Neutron-neutron scattering length from the ^{6}He(p,p'α)nn reaction

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Daniel Phillips
Institute of Nuclear & Particle Physics
Ohio University

with Matthias Göbel,
Hans-Werner Hammer, Tom Aumann,
Carlos Bertulani, Tobias Frederico

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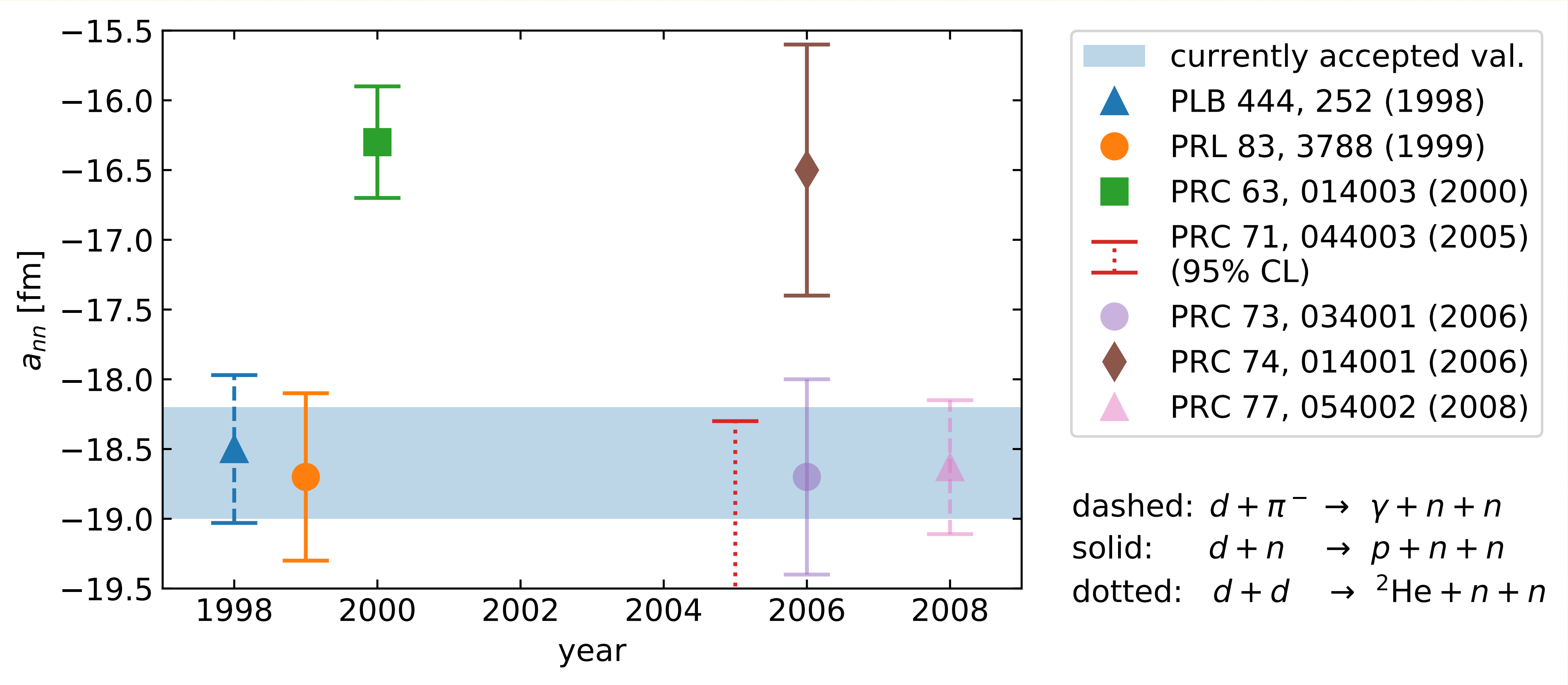
Outline

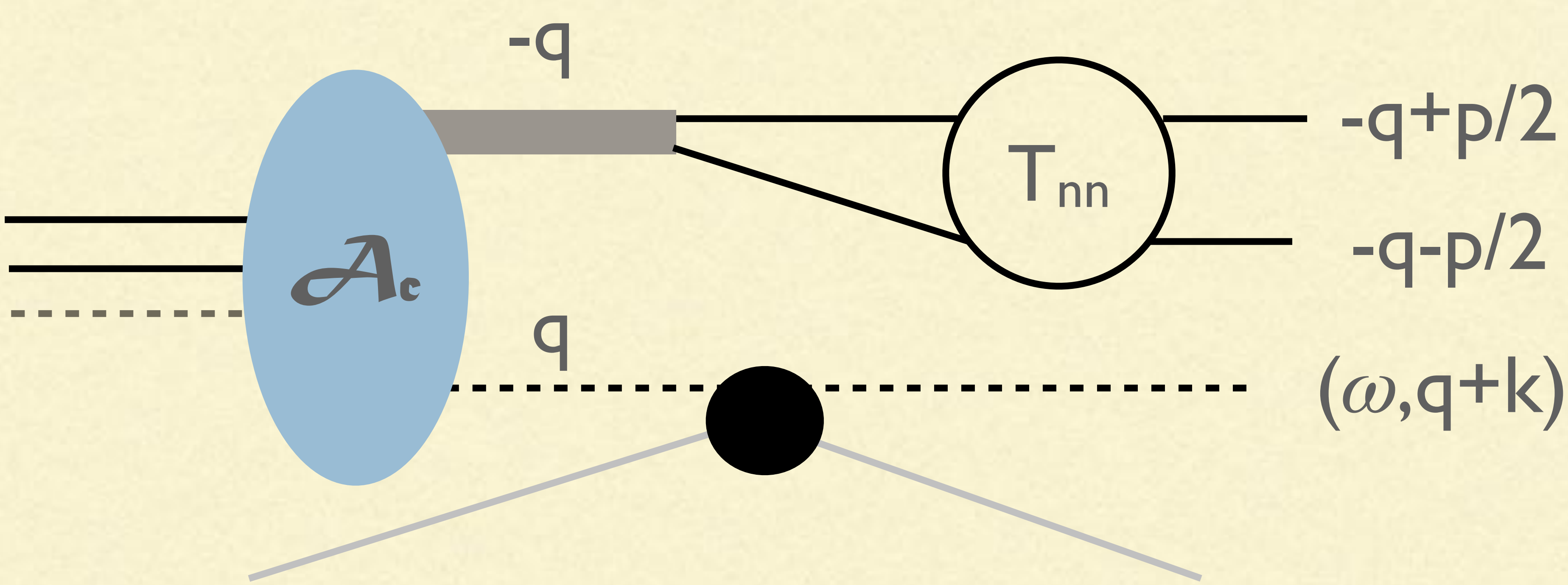
- Measuring a_{nn} using neutrons held by ^{6}He
    - Why a_{nn}?
    - The experimental proposal
    - Predictions for neutron spectra
- Halo EFT for ^{6}He
    - EFT for short-range p-wave interactions
    - 2n halo nuclei
    - LO EFT for ^{6}He structure
    - Phenomenological treatments of FSI
- Future improvements to theory
- Conclusion

Why a_{nn}?



- a_{nn} is really only "datum" on neutron-neutron interaction
- Key source of information on charge-symmetry breaking in NN force
- Extracted from reactions with (at least) three strongly-interacting particles
- Disagreement between nd breakup data that give -16.5 fm and "accepted value" of -18.6(4) fm (which also incorporates some nd breakup results)

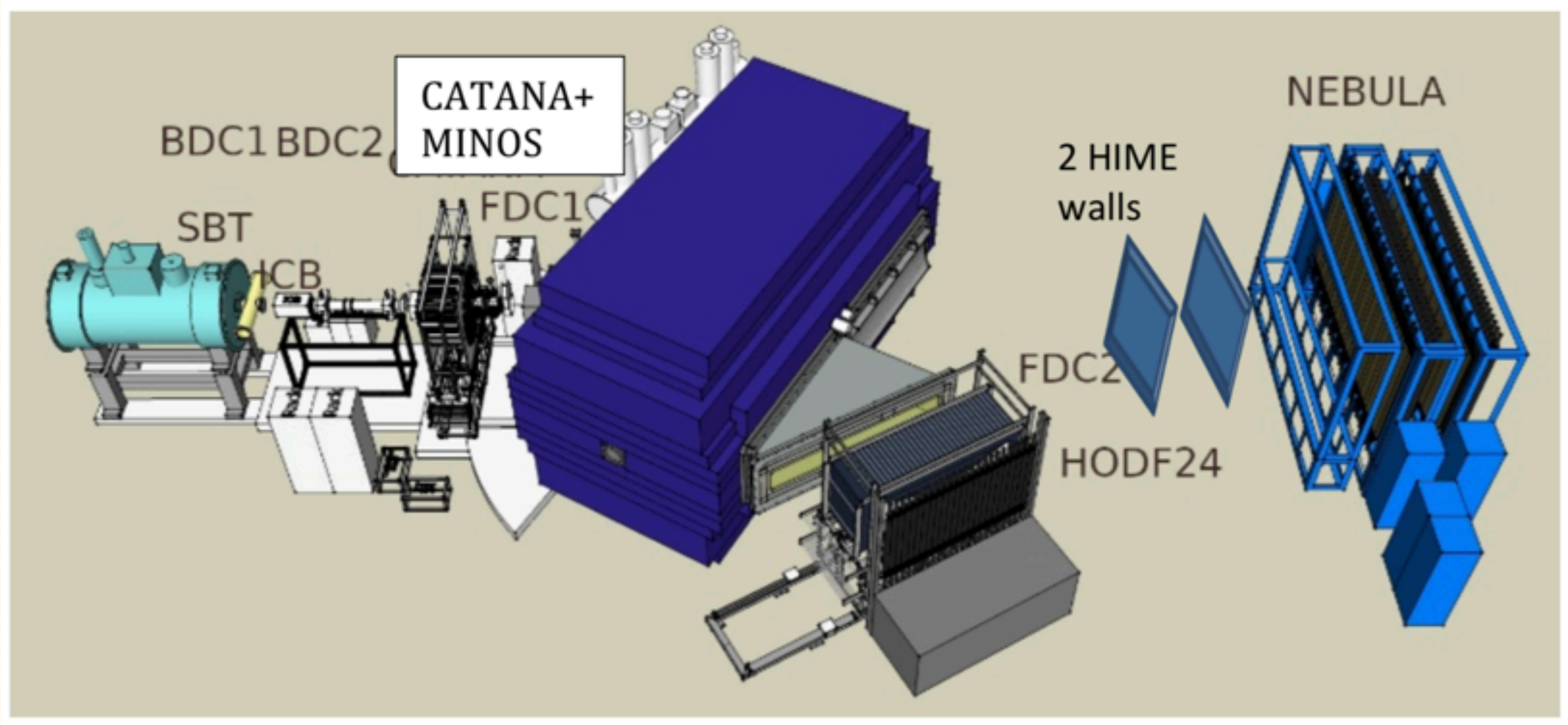
^{6}He(p,p'α) and the nn scattering length



- Quasi-free alpha-particle knockout can leave nn pair almost at rest
- Final-state interaction then generates significant dependence of neutron relative-energy spectrum $f(p^2/m_n)$ on a_{nn}
- ^{6}He acts as a "holder" for low-momentum neutrons
- Neutrons actually move fast in lab. frame: inverse kinematics

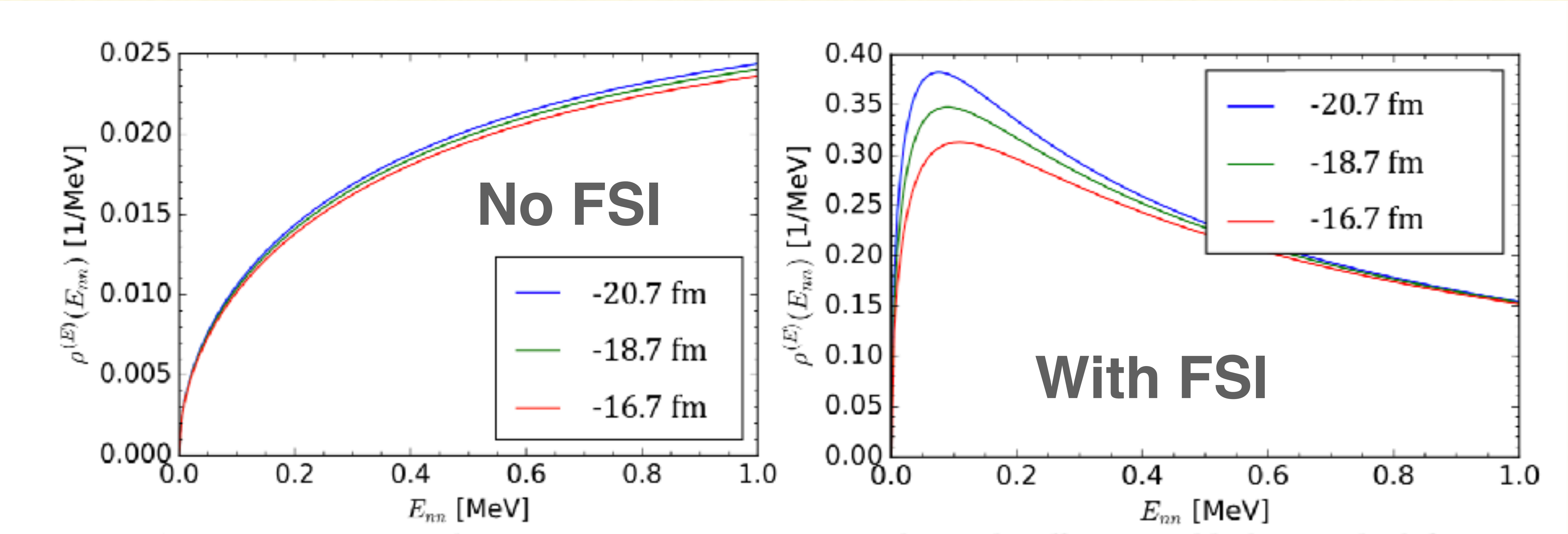
RIKEN experiment

Tom Aumann spokesperson



- Detect proton and alpha in TPC
- Detect neutrons in HIME + NEBULA: excellent energy resolution

Sensitive to a_{nn} from FSI **not** structure and **not** r_{nn}



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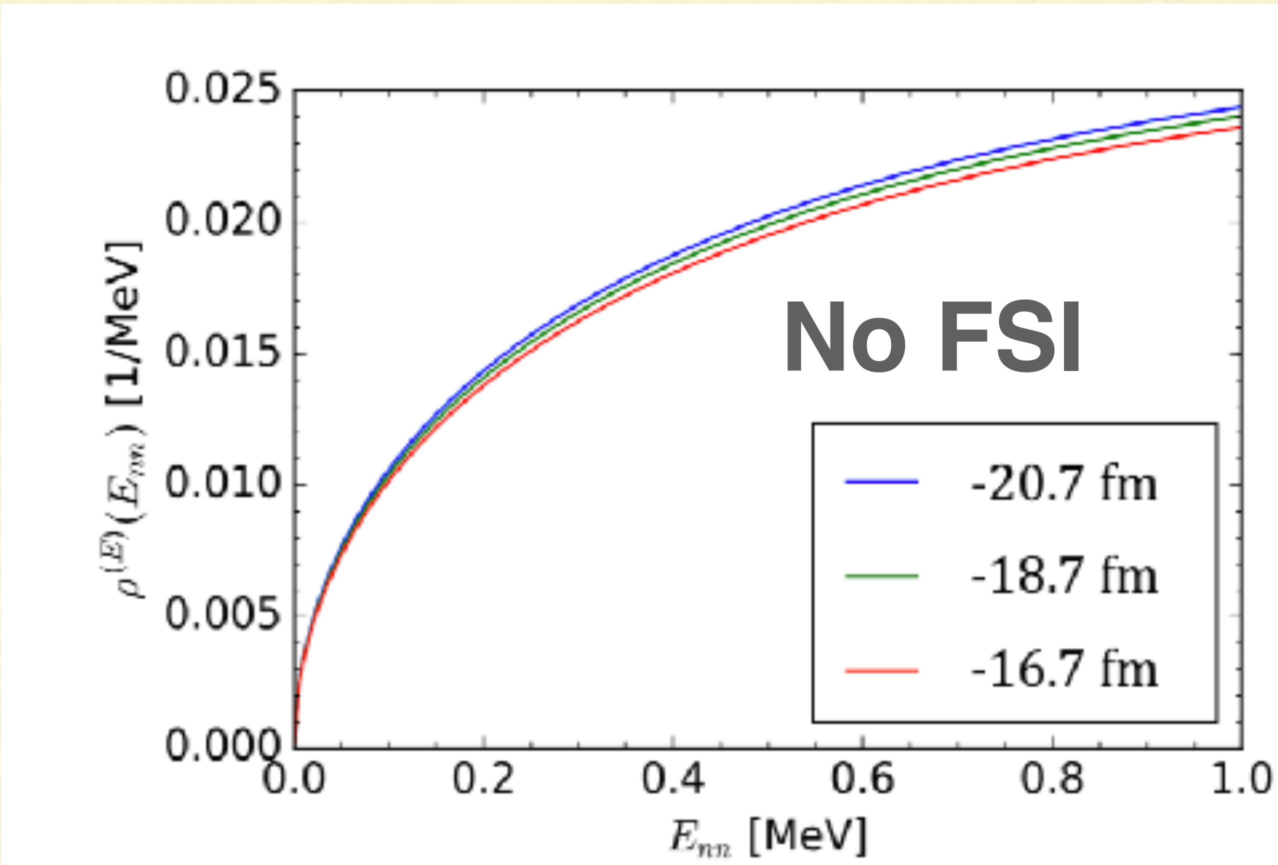

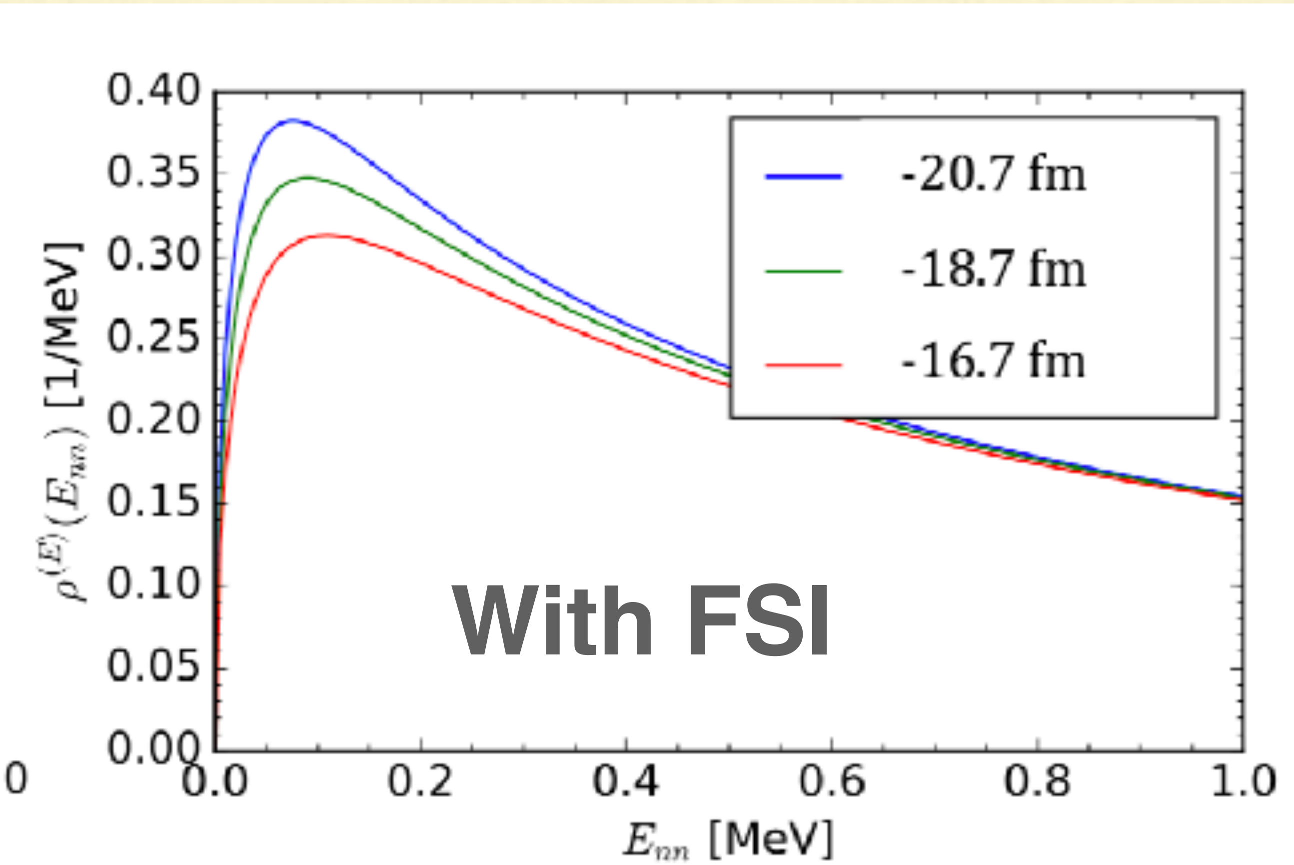

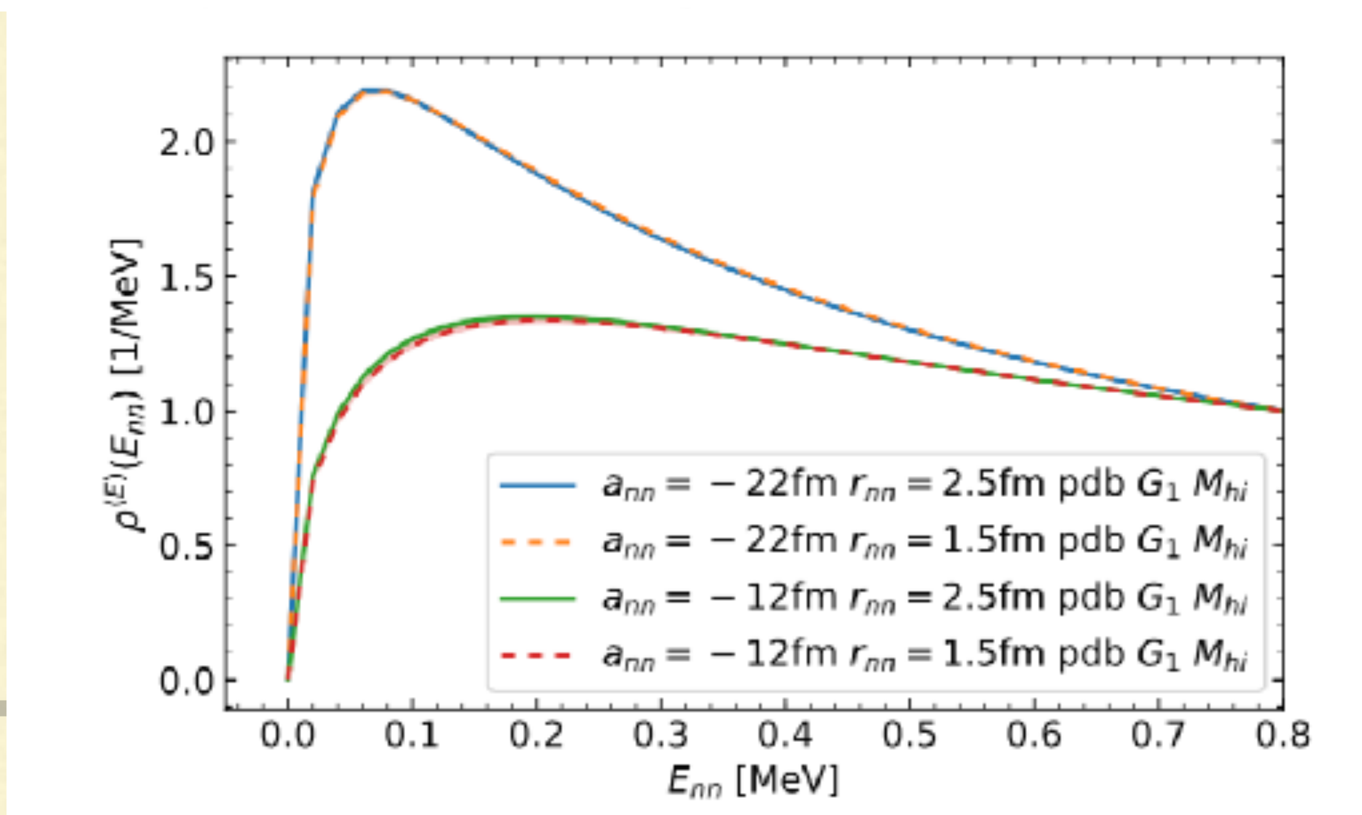

Note that since this is not an absolute measurement we need to decide how to normalize the spectra

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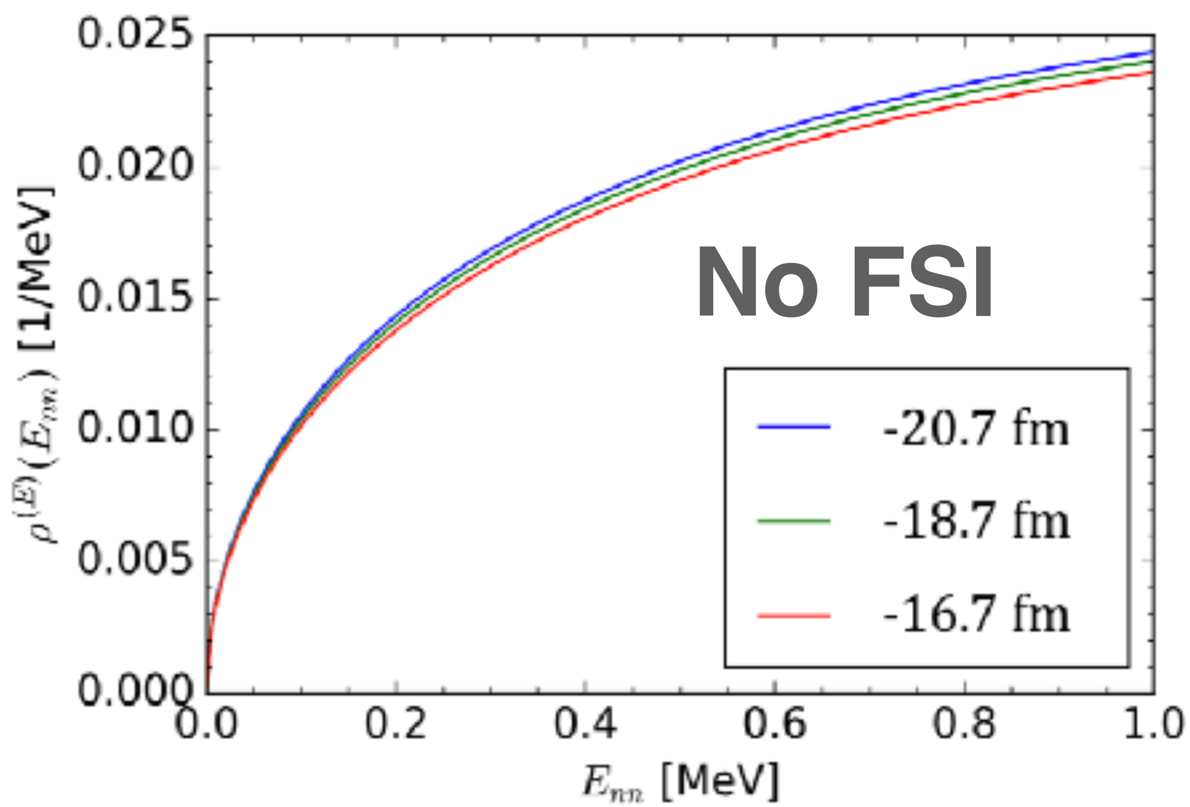

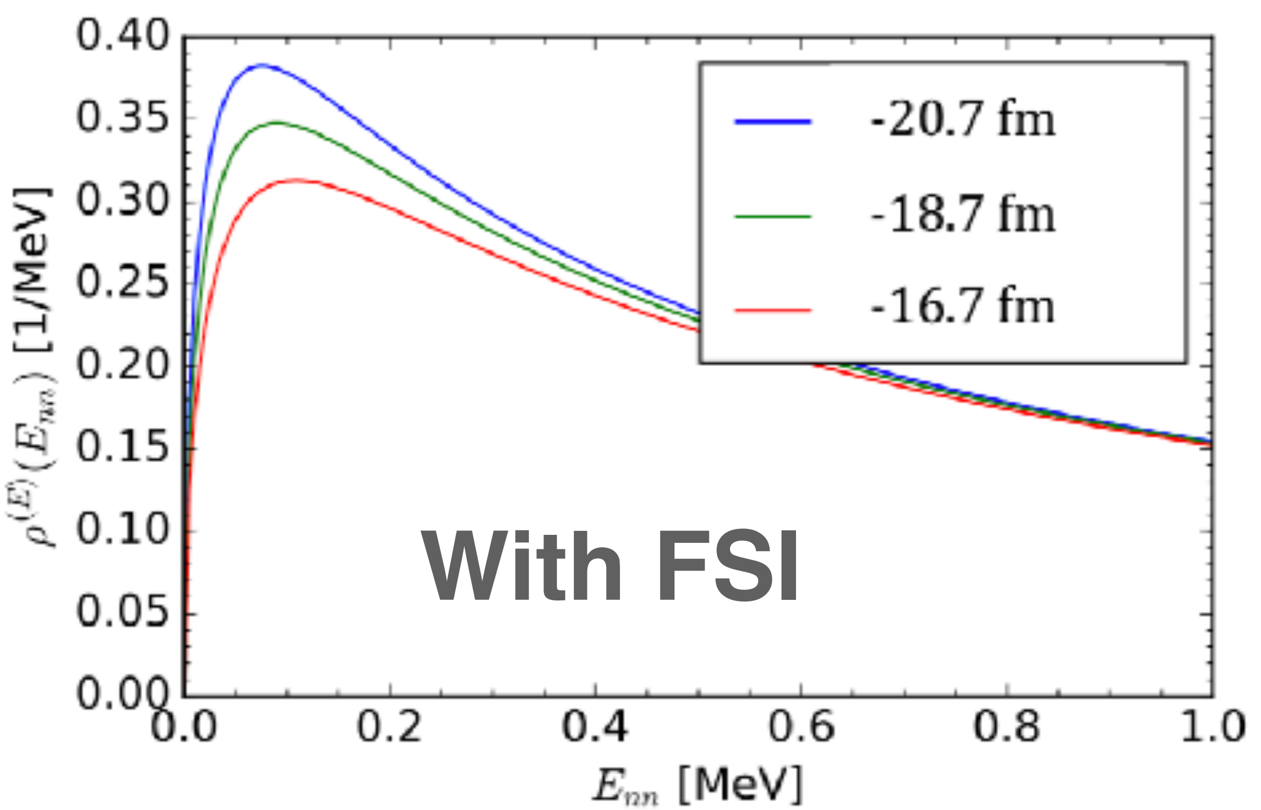

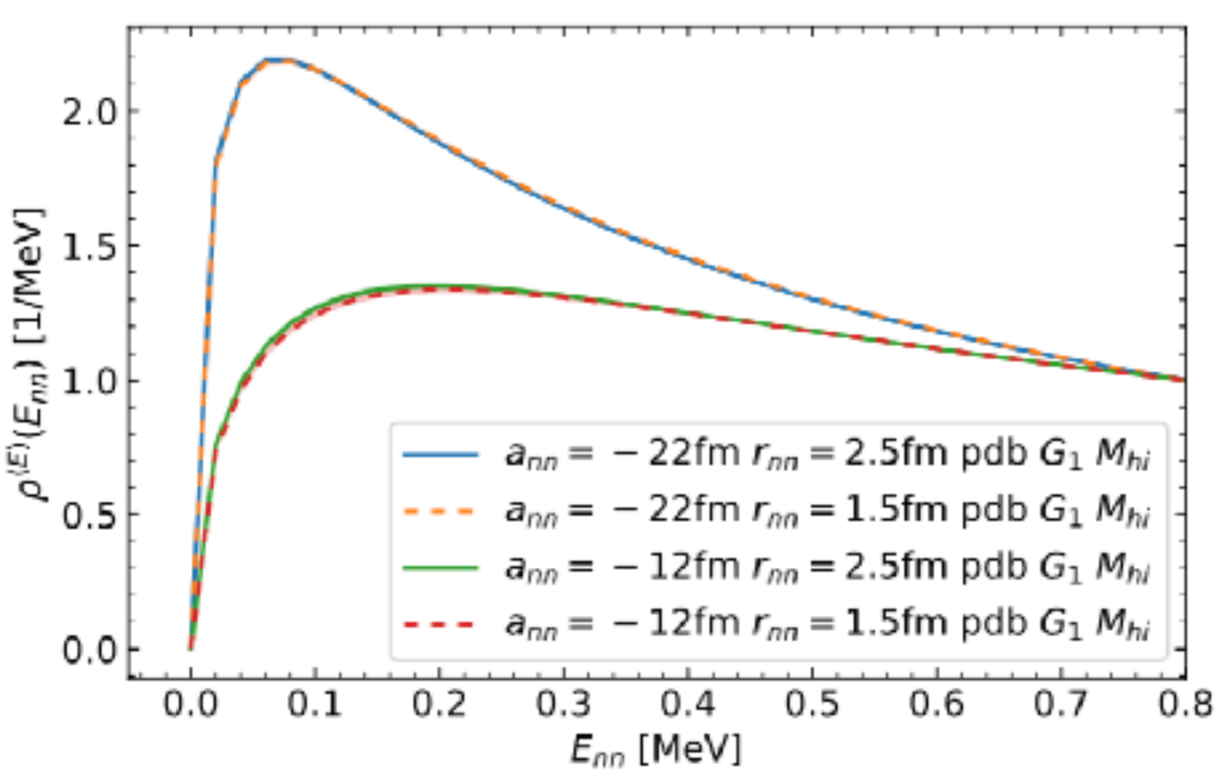

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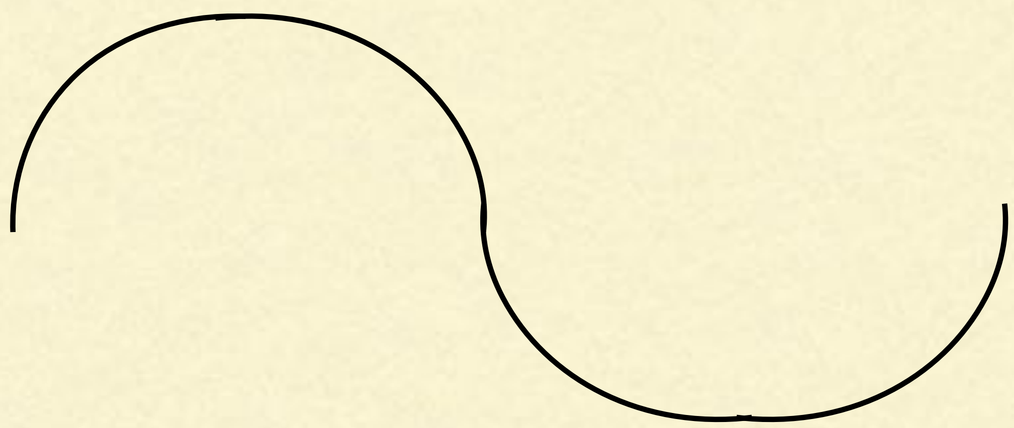
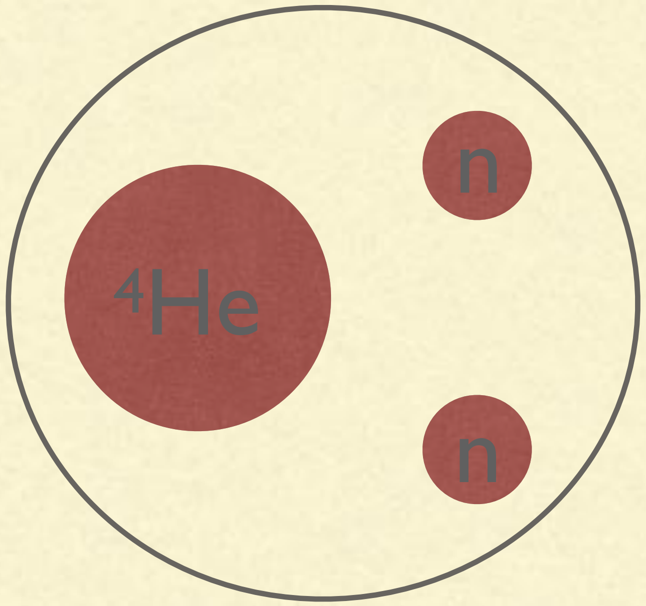
Theory uncertainties?

Halo EFT

$\lambda \gg R_{core}$; $\lambda \lesssim R_{halo}$





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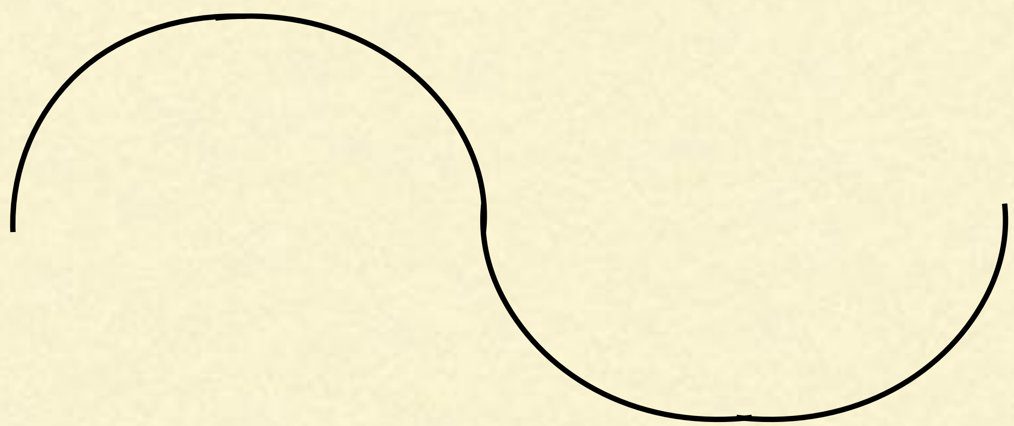

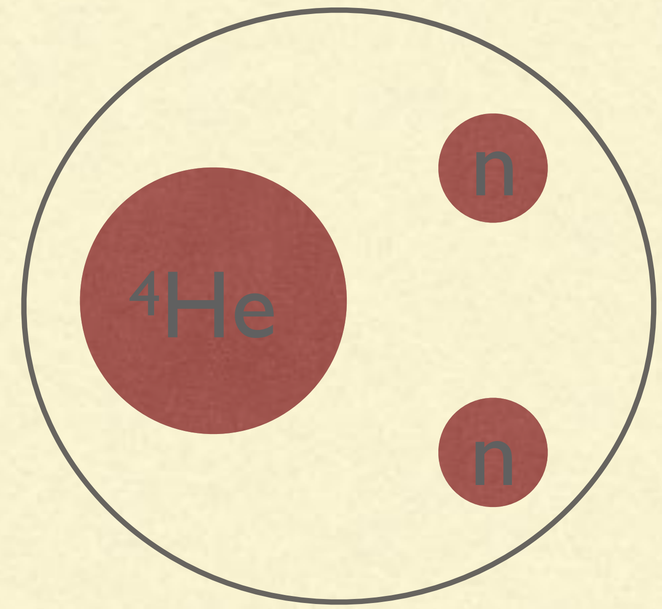

- Define $R_{halo}=\langle r^2\rangle^{1/2}$. Seek EFT expansion in R_{core}/R_{halo}. Valid for $\lambda \lesssim R_{halo}$
- Typically $R\equiv R_{core}\sim 2$ fm. Since $\langle r^2\rangle$ is related to the neutron separation energy we seek systems with neutron separation energies less than 1 MeV
- By this definition the deuteron is the lightest halo nucleus, and the pionless EFT for few-nucleon systems is a specific case of halo EFT
- ^{22}C, ^{11}Li, ^{12}Be, ^{62}Ca (hypothesized), and ^{3}H: all s-wave 2n halos

Lagrangian: shallow S- and P-states

$$\begin{aligned}
\mathcal{L} &= c^\dagger\left(i\partial_t + \frac{\nabla^2}{2M}\right)c + n^\dagger\left(i\partial_t + \frac{\nabla^2}{2m}\right)n \\
&+\sigma^\dagger\left[\eta_0\left(i\partial_t + \frac{\nabla^2}{2M_{nc}}\right) + \Delta_0\right]\sigma + \pi_j^\dagger\left[\eta_1\left(i\partial_t + \frac{\nabla^2}{2M_{nc}}\right) + \Delta_1\right]\pi_j \\
&-g_0\left[\sigma n^\dagger c^\dagger + \sigma^\dagger n c\right] - \frac{g_1}{2}\left[\pi_j^\dagger(n\, i\overleftrightarrow{\nabla}_j\, c) + (c^\dagger\, i\overleftrightarrow{\nabla}_j\, n^\dagger)\pi_j\right] \\
&-\frac{g_1}{2}\frac{M-m}{M_{nc}}\left[\pi_j^\dagger\, i\overrightarrow{\nabla}_j\,(nc) - i\overleftrightarrow{\nabla}_j\,(n^\dagger c^\dagger)\pi_j\right] + \ldots\,,
\end{aligned}$$

- c, n: “core”, “neutron” fields. c: boson, n: fermion
- σ, π_j: S-wave and P-wave fields
- Minimal substitution generates leading EM couplings
- Additional EM couplings at sub-leading order

Fun facts: p-wave scattering amplitude

$$\langle \mathbf{k} \,|\, t_{n\alpha}\left(p^2/(2\mu_{n\alpha})\right) |\, \mathbf{k}' \rangle = -\frac{6\pi}{\mu_{n\alpha}} \frac{\mathbf{k}\cdot\mathbf{k}'}{-\frac{1}{a_1} + \frac{1}{2} r_1 p^2 - i p^3}$$

Bethe (1949)

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Wigner (1955); Hammer & Lee (2009); Nishida (2012)

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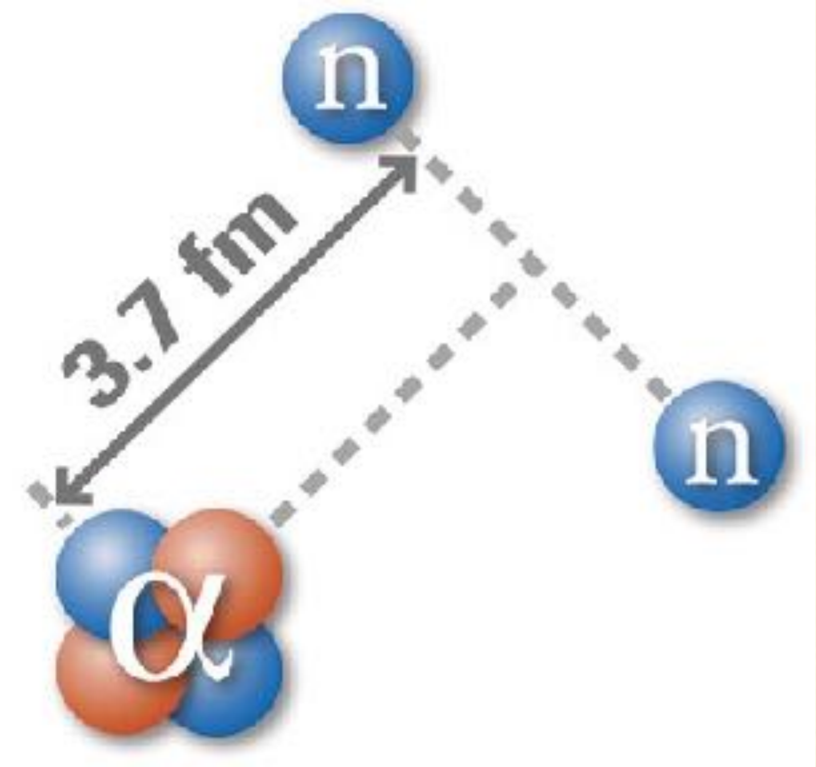
- So low-energy resonance/bound state would seem to have to arise due to cancellation between $-1/a_1$ and $1/2\, r_1 k^2$ terms.
- $a_1 \sim R/M_{lo}^2$ gives $k_R \sim M_{lo}$

Bedaque, Hammer, van Kolck (2003)

^{6}He as a 2n halo

http://www.anl.gov



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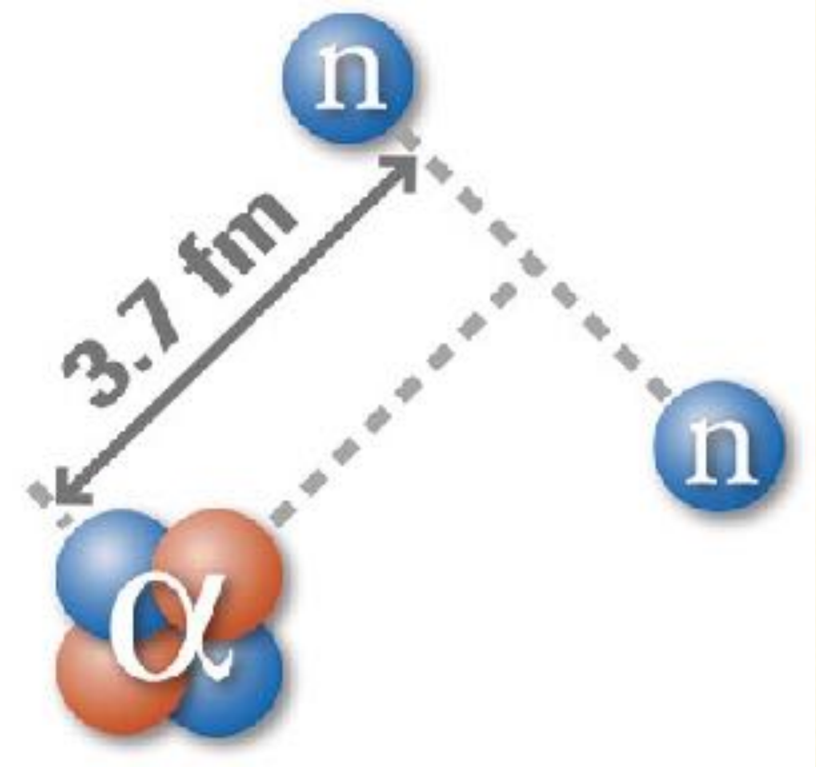

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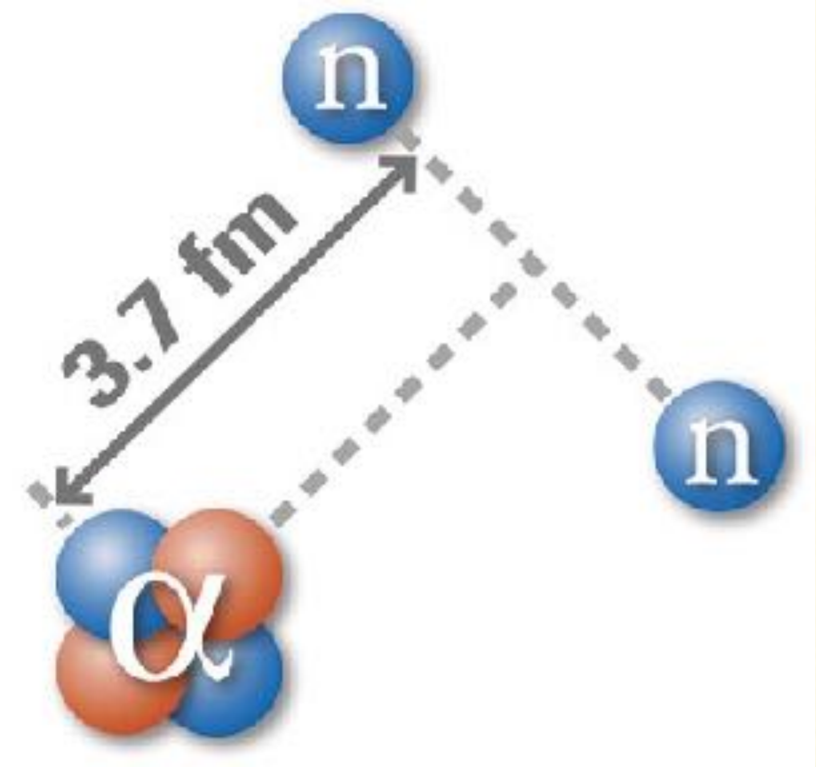

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- p-wave power counting only valid when not near the $^2P_{3/2}$ resonance

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- "Standard" counting for nn $^1S_0$: a_0 at leading order, r_0 at NLO

$$\langle \mathbf{k} \,|\, t_{nn}(p^2/(2\mu_{nn})) \,|\, \mathbf{k}' \rangle = -\frac{2\pi}{\mu_{nn}} \frac{1}{-\frac{1}{a_0} - ip}$$

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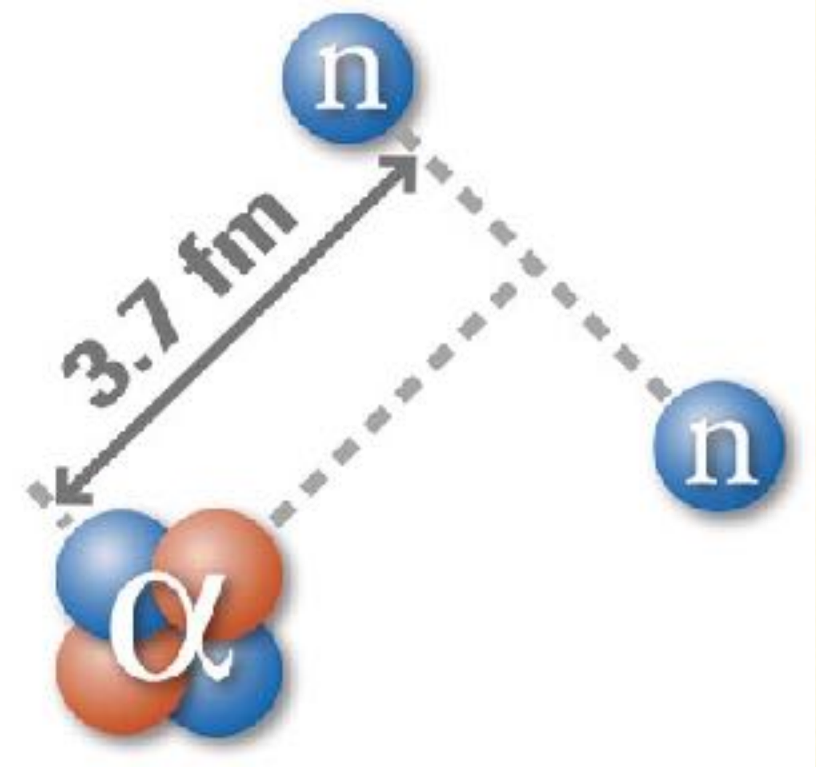

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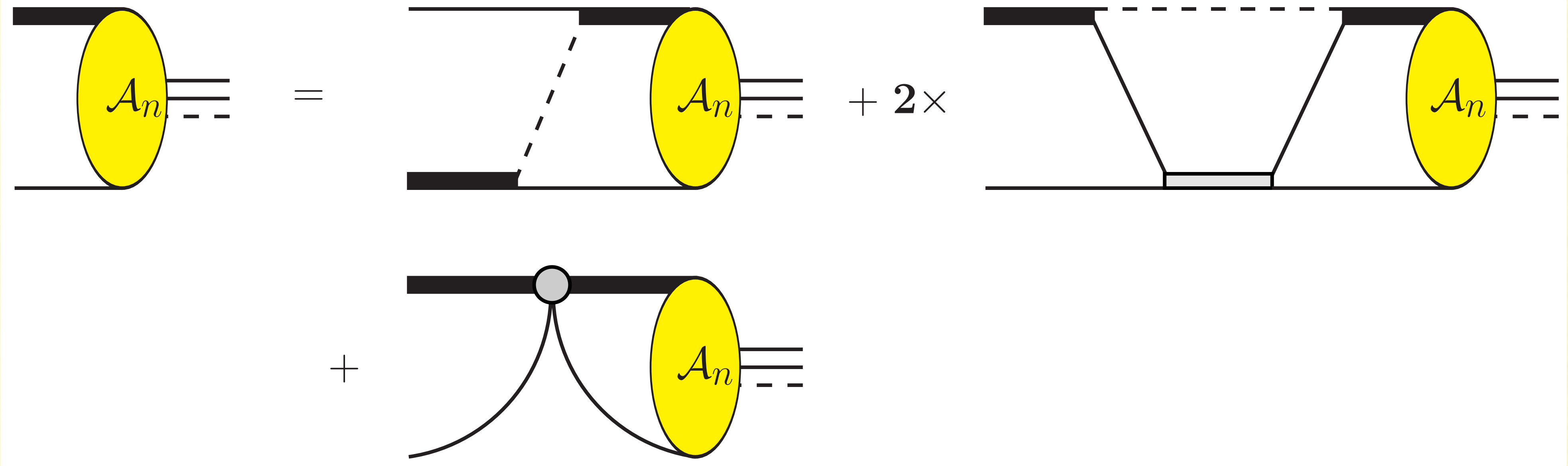
- nα $^2P_{3/2}$ at NLO: unitarity piece/width included perturbatively

Ji, Elster, DP (2014) cf. Rotureau and van Kolck (2013)

- nα $^2S_{1/2}$: NLO effect, since a_0=2.46 fm is "natural"

"STM" equation for ^{6}He

Ji, Elster, DP (2014)



- No longer just "s-wave" exchanges: Q_0, Q_1, and Q_2 enter in exchange kernel
- Asymptotic behavior stems from first term on right-hand side
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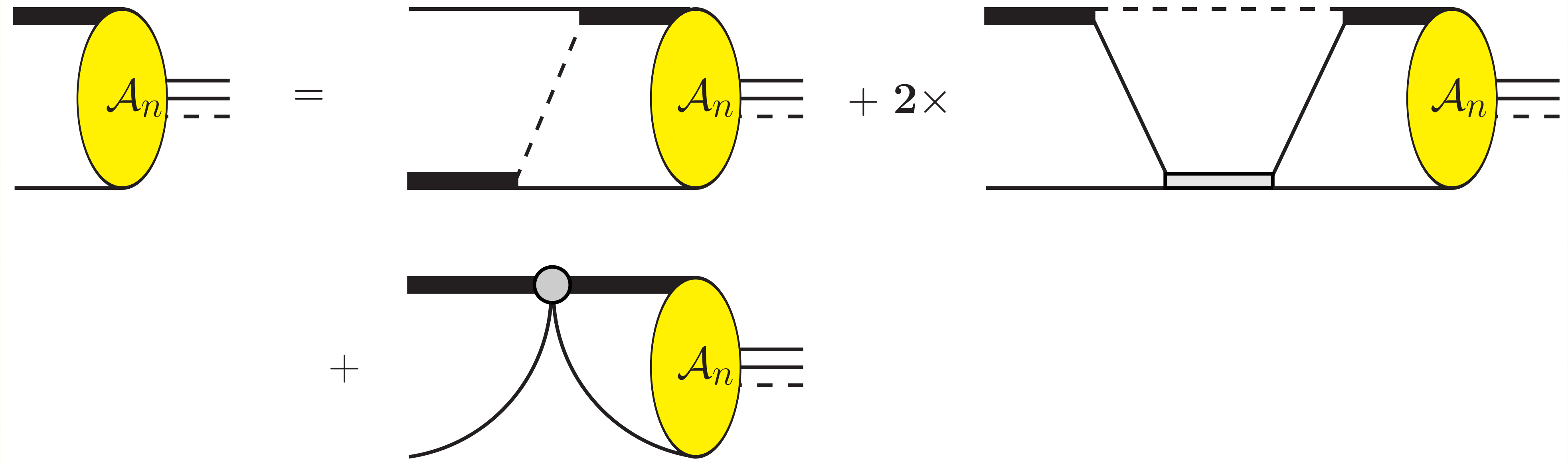

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  Jona-Lasinio, Pricoupenko, Castin (2008); Braaten, Hagen, Hammer, Platter (2011); Nishida (2012)
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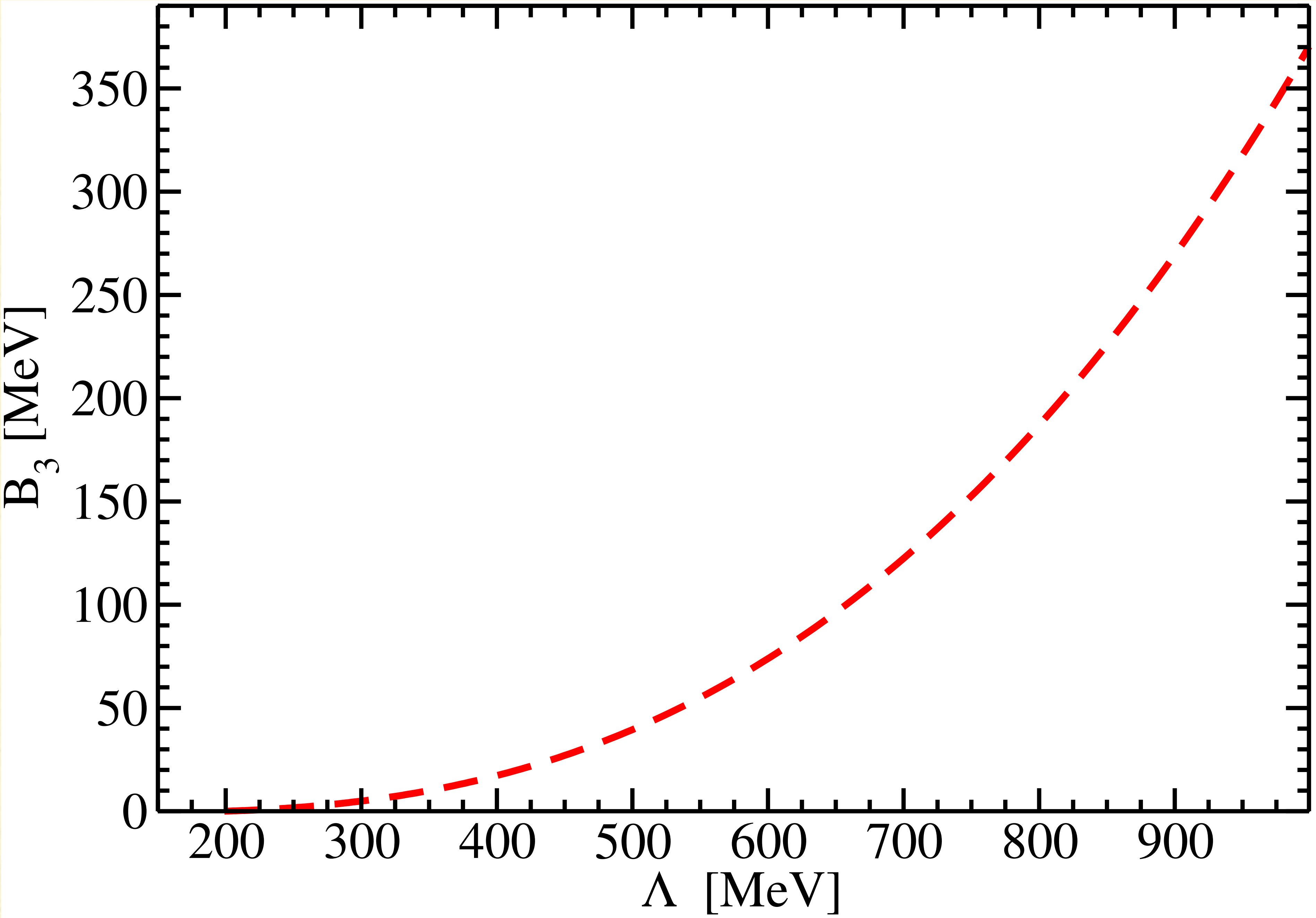
Renormalizing ^{6}He



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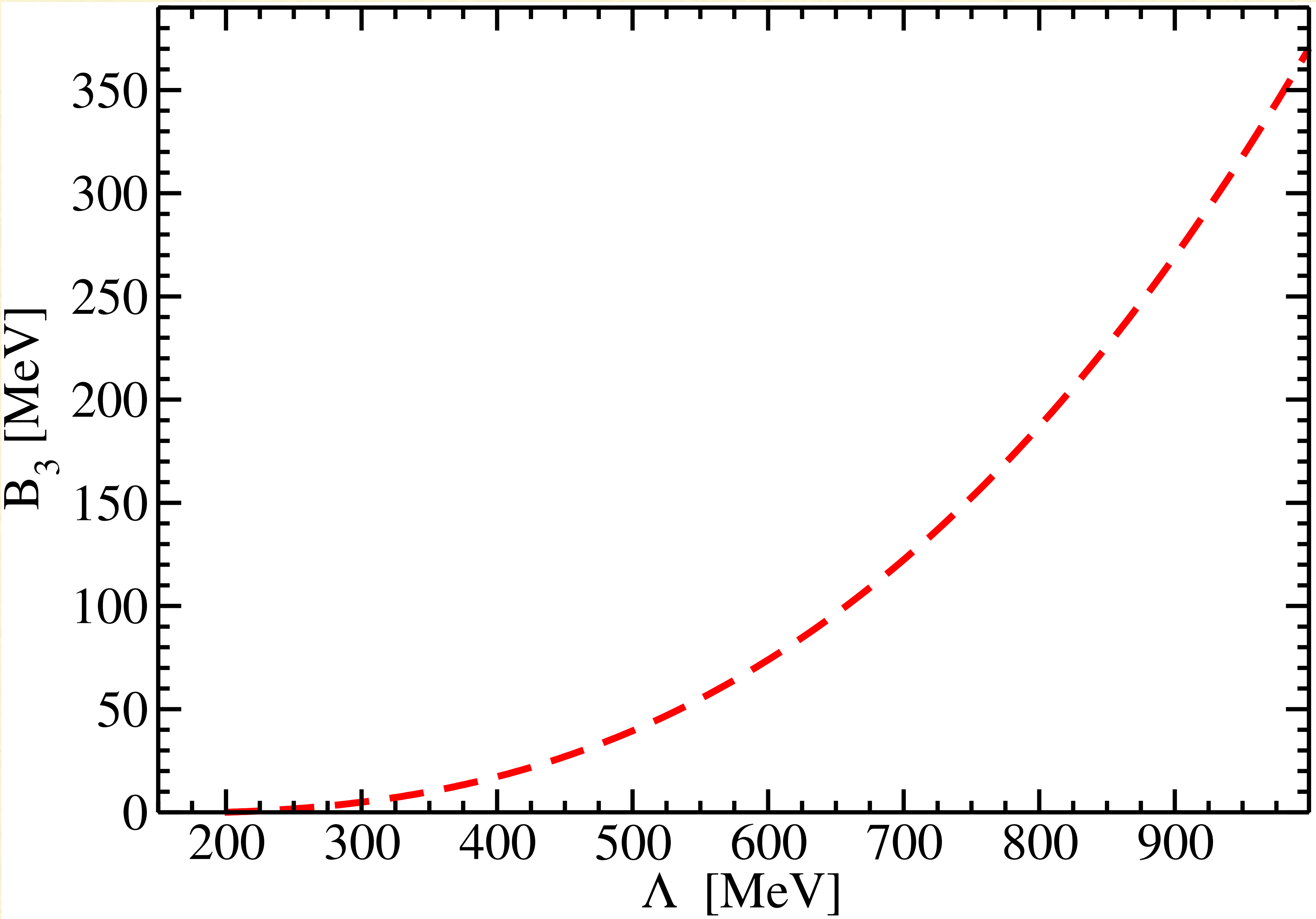

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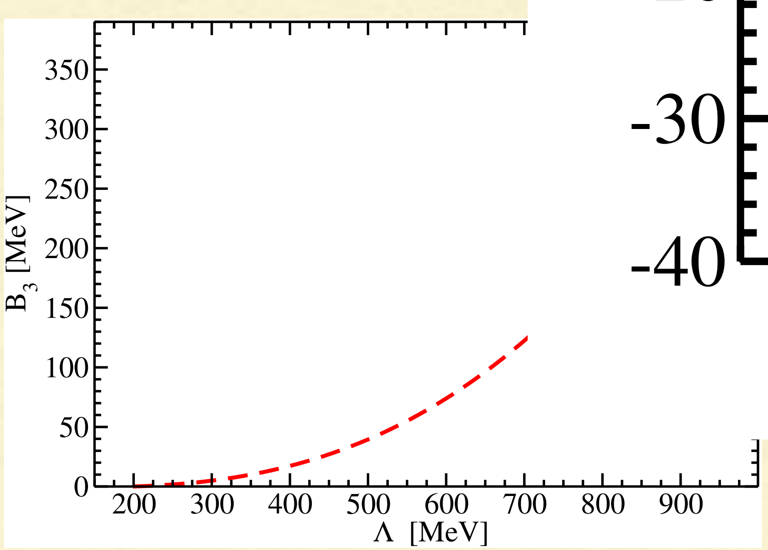
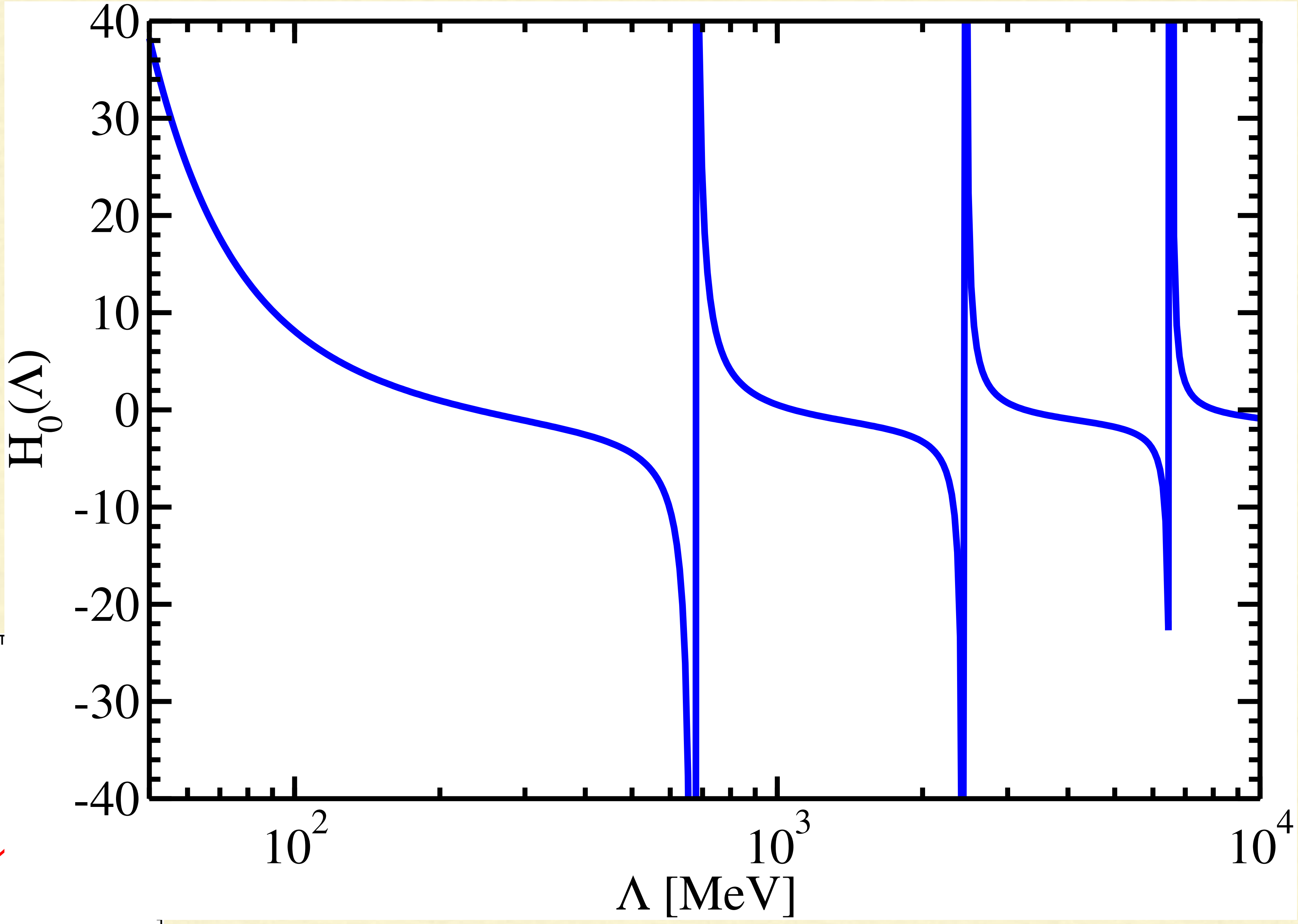
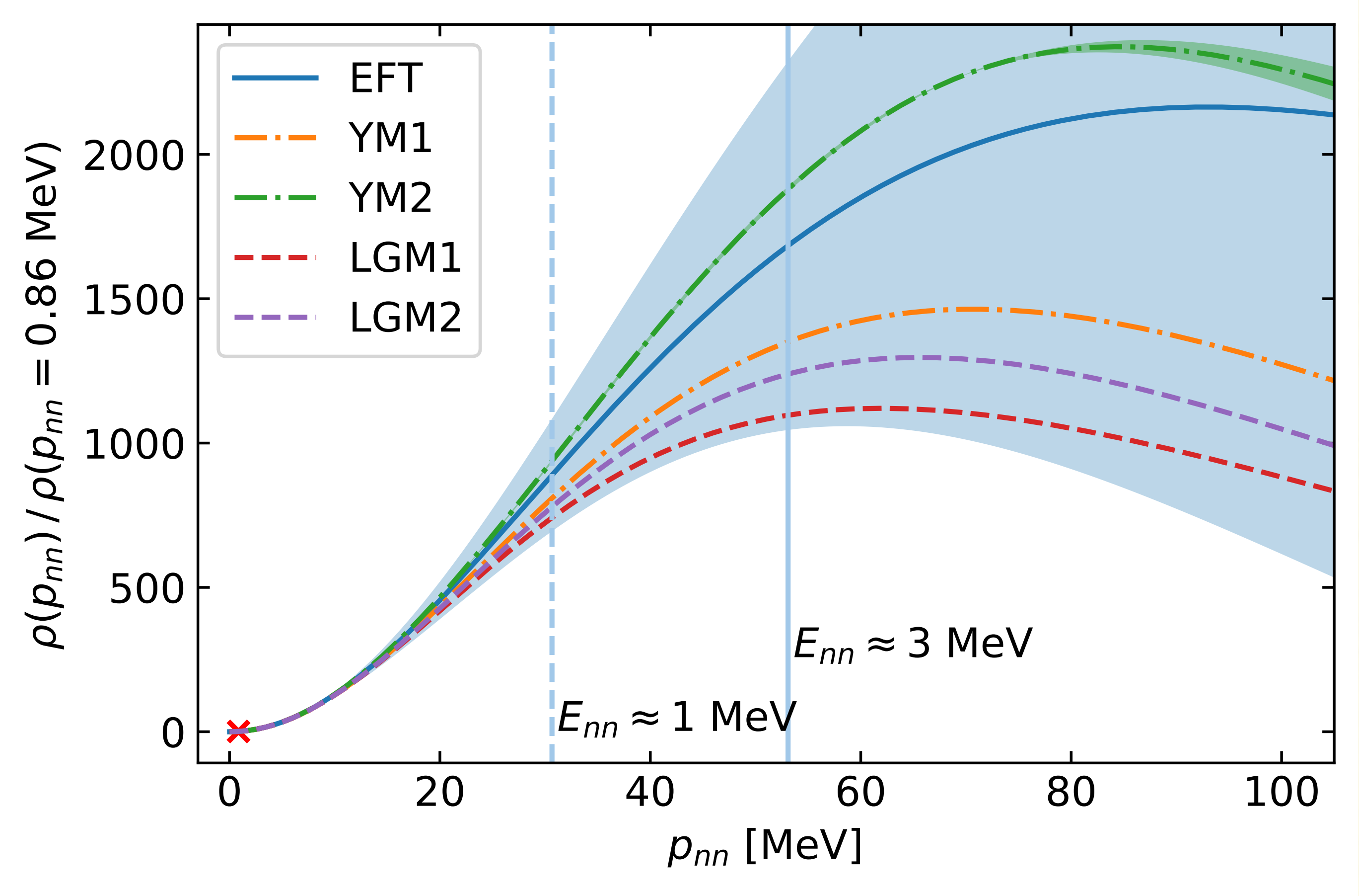




Energy spectrum without FSI



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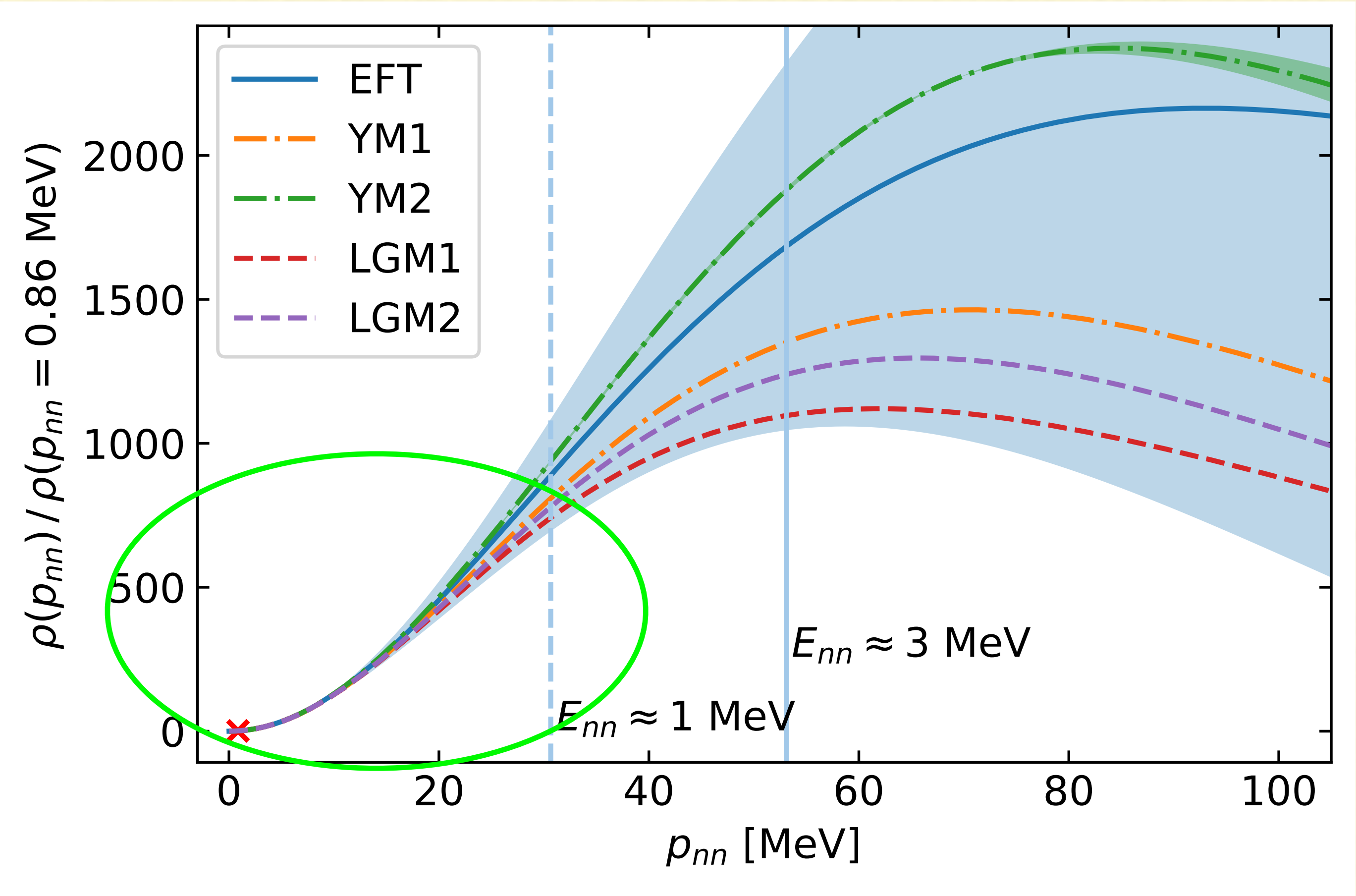

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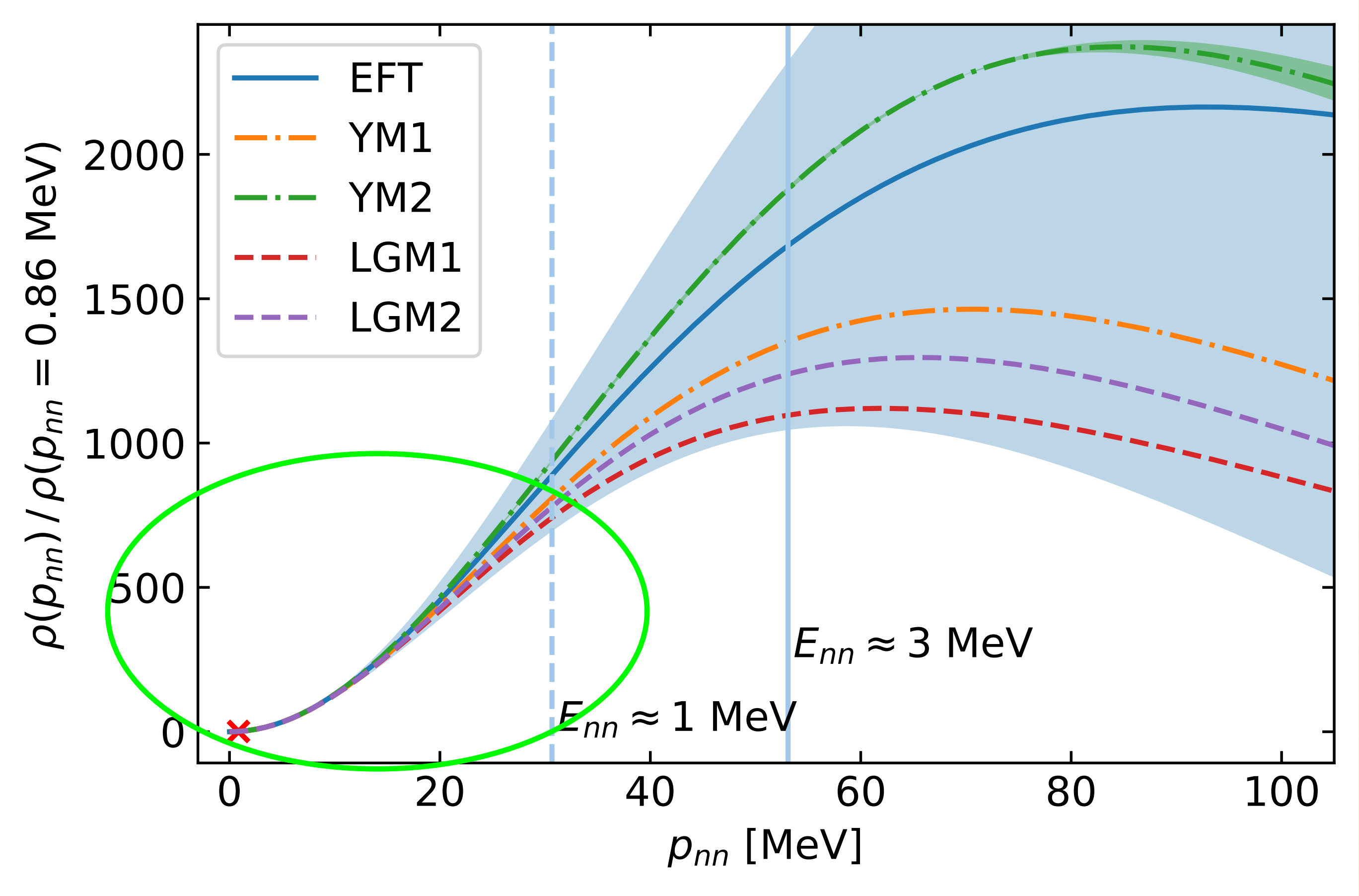

- EFT result shown with error band constructed as p_{nn}/Λ_b

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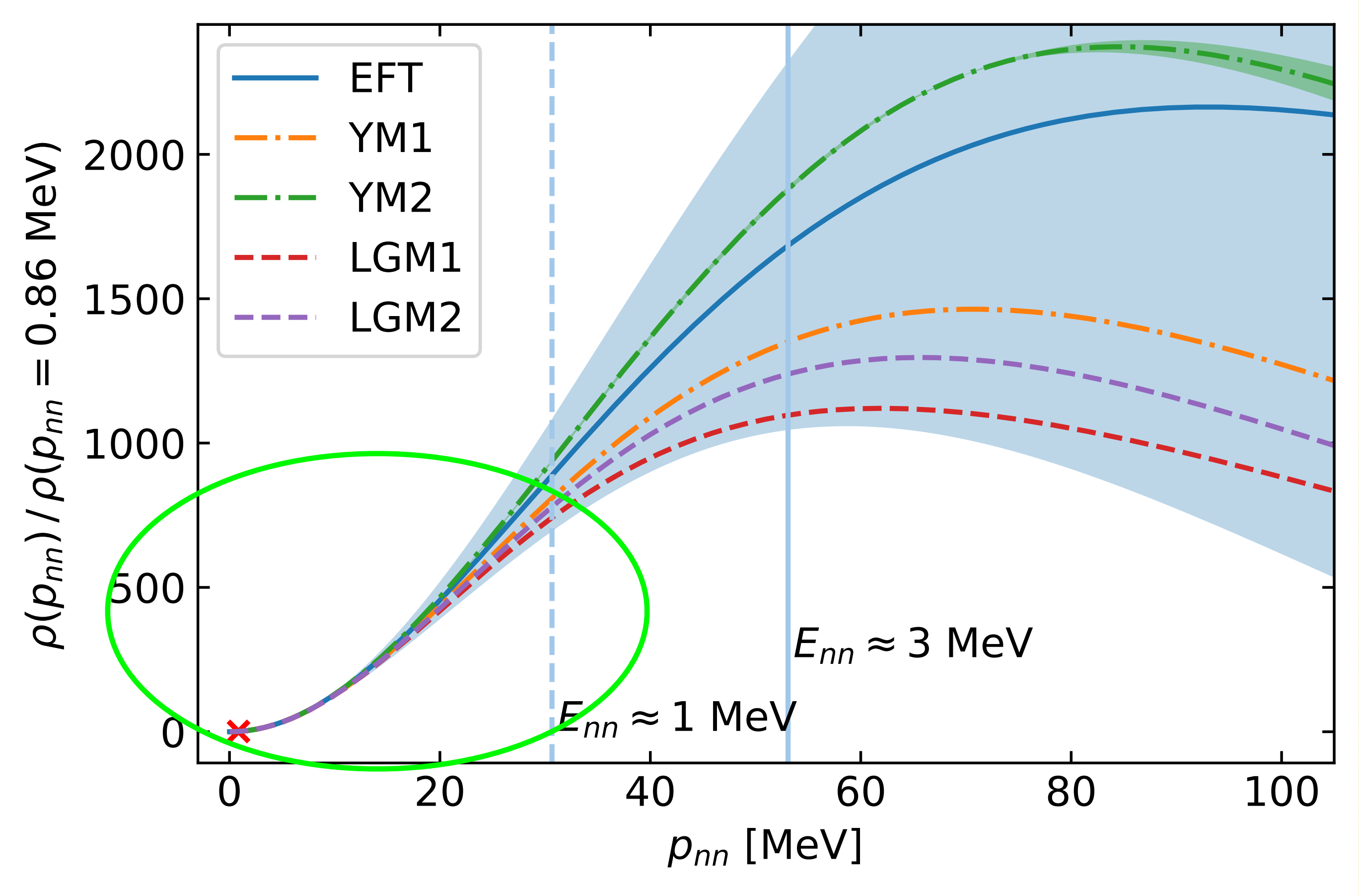

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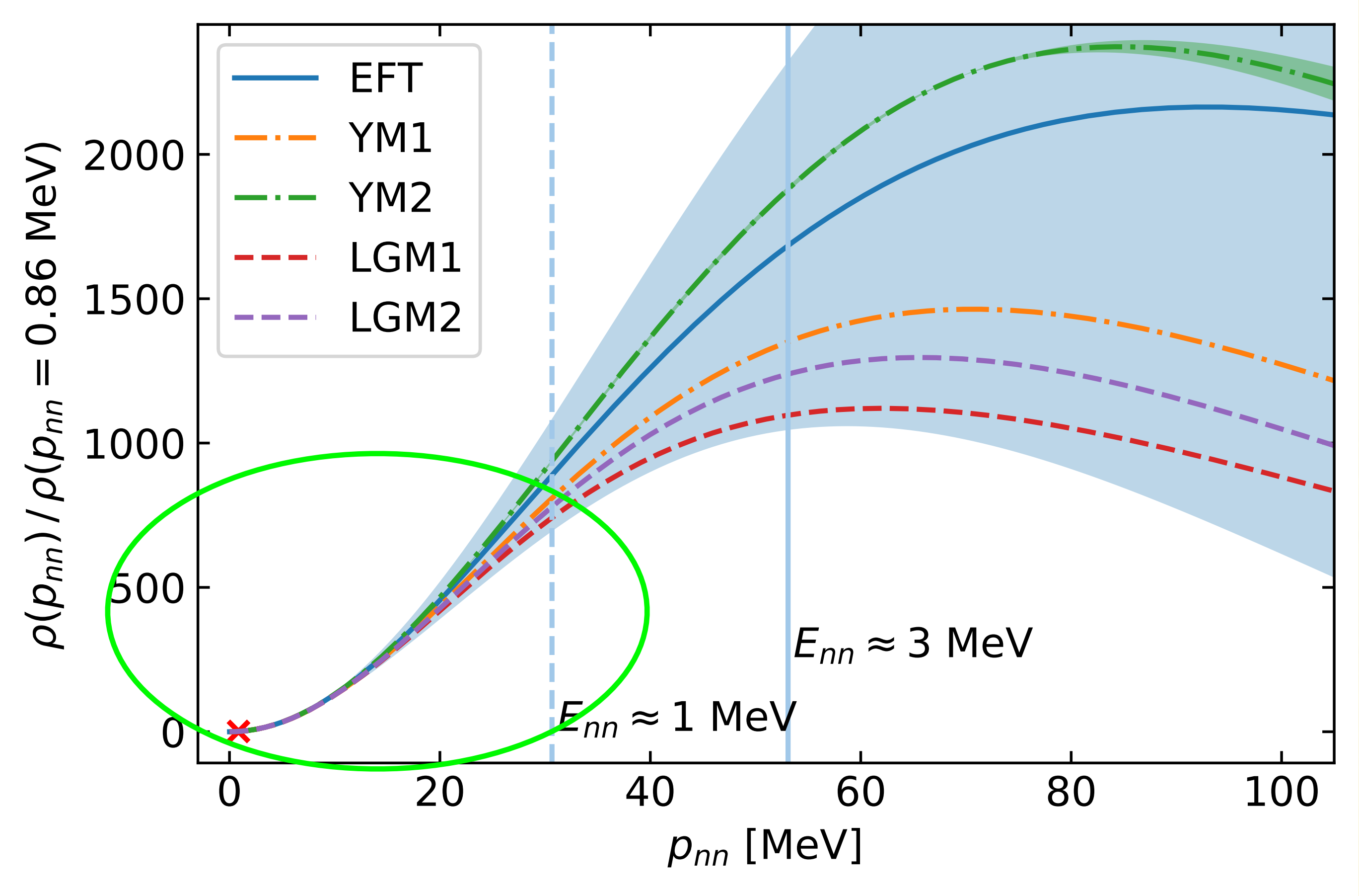

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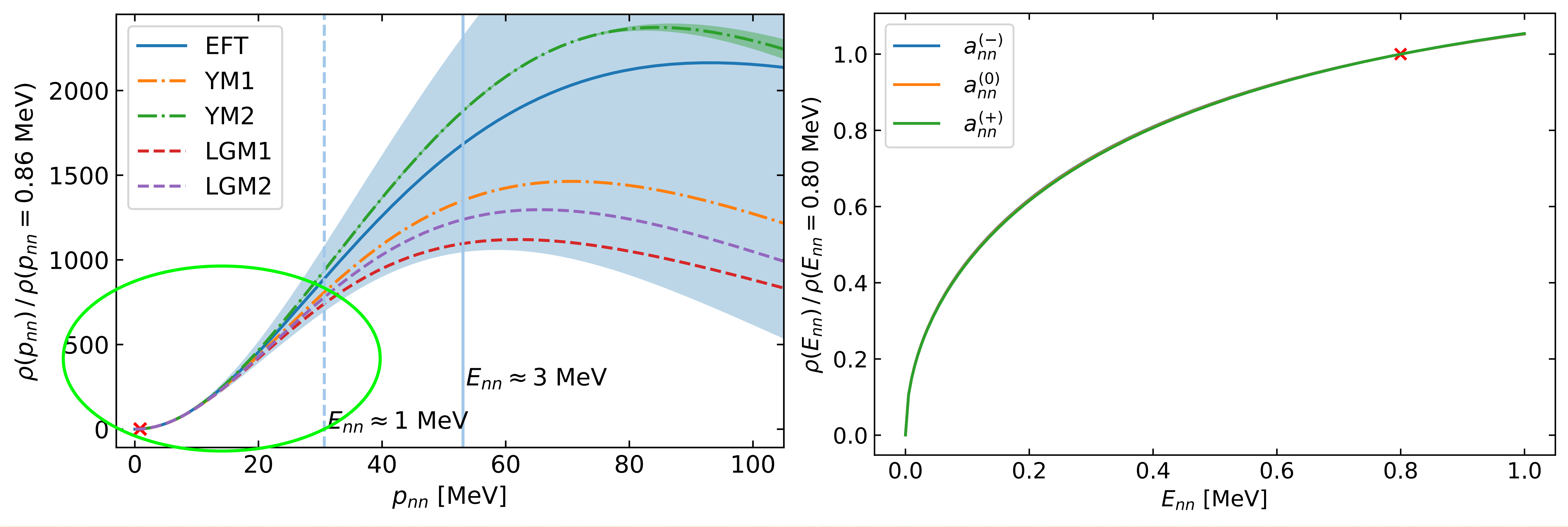

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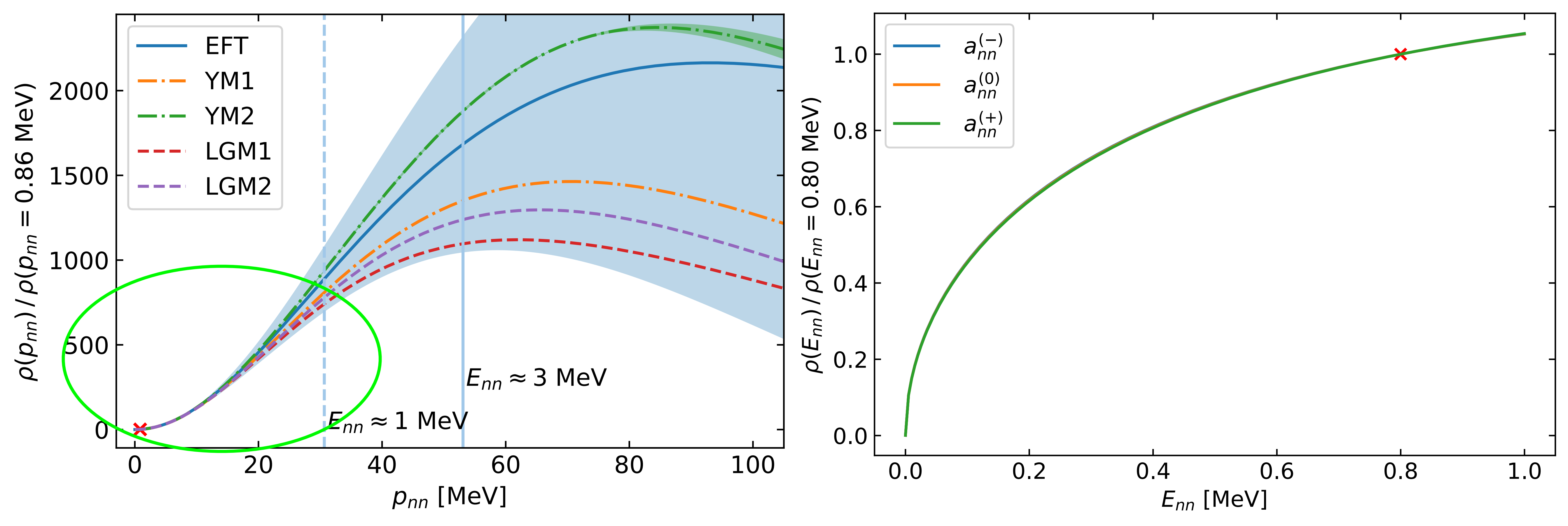

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- Encompasses results of both local Gaussian model and a Yamaguchi model
- Each of which includes several (and not the same) NLO effects
- And note again that Δa_{nn}=2.0 fm has no impact on non-FSI energy spectrum

Adding FSI

FSI enhancement factor ("G1"):

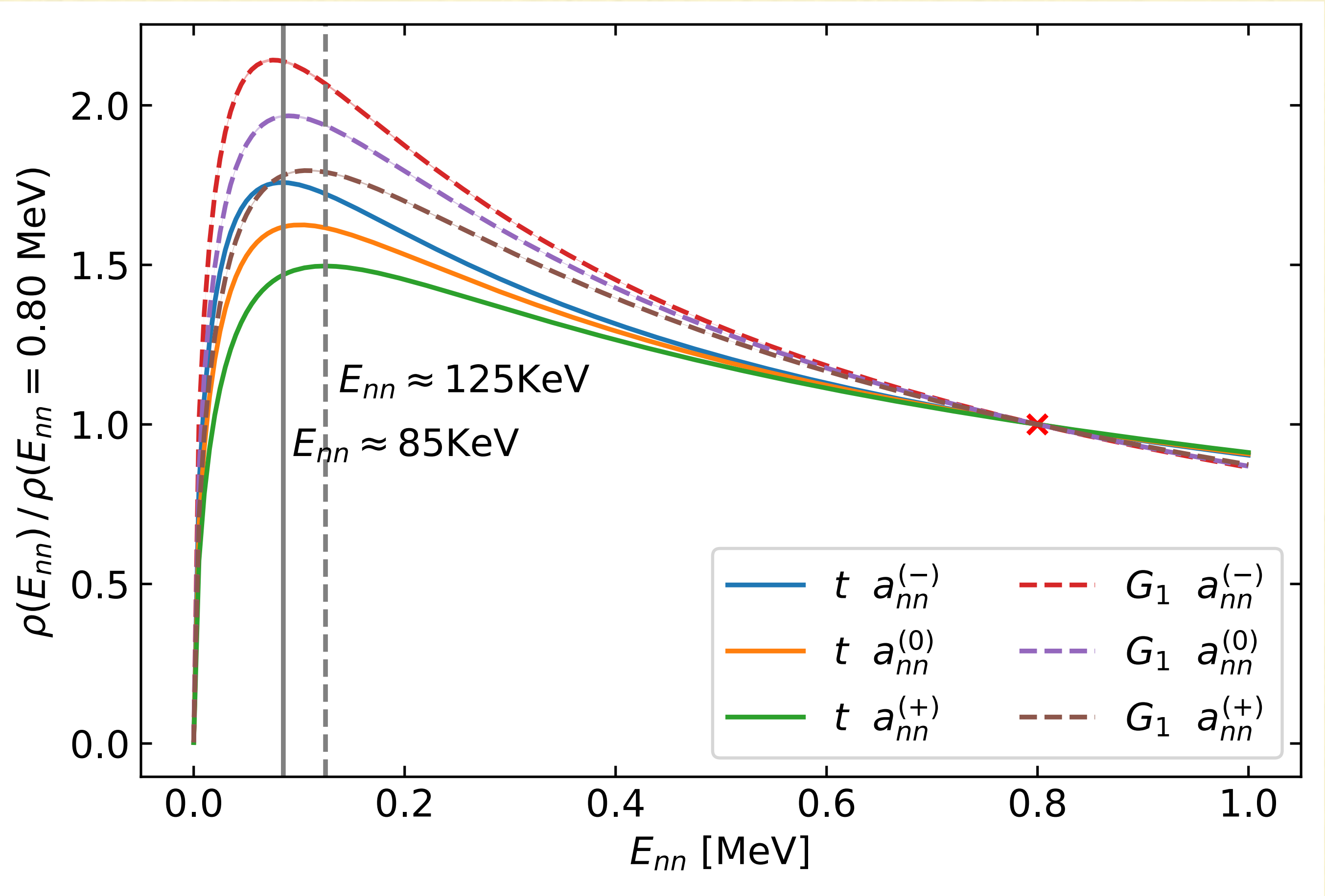
$$G_1(p) = \frac{((p^2+\alpha^2)r_{nn}/2)^2}{(-\frac{1}{a_{nn}}+\frac{r_{nn}}{2}p^2)^2+p^2}, \qquad \alpha = 1/r_{nn}(1+\sqrt{1-2r_{nn}/a_{nn}})$$

Slobodrian (1971)

Explicit calculation of rescattering ("t"):

$$\Psi^{\mathrm{wFSI}}(p,q) = \langle p,q\,|\,(\mathbb{1}+t_{nn}(E_p)G_0^{(nn)}(E_p))\,|\,\Psi\rangle$$

$$= \Psi(p,q) + \frac{2}{\pi}g_0(p)\frac{1}{a_{nn}^{-1}-\frac{r_{nn}}{2}p^2+ip}\int dp'\,p'^2 g_0(p')(p^2-p'^2+i\epsilon)^{-1}\Psi(p',q)$$



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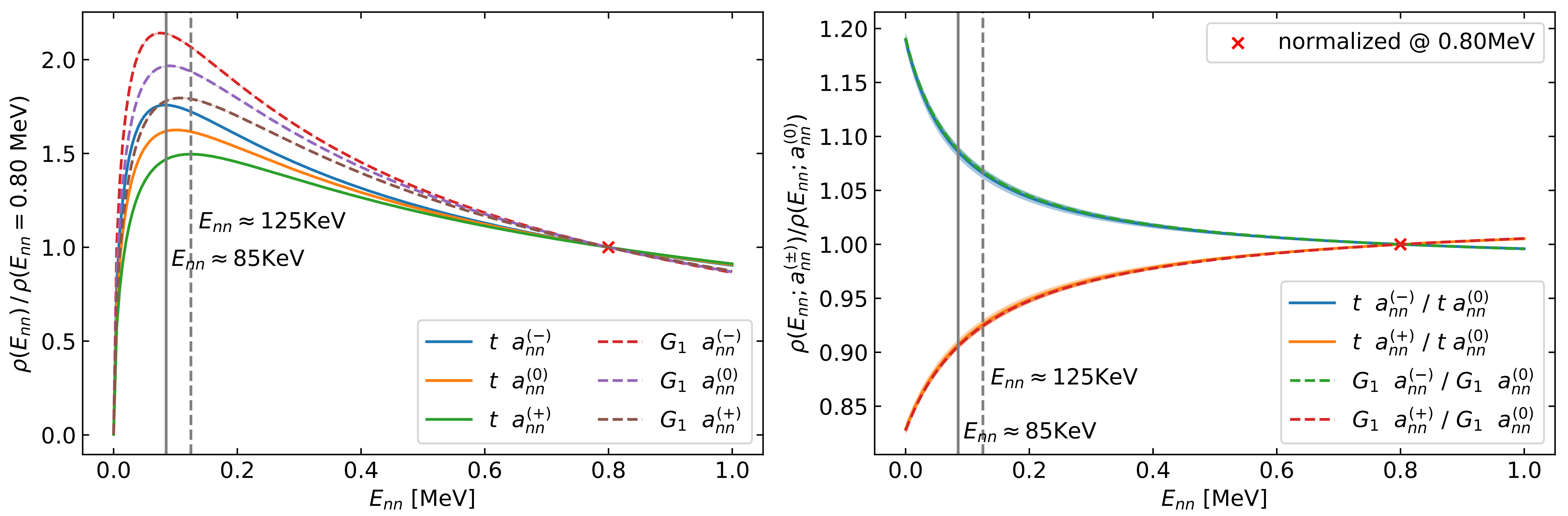

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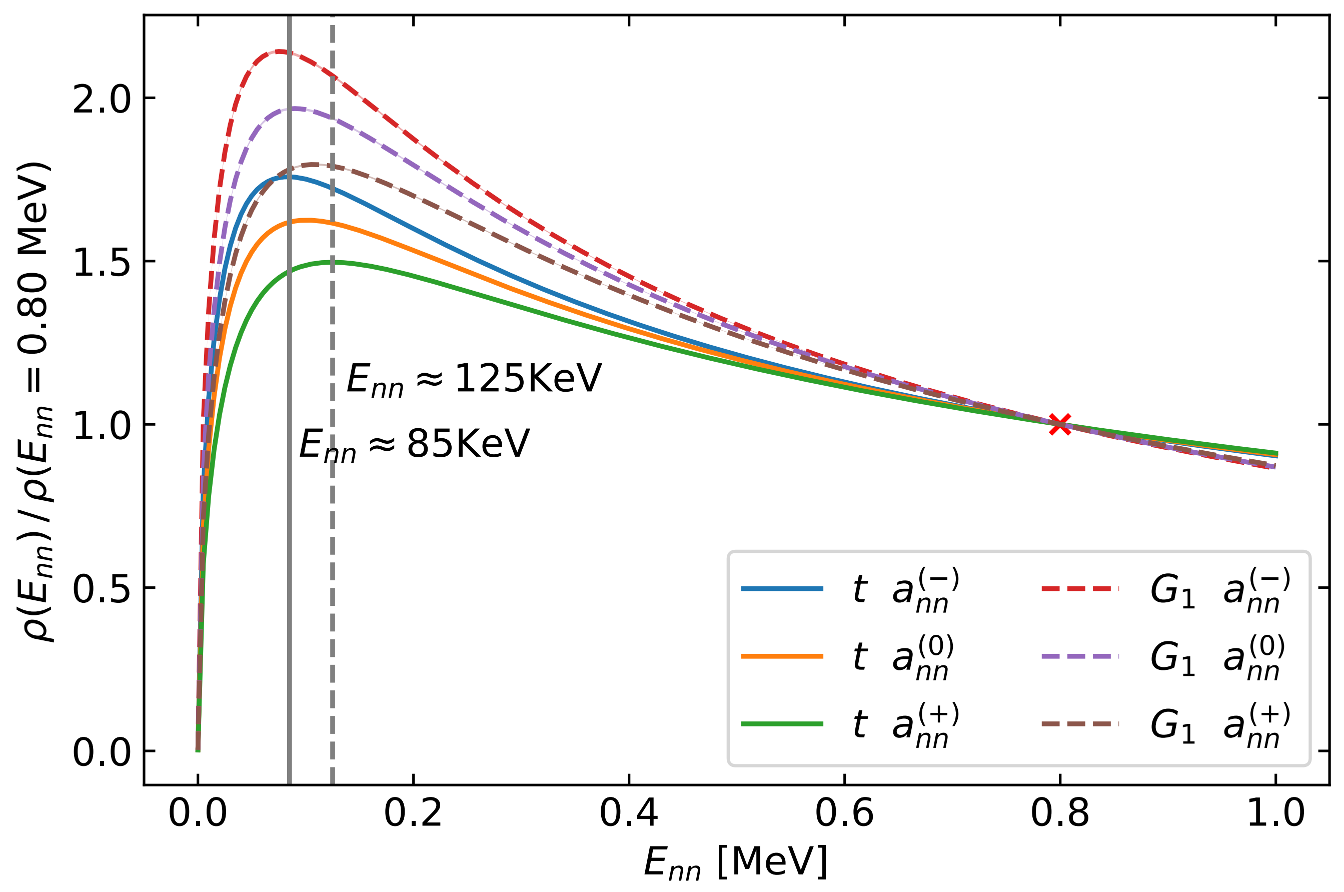
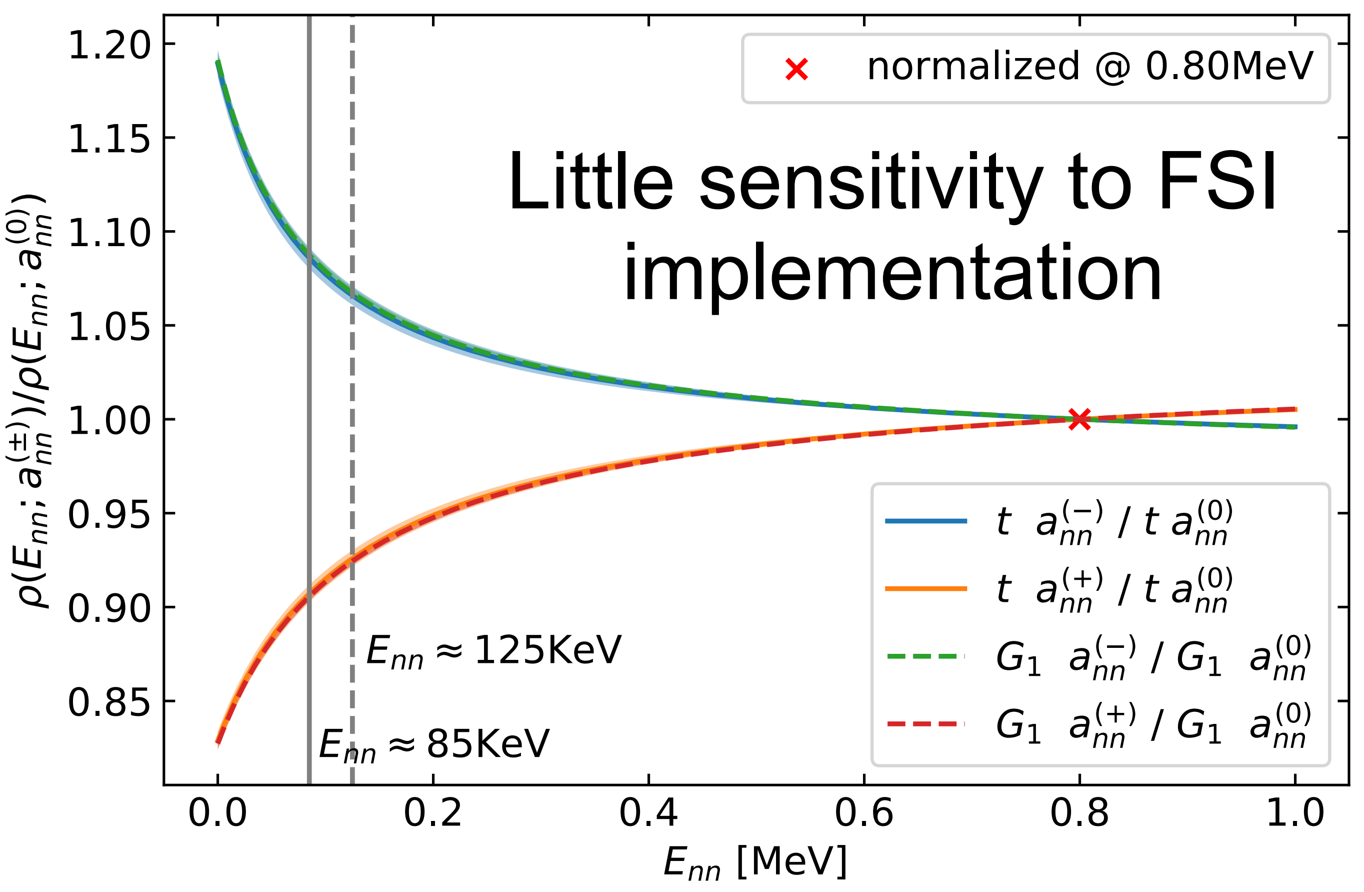
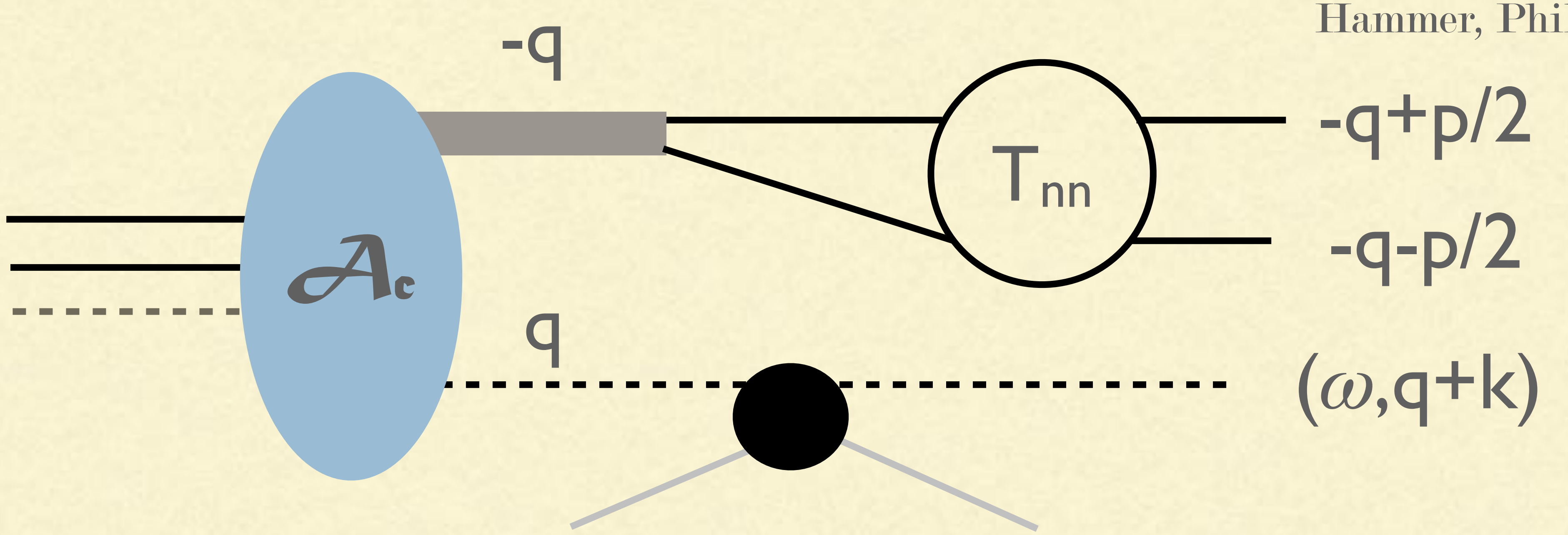
$$= \Psi(p,q) + \frac{2}{\pi}g_0(p)\frac{1}{a_{nn}^{-1} - \frac{r_{nn}}{2}p^2 + ip}\int dp' p'^2 g_0(p')(p^2 - p'^2 + i\epsilon)^{-1}\Psi(p',q)$$





Towards an EFT treatment of FSI

Hammer, Phillips, et al., in preparation



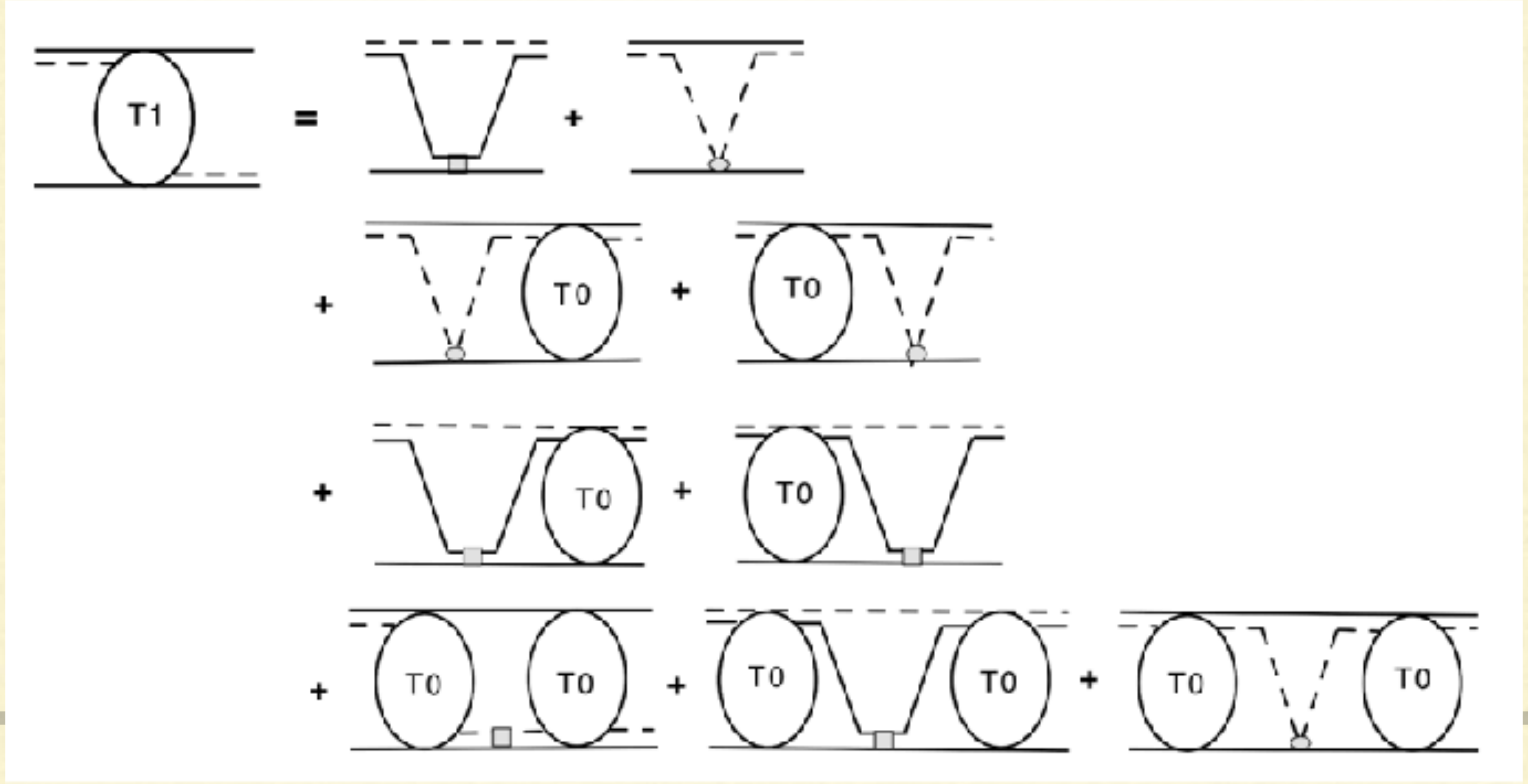
- k ≫ p, q, ɣ so count powers of p/k and q/k in each diagram

Eikonal like

- q∼k suppressed by $(\gamma/k)^4 \approx (50\ \text{MeV}/300\ \text{MeV})^4$
- This diagram∼q T_{nn} for small q and p compared to QF with no FSI: Enhanced
- Diagram calculable: $(1 + t_{nn}\, G_0)$ regularized by 3B wave function
- nα interaction∼$(q/k)^2\, T_{n\alpha}(E_{n\alpha})$
- Short-distance reaction mechanism dominates at large ω: different q behavior

^{6}He wave function at NLO

- Above results used LO in expansion in $R_{core}/R_{halo} \approx 1/4$ for wave function
- At NLO we need to consider impact of r_{nn} in nn $^1S_0$ and ik^3 in $^2P_{3/2}$
- Also include $^2S_{1/2}$ nα channel
- Accuracy expected $(R_{core}/R_{halo})^2 \approx 1/16$; note a_{nn} dependence of $|\psi\rangle$ small



Thapalaiya, Ji, DP;
Thapaliya Ph.D. thesis
(2016)

Conclusions & Implications for experiment

- Halo EFT provides a systematic way to treat weakly-bound nuclei

  Theoretical uncertainties assessed as $(R_{core}/R_{halo})^{n+1}$

- Establishes universal correlations

  Which quantities must be controlled for a given accuracy

- Can compute a_{nn} dependence of neutron spectrum in ^{6}He(p,p'α)

- Almost all a_{nn}-dependence comes from nn FSI

  Göbel et al., arXiv:2103.03224

- Very little dependence on ^{6}He structure or regulator or r_{nn}

- Phenomenological FSI treatment encouraging but want error estimates; EFT treatment under development.

- NLO wave function also in progress.

  Göbel, Hammer, Ji, DP, Thapaliya

- Binning data in q could reduce theory uncertainty and provide check

Backup Slides

Two-body t beyond LO

$$t_0^{2B}(E) = -\frac{2\pi}{m_R}\frac{1}{k\cot\delta(E) - ik}; \quad k = \sqrt{2m_R E}$$

$$k\cot\delta(E) = -\frac{1}{a} + \frac{1}{2}rk^2 + O(k^4R^3)$$

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- Effective-range expansion, valid for kR<1
- Typical situation |r|~R. Here we assume |r|≪|a|
- Expand t in r/a

$$t(E) = \frac{2\pi a}{m_R}\frac{1}{1+iak}\left[1 + \frac{1}{2}\frac{rk^2}{1/a+ik} + O\left(\frac{r^2}{a^2}\right)\right]$$

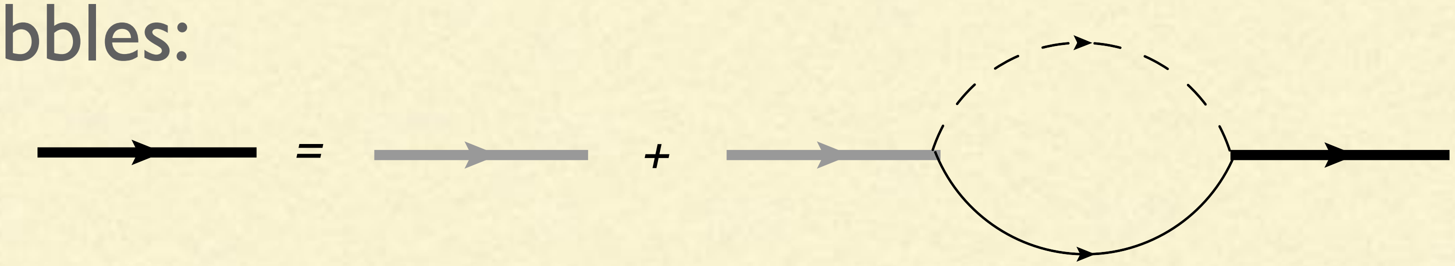
LO **NLO**

- ...provided k~1/a. As good as ERE?

Dressing the s-wave state

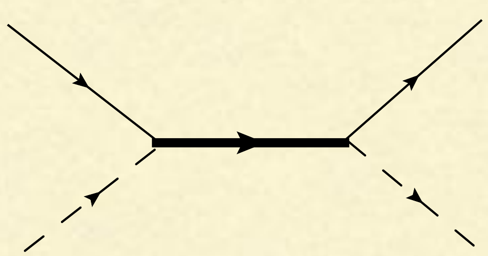
Kaplan, Savage, Wise; van Kolck; Gegelia; Birse, Richardson, McGovern

- σnc coupling g_0 of order R_{halo}, nc loop of order $1/R_{halo}$. Therefore need to sum all bubbles:



$$D_\sigma(p) = \frac{1}{\Delta_0 + \eta_0[p_0 - \mathbf{p}^2/(2M_{nc})] - \Sigma_\sigma(p)}$$

$$\Sigma_\sigma(p) = -\frac{g_0^2 m_R}{2\pi}\left[\mu + i\sqrt{2m_R\left(p_0 - \frac{\mathbf{p}^2}{2M_{nc}} + i\eta\right)}\right] \qquad \text{(PDS)}$$

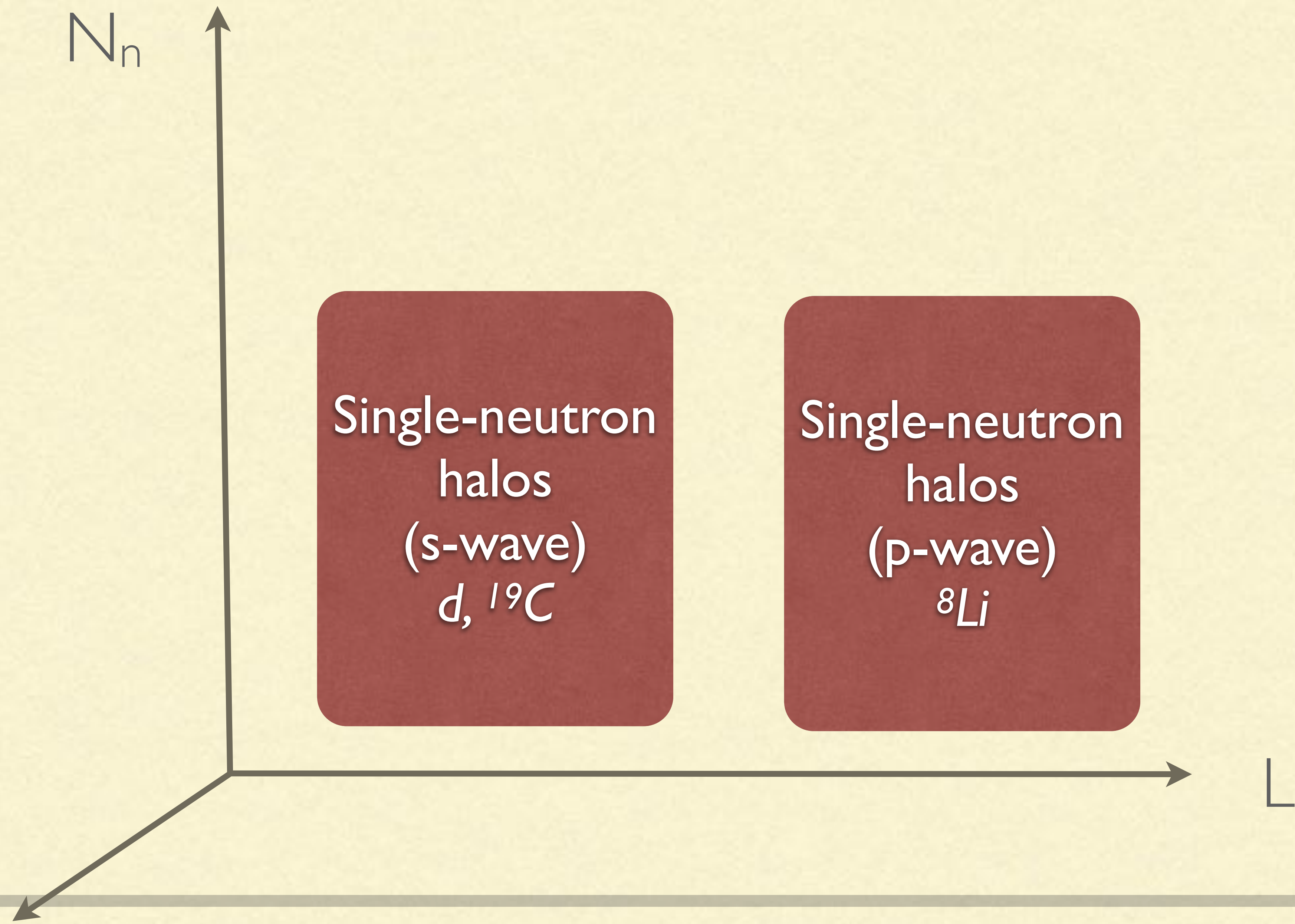


$$t = \frac{2\pi}{m_R}\frac{1}{\frac{1}{a_0} - \frac{1}{2}r_0 k^2 + ik}$$

$$D_\sigma(p) = \frac{2\pi\gamma_0}{m_R^2 g_0^2}\frac{1}{1 - r_0\gamma_0}\frac{1}{p_0 - \frac{\mathbf{p}^2}{2M_{nc}} + B_0} + \text{regular}$$

Counting in S waves:
$a_0 \sim R_{halo} \sim 1/\gamma_0$; $r_0 \sim R_{core}$.
$r_0 = 0$ at LO.

The multi-dimensional Halo EFT space



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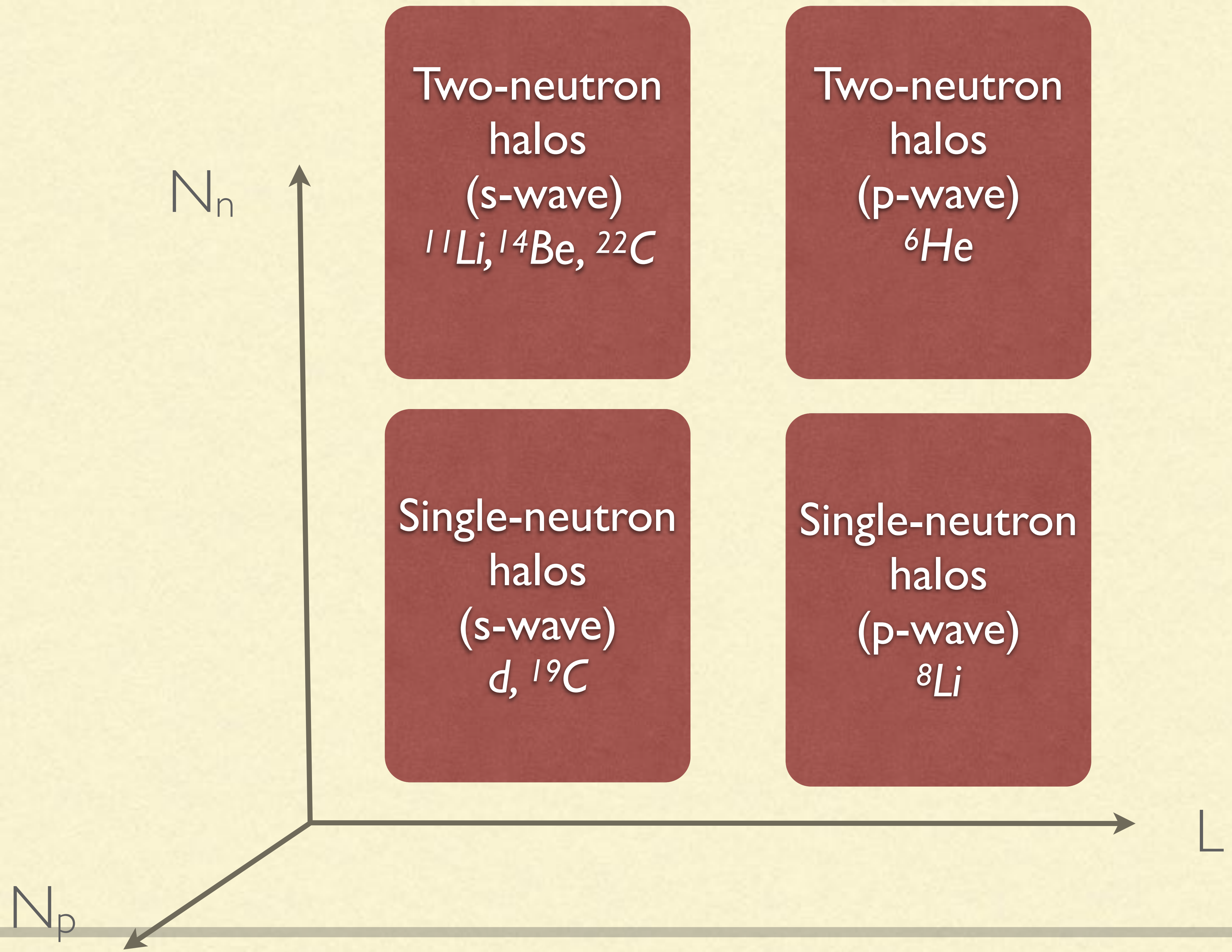

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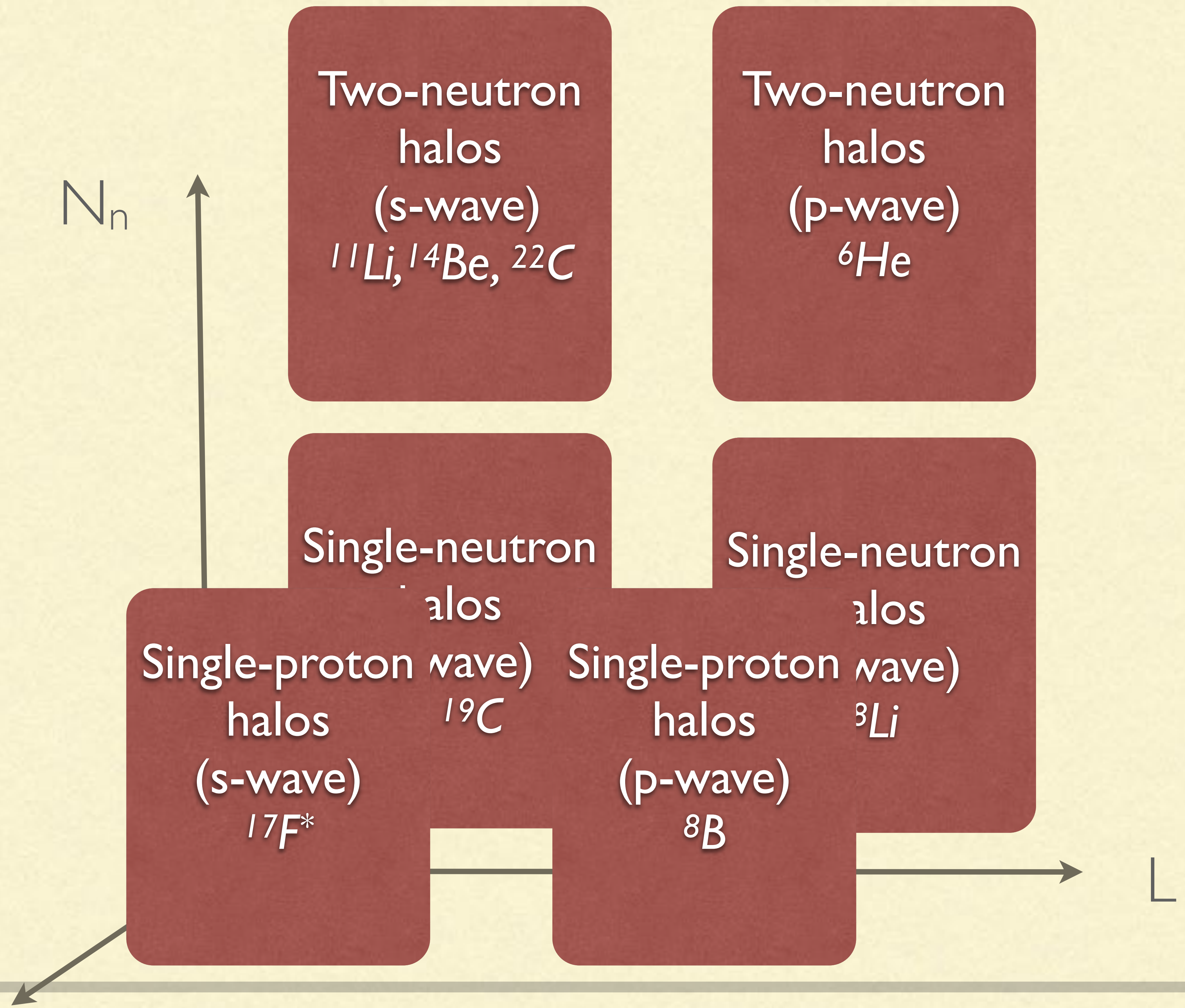

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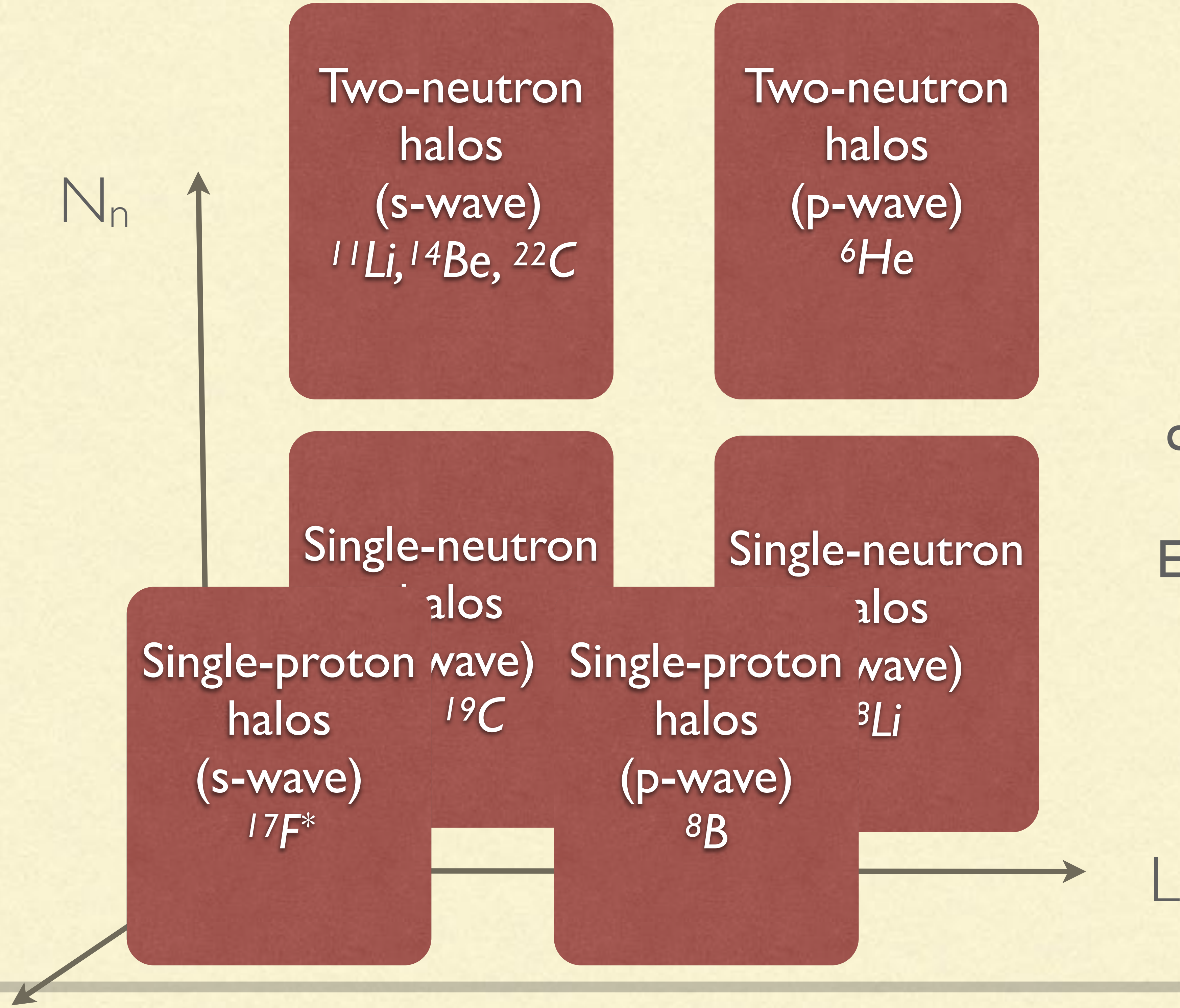

Plus complementary direction: N_α
E.g. ^{9}Be, $^{12}C^*$, etc.

Equations for s-wave 2n halo

Canham, Hammer (2008)

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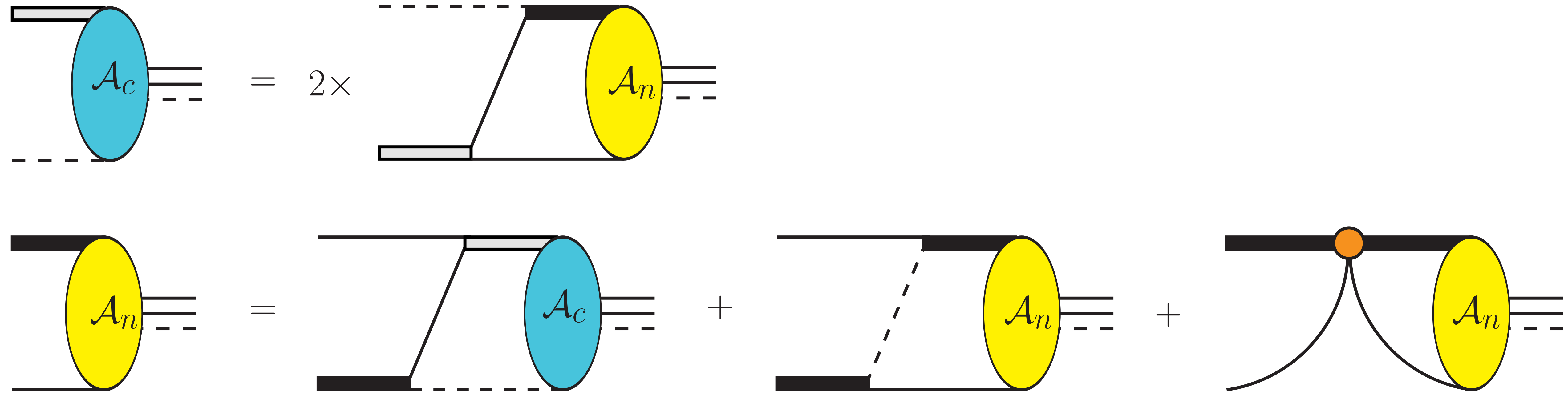
- Core-n and n-n contact interactions at leading order: solve 3B problem



- (cn)-n contact interaction to stabilize three-body system

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Canham, Hammer (2008)

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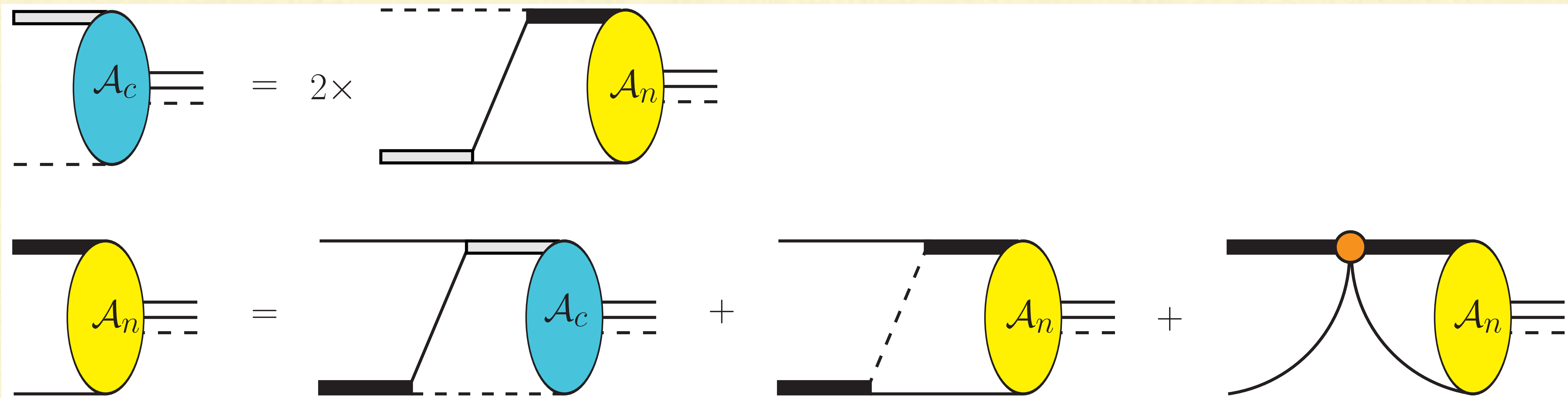

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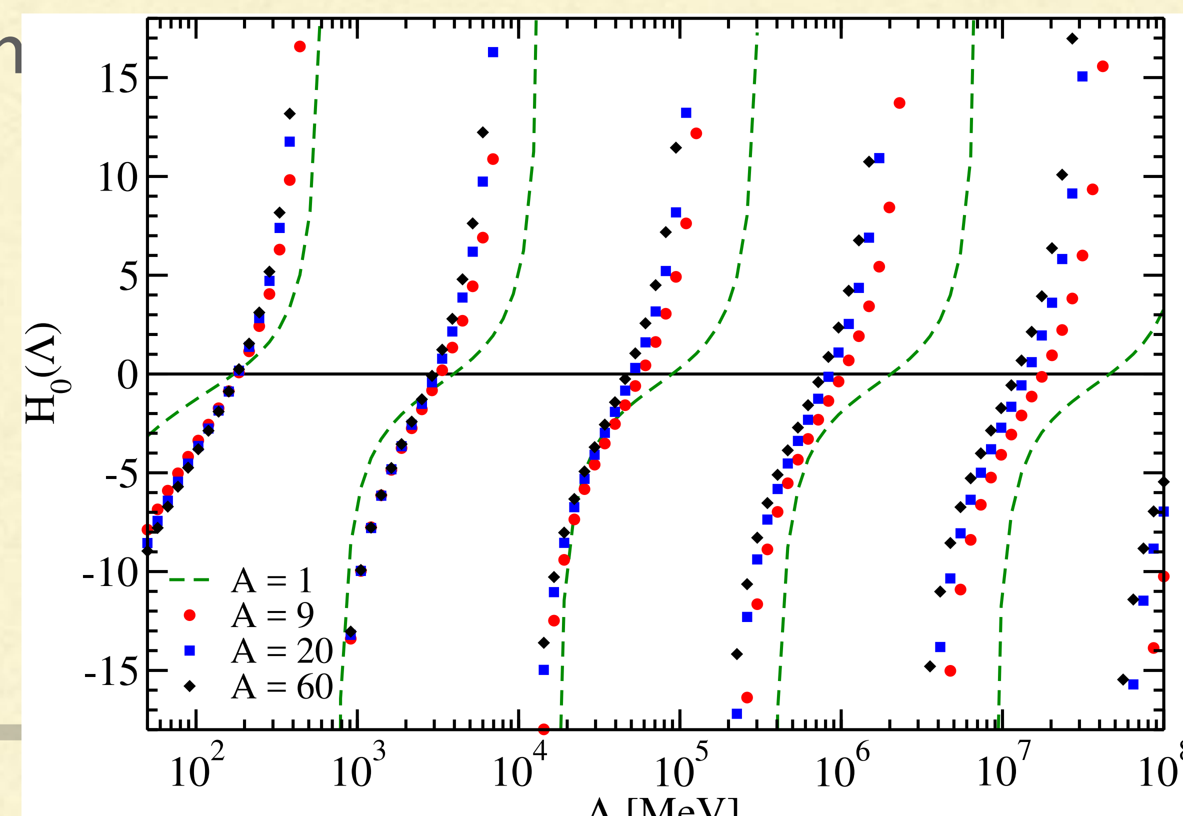

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Canham, Hammer (2008)

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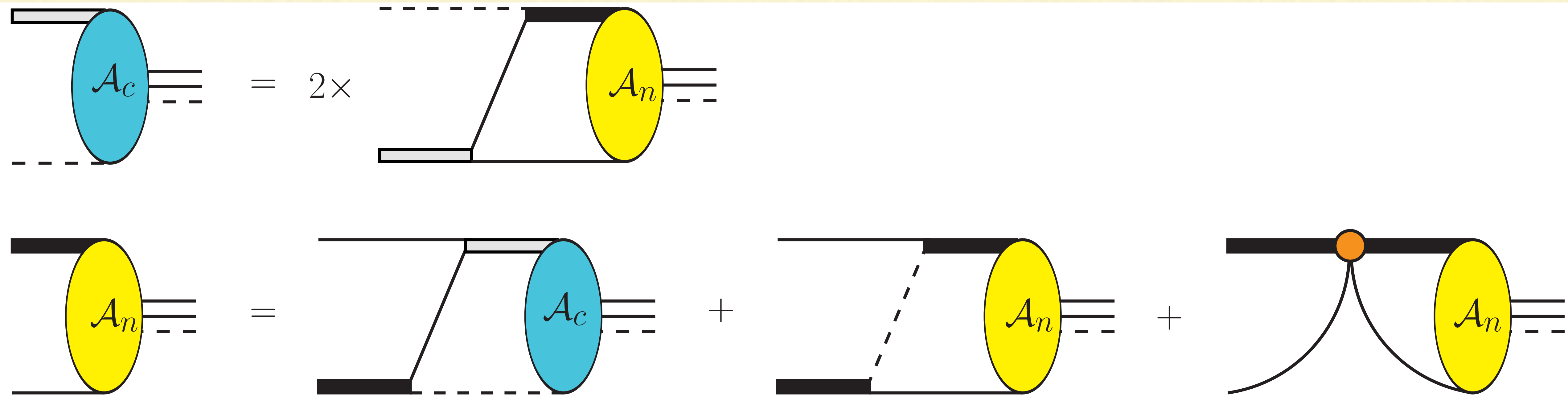
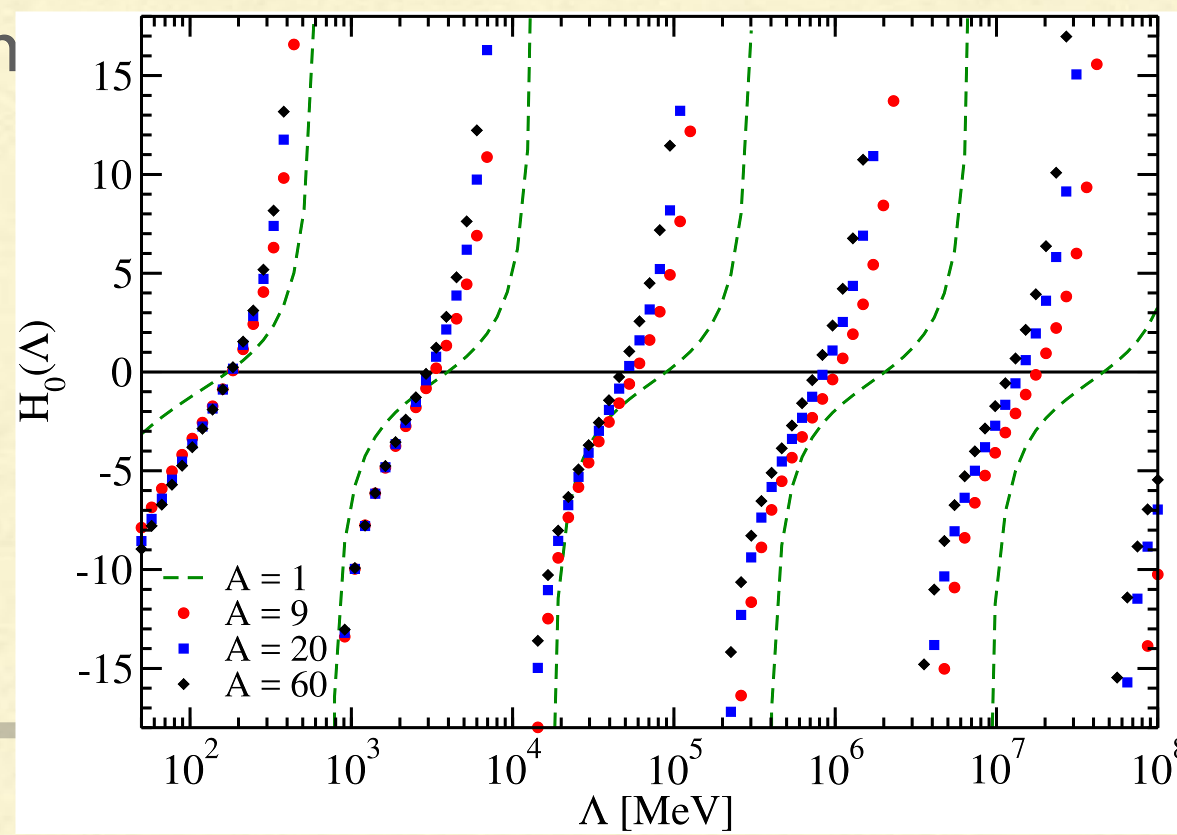


- (cn)-n contact interaction to stabilize th

- Efimov-Thomas effects

- Inputs: $E_{nn}=1/(m\ a_{nn}^2)$, E_{nc}, S_{2n} (=B)

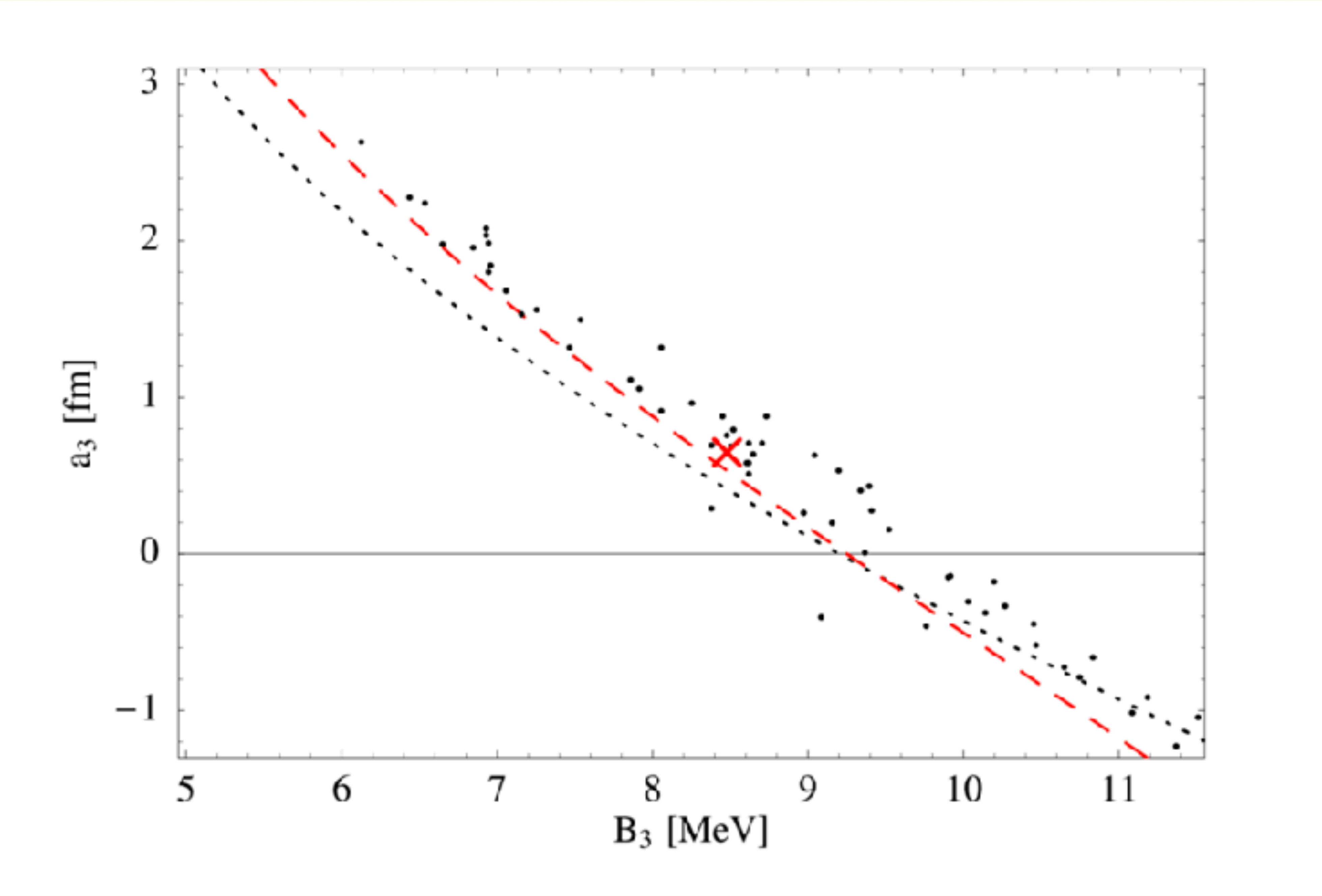
- Output: everything; up to $O(R_{core}/R_{halo})$



Universal correlation

Phillips (1968), Bedaque, Hammer, van Kolck (2000), Bedaque, Repak, Griesshammer, Hammer, (2002)

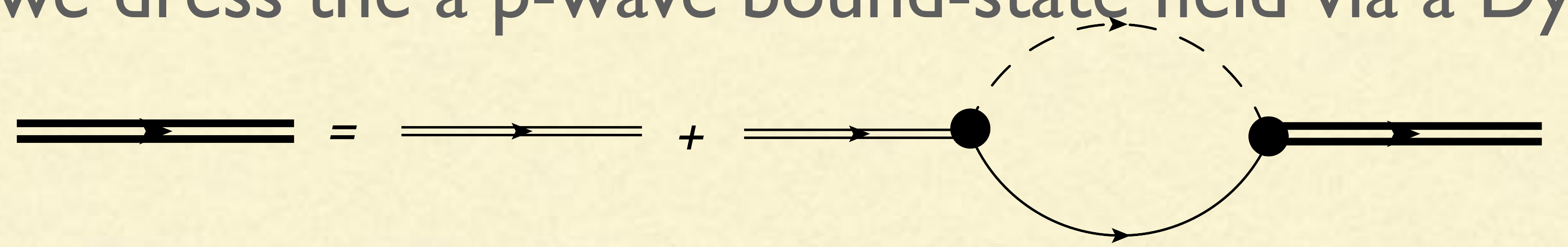
Plot a_{nd} ($S_{1/2}$ channel) vs. triton binding energy



Shallow p-wave resonance

Bertulani, Hammer, van Kolck (2002); Bedaque, Hammer, van Kolck (2003)

- Formally we dress the a p-wave bound-state field via a Dyson equation:



$$D_\pi(p) = \frac{1}{\Delta_1 + \eta_1[p_0 - \mathbf{p}^2/(2M_{nc})] - \Sigma_\pi(p)}$$

- Here both Δ_1 and g_1 are mandatory for renormalization at LO

$$\Sigma_\pi(p) = -\frac{m_R g_1^2 k^2}{6\pi}\left[\frac{3}{2}\mu + ik\right]$$

- Reproduces ERE. But here (cf. s waves) cannot take r_1=0 at LO

- Since resonance arises due to cancellation between larger Δ_1 and ηE we can neglect ik^3 (i.e. width) at leading order, as long as we are away from the resonance

Implications: ^{6}He calculation

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- **Cannot** predict S_{2n} for ^{6}He 0^+ ground state from nn and ^{5}He input alone
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Ryberg, Forssen, Platter (2017)

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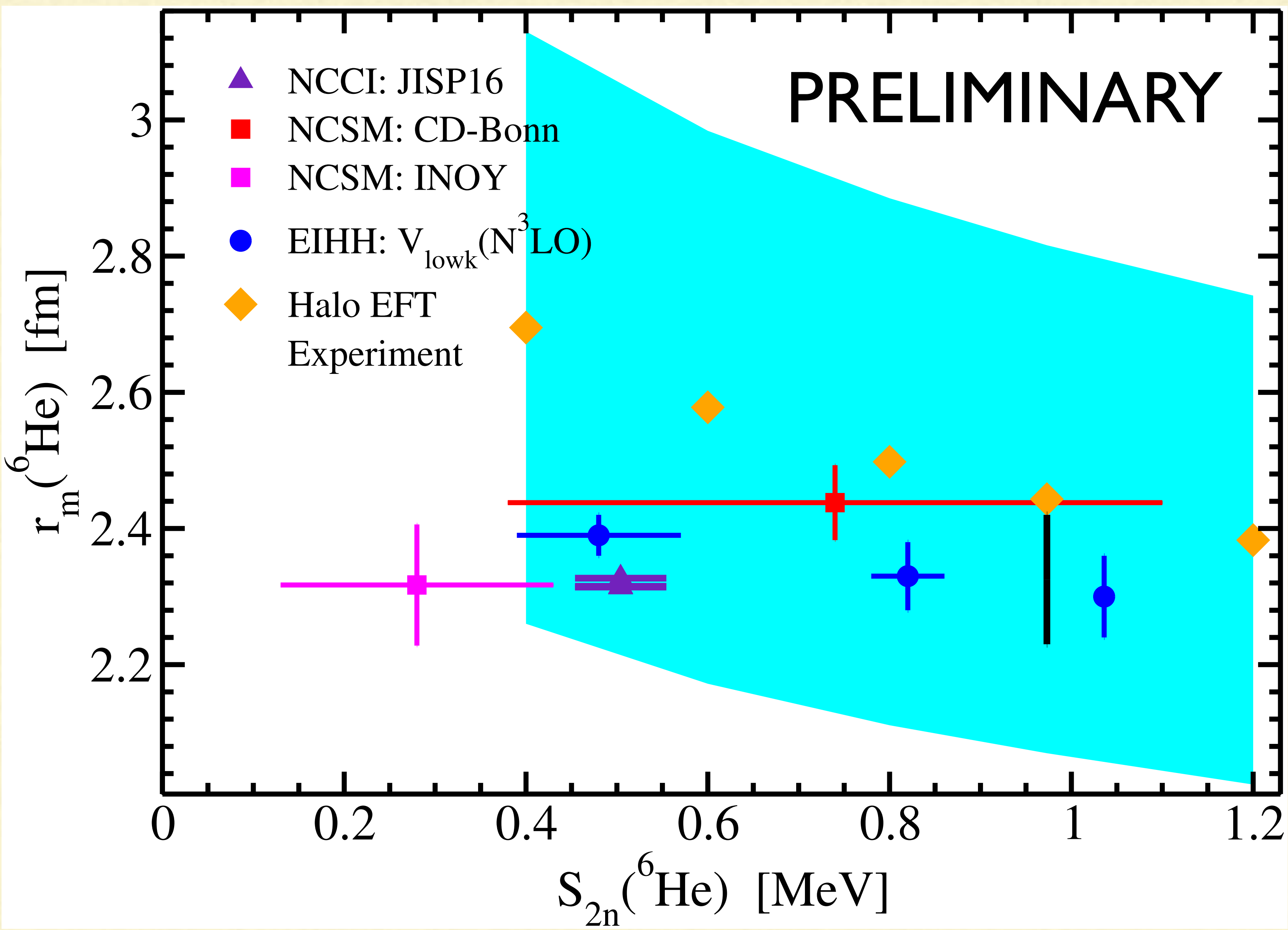
Ryberg, Forssen, Platter (2017)

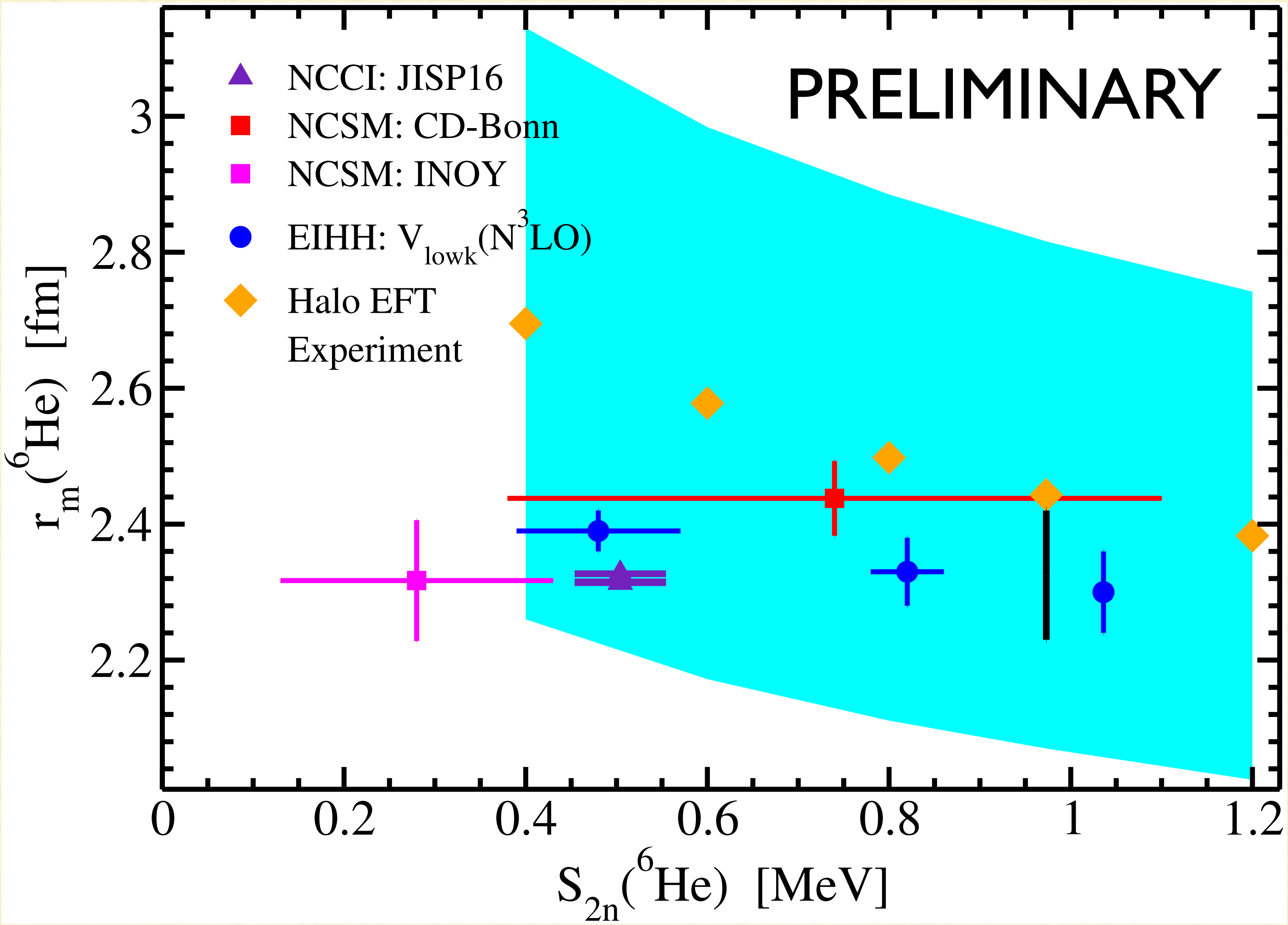
- (Need to fully treat ^{5}He resonances in three-body resonance regime)

A universal correlation in ^{6}He



A universal correlation in ^{6}He

Helium-6 matter radius as a function of S_{2n}



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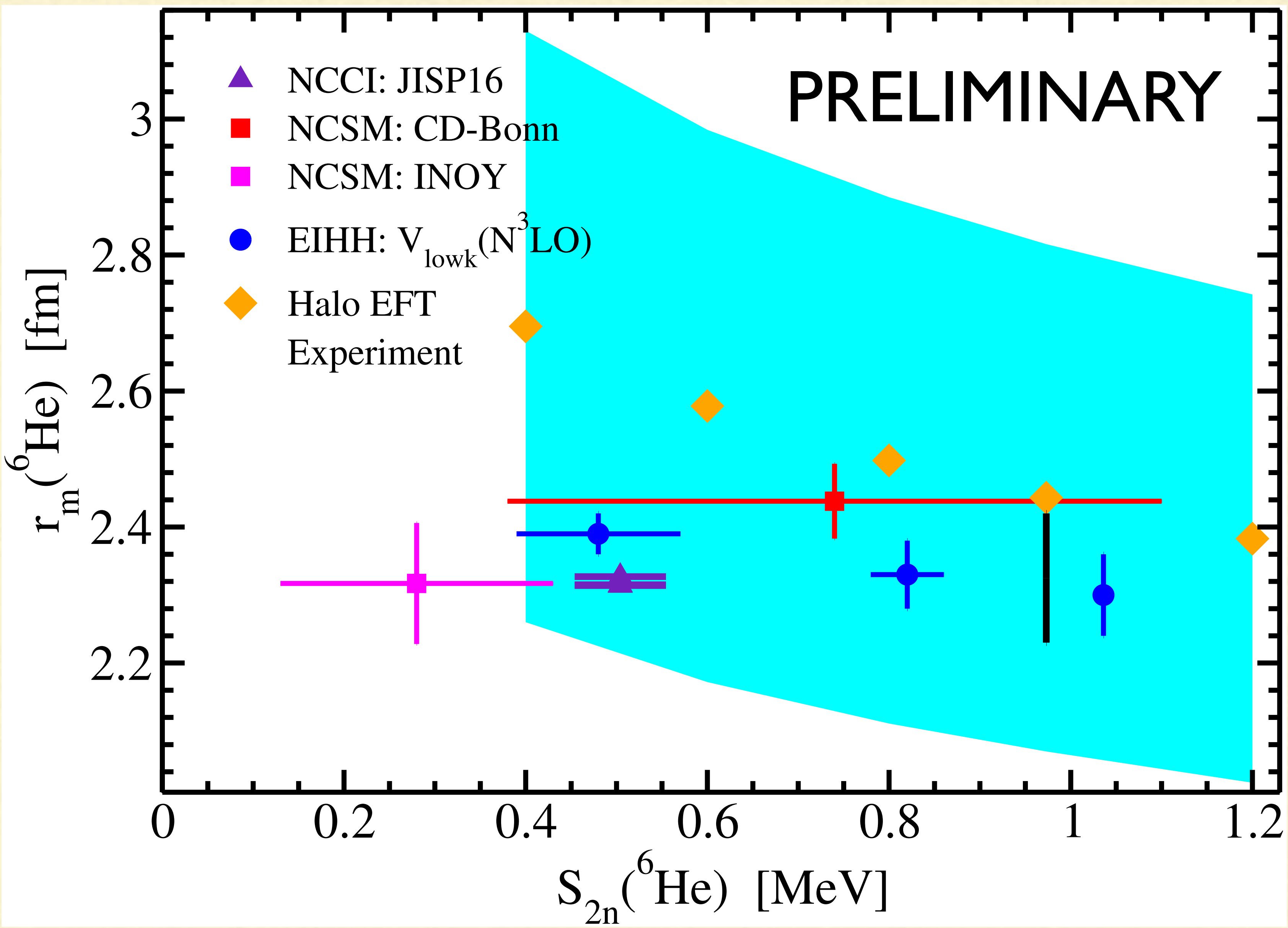
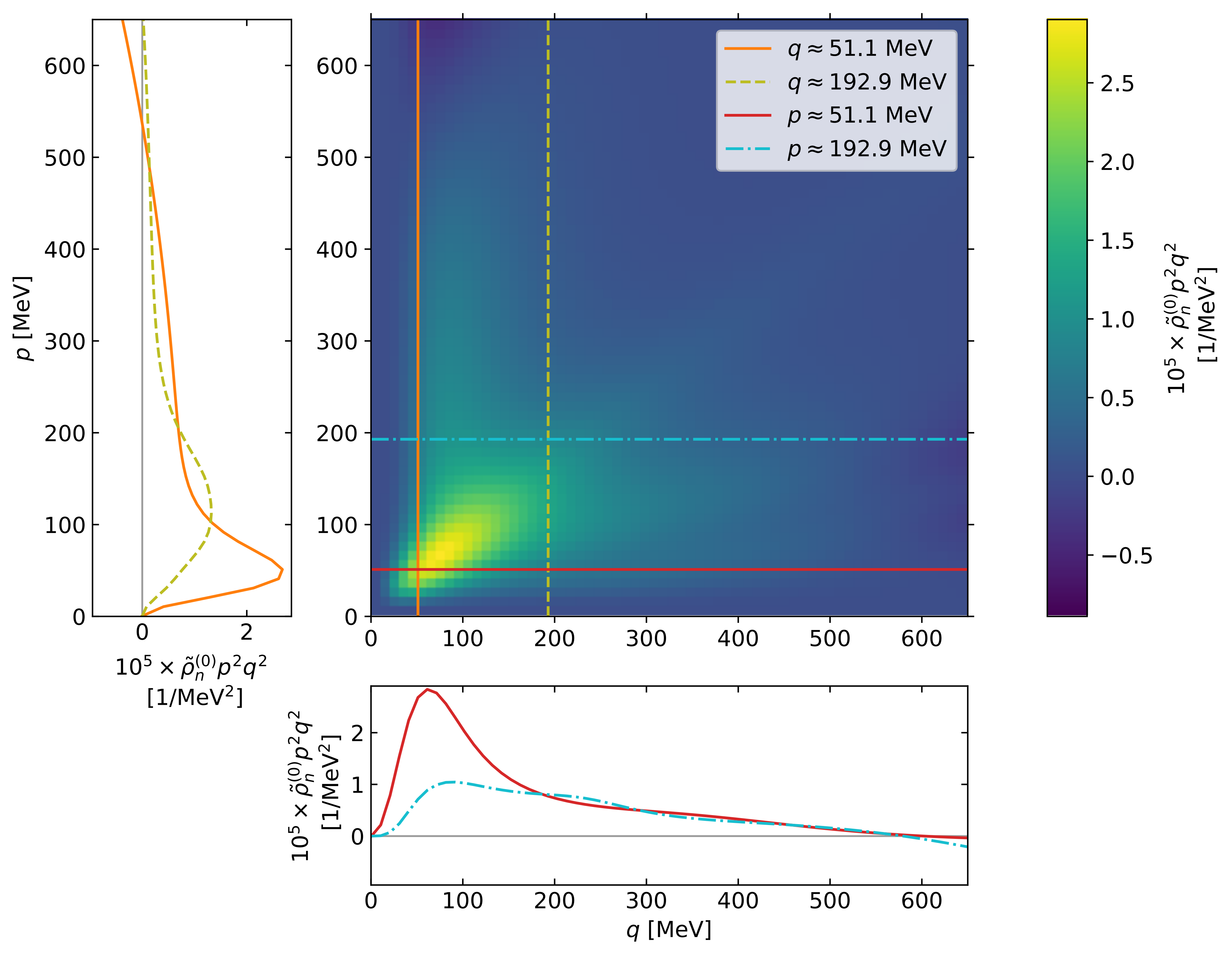


Don't need to compute full radius in *ab initio* model since "exterior" part of radius explained by Halo EFT

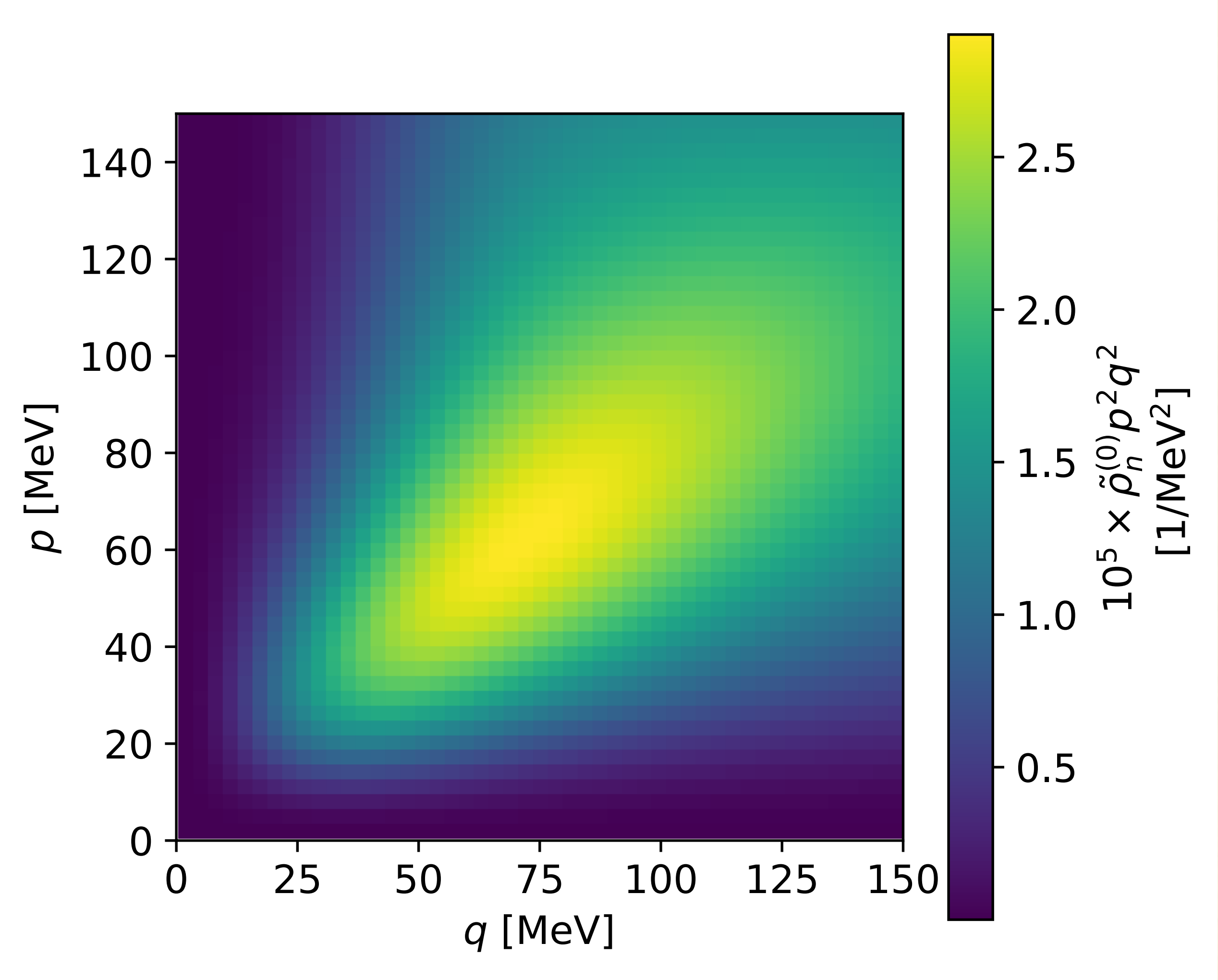
^{6}He probability distributions

Göbel, Hammer, Ji, Phillips, FBS (2019)



- Calculation done here using Faddeev equations and potentials that reproduce EFT amplitude up to a given order
- Energy-dependent potential already at LO; not as simple as just "get wave function and use quantum mechanics"

Cutoff independence



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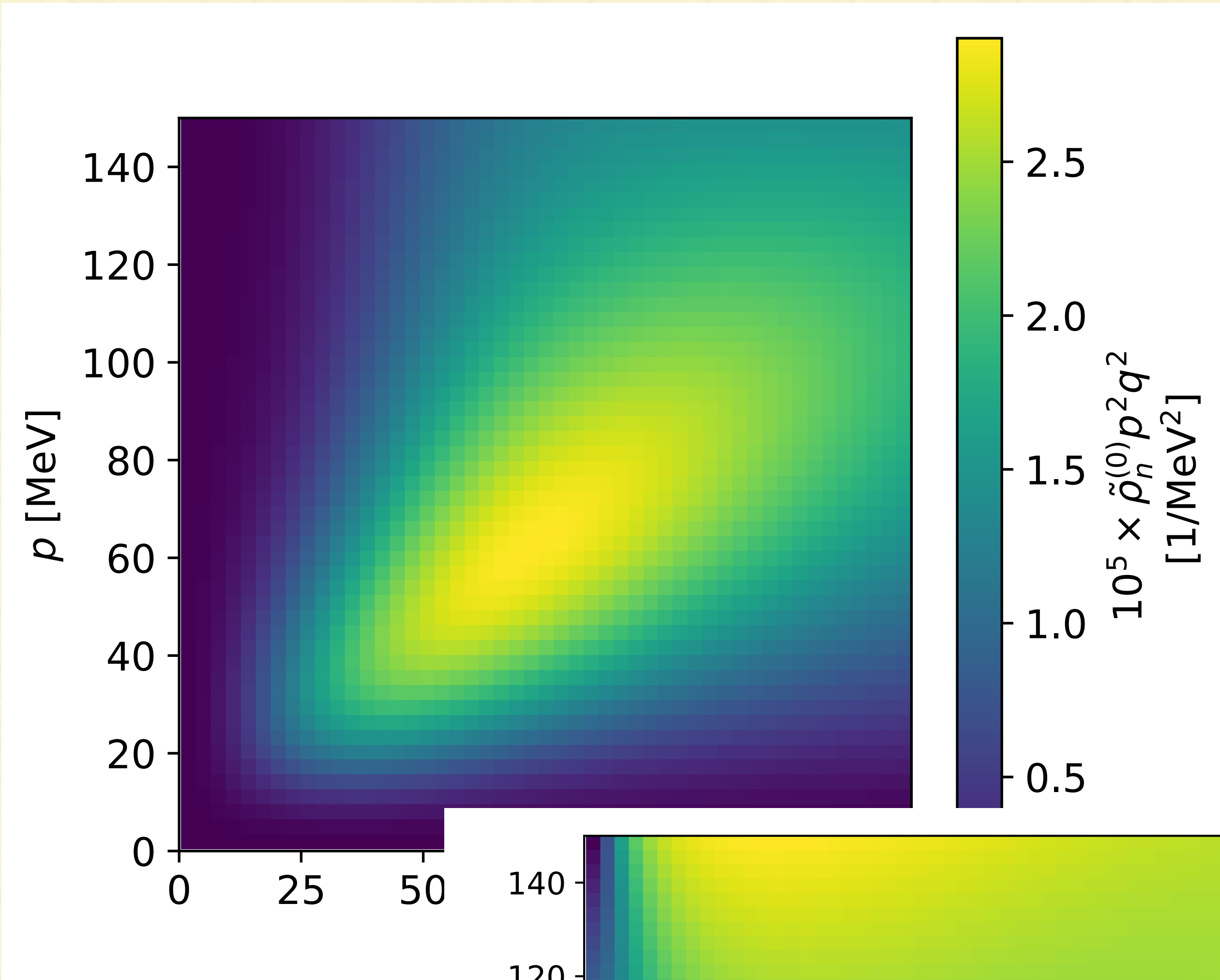
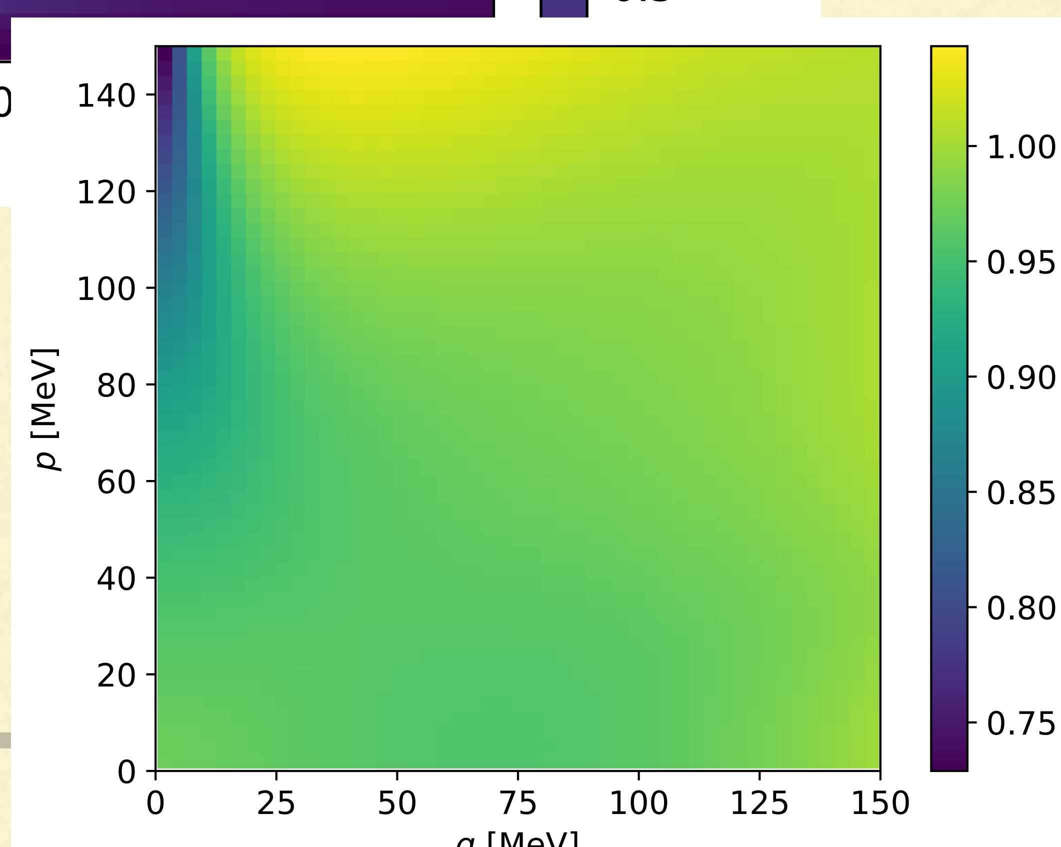
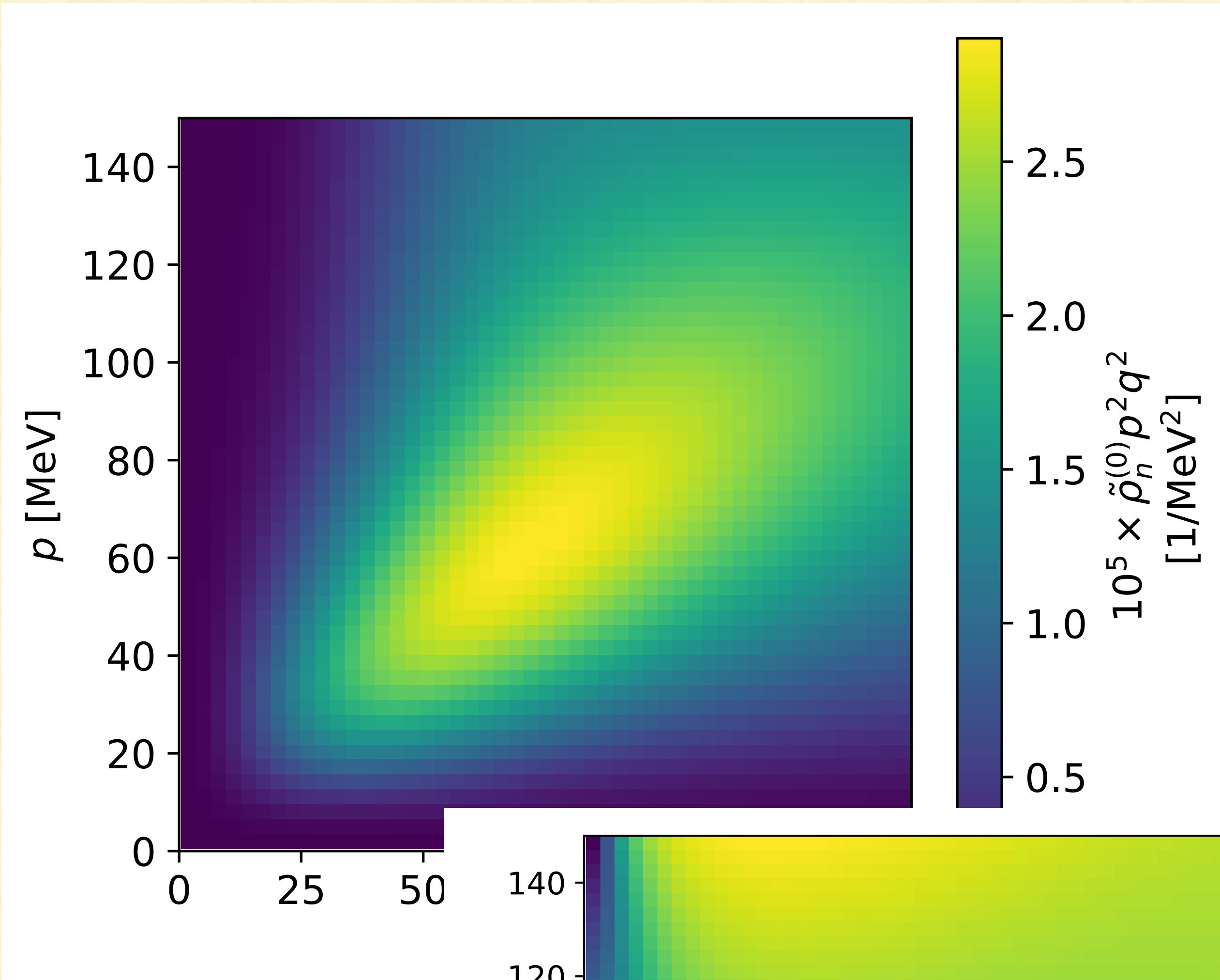




Sharp cutoff at 750 MeV vs. sharp cutoff at 1500 MeV

Cutoff independence



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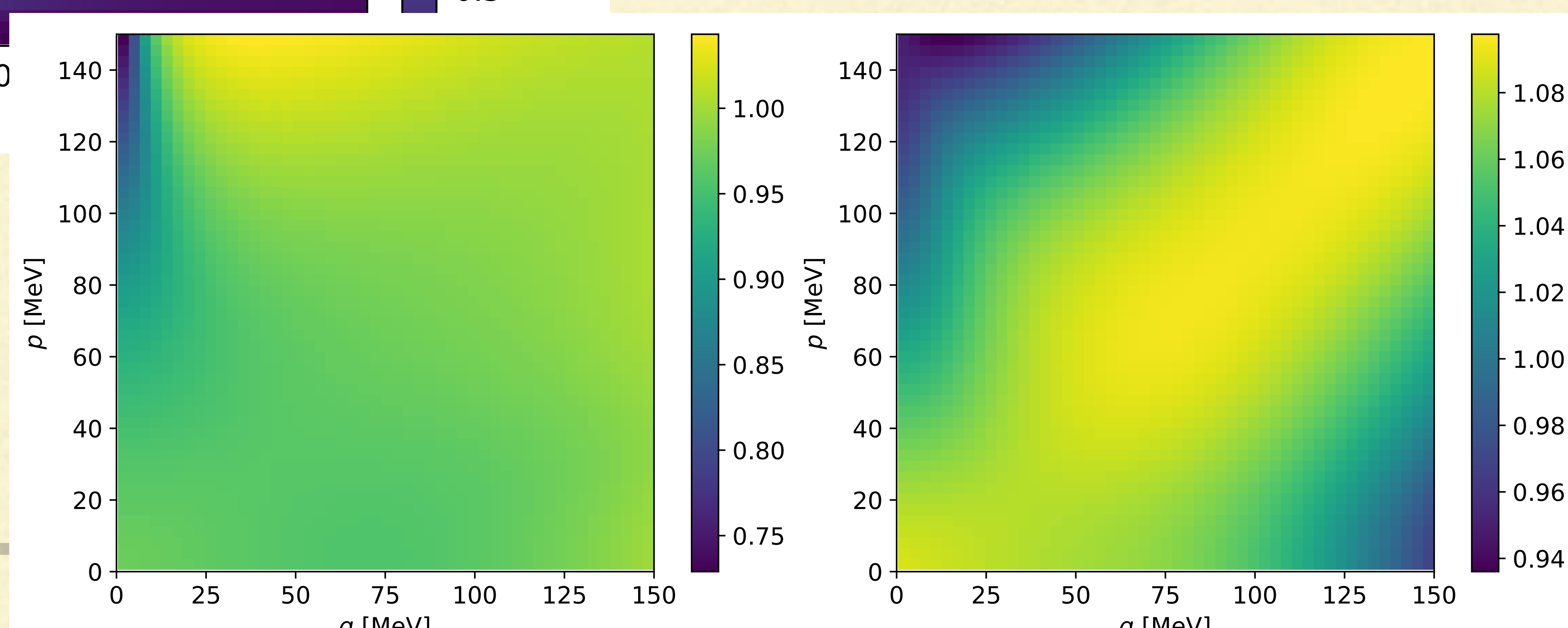
Sharp cutoff vs. Yamaguchi form factor



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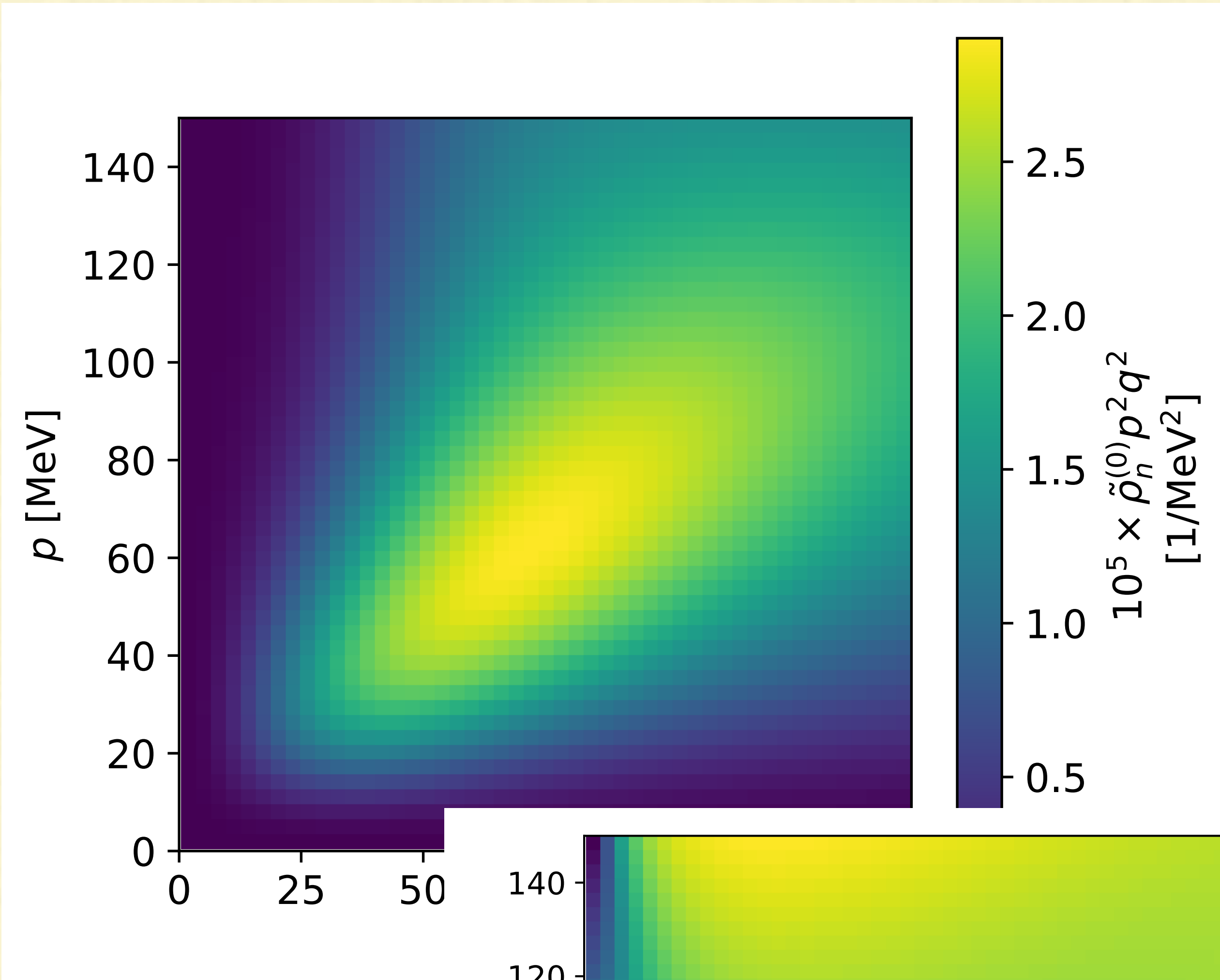

Low-momentum results are independent of form and value of cutoff

Sharp cutoff vs. Yamaguchi form factor

Sharp cutoff at 750 MeV vs. sharp cutoff at 1500 MeV