The Generalized Contact Formalism (GCF)

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The Hebrew University of Jerusalem

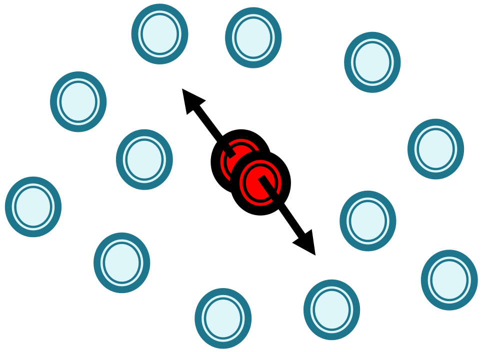
SRC EMC workshop – March 23, 2021

The GCF

- Effective theory for analyzing short-range correlations
- Quantitative study of SRC
- Clear definition of SRC abundances
- Comprehensive and consistent picture: Structure and Reaction
- Bridging the gap between experimental studies and ab-initio calculations ($A > 3$)
- Connection to the underlying interaction

The Factorization

- The factorization of the wave function:



$$\Psi(r_1, r_2, \ldots, r_A) \xrightarrow{r_{12}\to 0} \varphi(r) A\left(\boldsymbol{R}, \{\boldsymbol{r}_k\}_{k\neq 1,2}\right)$$

Universal function
Nucleus-**in**dependent
(depends on the potential)

Nucleus-dependent function

$\varphi(r) \equiv$ Solution of the **two-body** Schrodinger Eq.

RW et al., PRC 92, 0541311 (2015)

The Factorization

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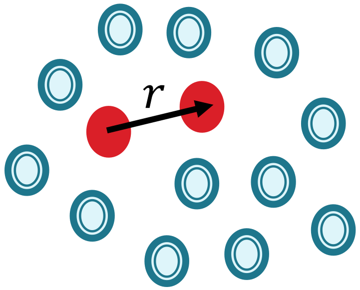
$$\Psi(r_1, r_2, \ldots, r_A) \xrightarrow{r_{12}\to 0} \varphi(r) A\left(\boldsymbol{R}, \{\boldsymbol{r}_k\}_{k\neq 1,2}\right)$$

- For any **short-range** two-body operator $\hat{O}$ (assuming that acts on protons):

$$\langle \hat{O} \rangle = \sum_{i<j} \langle \Psi | \hat{O}(\boldsymbol{r}_{ij}) | \Psi \rangle = \langle \varphi | \hat{O}(r) | \varphi \rangle \frac{Z(Z-1)}{2} \langle A | A \rangle$$

Describes the behavior of the pair

The probability to find a correlated pair (low-energy property)



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The pp contact $\quad C_{pp} \equiv \frac{Z(Z-1)}{2} \langle A | A \rangle$

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$$\langle \hat{O} \rangle = \langle \varphi | \hat{O}(r) | \varphi \rangle C_{pp}$$

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The contact formalism

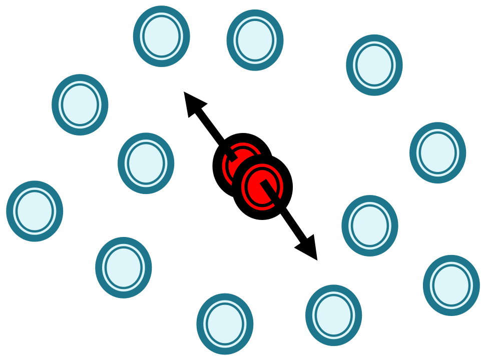
$$\Psi \xrightarrow{r_{ij\to 0}} \sum_{\alpha} \varphi_{ij}^{\alpha}(\boldsymbol{r}_{ij}) A_{ij}^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j}) \quad ; \quad \boldsymbol{C}_{ij}^{\alpha\beta} \propto \langle A_{ij}^{\alpha} | A_{ij}^{\beta} \rangle$$

Channels α
$= (\ell_2 S_2) j_2 m_2$

“universal“
function

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

3 matrices



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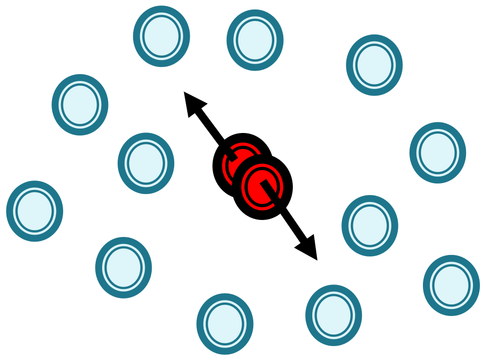
Main channels:

The **deuteron** channel: $\ell_2 = 0{,}2\,;\, s_2 = 1\,;\, j_2 = 1\,;\, t_2 = 0$

The **spin-zero** channel: $\ell_2 = 0\,;\, s_2 = 0\,;\, j_2 = 0\,;\, t_2 = 1$



RW et al., PRC 92,
0541311 (2015)

The generalized contact formalism

- Generalization of the **atomic contact theory**

S. Tan (2008)

$$\Psi \xrightarrow{r_{ij}\to 0} \left(\frac{1}{r_{ij}} - \frac{1}{a}\right) A\left(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j}\right)$$

$$C \propto \langle A|A\rangle$$

The generalized contact formalism

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  S. Tan (2008)

  $C \propto \langle A|A\rangle$

- Relies also on **significant nuclear physics works**:
  - Wave function factorization (not asymptotic form) [**Levinger** (1951), **Heidmann** (1950), **Brueckner** (1955)]
  - Universal high-momentum tail [**Amado** (1976), **Zabolitzky** (1978)]
  - Universal SRC pairs [**Frankfurt** and **Strikman** (1988)] $\sigma_{eA}/A = a_2\, \sigma_{ed}/2$
  - Asymptotic factorization with deuteron-like pairs [**Ciofi degli Atti** and **Simula** (1996)]
  - Modern ab-initio calculations, pp and nn contributions [**Feldmeier** (2011), **Alvioli** (2013), **Wiringa** (2014), **Ryckebusch** (2015)…]
  - Asymptotic high-momentum factorization with two-body universal function and state-dependent coefficient (the contact) [**Bogner** and **Roscher** (2012)]

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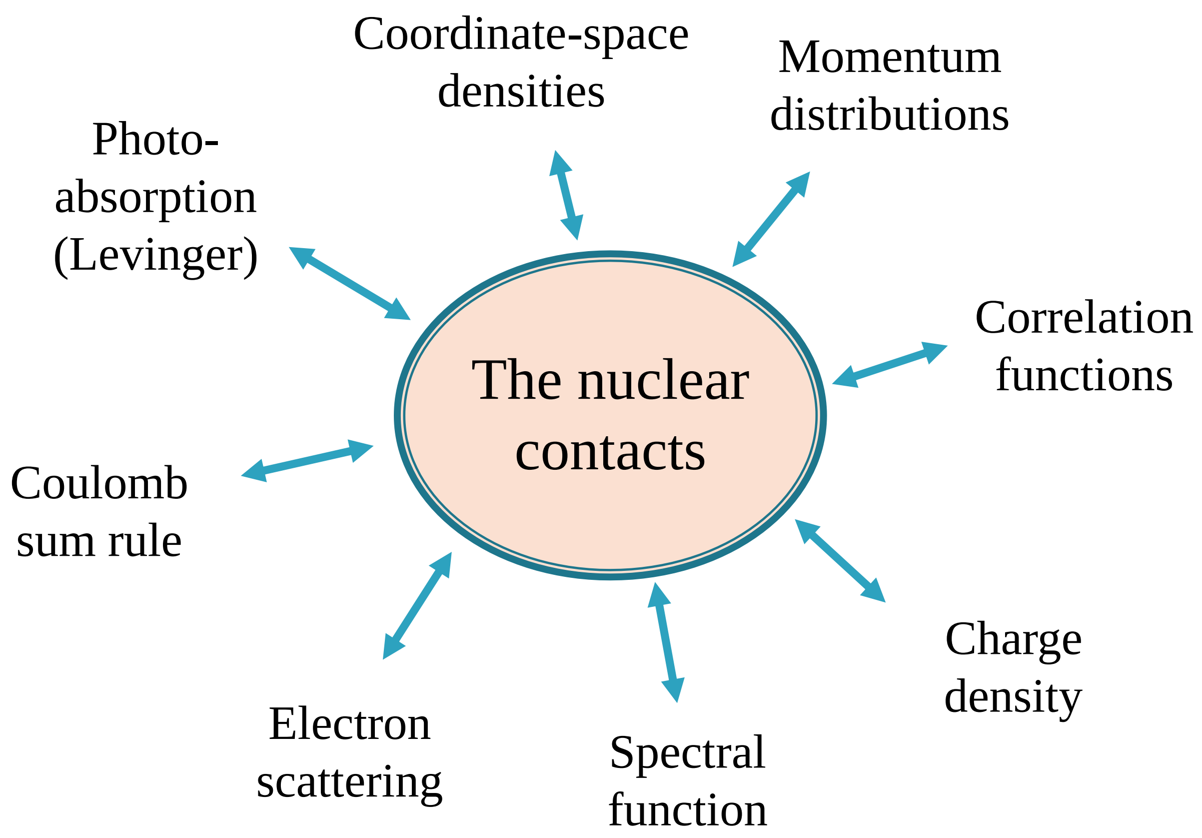
The nuclear contact relations

Contacts: Probability of having a correlated pair in a nucleus

Goal: Derive relations between the contacts and nuclear quantities

$$\langle \hat{O} \rangle = \sum_{i<j} \langle \Psi | \hat{O}(\boldsymbol{r}_{ij}) | \Psi \rangle = C \langle \varphi | \hat{O}(r) | \varphi \rangle$$

The nuclear contact relations

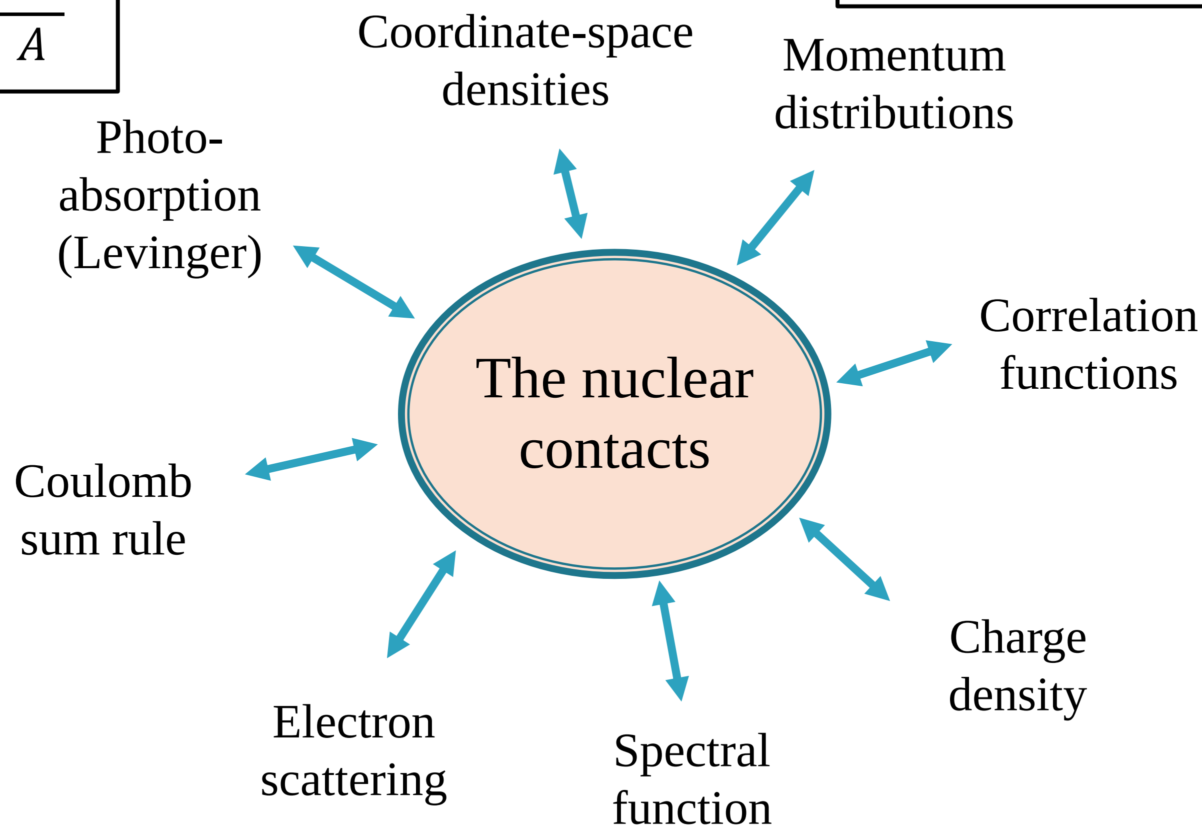


The nuclear contact relations

$$\rho_{pp}(\boldsymbol{r}) \xrightarrow{r\to 0} C_{pp}^{0}\left|\varphi_{pp}^{0}(\boldsymbol{r})\right|^{2}$$

$$\frac{C_{pn}^{d}({}_{Z}^{A}X)}{C_{pn}^{d}(d)} = L\frac{NZ}{A}$$

$$n_{pp}(k_{rel}) \xrightarrow[k\to\infty]{} C_{pp}^{0}\left|\varphi_{pp}^{0}(k_{rel})\right|^{2}$$

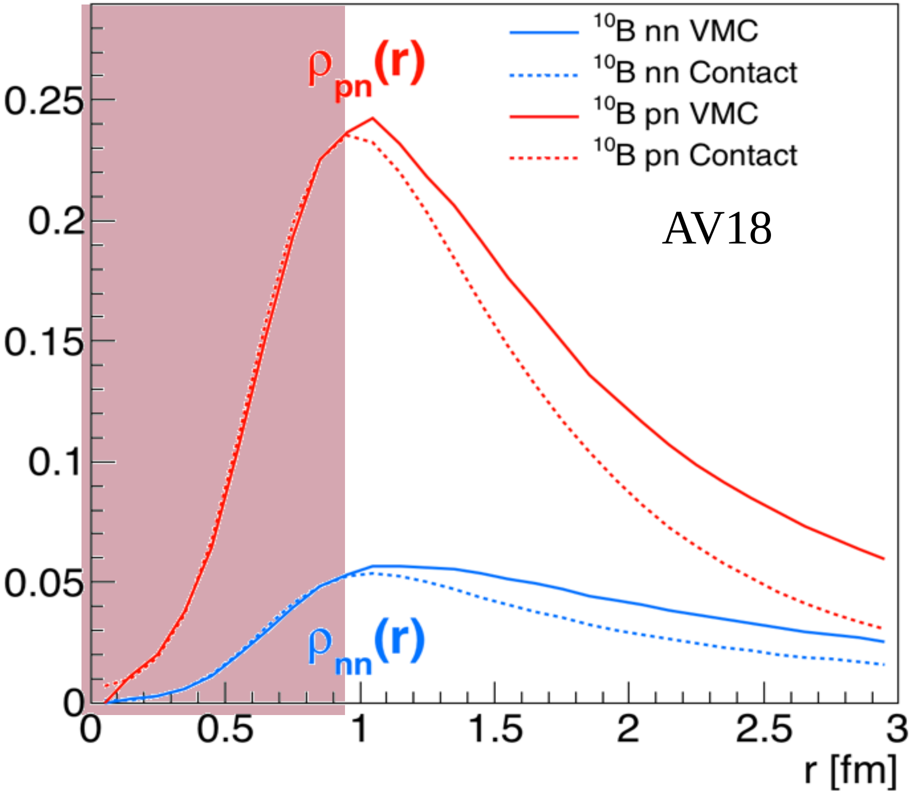


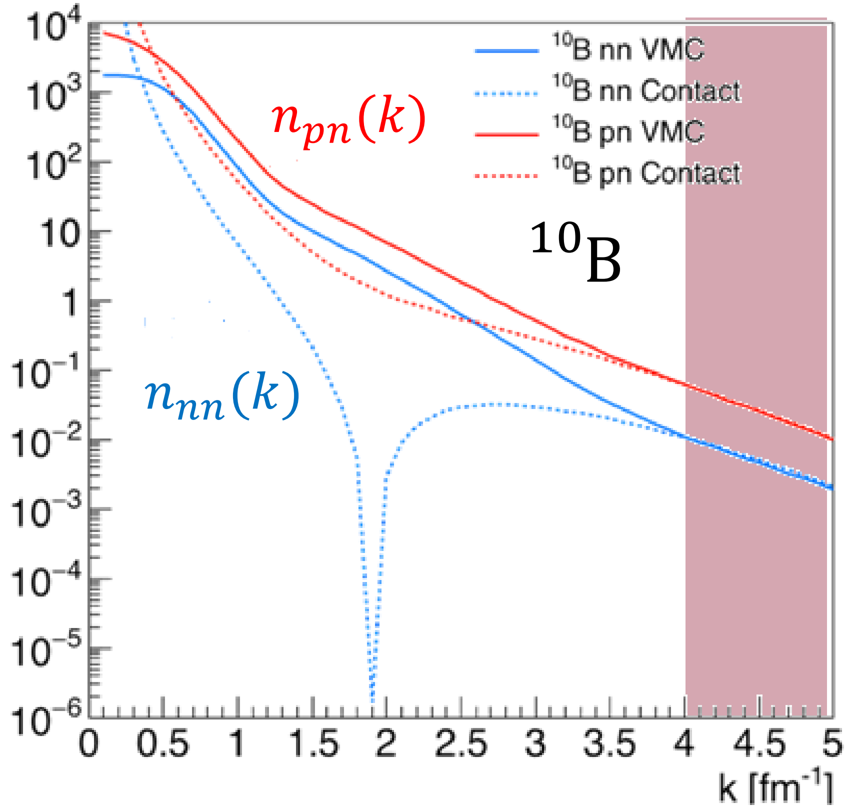
$$S^{p}(\boldsymbol{p_1},\epsilon_1) = C_{pn}^{1}S_{pn}^{1}(\boldsymbol{p_1},\epsilon_1) + C_{pn}^{0}S_{pn}^{0}(\boldsymbol{p_1},\epsilon_1) + 2C_{pp}^{0}S_{pp}^{0}(\boldsymbol{p_1},\epsilon_1)$$

Two-body densities

$$\rho_{nn}(\boldsymbol{r}) \xrightarrow{r\to 0} C^0_{nn}|\varphi^0_{nn}(\boldsymbol{r})|^2$$

$$n_{nn}(k_{rel}) \xrightarrow[k\to\infty]{} C^0_{nn}|\tilde{\varphi}^0_{nn}(k_{rel})|^2$$





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

VMC data from: *R.B Wiringa et. al., Phys. Rev. C 89, 024305 (2014)*

Two-body densities

$$\rho_{nn}(\boldsymbol{r}) \xrightarrow{r\to 0} C_{nn}^{0} |\varphi_{nn}^{0}(\boldsymbol{r})|^2 \qquad n_{nn}(k_{rel}) \xrightarrow[k\to\infty]{} C_{nn}^{0} |\tilde{\varphi}_{nn}^{0}(k_{rel})|^2$$

Short-range and high-momentum factorization!

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

See talk
by Diego

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

VMC data from: *R.B Wiringa et. al., Phys. Rev. C 89, 024305 (2014)*

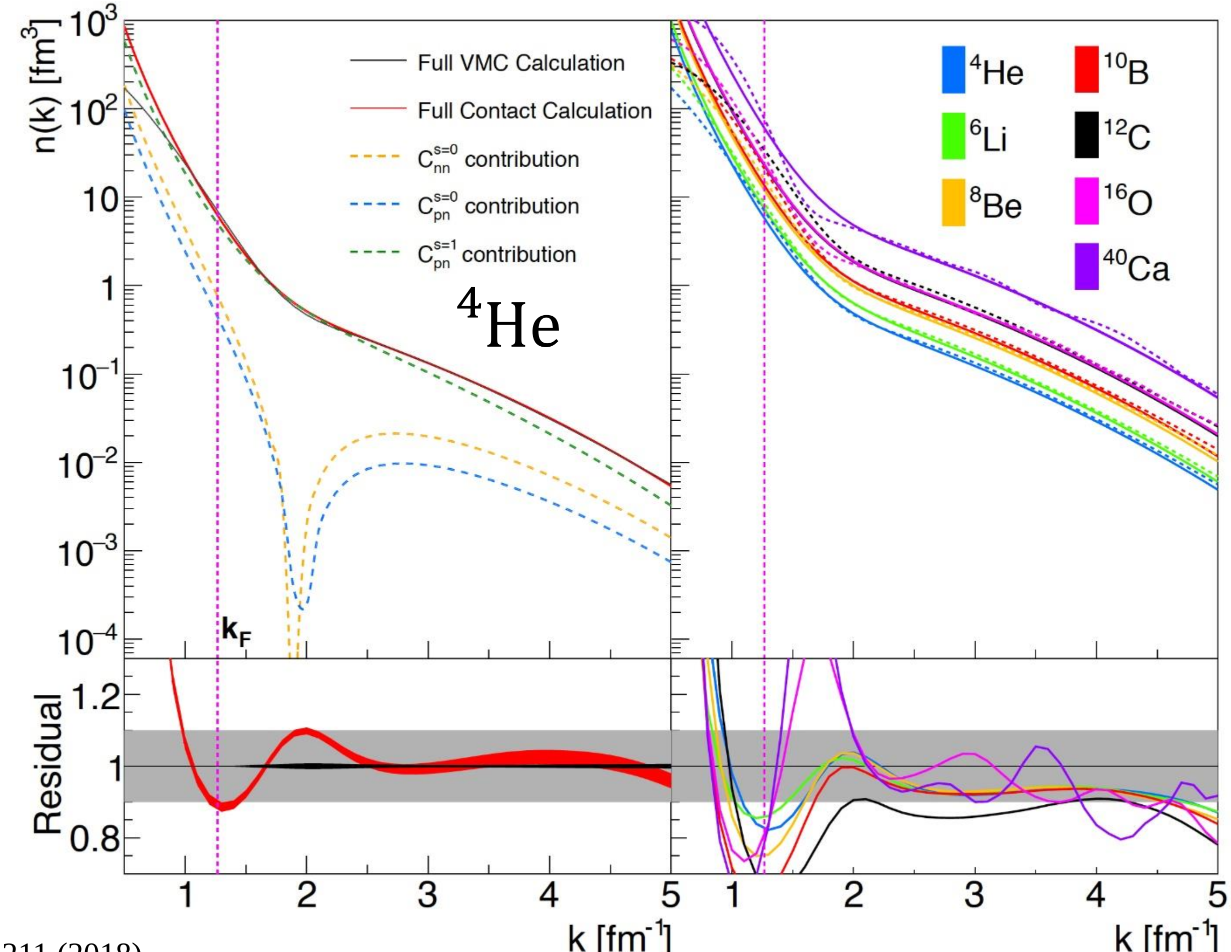
One-body momentum tail

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

One-body momentum tail

$$n_p(k) \xrightarrow[k\to\infty]{} C^d_{pn}\left|\varphi^d_{pn}(k)\right|^2 + C^0_{pn}\left|\varphi^0_{pn}(k)\right|^2 + 2C^0_{pp}\left|\varphi^0_{pp}(k)\right|^2$$

$n_p(k)$



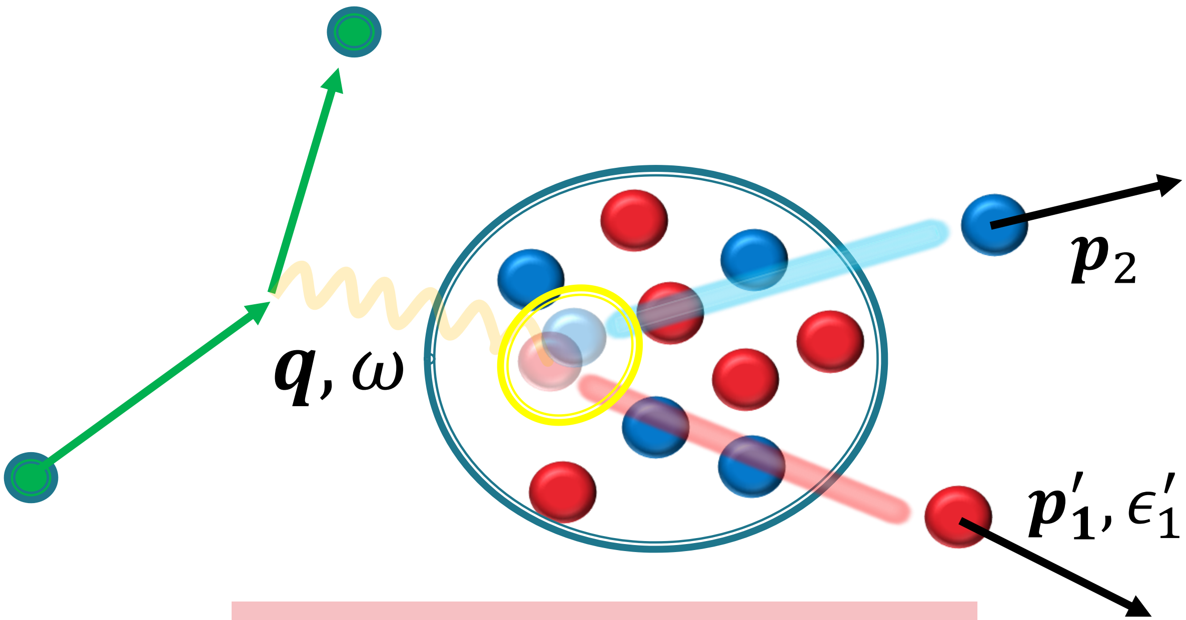
No fitting parameters!

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

Electron-scattering experiments

$A(e, e'N)$ in the plane-wave impulse approximation:

$$\frac{d^4\sigma}{d\Omega_{k'} d\epsilon'_k d\Omega_{p'_1} \epsilon'_1} = p'_1 \epsilon'_1 \sigma_{eN} S^N(\boldsymbol{p}_1, \epsilon_1)$$



Initial momentum: $\boldsymbol{p}_1 = \boldsymbol{p}'_1 - \boldsymbol{q}$
Initial energy: $\epsilon_1 = \epsilon'_1 - \omega$

The spectral function

$$S(\boldsymbol{p}_1, \epsilon_1) = \sum_s \sum_{f_{A-1}} \delta(\epsilon_1 + E_f^{A-1} - E_0) \left| \langle f_{A-1} | a_{\boldsymbol{p}_1, s} | \psi_0 \rangle \right|^2$$

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

The spectral function

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The initial wave function

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

The final wave function

$$|\psi_f^{12}\rangle=a_{\boldsymbol{p}_1,s}^\dagger|f_{A-1}\rangle\propto|\Psi_\nu^{A-2}\rangle e^{i\boldsymbol{p}_1\cdot r_1+i\boldsymbol{p}_2\cdot r_2}\chi_{s_1}\chi_{s_2}$$

Energy conservation:

$$E_f^{A-1}=\epsilon_2+(A-2)m-B_f^{A-2}+\frac{P_{12}^2}{2m(A-2)}$$

$$B_f^{A-2}\approx\langle B_f^{A-2}\rangle$$

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

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The initial wave function

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

The final wave function

$$|\psi_f^{12}\rangle = a_{\boldsymbol{p_1},s}^\dagger |f_{A-1}\rangle \propto |\Psi_\nu^{A-2}\rangle e^{i\boldsymbol{p_1}\cdot r_1 + i\boldsymbol{p}_2\cdot r_2} \chi_{s_1}\chi_{s_2}$$

Energy conservation:

$$E_f^{A-1} = \epsilon_2 + (A-2)m - B_f^{A-2} + \frac{P_{12}^2}{2m(A-2)}$$

$$S^p(\boldsymbol{p_1}, \epsilon_1) = C_{pn}^1 S_{pn}^1(\boldsymbol{p_1}, \epsilon_1) + C_{pn}^0 S_{pn}^0(\boldsymbol{p_1}, \epsilon_1) + 2C_{pp}^0 S_{pp}^0(\boldsymbol{p_1}, \epsilon_1)$$

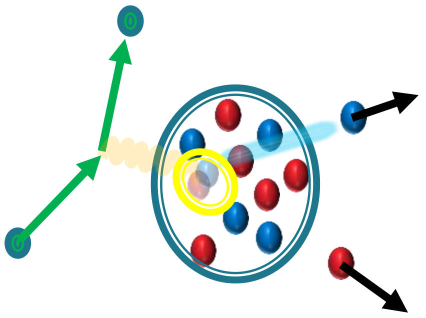
RW et al., PLB 791, 242 (2019)

S_{ij}^α expressed using φ_{ij}^α

Exclusive experiments

Using the spectral function

$$\frac{\#pp}{\#pn} = \frac{S_{pp}^{0}(p_1,\epsilon_1)}{\frac{\boldsymbol{C_{pn}^{1}}}{\boldsymbol{C_{pp}^{0}}} S_{pn}^{1}(p_1,\epsilon_1) + S_{pn}^{0}(p_1,\epsilon_1)}$$



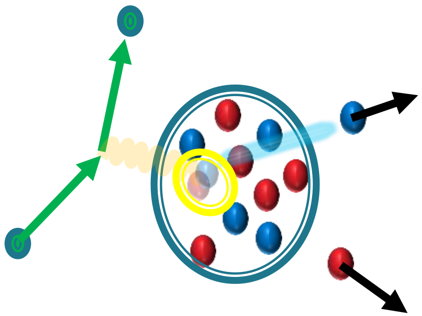
Assuming isospin symmetry for symmetric nuclei $C_{pp}^{0} \approx C_{pn}^{0}$

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

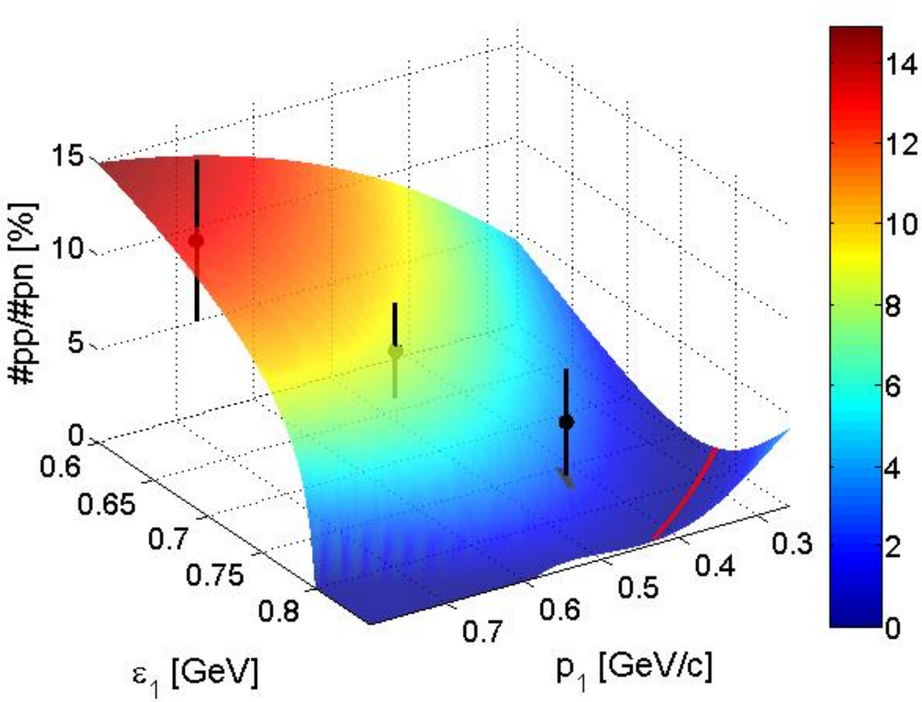
Exclusive experiments

Using the spectral function

$$\frac{\#pp}{\#pn} = \frac{S^0_{pp}(p_1,\epsilon_1)}{\frac{C^1_{pn}}{C^0_{pp}} S^1_{pn}(p_1,\epsilon_1) + S^0_{pn}(p_1,\epsilon_1)}$$



AV18 $\quad ^4$He



$$\frac{C^d_{pn}}{C^0_{pp}}(\,^4He) = 20 \pm 5$$

Previous results $\quad \frac{C^d_{pn}}{C^0_{pp}}(\,^4He) = 17 - 21$

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

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

GCF-based event generator

See talk
by Axel

A. Schmidt, J.R. Pybus, RW, E. P. Segarra, A. Hrnjic, A. Denniston, O. Hen*, et al. (CLAS collaboration), Nature 578, 540 (2020)*

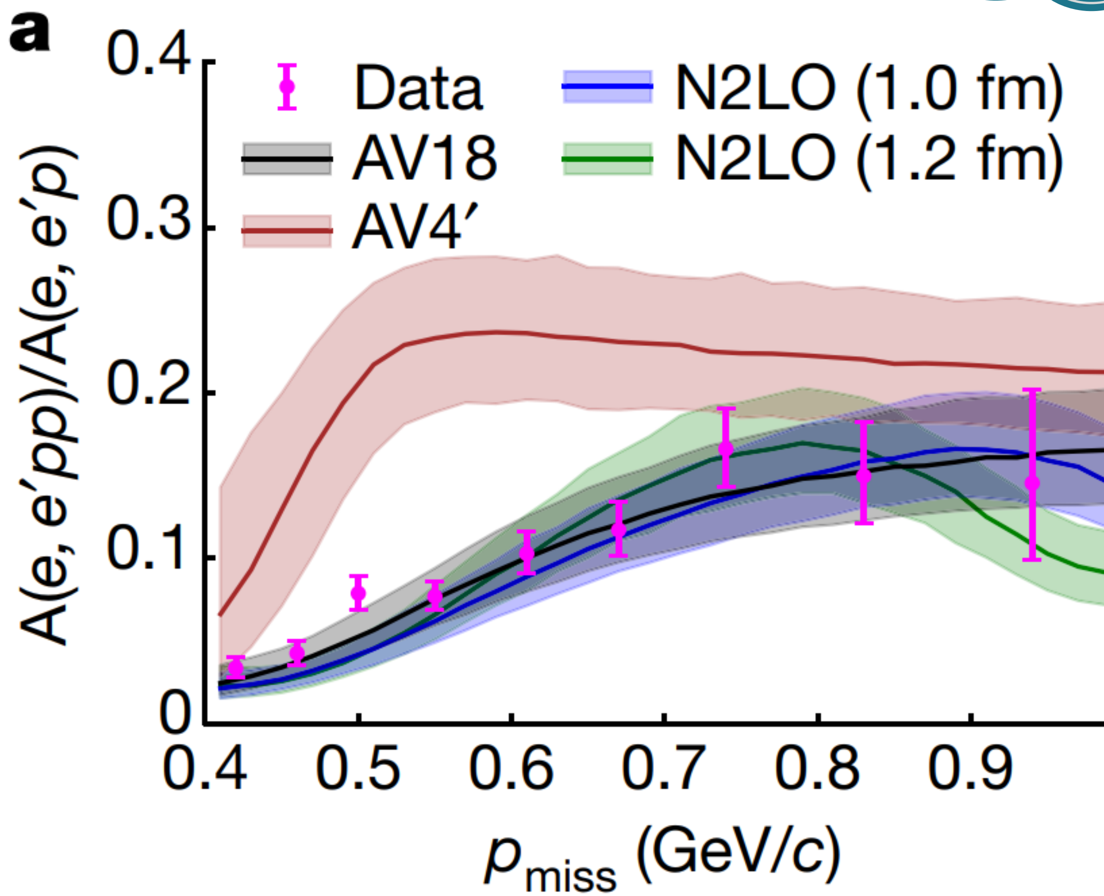
GCF-based event generator

See talk by Axel

Using the VMC Contact values

Direct connection to ab-intio calculations and NN-interaction models

^{12}C - $\#pp/\#p$



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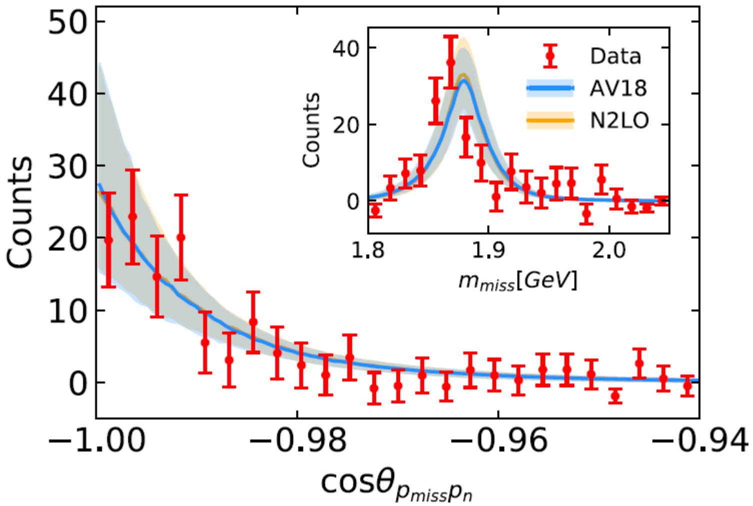
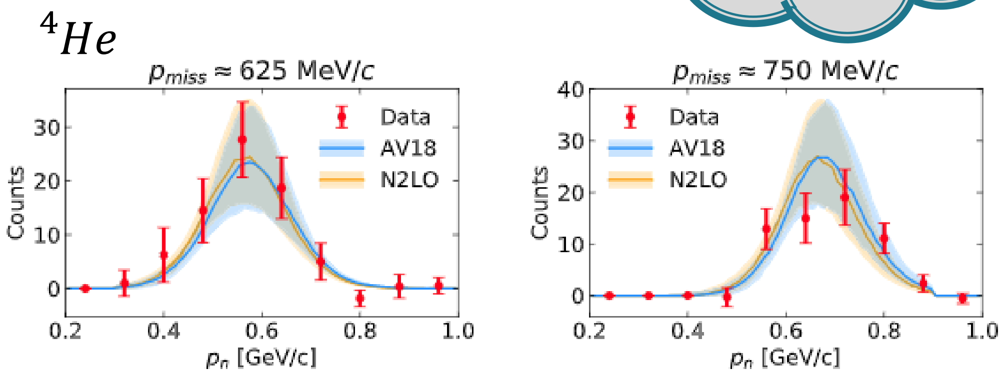
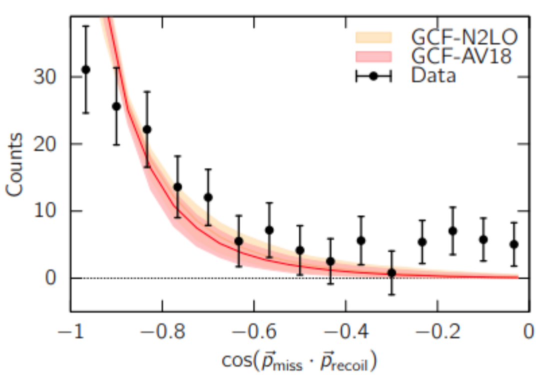
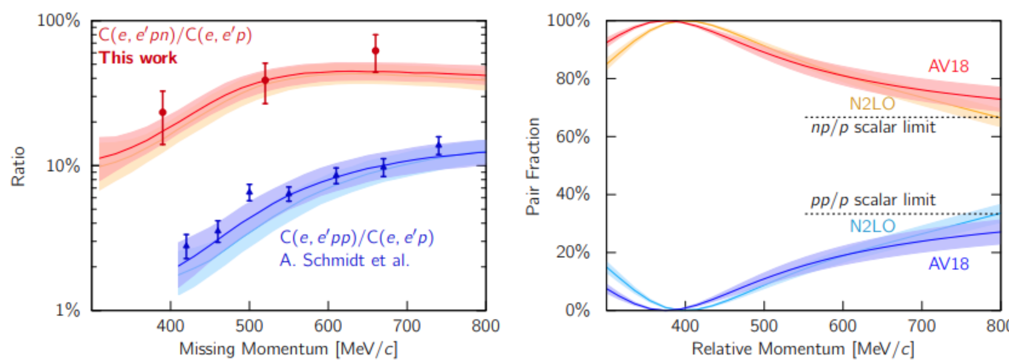
See talk by Jackson





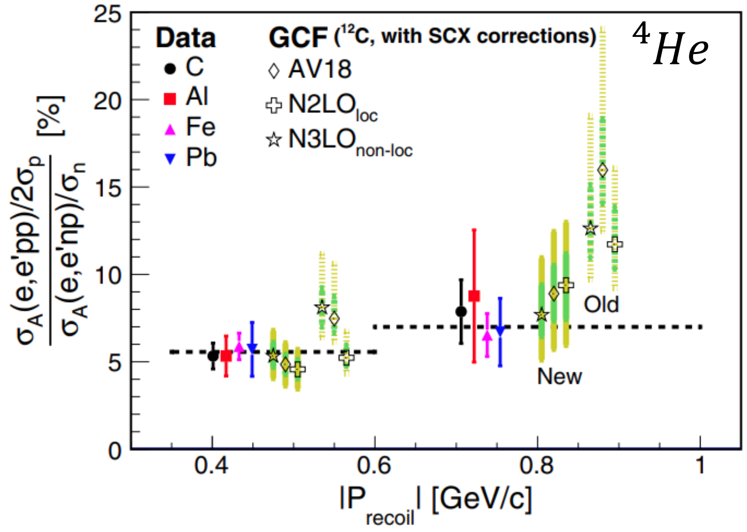
J.R. Pybus et al., PLB 805, 135429 (2020)

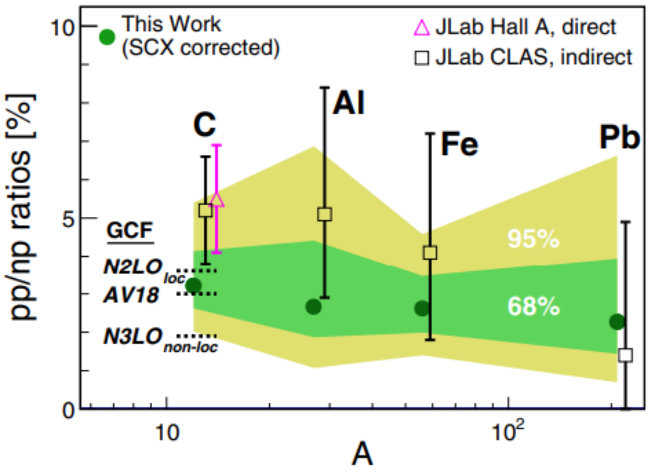




I. Korover et al., arXiv:2004.07304 (2020)

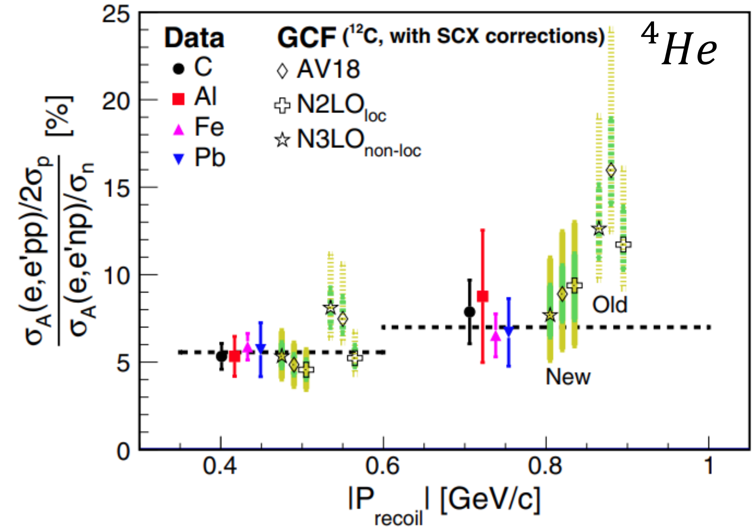
GCF-based event generator

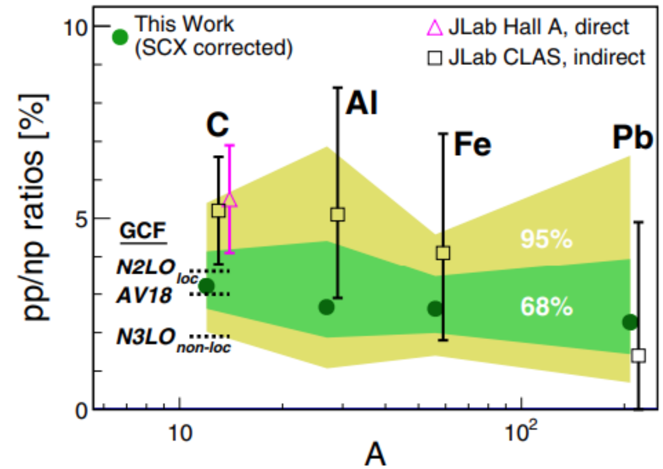




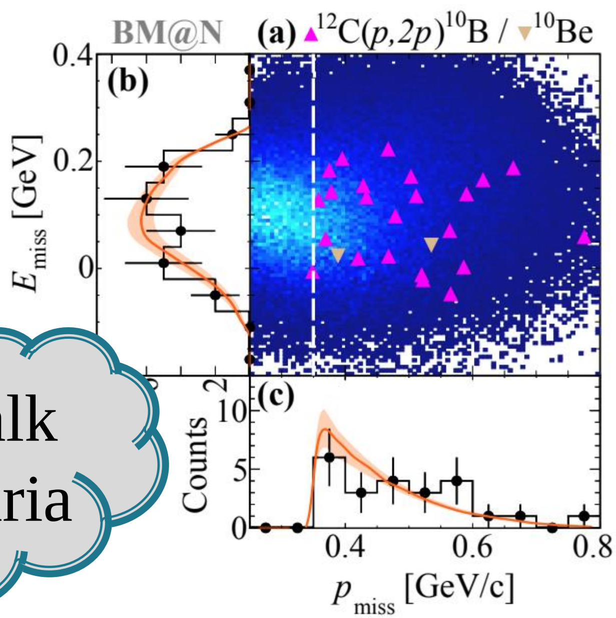
M. Duer et al., PRL 122, 172502 (2019)

GCF-based event generator



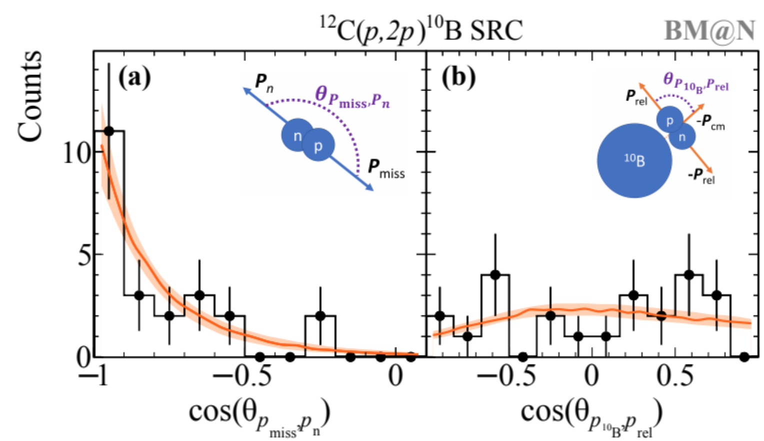


M. Duer et al., PRL 122, 172502 (2019)



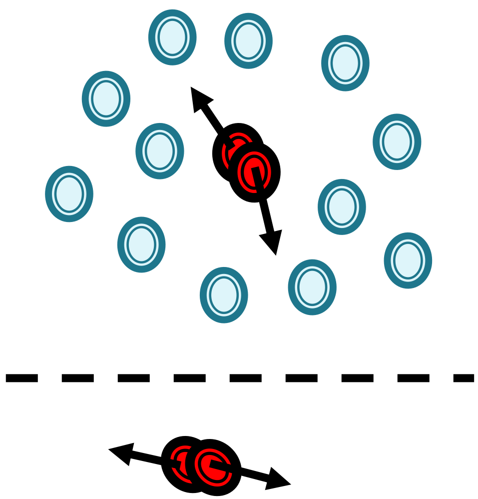
See talk
by Maria

07304 (2020)

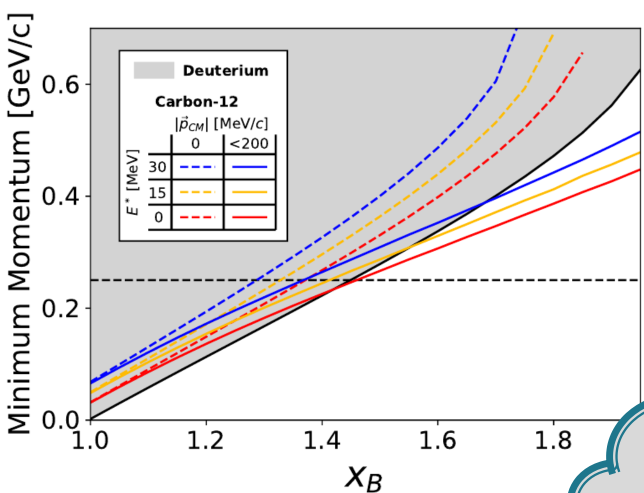


M. Patsyuk et al., arXiv:2102.02626 (2021)

Inclusive scattering

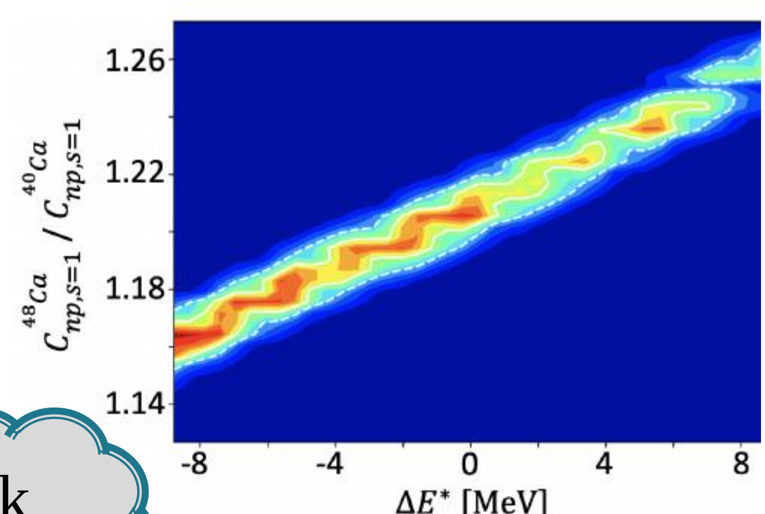


$$a_2 = 2/A\,\frac{\sigma_A(x_B,Q^2)}{\sigma_d(x_B,Q^2)} \approx 2/A\,\frac{C^1_{pn}(A)}{C^1_{pn}(d)}$$



RW, A. W Denniston, et al., PRC 103, L031301 (2021)

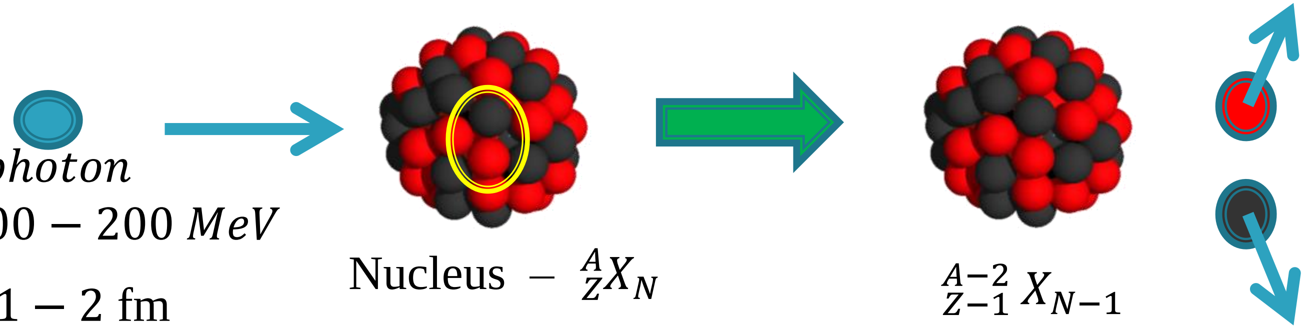
See talk
by Andrew



$\frac{48}{40} a(48Ca/40Ca)=1.165$

Data from: Nguyen et al. PRC 102, 064004 (2020)

Photo-absorption



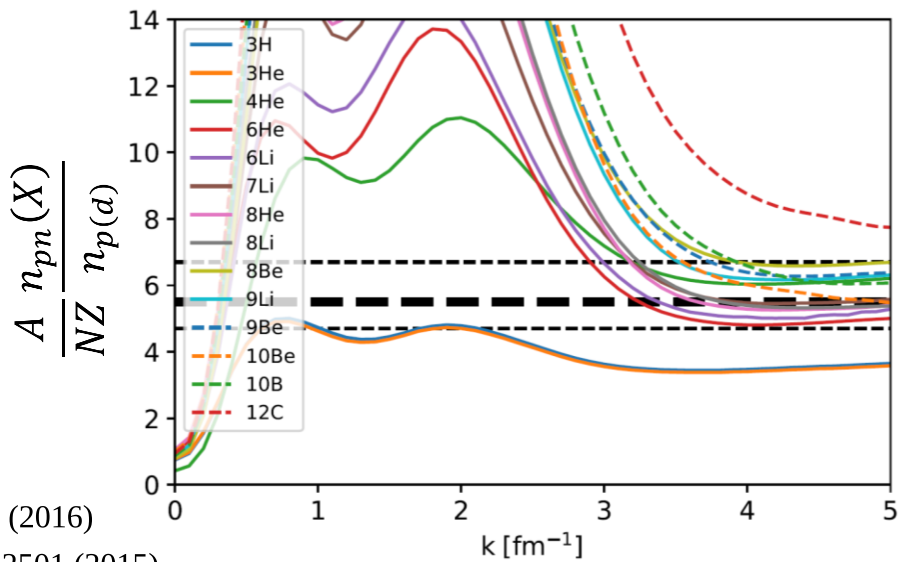
$\hbar\omega = 100 - 200\ MeV$

$\frac{1}{k} = 1 - 2$ fm

$\boldsymbol{k}_p \approx -\boldsymbol{k}_n \equiv \boldsymbol{k}$

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

$$\frac{C^d_{pn}\left(^{A}_{Z}X\right)}{C^d_{pn}(d)} = L\frac{NZ}{A}$$

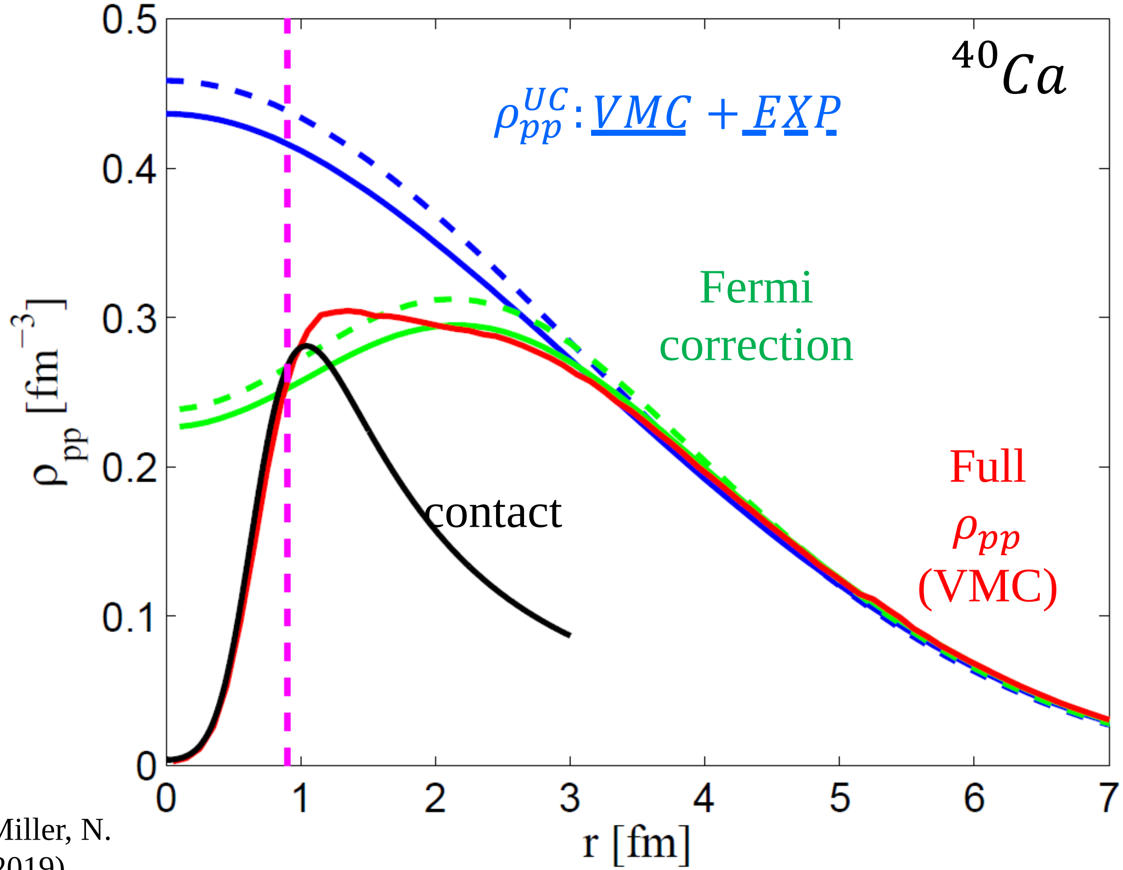


RW, B. Bazak, N. Barnea, EPJA 52, 92 (2016)
RW, B. Bazak, N. Barnea, PRL 114, 012501 (2015)

Charge density

$$r \to \infty: \rho_{pp}(\boldsymbol{r}) \propto \rho_{pp}^{UC} \equiv \int \mathrm{d}^3 R \rho_p(\boldsymbol{R}+\boldsymbol{r}/2)\rho_p(\boldsymbol{R}-\boldsymbol{r}/2)$$

$$\rho_{pp}(\boldsymbol{r}) \xrightarrow{r\to 0} C_{pp}\left|\varphi_{pp}(\boldsymbol{r})\right|^2$$



RW, A. Schmidt, G. A. Miller, N. Barnea, PLB 790, 484 (2019)

Neutrino-less double beta decay

In collaboration with Javier Menendez and Alessandro Lovato

Neutrino-less double beta decay

- Matrix elements $M_{\alpha}^{\beta} = \left\langle \Psi_f \middle| O_{\alpha}^{\beta} \middle| \Psi_{\mathrm{i}} \right\rangle$

$$\alpha = F, GT, T$$
$$\beta = V, AA, AP, PP, MM$$

(Vector, Axial, Pseudoscalar, Magnetic)

Neutrino-less double beta decay

- Matrix elements

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(Vector, Axial, Pseudoscalar, Magnetic)

$$O_F^{\beta} = (4\pi R_A) \sum_{a \neq b} V_F^{\beta}(r_{ab}) \tau_a^+ \tau_b^+$$

$$O_{GT}^{\beta} = (4\pi R_A) \sum_{a \neq b} V_{GT}^{\beta}(r_{ab}) (\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \tau_a^+ \tau_b^+$$

$$R_A = 1.2A^{1/3}$$

$$O_T^{\beta} = (4\pi R_A) \sum_{a \neq b} V_T^{\beta}(r_{ab}) S_{ab} \tau_a^+ \tau_b^+$$

Neutrino-less double beta decay

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$$O_{GT}^\beta = (4\pi R_A) \sum_{a \neq b} V_{GT}^\beta(r_{ab}) (\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \tau_a^+ \tau_b^+$$

$$R_A = 1.2A^{1/3}$$

$$O_T^\beta = (4\pi R_A) \sum_{a \neq b} V_T^\beta(r_{ab}) S_{ab} \tau_a^+ \tau_b^+$$

- SRC are commonly accounted for using correlation functions

Neutrino-less double beta decay

- Matrix elements

$$M_\alpha^\beta = \left\langle \Psi_f \left| O_\alpha^\beta \right| \Psi_\mathrm{i} \right\rangle$$

$\alpha = F, GT, T$

$\beta = V, AA, AP, PP, MM$

(Vector, Axial, Pseudoscalar, Magnetic)

$$O_F^\beta = (4\pi R_A) \sum_{a \neq b} V_F^\beta (r_{ab}) \tau_a^+ \tau_b^+$$

$$O_{GT}^\beta = (4\pi R_A) \sum_{a \neq b} V_{GT}^\beta (r_{ab}) (\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \tau_a^+ \tau_b^+$$

$R_A = 1.2A^{1/3}$

$$O_T^\beta = (4\pi R_A) \sum_{a \neq b} V_T^\beta (r_{ab}) S_{ab} \tau_a^+ \tau_b^+$$

- SRC are commonly accounted for using correlation functions

- Instead: Use directly GCF expressions!

Neutrino-less double beta decay

- Transition densities: (Fermi as an example)

$$\rho_F(r) = \frac{1}{4\pi r^2}\left\langle \Psi_f \left| \sum_{a<b} \delta(r - r_{ab})\, \tau_a^+ \tau_b^+ \right| \Psi_\mathrm{i} \right\rangle$$

$$M_F^\beta = (4\pi R_A)\int V_F^\beta(r_{ab})\rho_F(r) 4\pi r^2 dr \equiv \int \rho_F^\beta(r) dr$$

Neutrino-less double beta decay

- Transition densities: (Fermi as an example)

$$\rho_F(r) = \frac{1}{4\pi r^2}\left\langle \Psi_f \left| \sum_{a<b} \delta(r - r_{ab})\, \tau_a^+ \tau_b^+ \right| \Psi_{\mathrm{i}} \right\rangle$$

$$M_F^\beta = (4\pi R_A)\int V_F^\beta(r_{ab})\rho_F(r) 4\pi r^2 dr \equiv \int \rho_F^\beta(r) dr$$

- Short distances:

$$\boxed{\rho_F(r) \xrightarrow{r\to 0} |\varphi^0(r)|^2 C^0_{pp,nn}(f,i)}$$

$$C(f,i) \propto \langle A_f | A_i \rangle$$

Neutrino-less double beta decay

- Transition densities: (Fermi as an example)

$$\rho_F(r) = \frac{1}{4\pi r^2}\left\langle \Psi_f \left| \sum_{a<b} \delta(r - r_{ab})\, \tau_a^+ \tau_b^+ \right| \Psi_\mathrm{i} \right\rangle$$

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- Short distances:

$$\rho_F(r) \xrightarrow{r\to 0} |\varphi^0(r)|^2 C^0_{pp,nn}(f,i)$$

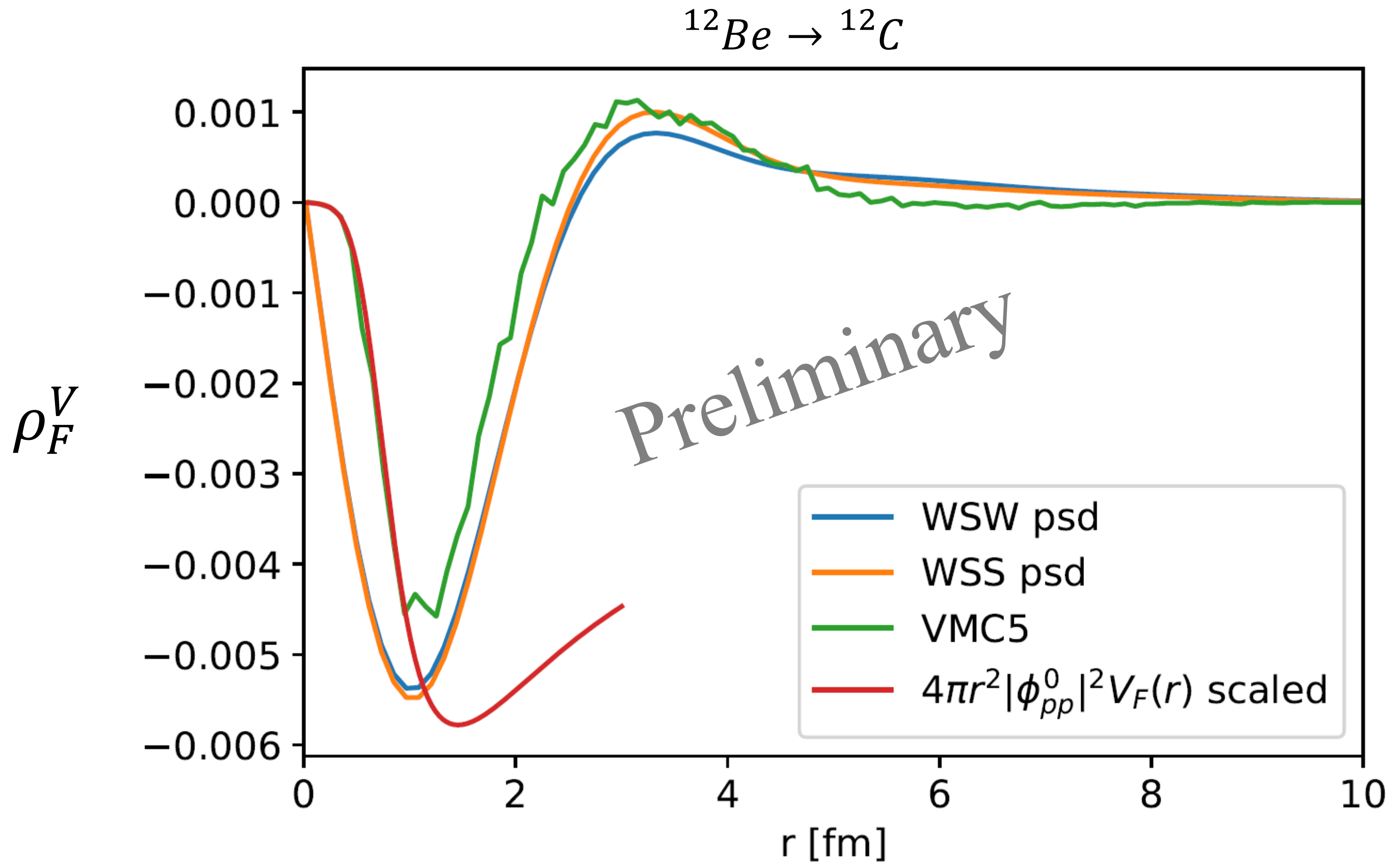
$$C(f,i) \propto \langle A_f | A_i \rangle$$

$$M_F^\beta = \int_0^{r_0} \rho_F^\beta(r) dr + \int_{r_0}^{\infty} \rho_F^\beta(r) dr$$

GCF

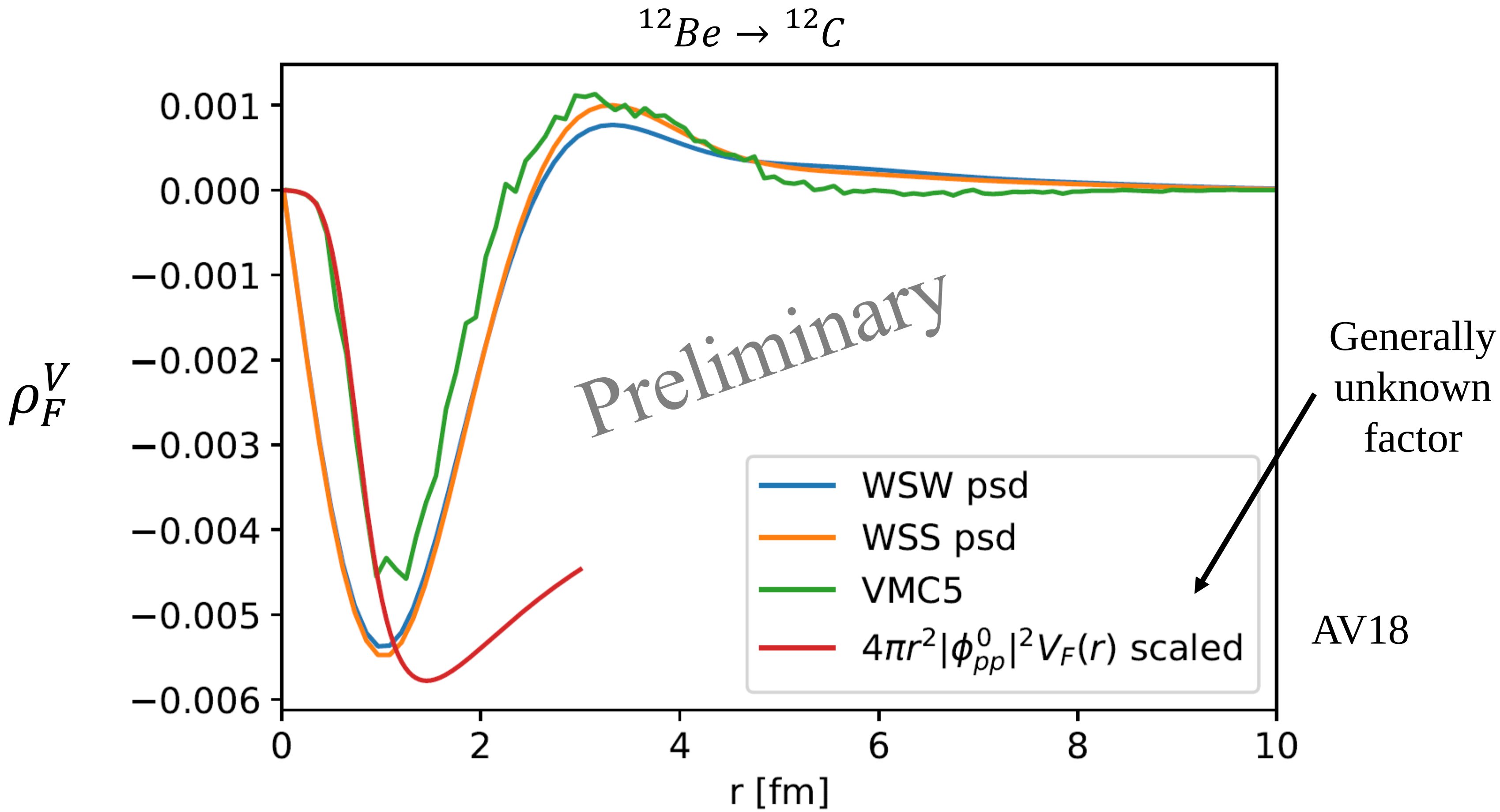
Shell Model

Neutrino-less double beta decay



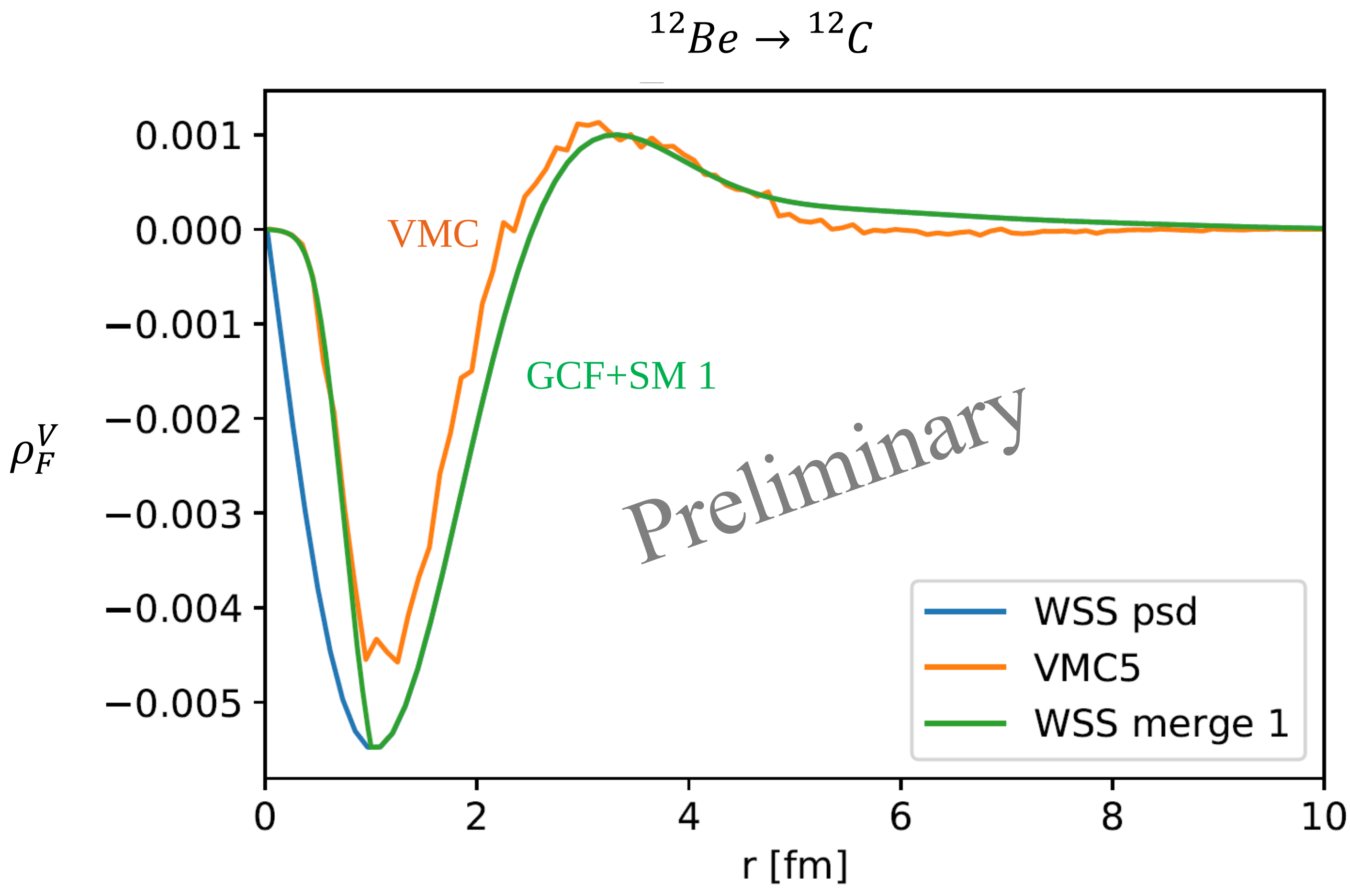
AV18

Neutrino-less double beta decay



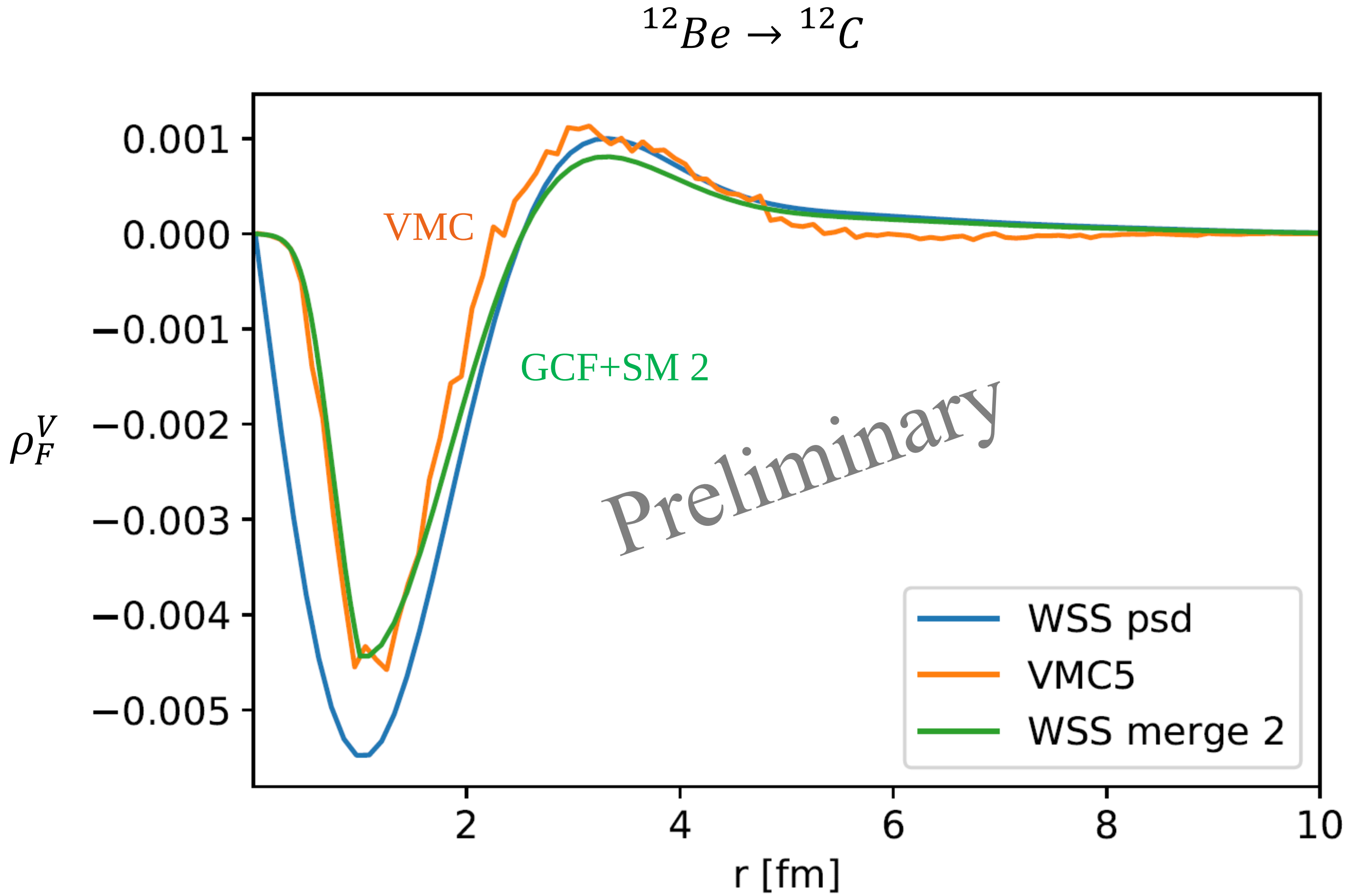
Neutrino-less double beta decay

Merging option 1: Continuity with SM



Neutrino-less double beta decay

Merging option 2: Assuming contact value is known



Neutrino-less double beta decay

Matrix element results

$$^{12}Be \rightarrow {}^{12}C$$

VMC: $M_F^V = -0.22$

Shell-Model (WSS psd): $M_F^V = -0.41$

GCF Merge 1: $M_F^V = -0.29$

GCF Merge 2: $M_F^V = -0.24$

Collaborators

Jerusalem: B. Bazak, N. Barnea

Experiment: O. Hen, E. Piasetzky, L. B. Weinstein , D. W. Higinbotham, A. Schmidt, R. Cruz-Torres, I. Korover, M. Duer, J. R. Pybus, A.W. Denniston

Theory: G. A. Miller, R. B. Wiringa, D. Lonardoni, M. Piarulli, E. Pazy, A. Lovato, J. Menendez

Summary

- The GCF provides a framework for quantitative studies of SRC pairs.
- Describes the effects of SRCs on nuclear structure and reactions.
- Good agreement with ab-initio structure calculations.
- Used to analyze, guide and design experiments (event generator)
- Allows confronting data with ab-initio structure calculations and different NN interaction models