

Generalized nuclear contacts and short-range correlations

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The Hebrew University of Jerusalem

GANIL workshop: Nuclear Structure and Reaction Theories

10/10/17

Outline

I. Introduction

- Nuclear short-range correlations
- The original contact theory

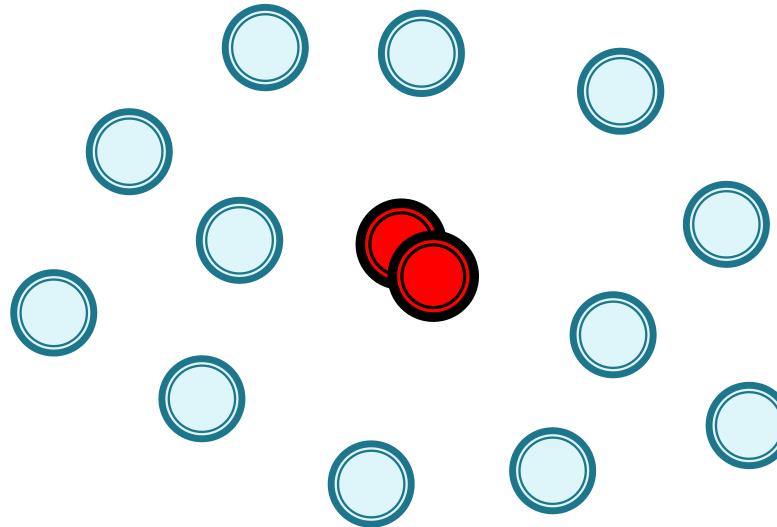
II. Generalized contacts for nuclear physics

- Definition
- Main results

III. Summary

Nuclear short-range correlations

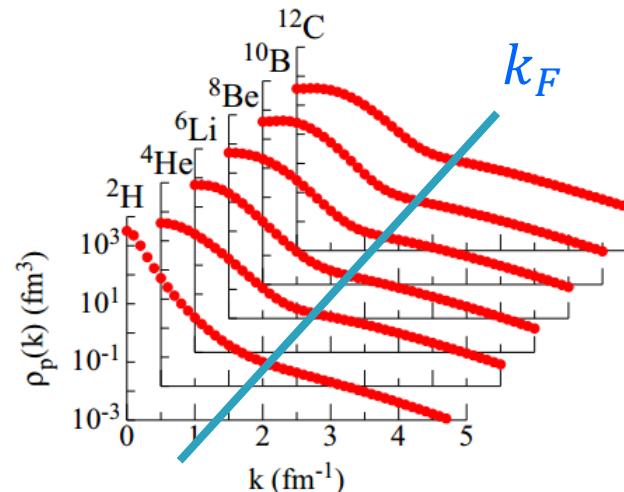
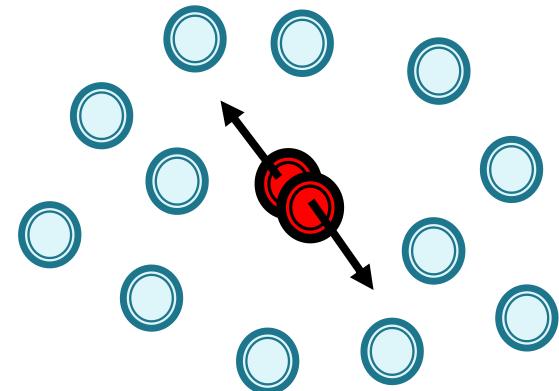
- ▶ Studying what happens when two particles get close to each other



- ▶ What are the properties of such pairs?
- ▶ Which nuclear quantities and reactions are affected?
- ▶ How are they connected to each other?

Nuclear short-range correlations

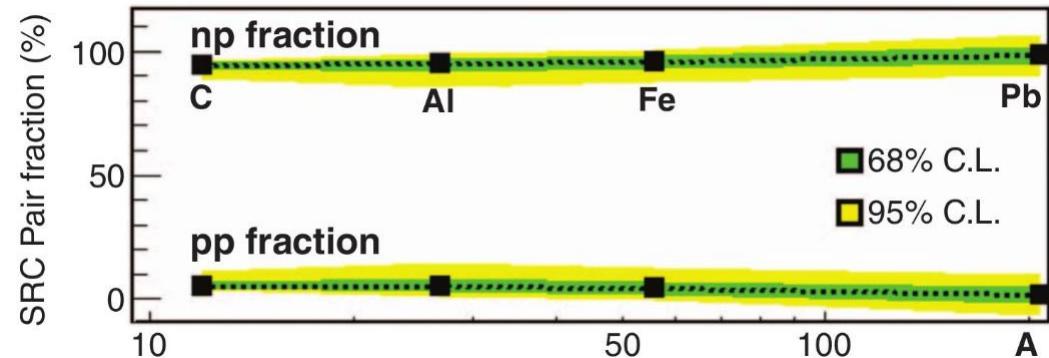
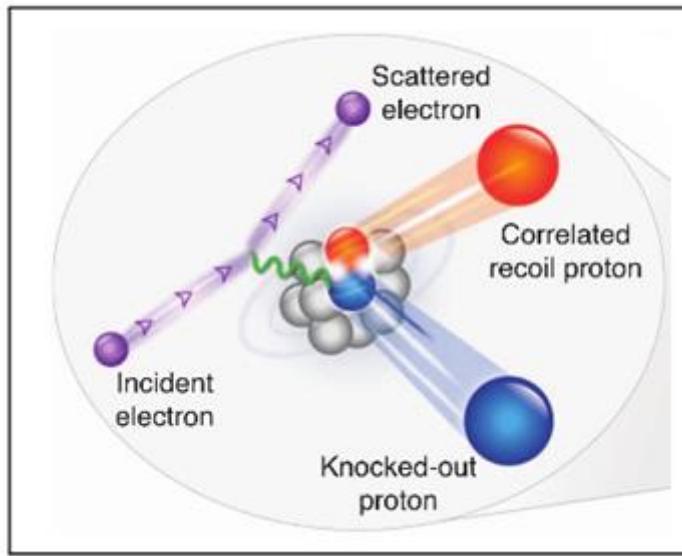
- ▶ A lot is already known
- ▶ Theory:
 - Existence of a **high momentum tail** in the momentum distribution
 - Different nuclei have similar high momentum tails



Nuclear short-range correlations

► Experiments

- Mainly electron scattering experiments
- Correlated pairs of nucleons with high momentum were measured
- A **dominance of neutron-proton pairs** with back-to-back momentum



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

Nuclear short-range correlations

► Experiments

- Mainly electron scattering experiments
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A complete effective theory describing nuclear short-range correlations is still missing

The atomic contact

- ▶ Zero-range condition:

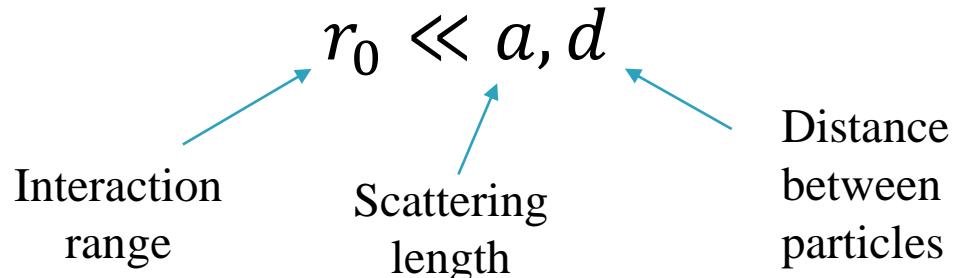
$$r_0 \ll a, d$$

Interaction range Scattering length Distance between particles

The diagram illustrates the zero-range condition $r_0 \ll a, d$. It features three blue arrows originating from the text labels 'Interaction range', 'Scattering length', and 'Distance between particles' and pointing towards the corresponding variables in the equation.

The atomic contact

- ▶ Zero-range condition:



- ▶ Many quantities are connected to the *contact C*:

$$n(k) = \mathbf{C}/k^4 \text{ for } k \rightarrow \infty$$

$$T + U = \frac{\hbar^2}{4\pi m a} \mathbf{C} + \sum_{\sigma} \frac{d^3 k}{(2\pi)^3} \frac{\hbar^2 k^2}{2m} \left(n_{\sigma}(k) - \frac{\mathbf{C}}{k^4} \right)$$

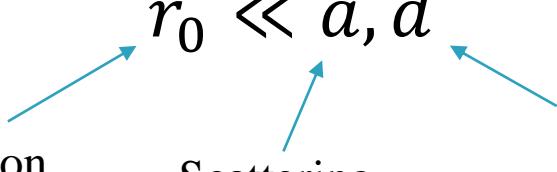
and many more...

The atomic contact

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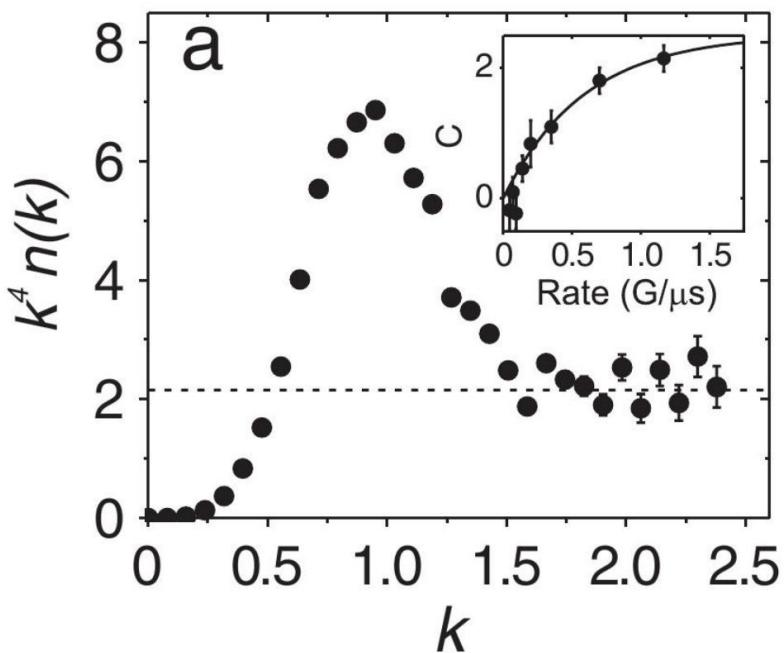
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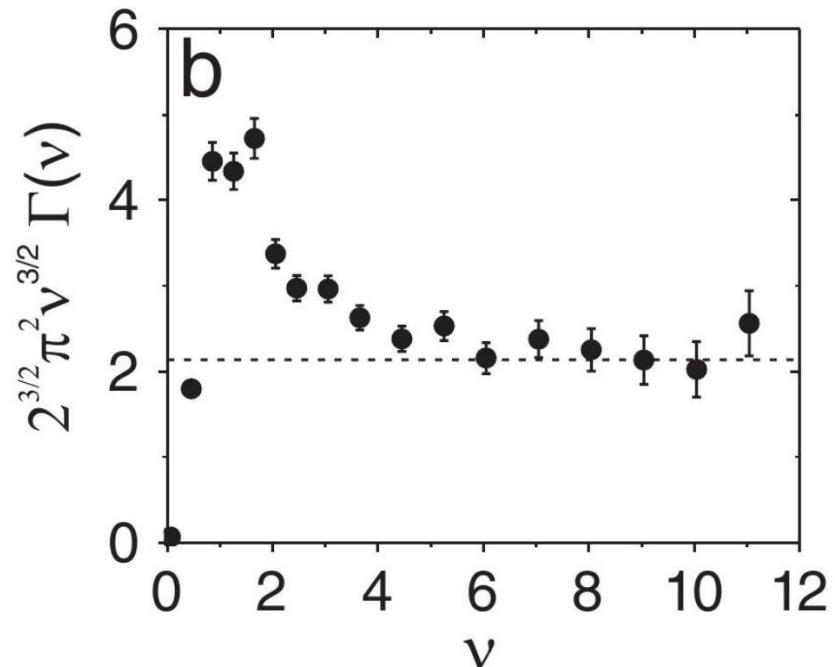
C ≈ The number of short range correlated pairs

The atomic contact

Momentum distribution



RF line shape



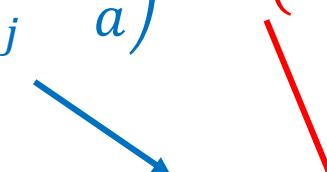
The atomic contact

- ▶ The basic **factorization** assumption:

$$\psi \xrightarrow{r_{ij} \rightarrow 0} \left(\frac{1}{r_{ij}} - \frac{1}{a} \right) \times A(R_{ij}, \{r_k\}_{k \neq i,j})$$

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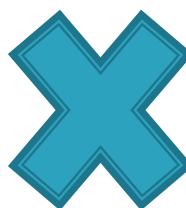
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NOT FOR NUCLEAR PHYSICS

$r_0 \ll d, a$ 

Generalized Nuclear contacts

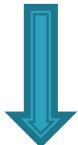
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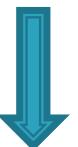
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Generalized Nuclear contacts

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$$\psi \xrightarrow{r_{ij} \rightarrow 0} \sum_{\alpha} \varphi_{ij}^{\alpha}(\mathbf{r}_{ij}) \times A_{ij}^{\alpha}(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k \neq i,j}) \quad ; \quad C_{ij}^{\alpha\beta} \propto \langle A_{ij}^{\alpha} | A_{ij}^{\beta} \rangle$$

Channels α
 $= (\ell_2 S_2) j_2 m_2$

“universal”
function

The pair kind
 $ij \in \{pp, nn, pn\}$

The nuclear contact relations

► Momentum & coordinate-space distributions

R. Weiss, B. Bazak, N. Barnea, PRC **92, 054311 (2015)**

M. Alvioli, CC. Degli Atti, H. Morita, PRC **94, 044309 (2016)**

R. Weiss, R. Cruz-Torres, N. Barnea, E. Piasetzky and O. Hen, arXiv:1612.00923 [nucl-th] (2016)

► The Levinger constant

R. Weiss, B. Bazak, N. Barnea, PRL **114, 012501 (2015)**

R. Weiss, B. Bazak, N. Barnea, EPJA **52, 92 (2016)**

► The Coulomb sum rule (and a review)

R. Weiss, E. Pazy, N. Barnea, Few-Body Systems **58, 9 (2017)**

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► The EMC effect

JW. Chen, W. Detmold, J. E. Lynn, A. Schwenk, arxiv 1607.03065 [hep-ph] (2016)

► Coupled-channels theory

R. Weiss, B. Bazak, N. Barnea, arXiv:1705.02592 [nucl-th] (2017)

and more...

Momentum distributions

One-body momentum distribution - $n_N(\mathbf{k})$ – The probability to find a proton/neutron with momentum \mathbf{k}

Two-body momentum distribution - $F_{NN}(\mathbf{k})$ – The probability to find an NN pair with relative momentum \mathbf{k}

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$$n_{\mathbf{p}}(\mathbf{k}) \xrightarrow{\mathbf{k} \rightarrow \infty} \sum_{\alpha, \beta} \left[\tilde{\varphi}_{pp}^{\alpha\dagger}(\mathbf{k}) \tilde{\varphi}_{pp}^{\beta}(\mathbf{k}) 2C_{pp}^{\alpha\beta} + \tilde{\varphi}_{pn}^{\alpha\dagger}(\mathbf{k}) \tilde{\varphi}_{pn}^{\beta}(\mathbf{k}) C_{pn}^{\alpha\beta} \right]$$

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Momentum distributions

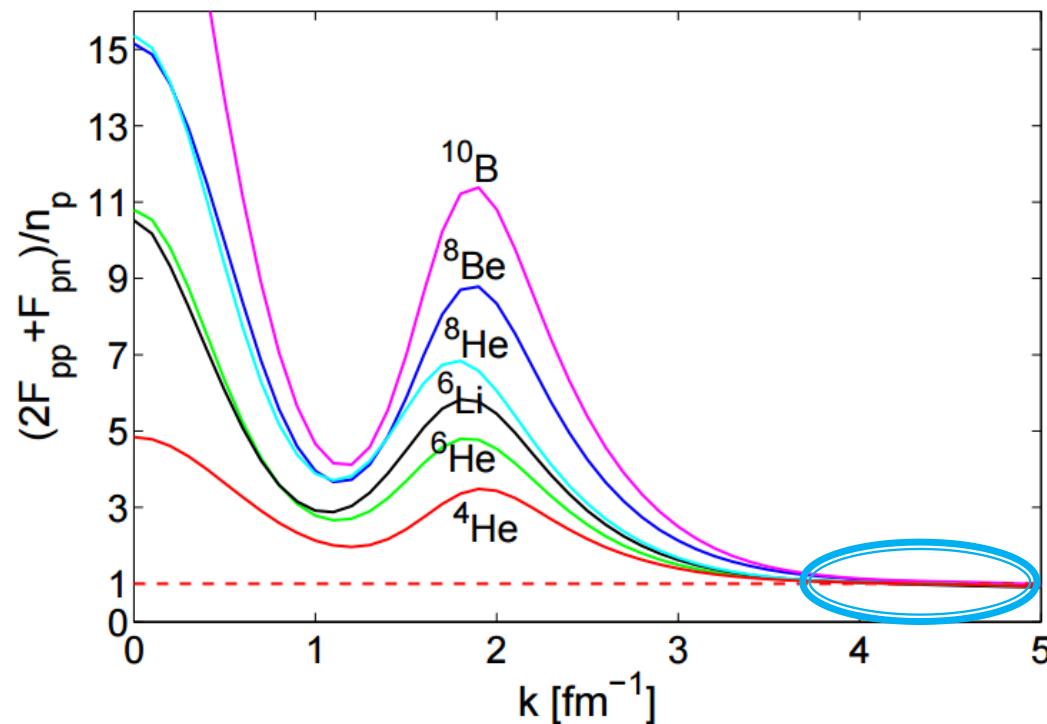
- As a result we get the asymptotic relation:

$$n_p(\mathbf{k}) \rightarrow F_{pn}(\mathbf{k}) + 2F_{pp}(\mathbf{k})$$

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Using the
variational
Monte Carlo
data (VMC)

Extracting the contacts

- ▶ Assuming only two significant channels:

The **deuteron** channel – L=0,2 ; S=1 ; J=1 ; T=0

The **pure s-wave** channel – L=0 ; S=0 ; J=0 ; T=1

- ▶ We get:

$$F_{ij}(\mathbf{k}) \xrightarrow{\mathbf{k} \rightarrow \infty} \sum_{\alpha, \beta} \tilde{\phi}_{ij}^{\alpha\dagger}(\mathbf{k}) \tilde{\phi}_{ij}^{\beta}(\mathbf{k}) C_{ij}^{\alpha\beta}$$

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$$F_{pn}(k) \xrightarrow{k \rightarrow \infty} C_{pn}^d |\varphi_{pn}^d(k)|^2 + C_{pn}^0 |\varphi_{pn}^0(k)|^2$$

$$F_{nn}(k) \xrightarrow{k \rightarrow \infty} C_{nn}^0 |\varphi_{nn}^0(k)|^2$$

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The VMC
data

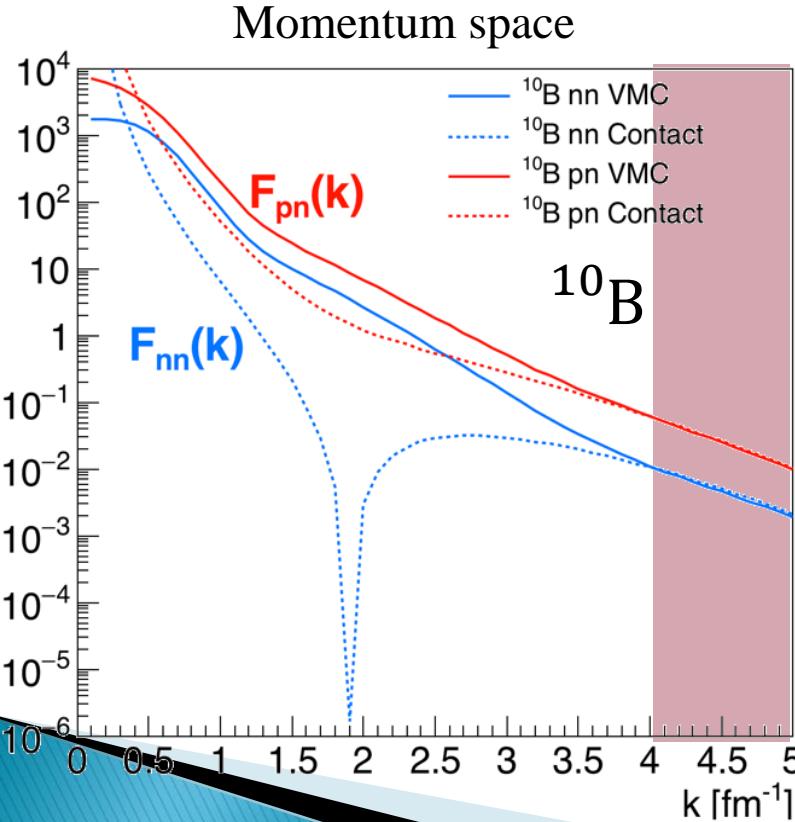
$$F_{nn}(k) \xrightarrow{k \rightarrow \infty} C_{nn}^0 |\varphi_{nn}^0(k)|^2$$

Zero-energy
solution of the
two-body
system (AV18)

Extracting the contacts

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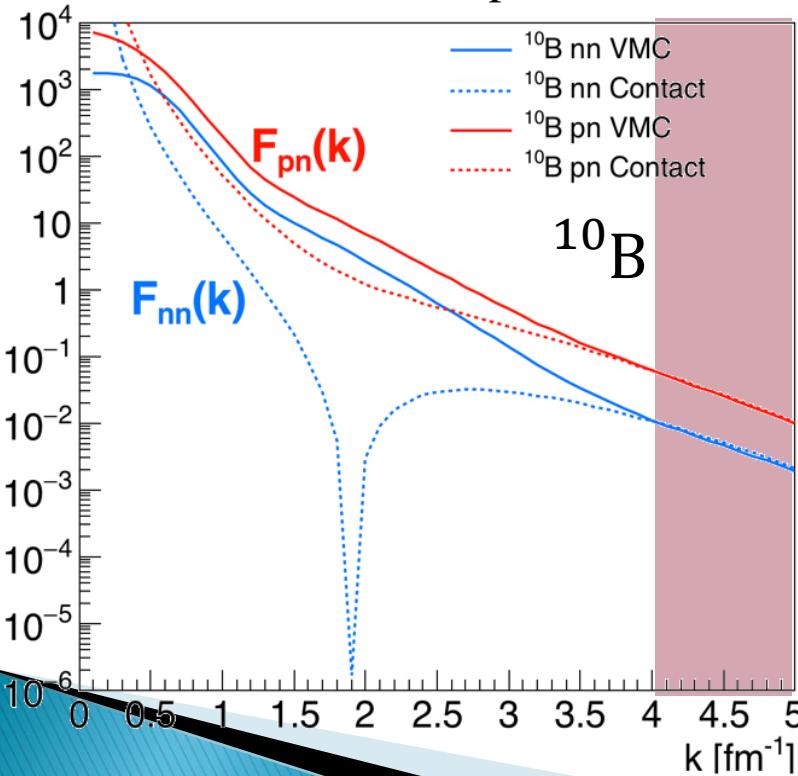


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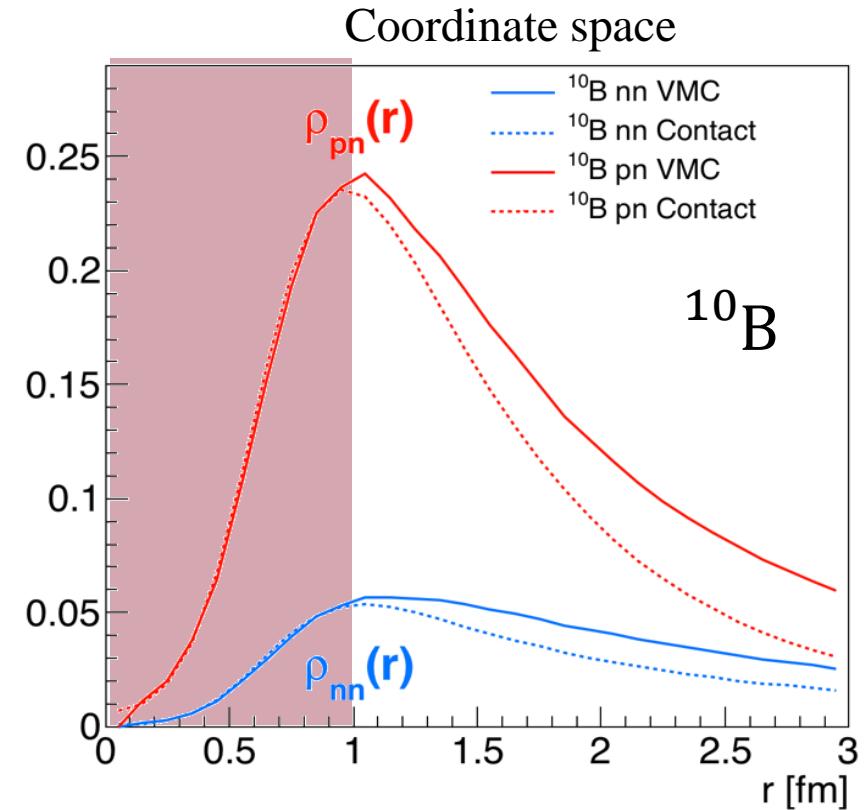
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Momentum space



Coordinate space



Extracting the contacts

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Universal functions -
Calculated for the two-
body system

Extracting the contacts

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Fitted to $F_{ij}(k)$
for
 $k > 4 \text{ fm}^{-1}$

Extracting the contacts

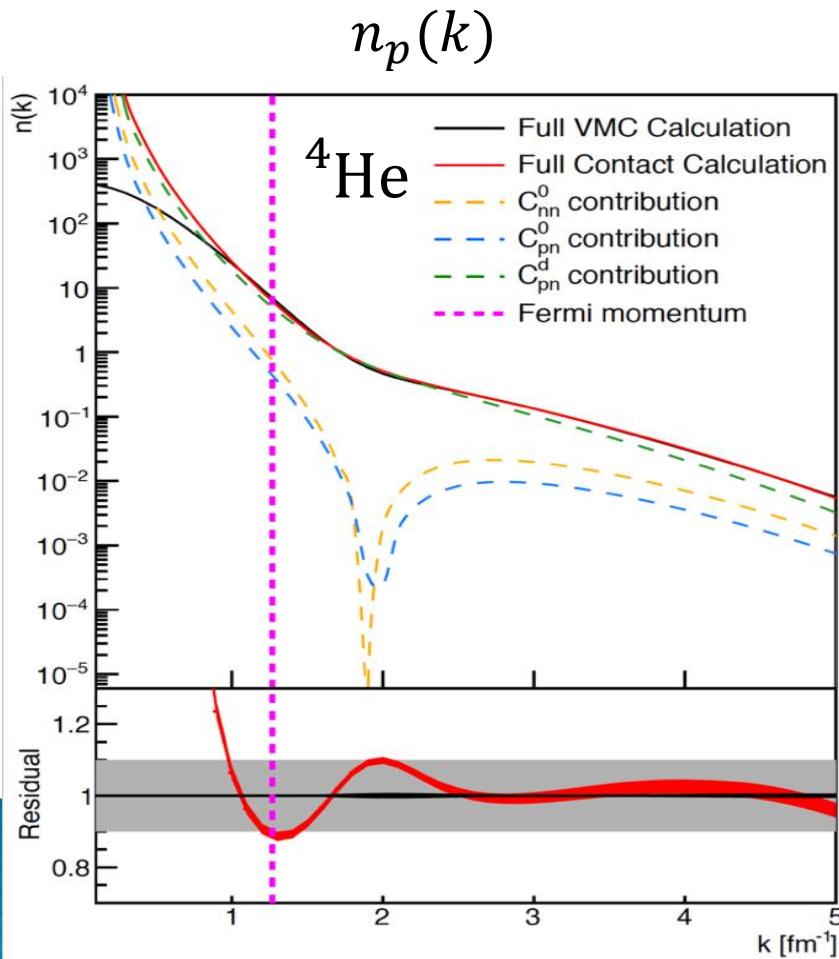
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The VMC
data



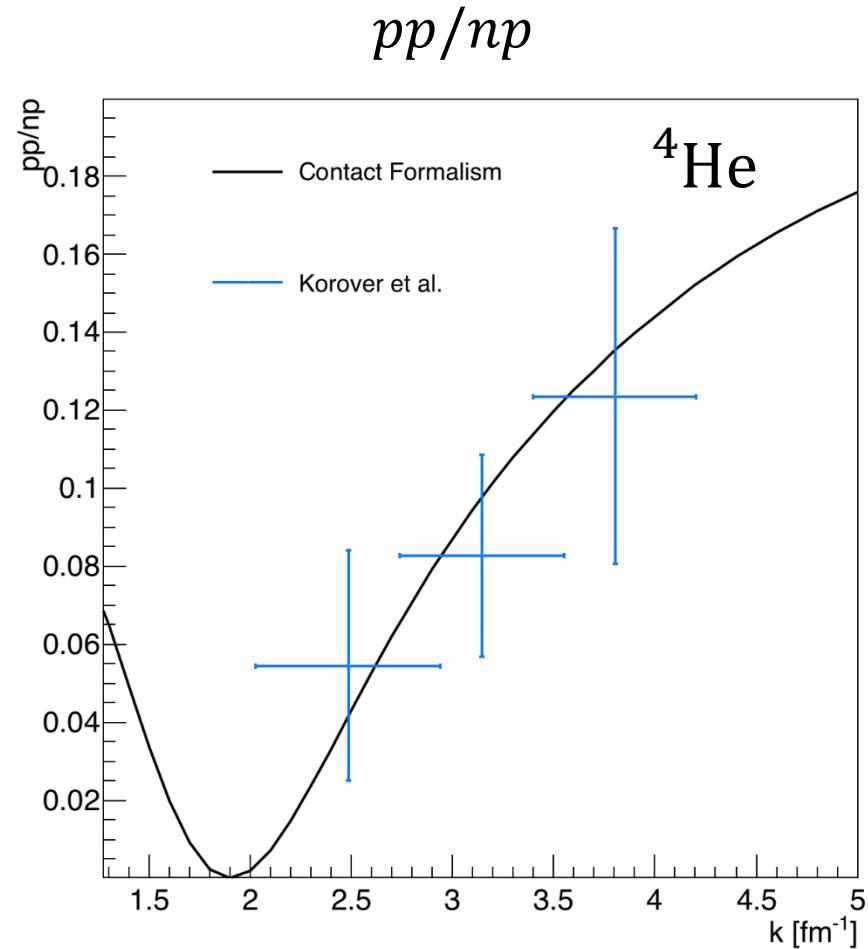
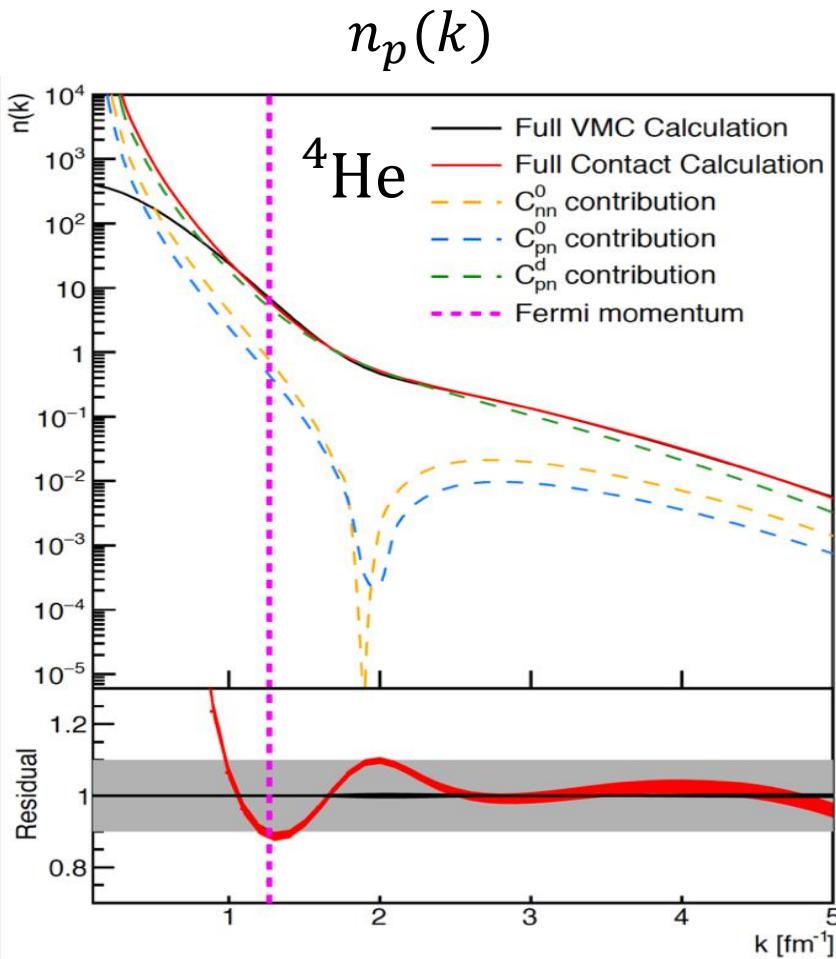
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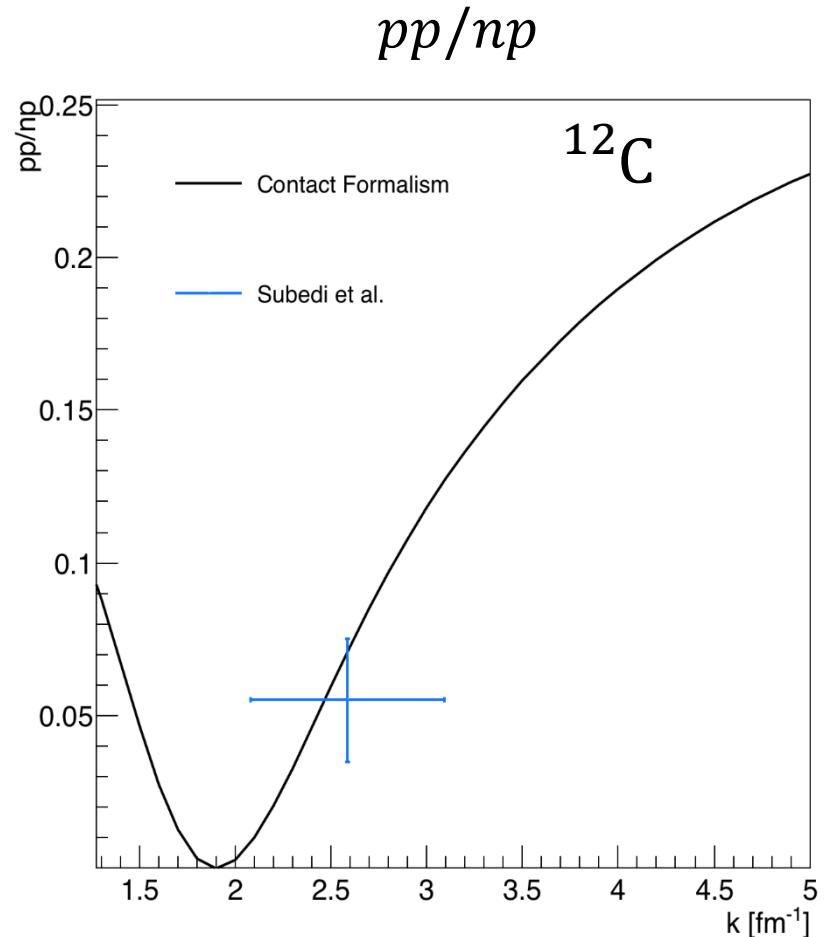
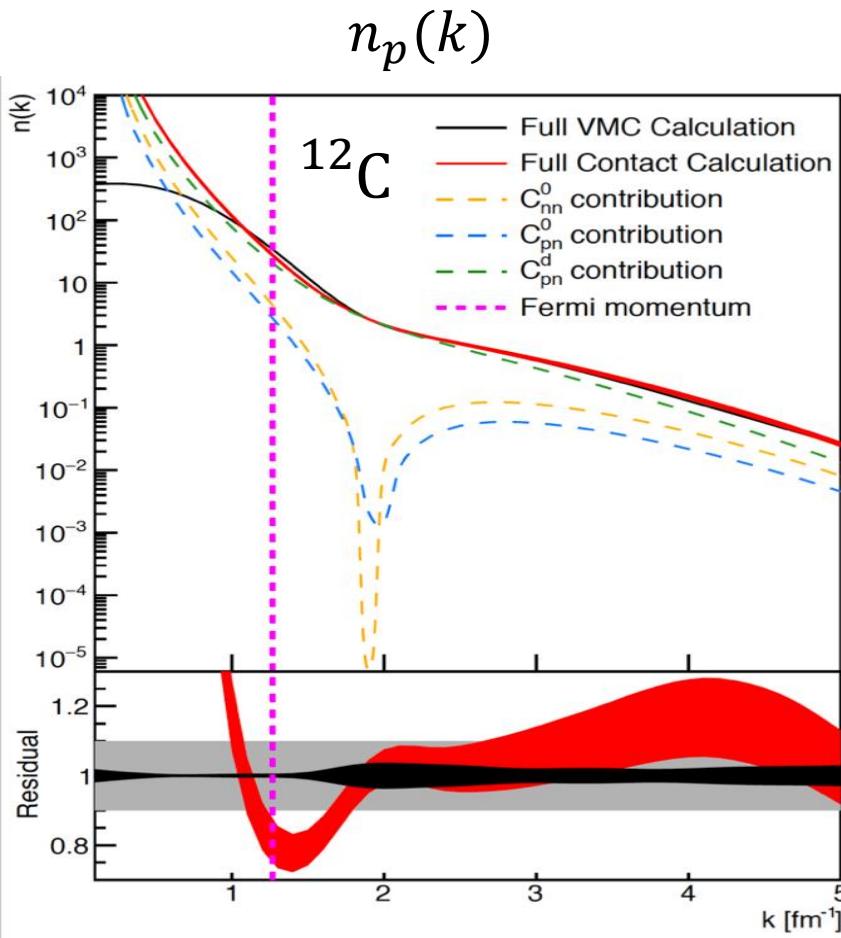
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Counting the SRCs (symmetric nuclei)

$$n_p(k) \xrightarrow[k \rightarrow \infty]{} C_{pn}^d |\varphi_{pn}^d(k)|^2 + C_{pn}^0 |\varphi_{pn}^0(k)|^2 + 2C_{pp}^0 |\varphi_{pp}^0(k)|^2$$

Normalization: $\int_{k_F}^{\infty} |\varphi_{ij}^{\alpha}|^2 d^3 k = 1$



$$\%SRC \equiv \frac{1}{Z} \int_{K_F}^{\infty} n_p(\mathbf{k}) d^3 k = \frac{1}{Z} [C_{pn}^d + C_{pn}^0 + 2C_{nn}^0]$$

Counting the SRCs



Total number of pairs:

$$\text{pp} - 1 \quad \text{np}-4$$

	$C_{pp}^0/Z (\%)$	$C_{pn}^0/Z (\%)$	$C_{pn}^d/Z (\%)$
k-space	0.65 ± 0.03	0.69 ± 0.03	12.3 ± 0.1

Neutron-proton
dominance

Counting the SRCs



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Counting the SRCs



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k-space	0.65 ± 0.03	0.69 ± 0.03	12.3 ± 0.1	14.3%
r-space		0.567 ± 0.004	11.61 ± 0.03	13.3%

Similar results are obtained for all the available nuclei in the VMC data

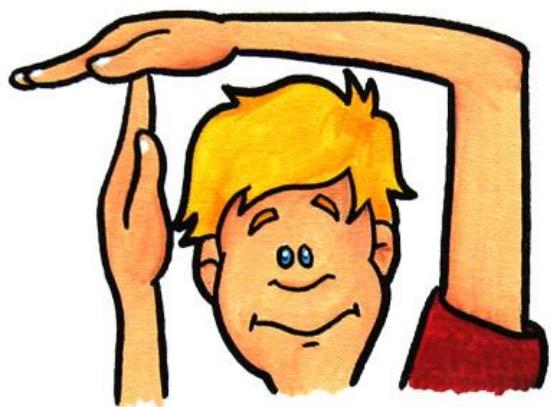
Mini-summary

Two-body
momentum
distribution for
 $k > 4 \text{ fm}^{-1}$

Two-body
coordinate density
for
 $r < 1 \text{ fm}$

Extracting the
contacts

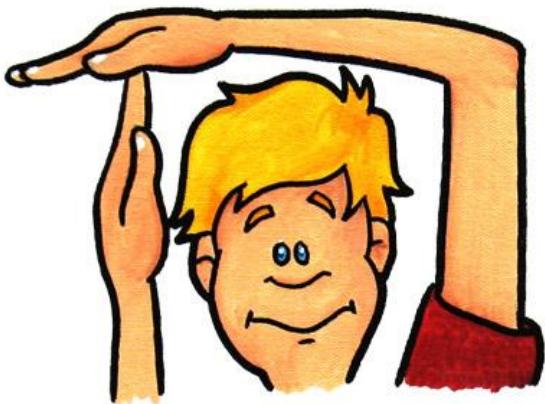
Many details
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 $k > k_F$



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Extracting the
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Many details
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 $k > k_F$

np dominance & pp/np

Isospin symmetry

%SRCs

Main (L, S, J, T)
channels

1B momentum
distribution

The nuclear contact relations

► Momentum & coordinate-space distributions

R. Weiss, B. Bazak, N. Barnea, PRC **92, 054311 (2015)**

M. Alvioli, CC. Degli Atti, H. Morita, PRC **94, 044309 (2016)**

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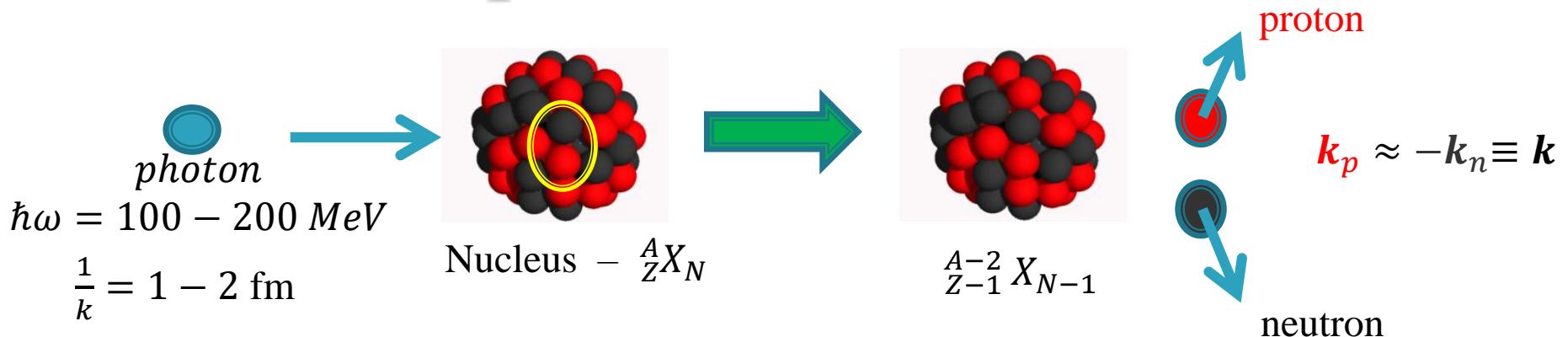
JW. Chen, W. Detmold, J. E. Lynn, A. Schwenk, arxiv 1607.03065 [hep-ph] (2016)

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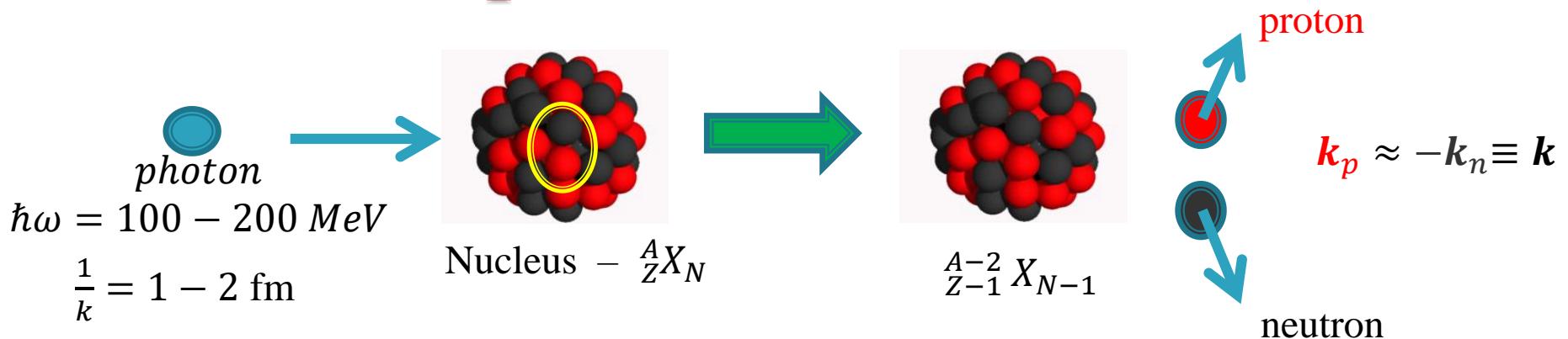
R. Weiss, B. Bazak, N. Barnea, arXiv:1705.02592 [nucl-th] (2017)

and more...

The quasi deuteron model



The quasi deuteron model



Levinger's quasi-deuteron model:

$$\sigma_X(\omega) = L \frac{NZ}{A} \sigma_d(\omega)$$

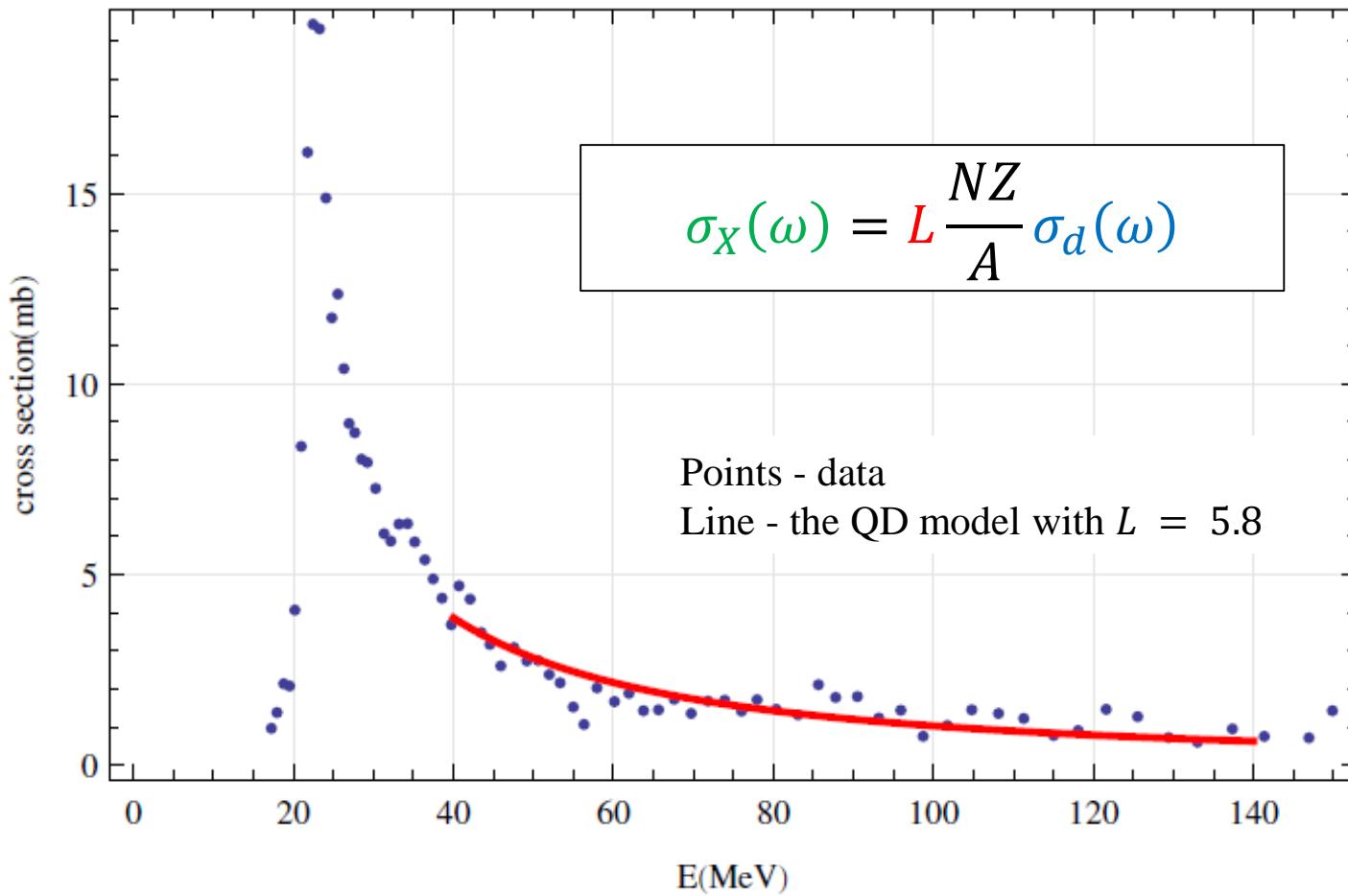
σ_X - The photo-absorption cross-section of the nucleus

σ_d - The deuteron cross-section

L - The Levinger constant

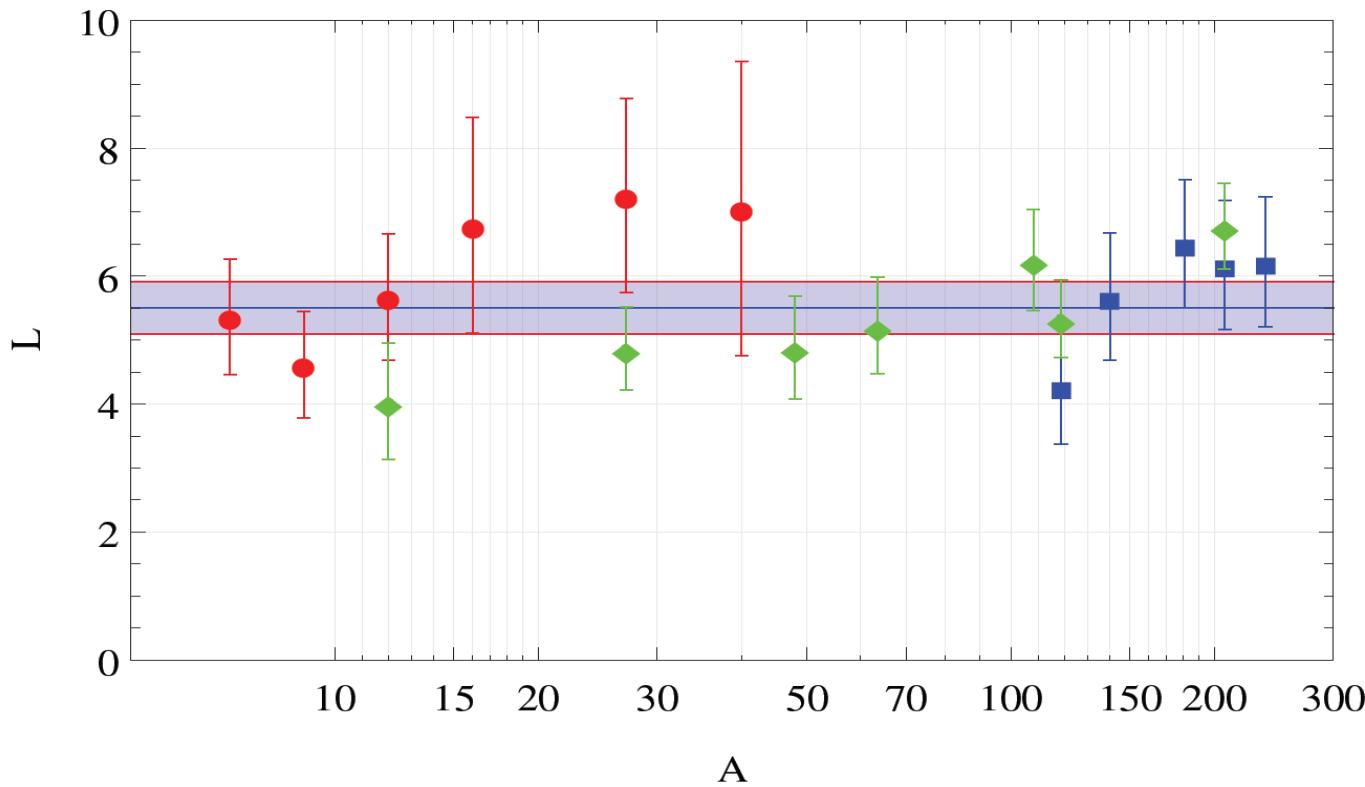
The quasi deuteron model

The ^{12}C photo-absorption cross section



The quasi deuteron model

From available analysis of photo-absorption experiments:



$$L = 5.50 \pm 0.21$$

The quasi deuteron model

Using the new contact formalism (and the dipole approximation):

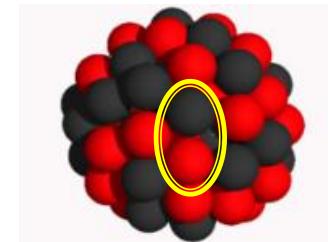
$$\sigma_X \propto \sum_i \sum_f \left| \langle \psi_f | \epsilon \cdot \hat{D} | \psi_0 \rangle \right|^2 \delta(E_f - E_0 - \hbar\omega)$$

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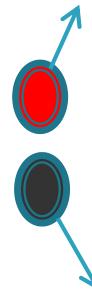
The quasi deuteron model

Using the new contact formalism (and the dipole approximation):

$$\sigma_X \propto \sum_i \sum_f \left| \langle \psi_f | \epsilon \cdot \hat{D} | \psi_0 \rangle \right|^2 \delta(E_f - E_0 - \hbar\omega)$$

$$\psi_0 \rightarrow \sum_{\alpha} \varphi_{ij}^{\alpha}(\mathbf{r}_{ij}) \times A_{ij}^{\alpha}(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k \neq i,j})$$

$$\psi_f \propto e^{-i\mathbf{k} \cdot \mathbf{r}_{pn}} \chi_{s\mu_s} A_{pn}^{\beta}(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k \neq i,j})$$



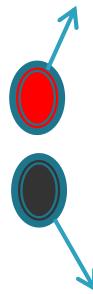
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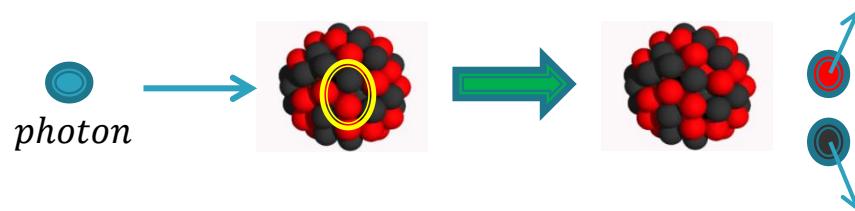


$$\sigma_X(\omega) \propto \sum_{\alpha,\beta} C_{pn}^{\alpha\beta}(X) R_{\alpha\beta}(\omega)$$

$$R_{\alpha\beta} = \int d\hat{k} \sum_{s\mu_s} \langle \mathbf{k}_s \mu_s | \epsilon \cdot \hat{D}_{pn} | \alpha \rangle^* \langle \mathbf{k}_s \mu_s | \epsilon \cdot \hat{D}_{pn} | \beta \rangle$$

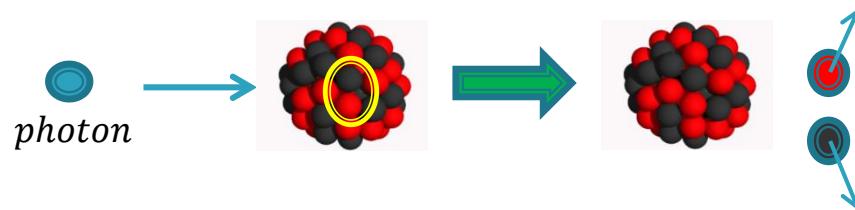
does not change along
the nuclear chart

The quasi deuteron model



$$\sigma_X(\omega) \propto \sum_{\alpha,\beta} C_{pn}^{\alpha\beta}(X) R_{\alpha\beta}(\omega) \xrightarrow{\text{Deuteron dominance}} \sigma_X(\omega) \propto C_{pn}^d(X) R_d(\omega)$$

The quasi deuteron model



$$\sigma_X(\omega) \propto \sum_{\alpha,\beta} C_{pn}^{\alpha\beta}(X) R_{\alpha\beta}(\omega) \longrightarrow \sigma_X(\omega) \propto C_{pn}^d(X) R_d(\omega)$$

Comparing to Levinger's model

$$\sigma_X(\omega) = L \frac{NZ}{A} \sigma_d(\omega)$$

$$\frac{C_{pn}^d({}_Z^AX)}{C_{pn}^d(d)} = L \frac{NZ}{A}$$

Momentum vs Levinger

$$\left\{ \begin{array}{l} n_p(d) \xrightarrow[k \rightarrow \infty]{} C_{pn}^d(d) |\varphi_{pn}^d(k)|^2 \\ \\ F_{pn}(X) \xrightarrow[k \rightarrow \infty]{} C_{pn}^d(X) |\varphi_{pn}^d(k)|^2 + C_{pn}^0(X) |\varphi_{pn}^0(k)|^2 \end{array} \right.$$



$$\boxed{\frac{F_{pn}(X)}{n_p(d)} \approx \frac{C_{pn}^d(X)}{C_{pn}^d(d)}}$$

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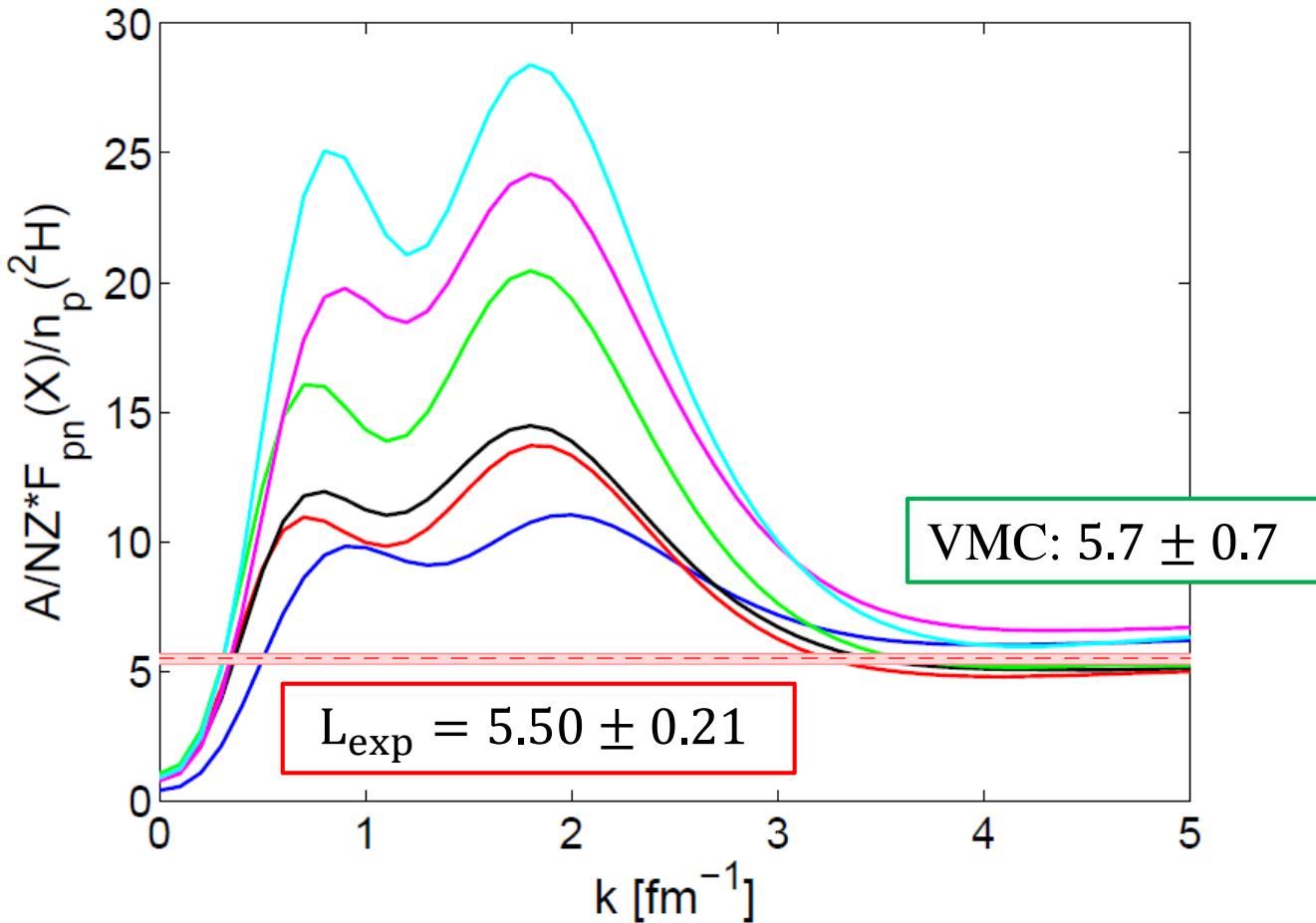


$$\frac{F_{pn}(X)}{n_p(d)} \xrightarrow[k \rightarrow \infty]{} L \frac{NZ}{A}$$

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Momentum vs Levinger

$$\frac{A}{NZ} \frac{F_{pn}(X)}{n_p(d)} \xrightarrow{k \rightarrow \infty} L$$



The nuclear contact relations

► Momentum & coordinate-space distributions

R. Weiss, B. Bazak, N. Barnea, PRC **92, 054311 (2015)**

M. Alvioli, CC. Degli Atti, H. Morita, PRC **94, 044309 (2016)**

R. Weiss, R. Cruz-Torres, N. Barnea, E. Piasetzky and O. Hen, arXiv:1612.00923 [nucl-th] (2016)

► The Levinger constant

R. Weiss, B. Bazak, N. Barnea, PRL **114, 012501 (2015)**

R. Weiss, B. Bazak, N. Barnea, EPJA **52, 92 (2016)**

► The Coulomb sum rule (and a review)

R. Weiss, E. Pazy, N. Barnea, Few-Body Systems **58, 9 (2017)**

► Electron scattering

O. Hen et al., PRC **92, 045205 (2015)**

► Symmetry energy

BJ. Cai, BA. Li, PRC **93, 014619 (2016)**

► The EMC effect

JW. Chen, W. Detmold, J. E. Lynn, A. Schwenk, arxiv 1607.03065 [hep-ph] (2016)

► Coupled-channels theory

R. Weiss, B. Bazak, N. Barnea, arXiv:1705.02592 [nucl-th] (2017)

and more...

Summary

- ▶ Nuclear short-range correlations can be described using the generalized nuclear contacts
- ▶ Different nuclear quantities and reactions are related to the contacts
- ▶ High momentum tails can be described using 3 parameters (contacts)
- ▶ Direct relation between momentum distributions and photo-absorption cross sections was identified

