The 18th International Conference on
Strangeness in Quark Matter (SQM 2019)
10-15 June 2019, Bari (Italy)

Shedding light on the hypertriton lifetime with ALICE at the LHC

Stefania Bufalino
Politecnico and INFN Torino (Italy)
on behalf of the ALICE Collaboration

Hypernuclei in heavy-ion collisions

Hypernuclei in heavy-ion collisions

Thermal Model

Coalescence Model

Hypernuclei in heavy-ion collisions

ALICE

Thermal Model

Coalescence Model

- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out (T_{chem})
- hypernuclei are very sensitive to T_{chem} because of their large mass (M)

—>Exponential dependence of the yield e($^{-M/T}$$_{chem}$)

- depends only on T, V and μ_B, which is basically zero at the LHC

Hypernuclei in heavy-ion collisions

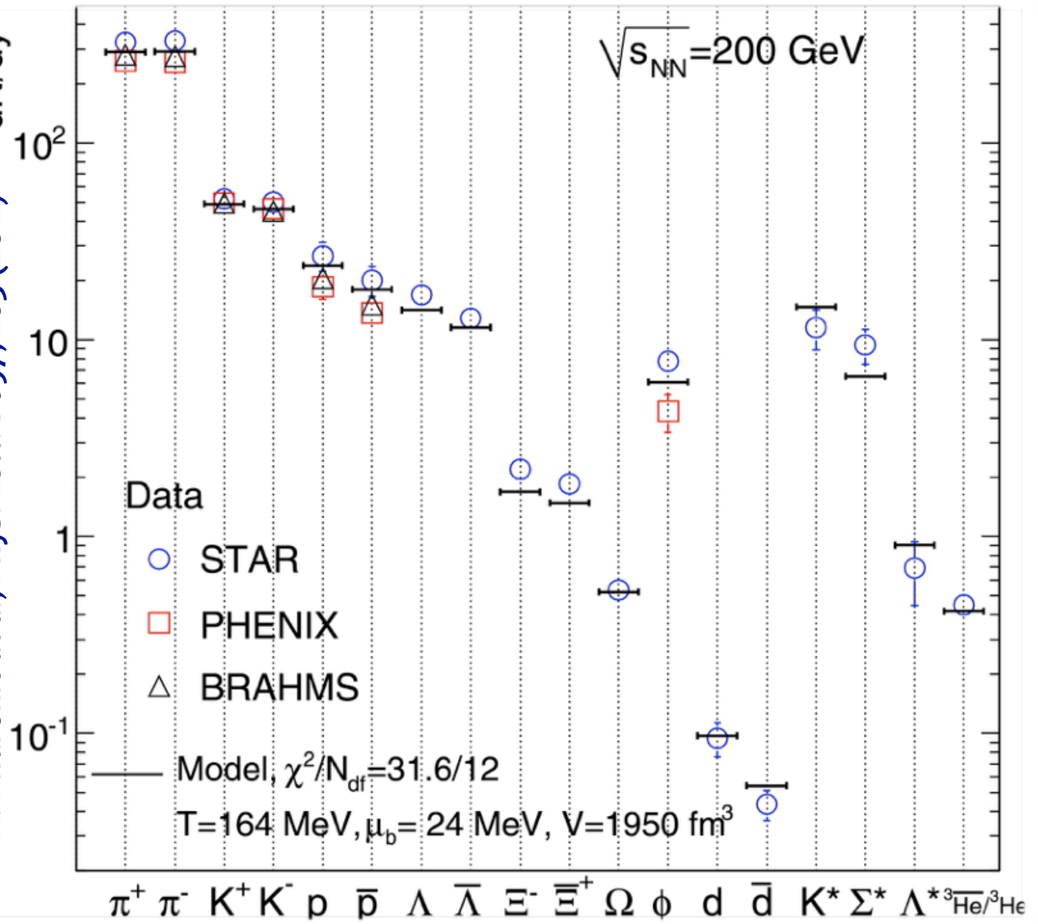
Thermal Model

Coalescence Model

- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out (T_{chem})
- hypernuclei are very sensitive to T_{chem} because of their large mass (M)

—>Exponential dependence of the yield $e^{(-M/T_{chem})}$

- depends only on T, V and μ_B, which is basically zero at the LHC



A. Andronic at al, Phys. Lett. B697, 203 (2011)

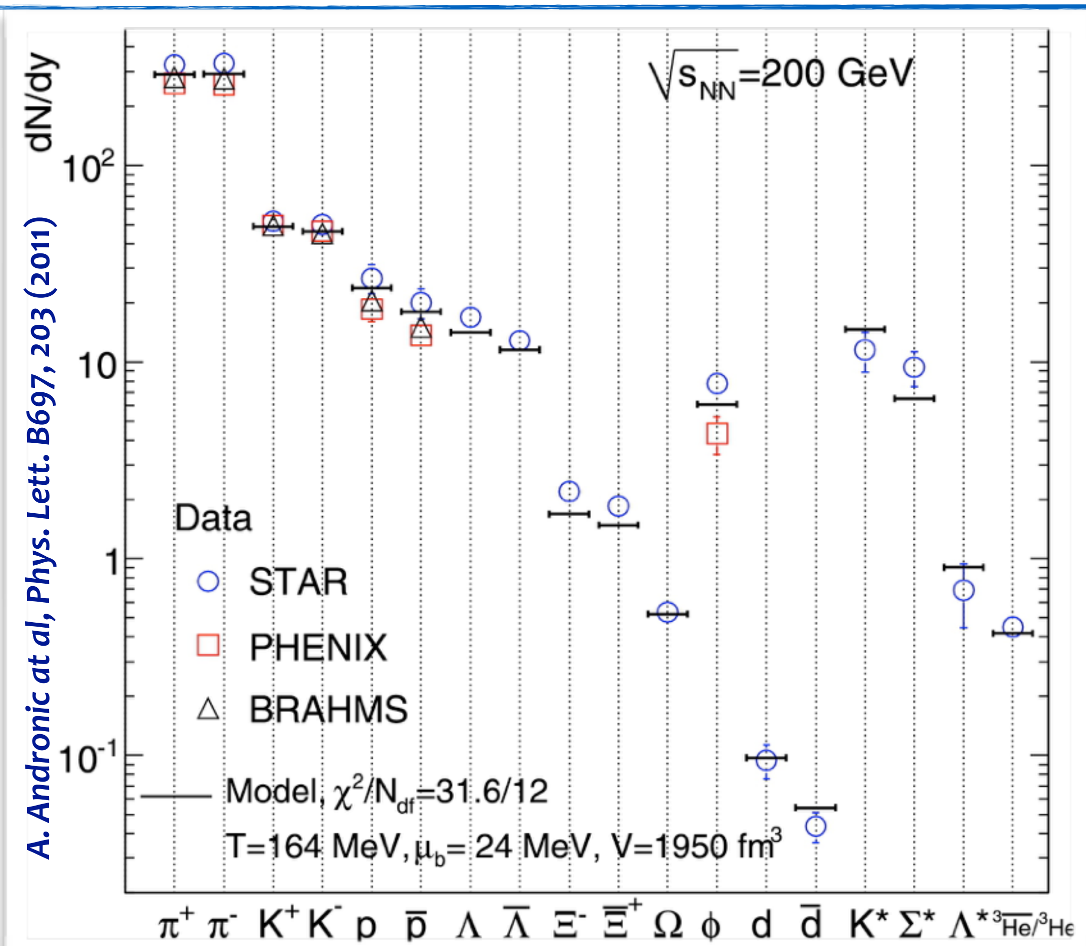
Hypernuclei in heavy-ion collisions

Thermal Model

- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out (T_{chem})
- hypernuclei are very sensitive to T_{chem} because of their large mass (M)

—>Exponential dependence of the yield $e^{(-M/T_{chem})}$

- depends only on T, V and μ_B, which is basically zero at the LHC



A. Andronic at al, Phys. Lett. B697, 203 (2011)

Coalescence Model

- If baryons at freeze-out are close enough in Phase Space an (anti-)hypernucleus can be formed
- Hypernuclei are formed by protons (Λ) and neutrons which have similar velocities after the freeze-out

Hypernuclei in heavy-ion collisions

Thermal Model

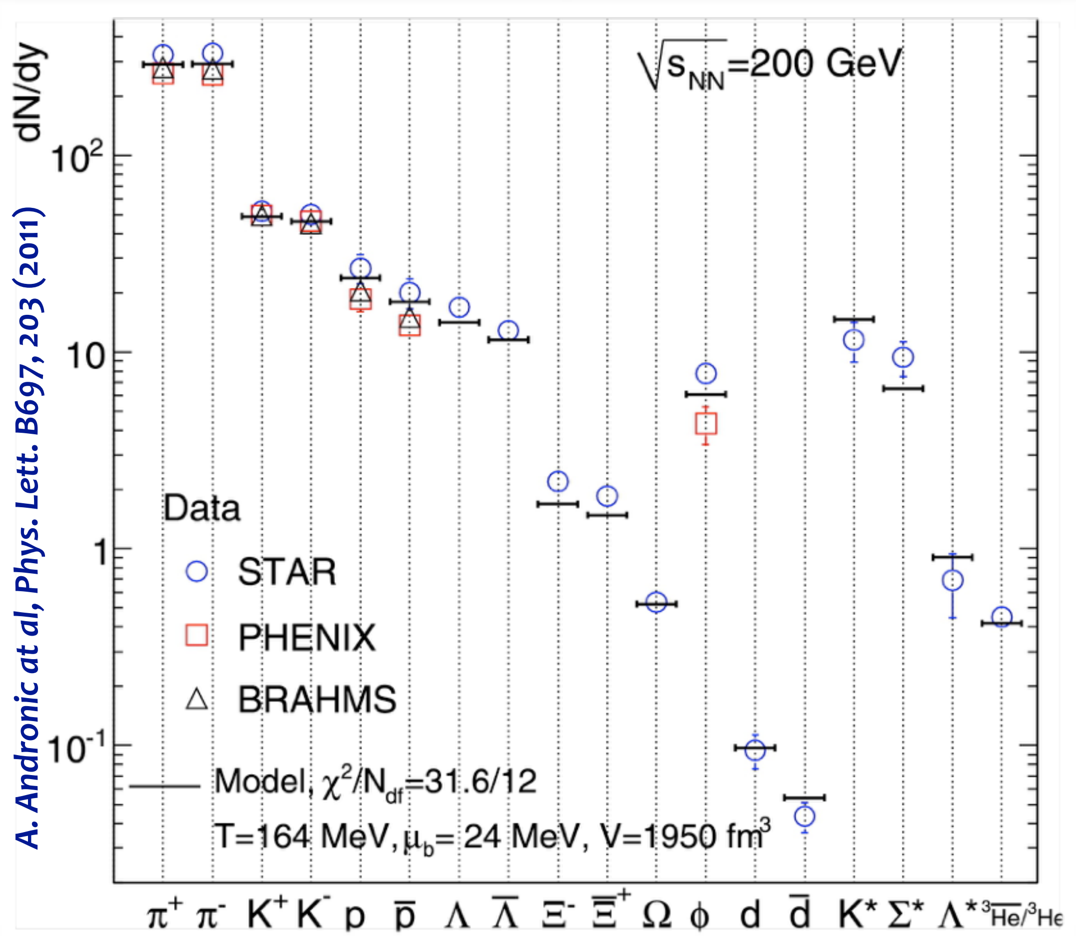
- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out (T_{chem})
- hypernuclei are very sensitive to T_{chem} because of their large mass (M)

—>Exponential dependence of the yield $e^{(-M/T_{chem})}$

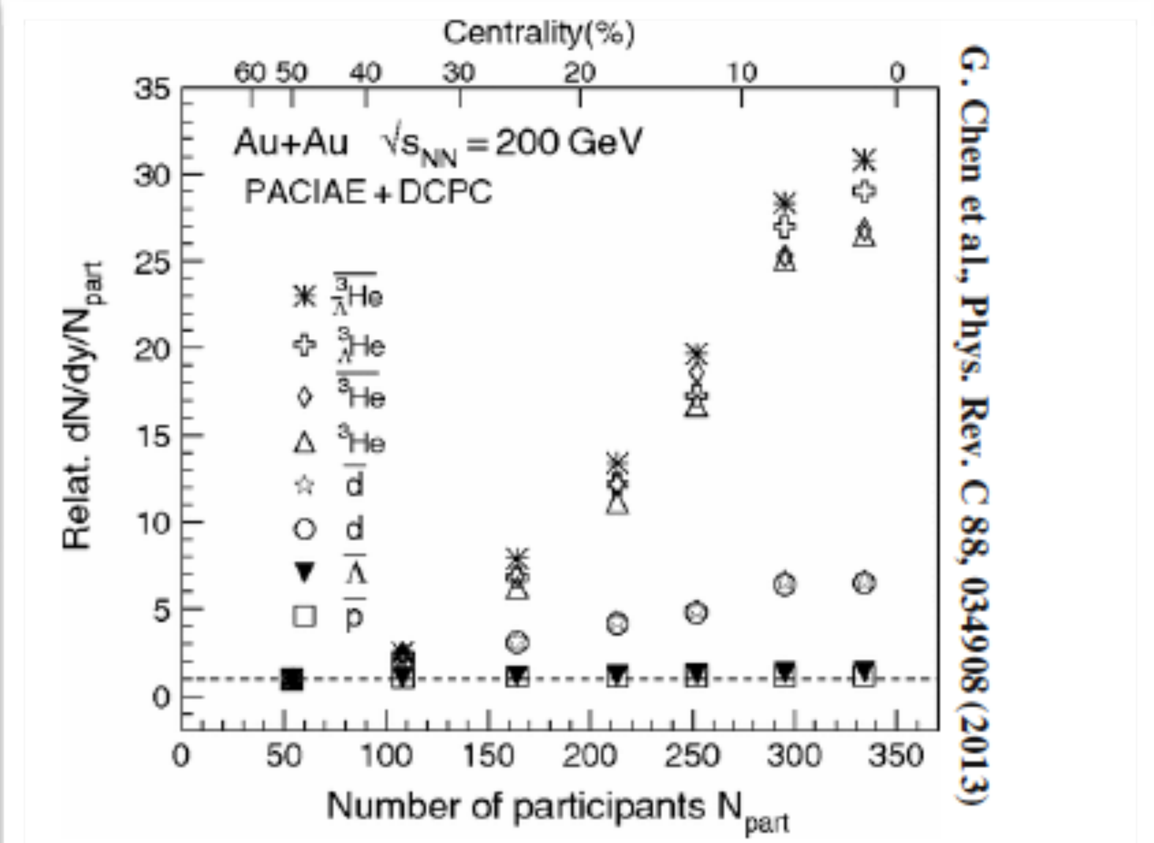
- depends only on T, V and μ_B, which is basically zero at the LHC

Coalescence Model

- If baryons at freeze-out are close enough in Phase Space an (anti-)hypernucleus can be formed
- Hypernuclei are formed by protons (Λ) and neutrons which have similar velocities after the freeze-out

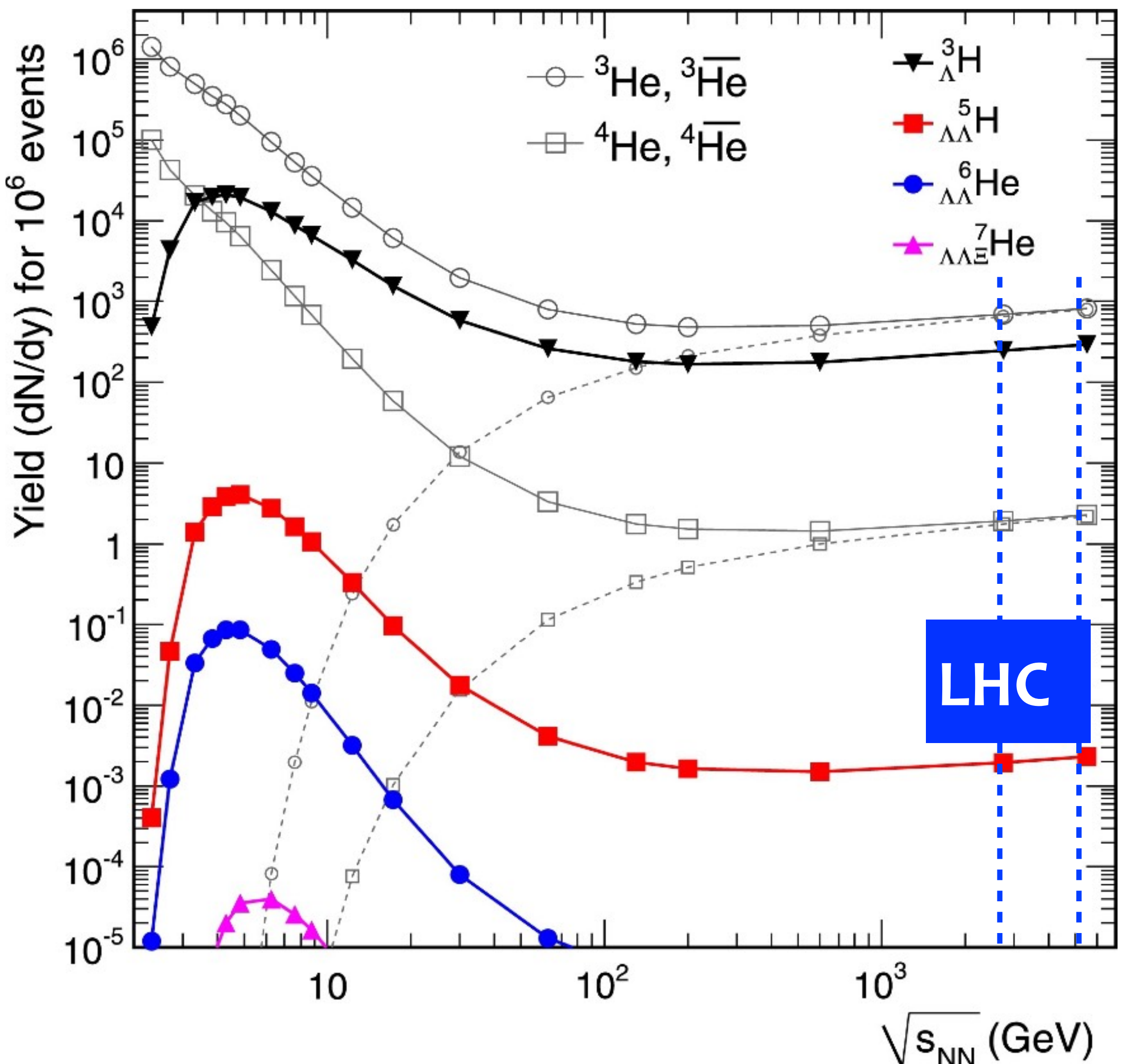


A. Andronic at al, Phys. Lett. B697, 203 (2011)



G. Chen et al., Phys. Rev. C 88, 034908 (2013)

Hypernuclei in heavy-ion collisions at the LHC



A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stocker.

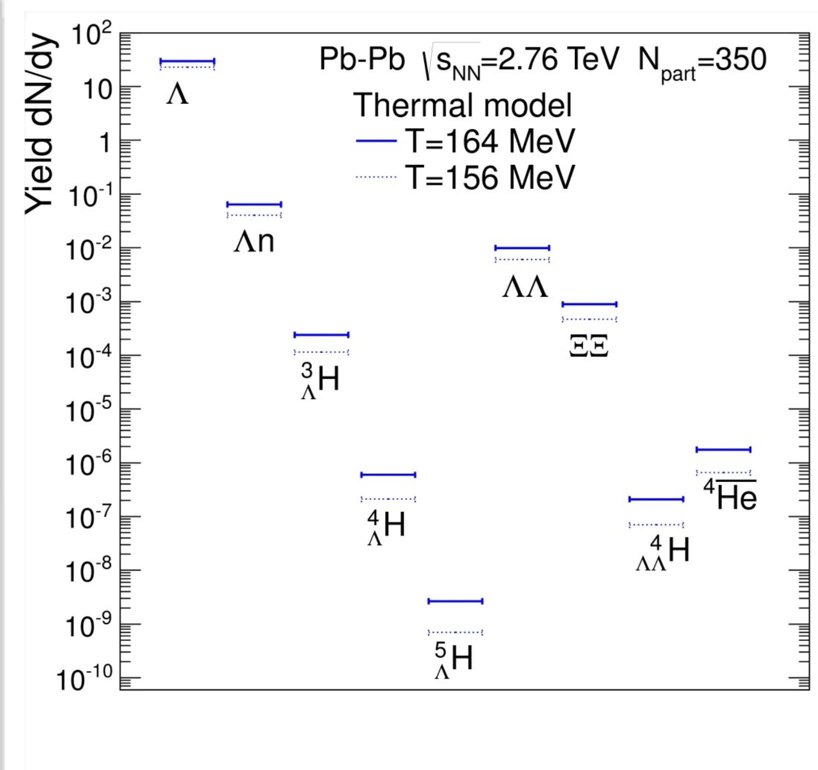
B. *Phys. Lett. B* 697, 203 (2011)

A. Andronic et al., Phys. Lett. B 697, 203 (2011)

	Yield/event at mid-rapidity and central collisions
π	~800
p	~40
Λ	~30
d	~0.17
^{3}He	~0.01
$^3_\Lambda$H	~0.003

- Hadrons emitted from the interaction region in statistical equilibrium once the *chemical freeze-out* temperature is reached
- Estimation for central heavy-ion collisions at LHC energies

A. Andronic, Private communication



Hypertriton measurement: methodology

Hypertriton: lightest know hypernucleus bound state of **p**, **n** and **Λ**

Mass[(2)] = 2.992 GeV/c^2

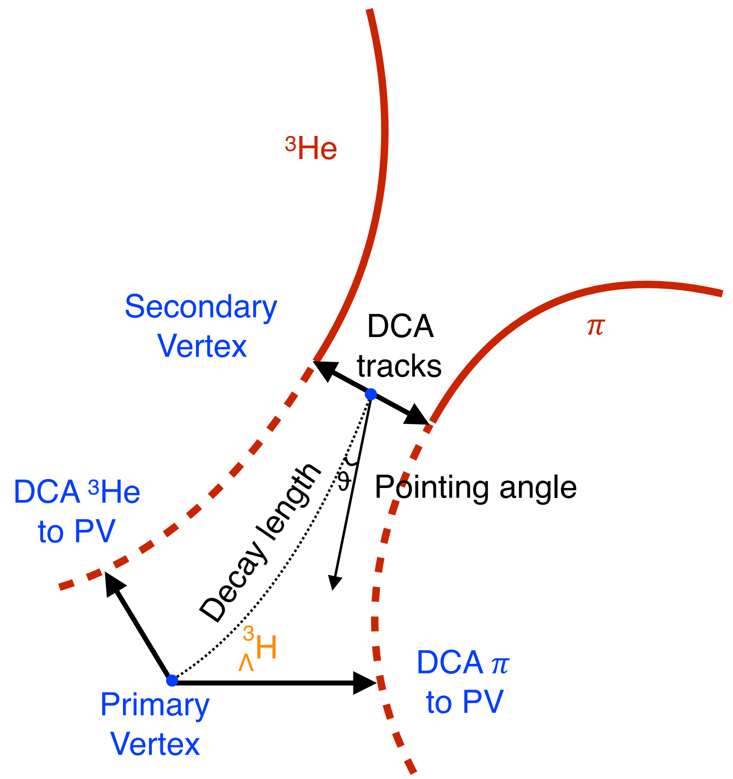
Λ-Lifetime[(3)] ~263 ps

Decay Channel:

1. Mesonic
2. Non Mesonic

Mesonic decay

Charged	Neutral
$^{3}_{\Lambda}H \longrightarrow {}^{3}He+\pi^{-}$	$^{3}_{\Lambda}H \longrightarrow {}^{3}H+\pi^{0}$
$^{3}_{\Lambda}H \longrightarrow d+p+\pi^{-}$	$^{3}_{\Lambda}H \longrightarrow d+n+\pi^{0}$
$^{3}_{\Lambda}H \longrightarrow n+p+p+\pi^{-}$	$^{3}_{\Lambda}H \longrightarrow n+n+p+\pi^{0}$



- Study of the production in the charged decay channel
  - 2 body (B.R.[(1)] ≅ 25%)
  - 3 body (B.R.[(1)] ≅ 41%)
- **Phys. Lett. B 754, 360-372 (2016)**

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

[3] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

[(1)] **B.R. predicted in H. Kamada et al., Phys. Rev. C 57 (1998) 1595-1603**

Hypertriton measurement: methodology

ALICE

Hypertriton: lightest know hypernucleus bound state of **p**, **n** and **Λ**

Mass[(2)] = 2.992 GeV/c^2

Λ-Lifetime[(3)] ~263 ps

Decay Channel:

1. Mesonic
2. Non Mesonic

Mesonic decay

Charged	Neutral
$^3_\Lambda H \longrightarrow {}^3He+\pi^-$	$^3_\Lambda H \longrightarrow {}^3H+\pi^0$
$^3_\Lambda H \longrightarrow d+p+\pi^-$	$^3_\Lambda H \longrightarrow d+n+\pi^0$
$^3_\Lambda H \longrightarrow n+p+p+\pi^-$	$^3_\Lambda H \longrightarrow n+n+p+\pi^0$

Signal extraction:

- Identify daughters (^{3}He,π) or (d,p,π)
- Apply topological cuts in order to:
  - Identify secondary decay vertex
  - Reduce combinatorial background
- Evaluate invariant mass

- Study of the production in the charged decay channel
  - 2 body (B.R.[(1)] ≅ 25%)
  - 3 body (B.R.[(1)] ≅ 41%)
- **Phys. Lett. B 754, 360-372 (2016)**

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

[3] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

[(1)] **B.R. predicted in H. Kamada et al., Phys. Rev. C 57 (1998) 1595-1603**

Hypertriton measurement with ALICE

Hypertriton: lightest know hypernucleus bound state of **p**, **n** and **Λ**

Mass[2] = 2.992 GeV/c^2

Λ-Lifetime[3] ~263 ps

Decay Channel:

1. Mesonic
2. Non Mesonic

Signal extraction:

- Identify daughters (^{3}He,π) or (d,p,π)
- Apply topological cuts in order to:
  - Identify secondary decay vertex
  - Reduce combinatorial background
- Evaluate invariant mass

Mesonic decay

Charged	B.R.[4]	System + Energy
$^3_\Lambda H \longrightarrow {}^3He+\pi^-$	25%	Pb-Pb at 2.76 TeV, 5.02 TeV
$^3_\Lambda H \longrightarrow d+p+\pi^-$	41%	Pb-Pb at 2.76 TeV

[2] D.H. Davis., Nucl. Phys. A 754 (2005) 3-13
[3] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)
[4] H. Kamada et al., Phys. Rev. C 57 (1998) 1595-1603

Hypertriton measurement with ALICE

Hypertriton: lightest know hypernucleus bound state of **p**, **n** and **Λ**

Mass[2] = 2.992 GeV/c^2

Λ-Lifetime[3] ~263 ps

Decay Channel:

1. Mesonic
2. Non Mesonic

Signal extraction:

- Identify daughters (^{3}He,π) or (d,p,π)
- Apply topological cuts in order to:
  - Identify secondary decay vertex
  - Reduce combinatorial background
- Evaluate invariant mass

Mesonic decay

Charged	B.R.[4]	System + Energy
$^3_\Lambda H \longrightarrow {}^3He+\pi^-$	25%	Pb-Pb at 2.76 TeV, 5.02 TeV
$^3_\Lambda H \longrightarrow d+p+\pi^-$	41%	Pb-Pb at 2.76 TeV

(2) D.H. Davis., Nucl. Phys. A 754 (2005) 3-13
[3] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)
(4) H. Kamada et al., Phys. Rev. C 57 (1998) 1595-1603

Hypertriton measurement with ALICE

Hypertriton: lightest know hypernucleus bound state of **p**, **n** and **Λ**

Mass(2) = 2.992 GeV/c²

Λ-Lifetime(3) ~263 ps

Decay Channel:

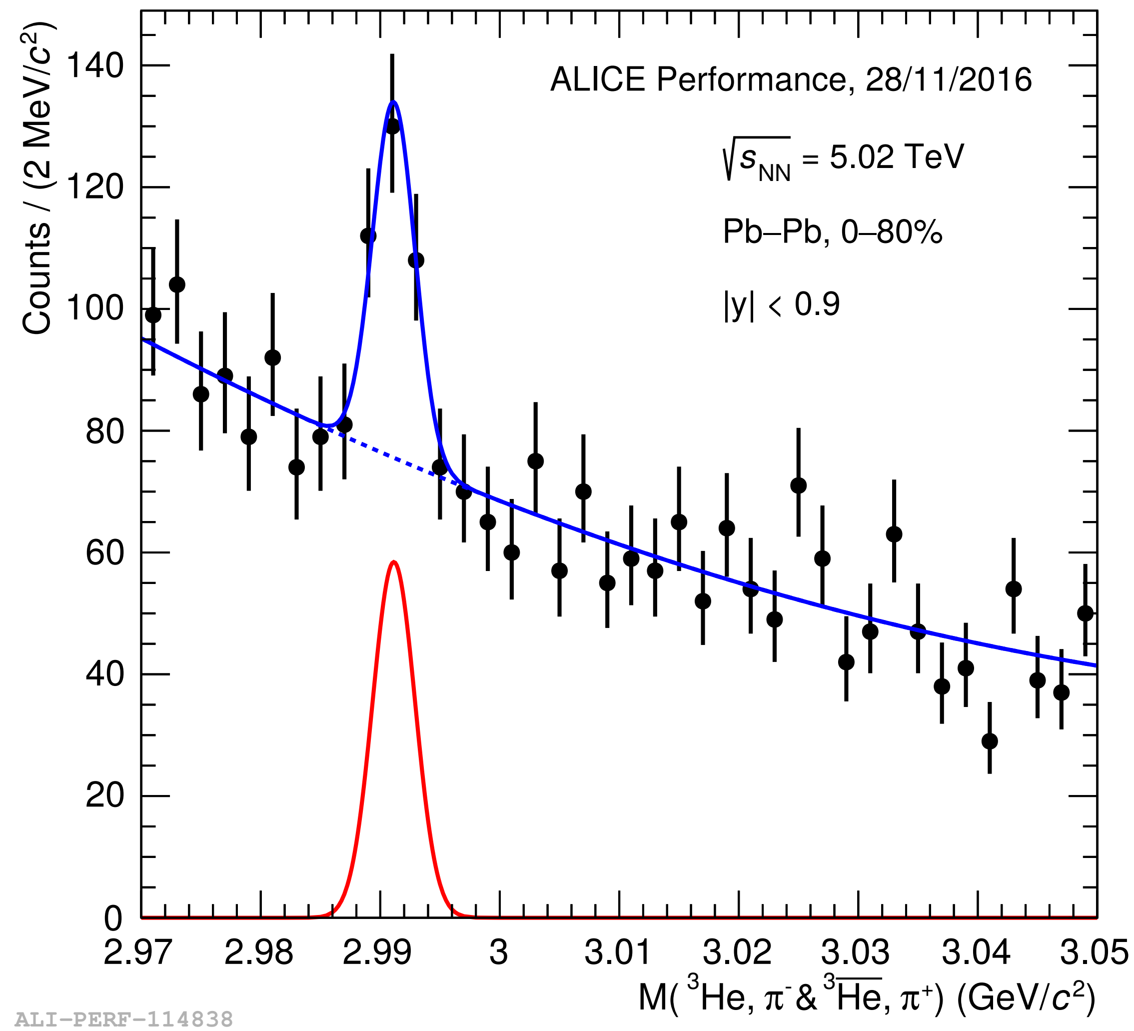
1. Mesonic
2. Non Mesonic

Mesonic decay

Charged	B.R.(4)	System + Energy
$^{3}_{\Lambda}H \longrightarrow {}^{3}He + \pi^{-}$	25%	Pb-Pb at 2.76 TeV, 5.02 TeV
$^{3}_{\Lambda}H \longrightarrow d + p + \pi^{-}$	41%	Pb-Pb at 2.76 TeV

Signal extraction:

- Identify daughters ($^{3}He,\pi$) or (d,p,π)
- Apply topological cuts in order to:
  - Identify secondary decay vertex
  - Reduce combinatorial background
- Evaluate invariant mass



(2) D.H. Davis., Nucl. Phys. A 754 (2005) 3-13

[3] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

(4) H. Kamada et al., Phys. Rev. C 57 (1998) 1595-1603

Hypertriton measurement with ALICE

Hypertriton: lightest know hypernucleus bound state of **p**, **n** and **Λ**

Mass(2) = 2.992 GeV/c²

Λ-Lifetime(3) ~263 ps

Decay Channel:

1. Mesonic
2. Non Mesonic

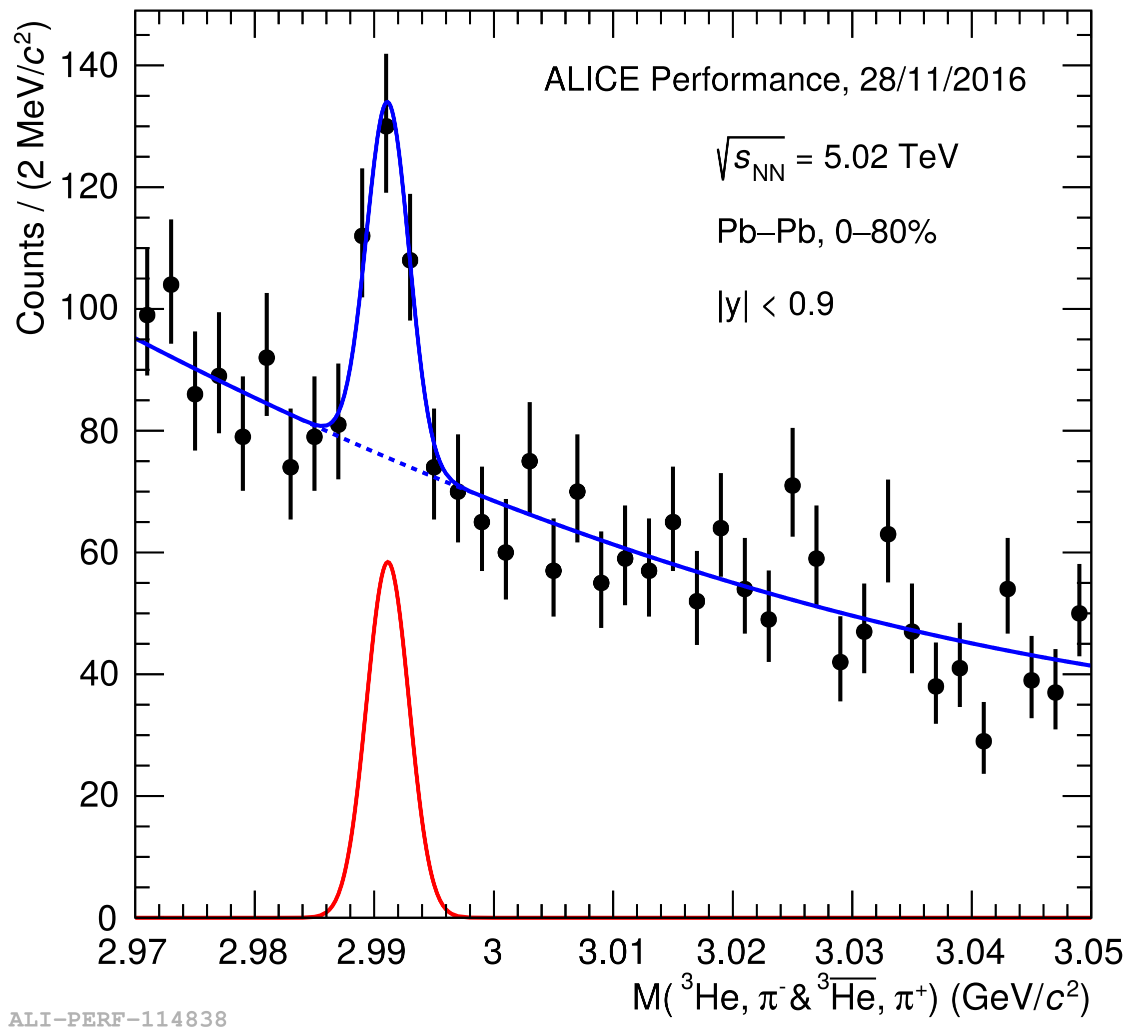
Signal extraction:

- Identify daughters (^{3}He,π) or (d,p,π)
- Apply topological cuts in order to:
  - Identify secondary decay vertex
  - Reduce combinatorial background
- Evaluate invariant mass

(2) D.H. Davis., Nucl. Phys. A 754 (2005) 3-13
[3] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)
(4) H. Kamada et al., Phys. Rev. C 57 (1998) 1595-1603

Mesonic decay

Charged	B.R.(4)	System + Energy
$^3_\Lambda H \longrightarrow {}^3He+\pi^-$	25%	Pb-Pb at 2.76 TeV, 5.02 TeV
$^3_\Lambda H \longrightarrow d+p+\pi^-$	41%	Pb-Pb at 2.76 TeV



Hypertriton measurement with ALICE

Hypertriton: lightest know hypernucleus bound state of **p**, **n** and **Λ**

Mass[2] = 2.992 GeV/c²

Λ-Lifetime[3] ~263 ps

Decay Channel:

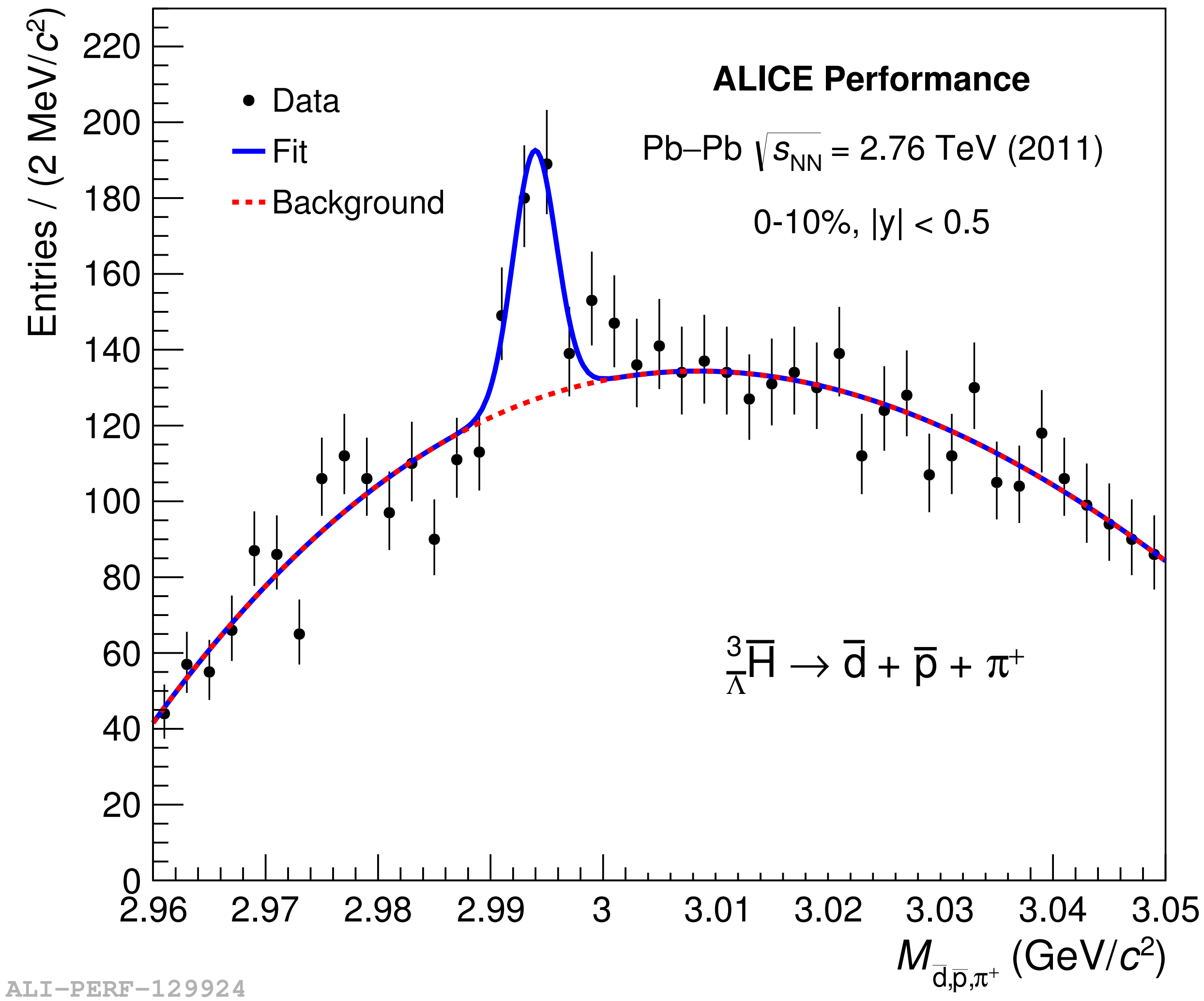
1. Mesonic
2. Non Mesonic

Mesonic decay

Charged	B.R.[4]	System + Energy
$^{3}_{\Lambda}H \longrightarrow {}^{3}He+\pi^{-}$	25%	Pb-Pb at 2.76 TeV, 5.02 TeV
$^{3}_{\Lambda}H \longrightarrow d+p+\pi^{-}$	41%	Pb-Pb at 2.76 TeV

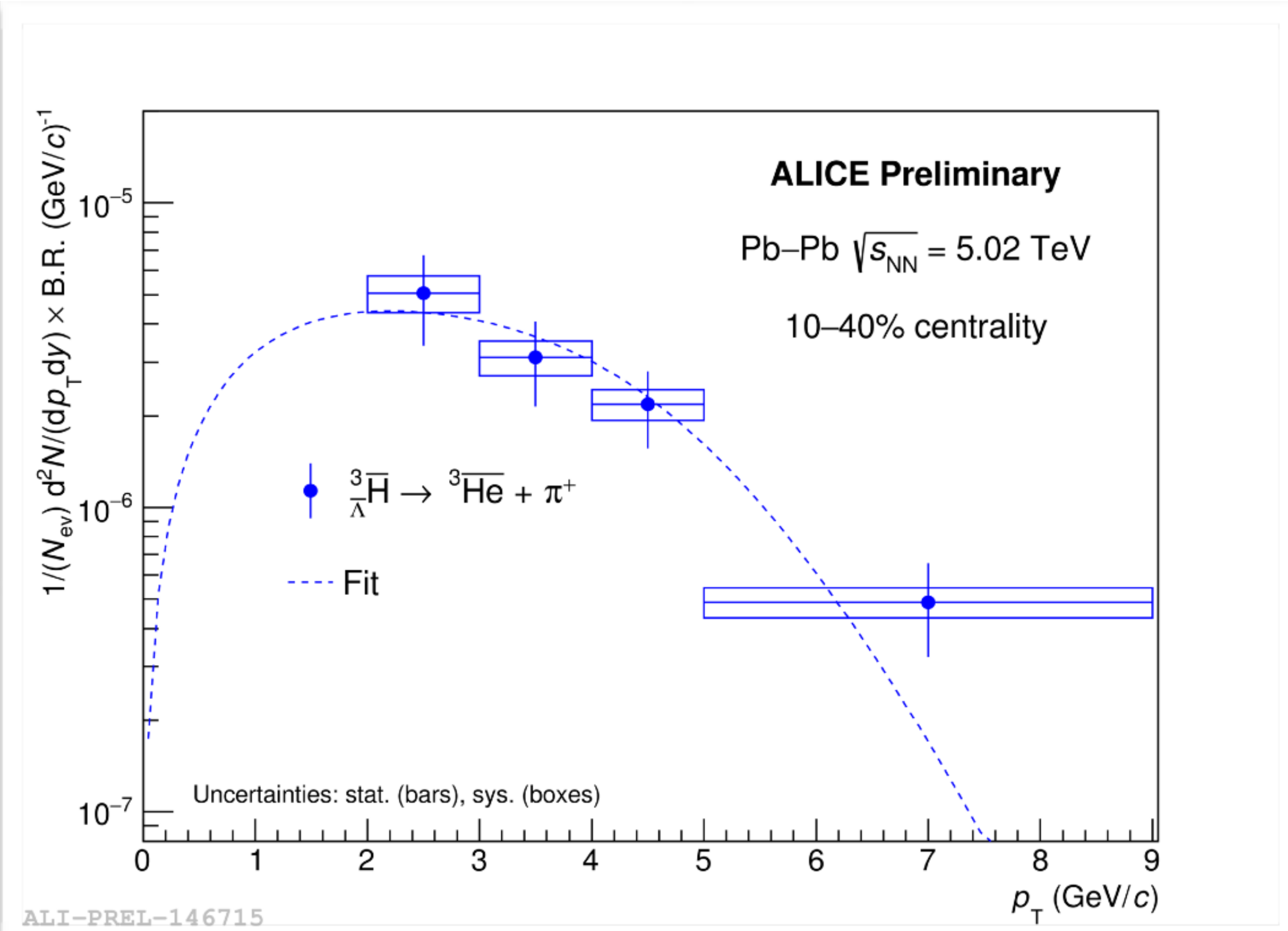
Signal extraction:

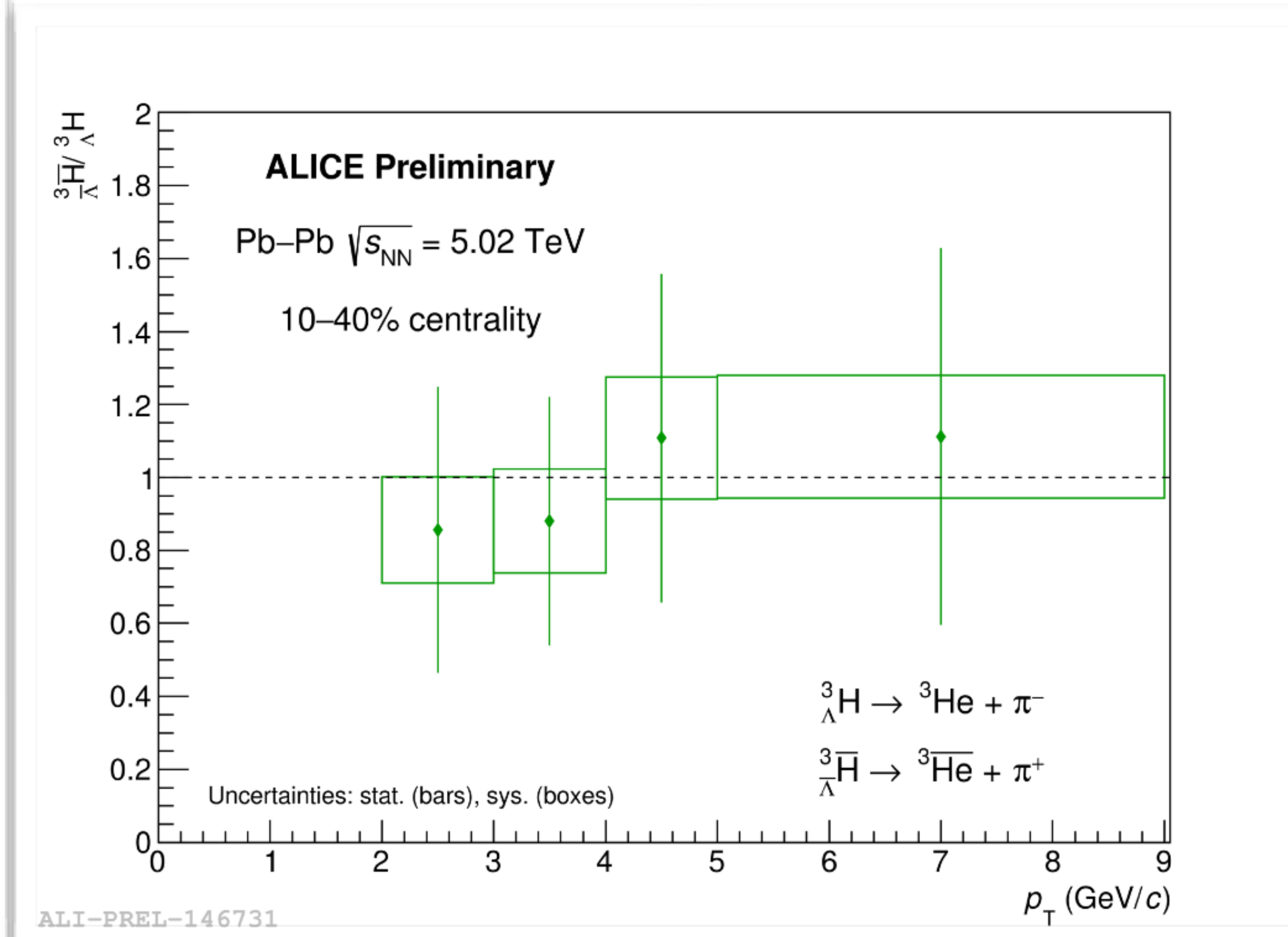
- Identify daughters (^{3}He,π) or (d,p,π)
- Apply topological cuts in order to:
  - Identify secondary decay vertex
  - Reduce combinatorial background
- Evaluate invariant mass



[2] D.H. Davis., Nucl. Phys. A 754 (2005) 3-13
[3] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)
[4] H. Kamada et al., Phys. Rev. C 57 (1998) 1595-1603

Hypertriton *production*

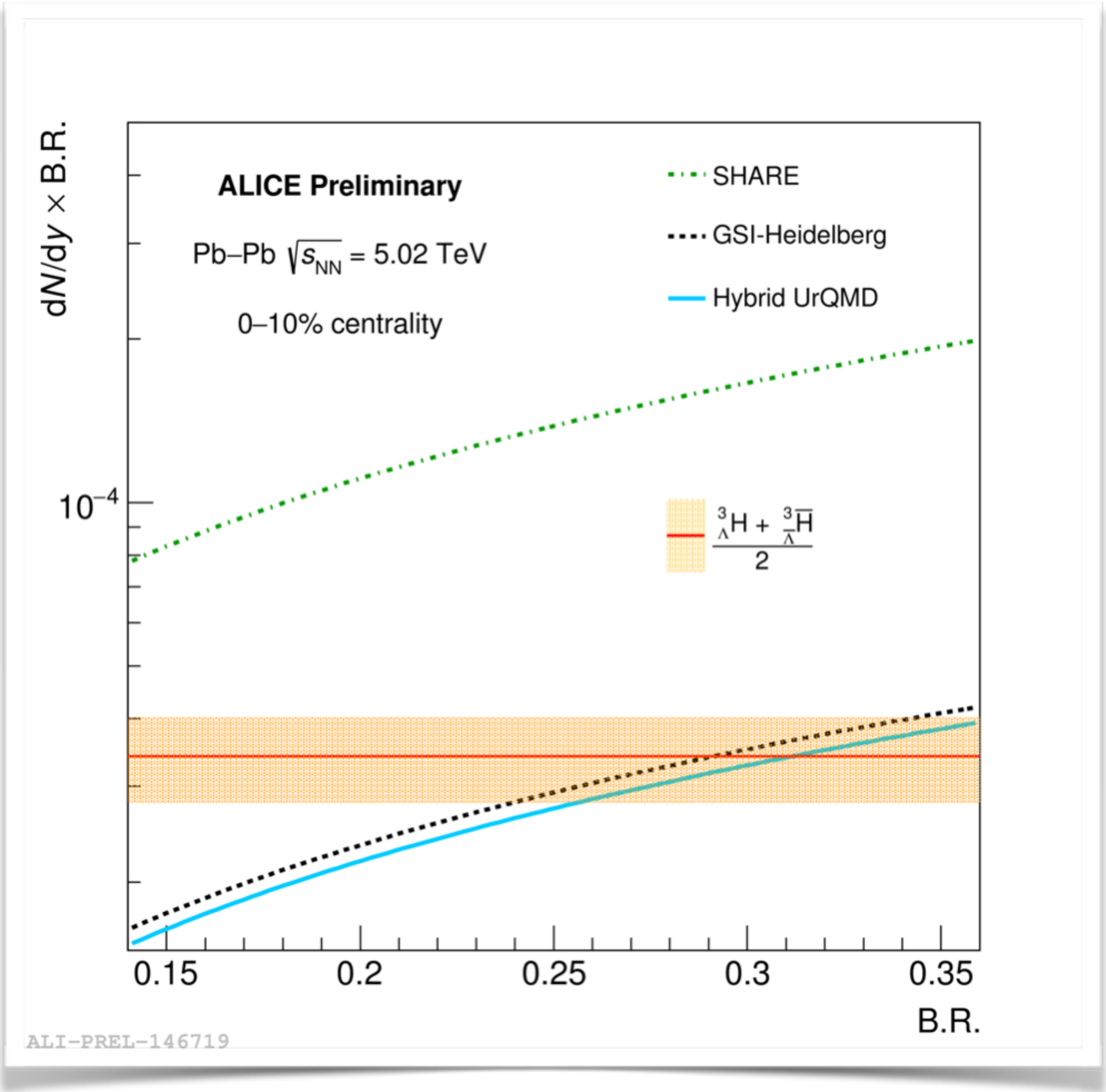




- **Measurement performed** in semi-central collisions (10-40%) for the first time at 5.02 TeV
- The measurement at 2.76 TeV was performed in 3 p_T bins and 2 centrality classes (0-10% and 10-50%)
- **Blast-Wave**[4] **distribution** used to extrapolate the yield in the unmeasured p_T region

[4] E. Schnedermann et al., Phys. Rev. C 48, 2462 (1993)

Hypertriton *production vs models*



dN/dy x B.R. vs B.R.

- Hyper-triton decay B.R. is not precisely known, only constrained by the ratio between all charged channels containing a pion.
- The study of the 3-body decay channel can help in improving our knowledge of B.R.

✓ Hybrid UrQMD: combines the hadronic transport approach with an initial hydrodynamical stage for the hot and dense medium

J. Steinheimer et al. *Phys. Lett. B* 714 (2012)

✓ GSI-Heidelberg: equilibrium statistical thermal model with T_{chem} = 156 MeV

A. Andronic et al. *Phys. Lett. B* 697,

\- SHARE: non-equilibrium thermal model with

M. Pétran et al. *Phys. Rev. C* 88 (3)

agreement with **equilibrium** thermal model **GSI-Heidelberg** and with Hybrid UrQMD in the B.R. range between 0.24 and 0.35

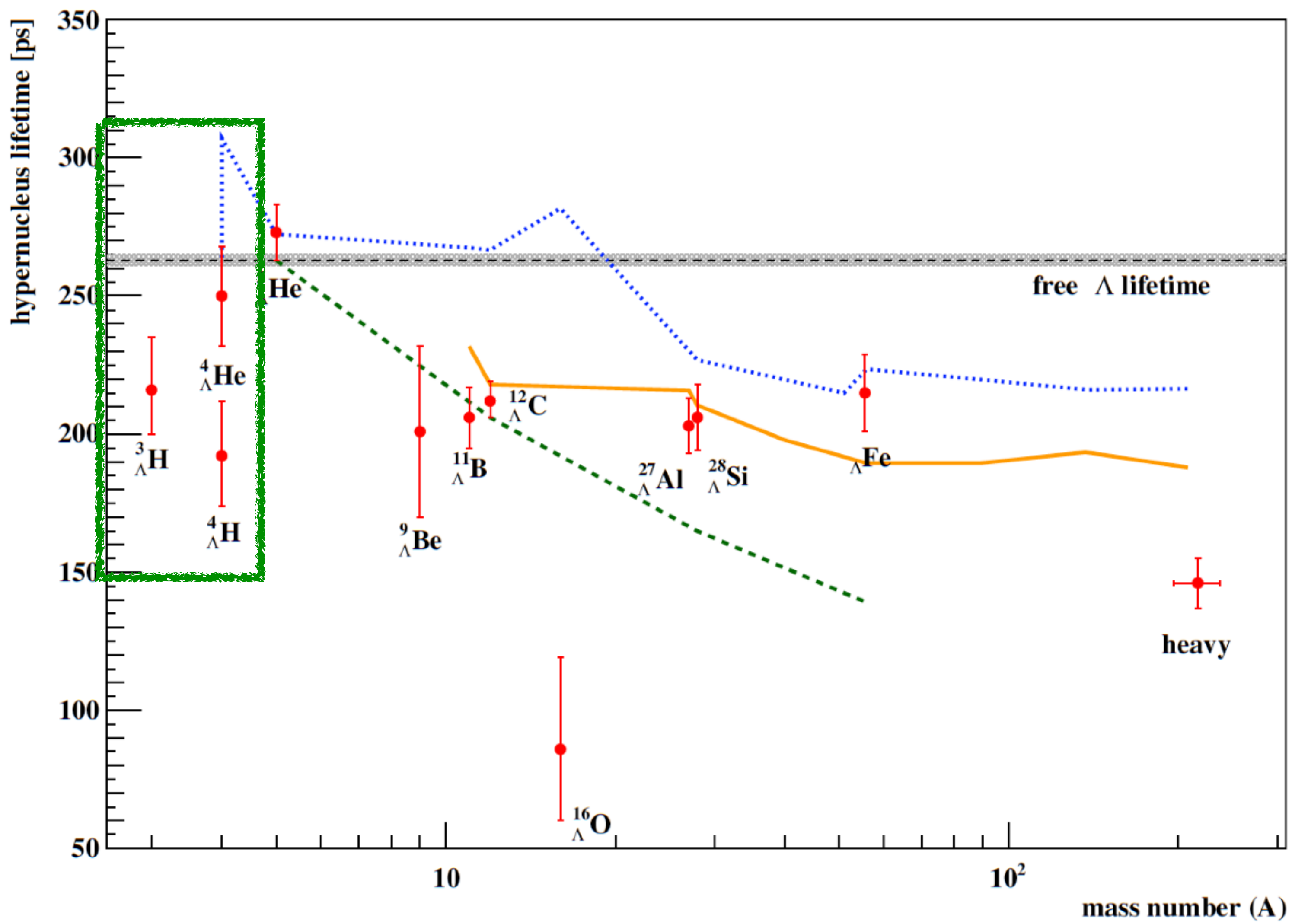
Hypernuclei lifetime: exp vs theory

ALICE

Small E_{B_Λ} (~130 keV) —> lifetime is slightly below the free Λ lifetime (263.2 ± 2 ps [5])

Hypothesis: Λ would spend most of its time far from the deuteron core due to the very small value of E_{B_Λ}

[5] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)



Nuovo Cimento- Vol. 38 n. 9 (2015) pp 387-448

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

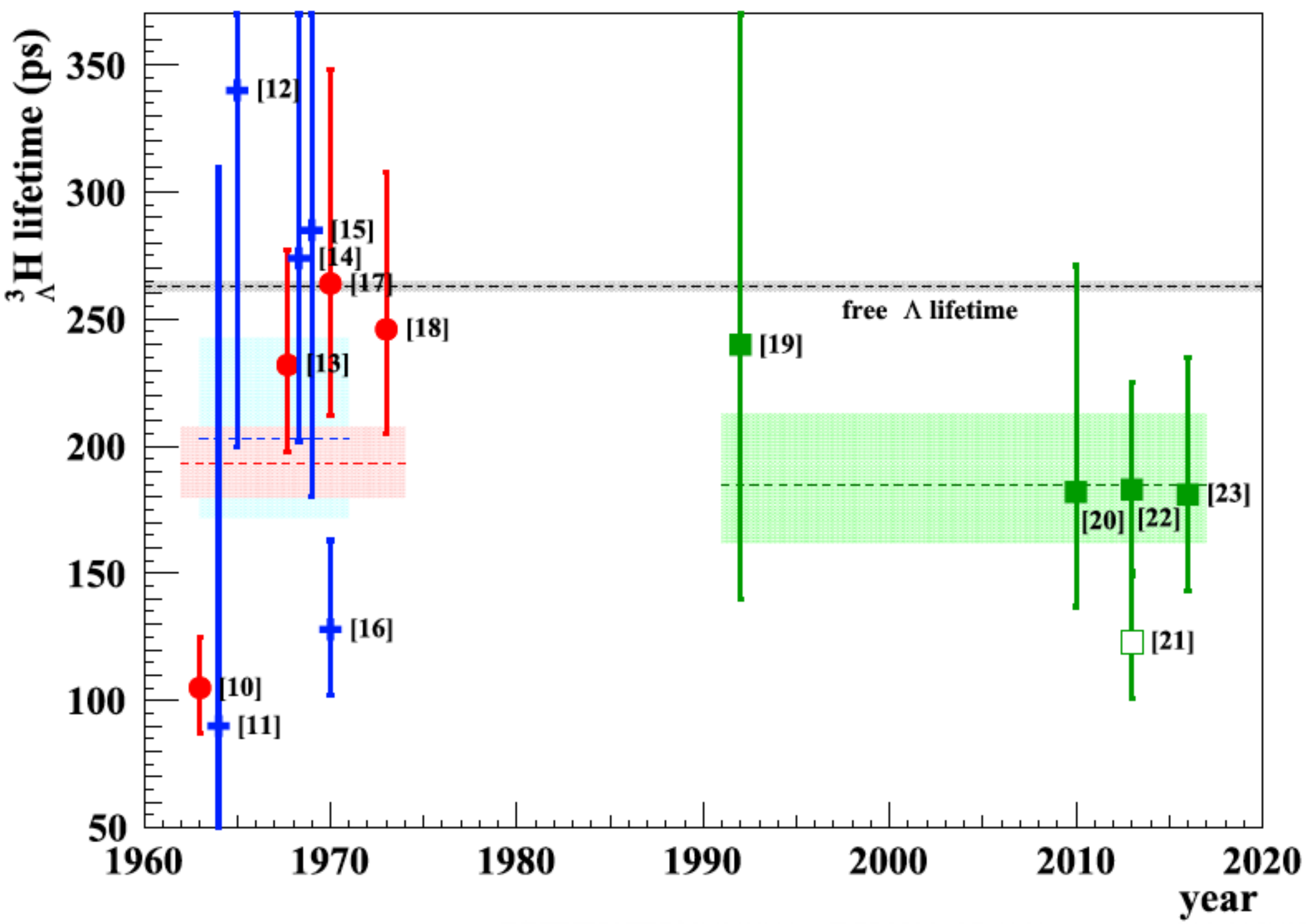
Bauer E. and Garbarino G., Phys. Rev. C, 81 (2010) 064315.
plus correction from
Motoba T. and Itonaga K., Prog. Theor. Phys. Suppl., 117 (1994) 477.
Better description of NN interaction and 2 Nucleon Non Mesonic Weak Decay taken into account

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

heavy = weighted average of lifetime for hypernuclei with 180<A<238

Hypertriton lifetime: experimental results

Nuclear Physics A 954 (2016) 176–198



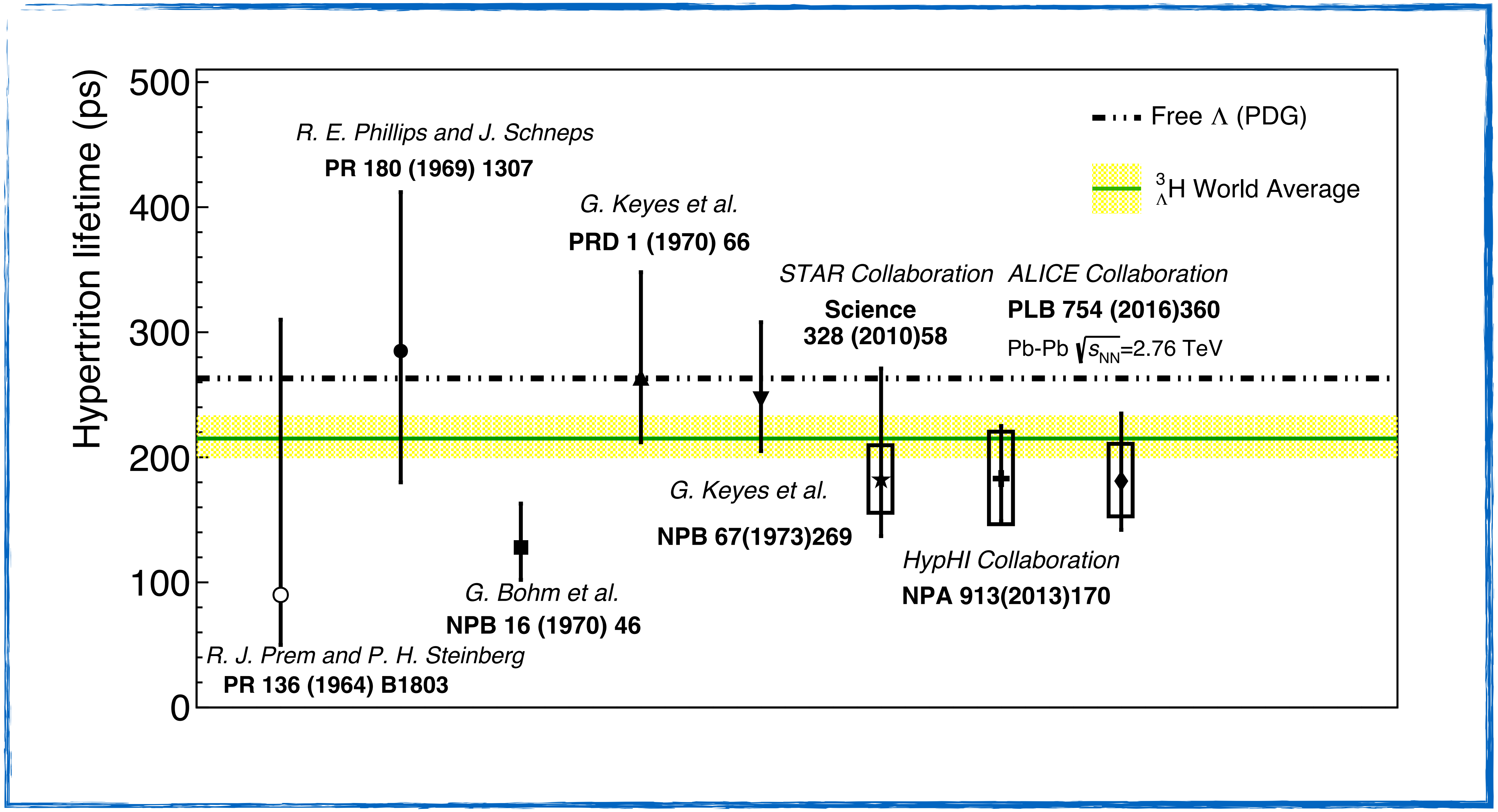
World averages and uncertainties grouping the measurements on the basis of the experimental technique

ALICE: ref [23]
STAR: ref [20,21]
For all the references in the plot: see slide17

emulsion technique: 203^{+40}_{-31} ps
He Bubble Chamber: 195^{+15}_{-13} ps
Digital readout: 185^{+28}_{-23} ps without [21]
Digital readout: 163^{+18}_{-16} ps with [21]

Hypertriton: the *lifetime puzzle*

Data compilation after LHC Run1

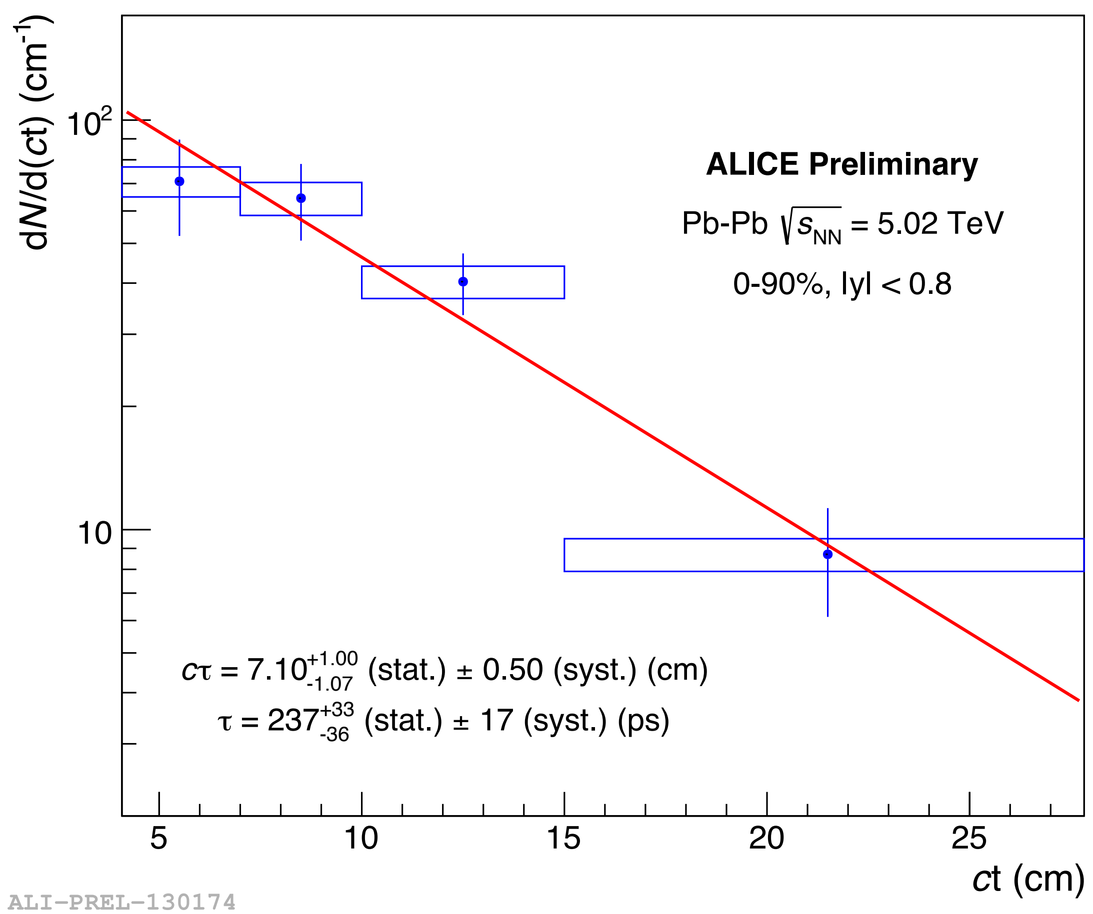


Re-evaluation of world average including ALICE result:

$$\tau = (215^{+18}_{-16})\ ps$$

ALICE value compatible with the computed average

Hypertriton *lifetime with Pb-Pb at 5 TeV*

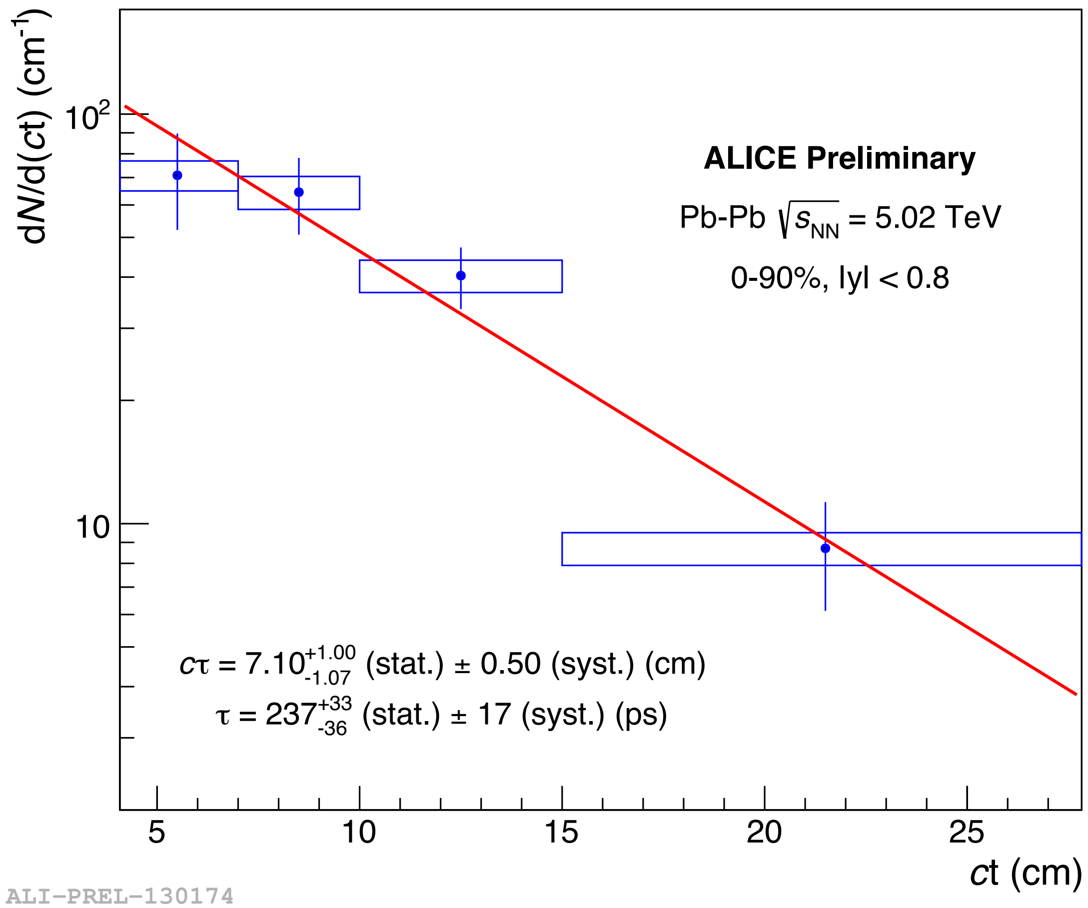


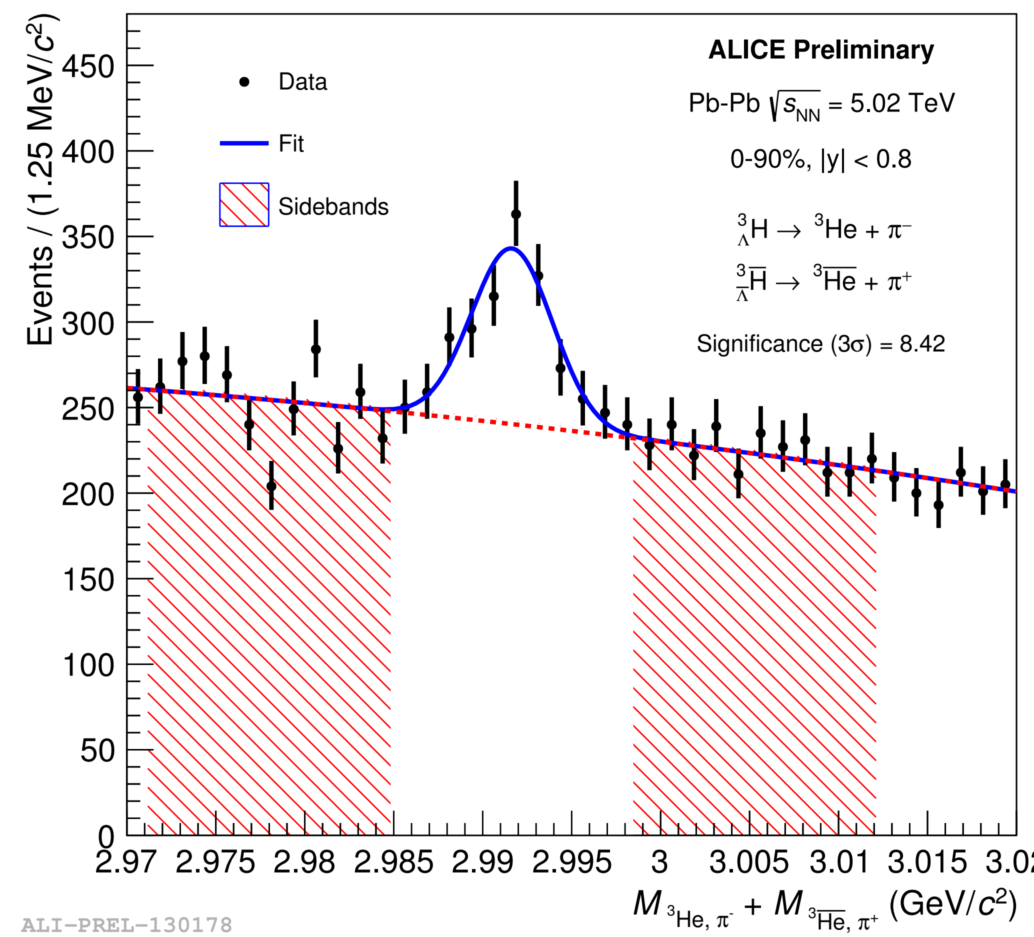
*c*t spectra (*default*)

- Exponential fit to the differential yield in different *c*t bins

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

Hypertriton *lifetime with Pb-Pb at 5 TeV*



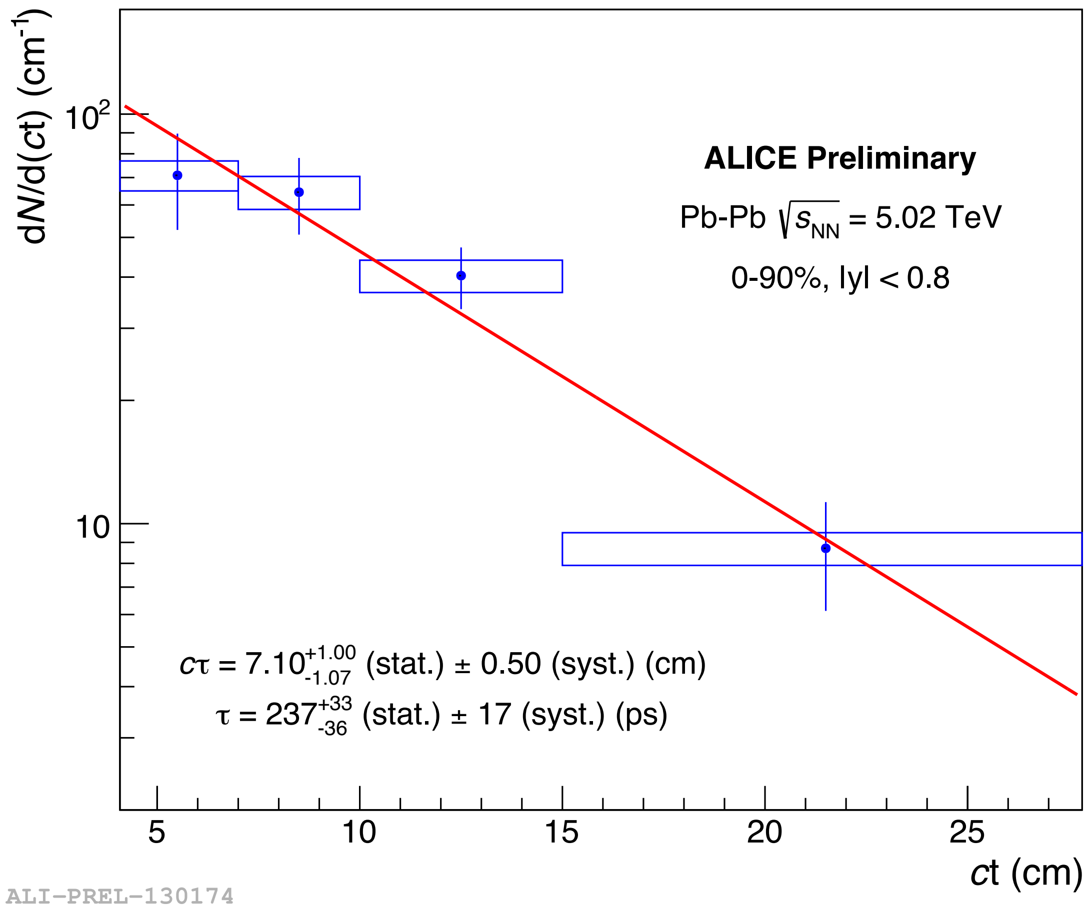


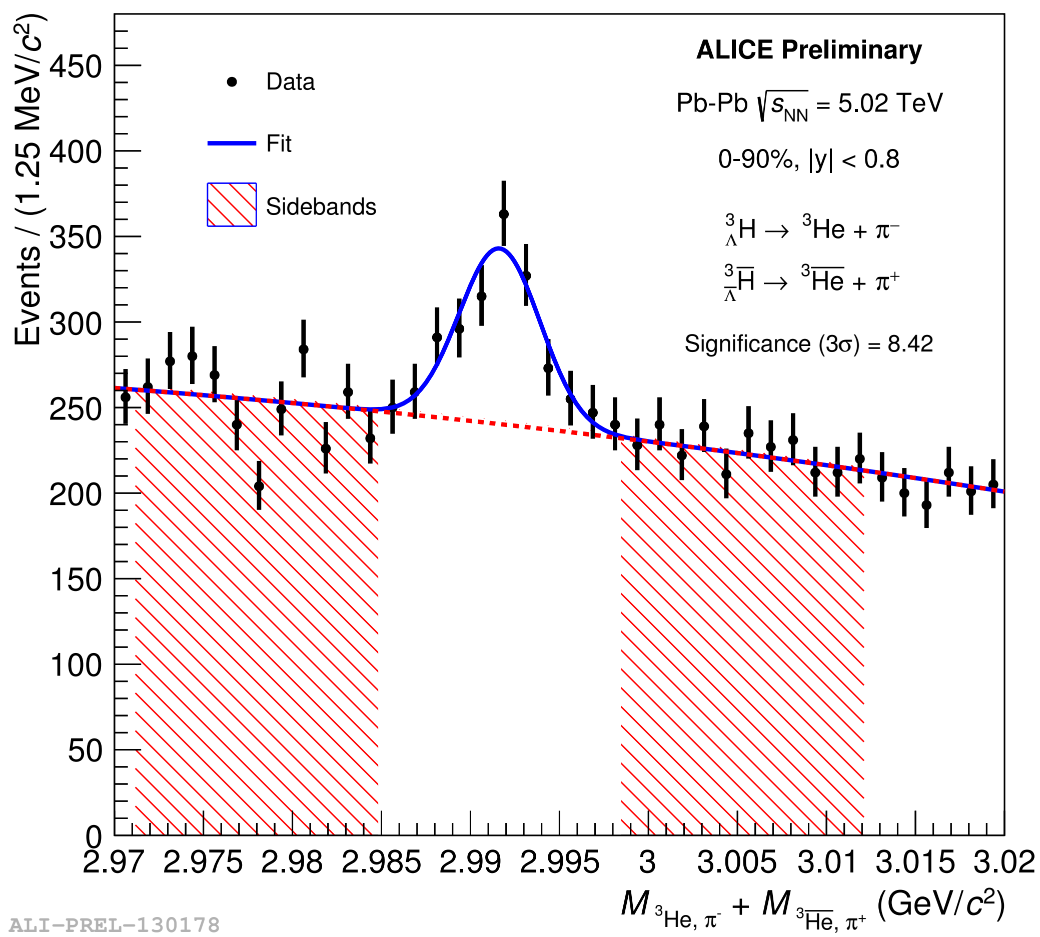
ct spectra (*default*)

- Exponential fit to the differential yield in different *ct* bins

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

Hypertriton *lifetime with Pb-Pb at 5 TeV*





*c*t spectra (*default*)

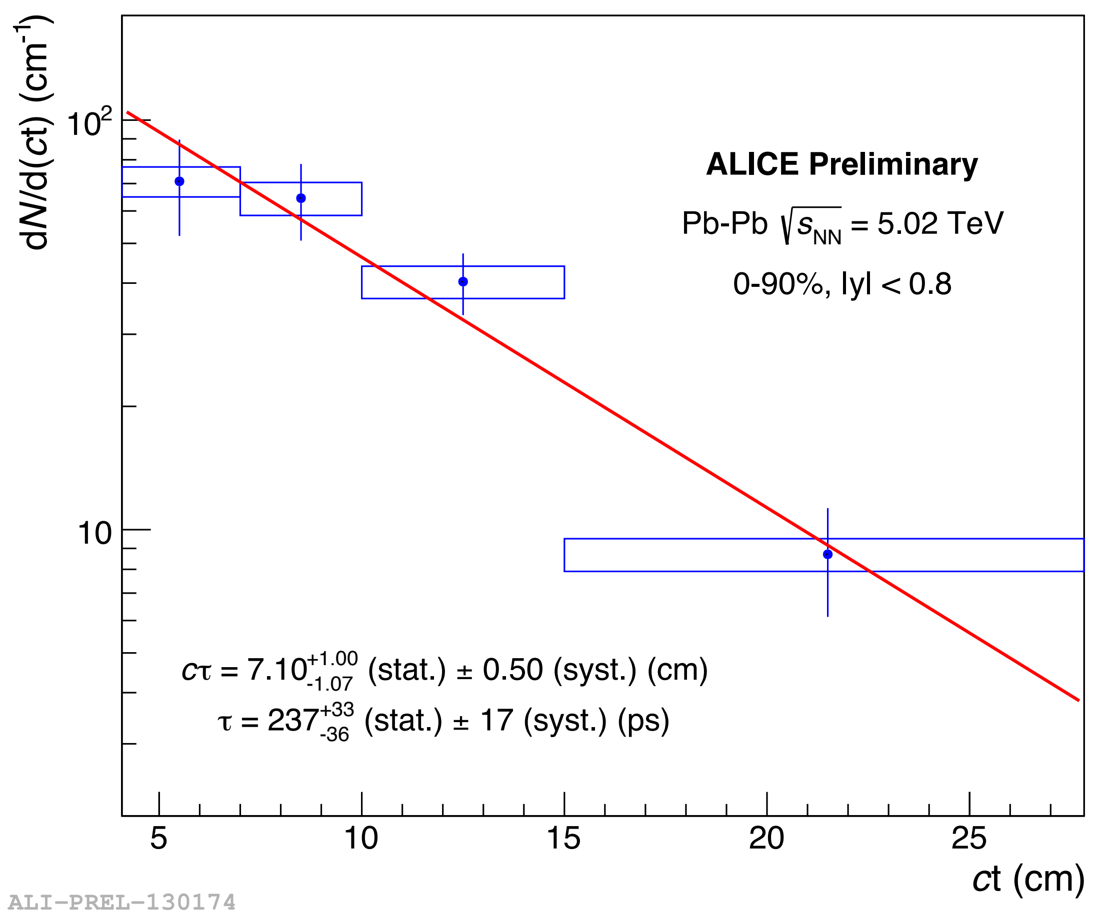
- Exponential fit to the differential yield in different *c*t bins

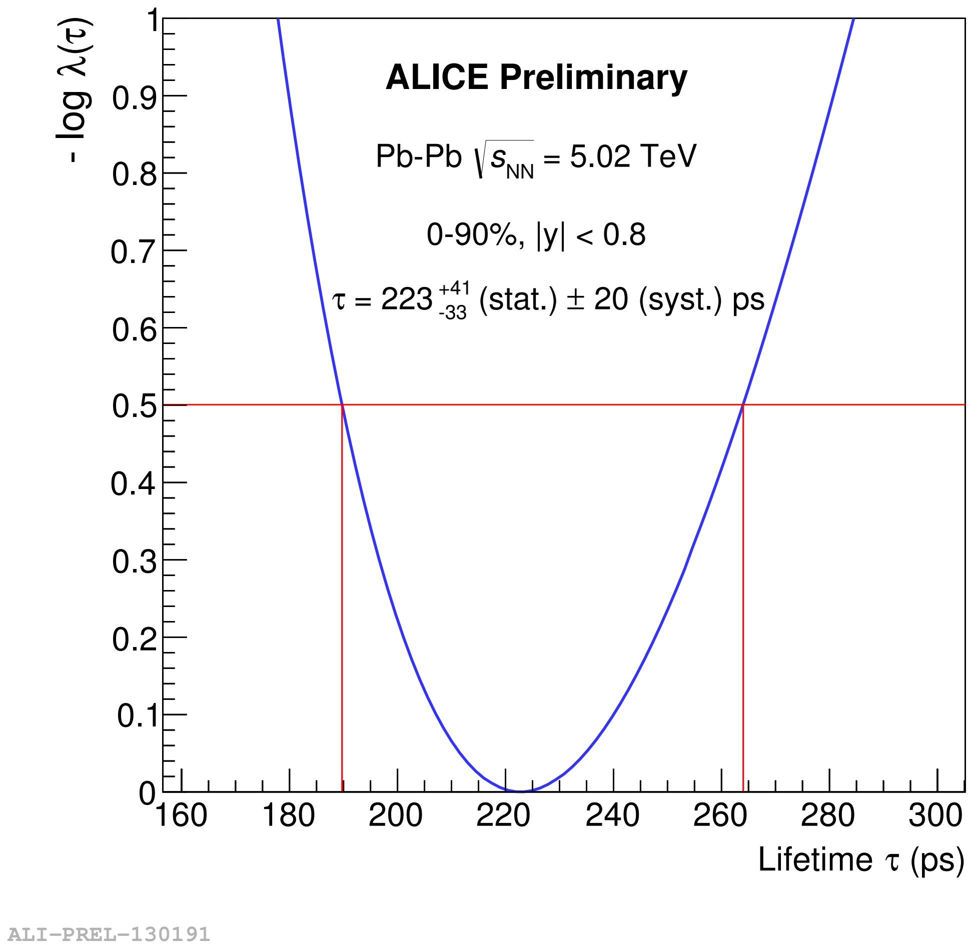
$$\tau = 237^{+33}_{-36}(stat.) \pm 17(syst.)\mathrm{ps}$$

Unbinned fit

- Crosscheck method
- Fit to the invariant mass distribution → σ used to define the signal range [+3σ,-3σ]

Hypertriton *lifetime* with Pb-Pb at 5 TeV





*c*t spectra (*default*)

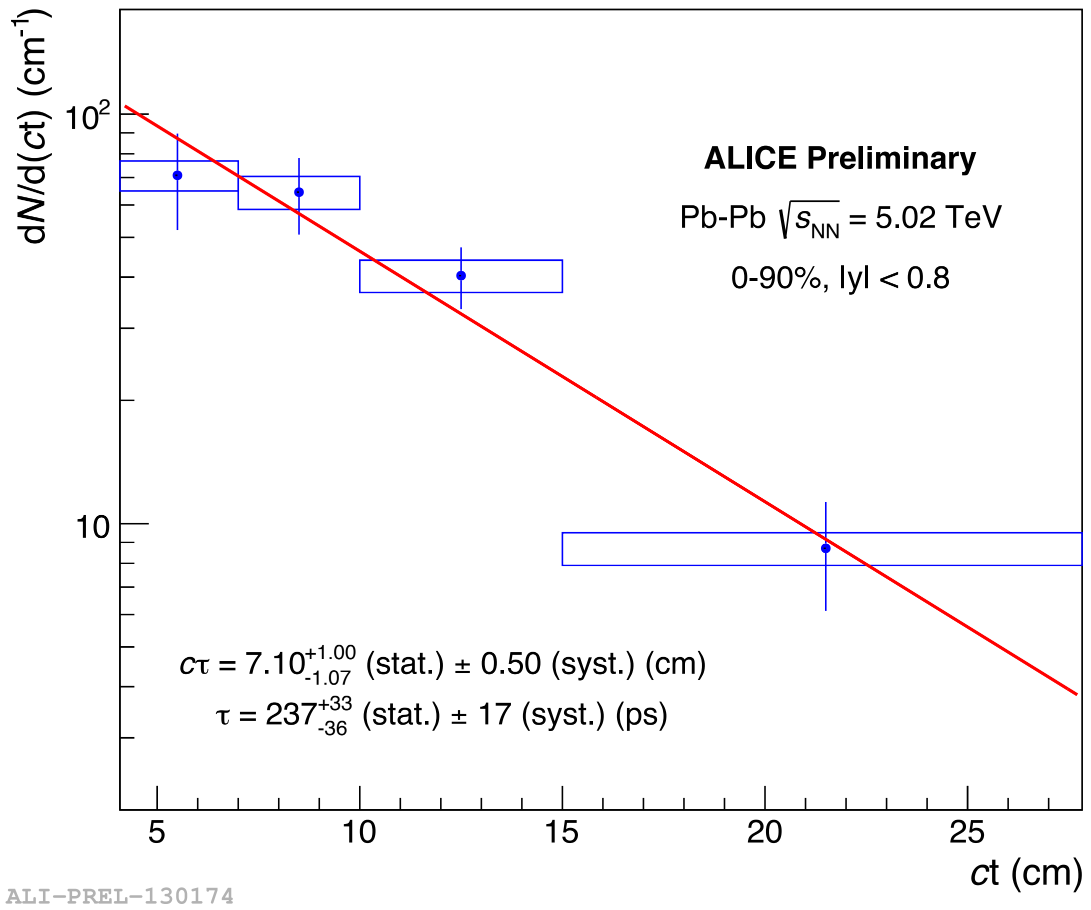
- Exponential fit to the differential yield in different *c*t bins

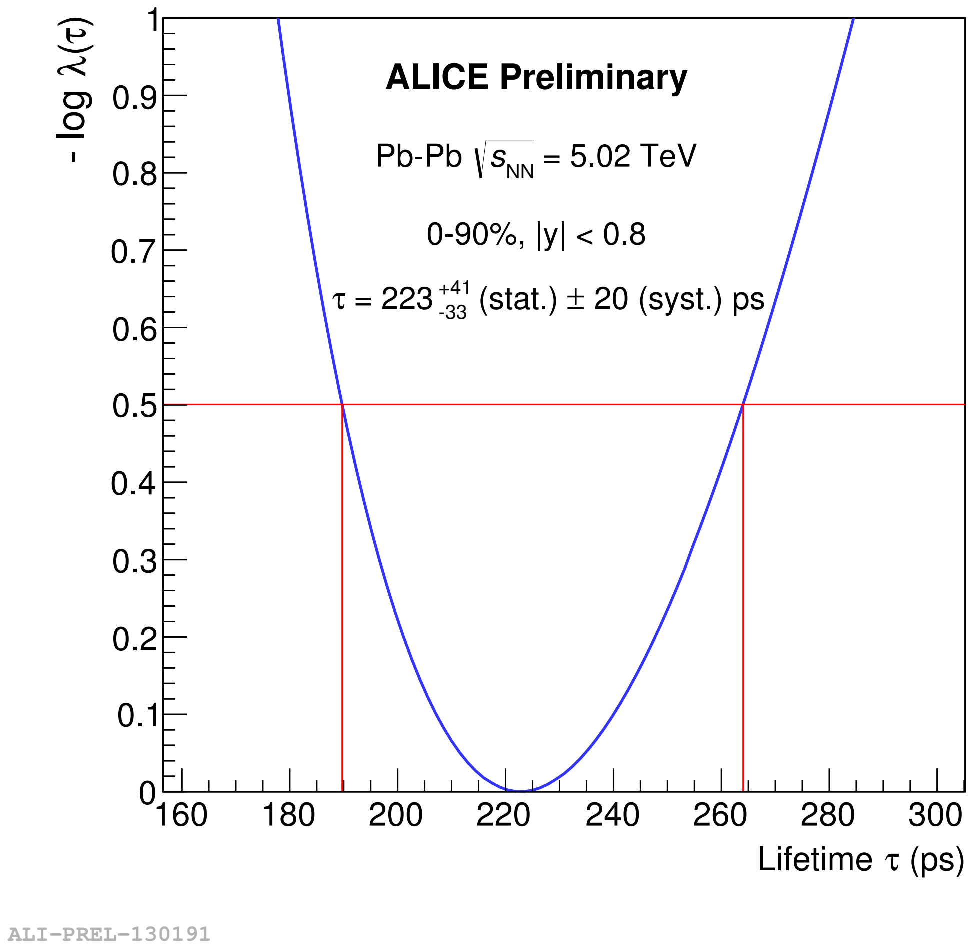
$$\tau = 237^{+33}_{-36}(stat.) \pm 17(syst.)\mathrm{ps}$$

Unbinned fit

- Crosscheck method
- Fit to the invariant mass distribution → σ used to define the signal range [+3σ,-3σ]

Hypertriton *lifetime* with Pb-Pb at 5 TeV





ct spectra (*default*)

- Exponential fit to the differential yield in different *ct* bins

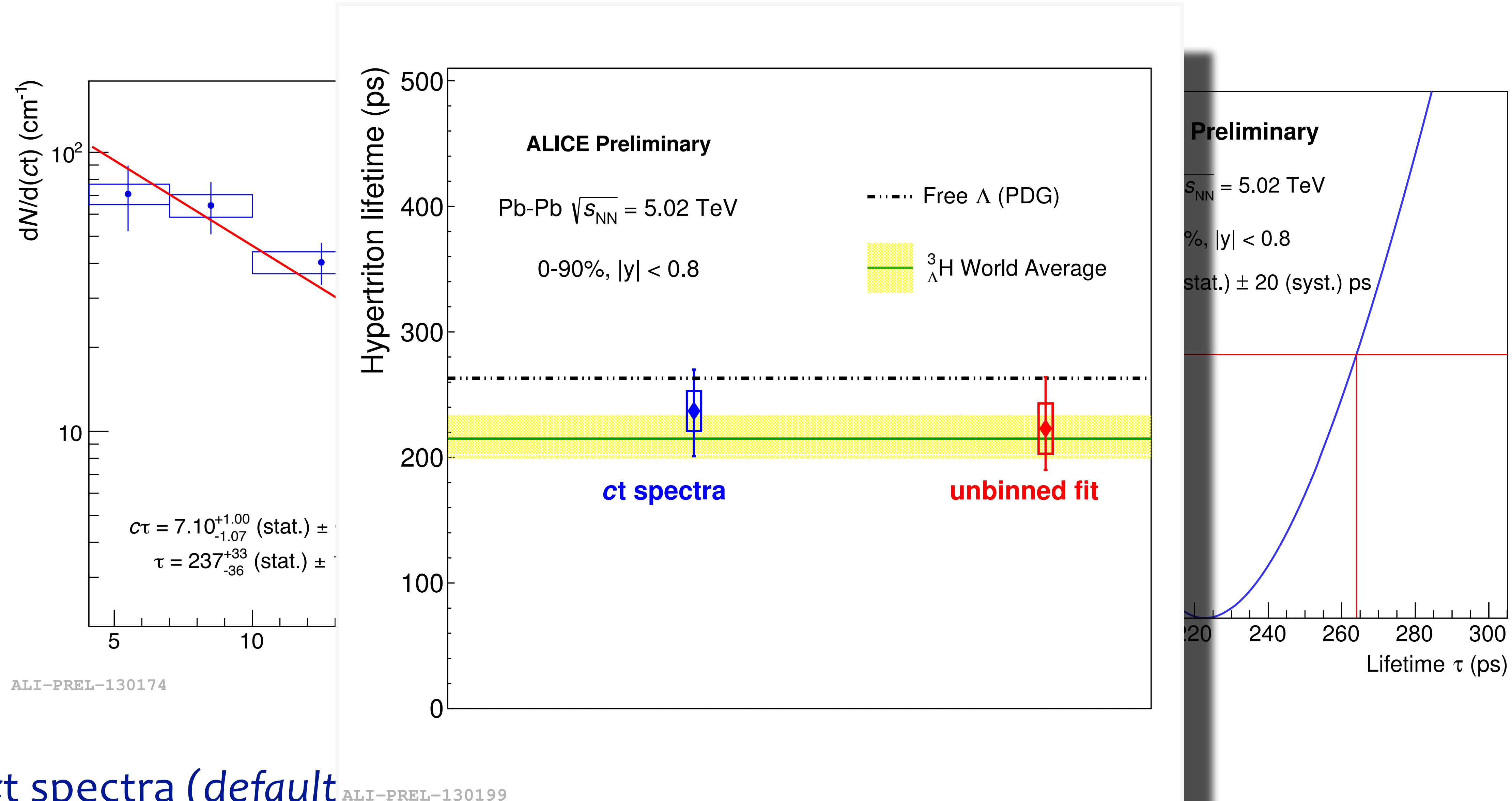
$$\tau = 237^{+33}_{-36}(stat.) \pm 17(syst.)\mathrm{ps}$$

Unbinned fit

- Fit to the *ct* distribution in the signal range with function:
  - *signal*: single exponential
  - *background*: double exponential

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

Hypertriton *lifetime with Pb-Pb at 5 TeV*



ct spectra (*default*

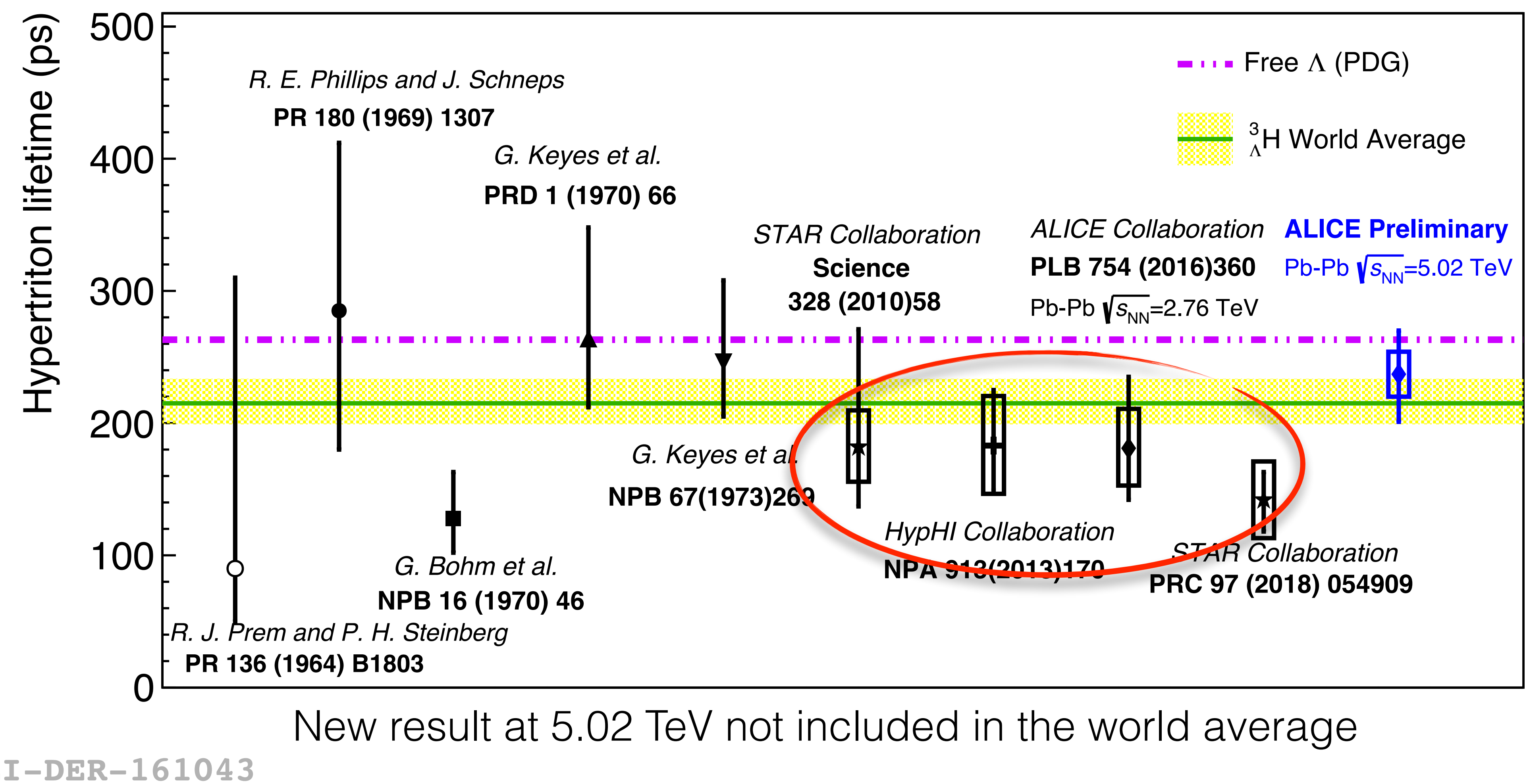
- Exponential fit to the differential yield in different *ct* bins

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

- Fit to the *ct* distribution in the signal range with function:
  - *signal*: single exponential
  - *background*: double exponential

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

Hypertriton *lifetime world data*



New result at 5.02 TeV not included in the world average

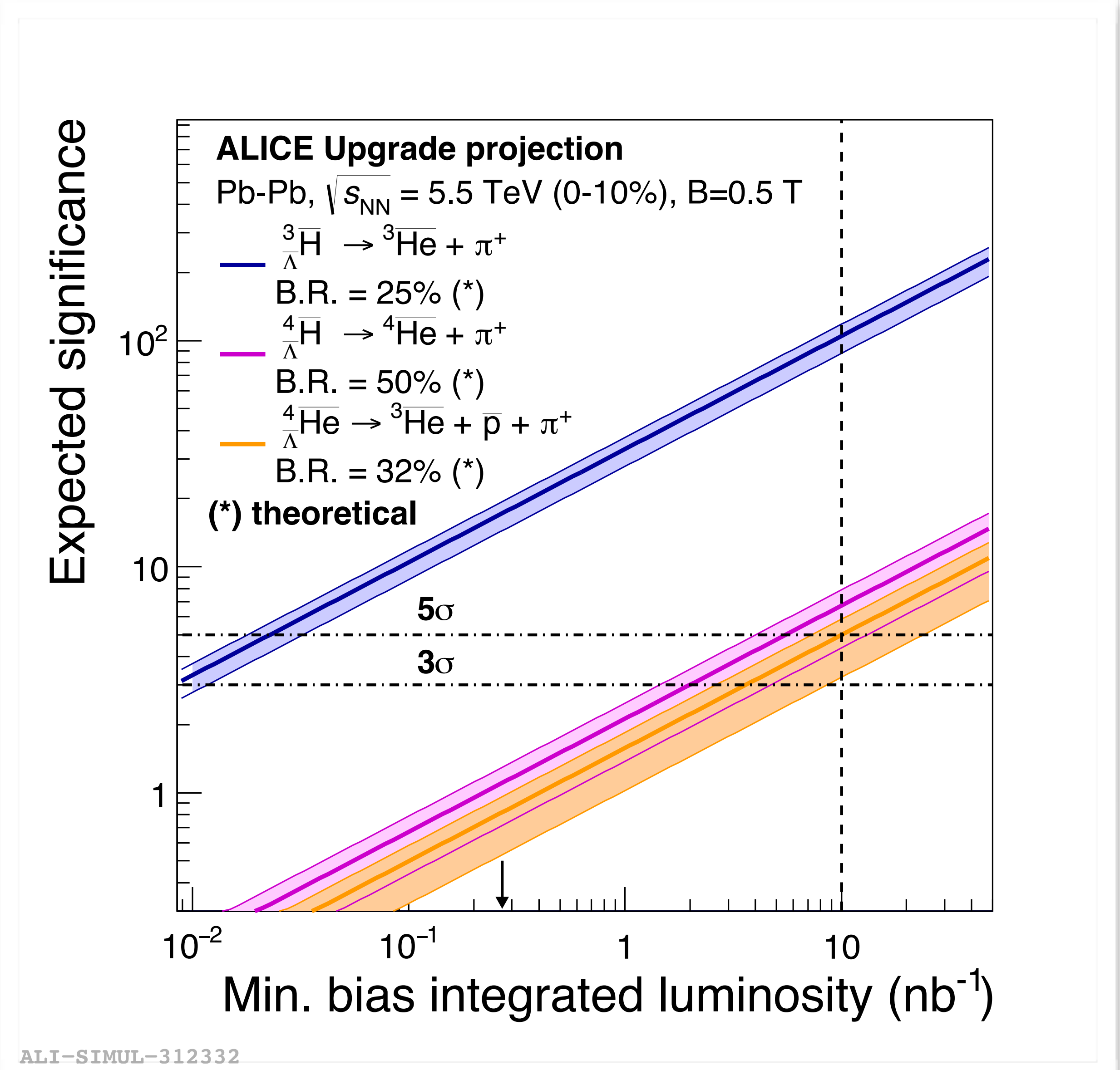
Previous heavy-ion experiment results show a trend **below** the free Λ lifetime
Result from Pb-Pb at 5.02 TeV: **improved precision** and value **compatible** with that of free Λ

Summary and perspectives

- Production and lifetime measurements of the (anti-)hypertriton performed in more centrality classes w.r.t. the results at 2.76 TeV and with improved precision thanks to Run 2 data
- Integrated **yields** are well described by thermal models
- Recent ALICE hypertriton **lifetime** measurement shows an improved precision and a value **closer** to the Λ lifetime with respect to the previous heavy-ion results
    - Lifetime determination via **3-body** decay channel will be important
    - New analysis approaches based on Machine Learning are ongoing *(poster by P. Fecchio)*
    - New **theoretical calculations** for the lifetime are needed as well as more precise measurements of the B_Λ

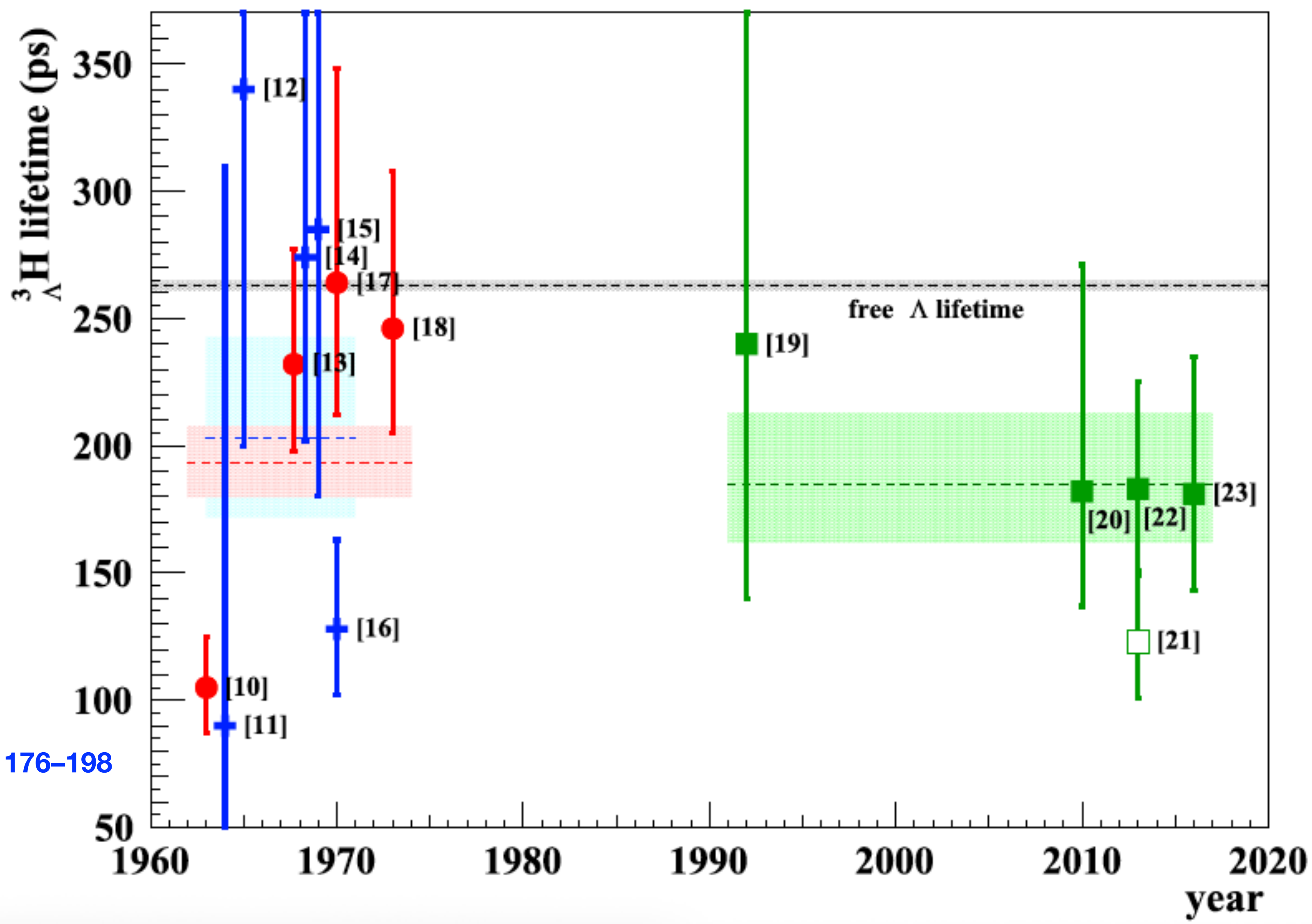
Longer term perspectives

Measurements with **higher significance** of anti-hypernuclei will be possible in central Pb–Pb collisions in **Runs 3 and 4 also for A>3**



BACKUP

Hyper-triton lifetime: experimental results



Nuclear Physics A 954 (2016) 176–198

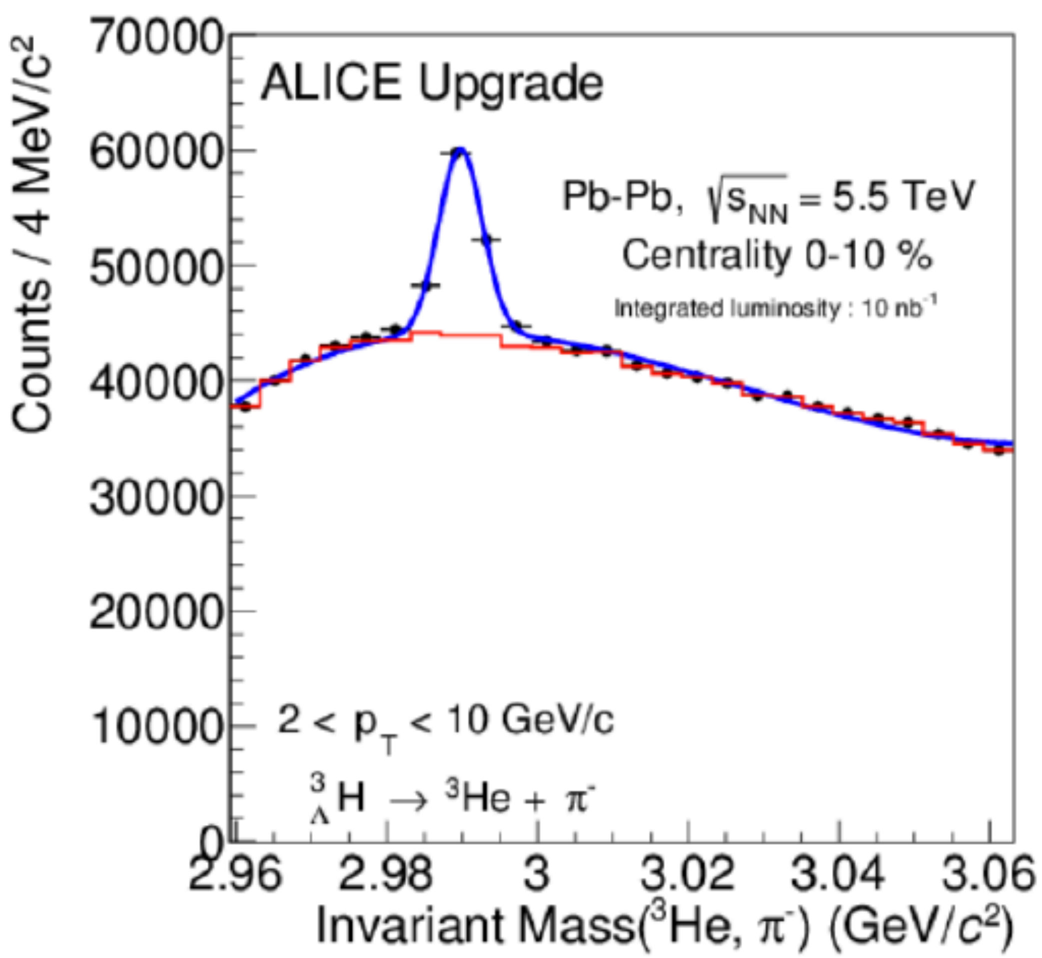
[10] M.M. Block, et al., in: Proc. of the International Conference on Hyperfragments, St. Cergue, 28–30 March 1963, p.63.
[11] R.J. Prem, P.H. Steinberg, Phys. Rev. 136 (1964) B1803.
[12] Y.V. Kang, et al., Phys. Rev. 139 (1965) B401.
[13] G. Keyes, et al., Phys. Rev. Lett. 20 (1968) 819.
[14] R.J. Phillips, 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.

Upgrade strategy

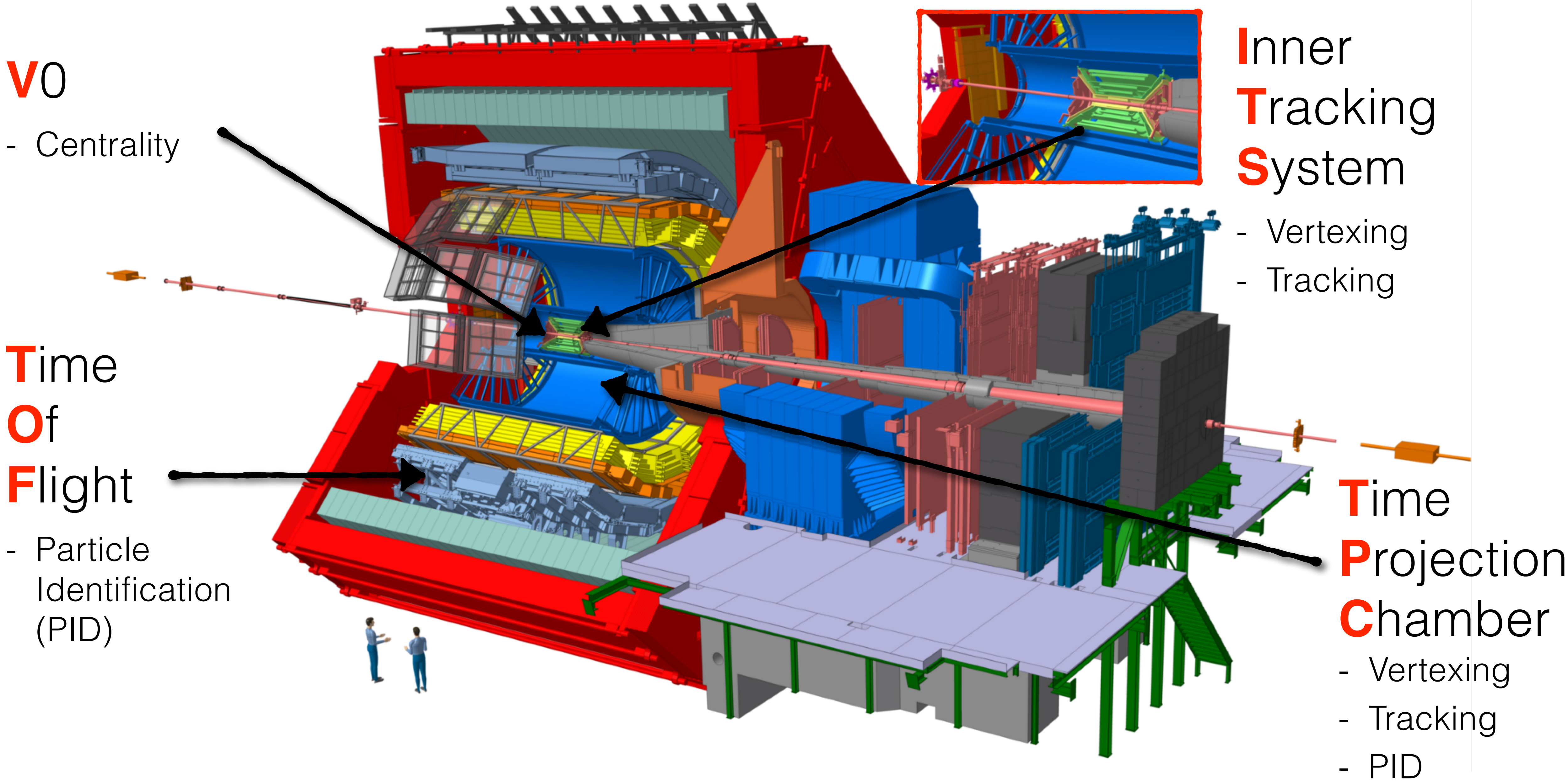
- Measurement of (anti-)hyper-triton yields and lifetime is an interesting topic and nice inputs come from the heavy-ion experiment
- New measurement from HI experiments gives a shorter lifetime than the expected free Lambda lifetime → recently confirmed by ALICE at a new energy (5.02 TeV)
- What about Run 3 & Run 4 of LHC? More statistics delivered (50 kHz Pb-Pb collision rate)

State	dN/dy	B.R.	$\langle Acc \times \epsilon \rangle$	Yield
$^{3}_{\Lambda}H$	1×10^{-4}	25%	11 %	44000
$^{4}_{\Lambda}H$	2×10^{-7}	50%	7 %	110
$^{4}_{\Lambda}He$	2×10^{-7}	32%	8 %	130

ITS Upgrade TDR: J. Phys. G 41, 087002 (2014)



Introduction: *ALICE*

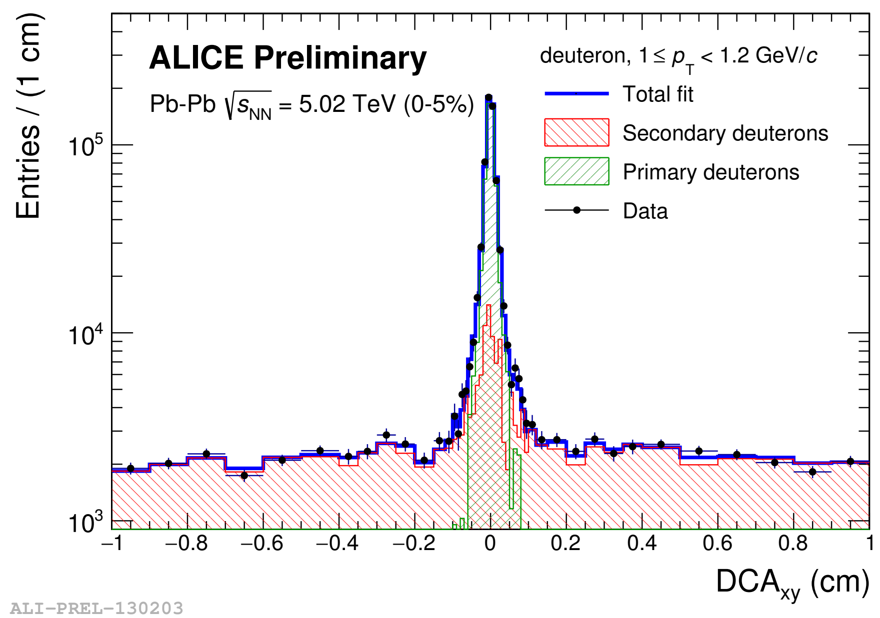


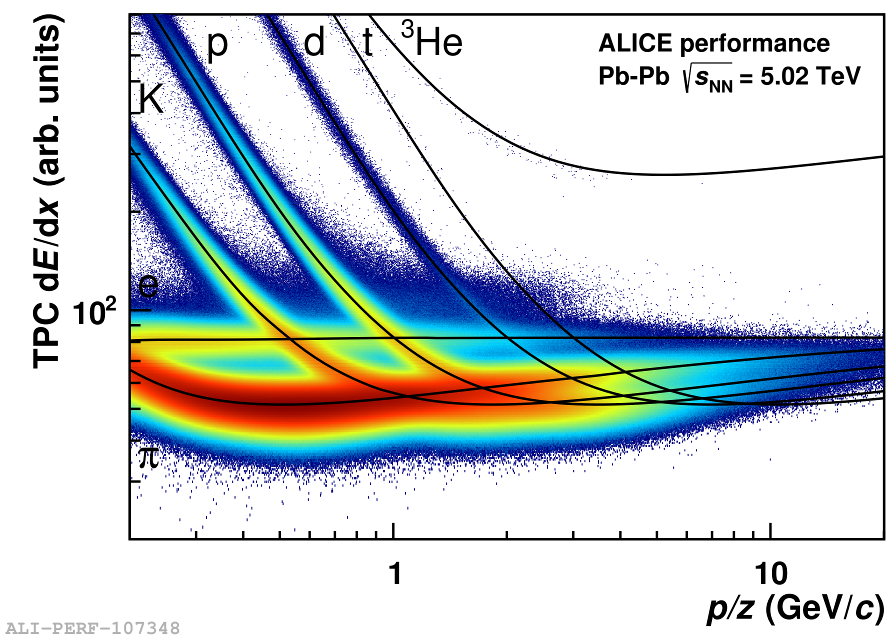
- General purpose heavy ion experiment
- Excellent particle identification (PID) capabilities and low material budget
- Most suited detector at the LHC to study the (anti-)(hyper-)nuclei produced in the collisions

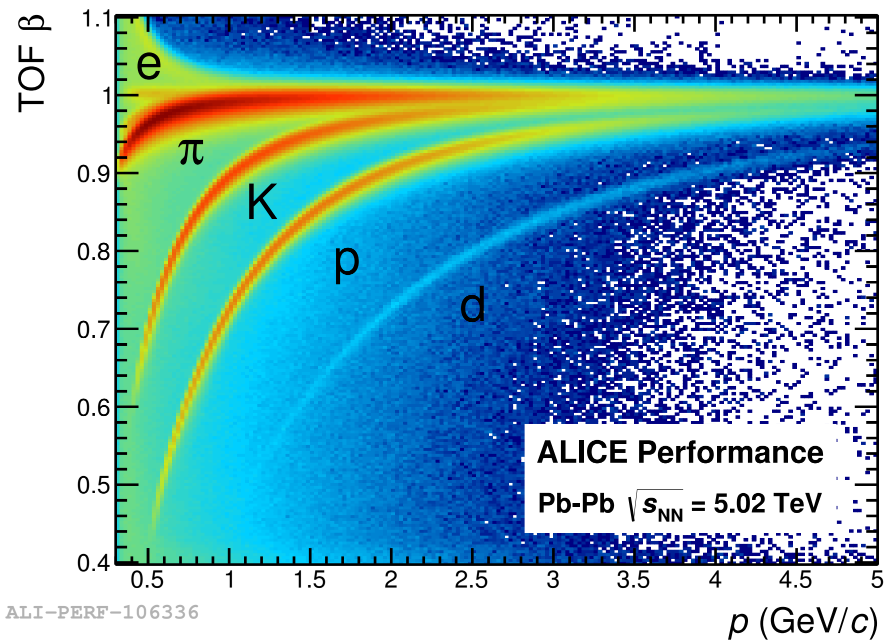
Particle identification in *ALICE*

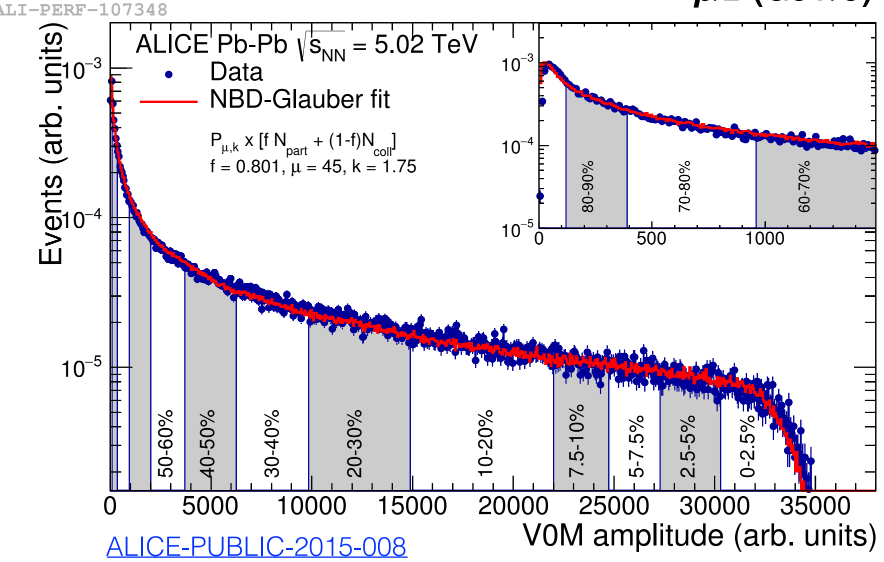
Detectors used for (anti-)(hyper-)nuclei analysis:

- **ITS**
  - Separation of primary and secondary nuclei from knock-out
  - $p_T > 0.5$ GeV/c → $\sigma_{DCAxy} < 100$ μm
- **TPC**
  - dE/dx in gas (Ar-CO_2)
  - $\sigma_{dE/dx} \sim 5.5\%$
- **TOF**
  - Time-of flight measurement
  - $\sigma_{TOF} \sim 80$ ps (Pb-Pb), 120 ps (pp)
- **V0**
  - Two arrays of 64 scintillators
  - determination of the centrality of a collision









ALICE-PUBLIC-2015-008