A05 Halos and clustering in nuclei

T. Aumann, H.-W. Hammer, P. Capel

previously "Clustering in nuclei: Halo nuclei and alpha clustering"

Deutsche
Forschungsgemeinschaft
DFG

SFB 1245

SFB 1245 meeting 27.03.2019

Outline

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- Theory advances and key experiments
  - Description of clustering and ^{A}C(p,pα)$^{A-4}$Be reactions
  - Halo EFT for deformed halos and breakup reactions of ^{31}Ne
- Theory publications: 14
- Highlights:
  - **“Effective field theory description of halo nuclei”**
    H.-W. Hammer, C. Ji and D. R. Phillips.
    arXiv:1702.08605 [nucl-th]
    J. Phys. G **44**, 103002 (2017)
  - **“Neutron transfer reactions in halo effective field theory”**
    M. Schmidt, L. Platter and H.-W. Hammer.
    arXiv:1812.09152 [nucl-th], submitted to Phys. Rev. C

Dipole response of ^{6}He and ^{8}He

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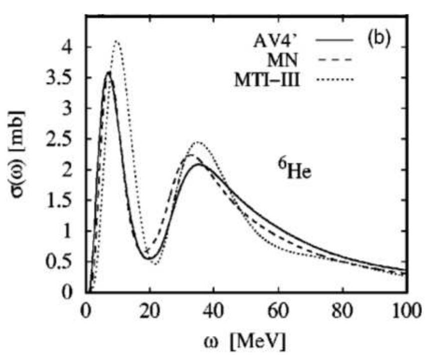
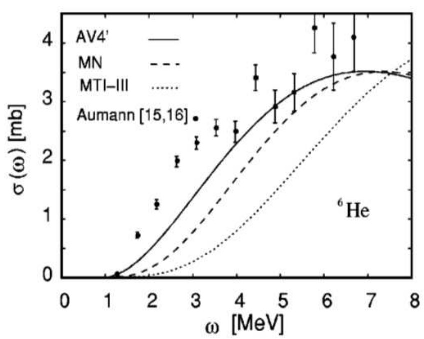
Motivation

- Study low-energy dipole response of ^{6,8}He via multi-neutron decay after heavy-ion induced electromagnetic excitation in inverse kinematics
- Measure differential cross section via invariant-mass method
- Extract dipole-strength distribution dB(E1)/dE

^{6}He

- Expand data from *Aumann et al., Phys. Rev. C 59 (1999) 1252* up to 15 MeV

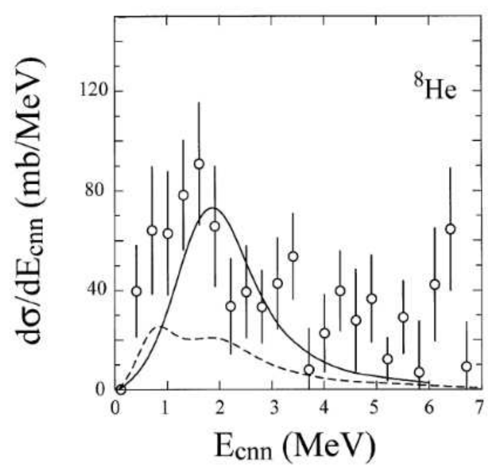




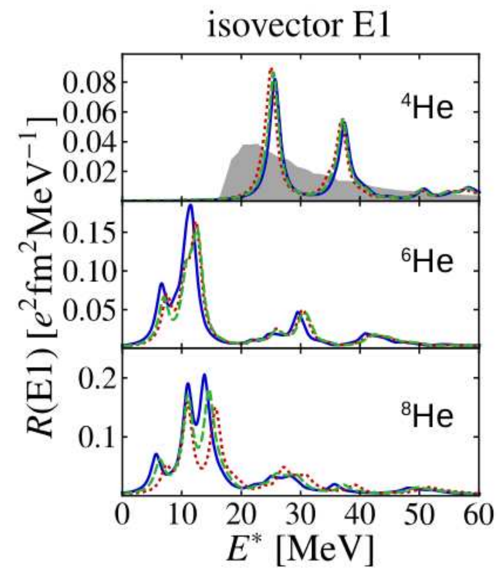
Pictures taken from S. Bacca et al., Phys. Rev. C 69 (2004) 057001

^{8}He

- Only 2n channel measured by *Meister et al., Nucl. Phys. A 700 (2002) 3*
- **Reconstruction of ^{8}He 4n channel possible for the first time with NeuLAND and NEBULA at RIKEN**



Picture taken from M. Meister et al., Nucl. Phys. A 700 (2002) 3

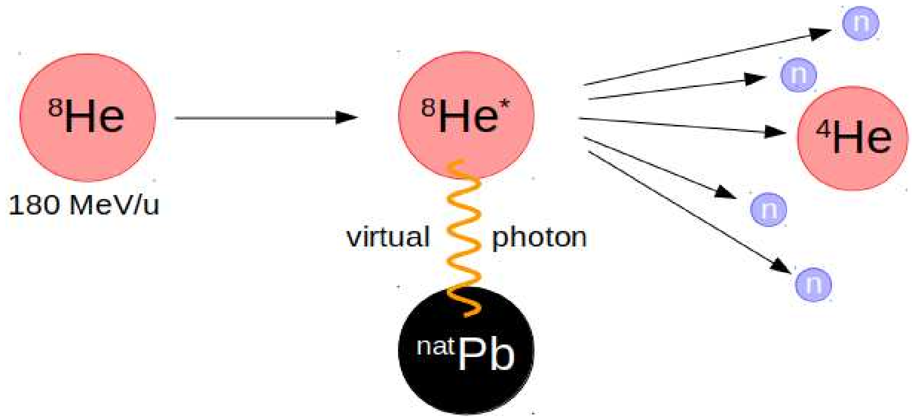


Modified picture taken from C. Stumpf, "Nuclear Spectra and Strength Distributions from Importance-Truncated Configuration-Interaction Methods", Dissertation, 2018

Dipole response of ^{6}He and ^{8}He

Experiment

- Carried out July 2017 at SAMURAI at RIBF.
- ^{18}O primary beam @ 220 AMeV
- ^{6}He and ^{8}He secondary beams @ 185 AMeV
- Beam rate ~100 kHz for both settings
- Series of targets with increasing Z: Pb, Sn, Ti, C, CH_2



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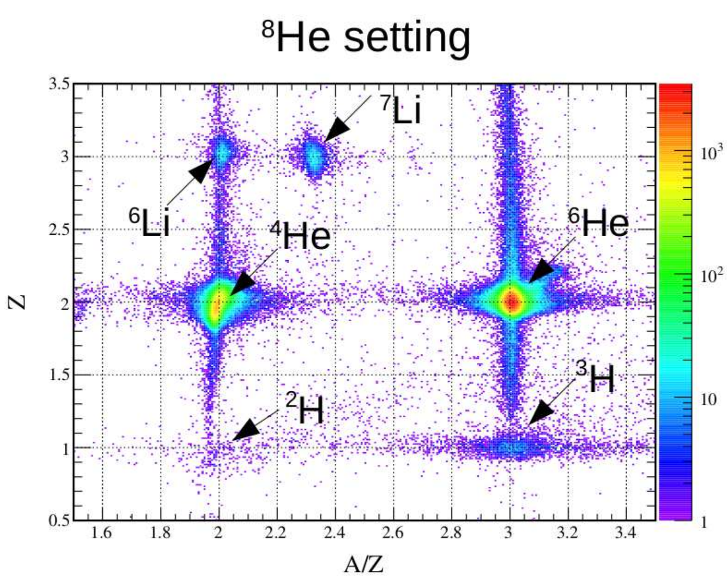

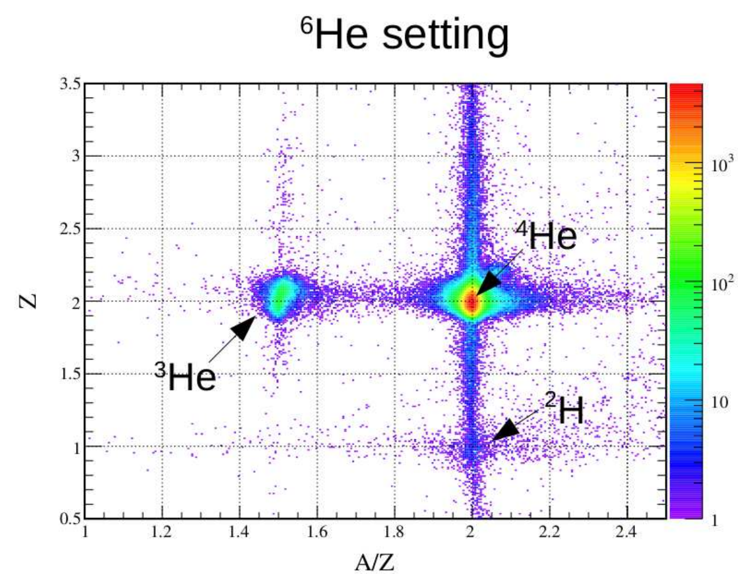

ToF – ΔE – Bρ method

$$Z \propto \sqrt{\Delta E \beta}$$

$$B\rho \propto \frac{A}{Z}\beta\gamma$$

Dipole response of ^{6}He and ^{8}He

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First physics data

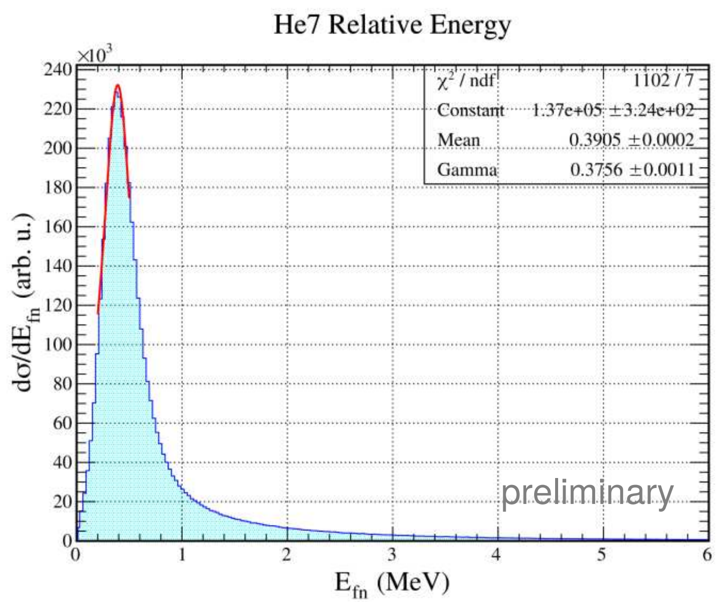
- Data is now fully calibrated
- ^{7}He and ^{5}He Ground state resonances as test cases to check calibration and resolution
- 1n knockout on carbon target
- In agreement with previous work:

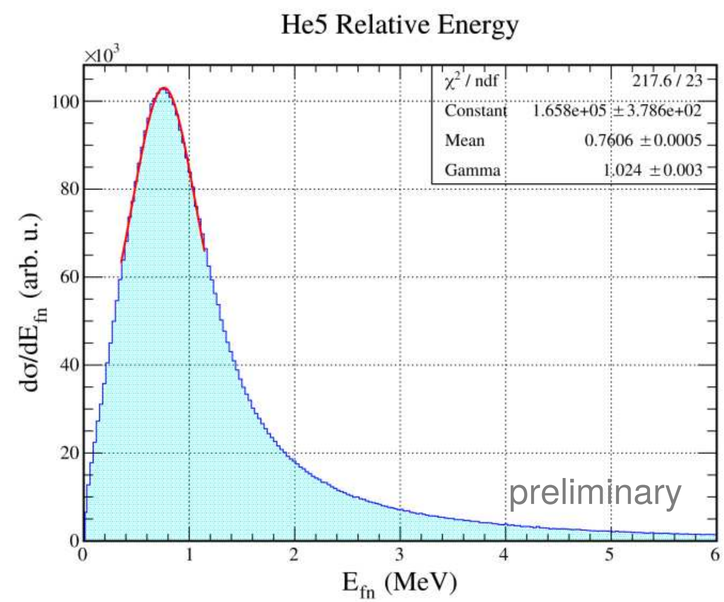
F. Renzi et al., Phys. Rev. C 94, 024619 (2016)
V. D. Efros and H. Oberhummer, Phys. Rev. C 54, 1485 (1996)
J.E. Bond and F.W.K. Kirk, Nucl. Phys. A287, 317 (1977).

Invariant-mass method

$$M_{inv} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2}$$

$$E_{rel} = \sqrt{\sum_j^N m_j^2 + \sum_{j \neq k}^N \gamma_j \gamma_k m_j m_k \left(1 - \beta_j \beta_k \cos\theta_{jk}^{LAB}\right)} - M_0$$





Nuclear EFTs

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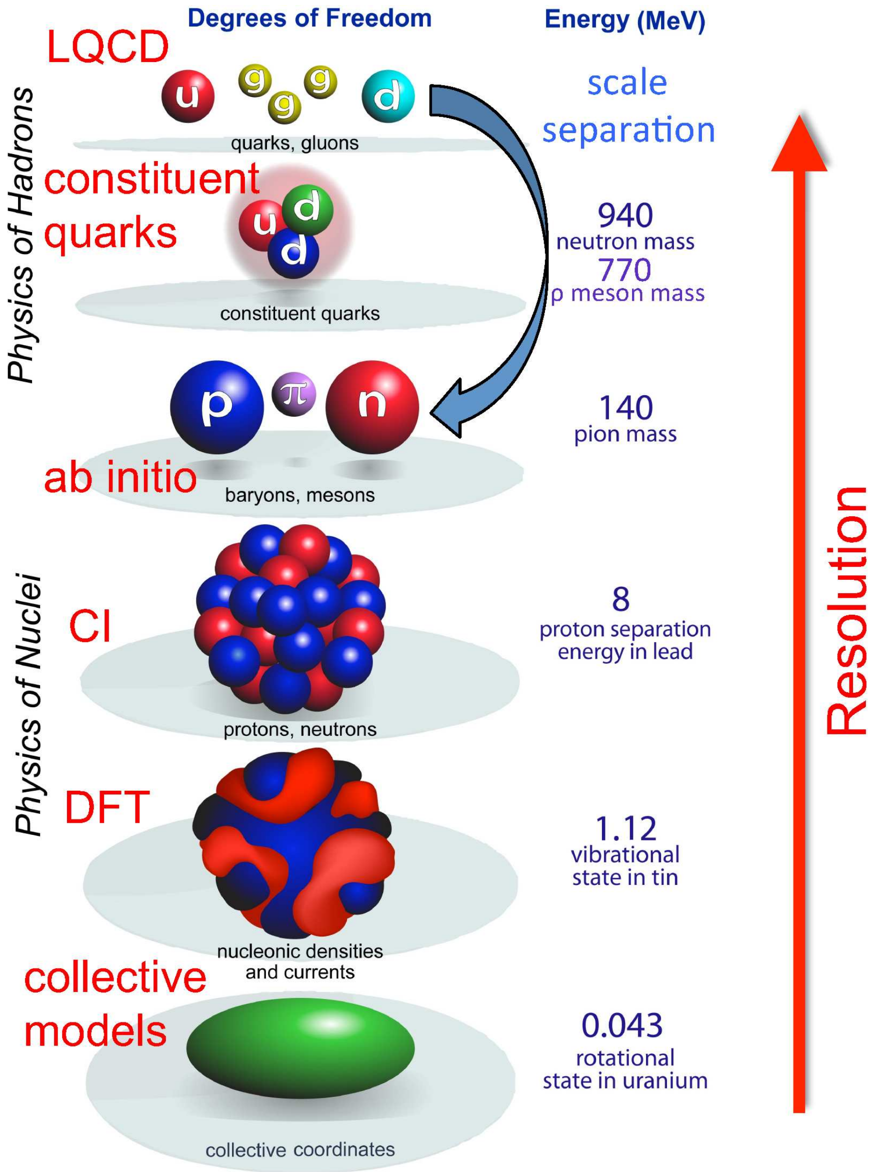
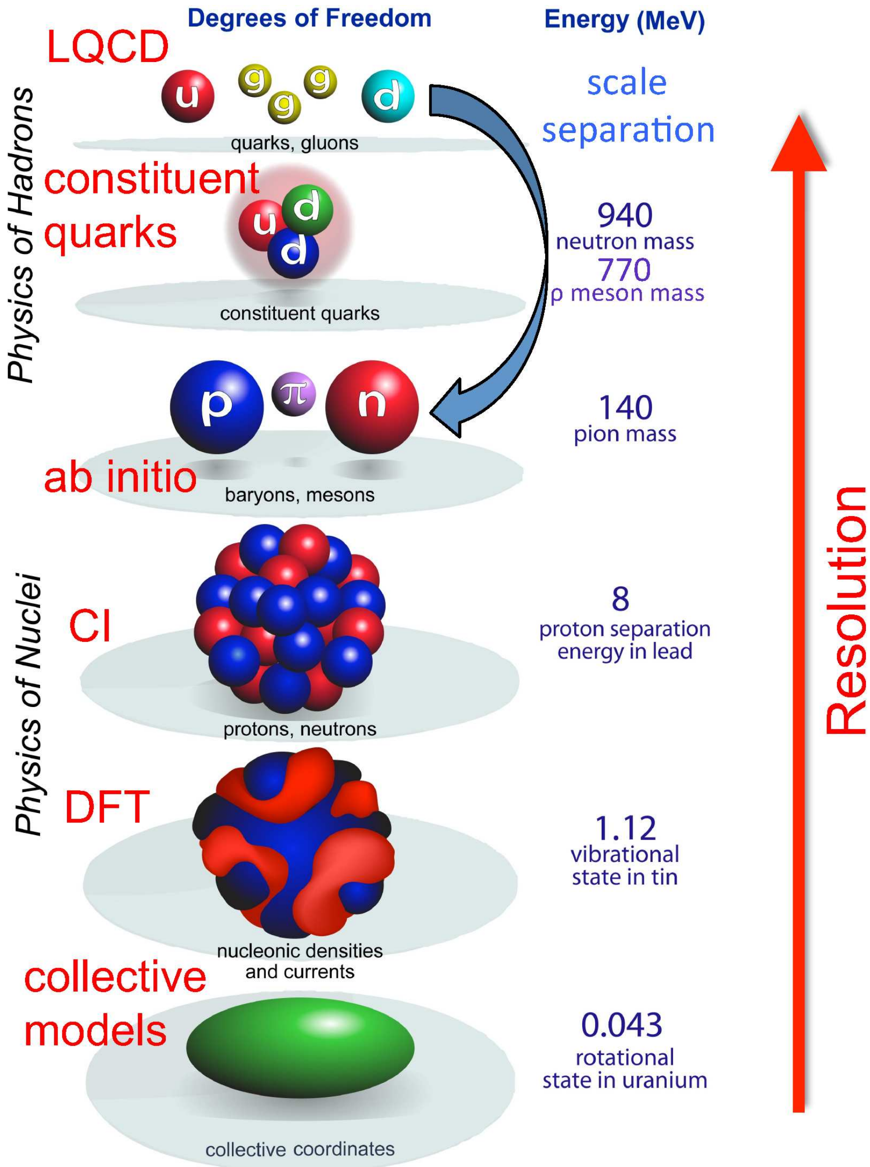


from Bertsch, Dean, Nazarewicz (2007)

Nuclear EFTs



from Bertsch, Dean, Nazarewicz (2007)

EFT exploits separation of scales

$\Downarrow$

EFT depends on resolution scale

- Chiral EFT: N, π, (Δ)
- Pionless EFT: N
- Halo EFT: N, clusters
- EFT for deformed nuclei: collective dof
- EFT at Fermi surface: quasi-N
- ...

Halo Effective Field Theory

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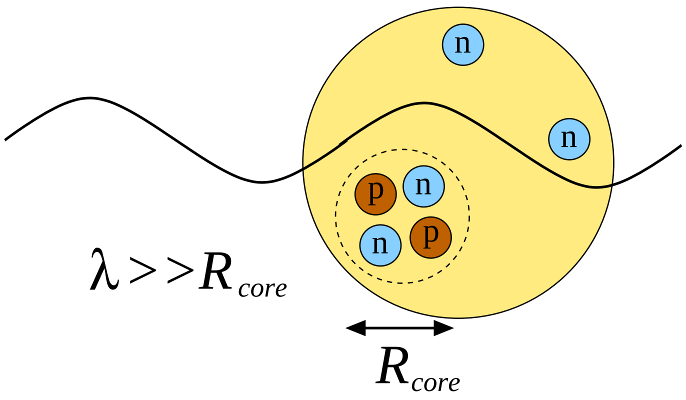
- Scales: $E \sim p^2/(2\mu) \sim 1/(2\mu R^2)$
- Separation of scales:
  $1/k = \lambda \gg R_{core}$
- Limited resolution at low energy:
  $\longrightarrow$ expand in powers of kR_{core}



- Short-distance physics not resolved
  $\longrightarrow$ capture in low-energy constants using renormalization
  $\longrightarrow$ include long-range physics explicitly

  Review article: HWH, Ji, Phillips, J. Phys. G **44** (2017) 103002

- Halo nuclei: P- and higher partial waves
- Universality: hadronic molecules, ultracold atoms, ...

Theory projects

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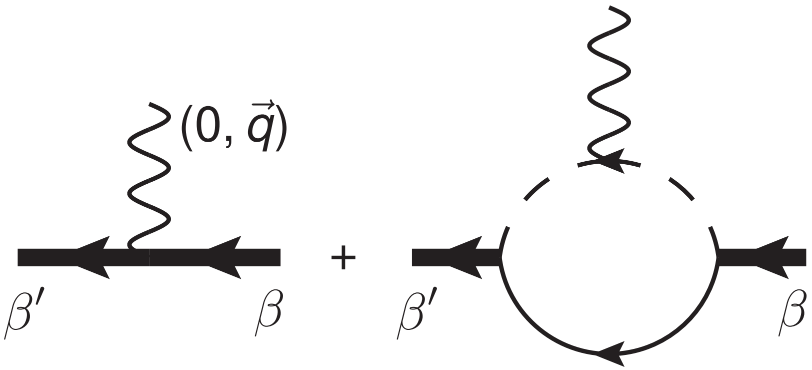
- Universality of S-, P-, D-wave halos, connection to χEFT
  (Jonas Braun, Wael Elkamhawy)
- Neutron transfer reactions
  (Marcel Schmidt)

  M. Schmidt, L. Platter and H.-W. Hammer, arXiv:1812.09152 [nucl-th]
- Deformation driven halos: ^{31}Ne [^{37}Mg] (W. Elkamhawy)
  - $1n$-removal reactions on C and Pb targets suggests:
    ^{31}Ne deformed nucleus with significant P-wave halo component
  - Develope a spherical Halo EFT formalism to describe electromagnetic properties
  - Form factors, correlations, Coulomb breakup
  - paper in preparation

Scalar Component of EM Current

$$-i\mathcal{A} = \langle \pi_{\beta'}(\vec{p}')|\, J_0 \,|\pi_\beta(\vec{p})\rangle =$$



$$= -i q_{\mathrm{tot}} G_{\mathrm{E0}}(q) \sqrt{4\pi}\, q^0\, Y_{00}(\vec{e}_{\vec{q}})\, \tilde{T}^{00}_{\beta'\beta} - i Q G_{\mathrm{E2}}(q) \frac{1}{2}\sqrt{\frac{4\pi}{5}}\, q^2 \sum_M Y_{2M}(\vec{e}_{\vec{q}})\, \tilde{T}^{2M}_{\beta'\beta}$$

$\lim_{q\to 0} G_{\mathrm{E0}}(q) \equiv 1$ (Charge conservation given by gauge-invariance)

$\lim_{q\to 0} G_{\mathrm{E2}}(q) \equiv 1 \quad \Rightarrow Q$ (this limit defines Q)

Electric Form Factors

Charge and quadrupole radii are defined by expanding the form factors in q^2:

$$G_{E0}(q) \approx 1 - \frac{1}{6} < r_{E0}^2 > q^2 + \ldots$$

$$G_{E2}(q) \approx 1 - \frac{1}{6} < r_{E2}^2 > q^2 + \ldots$$

Now compare to the expansion of the calculated form factors:

Charge & Quadrupole Radii

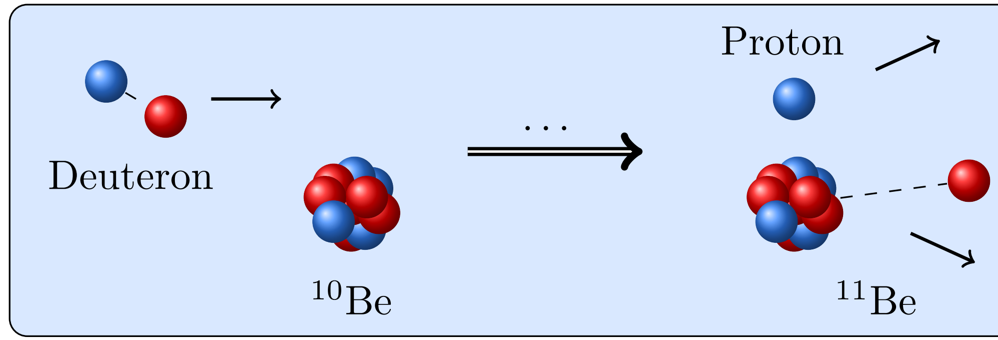
$$\Rightarrow < r_{E0}^2 > = \frac{5y^2}{2\gamma |r_1|} \qquad \Rightarrow \sqrt{< r_{E0}^2 >} \in [0.35, 0.46]\,\text{fm}$$

$$\Rightarrow < r_{E2}^2 > = \frac{3y^2}{5\gamma^2} \qquad \Rightarrow \sqrt{< r_{E2}^2 >} = 0.30\ \text{fm}$$

Motivation

Towards Reaction EFT

- Case study ^{10}Be(d, p)^{11}Be:



- Low momenta: Short-range details unresolved!

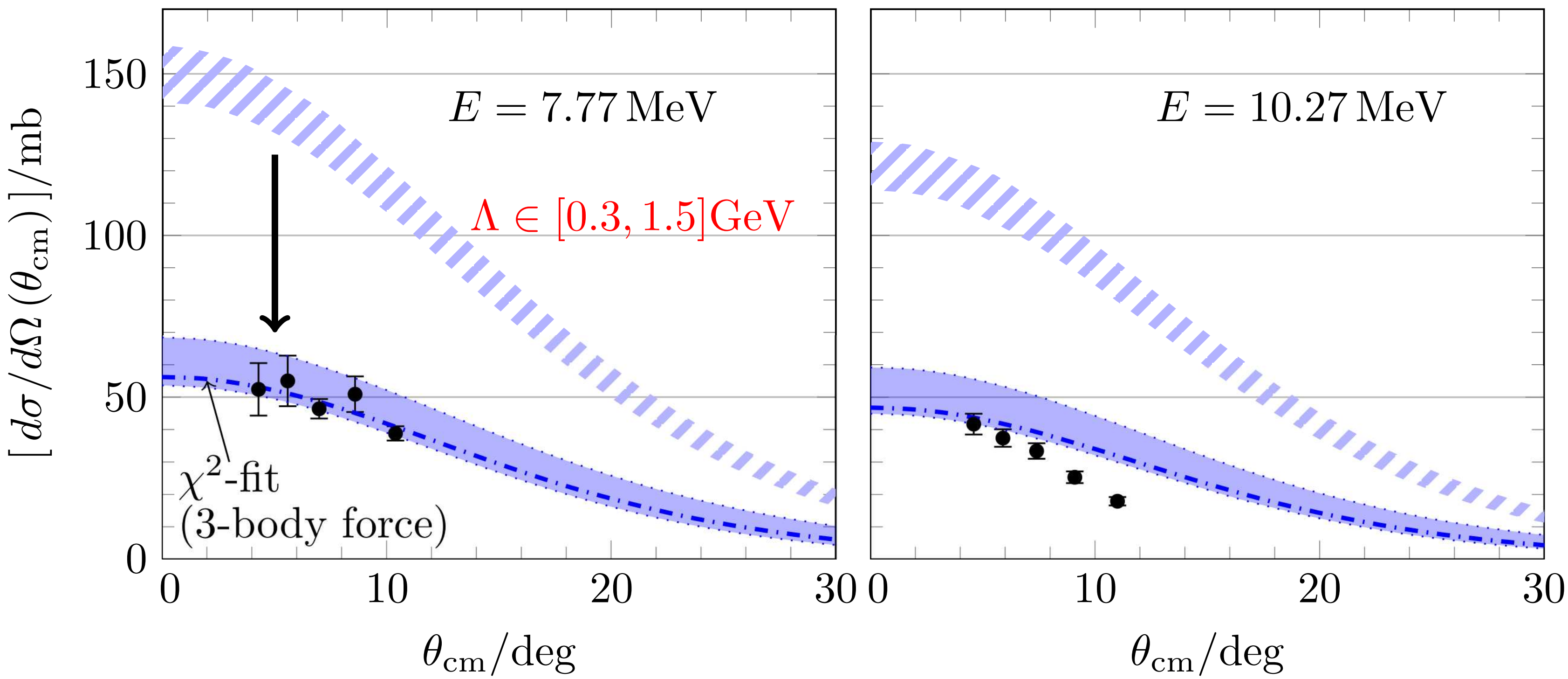
  ⇒ Contact-interactions (LECs)

- **EFT Expansion** of QCD in kR_{core} , $R_{\text{core}}/R_{\text{halo}} \ll 1$

Coulomb Force

Cross section

- LO: good agreement @ **low energies, forward angles**



[MS, Platter & Hammer, in preparation]

- Reaction **peripheral** [Yang & Capel, PRC **98** (2018)]
- Core excitations negligable [Deltuva *et al.*, PRC **94** (2016)

NLO Corrections

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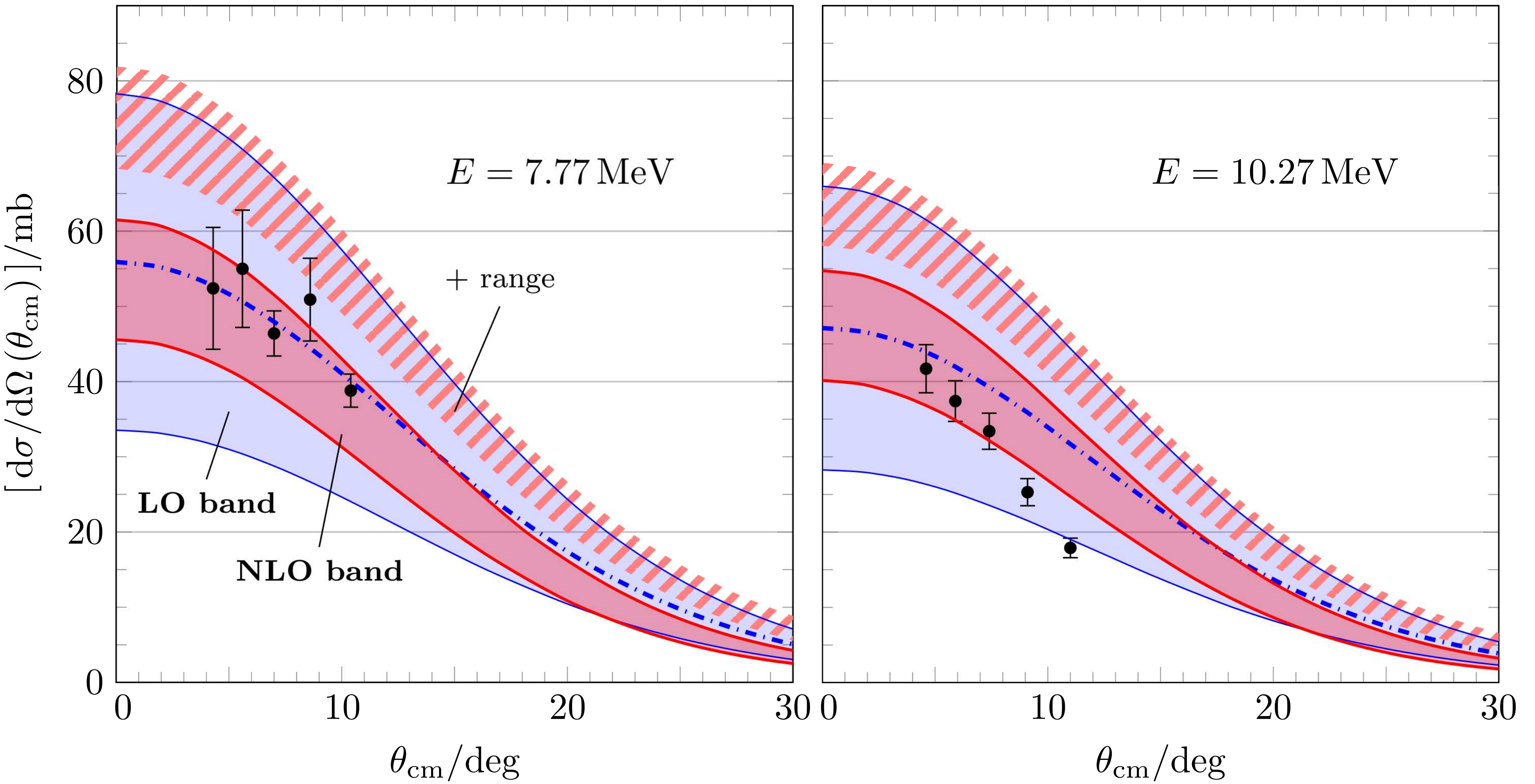

[MS, Platter & Hammer, in preparation]

Dissecting Reaction Calculations

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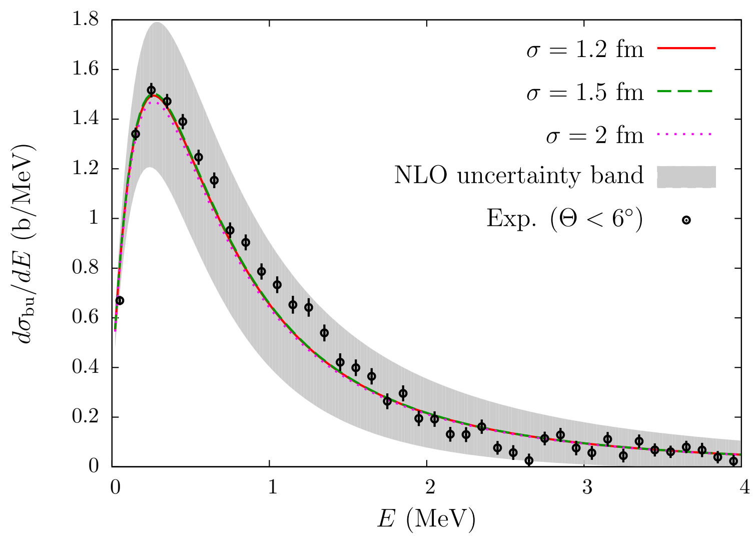
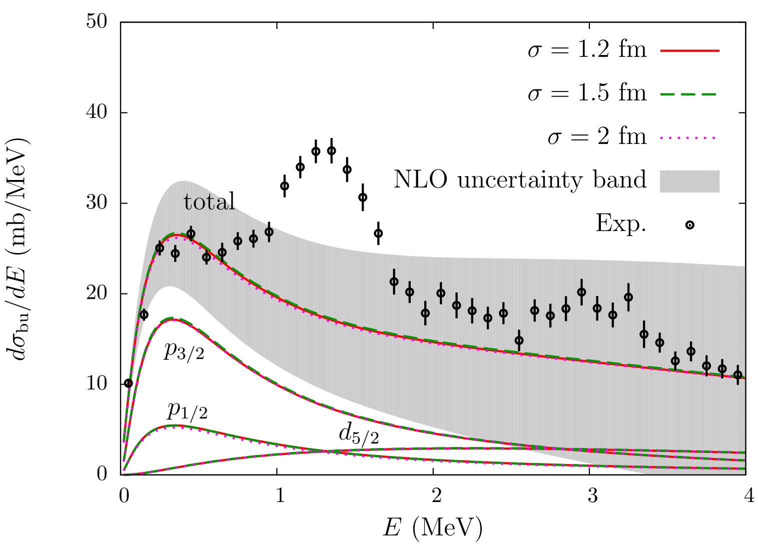
- Combine Halo EFT for projectile with standard reaction theory
- **"Dissecting reaction calculations using halo effective field theory and** $abinitio$ **input"**
  P. Capel, D. R. Phillips and H. W. Hammer.
  arXiv:1806.02712 [nucl-th]
  Phys. Rev. C **98**, 034610 (2018)



Pb target



C target

Future Plans

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- Key experimental advances
  - Finalising data analysis and interpretation of Coulomb breakup of ^{6}He and ^{8}He
  - Extraction of the neutron-neutron scattering length from ^{6}He$(p, p\alpha)2n$ and $t(p, 2p)2n$
- Key theoretical advances
  - Calculation of the neutron distribution in ^{6}He$(p, p\alpha)2n$ as a function of the neutron-neutron scattering length for small missing momentum of the α particle using halo EFT
    - Develop EFT for quasielastic scattering
  - Inclusion of halo EFT within precise models of nuclear reactions involving halo nuclei
    - Explore core excitation effects
    - Extend to other reactions

Scattering length measurement

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- Proposal for measurement at RIKEN

Proposal for a Nuclear-Physics Experiment at the RI Beam Factory

Determination of the nn scattering length from a high-resolution measurement of the nn relative-energy spectrum produced in the $^{6}He(p,p\alpha)^{2}n$, $t(p,2p)^{2}n$, and $d(^{7}Li,^{7}Be)^{2}n$ reactions

October 8th 2018

Spokesperson:	Thomas Aumann (TU Darmstadt)
Collaboration:	SAMURAI collaboration
Theory collaboration:	Hans-Werner Hammer (TU Darmstadt) Daniel Phillips (Ohio University) Carlos Bertulani (Texas A&M Commerce)

Scattering length measurement

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- Scattering length sensitivity

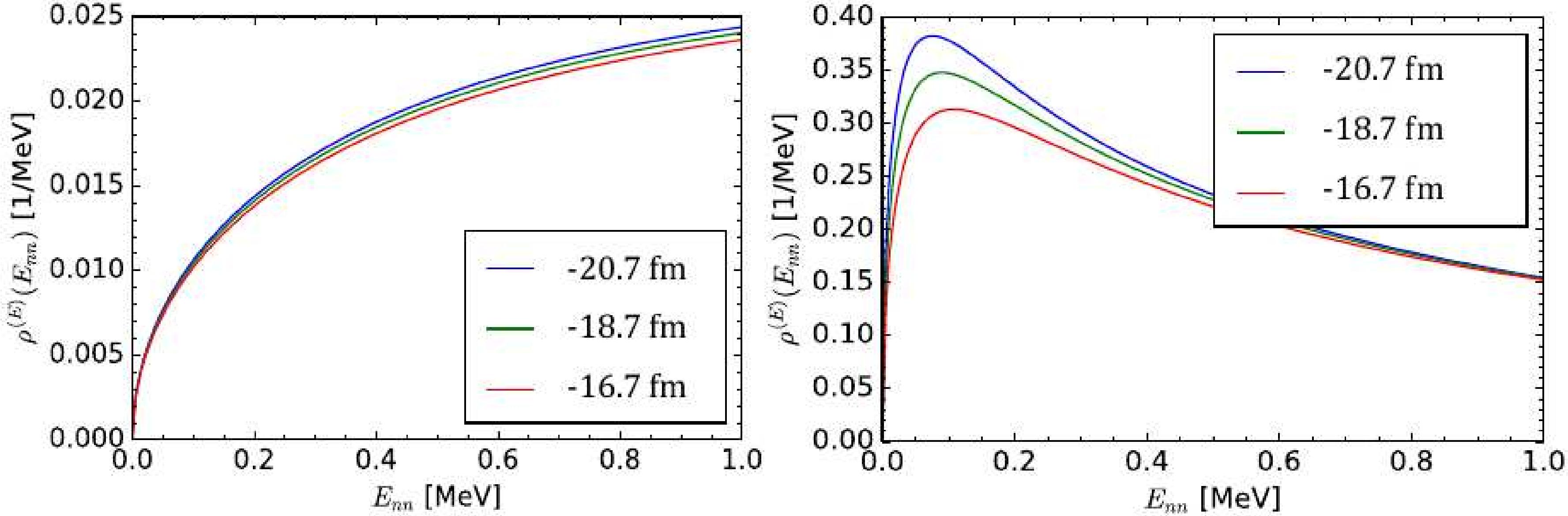

Figure 1. Neutron-neutron relative energy spectrum computed in Halo Effective Field Theory. The left part shows the nn distribution in the ^{6}He ground state. The right panel displays the nn final-state spectrum taking into account final-state interaction. The three curves represent calculations with three different values of the scattering length varying by ±2 fm.

calculation by Matthias Göbel (Master student)