TRIUMF Canada's National Laboratory for Particle and Nuclear Physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Light Exotic Nuclei in Effective Field Theory

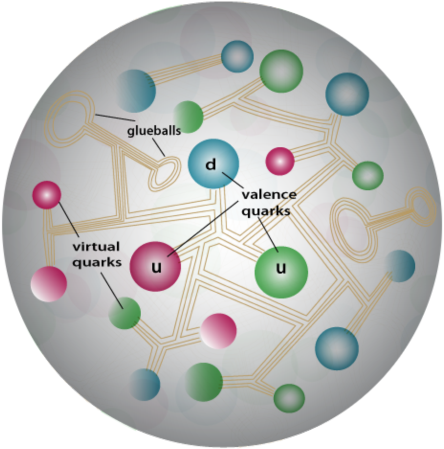
Chen Ji || TRIUMF

Reactions and Structure of Exotic Nuclei
INT, Mar 2-13, 2015

Effective Theories & Resolution Scales

- We study physics at different resolution scales with different effective theories

- describe nucleon structures
  - physics scale: $Q \gtrsim$ GeV
  - d.o.f.: quarks & gluons
  - effective theory: lattice QCD



Effective Theories & Resolution Scales

- We study physics at different resolution scales with different effective theories

- light/medium mass nuclei
  - physics scale: $Q \sim 200$ MeV
  - d.o.f.: nucleons & pions
  - effective theory: chiral EFT
  - use *ab initio* methods

Effective Theories & Resolution Scales

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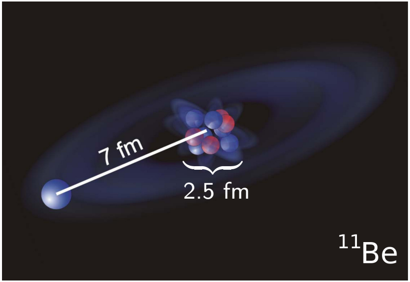
- We study physics at different resolution scales with different effective theories

- very light nuclei (d, t, ^{3}He, α)
  - physics scale: $Q \ll m_\pi$
  - d.o.f.: nucleons in contact
  - effective theory: pionless EFT
  - use few-body methods

Effective Theories for Halo Nuclei

- **halo nuclei** (core + valence N)
- **separation in length scales**

  $R_{\text{core}} \ll R_{\text{halo}}$



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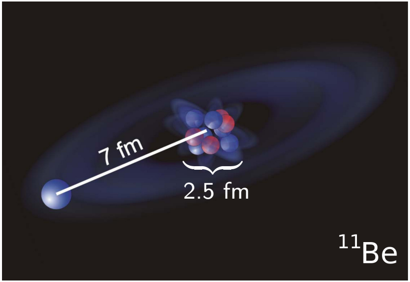
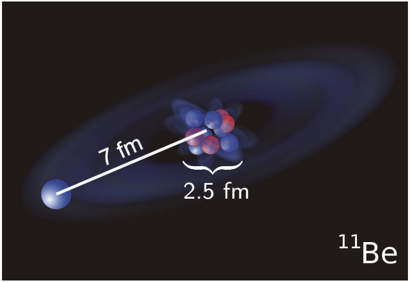


ab initio methods

- capture dynamics inside and outside the core
- numerically expensive for loosely bound systems

- **halo nuclei** (core + valence N)
- **separation in length scales** $R_{\rm core} \ll R_{\rm halo}$



ab initio methods

- capture dynamics inside and outside the core
- numerically expensive for loosely bound systems

halo effective field theory

- valence nucleon + core d.o.f.
- systematic expansion in $R_{\rm core}/R_{\rm halo}$
- capture only clustering mechanism
- numerically simpler
- complimentary to *ab initio* methods
- explain universal correlations in clustering physics

Halo Effective Field Theory

- We adopt EFT with contact interactions to describe clustering in halo nuclei

$$\mathcal{L} = \psi^\dagger \left(i\partial_0 + \frac{\nabla^2}{2m}\right)\psi + \eta\, d^\dagger \left(i\partial_0 + \frac{\nabla^2}{4m} - \Delta\right) d - \frac{g}{\sqrt{2}}\left(d^\dagger \psi\psi + \mathrm{h.c}\right) + h d^\dagger d \psi^\dagger \psi + \cdots$$

$\cdots$ are higher orders in $R_{\text{core}}/R_{\text{halo}}$ expansion

Halo Effective Field Theory

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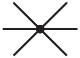
$\cdots$ are higher orders in $R_{\text{core}}/R_{\text{halo}}$ expansion

- 2-body contact (LO) introduce a two-body field

 $= -iC_0$ $\xrightarrow{C_0 = g^2/\Delta}$  $= -i\sqrt{2}g$

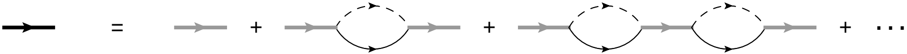
g determined by a 2-body observable

- 3-body contact (LO)

 $= -iD_0$ $\xrightarrow{D_0 = -3hg^2/\Delta^2}$  $= ih$

h determined by a 3-body observable [Bedaque, Hammer, van Kolck PRL '99]

- **EFT for $1n$ halo**



- **^{5}He shallow resonance ($P_{3/2}$)**

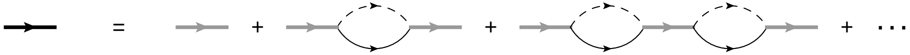
$$= \frac{1}{4\pi^2 \mu_{n\alpha}} \frac{\vec{p}\cdot\vec{q}}{-1/a_1 + r_1 k^2/2 - ik^3}$$

$a_1 = -62.95$ fm^3, $r_1 = -0.8819$ fm^{-1}

Ardnt et al. NPA '73

One-Neutron Halo Systems

- **EFT for $1n$ halo**



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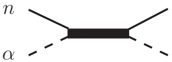

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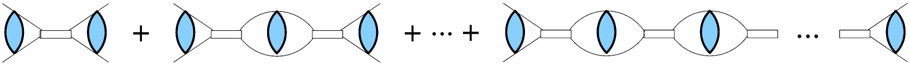
Ardnt et al. NPA '73

- **$n\alpha$ p-wave EFT power counting**

  two fine tunings: Bertulani, Hammer, van Kolck, NPA '02

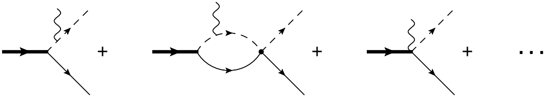
  one fine tuning: Bedaque, Hammer, van Kolck, PLB '02

- **EFT for $1p$ halo nucleus**



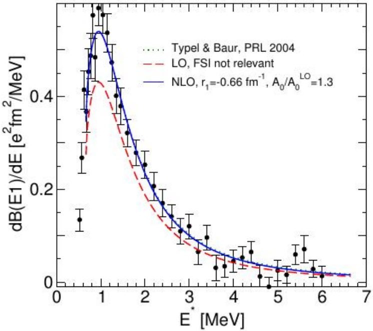
p-α and α-α scattering [Higa, Hammer, van Kolck, NPA '08; Higa, FBS '11]

^{17}F [Ryberg, Forssén, Hammer, Platter, PRC '14]



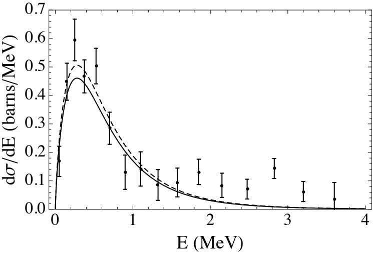
- **E1 transition**

^{11}Be photo-dissociation



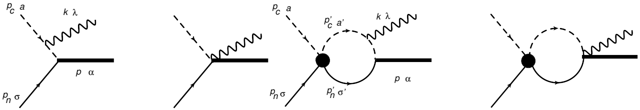
[Hammer, Phillips, NPA '11]

^{19}C photo-dissociation

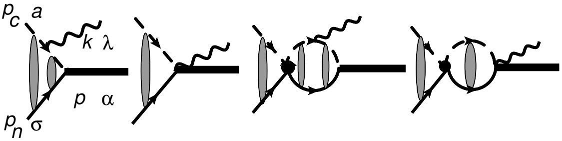


data: Nakamura *et al*, RIKEN, PRL '99; NPA '03;
theory: Acharya, Phillips, NPA '13

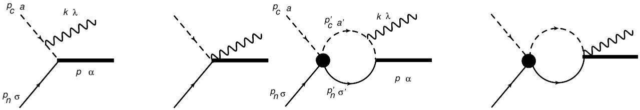
neutron captures



proton captures



neutron captures



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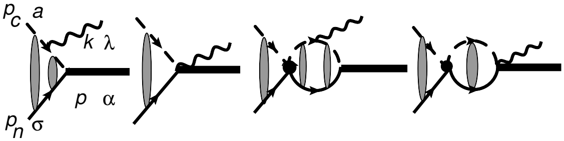


$^{7}\mathrm{Li} + n \to {}^{8}\mathrm{Li} + \gamma$

Rupak, Higga, PRL '11; Fernando, Higa, Rupak, EPJA '12;
Zhang, Nollett, Phillips, PRC '14

$^{14}\mathrm{C} + n \to {}^{15}\mathrm{C} + \gamma$

Rupak, Fernando, Vaghani, PRC '12

$^{7}\mathrm{Be} + p \to {}^{8}\mathrm{B} + \gamma$

Zhang, Nollett, Phillips, PRC '14; Ryberg, *et al.* EPJA '14

$^{16}\mathrm{O} + p \to {}^{17}\mathrm{F}^{*}(1/2^{+}) + \gamma$

Ryberg, Forssén, Hammer, Platter, PRC '14

E1 S-factor for $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$

- Zhang, Nollett, Phillips, PRC '14

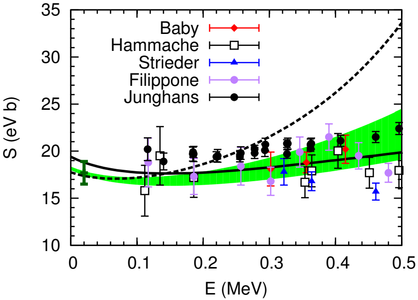
  —— NSCM-GRM result

  [Navratil, Roth, Quaglioni, PLB '11]

  ---- LO EFT: fit to NSCM-GRM ANC

  LO EFT: fit to ANC from VMC

  VMC [Nollett, Wiringa, PRC '11]



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E1 S-factor for ^{7}Be$(p,\gamma)^8$B

- Zhang, Nollett, Phillips, PRC '14

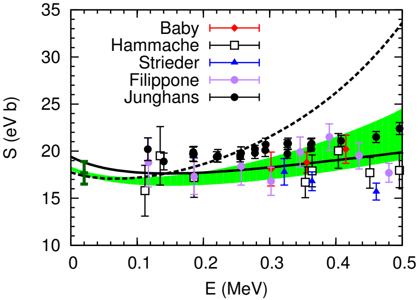
  —— NSCM-GRM result

  [Navratil, Roth, Quaglioni, PLB '11]

  - - - - LO EFT: fit to NSCM-GRM ANC

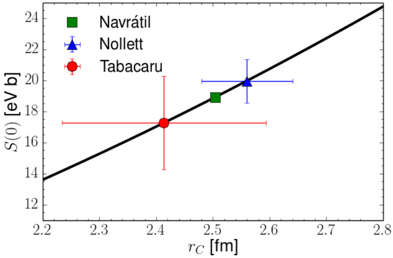
  LO EFT: fit to ANC from VMC

  VMC [Nollett, Wiringa, PRC '11]

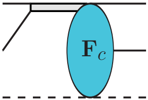


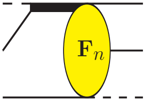
- Ryberg, Forssén, Hammer, Platter, EPJA '14

  correlation btw $S(0)$ and $r_C[^8\mathrm{B}]$



- **2n-halo wave functions**

$\Psi_x(p, q) =$ 

$+ \quad 2\times$ 

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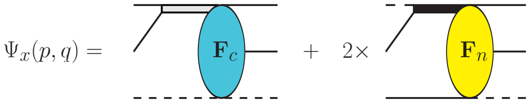
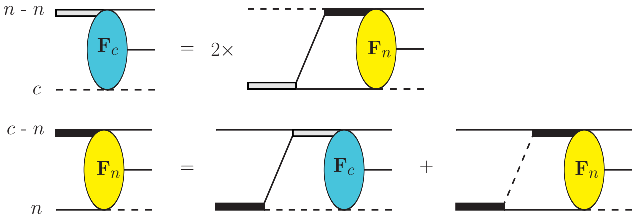


- **Three-body Faddeev equation**



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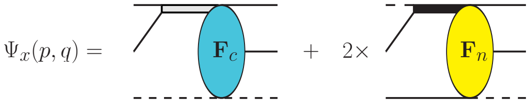

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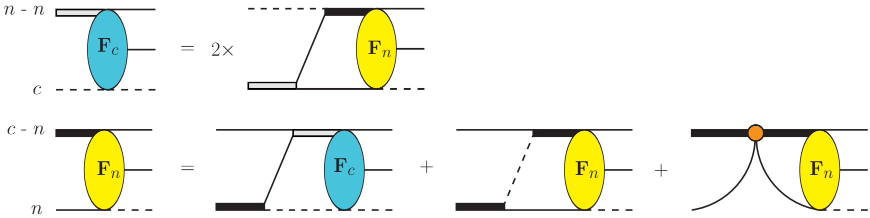
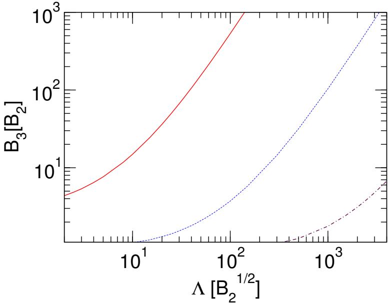
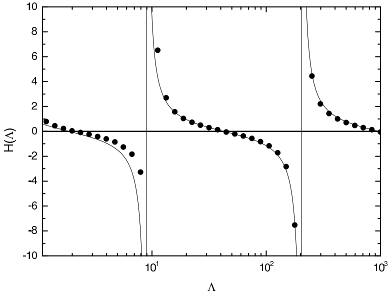


- **Without 3BF:**
  - 3-body spectrum:
    cutoff dependent ($\Lambda \sim 1/\ell$)
    Platter '09

- **LO 3BF h:**
  - tune $H(\Lambda) = \Lambda^2 h / 2mg^2$:
    fix one 3-body observable
  - limit cycle:
    $H(\Lambda)$ periodic for $\Lambda \to \Lambda(\text{const})^n$
    Bedaque *et al.* '00
  - $\to$ Efimov physics





EFT For $2n$ Halos

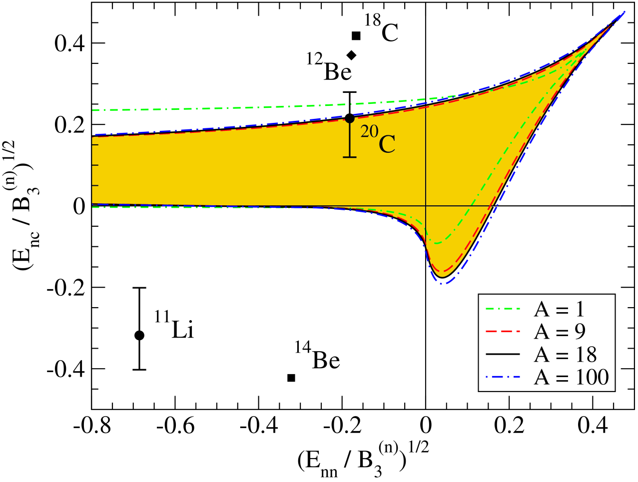
- n-core in s-wave virtual/real bound state:
  ^{11}Li, ^{12}Be, ^{20}C [Canham, Hammer, EPJA '08, NPA '10]
  ^{22}C [Yamashita, Carvalho, Frederico, Tomio, PLB '11]
  ^{22}C Acharya, C.J., Phillips, PLB 723 (2013)

- charge radius of 2n s-wave halos [Hagen, Hammer, Platter, EPJA '13]

- heaviest 2n s-wave halo:
  ^{62}Ca [Hagen, Hagen, Hammer, Platter, PRL '13]
  fit n-^{60}Ca scattering length from coupled-cluster calculations

- ^{6}**He:** n-α in p-wave resonance
  - EFT + Gamow shell model [Rotureau, van Kolck, FBS '13]
  - EFT + Faddeev Equations C.J., Elster, Phillips, PRC **90**, 044004 (2014)

- Implication of excited Efimov halo
  for an excited state with $S_{2n} > 0$



Canham, Hammer, EPJA '08

Universality in $2n$ s-wave halo

- Implication of excited Efimov halo
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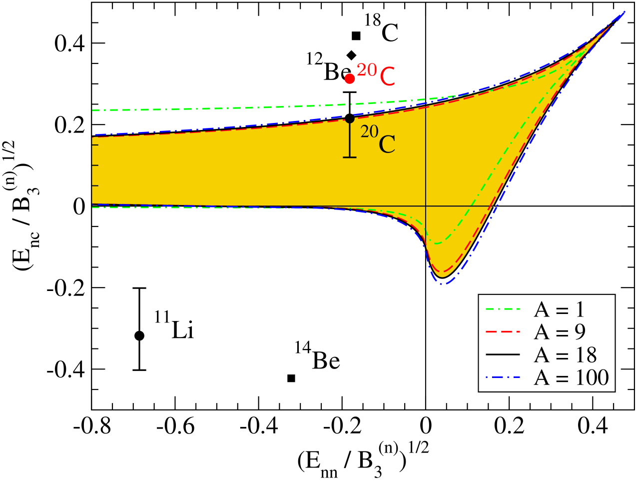

Canham, Hammer, EPJA '08

^{22}C: $2n$ Halo

	^{20}C	^{21}C	^{22}C
bound/unbound	bound		
ground state	0^+		
binding/virtual energy [MeV]	S_{2n}: $3.50(24)$ AME2012		
matter radius r_m [fm]	2.97(5) Ozawa et al. '01		

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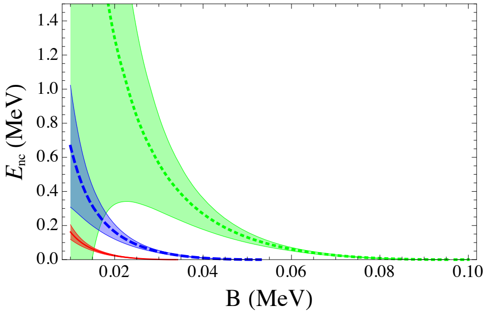
- Halo EFT [Acharya, C.J., Phillips, PLB **723** 196 (2013)]
  we fit to ^{22}C matter radius to constrain:
  - E_{nc} in ^{21}C ($a < 0$)
  - S_{2n} in ^{22}C

Constraints On ^{21}C and ^{22}C

Input: $r_m[^{22}\mathrm{C}] = 5.4^{+0.9}_{-0.9}$ fm



bands: uncertainty from higher-order EFT

Acharya, C.J., Phillips, PLB **723** 196 (2013)

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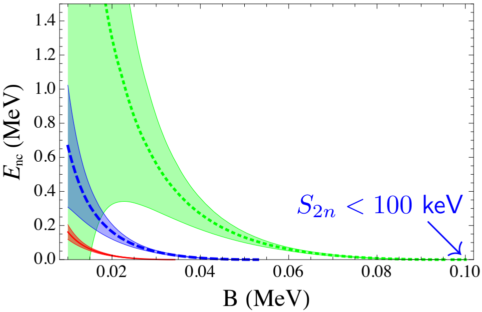

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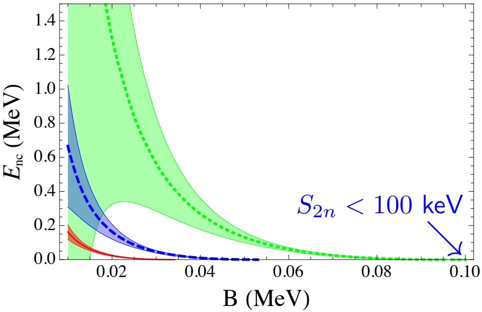

bands: uncertainty from higher-order EFT

Acharya, C.J., Phillips, PLB **723** 196 (2013)

c.f. Horiuchi & Suzuki, PRC '06 (theo) $\rightarrow S_{2n} < 570$ keV

Yamashita et al., PLB '11 (theo) $\rightarrow S_{2n} < 120$ keV

Fortune & Sherr, PRC '12 (theo) $\rightarrow S_{2n} < 220$ keV

AME2012 (expt) $\rightarrow S_{2n} < 170$ keV

Gaudefroy et al., PRL '12 (expt) $\rightarrow S_{2n} < 320$ keV

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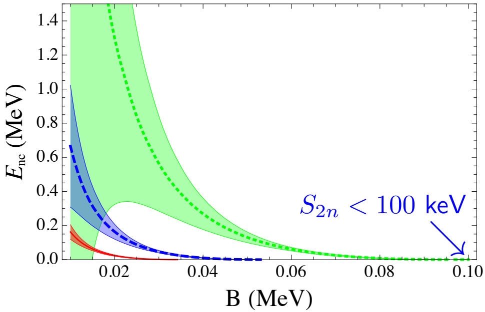

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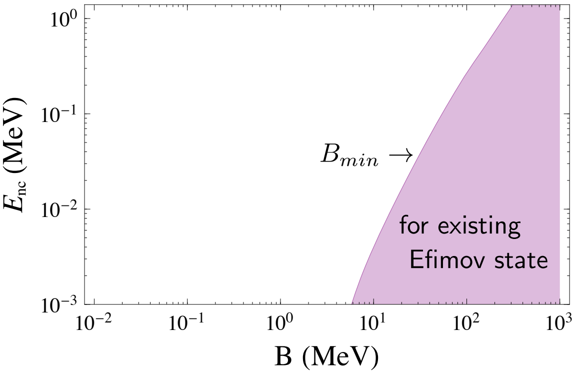
Mosby et al., NPA '13 $E_{nc} > 2.9$ MeV

Halo EFT $\rightarrow S_{2n} < 20$ keV

(inconsistent with other measurements)

Efimov States In ^{22}C ?

- possibility of finding Efimov excited states in ^{22}C
  Mazumdar *et al.* PRC '00; Frederico *et al.* PPNP '12; Acharya, C.J., Phillips PLB '13
- an Efimov excited state exists if G.S. $S_{2n} > B_{min}$



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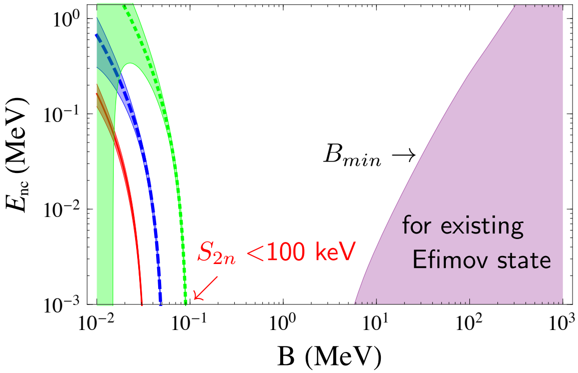

- The Efimov excited state only occurs in ^{22}C if:
  $\rightarrow$ the virtual energy of ^{21}C $E_{nc} < 1$ keV (unlikely)

^{23}N: $2n$ Halo Nucleus

	^{21}N	^{22}N	^{23}N
S_{1n} [MeV]	$4.59(11)$	$1.28(21)$	$1.79(36)$
S_{2n} [MeV]	$6.75(10)$	$5.87(20)$	$3.07(31)$

AME2012

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	^{21}N	^{22}N	^{23}N
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AME2012

- **We study ^{23}N in $n+n+^{21}$N cluster model**

  Zhang, Ren, Lyu, C.J., PRC 91, 024001 (2015)

	^{21}N	^{22}N	^{23}N
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AME2012

- **We study ^{23}N in $n + n +^{21}$N cluster model**
  Zhang, Ren, Lyu, C.J., PRC 91, 024001 (2015)
- **Faddeev equation in hyperspherical harmonics expansion**
  numerical tool: FaCE [Thompson, Nunes, Danilin, Comp. Phys. Comm. '04]

- realistic nn: Gogny-Pires-De Tourreil (GPT)
- phenomenological n-^{21}N: Wood Saxon

$$V_{n\text{-core}}(r) = -\frac{V_0}{1+\exp(\frac{r-r_0}{a})} - \frac{V_{\text{so}}}{ra}\frac{\exp(\frac{r-r_0}{a})}{(1+\exp(\frac{r-r_0}{a}))^2}\mathbf{L}\cdot\mathbf{S}$$

- core-neutrons occupy $(0s_{1/2})^2$ $(0p_{3/2})^4$ $(0p_{1/2})^2$ $(0d_{5/2})^6$ shells
  $\epsilon(0d_{5/2}) = S_{1n}[^{21}\text{N}]$
- valence neutrons occupy either $(1s_{1/2})^2$ or $(0d_{3/2})^2$
  $\epsilon(1s_{1/2}) = S_{1n}[^{22}\text{N}]$

^{23}N G.S. & Excited Halo States

- We tune $V_{n\text{-core}}$ to reproduce
  ^{21}N $S_{1n} = 4.59(11)$ MeV
  ^{22}N $S_{1n} = 1.28^{+21}_{-21}$ MeV
- We predict S_{2n} and r_m

S_{2n}	r_m	S^*_{2n}	r^*_m
MeV	fm	MeV	fm
4.13	2.969	0.315	4.272
3.64	2.985	0.185	4.358
3.13	3.004	0.069	4.476

Experiment: $S_{2n} = 3.07(31)$ MeV

TRIUMF

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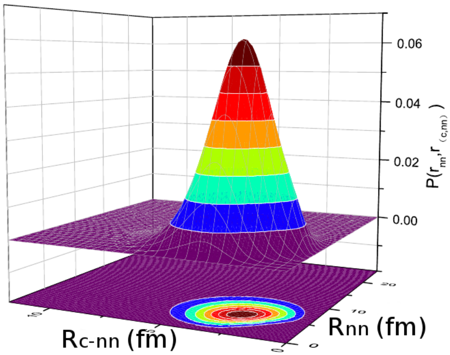
Experiment: $S_{2n} = 3.07(31)$ MeV

- add 3BF $V_3(\rho) = W_0 e^{-\rho^2/\rho_0^2}$ to reproduce
  ^{23}N $S_{2n} = 3.07$ MeV
- Predictions in S_{2n} and r_m

S_{2n}	r_m	S^*_{2n}	r^*_m
MeV	fm	MeV	fm
3.07	3.022	0.195	4.629
3.07	3.019	0.128	4.790
3.07	3.011	0.064	5.011

^{23}N Probability Density Distributions

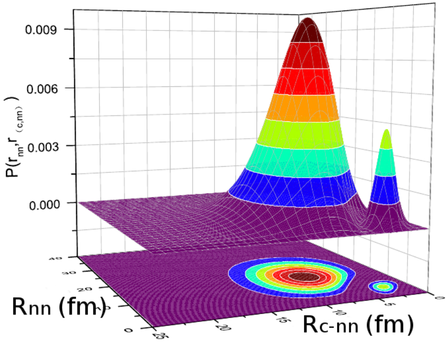
ground state



$(1s_{1/2})^2$ 95%

$(0d_{3/2})^2$ 5%

excited state



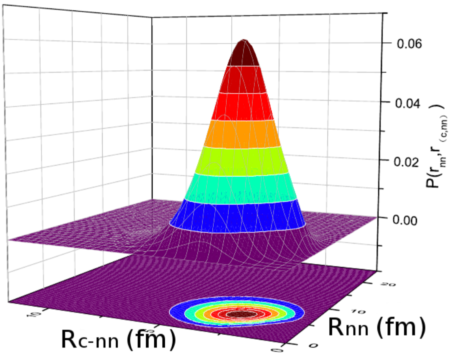
$(1s_{1/2})^2$ 77%

$(0d_{3/2})^2$ 23%

^{23}N Probability Density Distributions

TRIUMF

ground state



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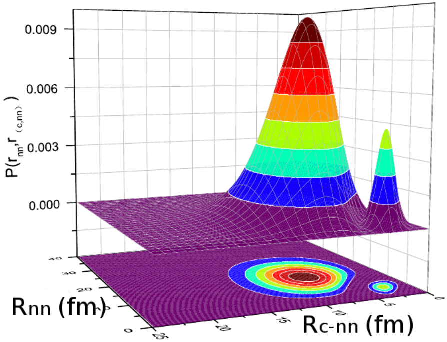


$(1s_{1/2})^2$ 77%

$(0d_{3/2})^2$ 23%

- future work: Halo EFT analysis of universal correlations in ^{23}N

- **experiment in ^{6}He**
  - matter radius Tanihata *et al.* '92, Alkhazov *et al.* '97, Kislev *et al.* '05
  - charge radius Wang *et al.* '04, Mueller *et al.* '07
  - ^{6}He mass Brodeur *et al.* '12

- **cluster model**
  - separable potential Ghovanlou, Lehman '74
  - variational method Funada *et al.* '94
  - density-dependent nn contact interaction Esbensen *et al.* '97
  - Wood Saxon $n\alpha$ + GPT nn Danilin, Thompson, Vaagen, Zhukov '98

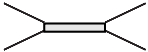
- ***ab intio* calculation**
  - no-core shell model Navrátil *et al.* '01; Sääf, Forssén '14
  - NCSM-RGM Romero-Redondo *et al.* '14
  - Green's function Monte Carlo Pieper *et al.* '01; '08
  - hyperspherical harmonics (EIHH) Bacca *et al.* '12

- **halo EFT**
  - explore **universal correlations** in ^{6}He
  - compare **predictions** with experiments and *ab initio* calculations

Rotureau, van Kolck Few Body Syst. **54** 725 2013

C.J., Elster, Phillips, PRC **90**, 044004 (2014)

- nn interaction is dominated by the $^1S_0$ state

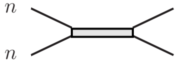


$$= \frac{1}{4\pi^2\mu_{nn}} \frac{1}{-1/a_0 + r_0 k^2/2 - ik}$$

$a_0 = -18.7$ fm, $r_0 = 2.75$ fm González Trotter *et al.* '99

$n - n$ interaction

- nn interaction is dominated by the $^1S_0$ state



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  $a_0 = -18.7$ fm, $r_0 = 2.75$ fm González Trotter *et al.* '99

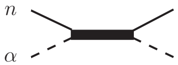
- LO EFT: $r_0 \to 0$

- $n\alpha$ interaction is dominated by the ${}^2P_{\frac{3}{2}}$ state

$$= \frac{1}{4\pi^2 \mu_{n\alpha}} \frac{\vec{p} \cdot \vec{q}}{-1/a_1 + r_1 k^2/2 - ik^3}$$

$a_1 = -62.95$ fm^3, $r_1 = -0.8819$ fm^{-1} Ardnt et al. '73

- $n\alpha$ interaction is dominated by the $^2P_{\frac{3}{2}}$ state



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$a_1 = -62.95$ fm^3, $r_1 = -0.8819$ fm^{-1} Ardnt et al. '73

- $r_1 \not\to 0$ Nishida '12
- keep both a_1 and r_1 in LO EFT

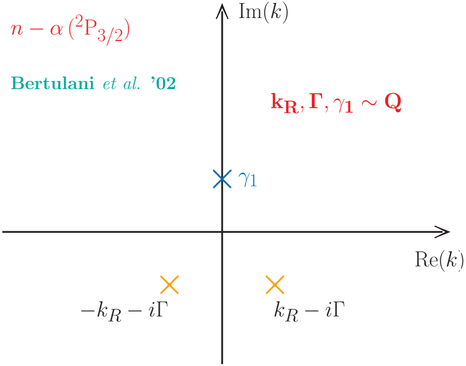
$n-\alpha$ p-wave power counting (Bertulani)

- $n\alpha$ EFT power counting: Bertulani, Hammer, van Kolck NPA '02
  - $a_1 \sim 1/(Q^3)$ $r_1 \sim Q$
  - two fine tunings at LO

- ${}^2P_{\frac{3}{2}}$:

  shallow resonance: $k_R, \Gamma \sim Q$

  shallow bound state: $\gamma_1 \sim Q$



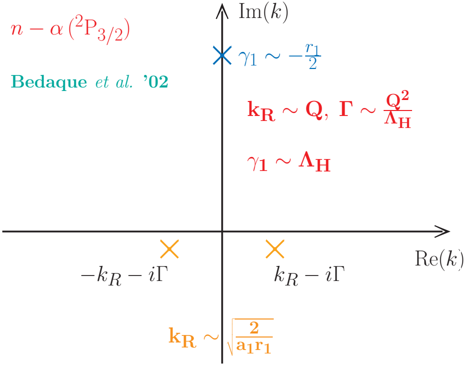
adopted by Rotureau, van Kolck Few Body Syst. (2013) for ^{6}He

- $n\alpha$ EFT power counting: Bedaque, Hammer, van Kolck PLB '02
  - $a_1 \sim 1/(Q^2\Lambda_H)$ $r_1 \sim \Lambda_H$
  - $Q/\Lambda_H \sim 0.15$
  - one fine tuning at LO
- ${}^2P_{\frac{3}{2}}$:

  shallow resonance:

  $$k_R \sim Q, \quad \Gamma \sim Q^2/\Lambda_H$$

  deep bound state: $\gamma_1 \sim \Lambda_H$



adopted by C.J., Elster, Phillips, PRC **90**, 044004 (2014) for ^{6}He

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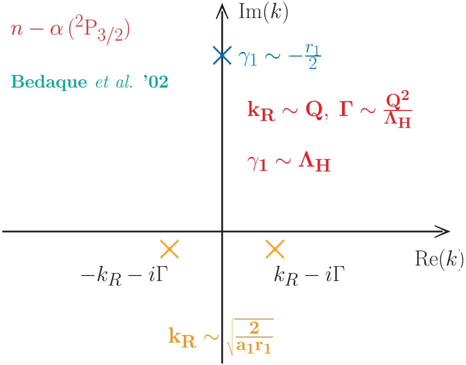

adopted by C.J., Elster, Phillips, PRC **90**, 044004 (2014) for ^{6}He

$n - \alpha$ p-wave power counting (Bedaque)

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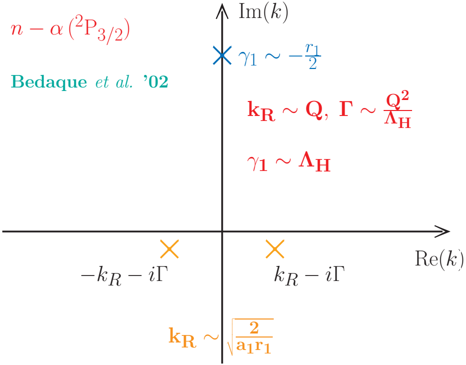
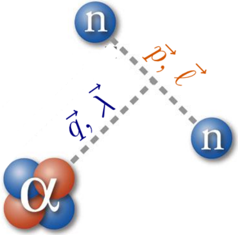


$n - \alpha\ {}^1S_{\frac{1}{2}}$ and ${}^2P_{\frac{1}{2}} \to$ beyond LO

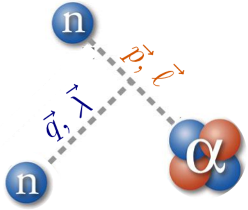
adopted by C.J., Elster, Phillips, PRC **90**, 044004 (2014) for ^{6}He

- **Jacobi-momentum**

α spectator



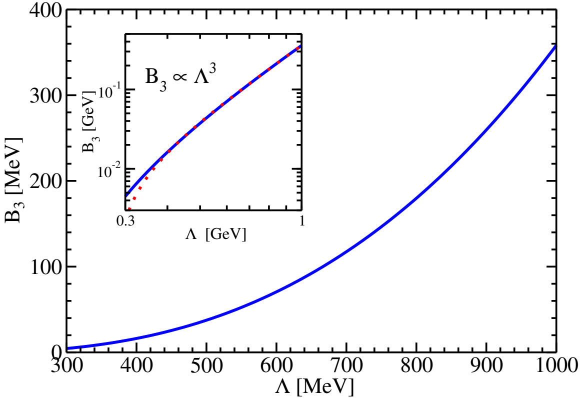
n spectator



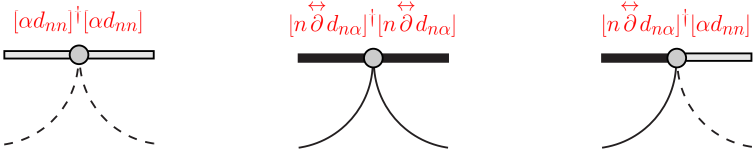
spin-orbit coupling for ^{6}He ($J = 0^+$)

pair, spec	pair	spectator	total L, S	total J
$nn,\ \alpha$	$\ell_{nn} = 0,\ s_{nn} = 0$	$\lambda_{\alpha\text{-}nn} = 0,\ s_{\alpha\text{-}nn} = 0$	$L = 0,\ S = 0$	$J = 0^+$
$n\alpha,\ n$	$\ell_{n\alpha} = 1,\ s_{n\alpha} = \frac{1}{2}$	$\lambda_{n\text{-}n\alpha} = 1,\ s_{n\text{-}n\alpha} = \frac{1}{2}$	$L = 0,\ S = 0$	
			$L = 1,\ S = 1$	

- **without $nn\alpha$ 3-body force:**
  - S_{2n} is strongly cutoff dependent: $S_{2n} \sim \Lambda^3$ $\leftarrow$ need 3body force!

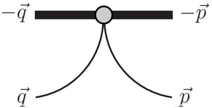


- **candiates for $nn\alpha$ counterterms**

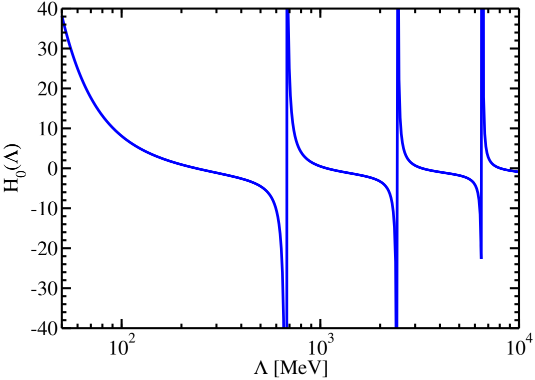


- **only needs $[n\overleftrightarrow{\partial} d_{n\alpha}]^\dagger[n\overleftrightarrow{\partial} d_{n\alpha}]$ counterterm**
  - Pauli principle
  - A similar p-wave three-body counterterm is discovered by Rotureau, van Kolck Few Body Syst. **54** 725 2013

- p-wave 3BF:
  reproduce $S_{2n} = 0.973$ MeV



$$= M_n \, qp \, \frac{H(\Lambda)}{\Lambda^2}$$



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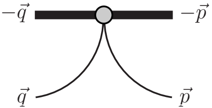
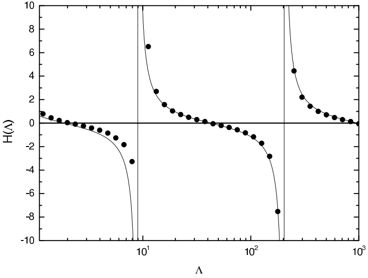
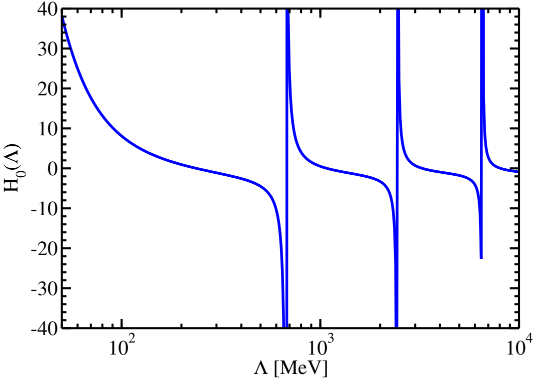


$$= M_n\, qp\, \frac{H(\Lambda)}{\Lambda^2}$$

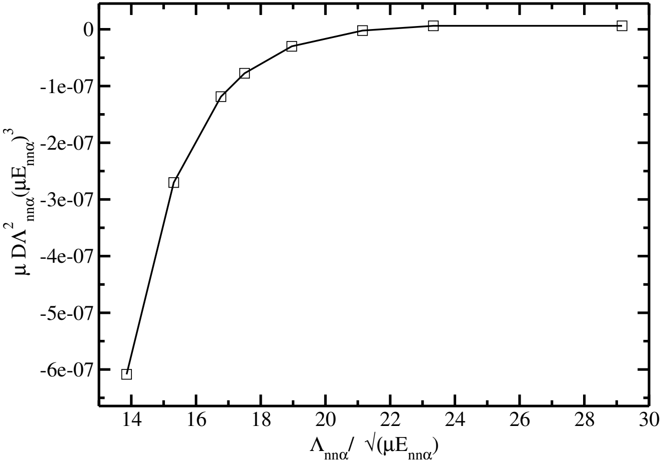
- log oscillation
- No limit cycle
  (c.f. 3-body in S-wave)





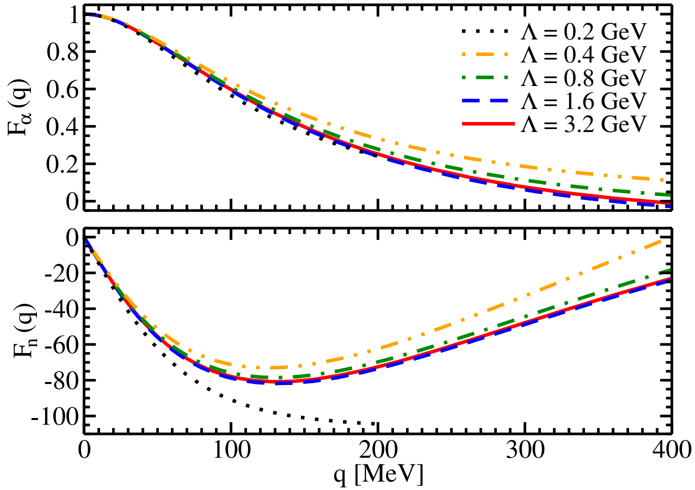
Compare with Rotureau 3BF

- Three-body force by Rotureau, van Kolck Few Body Syst. (2013) reproducing $S_{2n} = 0.973$ MeV



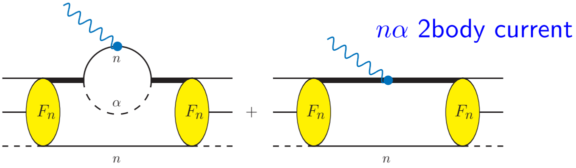
Renormalized Faddeev Components

$F_\alpha(\alpha, nn)$ **and** $F_n(n, \alpha n)$ **are cutoff independent**



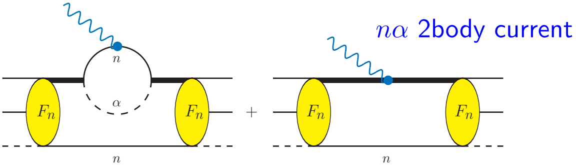
C.J., Elster, Phillips, PRC **90**, 044004 (2014)

- 3-body form factor (with p-wave n-core interactions)



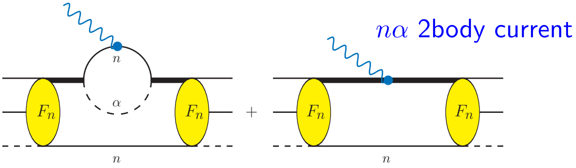
^{6}He Form Factors

- 3-body form factor (with p-wave n-core interactions)



- The $n\alpha$ two-body current counterterm is fixed by r_1 in $n\alpha$ $3/2^-$ state
- It does not require an additional 3-body input

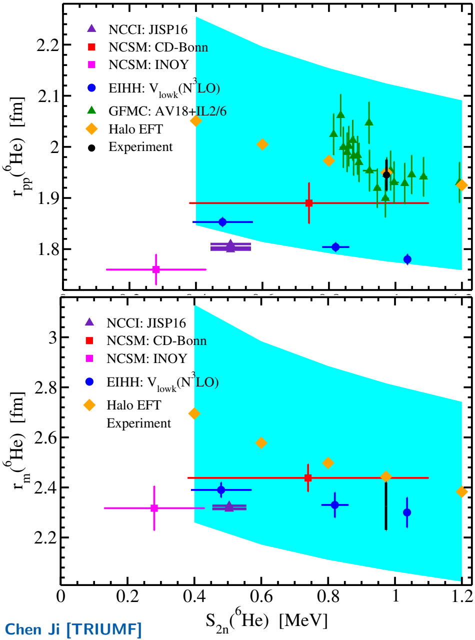
- 3-body form factor (with p-wave n-core interactions)



- The $n\alpha$ two-body current counterterm is fixed by r_1 in $n\alpha$ $3/2^-$ state
- It does not require an additional 3-body input
- matter/charge radii

$$F_{c(m)}(q^2) = 1 - \frac{1}{6}\langle r^2_{c(m)}\rangle q^2 + \cdots$$

^{6}He Radii



[Preliminary]

- He-6 point-proton radius
- He-6 matter radius

compare with

NCCI: Caprio, Maris, Vary, PRC '14

NSCM: Caurier, Navratil, PRC '06

GFMC: Pieper, RNC '08

EIHH: Bacca, Barnea, Schwenk, PRC '12

Halo EFT: preliminary (uncertainty)

Atomic Isotope Shift

- The nuclear charge radius can be extracted from the atomic isotope shifts:

$$\delta_{AA'} = \delta^{MS}_{AA'} + K_{FS}\,\delta\langle r^2\rangle_{AA'}$$

  - mass shift term $\delta^{MS}_{AA'}$
  - charge radii difference $\delta\langle r^2\rangle_{AA'} = \langle r^2_A\rangle - \langle r^2_{A'}\rangle$

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- The nuclear polarization δ_{pol} contribute to the mass shift term $\delta^{MS}_{AA'}$

$$\delta_{pol} = \mathcal{A}\underbrace{\left[\int_0^\infty d\omega\,\frac{\sigma_\gamma(\omega)}{\omega^2}\right]}_{\propto\,\alpha_E} + \mathcal{B}\underbrace{\left[\int_0^\infty d\omega\,\frac{\sigma_\gamma(\omega)}{\omega^2}\ln\frac{2\omega}{m}\right]}_{\propto\,\alpha_{E\log}} + \cdots$$

Pachucki, Moro PRA '07

Atomic Isotope Shift

TRIUMF

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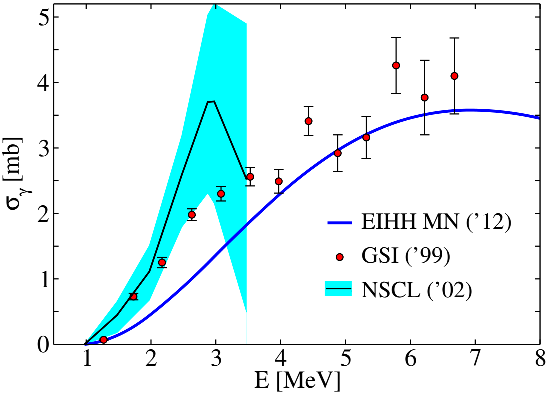
Pachucki, Moro PRA '07

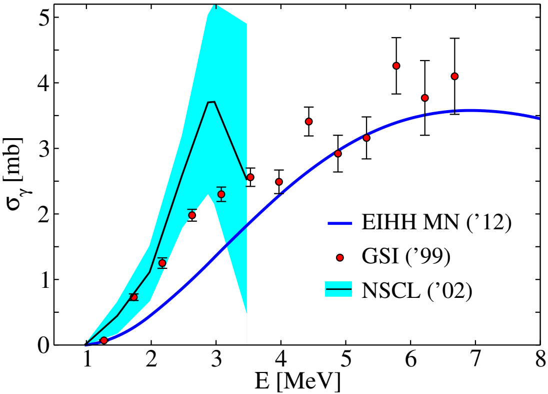
- δ_{pol} is larger in atoms with unstable nuclear isotopes (lower threshold energy)
halo nuclei: δ_{pol} is important for accurately extracting nuclear charge radii

^{6}He Photoabsorption Cross Section



Pic:
Goerke, Bacca, Barnea PRC '12

^{6}He Photoabsorption Cross Section

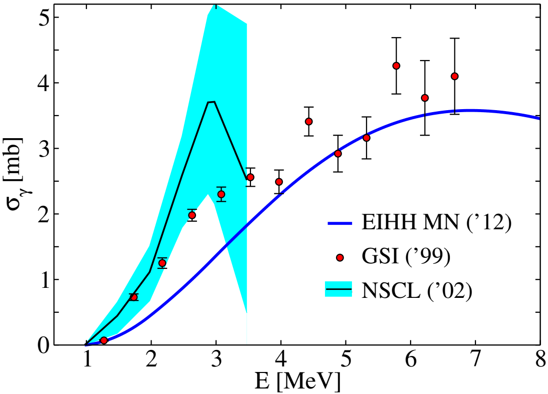


Pic:

Goerke, Bacca, Barnea PRC '12

σ_γ is dominated by physics at $\sim$ few MeVs

^{6}He Photoabsorption Cross Section

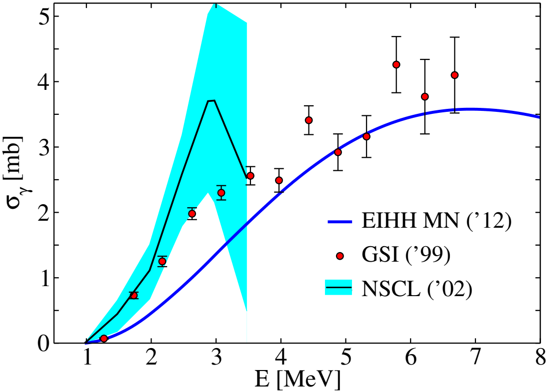


Pic:
Goerke, Bacca, Barnea PRC '12

σ_γ is dominated by physics at $\sim$ few MeVs

current data for $\sigma_\gamma(\omega)$ are not very accurate

^{6}He Photoabsorption Cross Section



Pic:
Goerke, Bacca, Barnea PRC '12

σ_γ is dominated by physics at $\sim$ few MeVs

current data for $\sigma_\gamma(\omega)$ are not very accurate

- *ab initio* methods are computationally expensive for halo systems / continuum
- halo EFT works economically at low energies
- future EFT calculations of σ_γ in ^{6}He ; δ_{pol} in ^{6}He isotope shift

Summary

- Halo EFT describes structure/reaction in halo nuclei in a systematic expansion of R_{core}/R_{halo}
- Halo EFT rejuvenate cluster models with a systematic uncertainty estimates
- Halo EFT can be complimentary to *ab initio* calculations
  - adopt inputs from *ab initio* results
  - benchmark with *ab initio* calculations
  - explain universal correlations from observables in *ab initio* work

Collaborators

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Liuyang Zhang
Mengjiao Lyu

Nanjing University


תודה
Dankie
Gracias
Спасибо
شكرًا
Merci
Takk
Köszönjük
Terima kasih
Grazie
Dziękujemy
Dėkojame
Ďakujeme
Vielen Dank
Paldies
Kiitos
Täname teid
谢谢
Thank You
Tak
感謝您
Obrigado
Teşekkür Ederiz
감사합니다
Σας Ευχαριστούμ
ขอบคุณ
Bedankt
Děkujeme vám
ありがとうございます
Tack