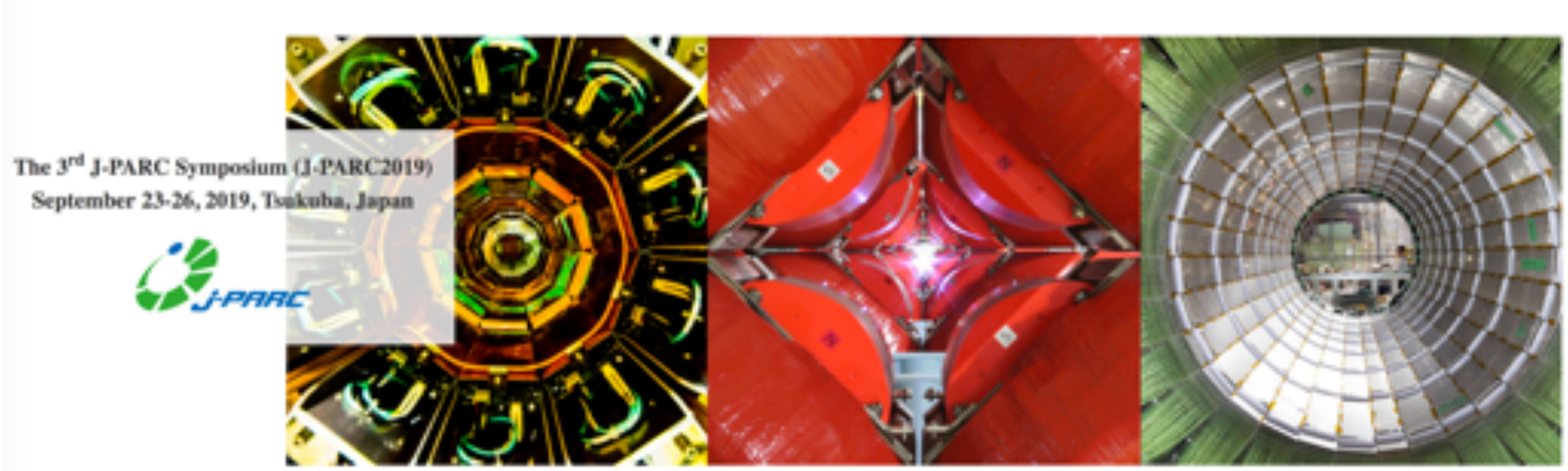
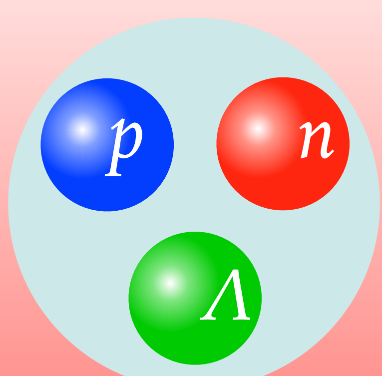
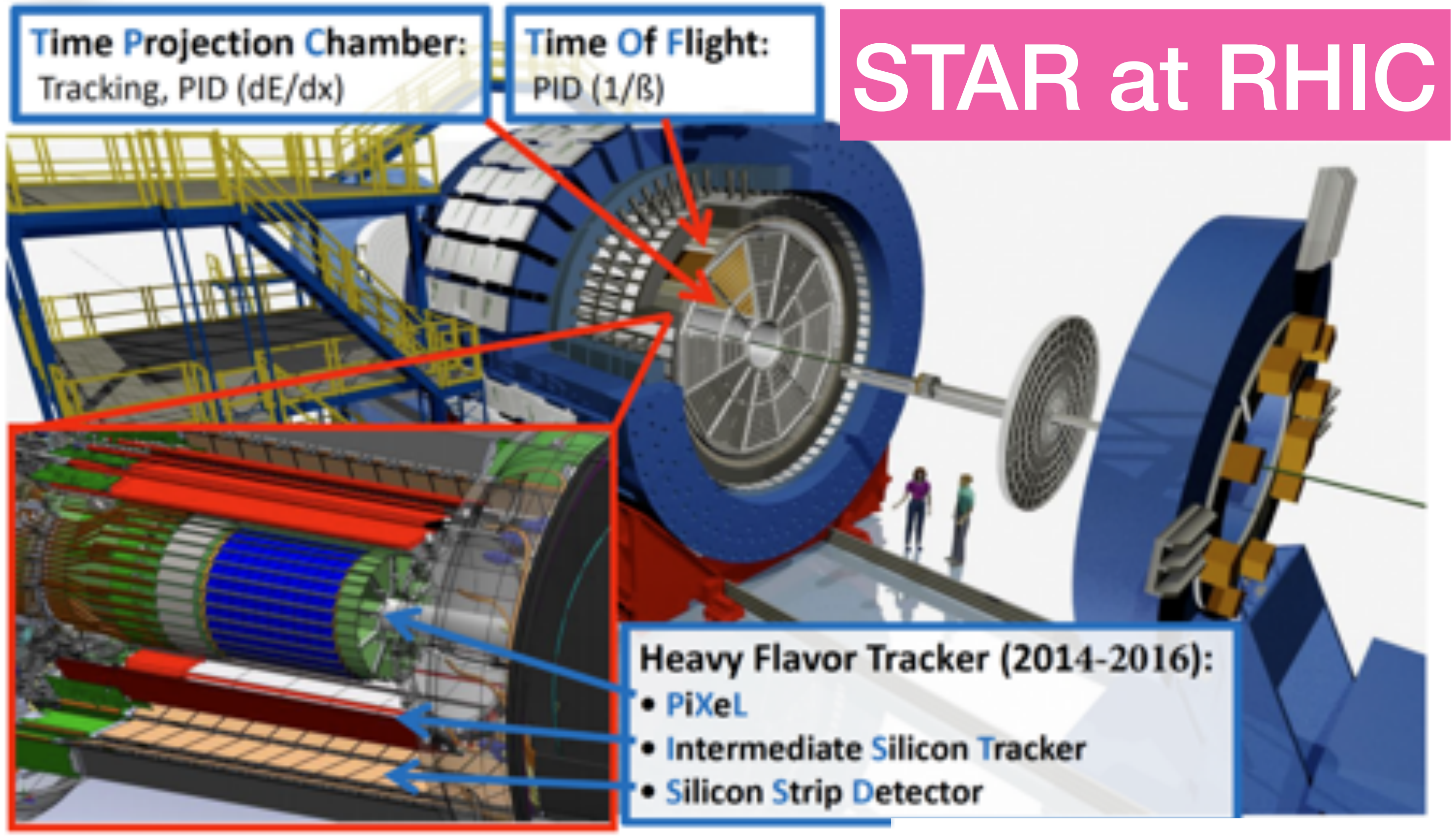


Status and perspectives of hypertriton lifetime determination in ultra-relativistic heavy ion collisions

Stefania Bufalino
Department of Applied Science and Technology
Politecnico of Turin (Italy)



Hypetriton lifetime in heavy ion physics: main players

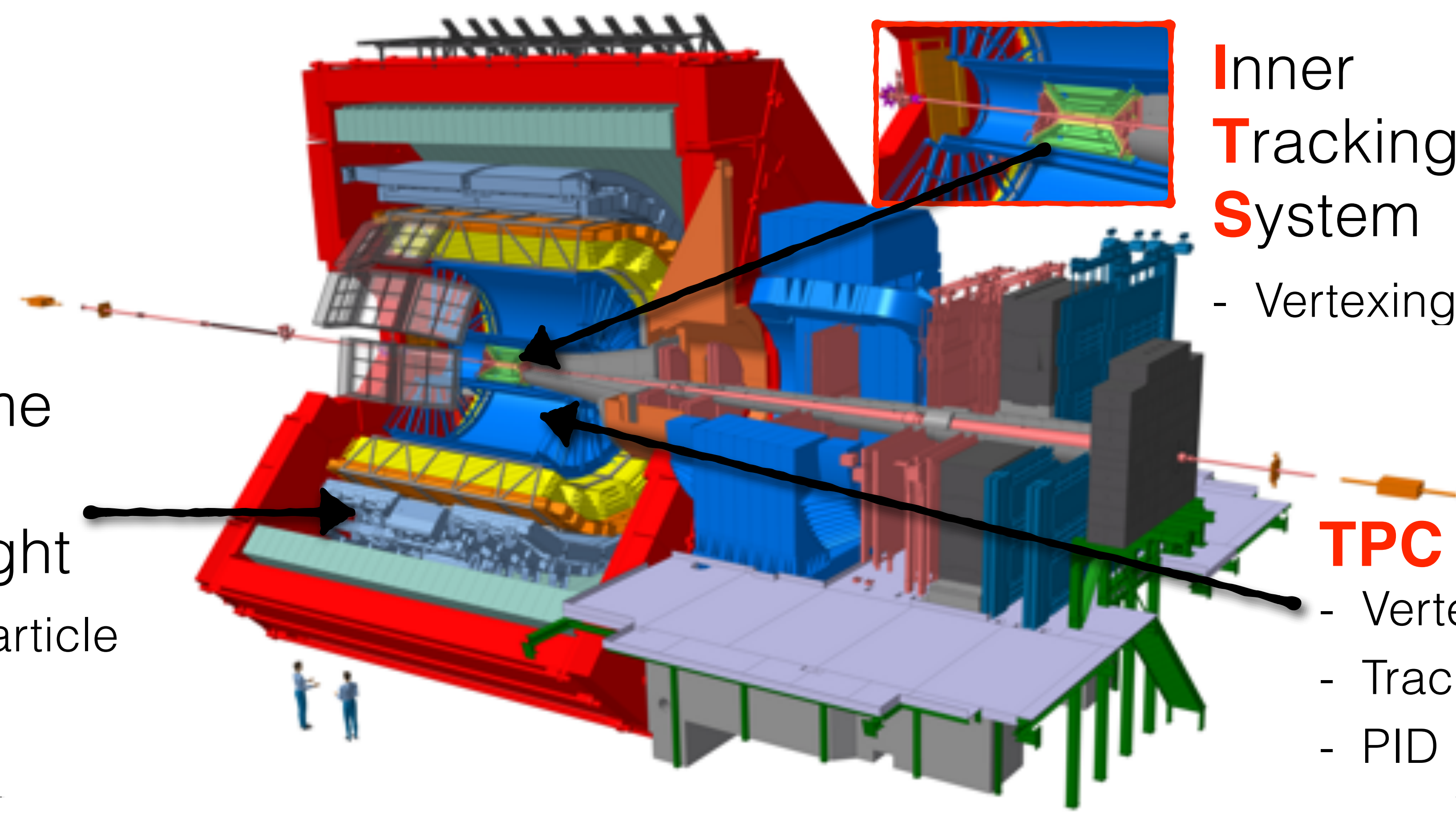


STAR at RHIC

Au-Au collisions (GeV regime)
Results from Beam Energy Scan
Au-Au collisions at energies ranging from 7.7 to 200 GeV

ALICE at the LHC

Pb-Pb collisions (TeV regime)
Results from Pb-Pb collisions at 2.76 and 5.02 TeV



Inner **T**racking **S**ystem
- Vertexing

Time **O**f **F**light
- Particle

TPC
- Vertexing
- Tracking
- PID

Hypertriton in a nutshell

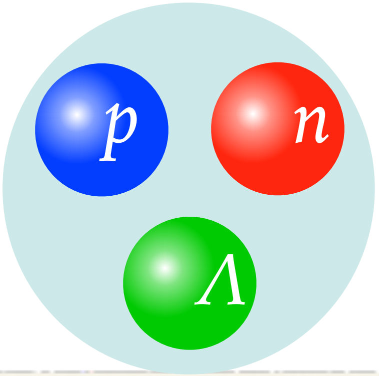
Hypernucleus

a nucleus that contains at least one hyperon in addition to nucleons

First observation in 1952 by Danysz and Pniewski Phil. Mag. 44 (1953) 348

Hypertriton ($^{3}_{\Lambda}H$): bound state of **p**, **n** and **Λ**, is the lightest known hypernucleus

- Mass = 2.99116 ± 0.00005 GeV/c^2 [1]
- Λ binding energy = 0.13 ± 0.05 MeV [1]
- decay channels:
  - ➡ Mesonic (**MWD**)
  - ➡ Non Mesonic (**NMWD**)



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

Mesonic channels

Channels	$^{3}He+\pi^{-}$ $^{3}H+\pi^{0}$	$d+p+\pi^{-}$ $d+n+\pi^{0}$	$n+p+p+\pi^{-}$ $n+n+p+\pi^{0}$
Branching Ratio [2]	37,3%	60,1%	0,94%

Study of the production in the accessible decay channels (charged products only)

- ➡ 2-body (B.R. ≅ 25%)
- ➡ 3-body (B.R. ≅ 41%)

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

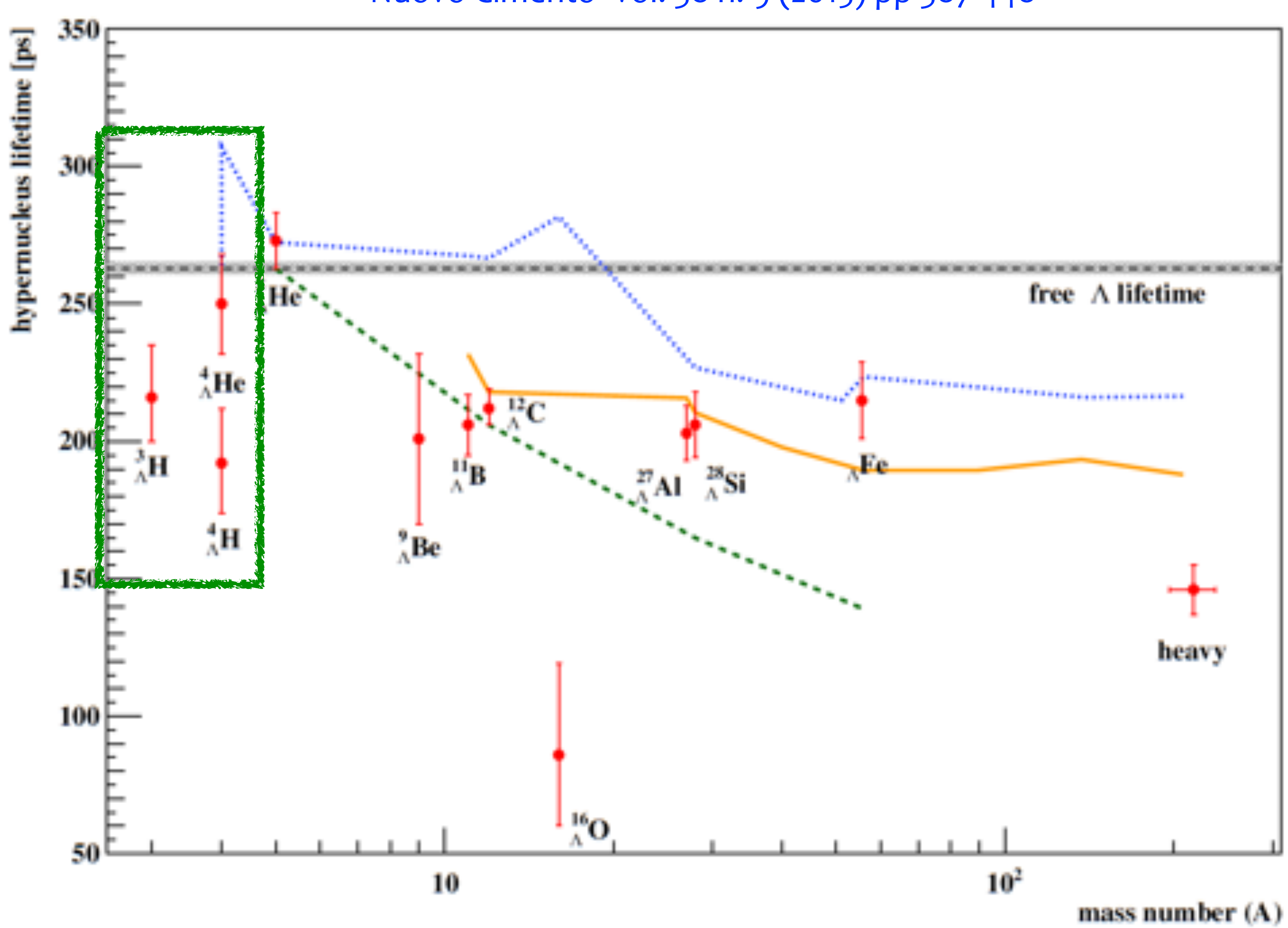
Hypertriton: the *lifetime*

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

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

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

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



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

▪▪▪▪▪

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

▬

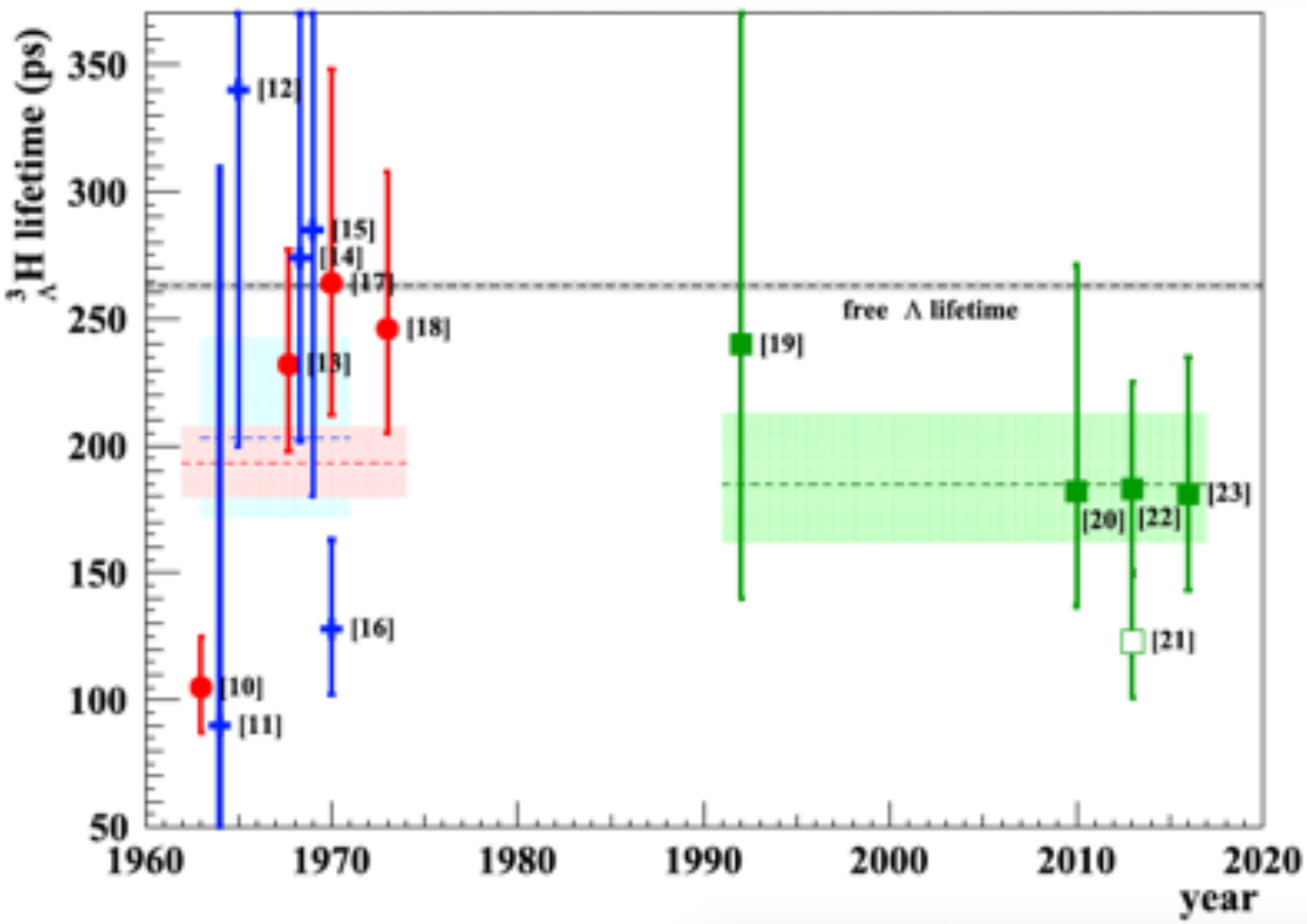
Bauer E. and Garbarino G., Phys. Rev. C, 81 (2010) 064315.
plus correction from
Motoba T. and Itonaga K., Prog. Theor. Phys. Suppl., 117 (1994) 477.
Better description of NN interaction and 2 Nucleon Non Mesonic Weak Decay taken into account

.....

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

Hypertriton: the *lifetime puzzle*

World averages and uncertainties grouping the measurements available by 2016 on the basis of the experimental technique

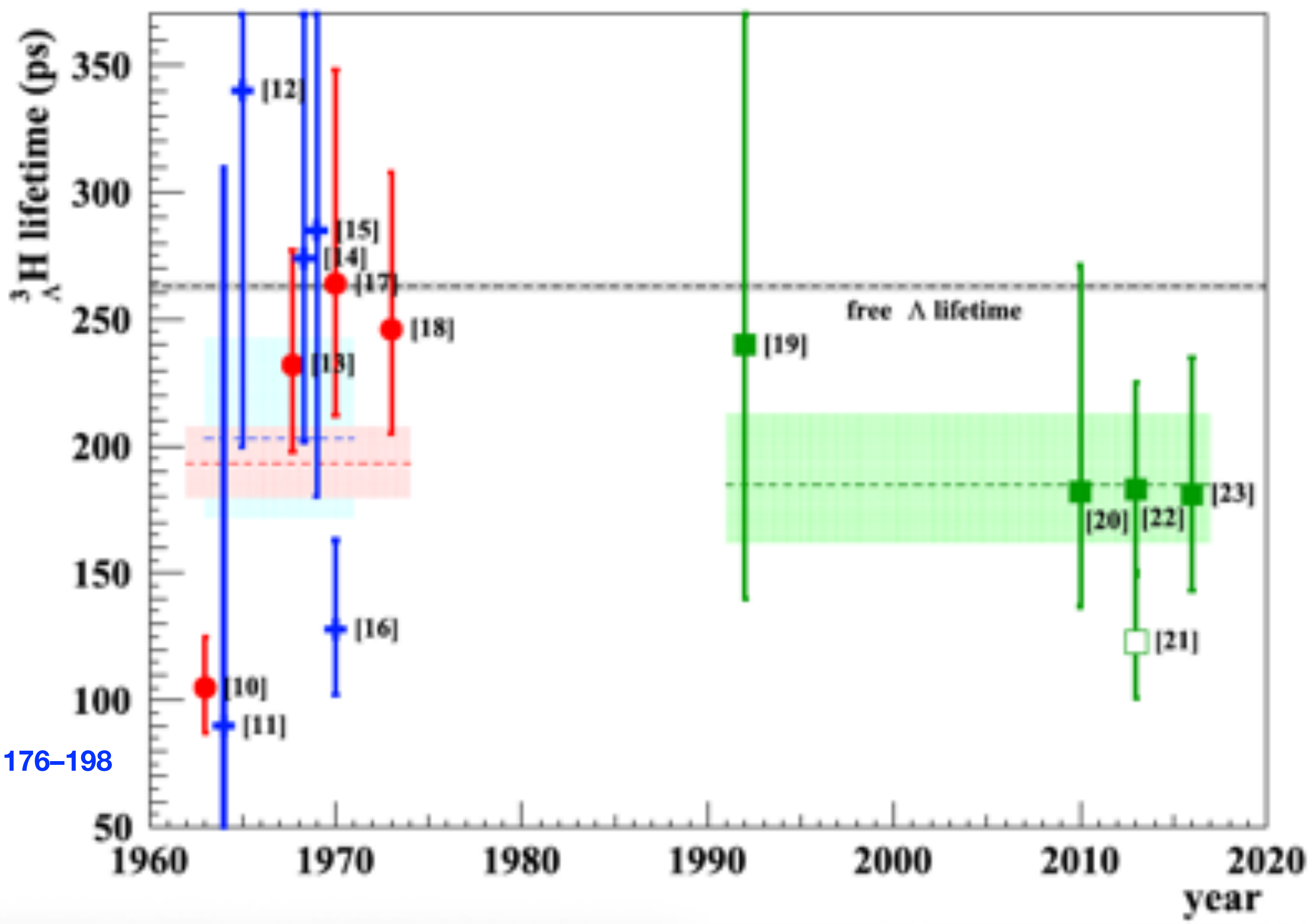


Nuclear Physics A 954 (2016) 176–198

Ultra-relativistic heavy ions reference:
ALICE: ref [23]
STAR: ref [20,21]
For all the references in the plot: see next slide

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*

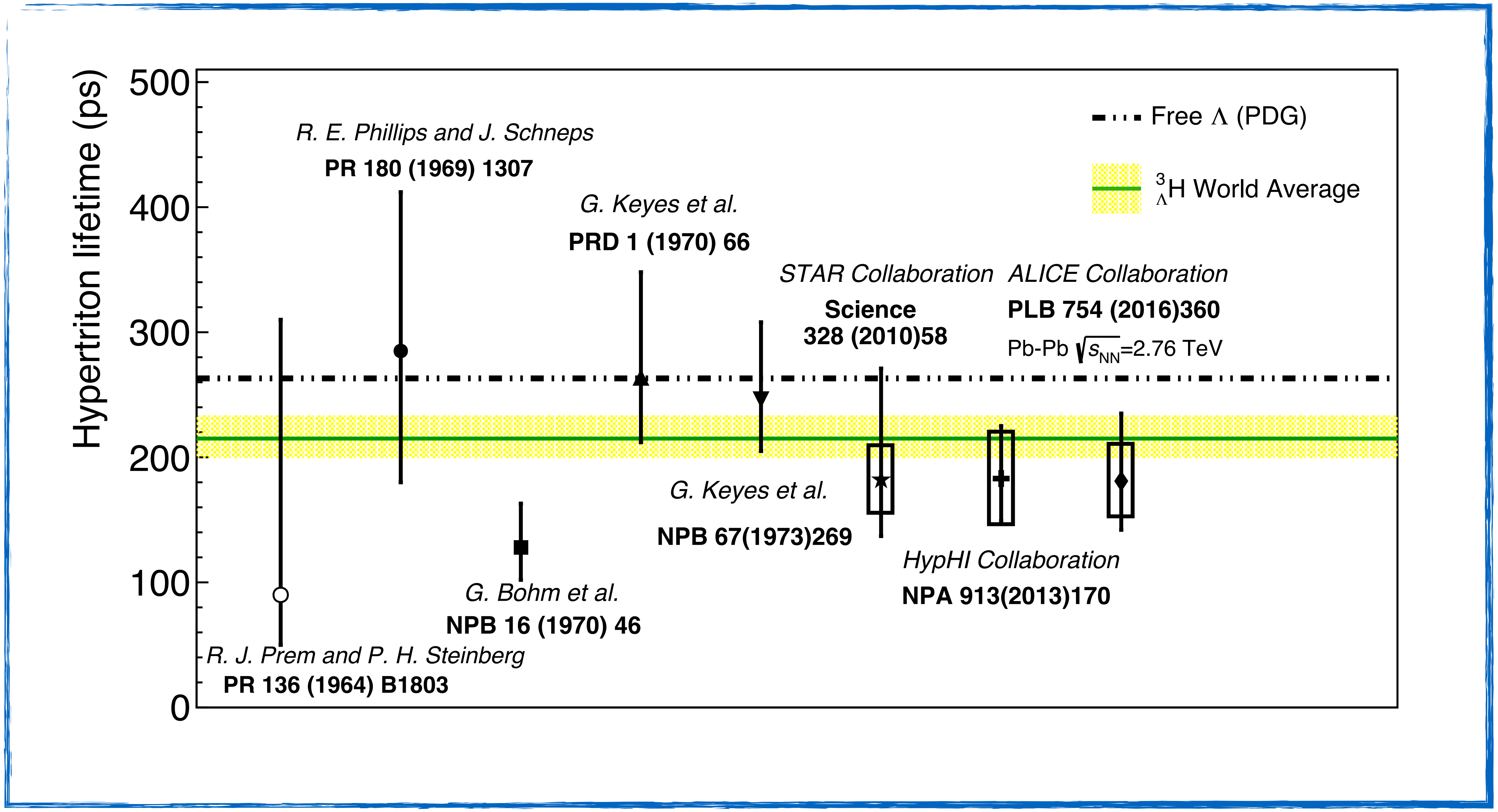


Nuclear Physics A 954 (2016) 176–198

[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.

Hypertriton: the *lifetime puzzle*

Data compilation at the end of LHC Run1



Re-evaluation of world average including ALICE result:

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

ALICE value compatible with the computed average

Hypernuclei in heavy-ion collisions

Hypernuclei in heavy-ion collisions

Thermal Model

Coalescence Model

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

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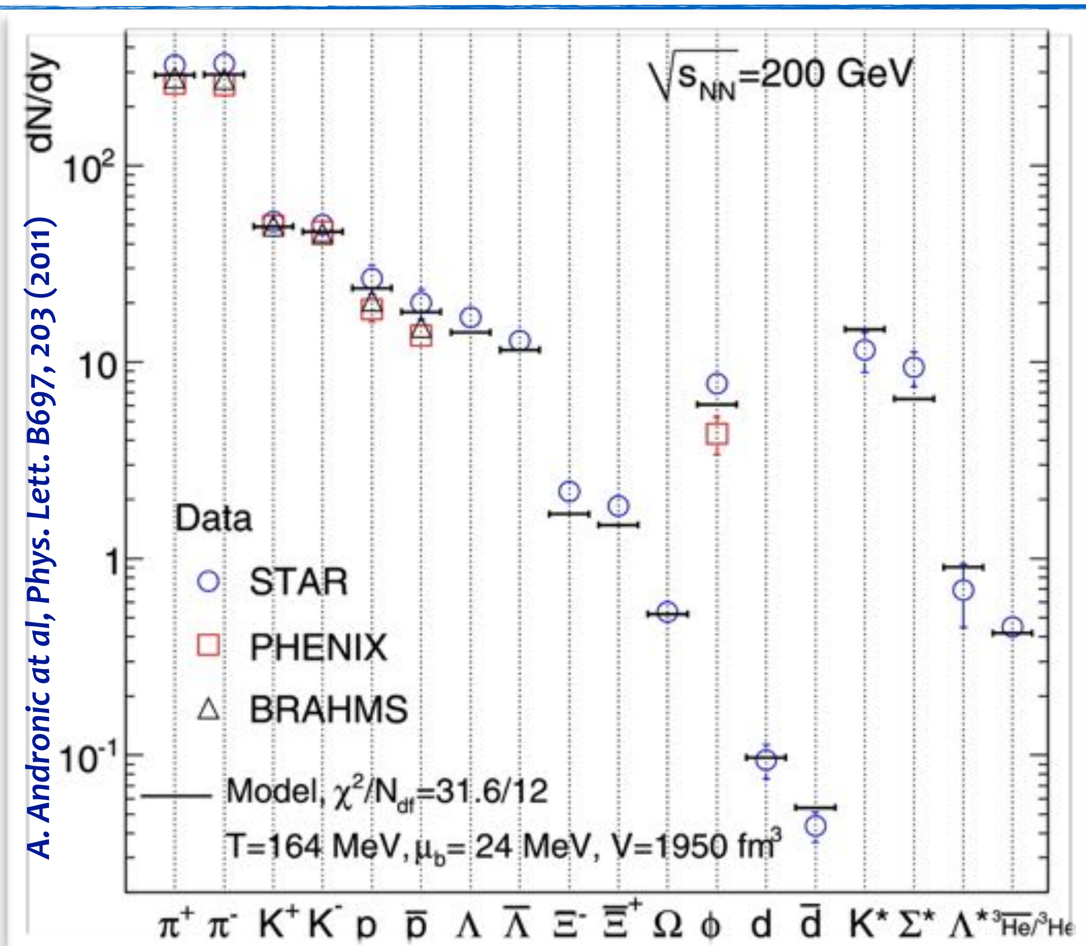

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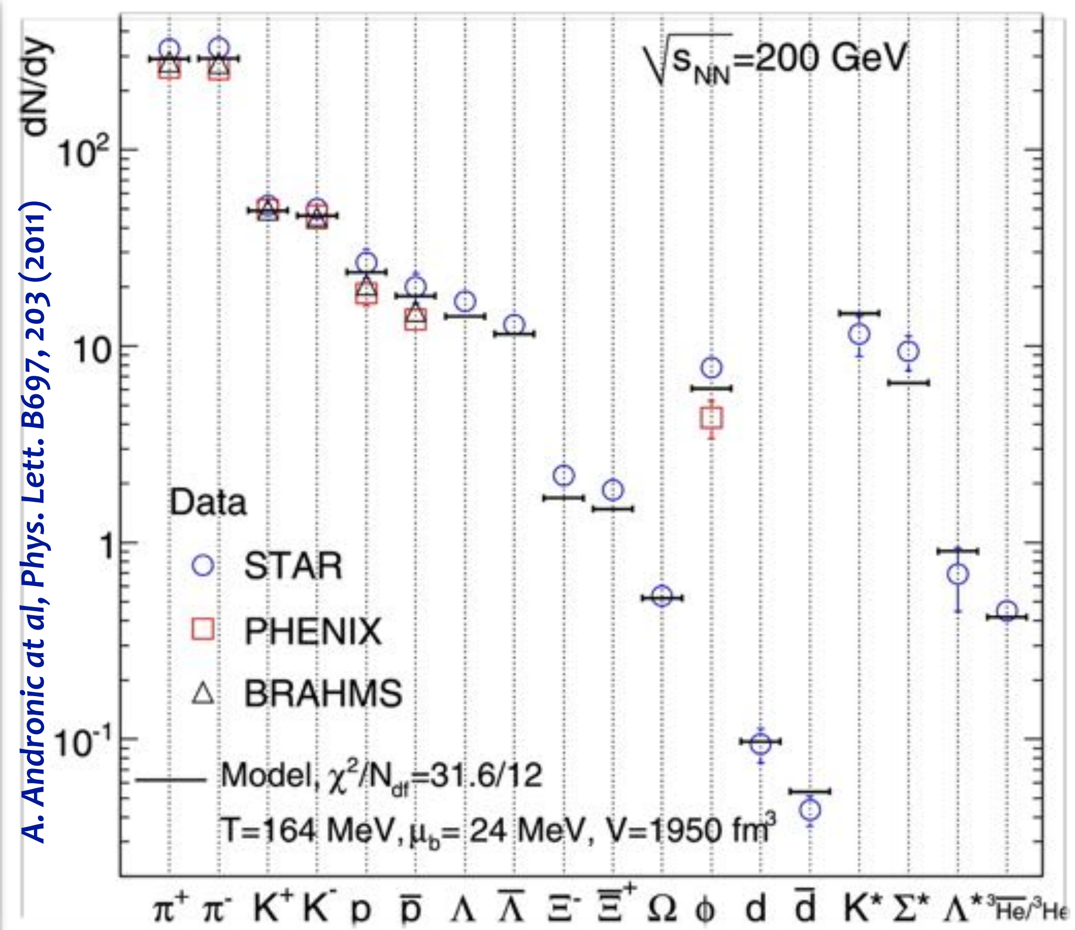

Coalescence Model

- 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

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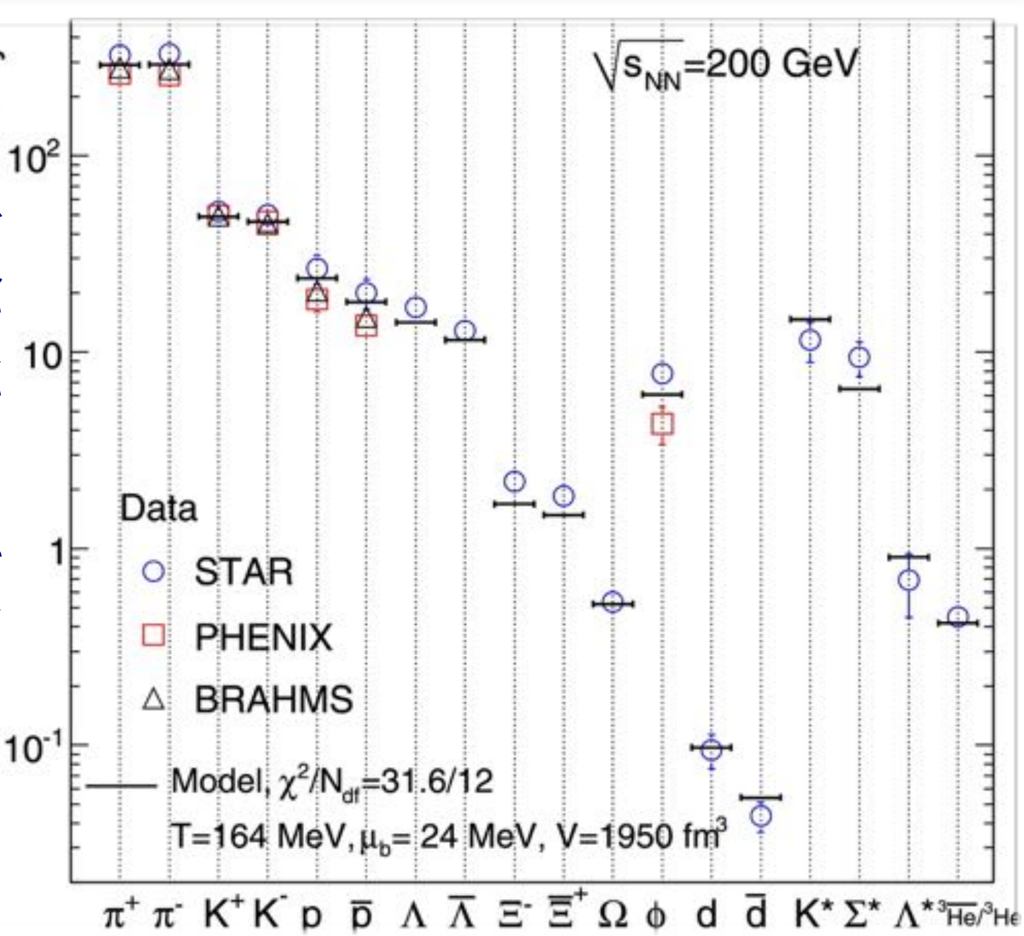

A. Andronic at al, Phys. Lett. B697, 203 (2011)

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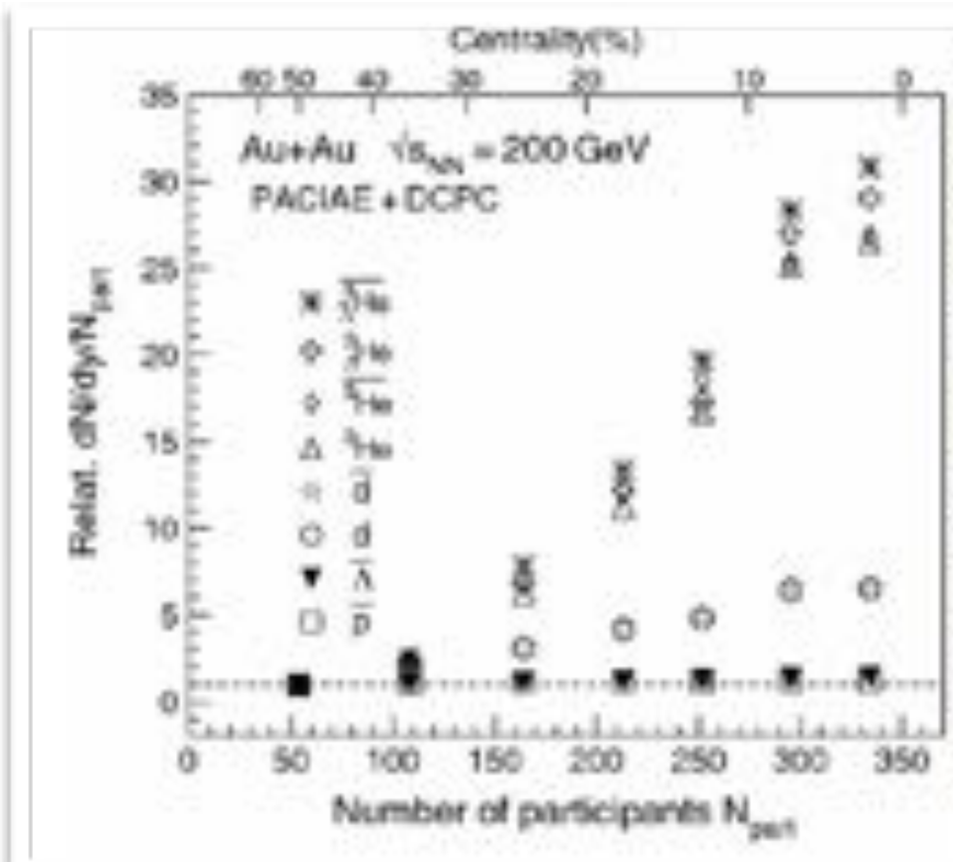
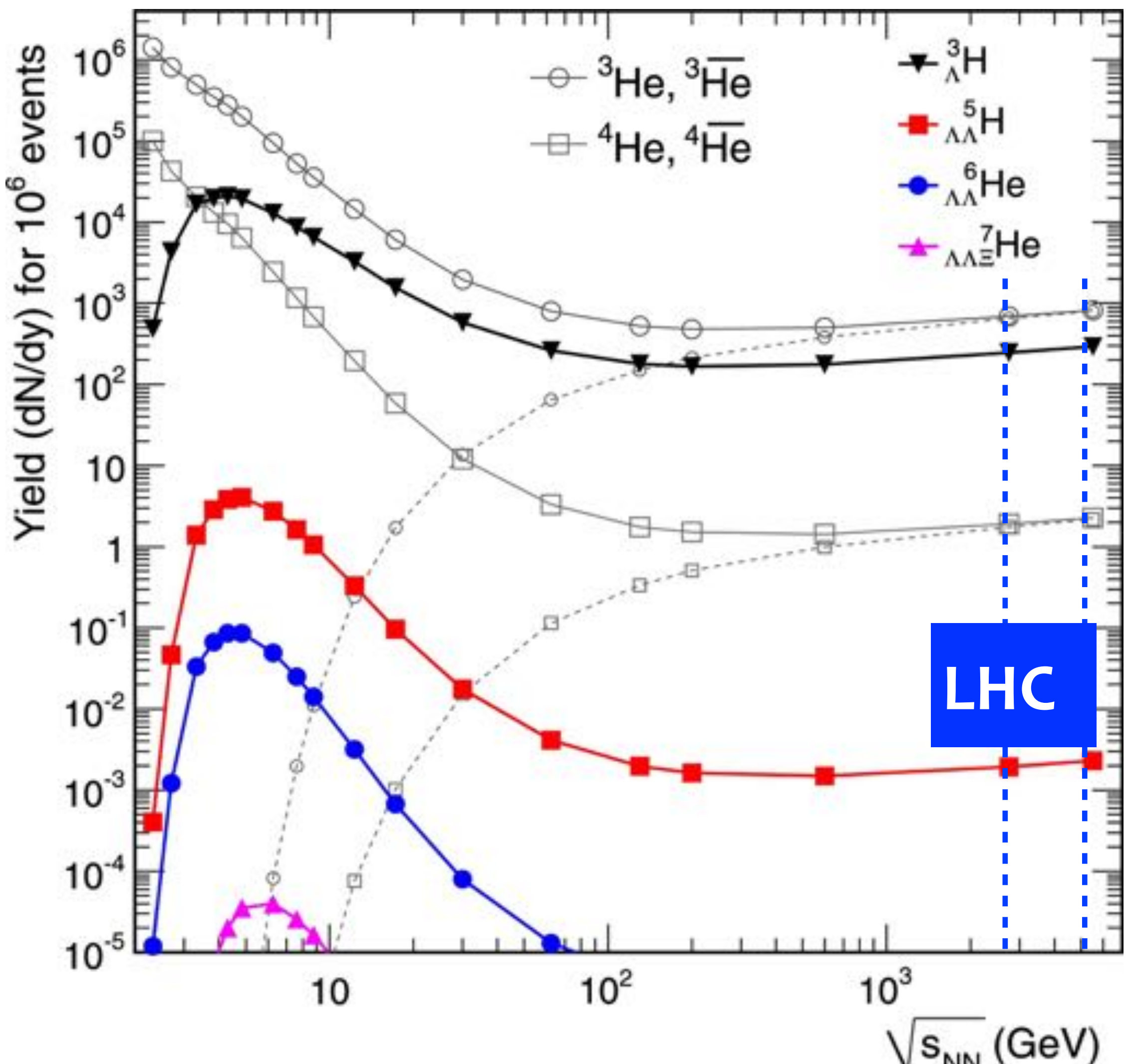


G. Chen et al., Phys. Rev. C 88, 034908 (2013)

Hypernuclei in heavy-ion collisions at the LHC

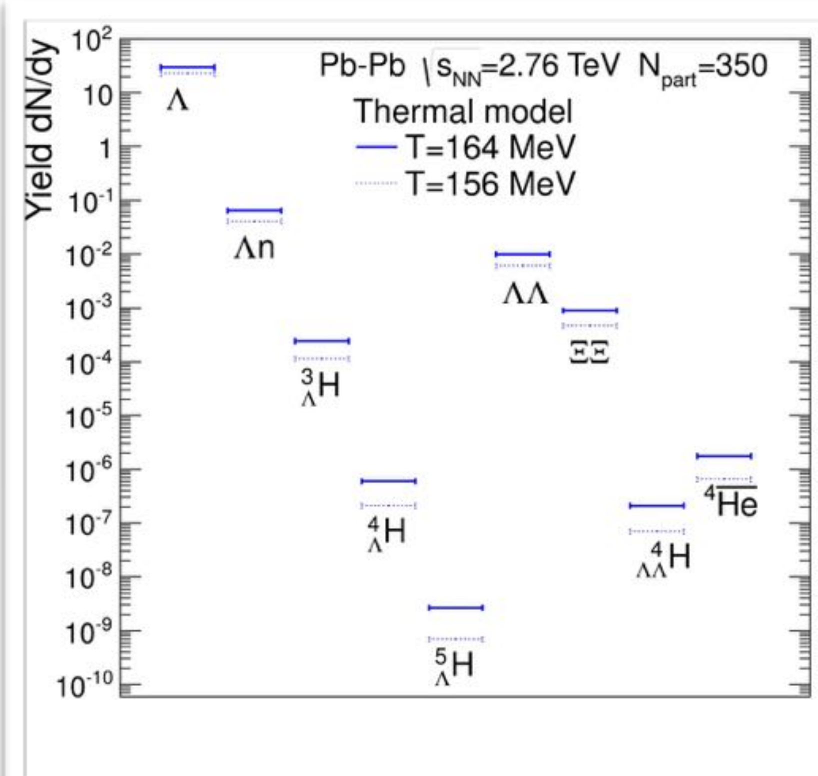


A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stocker.
B. *Phys. Lett. B* 697, 203 (2011)

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
³He	~0.01
$^{3}_{\Lambda}$H	~0.003

A. Andronic, Private communication



- 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

Hypertriton measurement: methodology

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	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)

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Signal extraction:

- Identify daughters (^{3}He,π) or (d,p,π)
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  - Reduce combinatorial background
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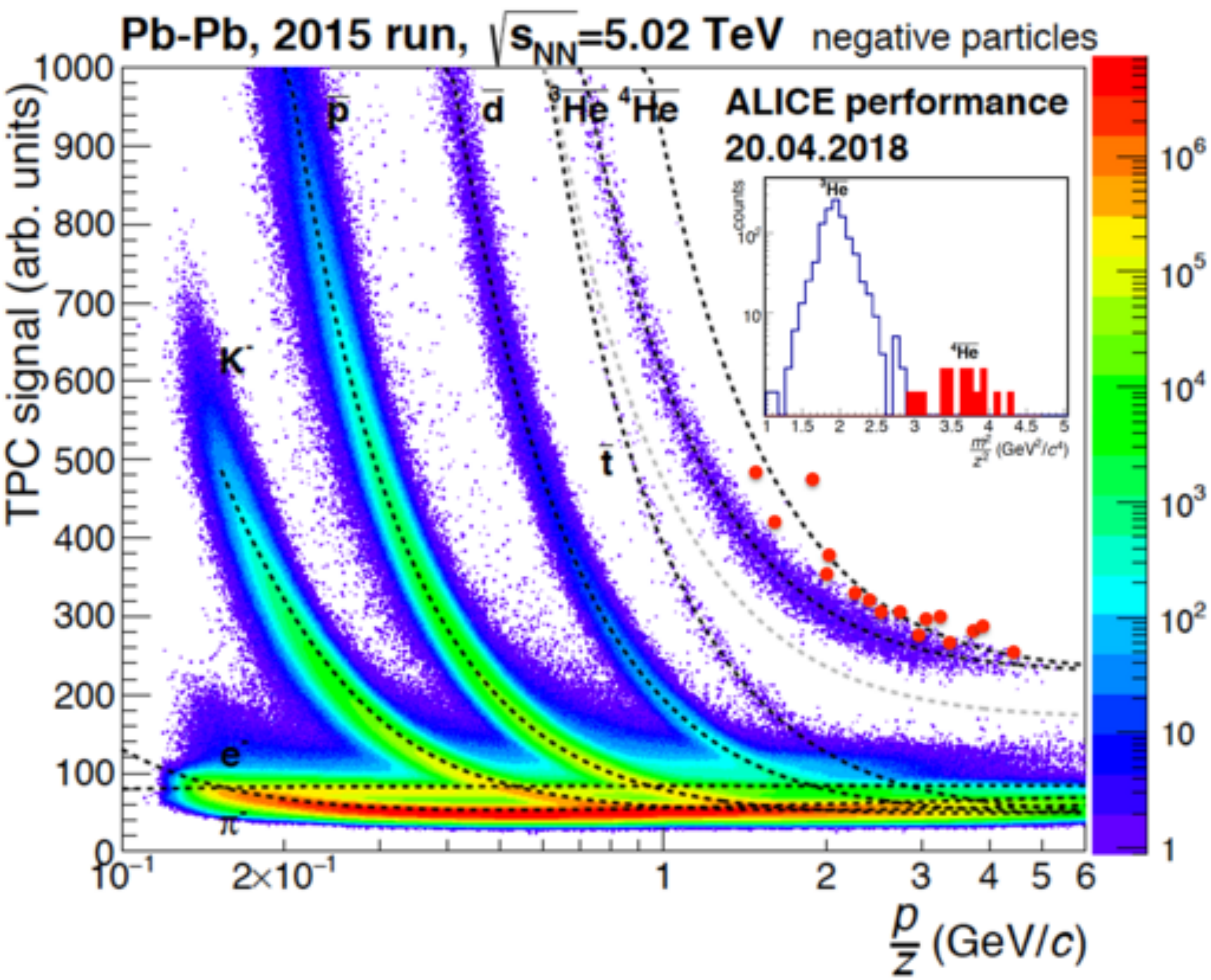
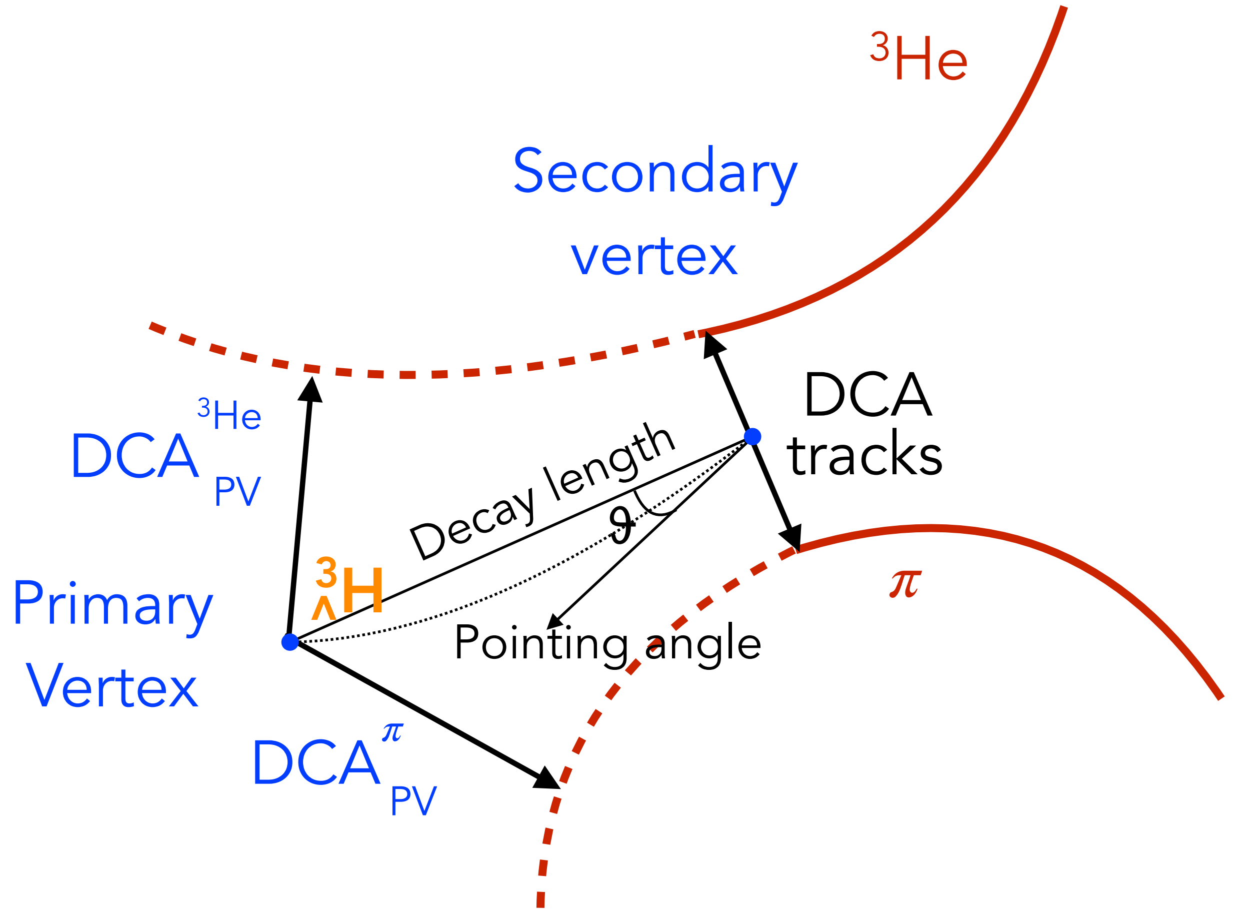
Hypertriton measurement with ALICE: methodology



Particle identification: crucial to identify the daughters in the decay

Track selection and topology cut to reduce the huge background many pions produced in each collision



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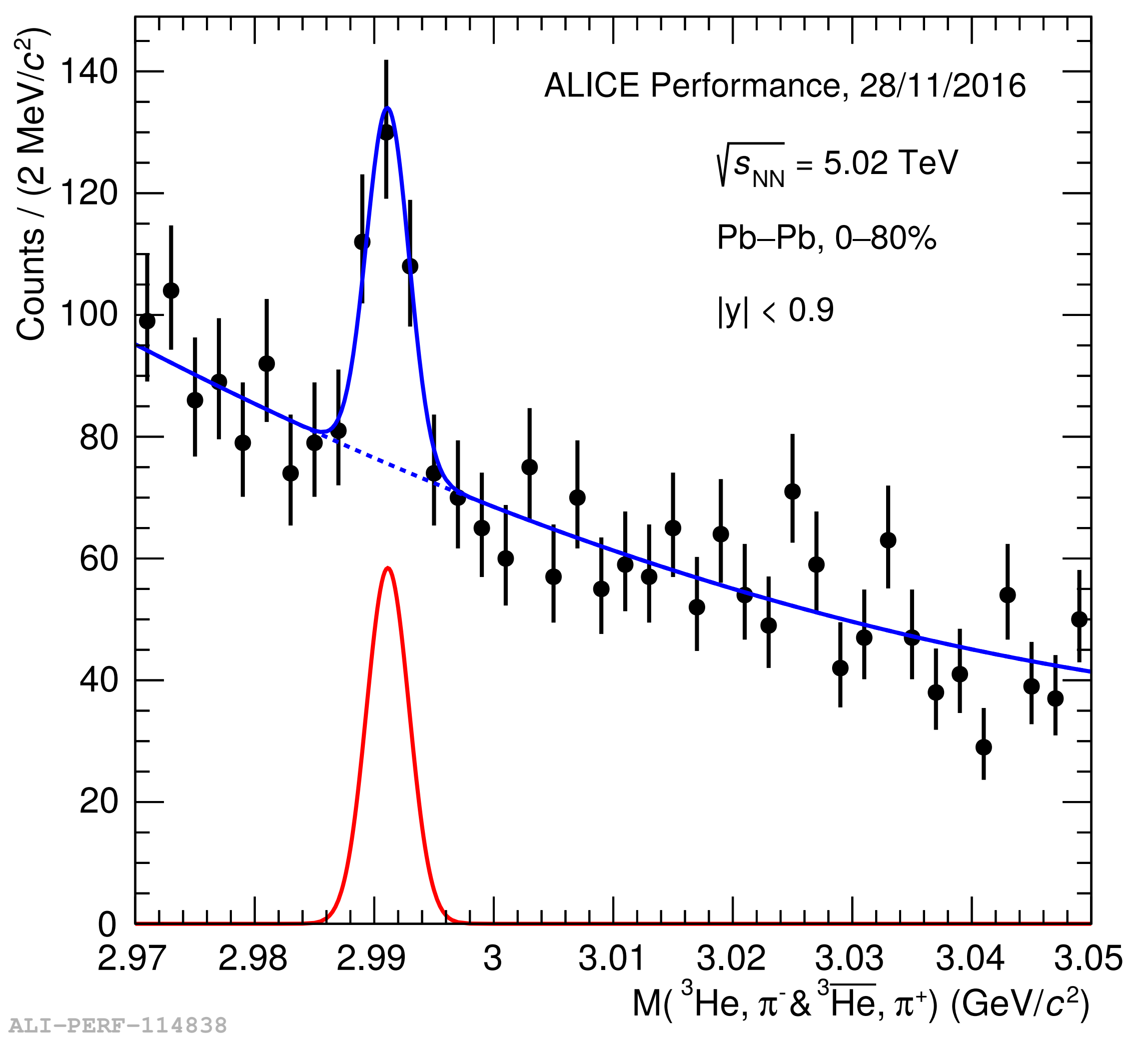

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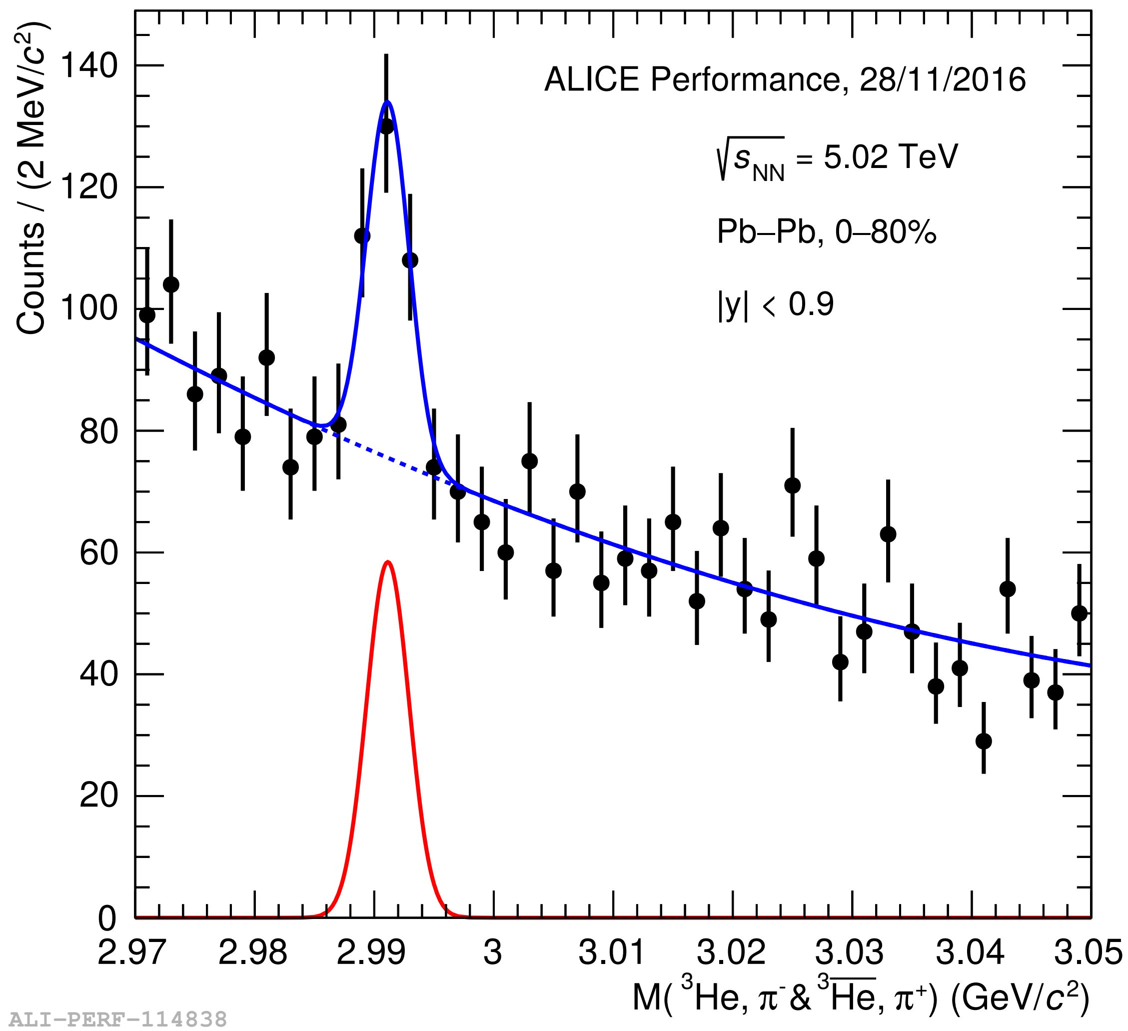

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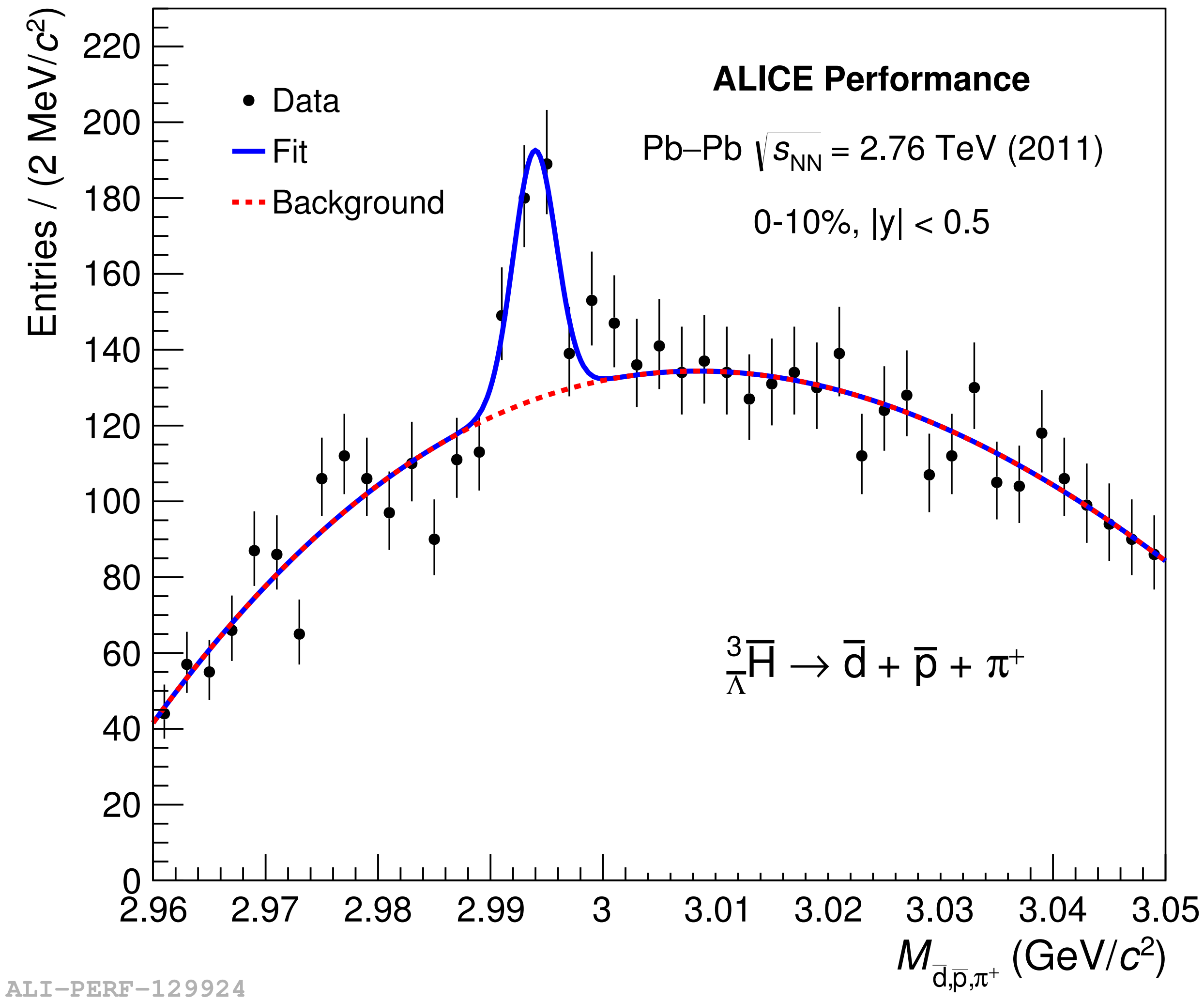

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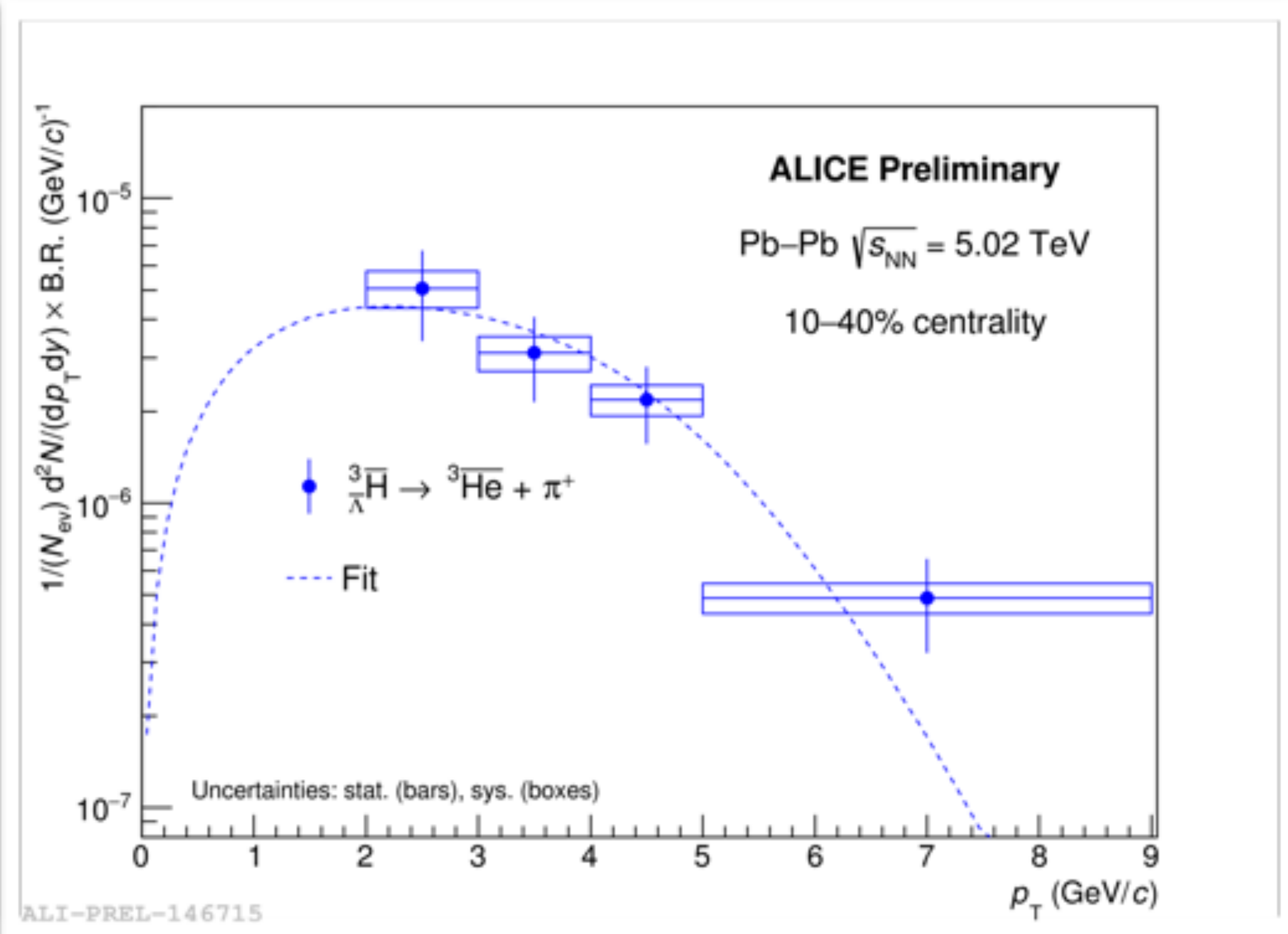
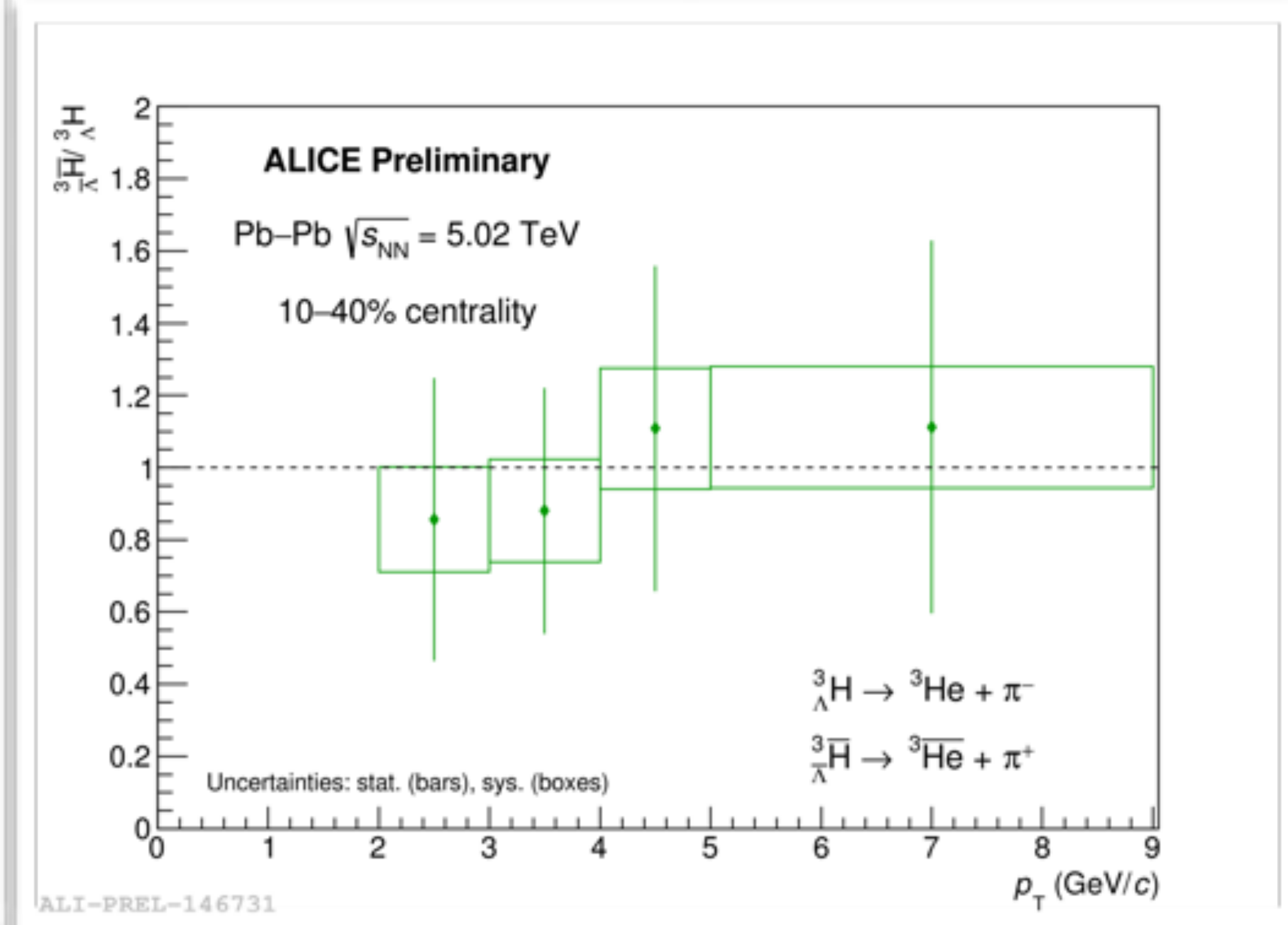
Hypertriton *production* with ALICE

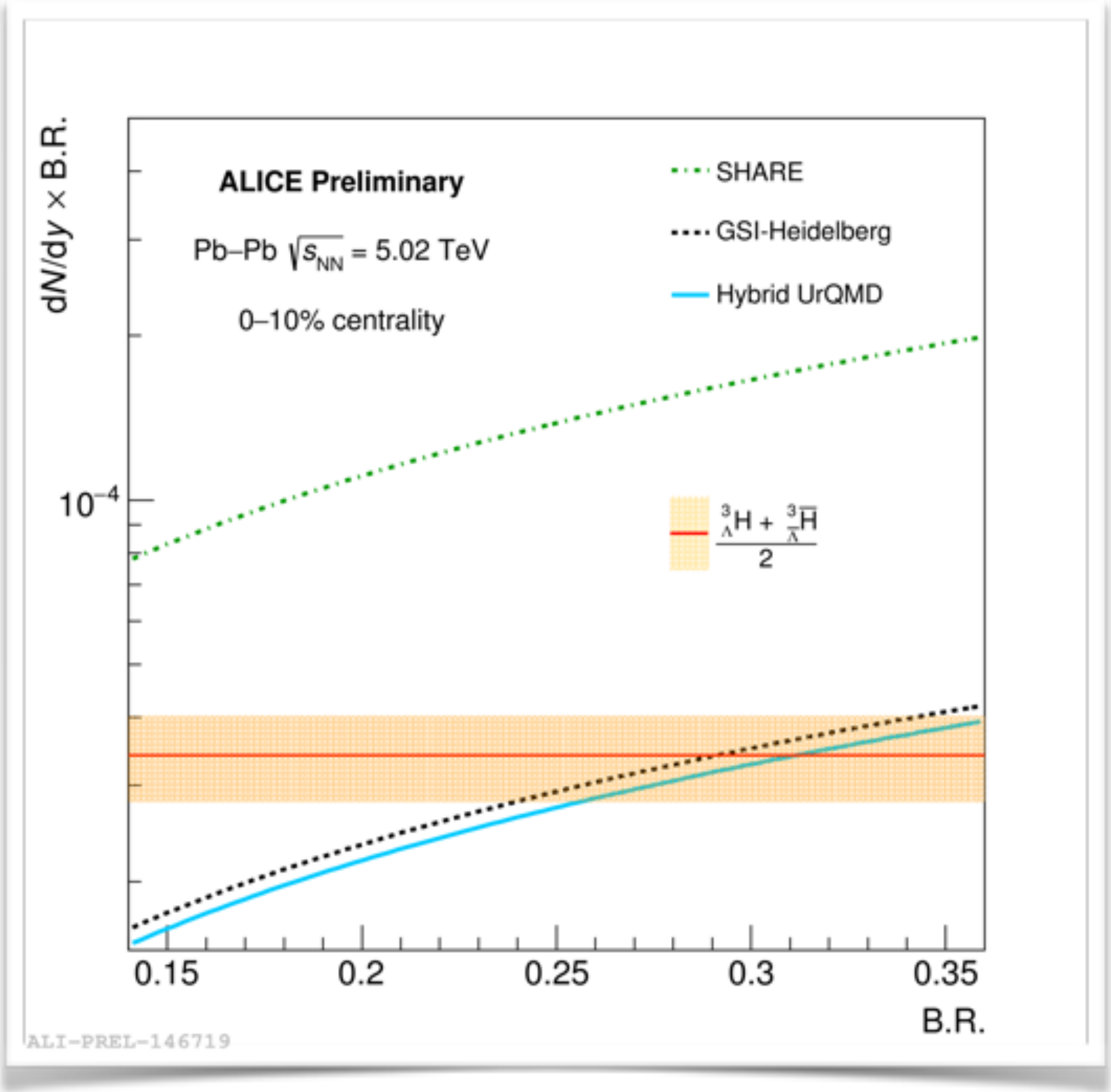




- **Measurement performed** in semi-central collisions (10-40%) for the first time at 5.02 TeV
- The measurement at 2.76 TeV was performed in 3 p_T bins and 2 centrality classes (0-10% and 10-50%)
- **Blast-Wave**[4] **distribution** used to extrapolate the yield in the unmeasured p_T region

[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

Hypertriton *lifetime with ALICE in Pb-Pb at 5 TeV*

New!
arXiv:1907.06906
Physics Letters B
797 (2019) 134905

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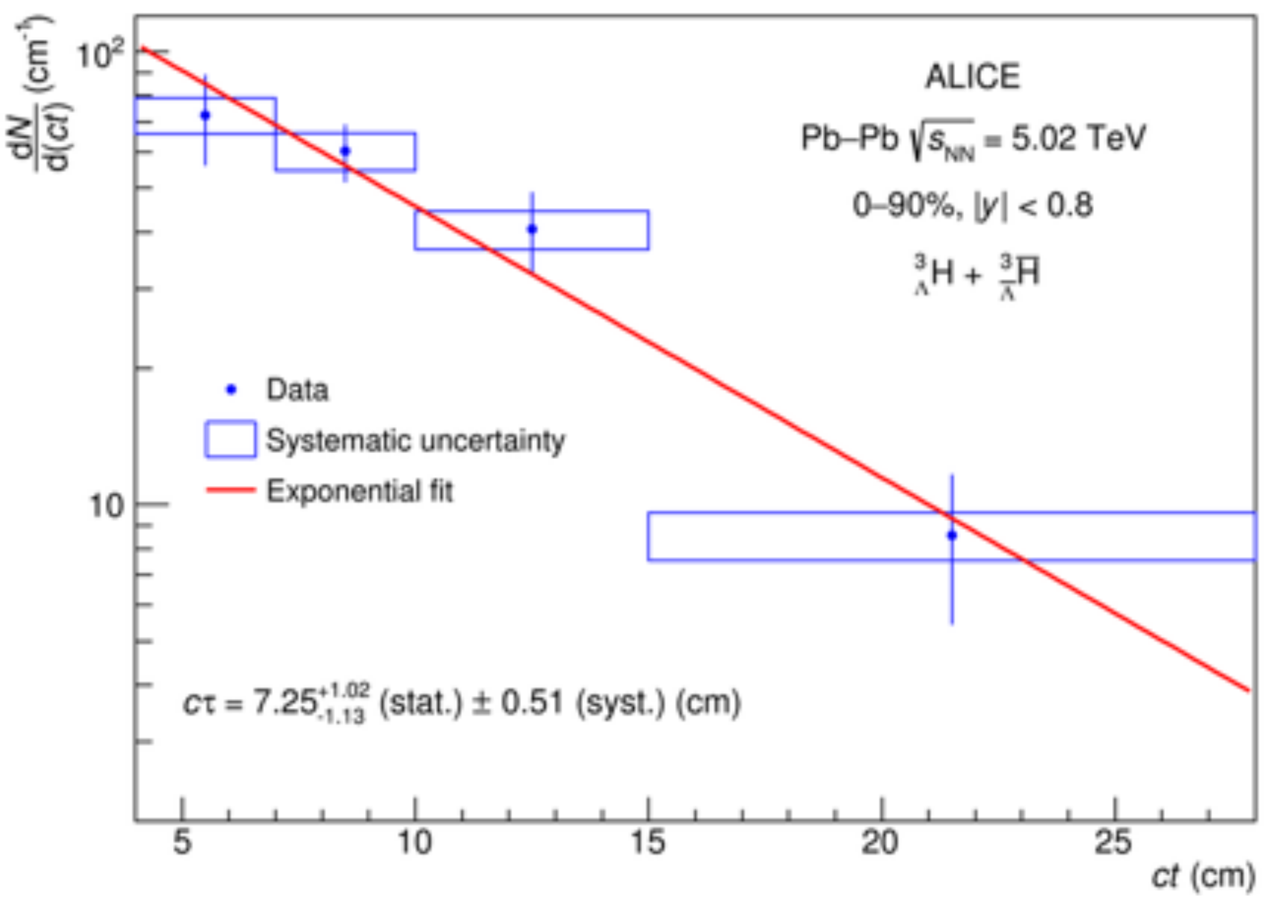

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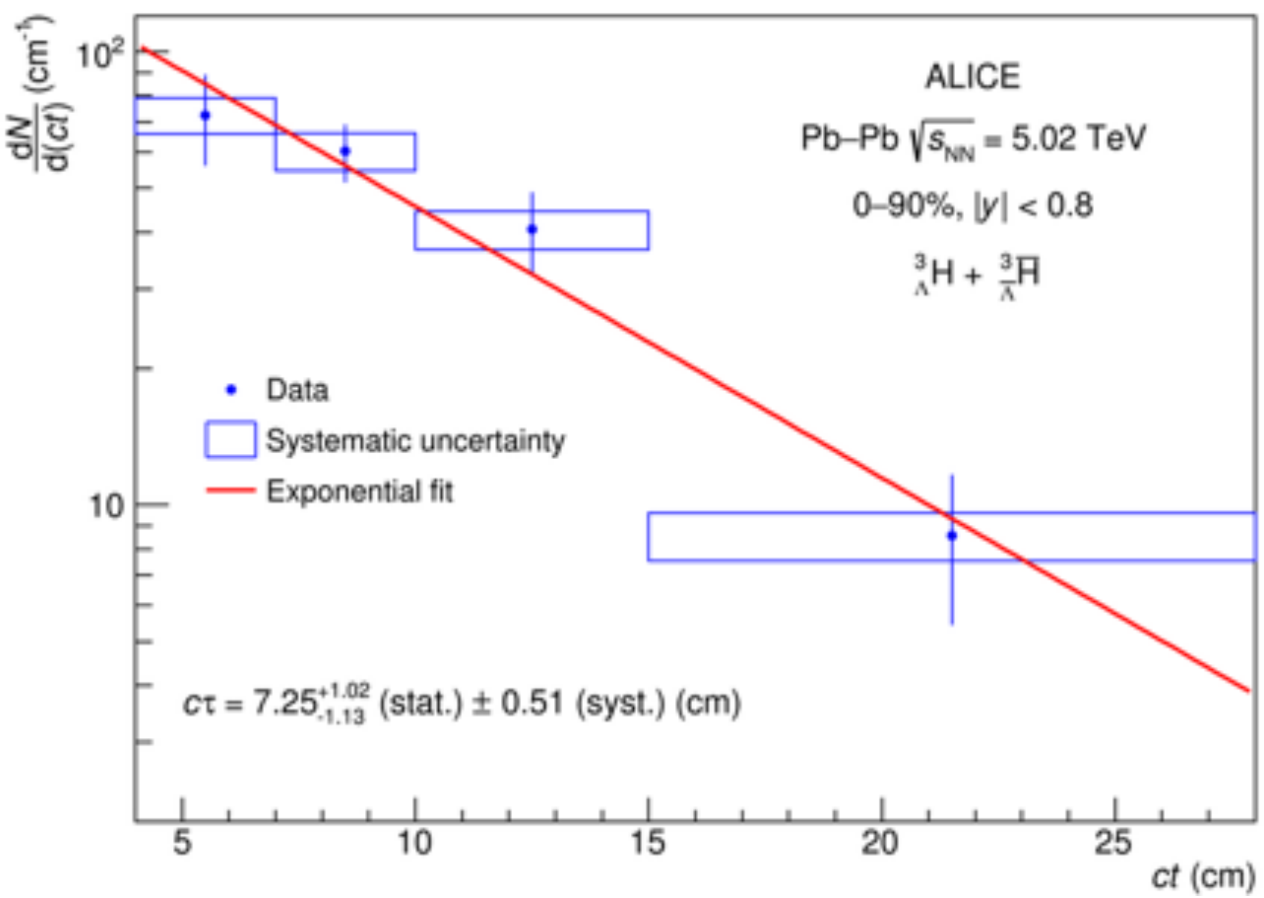

*c*t spectra (*default*)

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

$$\tau = 242^{+34}_{-38}\ (\text{stat.}) \pm 17\ (\text{syst.})\ \text{ps}$$

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New!
arXiv:1907.06906
Physics Letters B
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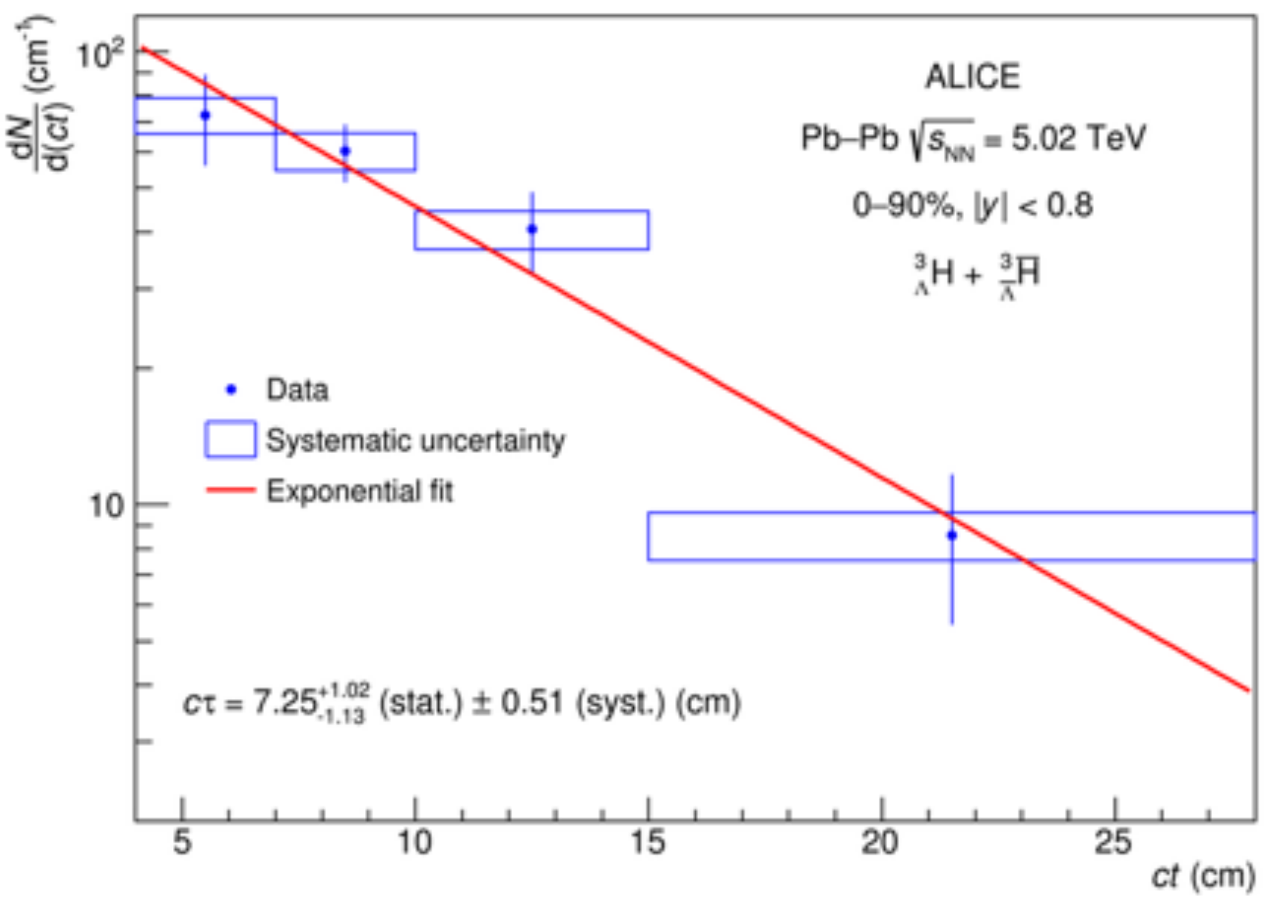

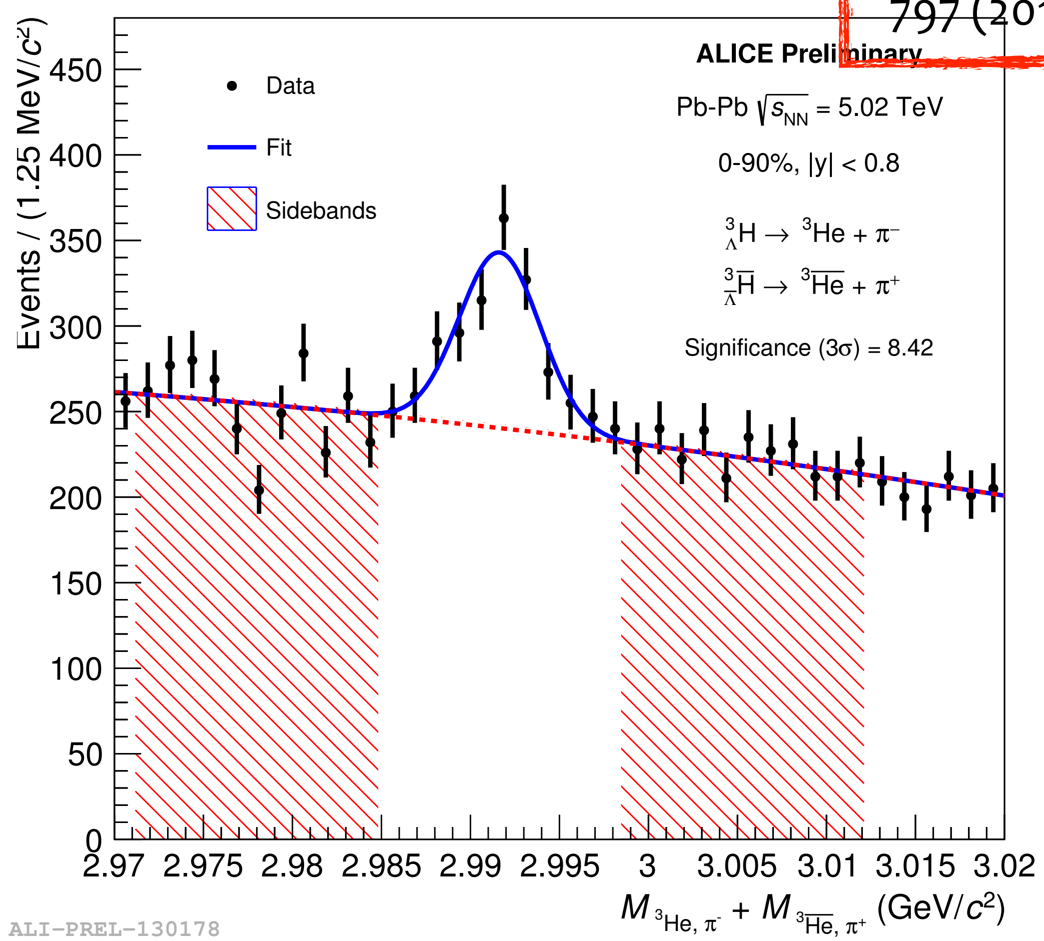

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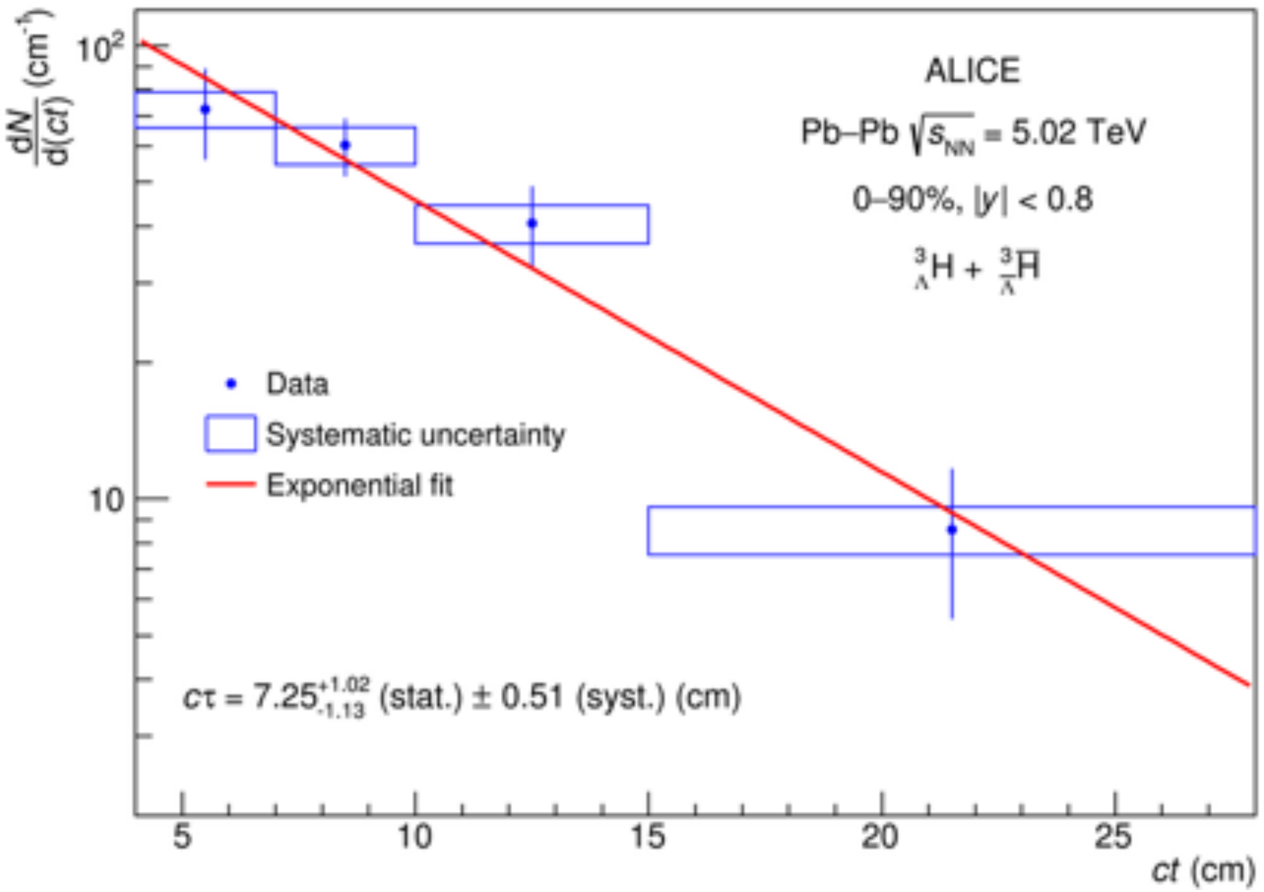
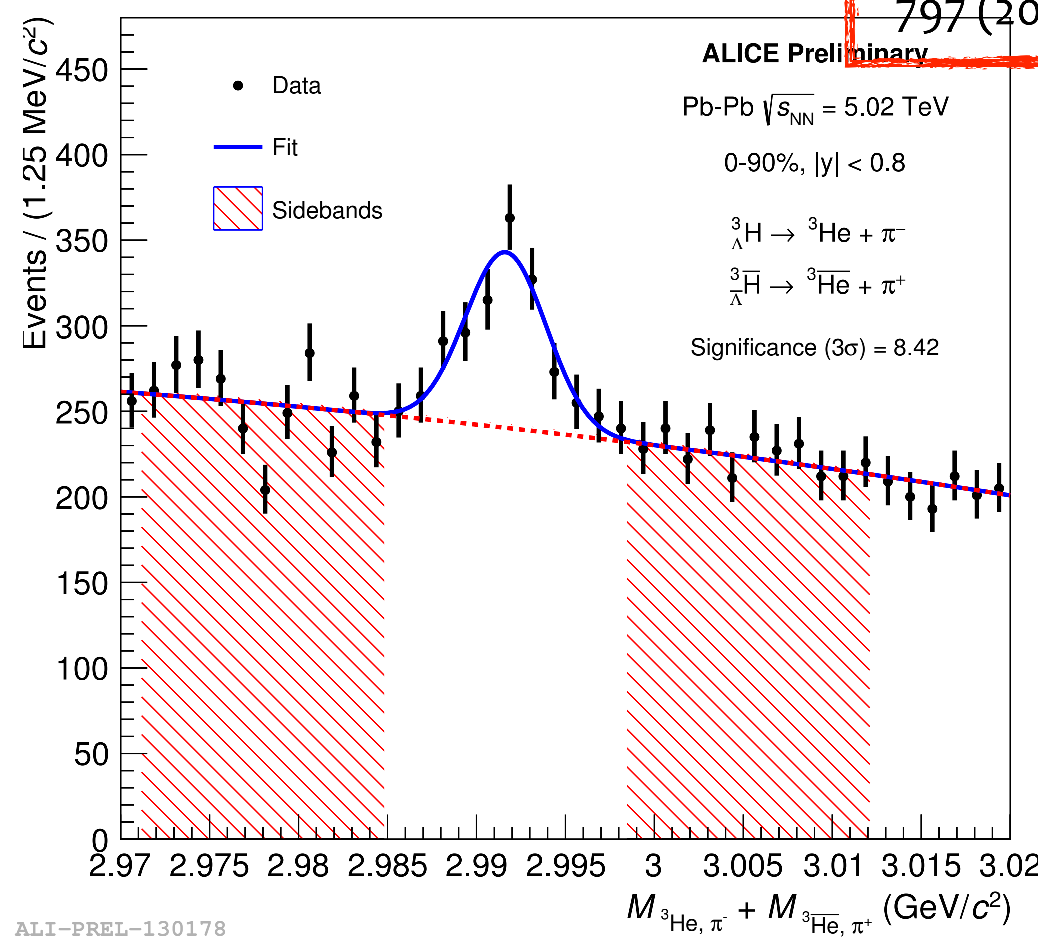
$$\tau = 242^{+34}_{-38}\ \text{(stat.)} \pm 17\ \text{(syst.) ps}$$

Hypertriton *lifetime with ALICE in Pb-Pb at 5 TeV*

New!
arXiv:1907.06906
Physics Letters B
797 (2019) 134905





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Unbinned fit

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

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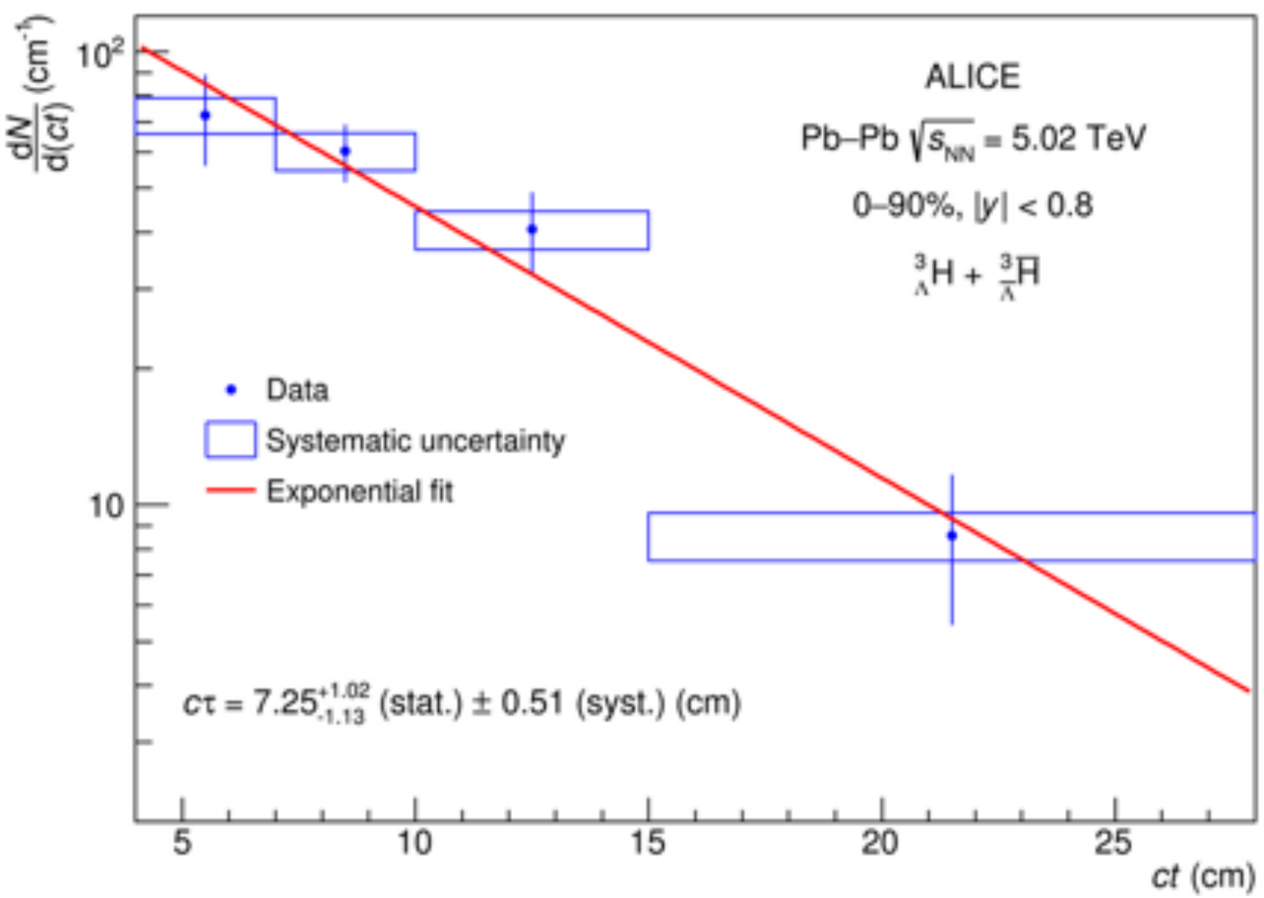

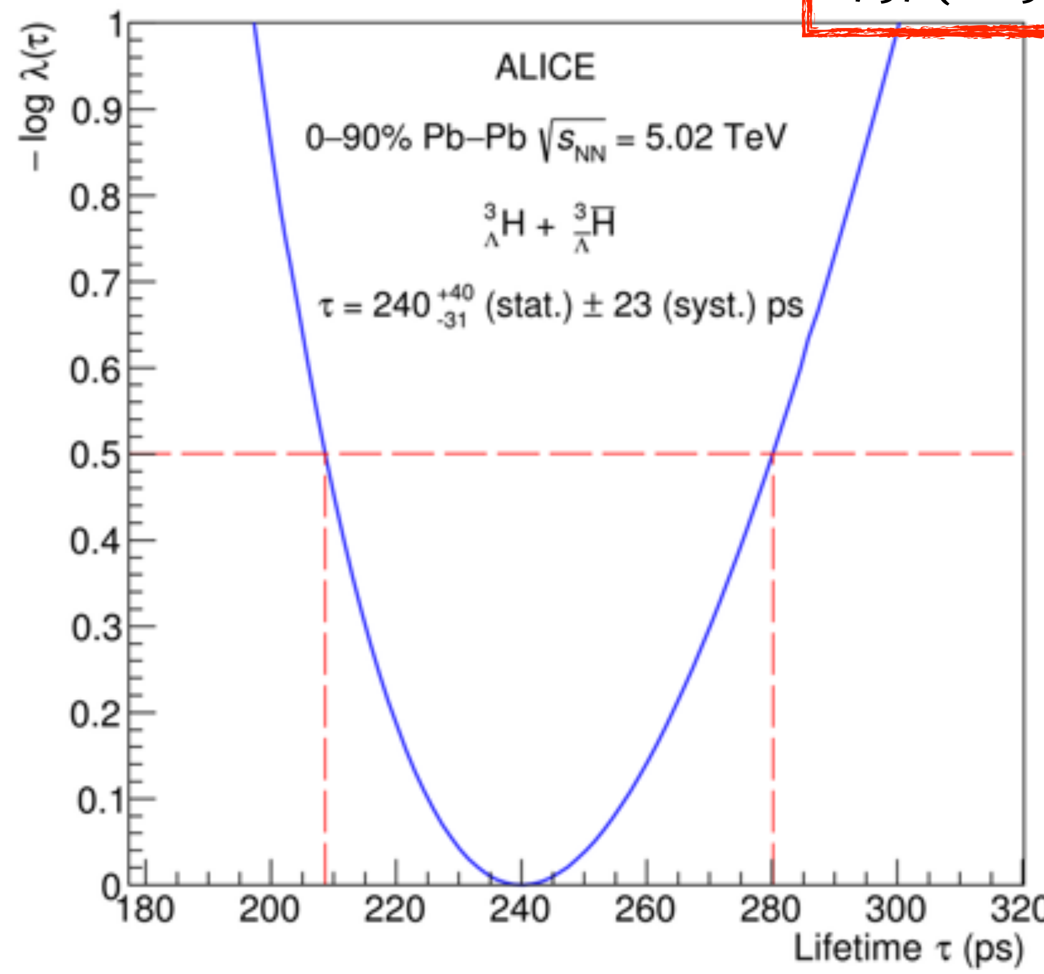

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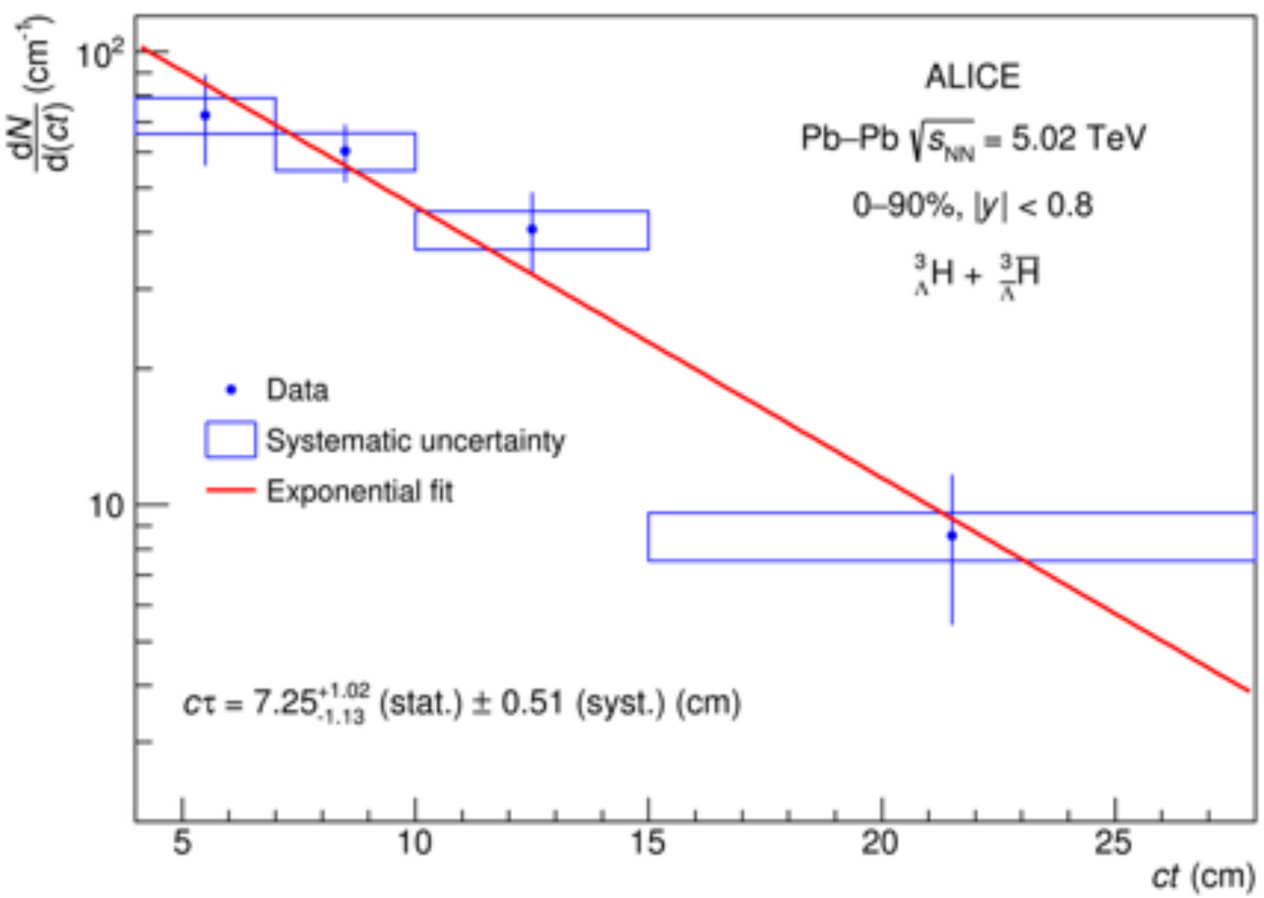
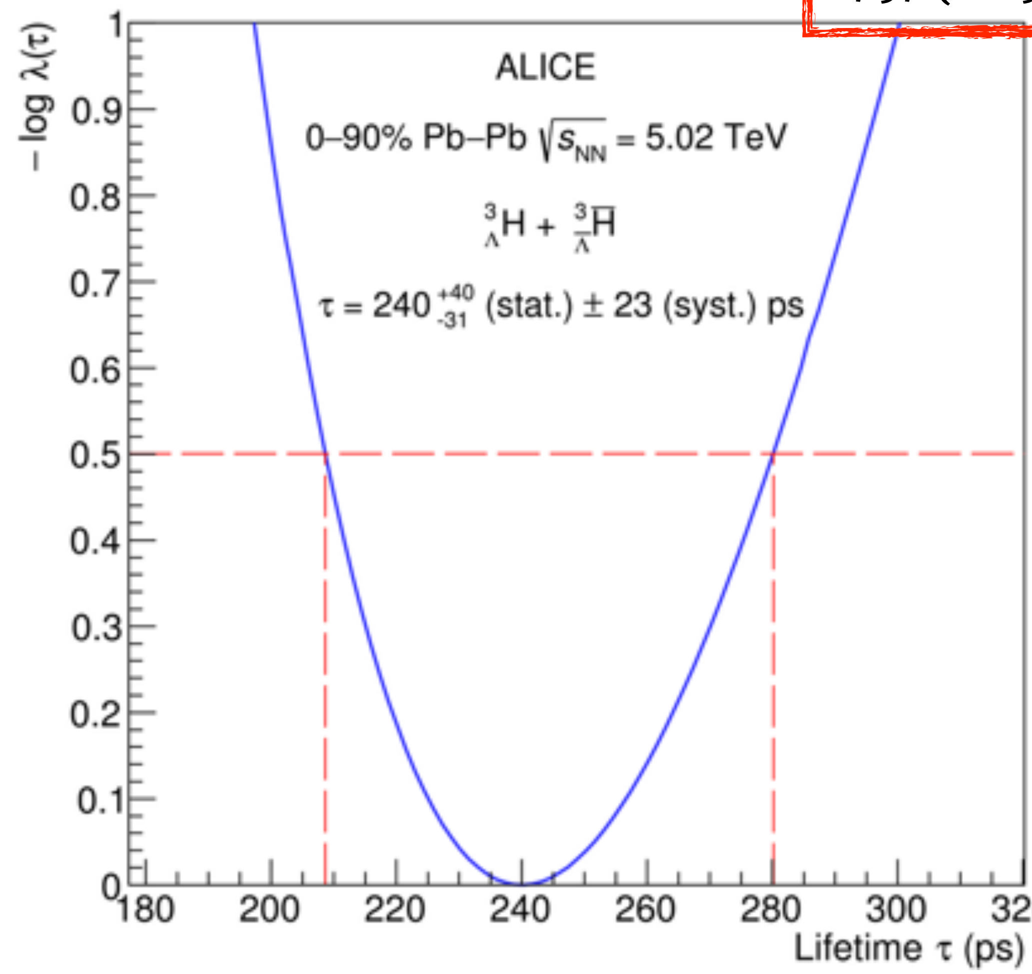




ct spectra (*default*)

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

$$\tau = 242^{+34}_{-38}\ (\text{stat.}) \pm 17\ (\text{syst.})\ \text{ps}$$

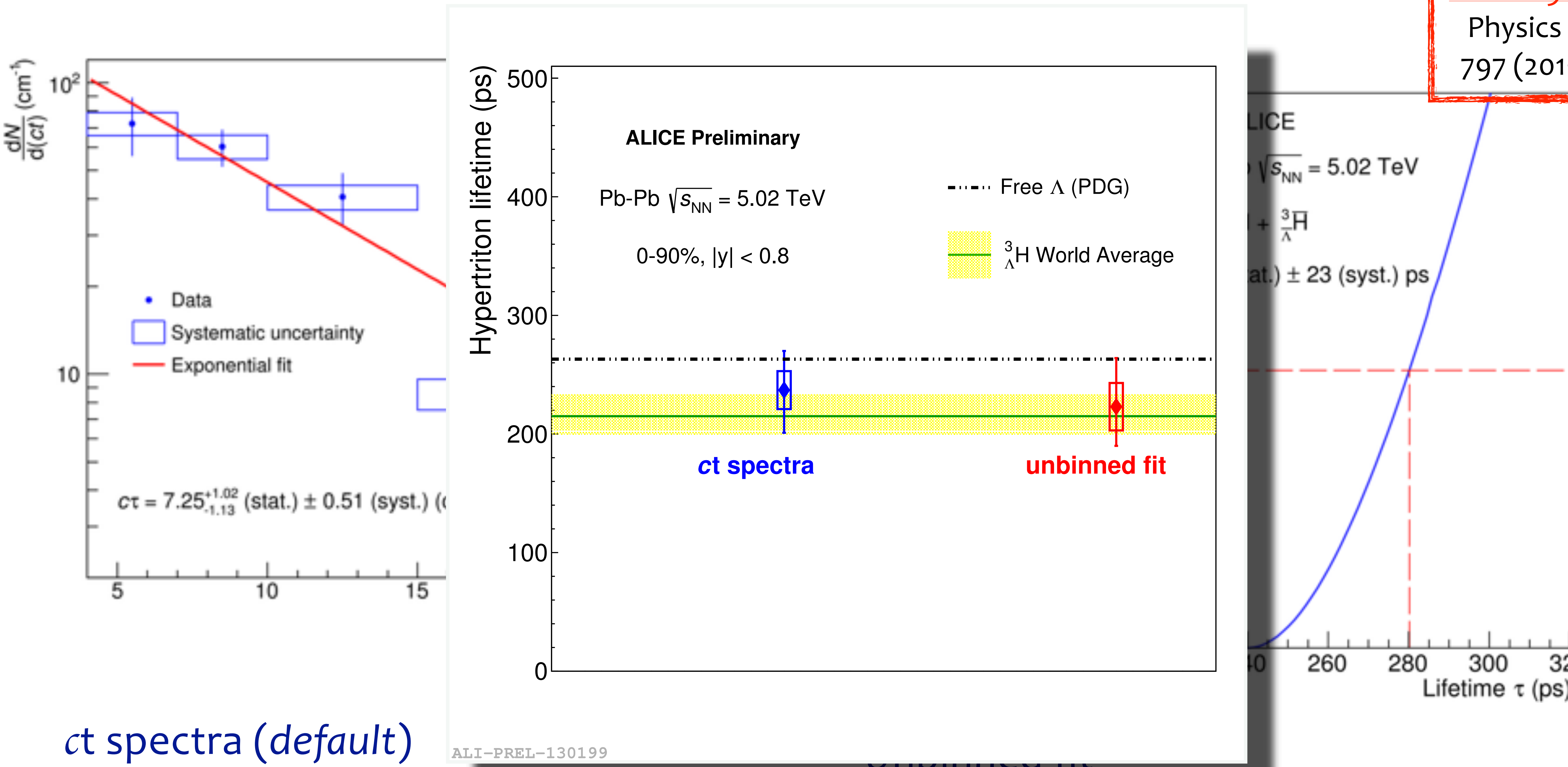
Unbinned fit

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

$$\tau = 240^{+40}_{-31}\ (\text{stat.})\ \pm\ 23\ (\text{syst.})\ \text{ps}$$

Hypertriton *lifetime with ALICE in Pb-Pb at 5 TeV*

New!
arXiv:1907.06906
Physics Letters B 797 (2019) 134905



*c*t spectra (*default*)

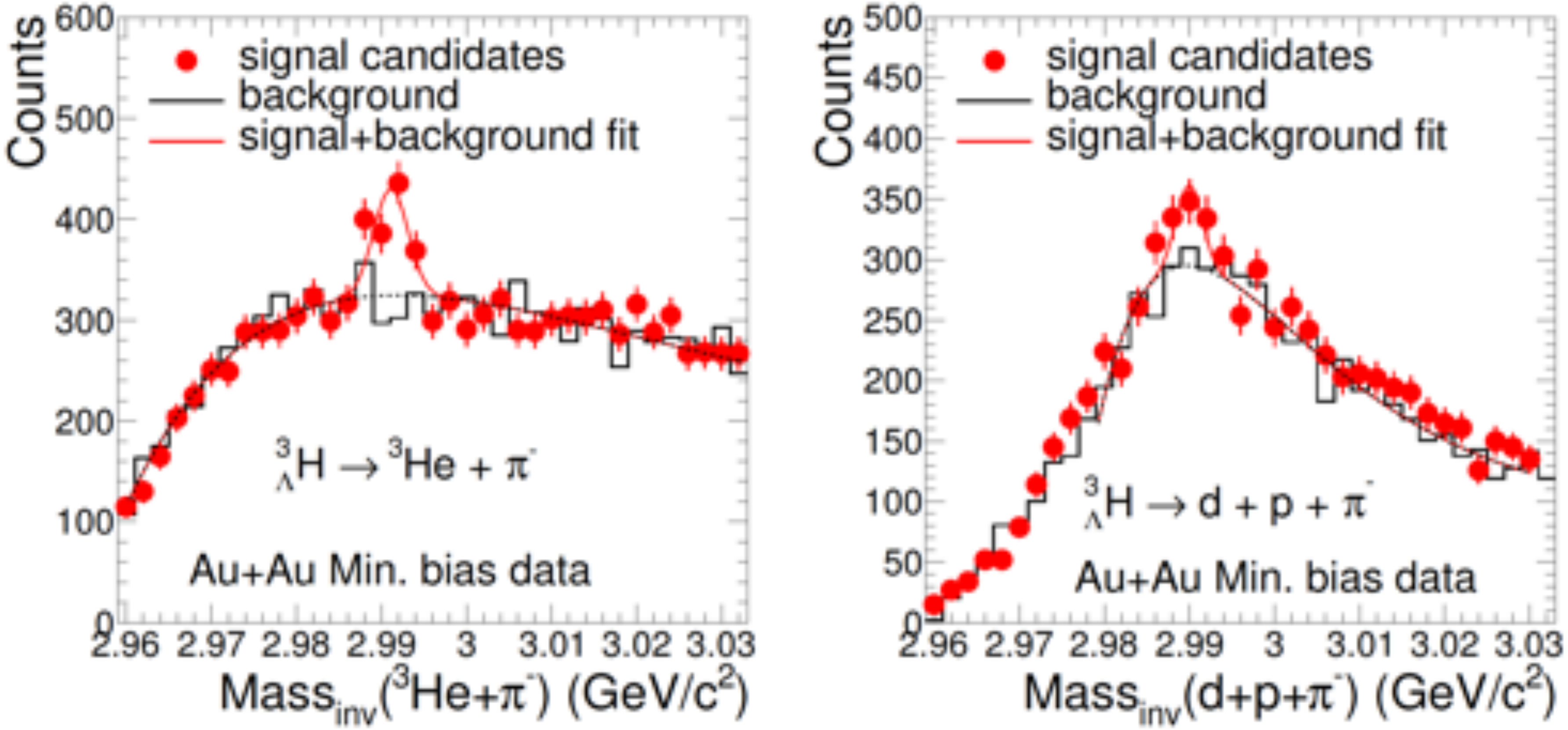
- Exponential fit to the differential yield in different *c*t bins

$$\tau = 242^{+34}_{-38}\ (\text{stat.}) \pm 17\ (\text{syst.})\ \text{ps}$$

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

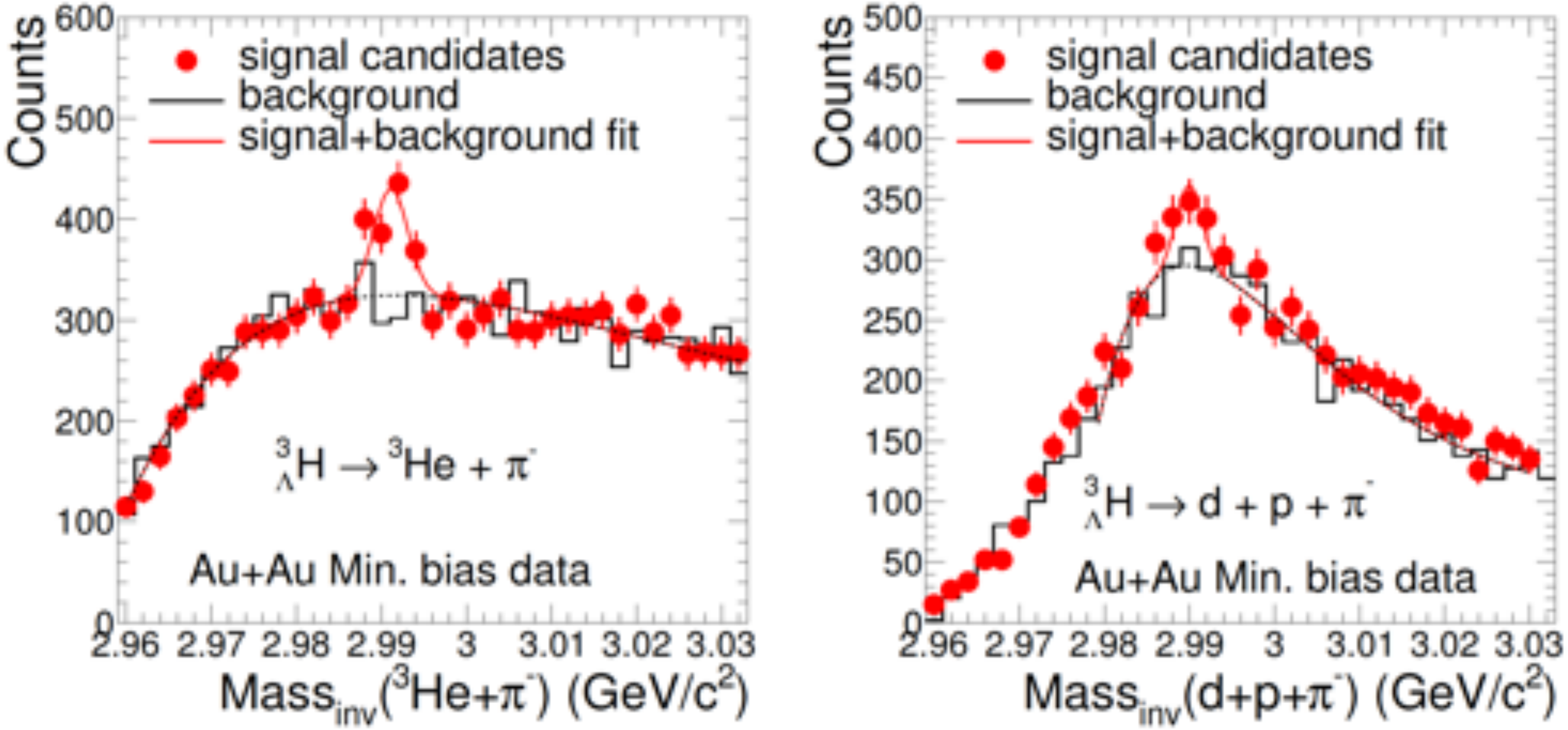
$$\tau = 240^{+40}_{-31}\ (\text{stat.})\ \pm\ 23\ (\text{syst.})\ \text{ps}$$

Hypertriton lifetime with STAR at RHIC



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

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



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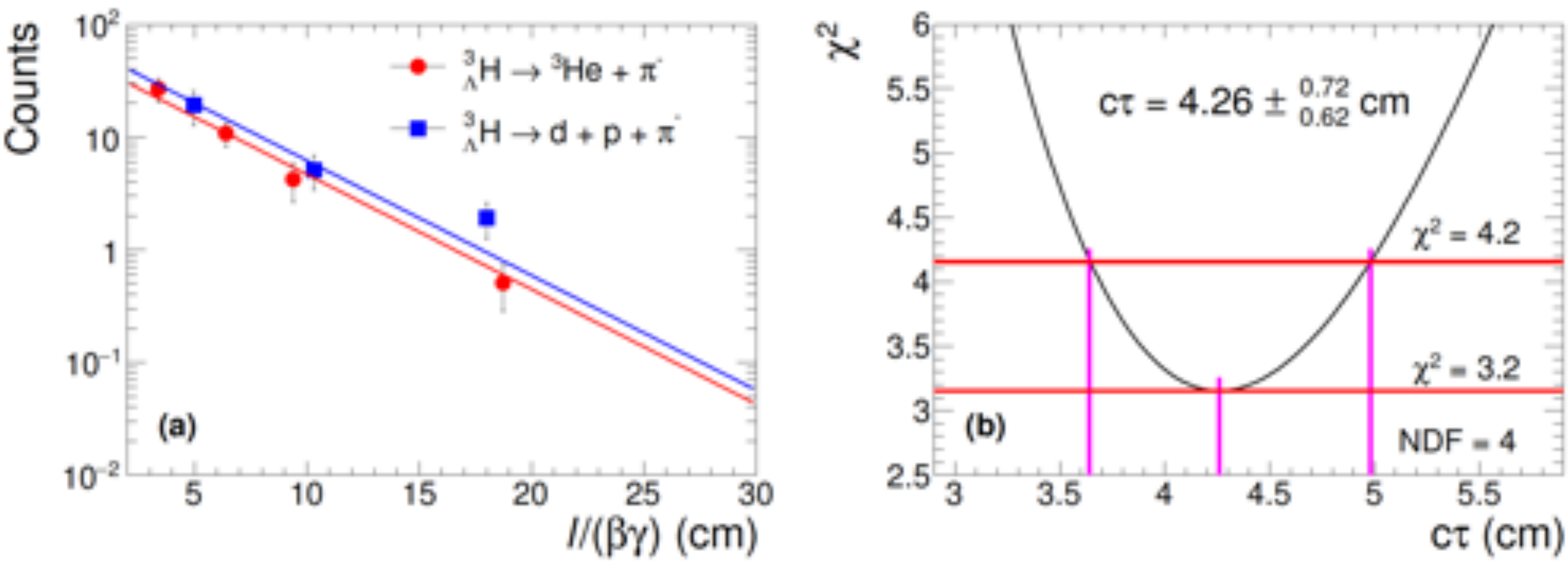


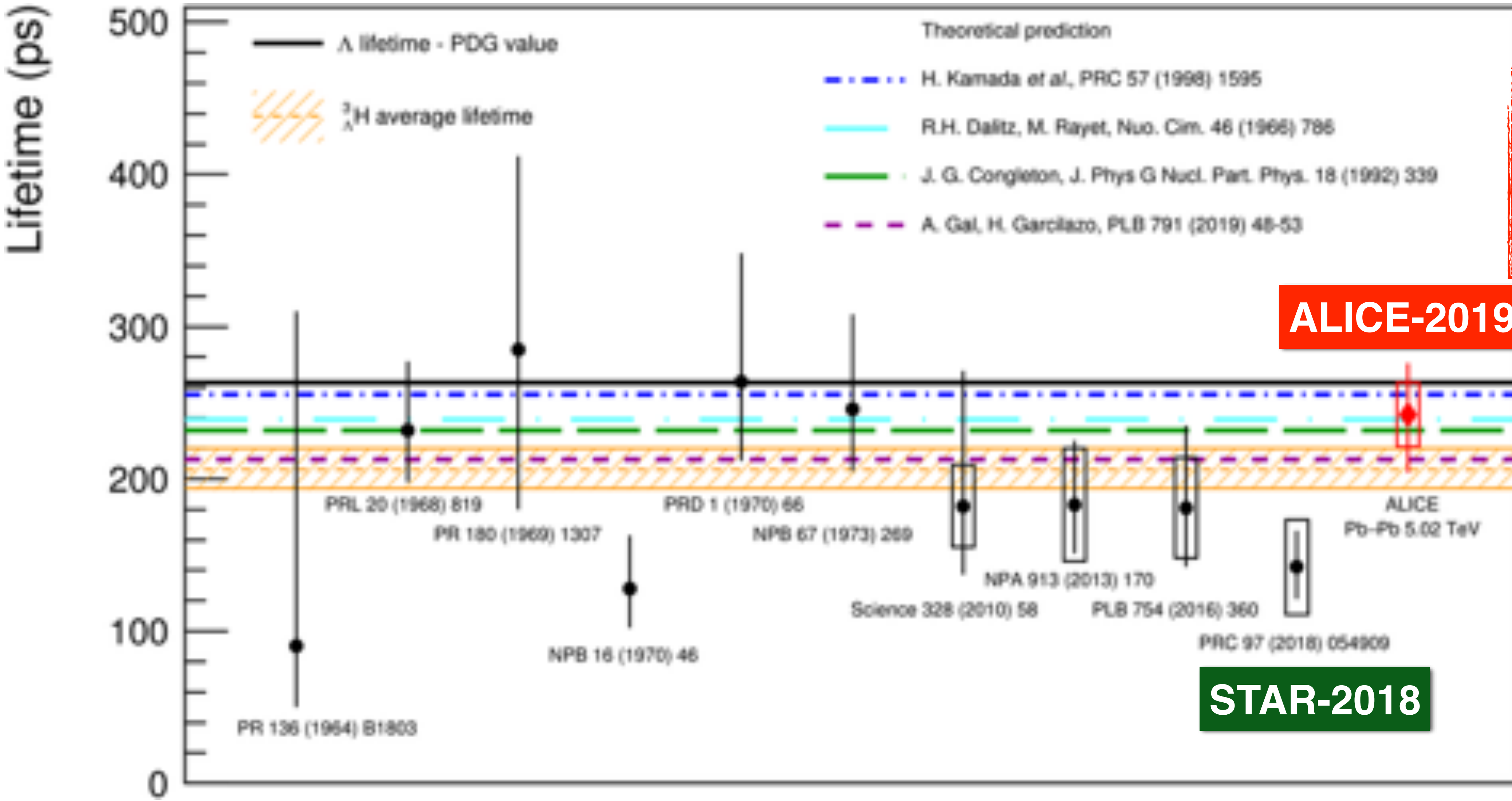
2 -body: $\tau=123^{+26}_{-21}$(stat) *ps*

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

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

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

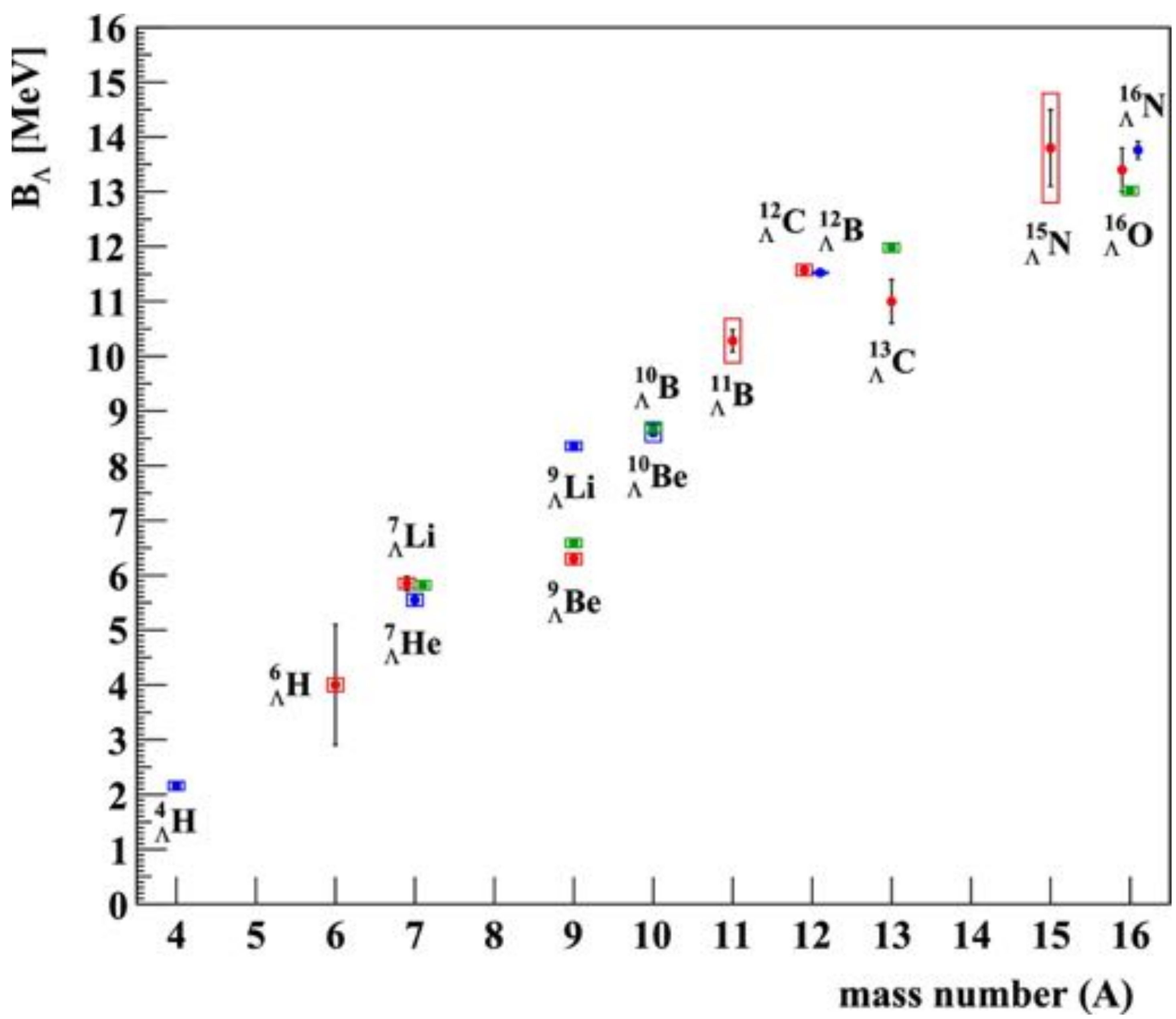
Hypertriton *lifetime world data*



New!
arXiv:1907.06906
Physics Letters B
797 (2019) 134905

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

Hypernuclei Binding energy measurements



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

Compilation of results from magnetic spectrometers from experiment at DAFNE and at KEK

Hypertriton binding energy

Emulsion experiment

From the observation of 82 examples of ${}^{3}_{\Lambda}H$, the binding energy of this hypernucleus is found to be 0.15 ± 0.08 MeV. An accurate determination of the binding energy of the ${}^{3}_{\Lambda}H$ 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 ${}^{3}_{\Lambda}H$ is found to be B_{Λ} = 0.13 ± 0.05 MeV.

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

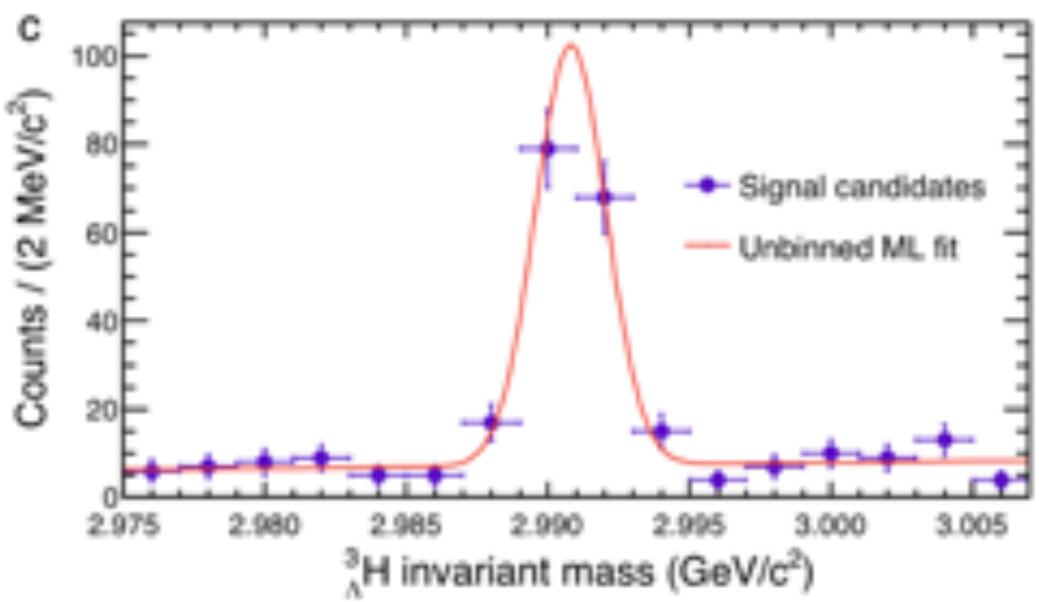
Binding energies for the s-shell hypernuclei.

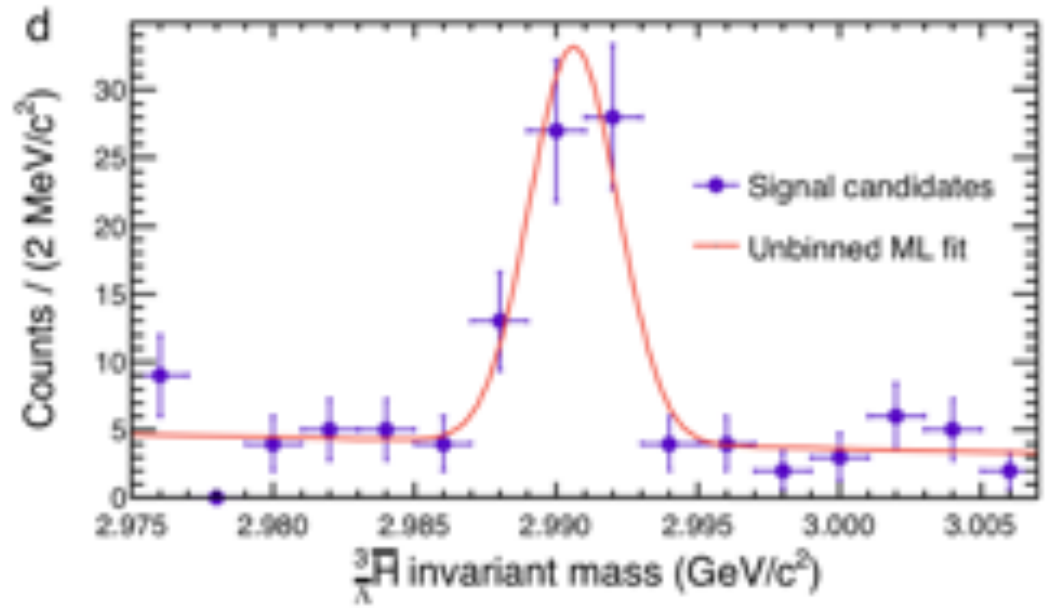
Hypernucleus	Decay mode	No of events	$B_{\Lambda} \pm \Delta B_{\Lambda}$ (MeV)
${}^{3}_{\Lambda}H$	$\pi^- + {}^1H + {}^2H$	24	0.23 ± 0.11
	$\pi^- + {}^3He$	58	0.06 ± 0.11
	total	82	0.15 ± 0.08
${}^{4}_{\Lambda}H$	$\pi^- + {}^1H + {}^3H$	56	2.14 ± 0.07
	$\pi^- + {}^2H + {}^2H$	11	1.92 ± 0.12
	total	67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

Hypertriton binding energy from STAR

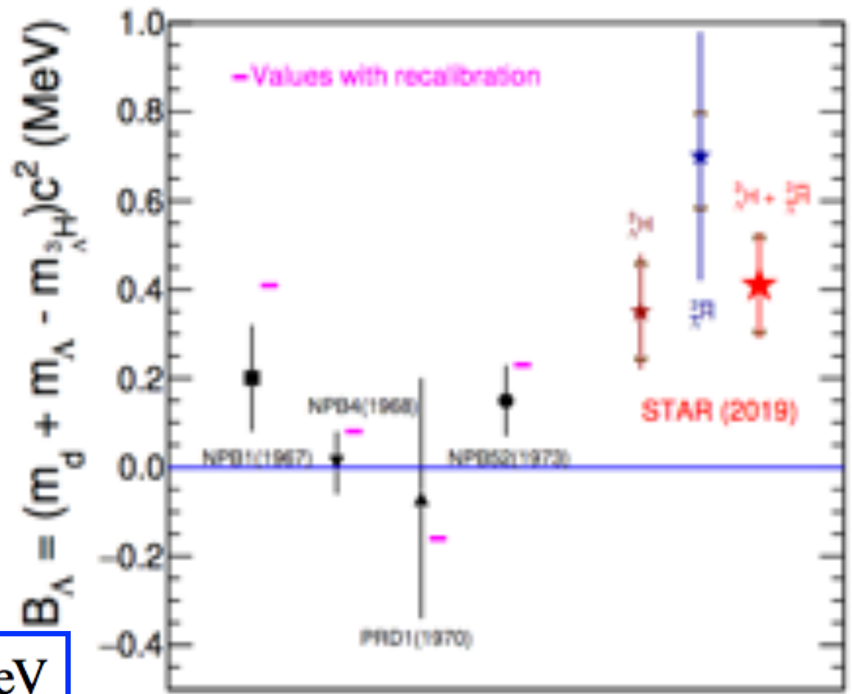
Preliminary result presented at Quark Matter 2018

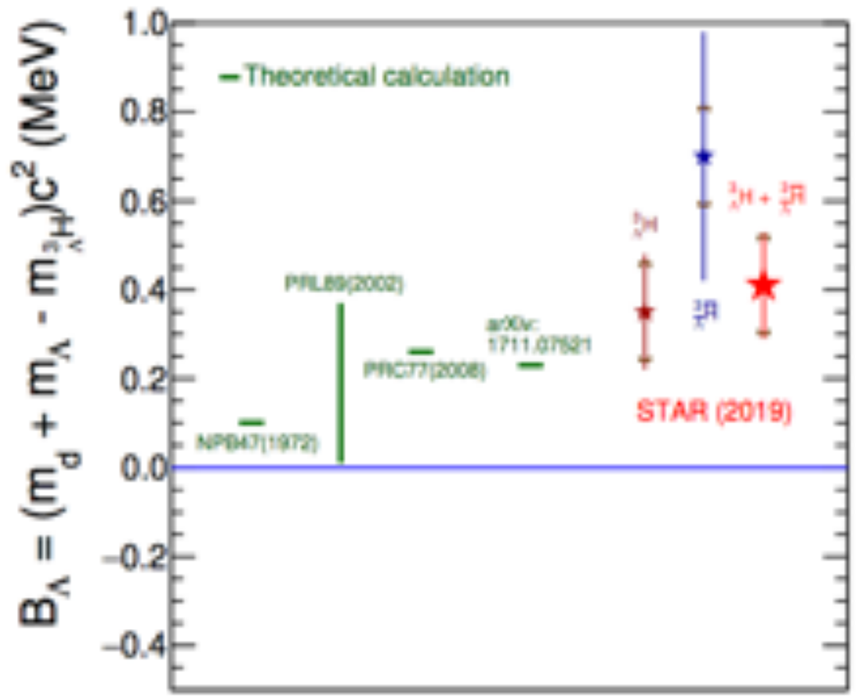
$$m = 2990.89 \pm 0.12(\text{stat.}) \pm 0.11(\text{syst.})\ \text{MeV}/c^2$$





Early values of the binding energy have been recalculated using the most precise mass values known today, and the recalibrated results are shown by short horizontal magenta lines





STAR value

$$B_\Lambda = 0.41 \pm 0.12(\text{stat.}) \pm 0.11(\text{syst.})\ \text{MeV}$$

https://arxiv.org/abs/1904.10520

Summary and perspectives

- Measurement of (anti-)hyper-triton yields and lifetime is an interesting topic and nice inputs come from the heavy-ion experiment

- Both STAR and ALICE have provided interesting experimental results in the study of the hypertriton production and for the determination of the hypertriton lifetime

- New preliminary results shown by the STAR Collaboration for the B_{Λ}

- **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**

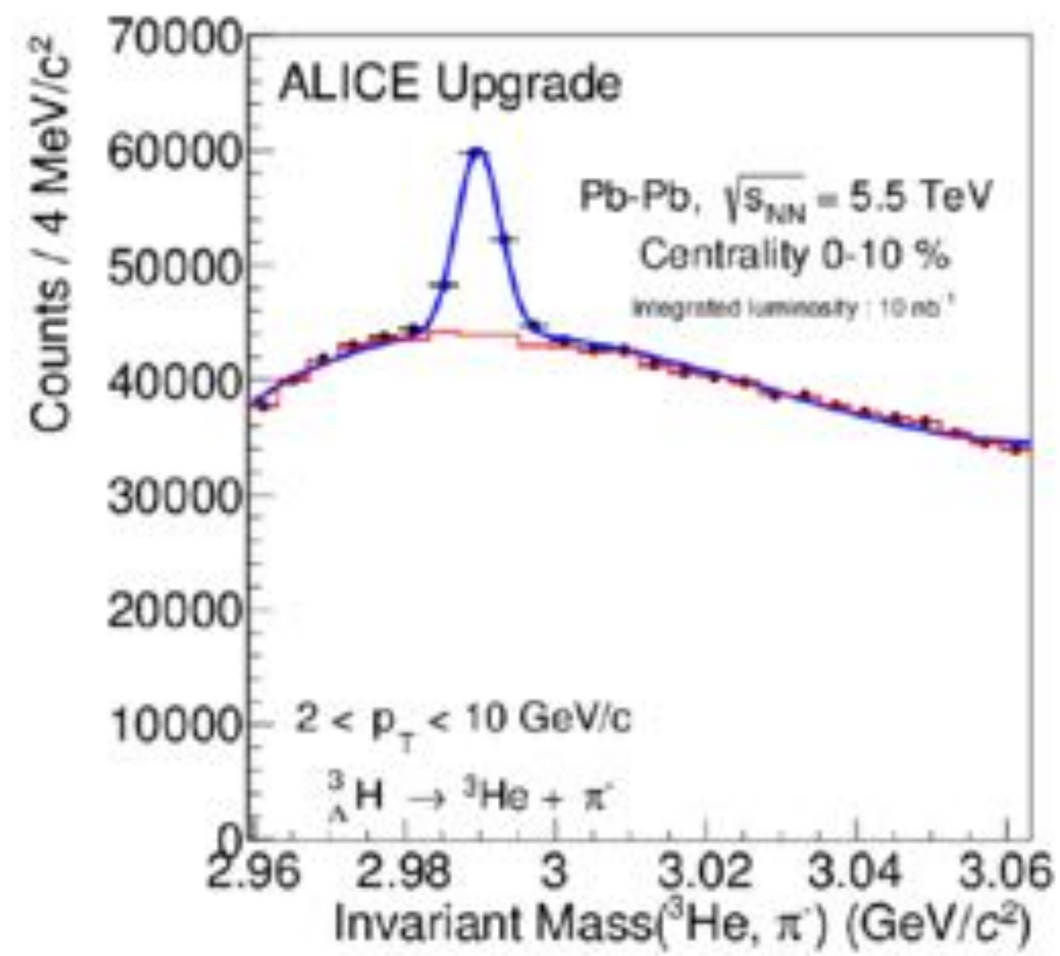
  - Lifetime determination with ALICE via 3-body decay channel will be important, also for comparison with STAR
  - New analysis approaches based on Machine Learning are ongoing in ALICE
  - **New theoretical calculations for the lifetime are needed as well as more precise measurements of the B_{Λ}**

Upgrade strategy at the LHC

- What about Run 3 & Run 4 of LHC? More statistics delivered (50 kHz Pb-Pb collision rate)
- The ALICE detector is now performing a major upgrade. A new Inner Tracking System (ITS) will be installed with a better secondary vertex resolution which is one of the key point in these measurements

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)

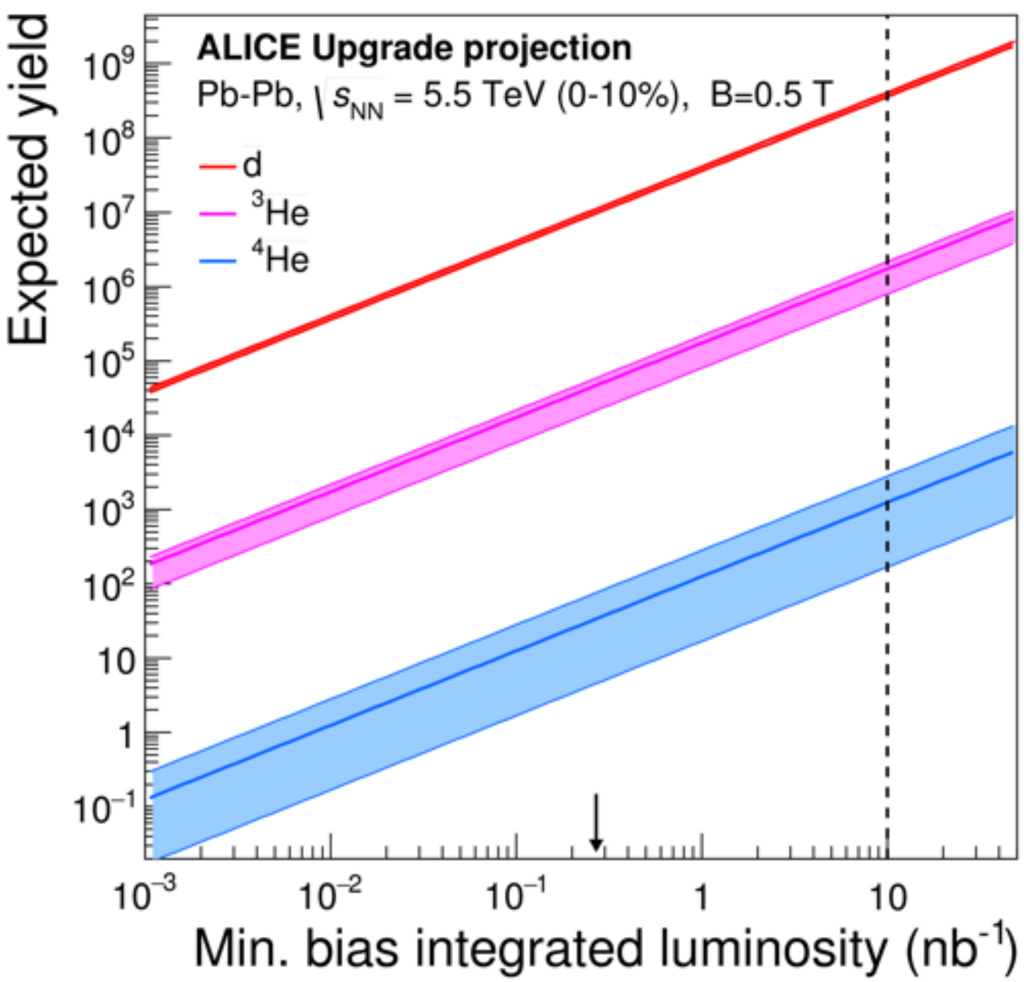


Longer term perspectives at the LHC

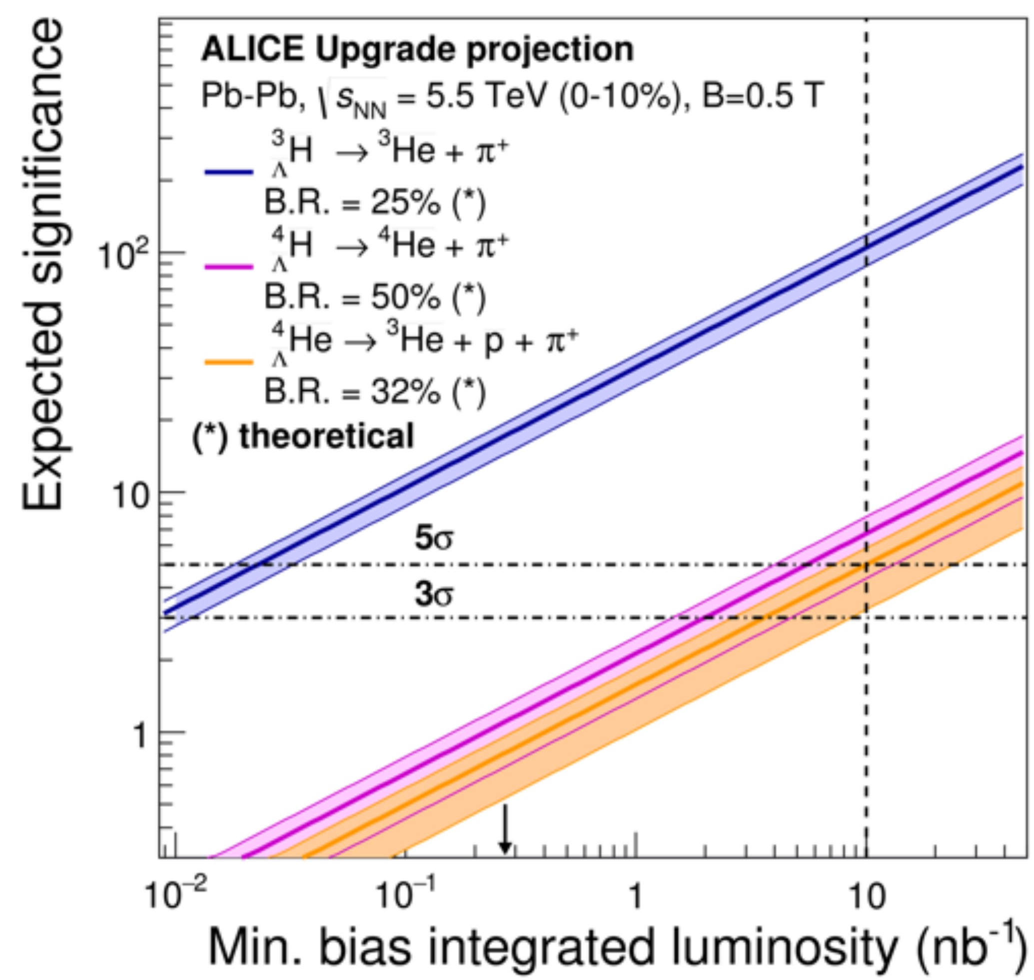
Measurements with **higher significance** of anti-hypernuclei will be possible in central Pb–Pb collisions in **Runs 3 and 4 also for A>3**

- more details in CERN Yellow Report arXiv:1812.06772
- hypertriton lifetime (Sec. 3.2.3, page 27)

With the expected integrated Pb–Pb luminosity at the end of the LHC Run 4, the statistical uncertainty on the lifetime will be reduced down to 1%. In parallel, a reduction of the systematic uncertainty (∼ 10% in the most recent ALICE measurements), will be achieved with the upgraded ALICE ITS that will allow for a reduction of the uncertainty due to tracking and material budget. To improve even fur-



ALI-SIMUL-312336

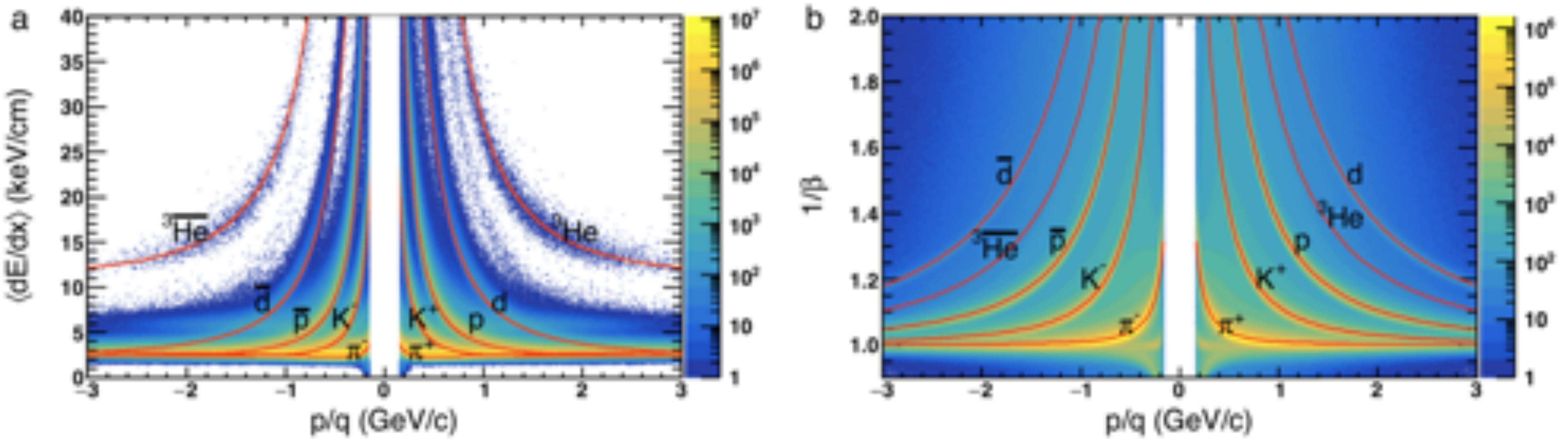


ALI-SIMUL-312332

thank you!

BACKUP

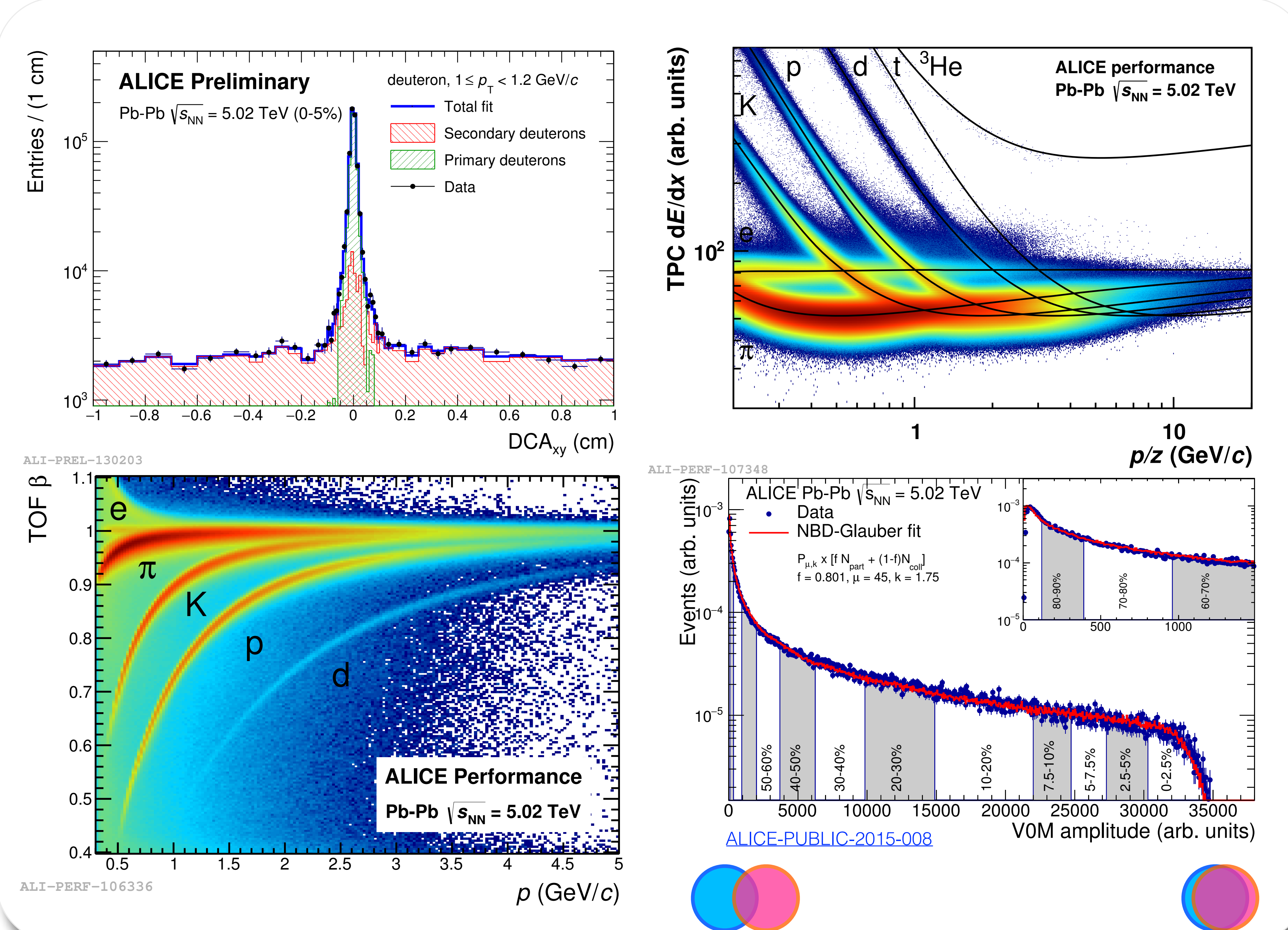
Hypertriton search with STAR at RHIC



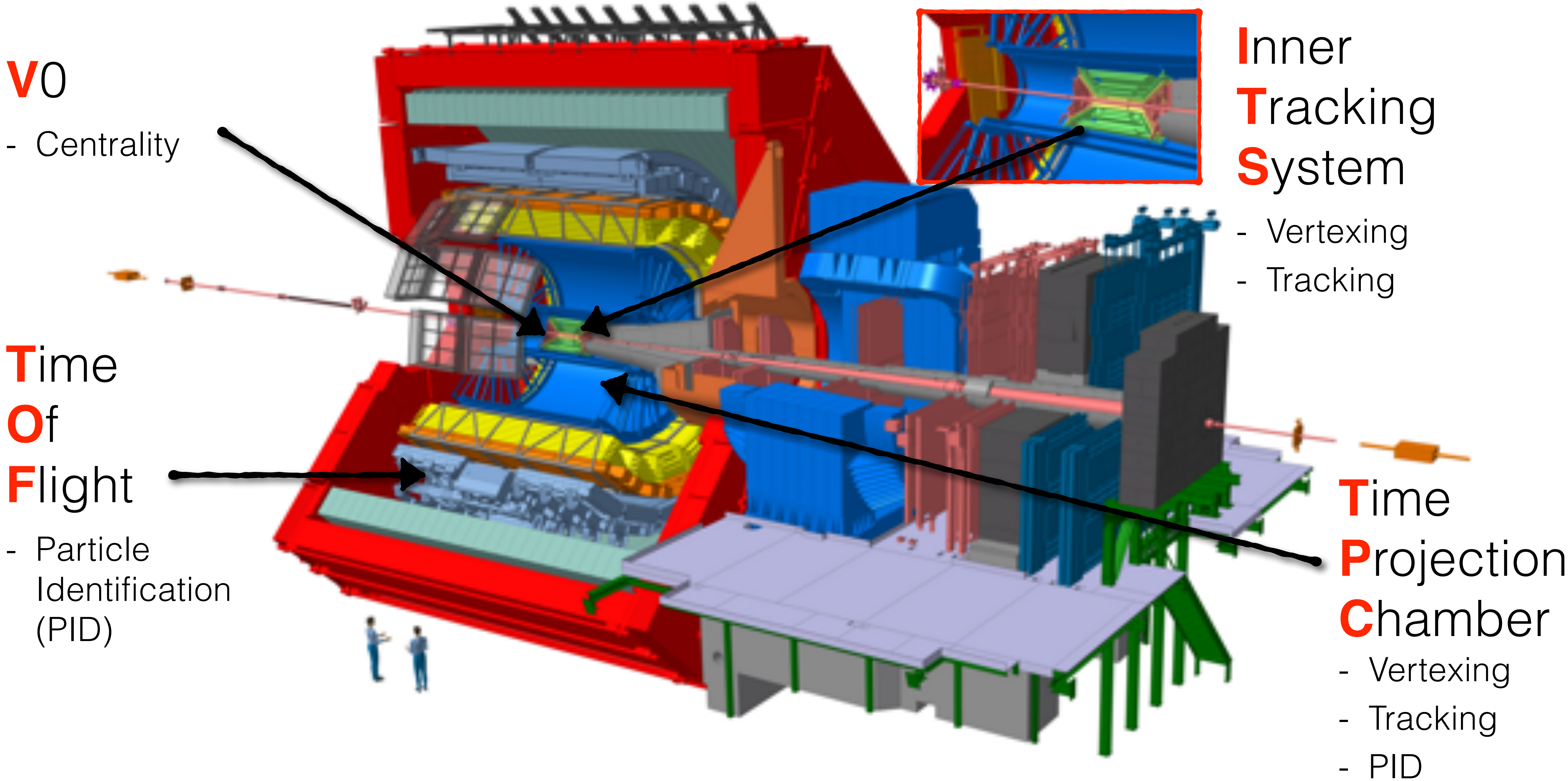
Particle identification in ALICE

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



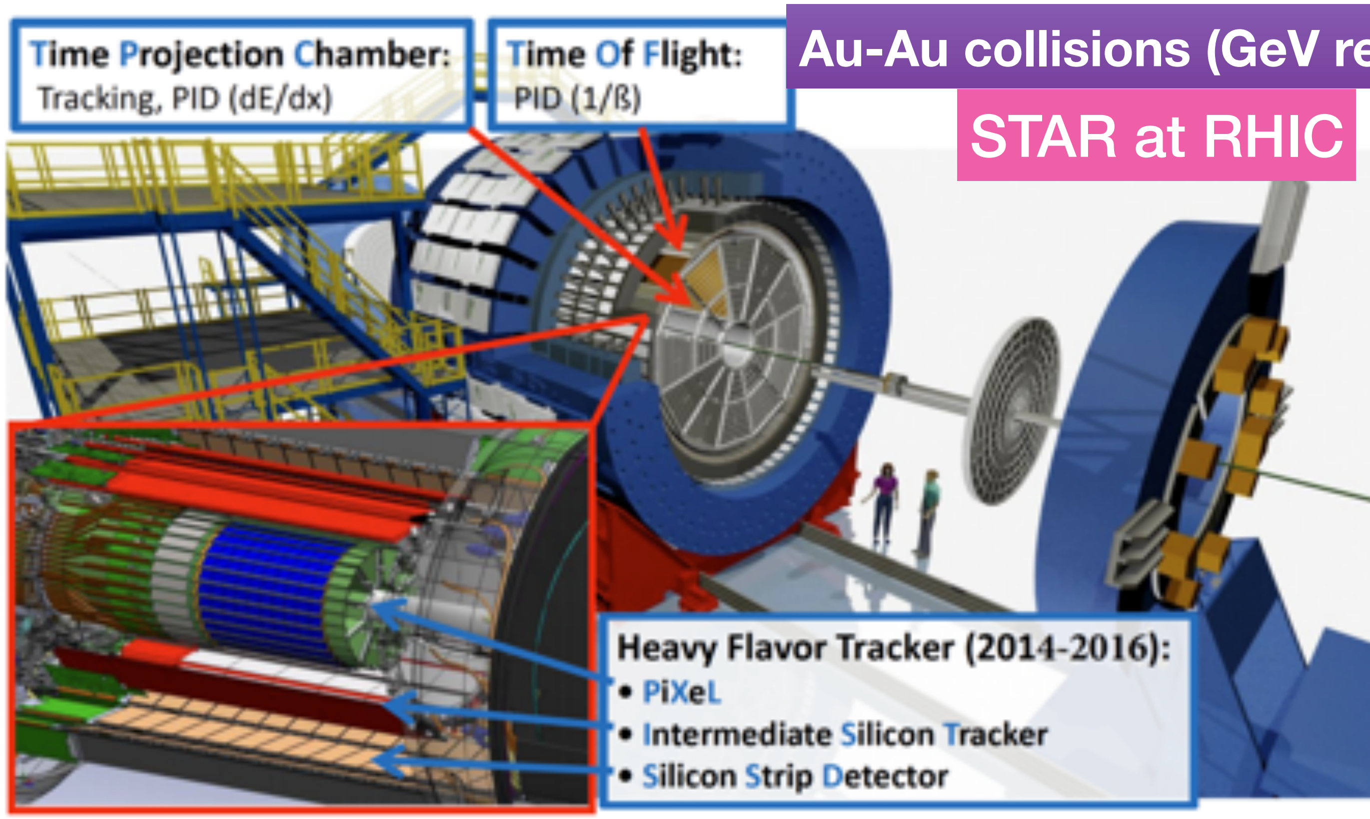
The ALICE detector



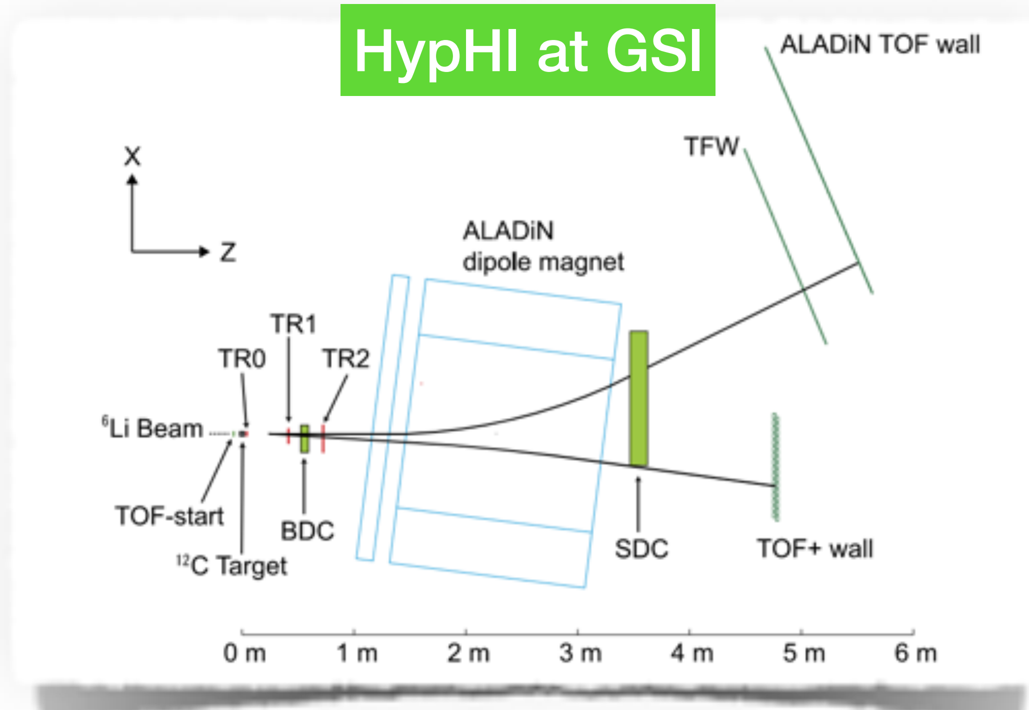
- General purpose heavy ion experiment
- Excellent particle identification (PID) capabilities and low material budget
- Most suited detector at the LHC to study the (anti-)(hyper-)nuclei produced in the collisions

Au-Au collisions (GeV regime)

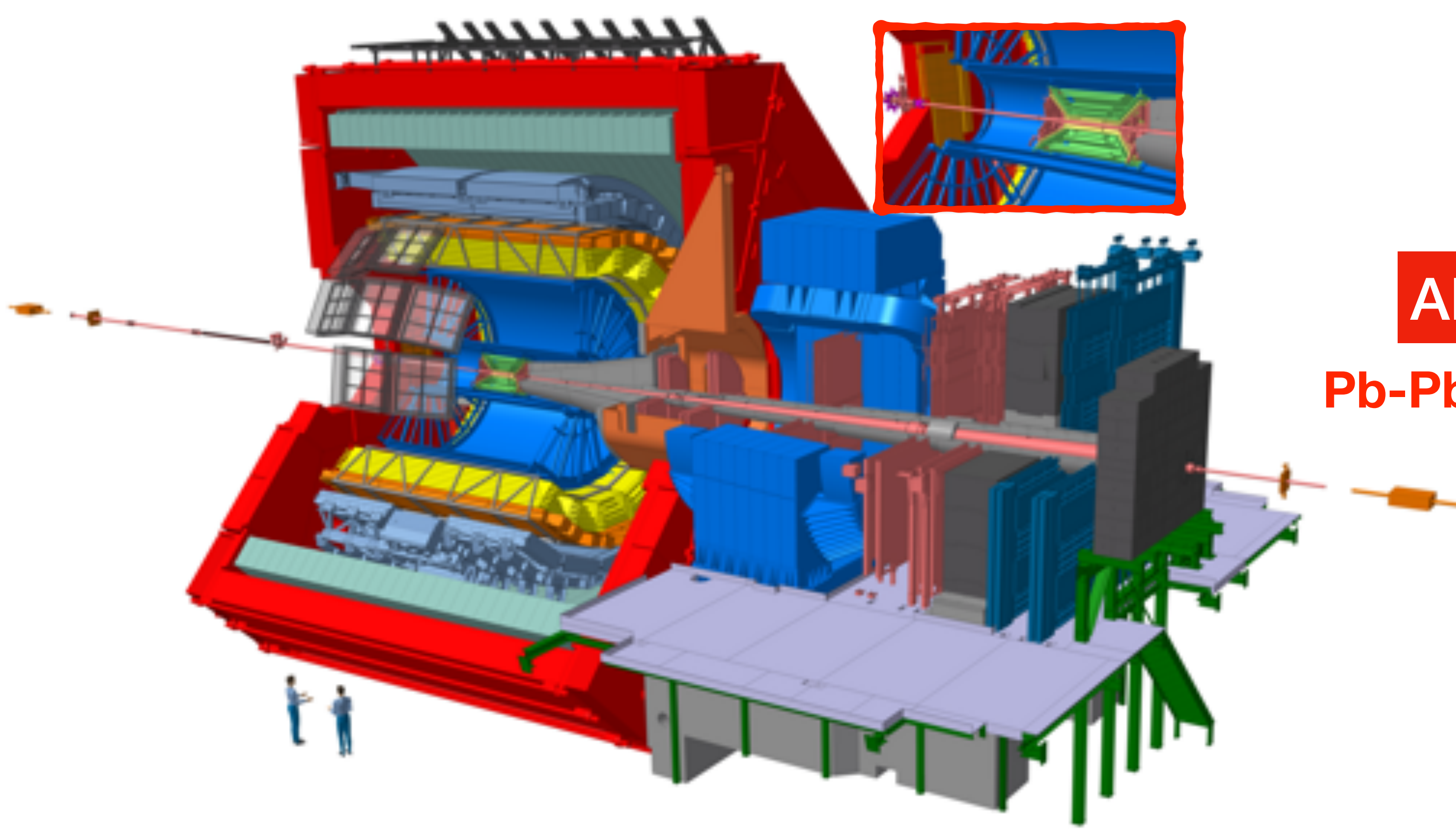
STAR at RHIC



HypHI at GSI



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



ALICE at the LHC

Pb-Pb collisions (TeV regime)