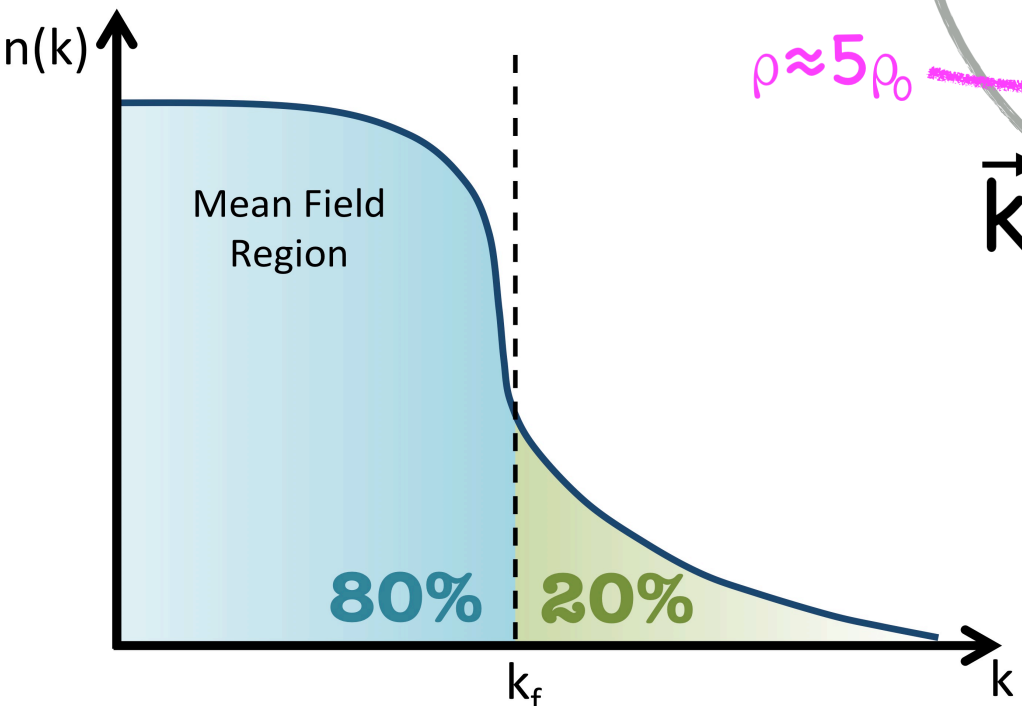

This populates a high-momentum tail above the Fermi momentum

The nuclear challenge

1. Many-body problem

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

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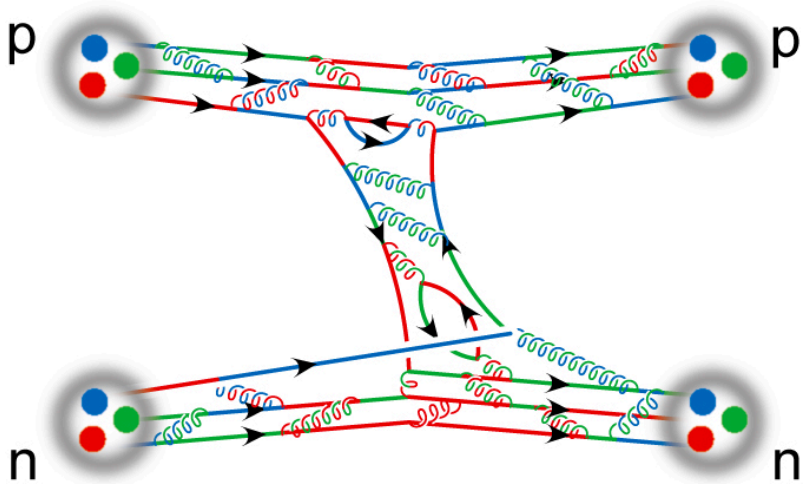
2. Complex QCD interaction



The nuclear challenge

1. Many-body problem

Numerical techniques -> Quantum Monte Carlo

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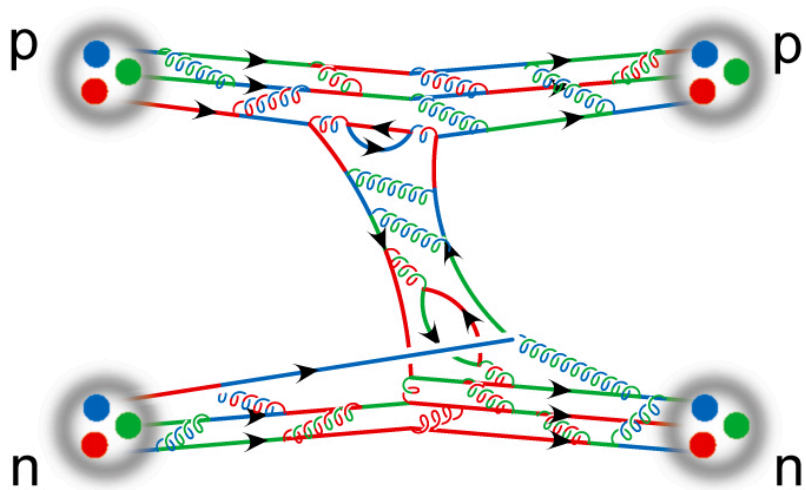
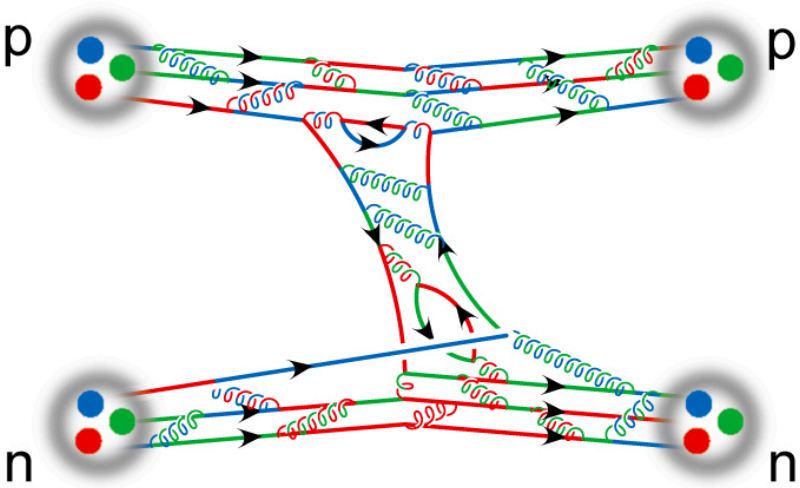


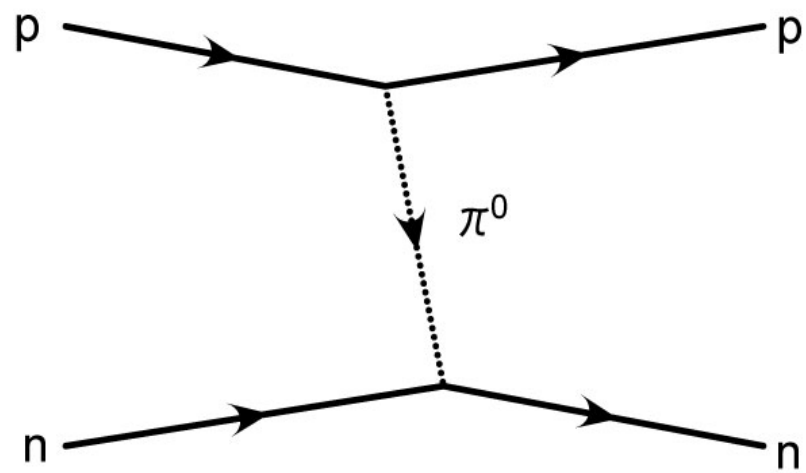
The nuclear challenge

1. Many-body problem

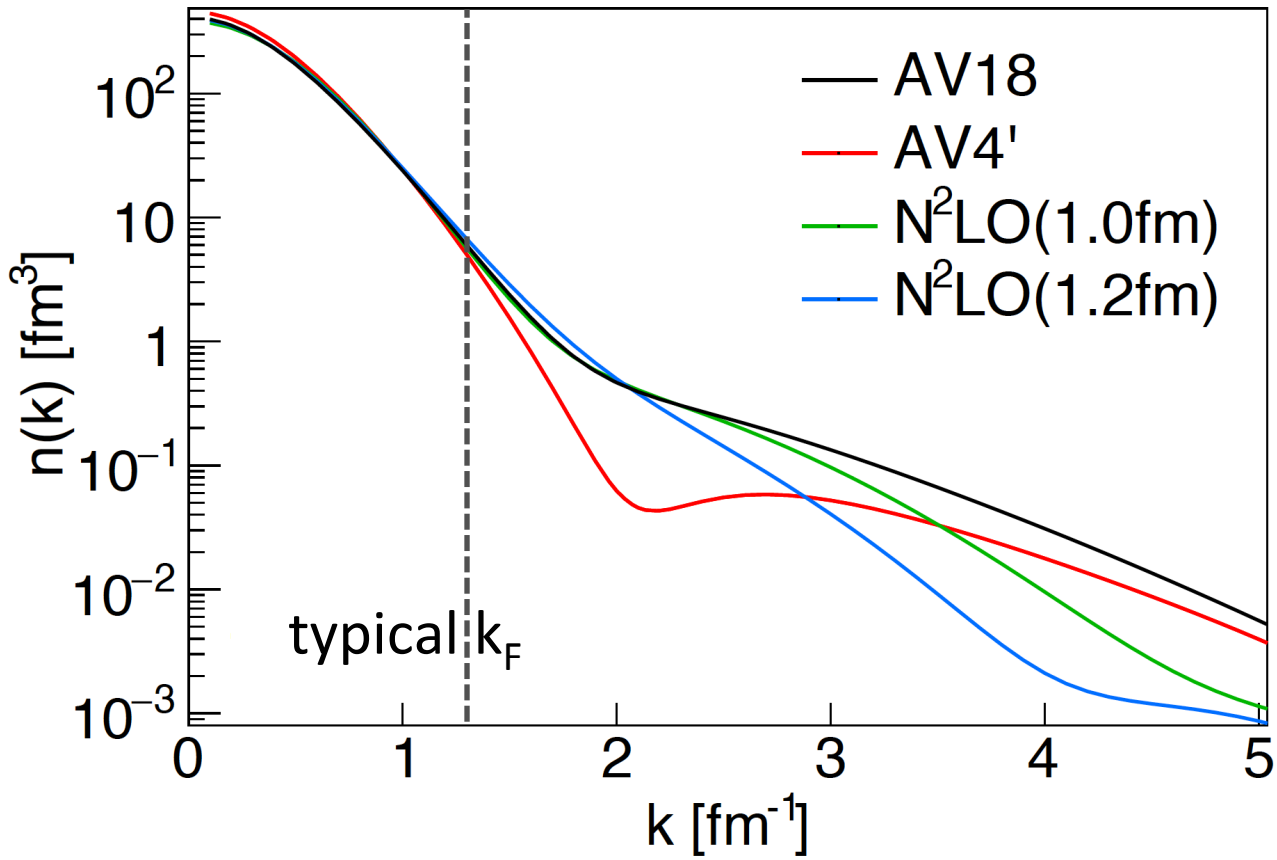
Numerical techniques -> Quantum Monte Carlo

2. Complex ~~QCD~~ **Effective interaction**





Variational (Quantum) Monte Carlo



Calculations agree in low-k but disagree for $k>k_F$

Need to put these to test!

Interpreting Short-Range Correlations:

Electron Scattering data

Generalized Contact Formalism

Experiment

Effective theory

Interpreting Short-Range Correlations:

Electron Scattering data

Generalized Contact Formalism

Hen Lab

Laboratory for Nuclear Science @ MIT

Jefferson Lab

Reynier Cruz Torres

JLab Users Meeting

June 26th, 2019

In this talk

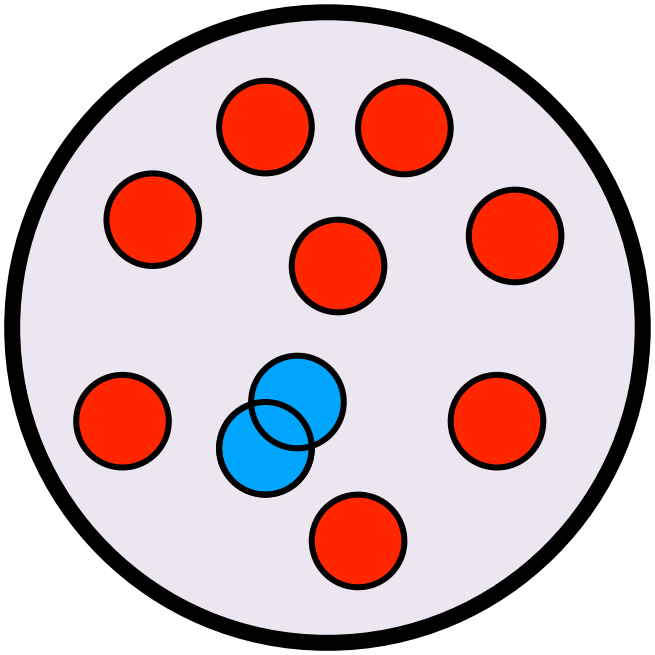
- ❑ Generalized Contact Formalism (GCF)
  - Scale separation in nuclear systems
- ❑ GCF across different NN models
  - short-r, high-k equivalence
  - Scale and Scheme (in)dependence of SRCs
- ❑ GFC application to electron-scattering cross sections
  - Accessing the NN repulsive core

Factorization in nuclear systems

Scale separation at short distances

⇩

Factorization of the nuclear wavefunction



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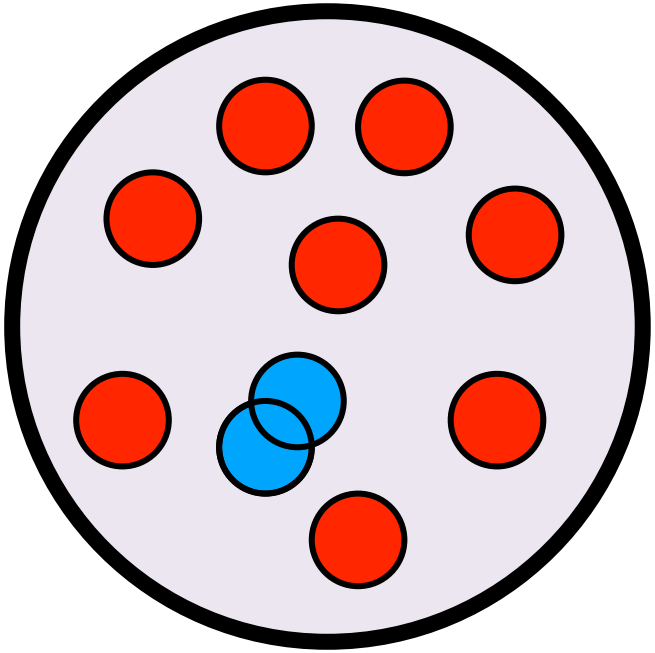
Factorization of the nuclear wavefunction



$$\Psi \xrightarrow{r_{ij} \to 0} \varphi(r_{ij}) \times A_{ij}(R_{ij}, \{r\}_{k \neq ij})$$

Many-body nuclear wave-function

two-body wave-function

A-2 residual system

Short-r 2-body density in the GCF

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

Short-r 2-body density in the GCF

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

Nuclear 2-body coordinate density

scaling constants called **Contacts**

(nucleus dependent)

zero-energy solution of 2-body Schrödinger equation

(universal)

High-k 2-body density in the GCF

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

$$\rho_A^{NN,\alpha}(q) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(q)|^2$$

Nuclear 2-body momentum density

scaling constants called **Contacts**

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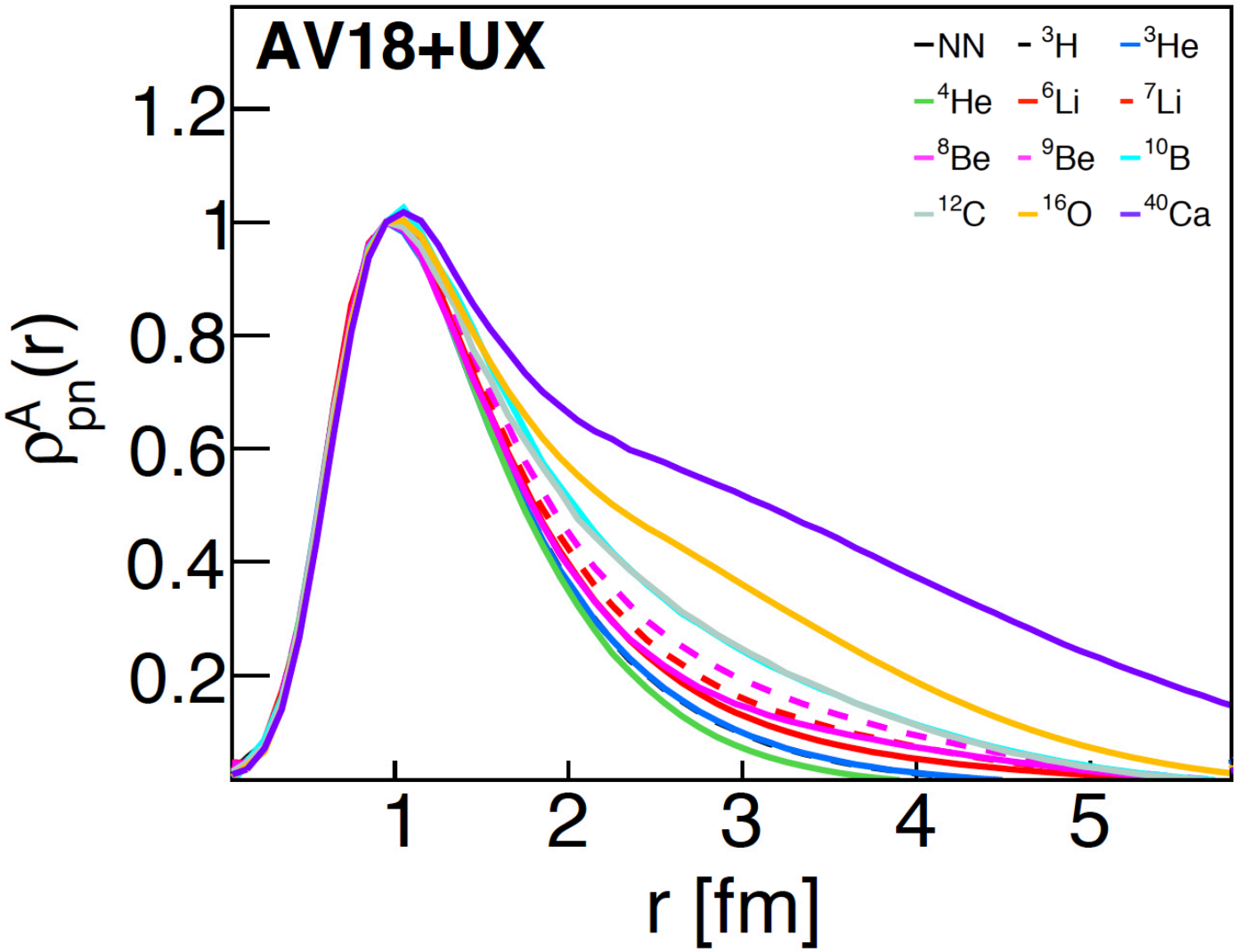
Short-r universality

$$\rho_A^{NN,\alpha}(r)$$



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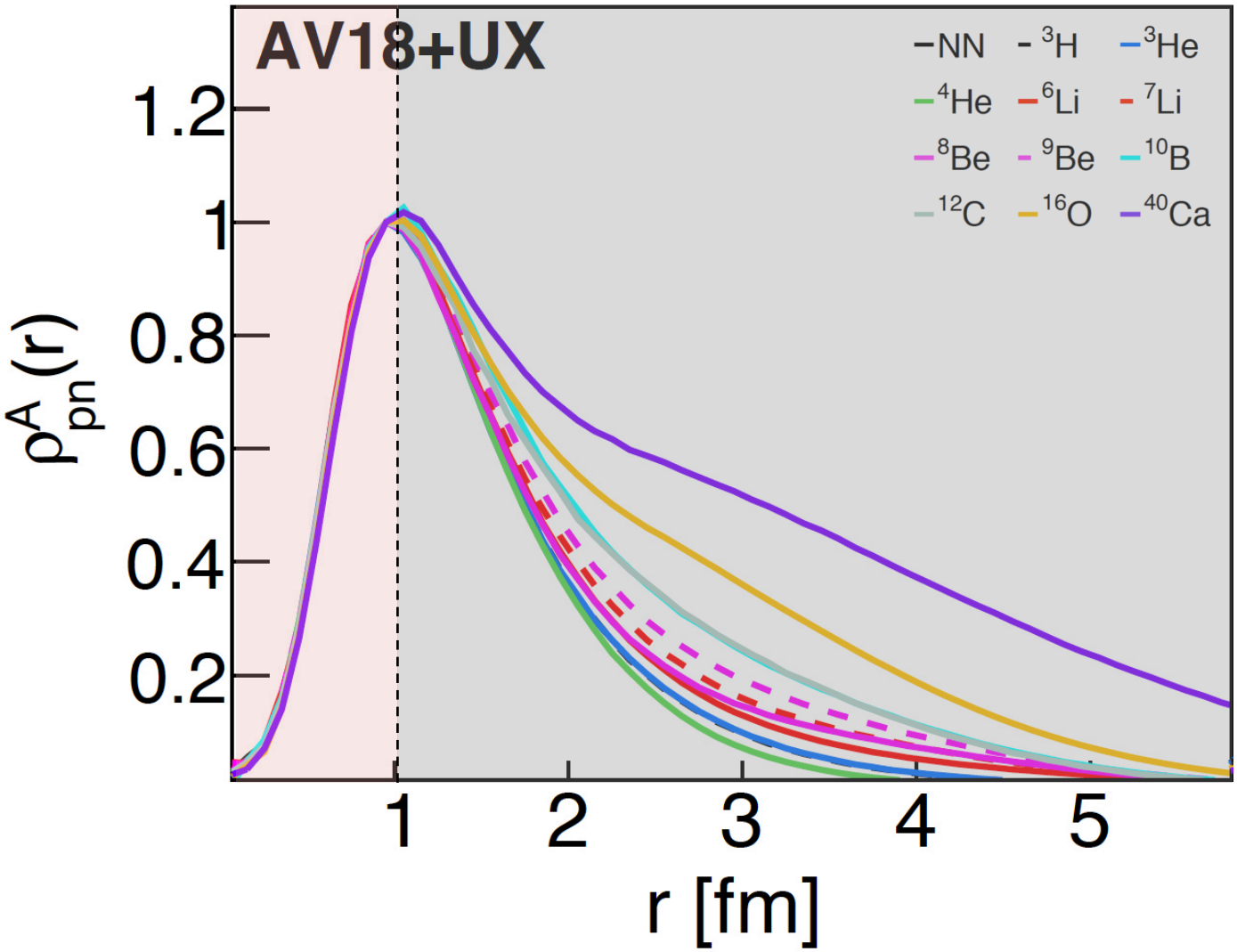

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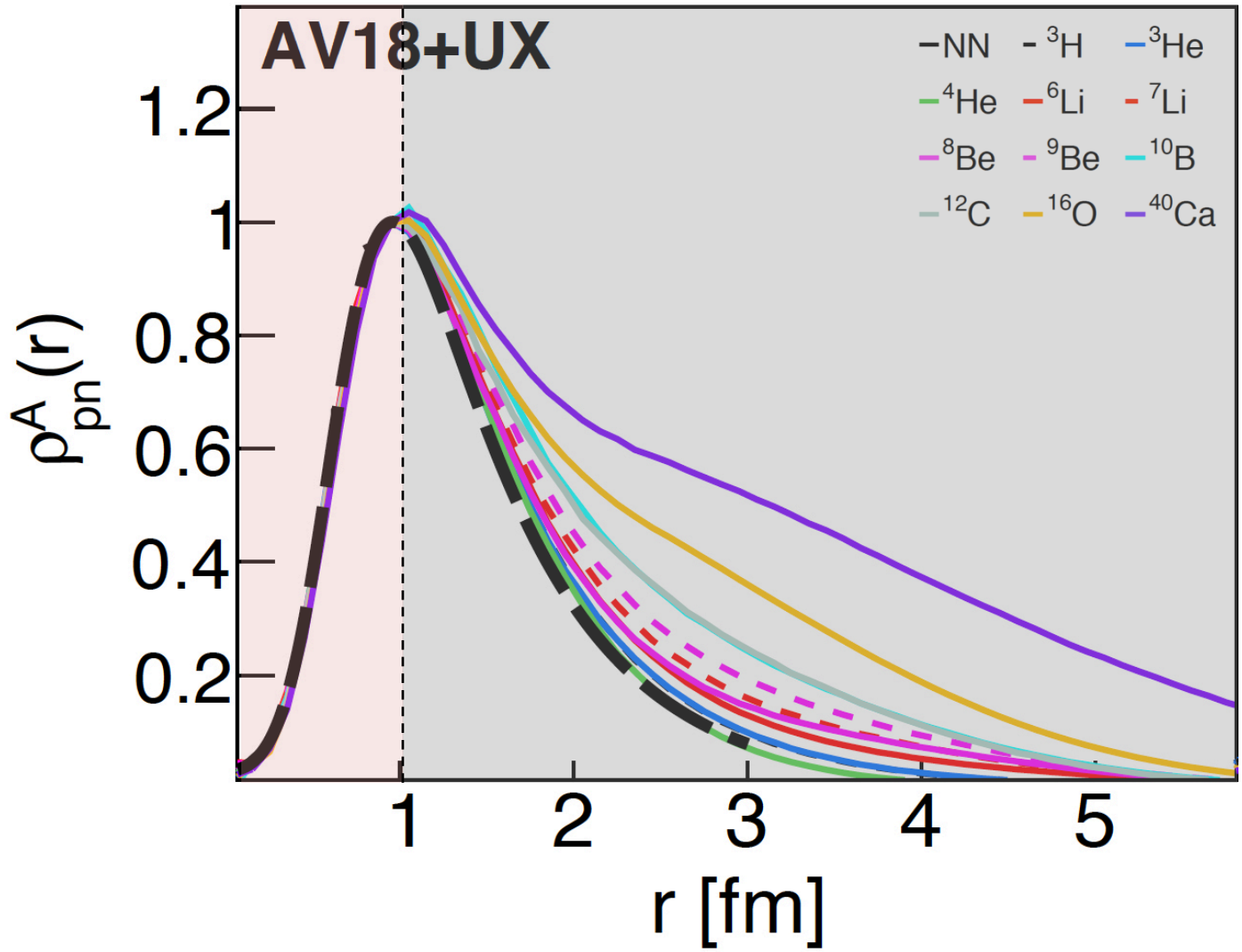

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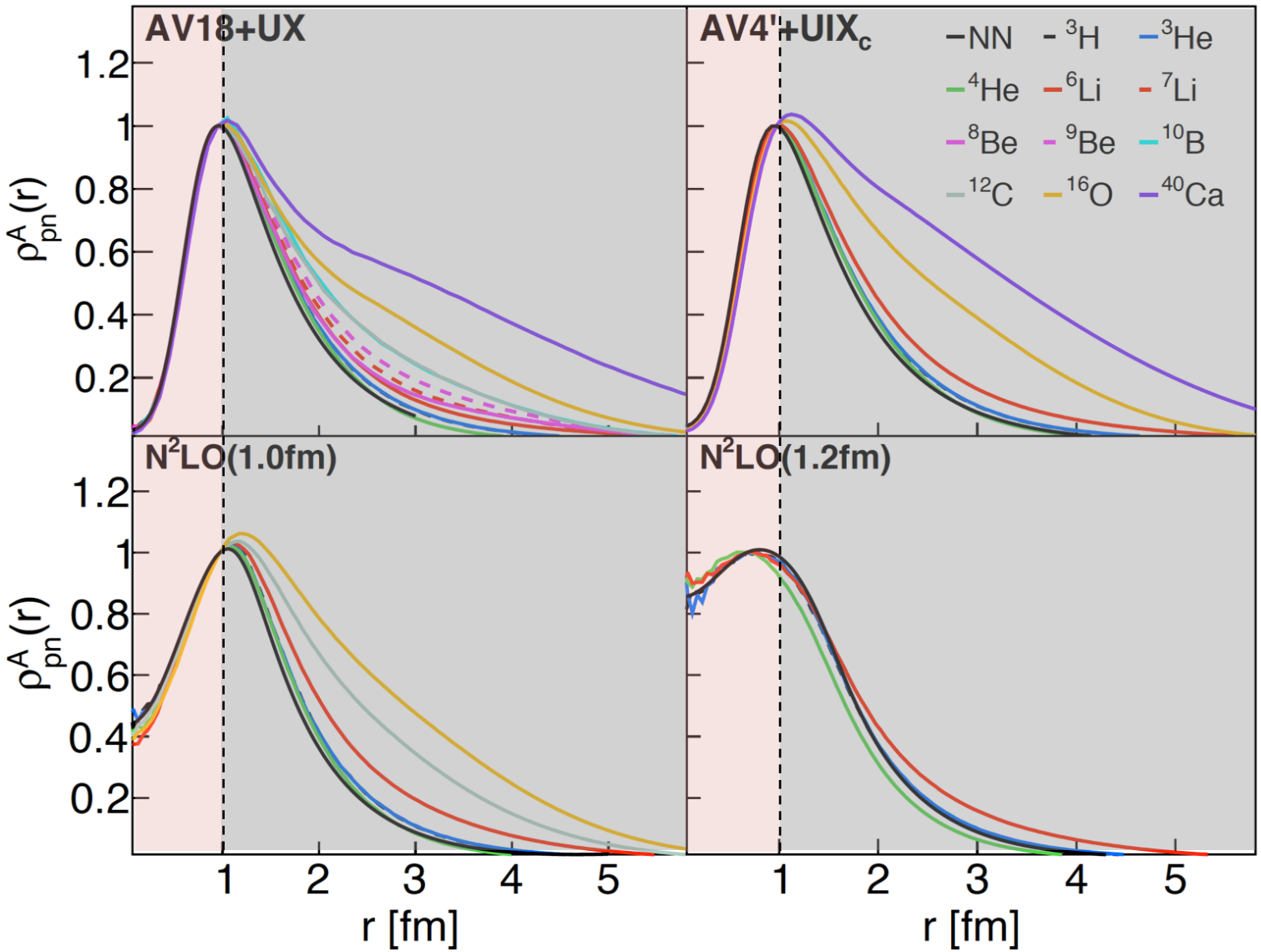
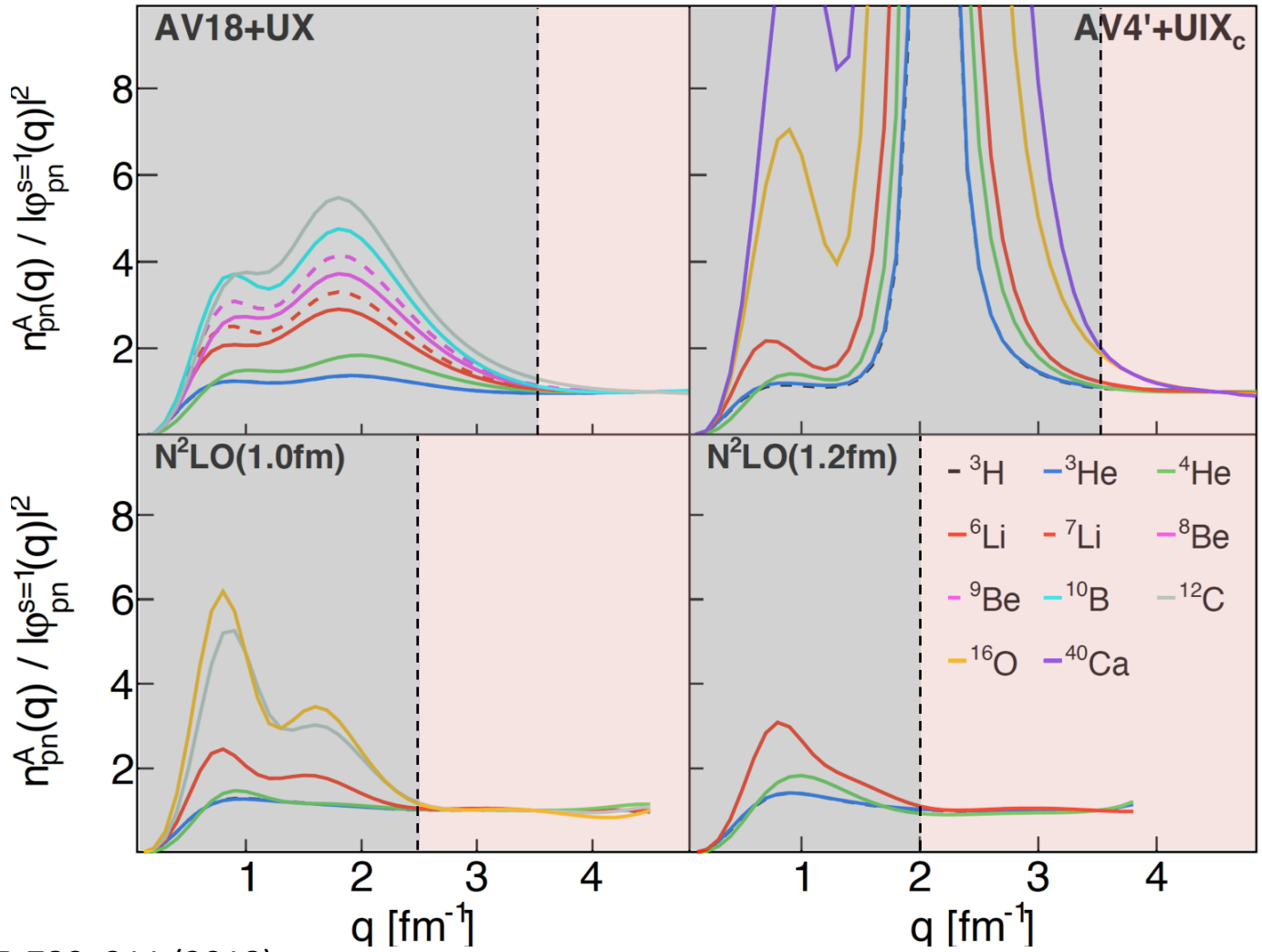


High-k universality

$$\frac{\rho_A^{NN,\alpha}(q)}{|\varphi_{NN}^{\alpha}(q)|^2} = C_A^{NN,\alpha}$$



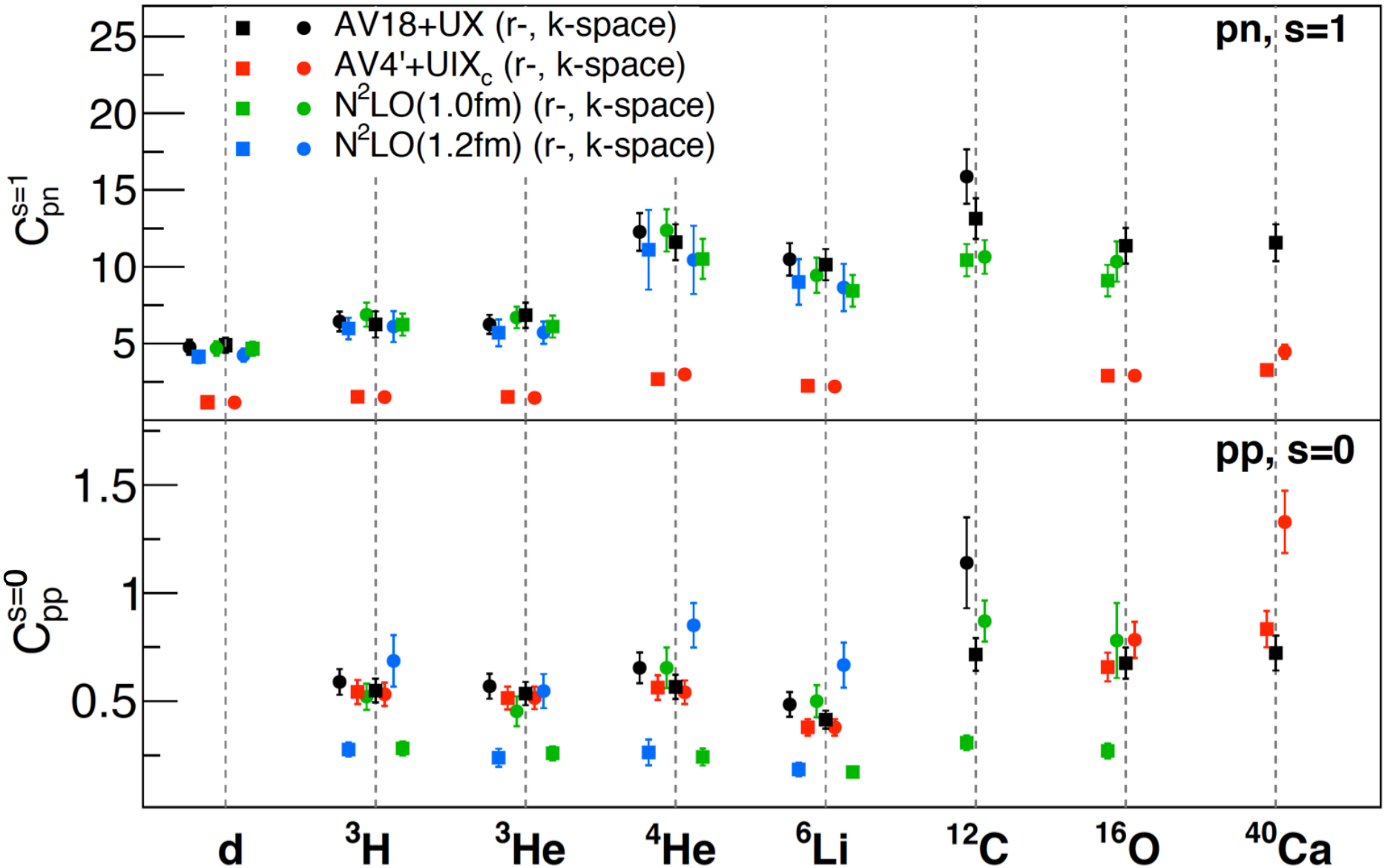
Weiss, **Cruz-Torres** et al., PLB 780, 211 (2018)

Cruz-Torres, Schmidt et al., PLB 785 304 (2018)

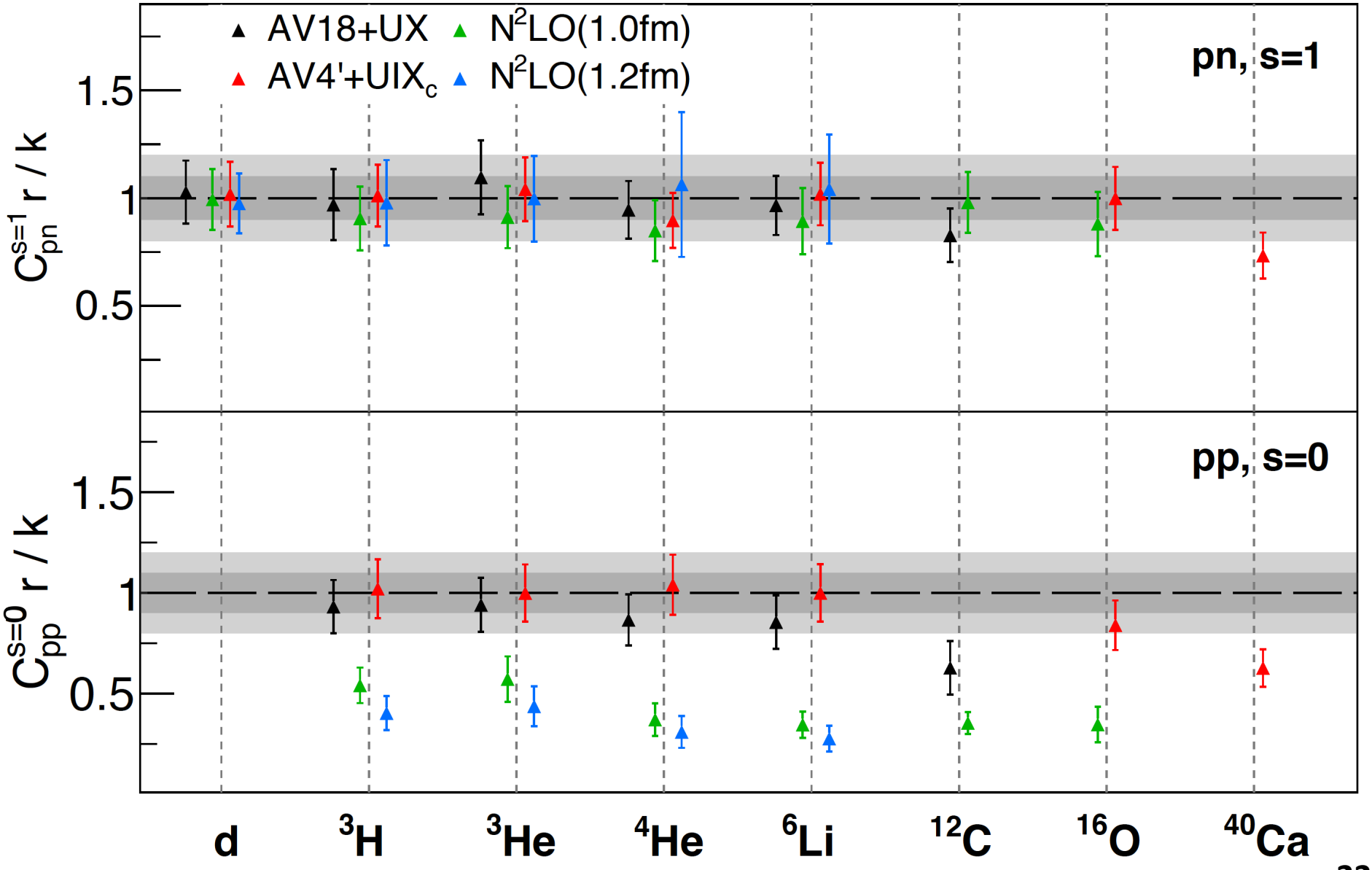
Weiss et al., PLB 791, 242 (2019)

Cruz-Torres, Lonardoni et al., In preparation (2019).

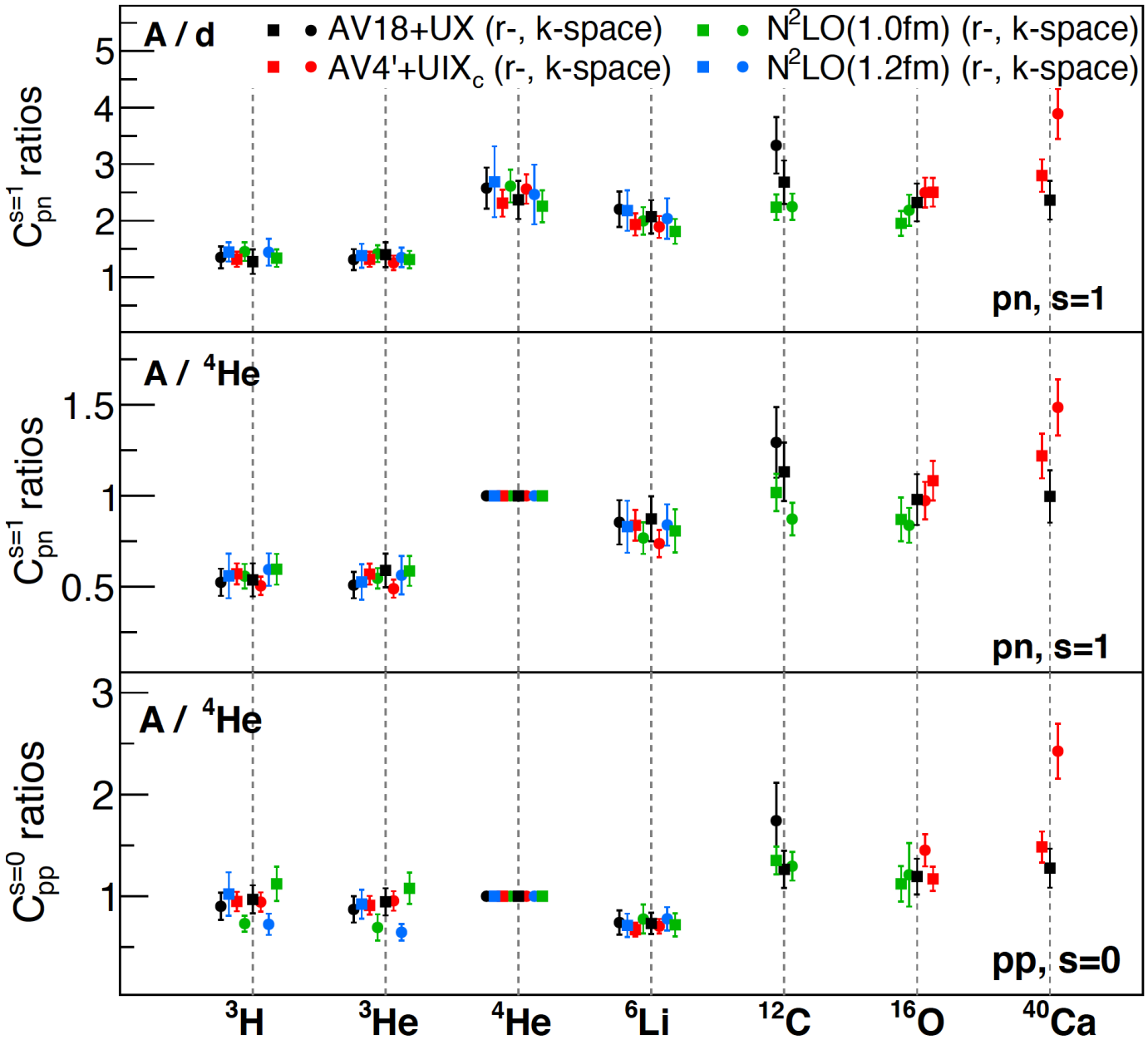
Nuclear Contacts



coordinate – momentum equivalence



Scale & Scheme Independence



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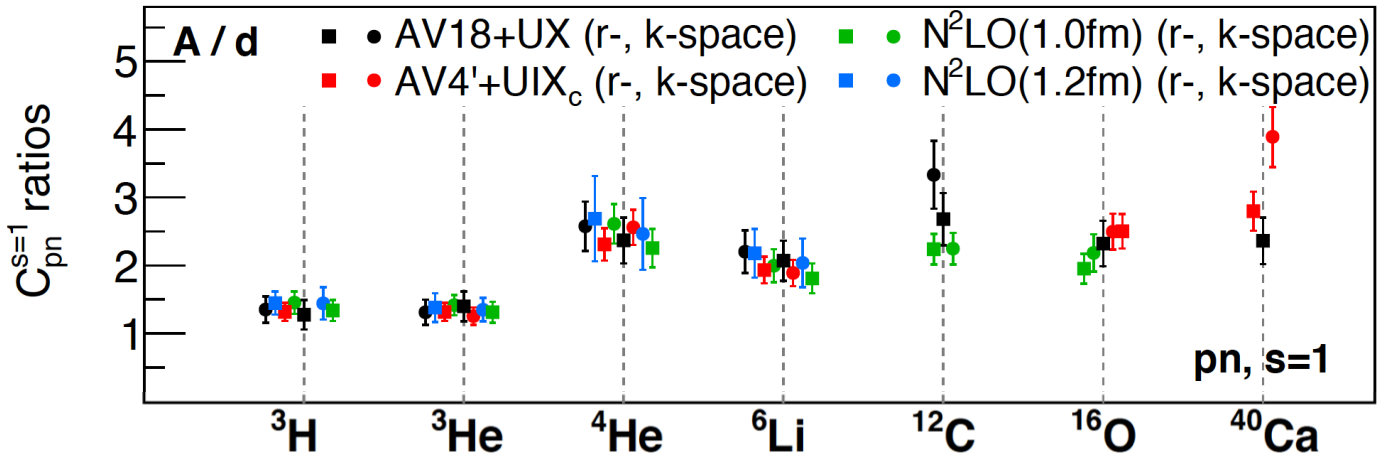
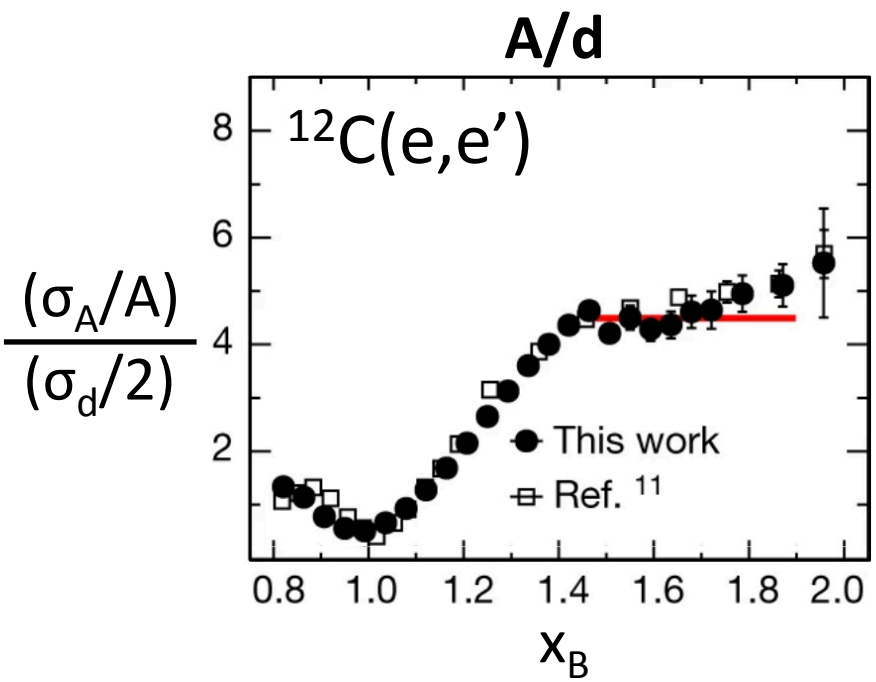
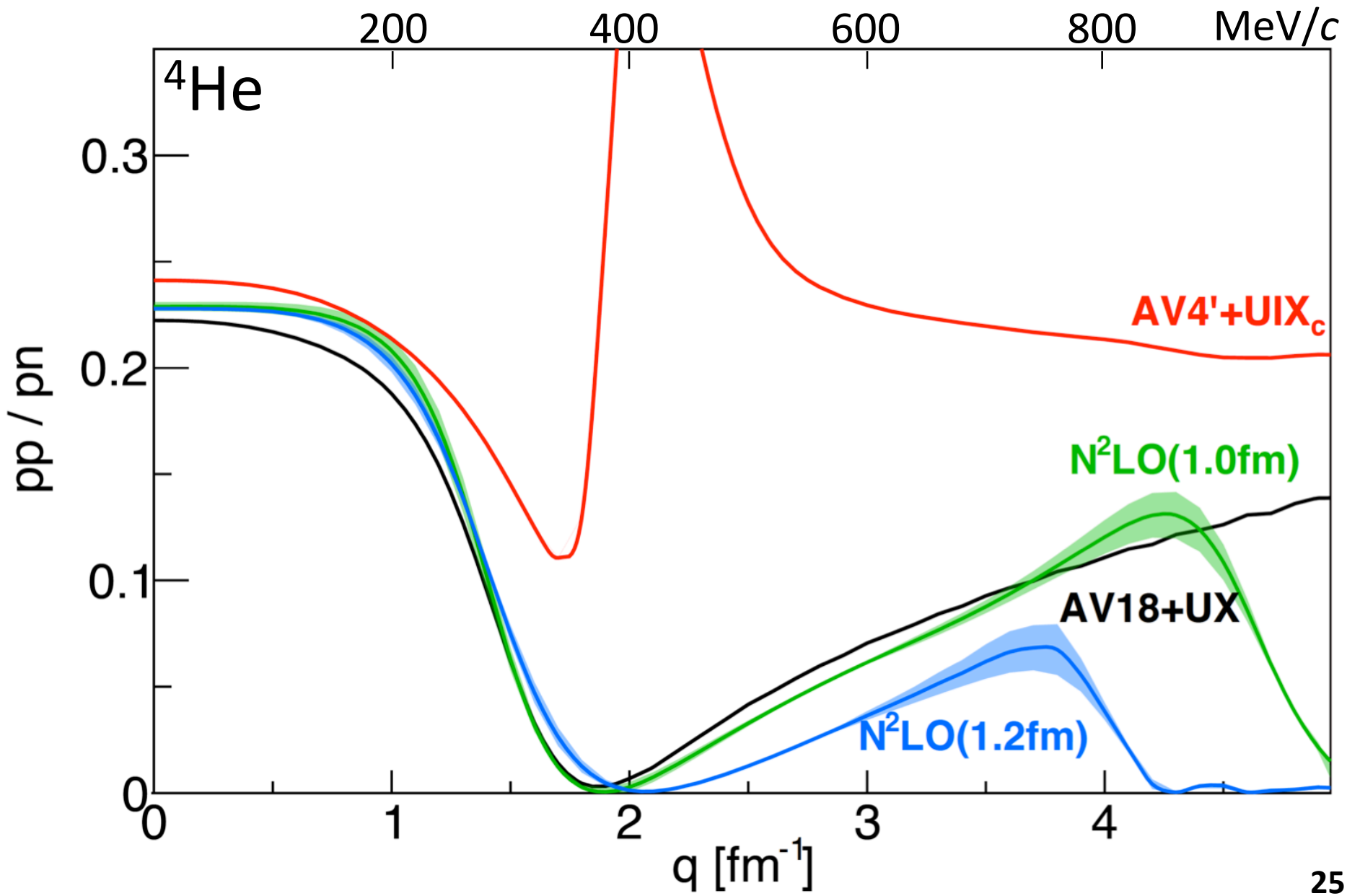


- SRC abundance is a Mean Field property.
- Inclusive measurements are insensitive to the NN interaction details at show distance.

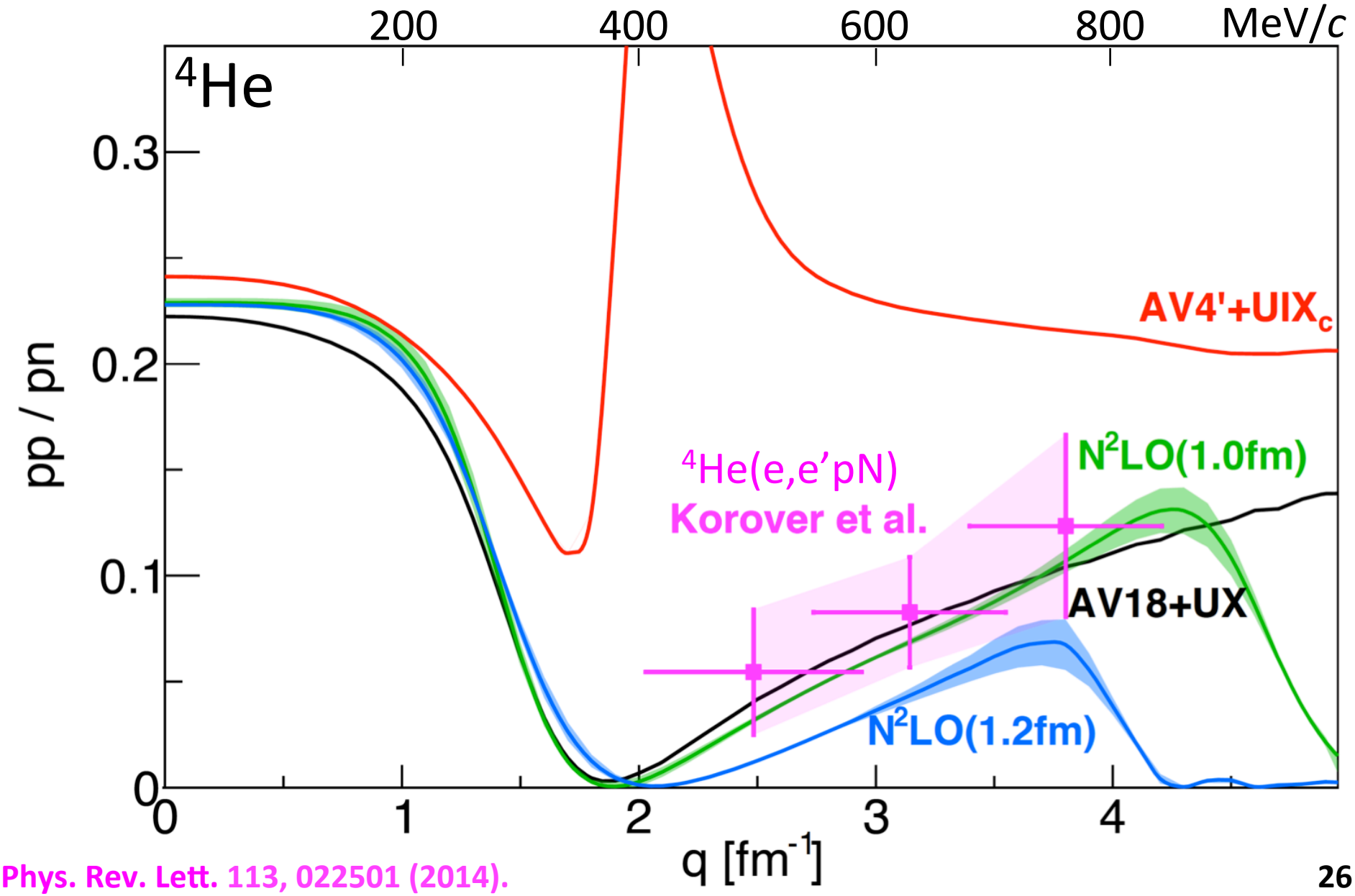


Fomin et al., PRL 108, 092502 (2012).
B.Schmookler, et al., Nature 566, 354-358 (2019)

pp / pn fraction

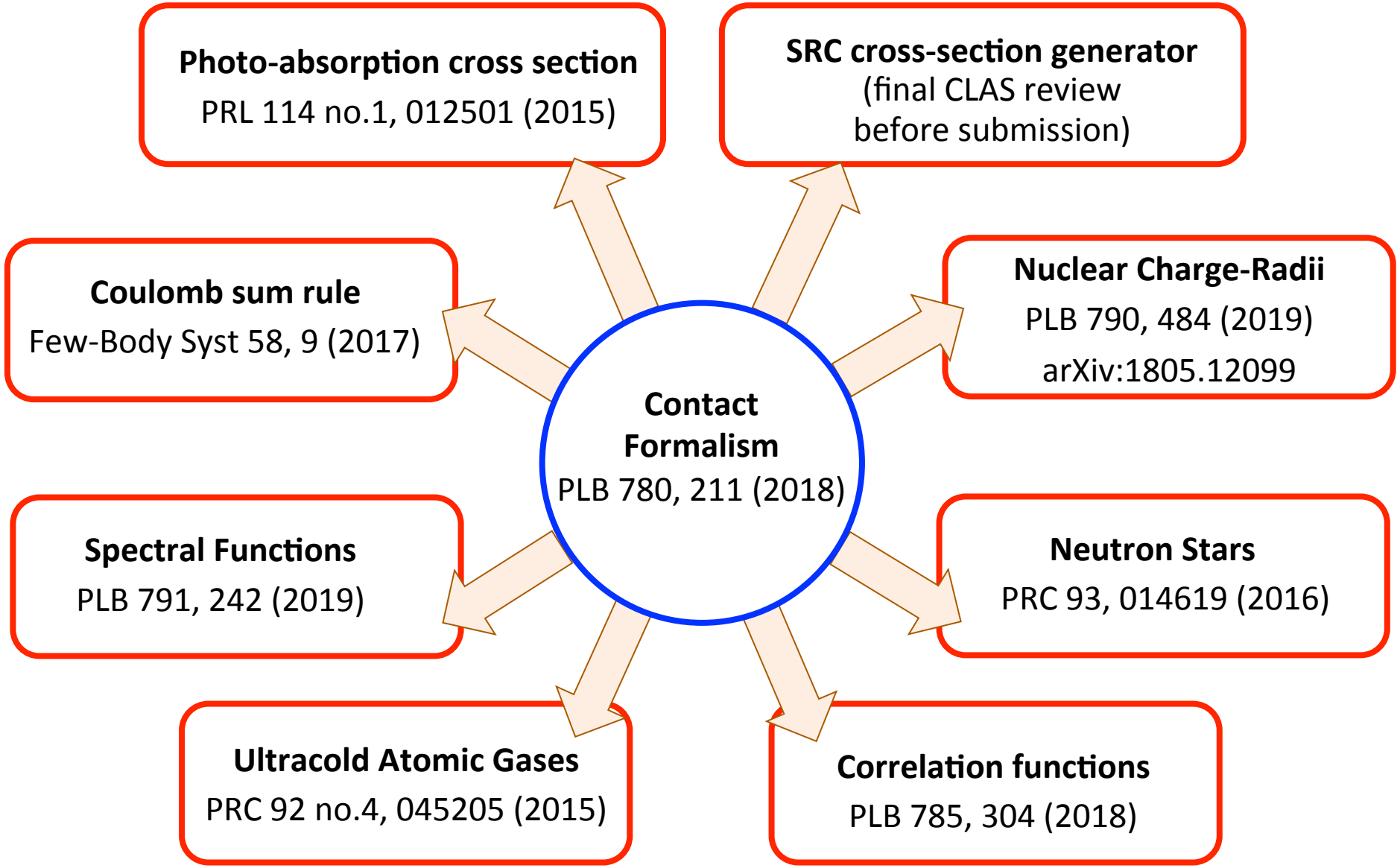


Exclusive measurements



Phys. Rev. Lett. 113, 022501 (2014).

Contact formalism is being applied to:



Contact formalism is being applied to:

Contact Formalism
PLB 780, 211 (2018)

Photo-absorption cross section
PRL 114 no.1, 012501 (2015)

SRC cross-section generator
(final CLAS review before submission)

Coulomb sum rule
Few-Body Syst 58, 9 (2017)

Nuclear Charge-Radii
PLB 790, 484 (2019)
arXiv:1805.12099

Spectral Functions
PLB 791, 242 (2019)

Neutron Stars
PRC 93, 014619 (2016)

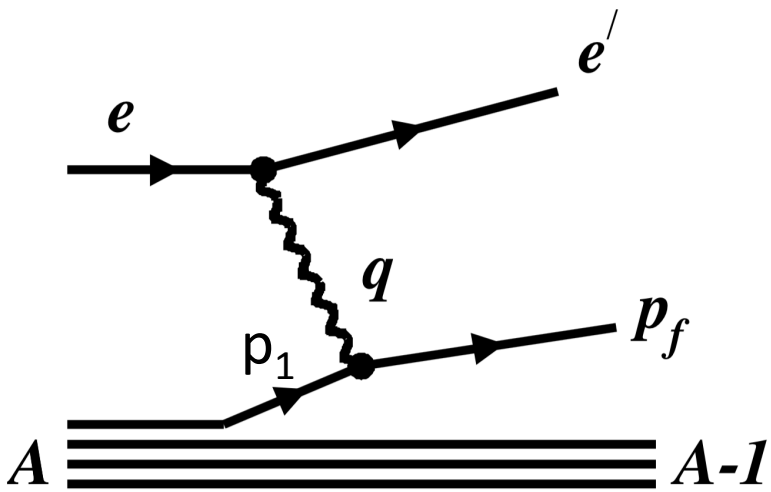
Ultracold Atomic Gases
PRC 92 no.4, 045205 (2015)

Correlation functions
PLB 785, 304 (2018)

Electron scattering and GFC Spectral Function

Spectral function: probability to find a nucleon with momentum p_1 and separation energy E_1.

$$d\sigma_{PWIA} \propto \sigma_{eN} \cdot S(E_1, p_1)$$



Assuming the q vector was absorbed by a single nucleon:

$$\vec{p}_1 = \vec{P}_{miss} = \vec{p}_f - \vec{q}$$

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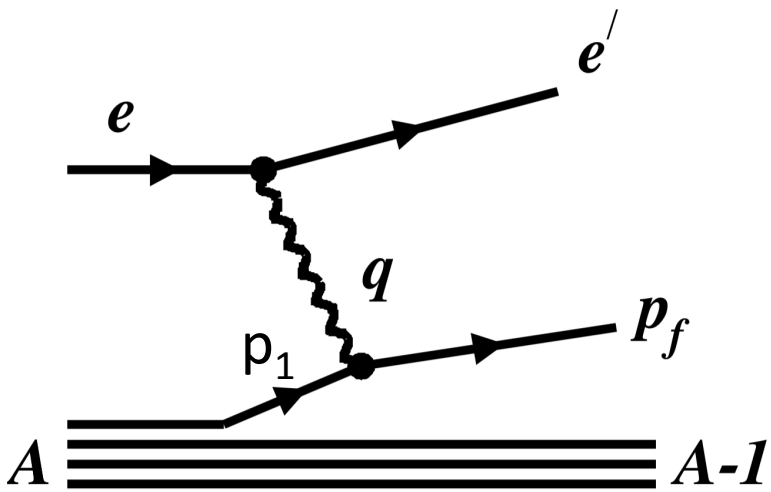

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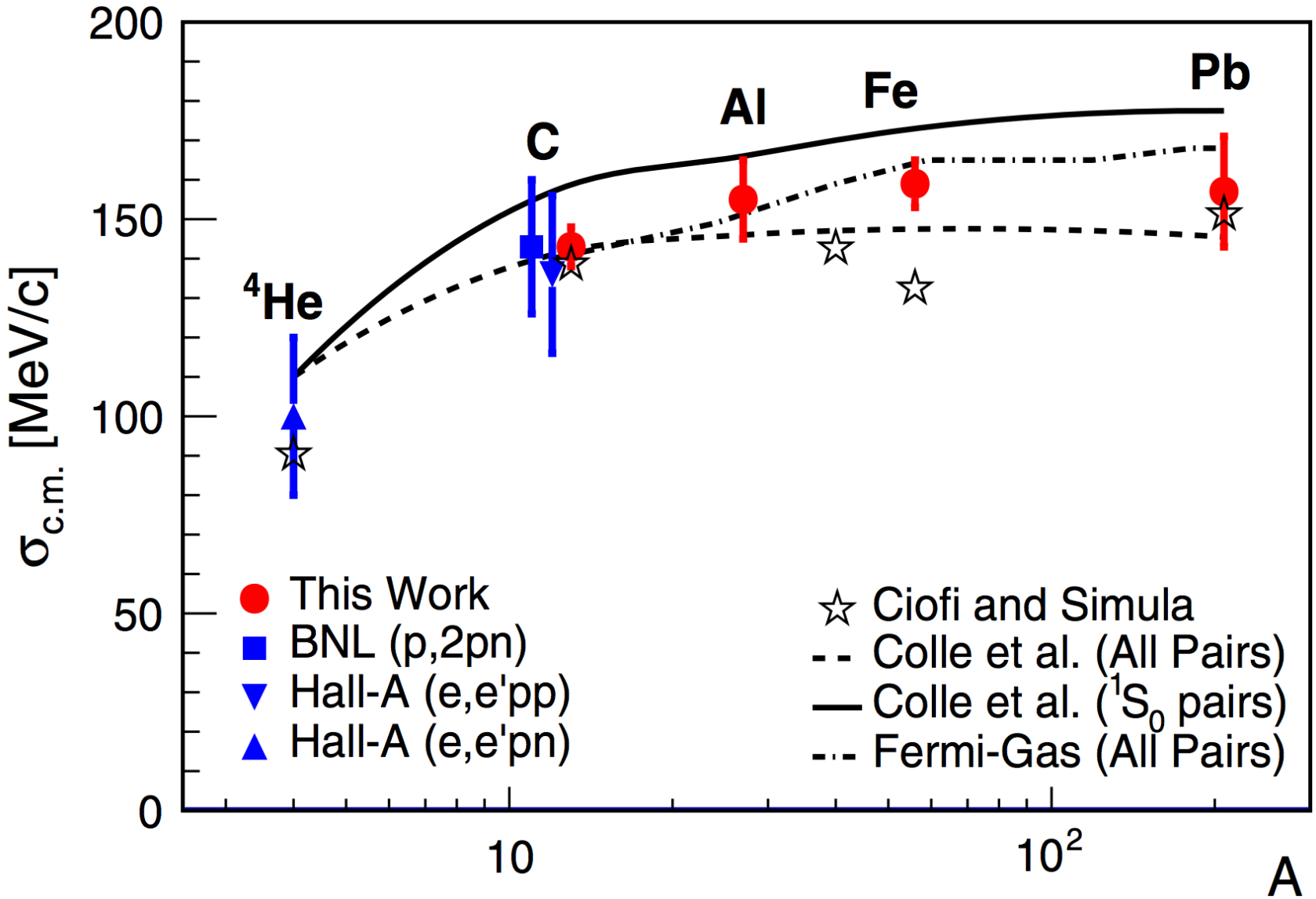
$$S(E_1, p_1) = \sum_{\alpha} C_A^{\alpha} \int \frac{d^3 p_2}{(2\pi)^3} |\varphi^{\alpha}(q)|^2 \, n(Q) \, \delta(E_i - E_f)$$

R. Weiss et al., PLB 790 p 241 (2019)

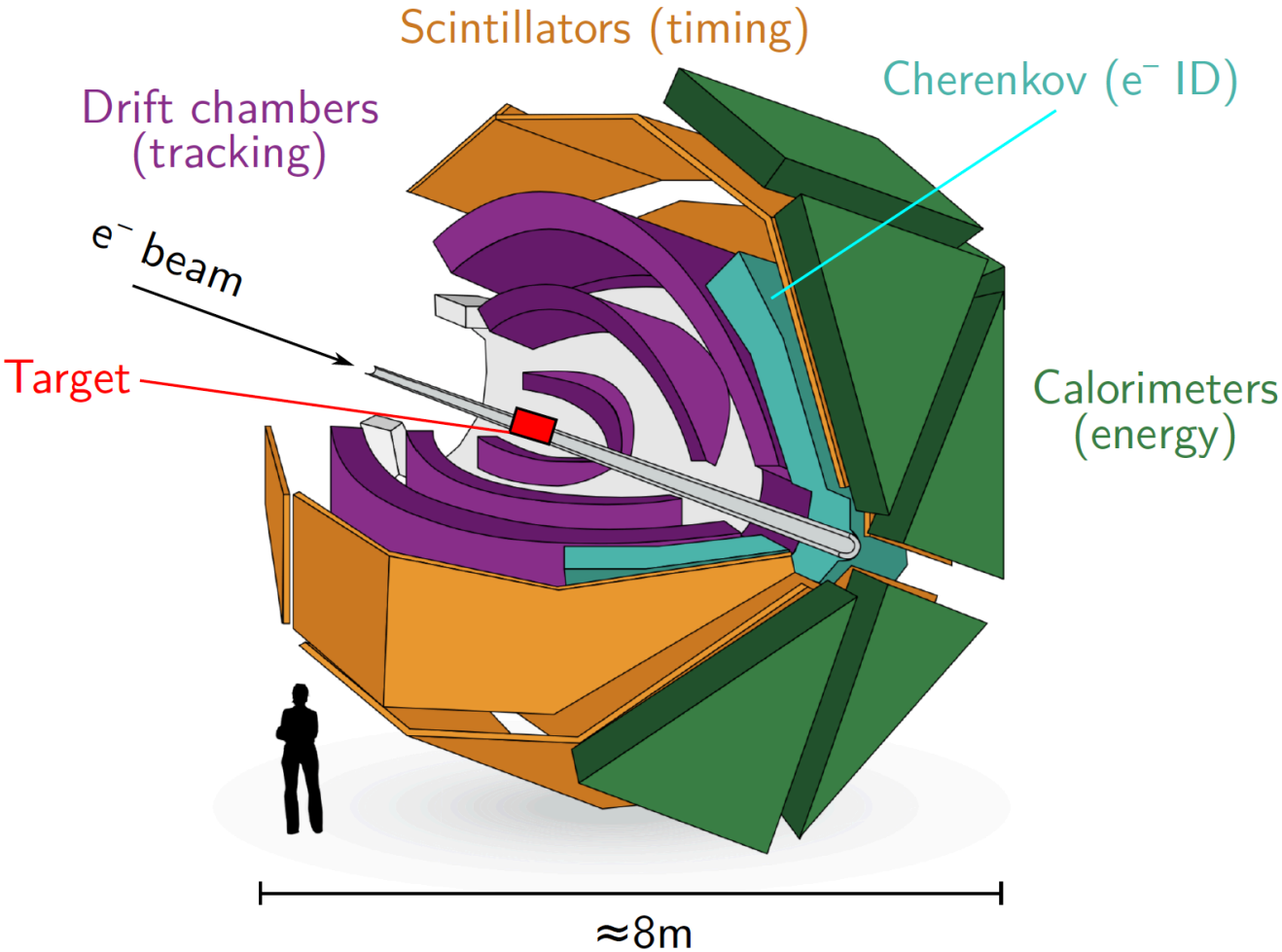
Center-of-mass momentum distribution



E.O. Cohen et al., PRL 121 092501 (2018)

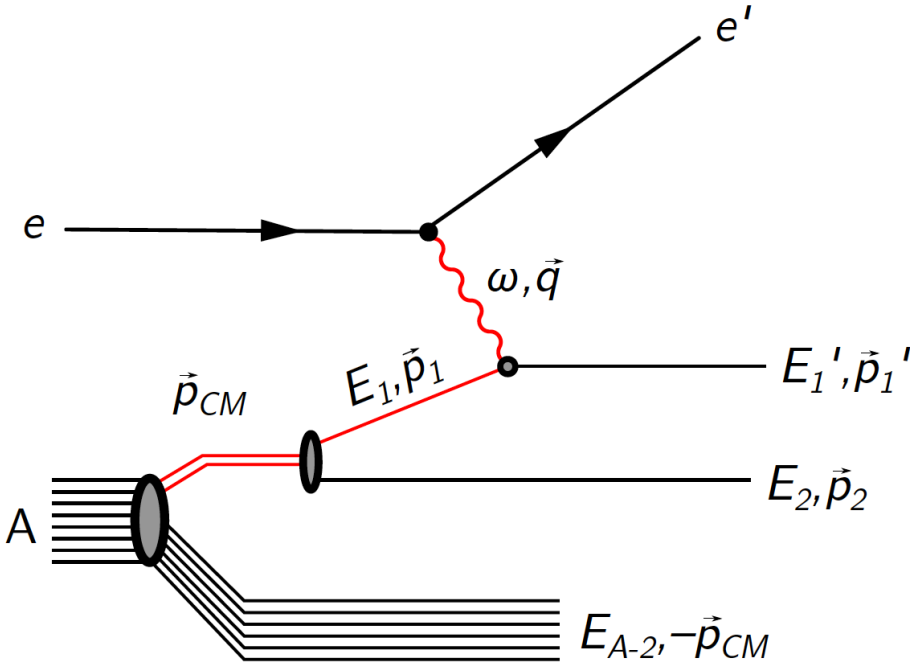
EG2 data from CLAS

- ❑ 5 GeV e- beam
- ❑ C, Al, Fe, Pb
- ❑ CLAS detector



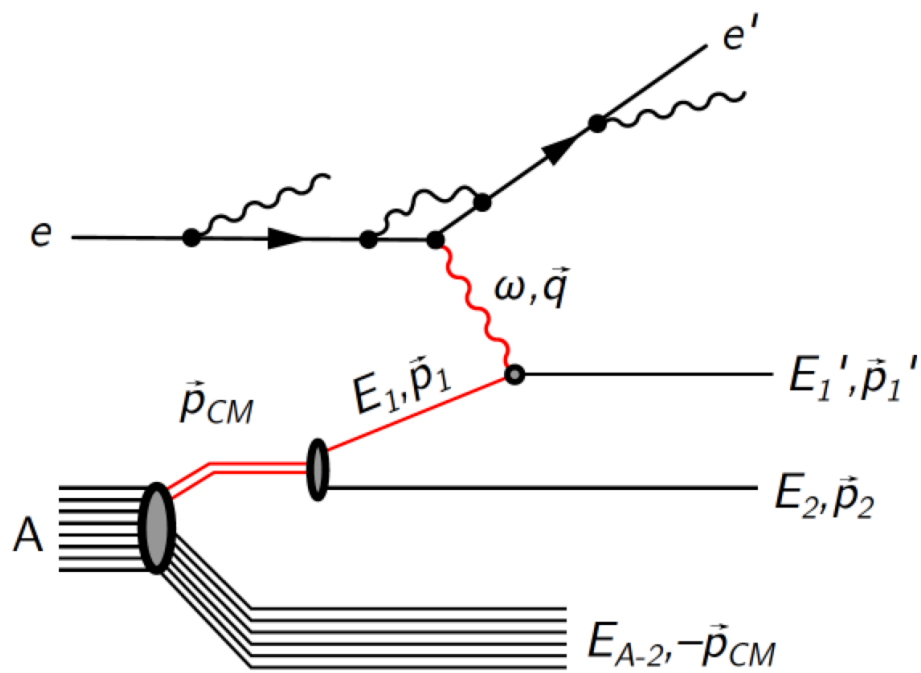
Forward-propagating the model to the data

1 Generate events according to GCF



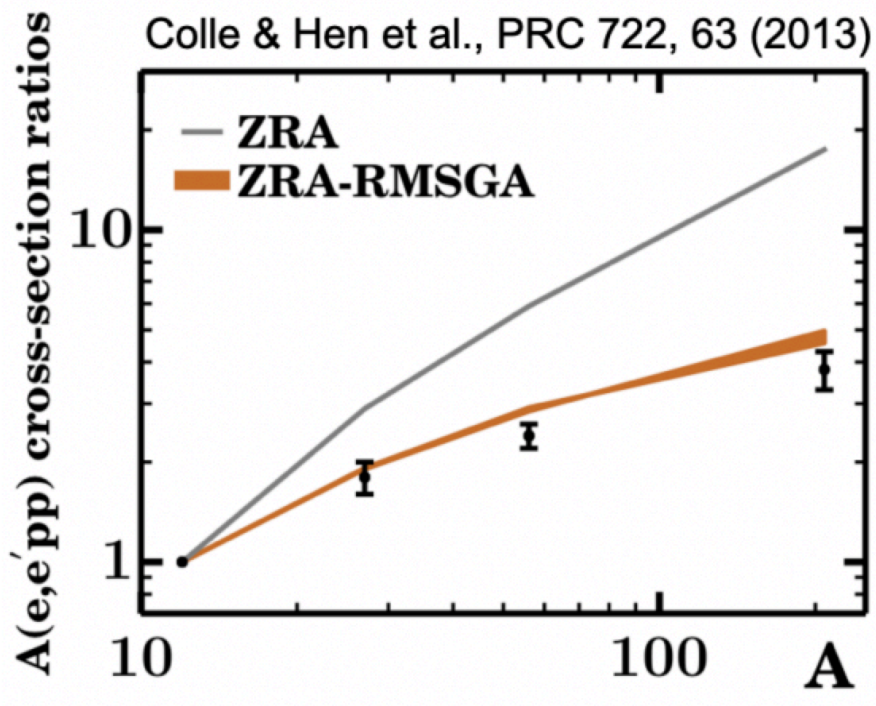
Forward-propagating the model to the data

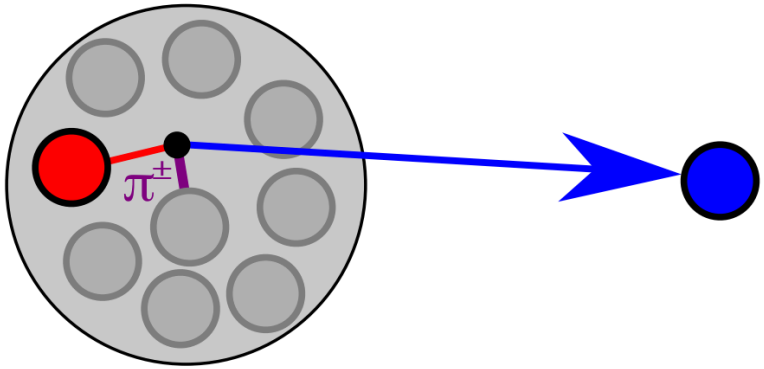
1. Generate events according to GCF
2. Radiative effects



Forward-propagating the model to the data

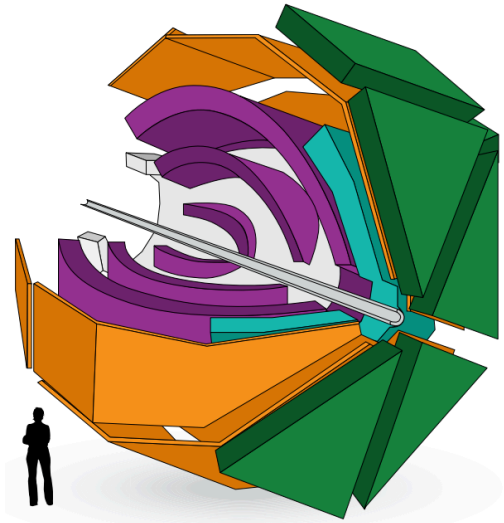
1. Generate events according to GCF
2. Radiative effects
3. Transparency/SCX using Glauber

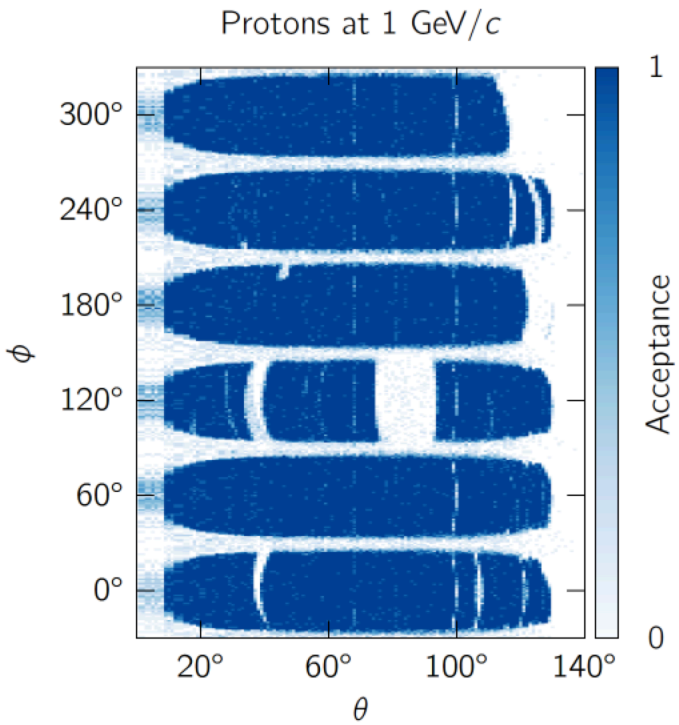




Forward-propagating the model to the data

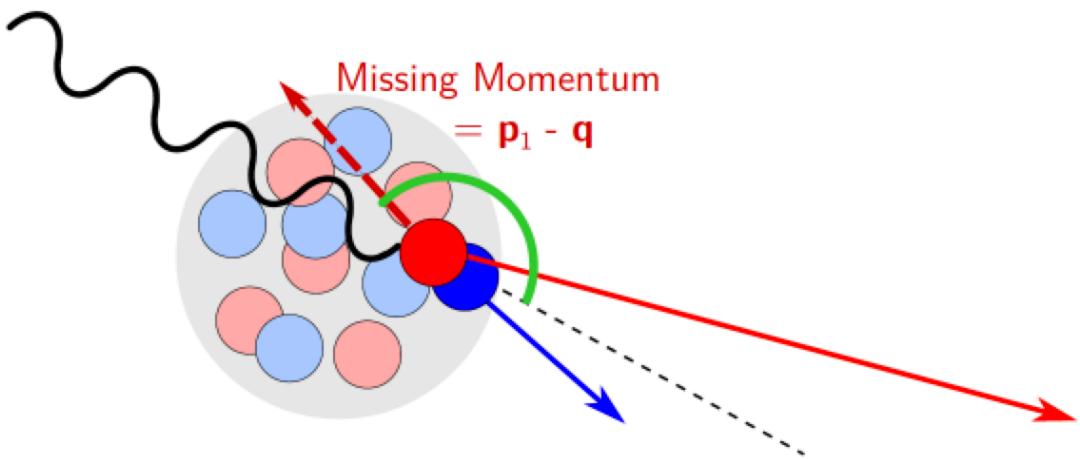
1. Generate events according to GCF
2. Radiative effects
3. Transparency/SCX using Glauber
4. Detector acceptance





Forward-propagating the model to the data

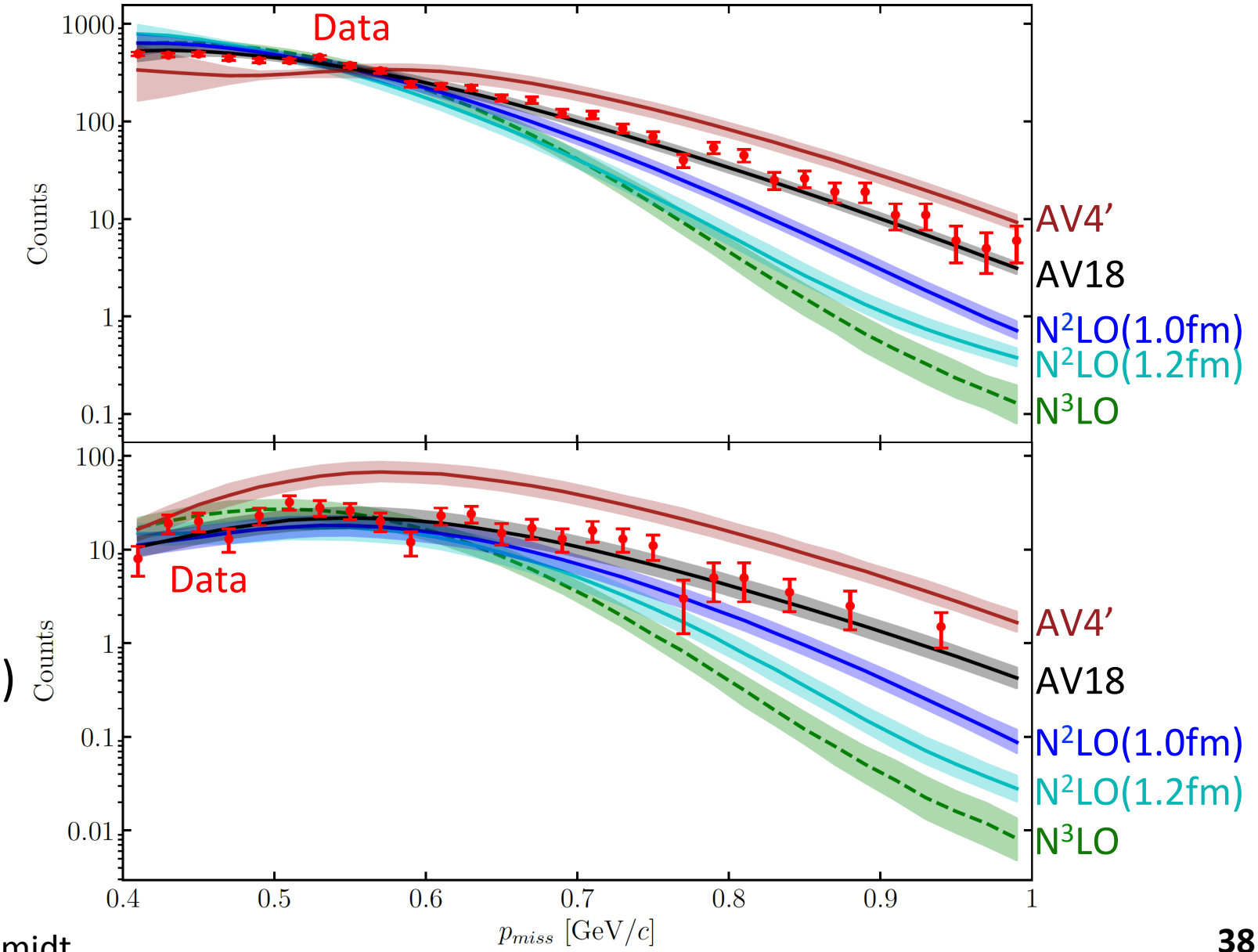
1. Generate events according to GCF
2. Radiative effects
3. Transparency/SCX using Glauber
4. Detector acceptance
5. Same event selection as data



Missing momentum distributions

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

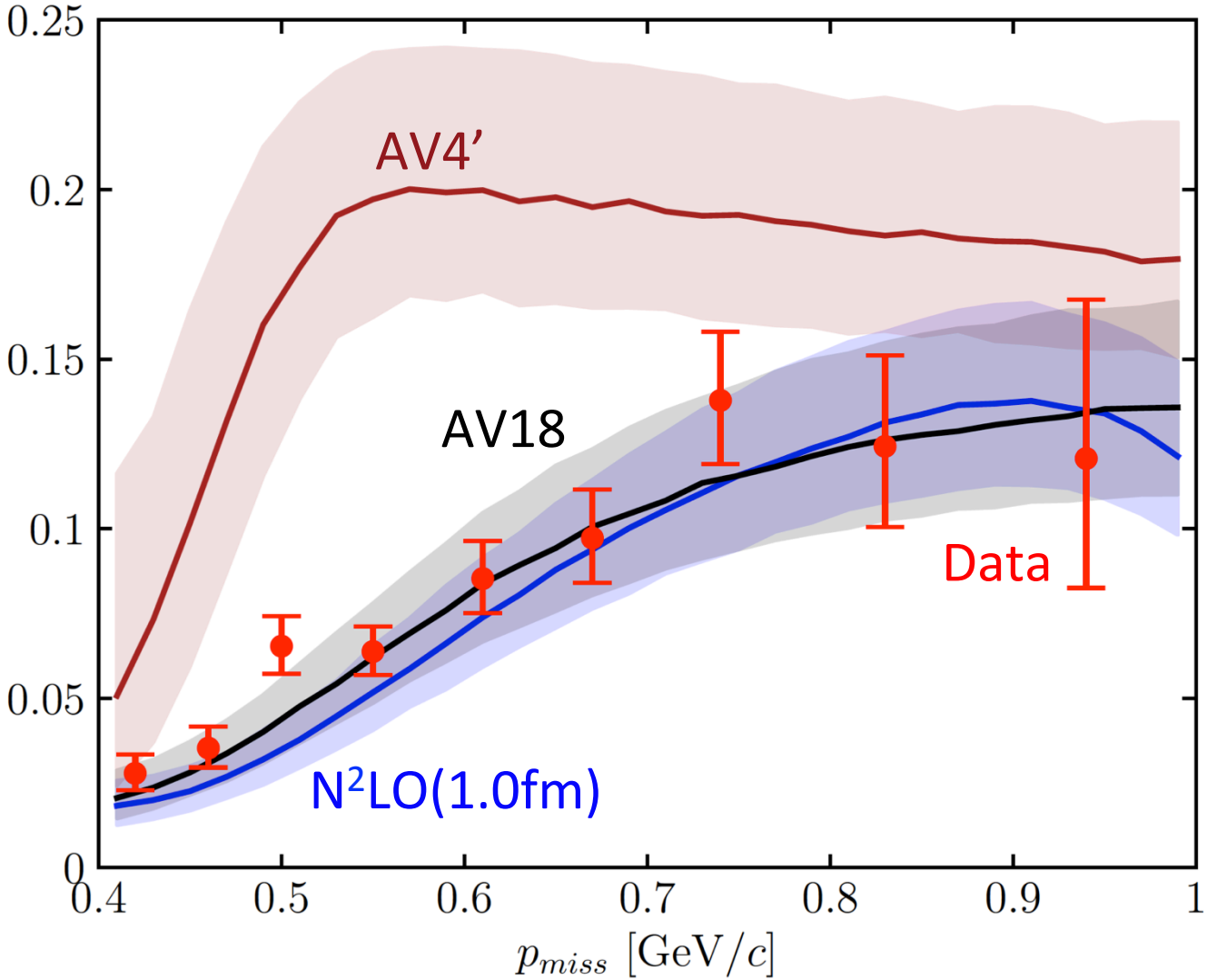
^{12}C(e,e'pp)



A. Schmidt

(e,e'pp)/(e,e'p) ratio

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



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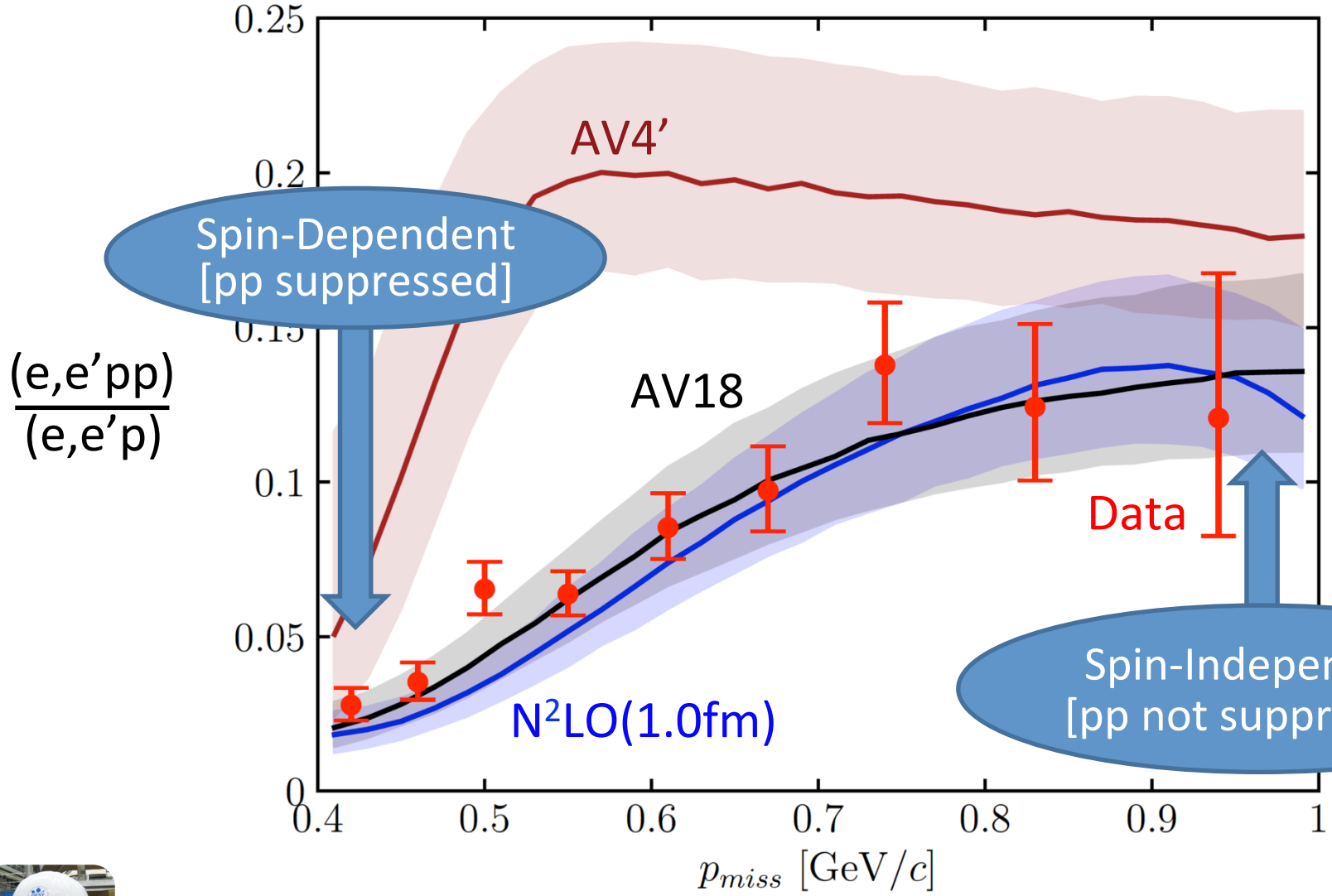
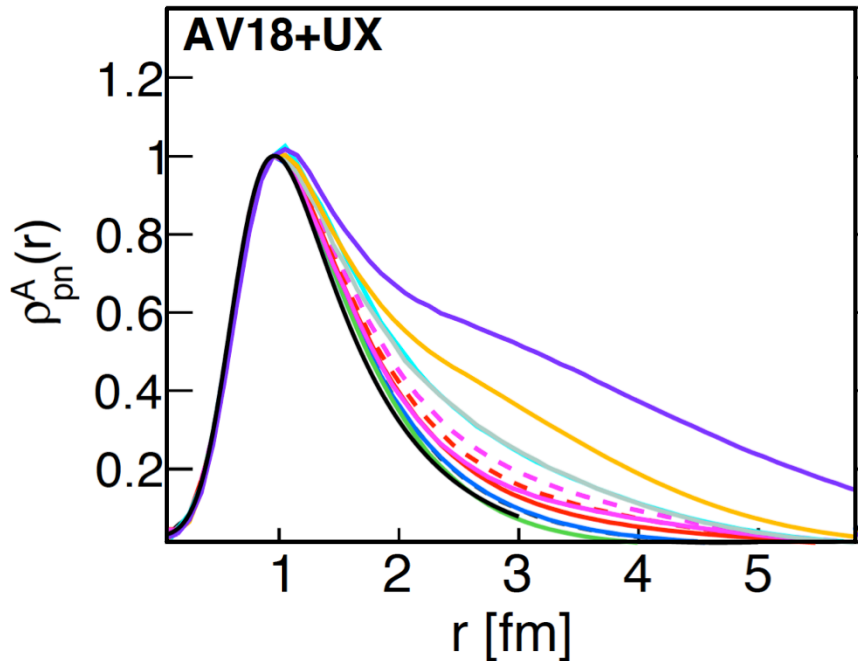


A. Schmidt

To recap:

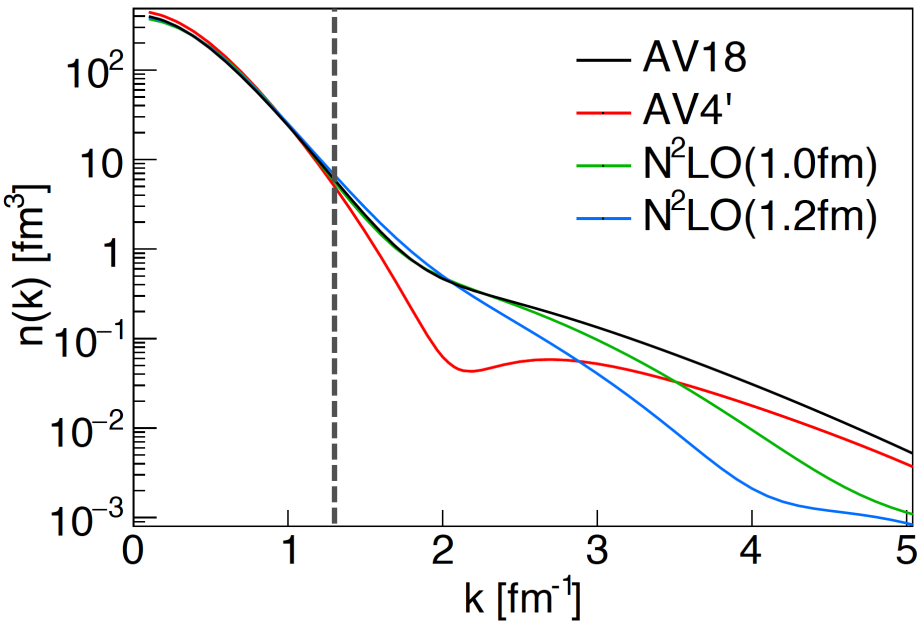
- The GCF describes the many-body nuclear wave-function where SRCs dominate.



To recap:

- The GCF describes the many-body nuclear wave-function where SRCs dominate.

- NN models differ significantly at short-r, high-k.

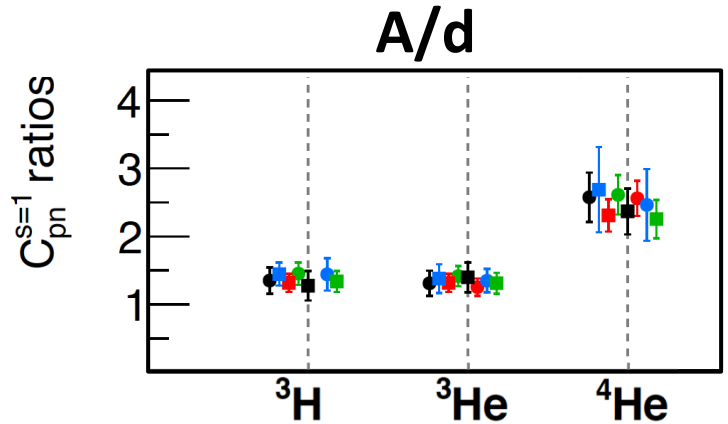


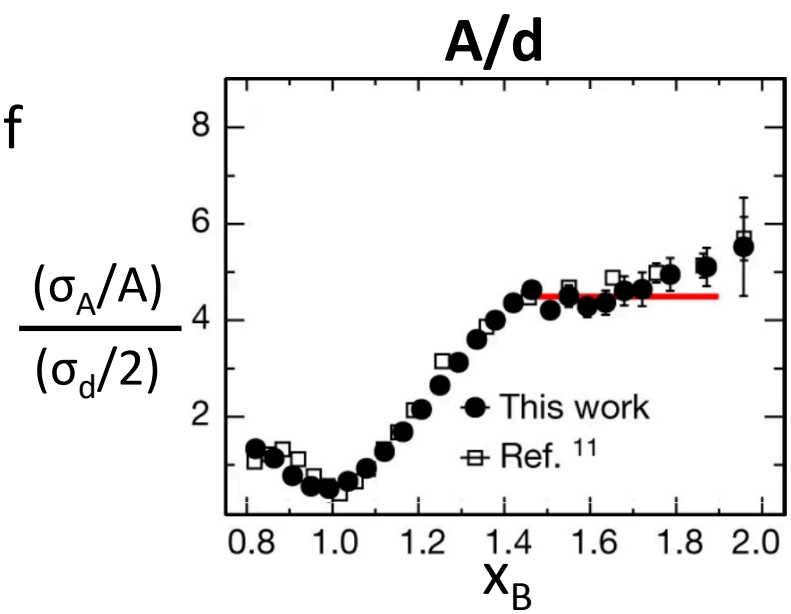
To recap:

- The GCF describes the many-body nuclear wave-function where SRCs dominate.

- NN models differ significantly at short-r, high-k.

- <u>Inclusive</u> (e,e') experiments are <u>insensitive</u> to the short-r structure of the NN interaction.





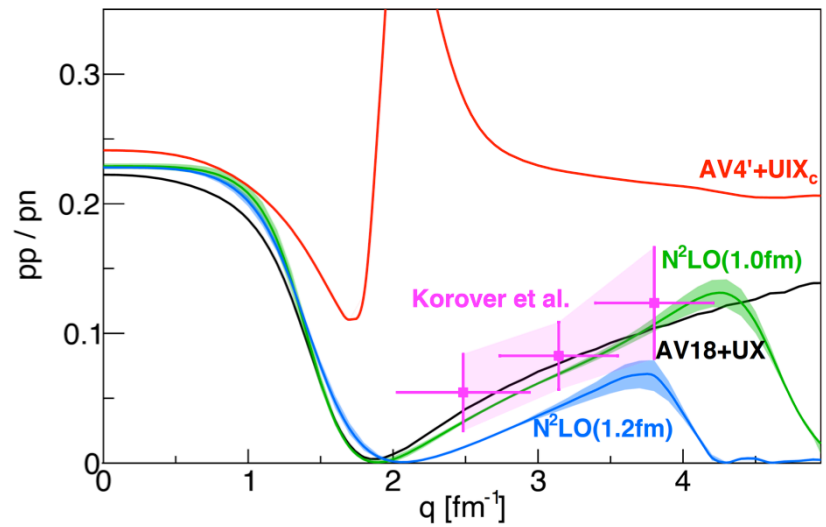
To recap:

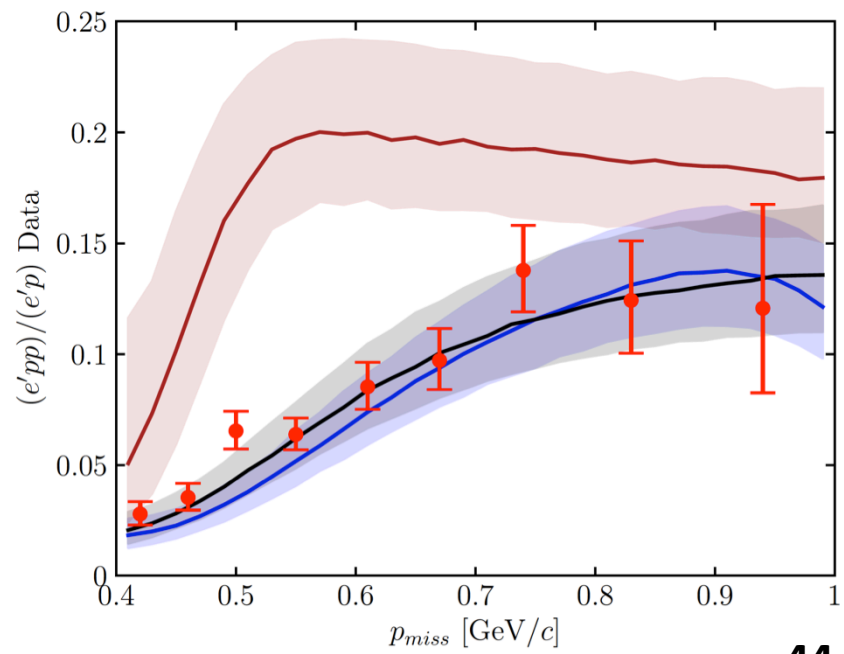
- The GCF describes the many-body nuclear wave-function where SRCs dominate.

- NN models differ significantly at short-r, high-k.

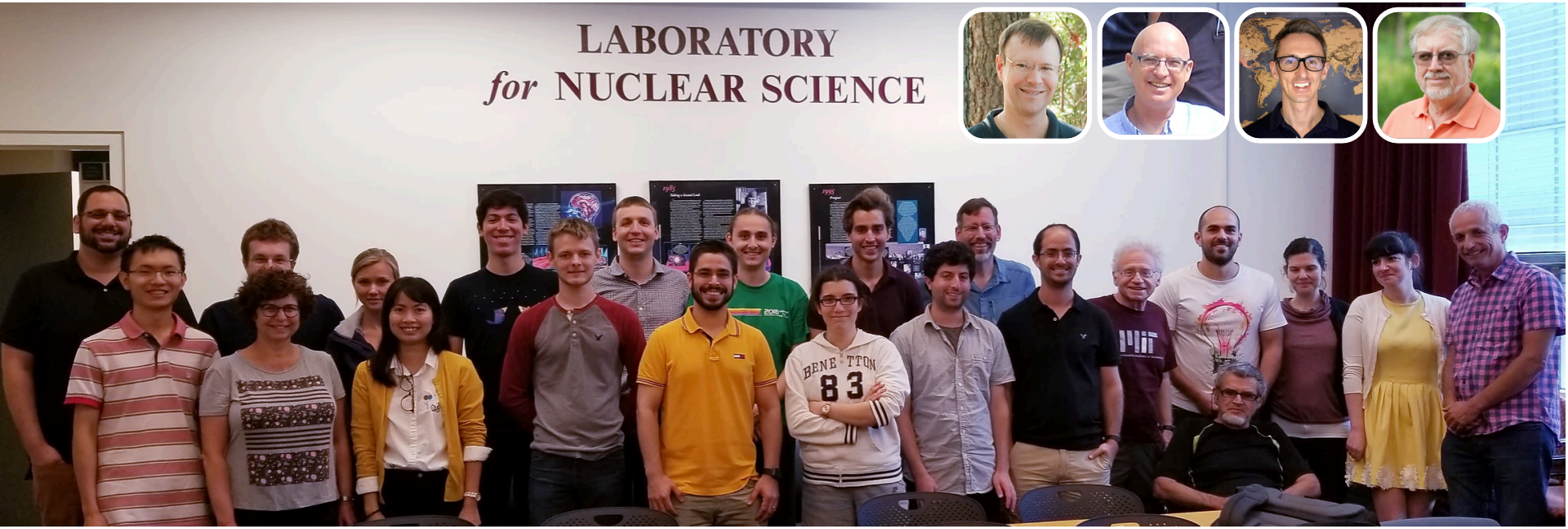
- <u>Inclusive</u> (e,e') experiments are <u>insensitive</u> to the short-r structure of the NN interaction.

- <u>Exclusive</u> (e,e'NN) experiments are <u>sensitive</u> to the short-r structure of the NN interaction.





Thank you!

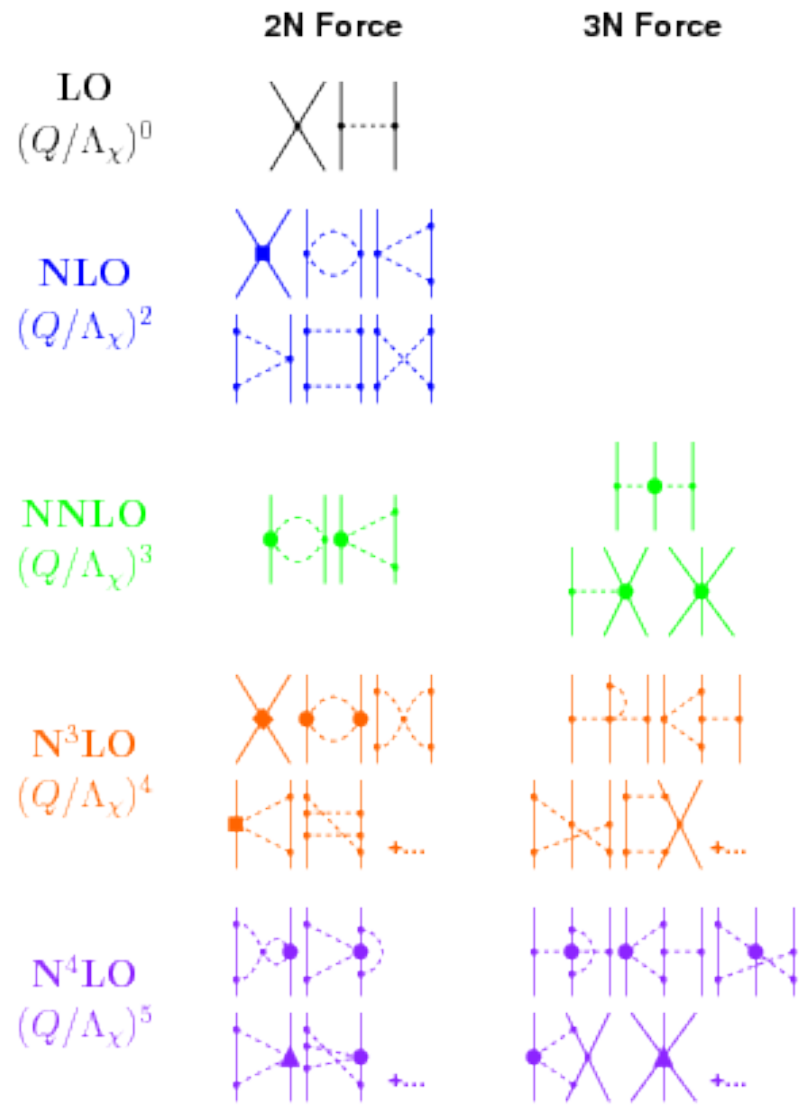


Backup slides

The Nuclear Interaction

Many ways to derive an effective interaction.

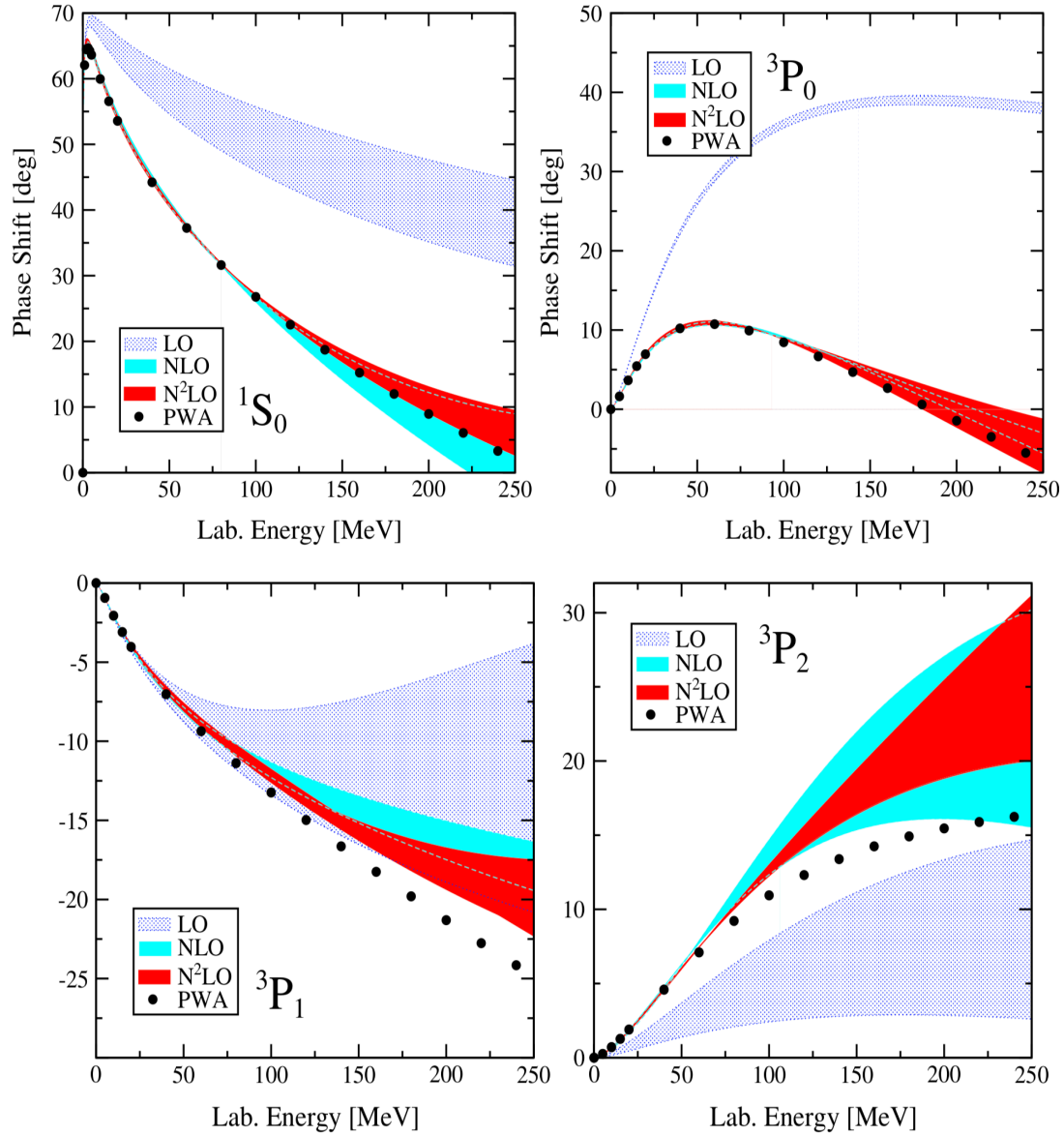
All models contain experimentally determined parameters.



The Nuclear Interaction

NN phase shifts constrain models up to pion threshold (~**400 MeV/c** c.m.)

No significant constrains at higher momenta.



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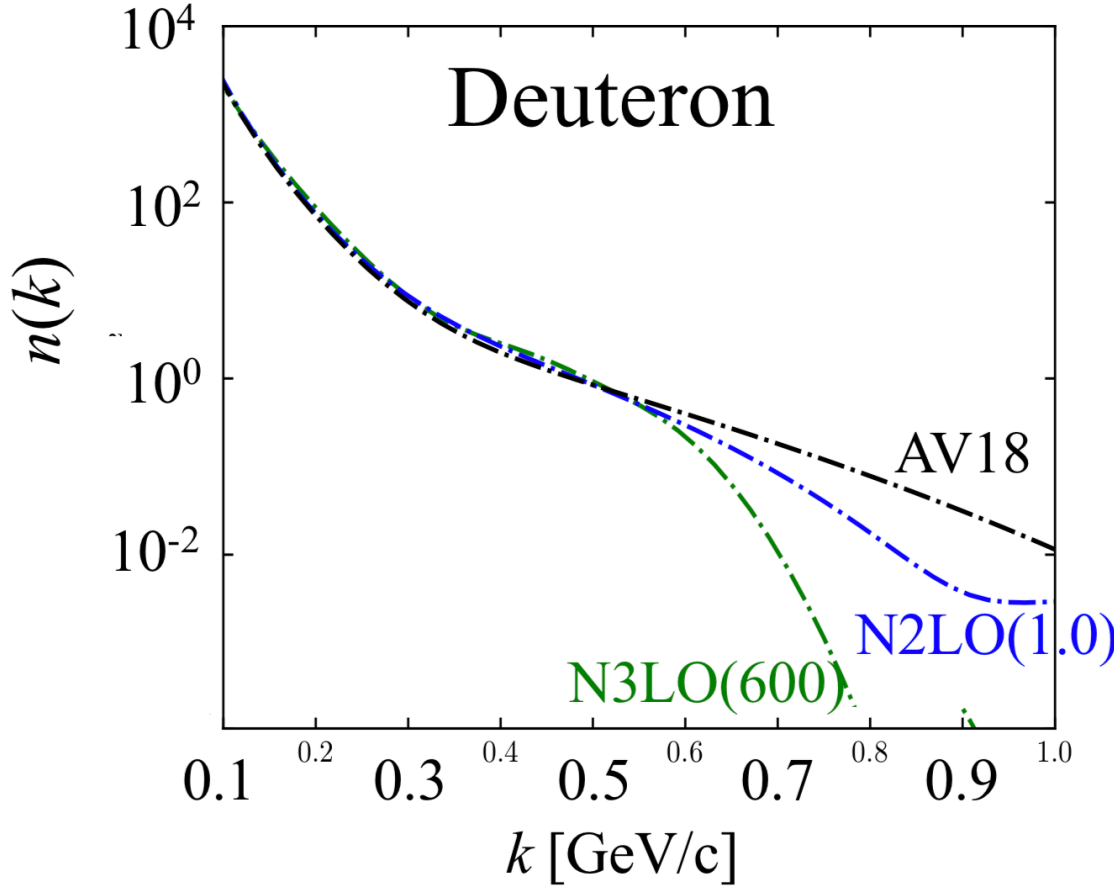
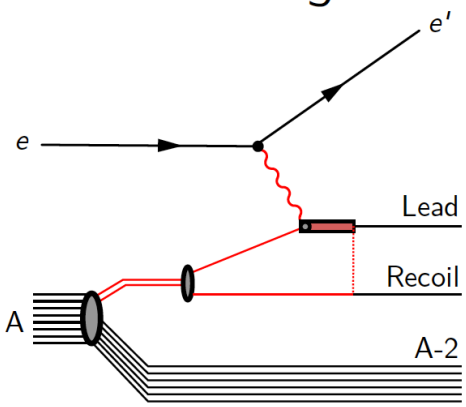
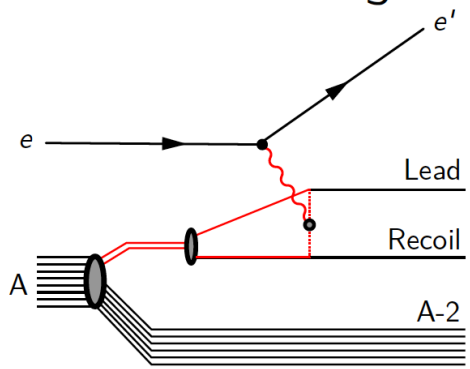


FSI and Reaction Mechanisms

Isobar Config.

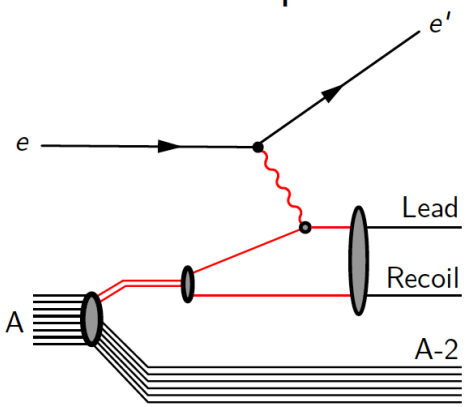


Meson-exchange curr.

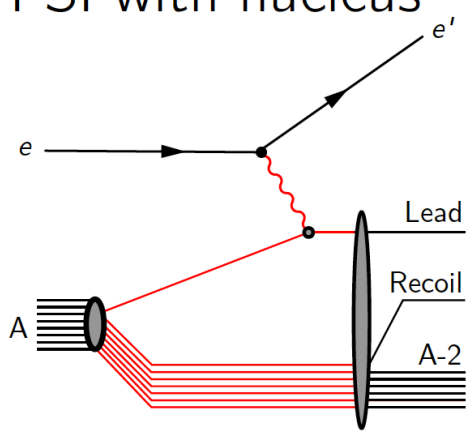


- $x_B > 1.2$
- High Q^2

FSI within pair

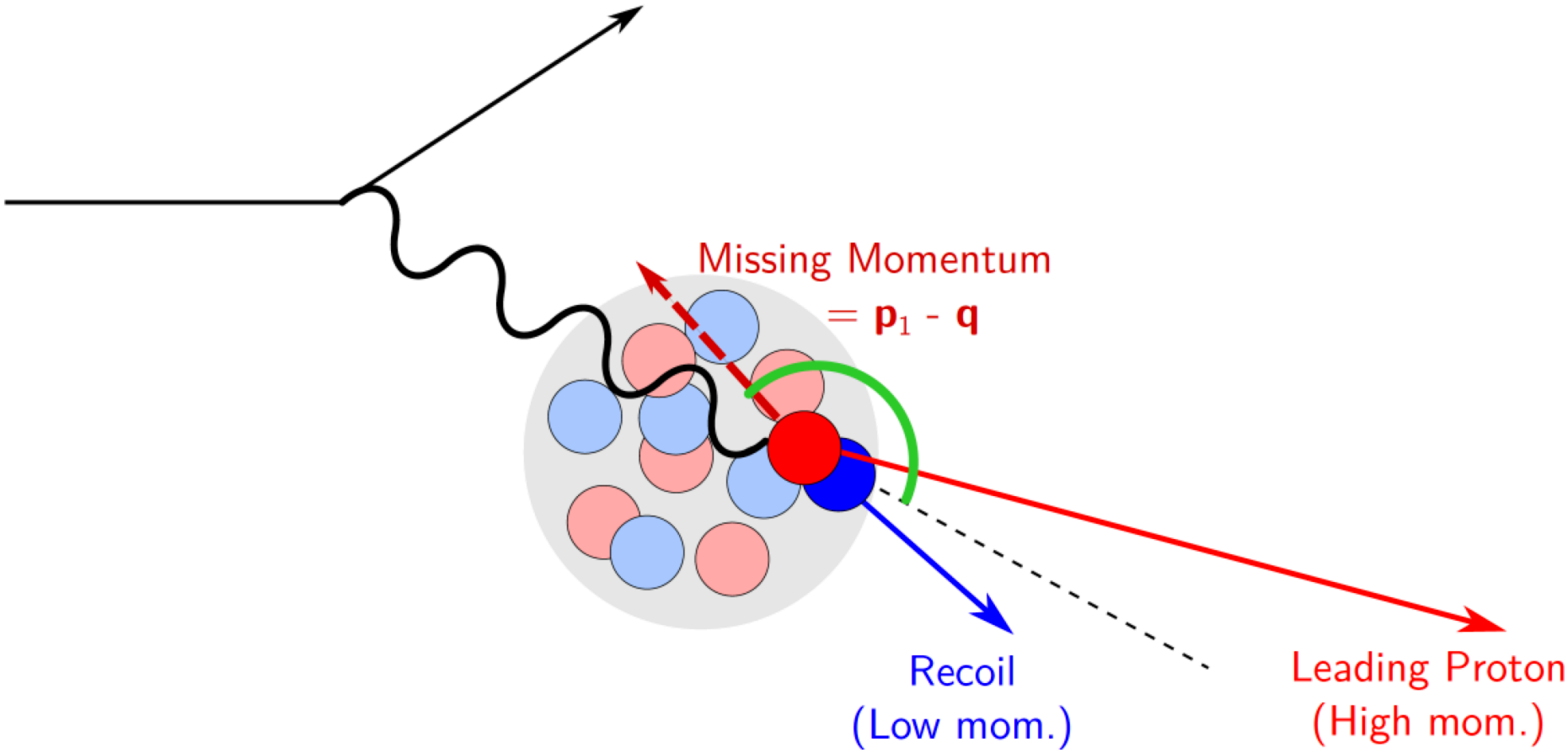


FSI with nucleus

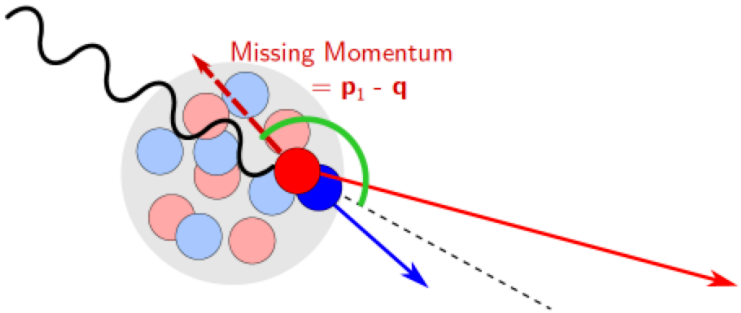


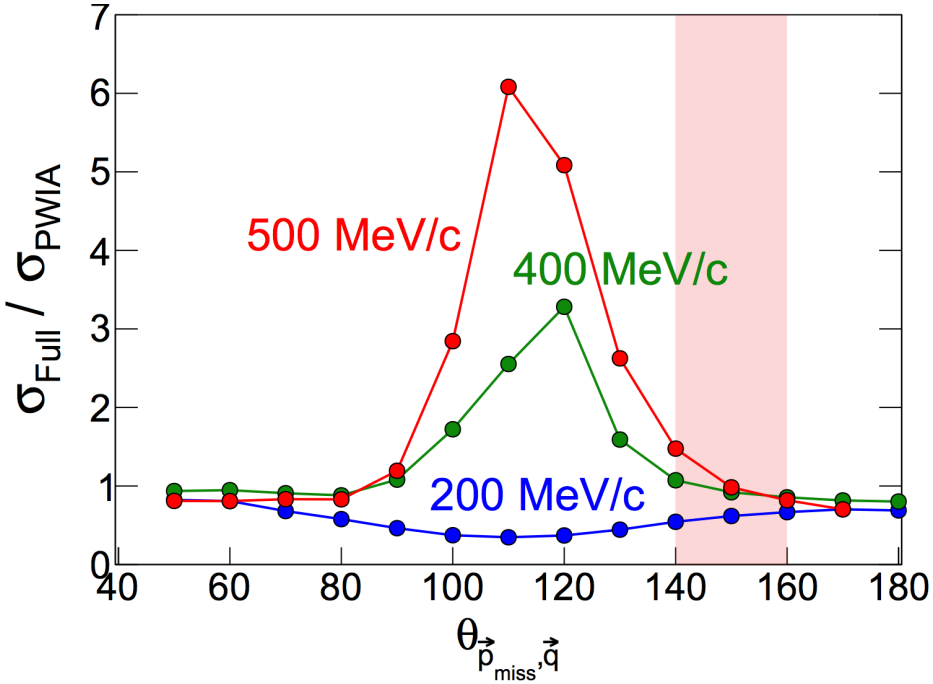
- Anti-parallel kinematics

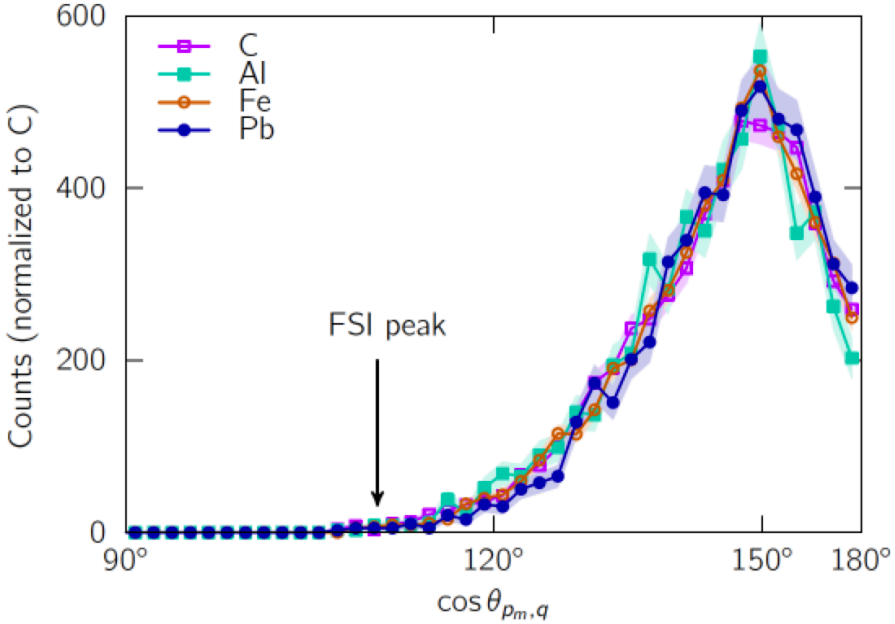
FSI minimized in anti-parallel kinematics



FSI minimized in anti-parallel kinematics

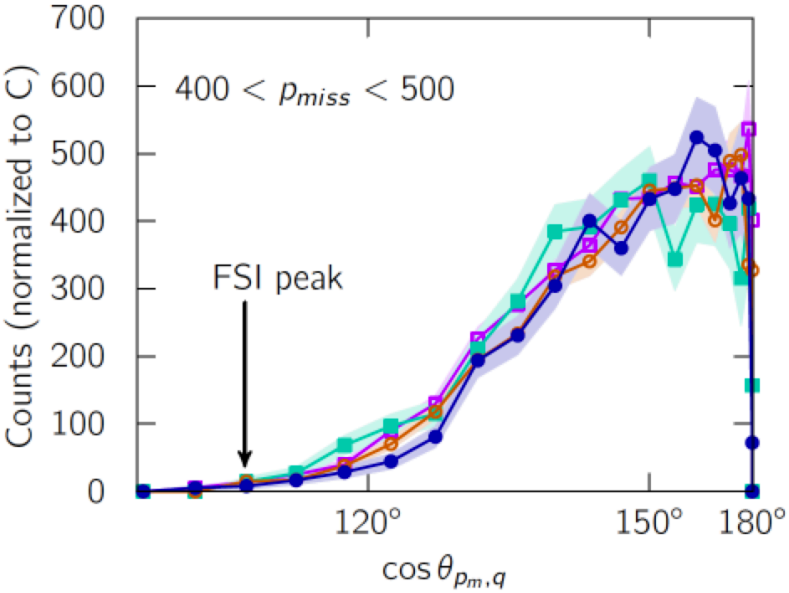


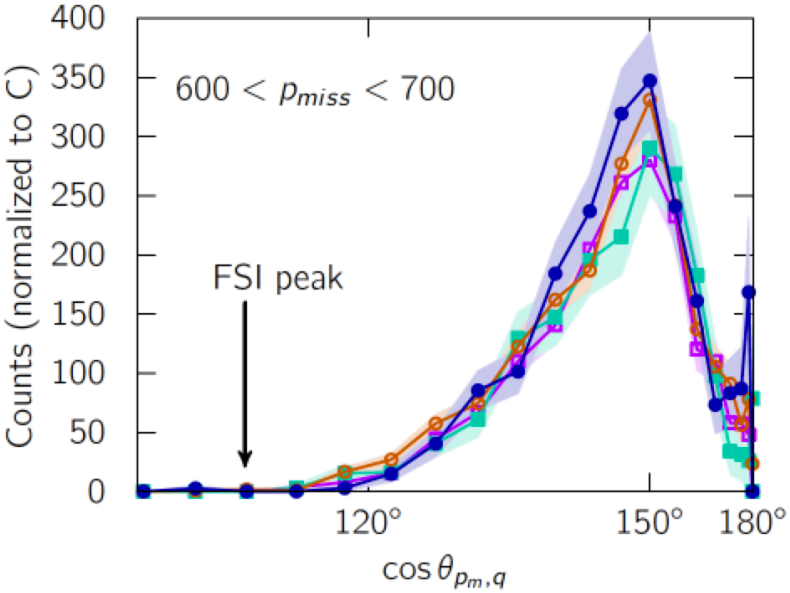


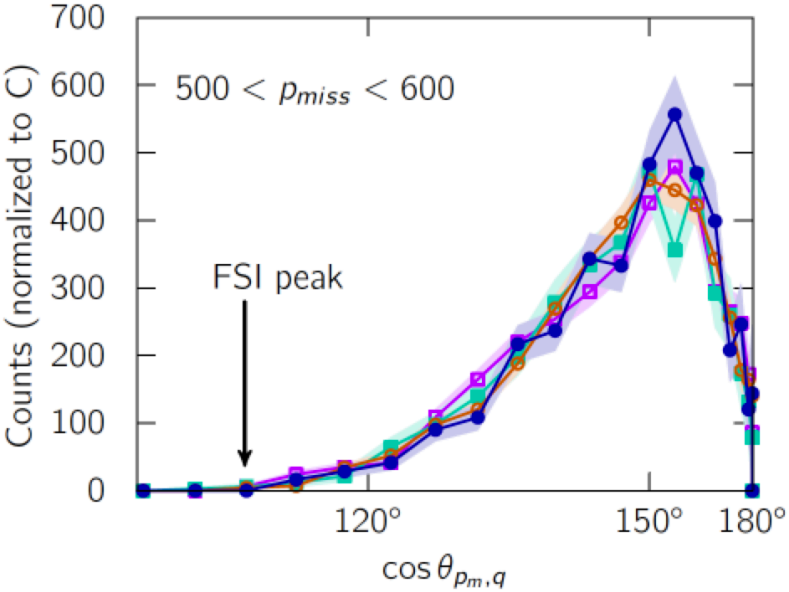


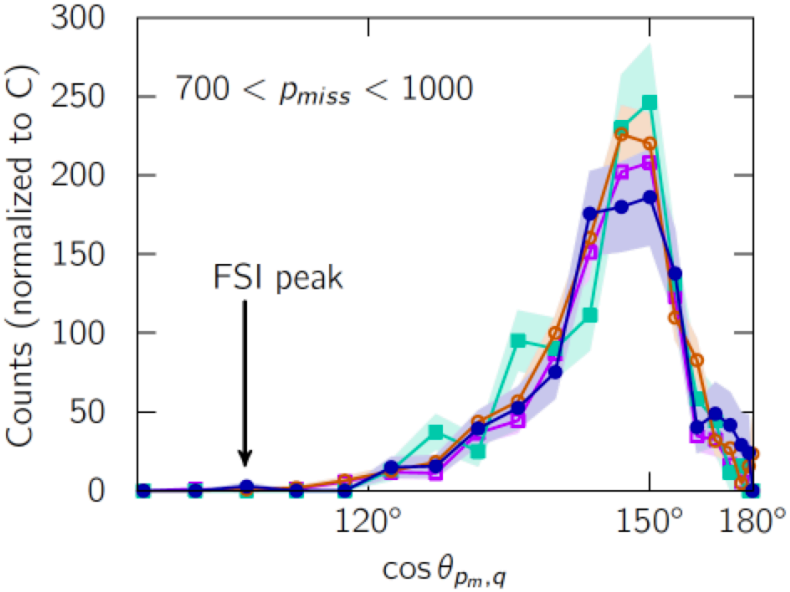
Calculation by M. Sargsian

FSI minimized in anti-parallel kinematics







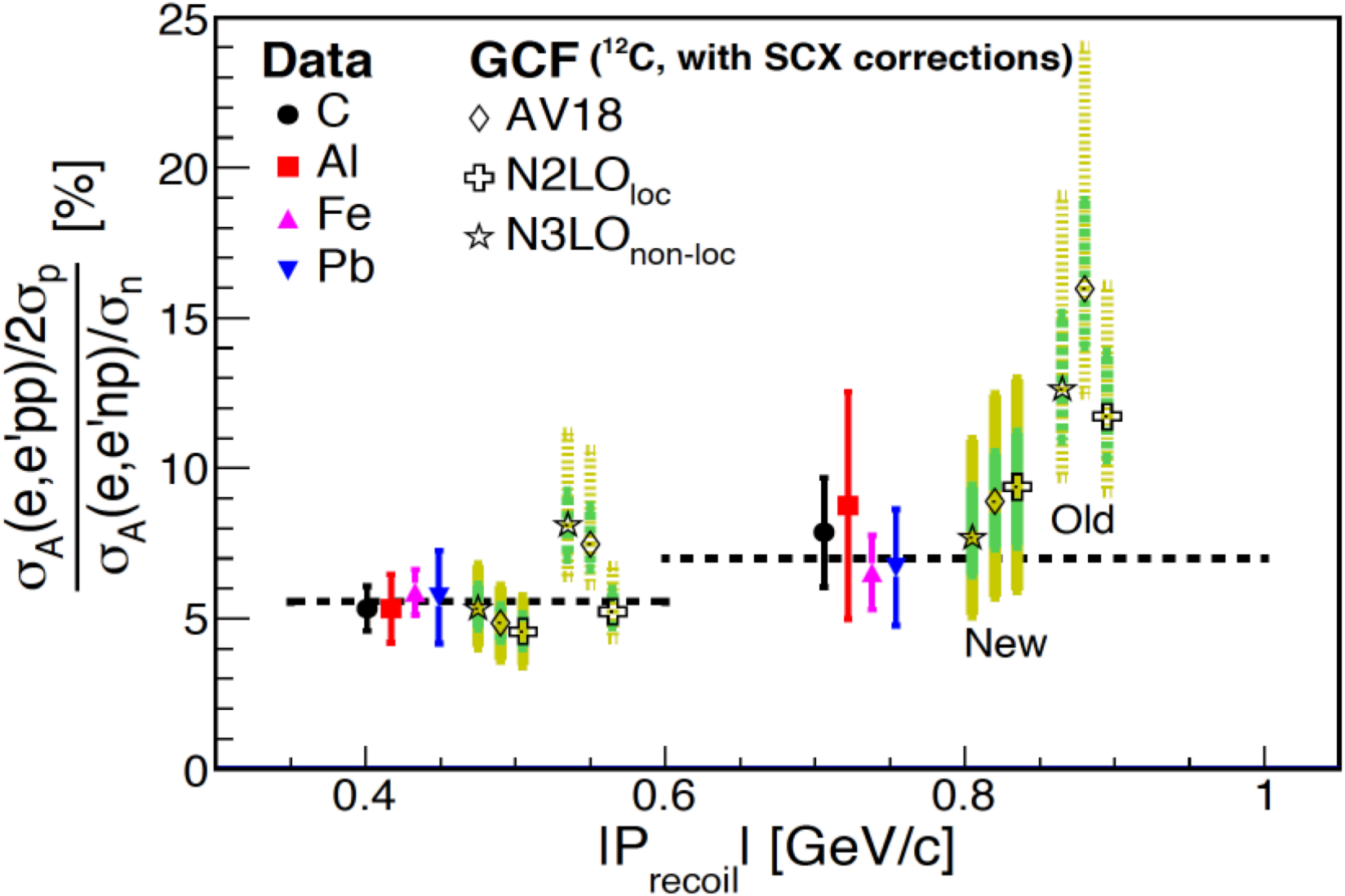


Studied reactions

- $^{12}C(e, e'np)$
  - $0.4 < p_{miss} < 1.0 \quad GeV/c$
  - Only a few dozen neutron events
  - arXiv:1810.05343, just accepted to PRL

- $^{12}C(e, e'p)$ and $^{12}C(e, e'pp)$
  - $0.4 < p_{miss} < 1.0 \quad GeV/c$
  - Few hundred to few thousand events
  - Analysis under review (still preliminary!)

$^{12}C(e,e'pp)/^{12}C(e,e'np)$



M. Duer et al. (CLAS Collaboration) PRL 122, 172502 (2019)

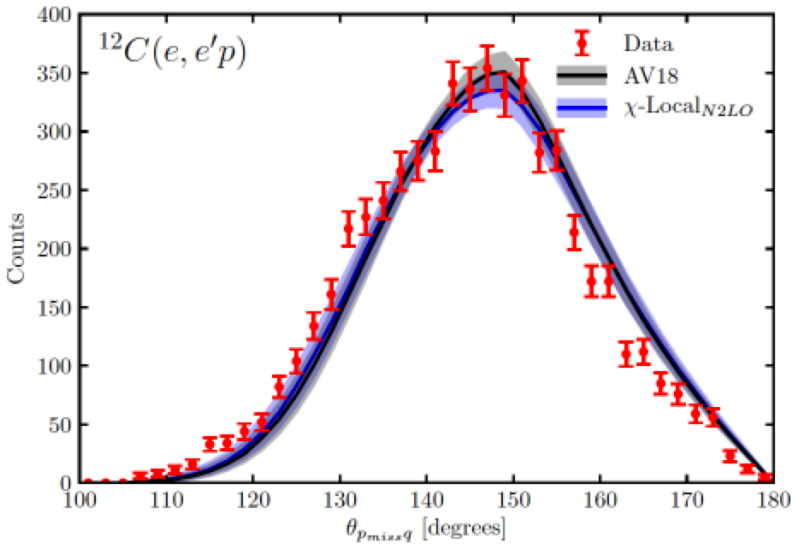
Comparison to ^{12}C(e,e'p) and ^{12}C(e,e'pp)

- Carbon data only
  - Contacts determined from fits to ab initio VMC
- *NN* interactions
  - AV18
  - Local χPT N2LO (1 fm cut-off)
- Model uncertainty from:

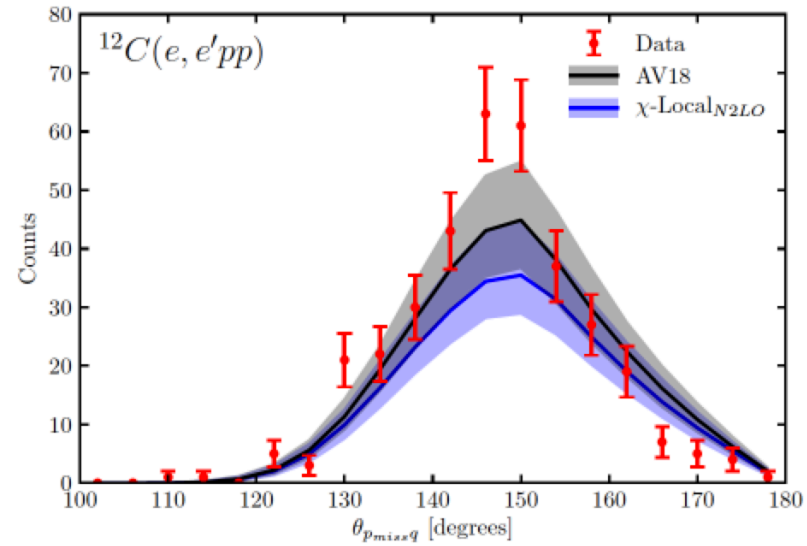
- Contacts
- σ_{CM}
- SCX prob.
- Transparency
- $A-2$ excitation E^*
- $p_{\text{rel.}}$ cut-off
- e^- res.
- p res.

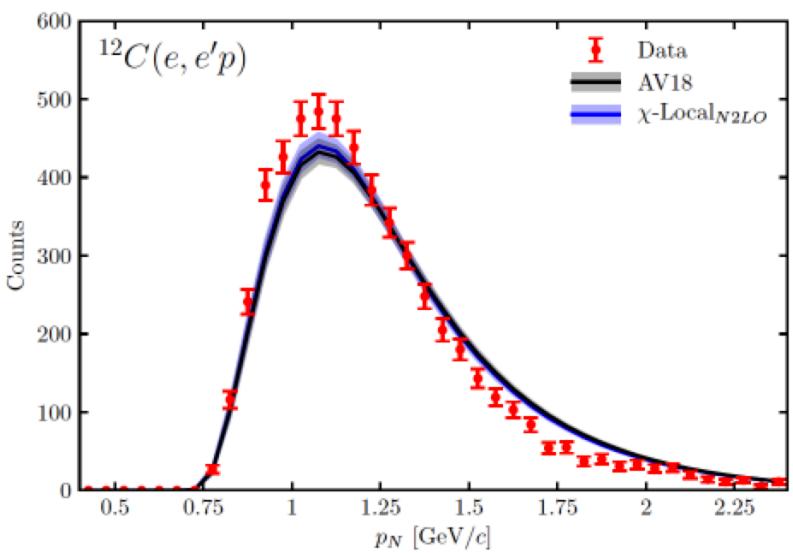
Model prediction of the kinematics

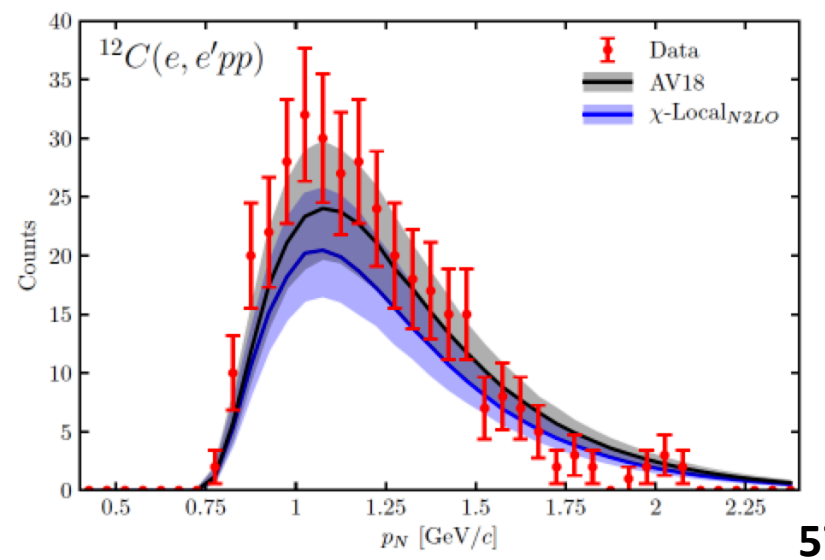
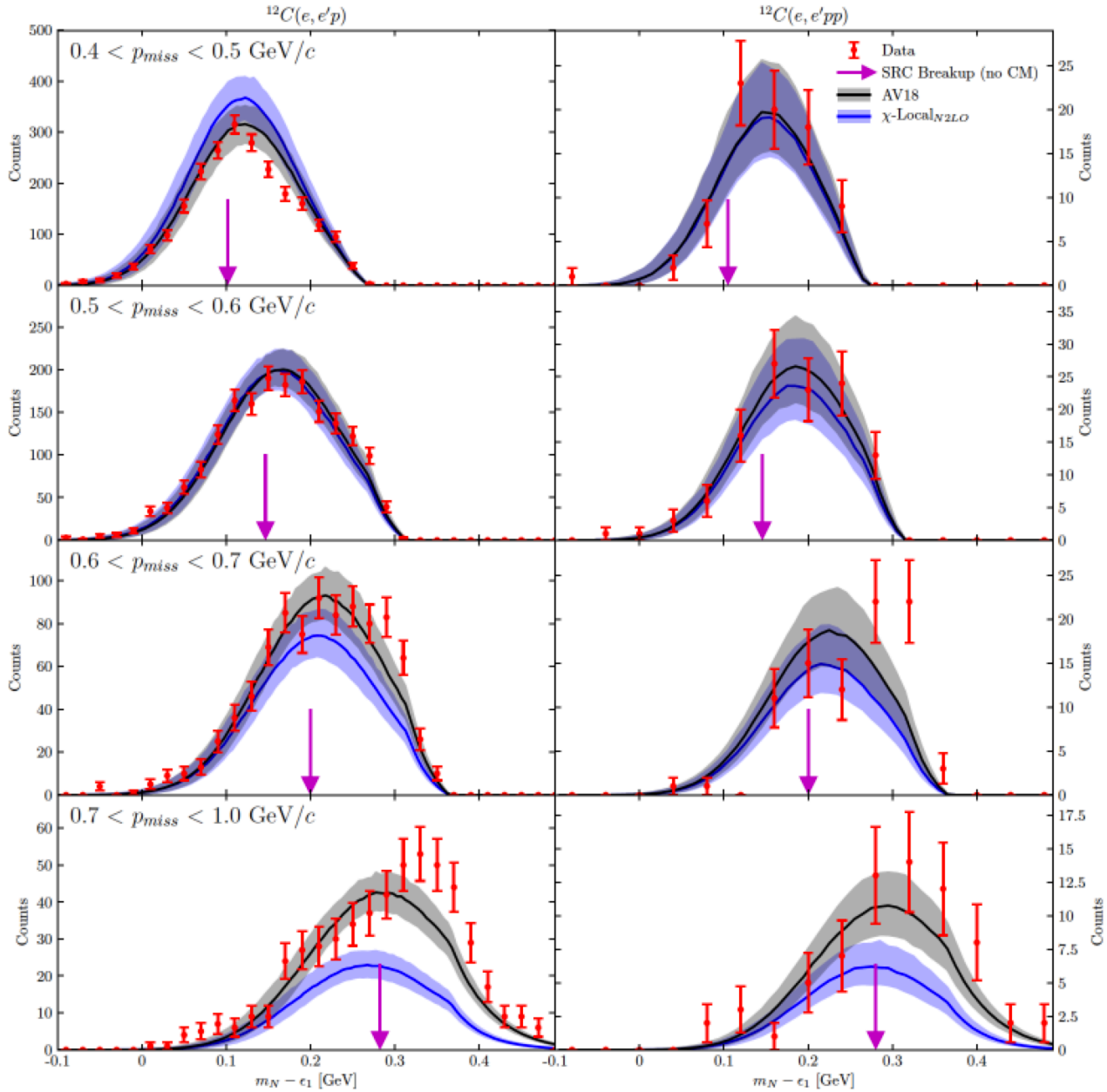
$C(e, e'p)$



$C(e, e'pp)$







Missing momentum and energy