



On the Hypertriton Lifetime

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GEFÖRDERT VOM



Bundesministerium
für Bildung
und Forschung

- ▶ Theoretical Framework
 - ▶ Motivation for our Calculation
-
- ▶ Weak interaction and Final State Interactions
 - ▶ Phase Space
-
- ▶ Our Results
 - ▶ Analysis and Summary



Theoretical Framework

⇒ Pionless EFT



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Shallow S-Wave State

$$J^P = \frac{1}{2}^+$$

Distinguishable

${}^3\Lambda$

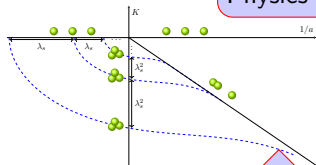
Theoretical Framework

⇒ Pionless EFT



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Physics Determined by a and Λ_*

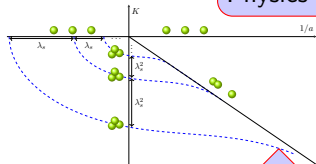


Shallow S-Wave State

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Large Scattering Length

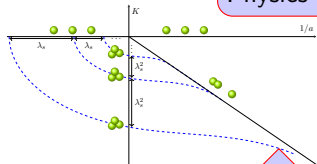
Physics Determined by a and Λ_* Universal Relations
Between Observables

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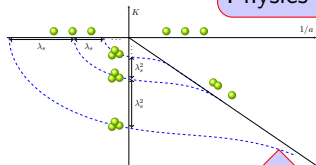
Physics Determined by a and Λ_* Universal Relations
Between Observables B_Λ and $\langle r^2 \rangle$ B_Λ and τ B_Λ and $a_{\Lambda d}$

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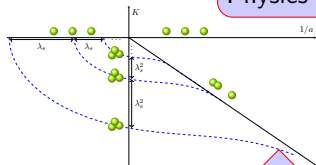
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Pionless EFT
Controllable Uncertainties
Systematic Improvement

Physics Determined by a and Λ_* Universal Relations
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Systematic ImprovementFocus Today B_Λ and τ

${}^3_\Lambda\text{H}$ ${}^3_\Lambda\text{n}$

Lagrangian Hypertriton and Λnn

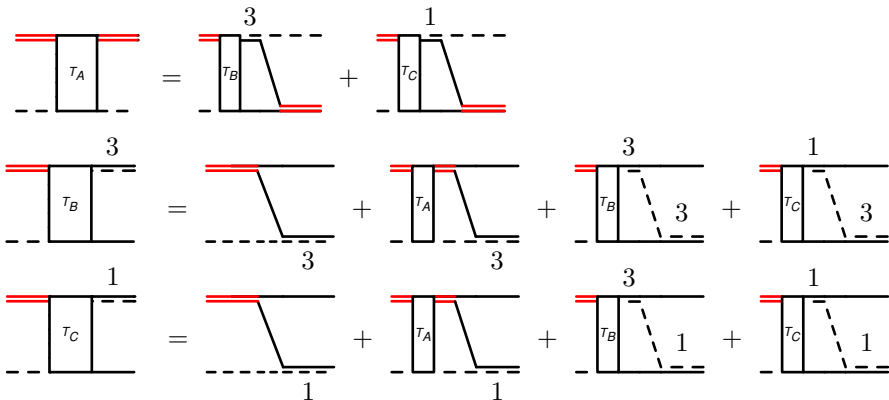


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$$\begin{aligned} \mathcal{L} = & \quad \text{N} \quad + \quad \Lambda \\ & \text{---} \quad + \quad \text{---} \\ & + \quad {}^1S_0(NN) \quad + \quad {}^3S_1(NN) \quad + \quad {}^3S_1(\Lambda N) \quad + \quad {}^1S_0(\Lambda N) \\ & + \quad \text{---} \quad + \quad \text{---} \quad + \quad \frac{\text{---}}{3} \quad + \quad \frac{\text{---}}{1} \\ & + \quad \text{---} \quad + \quad \text{---} \quad + \quad \frac{\text{---}}{3} \quad + \quad \frac{\text{---}}{1} \\ & + \quad \dots \end{aligned}$$

The diagram illustrates the Lagrangian \mathcal{L} for Hypertriton and Λnn systems. It is composed of several terms:

- N : A solid horizontal line representing a nucleon.
- Λ : A dashed horizontal line representing a lambda baryon.
- ${}^1S_0(NN)$: A blue double horizontal line representing a nucleon-nucleon interaction in the 1S_0 state.
- ${}^3S_1(NN)$: A red double horizontal line representing a nucleon-nucleon interaction in the 3S_1 state.
- ${}^3S_1(\Lambda N)$: A dashed horizontal line with a solid line above it, representing a lambda-nucleon interaction in the 3S_1 state. The coefficient $\frac{\text{---}}{3}$ indicates a weight of 1/3.
- ${}^1S_0(\Lambda N)$: A dashed horizontal line with a solid line above it, representing a lambda-nucleon interaction in the 1S_0 state. The coefficient $\frac{\text{---}}{1}$ indicates a weight of 1.
- Diagrammatic terms: Each of the four interaction terms above is followed by a diagrammatic representation. The first two (blue and red) show a double line splitting into two lines. The last two (dashed/solid) show a dashed line and a solid line splitting into two lines, with the dashed line being solid and the solid line being dashed. The coefficients $\frac{\text{---}}{3}$ and $\frac{\text{---}}{1}$ are placed below these diagrams.
- \dots : An ellipsis indicating additional terms in the Lagrangian.

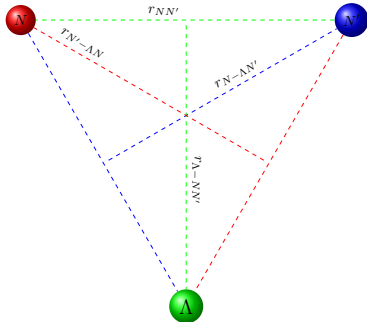


The diagram illustrates the integral equations for the transition amplitudes T_A , T_B , and T_C in the hypertriton system. Each equation is represented by a diagrammatic equation where a transition amplitude is equal to a sum of diagrams representing various interaction channels.

Equation 1: T_A is equal to the sum of two diagrams. The first diagram shows a transition from a state with two particles (1 and 2) to a state with three particles (1, 2, and 3), with a red line indicating a transition. The second diagram shows a transition from a state with one particle (1) to a state with two particles (1 and 2), with a red line indicating a transition.

Equation 2: T_B is equal to the sum of four diagrams. The first diagram shows a transition from a state with two particles (1 and 2) to a state with three particles (1, 2, and 3), with a red line indicating a transition. The second diagram shows a transition from a state with one particle (1) to a state with two particles (1 and 2), with a red line indicating a transition. The third diagram shows a transition from a state with two particles (1 and 2) to a state with three particles (1, 2, and 3), with a red line indicating a transition. The fourth diagram shows a transition from a state with one particle (1) to a state with two particles (1 and 2), with a red line indicating a transition.

Equation 3: T_C is equal to the sum of four diagrams. The first diagram shows a transition from a state with two particles (1 and 2) to a state with three particles (1, 2, and 3), with a red line indicating a transition. The second diagram shows a transition from a state with one particle (1) to a state with two particles (1 and 2), with a red line indicating a transition. The third diagram shows a transition from a state with two particles (1 and 2) to a state with three particles (1, 2, and 3), with a red line indicating a transition. The fourth diagram shows a transition from a state with one particle (1) to a state with two particles (1 and 2), with a red line indicating a transition.



Calculation of Form Factors out of the Wave Functions:

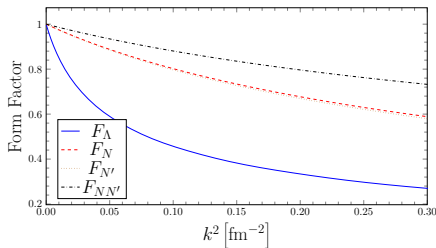
$$F_i(\mathbf{k}^2) = \int d^3p \int d^3q \Psi_i(p, q) \Psi_i(p, |\mathbf{q} - \mathbf{k}|)$$

Directly Related to Different Matter Radii as Expansion in k^2

$$F_i(\mathbf{k}^2) = 1 - \frac{1}{6} \mathbf{k}^2 \langle r_{i-jk}^2 \rangle + \dots$$

2-Body \Rightarrow One Radius
3-Body \Rightarrow Many Radii

Most Interesting
 $r_{\Lambda-NN'} \Leftrightarrow r_{\Lambda d}$

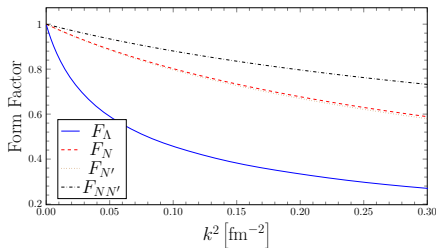


Expectation from Two-Body Calculation:

$$B_2 = \frac{1}{2\mu a^2} \quad \text{and} \quad \langle r^2 \rangle = \frac{a^2}{2}$$

$$\Rightarrow \sqrt{\langle r_{NN'}^2 \rangle} \approx 3.04 \text{ fm}$$

$$\sqrt{\langle r_{\Lambda-NN'}^2 \rangle} \approx 10.34 \text{ fm}$$



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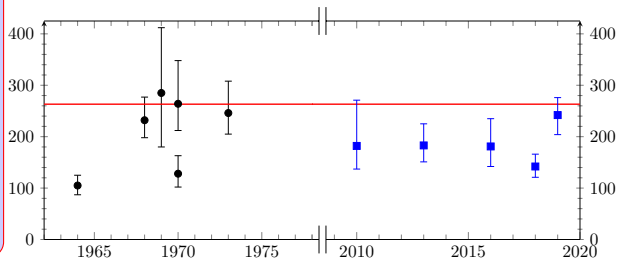
$\sqrt{\langle r_{\Lambda-NN'}^2 \rangle}$ [fm]	$\sqrt{\langle r_{N'-\Lambda N}^2 \rangle}$ [fm]	$\sqrt{\langle r_{N-N'\Lambda}^2 \rangle}$ [fm]	$\sqrt{\langle r_{NN'}^2 \rangle}$ [fm]
10.79	3.96	4.02	2.96
+3.04/-1.53	+0.40/-0.25	+0.41/-0.25	+0.06/-0.05

 Insensitive
to Details
of Λ -N In-
teraction

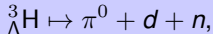
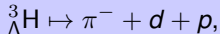
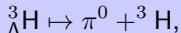
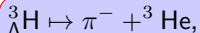


Lifetime Hypertriton Channels and Isospin Rule

- ▶ Two-Body Picture Works
- ▶ Calculate Lifetime in a Theory with Fundamental Deuteron
- ▶ Focus on B_{Λ} Dependence



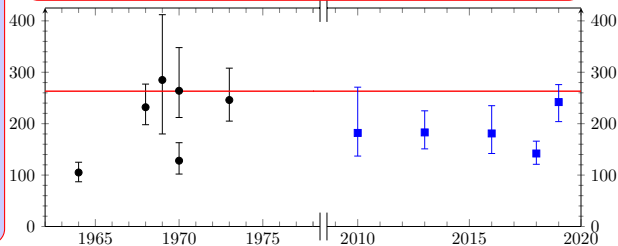
Lifetime Hypertriton Channels and Isospin Rule



Charged and Uncharged Channel Are Related by the $\Delta I = \frac{1}{2}$ Rule
 \Rightarrow Calculate only one

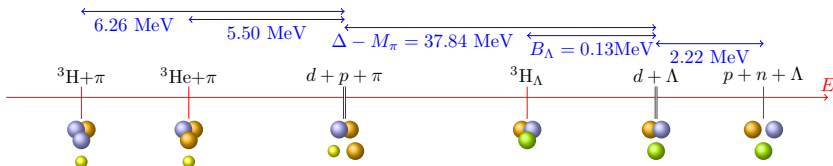
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Leptonic and Non-Mesonic Decays are Negligible



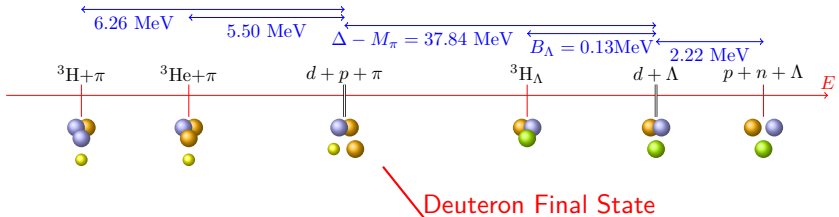
${}^3_{\Lambda}\text{H}$

Lifetime Hypertriton Thresholds and Feynman Diagrams

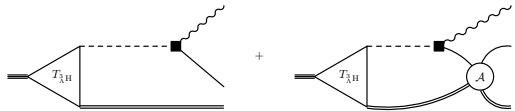


${}^3_{\Lambda}\text{H}$

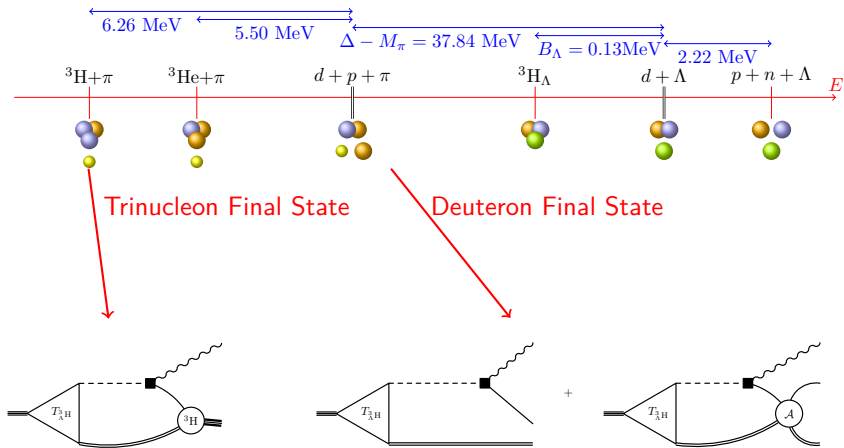
Lifetime Hypertriton Thresholds and Feynman Diagrams



Deuteron Final State



Lifetime Hypertriton Thresholds and Feynman Diagrams



$$\mathcal{M}_{\Lambda \rightarrow n\pi^0} = -iG_F M_\pi^2 \bar{u}(\mathbf{p}') [\tilde{A}_\pi + \tilde{B}_\pi \gamma_5] u(\mathbf{p})$$

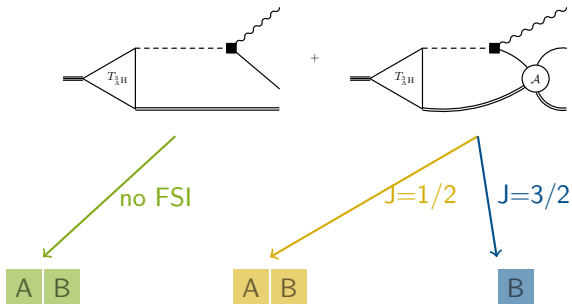
non-relativistic reduction

$$\mathcal{M}_{\Lambda \rightarrow n\pi^0}^{\text{reduced}} = -iG_F M_\pi^2 \left(A_\pi + \frac{B_\pi}{M_\Lambda + m} \boldsymbol{\sigma} \cdot \mathbf{k} \right)$$

two contributions A_π and B_π

A

B



square product leads towards
interference terms

${}^3_{\Lambda}\text{H}$

Contributions to the Deuteron Final State



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A B

A B

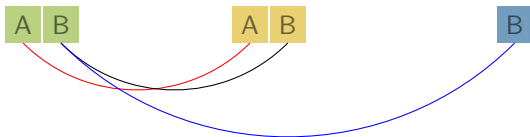
B

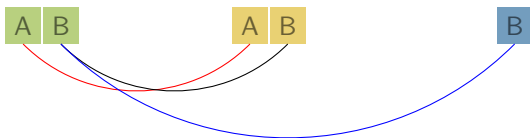
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Contributions to the Deuteron Final State



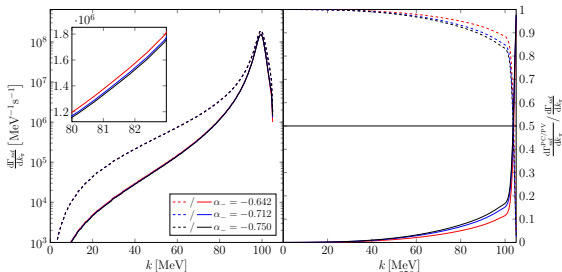
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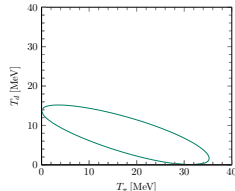
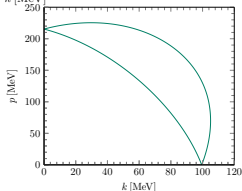
$$\Gamma = A^2 + A^2 + A A + B^2 + B^2 + B^2 + B B + B B$$

not small !



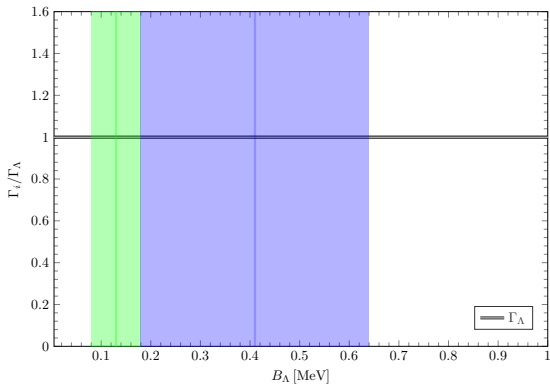
- ▶ dependence on α negligible
- ▶ small changes in PC and PV contributions
- ▶ final state interactions are important

- ▶ main contribution at high k_π
- ▶ full phase space calculation



${}^3_{\Lambda}\text{H}$

Hypertriton Width and Branching Ratios

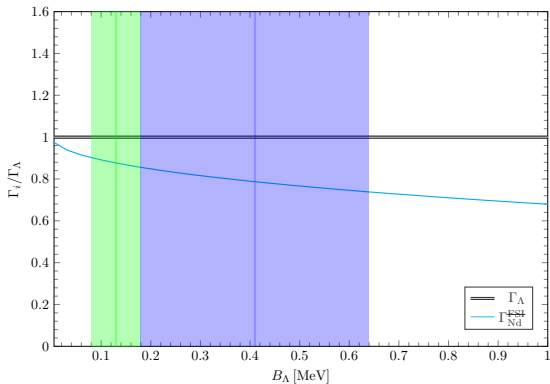


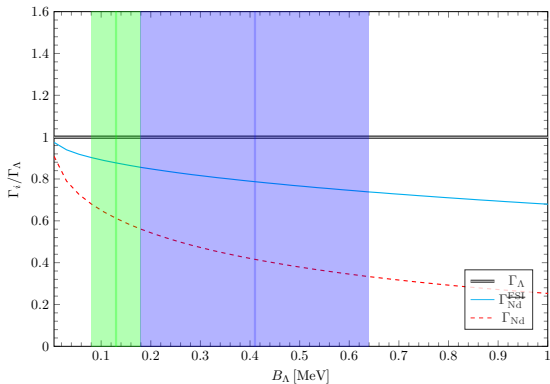
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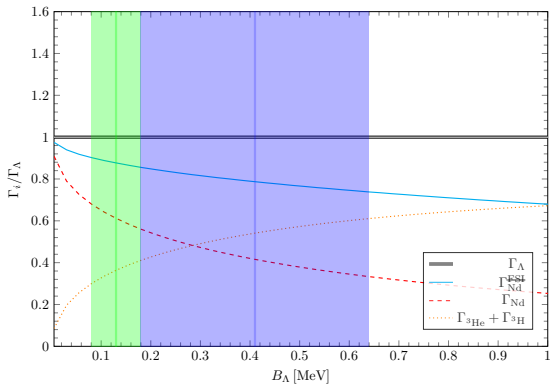
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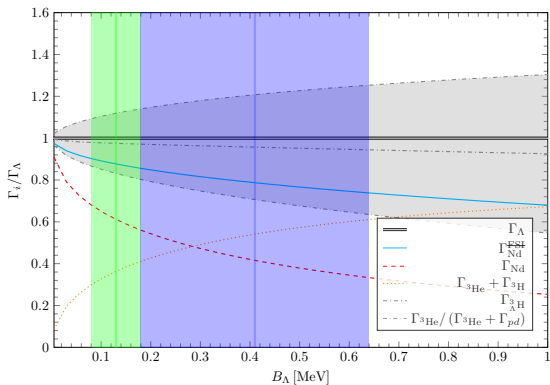


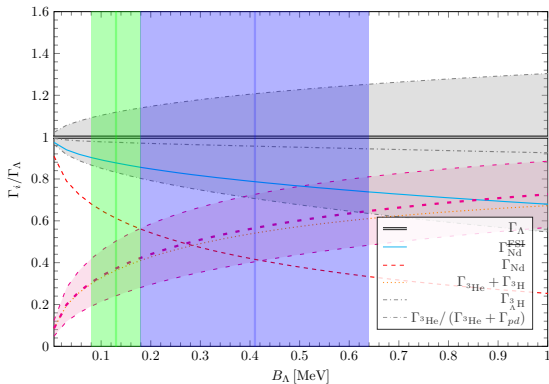
${}^3_{\Lambda}\text{H}$

Hypertriton Width and Branching Ratios



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- ▶ Γ_{3H} Barely Depends on B_{Λ}
- ▶ Final State Interactions are Important
- ▶ $\Gamma_{3He}/(\Gamma_{3He} + \Gamma_{pd})$ Depends Strongly on B_{Λ}
- ▶ STAR Branching ratio $0.32(5)(8)$

Emulsion Data: $R = \Gamma_{3He}/(\Gamma_{3He} + \Gamma_{pd}) = 0.3 - 0.4$



Our Results:

- ▶ $\Gamma_{\Lambda}({}^3_{\Lambda}H(0.13)) = 0.98 \pm 0.15\Gamma_{\Lambda}$
- ▶ $\Gamma_{\Lambda}({}^3_{\Lambda}H(0.41)) = 0.98 \pm 0.25\Gamma_{\Lambda}$
- ▶ $R(0.13) = 0.38 \pm 0.05$
- ▶ $R(0.41) = 0.57 \pm 0.11$



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Consistent:

- ▶ Calculation by Congleton for Γ and R
- ▶ Calculation by Kamada for Γ and R
- ▶ Emulsion Data
 $0.05\text{MeV} \lesssim B_{\Lambda} \lesssim 0.2\text{MeV}$



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Slight Tension:

- ▶ STAR results Branching ratio $R = 0.32 \pm 0.05 \pm 0.08$



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Good part:

- ▶ EFT systematic improvement possible
- ▶ Go to NLO or three-body

Summary

- ▶ Elegant theory with few input parameters
- ▶ Branching ratio as results and not as input
- ▶ Consistent results with a fundamental deuteron including the full three-body phase space
- ▶ Branching ratio favors small binding energies
- ▶ Systematic improvement possible in the future
- ▶ Important to combine different observables: binding energy, lifetime and branching ratios to resolve the hypertriton puzzle