LIFETIME OF THE HYPERTRITON

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MANY THANKS TO MY COLLABORATORS

- Petr Navrátil
  (TRIUMF, Canada)
- Christian Forssén
  (Chalmers University of Technology, Sweden)
- **Axel Pérez-Obiol**
  (Barcelona Supercomputing Center, Spain)
- **Avraham Gal, Eli Friedman**
  (The Hebrew University of Jerusalem, Israel)

MOTIVATION

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Hypertriton

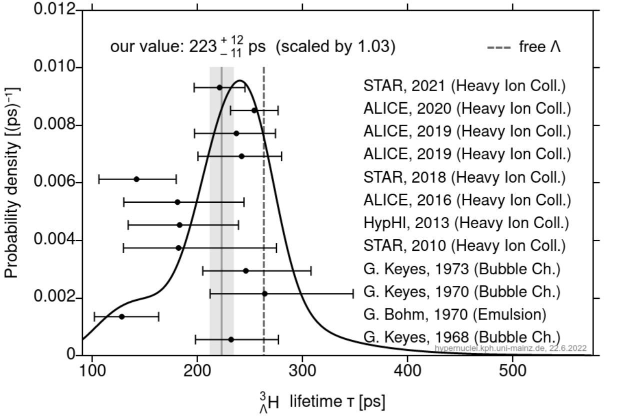
- The lightest bound hypernucleus with spin-parity $J^\pi = \frac{1}{2}^+$
- A 'Λpn' bound state with tiny Λ hyperon separation energy $B_\Lambda = 0.165 \pm 0.044$ MeV, implying a $\Lambda - {}^2$H mean distance $\approx 10\,$fm
- Is expected to have lifetime within few % of the free Λ lifetime τ_Λ, governed to 99.7% by nonleptonic $\Lambda \to N\pi$ weak decay

Hypertriton lifetime puzzle

- World average of measured $\tau({}^3_\Lambda\mathrm{H})$ is $\sim$20% shorter than τ_Λ=263$\pm$2 ps!
- HypHI $\tau({}^3_\Lambda\mathrm{H}) = 183^{+42}_{-32} \pm 37\,$ps [Rappold et al., NPA 913, 170 (2013)]
- STAR $\tau({}^3_\Lambda\mathrm{H}) = 142^{+24}_{-21} \pm 29\,$ps [Adamczyk et al., PRC 97, 054909 (2018)]
- ALICE $\tau({}^3_\Lambda\mathrm{H}) = 242^{+34}_{-38} \pm 17\,$ps [Acharya et al., PLB 797, 134905 (2019)]
- STAR $\tau({}^3_\Lambda\mathrm{H}) = 221 \pm 15 \pm 19\,$ps [Abdallah et al., PRL 128 202301 (2022)]
- Similar spread with larger uncertainties reported in old emulsion and BC experiments

MOTIVATION

$\tau(^3_\Lambda\text{H})$ measurements



[Taken from `hypernuclei.kph.uni-mainz.de`]

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

$1.14\,\tau_\Lambda$

[Rayet, Dalitz (1966)]

$1.15\,\tau_\Lambda$

[Congleton (1992)]

$1.06\,\tau_\Lambda$

[Kamada et al. (1998)]

$1.23\,\tau_\Lambda$

[Gal, Garcilazo (2019)]

$\approx\tau_\Lambda$

[Hildenbrand, Hammer (2020)]

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 $\Lambda N \leftrightarrow \Sigma N$ coupling
- Study the relation of the hypertriton lifetime $\tau({}^3_\Lambda\mathrm{H})$ and the Λ hyperon separation energy $B_\Lambda({}^3_\Lambda\mathrm{H})$
- Quantify theoretical uncertainties

METHOD

HYPERTRITON LIFETIME

Hypertriton decay channels

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

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

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

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

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

(ii) Add contributions from all π^- decay modes using the R_3 branching ratio determined in He BC experiments [Keyes et al., NPB 67, 269 (1973)]

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

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

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

(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

Two-body π^- decay rate $\Gamma({}^3_\Lambda\text{H} \to {}^3\text{He} + \pi^-)$

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

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

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

$$\mathcal{O}^{PV} = 1,$$

$$\mathcal{O}^{PC} = \vec{\sigma}\cdot\hat{q}$$

- ϕ_π – pion wave function (plane or distorted wave)
- $\Psi_{^3\text{He}}$, $\Psi_{{}^3_\Lambda\text{H}}$ – ^{3}He, ${}^3_\Lambda$H ground-state wave functions from *ab initio* no-core shell model (NCSM)

INPUT WAVE FUNCTIONS FROM NCSM

AB INITIO NO-CORE SHELL MODEL

Quasi-exact method to solve the nuclear many-body problem:

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

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

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

- Systematically improvable: converges to exact results for $N_{max}\to\infty$

Input Hamiltonians

- Chiral NNLO$_{sim}$ $NN+NNN$ potential family

  [Carlsson et al., PRX 6, 011019 (2016)]
- Chiral LO YN potential [Polinder *et al.*, NPA 779, 244 (2006)]
  - $\Lambda N-\Sigma N$ mixing explicitly taken into account
  - Coupled-channel Λ-hypernucleus–Σ-hypernucleus problem!

INPUT ^{3}He WAVE FUNCTIONS FROM NCSM

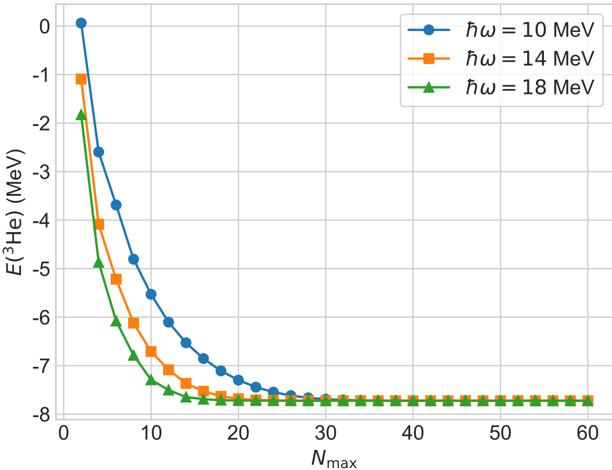


Figure 1: ^{3}He g.s. energies calculated using NCSM for several HO frequencies ω as functions of the model-space truncation N_{max}.

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

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

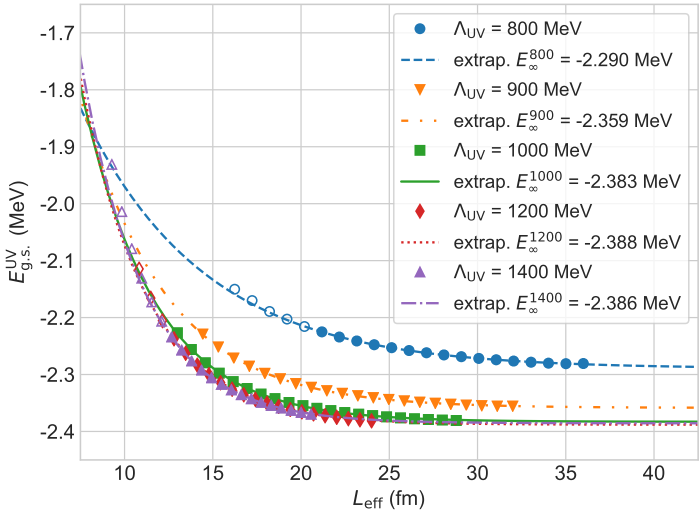


Figure 2: ${}^{3}_{\Lambda}$H g.s. energies calculated using NCSM for several Λ_{UV} cutoffs as functions of the IR length scale L_{eff}.

- L_{eff}, Λ_{UV} functions of N_{max}, $\hbar\omega$; $E^{UV}(L_{eff}) = E_\infty + ae^{-b\,L_{eff}} + \cdots$
- UV convergence for $\Lambda_{UV} \gtrsim 1\,$GeV
- $\sim$keV accuracy reached for $N_{max} \sim 70$

TWO-BODY π^- DECAY RATE

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

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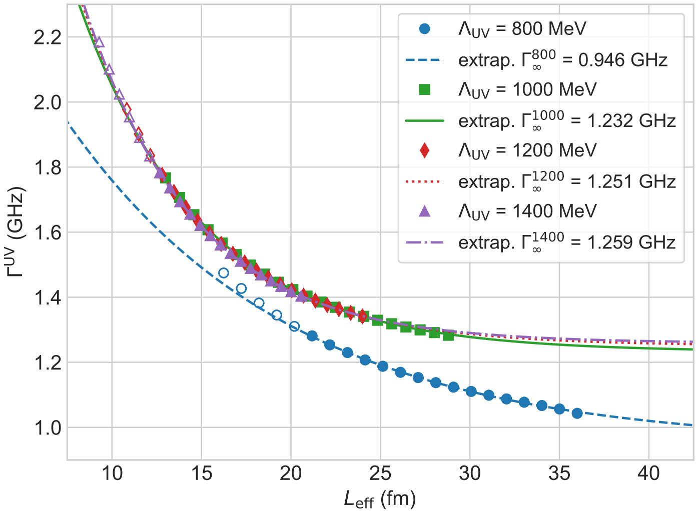

Figure 3: Calculated two-body decay rates $\Gamma({}^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He})$ using NCSM wave functions of ${}^3_\Lambda\mathrm{H}$ and ${}^3\mathrm{He}$ as functions of the IR length scale $L_{\rm eff}$ for several values of the $\Lambda_{\rm UV}$ cutoff.

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

PION FINAL STATE INTERACTIONS

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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 $\pi^- - {}^3\mathrm{He}$ c.m. system

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

- $\phi_\pi(\vec{r}; q)$ 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, Phys. Lett. B 811, 135916 (2020)]

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

ΣNN ADMIXTURES IN $^3_\Lambda$H

$^3_\Lambda$H structure

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

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

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

$^3_\Lambda$H decay

- New Σ hyperon two-body decay channels

$$\Sigma^- \to n + \pi^- \text{ and } \Sigma^0 \to p + \pi^-$$

  become available in $^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-$
- Amplitudes

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

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

[A. Pérez-Obiol, DG, E. Friedman, A. Gal, Phys. Lett. B 811, 135916 (2020)]

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

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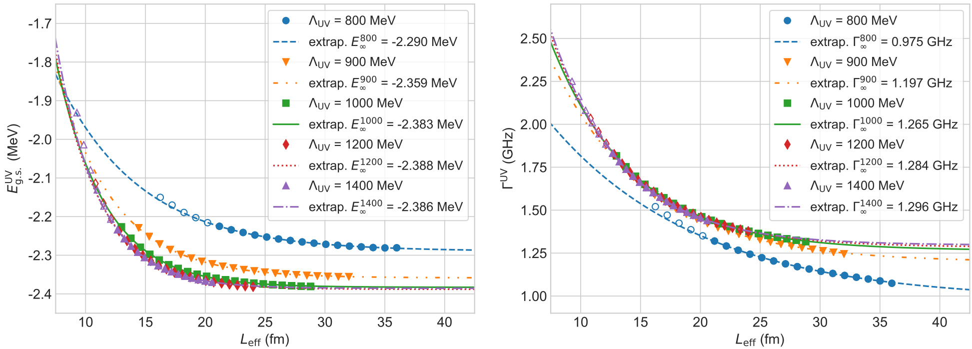
- $B_\Lambda({}^3_\Lambda\mathrm{H}) = 165 \pm 44$ keV, not known precisely
- Use the Λ_{UV} dependence of B_Λ and $\Gamma({}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-)$



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

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

Λ_{UV} (MeV)	B_Λ (keV)	$\Gamma({}^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-)$ (GHz)	$\tau({}^3_\Lambda\mathrm{H})$ (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(18) lifetime value when extrapolated to $B_\Lambda^{\mathrm{STAR}} = 0.41 \pm 0.12 \pm 0.11$ MeV (almost coincides when R_3^{STAR} is used)

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QUANTIFYING UNCERTAINTIES (Ongoing)

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Theoretical (hyper)nuclear-structure uncertainties in $\Gamma({}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-)$

- Method
  - Schödinger equation solver, extrapolation
  - Under control for $A = 3$ (at least for energies)
  - Methods are more precise than input Hamiltonians
- Model
  - *YN* interaction – poor data base of scattering data suffering from large uncertainties; cutoff dependence as a diagnostic tool(?)
  - *NN*+*NNN* interaction – rich data base of low-energy observables

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

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

(HYPER)NUCLEAR-STRUCTURE UNCERTAINTIES in $\Gamma({}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-)$

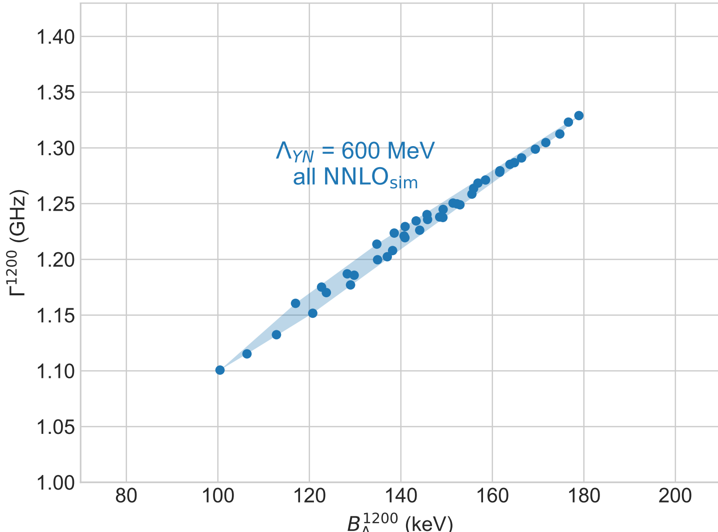
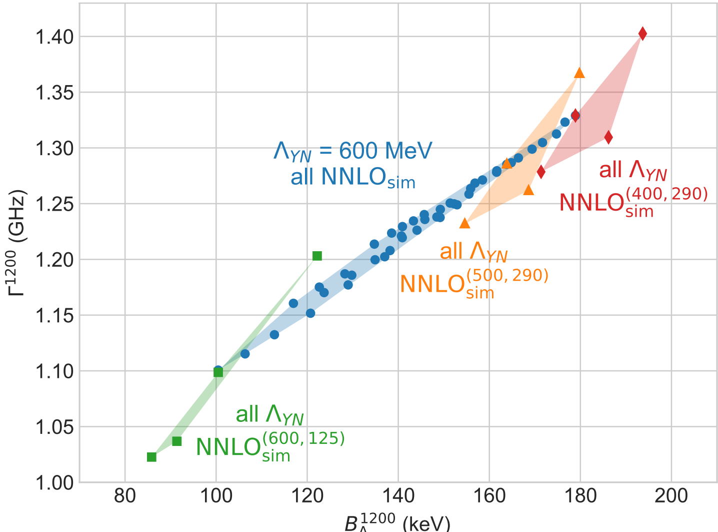


Figure 4: Calculated two-body decay rates $\Gamma({}^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He})$ and Λ separation energies B_Λ for all 42 NNLO_{sim} Hamiltonians.

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



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SUMMARY

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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 ${}^3_\Lambda\mathrm{H}$ decay rate $\Gamma({}^3_\Lambda\mathrm{H})$ by $\sim 15\%$
- ΣNN admixtures in ${}^3_\Lambda\mathrm{H}$ 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(18) 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!