Uncertainties in constraining low-energy constants from ^{3}H β decay

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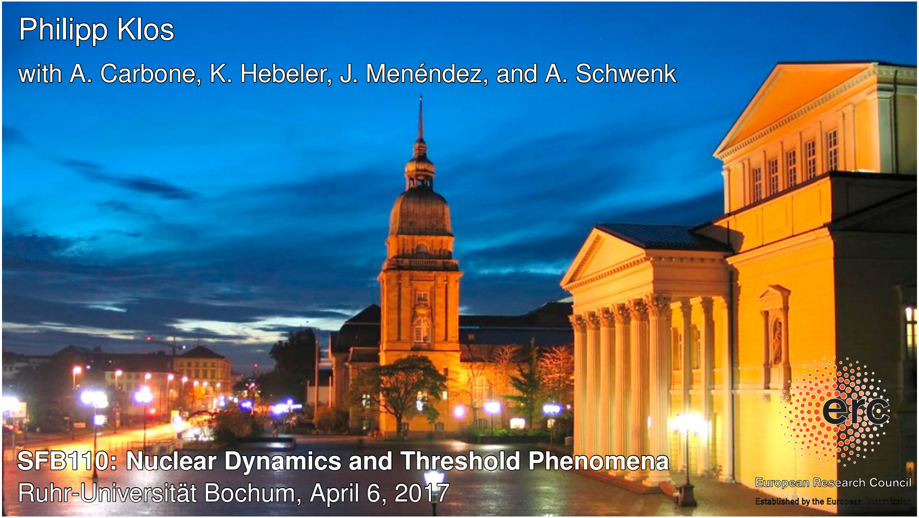
Philipp Klos

with A. Carbone, K. Hebeler, J. Menéndez, and A. Schwenk



SFB110: Nuclear Dynamics and Threshold Phenomena

Ruhr-Universität Bochum, April 6, 2017

European Research Council
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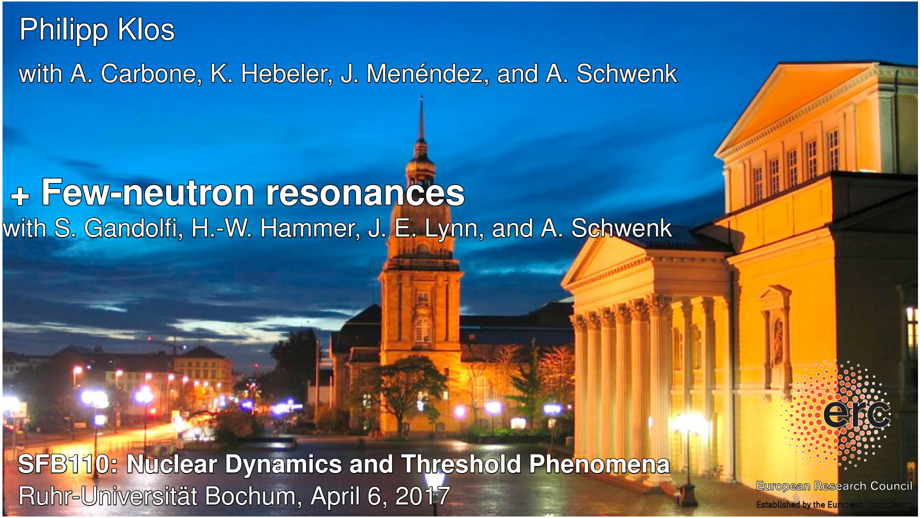

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+ Few-neutron resonances

with S. Gandolfi, H.-W. Hammer, J. E. Lynn, and A. Schwenk

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Uncertainties in constraining low-energy constants from ^{3}H β decay

- Motivation
- Constraining c_D and c_E
- Chiral currents for ^{3}H beta decay

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Chiral effective field theory

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- Chiral EFT describes consistently both nuclear forces and currents

  Epelbaum, Hammer, and Meißner, RMP **81**, 1773 (2009)

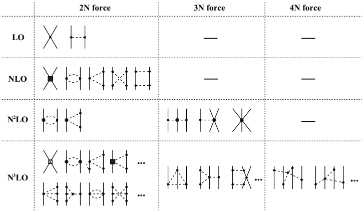
- Same low-energy constants appear in nuclear forces and currents

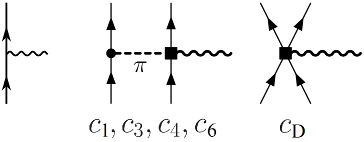
- Leading axial-vector two-body currents completely determined

  Park *et al.*, PRC **67**, 055206 (2003)

  Gårdestig and Phillips, PRL **96**, 232301 (2006)

  Gazit, Quaglioni, and Navrátil, PRL **103**, 102502 (2009)





Constraining low-energy constants

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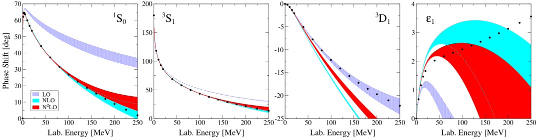
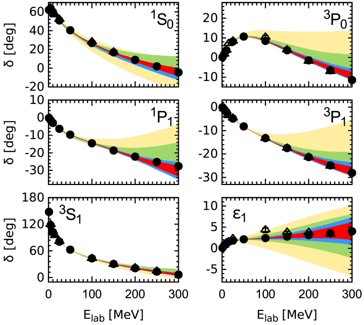
- Low-energy constants in principle defined through underlying theory of QCD
- In practice fit to experimental data
- Up to NLO low-energy constants fit to *NN* and πN scattering data

  Patrick Reinert's talk yesterday



Gezerlis et al., PRL **111**, 032501 (2013)



E. Epelbaum et al., PRL **115**, 122301, (2015)

Regulators

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Chiral forces need to be regularized

Local regulator

$$f_\Lambda^{\text{loc}}(\mathbf{p}, \mathbf{p}') = \exp\left[-\frac{(\mathbf{p} - \mathbf{p}')^4}{\Lambda^4}\right]$$

Non-local regulator

$$f_\Lambda^{\text{non-loc}}(p^2, p'^2) = \exp\left[-\frac{(p^{2n} + p'^{2n})}{\Lambda^{2n}}\right]$$

with cutoff Λ

Many different regularization schemes and cutoffs currently used!

NN potentials and regulators

	Potentials	Regulators
Nonlocal	e.g. EM, EGM; Carlsson et al., PRX 6, 011019 (2016)	$\exp\left[-(p^{2n}+p'^{2n})/\Lambda^{2n}\right]$
Local	Gezerlis et al., PRL 111, 122301 (2013)	$(1-\exp(-(r/R_0)^4)$
Semilocal	Epelbaum et al., EPJ A 51, 53 (2015), PRL 115, 122301 (2015)	mixture

Uncertainties in constraining low-energy constants from ^{3}H β decay

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- Motivation
- Constraining c_D and c_E
- Chiral currents for ^{3}H beta decay

c_D and c_E

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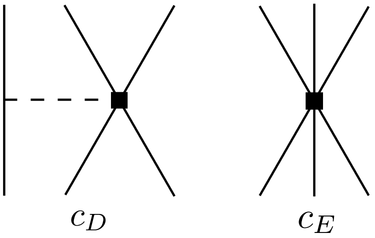
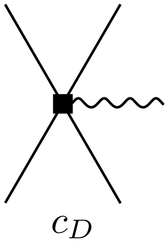
At N^{2}LO two additional LECs enter:

3N forces



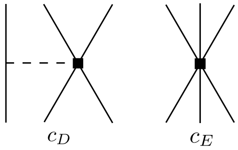
2b currents

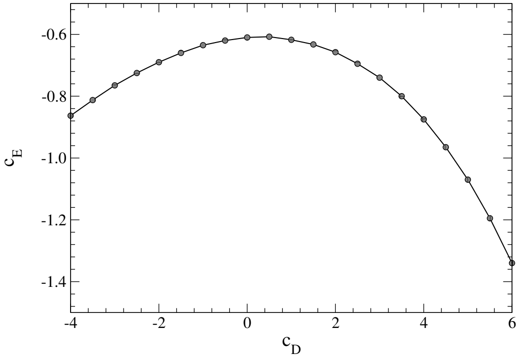


Fits to three-body observables necessary.

Binding energy of triton

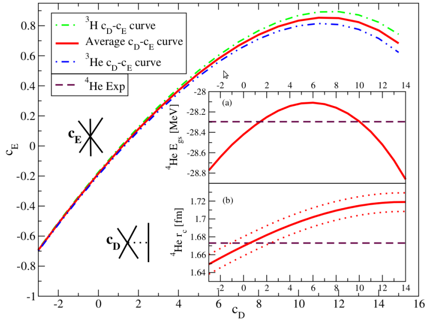
Binding energy of ^{3}H yields relation between c_D and c_E.
Calculation based on non-local EM500 with non-local 3N forces at N^2LO.



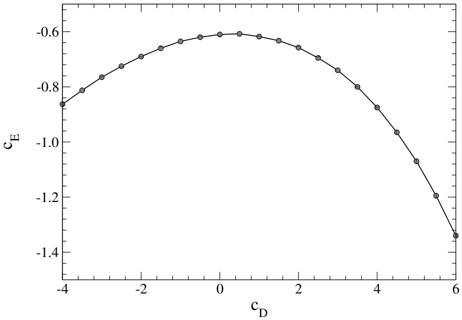


Binding energy of triton

Local 3N regulator



Non-local 3N regulator



Navrátil et al., PRL **99**, 042501 (2007)

Impact of 3N regulator significant

Uncertainties in constraining low-energy constants from ^{3}H β decay

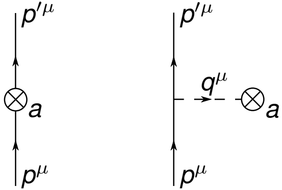
- Motivation
- Constraining c_D and c_E
- Chiral currents for ^{3}H beta decay

One-body currents

Axial current at chiral order Q^0

$$A^{a\mu}_{1b} = -g_A \bar{u}(p')\gamma_5 \left(\gamma^\mu - \not{q}\frac{q^\mu}{q^2 - m_\pi^2}\right) \frac{\tau^a}{2} u(p)\,,$$

Pion-decay is momentum dependent



One-body currents

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Axial current at chiral order Q^0

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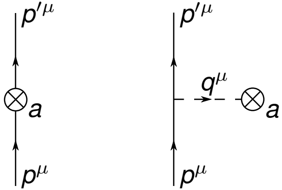


Pion-decay is momentum dependent

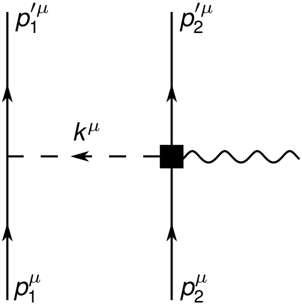
Non-relativistic limit including loop corrections at Q^2:

$$A^{0a}_{1b} = \frac{\tau^a}{2} g_A(\mathbf{q}^2)\frac{\boldsymbol{\sigma}\cdot\mathbf{P}}{2M} \qquad \mathbf{A}^a_{1b} = \frac{\tau^a}{2}\left(g_A(\mathbf{q}^2)\boldsymbol{\sigma} - \frac{g_P(\mathbf{q}^2)}{2M}(\mathbf{q}\cdot\boldsymbol{\sigma})\,\mathbf{q}\right)$$

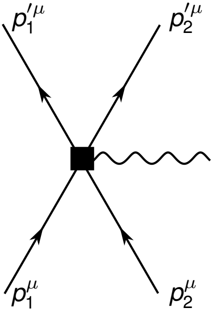
$\mathbf{q}$ momentum transfer, $\mathbf{P} = \mathbf{p} + \mathbf{p}'$ total momentum

Two-body currents

At order Q^3, 2b currents enter:



Pion exchange currents
c_1, c_3, c_4, c_6

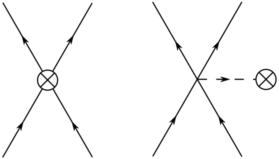


Contact currents
d_1, d_2

Application to many-body nuclear states

Apply two-body antisymmetrizer: $\mathcal{A} = \frac{1}{2}(1 - P_{ij})$ on contact currents:

$$\mathcal{A}\,\mathbf{A}_{12\text{contact}} = (d_1 + 2d_2)\mathcal{O}_{12}$$



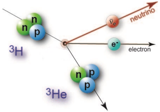
with $\mathcal{O}_{12}$ operator structure of the 2b current

Replace the two constants d_1 and d_2 by one single constant:

$$c_D = \Lambda_\chi F_\pi^2 (d_1 + 2d_2)$$

NOTE: This is no longer strictly the case for local regulators

Fit to ^{3}H β decay



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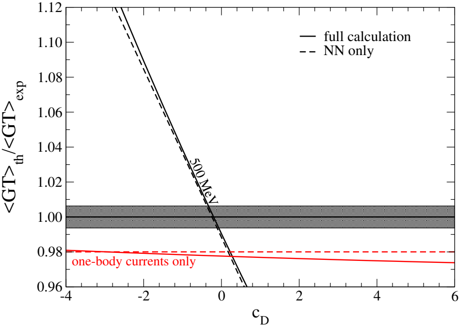
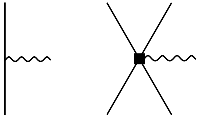
- Beta-decay of triton to determine c_D
  - ^{3}H half-life precisely known
  - Uncorrelated with ^{3}H binding energy
- c_D and c_E fully determined from independent three-body observables



Gamow-Teller matrix element

$$\langle \mathrm{GT} \rangle = \frac{1}{g_A} \langle {}^3\mathrm{He} \| \sum_{i=1}^{3} \mathbf{J}^{+}_{i,1b} + \sum_{i<j} \mathbf{J}^{+}_{ij,2b} \| {}^3\mathrm{H} \rangle$$



2b current regulator

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Similar to the nuclear forces currents need to be regulated.

Local regulator

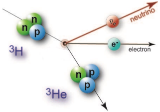
$$f_\Lambda^{\text{loc}}(\mathbf{p}, \mathbf{p}') = \exp\left[-(\mathbf{p} - \mathbf{p}')^4/\Lambda_{2\text{bc}}^4\right]$$

with cutoff $\Lambda_{2\text{bc}}$ Gazit, Quaglioni, Navrátil, PRL **103**, 102502 (2009)

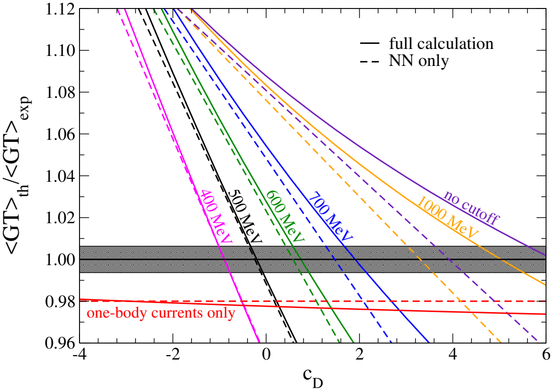
- Unclear how to choose regulator and cutoff consistently in both forces and currents
- Continuity equation needs to be checked

  Krebs et al., Annals Phys. **378** (2017)
- Here: Study cutoff dependence in 2b currents only

Cutoff dependence of c_D



Consider different cutoffs for two-body currents using local 2bc regulator:



Carbone, Hebeler, Menéndez, Schwenk, PK, arXiv 1612.08010

Significant current-regulator dependence of c_D!

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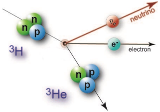
Cutoff dependence of c_D



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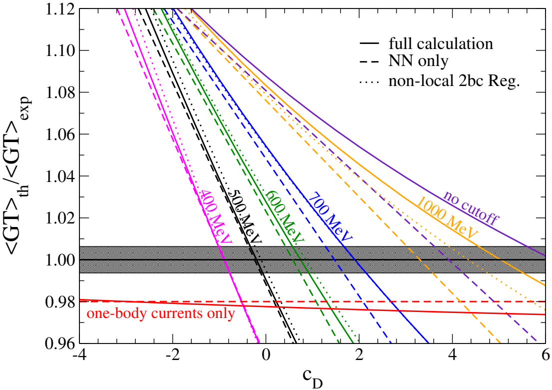
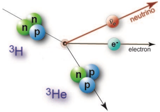
Consider different cutoffs for two-body currents using non-local 2bc regulator:



Carbone, Hebeler, Menéndez, Schwenk, PK, arXiv 1612.08010

Significant current-regulator dependence of c_D!

Cutoff dependence of $\langle \mathrm{GT} \rangle_{\mathrm{th}}$



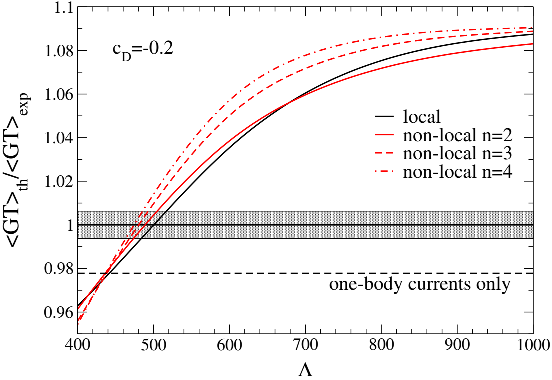
Cutoff-dependence in two-body currents can be larger than two-body-current contribution

Local regulator

$$f_\Lambda^{\mathrm{loc}}(\mathbf{p}, \mathbf{p}') = \exp\left[-(\mathbf{p} - \mathbf{p}')^4/\Lambda_{2\mathrm{bc}}^4\right]$$

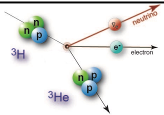
Nonlocal regulator

$$f_\Lambda^{\mathrm{non\text{-}loc}}(p^2, p'^2) = \exp\left[-(p^{2n} + p'^{2n})/\Lambda^{2n}\right]$$



Carbone, Hebeler, Menéndez, Schwenk, PK, arXiv 1612.08010

Cutoff dependence of $\langle GT \rangle_{th}$



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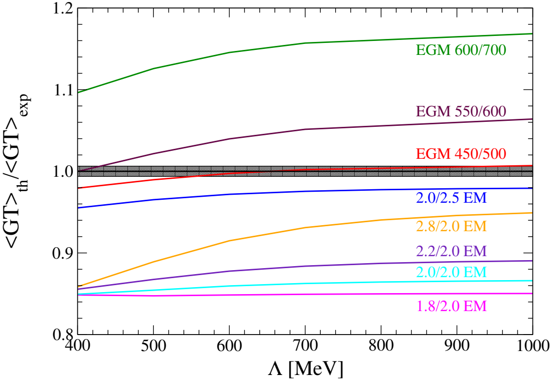
Generally not possible to simultaneously fit all experimental observables



Carbone, Hebeler, Menéndez, Schwenk, PK, arXiv 1612.08010

Impact on nuclear matter

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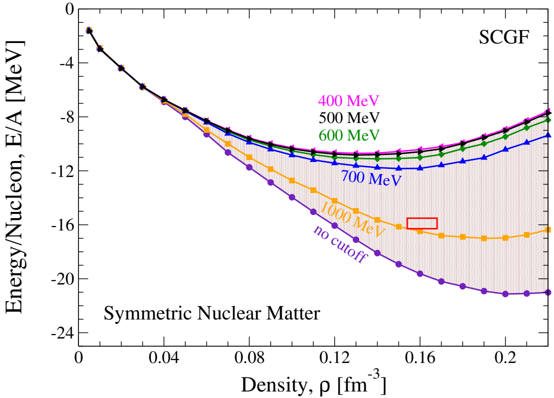
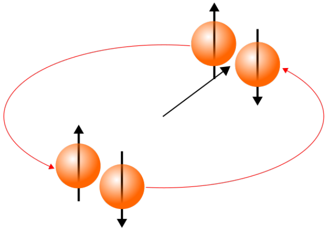
Nuclear matter calculation with c_D, c_E taken from the triton fit



Carbone, Hebeler, Menéndez, Schwenk, PK, arXiv 1612.08010

Few-neutron resonances



Four-neutron resonances

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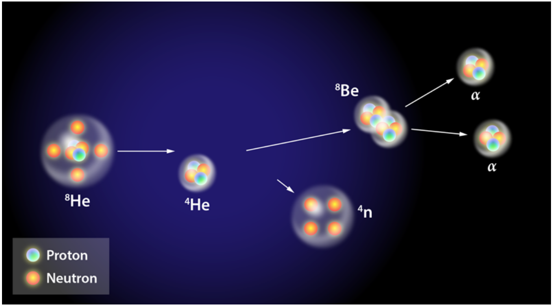
Double charge-exchange reaction ^{8}He+^{4}He$\rightarrow$^{8}Be+^{4}n at RIKEN



APS/Alan Stonebraker

Tetraneutron resonance at 0.83$\pm$0.65(stat)$\pm$1.25(syst.) MeV

Kisamori et al., PRL **116**, 052501 (2016)

Quantum Monte Carlo

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QMC in three lines:

Ground state: $H|\Psi_0\rangle = E_0|\Psi_0\rangle$

Trial state: $|\Psi_T\rangle = \sum_i \alpha_i |\Psi_i\rangle$

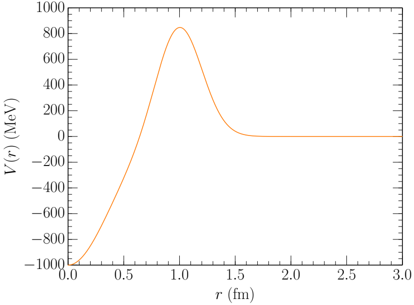
Propagate: $\lim_{\tau\to\infty} e^{-H\tau}|\Psi_T\rangle \to |\Psi_0\rangle$

QMC in more than three lines:
J. Carlson *et al.*, RMP **87**, 1067 (2015).

- Exact method to solve Schrödinger equation
- Very successful for light nuclei
- However, simulates bound states only

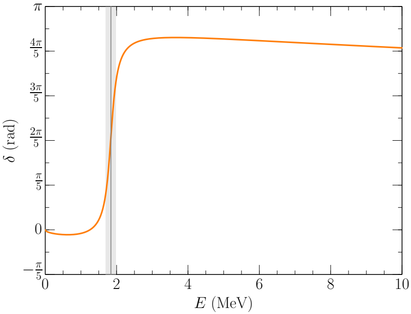
QMC for unbound states

2n test potential



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

Phaseshift

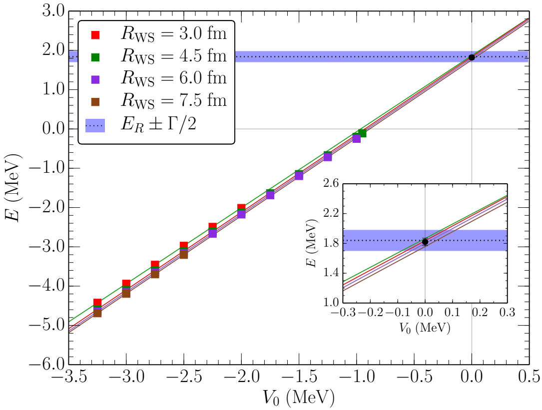


adjusted to have a clear resonance
E_R = 1.84 MeV, Γ = 0.282 MeV

Two-body test potential

- Add external Woods-Saxon to make the system bound

$$V_{\mathrm{WS}} = \frac{V_0}{1 + e^{(r - R_{\mathrm{WS}})/a}}$$



Two-body test potential

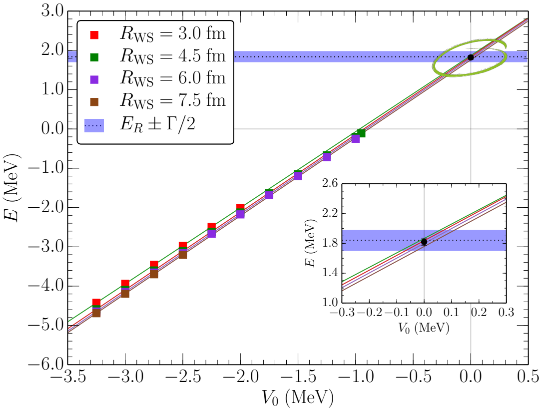
- Add external Woods-Saxon to make the system bound

$$V_{\mathrm{WS}} = \frac{V_0}{1 + e^{(r - R_{\mathrm{WS}})/a}}$$

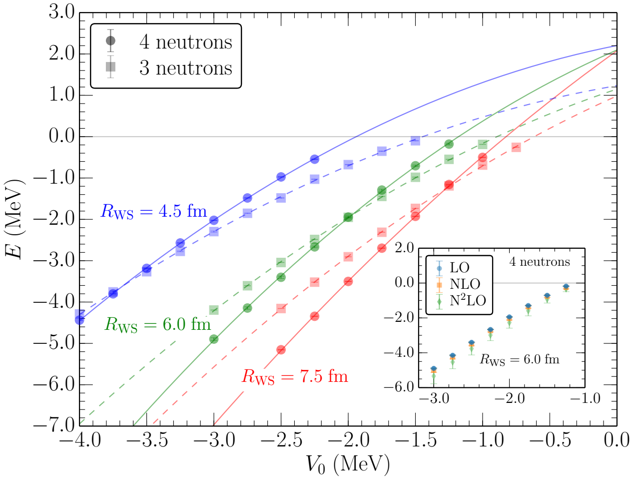
- Extrapolation to vanishing external potential yields

  $E_R = 1.83(5)$ MeV
  (Compare to 1.84 MeV)

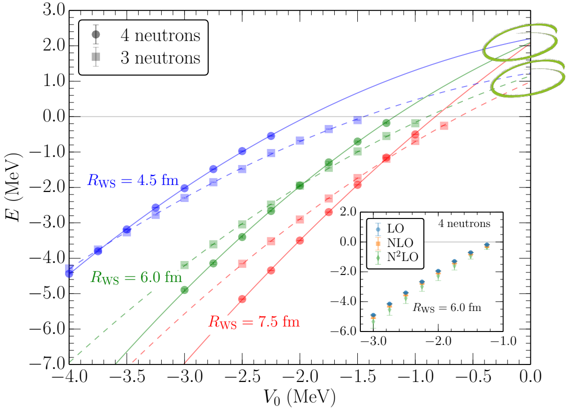
- Independent of trap geometry



Three- and four-neutron resonances



Three- and four-neutron resonances



- E_{3n} = 1.1(2) MeV
  E_{4n} = 2.1(2) MeV
- ^{3}n resonance lower than ^{4}n resonance
- identical results without 3N forces/different cutoffs

One-body densities

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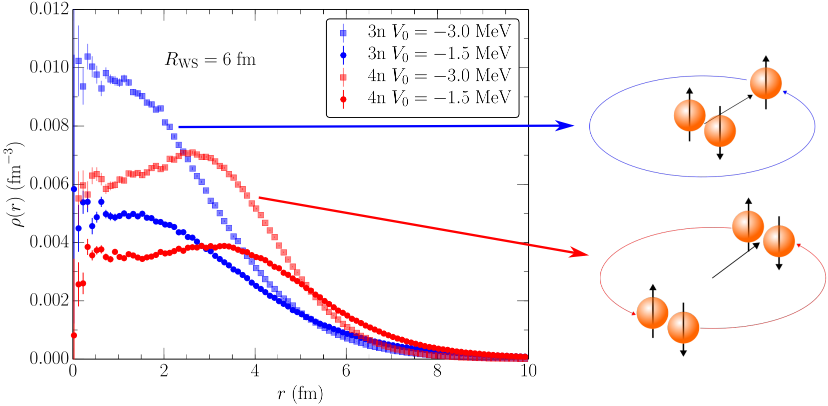

- ^{3}n and ^{4}n are very dilute

Helium chain

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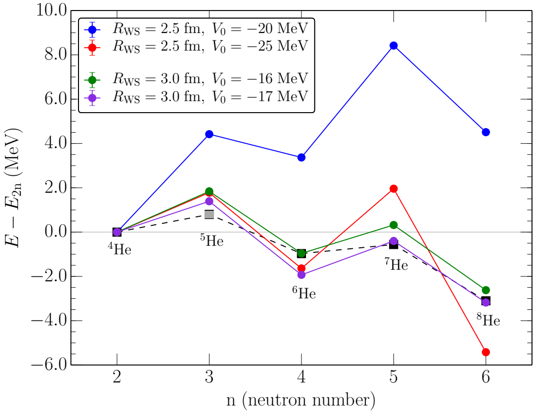

- Odd isotopes always higher in energy than even
- Ordering of ^{3}n and ^{4}n resonances not an artifact of the trap

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Summary

^{3}H β decay: arXiv 1612.08010

- Significant current-cutoff dependence when fitting c_D
- Additional uncertainties from cutoff variation need to be taken into account
- Generally not possible to simultaneously fit all experimental observables
- **How do we choose regulators consistently in forces and currents?**

Few-neutron resonances: arXiv 1612.01502

- Chiral EFT interaction supports tetraneutron resonance
- Three neutron resonance potentially lower than tetraneutron resonance (experimentally observable?)
- Dependence on three-body forces and regulator choice insignificant due to diluteness of the system