

Hypertriton lifetime puzzle

Stefania Bufalino
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LIGHT UP Workshop @ CERN, June 14-16, 2018

Hypertriton lifetime: can we still talk about a puzzle?

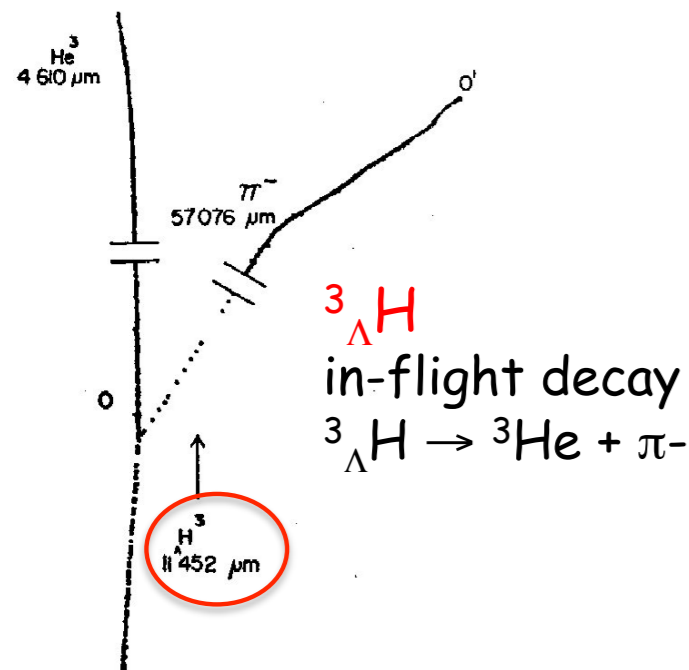
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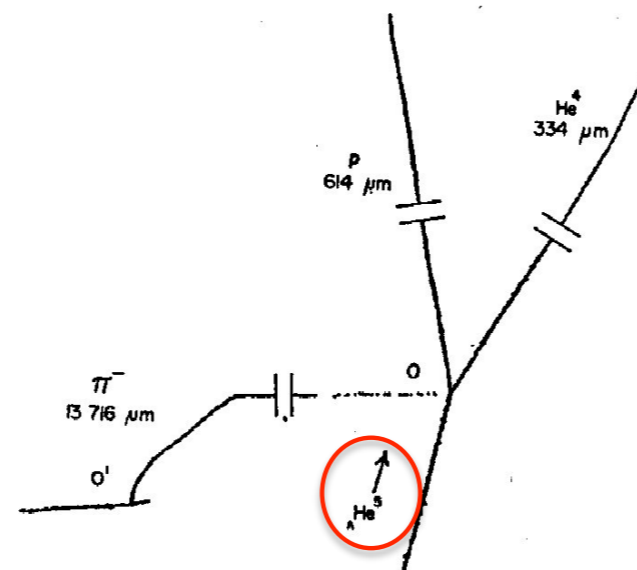
Lifetime measurement: experimental techniques

Hypernuclei discovered in 1953 (M.Danysz, J.Pniewski, Philos. Mag. 44 (1953) 348) in photographic emulsions, through the Mesonic Weak Decay (MWD).

- Light hypernuclei/hyperfragments uniquely identified via their π^- MWD (kinematics of the decay reaction) with visualizing techniques (emulsions /bubble chambers exposed to energetic K^- beams)
- observation of charged decay modes
- assignment of spin/parity of light hypernuclei ground state ($^3_\Lambda\text{H}$, $^4_\Lambda\text{H}$, $^4_\Lambda\text{He}$, $^8_\Lambda\text{Li}$, $^{11}_\Lambda\text{B}$ and $^{12}_\Lambda\text{B}$) through properties of π^- MWD ($^7_\Lambda\text{Li}$)
- Λ -N spin dependent interaction ($J_{\text{hyp g.s.}} = J_{\text{core}} - 1/2$)



$^5_\Lambda\text{He}$
in-flight decay
 $^5_\Lambda\text{He} \rightarrow ^4\text{He} + p + \pi^-$



Lifetime obtained from the spatial distribution of the π^- -MWD vertices around the formation point of the hypernucleus

Lifetime measurement: experimental techniques

Limitations of visualizing techniques:

- no timing information (τ);
- no neutron, γ detection - only charged WD modes observed;
- formed hypernuclei not counted and no Branching Ratio determination
- spatial distribution of the π -MWD vertices around the formation point of ${}^3_{\Lambda}\text{H}$

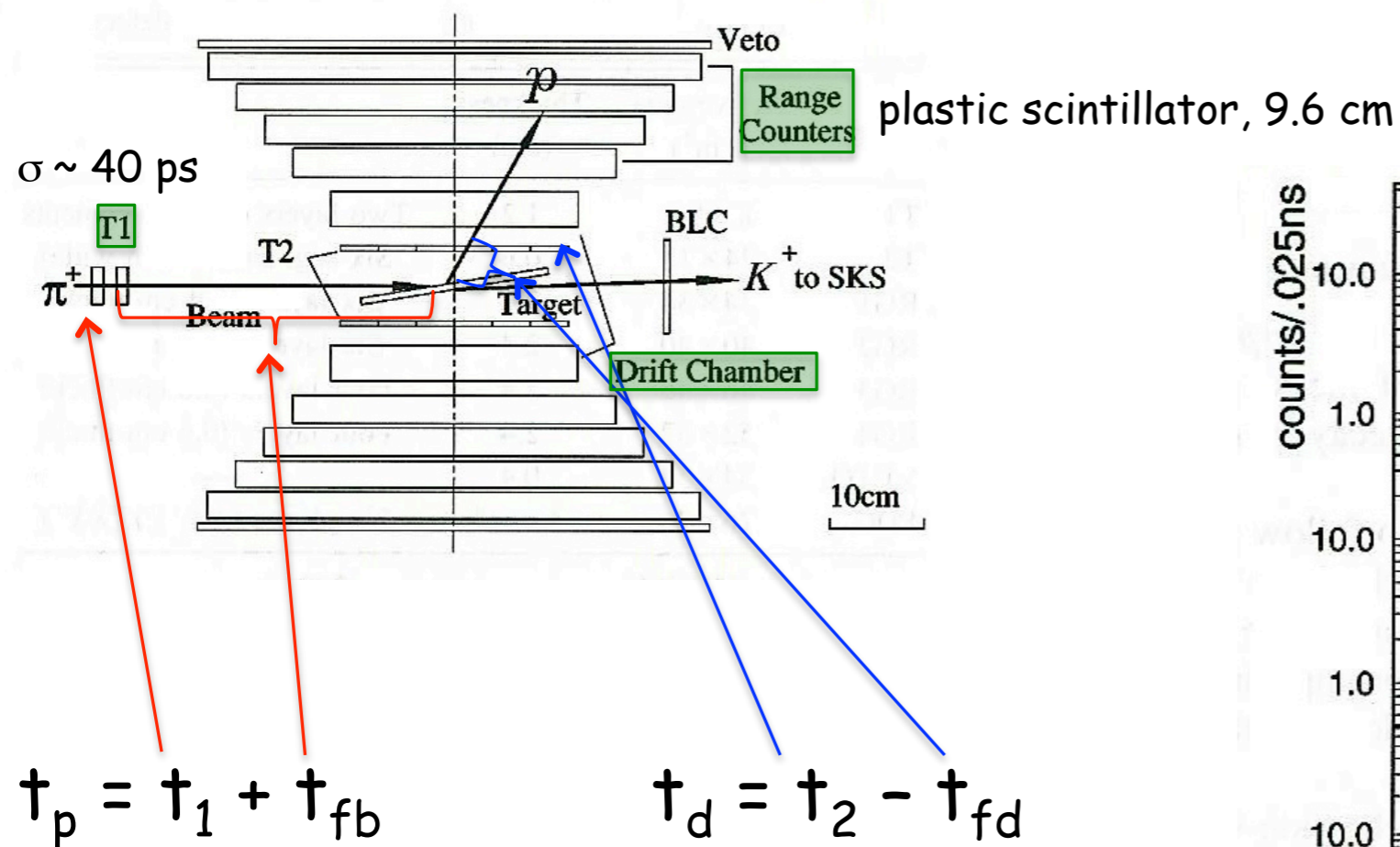
WD studies at accelerators (BNL AGS, KEK PS) with **counter experiments**, from '80 on;

1. (K^- , π^-) and (π^+ , K^+) reactions
2. high intensity K^-/π^+ beams
3. coincidence measurements with large solid angle spectrometers

Lifetime measurement: experimental techniques

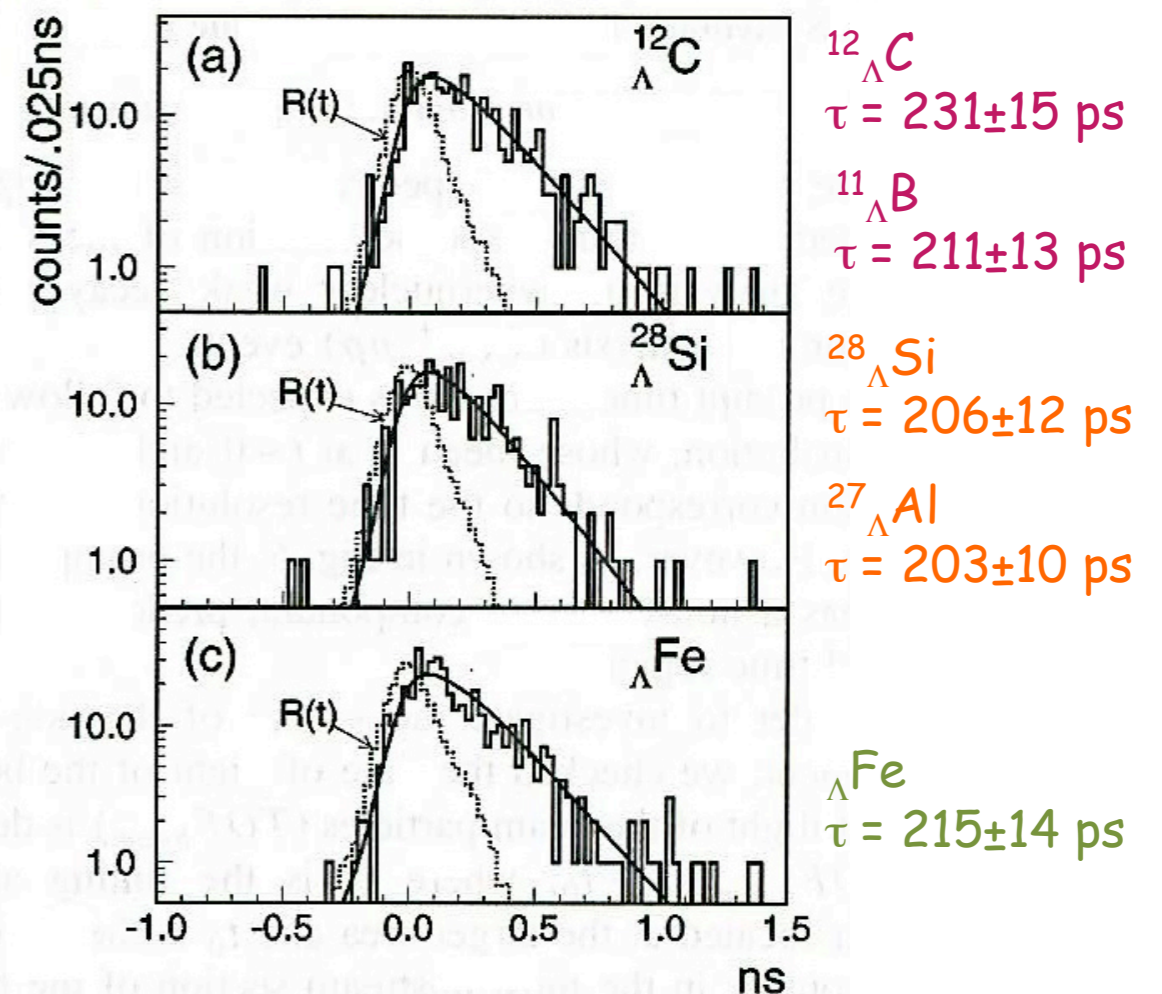
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1. (K^-, π^-) and (π^+, K^+) reactions
2. high intensity K^-/π^+ beams
3. coincidence measurements with large solid angle spectrometers
4. direct timing measurement techniques



$$\Delta t = t_d - t_p$$

Medium Mass Number hypernuclei



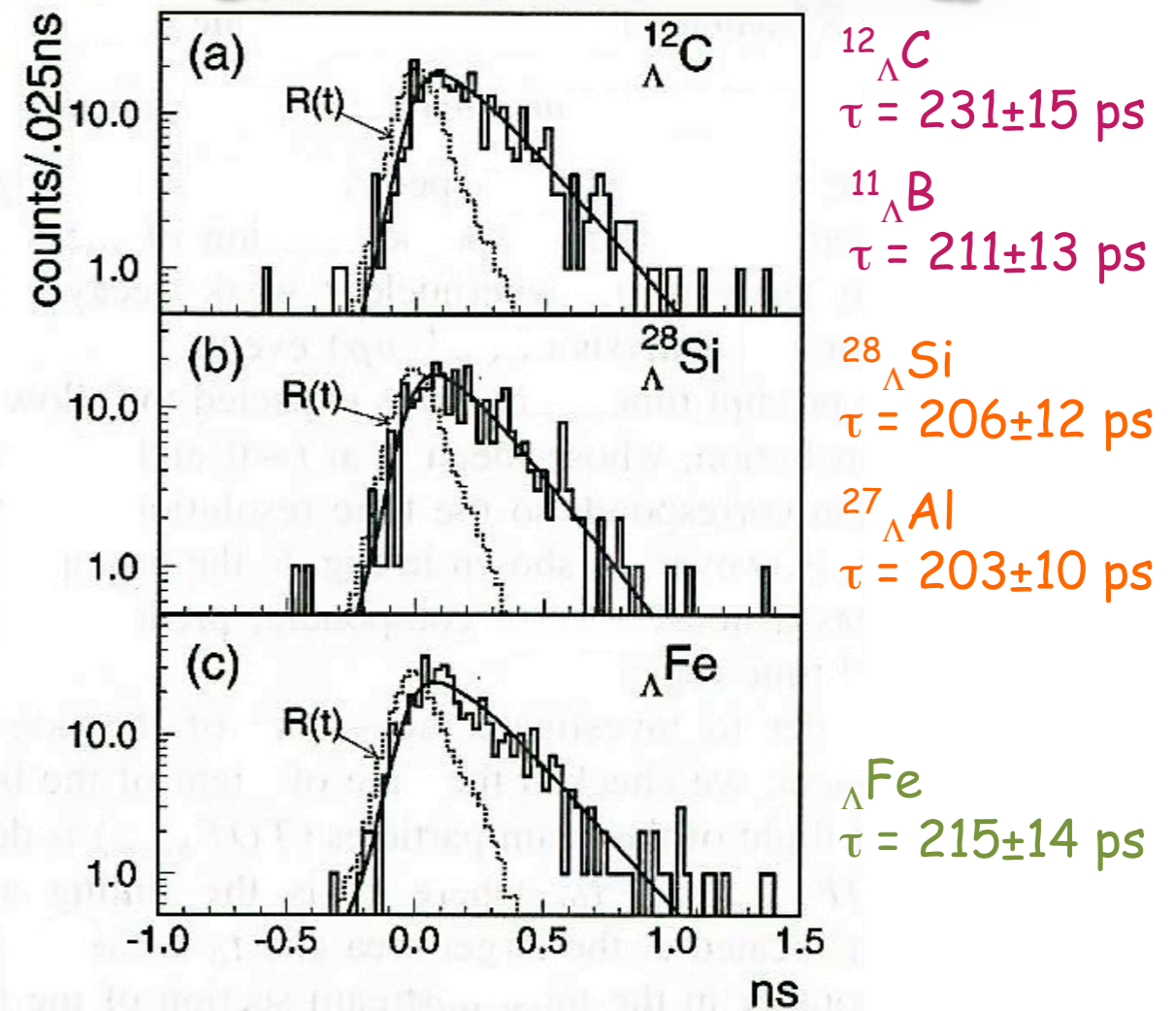
Lifetime measurement: experimental techniques

WD studies at accelerators (BNL AGS, KEK PS) with **counter experiments**, from '80 on;

1. (K^- , π^-) and (π^+ , K^+) reactions
2. high intensity K^-/π^+ beams
3. coincidence measurements with large solid angle spectrometers

The experimental technique **could not be applied to the hydrogen hyperisotopes** since the two-body reactions having an incoming charged meson and a charged outgoing meson require **targets of radioactive ^3H , which are hard to deal with, or of ^4H , which does not exist.**

Medium Mass Number hypernuclei

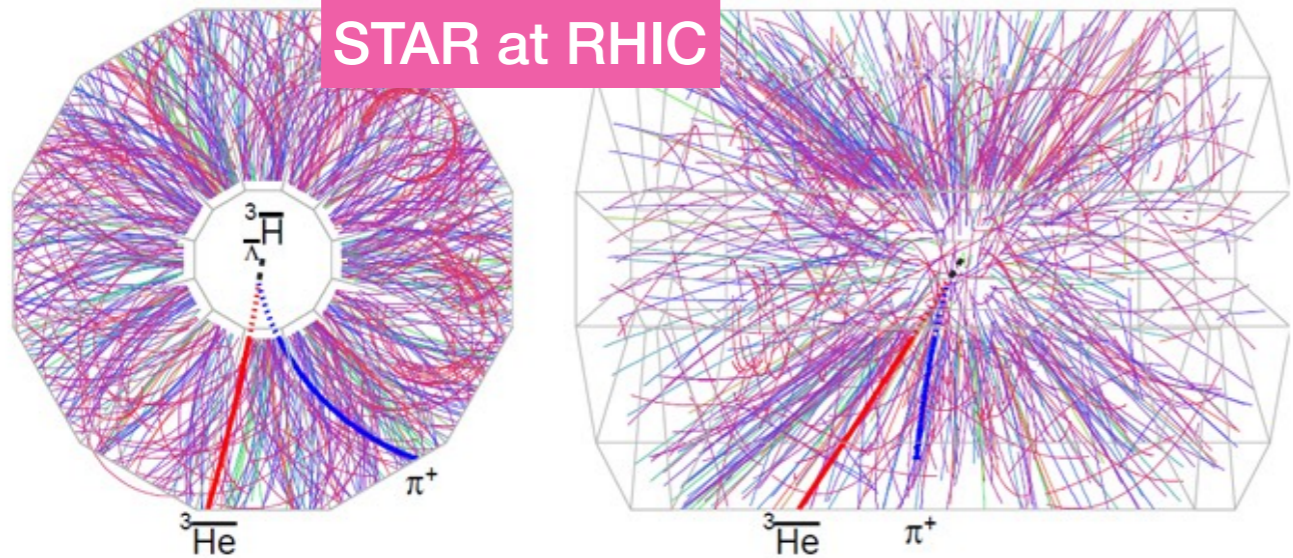


Lifetime measurement: **experimental techniques**

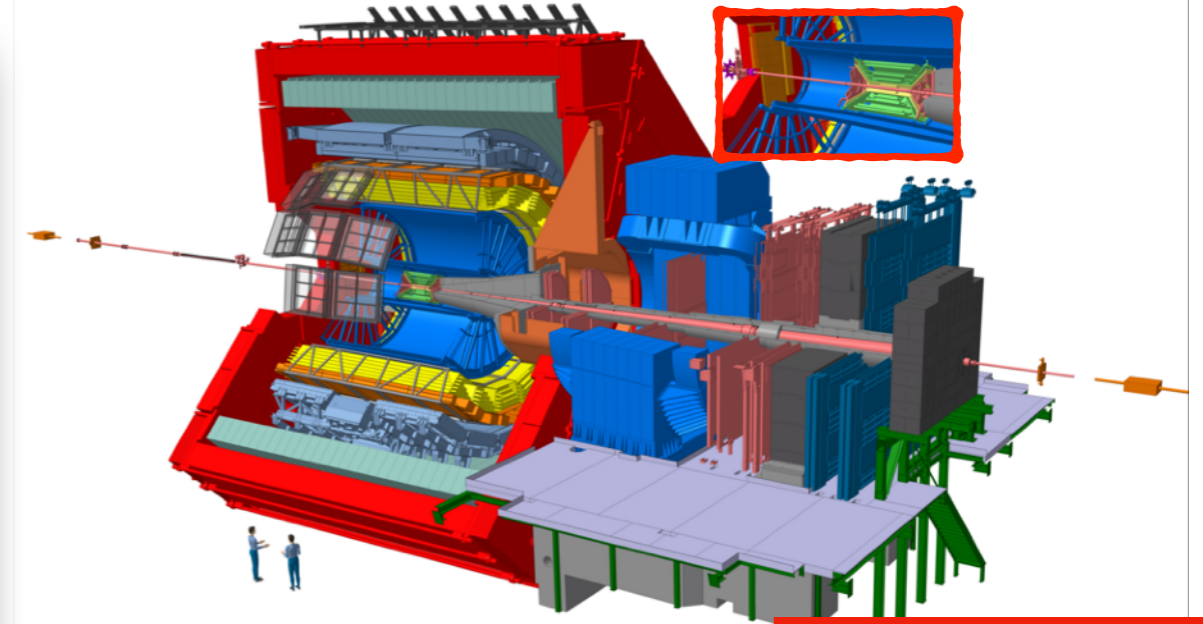
Heavy ion collisions: production of light (anti-)hypernuclei measured via invariant mass of decay products in mesonic decay channels

Au-Au collisions (GeV regime)

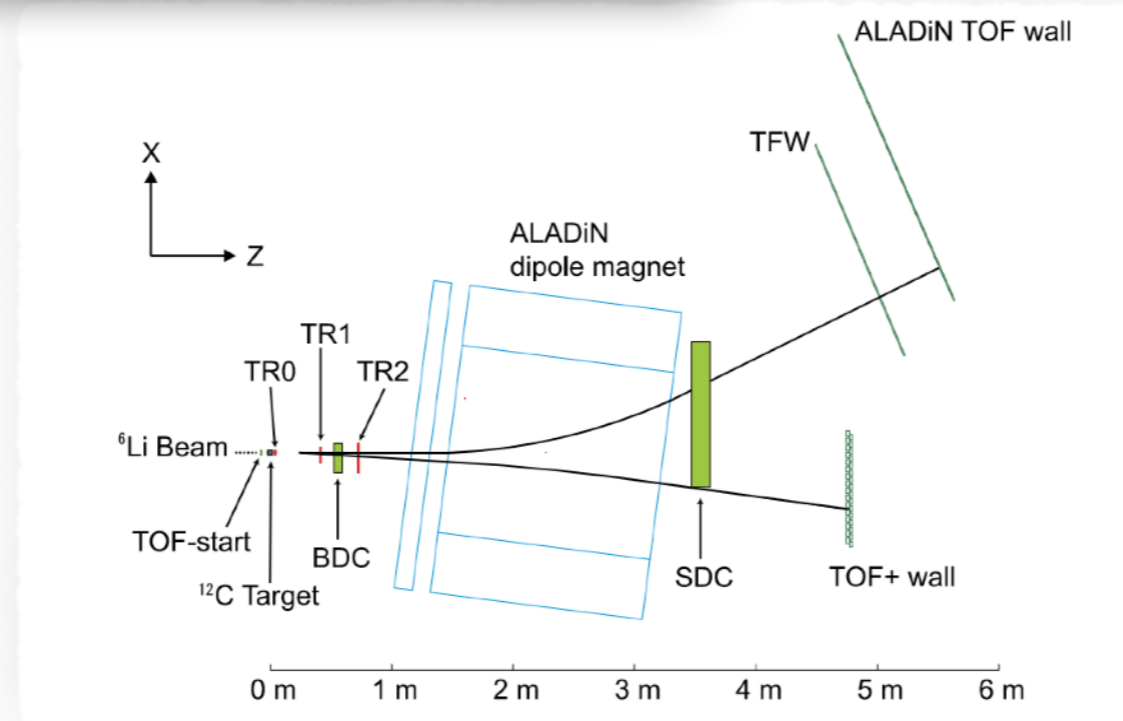
STAR at RHIC



Pb-Pb collisions (TeV regime)



ALICE at the LHC



HypHI at GSI

projectile fragmentation reactions of ${}^6\text{Li}$ at 2 AGeV delivered on a carbon target.

Hypertriton lifetime: expectation vs experimental results

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

- bound state of **p**, **n** and **Λ** , is the lightest known hypernucleus
 - mass = $2.99131 \pm 0.00005 \text{ GeV}/c^2$ [1]
 - $B_{\Lambda} = 2.35 \pm 0.05_{\text{(stat)}} \pm 0.04_{\text{(sys)}} \text{ MeV}$ [1]
 - Λ separation energy $E_{B_{\Lambda}} = 0.13 \pm 0.05 \text{ MeV}$ [1]
 - lifetime: world average = $216^{+16}_{-19} \text{ ps}$ [2]
 - decay channels: \rightarrow Mesonic
 - \rightarrow Non Mesonic (B.R. < 0.02%)

Possible MWD channel

$${}^3_{\Lambda}\text{H} \rightarrow \pi^{-} + {}^3\text{He},$$

B.R. 37,3%

$${}^3_{\Lambda}\text{H} \rightarrow \pi^0 + {}^3\text{H},$$

$${}^3_{\Lambda}\text{H} \rightarrow \pi^{-} + d + p,$$

B.R. 60,1%

$${}^3_{\Lambda}\text{H} \rightarrow \pi^0 + d + n,$$

$${}^3_{\Lambda}\text{H} \rightarrow \pi^{-} + p + p + n,$$

B.R. 0,94%

$${}^3_{\Lambda}\text{H} \rightarrow \pi^0 + p + n + n.$$

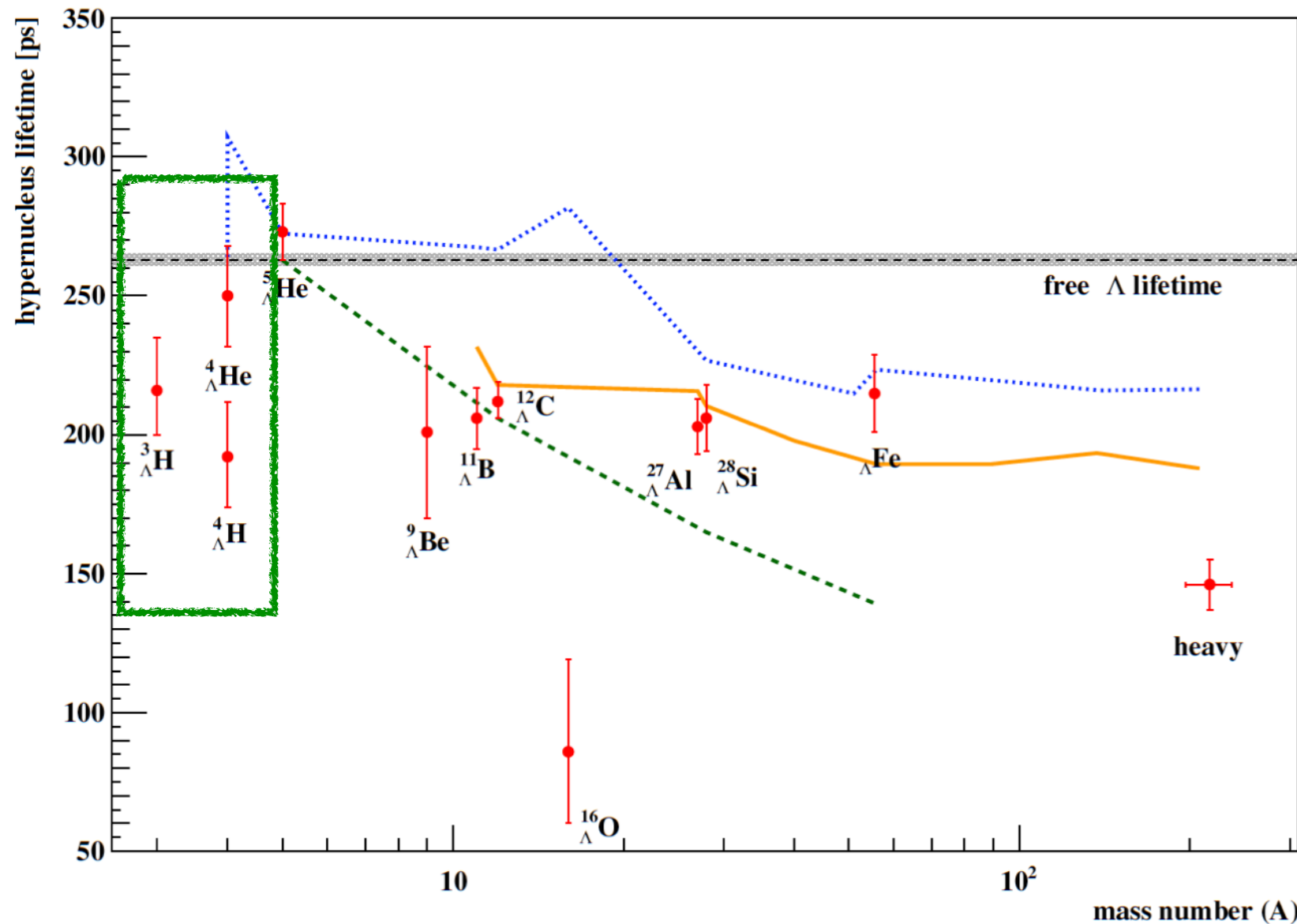
Very small $E_{B_{\Lambda}}$ ($\sim 130 \text{ keV}$) led to the hypothesis that the ${}^3\text{H}$ lifetime is slightly below the free Λ lifetime ($263.2 \pm 2 \text{ ps}$ [3])
natural consequence of the hypothesis that the Λ would spend most of its time far from the deuteron core due to the very small value of B . Several theoretical calculations also supported such a hypothesis.

[1] [D.H. Davis., Nucl. Phys. A 754 \(2005\) 3-13](#)

[2] [C. Rappold et al., Phys. Lett. B 728, 543 \(2014\)](#)

[3] [C.Patrignani et al. \(Particle Data Group\), Chin. Phys. C 40 100001 \(2016\)](#)

Hypernuclei lifetime: exp vs theory



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Itonaga K. et al., Nucl. Phys. A, 639 (1998) 329c.
one-pion exchange (OPE) model approach with the addition of $2\pi/\sigma$ and $2\pi/\rho$ exchange terms to the OPE exchange potential

————

Bauer E. and Garbarino G., Phys. Rev. C, 81 (2010) 064315.

plus correction from

Motoba T. and Itonaga K., Prog. Theor. Phys. Suppl., 117 (1994) 477.

Better description of NN interaction and 2 Nucleon Non Mesonic Weak Decay taken into account

.....

Itonaga K. and Motoba T., Prog. Theor. Phys. Suppl., 185 (2010) 252.

one-pion exchange (OPE) model approach with the addition of many exchange terms to the OPE exchange potential

Status and perspectives of experimental studies on hypernuclear weak decays.
by E. Botta, T. Bressani, S. Bufalino, A. Feliciello
Nuovo Cimento- Vol. 38 n. 9 (2015) pp 387-448

Hypertriton lifetime measurement experimental knowledge

Year	Laboratory	Beam	Exp. method	Lifetime (ps)	Reference
1963	LBL Bevatron	stopped K^-	He bubble chamber	105^{+20}_{-18}	[10]
1964	BNL AGS	K^- , 2.3–2.5 GeV/c	ph. emulsions	90^{+220}_{-40}	[11]
1965	BNL AGS and LBL Bevatron	K^- , 2.3 GeV/c K^- 790 MeV/c	ph. emulsions	340^{+820}_{-140}	[12]
1968	ANL ZGS	stopped K^-	He bubble chamber	232^{+45}_{-34}	[13]
1968	LBL Bevatron	K^- 1.1 GeV/c	ph. emulsions	274^{+110}_{-72}	[14]
1969	BNL AGS	K^- 1.1 GeV/c	ph. emulsions	285^{+127}_{-105}	[15]
1970	CERN PS	stopped K^-	ph. emulsions	128^{+35}_{-26}	[16]
1970	ANL ZGS	stopped K^-	He bubble chamber	264^{+84}_{-52}	[17]
1973	ANL ZGS	stopped K^-	He bubble chamber	246^{+62}_{-41}	[18]
1992	Dubna Synchrophasotron	He, Li ions 2.2–5 AGeV rHIC	counter experiment	240^{+170}_{-100}	[19]
2010	BNL RHIC	Au–Au $\sqrt{s_{NN}} = 200$ GeV central urHIC	counter experiment	182^{+89}_{-45}	[20]
2013	BNL RHIC	Au–Au $\sqrt{s_{NN}} = 7.7–200$ GeV central urHIC	counter experiment	123^{+26}_{-22}	[21]
2013	GSIS	Li ions 2 AGeV peripheral rHIC	counter experiment	183^{+42}_{-32}	[22]
2016	CERN LHC	Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV central urHIC	counter experiment	181^{+54}_{-38}	[23]

M. Agnello, E. Botta, T. Bressani, S. Bufalino and A. Feliciello
Nuclear Physics 954 (2016) 176–198

[10] M.M. Block, et al., in: Proc. of the International Conference on Hyperfragments, St. Cergue, 28–30 March 1963, p.63.

[11] R.J. Prem, P.H. Steinberg, Phys. Rev. 136 (1964) B1803.

[12] Y.V. Kang, et al., Phys. Rev. 139 (1965) B401.

[13] G. Keyes, et al., Phys. Rev. Lett. 20 (1968) 819.

[14] R.J. Phillips, J. Schneps, Phys. Rev. Lett. 20 (1968) 1383.

[15] R.J. Phillips, J. Schneps, Phys. Rev. 180 (1969) 1307.

[16] G. Bohm, et al., Nucl. Phys. B 16 (1970) 46.

[17] G. Keyes, et al., Phys. Rev. D 1 (1970) 66.

[18] G. Keyes, et al., Nucl. Phys. B 67 (1973) 269.

[19] S. Avramenko, et al., Nucl. Phys. A 547 (1992) 95c.

[20] STAR Collaboration, Science 328 (2010) 58.

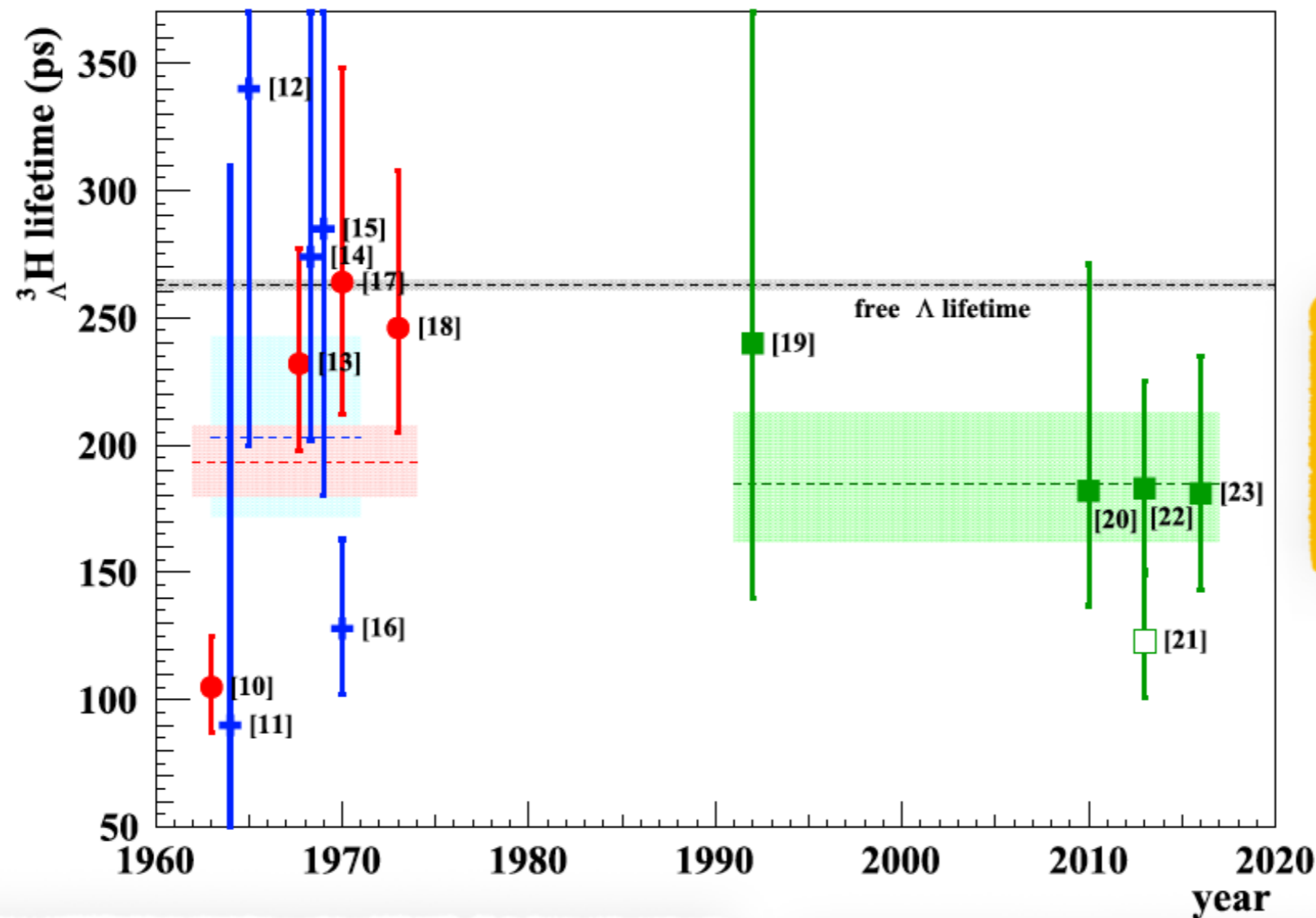
[21] J. Zhu, Nucl. Phys. A 904 (2013) 551c.

[22] C. Rappold, et al., Nucl. Phys. A 913 (2013) 170.

[23] ALICE Collaboration, J. Adam, et al., Phys. Lett. B 754 (2016) 360.

Hypertriton lifetime measurement

experimental knowledge



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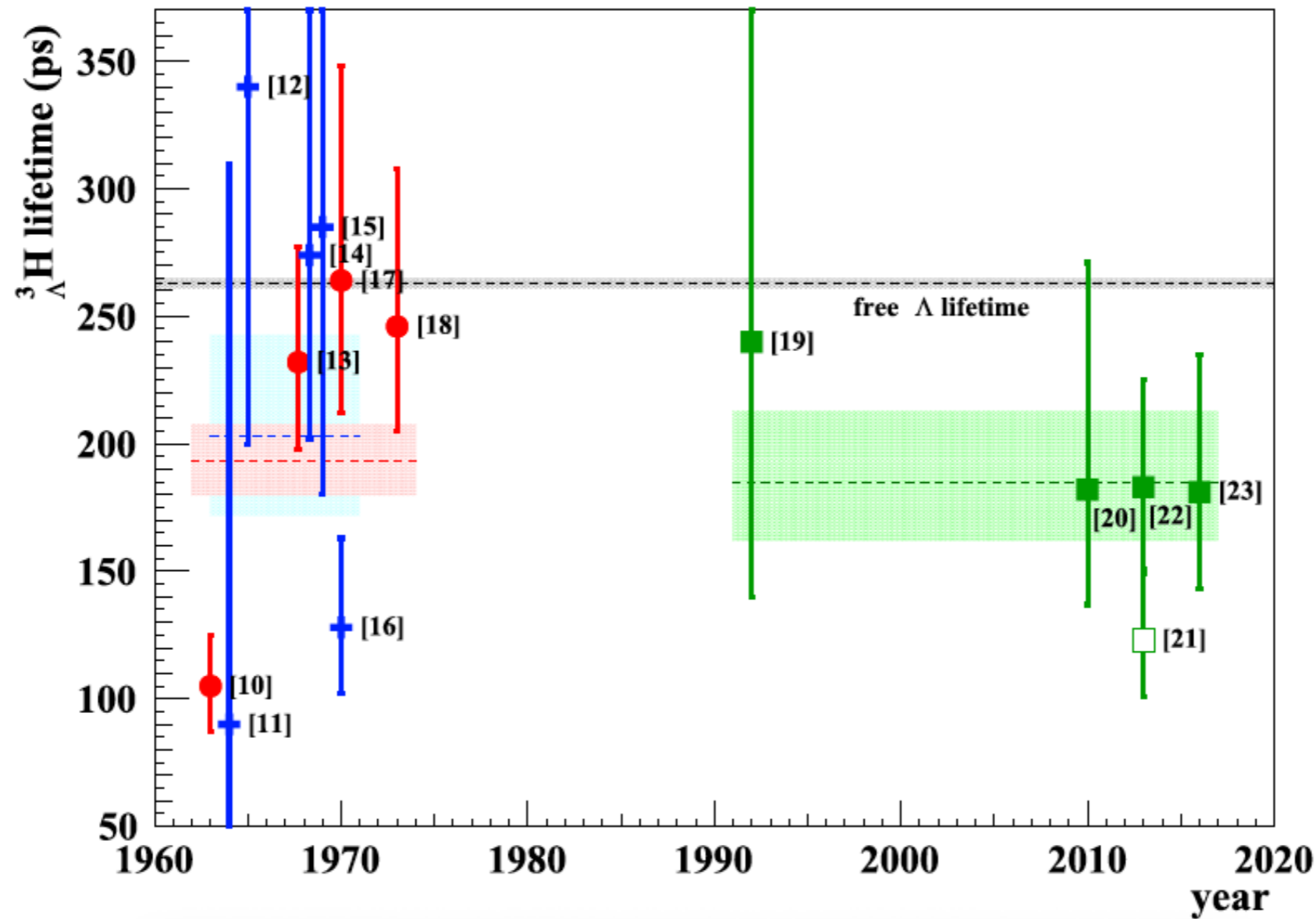
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[22] C. Rappold, et al., Nucl. Phys. A 913 (2013) 170.

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Hypertriton lifetime measurement

present knowledge



M. Agnello, E. Botta, T. Bressani, S. Bufalino and A. Feliciello
Nuclear Physics 954
(2016) 176–198

emulsion technique: 203^{+40}_{-31} ps

He Bubble Chamber: 195^{+15}_{-13} ps

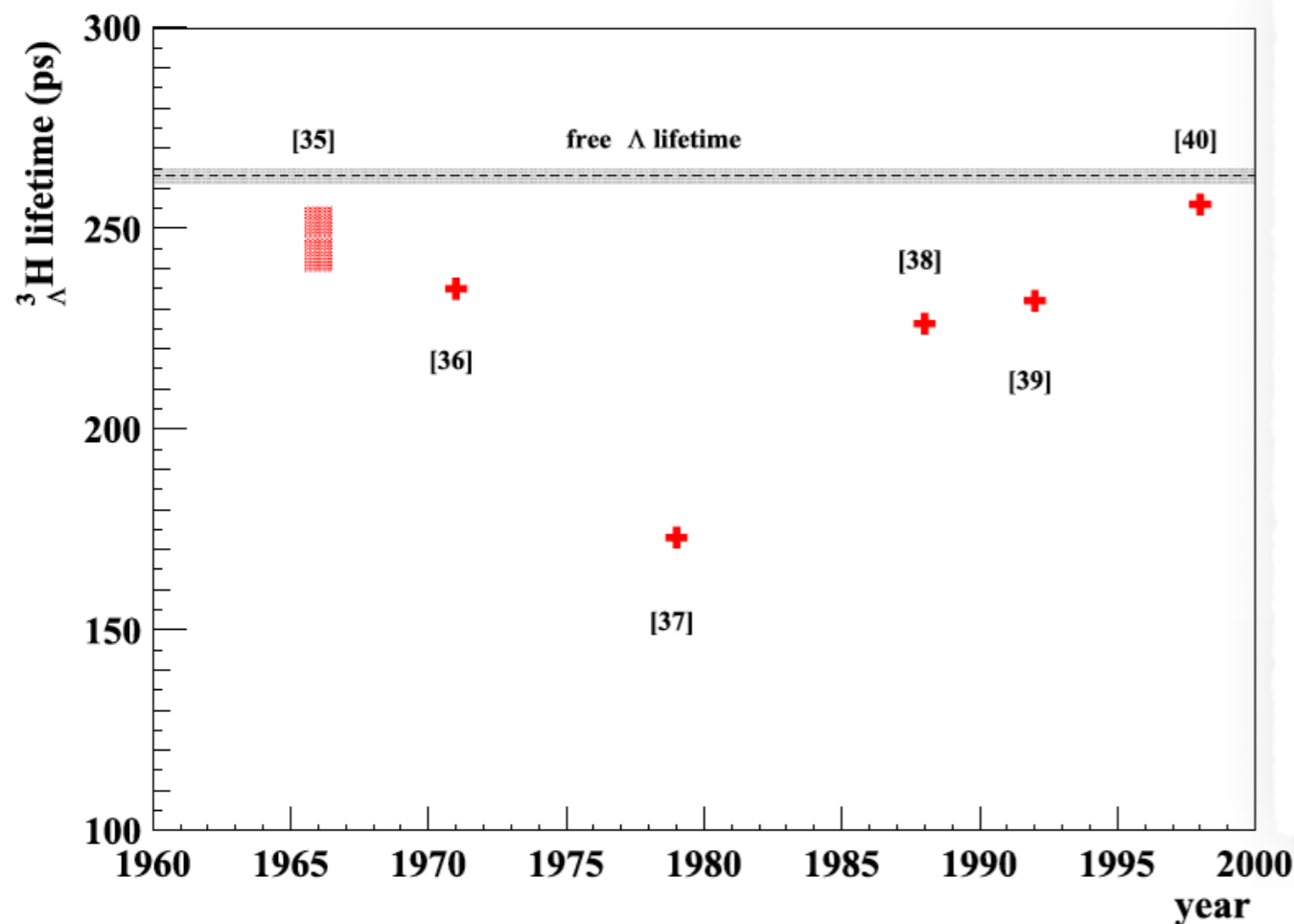
Electronic techniques: 185^{+28}_{-23} ps without [21]

Electronic techniques: 163^{+18}_{-16} ps with [21]

Hypertriton lifetime measurement

theoretical predictions

Dalitz and soon afterward Leon introduced the basic π -mesonic interaction from which the equations needed to calculate the observables related to the WD of hypertriton were deduced



[35] M. Rayet, R.H. Dalitz, *Il Nuovo Cim. A* 46 (1966) 786.

Phase space factor and the Pauli principle effect were accurately taken into account. Corrections accounting for the final-state pion scattering and for NMWD channels were considered.

The calculated values for τ were found to range from 239.3 ps to 255.5ps.

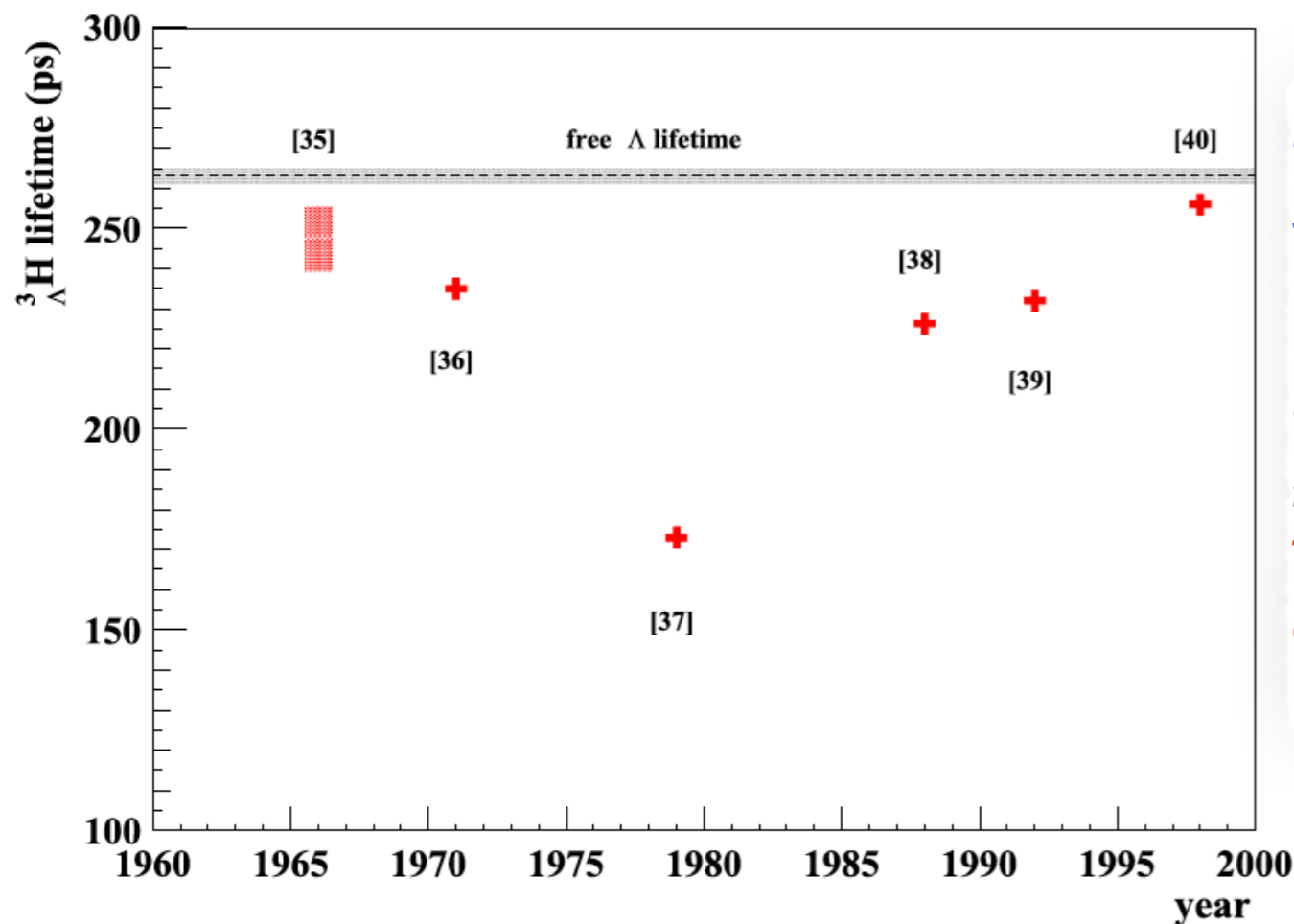
The uncertainty is related to the mean value of the π -momentum chosen to evaluate the space phase factor.

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S. Bufalino and A. Feliciello
Nuclear Physics 954 (2016) 176–198

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[36] M. Ram, W. Williams, Nucl. Phys. B 28 (1971) 566.

investigated whether hard core corrections introduced in the Lambda-N and NN potentials used to calculate the wave functions could affect significantly the values for τ .

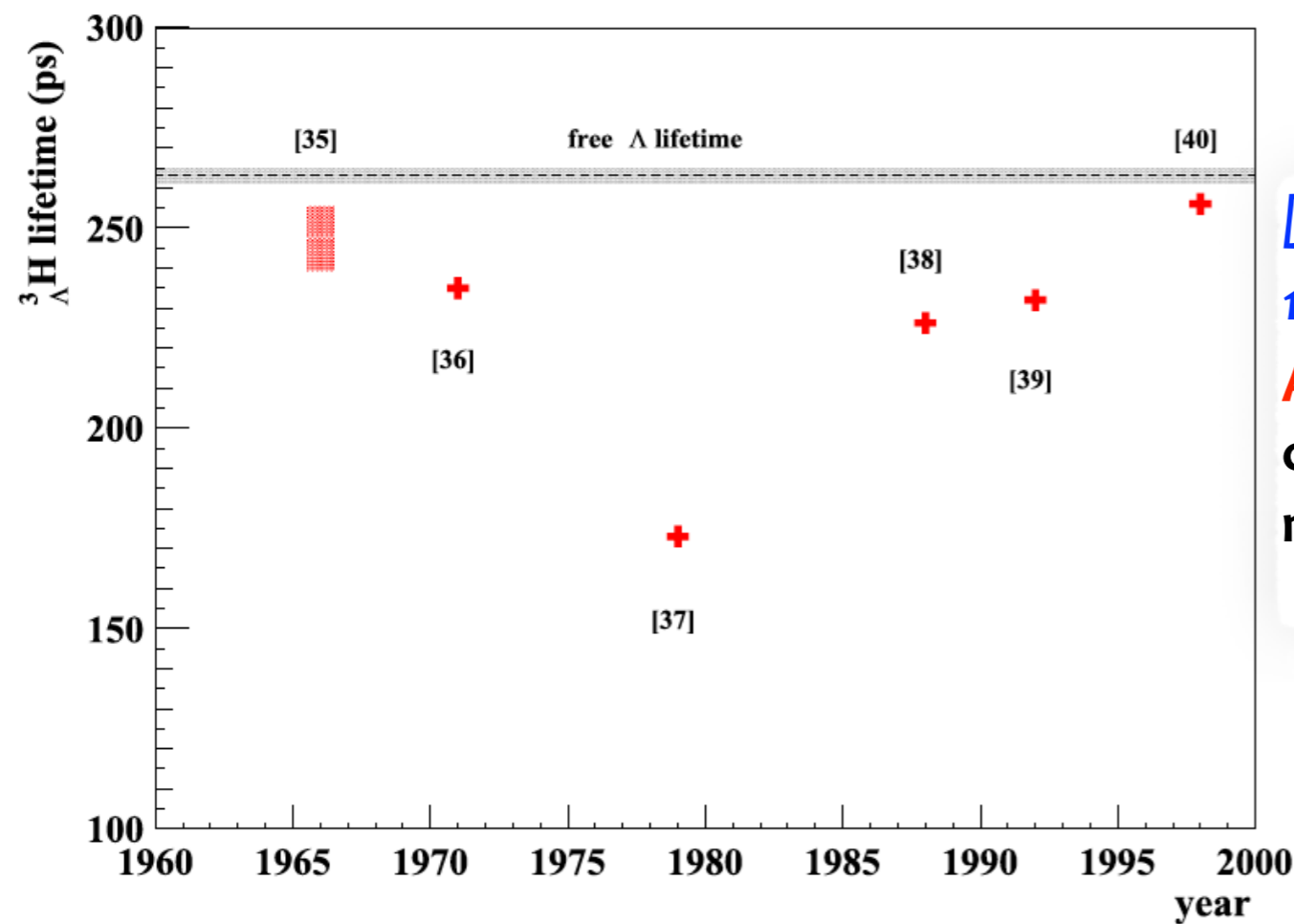
The result was negative and a value of 235 ps was deduced

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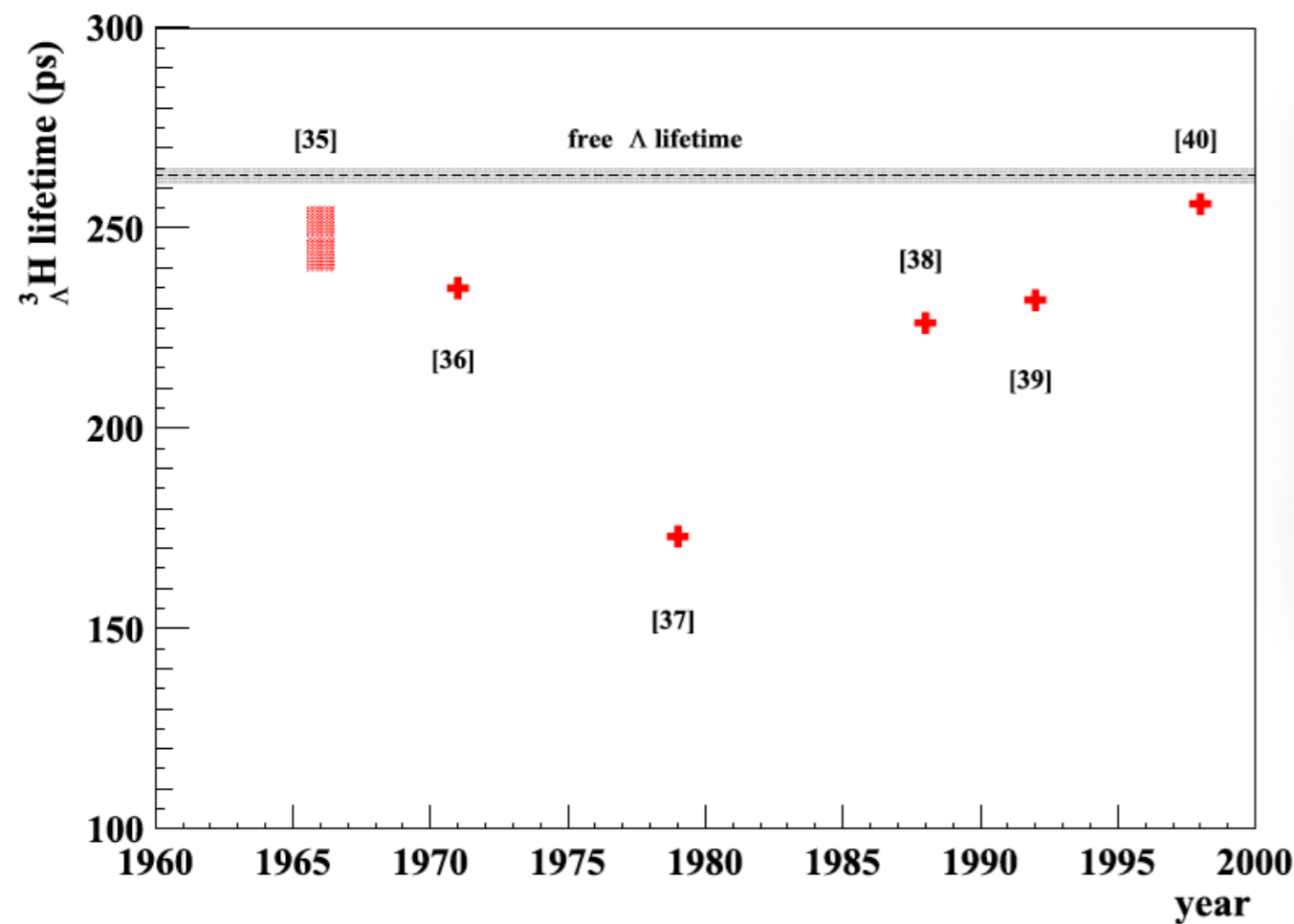
A lower value of 173 ps was inferred by means of a calculation based on an explicit inclusion of the nucleon induced pionic emission ($\Lambda N \rightarrow NN\pi$)

M. Agnello, E. Botta, T. Bressani,
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Nuclear Physics 954 (2016) 176–198

Hypertriton lifetime measurement

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[38] N. Kolesnikov, V. Kopylov, *Sov. Phys. J.* 31 (1988) 210.

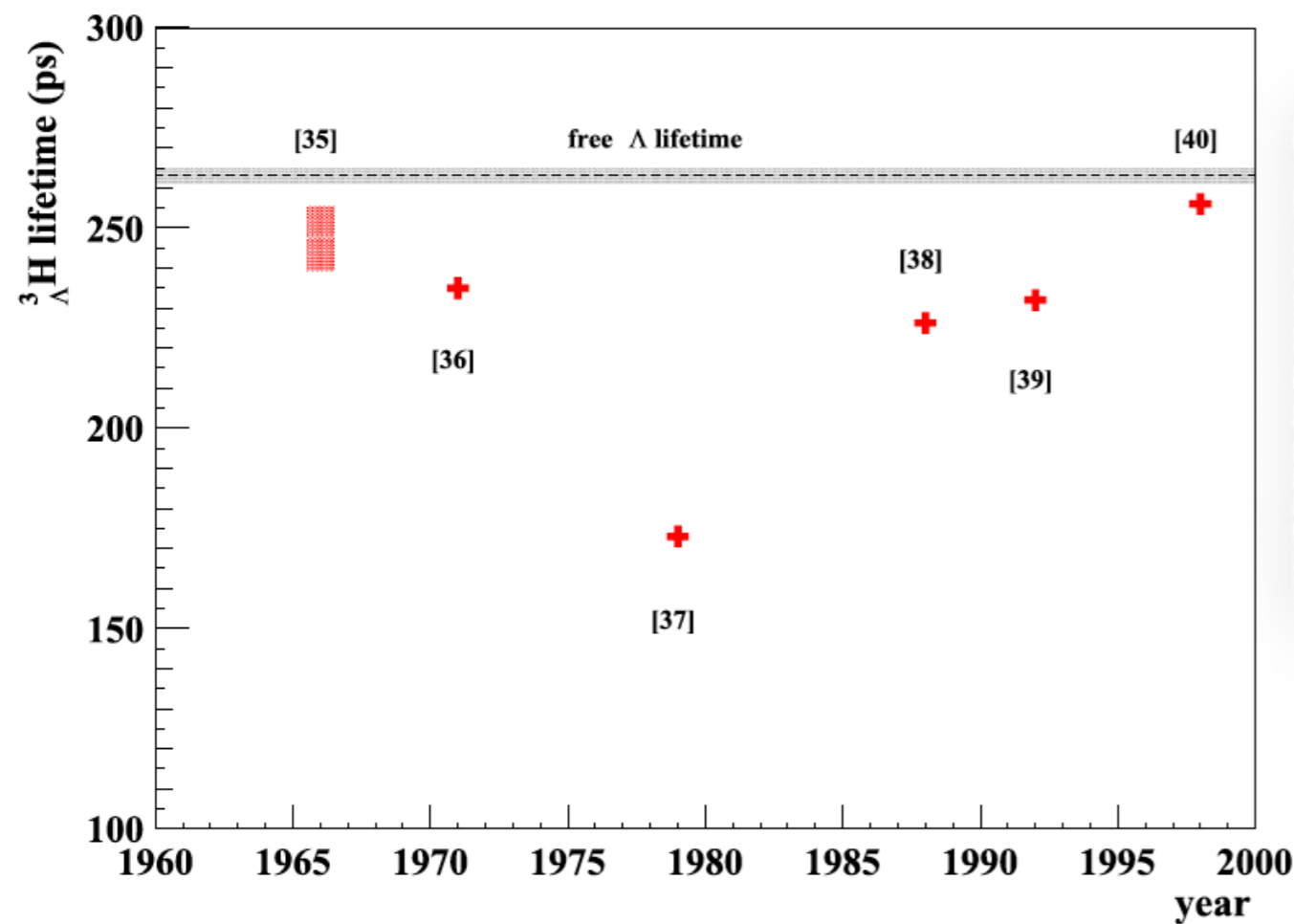
A value of 226.3 ps was determined by using wave functions found by multiparameter variation calculations employing five different LambdaN potentials

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[39] J.G. Gongleton, *J. Phys. G, Nucl. Part. Phys.* 18 (1992) 339.

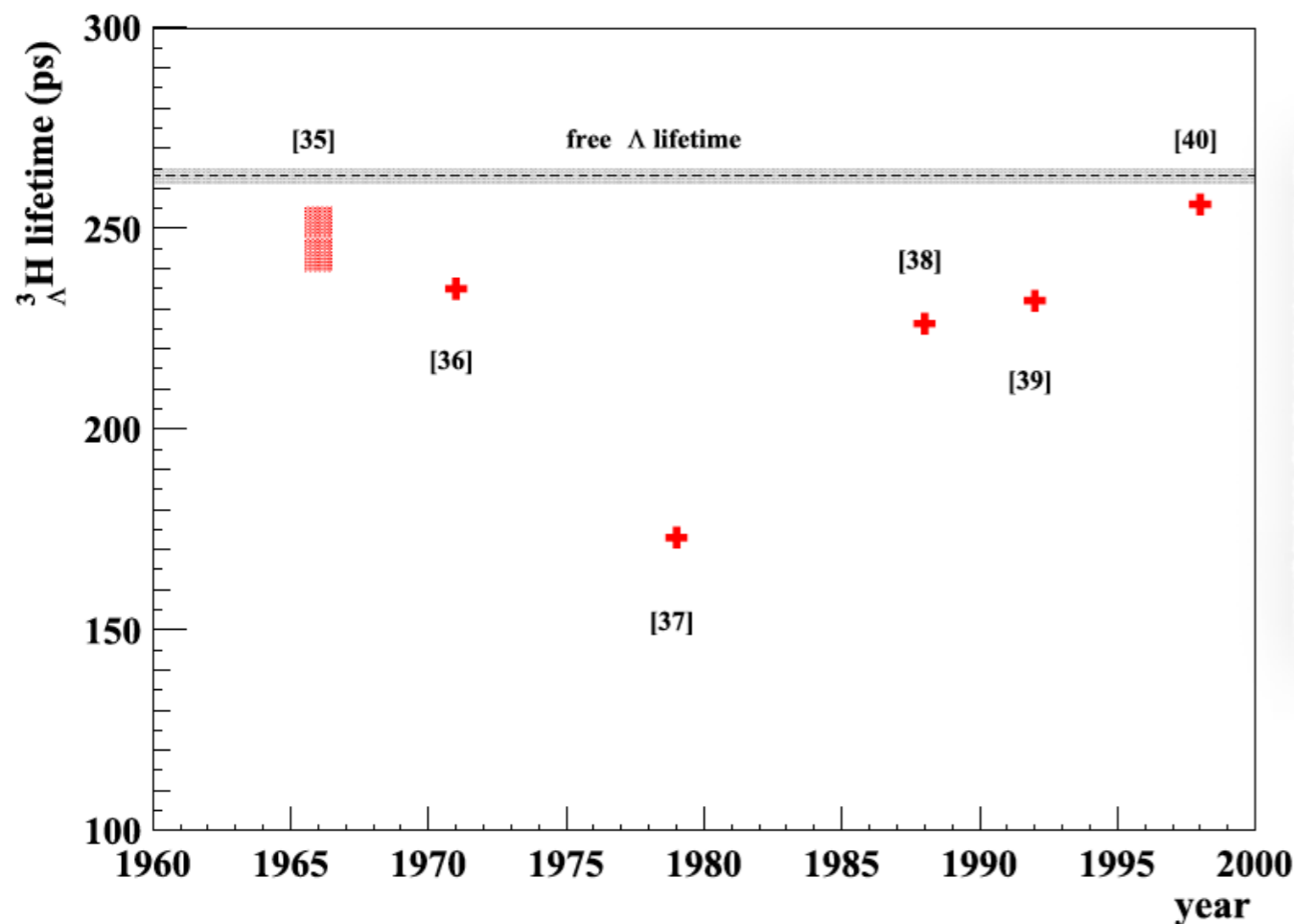
A quite close determination (232 ps) using updated values for the NN (Bonn and Paris) and for the YN (Nijmegen) potentials to determine the wave functions

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[40] H. Kamada, J. Golak, K. Miyagawa, H. Witala, W. Glockle, *Phys. Rev. C* 57 (1998) 1595.

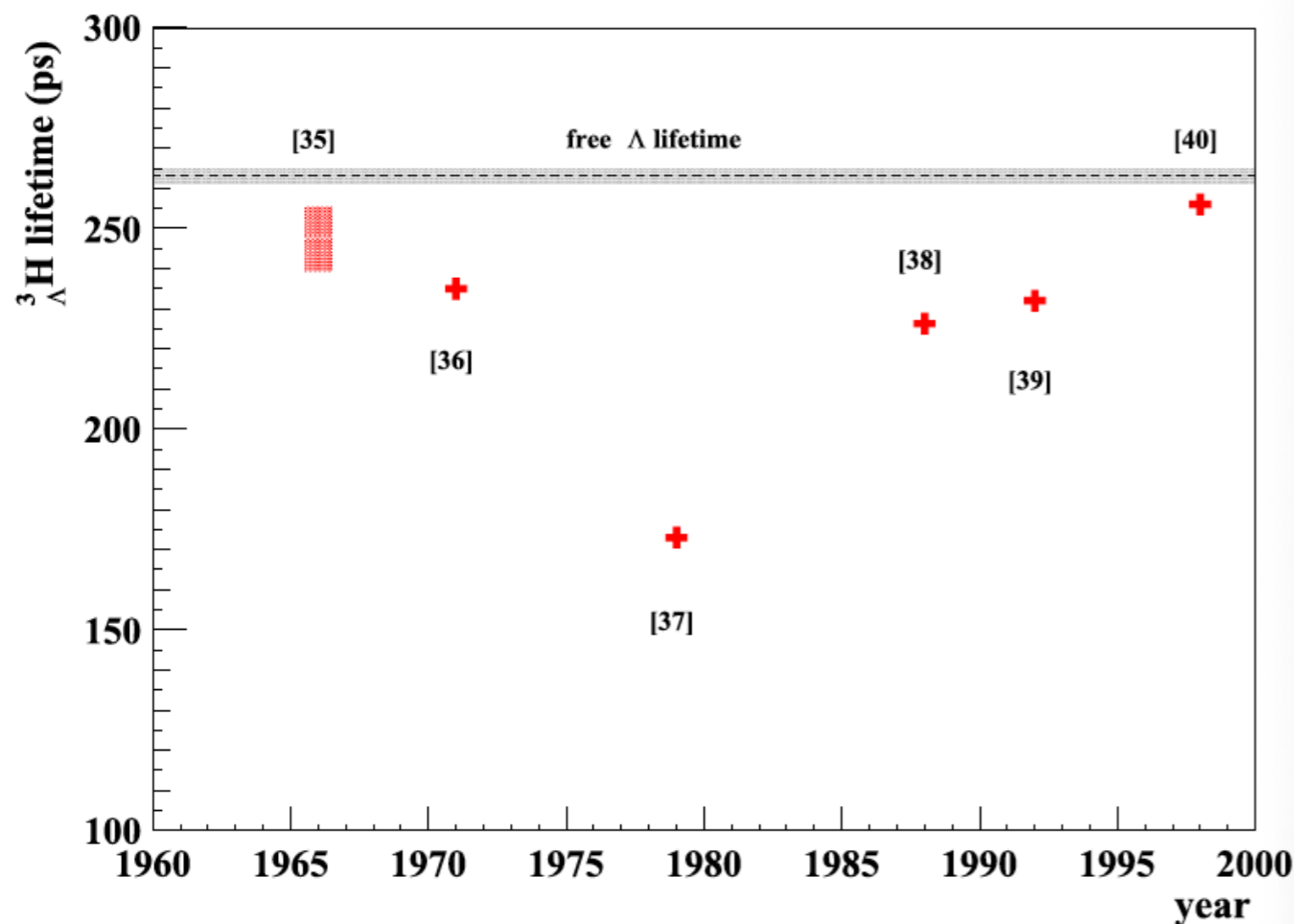
rigorous solutions of three-body Faddeev equations for the hypernucleus wave function and for the 3N scattering states, in which realistic NN and YN interactions were used. **A value of 256 ps was finally predicted**

M. Agnello, E. Botta, T. Bressani,
S. Bufalino and A. Feliciello
Nuclear Physics 954 (2016) 176–198

Hypertriton lifetime measurement

theoretical predictions

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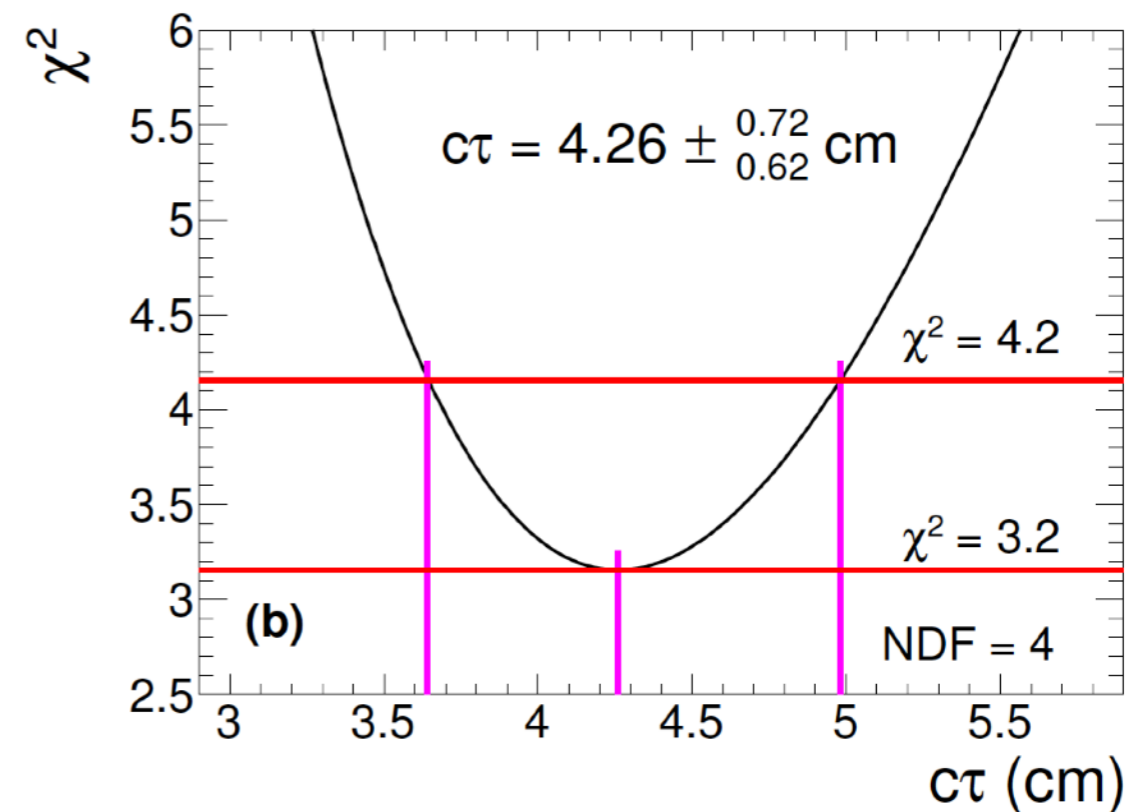
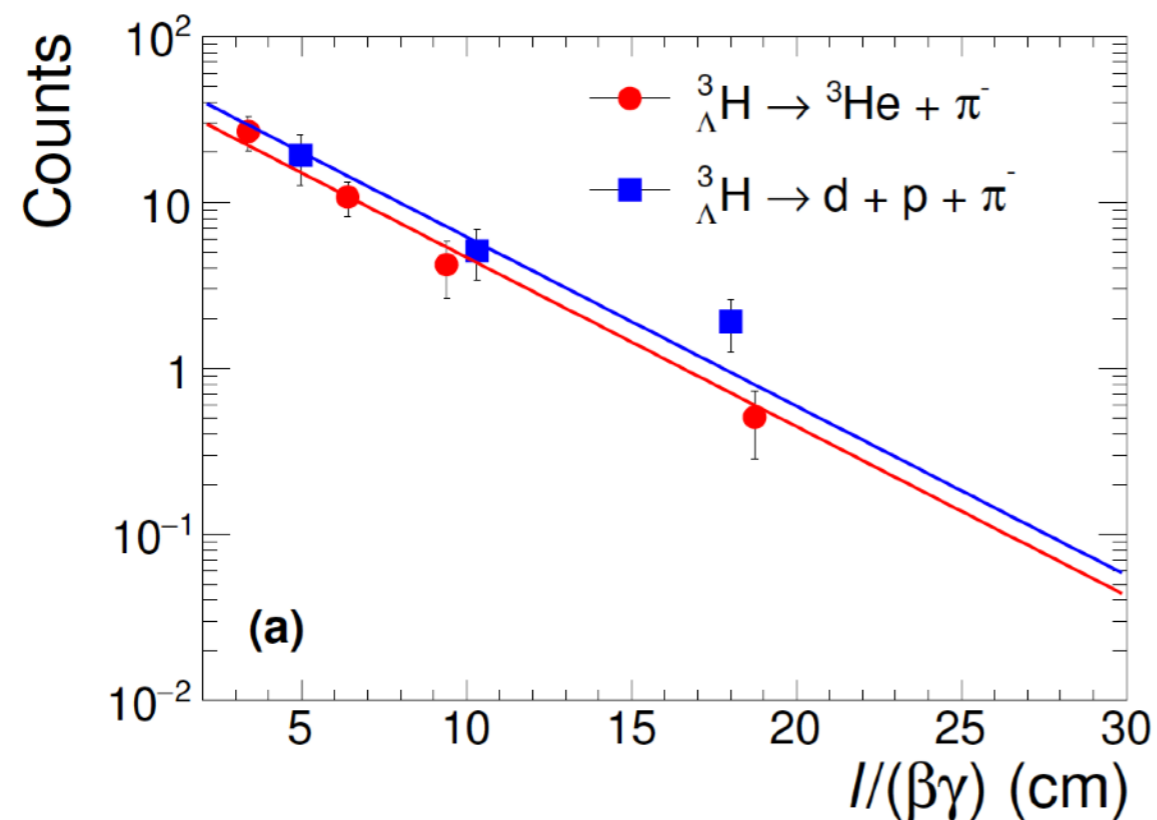
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Hypertriton search with **STAR** at RHIC

Determination of ${}^3_{\Lambda}\text{H}$ lifetime via both 2- and 3-body decay

Invariant mass spectra from both 2- and 3-body decay

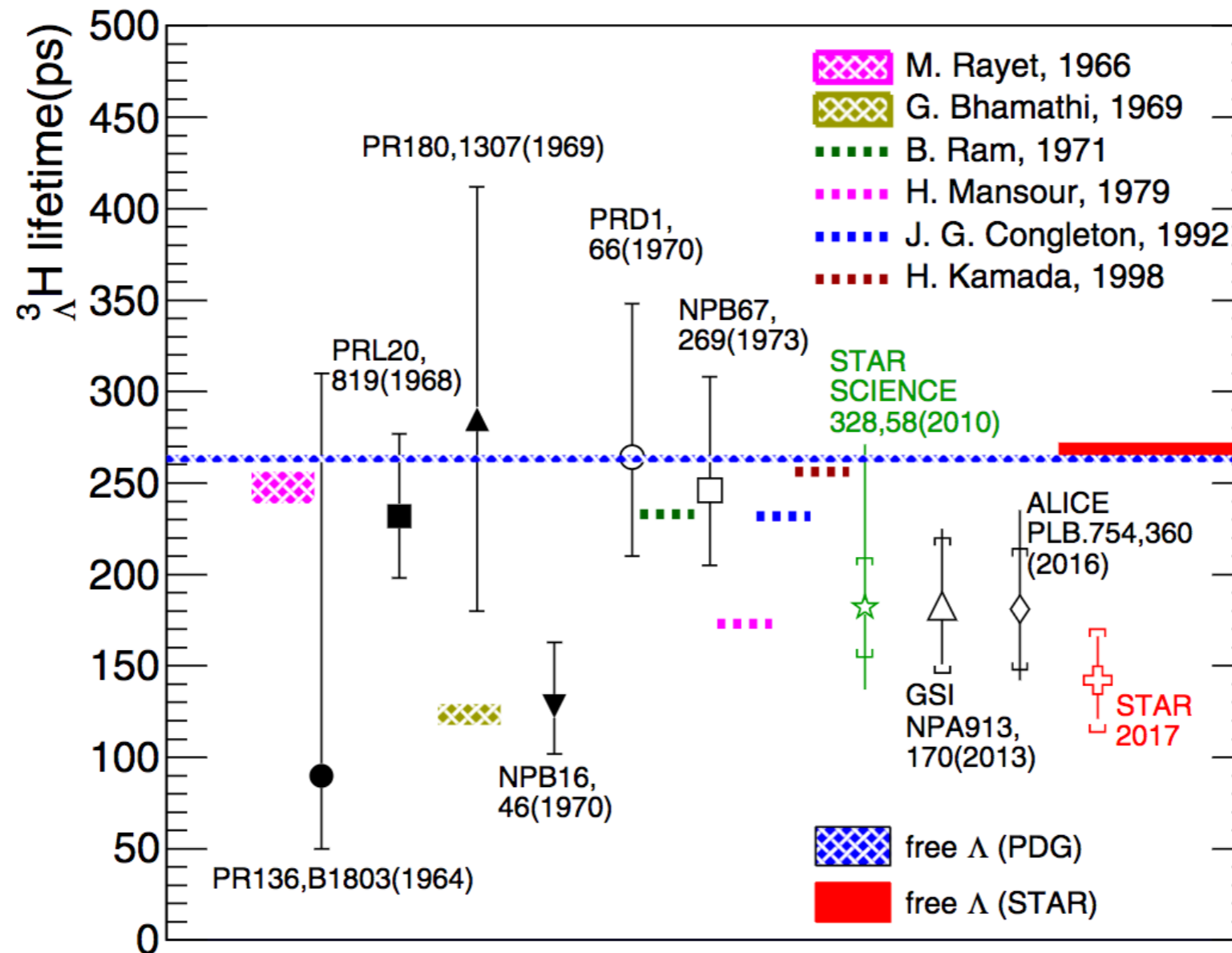


2 -body: $\tau = 123^{+26}_{-21}(\text{stat})$ ps

3-body: $\tau = 193^{+82}_{-48}(\text{stat})$ ps

final value $\tau = 142^{+24}_{-21}(\text{stat}) \pm 29$ (sys) ps

World lifetime measurement: published results

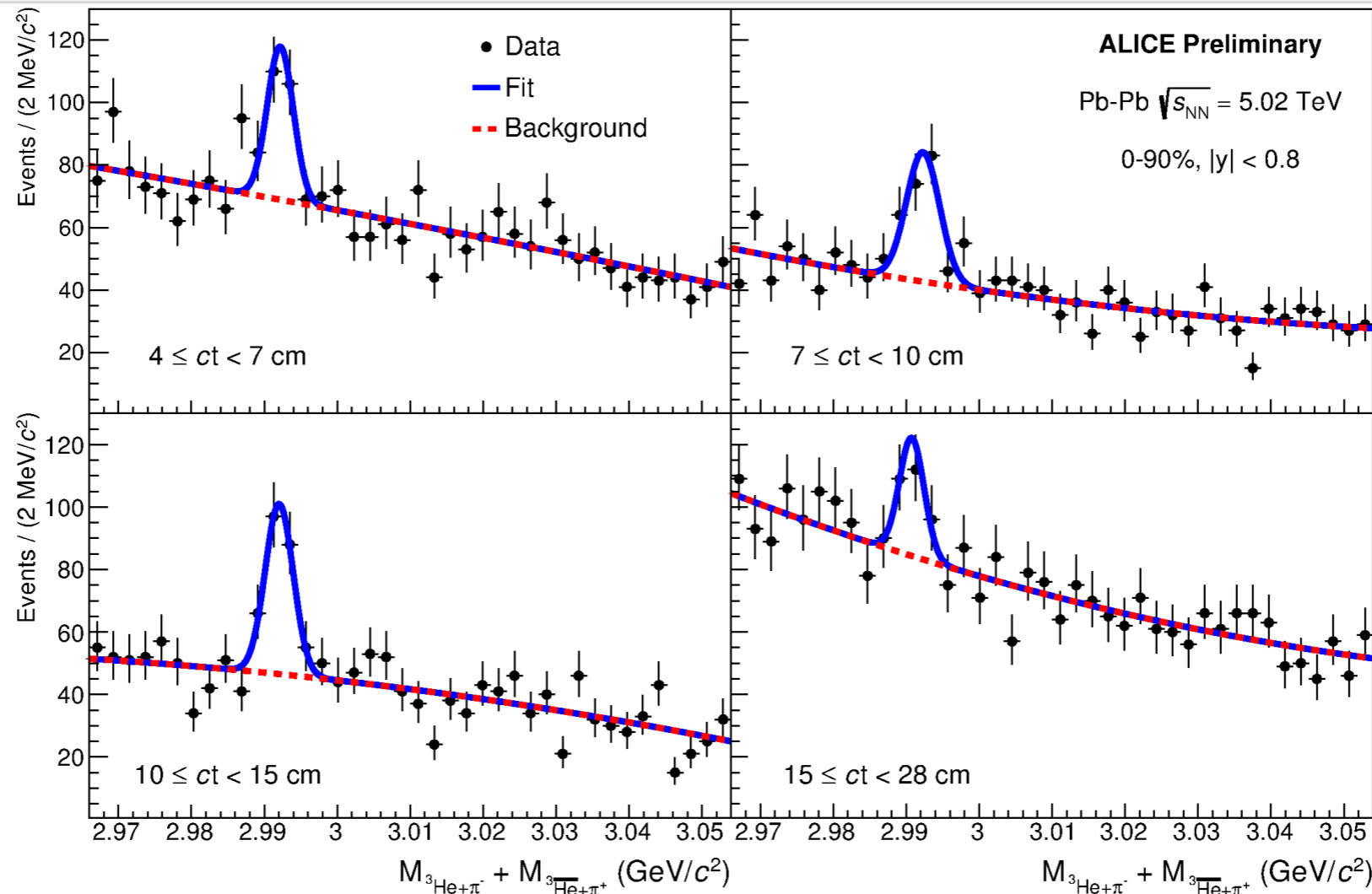


The STAR Collaboration - Physical Review C 97, 054909 (2018)

ALICE new preliminary results

The lifetime estimate is performed:

- using the full data sample of Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV collected in 2015
- selecting both **hypertriton and anti-hypertriton candidates (only in HI)**



ALI-PREL-130170

Signal extraction in four different ct bins (“**ct spectra**” method [default])

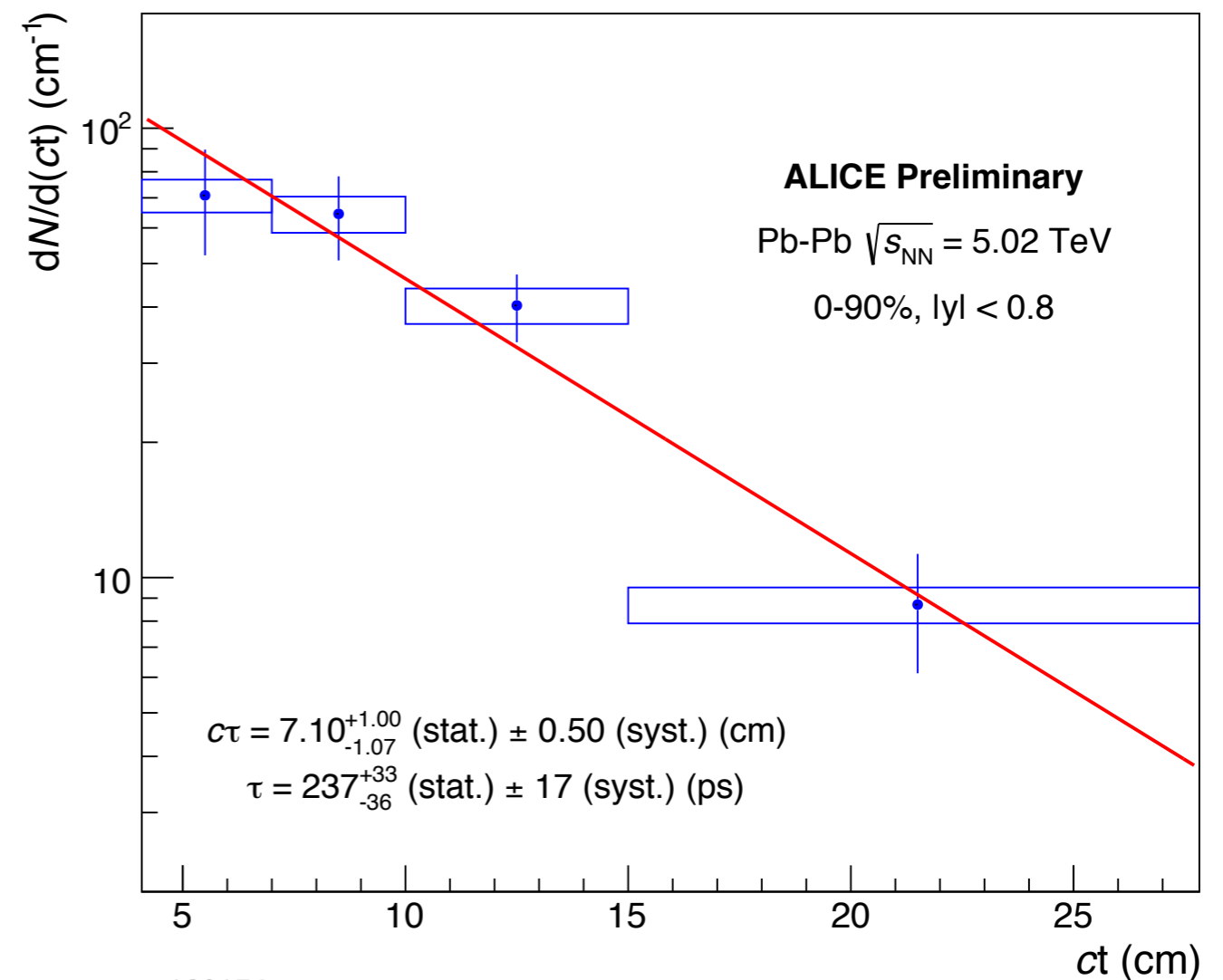
4-7, 7-10, 10-15, 15-28 cm

ALICE new preliminary results

- Signal extraction in four different ct bins (“ct spectra” method [default])
 - 4-7, 7-10, 10-15, 15-28 cm
- Exponential fit to the corrected dN/ct spectrum for the lifetime estimate

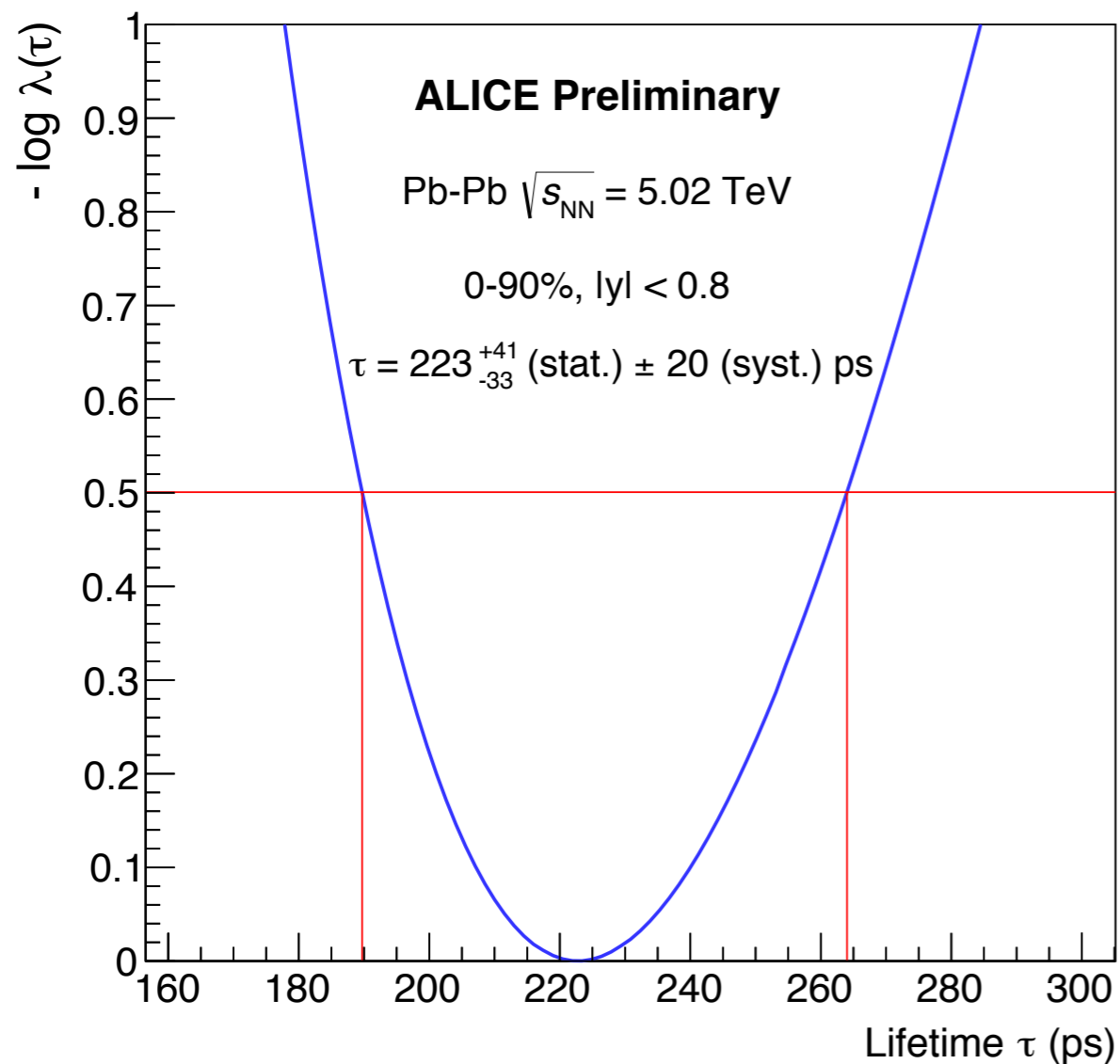
$$\tau = 237_{-36}^{+33}(\text{stat.}) \pm 17(\text{syst.})\text{ps}$$

- Result with the highest precision at the moment with improved resolutions with respect to the previous result at 2.76 TeV



ALI-PREL-130174

ALICE new preliminary results



- Fit to the invariant mass distribution to define the **signal range** and the **sidebands**
- Fit in the **sidebands** with two exponential is performed (background)
- Fit in the **signal range** for the lifetime estimate
 - signal: exponential function multiplied for the efficiency
 - background: from the sidebands fit

Lifetime value

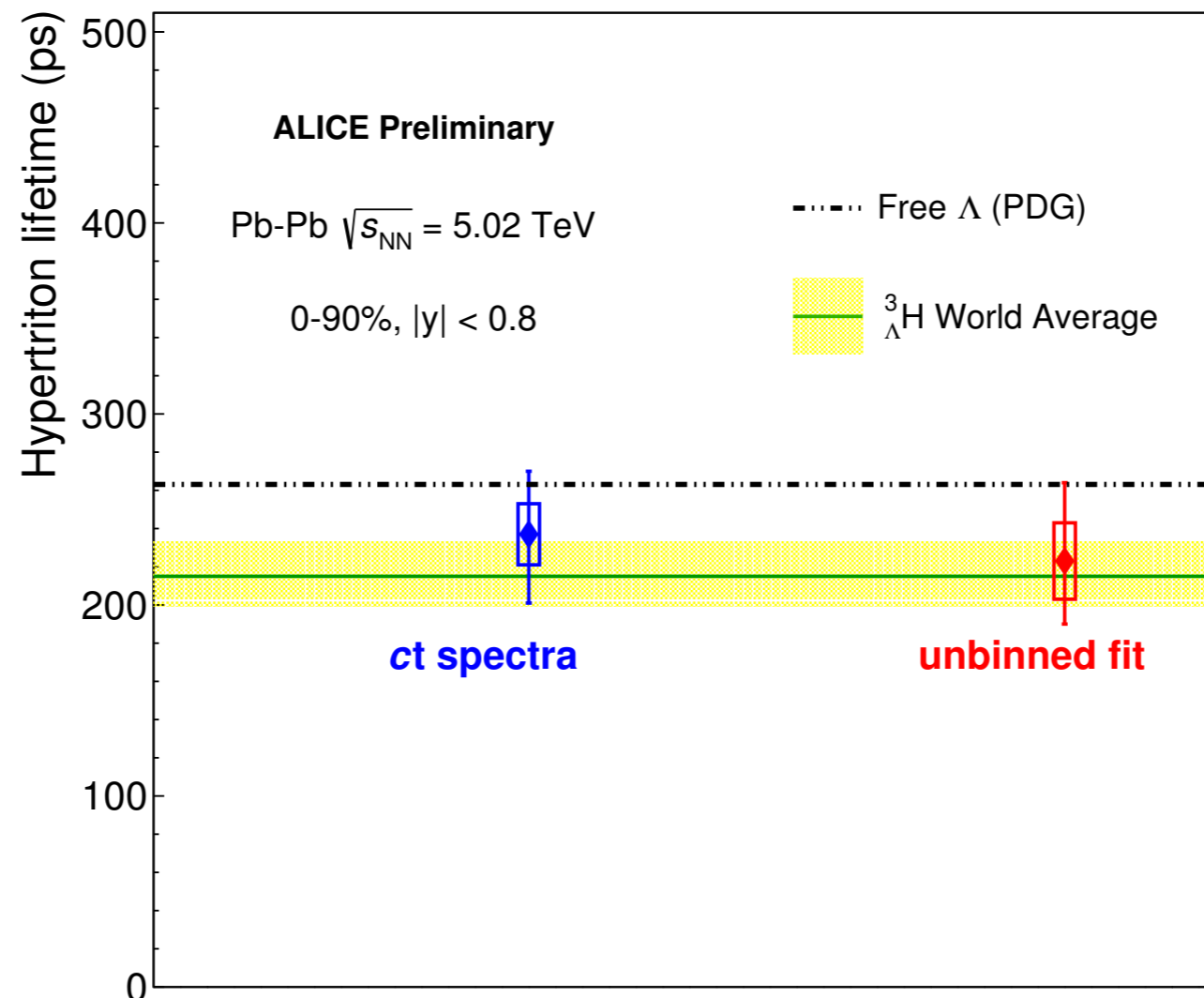
$$\tau = 223_{-33}^{+41} (stat.) \pm 20 (syst.) ps$$

ALI-PREL-130191

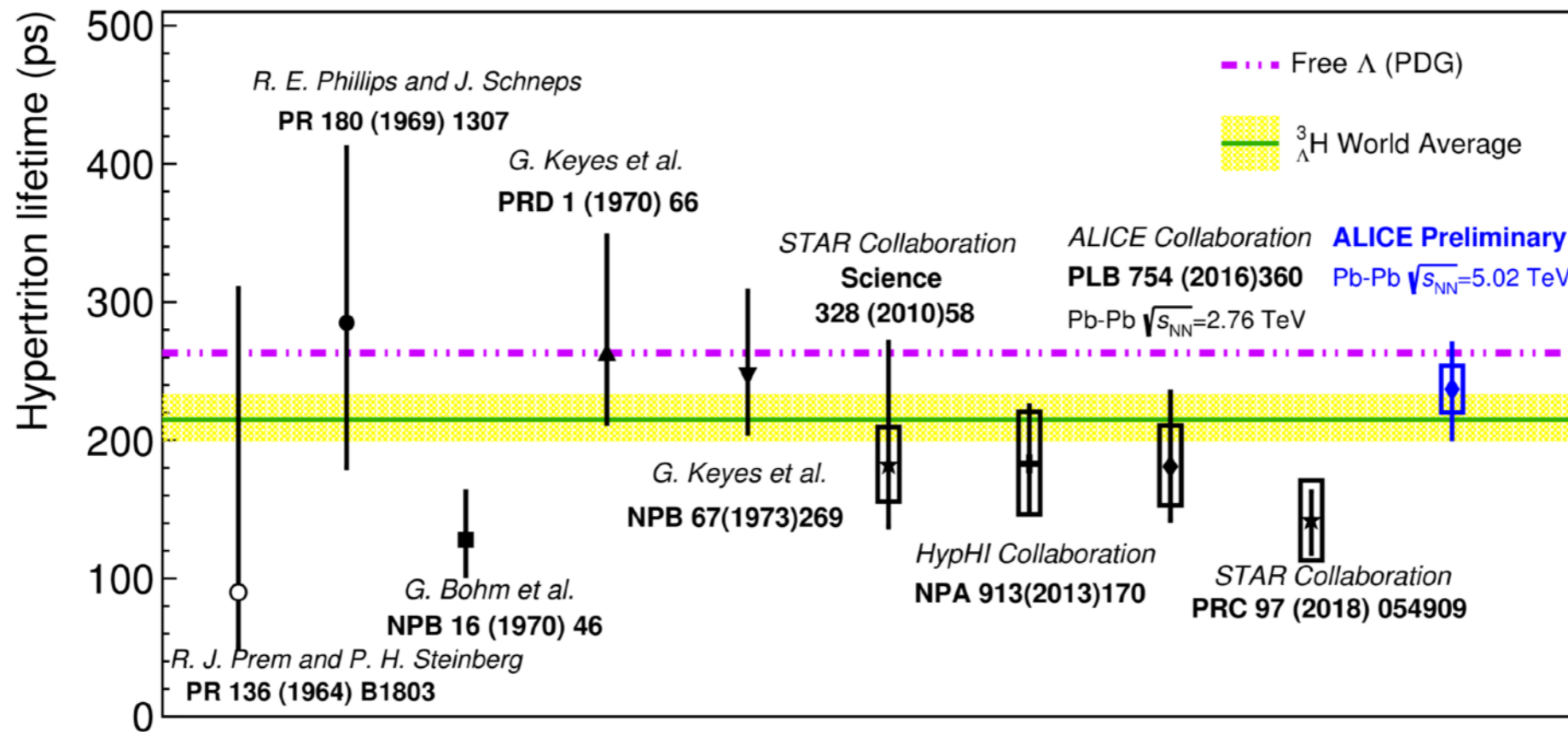
ALICE new preliminary results

The lifetime estimate is performed:

- using the full data sample of Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV collected in 2015
- selecting both **hypertriton** and **anti-hypertriton** candidates (**only in HI**)
- using two methods: **“ct spectra”** (default) and **unbinned fit** (crosscheck)



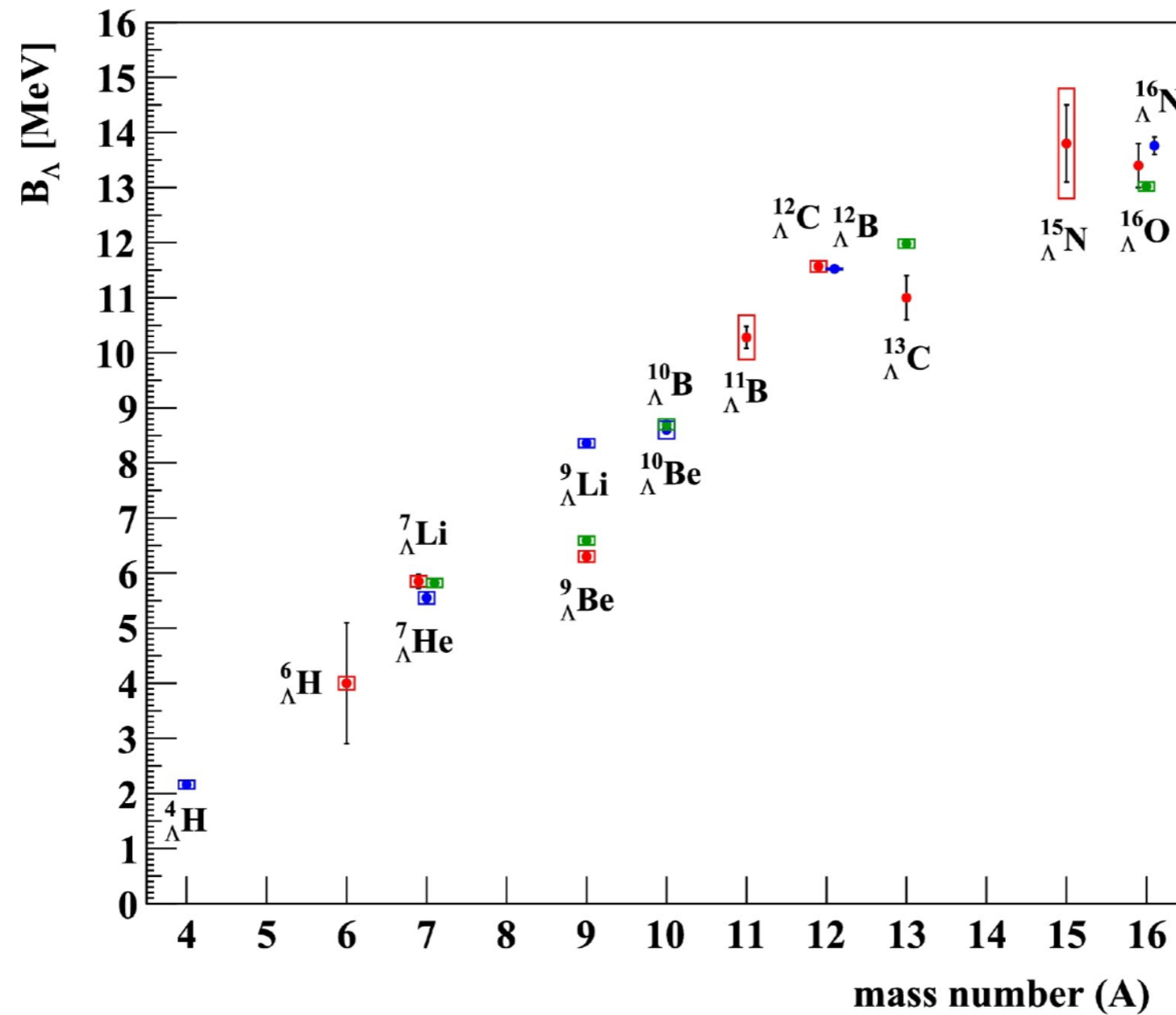
Hypertriton lifetime *world data*



ALI-DER-161043

- Previous heavy-ion experiment results show a trend systematically below the free Λ lifetime
- ALICE result from Pb-Pb at 5.02 TeV is **closer to the free Λ and $\sim 2\sigma$ higher than the latest STAR result (in terms of ALICE uncertainties)**
- More **precision**, reducing the statistical uncertainties can be reached increasing the statistics
- lifetime measured in the 3-body decay channel by ALICE as additional exp. constraint

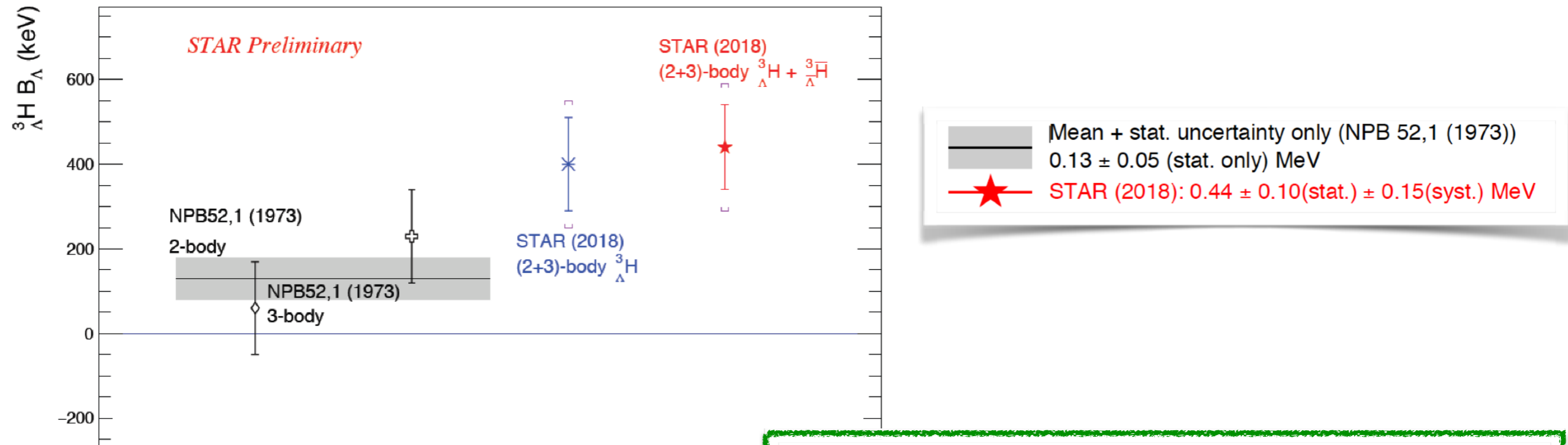
Hypernuclei Binding energy measurements



E. Botta, T. Bressani,
and A. Feliciello
Nuclear Physics 960
(2017) 165–179

Hypertriton binding energy from STAR

Preliminary result presented at QM2018



Emulsion experiment

M. Juric et al., Nucl. Phys. B Volume 52,
Issue 1, 15 January 1973, pp 1-30

From the observation of 82 examples of ${}^3_{\Lambda}\text{H}$, the binding energy of this hypernucleus is found to be 0.15 ± 0.08 MeV. An accurate determination of the binding energy of the ${}^3_{\Lambda}\text{H}$ hypernucleus is of great importance to estimate the strength of the ΛN interaction in the singlet state. Combining the result obtained in this experiment with the data compiled by Bohm et al. [2], reanalysed using the methods and selection criteria defined in the present work, the best estimate for the binding energy of ${}^3_{\Lambda}\text{H}$ is found to be $B_{\Lambda} = 0.13 \pm 0.05$ MeV.

Binding energies for the s-shell hypernuclei.

Hypernucleus	Decay mode	No of events	$B_{\Lambda} \pm \Delta B_{\Lambda}$ (MeV)
${}^3_{\Lambda}\text{H}$	$\pi^- + {}^1\text{H} + {}^2\text{H}$	24	0.23 ± 0.11
	$\pi^- + {}^3\text{He}$	58	0.06 ± 0.11
	total	82	0.15 ± 0.08
${}^4_{\Lambda}\text{H}$	$\pi^- + {}^1\text{H} + {}^3\text{H}$	56	2.14 ± 0.07
	$\pi^- + {}^2\text{H} + {}^2\text{H}$	11	1.92 ± 0.12
	total	67	2.08 ± 0.06
${}^4_{\Lambda}\text{He}$	$\pi^- + {}^1\text{H} + {}^3\text{He}$	83	2.42 ± 0.05
	$\pi^- + {}^1\text{H} + {}^1\text{H} + {}^2\text{H}$	15	2.44 ± 0.09
	total	98	2.42 ± 0.04
${}^5_{\Lambda}\text{He}$	$\pi^- + {}^1\text{H} + {}^4\text{He}$	798	3.19 ± 0.02
	$\pi^- + {}^1\text{H} + {}^1\text{H} + {}^3\text{He}$	8	2.95 ± 0.07
	$\pi^- + {}^2\text{H} + {}^3\text{He}$	15	3.04 ± 0.06
	$\pi^- + {}^1\text{H} + {}^2\text{H} + {}^2\text{H}$	1	3.49 ± 0.14
	total	822	3.17 ± 0.02

Conclusions

- If we talk about a “puzzle” we have many hints indicating the puzzle is an experimental one with two main players at present
 - **STAR at RHIC:** results from 2-body and 3-body decays with values systematically lower than the free Lambda lifetime
 - **ALICE at the LHC:** new result with the best precision and featuring a value close to that of the free Lambda
- **What do we need?**
 - more statistics: change cut variation reducing combinatorial (LHC Run 3 will be crucial in this sense)
 - separate hypermatter and anti-hypermatter with high statistics (no anti-hypernuclei, no high systematics on absorption correction)
- **Binding energy measurement:** useful to understand how the Lambda behaves in the hypertriton but not too much sense using the invariant mass analysis method