REVISITING THE HYPERTRITON LIFETIME PUZZLE

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A. Pérez-Obiol, DG, E. Friedman, A. Gal, arXiv:2006.16718 [nucl-th] (2020)
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MOTIVATION

MOTIVATION

Hypertriton

- The lightest bound hypernucleus with spin-parity $J^{\pi} = \frac{1}{2}^{+}$
- A 'Λpn' bound state with tiny Λ hyperon separation energy $B_{\Lambda} = 0.13 \pm 0.05$ MeV, implying a $\Lambda - {}^{2}H$ mean distance ≈ 10 fm
- Is expected to have lifetime within few % of the free Λ lifetime τ_{Λ} governed to 99.7% by nonleptonic $\Lambda \rightarrow N\pi$ weak decay

Hypertriton lifetime puzzle

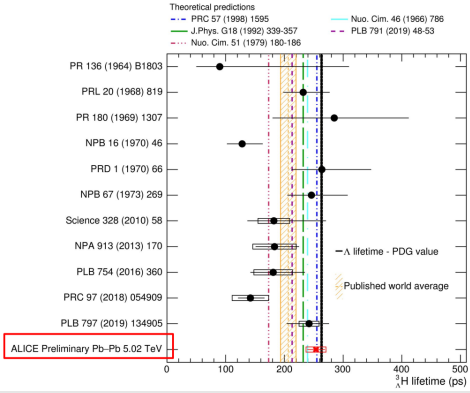
- World average of measured $\tau({}^{3}_{\Lambda}H)$ is $\sim 30\%$ shorter than τ_{Λ}=263±2 ps!
- HypHI $\tau({}^{3}_{\Lambda}H) = 183^{+42}_{-32} \pm 37$ ps [Rappold et al., NPA 913, 170 (2013)]
- STAR $\tau({}^{3}_{\Lambda}H) = 142^{+24}_{-21} \pm 29$ [Adamczyk et al., PRC 97, 054909 (2018)]
- ALICE $\tau({}^{3}_{\Lambda}H) = 242^{+34}_{-38} \pm 17$ [Acharya et al., PLB 797, 134905 (2019)]
- Similar spread with larger uncertainties reported in old emulsion and BC experiments

MOTIVATION

$\tau({}^{3}_{\Lambda}\mathrm{H})$ calculations

Rayet, Dalitz (1966)
$1.14\tau_\Lambda$
Congleton (1992)
$1.15\tau_\Lambda$
Kamada et al. (1998)
$1.06\tau_\Lambda$
Gal, Gacilazo (2019)
$1.23\tau_\Lambda$
Hildenbrand, Hammer (2020)
$\approx\tau_\Lambda$
Exp.
$\sim 1.3\tau_\Lambda$

Next week's talk



[Taken from ICHEP2020 talk of F. Mazzaschi.]

MOTIVATION

Our aims

- Revisit $\tau({}^3_\Lambda\mathrm{H})$ employing ${}^3_\Lambda\mathrm{H}$ and ${}^3\mathrm{He}$ wave functions obtained using state-of-the-art nuclear and hypernuclear Hamiltonians (derived from chiral EFT)
- Include pion final state interactions, both s- and p-wave contributions
- Consider the effect of ΣNN admixtures in ${}^3_\Lambda\mathrm{H}$ due to $\Lambda\mathrm{N} \leftrightarrow \Sigma\mathrm{N}$ coupling
- Study the relation of the hypertriton lifetime $\tau({}^3_\Lambda\mathrm{H})$ and the Λ hyperon separation energy $\mathrm{B}_\Lambda({}^3_\Lambda\mathrm{H})$

METHOD

HYPERTRITON LIFETIME

Hypertriton decay channels

- Mesonic modes due to $\Lambda \to \pi N$
  (not Pauli blocked as in heavier hypernuclei)
  $^3_\Lambda H \to \pi^- + {}^3He$ $\quad$ $^3_\Lambda H \to \pi^0 + {}^3H$
  $^3_\Lambda H \to \pi^- + d + p$ $\quad$ $^3_\Lambda H \to \pi^0 + d + n$
  $^3_\Lambda H \to \pi^- + p + p + n$ $\quad$ $^3_\Lambda H \to \pi^0 + p + n + n$
- Rare non-mesonic modes due to $\Lambda N \to NN$
  $^3_\Lambda H \to n + d$ $\quad$ $^3_\Lambda H \to n + n + p$

Hypertriton lifetime $\tau(^3_\Lambda H)$

- It is possible to deduce the hypertriton half life $\tau(^3_\Lambda H)$ from two-body π^- decay rate $\Gamma_{^3_\Lambda H \to {}^3He + \pi^-}$

HYPERTRITON LIFETIME

From $\Gamma_{^3_\Lambda H \to {}^3He + \pi^-}$ to $\tau(^3_\Lambda H)$

(i) Compute $\Gamma_{^3_\Lambda H \to {}^3He + \pi^-}$ two-body π^- decay rate

(ii) Add contributions from all π^- decay modes by using branching ratio

$$R_3 = \frac{\Gamma(^3_\Lambda H \to {}^3He + \pi^-)}{\Gamma_{\pi^-}(^3_\Lambda H)} = 0.35 \pm 0.04$$

determined in He BC experiments [Keyes et al., NPB 67, 269 (1973)]

(iii) Add contributions from π^0 decay modes using $\Delta I = 1/2$ rule:

$$\Gamma_\pi(^3_\Lambda H) = \frac{3}{2}\Gamma_{\pi^-}(^3_\Lambda H)$$

(iv) Add $\approx 1.5\%$ contribution from $\Lambda N \to NN$
[Rayet, Dalitz, NC 46A, 786 (1966); Golak et al., PRC 55, 2196 (1997);
Pérez-Obiol et al., JPCPS 1024, 012033 (2018)]

(v) Add $\approx 0.8\%$ contribution from $\pi NN \to NN$ pion true absorption estimated from pion optical potential

HYPERTRITON LIFETIME

Two-body π^- decay rate

$$\frac{\Gamma_{{}^3_\Lambda\mathrm{H}\to{}^3\mathrm{He}+\pi^-}}{(G_F m_\pi^2)^2} = 3\frac{q}{\pi}\frac{M_{{}^3\mathrm{He}}}{M_{{}^3\mathrm{He}}+\omega_\pi}\left[\mathcal{A}_\Lambda^2|F^{PV}(\vec{q})|^2 + \mathcal{B}_\Lambda^2|F^{PC}(\vec{q},\vec{\sigma})|^2\left(\frac{k_\pi}{2\bar{M}}\right)^2\right]$$

with $\Lambda \to p\pi^-$ parity-violating $\mathcal{A}_\Lambda$ and parity-conserving $\mathcal{B}_\Lambda$ amplitudes accompanied by nuclear form factors

$$F^j(\vec{q},\vec{\sigma}) = \langle \Psi_{{}^3\mathrm{He}}\, \phi_\pi | \mathcal{O}^j(\vec{q},\vec{\sigma}) | \Psi_{{}^3_\Lambda\mathrm{H}} \rangle$$

$$\mathcal{O}^{PV} = 1, \quad \mathcal{O}^{PC} = \vec{\sigma}\cdot\hat{q}$$

- ϕ_π – pion wave function
- $\Psi_{{}^3\mathrm{He}}$, $\Psi_{{}^3_\Lambda\mathrm{H}}$ – ^{3}He, ${}^3_\Lambda$H wave functions from ab initio no-core shell model (NCSM)

AB INITIO NO-CORE SHELL MODEL

AB INITIO NO-CORE SHELL MODEL

Quasi-exact method to solve the A-body eigenvalue problem:

$$\left[\sum_{i\leq A}\frac{\hat{\mathbf{p}}_i^2}{2m_i}+\sum_{i<j\leq A-1}\hat{V}_{NN;ij}+\sum_{i<j<k\leq A-1}\hat{V}_{NNN;ijk}+\sum_{i<j=A}\hat{V}_{NY;ij}\right]\Psi=E\Psi$$

Ab initio

- all particles are active (no rigid core)
- exact Pauli principle
- realistic baryon–baryon interactions
- controllable approximations

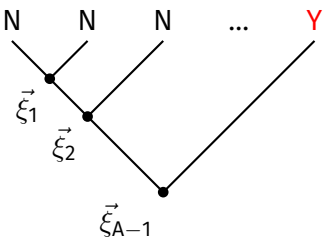
- Hamiltonian is diagonalized in a finite A-particle harmonic oscillator (HO) basis

$$\Psi(\mathbf{r}_1,\ldots,\mathbf{r}_A)=\sum_{n\leq N_{max}}\Phi_n^{HO}(\mathbf{r}_1,\ldots,\mathbf{r}_A)$$

  (matrix dimensions up to $\sim 10^{10}$ with $\sim 10^{14}$ nonzero elements)
- Systematically improvable: converges to exact results for $N_{max}\to\infty$

AB INITIO NO-CORE SHELL MODEL

NCSM formulated in relative Jacobi-coordinate HO basis



$$\vec{\xi}_0 \propto \text{center of mass}$$

$$\vec{\xi}_1 = \sqrt{\frac{1}{2}}\left(\vec{r}_1 - \vec{r}_2\right)$$

$$\vec{\xi}_2 = \sqrt{\frac{2mm_Y}{2m+m_Y}}\left[\frac{1}{2\sqrt{m}}(\vec{r}_1 + \vec{r}_2) - \frac{1}{\sqrt{m_Y}}\vec{r}_3\right]$$

$$\vdots$$

$$\vec{\xi}_{A-1} = \sqrt{\frac{(A-1)mm_Y}{(A-1)m+m_Y}}\left[\frac{1}{(A-1)\sqrt{m}}(\vec{r}_1 + \cdots \vec{r}_{A-1}) - \frac{1}{\sqrt{m_Y}}\vec{r}_A\right]$$

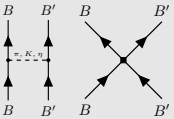
- Basis states: $|\alpha\rangle \equiv |\underbrace{NiJ_1T_1}_{\text{antisymmetric (A-1)N state}}, \overbrace{n_Y l_Y j_Y t_Y}^{\text{Y state}}, JT\rangle$
- No spurious center-of-mass contributions

INPUT HAMILTONIANS

Potentials derived from chiral EFT

- long-range part (π, K, η-exchange) predicted by χPT
- short-range part parametrized by contact interactions, LECs fitted to experimental data

At LO:



NN+NNN interaction

- $\mathrm{NNLO_{sim}}$ NN + NNN potential family [Carlsson et al., PRX 6, 011019 (2016)]

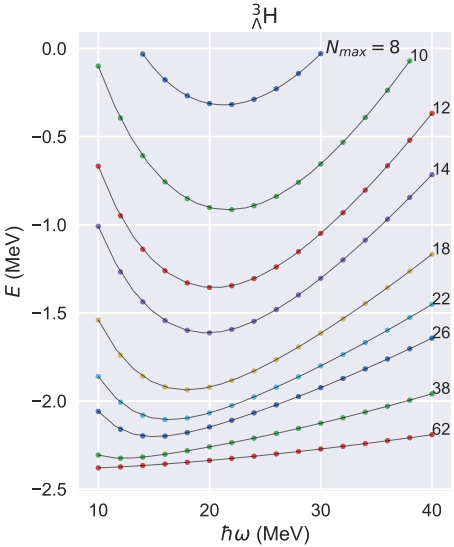
NY interaction

- chiral LO potential [Polinder et al., NPA 779, 244 (2006)]
- ΛN − ΣN mixing explicitly taken into account:

$$V_{NY} = \begin{pmatrix} V_{\Lambda N-\Lambda N} & V_{\Lambda N-\Sigma N} \\ V_{\Sigma N-\Lambda N} & V_{\Sigma N-\Sigma N} \end{pmatrix} + \Delta m$$

Coupled-channel Λ-hypernucleus – Σ-hypernucleus problem!

AB INITIO NO-CORE SHELL MODEL



- Bare interactions used
- Model space parameters: N_{max}, $\hbar\omega$

Convergence in finite HO spaces

- What is the equivalent of Lüscher formula?
- (N_{max}, $\hbar\omega$) imposes cutoffs in momentum space (UV) and in position space (IR)
- In a regime with negligible UV corrections, IR corrections are universal for short-range interactions

$$E(L_{eff}) = E_\infty + e^{-k_\infty L_{eff}} + \cdots$$

- L_{eff} identified as the size of the hyperspherical cavity associated with (N_{max}, $\hbar\omega$) [Wendt et al., PRC 91, 061391 (2015)]

INPUT WAVE FUNCTIONS FROM NCSM

INPUT ^{3}He WAVE FUNCTIONS FROM NCSM

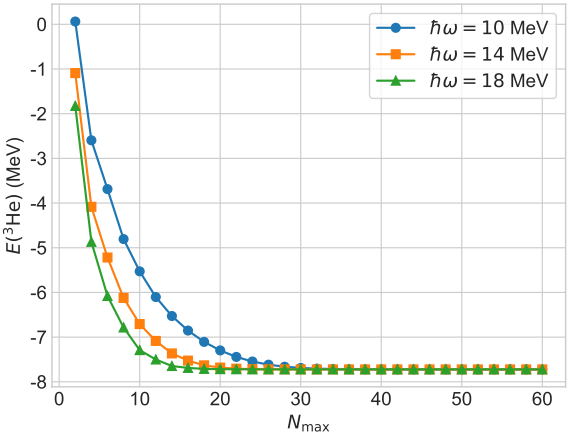


Figure 1: ^{3}He g.s. energies calculated using NCSM for several HO frequencies ω as functions of the model-space truncation N_{max}.

- 10^{-3} MeV accuracy reached for $N_{\text{max}} \sim 30$ for a wide range of frequencies ω
- $E(^3\text{He}) = -7.723$ MeV for $\text{NNLO}_{\text{sim}}^{(500,290)}$ (exp. -7.718(19) MeV)

INPUT $^3_\Lambda$H WAVE FUNCTIONS FROM NCSM

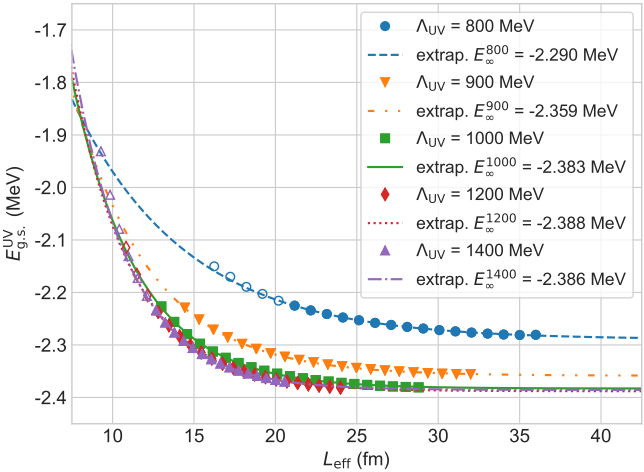


Figure 2: $^3_\Lambda$H g.s. energies calculated using NCSM for several Λ_{UV} cutoffs as functions of the IR length scale L_{eff}.

- UV convergence for $\Lambda_{UV} \gtrsim 1\,\text{GeV}$
- 10^{-3} MeV accuracy reached for $N_{max} \sim 70$

TWO-BODY DECAY RATE

$\Gamma({}^{3}_{\Lambda}\mathrm{H} \to \pi^{-} + {}^{3}\mathrm{He})$

TWO-BODY DECAY RATE $\Gamma({}^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He})$

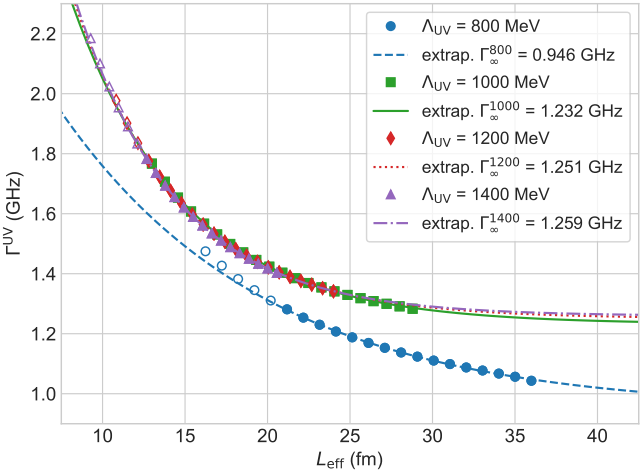


Figure 3: Calculated two-body decay rates $\Gamma({}^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He})$ using NCSM wave functions of ${}^3_\Lambda\mathrm{H}$ and ${}^3\mathrm{He}$ as functions of the IR length scale L_{eff} for several values of the Λ_{UV} cutoff.

- UV convergence reached for $\Lambda_{UV} = 1\,\mathrm{GeV}$
- Convergence with L_{eff} (N_{max}) is slower than for the g.s. energies $\to$ $\Gamma^{UV}(L_{eff}) = \Gamma^{UV}_\infty + a\,e^{-b\,L_{eff}}$ extrapolation

PION FINAL STATE INTERACTIONS

PION FINAL STATE INTERACTIONS

π^-–nucleus interaction

- Influences the emitted π^- in ${}^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He}$
- Understood in terms of π^-–nucleus optical potentials constrained by fits to π^--atom level shifts and widths from Ne to U
  - Reproduces 1S level shift and width of π^- atoms of ^{3}He
- Supplemented by πN and πA scattering to extrapolate from near-threshold to q $= 114.4$ MeV in the $\pi^- - {}^3$He c.m. system

π^- distorted waves in ${}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-$

- $\phi_\pi(\vec{r}; \mathrm{q})$ plane wave replaced by distorted wave
- Interplay of s- and p-wave parts of the optical potential produces robust attractive π^- FSI
- Increases $\Gamma_{{}^3_\Lambda\mathrm{H}\to{}^3\mathrm{He}+\pi^-}$ by 15 %!

[A. Pérez-Obiol, DG, E. Friedman, A. Gal, arXiv:2006.16718 [nucl-th]]

ΣNN **ADMIXTURES IN** $^{3}_{\Lambda}$H

ΣNN ADMIXTURES IN ${}^3_\Lambda$H

${}^3_\Lambda$H structure

- Strong interaction $\Lambda N \leftrightarrow \Sigma N$ transitions couple ΛNN and ΣNN hypernuclear sectors

$$|{}^3_\Lambda \mathrm{H}\rangle = \alpha\,|\Lambda \mathrm{pn}\rangle + \beta\,|\Sigma^0 \mathrm{pn}\rangle + \gamma\,|\Sigma^- \mathrm{pp}\rangle + \delta\,|\Sigma^+ \mathrm{nn}\rangle$$

- ΣNN contributes $\lesssim 0.5\%$ to the norm

${}^3_\Lambda$H decay

- New Σ hyperon two-body decay channels $\Sigma^- \to \mathrm{n}\pi^-$ and $\Sigma^0 \to \mathrm{p}\pi^-$ become available in ${}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-$
- Amplitudes

$$\mathcal{A}_\Lambda \mathrm{F}^{\mathrm{PV}} \to \mathcal{A}_\Lambda \mathrm{F}^{\mathrm{PV}}_{\mathrm{I}=0} + \tfrac{1}{3}(\sqrt{2}\mathcal{A}_{\Sigma^-} + \mathcal{A}_{\Sigma^0})\mathrm{F}^{\mathrm{PV}}_{\mathrm{I}=1}$$

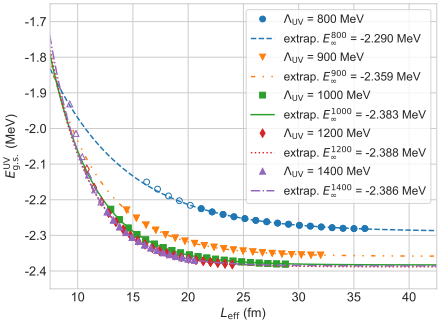
  interfere in $\Gamma_{{}^3_\Lambda\mathrm{H}\to{}^3\mathrm{He}+\pi^-} \propto (\mathcal{A}_\Lambda|\mathrm{F}^{\mathrm{PV}}|)^2$
- Two-body π^- decay rate found to be reduced $\gtrsim 10\%$

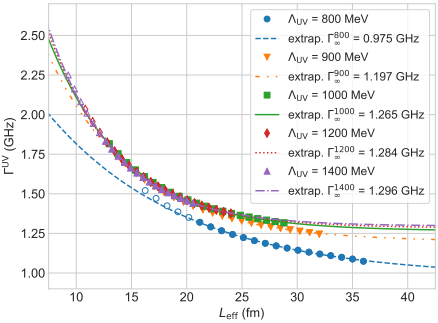
[A. Pérez-Obiol, DG, E. Friedman, A. Gal, arXiv:2006.16718 [nucl-th]]

RELATIONSHIP OF $\Gamma_{^3_\Lambda H \to {}^3He + \pi^-}$ TO B_Λ

RELATIONSHIP OF $\Gamma_{^3_\Lambda H \to {}^3He + \pi^-}$ TO B_Λ

- $B_\Lambda(^3_\Lambda H) = 130 \pm 50$ (stat.) $\pm$? (syst.) keV, not known precisely
- Use the Λ_{UV} dependence of B_Λ and $\Gamma_{^3_\Lambda H \to {}^3He + \pi^-}$





- Correlation between B_Λ and $\Gamma_{^3_\Lambda H \to {}^3He + \pi^-}$ at different Λ_{UV} seems robust (despite of missing UV corrections in the extrapolation scheme)

RELATIONSHIP OF $\Gamma_{^3_\Lambda H \to {}^3He + \pi^-}$ TO B_Λ (cont.)

Λ_{UV} (MeV)	B_Λ (keV)	$\Gamma_{^3_\Lambda H \to {}^3He + \pi^-}$ (GHz)	$\tau(^3_\Lambda H)$ (ps)	
800	69	0.975	234 ± 27	(a)
900	135	1.197	190 ± 22	(b)
1000	159	1.265	180 ± 21	(b)
–	410	1.403	163 ± 18	(c)

(a) Agrees with recent ALICE lifetime measurement and also with [Kamada et al., PRC 57, 1595 (1998)]

(b) Agrees with HypHI lifetime measurement

(c) Has substantial overlap with STAR lifetime value when extrapolated to $B_\Lambda^{STAR} = 0.41 \pm 0.12 \pm 0.11$ MeV (almost coincides when R_3^{STAR} is used)

[A. Pérez-Obiol, DG, E. Friedman, A. Gal, arXiv:2006.16718 [nucl-th]]

THEORETICAL UNCERTAINTIES (Ongoing)

THEORETICAL UNCERTAINTIES

Quantifying theoretical uncertainties

- Many-body methods to solve Schrödinger euqation
  - Under control for light hypernuclei
  - Methods are more precise than the input Hamiltonians
- NY interaction
  - Poor data base of NY scattering data suffering from large uncertainties
  - EFT cutoff dependence as a diagnostic tool?
- NN + NNN interaction
  - Rich data base of low-energy observables
  - Propagation of experimental errors into the parameters (LECs) of the nuclear Hamiltonian possible

THEORETICAL UNCERTAINTIES

Aim

What are the theoretical uncertainties of hypernuclear properties resulting from the remaining freedom in the constructions of nuclear NN+NNN interactions?

The NNLO_{sim} family of NN+NNN potentials

- Parameters fitted to reproduce simultaneously πN, NN, and NNN low-energy observables
- Family of 42 Hamiltonians where the experimental uncertainties propagate into the LECs of the χEFT Lagrangian

$$\left.\begin{array}{ll} T_{NN}^{lab,max} & \leq 125, \ldots, 290 \text{ MeV} \\ \Lambda_{EFT} & \leq 450, \ldots, 600 \text{ MeV} \end{array}\right\} 42\ V_{NN}+V_{NNN} \text{ potentials}$$

- All Hamiltonians give equally good description of the fit data
- Note that $\Delta E^{(^3He/^3H)} \approx 0$ (fitted) while $\Delta E_{g.s.}^{(^4He)} \approx 1.5$ MeV

[Carlsson et al., PRX 6, 011019 (2016)]

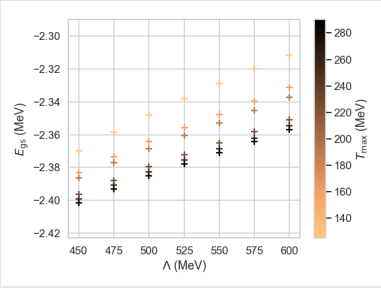
THEORETICAL UNCERTAINTIES

^{2}H, ^{3}H, ^{3}He

- Energies and radii in the pool of fit data

	NNLO$_{sim}$	Exp.
E(^{2}H)	$-2.224^{(+0)}_{(-1)}$	-2.225
E(^{3}H)	$-8.482^{(+26)}_{(-30)}$	-8.482(28)
E(^{3}He)	$-7.717^{(+17)}_{(-21)}$	-7.718(19)

$^3_\Lambda$H



- V_{NY} fixed ($\Lambda_{EFT} = 600$ MeV)
- $\Delta B_\Lambda(^3_\Lambda H) \approx 100$ keV for all 42 NNLO$_{sim}$ Hamiltonians

THEORETICAL UNCERTAINTIES

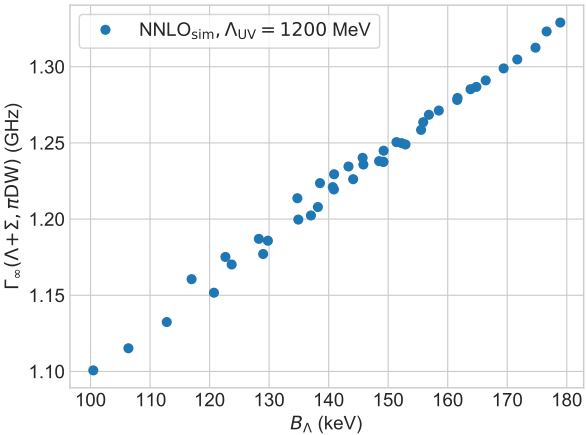


Figure 4: Calculated two-body decay rates $\Gamma({}^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He})$ and Λ separation energies B_Λ for all 42 NNLO$_{sim}$ Hamiltonians.

- $\Delta B_\Lambda(\mathrm{NNLO_{sim}}) \approx 80\,\mathrm{keV} \leftrightarrow \Delta\Gamma_{{}^3_\Lambda\mathrm{H}\to{}^3\mathrm{He}+\pi^-}(\mathrm{NNLO_{sim}}) \approx 0.35\,\mathrm{GHz}$

SUMMARY

SUMMARY

Hypertriton lifetime

- Performed new microscopic three-body calculation of two-body decay rate $\Gamma_{^3_\Lambda\mathrm{H}\to{}^3\mathrm{He}+\pi^-}$
- Using the $\Delta I = 1/2$ rule and a branching ratio R_3 from experiment we deduced the value of hypertriton lifetime $\tau(^3_\Lambda\mathrm{H})$
- Pion FSI increase the $^3_\Lambda$H decay rate $\Gamma(^3_\Lambda\mathrm{H})$ by $\sim 15\%$
- ΣNN admixtures in $^3_\Lambda$H decrease the $\Gamma(^3_\Lambda\mathrm{H})$ by $\sim 10\%$
- $\tau(^3_\Lambda\mathrm{H})$ varies strongly with the poorly known Λ separation energy B_Λ – it is possible to correlate each of the reported lifetime values from ALICE, HypHI, and STAR to its own underlying B_Λ value
- New experiments proposed at MAMI, Jlab, J-PARC, and ELPH will hopefully pin down B_Λ to better than 50 keV and lead to a resolution of the 'hypertriton lifetime puzzle'

Thank you!