On the hypertriton decay rate

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Outline

1. Introduction & motivation

Why the hypertriton?

2. Calculation

From partial decay rate to lifetime

NCSM and nuclear w.f.

Pion w.f.

Weak operator

3. Results

Uncertainties

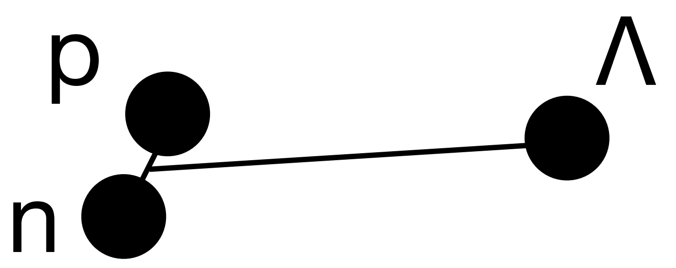
Summary

Hypertriton

Λ+p+n bound state with I=0, $J^P = 1/2^+$

Λ very loose: $B_\Lambda = 0.13 \pm 0.05$ MeV

Decay is mostly non-leptonic $\Lambda \rightarrow N+\pi$



Avg. pn-Λ dist.
~10 fm

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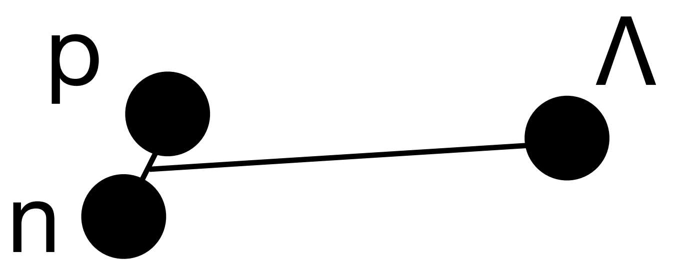

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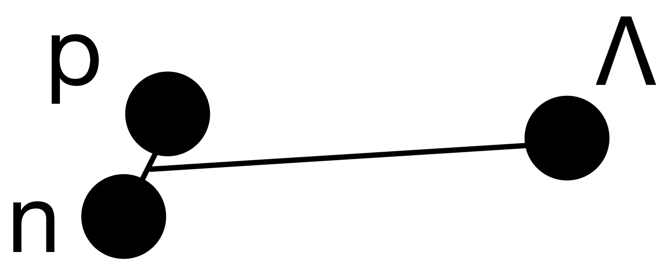

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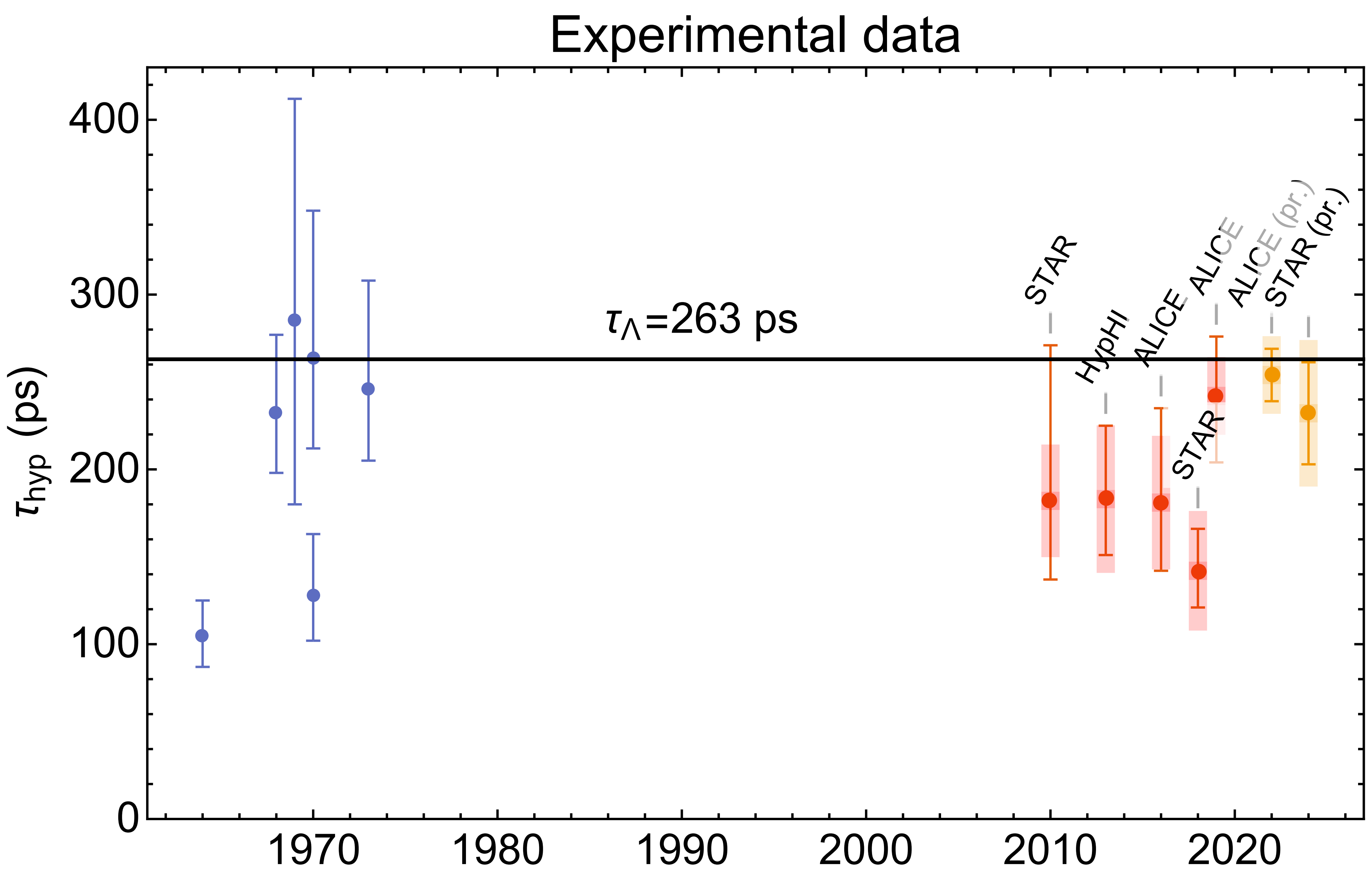
Emulsion/BC experiments

- Block *et al.*, YRC-1964-001, 63 (1964)
- Keyes *et al.*, PRL **20**, 819 (1968).
- Phillips and J. Schneps, PR **180**, 1307 (1969).
- Keyes *et al.*., PRD **1**, 66 (1970).
- Bohm *et al.*, NPB **16**, 46 (1970).
- Keyes *et al.*, NPB **67**, 269 (1973).



HIC experiments

- Abelev *et al.* (STAR), Science **328**, 58 (2010).
- Rappold *et al.*, (HypHI) NPA **913**, 170 (2013).
- Adam *et al.* (ALICE), PLB **754**, 360 (2016).
- Adamczyk *et al.* (STAR), PRC **97**, 054909 (2018).
- Acharya *et al.* (ALICE), PLB **797**, 134905 (2019).
- Mazzaschi (ALICE, prel.), ICHEP (2020).
- Leung (STAR, prel.), REIMEI-THEIA (2021).

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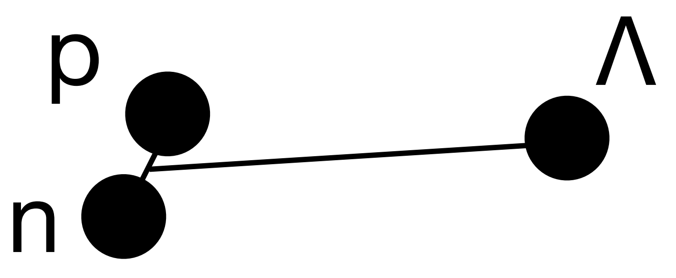

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➡ **How different is τ_{hyp} from $\tau_\Lambda = 263 \pm 2$ ps ?**

<u>Theory:</u>

- Rayet, Dalitz (1966): $\tau_{hyp} = 1.14\ \tau_\Lambda$ ➡ Variational w.f., closure approx.
- Congleton (1992): $\tau_{hyp} = 1.15\ \tau_\Lambda$ ➡ d+Λ w.f., closure approx.
- Kamada et al. (1998): $\tau_{hyp} = 1.06\ \tau_\Lambda$ ➡ Genuine 3B, Nijmegen SC NN+YN pot.
- Gal, Garcilazo (2019): $\tau_{hyp} = 1.23\ \tau_\Lambda$ ➡ 3B w.f., closure approx., π DW enhances Γ
- Hildenbrand, Hammer (2020): $\tau_{hyp} \approx \tau_\Lambda$ ➡ d+Λ w.f., EFT approach, B_Λ analysis

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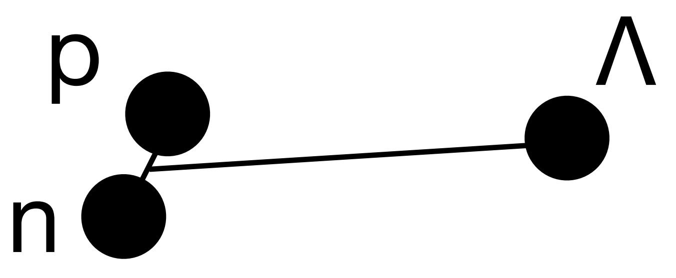

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- P.-O., Gazda, Friedman, Gal (2020): $\tau_{hyp} = 0.6\text{-}0.76\ \tau_\Lambda$

★ Focus on ${}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-$ and deduce τ_{hyp}

★ Full EFT w.f., $\Sigma N\pi$, π DW, relation to B_Λ

From Γ(³H —> π⁻ + ³He) to τ_{hyp}

non-leptonic modes, Λ —> N + π

non-mesonic modes, ΛN —> NN, and pion true absorption

$$\Gamma_{\pi^-}\left|\begin{array}{l}\boxed{\Gamma({}^3_\Lambda H \rightarrow \pi^- + {}^3He)}\\ \Gamma({}^3_\Lambda H \rightarrow \pi^- + d + p)\\ \Gamma({}^3_\Lambda H \rightarrow \pi^- + p + p + n)\end{array}\right.$$

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From $\Gamma(^3\text{H} \rightarrow \pi^- + {}^3\text{He})$ to τ_{hyp}

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1. Use He BC experimental ratio $R_3 = \dfrac{\Gamma({}^3_\Lambda \mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-)}{\Gamma_{\pi^-}({}^3_\Lambda \mathrm{H})} = 0.35 \pm 0.04$ to add 3- and 4-body π^- modes

Keyes, Sacton, Wickens, Block, NPB 67 (1973) 269.

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   Golak, Miyagawa, Kamada, Witala, Glöckle, Parreño, Ramos, Bennhold, PRC 55, 2196 (1997)

   Pérez-Obiol, Gazda, Friedman, Gal, PLB 811 (2020) 135916

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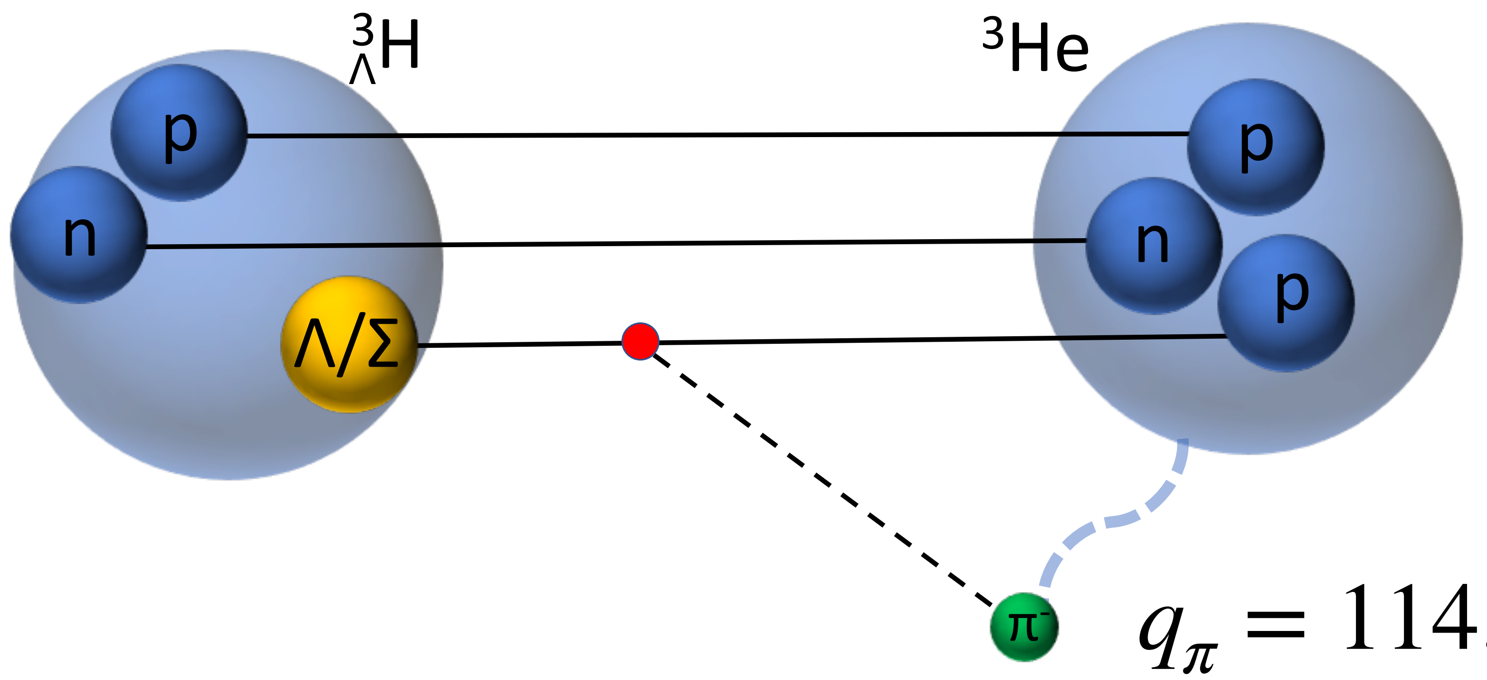
$$\Gamma({}^3_\Lambda H \to \pi^- + {}^3He) \xrightarrow{\times 1/R_3} \Gamma_{\pi^-} \xrightarrow{\times 3/2} \Gamma_{\pi^-} + \Gamma_{\pi^0} \xrightarrow{\times 1.023} \Gamma_{\pi^-} + \Gamma_{\pi^0} + \Gamma_{nm}$$

Decay rate for ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$

$$\Gamma_{m}^{{}^3\mathrm{He}} = \frac{3}{4\pi} \frac{M_{{}^3\mathrm{He}}\, q_\pi}{M_{{}^3\mathrm{He}} + E_\pi} \sum_{m_{{}^3_\Lambda \mathrm{H}}} \sum_{m_{{}^3\mathrm{He}}} \left| \langle \psi_{{}^3\mathrm{He}} \phi_\pi | \hat{O} | \psi_{{}^3_\Lambda \mathrm{H}} \rangle \right|^2$$

We need to input:

1. Nuclear wave functions
2. Pion wave function
3. Weak operator



$q_\pi = 114.4 \quad \mathrm{MeV}$

$E_\pi = 170.3 \quad \mathrm{MeV}$

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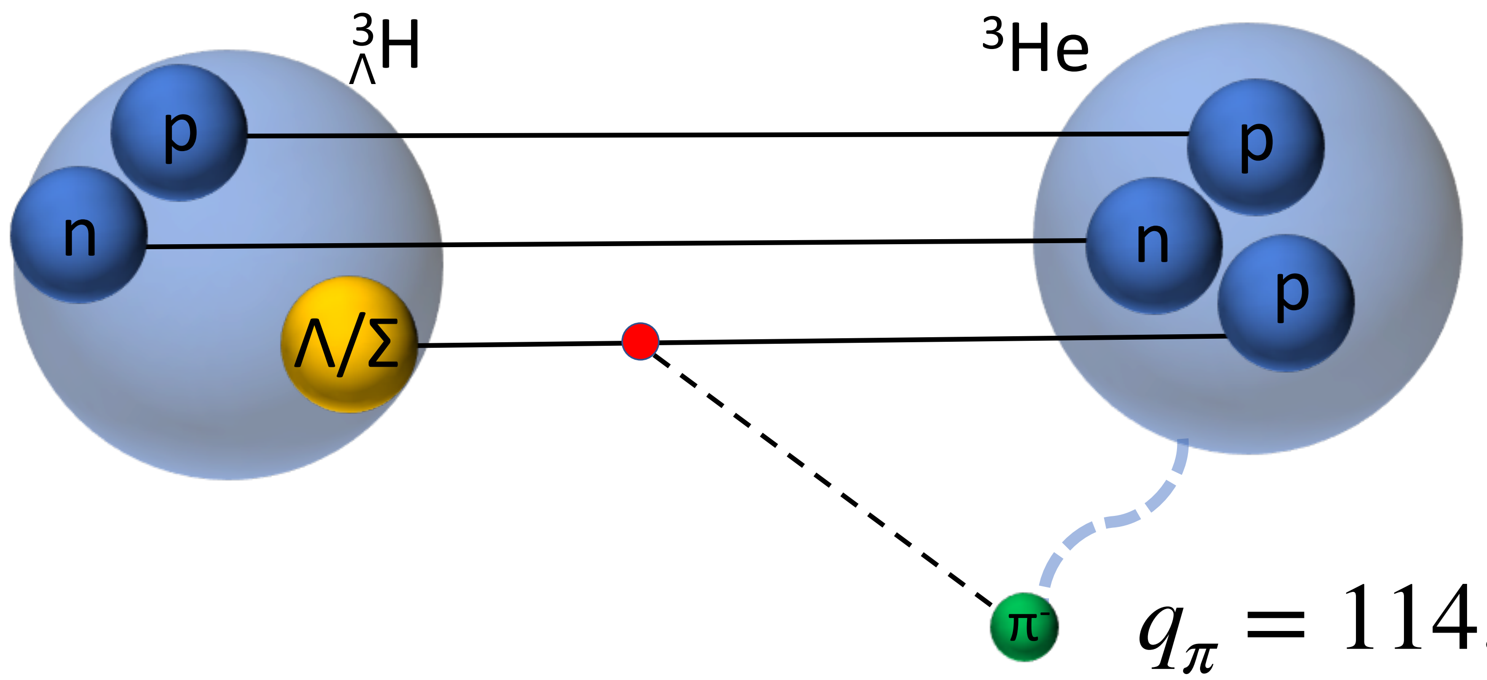

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We can approximate to only d+Λ and d+p main amplitudes

$t_{12}=l_{12}=0$, $s_{12}=1$, $l_3=0$

$$\Gamma_{{}^{13}S_1}^{{}^3He} = \frac{3}{4\pi}\frac{(G_F m_\pi^2)^2\, M_{{}^3He}\, q}{M_{{}^3He} + E_\pi}\left(A_\Lambda^2 + \frac{1}{36}\frac{B_\Lambda^2\, q_\pi^2}{\overline{M}^2_{\Lambda N}}\right) \times \left| \int dp'_{12}\, p'^2_{12} \int dp'_3\, p'^2_3 \int d(\cos(\theta_{p'_3}) \times \psi_{{}^{13}S_1}(p'_{12}, |p'_3\hat{p}'_3 + r\vec{q}_\pi|)\, \psi'_{{}^{13}S_1}(p'_{12}, p'_3) \right|^2$$

$\Psi_{^3\mathrm{He}}$ and $\Psi_{^3_\Lambda\mathrm{H}}$ with ab initio no core shell model:

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

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

- ★All particles are active (no rigid core)
- ★Exact Pauli principle
- ★Realistic baryon–baryon interactions
- ★Controllable approximations

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- Diagonalize in A-particle H.O. basis with frequency ω and N_{max} states

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- Relative Jacobi coordinates

$$\vec{p}_{12}=\left(m_2\,\vec{p}_1-m_1\,\vec{p}_2\right)/(m_1+m_2),$$
$$\vec{p}_3=\left[m_3(\vec{p}_1+\vec{p}_2)-(m_1+m_2)\,\vec{p}_3\right]/(m_1+m_2+m_3)\,.$$

Basis states $|n_{12}(l_{12}s_{12})j_{12}t_{12},n_3(l_3s_3)I_3t_3\rangle$

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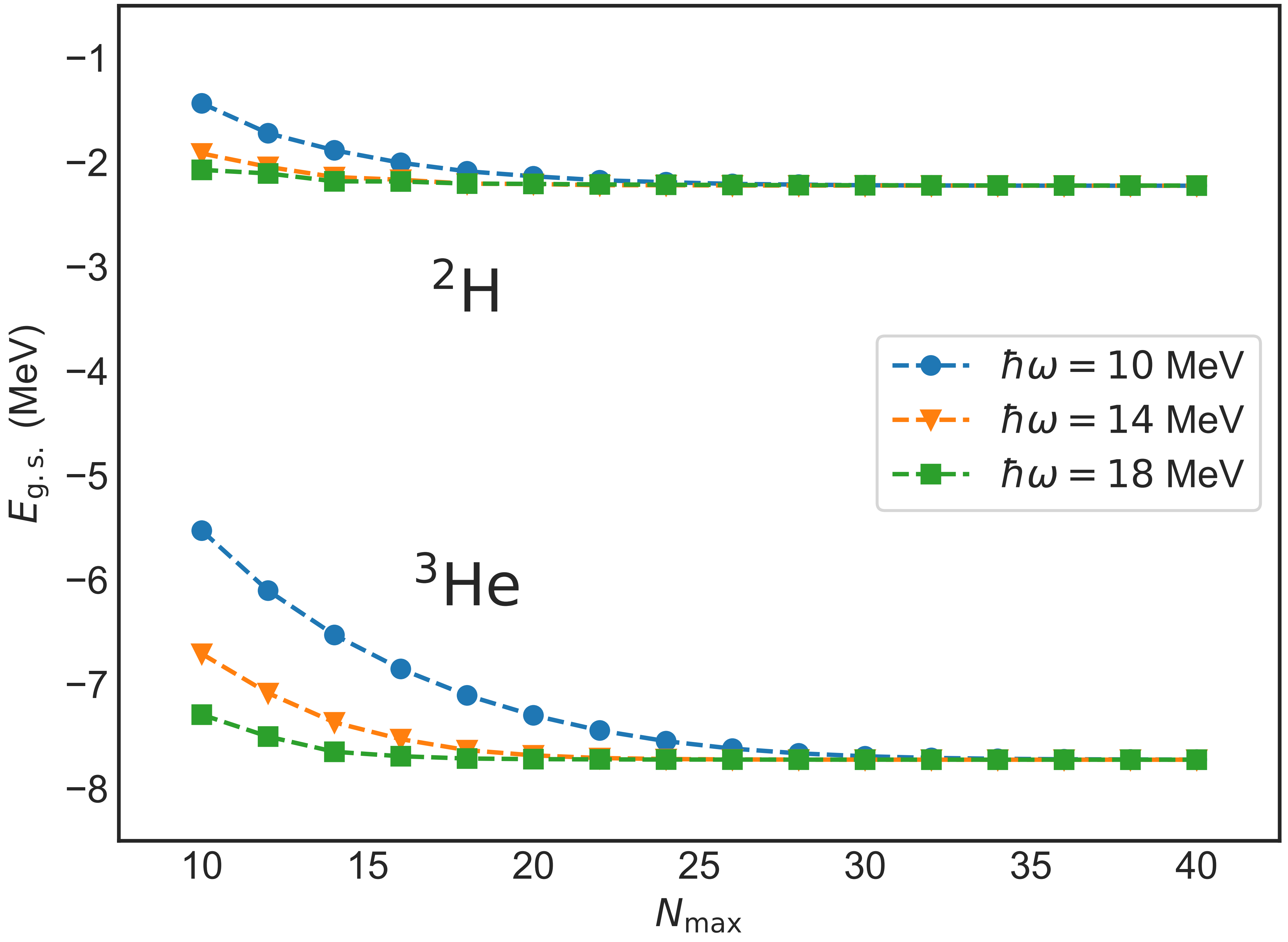
- Effective field theory potentials (long range part by χ_{PT} π, K, η exchanges + parametrized short range)

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

  - EFT LO NY (incl. ΛN <—> ΣN) [Polinder et al., NPA 779, 244 (2006)]

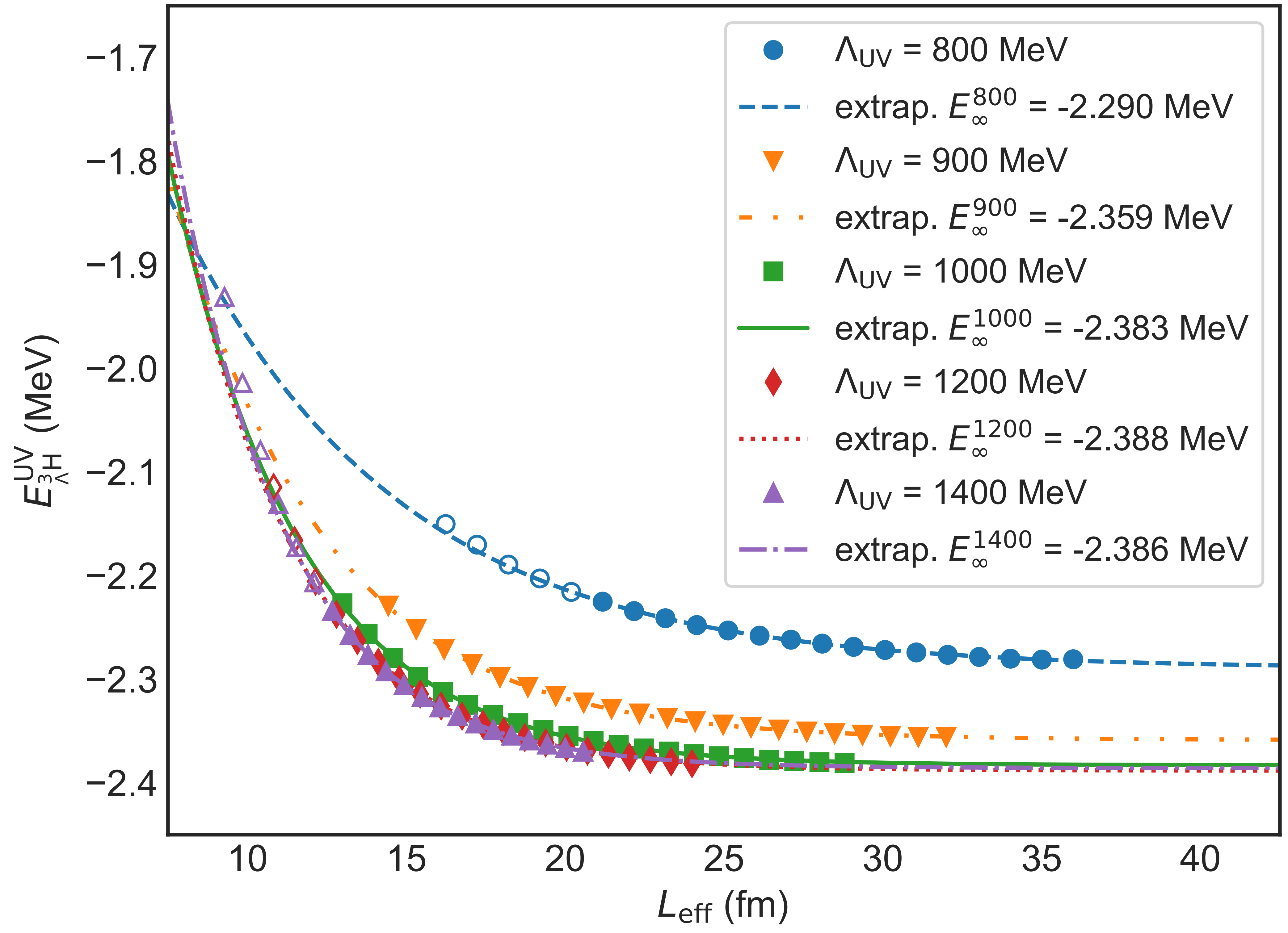
^{3}He (and ^{2}H) wave function



➡ 10^{-3} MeV accuracy for N_{max} ~ 30 and a wide range of frequencies ω

➡ E(^{3}He) = -7.723 MeV (NNLO$_{sim}$) (exp. -7.718(19) MeV)

${}^{3}_{\Lambda}$H wave function



- ω and N_{max} introduce UV and IR cutoffs. For ${}^{3}_{\Lambda}$H, fix UV cutoff Λ_{UV}, extrapolate in effective IR length L_{eff}

$$E^{UV}(L_{eff}) = E_{\infty} + a_0\, e^{-a_1 L_{eff}}$$

Wendt et al., PRC 91, 061301 (2015)

Furnstahl et al., PRC 86, 031301 (2012)

➡ UV convergence for Λ_{UV} > 1 GeV a

➡ 10^{-3} MeV accuracy for N_{max} ~ 70

ϕ_π distorted wave

- π^- - nucleus interaction influences emitted π^-
  - ➡ Understood in terms of π^- - nucleus optical potentials constrained by π^- - atom level shifts and widths from Ne to U
  - ➡ Supplemented by πN and πA scattering to extrapolate from near-threshold to $q = 114.4$ MeV in our π^- - ^3He system
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π^- FSI **increase rate ~15%**

Possible weak transitions $\Lambda/\Sigma \longrightarrow N + \pi^-$

- $\Lambda \longrightarrow p + \pi^-$

- $\Sigma^- \longrightarrow n + \pi^-$
- $\Sigma^0 \longrightarrow p + \pi^-$

* $|M_\Sigma|^2 \sim 0.4\%$

$\Gamma \sim |M_\Sigma + M_\Lambda|^2$

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$$\hat{O}_\Lambda = i\sqrt{2}G_F m_\pi^2 \left(A_\Lambda + \frac{B_\Lambda}{2\overline{M}_{\Lambda N}} \vec{\sigma} \cdot \vec{q}_\pi \right) \hat{O}_{t_{12}=0}$$

➡ A_Λ=1.024, B_Λ=-9.431 fixed by τ_Λ=263 ps and Γ_{PC}/Γ_{PV}= 0.203

M. Ablikim, et al., BESIII Collaboration, Nat. Phys. 15 (2019) 631

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$$\hat{O}_\Sigma = iG_F m_\pi^2 \left(\frac{\sqrt{2}}{3} A_{\Sigma^-} + \frac{1}{3} A_{\Sigma^0} \right) \hat{O}_{t_{12}=1}$$

➡ Neglect B_Σ and A_{Σ^-}=1.364 fixed by τ_{Σ^-}=147.9 ps and chiral $A_{\Sigma 0}=A_{\Sigma^-}/\mathrm{sqrt}(2)$

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$$\hat{O}_\Lambda = i\sqrt{2} G_F m_\pi^2 \left(A_\Lambda + \frac{B_\Lambda}{2\overline{M}_{\Lambda N}} \vec{\sigma} \cdot \vec{q}_\pi \right) \hat{O}_{t_{12}=0}$$

➡ A_Λ=1.024, B_Λ=-9.431 fixed by τ_Λ=263 ps and Γ_{PC}/Γ_{PV}= 0.203

M. Ablikim, et al., BESIII Collaboration, Nat. Phys. 15 (2019) 631

$$\hat{O}_\Sigma = i G_F m_\pi^2 \left(\frac{\sqrt{2}}{3} A_{\Sigma^-} + \frac{1}{3} A_{\Sigma^0} \right) \hat{O}_{t_{12}=1}$$

➡ Neglect B_Σ and A_{Σ^-}=1.364 fixed by τ_{Σ^-}=147.9 ps and chiral $A_{\Sigma 0}=A_{\Sigma^-}/$sqrt(2)

Σ contributions **decrease rate ~10%**

Extrapolated decay rate for ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$
for $\Lambda_{UV} = 1$GeV (in GHz)

	$P({}^{3}\mathrm{He})$	$P_{\Lambda}({}^{3}_{\Lambda}\mathrm{H})$	$P_{\Sigma}({}^{3}_{\Lambda}\mathrm{H})$	$\Gamma^{\mathrm{UV}}_{\mathrm{PW}}$
approx.	46.81	95.87	–	1.141

Extrapolated decay rate for ${}^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$

for $\Lambda_{UV} = 1$GeV (in GHz)

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Λ	100	99.61	–	+8% 1.232

Extrapolated decay rate for ${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^{-}$
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	$P({}^{3}\mathrm{He})$	$P_{\Lambda}({}^{3}_{\Lambda}\mathrm{H})$	$P_{\Sigma}({}^{3}_{\Lambda}\mathrm{H})$	$\Gamma^{\mathrm{UV}}_{\mathrm{PW}}$
approx.	46.81	95.87	–	1.141
Λ	100	99.61	–	1.232
$\Lambda + \Sigma$	100	99.61	0.39	1.099

+8%
-9%

Extrapolated decay rate for ${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^-$
for $\Lambda_{UV} = 1$GeV (in GHz)

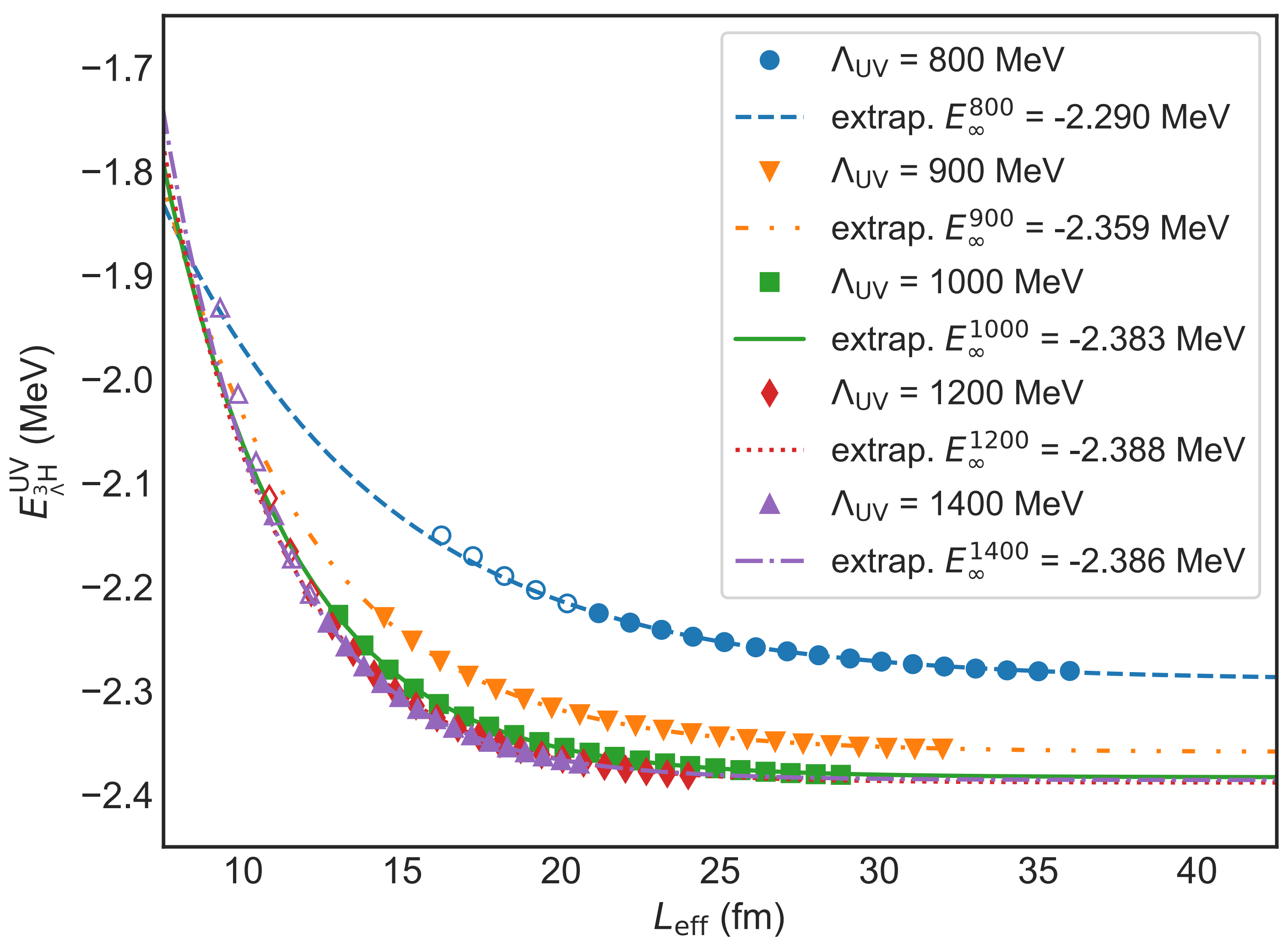
+15%

	$P({}^3\mathrm{He})$	$P_\Lambda({}^3_\Lambda\mathrm{H})$	$P_\Sigma({}^3_\Lambda\mathrm{H})$	$\Gamma^{\mathrm{UV}}_{\mathrm{PW}}$	$\Gamma^{\mathrm{UV}}_{\mathrm{DW}}$
approx.	46.81	95.87	–	1.141	–
Λ	100	99.61	–	1.232	1.413
$\Lambda + \Sigma$	100	99.61	0.39	1.099	1.265

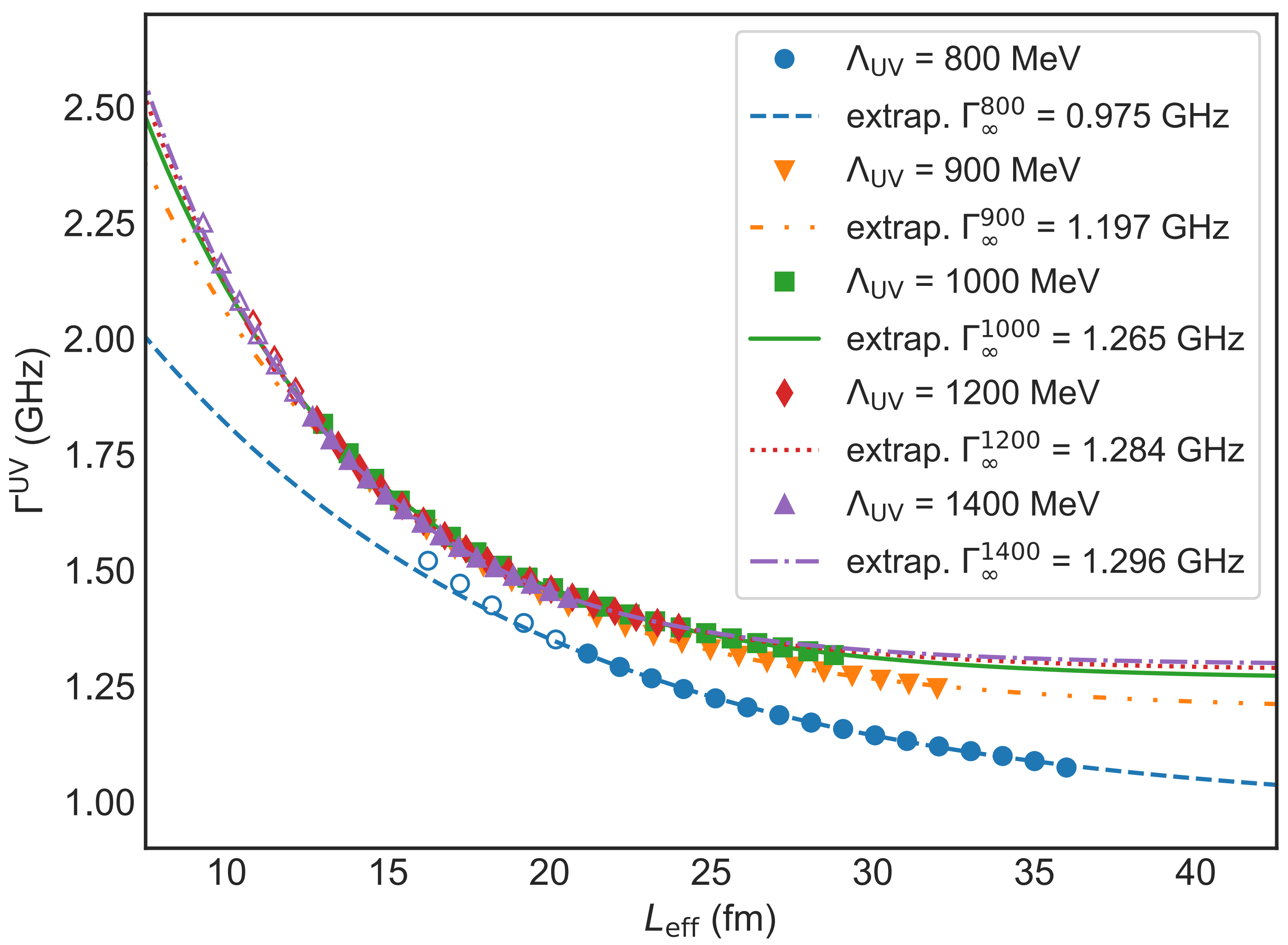
+8%

-9%

Two-body decay rates for different Λ_{UV} are correlated with B_Λ



$$E^{UV}(L_{eff}) = E_\infty + a_0\, e^{-a_1 L_{eff}}$$



$$\Gamma^{UV}(L_{eff}) = \Gamma_\infty + b_0\, e^{-b_1 L_{eff}}$$

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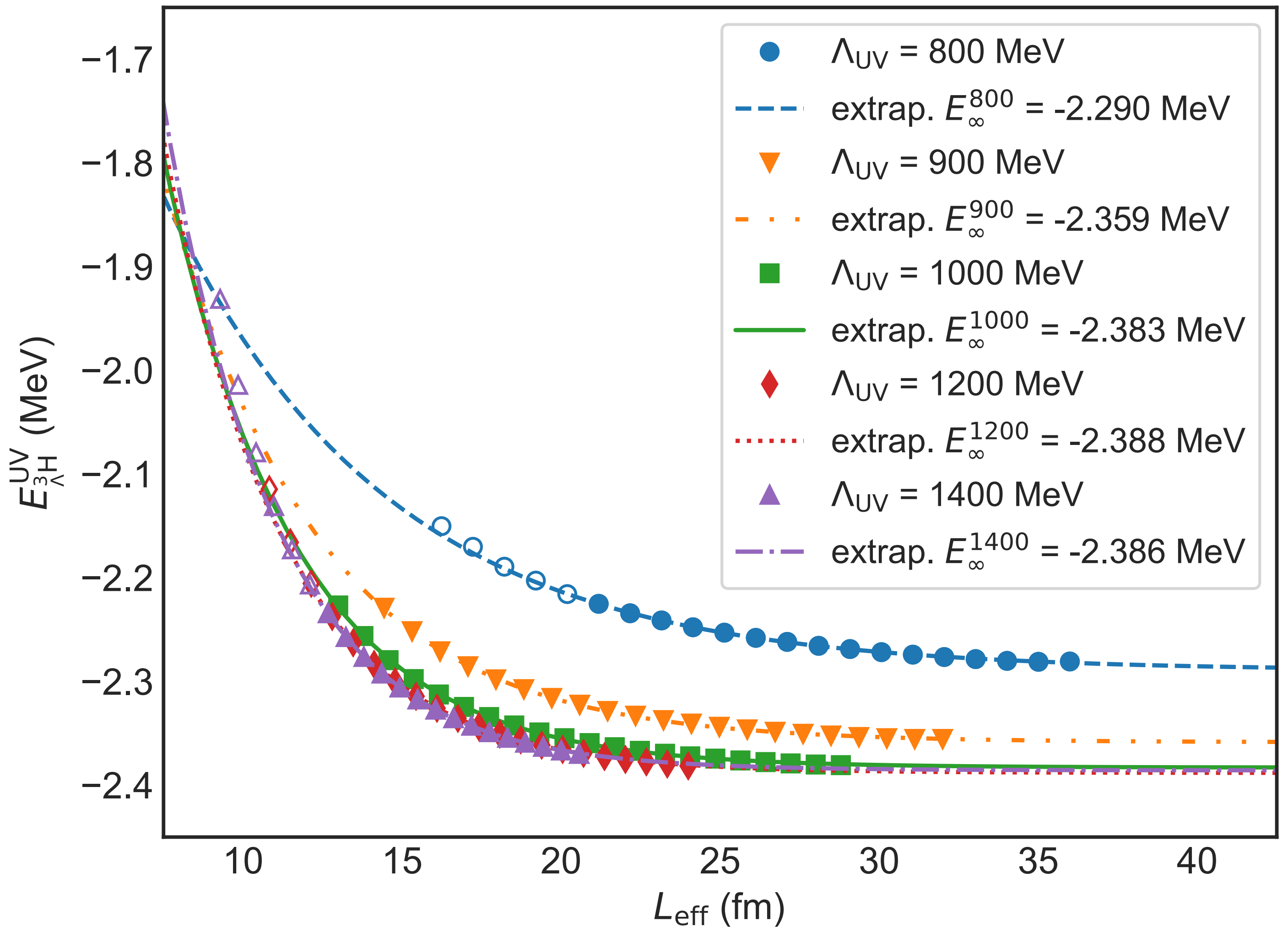

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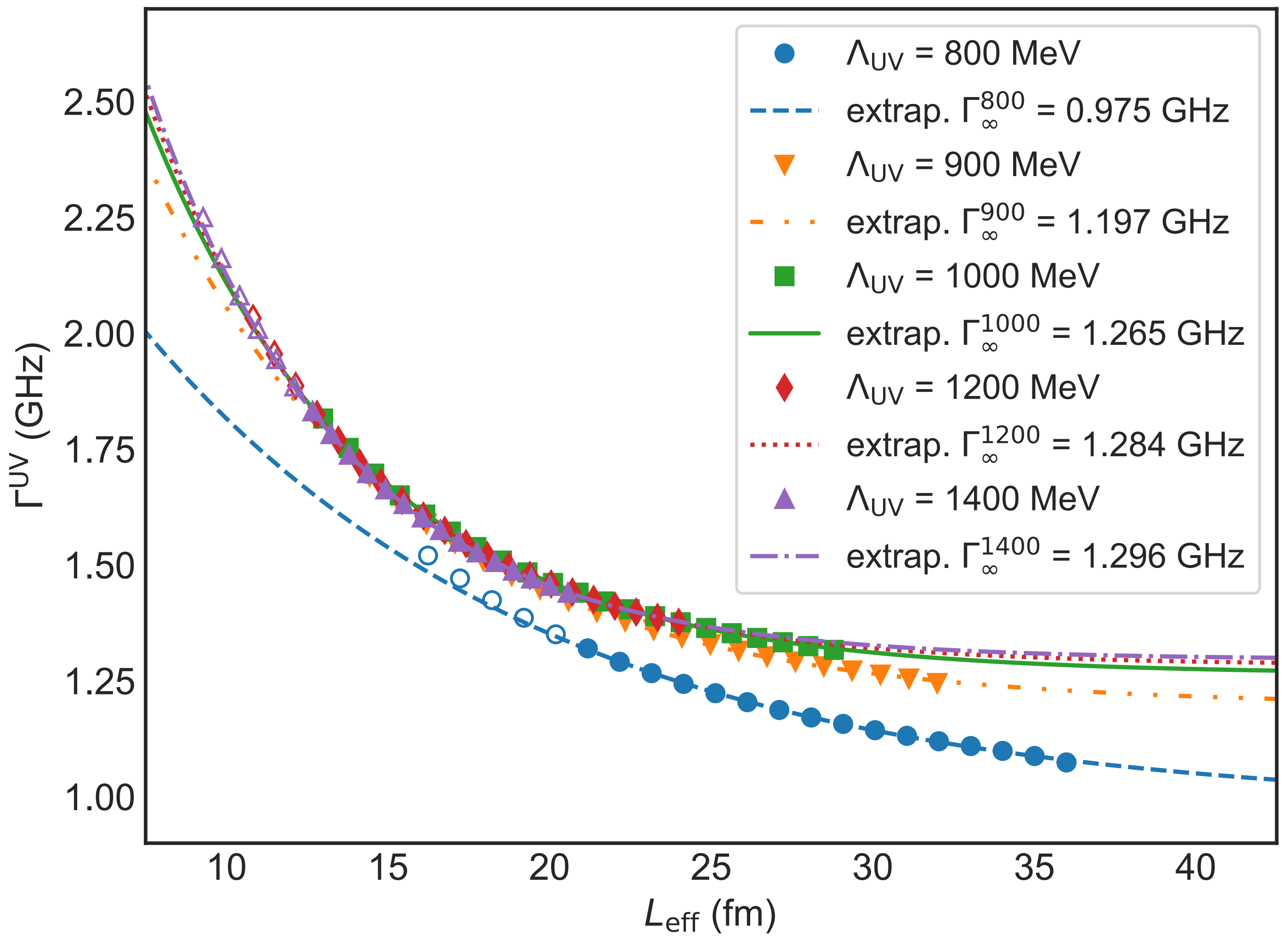

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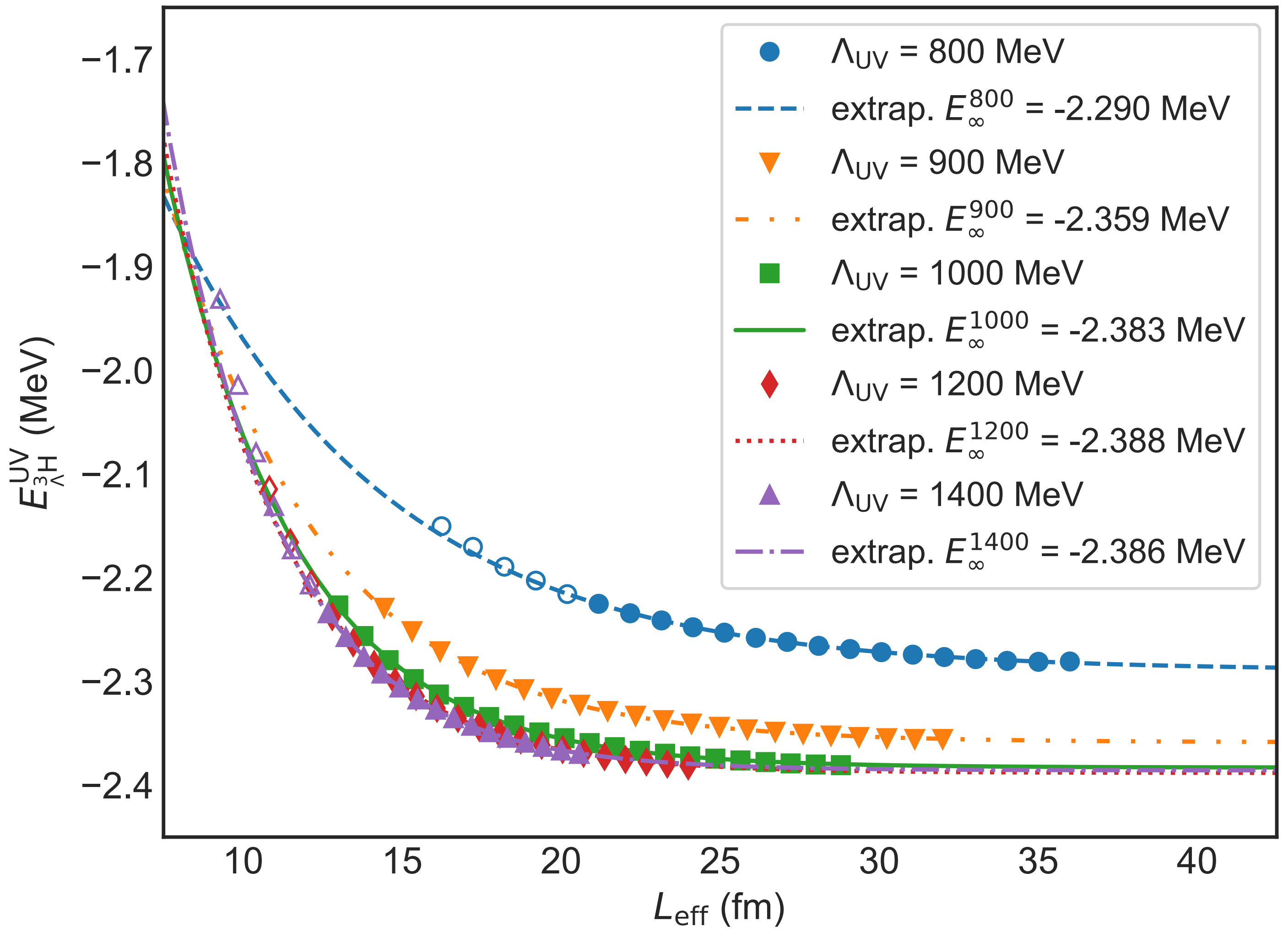
Corresponding lifetimes and relation to B_Λ

Λ_{UV} (MeV)	B_Λ (KeV)	Γ (GHz)	τ (ps)
800	69	0,975	234±27
900	135	1,197	190±22
1000	159	1,265	180±21

→ compatible with ALICE

→ compatible with HypHI

Two-body decay rates for different Λ_{UV} are correlated with B_Λ



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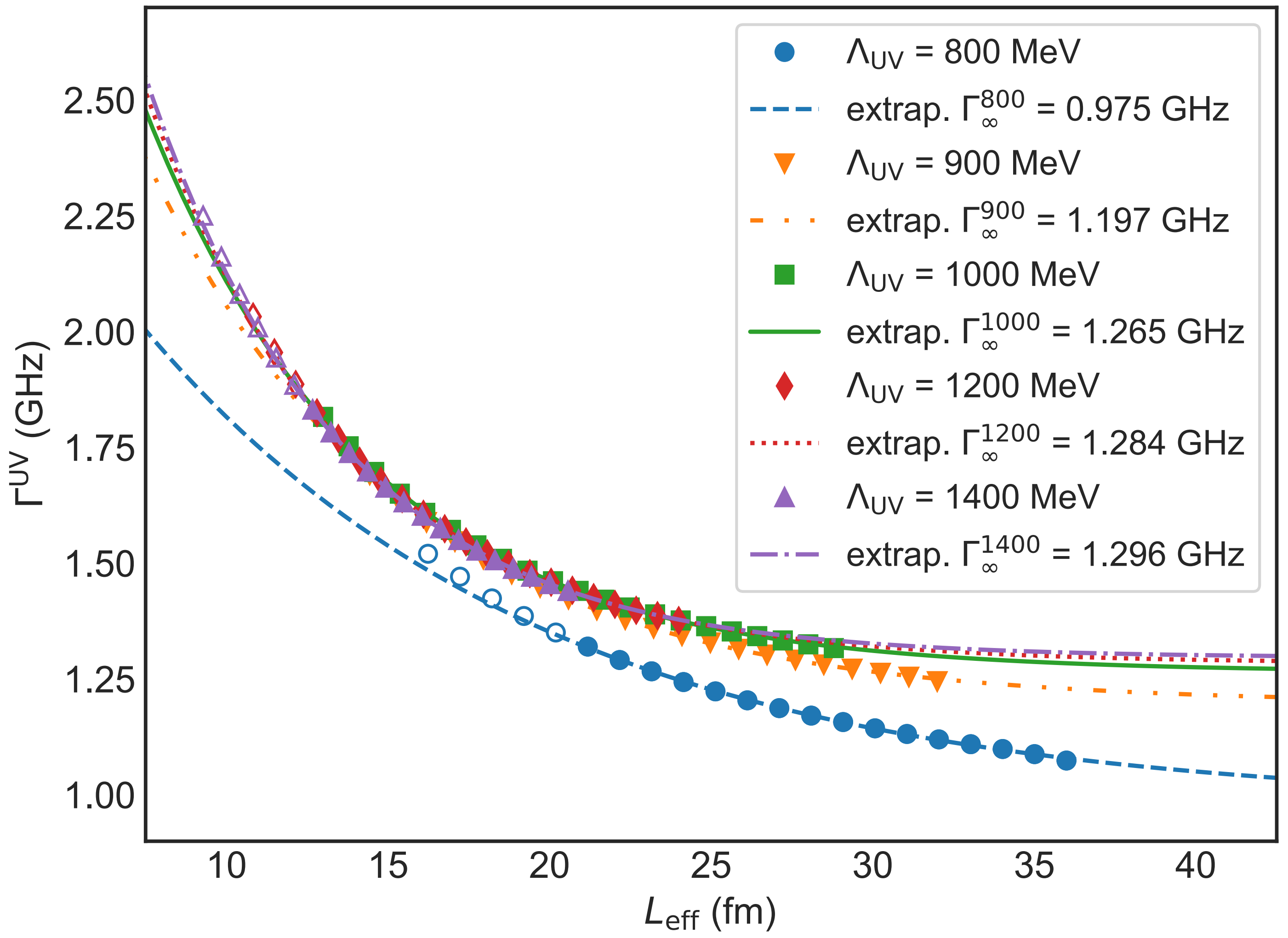

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Corresponding lifetimes and relation to B_Λ

Λ_{UV} (MeV)	B_Λ (KeV)	Γ (GHz)	τ (ps)
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	410	1,403	163±18

compatible with ALICE

compatible with HypHI

Overlaps with STAR when extrapolating to their B_Λ = 0.41± 0.12 ±0.11 MeV

Theoretical uncertainities

- From partial decay rate to lifetime

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

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➡ More precise than input hamiltonians

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- Nuclear forces:

➡ Poor NY data and potentials

$$\Lambda_{YN} \in (550,\ 700) \quad \mathrm{M}eV$$

➡ NNLOsim family of 42 Hamiltonians:

$$T_{NN}^{lab,max} \leq 125,\ 158,\ 191,\ 224,\ 257,\ 290 \quad \mathrm{M}eV$$

$$\Lambda_{EFT} = 450,\ 475,\ 500,\ 525,\ 550,\ 575,\ 600 \quad \mathrm{M}eV$$

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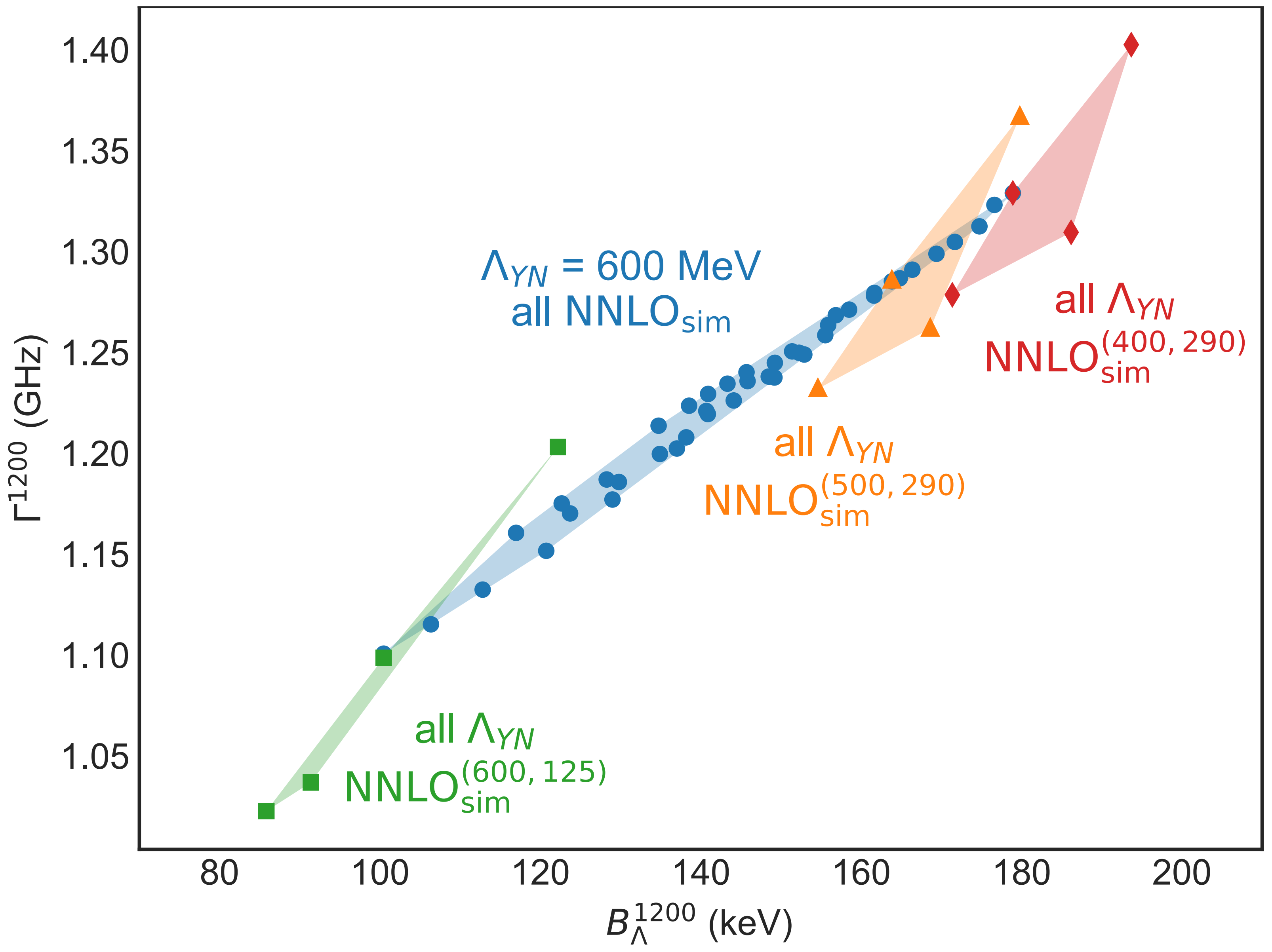
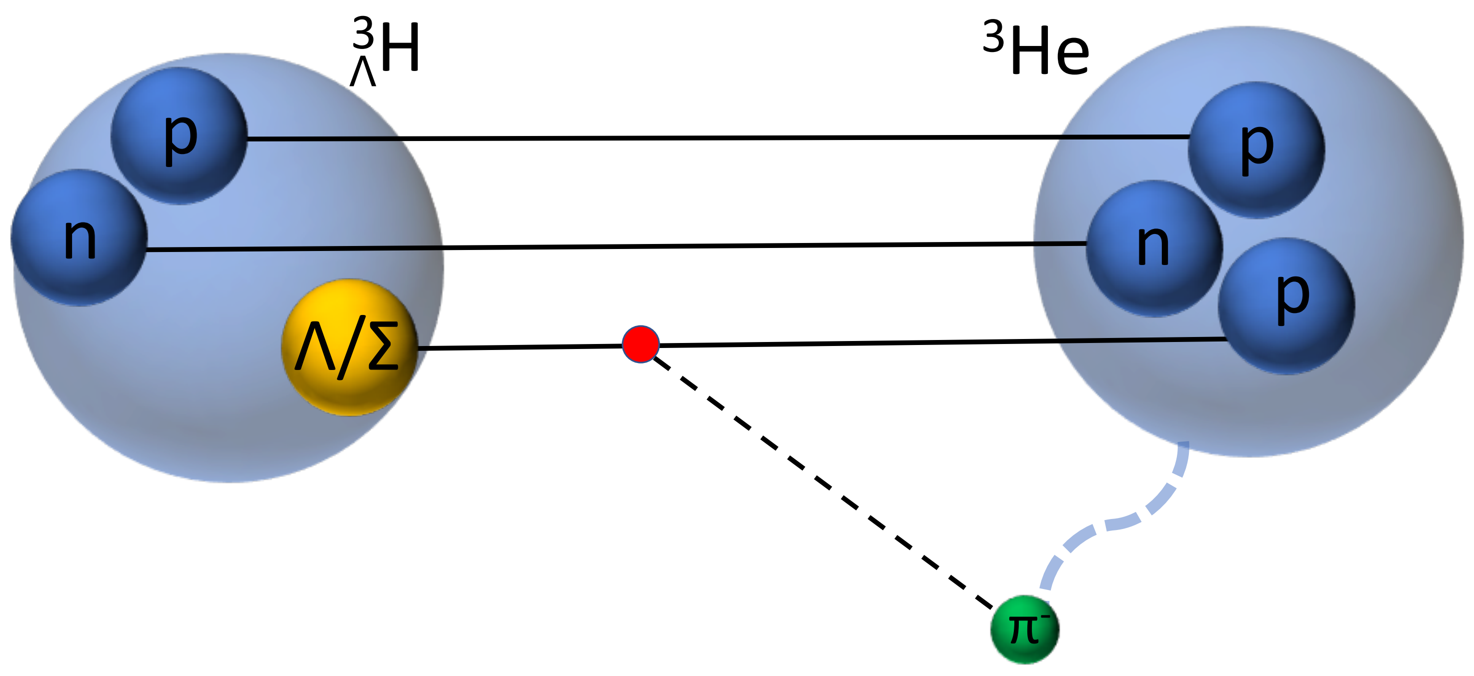
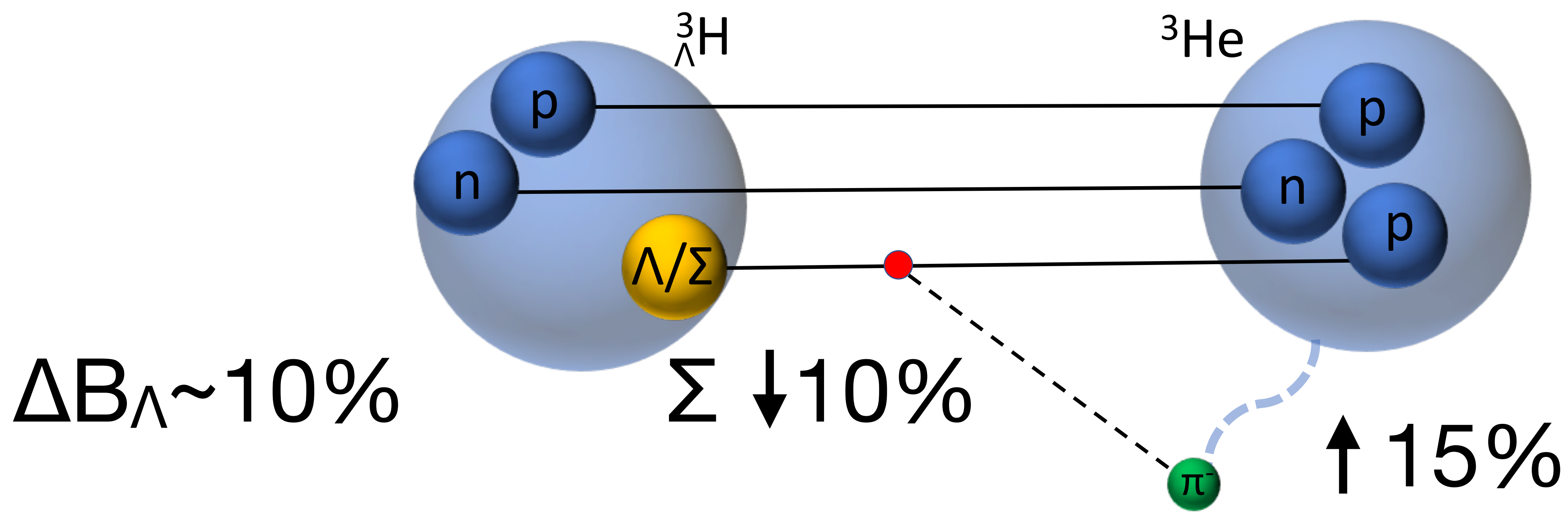


Summary



➡ New microscopic $\Gamma(^3H \longrightarrow \pi^- + {}^3He)$ computation

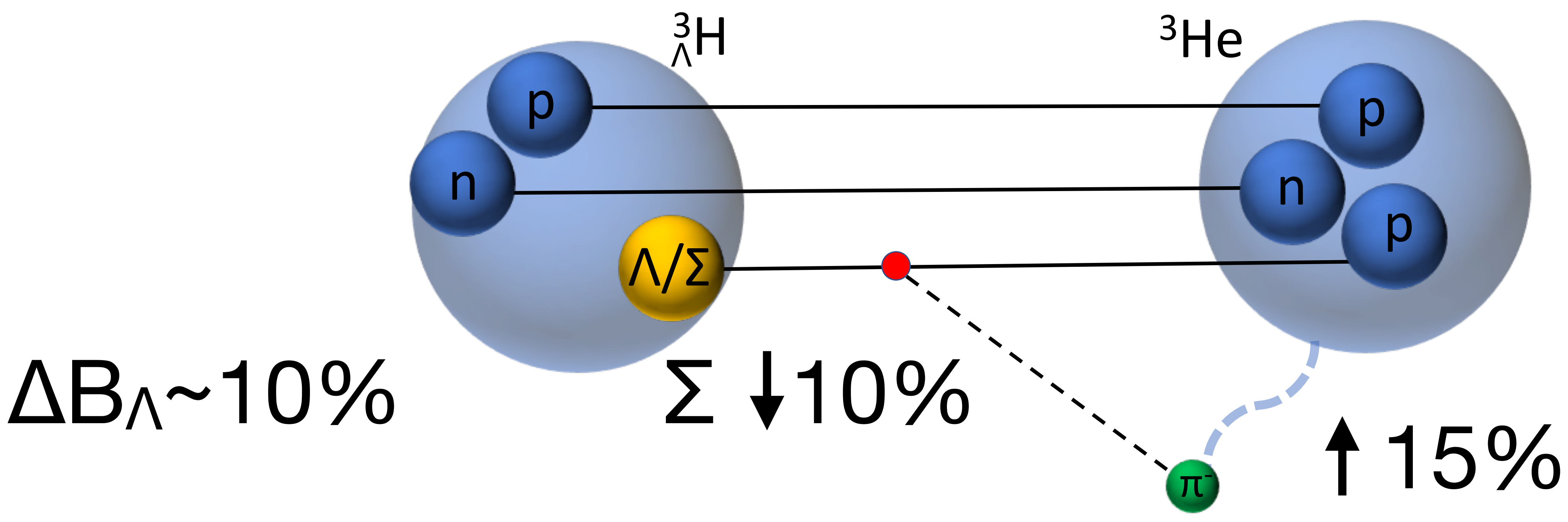
Summary



➡ New microscopic Γ(^{3}H —> π⁻ + ^{3}He) computation

- Inclusion of π⁻ distortion increases rate ~15%
- Small Σ contribution decreases rate ~10%
- Strong dependence on B_{Λ}

Summary



➡ New microscopic Γ(^{3}H —> π$^-$ + ^{3}He) computation

- Inclusion of π$^-$ distortion increases rate ~15%
- Small Σ contribution decreases rate ~10%
- Strong dependence on B_Λ
- Deduced lifetimes correlate with ALICE, HypHI, and STAR results, each with different B_Λ

Many thanks to my collaborators

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