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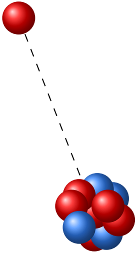


2nd Workshop of the SFB 1245

October 4 - 6, 2017

Schloss Waldthausen, Budenheim

Marcel Schmidt

Institute of Nuclear Physics

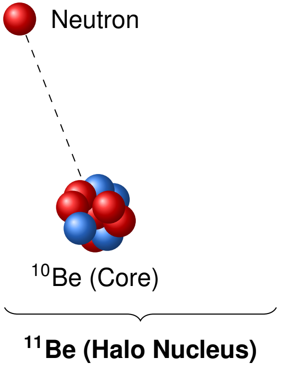
Technische Universität Darmstadt

Project A05

October 5, 2017

SFB 1245

Motivation: *Halo Nuclei*



- Deeply-bound core vs. Weak valence binding

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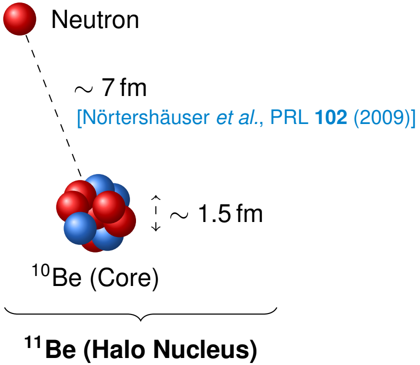
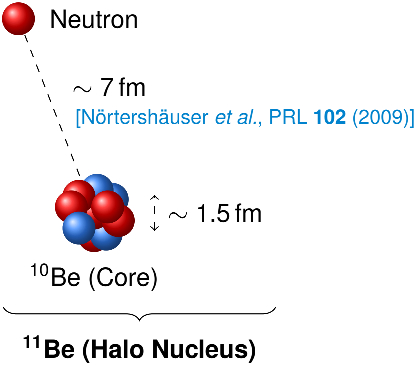
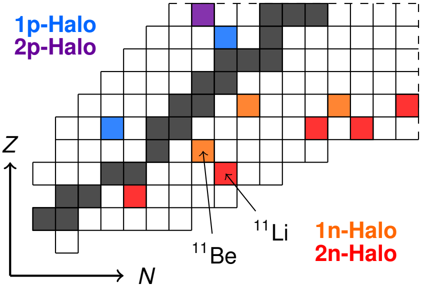


- Deeply-bound core vs. Weak valence binding → Scale Separation!





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- Many more near dripline

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Motivation: *Transfer Reactions*

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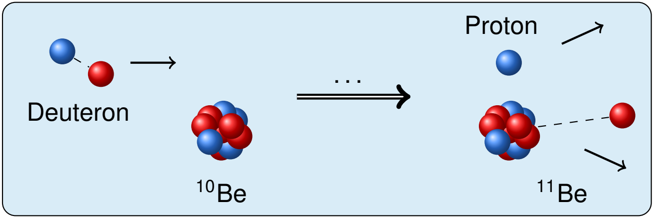

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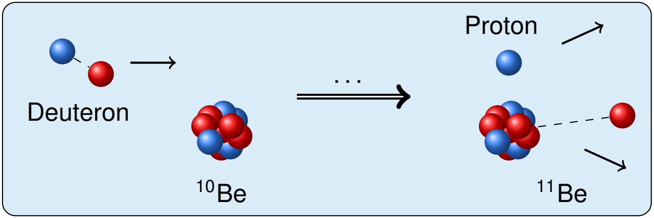
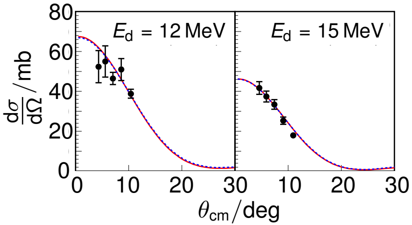


- Cross section data (ORNL) [Schmitt *et al.*, PRL **108** (2012)]



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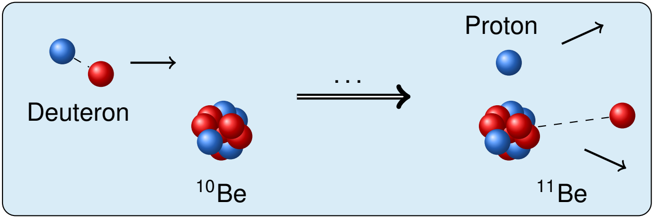

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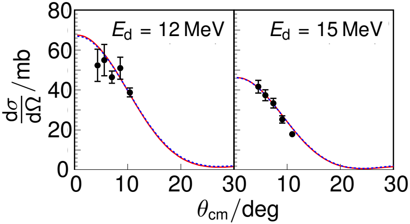

Traditional Reaction Models

$\rightarrow$ No uncertainty quantification

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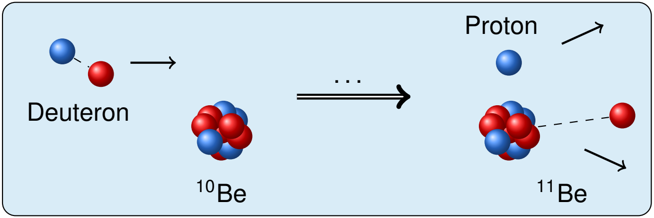

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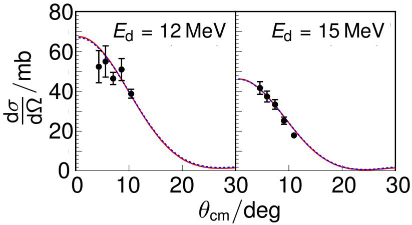

Traditional Reaction Models

→ No uncertainty quantification

Halo EFT [Bertulani *et al.*, NPA **712** (2002)]

→ Power counting

→ Unify structure & reaction

Project Goals & Contents

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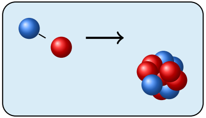
I. Develop **EFT for halo reactions**. Focus on...
   - ... 1n-halos $\rightarrow$ Beryllium-11
   - ... strong interaction



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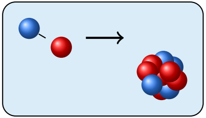

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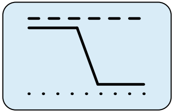

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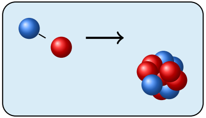

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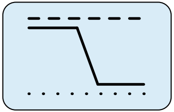
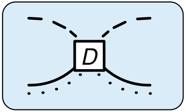
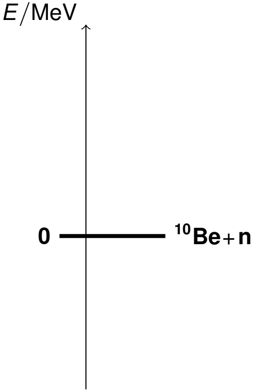


III. Introduce **3-body forces** for...
- ... renormalization
- ... loss effects



I. EFT for ^{10}Be(d, p)^{11}Be: *Phenomenology*



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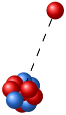

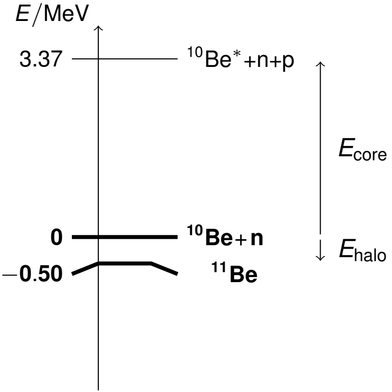

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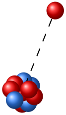

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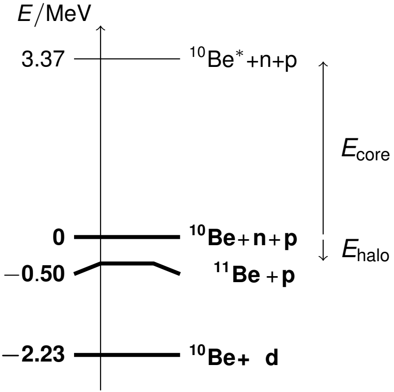

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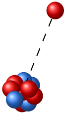

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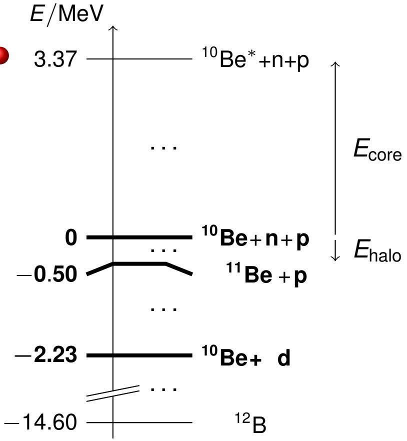

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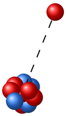

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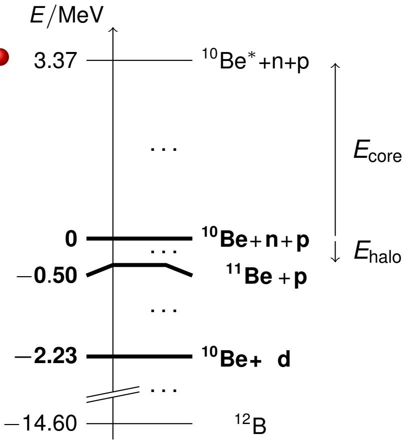

Long-range physics
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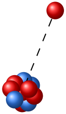

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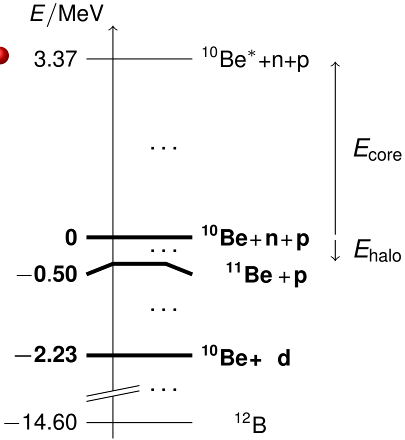

Long-range physics **explicit** vs. Short-range physics **implicit**

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$\mathcal{L}_{\text{LO}} =$

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- Kinetic part: ^{10}Be (dashed line) + neutron (solid line) + proton (dotted line) } non-relativistic

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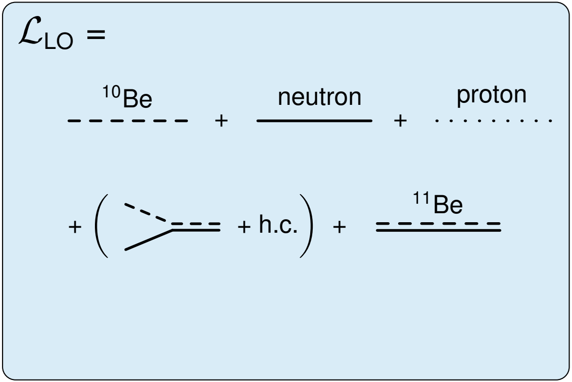
- ^{10}Be-n part:



non-relativistic

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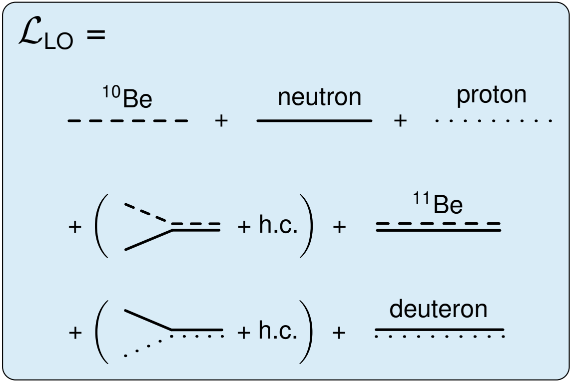

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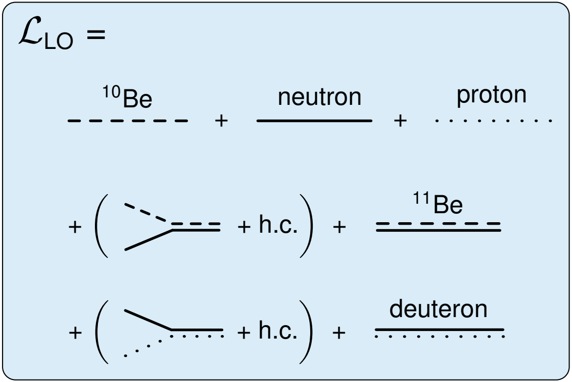

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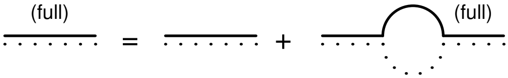
- **Full propagators**:



$\rightarrow$ effective range expansion

II. Scattering Amplitude: *Construction*

- Iterate **neutron exchanges**:

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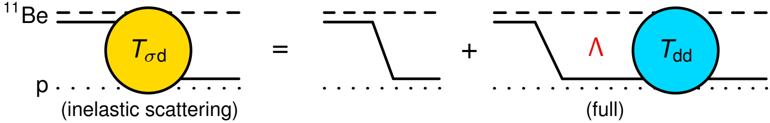

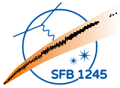

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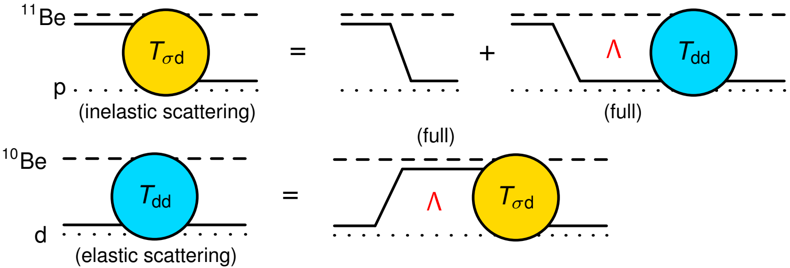

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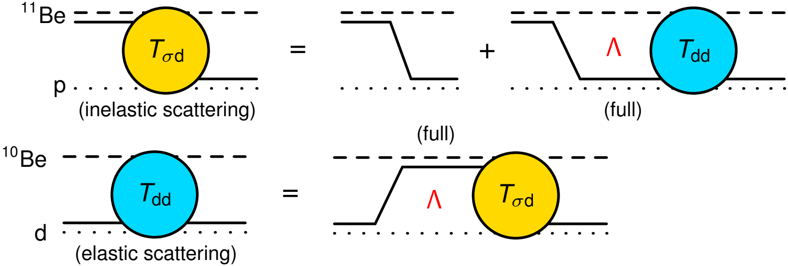

- $\vec{J} \equiv \vec{L} + \vec{S}$ and parity conserved $\rightarrow$ Project onto J^{π} channels

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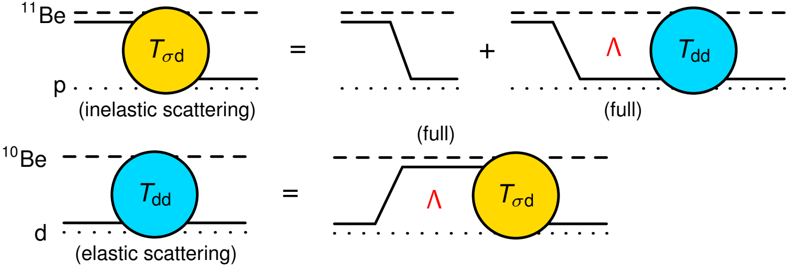

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potential vector — potential matrix

$$\vec{\mathcal{T}}_{J^\pi}(p,p') = -\vec{\mathcal{V}}_{J^\pi}(p,p') + \int_0^{\Lambda} \frac{dq\,q^2}{(2\pi)^3}\, \underline{\underline{\mathcal{V}}}_{J^\pi}(p,q)\, \underline{\underline{\mathcal{G}}}(q)\, \vec{\mathcal{T}}_{J^\pi}(q,p')$$

amplitude vector — Propagator matrix

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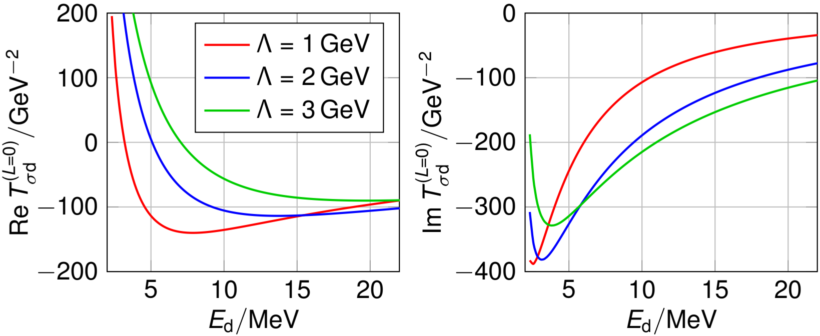

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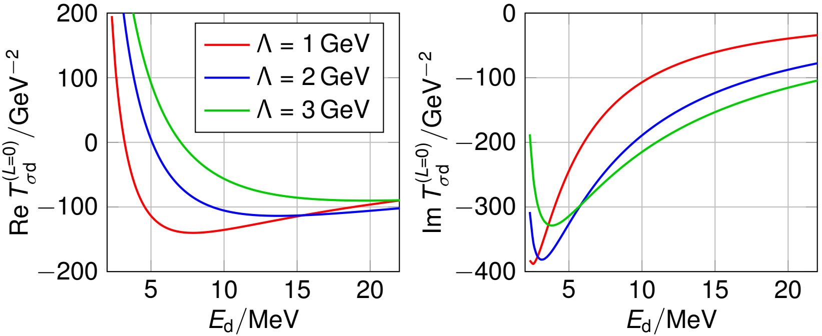

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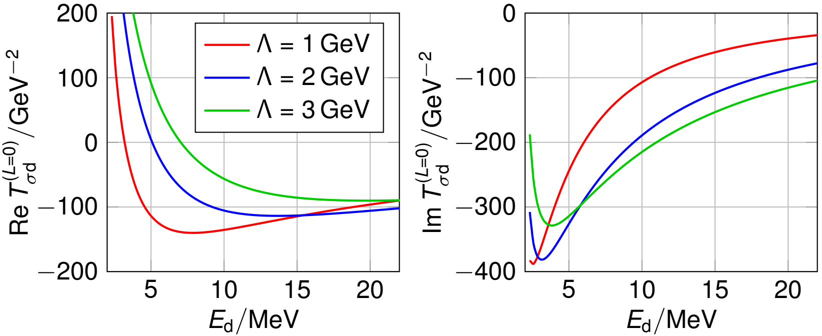
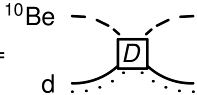


- Even more: Unphysical Efimov states
- Renormalize w/ **3-body force**!

III. 3-Body Force: *Reproducing Data*

- Adjust 3-body force $D(\Lambda) =$  $(L = 0)$

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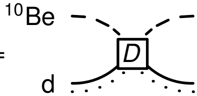
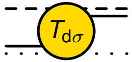
- Adjust 3-body force $D(\Lambda) =$ 

$(L = 0)$ such that

- **cross section** $\frac{d\sigma}{d\Omega} \propto \Big|$ 

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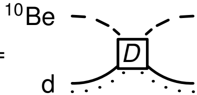
- Adjust 3-body force $D(\Lambda) =$ 

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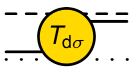
- **cross section** $\frac{d\sigma}{d\Omega} \propto \left| \right.$ 

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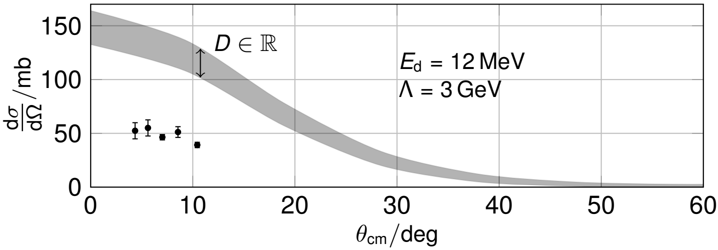

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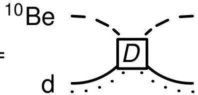
- Adjust 3-body force $D(\Lambda)$ = 

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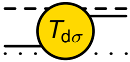
- **cross section** $\frac{d\sigma}{d\Omega} \propto \left| \right.$ 

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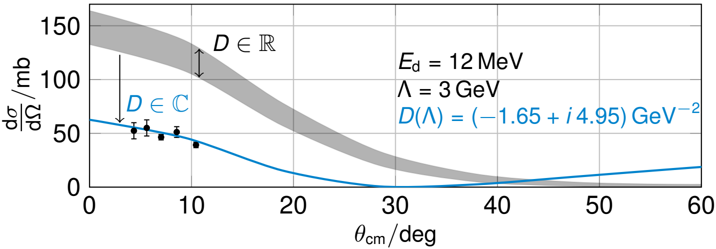

- **Complex *D* needed**! Cross section Λ-independent!

III. 3-Body Force: *Loss Channels*

- Im(D) introduces **loss channels** outside the EFT's scope
  e.g. ^{10}Be+d$\rightarrow$ ^{12}B (1^+): B_3 = 12.37 MeV (deeply inelastic)

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- Im(D) introduces **loss channels** outside the EFT's scope
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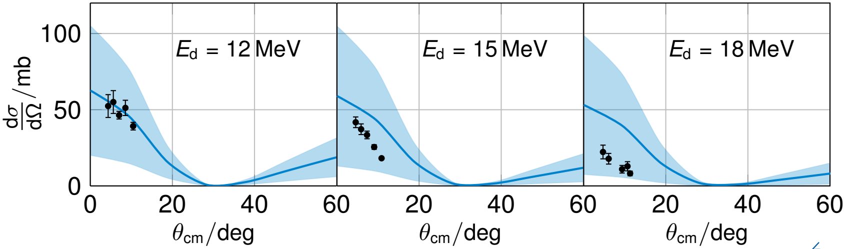
- **Predictions** at LO:



Agreement within NLO bands!

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IV. Summary & Outlook

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- **EFT for halo reactions**
  - LO: Auxiliary fields for ^{11}Be and deuteron ✓

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Appendix

I. EFT for ^{10}Be(d, p)^{11}Be: *Halo EFT Part*

[Hammer, Phillips, NPA **865** (2011)]

Non-relativistic fields

$$\mathcal{L}_{^{11}\mathrm{Be}} = n_\alpha^\dagger \left(i\partial_0 + \frac{\boldsymbol{\nabla}^2}{2m_\mathrm{N}} \right) n_\alpha \quad + \quad c^\dagger \left(i\partial_0 + \frac{\boldsymbol{\nabla}^2}{2m_\mathrm{c}} \right) c$$

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Auxiliary fields

$$+ \sigma_\alpha^\dagger \left[- \left(i\partial_0 + \frac{\nabla^2}{2M_\mathrm{Nc}} \right) + \Delta_\sigma + \ldots \right] \sigma_\alpha - g_\sigma \left[(n_\alpha c)^\dagger \sigma_\alpha + \mathrm{h.c.} \right]$$

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- Parameters: g_σ, Δ_π, g_π (LO) and Δ_σ (NLO)
- Fix with γ_σ, γ_π and effective ranges r_π, r_σ from experiment

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I. EFT for ^{10}Be(d, p)^{11}Be: *Full Two-Body Propagator*

- Full propagator: Resum two-body loops!

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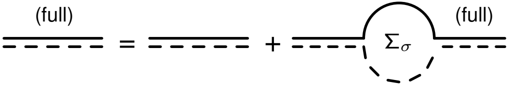
$\rightarrow$ ^{11}Be (*s*-wave):



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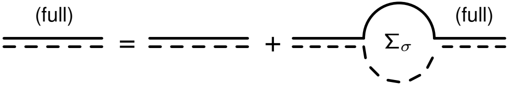
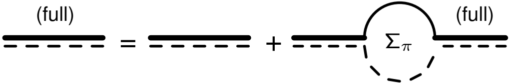


$\rightarrow$ ^{11}Be* (p-wave):



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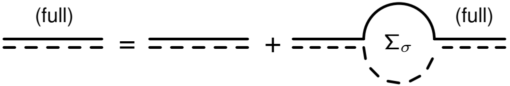

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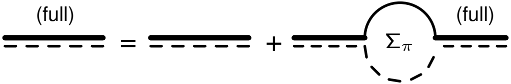
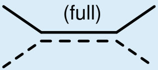


- Amplitudes:

$T_{l=0}$ =



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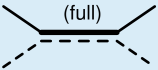

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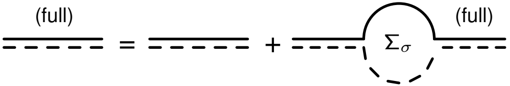

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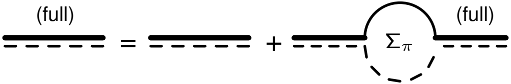

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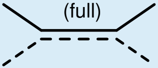

$$\sim\left(-a_\sigma^{-1}+r_\sigma\frac{k^2}{2}+\ldots-i\,k\right)^{-1}$$

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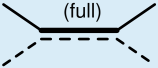

$$\sim k^2\left(-a_\pi^{-1}+r_\pi\frac{k^2}{2}+\ldots-i\,k^3\right)^{-1}$$

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- Partial wave projected amplitudes for $J \in \mathbb{N}_0$, $L \in \{J-1,\ J,\ J+1\}$:

$$\begin{pmatrix} T^{^3L_J}_{\sigma\mathrm{d}} \\ T^{^3L_J}_{\mathrm{dd}} \end{pmatrix}(p,p') = \frac{2\sqrt{\gamma_\mathrm{d}\gamma_\sigma}}{\mu_\mathrm{Nc}} \begin{pmatrix} I_L(p,p';E) \\ 0 \end{pmatrix} + \int \frac{\mathrm{d}q\, q^2}{(2\pi)^3} \begin{pmatrix} (1+y)\sqrt{\frac{\gamma_\sigma}{\gamma_\mathrm{d}}} \frac{I_L(q,p;E)}{-\gamma_\mathrm{d}+\sqrt{\frac{1+2y}{4}q^2 - m_\mathrm{N}(E+i\epsilon)}}\, T^{^3L_J}_{\mathrm{dd}}(q,p') \\ 2\sqrt{\frac{\gamma_\mathrm{d}}{\gamma_\sigma}} \frac{I_L(p,q;E)}{-\gamma_\sigma+\sqrt{\frac{1+2y}{(1+y)^2}q^2 - 2\mu_\mathrm{Nc}(E+i\epsilon)}}\, T^{^3L_J}_{\sigma\mathrm{d}}(q,p') \end{pmatrix}$$

with $\gamma_\mathrm{d} = 46\,\mathrm{MeV}$, $\gamma_\sigma = 29\,\mathrm{MeV}$, $y \equiv \frac{m_\mathrm{N}}{m_\mathrm{c}} = 0.1$, $\mu_\mathrm{Nc} \equiv m_\mathrm{N} m_\mathrm{c}/(m_\mathrm{N}+m_\mathrm{c})$ and

$$I_L(p,q;E) \equiv \frac{-2}{pq} Q_L\left(\frac{m_\mathrm{N}E}{pq} - \frac{p}{q} - \sqrt{\frac{1+y}{2}}\frac{q}{p} + i\epsilon\right),$$

where Q_L is Legendre function of 2^{nd} kind.

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- $L > 0$ integrals converge as $\Lambda \to \infty$, $L = 0$ integrals don't

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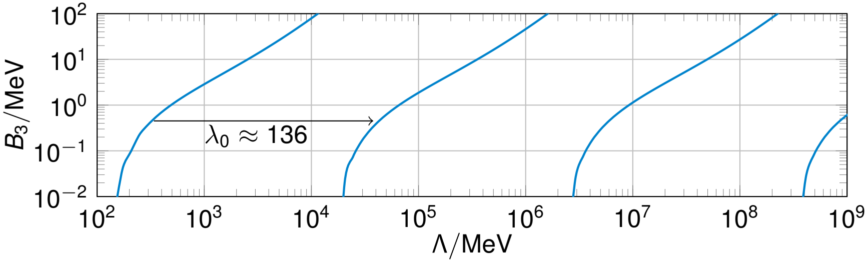

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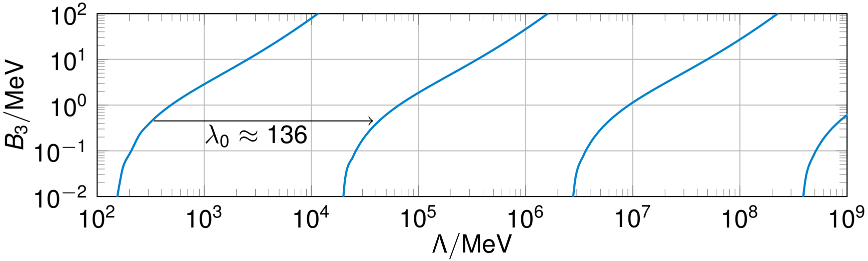

- (Unphysical) **Efimov states**: Discrete scale invariance $\Lambda \to \lambda_0 \Lambda$

[Efimov, PLB **33** (1970)]

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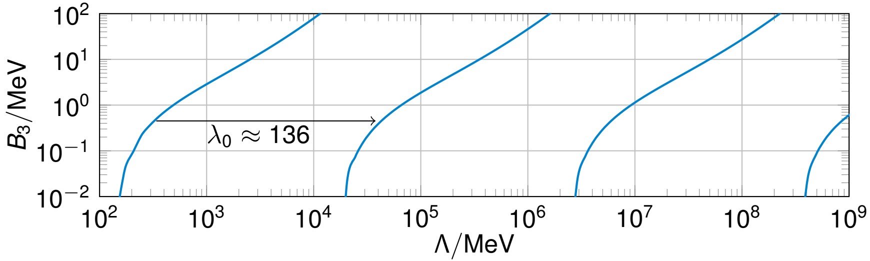

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- Renormalize w/ **3-body force**!

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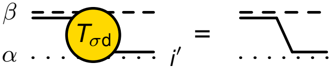
- Insert $|\pi\rangle \equiv \left|{}^{11}\mathrm{Be}^* + \mathrm{p}\right\rangle$ and $|\mathrm{v}\rangle \equiv \left|{}^{10}\mathrm{Be} + \mathrm{np}({}^1S_0)\right\rangle$ at NLO:



(reaction channel)

with $\alpha, \beta \in \{-1/2, +1/2\}$ and $i, i' \in \{-1, 0, +1\}$

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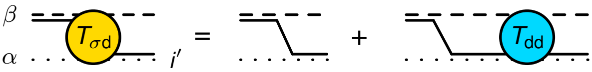

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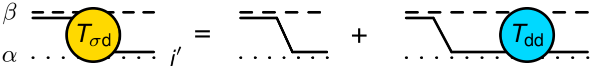

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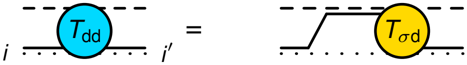

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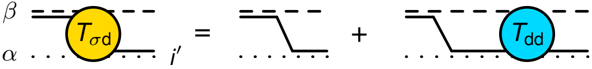

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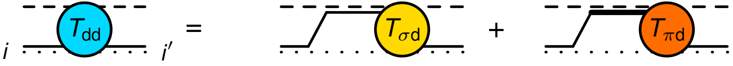

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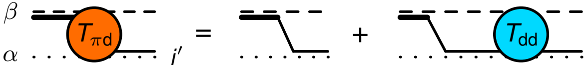

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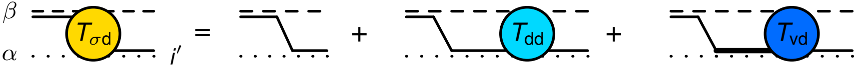

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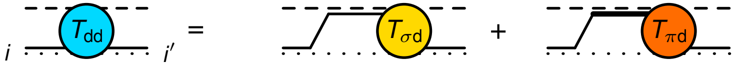

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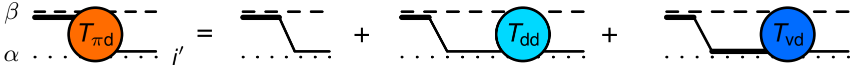

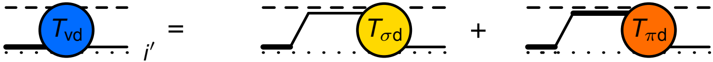

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III. 3-Body Force: *Renormalization w/o Losses*

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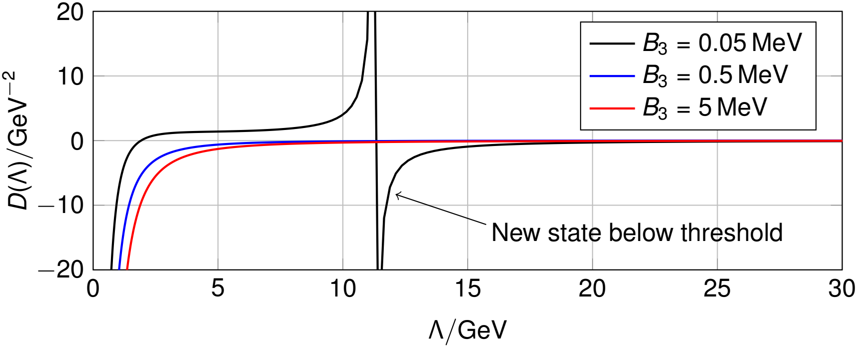
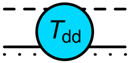
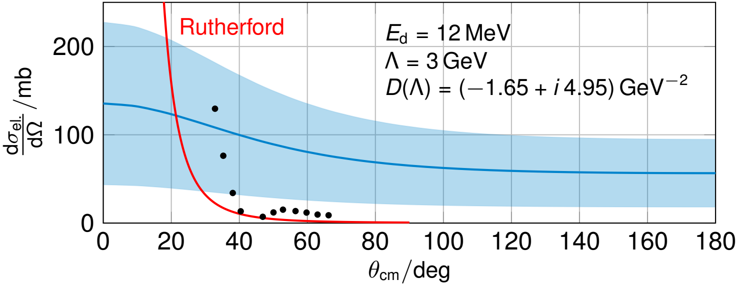
- Demand pole in T_{dd} below d-^{10}Be threshold at binding energy B_3



III. 3-Body Force: *Elastic Channel*

- Elastic scattering $^{10}\text{Be}(\text{d},\text{d})^{10}\text{Be}$
- **cross section** $\frac{d\sigma_{el.}}{d\Omega} \propto \Big|$  $\Big|^2$



- **Need Coulomb force**!