Measurement of the hypertriton properties and production with ALICE

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on behalf of the ALICE Collaboration
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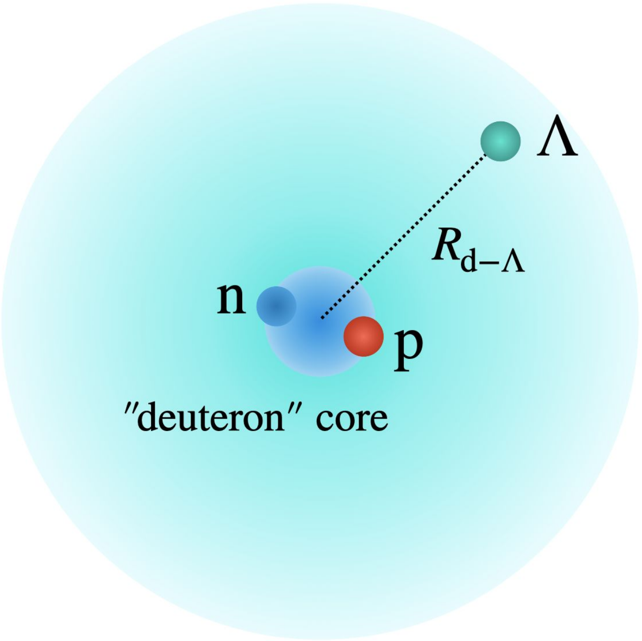
Hypertriton ($^{3}_{\Lambda}H$)

- Lightest known hypernucleus
  - bound state of a neutron, a proton and a Λ
  - discovered in early 50s by Polish physicists
    - M. Danysz and J. Pniewski [1]
- $^{3}_{\Lambda}H$ approximated as a bound state of a deuteron and a Λ with an expected radius of ~ 10 fm [2]
  - two-body halo nucleus
- Unique probe for understanding the Λ-nucleus interaction
  - strong implications for astro-nuclear physics
  - hyperons expected to be produced in the inner core of neutron stars [3]

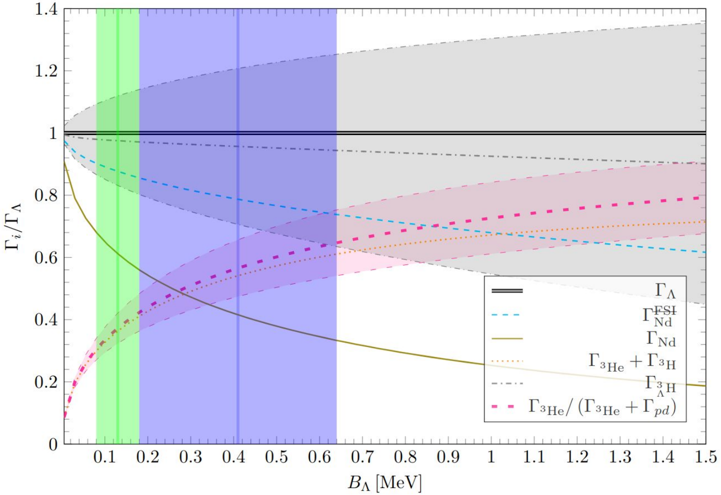


[1] M. Danysz, J. Pniewski, Philos. Mag. 44, 348, (1953)
[2] Hildenbrand F. et al., Phys. Rev. C, 100(3), 034002 (2019)
[3] Tolos L. et al., Progress in Particle and Nuclear Physics, 112 (2020)

$^{3}_{\Lambda}$H in ALICE

$^{3}_{\Lambda}$H in large systems (Pb-Pb collisions): lifetime and B_{Λ}

- $^{3}_{\Lambda}$H lifetime and B_{Λ} reflect its structure
  - Most of the theoretical models assume $B_{\Lambda} \approx$ 130 keV and predict lifetime close to the free Λ one
  - latest models based on EFT give lifetime predictions as a function of the B_{Λ}
- recent results suggest that $^{3}_{\Lambda}$H could be more compact than expected [1, 2]
  - precise measurements required to shed light on the $^{3}_{\Lambda}$H structure



Hildenbrand F. et al., *Physical Review C*, vol. 102, no. 6 (2020)

Λ_{uv}	B_{Λ} (keV)	τ (ps)
800	69	234±27
900	135	190±22
1000	159	180±21
-	410	163±18

Pérez-Obiol A., *Physics Letters B*, vol. 811 (2020)

[1] STAR, Phys. Rev. C 97, 5, 054909 (2018)
[2] STAR, Nature Physics 16, 409–412 (2020)

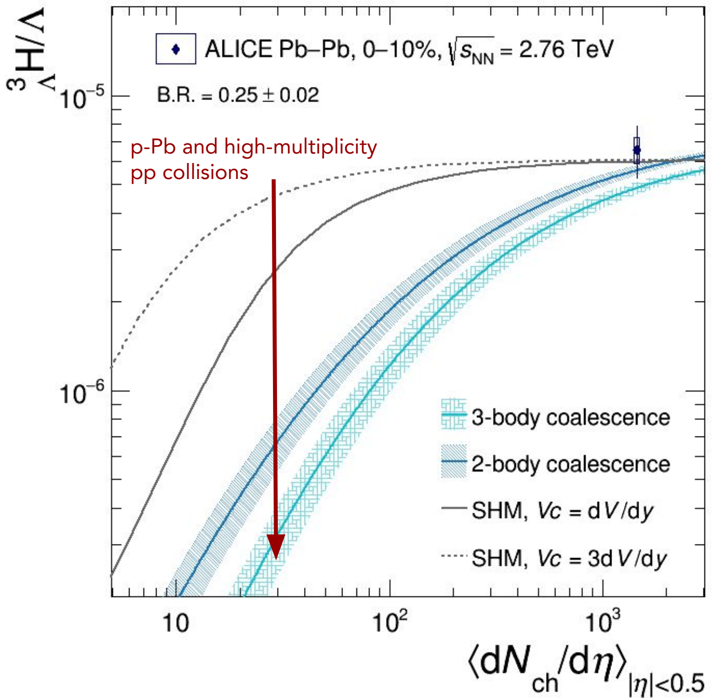
${}^{3}_{\Lambda}H$ in ALICE

${}^{3}_{\Lambda}H$ production in small systems (pp and p-Pb collisions)

- loosely bound nature of ${}^{3}_{\Lambda}H$ has strong implications for its production mechanism
  - thermal (SHM)[1] and coalescence[2] predictions well separated at low charged-particle multiplicity density
    - coalescence relies on the radius of the particle while SHM don't

- ${}^{3}_{\Lambda}H$ production in pp and p-Pb is a key to understand the nuclear production mechanism in hot and dense matter

ALICE Collaboration (2016). *Phys. Lett. B, 754, 360–372.*



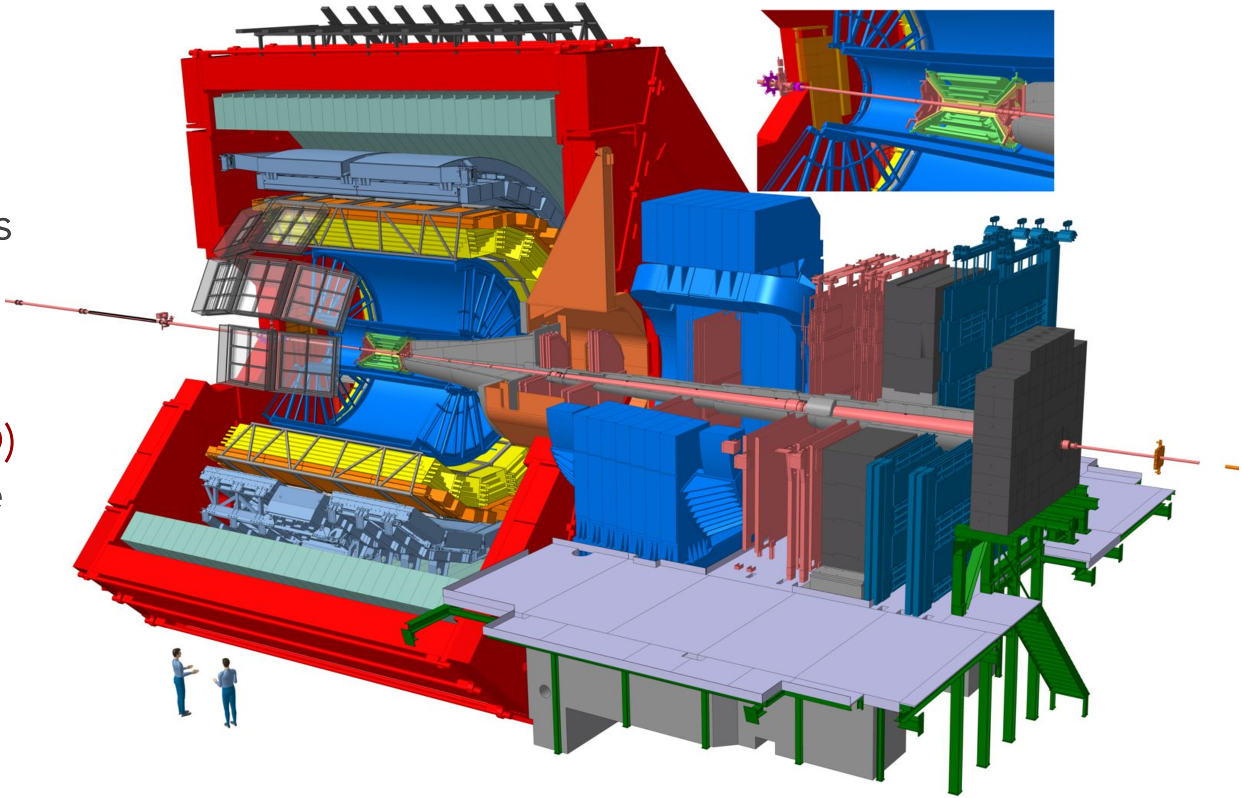
[1] Vovchenko, et al., *Phys. Lett., B785, 171-174,* (2018)
[2] Sun. et al., *Phys. Lett. B, 792, 132–137,* (2019)

Hypertriton in large systems

Precision measurements of lifetime and B_{Λ} in Pb-Pb collisions

The ALICE detector

- We can identify the hypertriton daughter particles (^{3}He and π^-) exploiting the excellent particle identification (PID) capabilities of the ALICE apparatus



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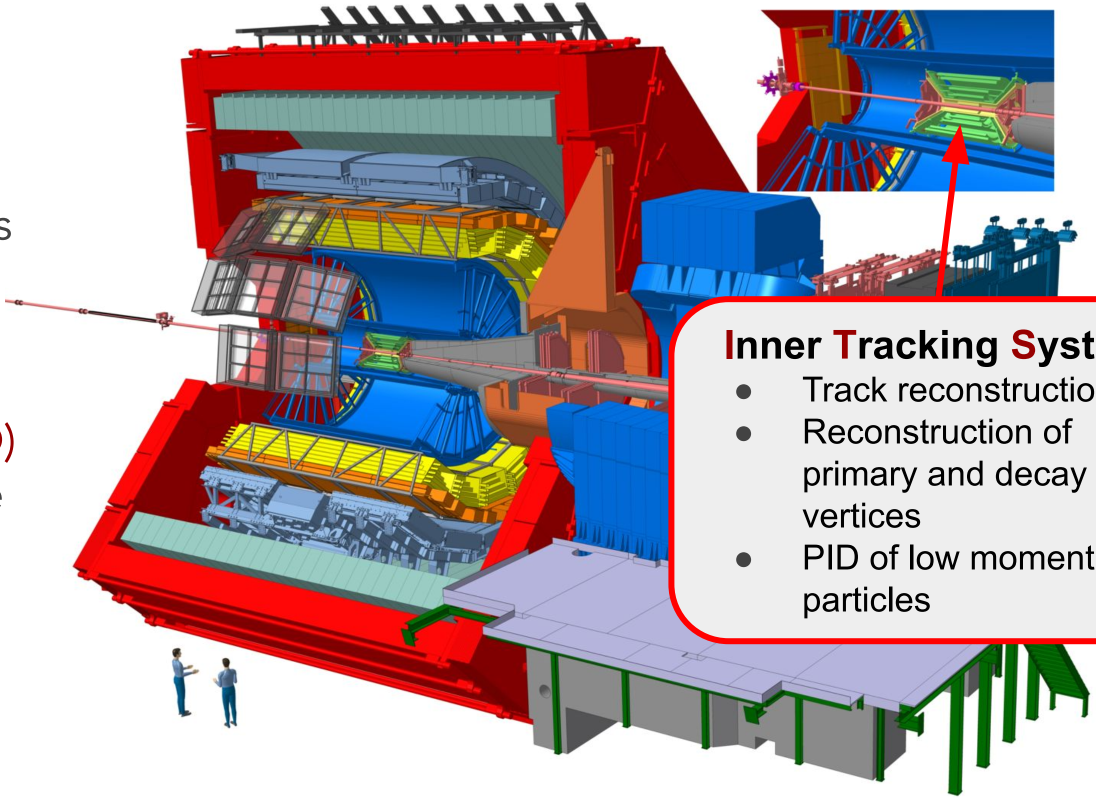

Inner Tracking System
- Track reconstruction
- Reconstruction of primary and decay vertices
- PID of low momentum particles

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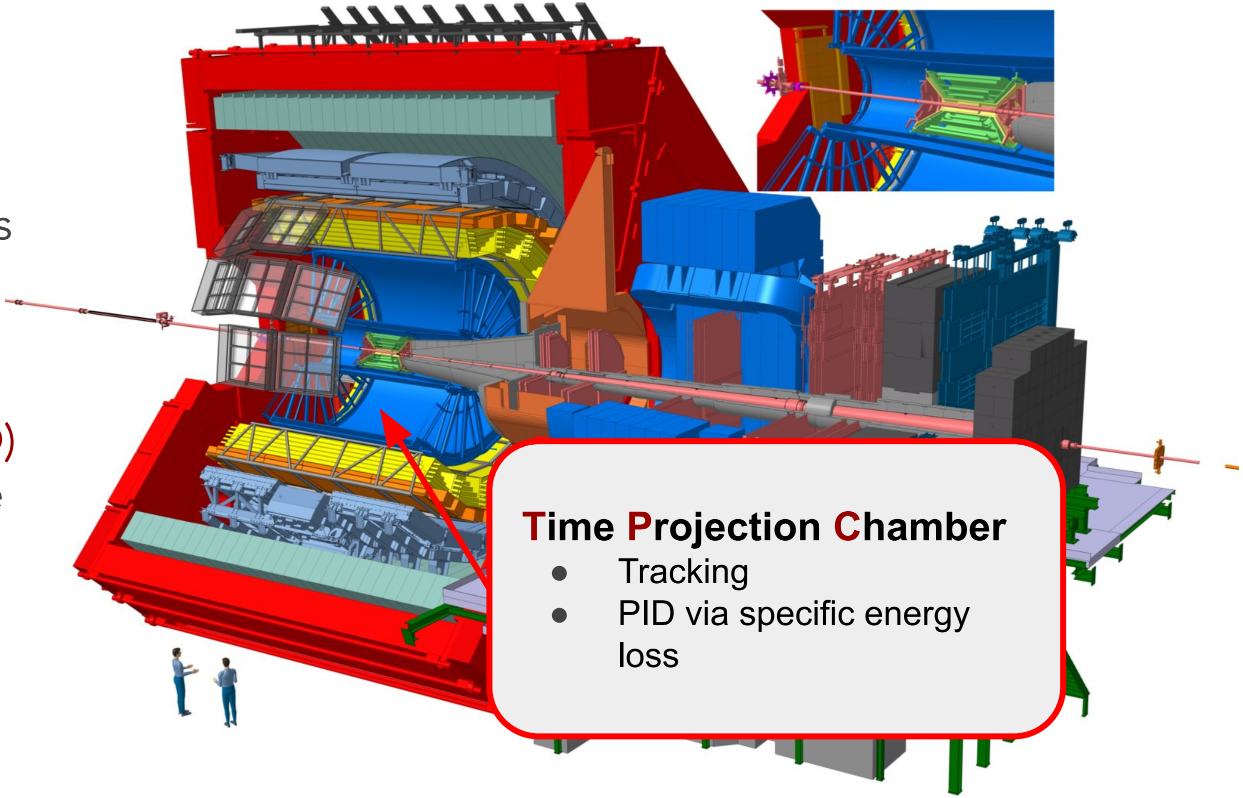

Time Projection Chamber
- Tracking
- PID via specific energy loss

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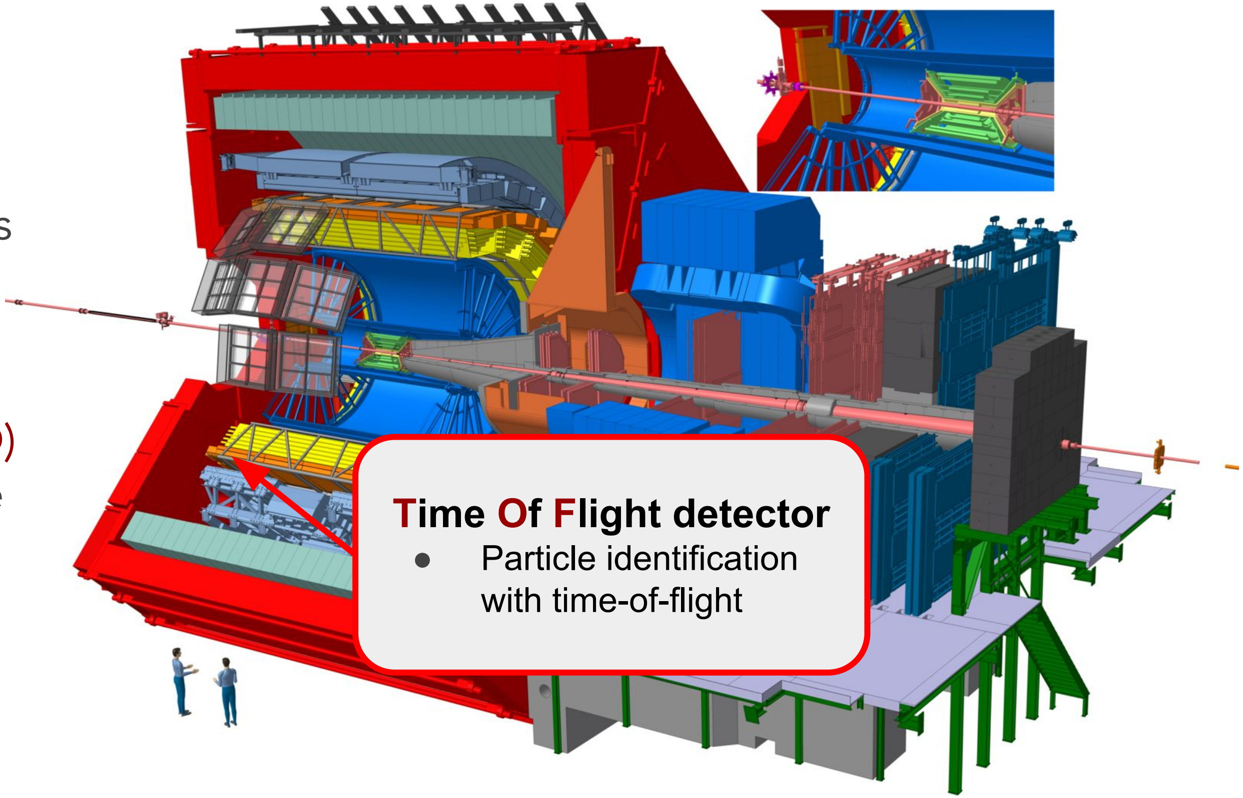

The ALICE detector

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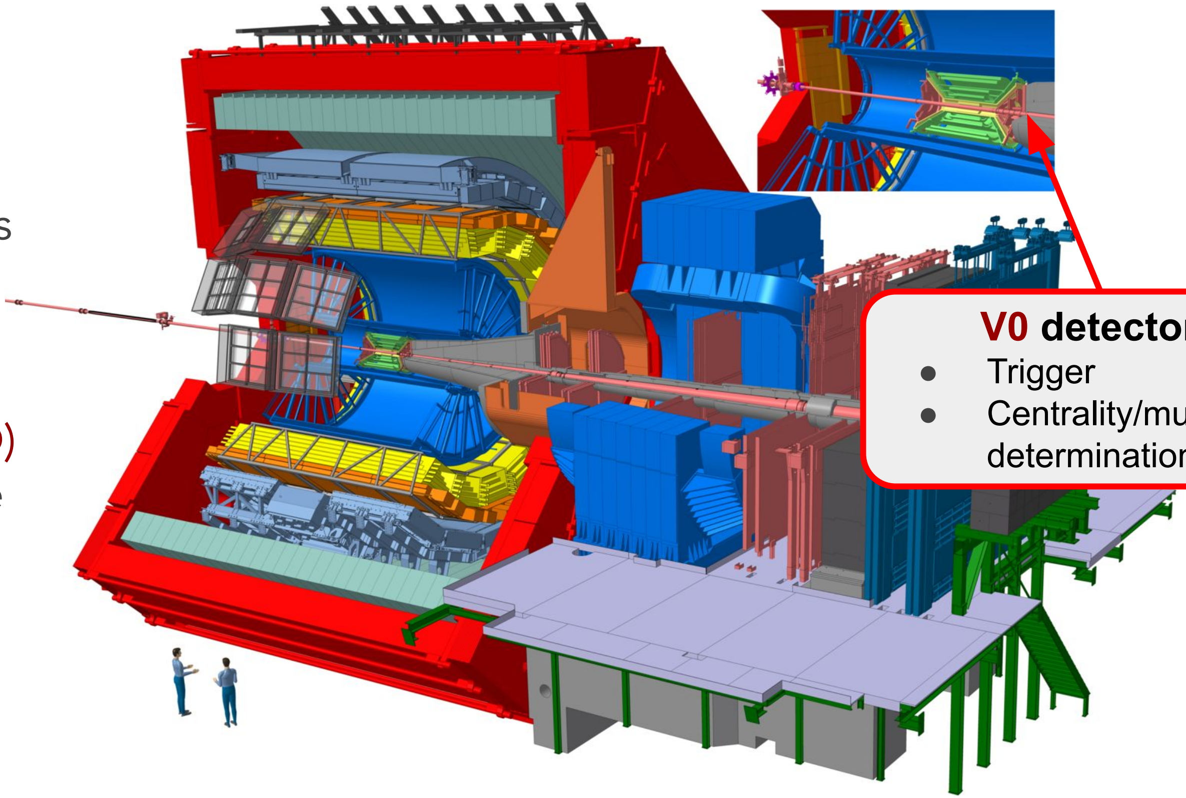
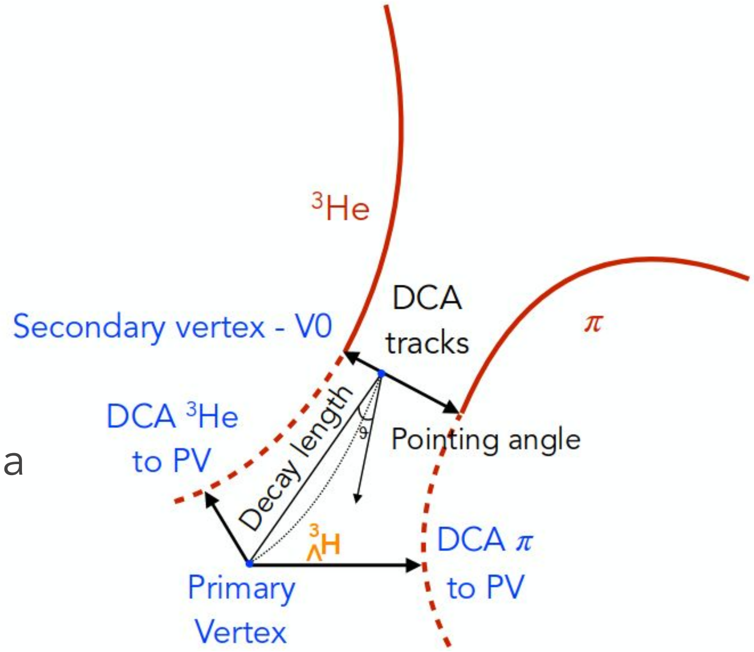


V0 detectors
- Trigger
- Centrality/multiplicity determination

${}^{3}_{\Lambda}H$ in large systems

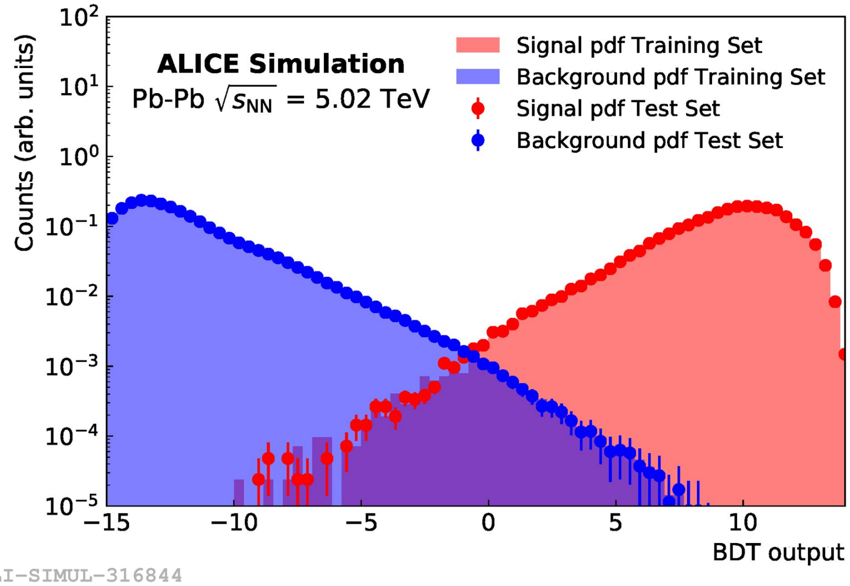
- Analysed data sample:
  - Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected by ALICE in 2018
- ${}^{3}_{\Lambda}H$ candidate: ${}^{3}He + \pi^{-}$ pairs (and related charge conjugated states)
- Secondary vertex reconstruction
  - matching of ${}^{3}He + \pi^{-}$ tracks coming from a common vertex
- Huge combinatorial background



$^{3}_{\Lambda}H$ selection: machine learning approach

Boosted Decision Trees Classifier (BDT) trained on a dedicated sample

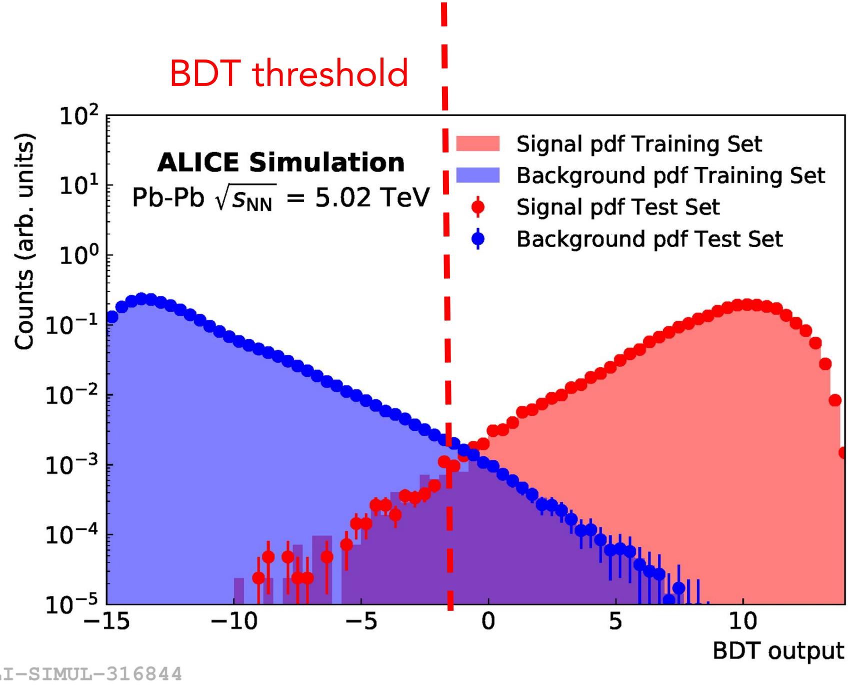
- BDT output (independent trainings for each bin) :
  - Score related to the probability of the candidate to be signal or background



$^{3}_{\Lambda}H$ selection: machine learning approach

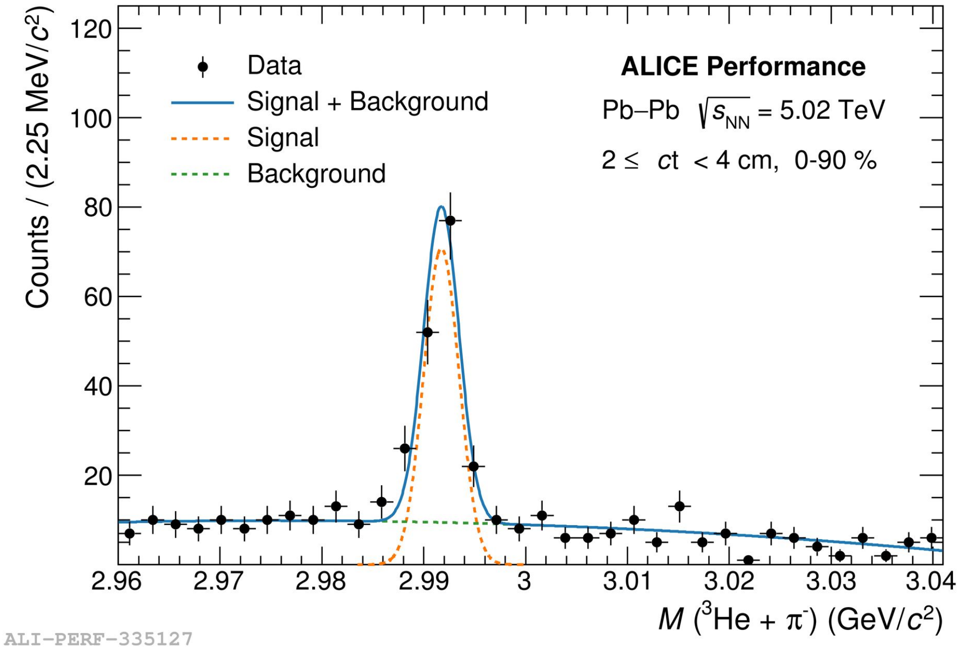
Boosted Decision Trees Classifier (BDT) trained on a dedicated sample

- Selection applied on the BDT score
  - maximisation of the expected significance (assuming thermal production)



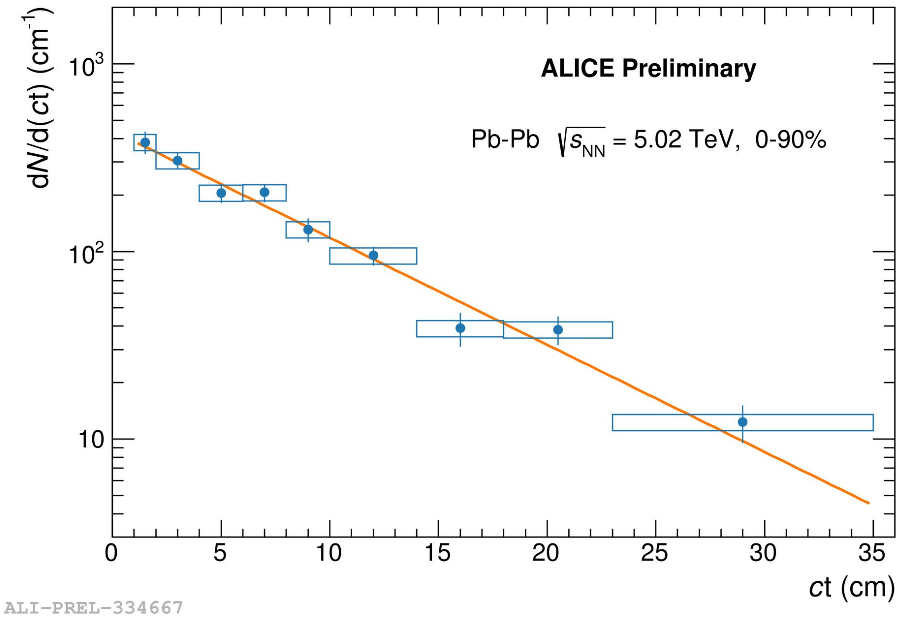
Signal extraction

- Signal extracted with a fit to the invariant mass spectrum of the selected candidates
- high significance over a wide range
    - 9 *ct* bins from 1 to 35 cm



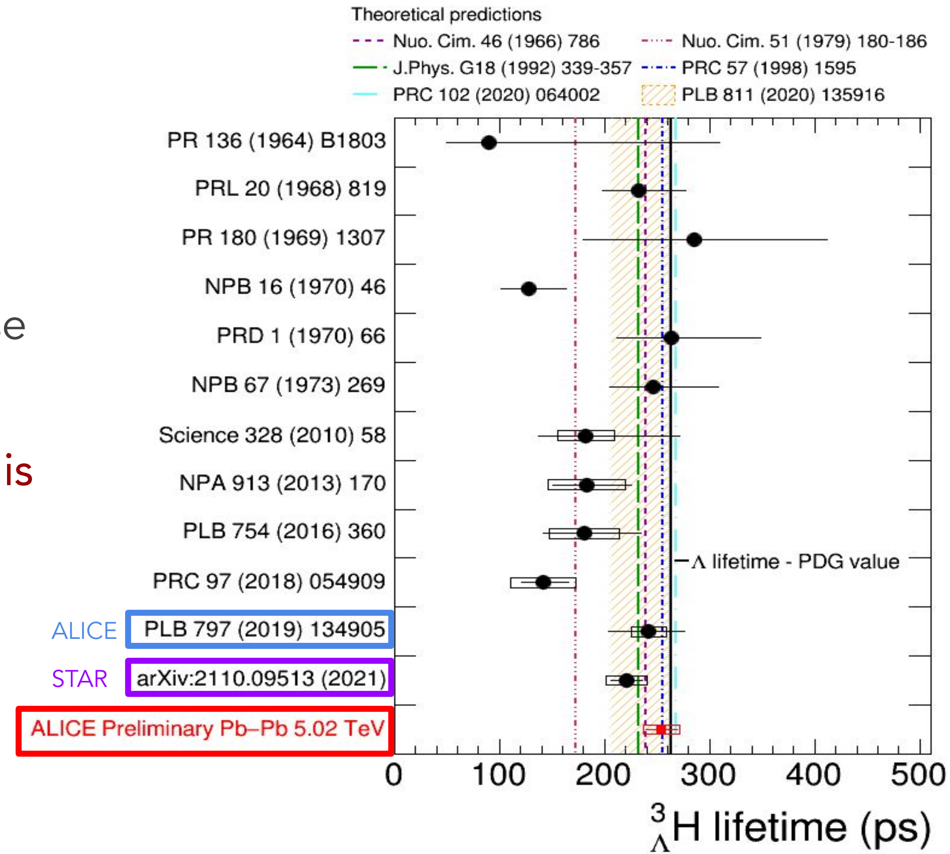
$^{3}_{\Lambda}H$ Lifetime

- Corrected *ct* spectrum fitted with an exponential function
- Lifetime value from the fit
  - Statistical uncertainty ~ 6%
  - Systematic uncertainty ~ 7%
- Most precise measurement of the lifetime ever done so far



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

- Most precise measurement
- Compatible with latest STAR measurement
- Models predicting a lifetime close to the free Λ one are favoured
  - strong hint that hypertriton is weakly bound, but B_Λ is still needed to solve the puzzle

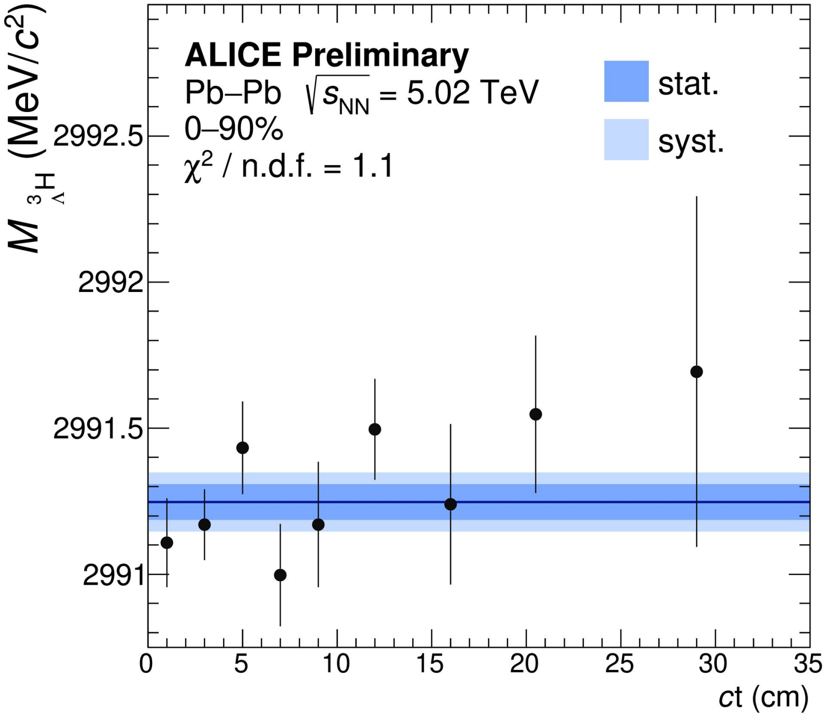


≥ 2020 models: assuming B_Λ = 70 keV
< 2020 models: assuming B_Λ = 130 keV

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

New @ QM

- Same signal extraction technique and *ct* bins used for the lifetime: precise mass measurement needed to obtain B_{Λ}
- Extremely precise measurement
  - 0.0016% stat.
- Systematic uncertainty of ~100 keV (0.003%)

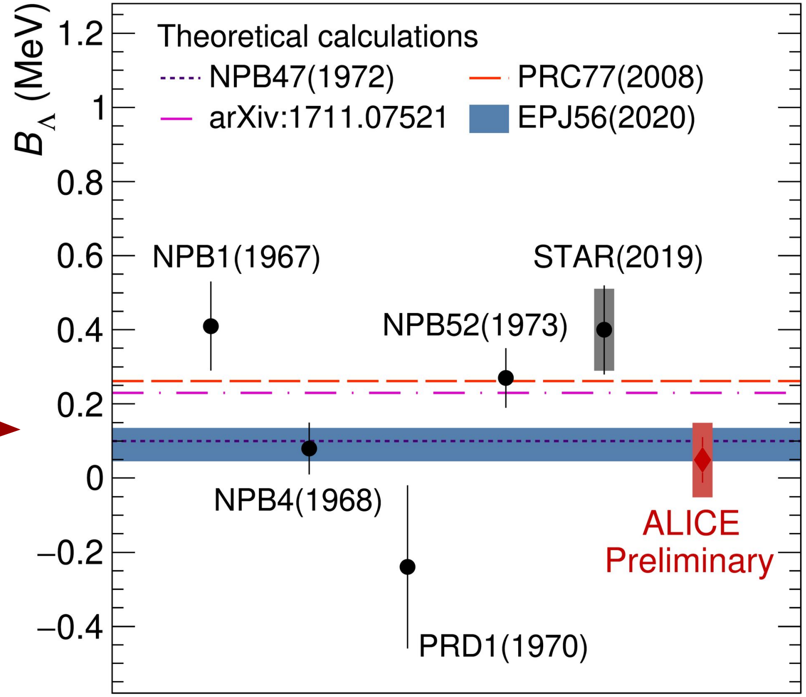


ALI-PREL-486366

B_Λ

- From the mass measurement to B_Λ
  - $$B_\Lambda = M_\Lambda + M_{\rm d} - M_{^3_\Lambda{\rm H}}$$
- Weakly bound nature of $^3_\Lambda$H is confirmed by the latest ALICE measurement
  - B_Λ compatible with zero
  - in agreement within 1σ with Dalitz and χEFT based predictions
  - fully consistent with the lifetime measurement according to recent theoretical calculations [1,2]

New @ QM



ALI-PREL-486370

[1] Hildenbrand F. et al., *Physical Review C*, vol. 102, no. 6, Dec. 2020
[2] Pérez-Obiol A., *Physics Letters B*, vol. 811, Dec. 2020

Hypertriton in small systems

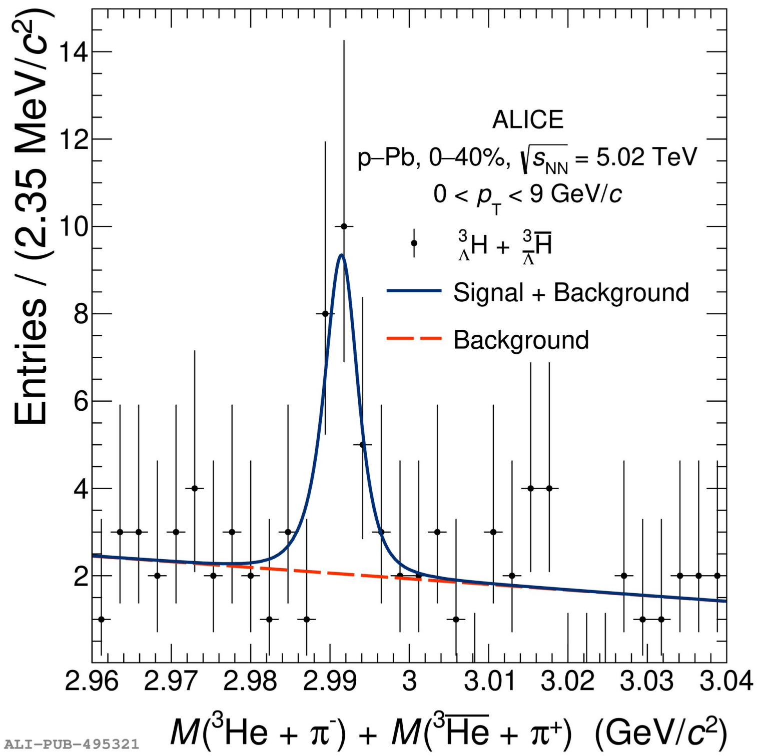
First measurements of ${}^{3}_{\Lambda}H$ production in pp and p-Pb collisions

$^{3}_{\Lambda}$H selection in pp and p-Pb collisions

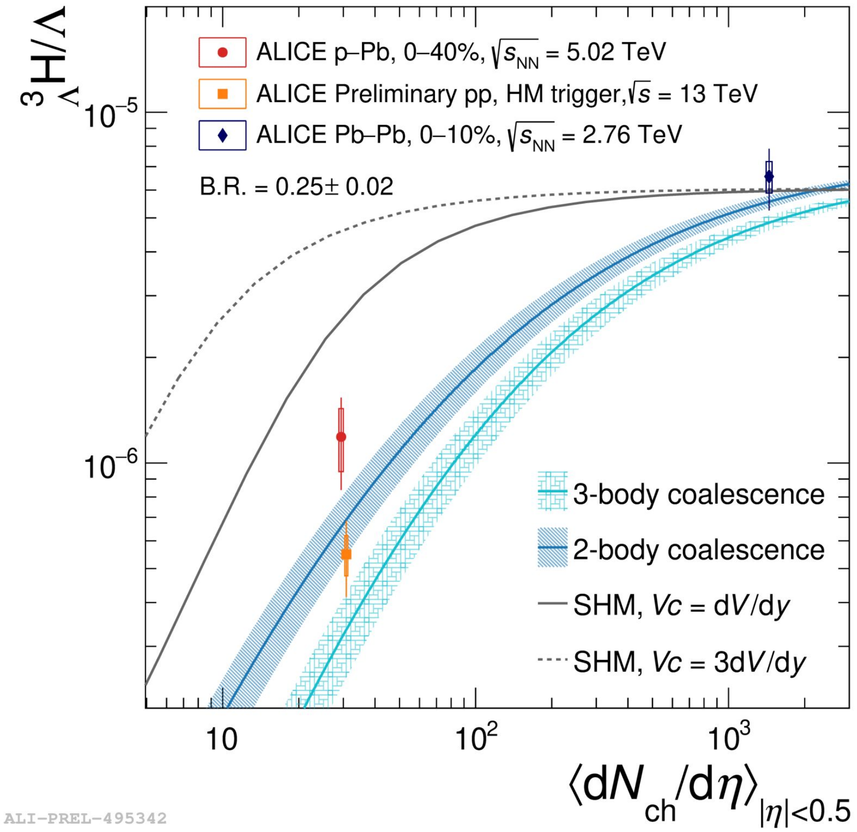
- Data samples:
  - pp at $\sqrt{s}$ = 13 TeV and p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV collisions collected during Run 2
- $^{3}_{\Lambda}$H selection in pp: trigger on high multiplicity events using V0 detectors + topological cuts on triggered events
- $^{3}_{\Lambda}$H selection in p-Pb: 40% most central collisions + BDT Classifier
- Significance > 4σ both in pp and p-Pb

New @ QM

ALICE, arXiv:2107.10627 (2021)



$^{3}_{\Lambda}H$ / Λ in pp and p-Pb collisions



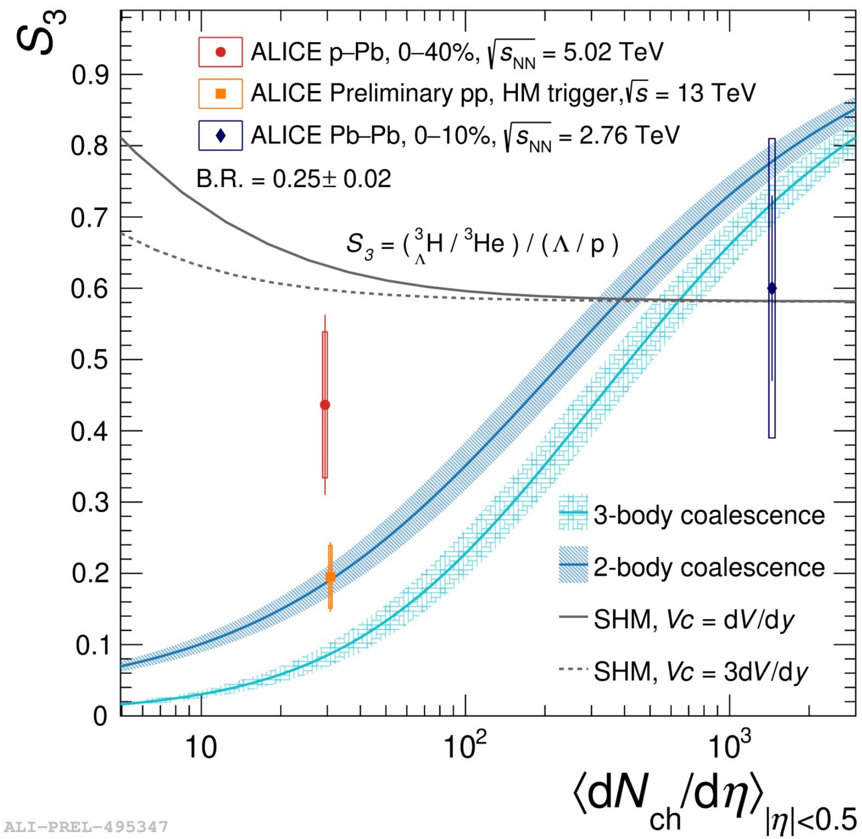
New @ QM

- $^{3}_{\Lambda}H$ / Λ in small systems:
  - large separation between production models
  - **measurements in good agreement with 2-body coalescence [2]**
  - tension with SHM [1] at low charged-particle multiplicity density
    - configuration with V_C = 3d*V*/d*y* is excluded at level of more than 6σ

ALICE, arXiv:2107.10627 (2021)

[1] Vovchenko, et al., *Phys. Lett., B785, 171-174,* (2018)
[2] Sun. et al., *Phys. Lett. B, 792, 132–137,* (2019)

S_3 in pp and p-Pb collisions



New @ QM

- S_3 : strangeness population factor

$$({}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He})/(\Lambda/\mathrm{p})$$

- S_3 in small systems:
  - same conclusions as for ${}^{3}_{\Lambda}\mathrm{H} / \Lambda$ but with a lower sensitivity
  - **Run 3** will be crucial to finally distinguish between SHM [1] and coalescence [2] and explore the multiplicity dependence of S_3!

ALICE, arXiv:2107.10627 (2021)

[1] Vovchenko, et al., *Phys. Lett., B785, 171-174,* (2018)
[2] Sun. et al., *Phys. Lett. B, 792, 132–137,* (2019)

Summary and perspectives

- ${}^{3}_{\Lambda}H$ in large systems:
  - precise measurements of lifetime and B_{Λ} in Pb-Pb collisions
    - weakly bound nature of ${}^{3}_{\Lambda}H$ confirmed

- ${}^{3}_{\Lambda}H$ in small systems:
  - first measurement of ${}^{3}_{\Lambda}H$ production in pp and p-Pb collisions
  - concrete possibility to distinguish with high significance between the two nucleosynthesis mechanisms
    - it will be possible in Run 3!

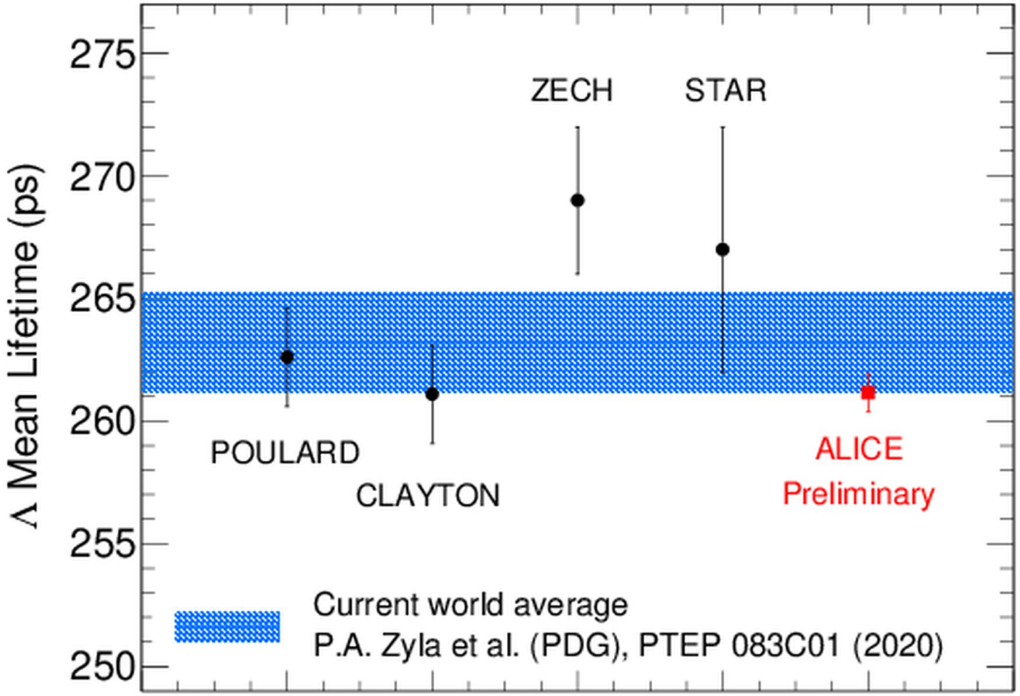
Thanks for your attention!

Backup

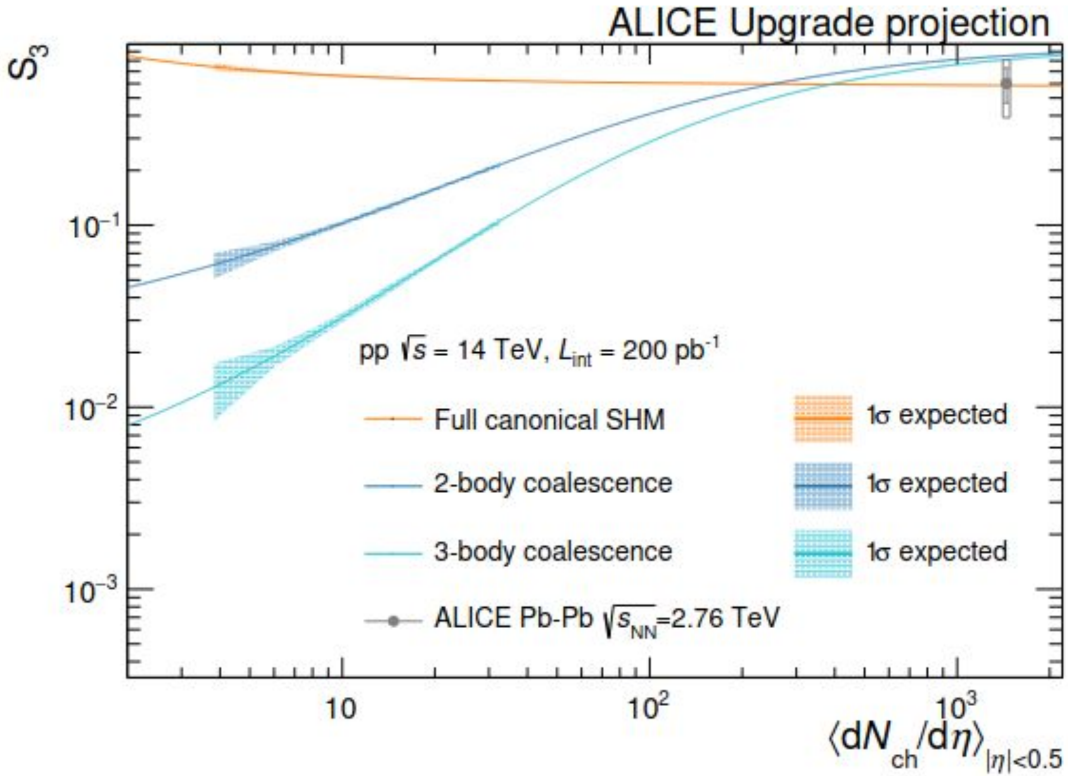
Precision measurement of the Λ lifetime

New @ QM

- Precision measurement of the Λ lifetime in ALICE
  - factor 3 more precise than the current world average taken from the PDG
  - important reference for hypertriton
  - confirms the excellent capabilities of the ALICE detector for lifetime measurements



Expected S_3 performance for Run 3



ALICE Run 3 pp program public note