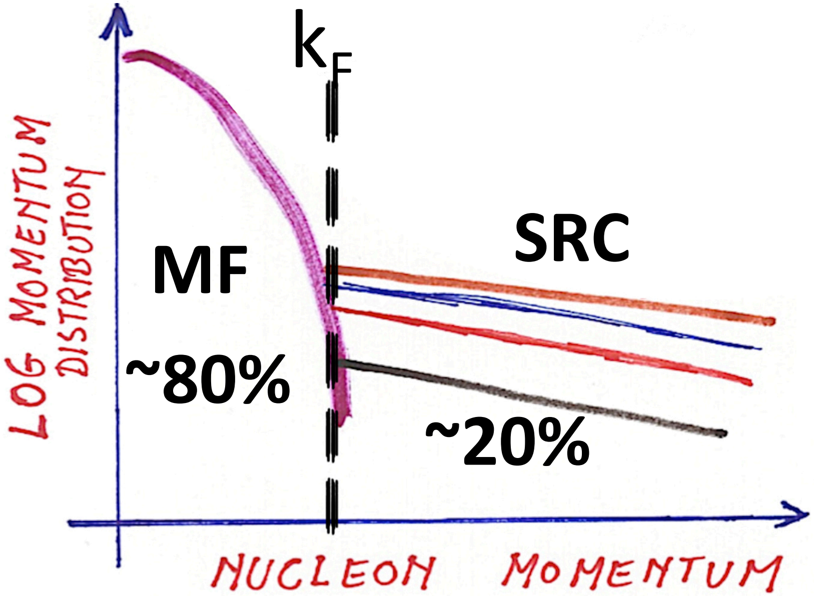
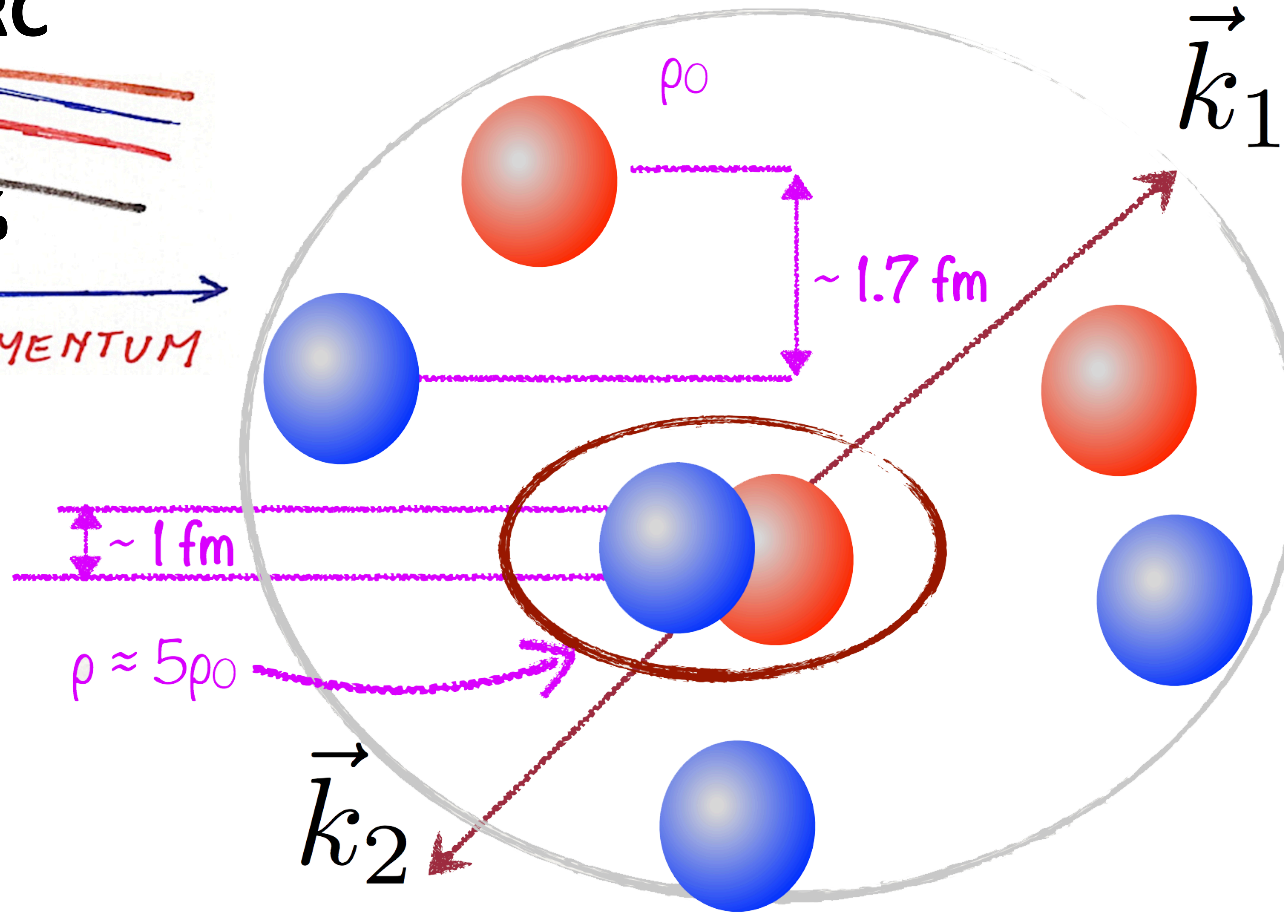
Short-Range Correlations, Generalized Contact Formalism, and their Implications

Reynier Cruz Torres

Jlab Users Group Meeting
June 18, 2018

SRC 101


LOG MOMENTUM DISTRIBUTION
k_F
MF
~80%
SRC
~20%
NUCLEON MOMENTUM

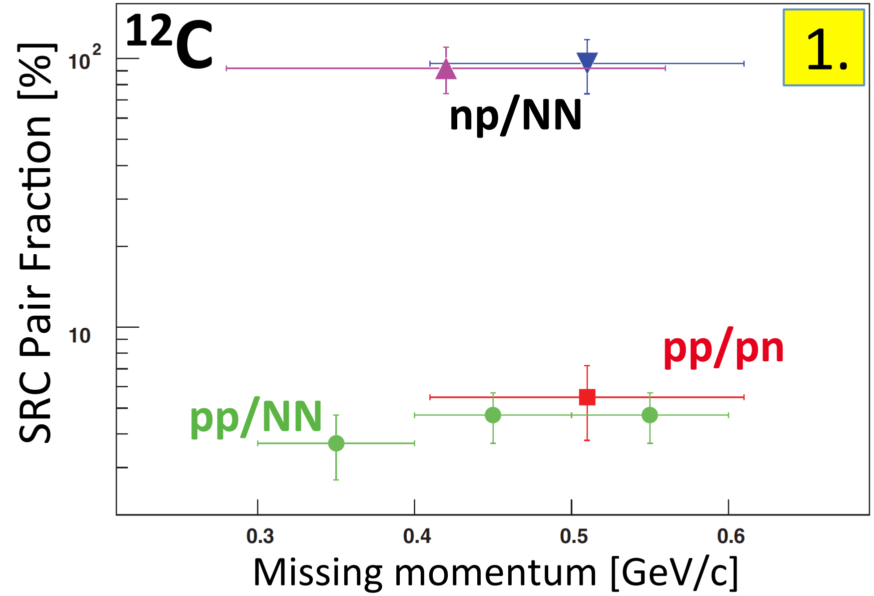

ρ_0
~ 1.7 fm
$\vec{k}_1$
~ 1 fm
$\rho \approx 5\rho_0$
$\vec{k}_2$

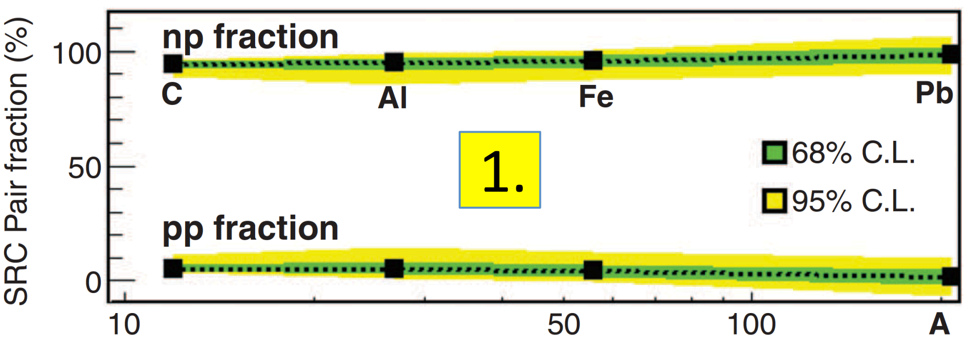
SRC 101

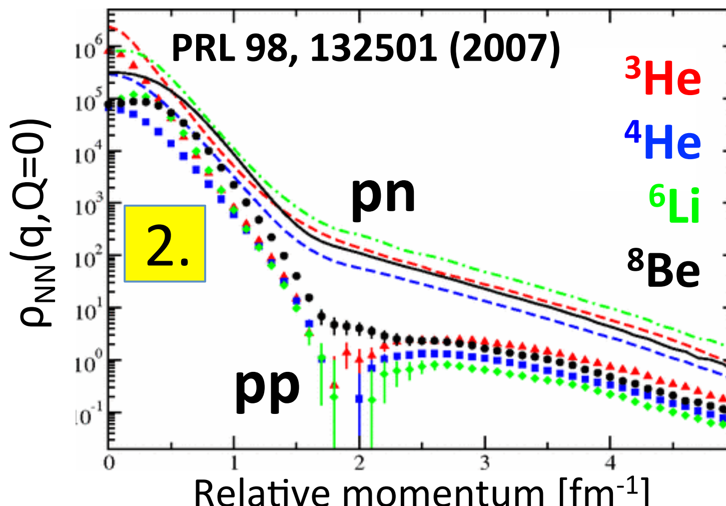
1. Probability for np-SRC is ~18 times larger than pp-SRC. Also true for heavy asymmetric nuclei.
2. Dominant NN force in 2N-SRC is tensor force.

   High momentum tail (300-600 MeV/c) is dominated by L=0,2 S=1 pn-SRC pairs.

PRL 162504 (2006); Science 320, 1476 (2008)







Contact Formalism

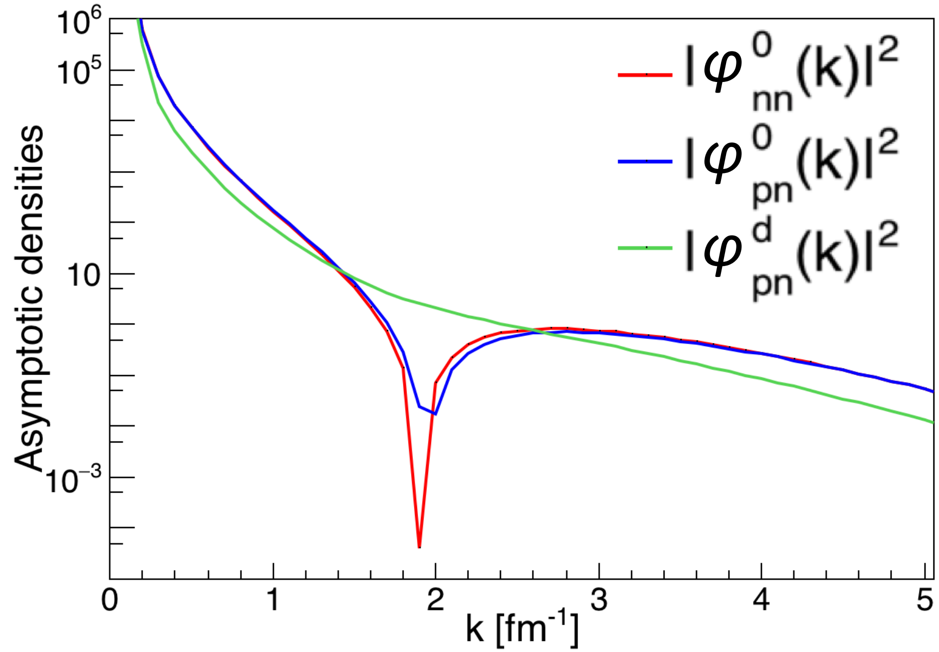
for k->∞, approximate two-body momentum densities:

$$\tilde{\rho}_2^{pp} = C_{pp}^{s=0} \left| \tilde{\varphi}_{pp}^{s=0}(k) \right|^2$$

$$\tilde{\rho}_2^{pn} = C_{pn}^{s=0} \left| \tilde{\varphi}_{pn}^{s=0}(k) \right|^2 + C_{pn}^{s=1} \left| \tilde{\varphi}_{pn}^{s=1}(k) \right|^2$$

φ_{ij} : zero-energy solution of 2-body Schrödinger equation (universal)

C^{α}_{ij}: scaling constants called **Contacts** (nucleus dependent)

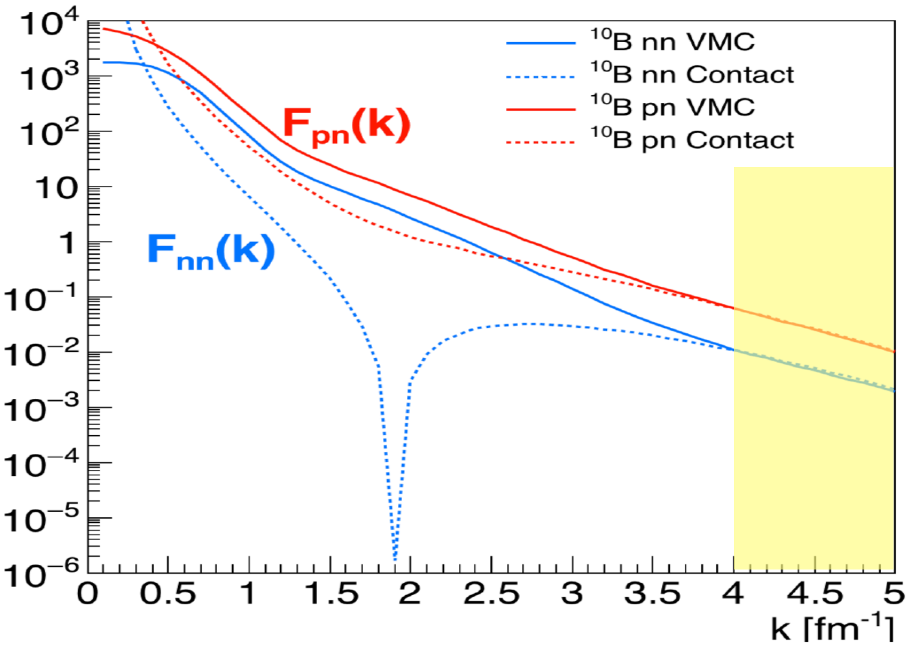


and the one-body momentum density:

$$n(k) = 2C_{pp}^{s=0} \left| \tilde{\varphi}_{pp}^{s=0}(k) \right|^2 + C_{pn}^{s=0} \left| \tilde{\varphi}_{pn}^{s=0}(k) \right|^2 + C_{pn}^{s=1} \left| \tilde{\varphi}_{pn}^{s=1}(k) \right|^2$$

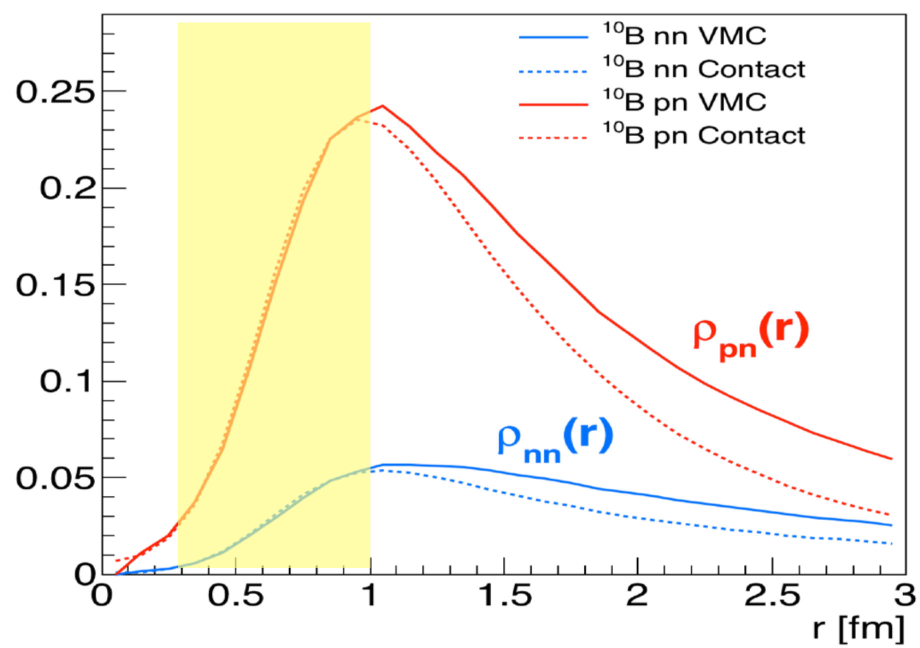
Contact Extraction

Extraction at <u>high momentum</u>



Fitting range ~ 4-5 fm^{-1}

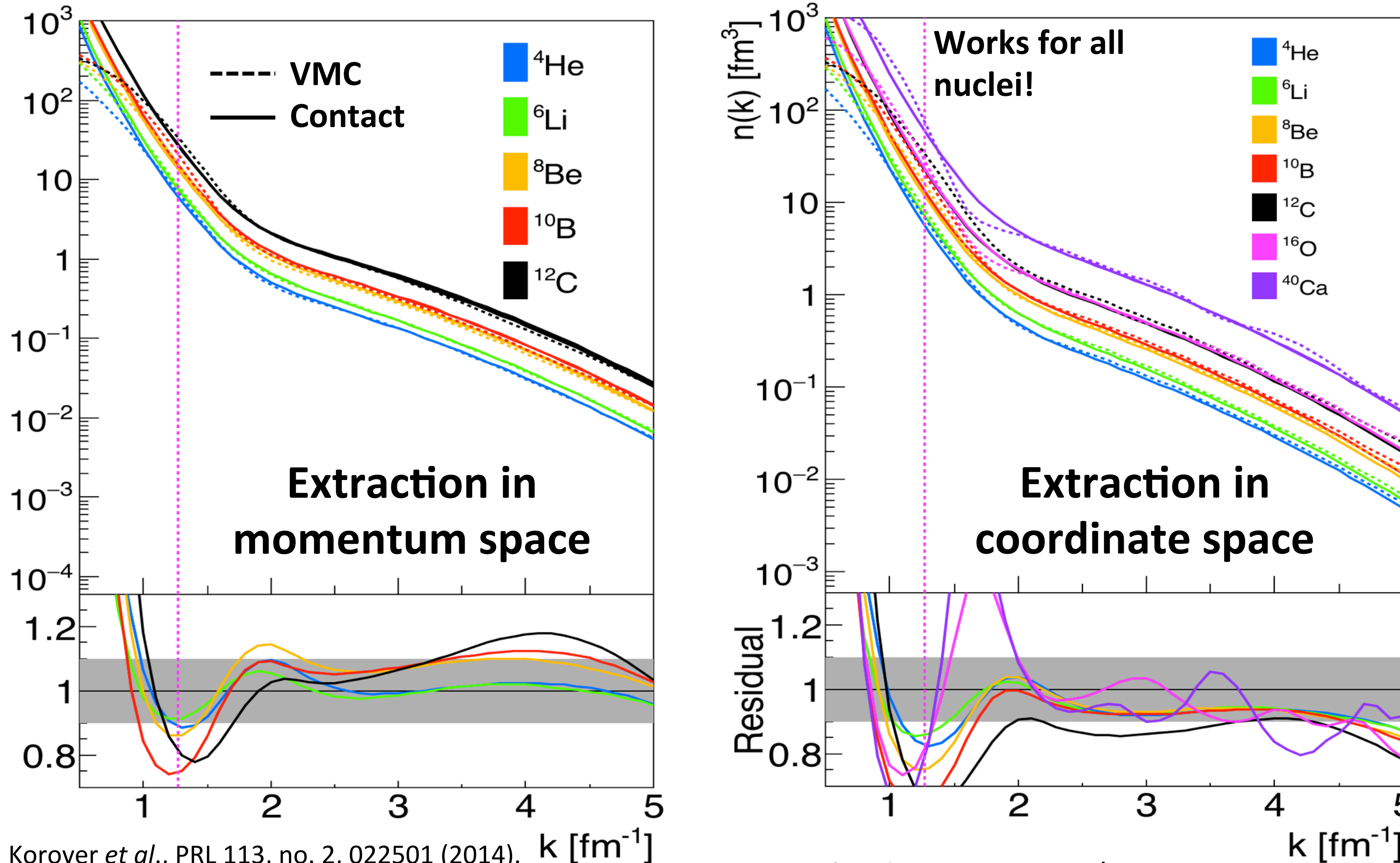
Extraction at <u>short distance</u>



Fitting range ~ 0.25-1 fm

R. B. Wiringa *et al.*, PRC 89, no. 2, 024305 (2014).

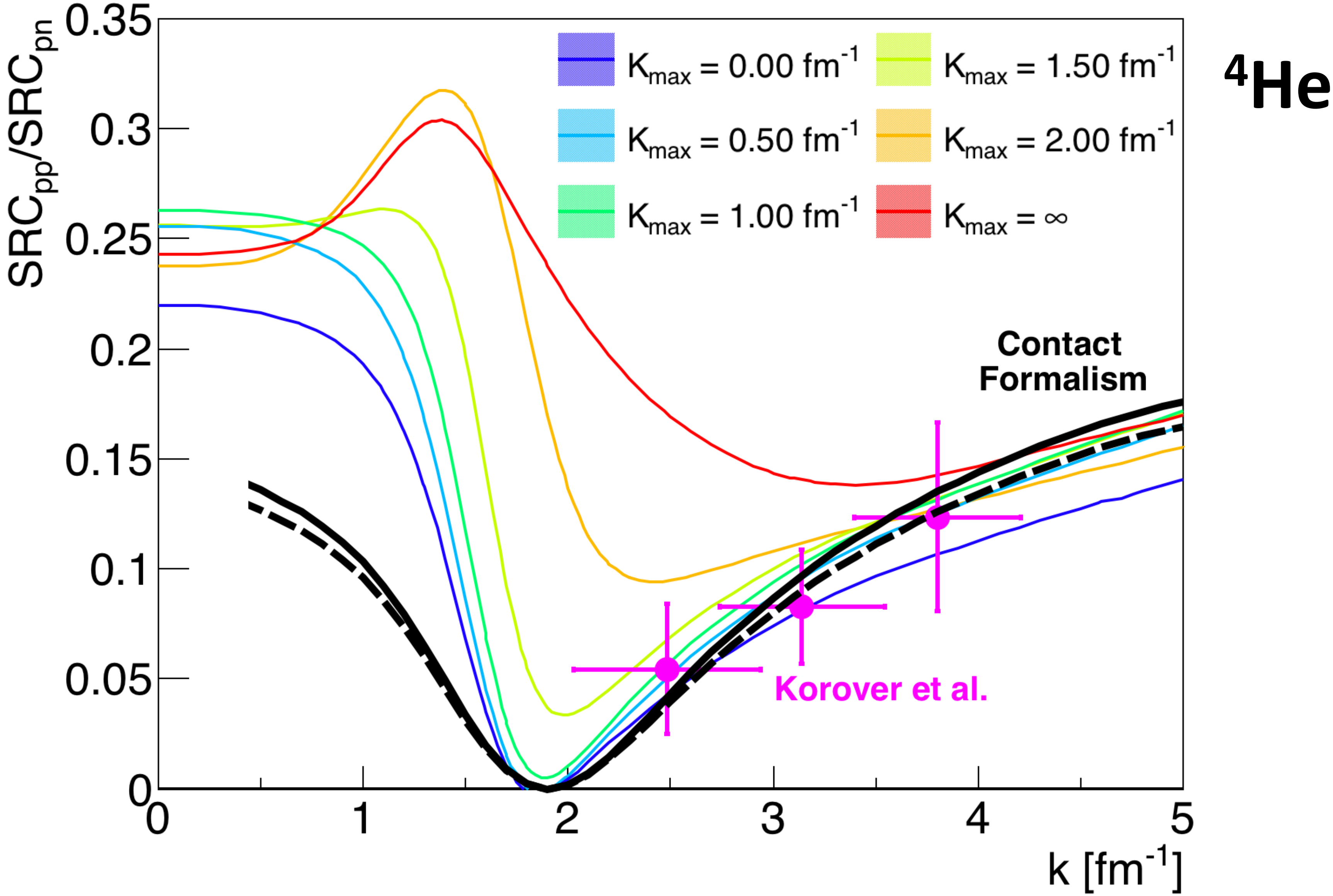
Results 1-body distributions



I. Korover *et al.*, PRL 113, no. 2, 022501 (2014).
E. J. Moniz *et al.*, PRC 26, 445 (1971).
R. B. Wiringa *et al.*, PRC 89, no. 2, 024305 (2014).

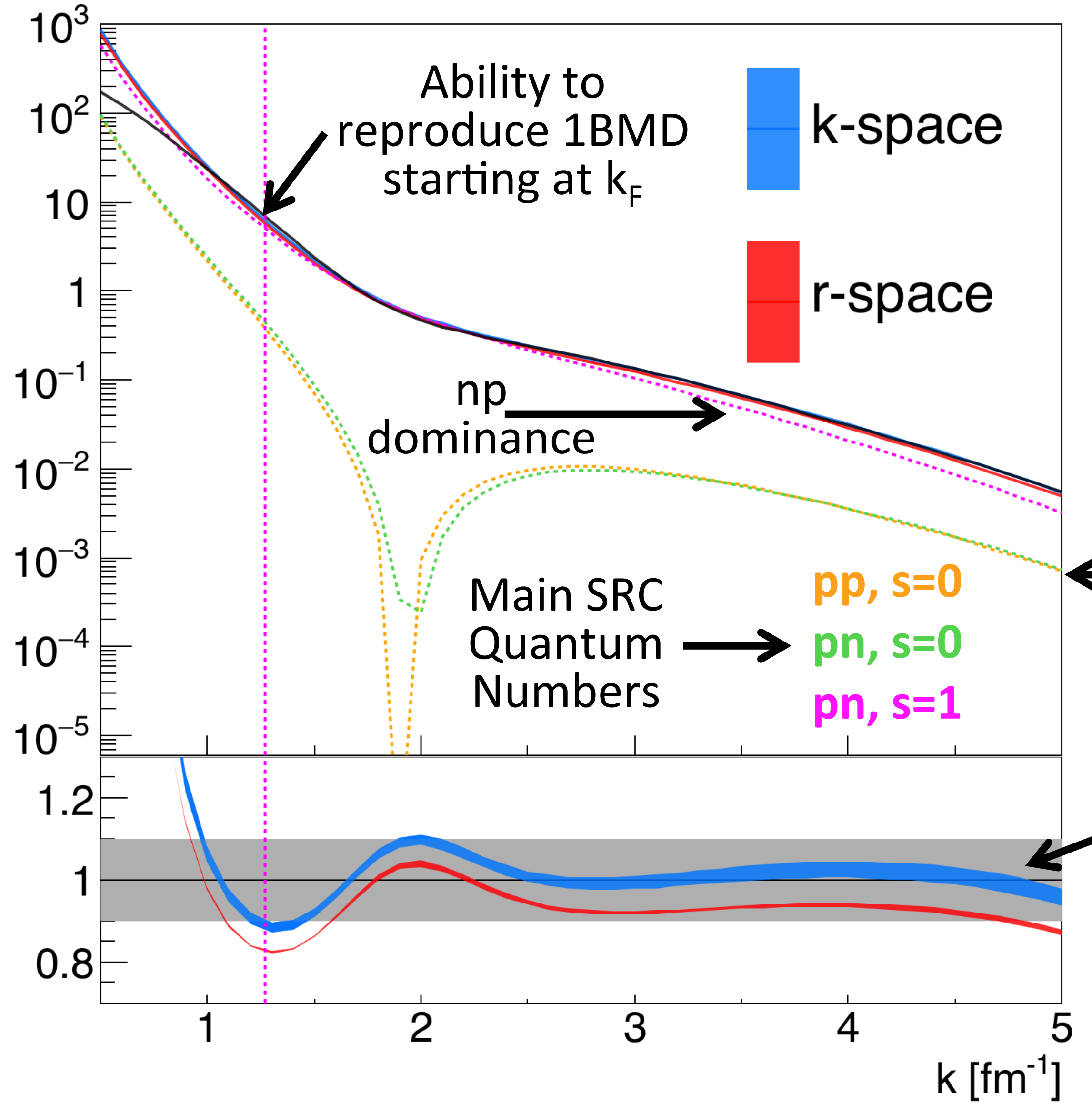
Weiss, **Cruz-Torres**, *et al.* – Phys. Lett. B 780 (2018) 211-215

pp/pn fraction



Weiss, **Cruz-Torres**, Barnea, Piasetzky, and Hen –Phys. Lett. B 780 (2018) 211-215

What we've learned



% SRC

Ability to extract contacts from experimental data

non-combinatorial isospin symmetry

Quantitative agreement between short distance and high momentum

Correlation Function - Applications

Effective calculations of:

- **Neutrino-less double beta decay.**

  M. Kortelainen, O. Civitarese, J. Suhonen, J. Toivanen, Phys. Lett. B 647 (2007) 128–132.
  M. Kortelainen, J. Suhonen, Phys. Rev. C 75 (2007) 051303.
  M. Kortelainen, J. Suhonen, Phys. Rev. C 76 (2007) 024315.
  F. Simkovic, A. Faessler, H.Muther, V. Rodin, M. Stauf, Phys. Rev. C 79 (2009) 055501.
  J. Engel, G. Hagen, Phys. Rev. C 79 (2009) 064317.

- **Nuclear transparency in quasi-elastic scattering**

  I. Mardor, Y. Mardor, E. Piasetzky, J. Alster, M. M. Sargsian, Phys. Rev. C46 (1992) 761–767.
  S. Frankel, W. Frati, N. Walet, Nucl. Phys. A580 (1994) 595–613.
  B. Kundu, P. Jain, J. P. Ralston, J. Samuelsson, Perspectives in hadronic physics. Proceedings, 2nd International Conference, Trieste, Italy, May 10-14, 1999, pp. 87–96.
  B. Kundu, J. Samuelsson, P. Jain, J. P. Ralston, Phys. Rev. D62 (2000) 113009.
  T. S. H. Lee, G. A. Miller, Phys. Rev. C45 (1992) 1863–1870.

- **Shadowing in deep inelastic scattering**

  G. Baym, B. Blattel, L. L. Frankfurt, H. Heiselberg, M. Strikman, Phys. Rev. C 52 (1995) 1604–1617.

- **Parity violation in nuclei**

  E. G. Adelberger,W. C. Haxton, Ann. Rev. Nucl. Part. Sci. 35 (1985) 501–558.

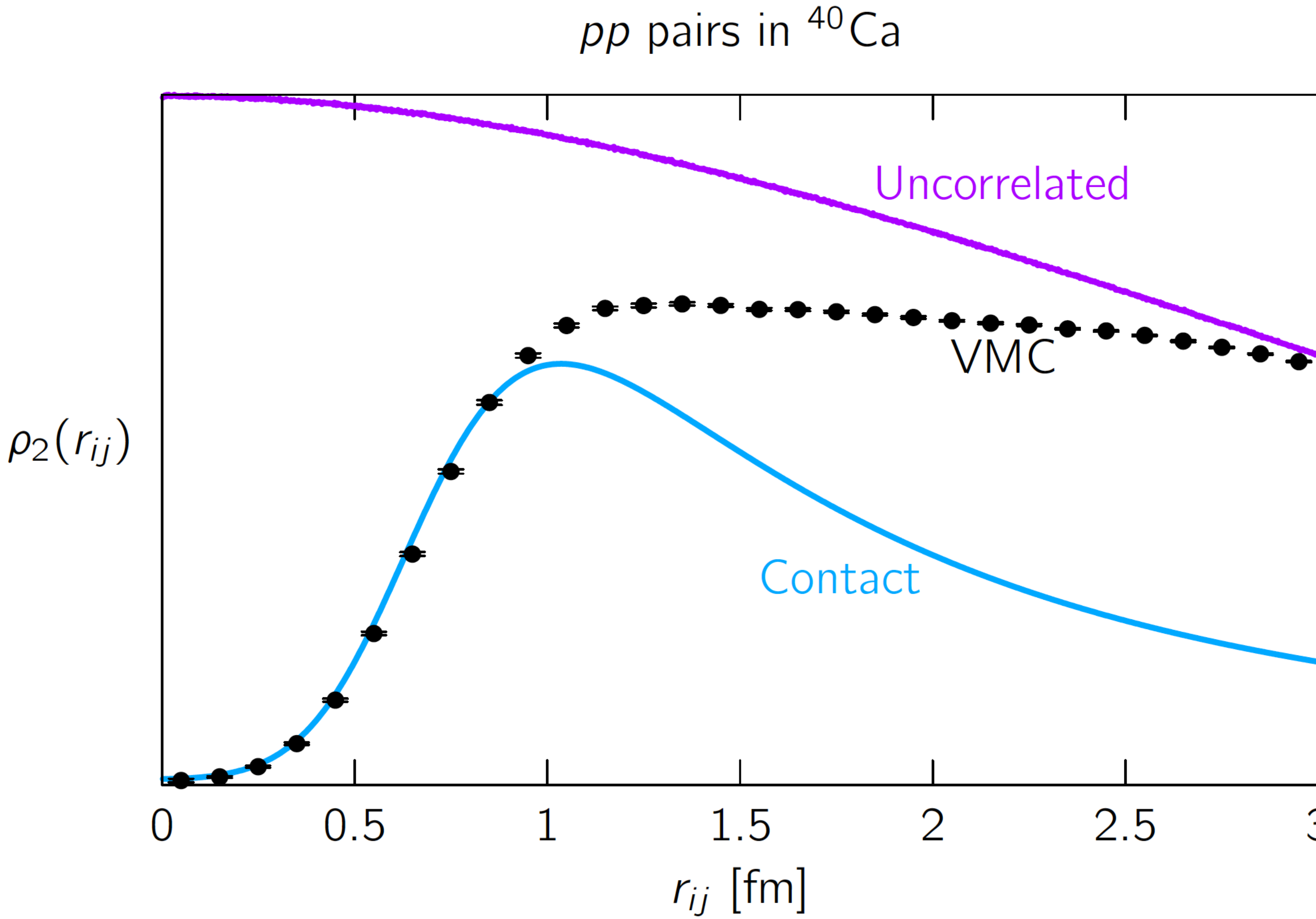
Correlation Functions

$$\rho_2(\vec{x},\vec{y}) = F(\vec{x},\vec{y}) \times \rho(\vec{x})\rho(\vec{y})$$

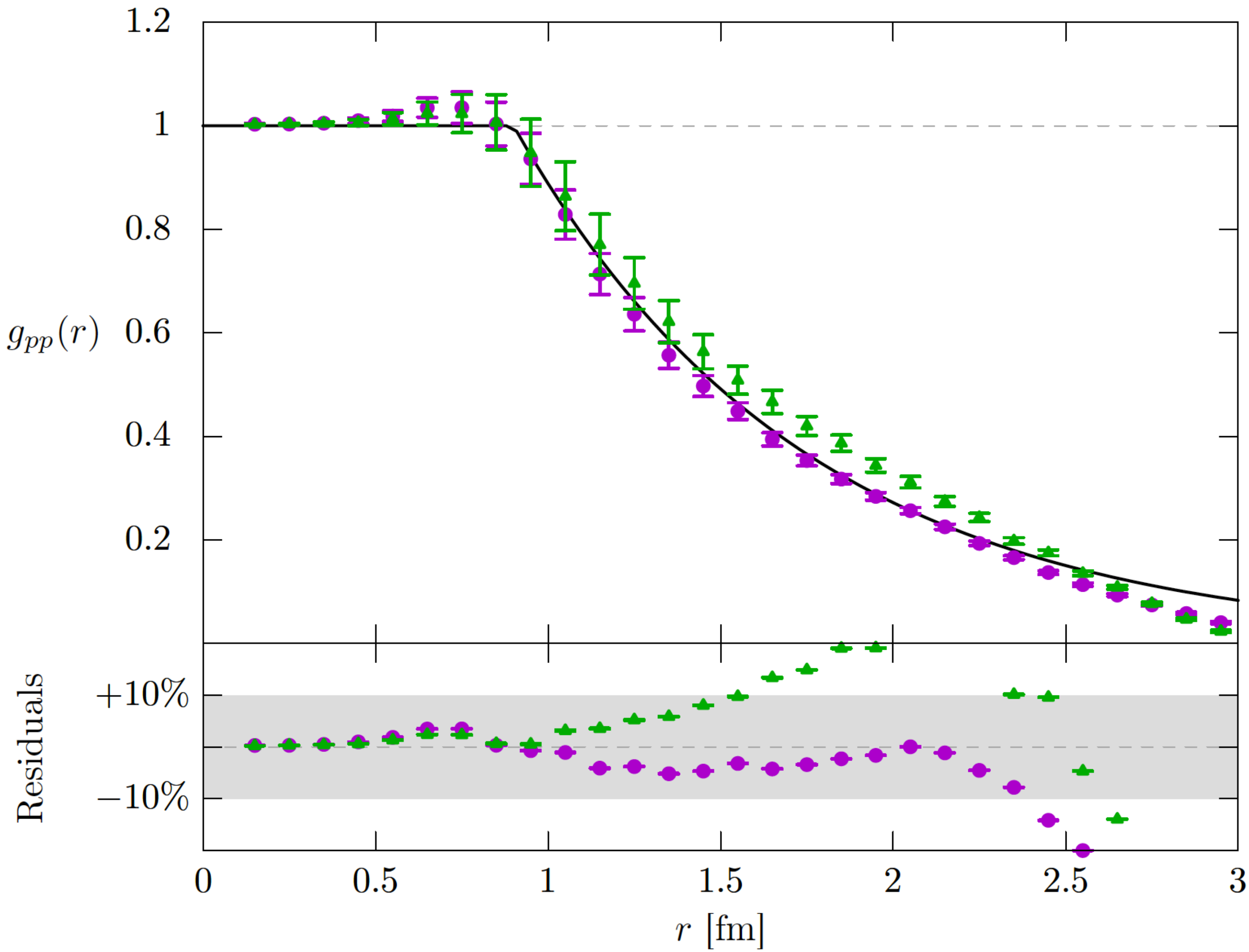
$$\rho_2(r) = F(r) \int \mathrm{d}^3\vec{R}\rho(\vec{R}+\vec{r}/2)\rho(\vec{R}-\vec{r}/2)$$

$$\rho_2(r) = F(r)\rho_2^{\mathrm{uncorr.}}(r)$$

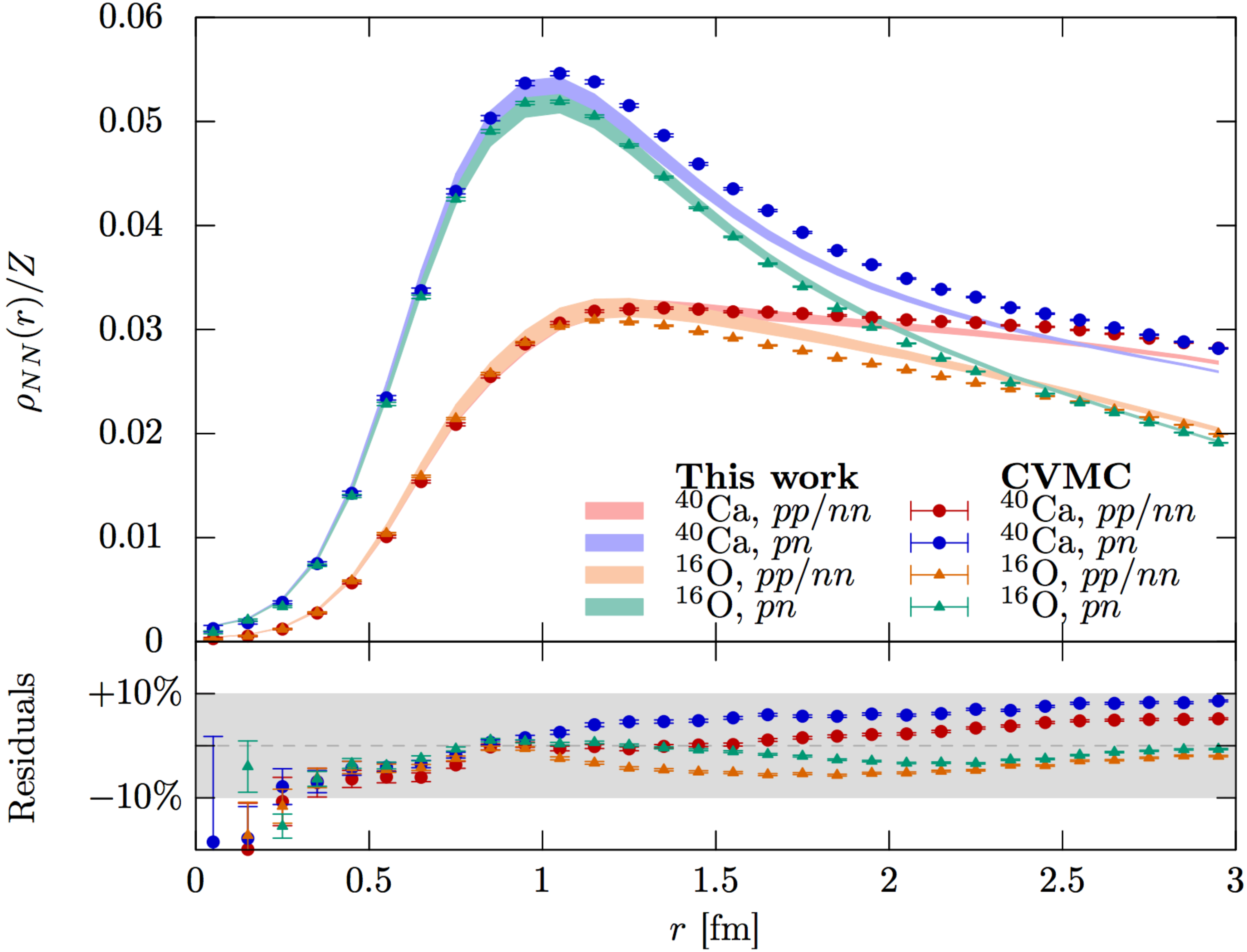
Blending Function



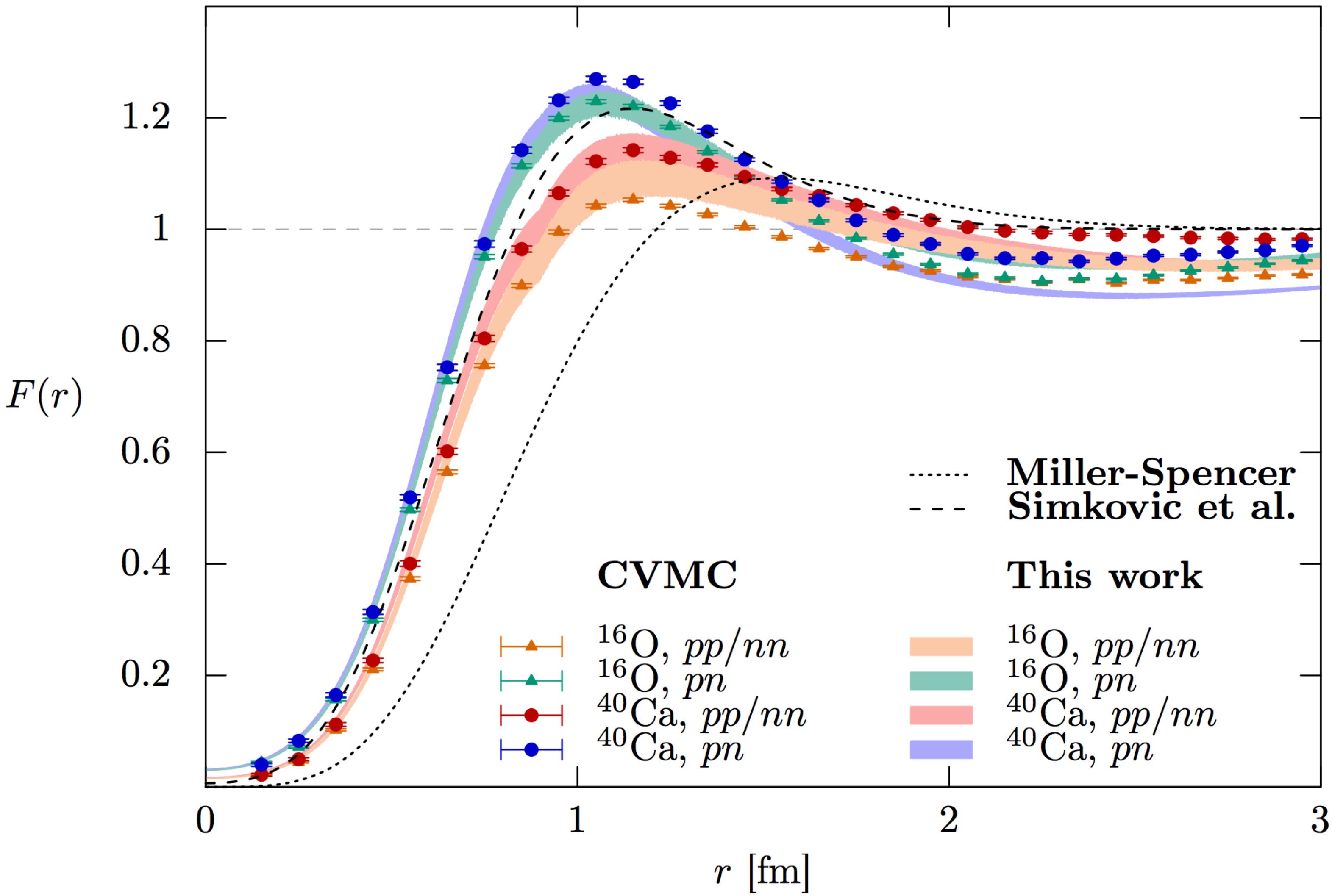
Blending Function



2-Body Density



Correlation Functions



Cruz-Torres, Schmidt, Miller, Weinstein, Barnea, Weiss, Piasetzky, Hen.
arXiv:1710.07966, submitted to Phys. Lett. B

Summary and Conclusions

- The study of short-range interactions is a great challenge in nuclear physics.
- We set out to examine the ability to describe short-range physics in nuclei in terms of scale separation and factorization (i.e. contact formalism).
- We show that the theory of contact interactions can be used to describe the high-momentum (short-range) nucleon momentum distribution where the NN potential is least constrained.
- This simple model reveals the physics and origin of 2N-SRC pairs in the high-momentum tail.

Summary and Conclusions

- We have extracted the nuclear contacts for several nuclei.
- We have started applying the contact formalism to several topics.
- Correlation functions can be used to characterize the effects of correlations in nuclear systems.
- The use of the Contact Formalism allows for the isospin decomposition of Correlation Functions.
- We benchmarked our model against ^{16}O and ^{40}Ca CVMC calculations and other extractions such as Simkovic and Miller-Spencer.

Thank you!

Collaborators:

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UNIVERSITY of WASHINGTON

G. Miller

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

N. Barnea, R. Weiss

OLD DOMINION UNIVERSITY

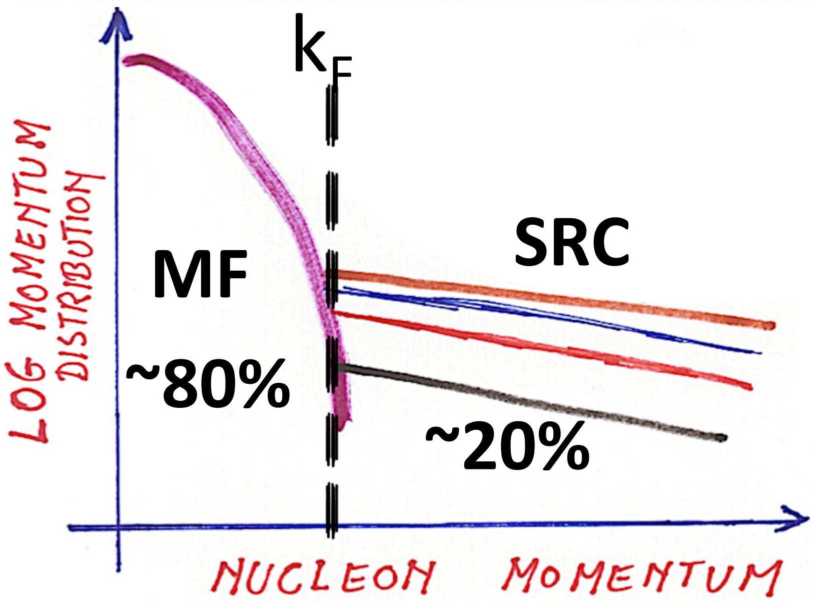
L. B. Weinstein

Massachusetts Institute of Technology

A. Schmidt, O. Hen

Backup slides

SRC 101



Account for ~20% of all nucleons in any nucleus.

Dominate the momentum distribution above the Fermi momentum (k_F).

Nucleons in the pair have high relative momentum and low center of mass momentum relative to k_F.

O. Hen et al., Science 364 (2014) 614.
Korover et al., PRL 113 (2014) 022501.
N. Fomin et al., PRL 108, 092502 (2012).
R. Subedi et al., Science 320 (2008) 1476.
K. Sh. Egiyan et al., PRC 68, 014313 (2003).
H. Baghdasaryan et al., PRL 105, 222501 (2010).
O. Hen, L. B. Weinstein, E. Piasetzky, *et al.*, PRC 92, no. 4, 045205 (2015).

Short range factorization

Contact interaction is represented through a boundary condition (B.C.)

Imposing this B.C. on the Schrödinger equation yields an asymptotic wavefunction when two nucleons get very close

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_\alpha \varphi_{ij}^{\alpha}(\boldsymbol{r}_{ij}) \times A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq ij})$$

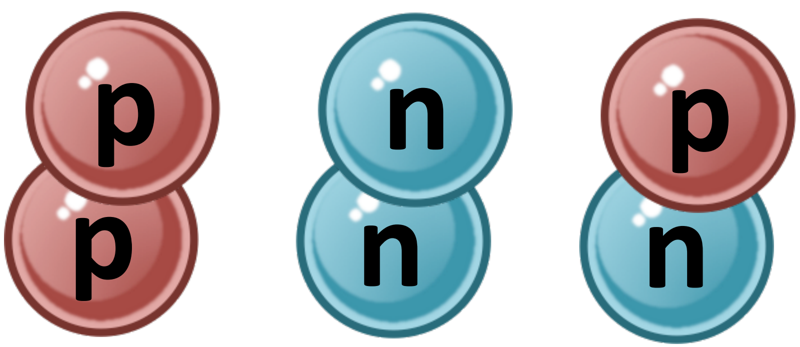
Short range factorization

<u>Consider the factorized wave function:</u>

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_\alpha \varphi_{ij}^{\alpha}(\boldsymbol{r}_{ij}) \times A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq ij})$$

In nuclear physics we have 3 possible types of pairs:

ij = {pp, nn, pn}



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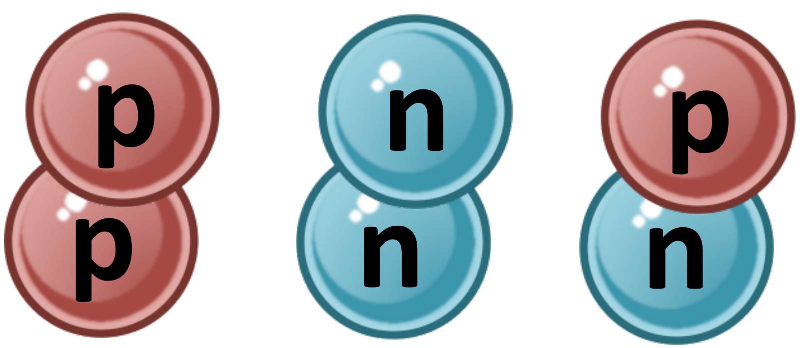
In nuclear physics we have 3 possible types of pairs:

ij = {pp, nn, pn}

\+

For each pair we have different channels

α = (s,l)jm



↓ ↑

Short range factorization

Consider the factorized wave function:

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_\alpha \varphi_{ij}^{\alpha}(\boldsymbol{r}_{ij}) \times A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq ij})$$

In nuclear physics we have 3 possible types of pairs:

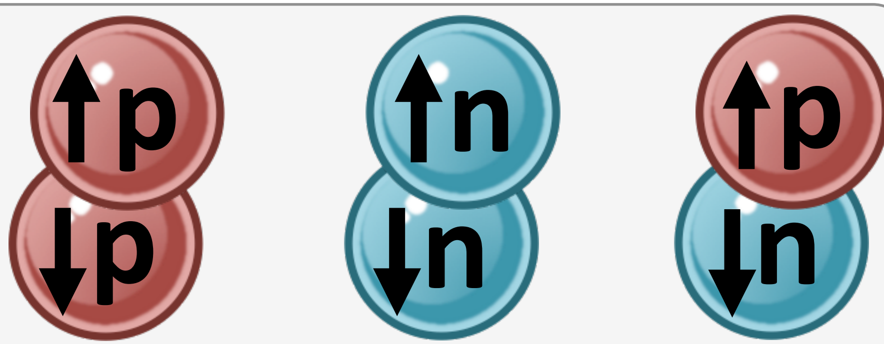
ij = {pp, nn, pn}

For each pair we have different channels

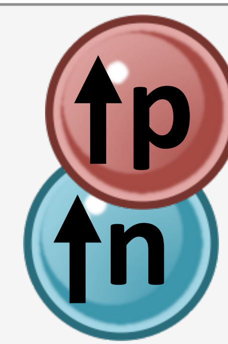
α = (s,l)jm

4 Contacts for l = 0

S=0



S=1



Short range factorization

Consider the factorized wave function:

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_{\alpha} \varphi_{ij}^{\alpha}(\boldsymbol{r}_{ij}) \times A_{ij}^{\alpha}(\boldsymbol{R}_{ij},\{\boldsymbol{r}_k\}_{k\neq ij})$$

In nuclear physics we have 3 possible types of pairs:

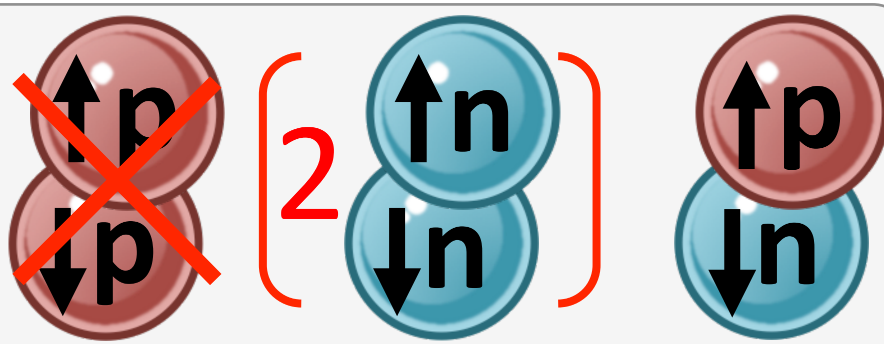
ij = {pp, nn, pn}

For each pair we have different channels

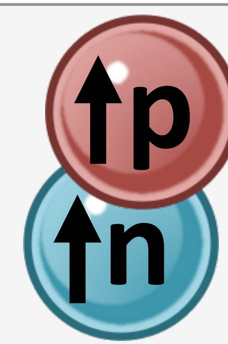
α = (s,l)jm

Number reduced to 3 from symmetry considerations

S=0



S=1



Short range factorization

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_\alpha \varphi_{ij}^{\alpha}(\boldsymbol{r}_{ij}) \times A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq ij})$$

One Body:

$$\mathrm{n}_p(\boldsymbol{k}) \xrightarrow{k\to\infty} \sum_\alpha \left[\left|\tilde{\varphi}_{pp}^{\alpha}(\boldsymbol{k})\right|^2 2C_{pp}^{\alpha} + \left|\tilde{\varphi}_{pn}^{\alpha}(\boldsymbol{k})\right|^2 C_{pn}^{\alpha}\right]$$

Short range factorization

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_\alpha \varphi_{ij}^{\alpha}(\boldsymbol{r}_{ij}) \times A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq ij})$$

One Body:

$$n_p(\boldsymbol{k}) \xrightarrow{k\to\infty} \sum_\alpha \left[\left|\tilde{\varphi}_{pp}^{\alpha}(\boldsymbol{k})\right|^2 2C_{pp}^{\alpha} + \left|\tilde{\varphi}_{pn}^{\alpha}(\boldsymbol{k})\right|^2 C_{pn}^{\alpha}\right]$$

Universal

Nucleus Dependent

Short range factorization

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_\alpha \varphi_{ij}^{\alpha}(\boldsymbol{r}_{ij}) \times A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq ij})$$

One Body:

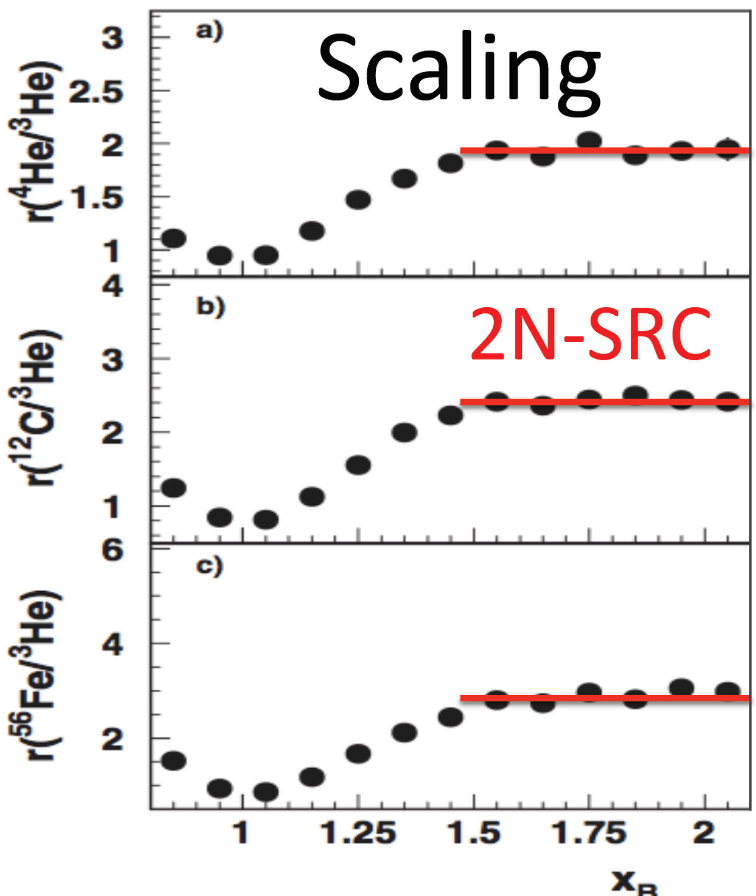
$$\mathrm{n}_p(\boldsymbol{k}) \xrightarrow{k\to\infty} \sum_\alpha \left[\left|\tilde{\varphi}_{pp}^{\alpha}(\boldsymbol{k})\right|^2 2C_{pp}^{\alpha} + \left|\tilde{\varphi}_{pn}^{\alpha}(\boldsymbol{k})\right|^2 C_{pn}^{\alpha} \right]$$

Two body:

$$\mathrm{F}_{ij}(\boldsymbol{k}) \xrightarrow{k\to\infty} \sum_\alpha \left|\tilde{\varphi}_{ij}^{\alpha}(\boldsymbol{k})\right|^2 C_{ij}^{\alpha}$$

Extraction from experimental data

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



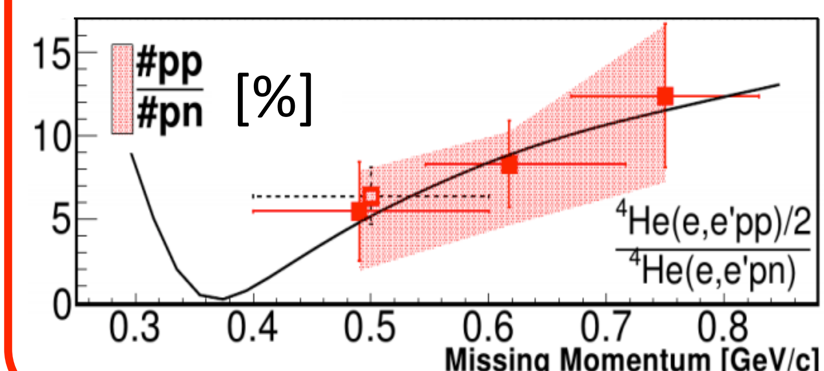
A(e,e')

$$a_2(A/d) \propto \sum_{\alpha} C_{ij}^{\alpha}$$

$$\frac{\#pp}{\#pn}(k) = \frac{F_{pp}(\boldsymbol{k})}{F_{pn}(\boldsymbol{k})}$$

$$F_{ij}(\boldsymbol{k}) \xrightarrow{k\to\infty} \sum_{\alpha} \left|\tilde{\varphi}_{ij}^{\alpha}(\boldsymbol{k})\right|^2 C_{ij}^{\alpha}$$

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



Pauli Term

Classical:

$$\rho_2^{\text{uncorr.}}(r) \equiv \int d^3 R \rho(\vec{R} + \vec{r}/2)\rho(\vec{R} - \vec{r}/2)$$

Accounting for exchange:

$$\rho_2^{\text{uncorr.}}(r) \equiv \sum_{i,j} \int d^3 R \psi_i^*(\vec{R} + \vec{r}/2)\psi_j^*(\vec{R} - \vec{r}/2)$$

$$\times \left[\psi_i(\vec{R} + \vec{r}/2)\psi_j(\vec{R} - \vec{r}/2) - \psi_i(\vec{R} - \vec{r}/2)\psi_j(\vec{R} + \vec{r}/2)\right]$$