Creation of fragile anti-matter at the LHC

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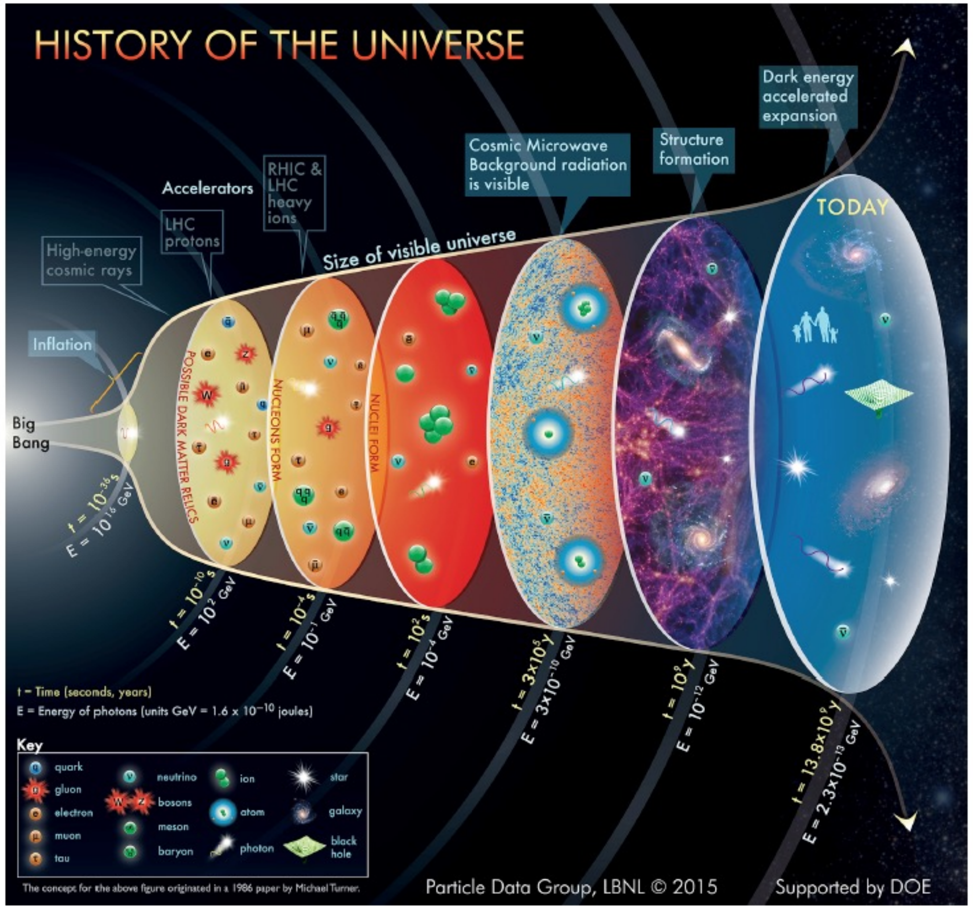
Joint THEIA-STRONG2020 and JAEA/Mainz REIMEI Web-Seminar
15.12.2021

Probing the emergence of the universe at the LHC

As far as we know…

- Universe was created in a „Big Bang“
- An expansion of time and space started
- In the beginning, Quarks and Gluons were deconfined in a hot, dense environment.
- While freezing out, hadrons were formed which built nuclei and later the galaxies, stars and planets that we know (or not).



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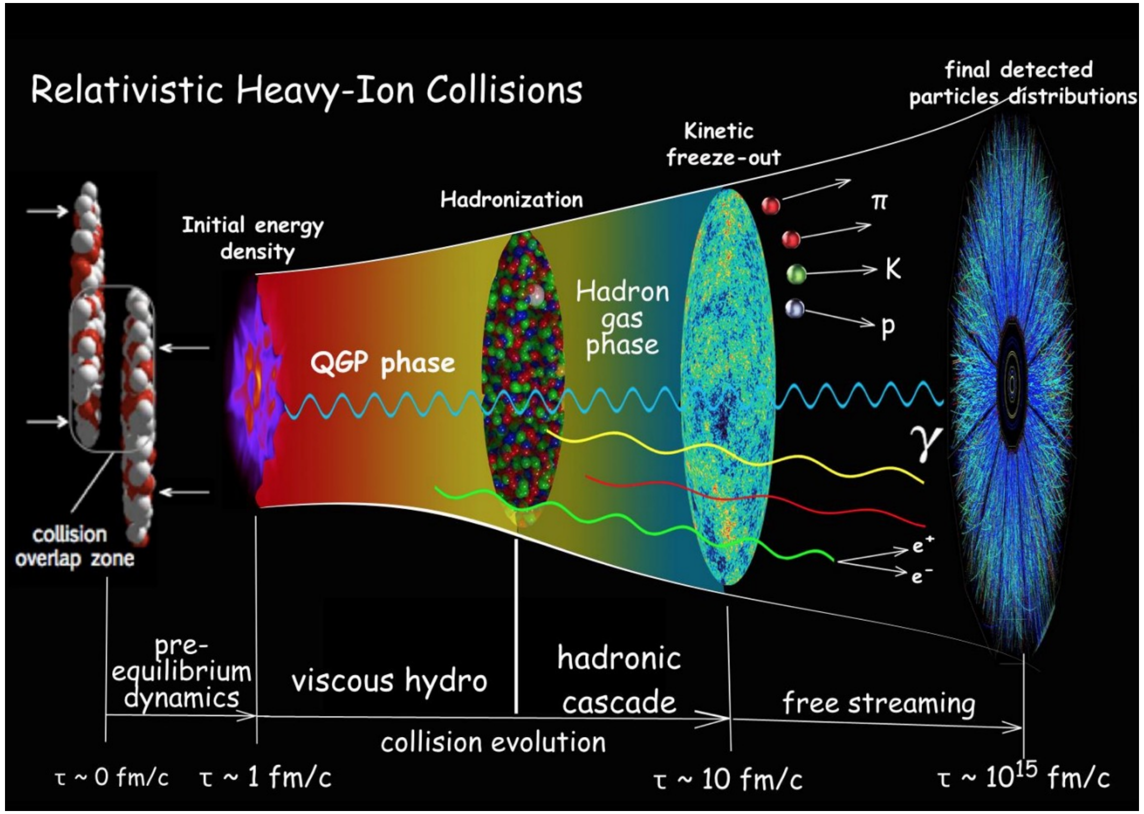
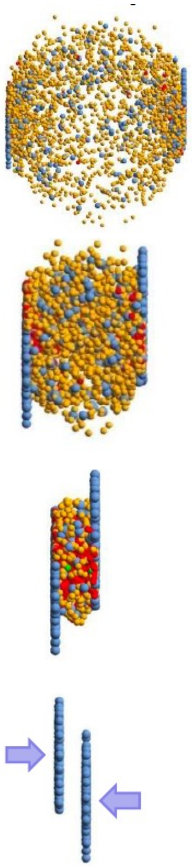
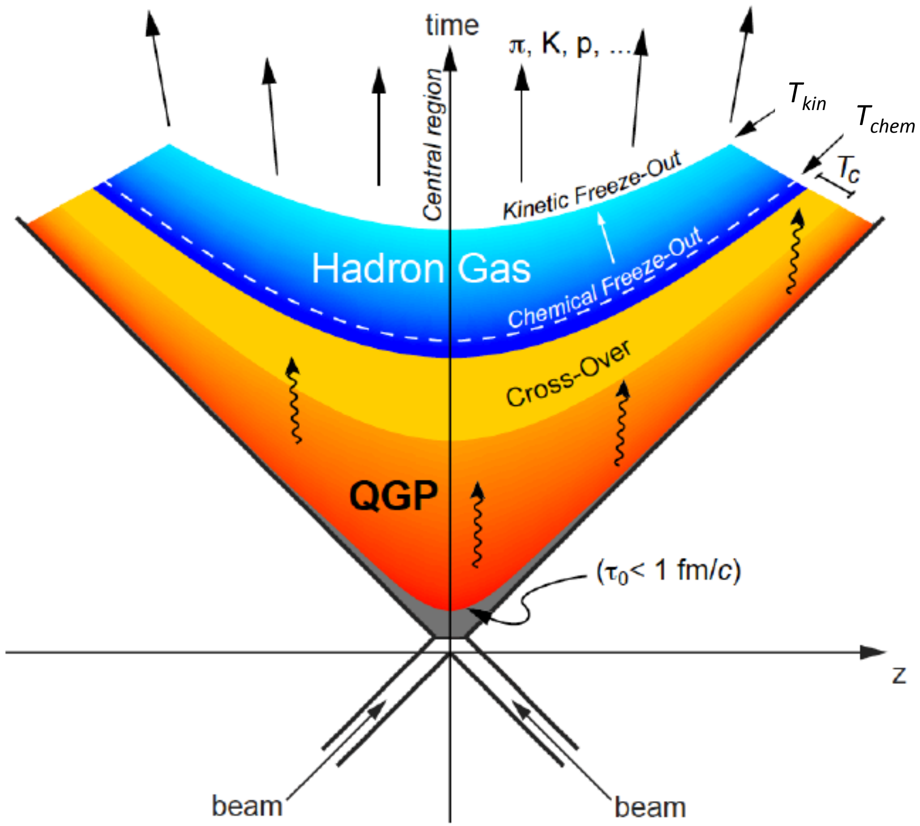


Probing the emergence of the universe at the LHC

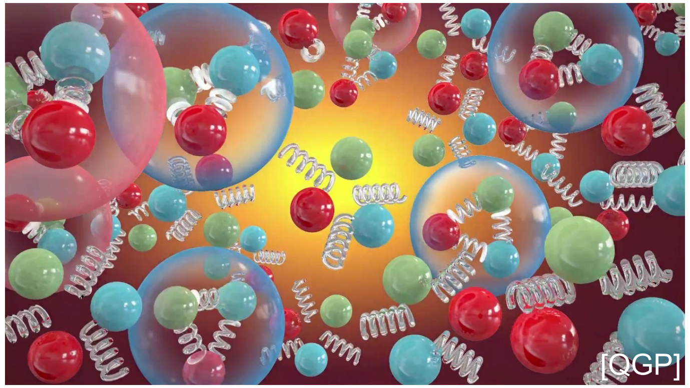
At the LHC…

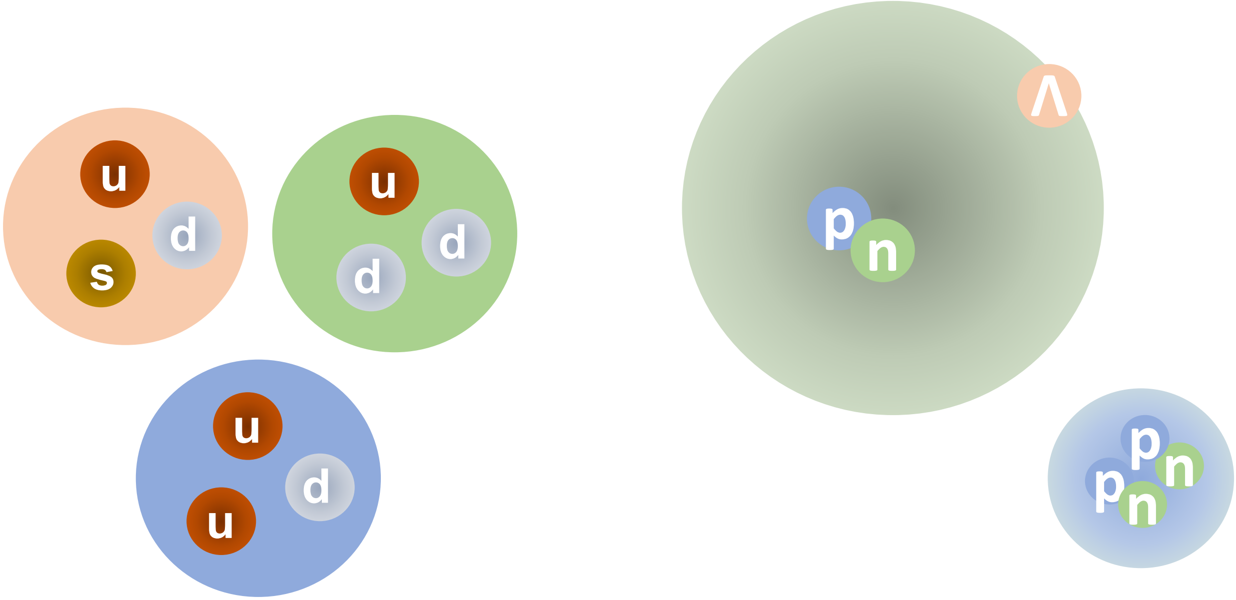
- After a pre-equilibrium state a hot, dense environment is created in Pb-Pb collisions.
- QGP (Quark-Gluon-Plasma): deconfined, thermalized state of quarks and gluons
- QGP „freezes-out“ in two stages:
  - chemical freeze-out: number of produced particles is stable
  - kinetic freeze-out: hadrons stop scattering





Hyperons and Hypernuclei





From a „soup“ of quarks and gluons

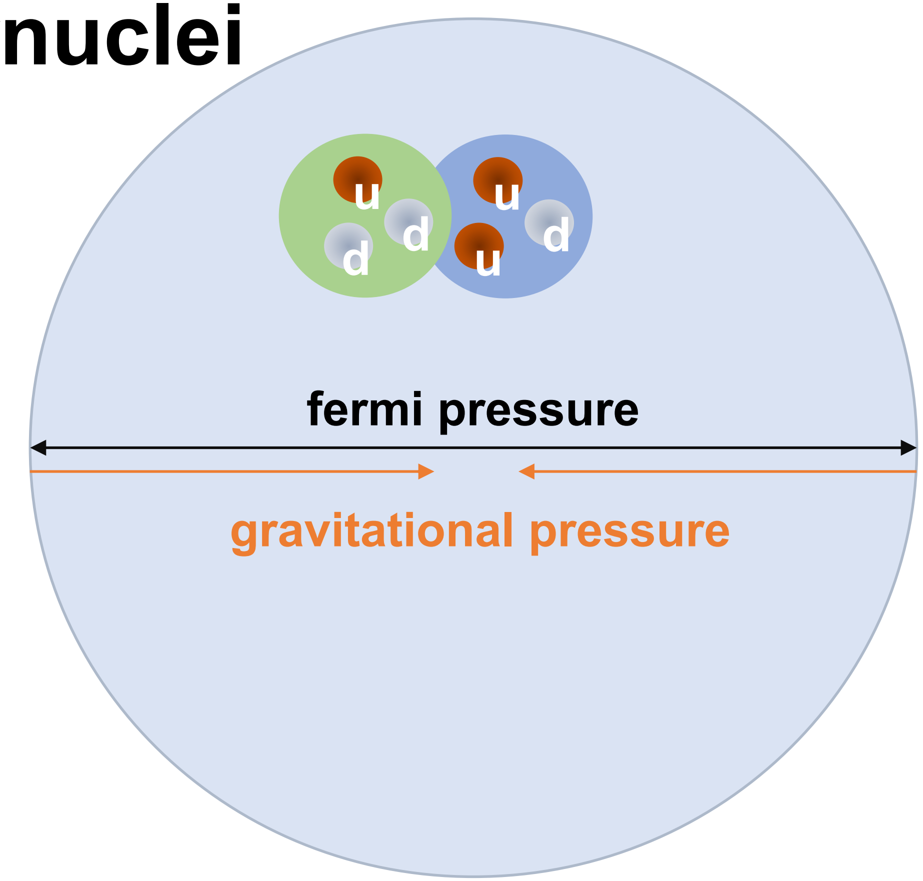
to baryons

to bound (hyper-)nuclei

understanding the
hot and dense QGP

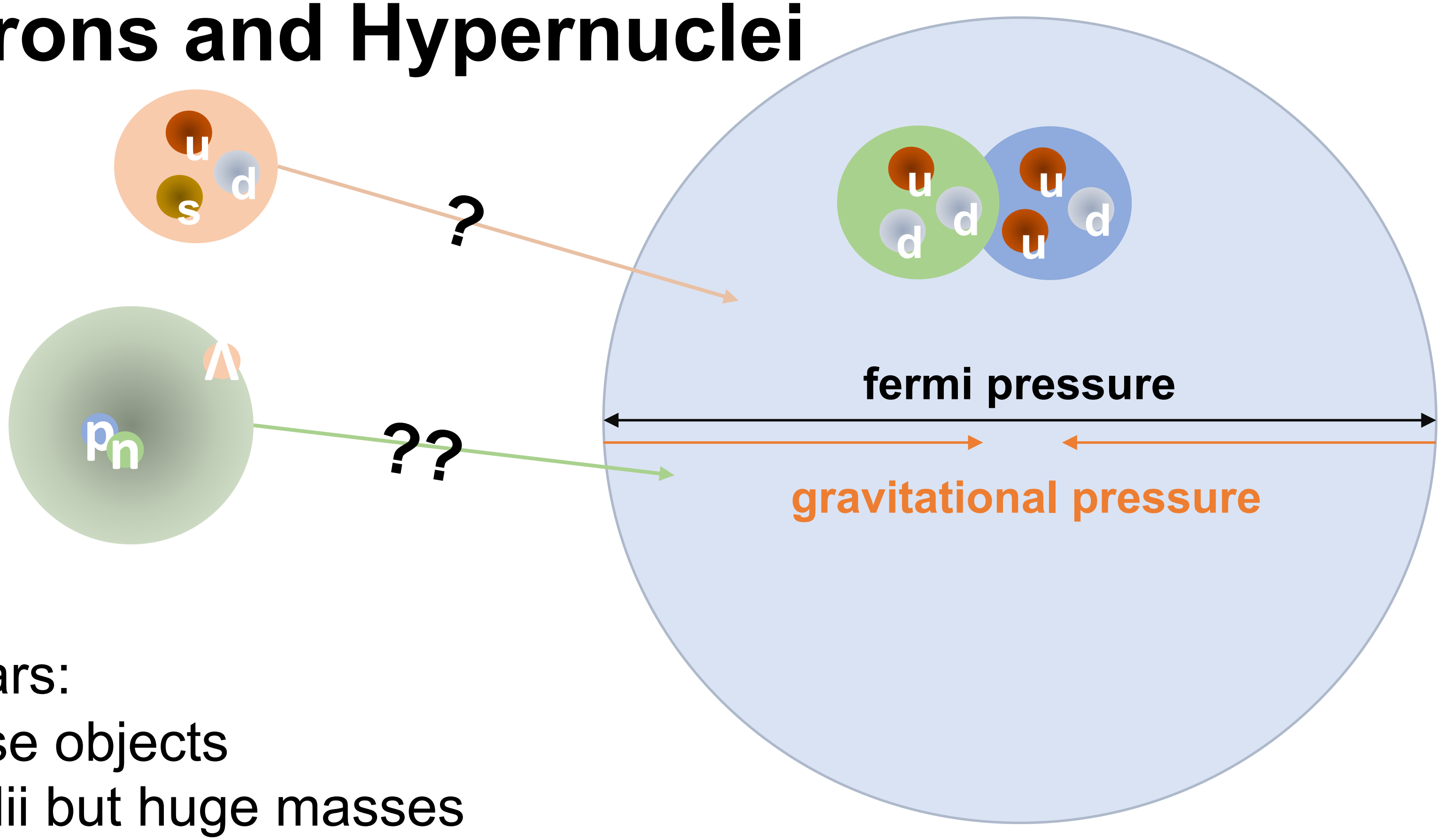
understanding the formation of
(hyper-)nuclei

Hyperons and Hypernuclei



Neutron Stars:
- Hot, dense objects
- Small radii but huge masses
- Stabilized through fermi pressure

Hyperons and Hypernuclei



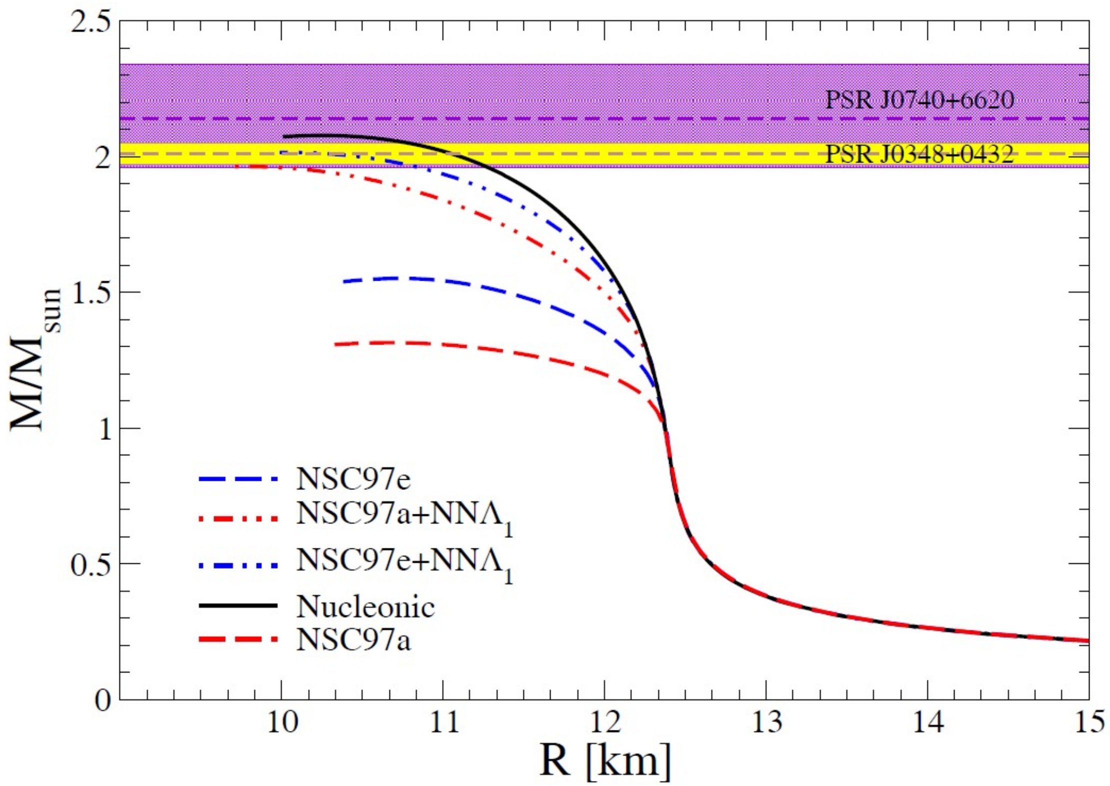
Neutron Stars:

- Hot, dense objects
- Small radii but huge masses
- Stabilized through fermi pressure
- Putting hyperons (or even hypernuclei) in it → Opens up a new potential for strange matter

Hyperons and Hypernuclei

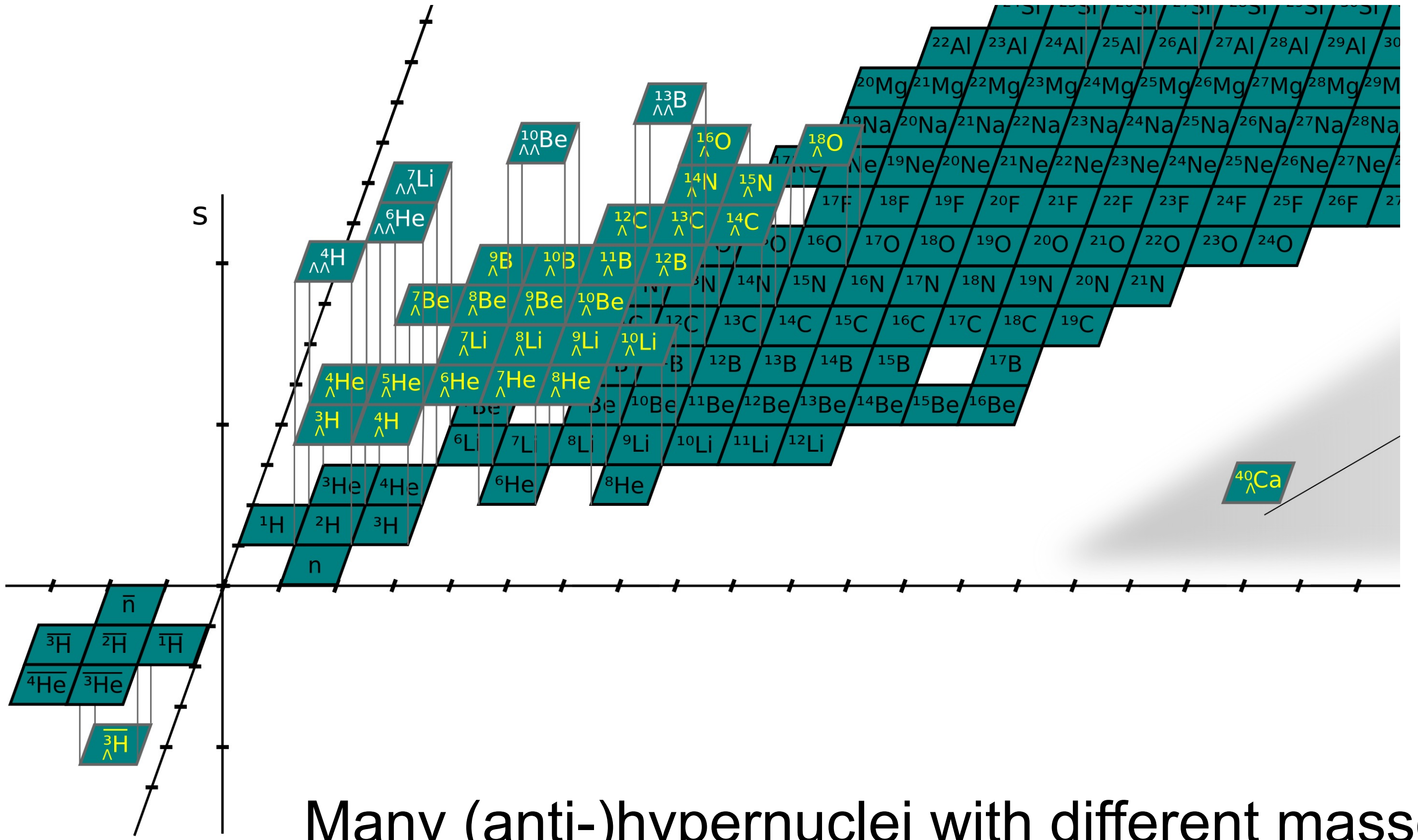
- Formation of (hyper-)nuclei
  (in the early universe, in HIC)
- Hyperons/Hypernuclei
  in neutron stars?
- Equation of State?

- Improve the understanding
  of Y-Y and Y-N interaction



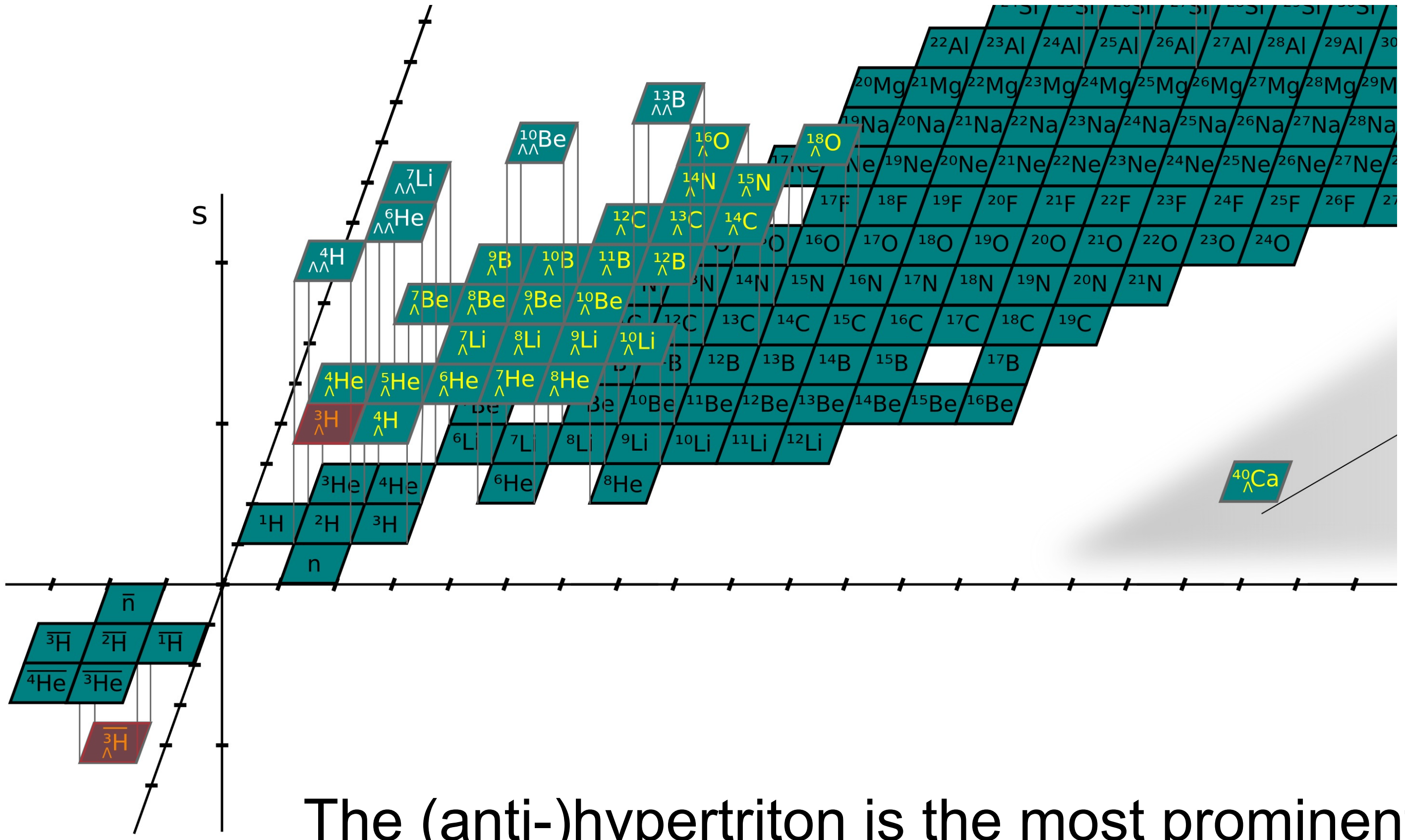
D. Logoteta, I. Vidana, I. Bombaci, Eur. Phys. J. A (2019) 55: 207

Hyperons and Hypernuclei



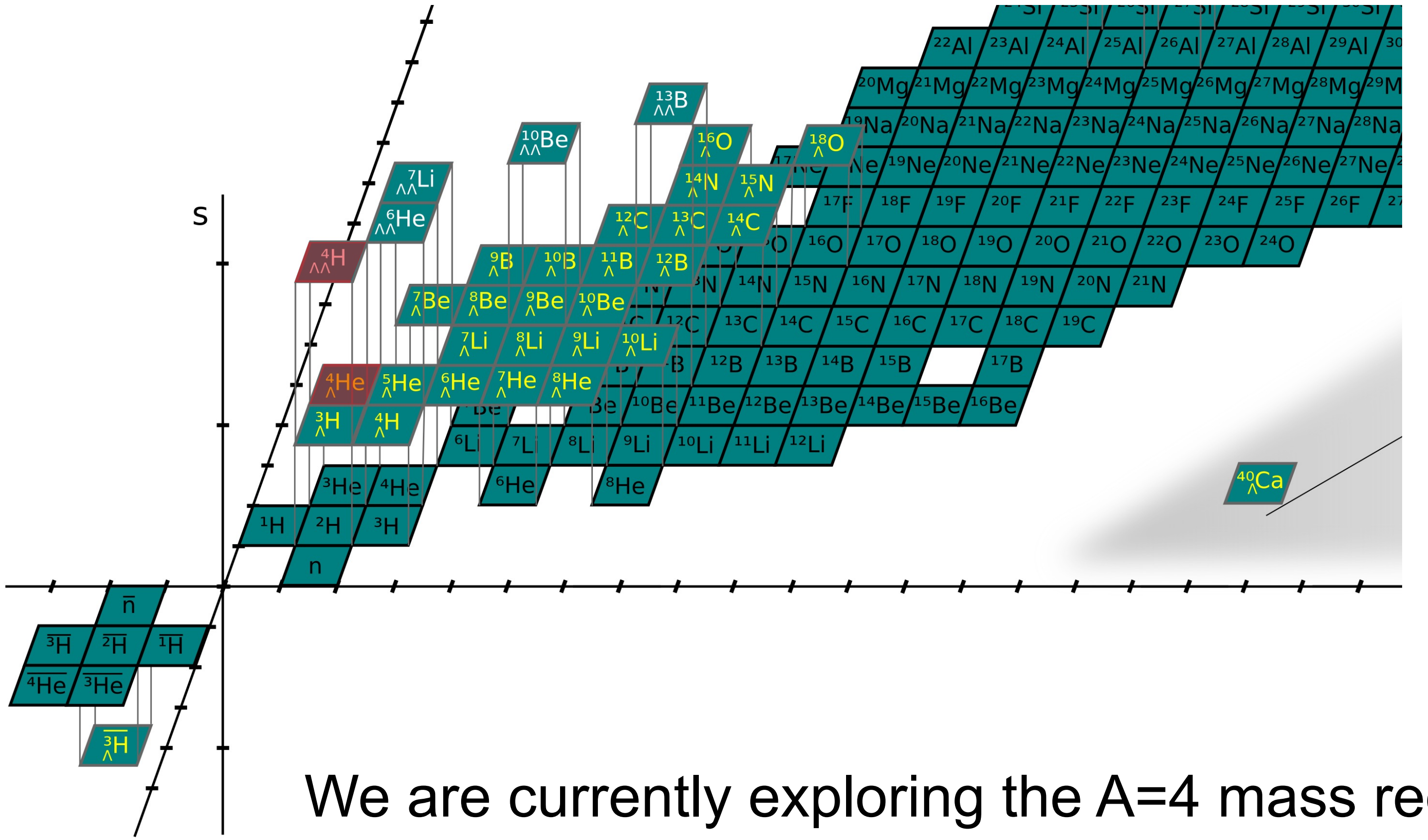
Many (anti-)hypernuclei with different masses and properties…

Hyperons and Hypernuclei



The (anti-)hypertriton is the most prominent one.

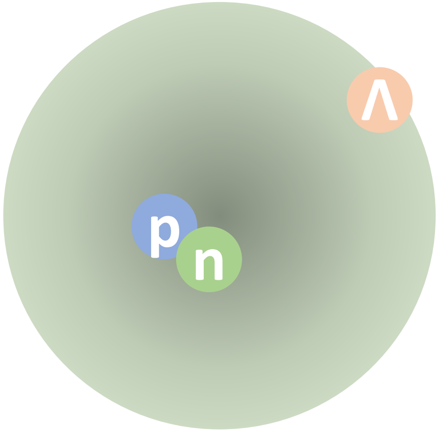
Hyperons and Hypernuclei



We are currently exploring the A=4 mass region.
This is ongoing work…

Hypertriton

- Λ, p, n bound state
- Lightest known hypernucleus and very loosely bound
- Mass ≈ 2.991 GeV/c^2
- Λ separation energy ≈ 130 keV
- Recent calculations predict a large radius for the hypertriton wave function. *[F. Hildenbrand, H.-W. Hammer, Phys. Rev. C 100, 034002]*



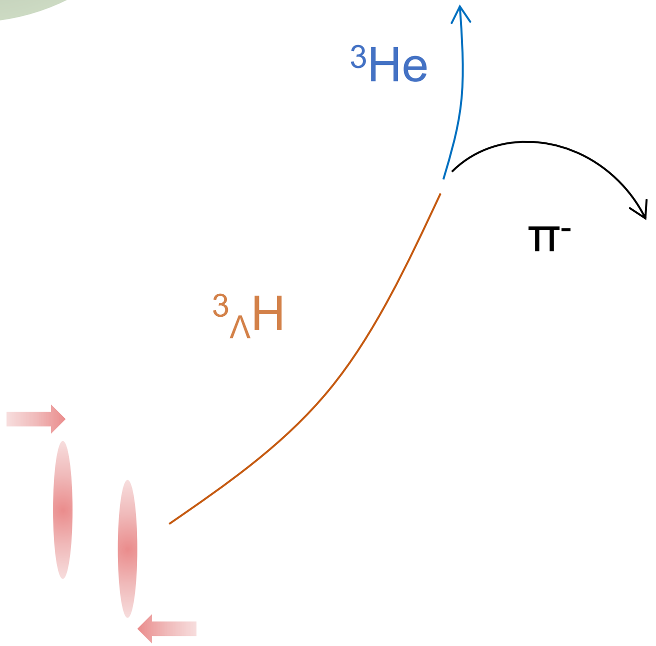
- Decay modes:

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

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

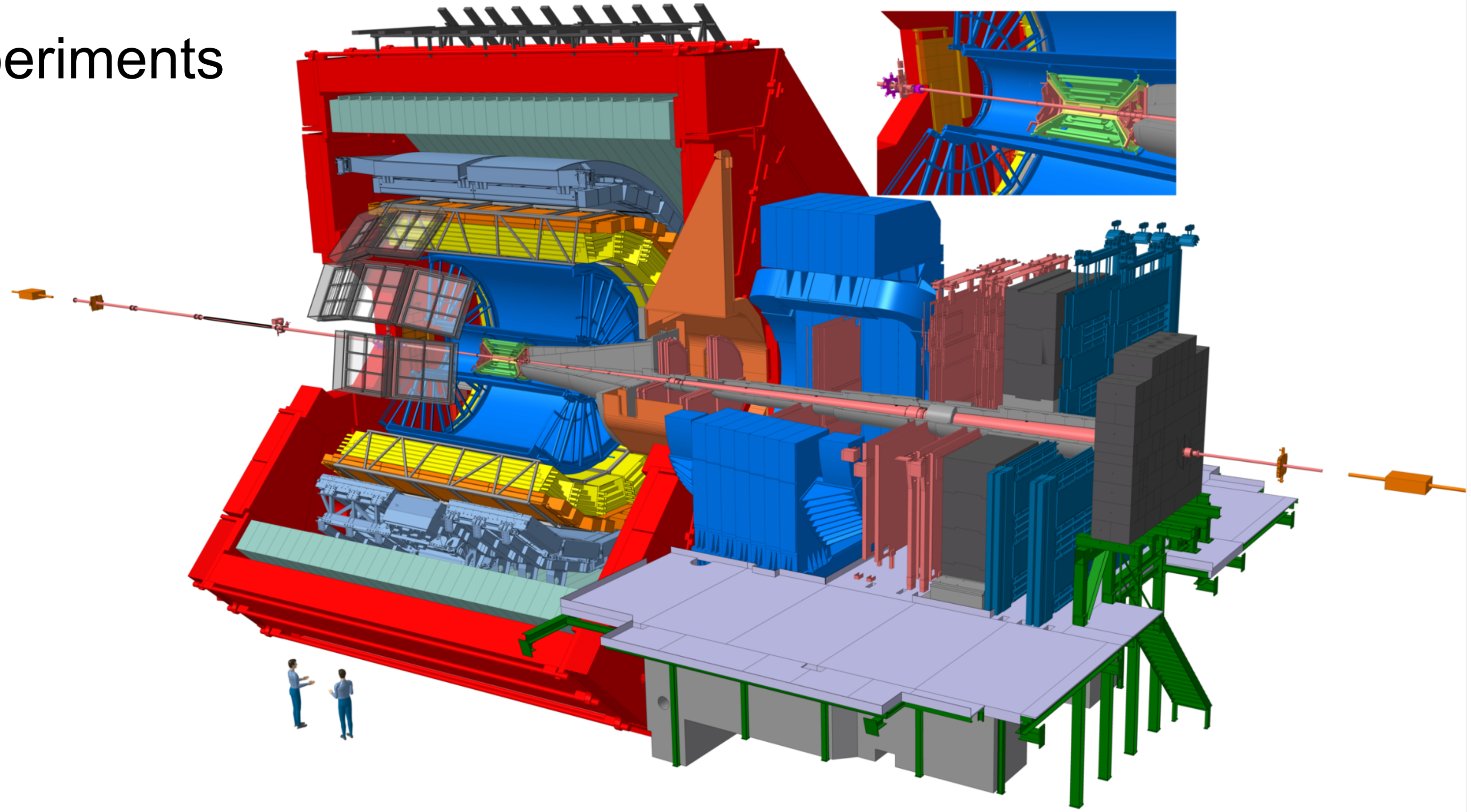
$^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$

$^{3}_{\Lambda}H \rightarrow d + p + \pi^{0}$



ALICE detector

- One of the four major LHC experiments
- Specialized in tracking and particle identification from low to high momenta using different detector technologies



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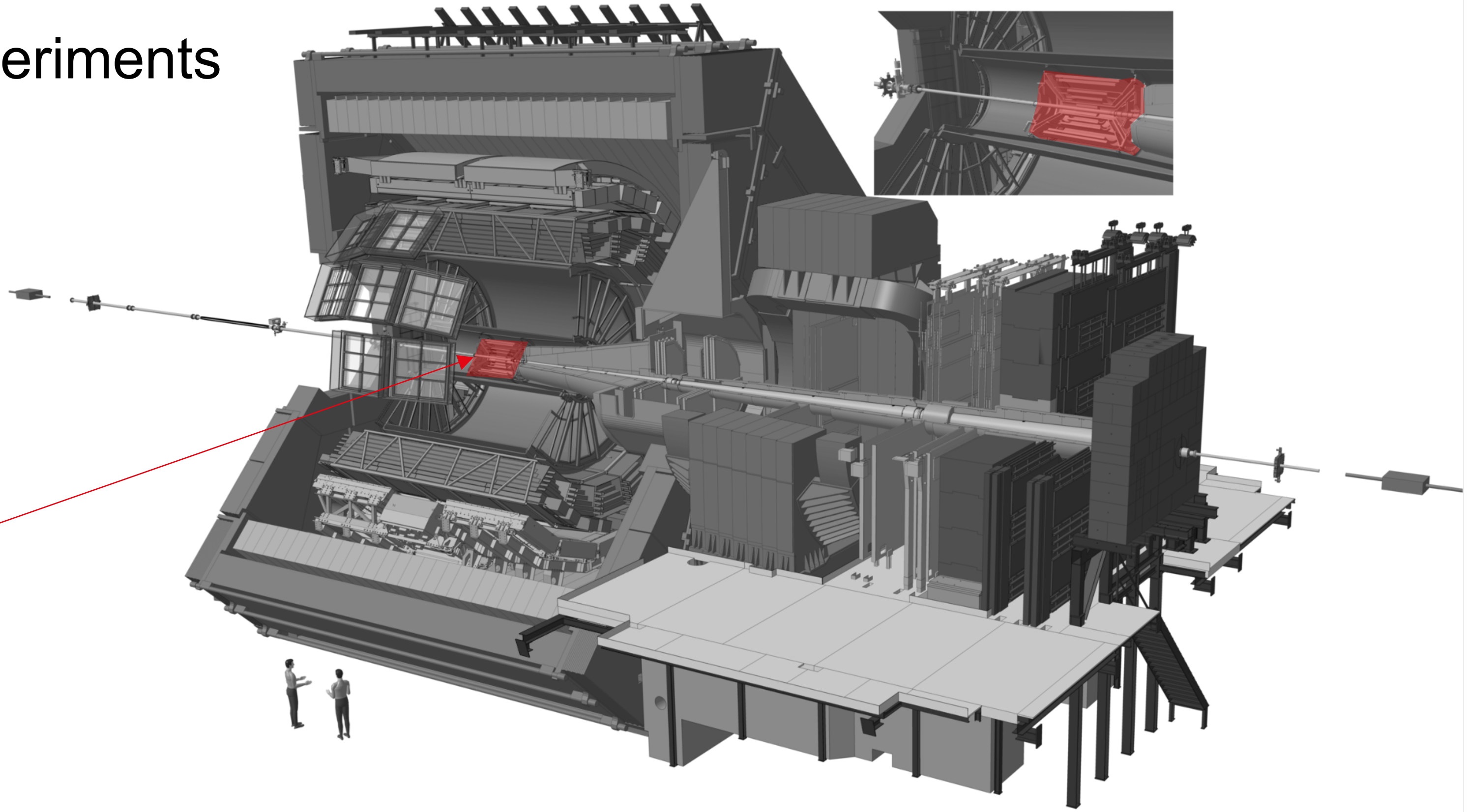

ITS (Inner Tracking System)

- Reconstruction of primary and decay vertices
- Track reconstruction
- Particle identification for low momentum particles

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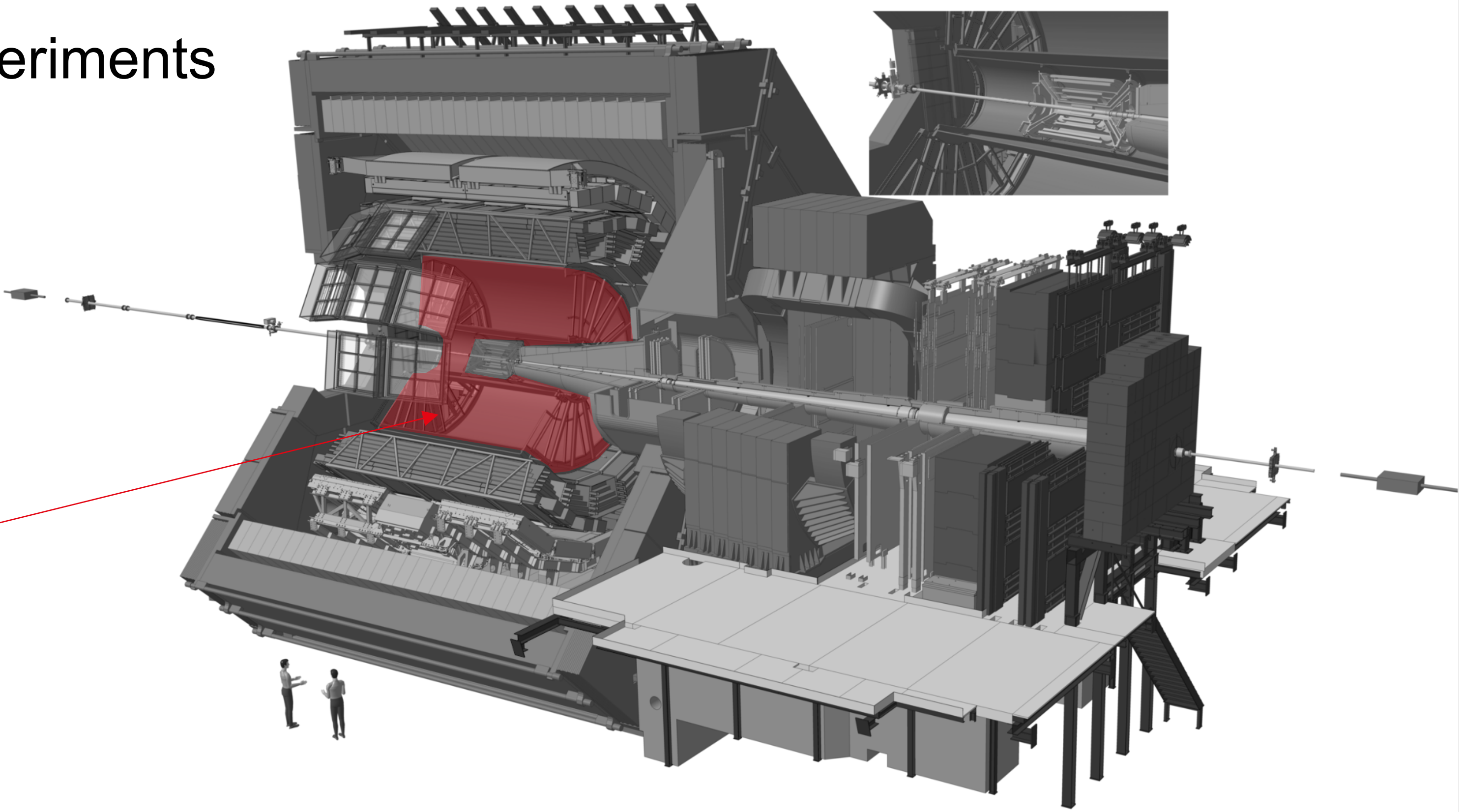

TPC (Time Projection Chamber)

- Tracking
- Particle identification via dE/dx measurement

ALICE detector

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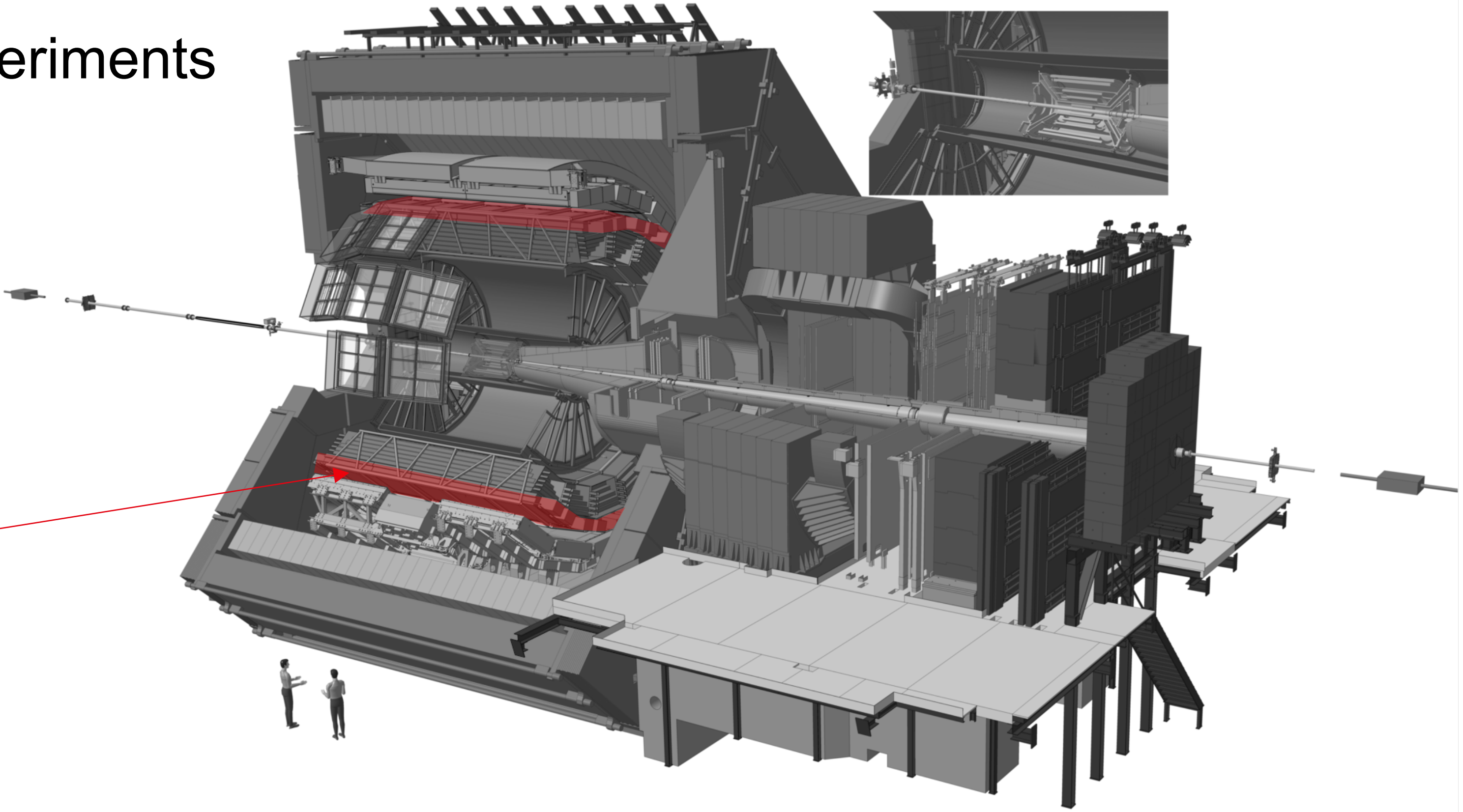
TOF detector (Time Of Flight)

- Particle identification with time-of-flight measurement



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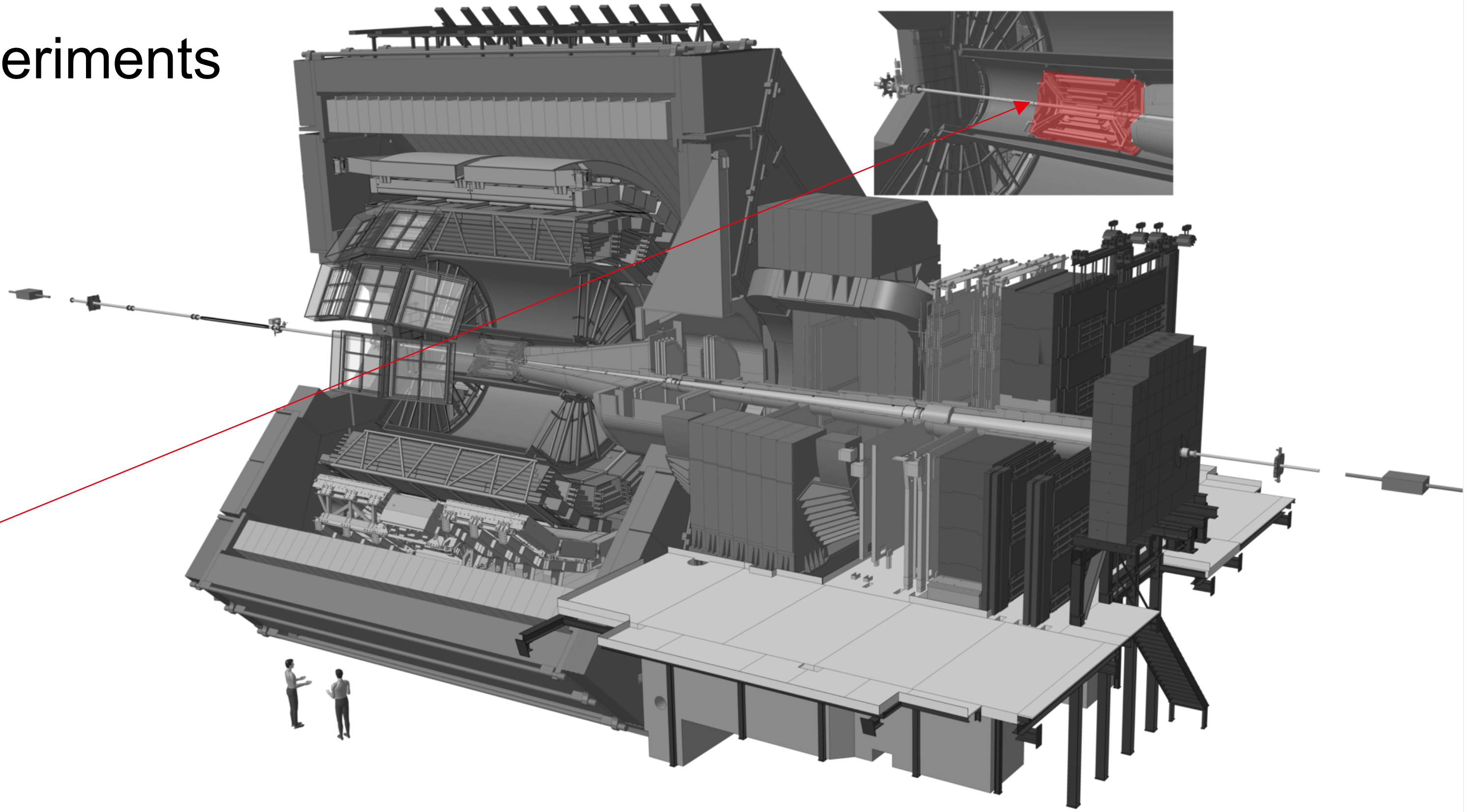


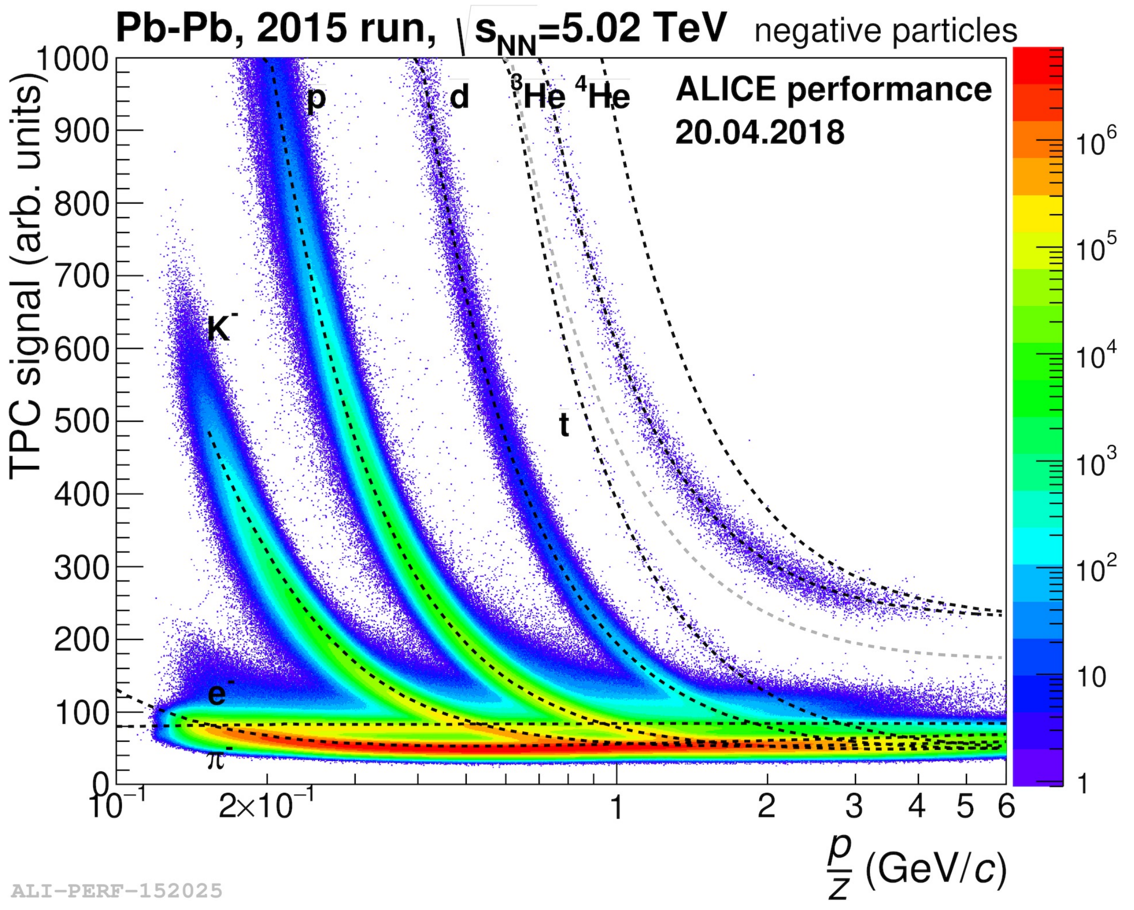
V0 detectors

- Centrality / multiplicity determination
- Trigger

Hypertriton reconstruction

- **Step 1**: find and identify the daughter particle tracks

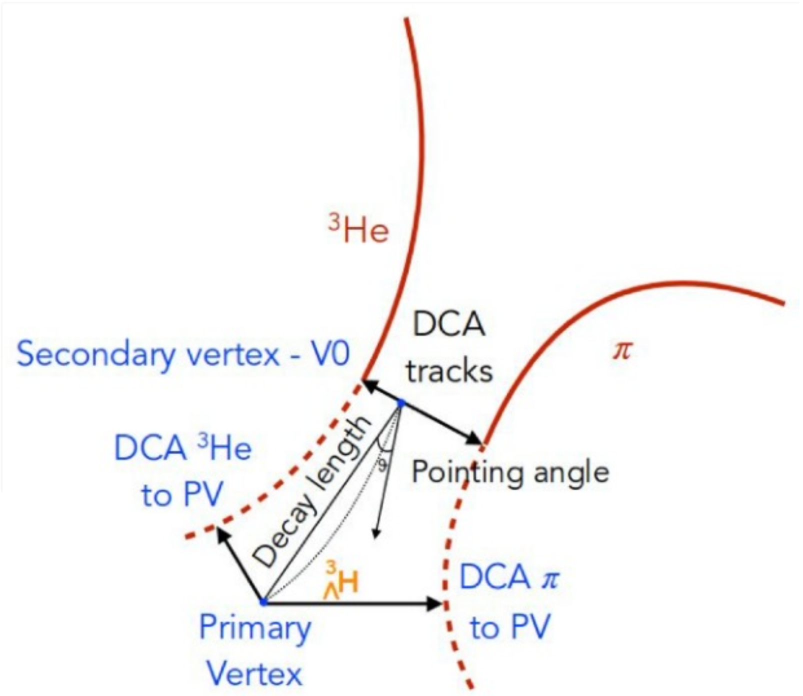
  - Using the TPC PID via the specific energy loss
  - Excellent separation of different particle species



Hypertriton reconstruction

- **Step 1**: find and identify the daughter particle tracks
- **Step 2**: reconstruct the decay vertex of the hypertriton

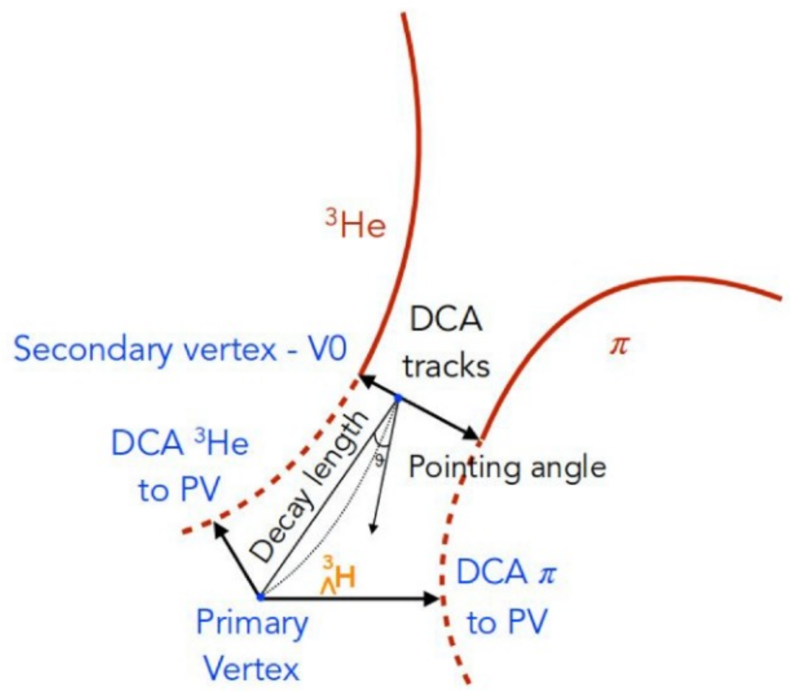
  - The identified daughters are assumed to come from a common vertex.
  - Their tracks are matched by algorithms to find the best possible decay vertex.



- Problem: huge combinatorial background
- Solution: topological and kinematical cuts or machine learning approach

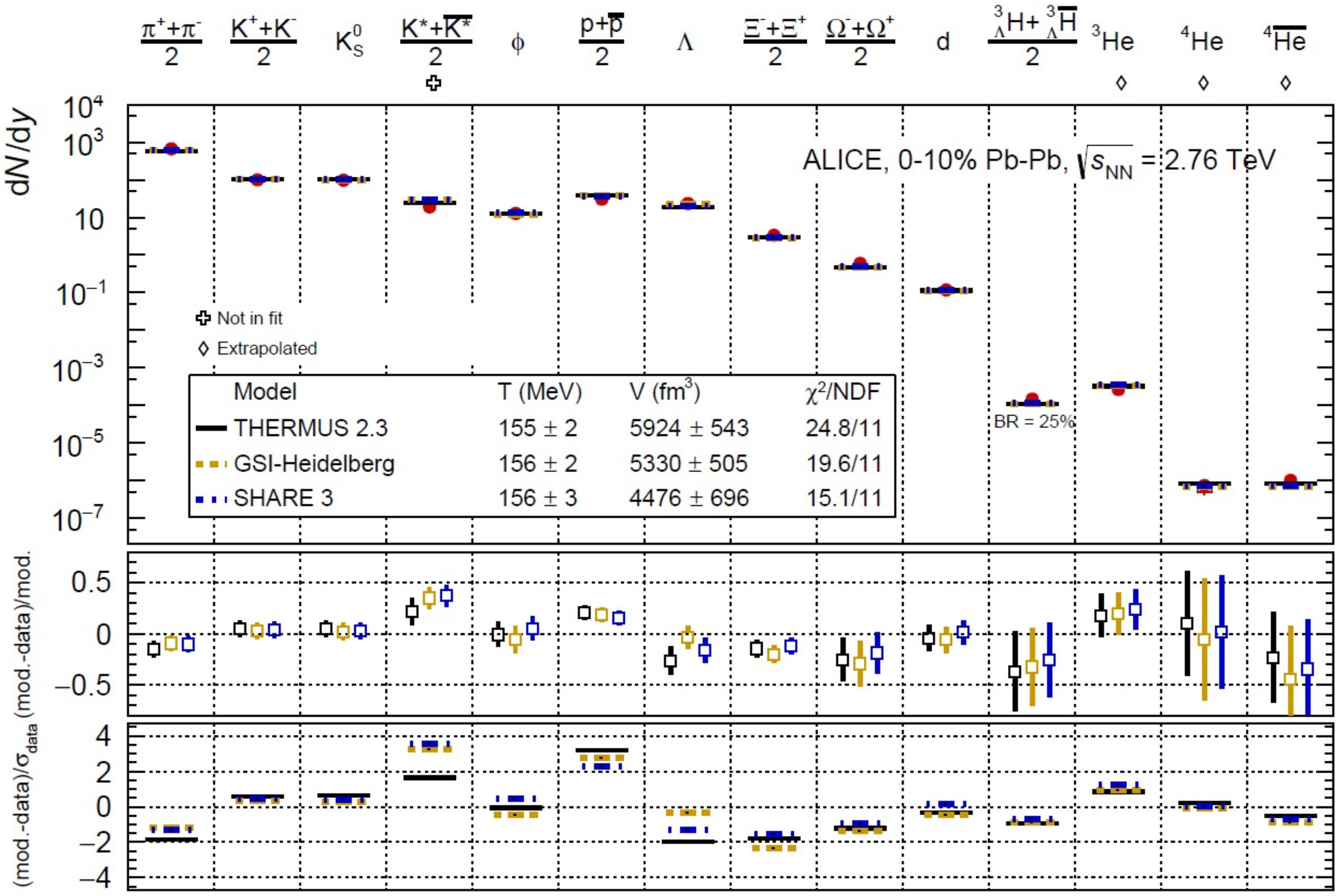
Hypertriton reconstruction

- **Step 1**: find and identify the daughter particle tracks
- **Step 2**: reconstruct the decay vertex of the hypertriton
- **Step 3**: applying corrections
  - Tracking efficiency and detector acceptance
  - Assuming a branching ratio of 25%



Hypertriton production

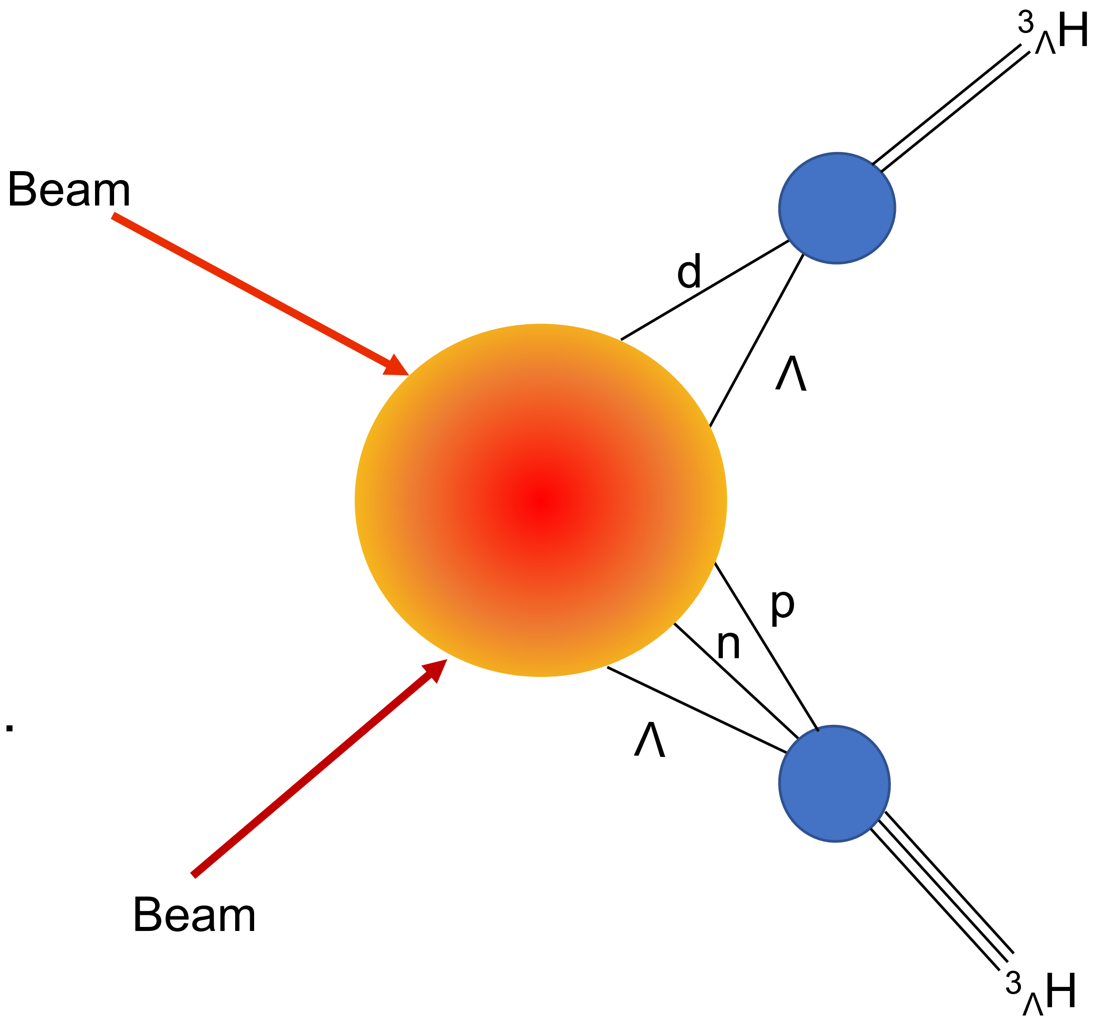
- Hypertriton production in heavy-ion collisions since LHC Run 1
- Integrated yield well described by the Statistical Hadronization Model (SHM)
- SHM assumes hadron abundances from statistical equilibrium at the common chemical freeze-out temperature T_{ch} = 156 MeV.
How hypernuclei can survive in this environment is not clear.



ALICE Collaboration, S. Acharya et al., "Production of ^{4}He and $^4\overline{He}$ in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV at the LHC", Nucl. Phys. A 971 (2018) 1–20, arXiv:1710.07531 [nucl-ex]

Hypertriton production

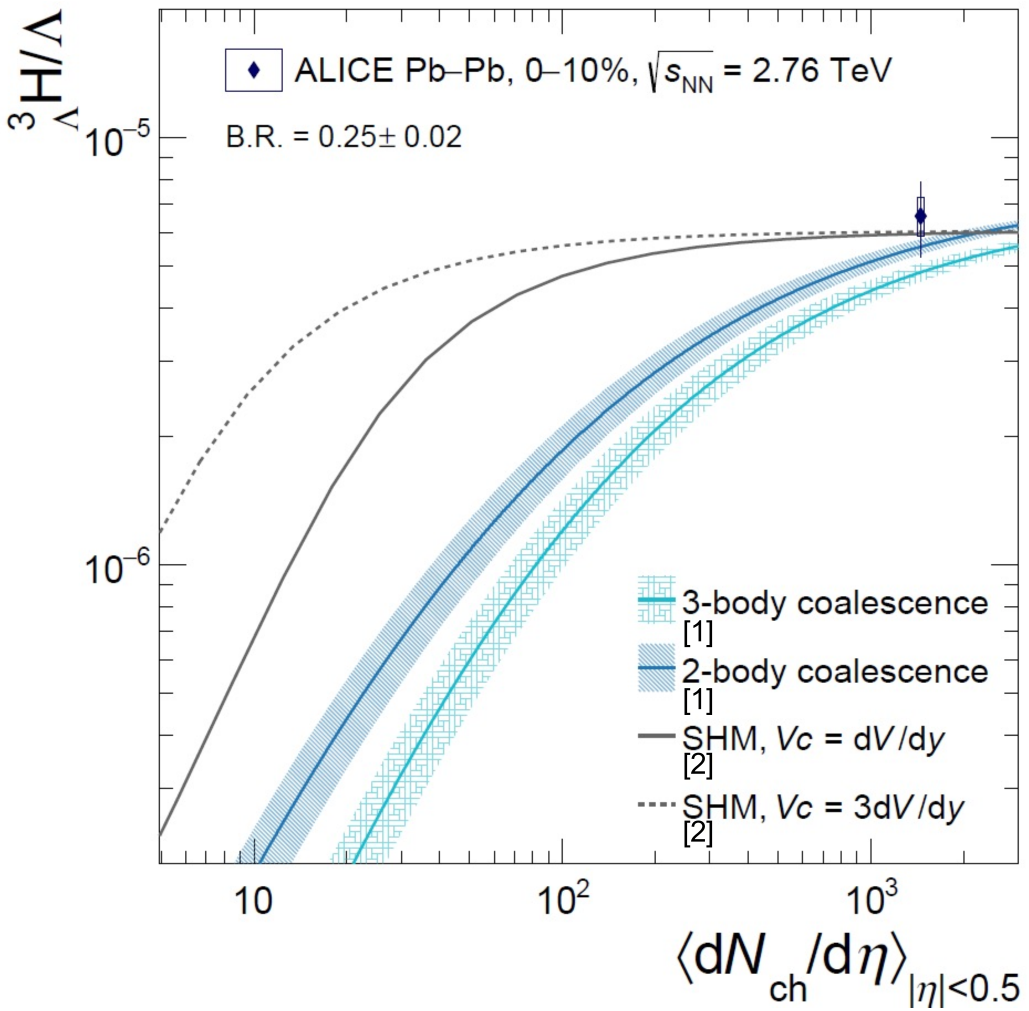
- Hypertriton production in heavy-ion collisions since LHC Run 1
- Coalescence Model:
  Nucleons that are close in phase space at the freeze-out can form a nucleus via coalescence.
  The key concept is the overlap between the nuclear wave functions and the phase space of the nucleons.



Hypertriton production

- $^{3}_{\Lambda}H$ / Λ ratio vs. multiplicity

- Extremely sensitive to the nuclei production mechanism:
  - In statistical hadronization models (SHM) the object size is not taken into account.
  - In a coalescence picture large suppression of the production in small systems expected.



Hypertriton production

- $S_3 = ({}^{3}_{\Lambda}H \,/\, {}^{3}He) \,/\, (\Lambda \,/\, p)$ vs. multiplicity

- Strangeness population factor for the measurement of baryon-strangeness correlations
- Extremely sensitive to the nuclei production mechanism:
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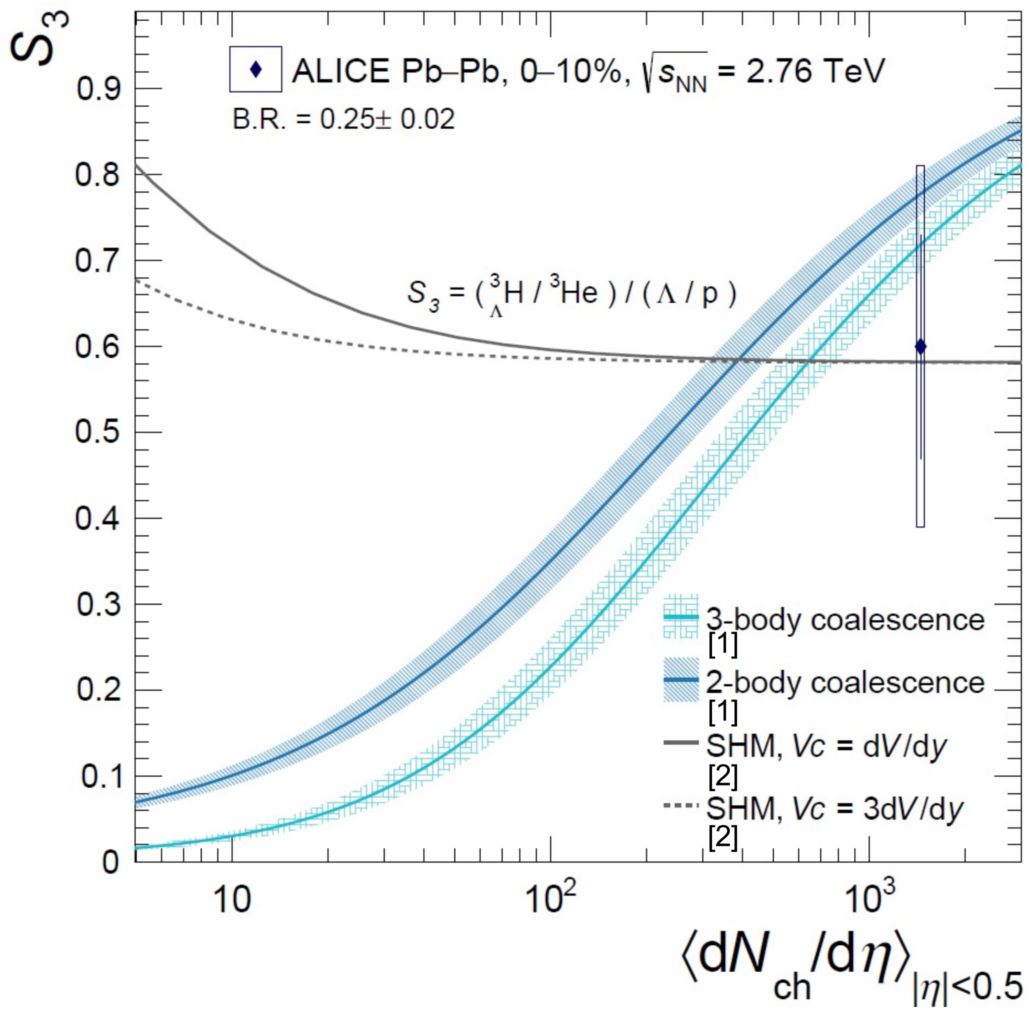
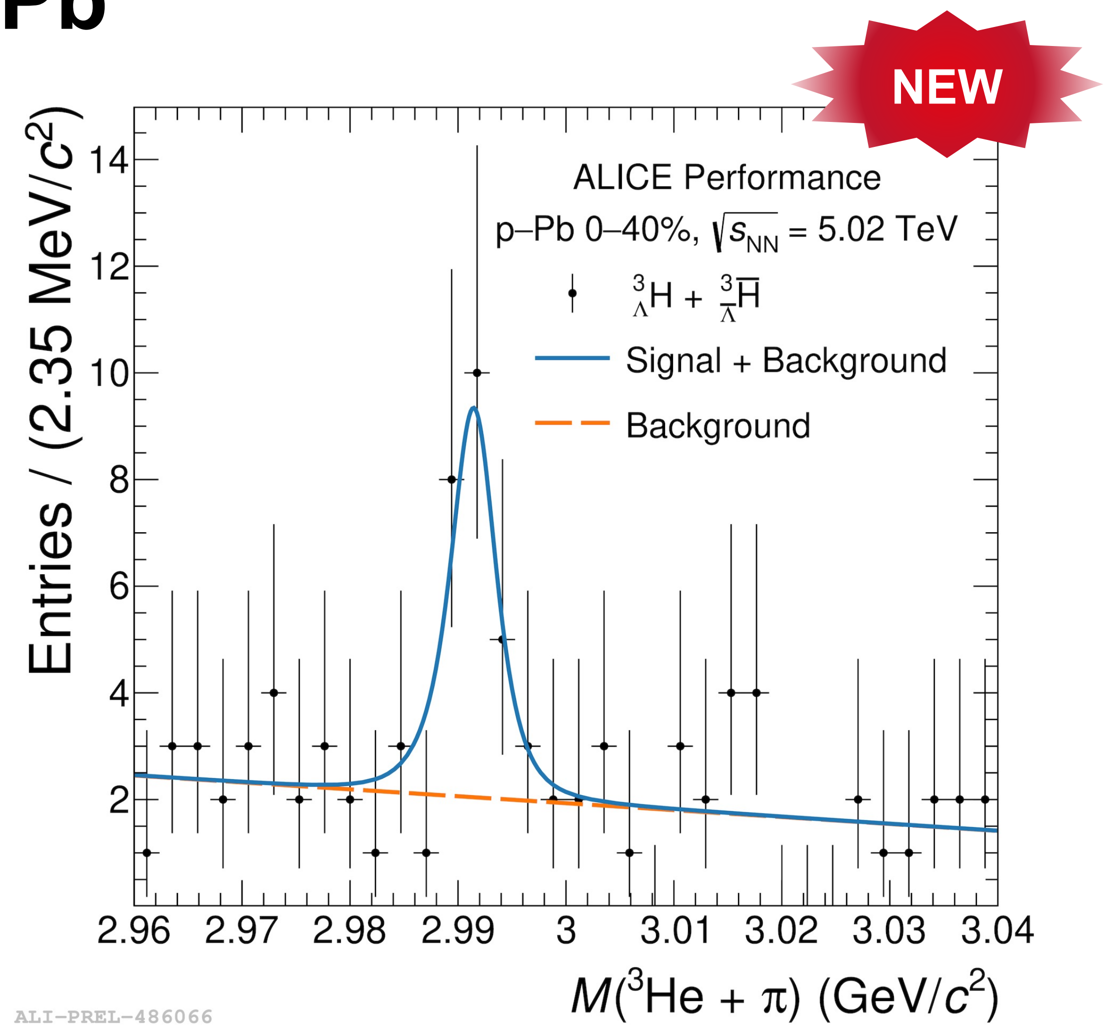
  - In a coalescence picture large suppression of the production in small systems expected.



Hypertriton measurement in p-Pb

- First measurement of the hypertriton in Run 2 p-Pb collisions at 5.02 TeV
- Signal extraction by using a machine learning approach
- Using a boosted decision tree (BDT) and hyper parameter optimisation



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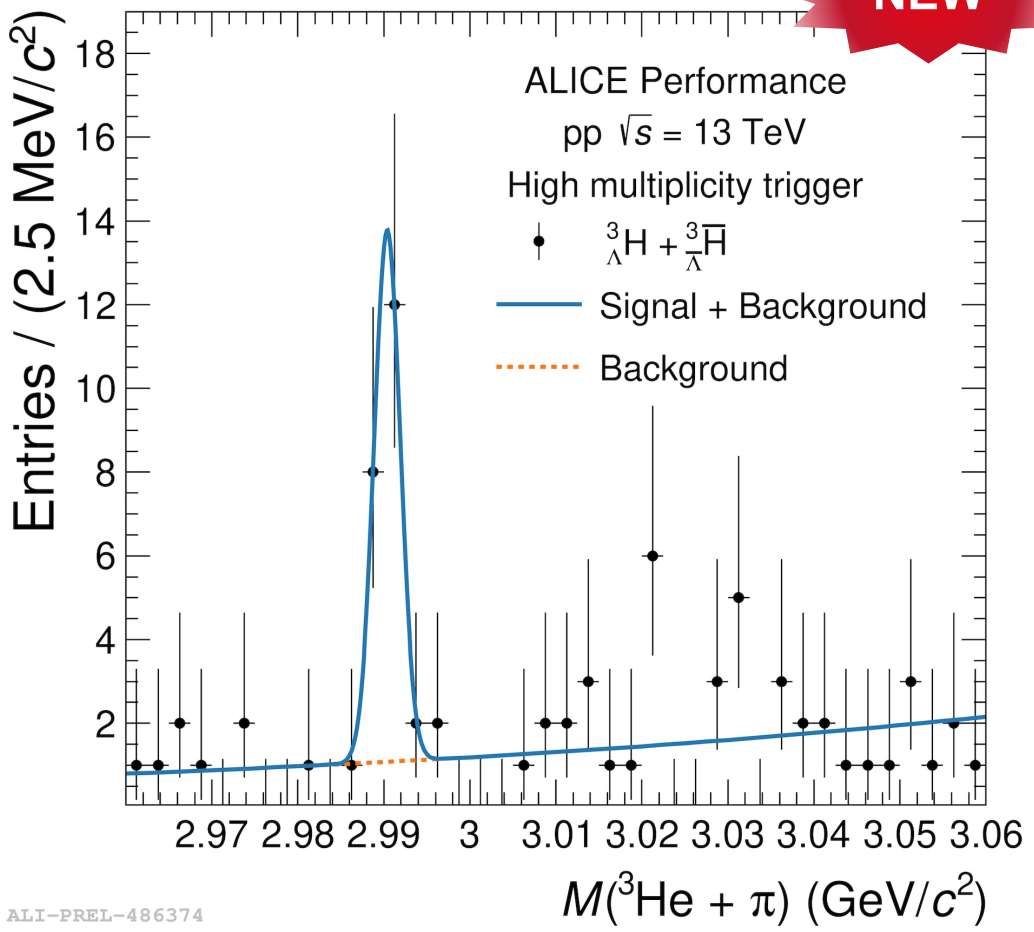
ALICE

Hypertriton measurement in pp

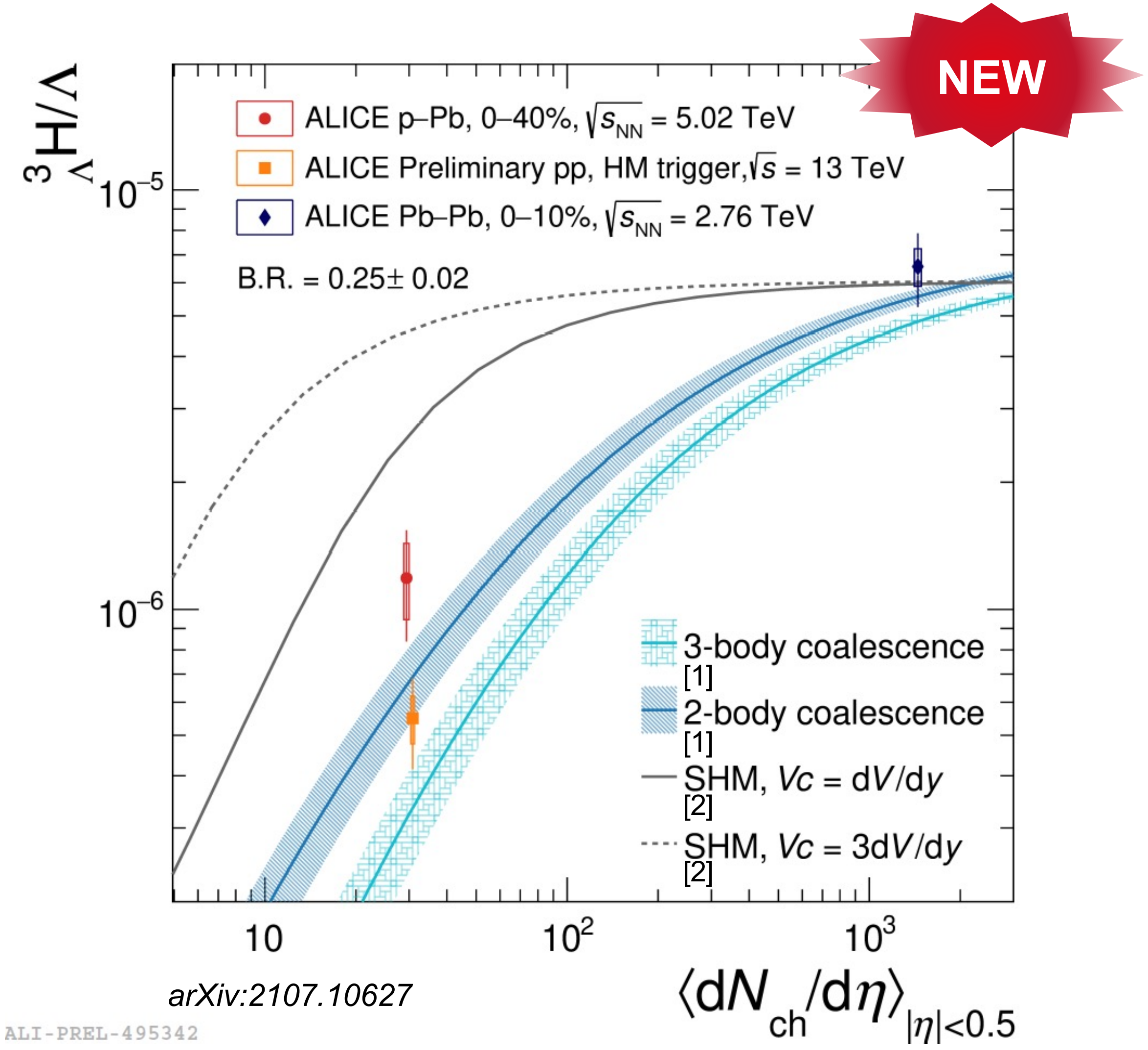
- First measurement of the hypertriton in Run 2 pp collisions at 13 TeV
- Topological and kinematical cuts applied to optimize the signal-to-background ratio and improve the significance in a traditional analysis.

NEW



$^{3}_{\Lambda}H$ / Λ ratio

- Measurements in pp and p-Pb:
  Two new points at different multiplicities
- Points slightly favour the two-body coalescence
- But do not exclude three-body coalescence



arXiv:2107.10627

S_3

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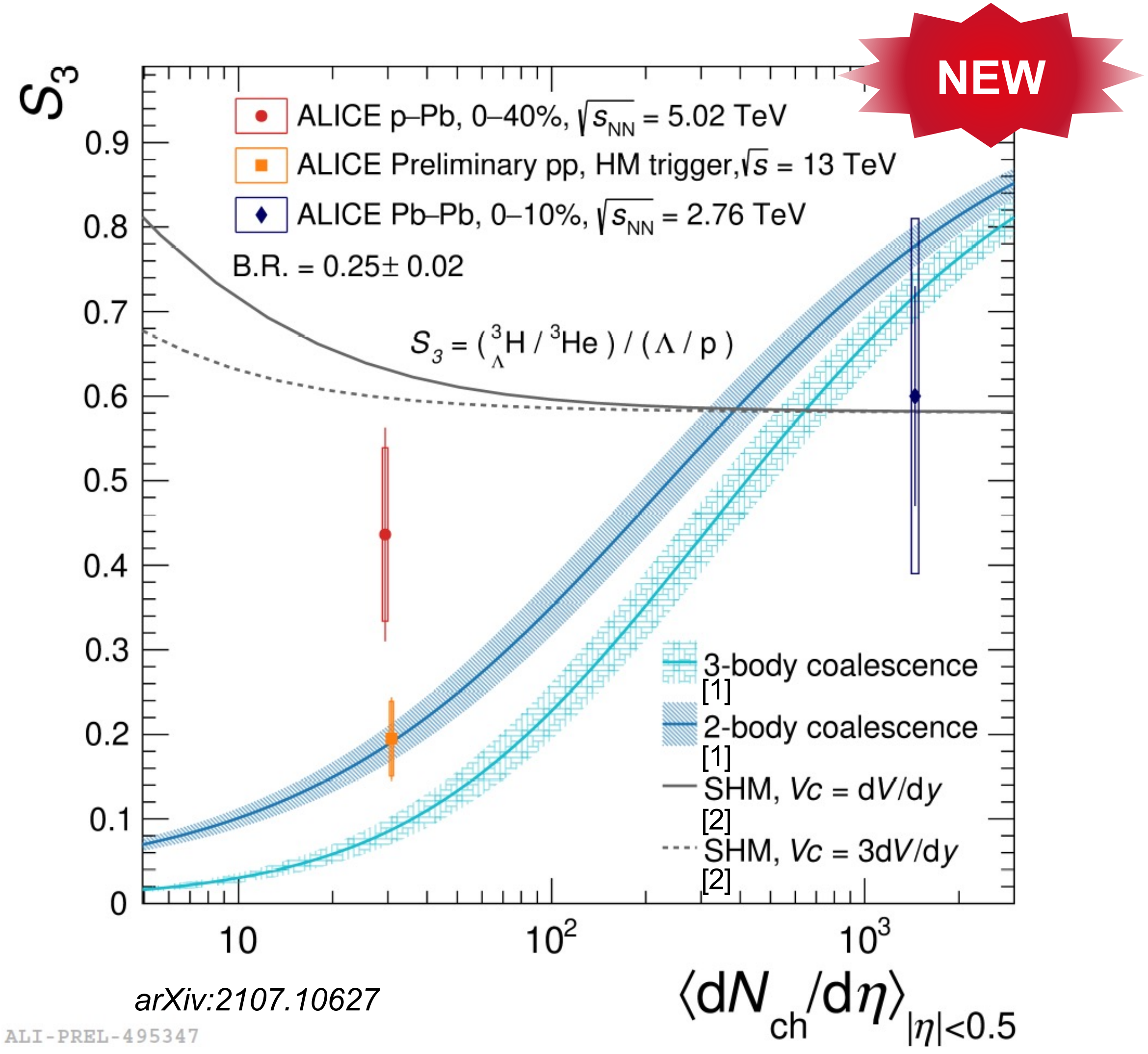
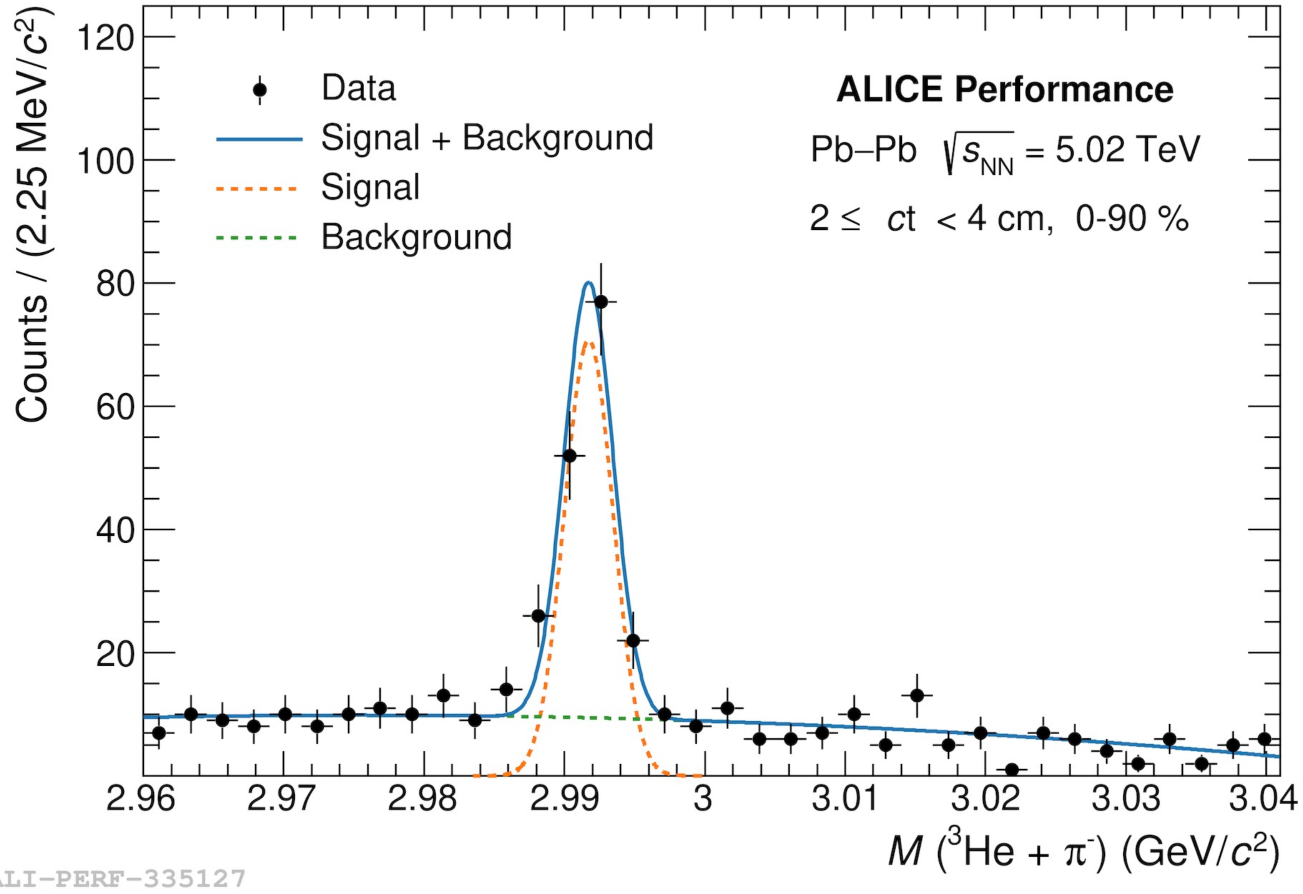


arXiv:2107.10627

Hypertriton lifetime

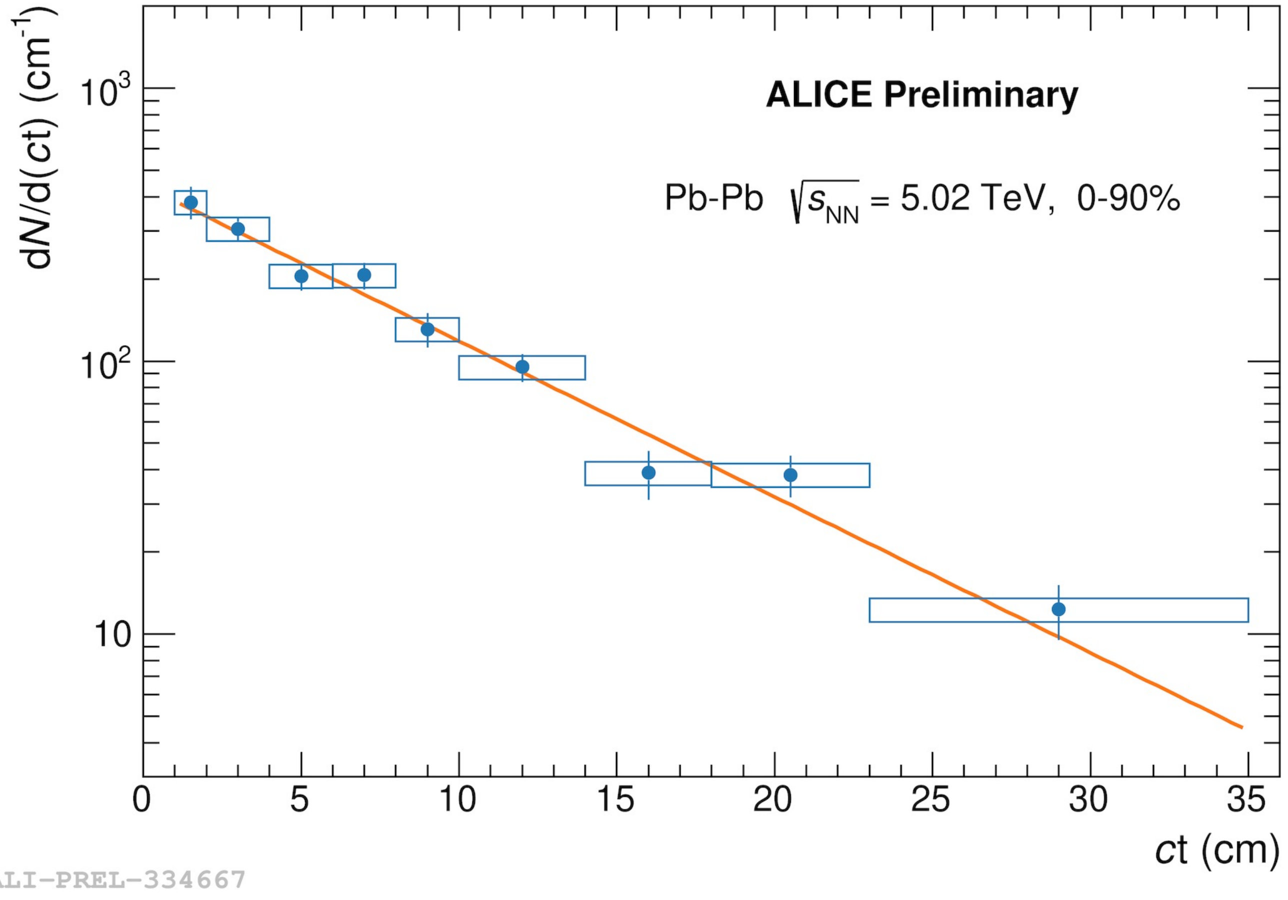
- Recent measurement in Run 2 Pb-Pb collisions at 5.02 TeV
- Signal extraction by using a machine learning approach
- Using a boosted decision tree (BDT) and hyper parameter optimisation
- Here: Hypertriton mass in a specific *c*t range



Hypertriton lifetime

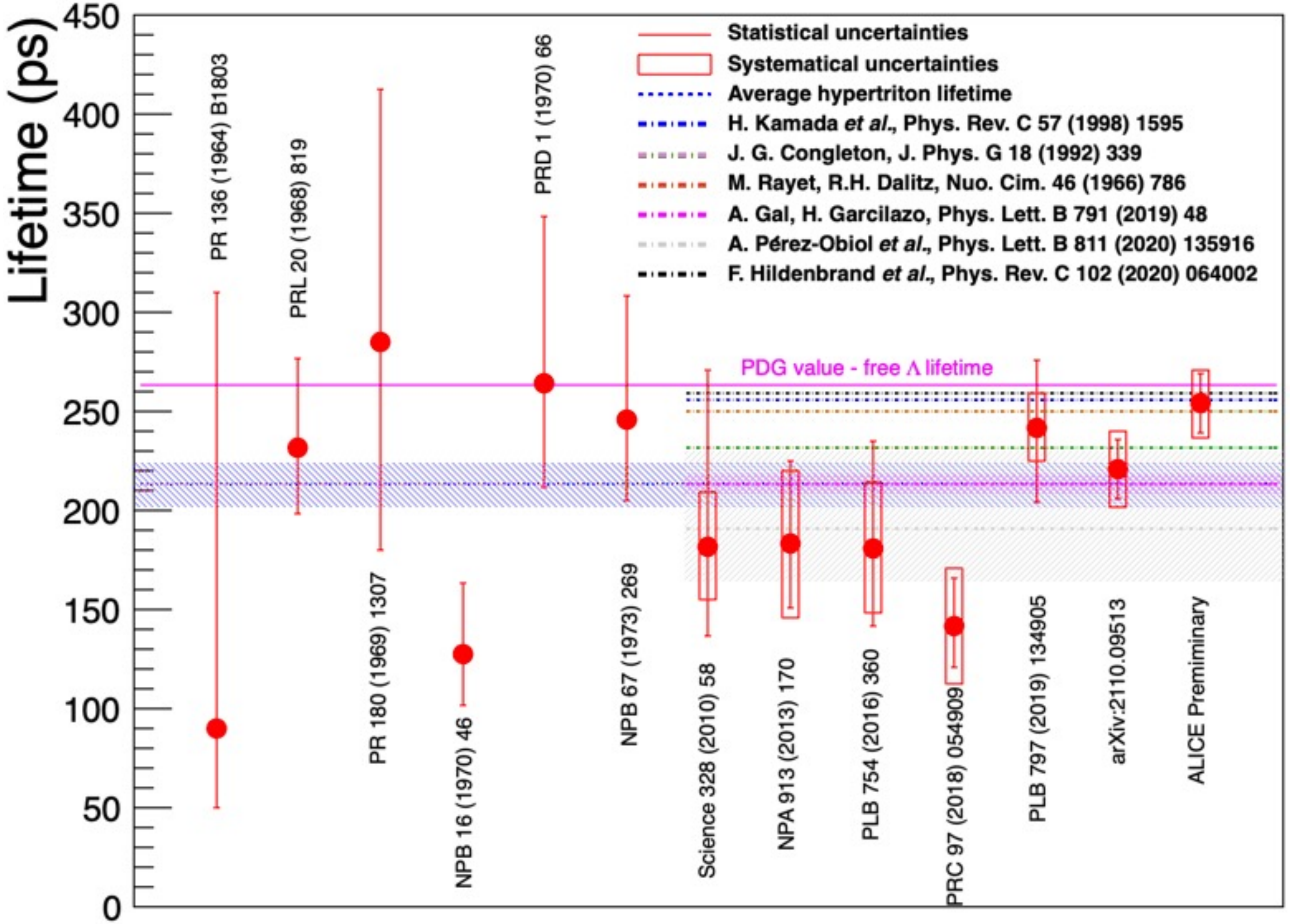
- Preliminary result for QM2019
- Corrected hypertriton yield for *c*t intervals
- Lifetime obtained from fit

- Recent studies show a better constraint and smaller statistical uncertainties (will be published soon).



Hypertriton lifetime

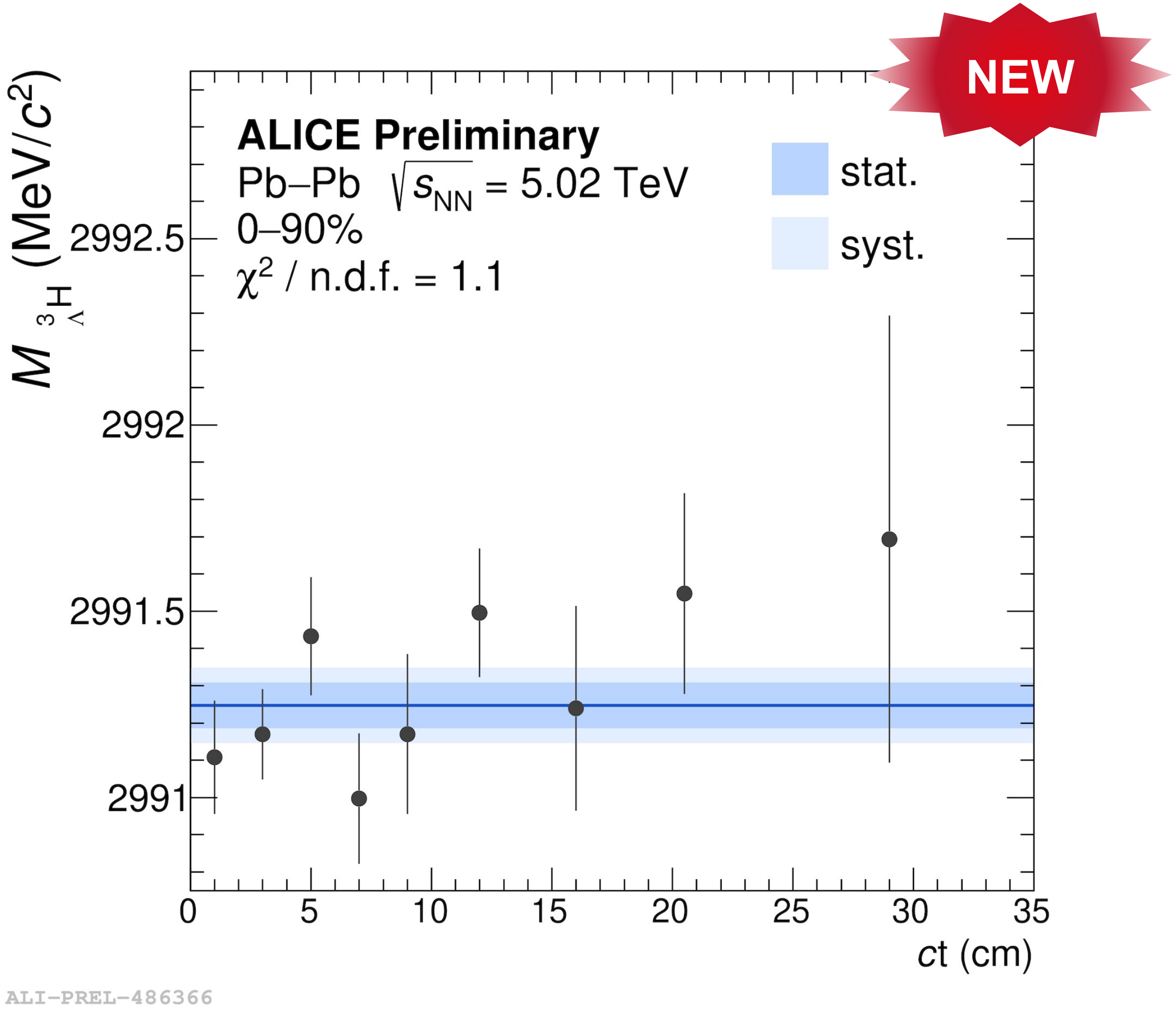
- Latest published ALICE result has larger statistical uncertainties.
- Is compatible with the free Λ lifetime and world average within its uncertainties
- New preliminary result will push the average lifetime a little up.
- Recent studies show a better constraint and smaller statistical uncertainties (will be published soon).



Hypertriton binding energy

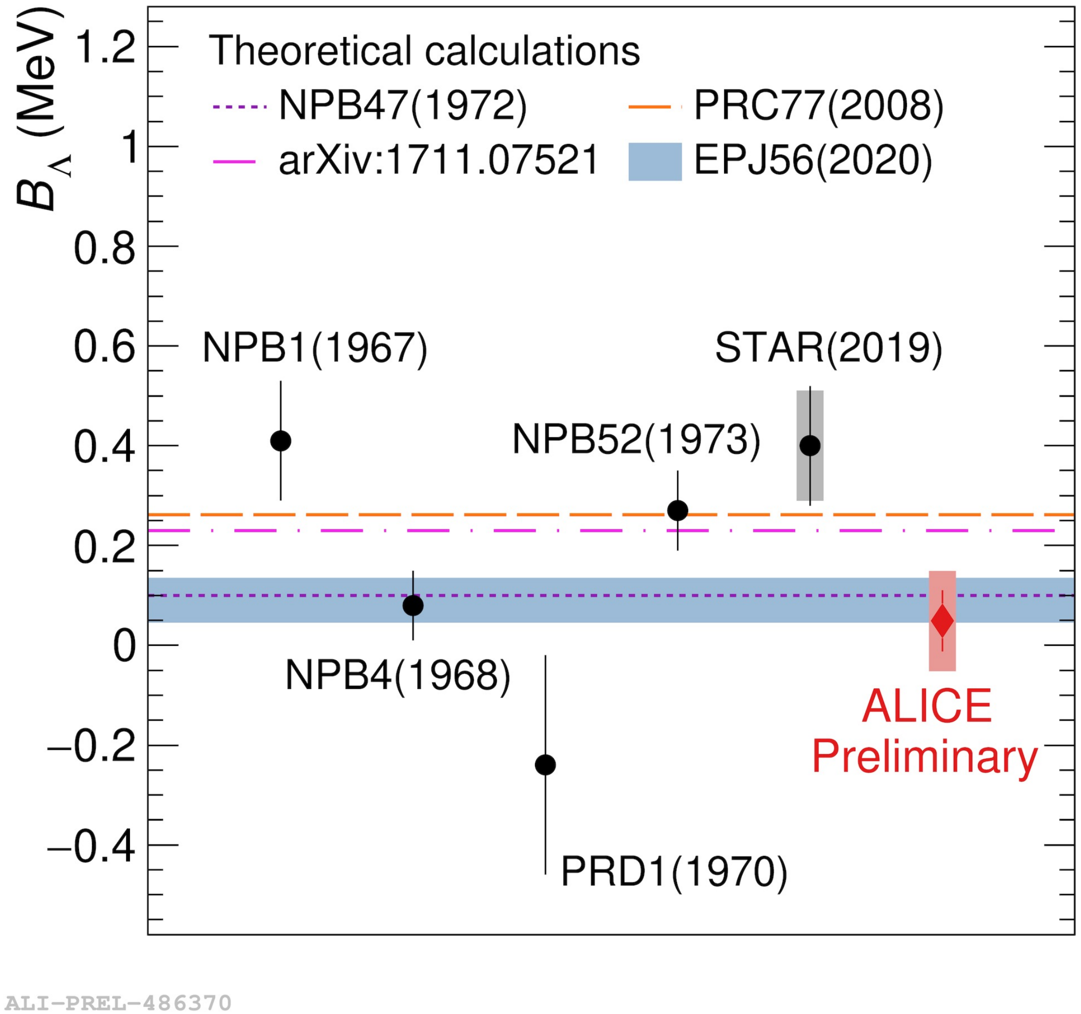
- Preliminary result for SQM2021
- The value obtained by this fit is $B_\Lambda = 55 \pm 62$ keV

- Recent studies show a better constraint and smaller statistical uncertainties (will be published soon).



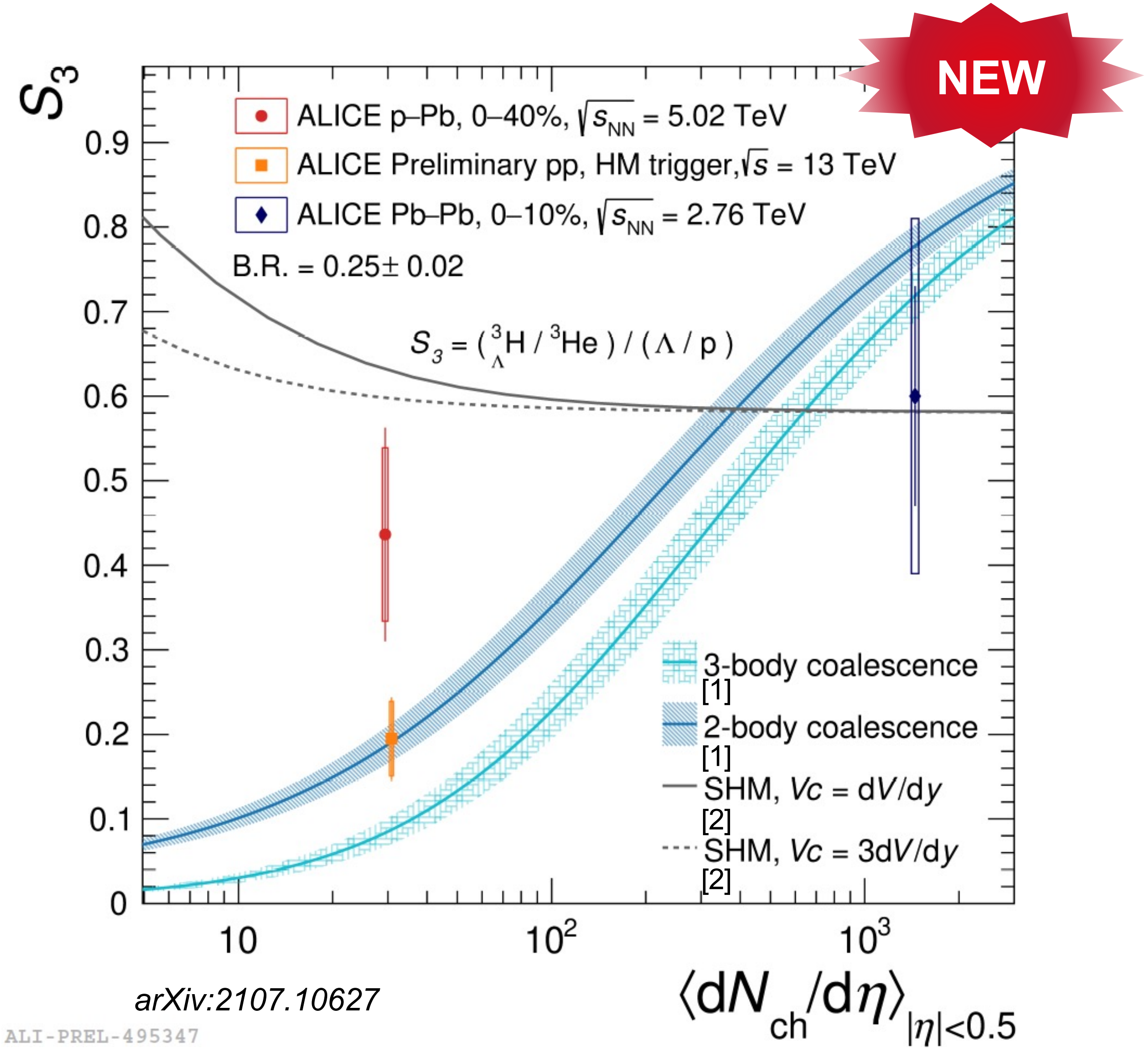
Hypertriton binding energy

- Preliminary Result for SQM2021
- This measurement has a value of about 55 ± 62 keV for B_Λ.
- Is compatible within the theoretical predictions
- Recent studies show a better constraint and smaller statistical uncertainties (will be published soon).



Outlook

- Studies of the hypertriton production in different multiplicities are the key to explore the formation mechanism:
  - We are currently performing studies on a different triggered dataset, which will allow us to set another point.
  - There is another p-Pb dataset available which could also give an additional point.



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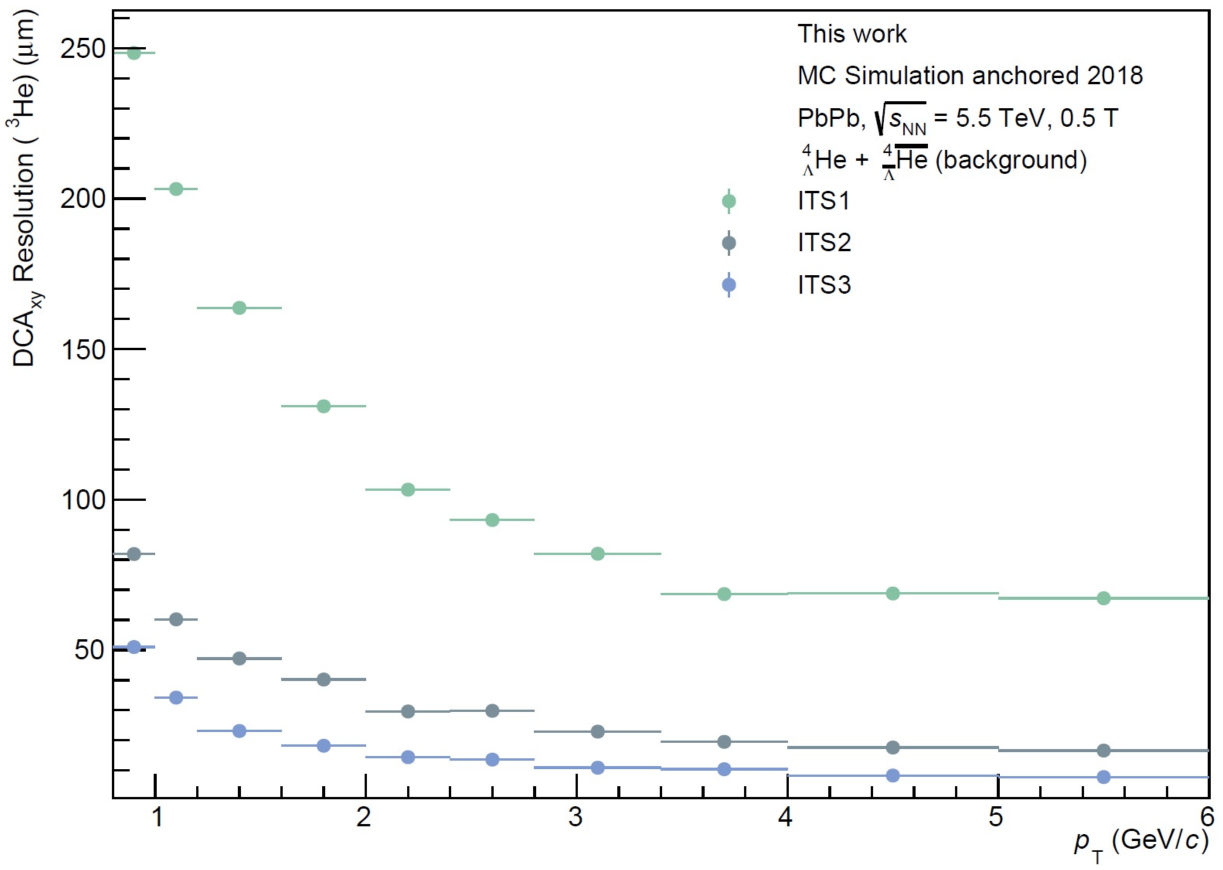
Outlook

- Studies of the hypertriton production in different multiplicities are the key to explore the formation mechanism.
- The upcoming Run 3 of the LHC will add significantly more statistics also for small systems:
  - Expecting higher statistics, by running at 50kHz collision rate
  - Upgrade of important detector parts especially ITS and TPC
  - ITS2 will allow to better distinguish between signal and background.
  - A planned ITS upgrade for Run 4 will once more increase the resolution and help to reduce the background.



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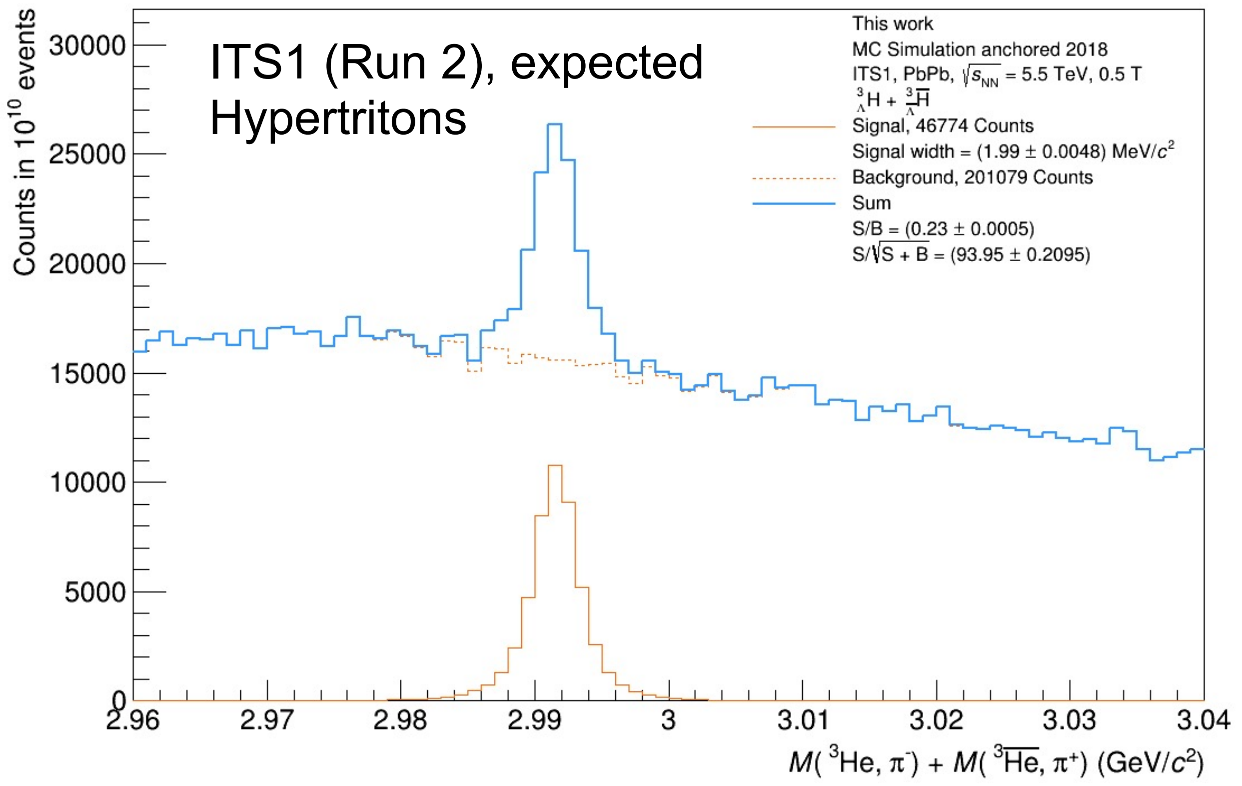

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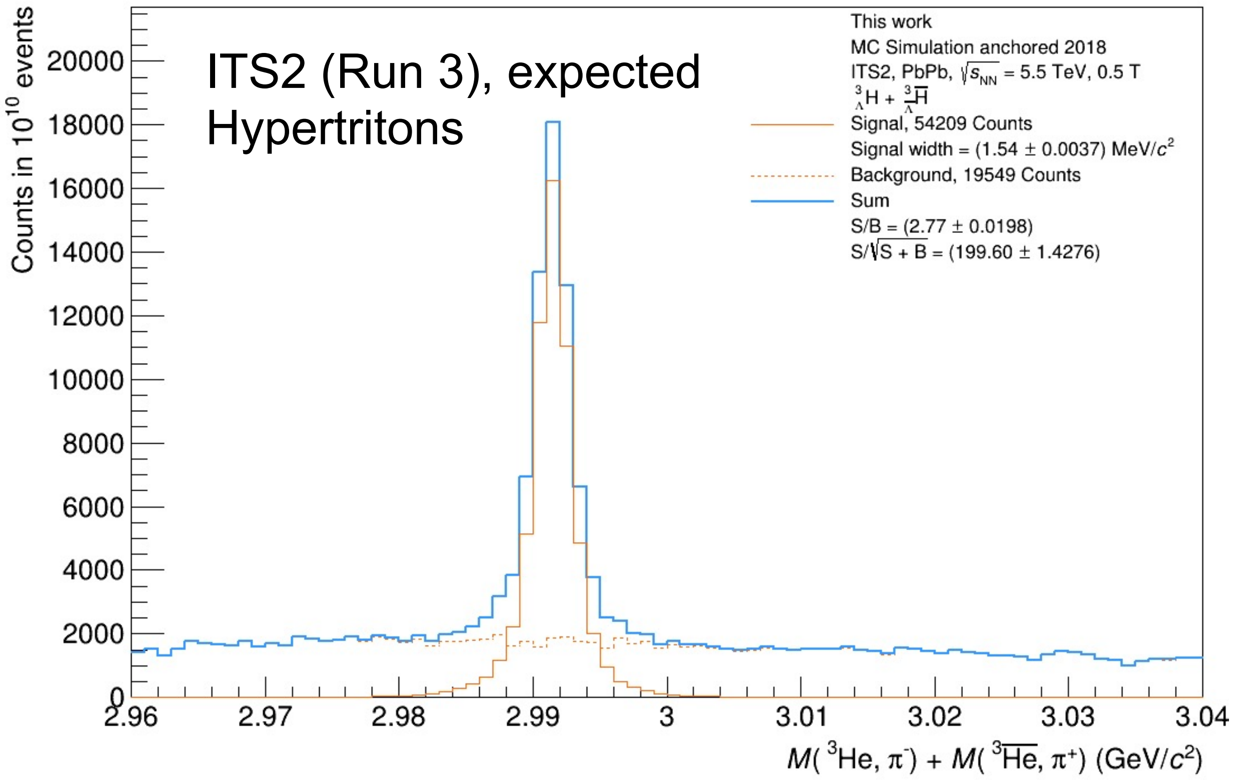

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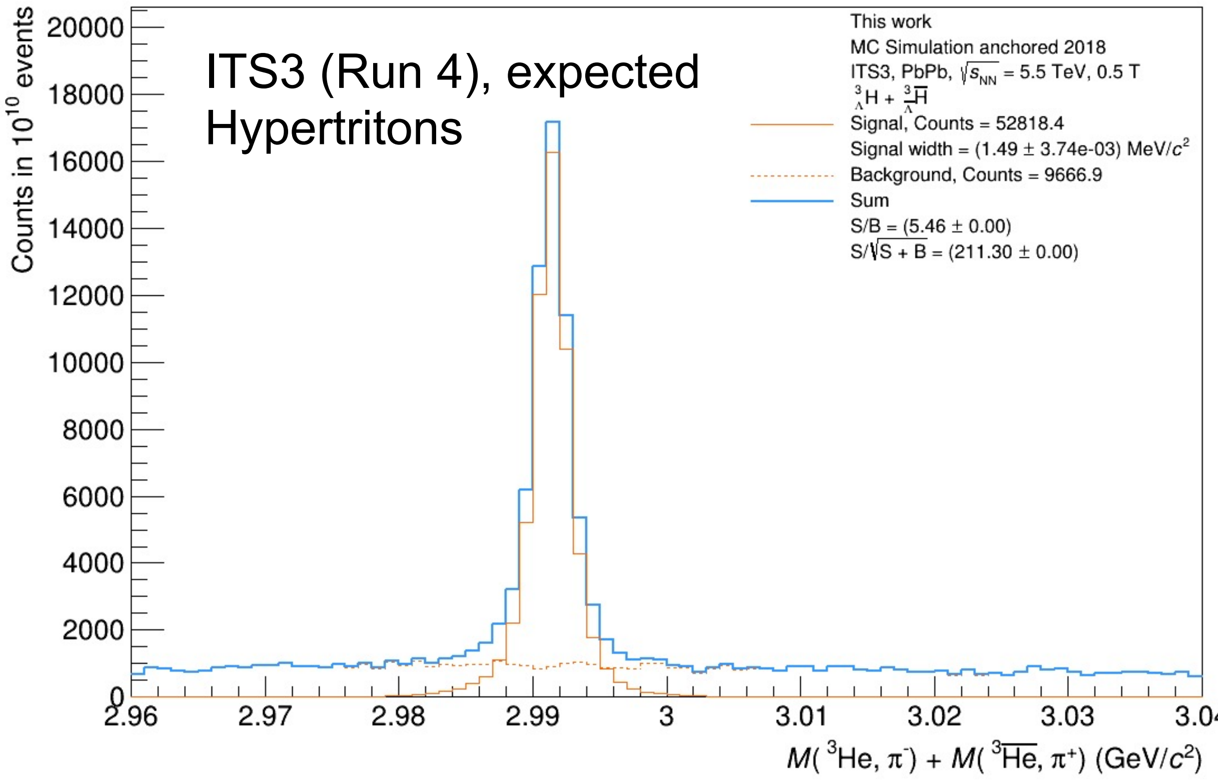
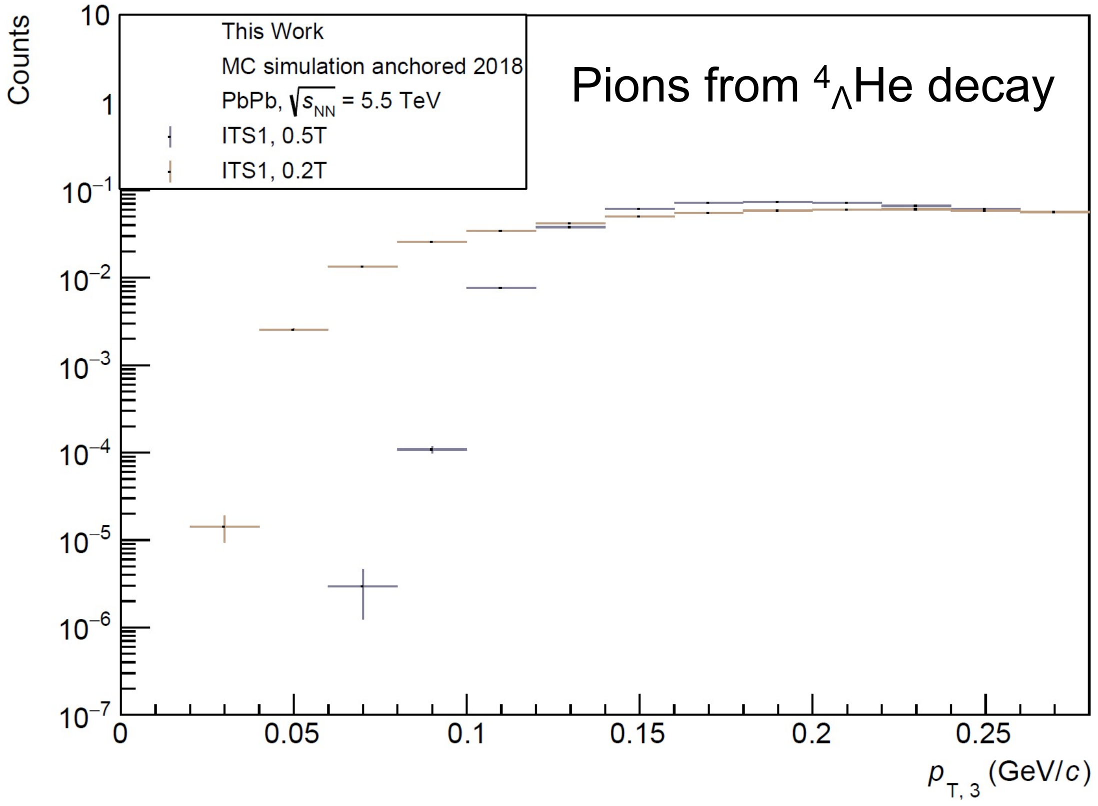


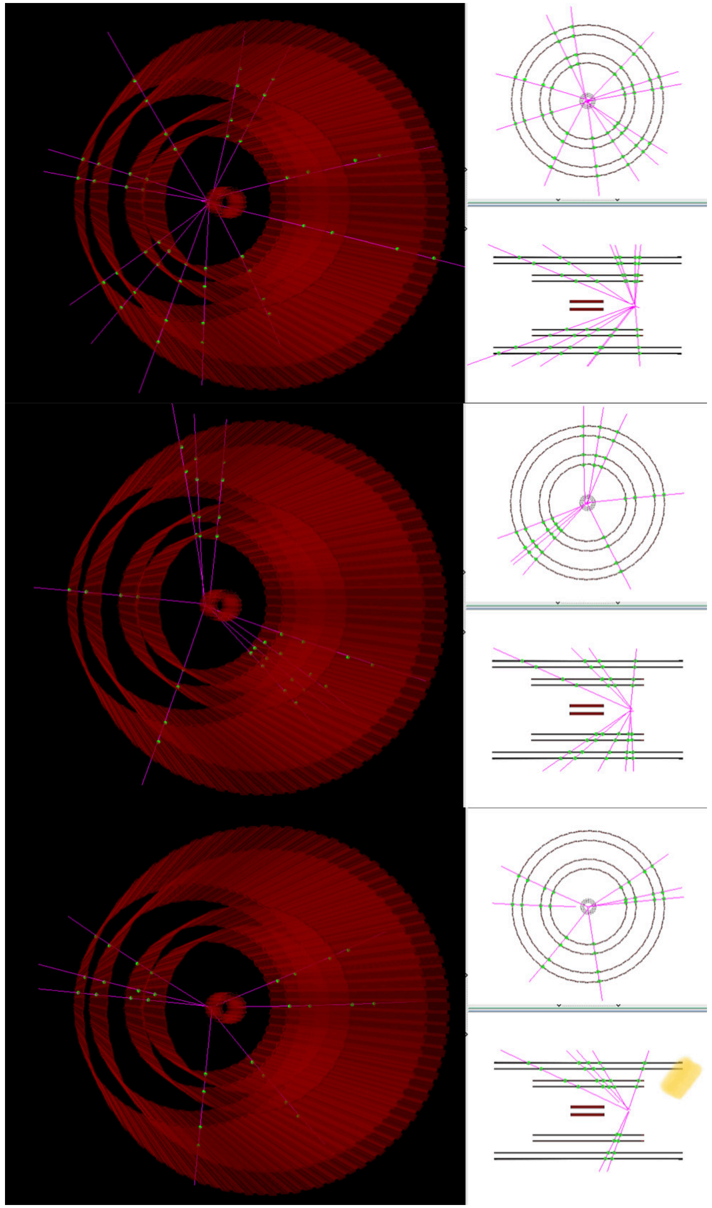
Outlook

- Studies of the hypertriton production in different multiplicities are the key to explore the formation mechanism.
- The upcoming Run 3 of the LHC will add significantly more statistics also for small systems.
- The charged particle tracks are bend by a magnetic field:
  - The strength of this field effects the measurement of particles with low momenta.
  - For us: Impact especially on pions
  - Lower magnetic field enhances the reconstruction of soft pions



Summary

- ALICE is the perfect apparatus to study the production and properties of light (anti-)(hyper-)nuclei.
- The latest (preliminary) results show small uncertainties and a good agreement with the theoretical predictions.
- The upcoming Run 3 and Run 4 will add large statistics for the measurement of those particles and provide high precision data.
- This may also give the possibility of a more conclusive answer to the question of the correct production model.



ITS2 event displays of first testbeam collisions in 11/2021.

Thanks For Your Attention!

References

- [QGP] QGP Picture:
  - *https://i.ytimg.com/vi/uLWwq5xXUDo/maxresdefault.jpg*
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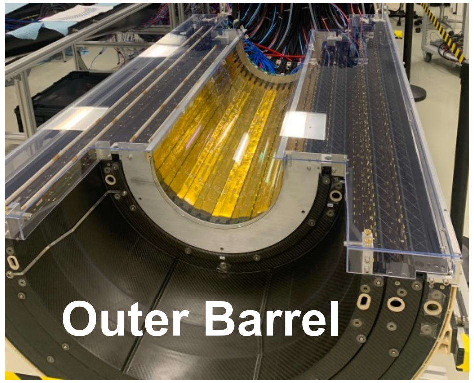
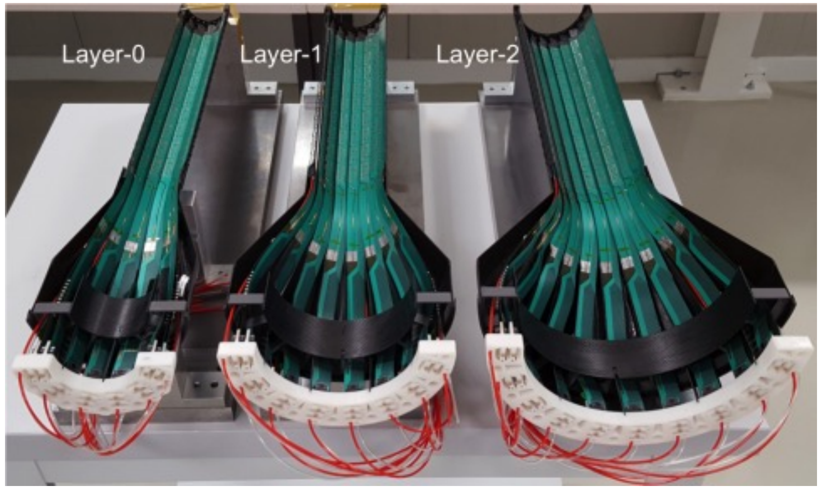
- [2] Statistical Hadronization Model calculations:
  - *V. Vovchenko, B. Dönigus and H. Stoecker, “Multiplicity dependence of light nuclei production at LHC energies in the canonical statistical model,” Phys. Lett. B 785 (2018)171–174, arXiv:1808.05245 [hep-ph]*

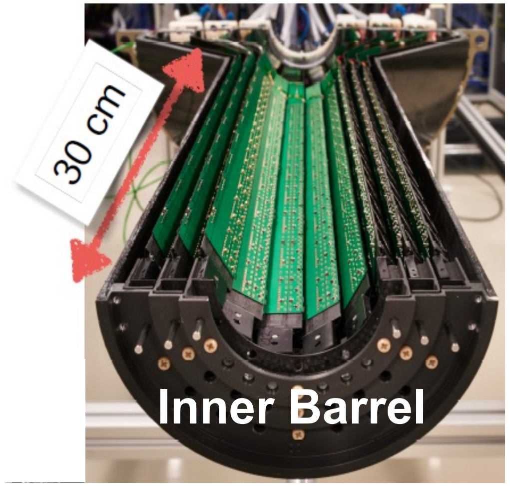
Backup

Upgrade of the Inner Tracking System (ITS2)

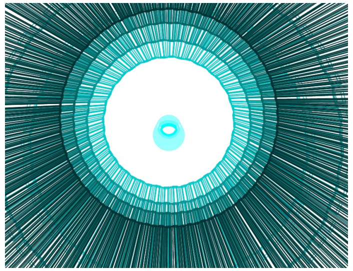
- **ITS2**
  - 7 Layers split in Inner Barrel (IB) and Outer Barrel (OB)
    - OB Layer 3-6 from 194.4mm to 391.8mm
    - IB Layer 0-2 from 22.4mm to 37.8mm
  - Beam pipe diameter: 18.2mm
  - Significant reduction of the material budget
  - All pixel detector



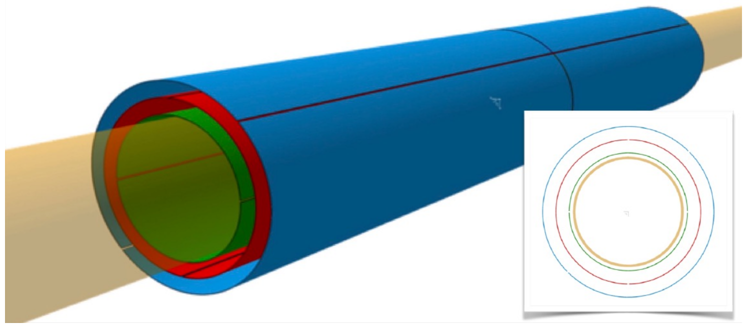


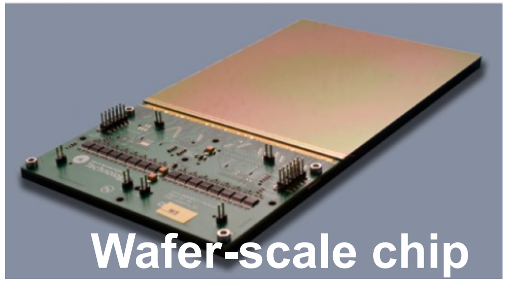


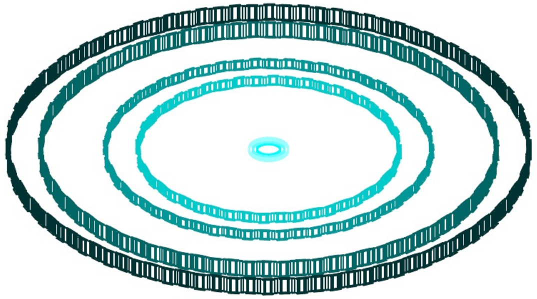
Upgrade of the Inner Tracking System (ITS3)



- **ITS3**
  - ITS2 Outer Barrel
  - New Inner Barrel (L0 ~18mm, L1 ~24mm, L3 ~30mm)
  - Beam pipe diameter: 16.5mm
  - New Sensors „Wafer-scale chips“ manufactured by using a new technology called stitching, allow larger sizes of a single chip
  - → Strong reduction of material budget (essentially no material!)

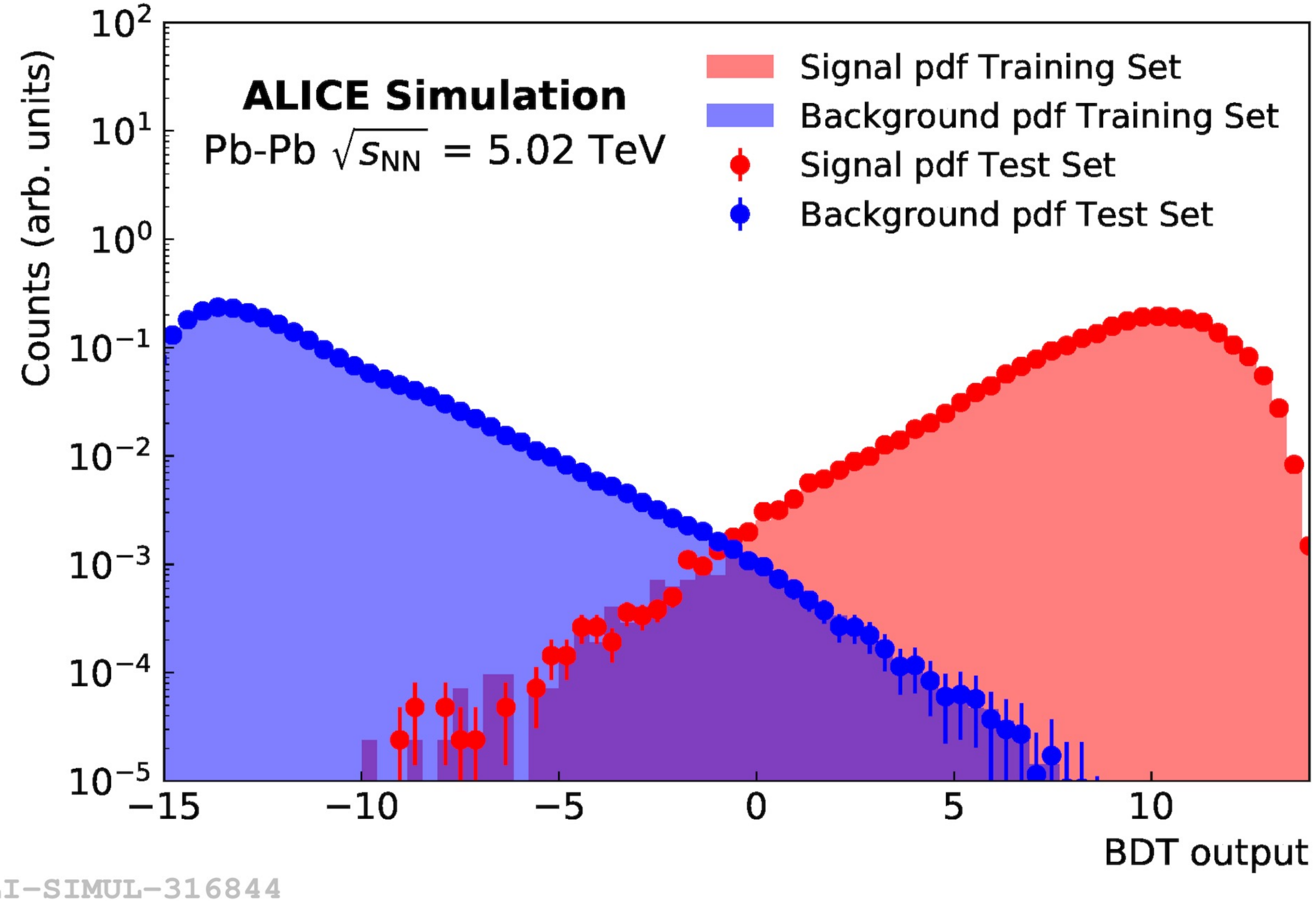




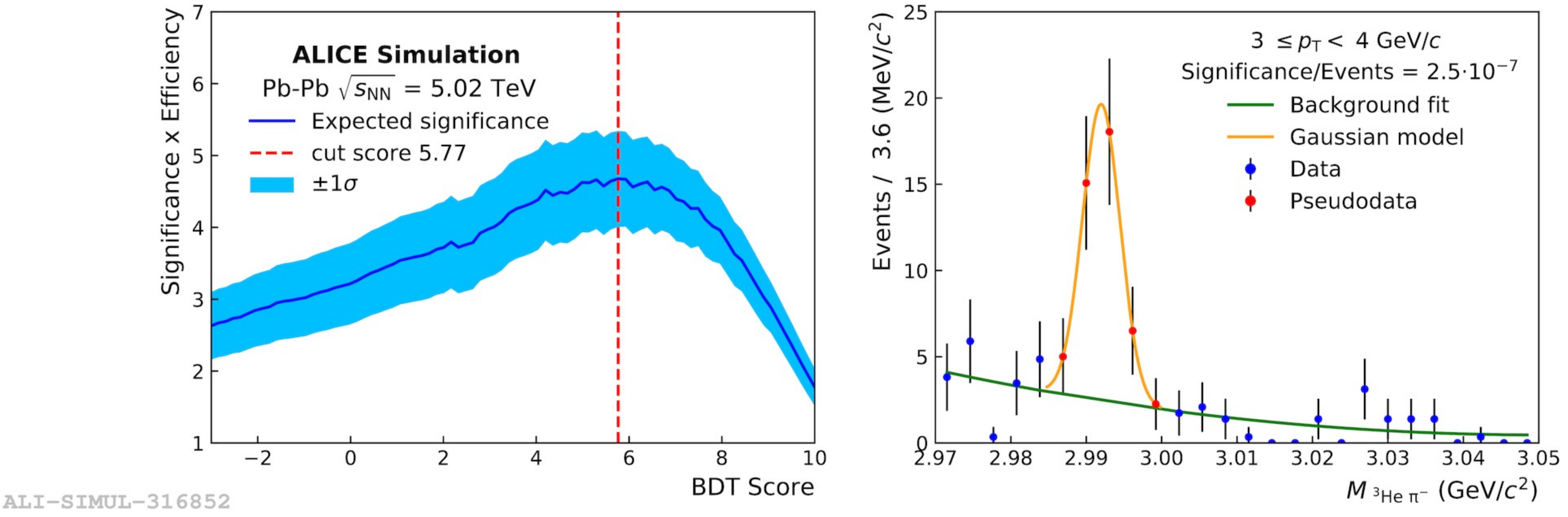


Boosted decision tree score for signal and background

- Increase signal to background ratio by using a machine learning approach.
- Machine is „trained" by using signal and background distributions from MC and data.
- Using a test sample and comparing to the training samples, the boosted decision tree works nicely.
- Visible for example on the next slide for a defined p_T range.

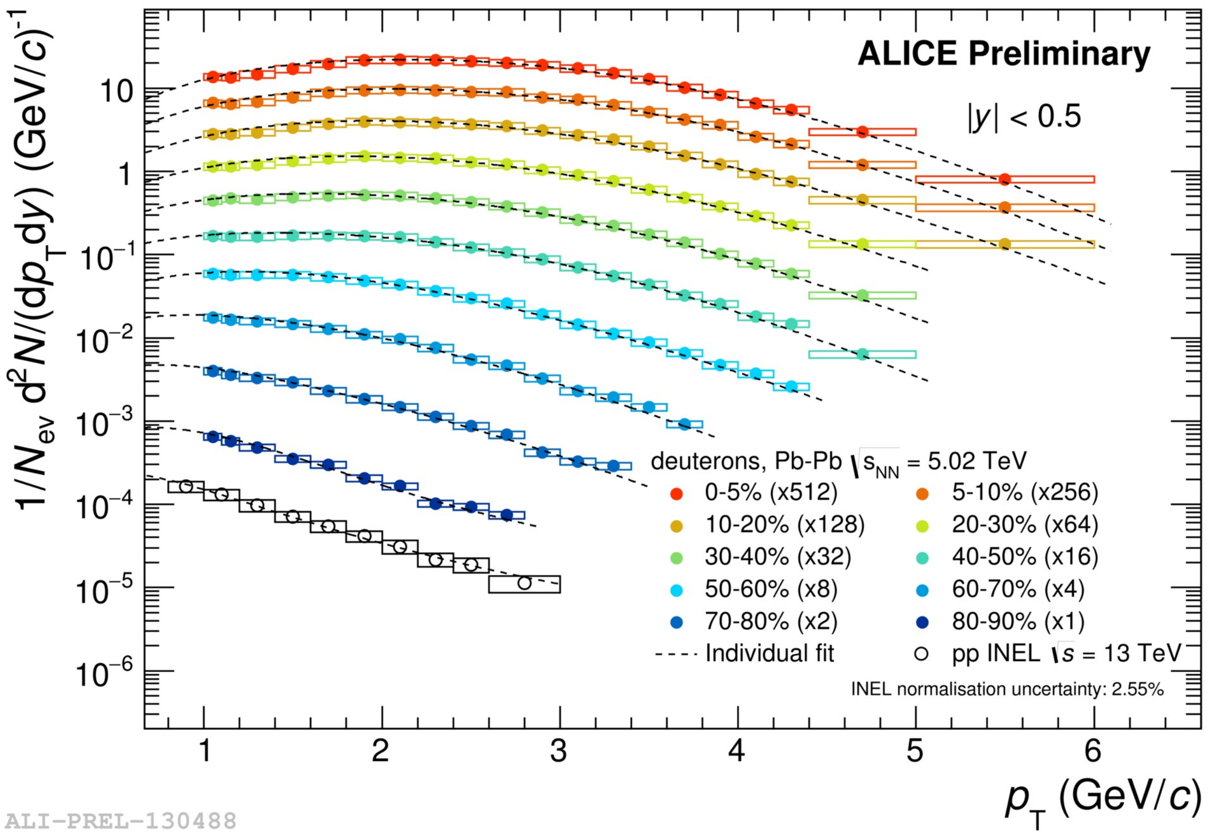


Significance scan using machine learning



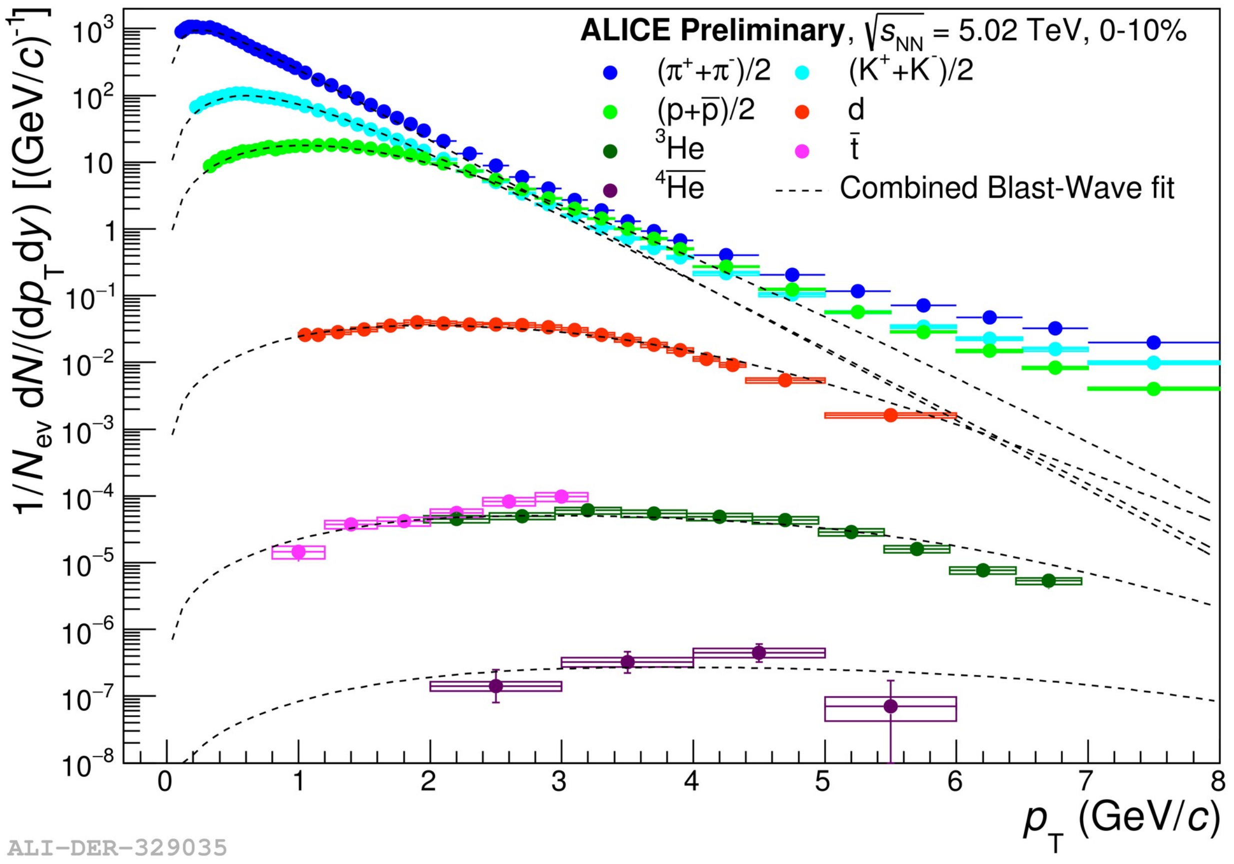
Deuteron blast wave spectra

- Blast-wave fit to deuteron spectra for different centrality classes
- Centrality means the overlap of the colliding nuclei (maximum overlap at 0%).
- The more central the collision, the more hardens the spectrum.
- The hardening is a sign for radial flow.
- Radial flow is not visible in pp.



Combined blast-wave spectra

- Simultaneous blast-wave fit to π, K, p, d, t, ^{3}He and ^{4}He in central Pb-Pb collisions
- Extracted blast-wave parameters quite similar to the ones resulting from a fit only to π, K, p.
- All spectra can be nicely described by the blast-wave model.
- All particles flow with a common mean velocity ‹ β ›.
- Mean momentum scales with mass.



Hypertriton spectrum

- 2015 Pb-Pb spectrum
- Can be described by the blast-wave model
- Hypertriton has radial flow, like the other particles.
- More statistics needed to investigate this further.