Few-Neutron Resonances From Chiral Effective Field Theory

1st Workshop of the SFB 1245

SFB 1245

TECHNISCHE UNIVERSITÄT DARMSTADT

erc European Research Council

Hessisches Kompetenzzentrum für Hochleistungsrechnen

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S. Gandolfi, H.-W. Hammer, P. Klos, and A. Schwenk

November 23, 2016

A Recent History


2003
2005
Experiment
2002
Theory

F. M. Marqués et al. Phys. Rev. C **65**, 052501.

Experimental claim of a bound tetraneutron from detection of neutron clusters from ^{14}Be fragmentation.

~6 events!

2003

2005

Experiment

Theory

2002

Experiment

Theory

2002

2003

2005

1) C. A. Bertulani and V. Zelevinksy, J. Phys. G **29**, 2431 (2003),
2) N. K. Timofeyuk J. Phys. G **29**, L9 (2003).

No bound tetraneutron using 1) a dineutron-dineutron molecule model and 2) a toy *NN* potential.

2003 2005

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2002

1) C. A. Bertulani and V. Zelevinksy, J. Phys. G **29**, 2431 (2003),
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No bound tetraneutron using 1) a dineutron-dineutron molecule model and 2) a toy *NN* potential.

S. C. Pieper Phys. Rev. Lett. **90**, 252501.
Modern nuclear Hamiltonians cannot tolerate a bound tetraneutron.
But...
“This suggests that there might be a ^4n resonance near 2 MeV"

2003

2005

Experiment

Theory

2002

R. Lazauskas and J. Carbonell, Phys. Rev. C **72**, 034003.

Complex scaling w/Reid 93 potential (*NN* only!)

Low-lying ^4n resonance not seen.

2003

2005

2002

Experiment

Theory

Experiment
Theory

2016

2015

Future

K. Kisamori et al., Phys. Rev. Lett. **116**, 044006.

A recent double-charge-exchange reaction $^{8}_{2}\mathrm{He}+^{4}_{2}\mathrm{He} \rightarrow ^{8}_{4}\mathrm{Be} + ^{4}n$ measurement at the RIKEN radioactive ion beam factory (RIBF) suggests a tetraneutron resonance at **0.83±0.65(stat)±1.25(syst) MeV.**

Experiment

Theory

2016

2015

Future

E. Hiyama, R. Lazauskas, J. Carbonell, and M. Kamimura, Phys. Rev. C **93**, 044004.
Complex scaling w/AV8’ potential + toy T = 3/2 3N interaction. Low-lying ^4n resonance only possible if other well-known resonance structure in light nuclei are strongly perturbed.

Experiment

Theory

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2016

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E. Hiyama, R. Lazauskas, J. Carbonell, and M. Kamimura, Phys. Rev. C **93**, 044004.
Complex scaling w/AV8' potential + toy $T = 3/2$ $3N$ interaction. Low-lying ^4n resonance only possible if other well-known resonance structure in light nuclei are strongly perturbed.

A. M. Shirokov, G. Papadimitriou, A. I. Mazur, R. Roth, J. P. Vary, Phys. Rev. Lett. **117**, 1825022.
No-Core Shell Model + Single-State Harmonic Oscillator Representation of Scattering equations. Compelling confirmation of a ^4n resonance at 0.8 MeV with **JISP** NN interaction.

T. Aumann, D. Rossi, S. Shimoura, S. Paschalis et al., RIBF Experimental Proposal **SFB 1245 A06**

NP1406-SAMURAI19.

$^{8}_{2}\mathrm{He}(p, p\alpha)^{4}n$

Experiment

Theory

2015

2016

Future

T. Aumann, D. Rossi, S. Shimoura, S. Paschalis et al., RIBF Experimental Proposal SFB 1245 A06
NP1406-SAMURAI19.
$^{8}_{2}\mathrm{He}(p, p\alpha)^{4}n$

K. Kisamori et al., RIKEN-RIBF proposal
"Many-neutron systems: search for superheavy ^{7}H and its tetraneutron decay," NP-1512-SAMURAI34.

Experiment
Theory

2015 | 2016 | Future

T. Aumann, D. Rossi, S. Shimoura, S. Paschalis et al., RIBF Experimental Proposal SFB 1245 A06 NP1406-SAMURAI19. ${}^{8}_{2}\mathrm{He}(p, p\alpha)^{4}n$

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S. Shimoura et al., RIKEN-RIBF proposal "Tetraneutron resonance produced by exothermic double-charge exchange reaction," NP1512-SHARAQ10.

Experiment

Theory

2015

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Future

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Experiment

2016

Theory

2015

Future

What's still missing?

An *ab initio* calculation with chiral *NN* and 3*N* interactions.

Initial efforts using Quantum Monte Carlo calculations with chiral interactions.

(This talk!)

Outline

- Quantum Monte Carlo Methods
- Chiral EFT
    - Three-Nucleon Interactions
    - Fitting c_D and c_E
- Few-body resonances

Quantum Monte Carlo (QMC) Methods

QMC Methods

QMC methods in two lines:

$$H|\Psi\rangle = E|\Psi\rangle$$
$$\lim_{\tau\to\infty} e^{-H\tau}|\Psi_T\rangle \to |\Psi_0\rangle$$

QMC methods in more than two lines:

J. Carlson et al, RMP **87**, 1067 (2015).

QMC Methods - Variational Monte Carlo (VMC) Method

1. Guess a trial wave function Ψ_T and generate a random position: $\mathrm{R} = \mathrm{r}_1, \mathrm{r}_2, \ldots, \mathrm{r}_A$.

2. Use the Metropolis algorithm to generate new positions R' based on the probability $P = \frac{|\Psi_T(\mathrm{R}')|^2}{|\Psi_T(\mathrm{R})|^2}$. (Yields a set of "walkers" distributed according to $|\Psi_T|^2$).

3. Invoke the variational principle: $E_T = \frac{\langle \Psi_T | H | \Psi_T \rangle}{\langle \Psi_T | \Psi_T \rangle} > E_0$.

QMC Methods - Diffusion Monte Carlo Method

- The wave function is imperfect: $|\Psi_T\rangle = \sum_{i=0}^{\infty} \alpha_i |\Psi_i\rangle$.
- Propagate in imaginary time to project out the ground state $|\Psi_0\rangle$.

$$
\begin{aligned}
|\Psi(\tau)\rangle &= e^{-(H-E_T)\tau} |\Psi_T\rangle \\
&= e^{-(E_0-E_T)\tau}[\alpha_0 |\Psi_0\rangle + \sum_{i\neq 0} \alpha_i e^{-(E_i-E_0)\tau} |\Psi_i\rangle].
\end{aligned}
$$

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\end{aligned}
$$

$$
|\Psi(\tau)\rangle \xrightarrow{\tau\to\infty} |\Psi_0\rangle .
$$

The Hamiltonian

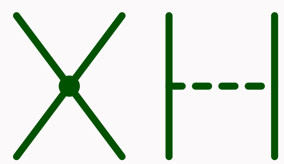
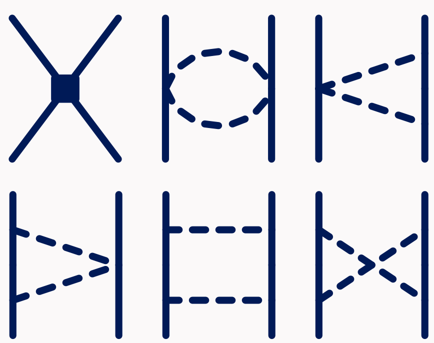
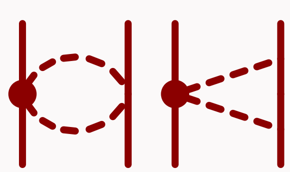
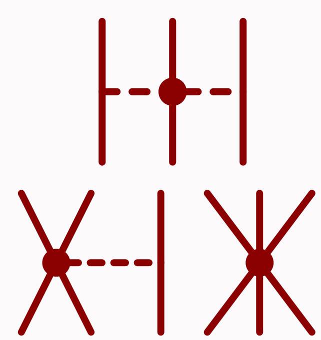
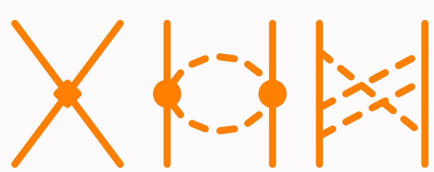
Of course, the nuclear Hamiltonian is complicated.

$$H = \sum_{i=1}^{A} \frac{\mathbf{p}_i^2}{2m_i} + \sum_{i<j}^{A} v_{ij} + \sum_{i<j<k}^{A} V_{ijk} + \cdots$$

Where should it come from?

Chiral EFT

Chiral EFT

		NN	*NNN*
LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^0$		–
NLO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^2$		–
N^{2}LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^3$	 $+\cdots$	
N^{3}LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^4$	 $+\cdots$	 $+\cdots$

- Chiral EFT: Expand in powers of Q/Λ_b.
  $Q \sim m_\pi \sim 100$ MeV
  $\Lambda_b \sim 500$ MeV
- Long-range physics: π exchanges.
- Short-range physics: Contacts × LECs.
- Many-body forces & currents enter systematically.

Chiral EFT

Local construction possible[1] up to N^2LO.

Definitions.

$$\mathbf{q} = \mathbf{p} - \mathbf{p}', \ \mathbf{k} = \mathbf{p} + \mathbf{p}'$$

Regulator:

$$f(p, p') = e^{-(p/\Lambda)^n} e^{-(p'/\Lambda)^n}$$

Contacts:

$\propto \mathbf{q}$ and $\mathbf{k}$

[1]A. Gezerlis et al, PRL **111** 032501 (2013); JEL et al, PRL **113** 192501 (2014); A. Gezerlis et al, PRC **90** 054323 (2014)

Chiral EFT

Local construction possible[1] up to N^2LO.

Definitions.

$$\mathbf{q} = \mathbf{p} - \mathbf{p}', \ \mathbf{k} = \mathbf{p} + \mathbf{p}'$$

Regulator:

~~$f(p, p') = e^{-(p/\Lambda)^n} e^{-(p'/\Lambda)^n}$~~

$$\rightarrow f_{\text{long}}(r) = 1 - e^{-(r/R_0)^4} : \ R_0 = 1.0, 1.1, 1.2 \text{ fm}.$$

Contacts:

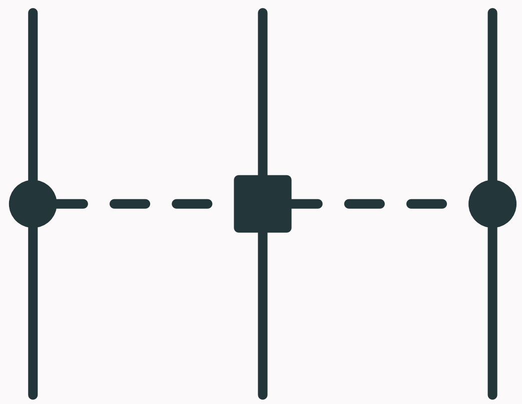
~~$\propto \mathbf{q}$ and $\mathbf{k}$~~

$\rightarrow$ Choose contacts $\propto \mathbf{q}$ (As much as possible!)

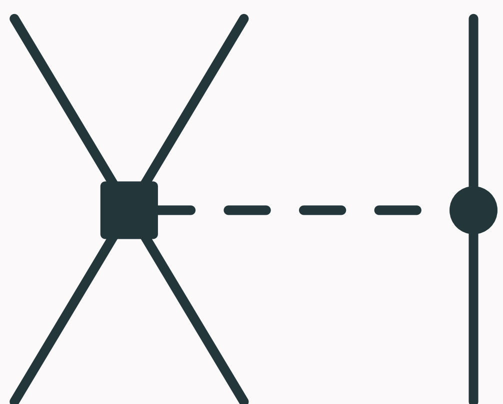
[1]A. Gezerlis et al, PRL **111** 032501 (2013); JEL et al, PRL **113** 192501 (2014); A. Gezerlis et al, PRC **90** 054323 (2014)

Three-Nucleon Interactions

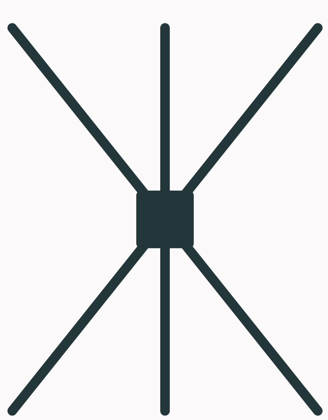
Three-Nucleon Interaction



c_1, c_3, c_4

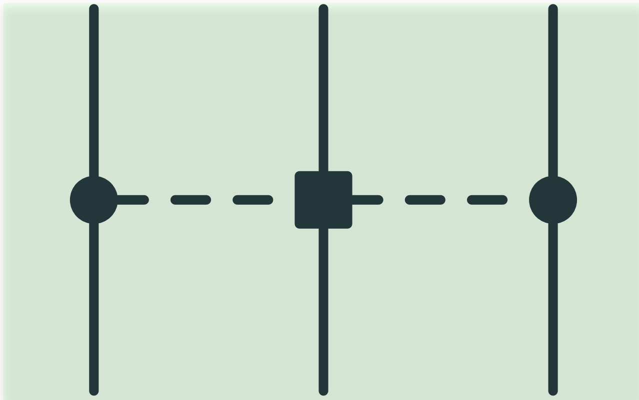


c_D

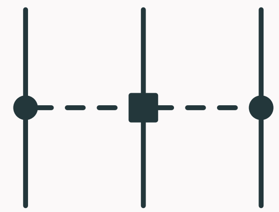


c_E

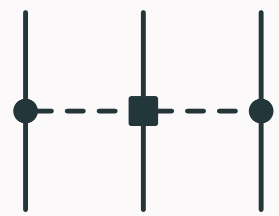
Three-Nucleon Interaction



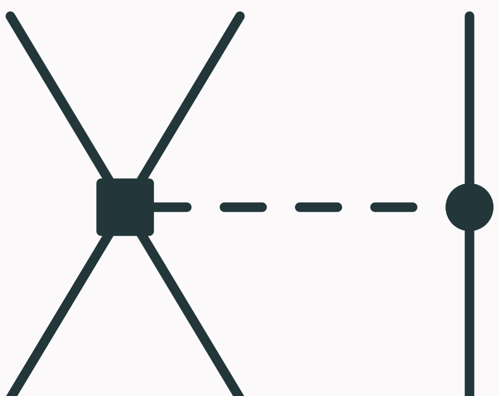
c_1, c_3, c_4

$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow\sim$ Tucson-Melbourne a' Term

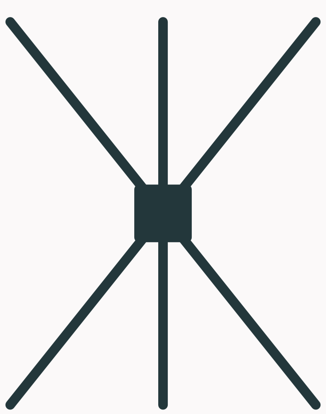
c_1

$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow\sim$ Fujita-Miyazawa

c_3, c_4

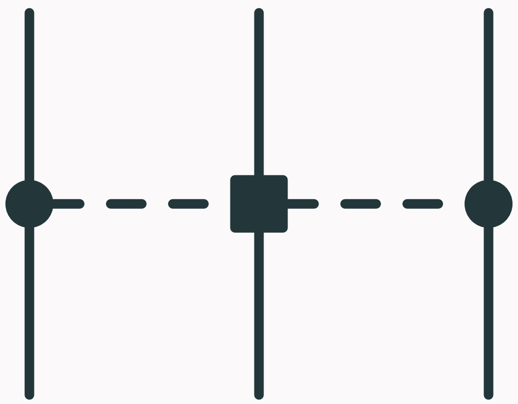


c_D

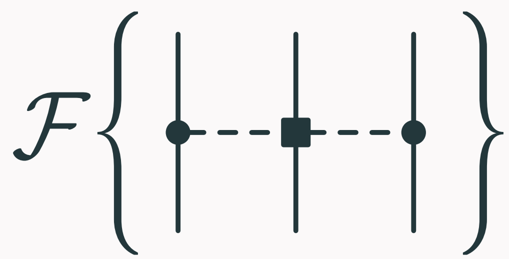


c_E

Three-Nucleon Interaction



$c_1,\ c_3,\ c_4$



c_1

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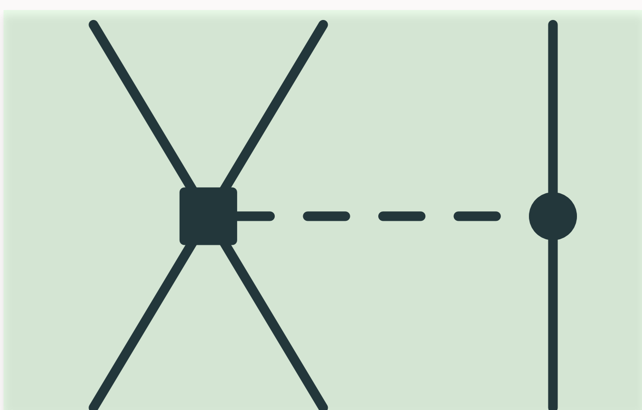
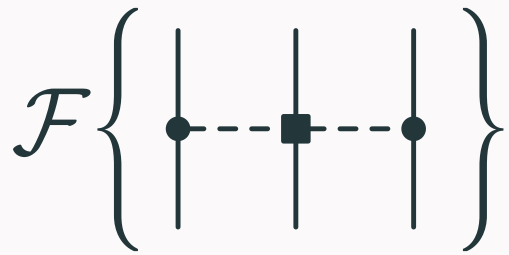
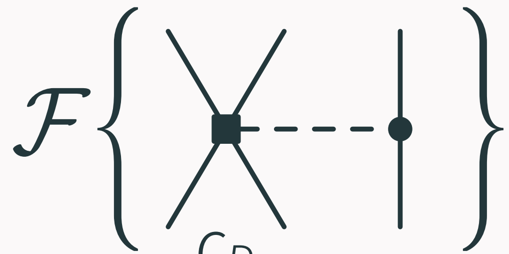


c_D



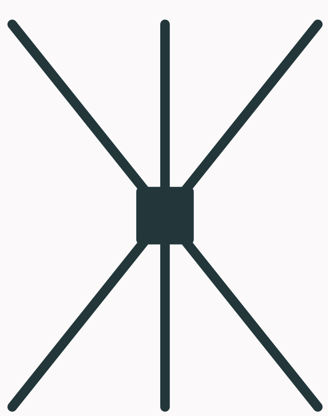
$c_3,\ c_4$

$\rightarrow\sim$ Fujita-Miyazawa



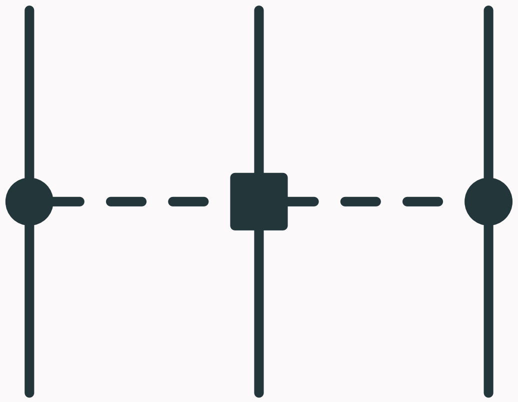
c_D

$\rightarrow$ 1π-Exchange + Contact

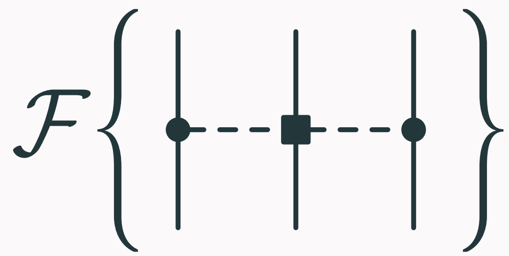


c_E

Three-Nucleon Interaction

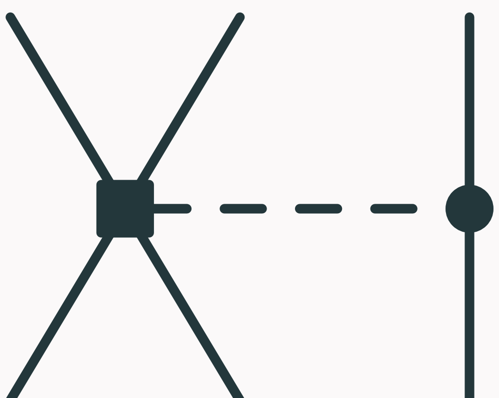


$c_1,\ c_3,\ c_4$

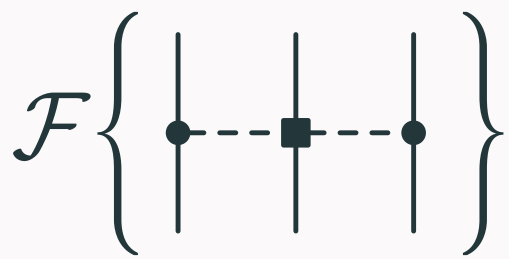


c_1

$\rightarrow\sim$ Tucson-Melbourne a' Term

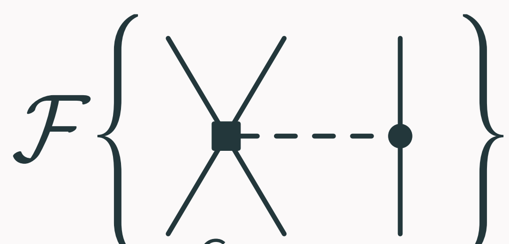


c_D



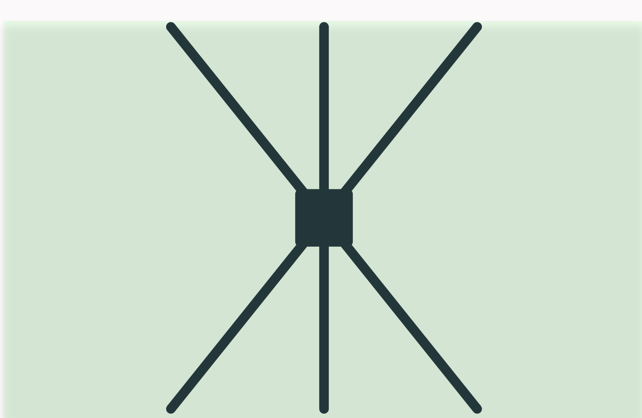
$c_3,\ c_4$

$\rightarrow\sim$ Fujita-Miyazawa

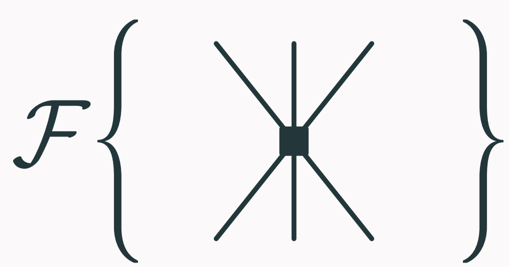


c_D

$\rightarrow$ 1π-Exchange + Contact



c_E



c_E

$\rightarrow$ Contact

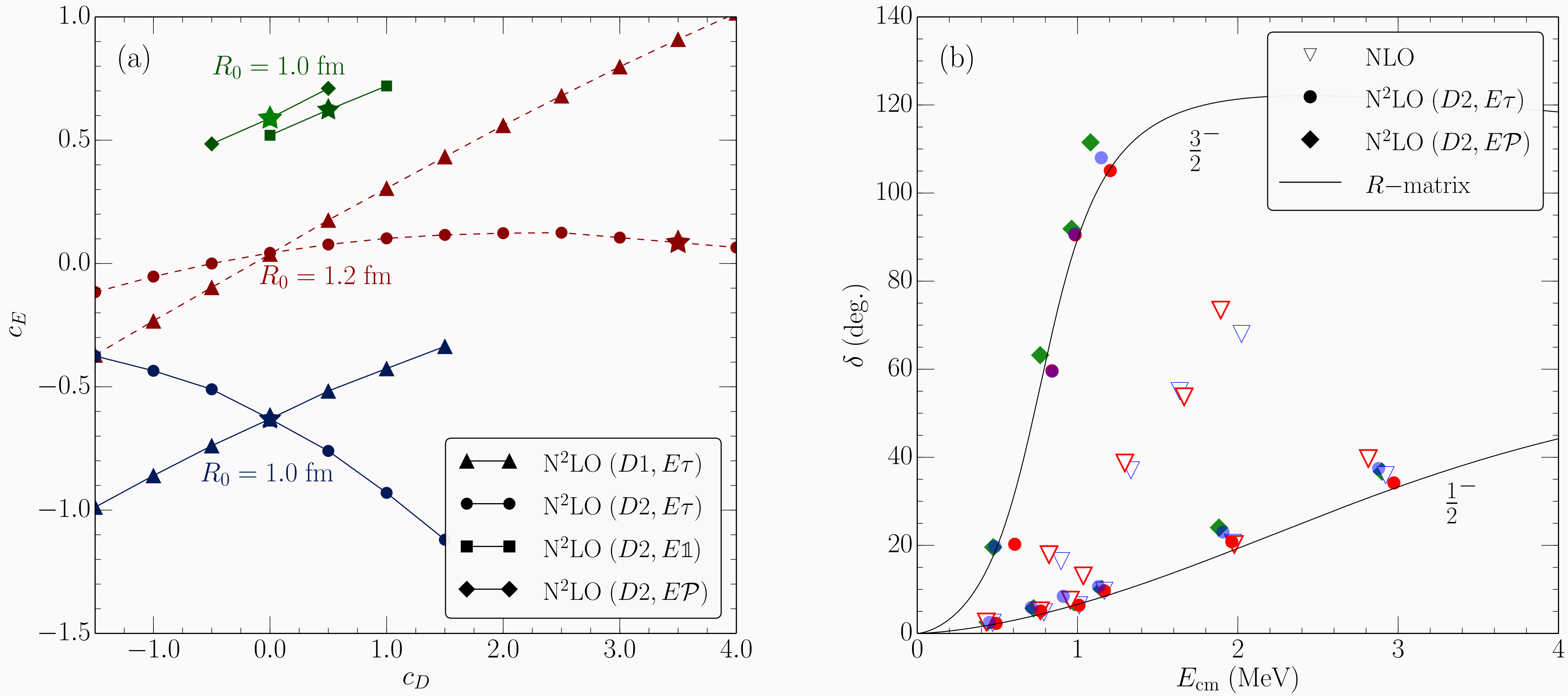
Fitting c_D And c_E

Choosing Observables

What to fit c_D and c_E to?

- Uncorrelated observables.
- Probe properties of light nuclei: ^{4}He E_B.
- Probe $T = 3/2$ physics: n-α scattering phase shifts.

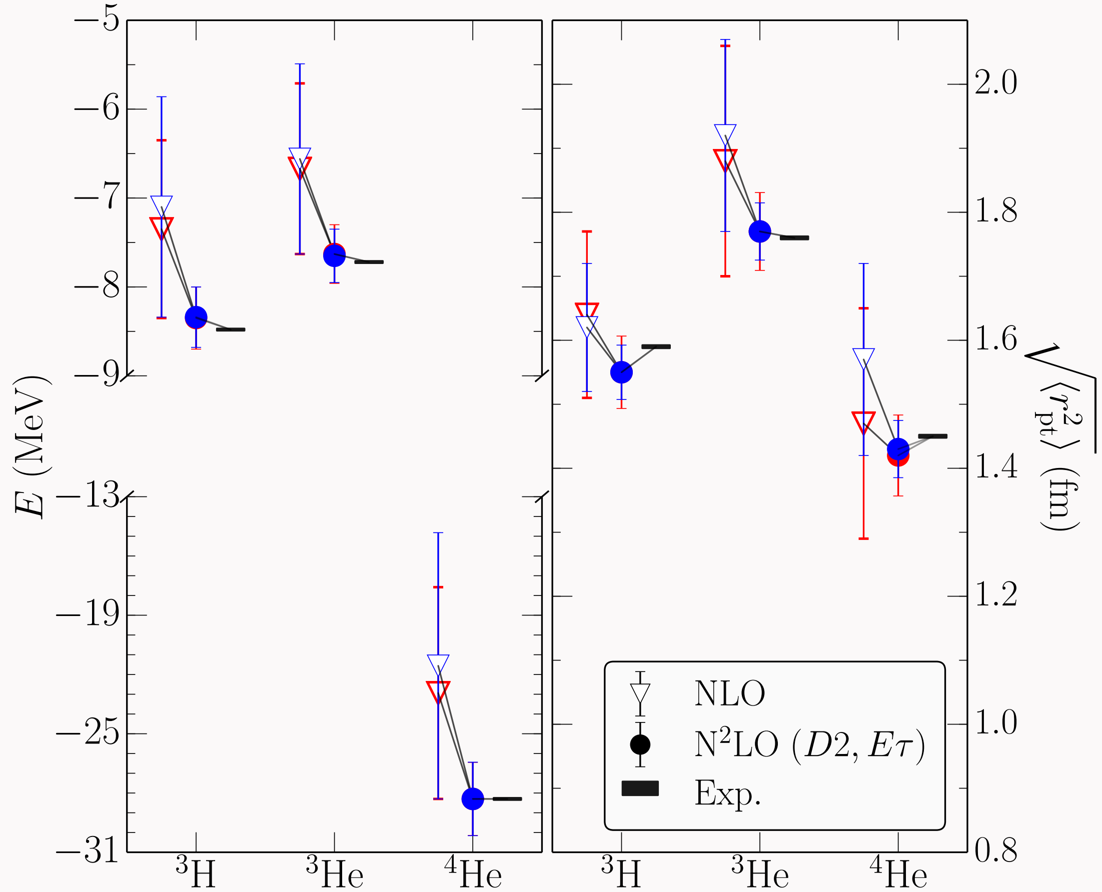
Fits

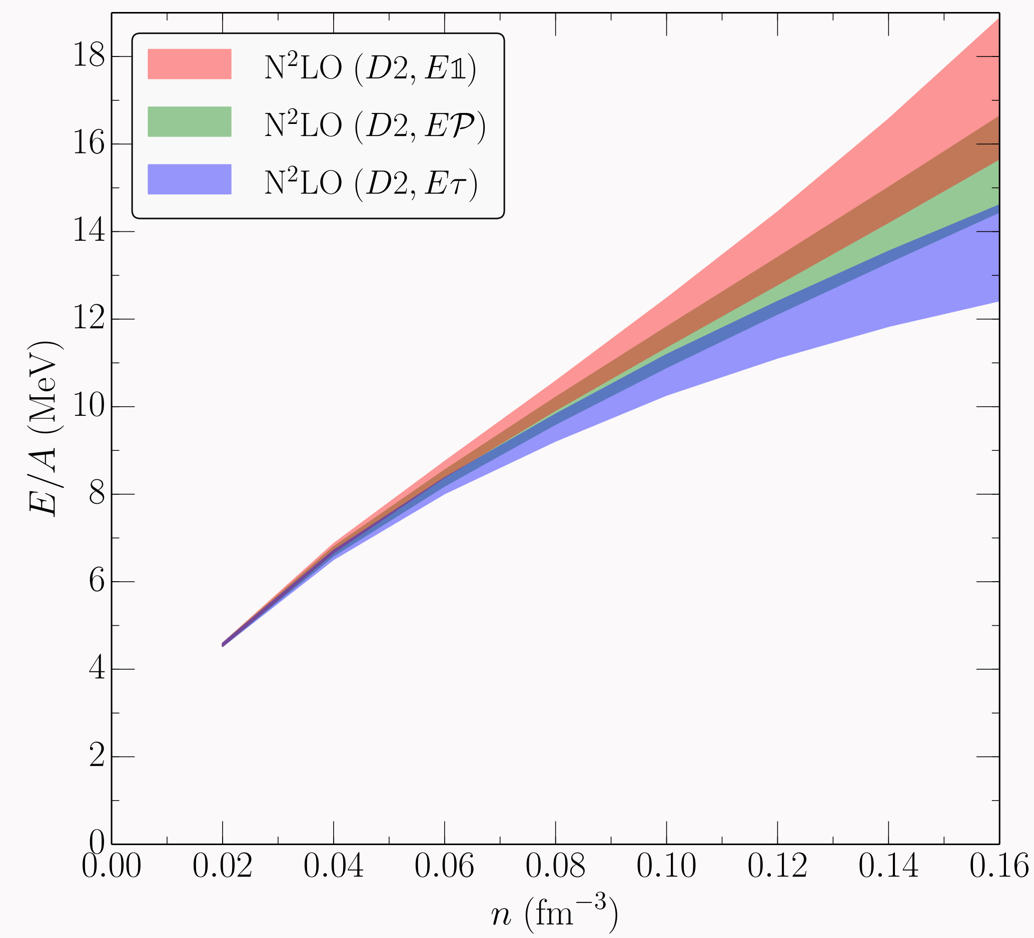


JEL et al, PRL **116**, 062501 (2016)

Results

A simultaneous description of properties of light nuclei, n-α scattering and neutron matter is possible. Uncertainty analysis as in E. Epelbaum et al, EPJ **A51**, 53 (2015).





JEL et al, PRL **116**, 062501 (2016)

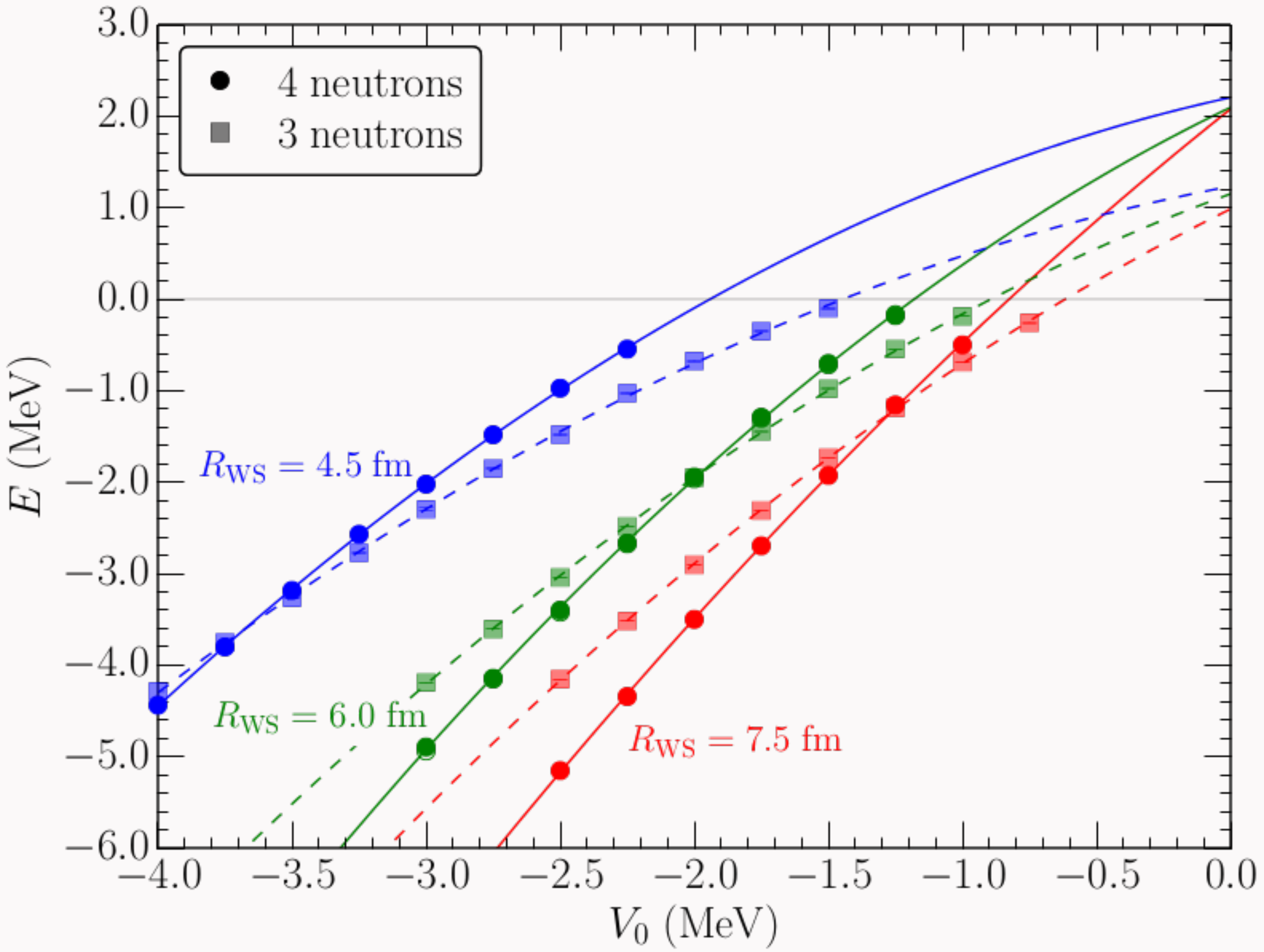
Few-Body Resonances

Neutrons In A Trap

We confine the neutrons in an external potential.

$$H = -\sum_i \frac{\hbar^2}{2m}\nabla_i^2 + \sum_i V_{\mathrm{WS}}(r_i) + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk},$$

$V_{\mathrm{WS}}(r) = V_0/[1 + e^{(r-R_{\mathrm{WS}})/a}]$, fixed diffuseness $a = 0.65$ fm



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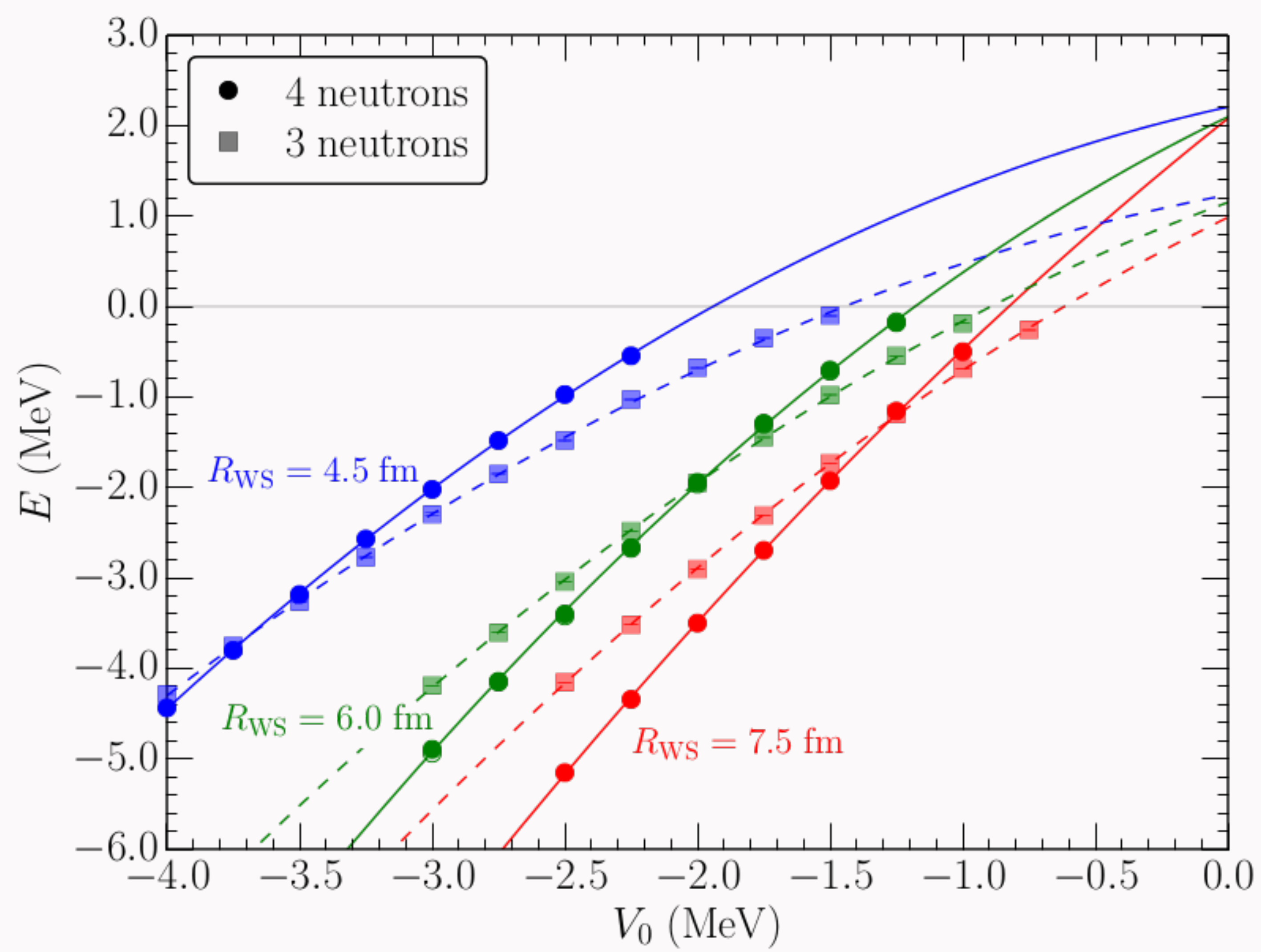
- Changing cutoff/ removal of 3N interaction gives indistinguishable results.
- $E_{3n} = 1.1(2)$ MeV, $E_{4n} = 2.1(2)$ MeV.
- ^3n resonance lower than ^4n resonance.



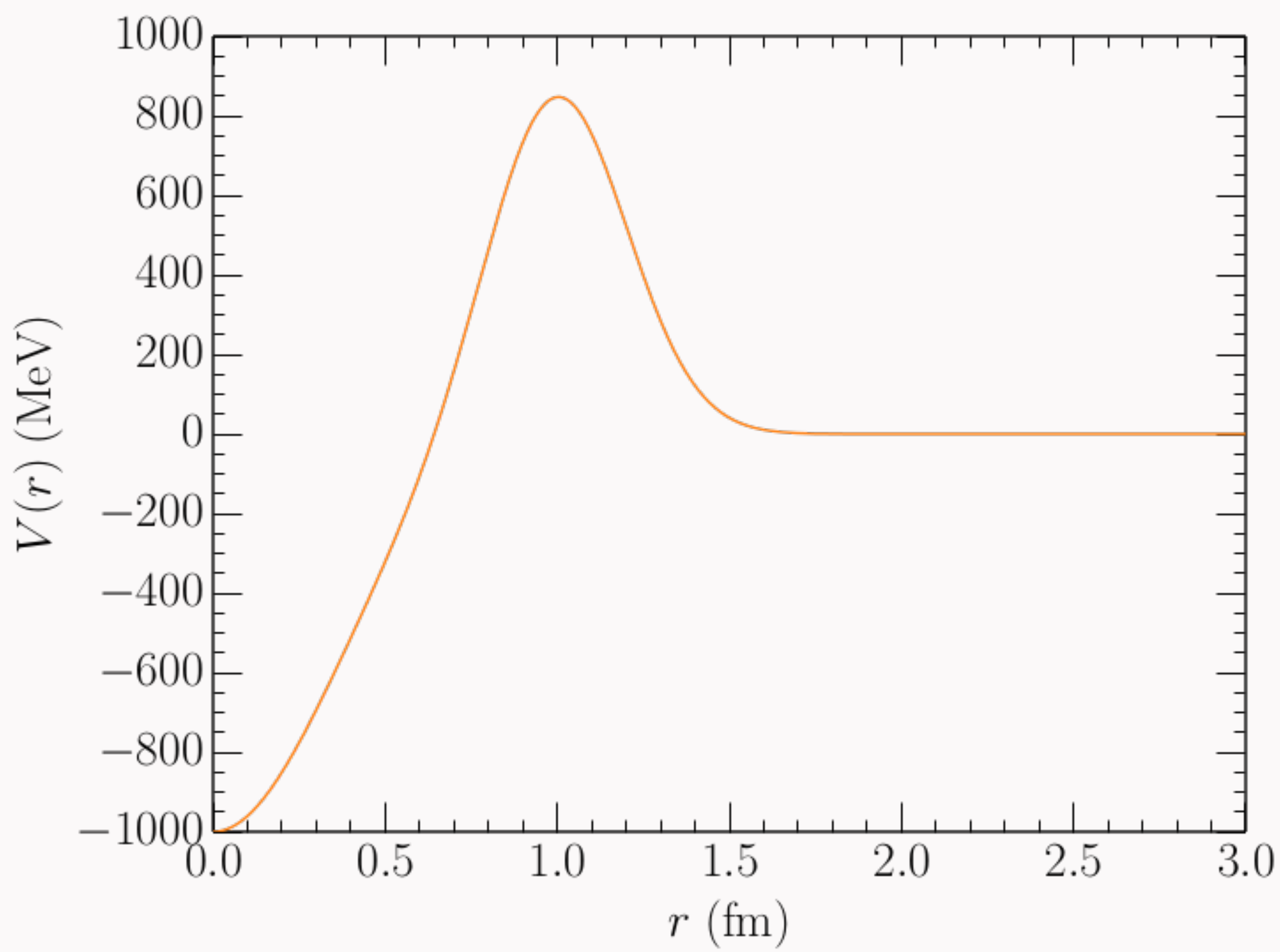
A Two-Body Test

A simple S-wave potential:

$$V(r) = V_1 e^{-\left(\frac{r}{R_1}\right)^2} + V_2 e^{-\left(\frac{r-r_2}{R_2}\right)^2}$$

$$V_1 = -1000 \text{ MeV}, \ R_1 = 0.4981 \text{ fm},$$

$$V_2 = 865 \text{ MeV}, \ R_2 = 0.2877 \text{ fm}, \ r_2 = 0.9972 \text{ fm}$$



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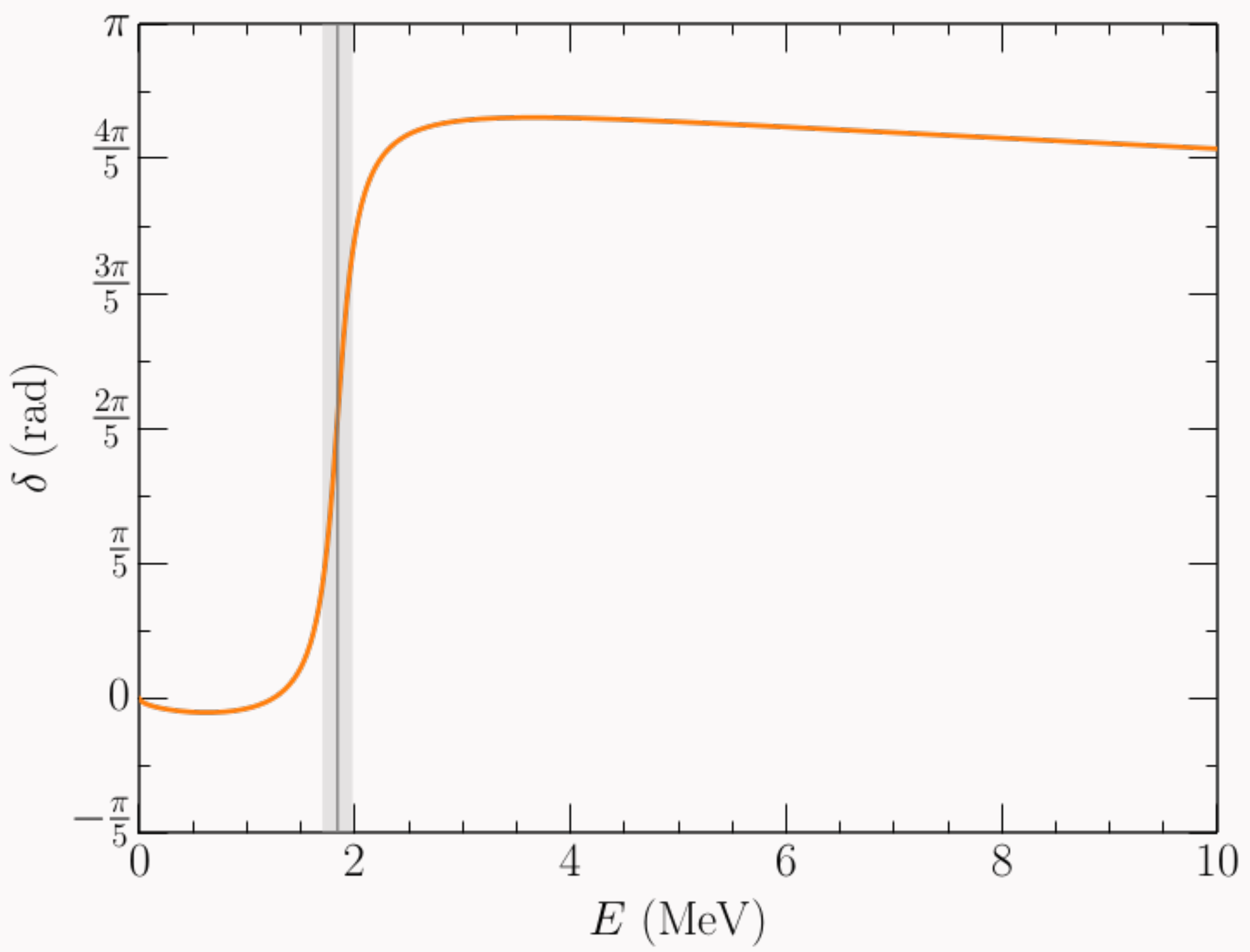
$$E_R = 1.84 \text{ MeV}, \;\; \Gamma = 0.282 \text{ MeV}$$

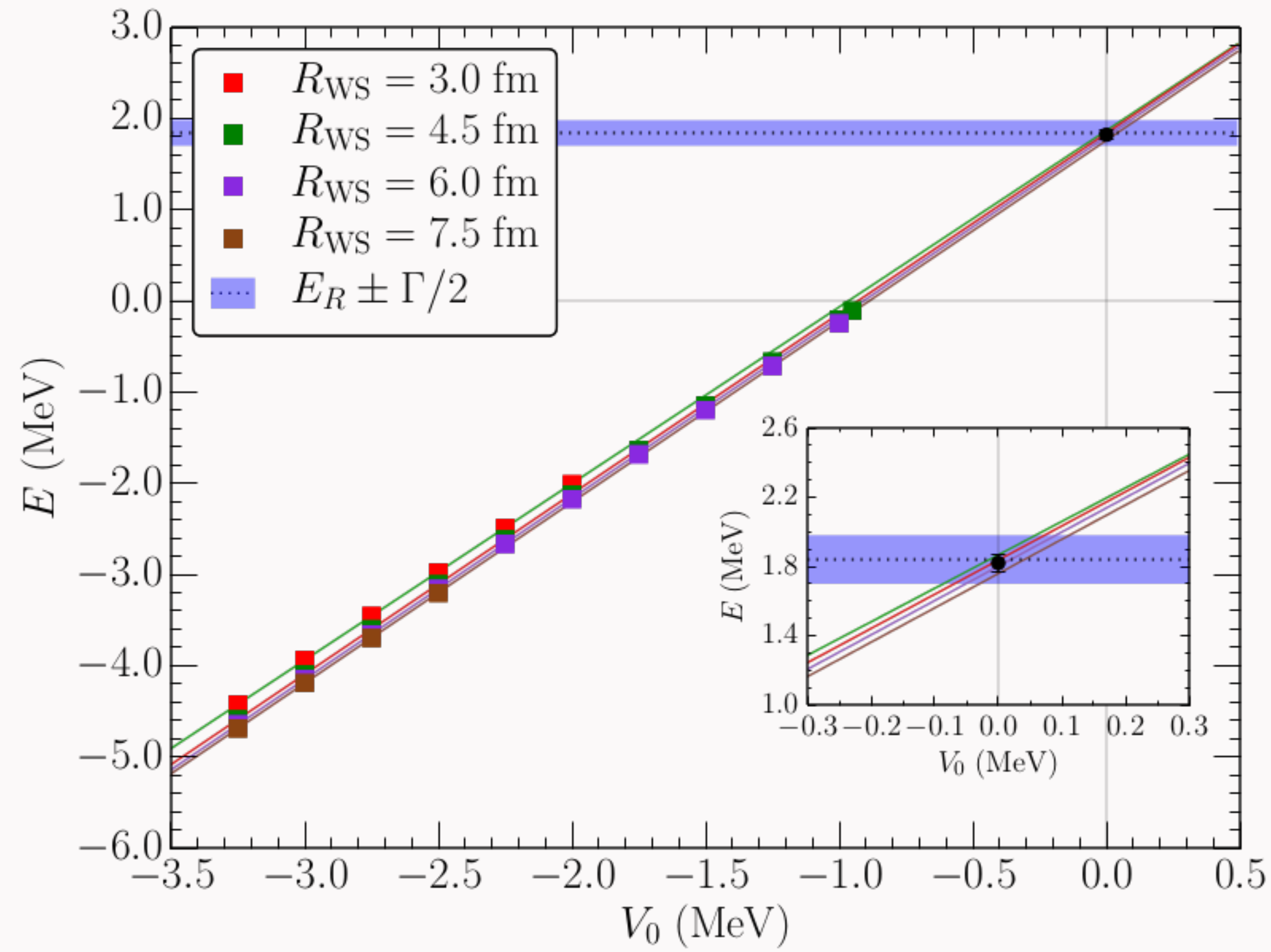


A Two-Body Test

A simple S-wave potential + Woods-Saxon:

$$V(r) = V_1 e^{-\left(\frac{r}{R_1}\right)^2} + V_2 e^{-\left(\frac{r-r_2}{R_2}\right)^2}$$

$$V_{WS}(r) = V_0/[1 + e^{(r-R_{WS})/a}],\ \text{fixed diffuseness } a = 0.65 \text{ fm}$$



A Two-Body Test

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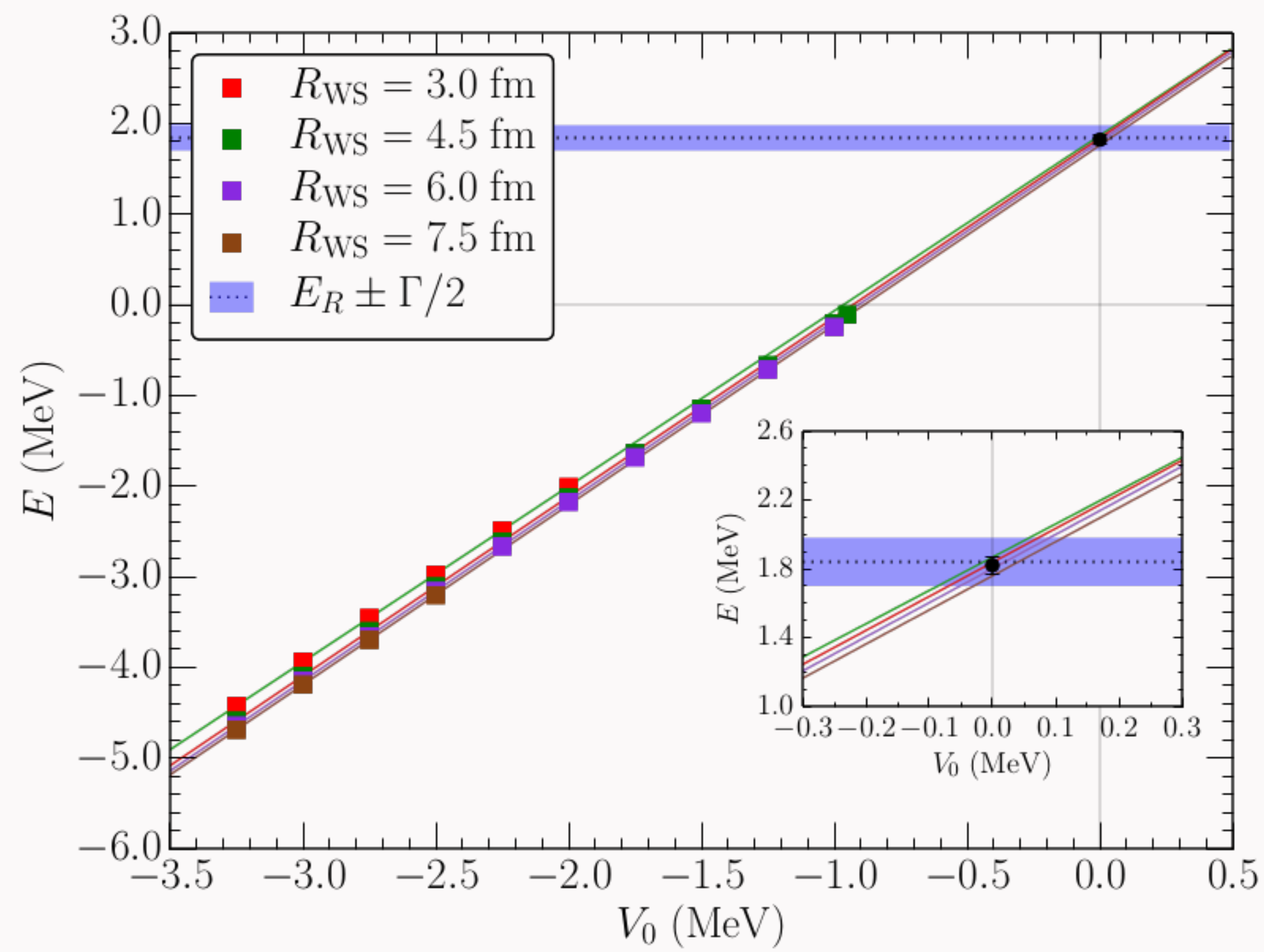
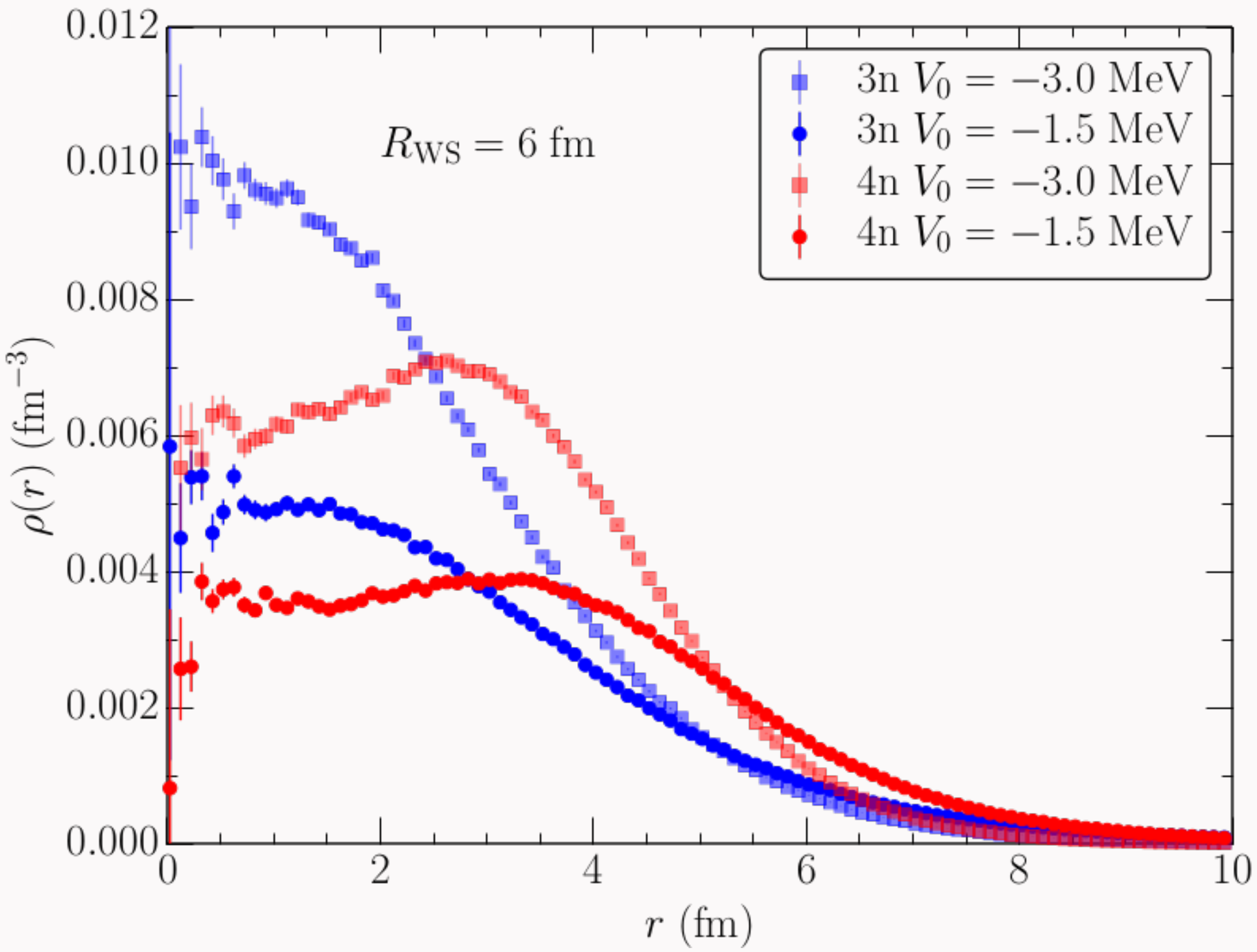
$$V_{\mathrm{WS}}(r) = V_0/[1 + e^{(r-R_{\mathrm{WS}})/a}], \text{ fixed diffuseness } a = 0.65 \text{ fm}$$

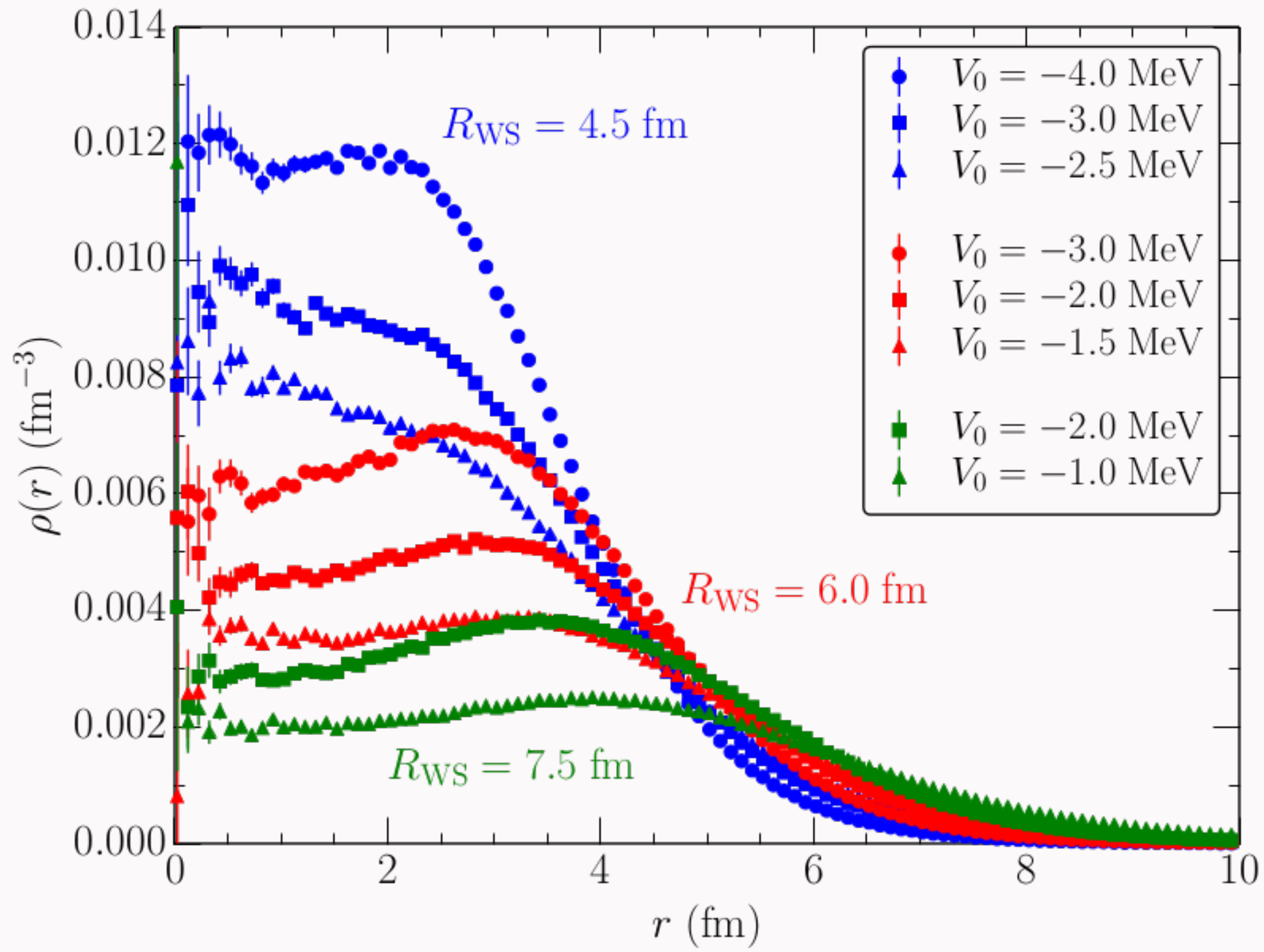
- Different Woods-Saxon radii: Independence of trap geometry.
- Extrapolations give 1.83(5) MeV. (Compare to 1.84 MeV).



One-Body Densities

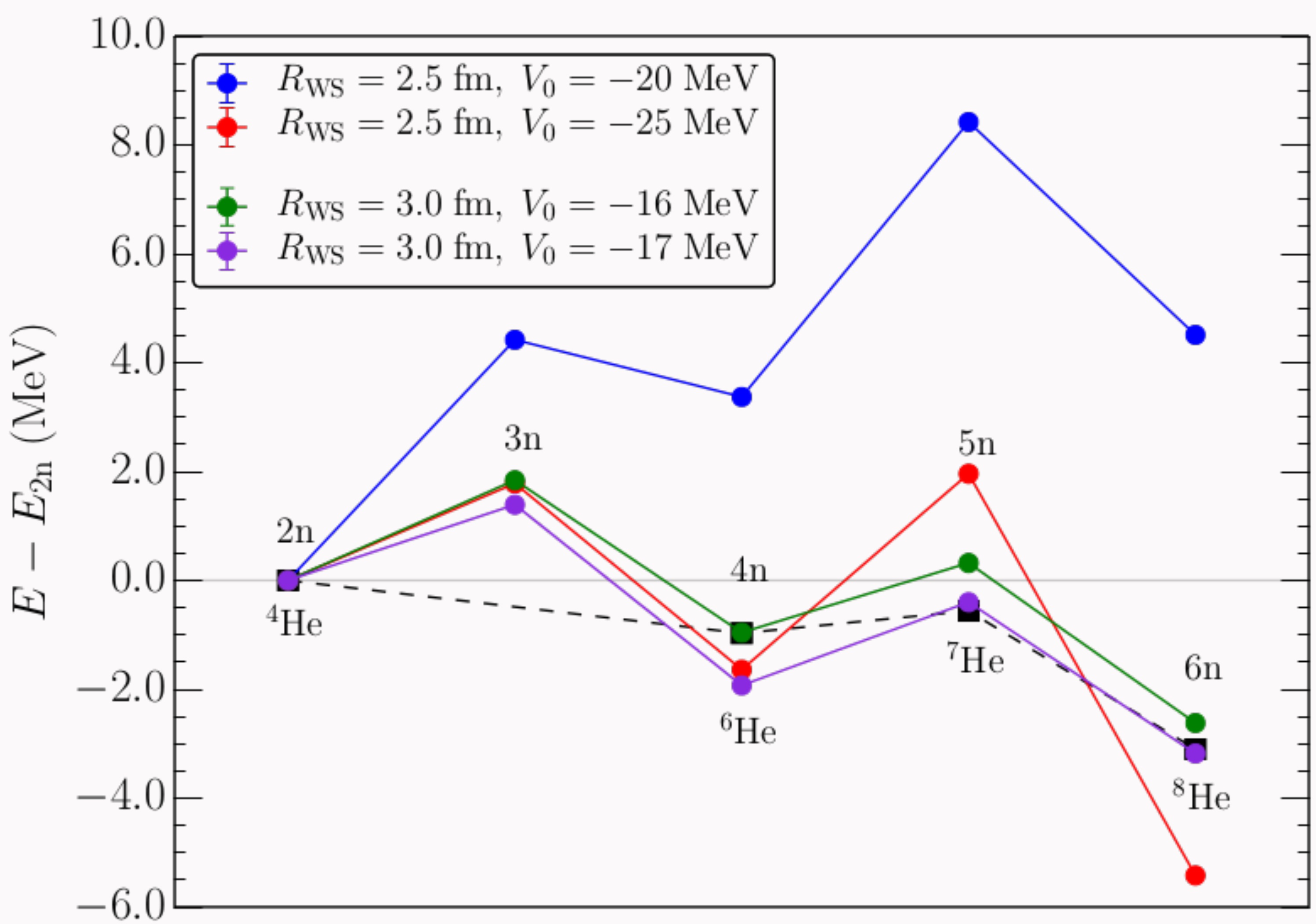
- The ^3n and ^4n systems are very dilute.
- ^3n and ^4n systems show different short-distance structure.





Helium Chain

- That ^3n is lower than ^4n is not an artifact of the Woods-Saxon potential.
- In helium chain, ^3n is always higher than ^4n.



Cold Atoms Connections

- Extrapolated energies for ^3n and ^4n are consistent with scaling like the number of pairs. $E_{A_n} \sim \frac{A(A-1)}{2}$
- Mean-field interaction of dilute gas of spin-1/2 fermions: $E_{\mathrm{MF}}/A = \frac{k_F^2}{2m}\frac{2}{3\pi}(k_F a) \sim A \Rightarrow E_{\mathrm{MF}} \sim A^2$
- Cold atomic gas experiments could determine if one-body density behavior is governed by large-scattering-length physics or details of nuclear interactions.

Summary

- A recent experiment suggests the possibility of a low-lying tetraneutron resonance.
- More experiments are needed (Coming soon!)
- Chiral two- and three-nucleon interactions at N^2LO support a tetraneutron resonance at 2.1(2) MeV compatible with the experimental claim.
- A trineutron resonance might be lower in energy than a tetraneutron resonance and therefore might be observable as well.
- Given the diluteness of the systems, connections to cold atomic gas experiments are possible.

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Thank you for your attention!