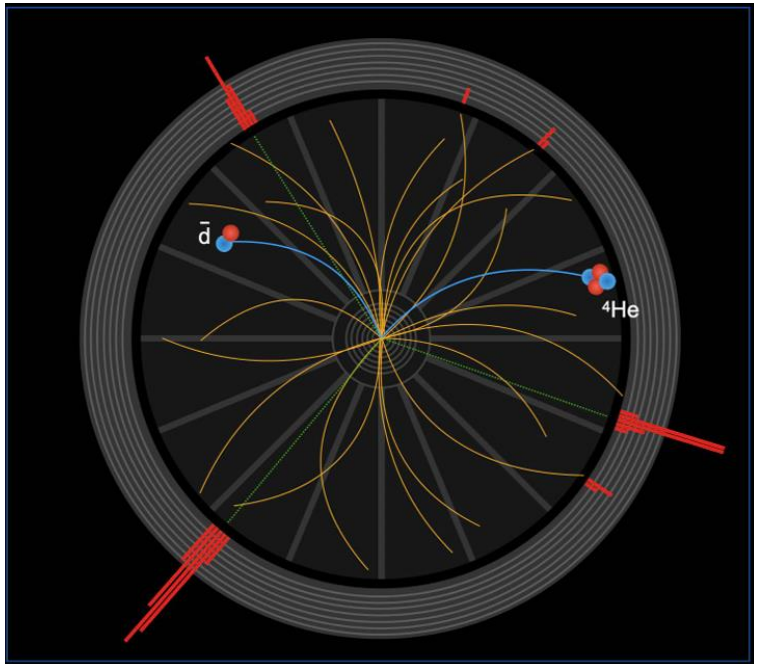
A = 4 (anti)hypernuclei production & Perspectives for hypernuclei production at LHC and RHIC

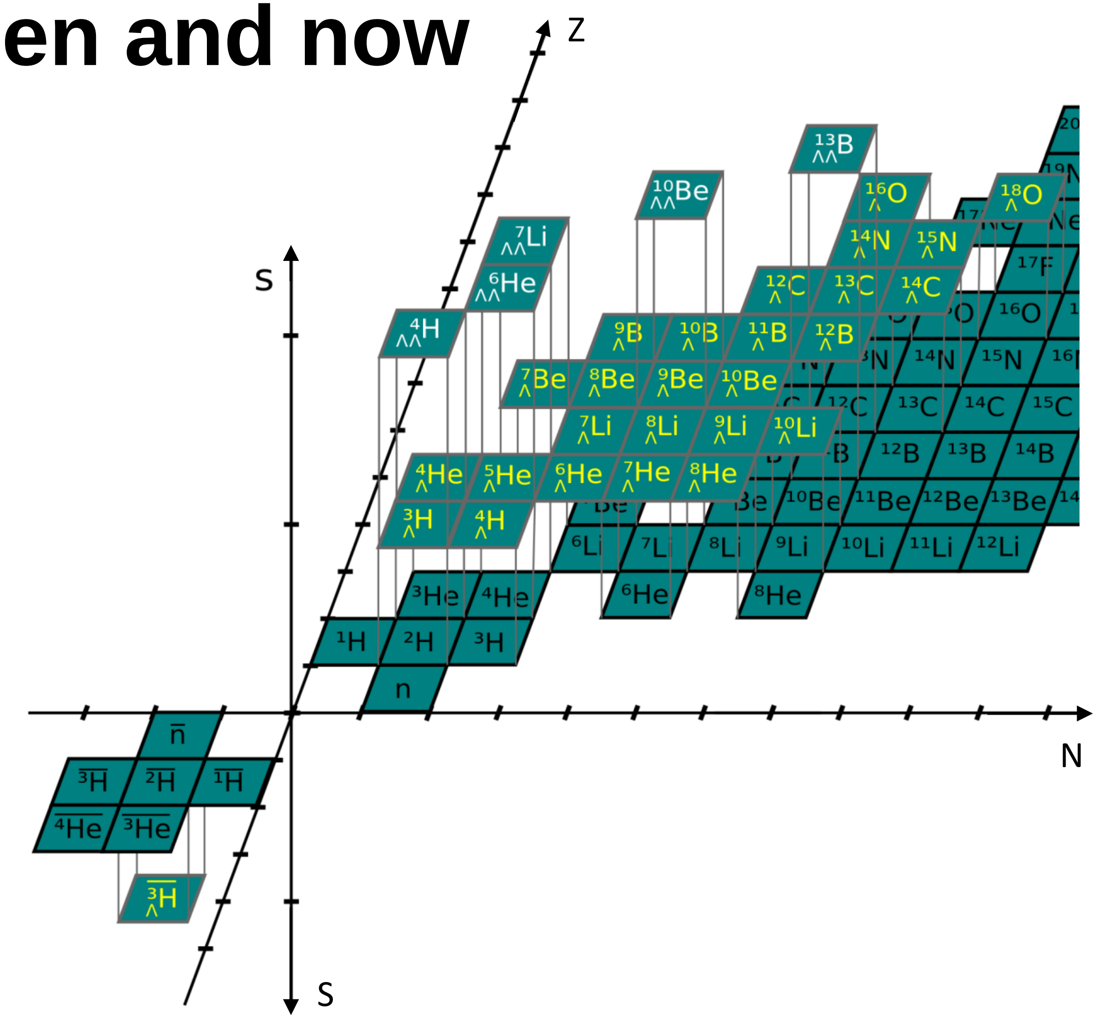
Janik Ditzel

RRTF Workshop 2024
Understanding light (anti-)nuclei production at RHIC and LHC
GSI Darmstadt



Hypernuclei production then and now

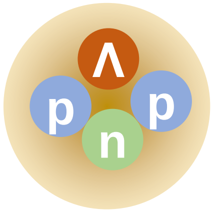
- In the last couple of years, several precise results on the (anti)hypertriton production and properties were presented by the collaborations at the LHC and RHIC



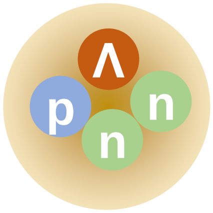
N. Löher, 2014

Hypernuclei production then and now

- In the last couple of years, several precise results on the (anti)hypertriton production and properties were presented
- Are we able to also study heavier hypernuclei?



$^{4}_{\Lambda}He \rightarrow {}^{3}He + p + \pi^{-}$



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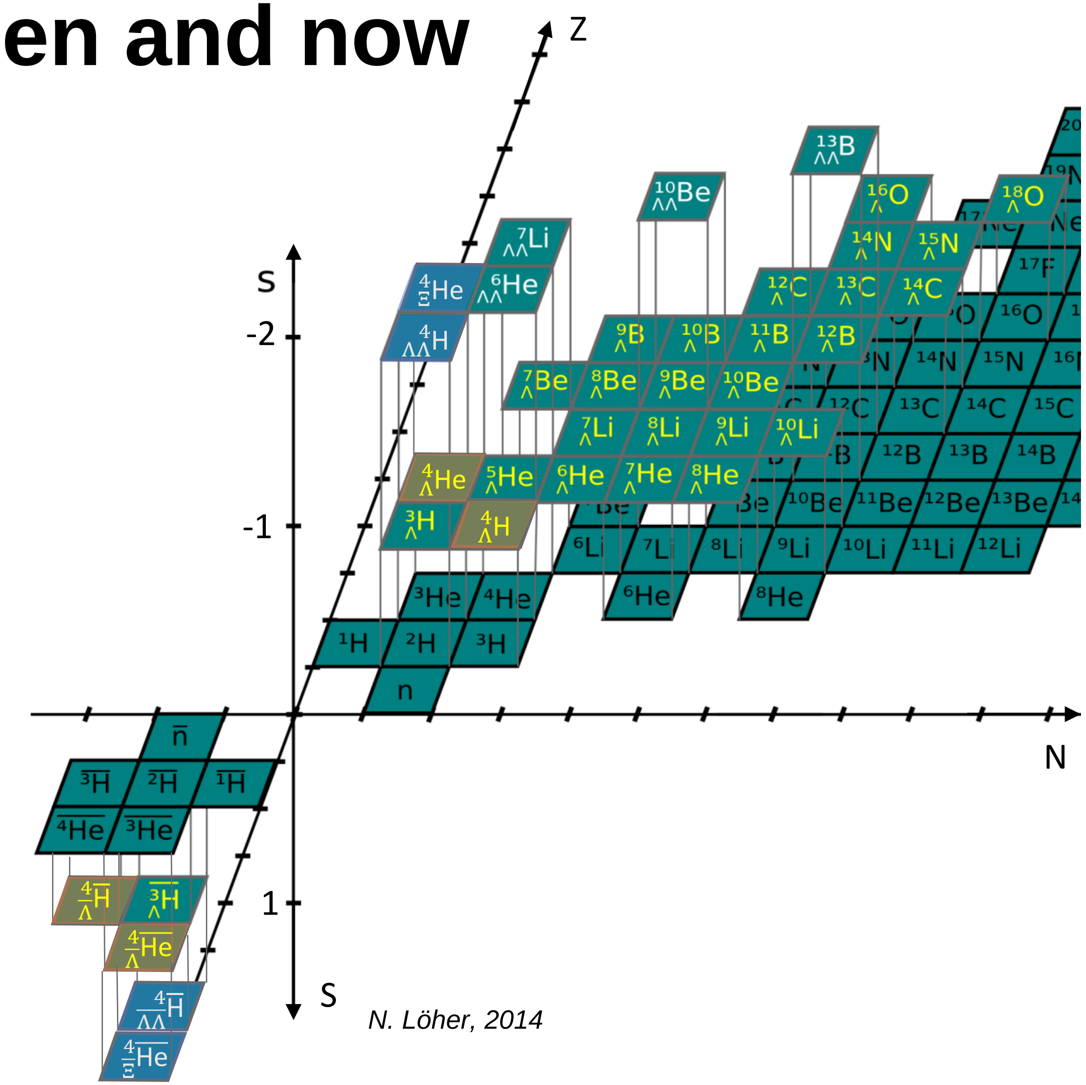
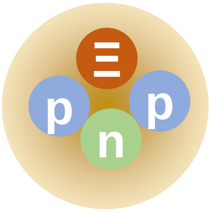


N. Löher, 2014

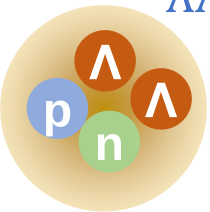
Hypernuclei production then and now

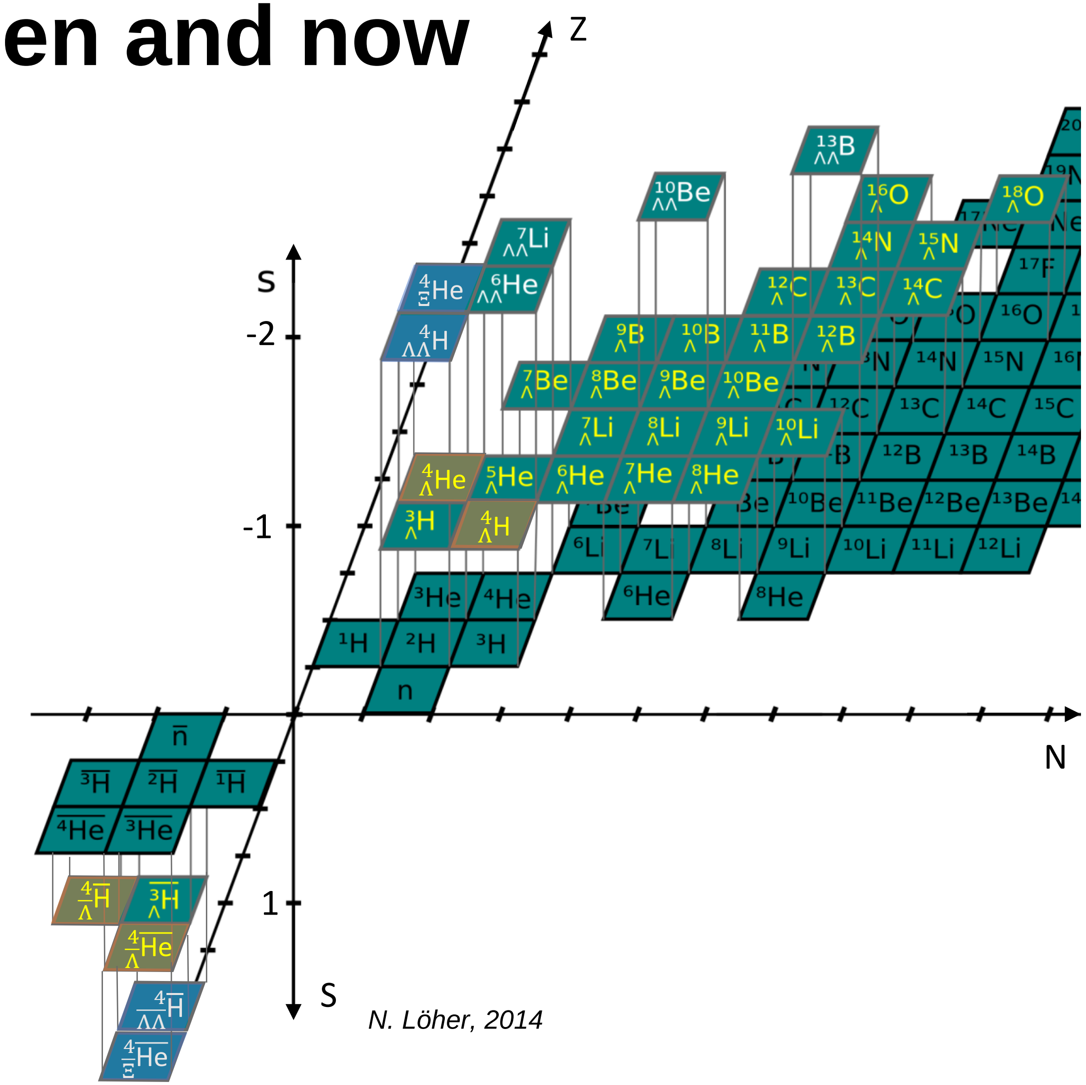
- In the last couple of years, several precise results on the (anti)hypertriton production and properties were presented
- Are we able to also study heavier hypernuclei?
- Or yet stranger hypernuclei?

$^{4}_{\Xi^-}\mathrm{He}$



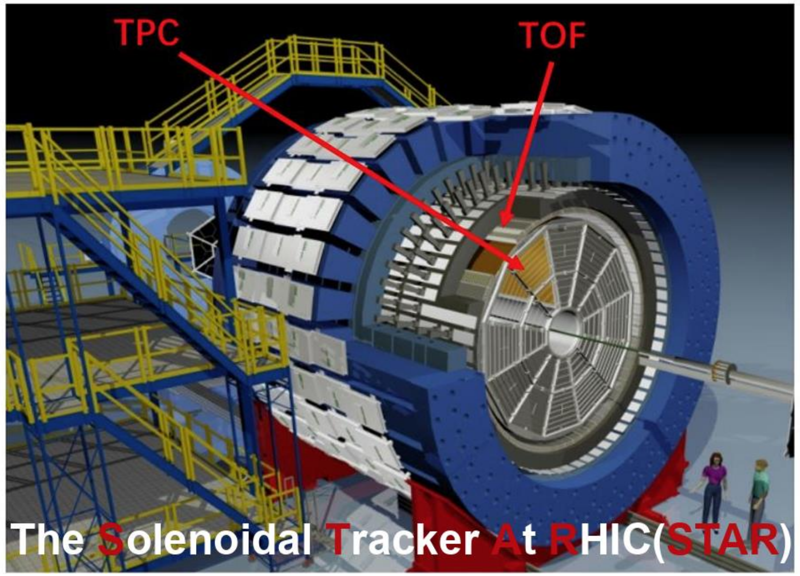
$^{4}_{\Lambda\Lambda}\mathrm{H}$

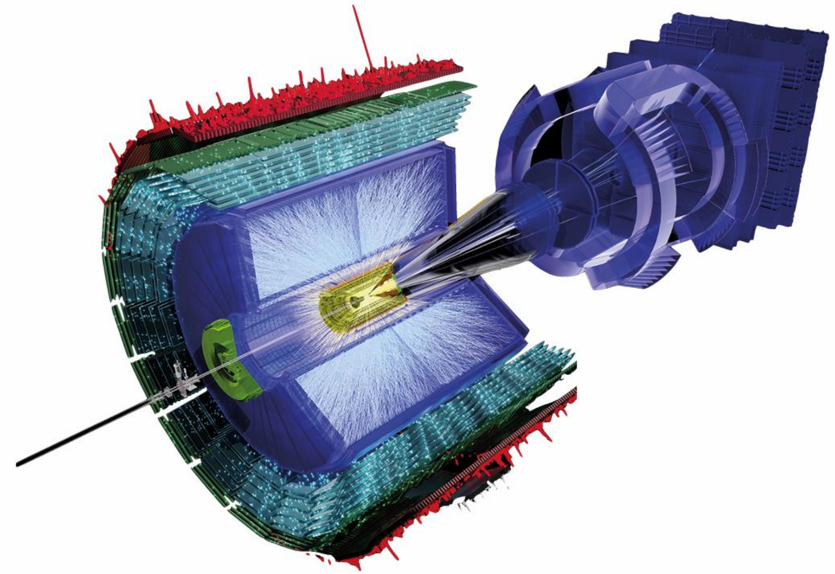




N. Löher, 2014

The two main players in the game

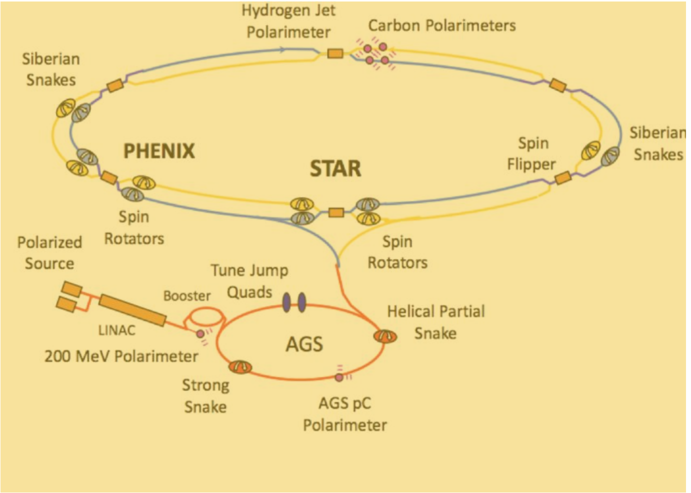


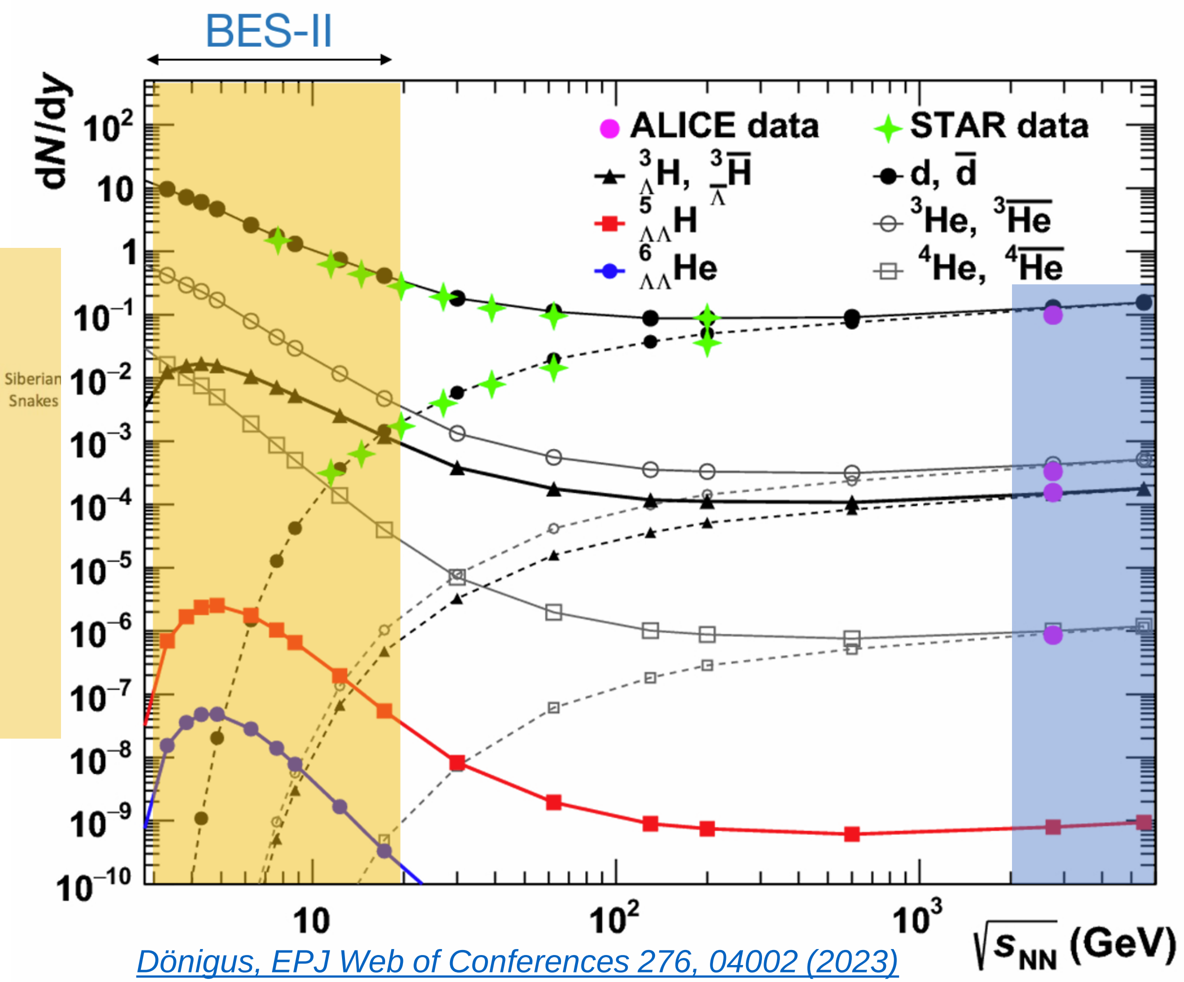


STAR

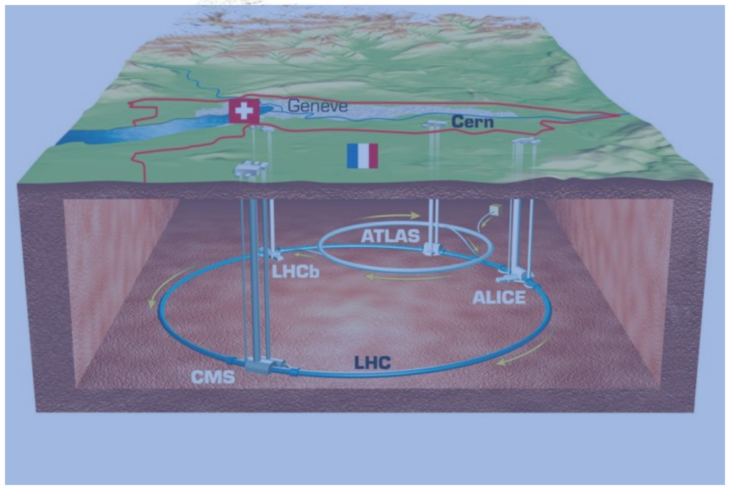
ALICE

Predicted production yields



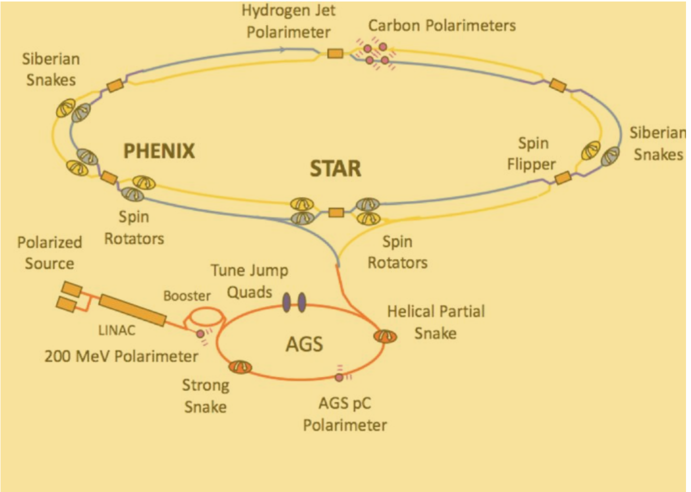


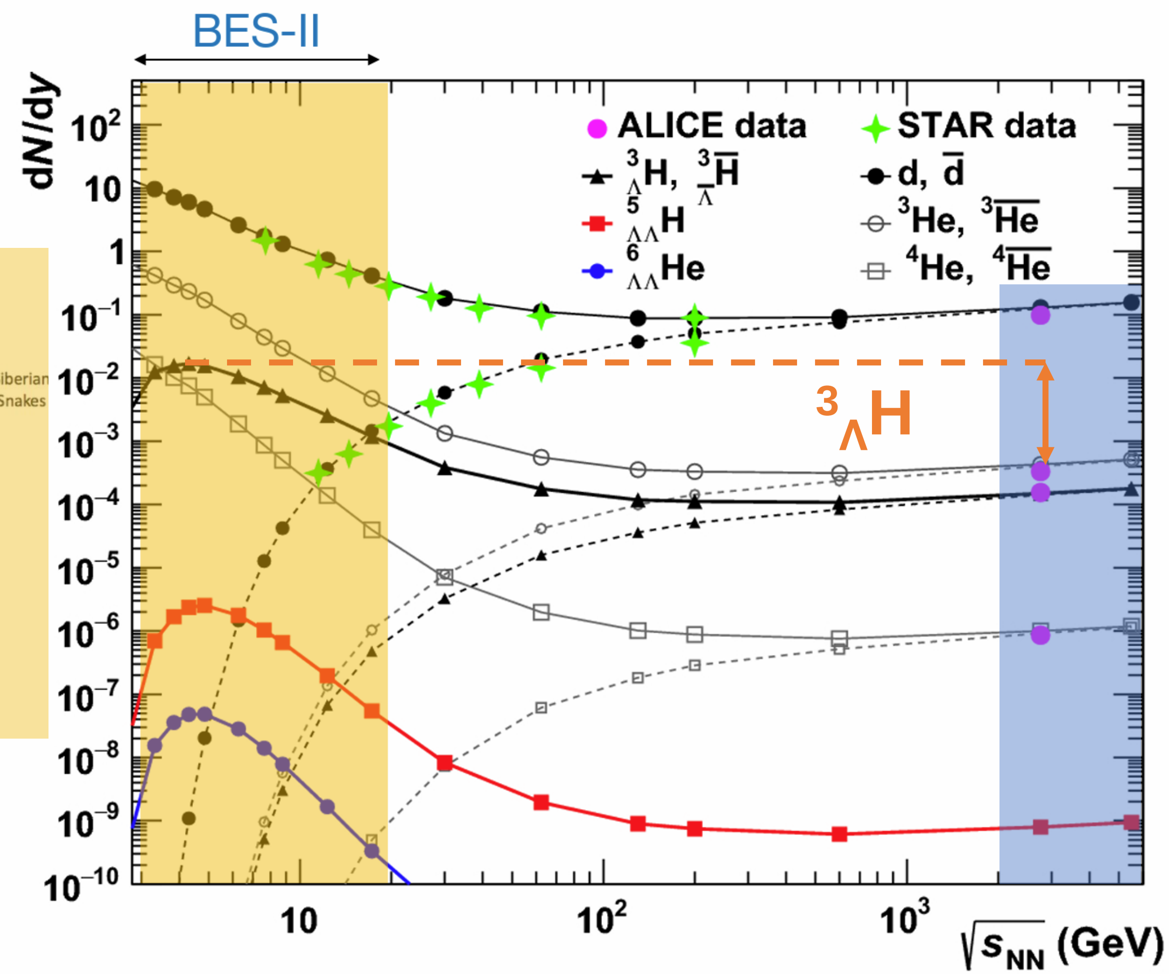
Dönigus, EPJ Web of Conferences 276, 04002 (2023)

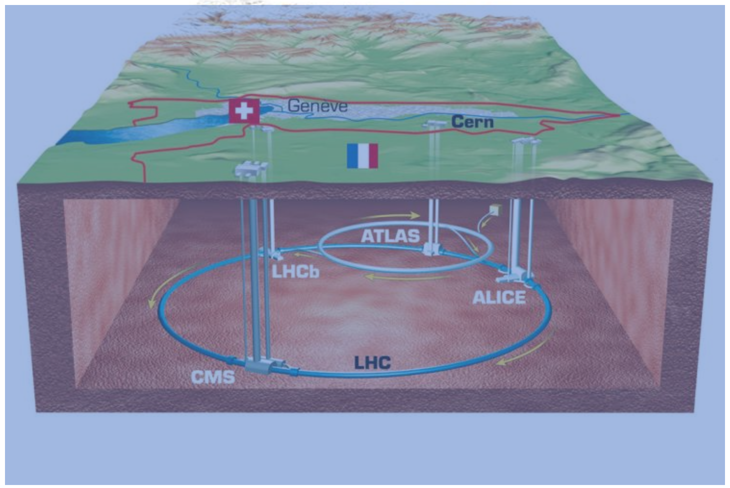


Predicted production yields

High baryon density → enhanced production yields







Dönigus, EPJ Web of Conferences 276, 04002 (2023)

Predicted production yields

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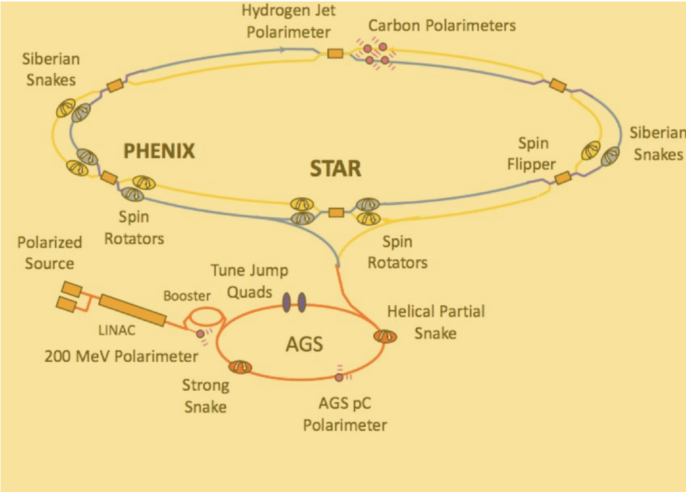
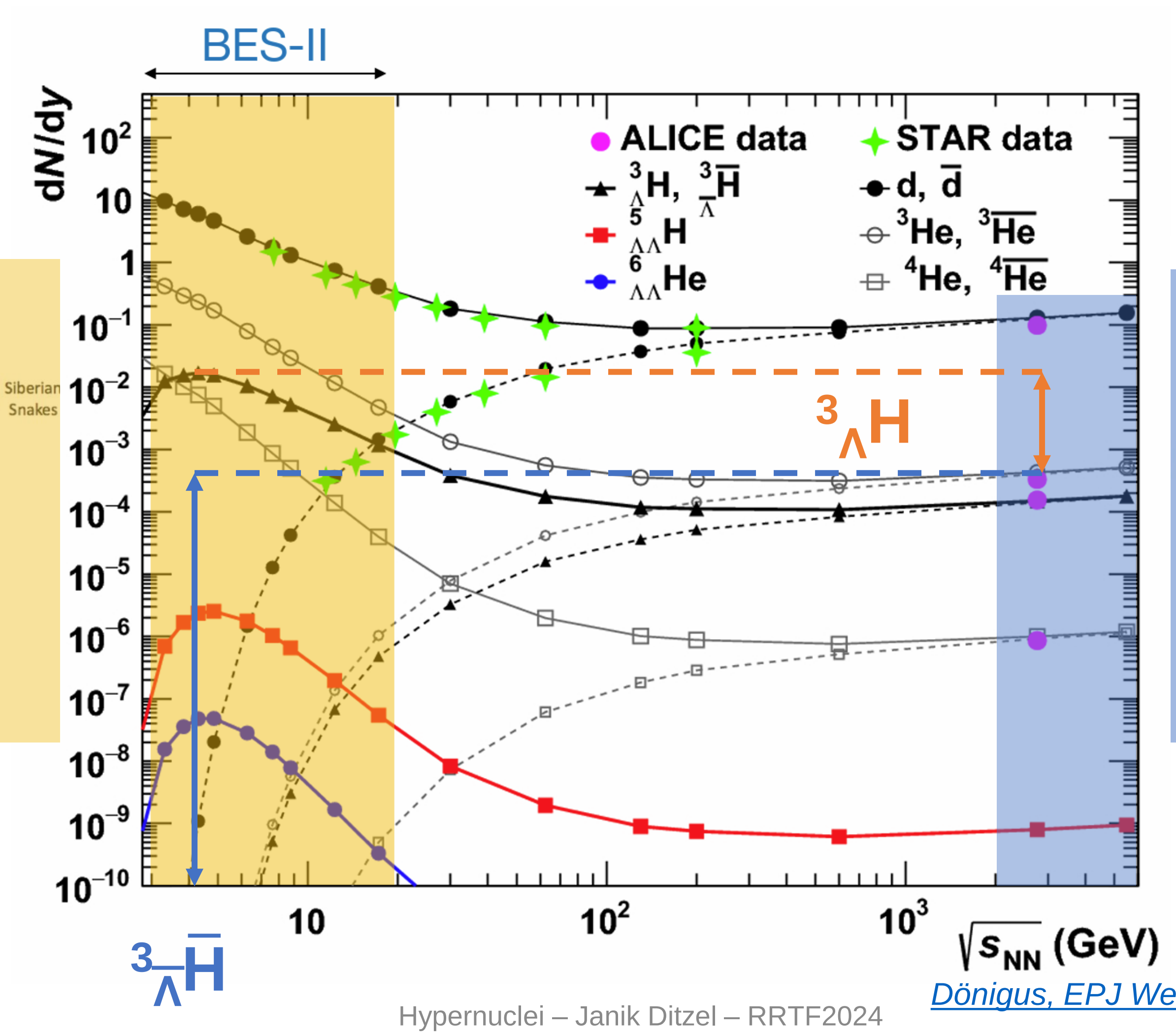
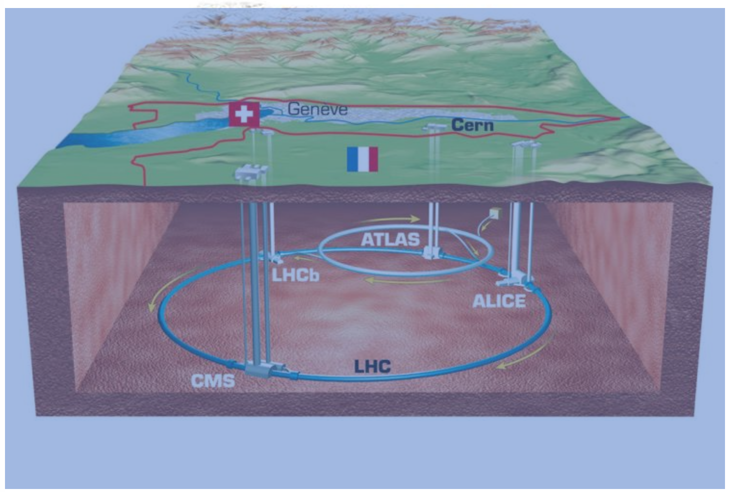




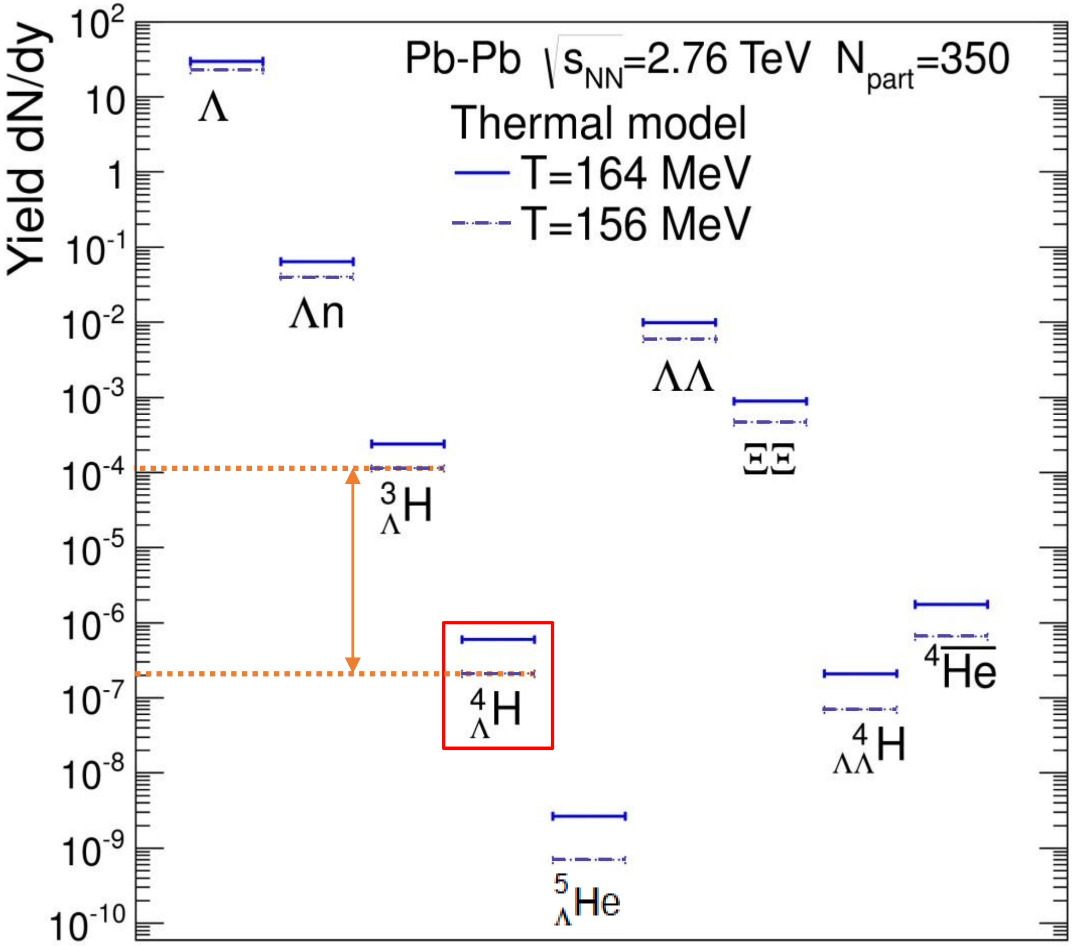
Lower production yields, but equal amount of anti-particles



Dönigus, EPJ Web of Conferences 276, 04002 (2023)

A = 4 hypernuclei

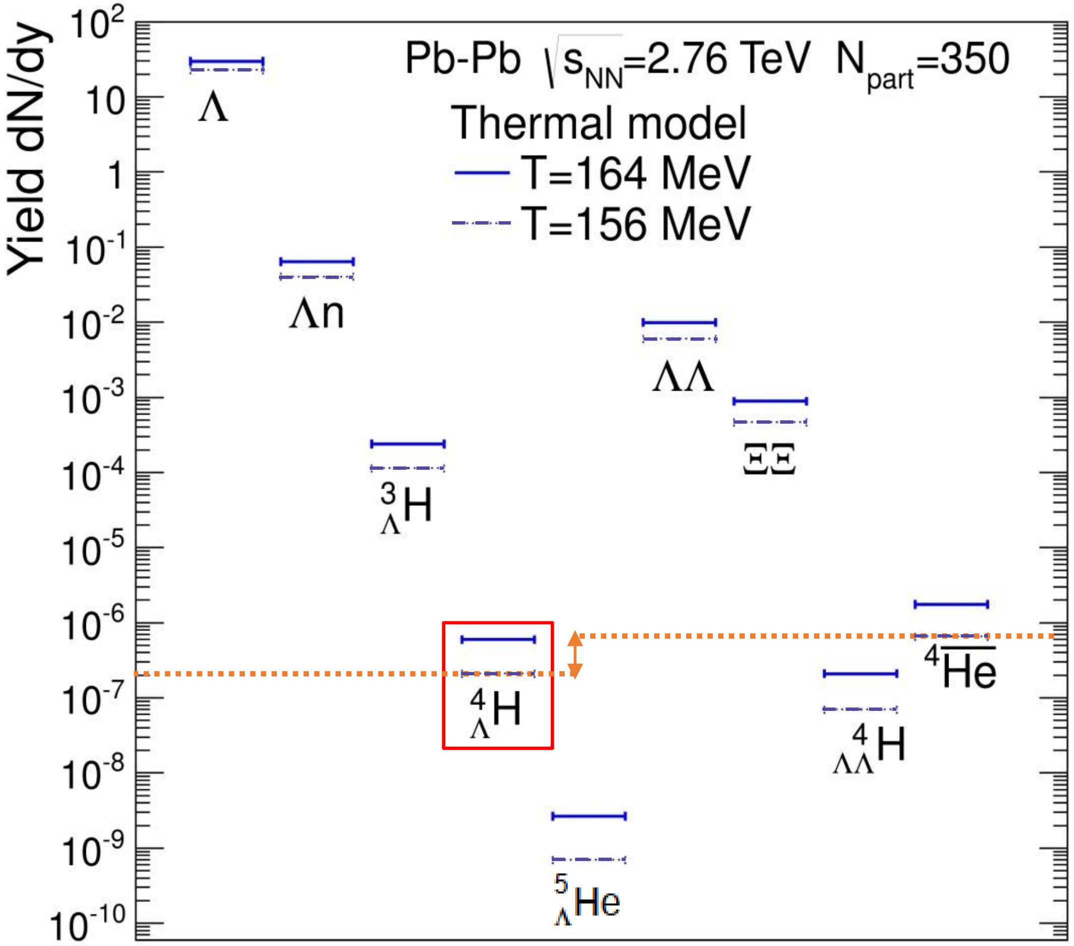
- Expectations for hypernuclei from the statistical hadronization model at T_{ch} = 156 MeV for the LHC
- Penalty factor by adding one nucleon to a particle ≈ 300 in Pb-Pb collisions



A. Andronic, private communication
model from A. Andronic et al., Phys. Lett. B 697, 203 (2011)

A = 4 hypernuclei

- Expectations for hypernuclei from the statistical hadronization model at T_{ch} = 156 MeV for the LHC
- Penalty factor by adding one nucleon to a particle ≈ 300 in Pb-Pb collisions
- Further suppression due to strangeness content wrt the antialpha
- Large statistics needed



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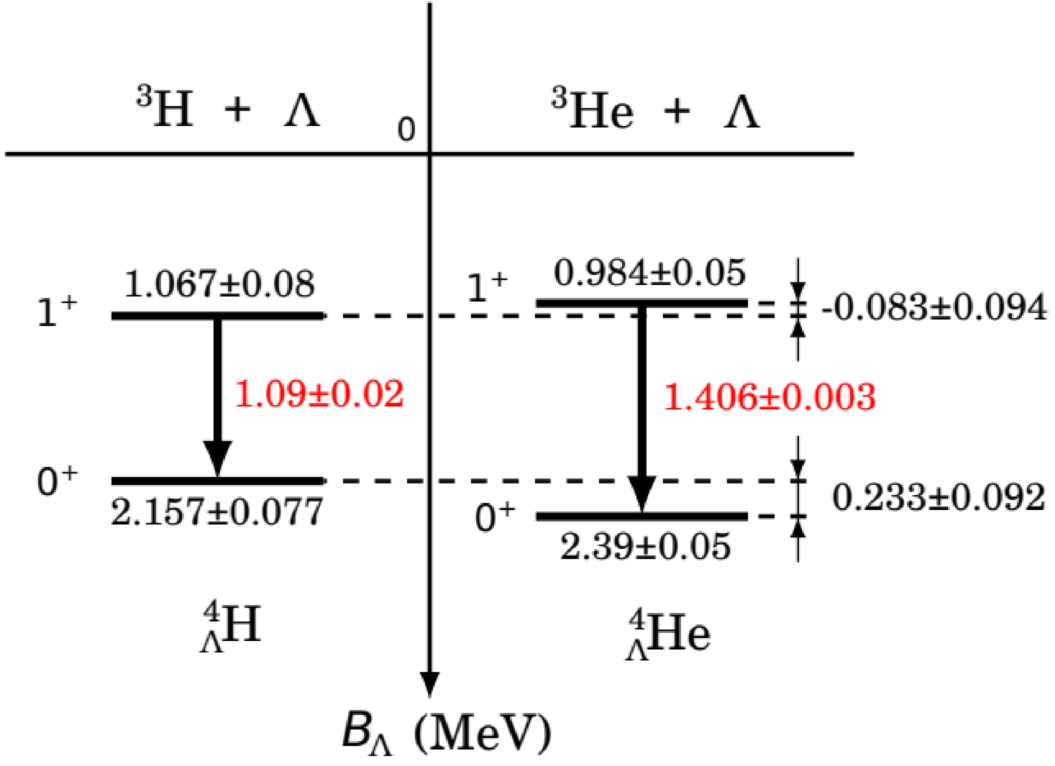
model from A. Andronic et al., Phys. Lett. B 697, 203 (2011)

A = 4 hypernuclei

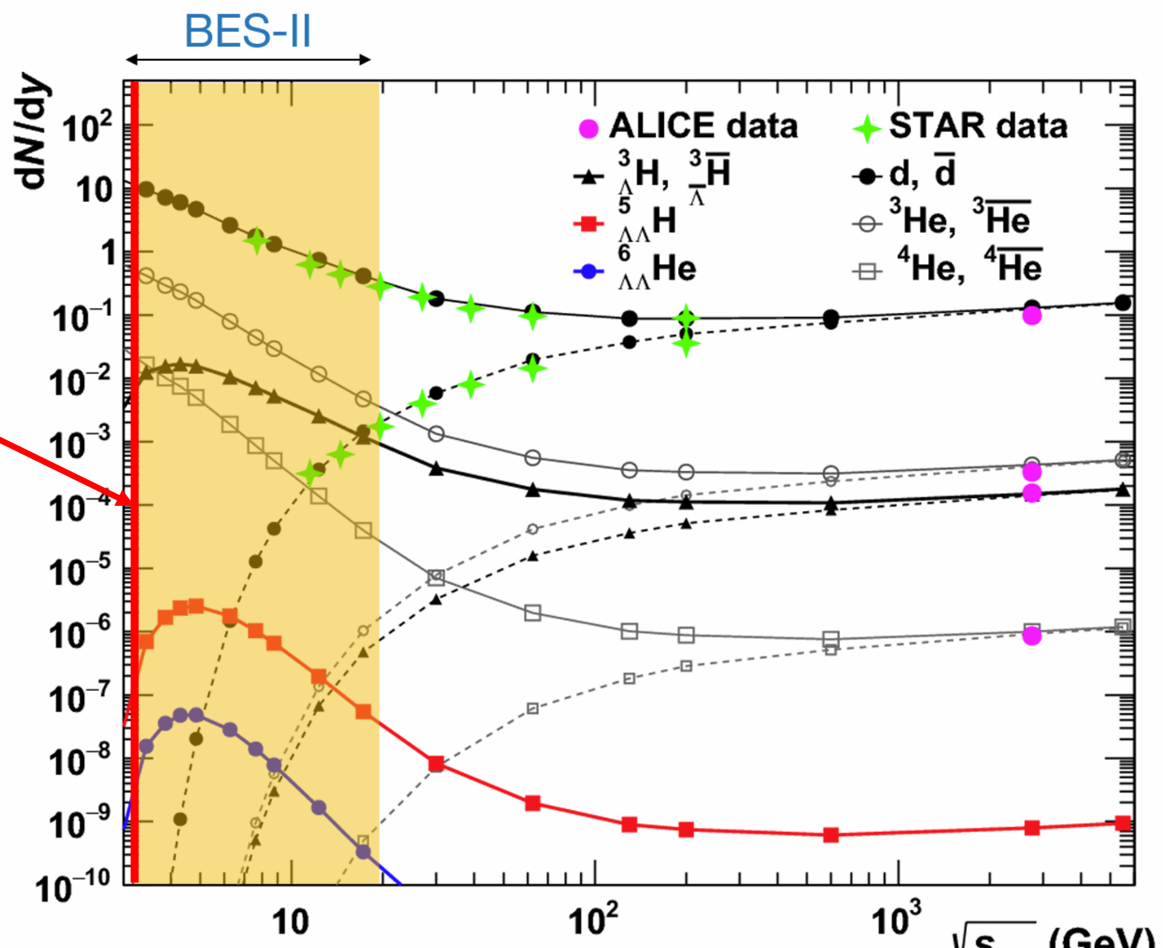
- A = 4 hypernuclei are more deeply bound and each has an excited state
  Phys. Rev. Lett. 115, 222501 (2015)
- The yields of these hypernuclei are enhanced with respect to the ground state due to the feed-down
- Also the yields of the SHM scale with the spin-degeneracy
- Resulting in a total enhancement of a factor 4 for both hypernuclei
  B. Dönigus, EPJ Web Conf. 276 (2023) 04002



M. Schäfer, N. Barnea, A. Gal, Phys.Rev.C 106, L031001 (2022)

A = 4 hypernuclei at RHIC

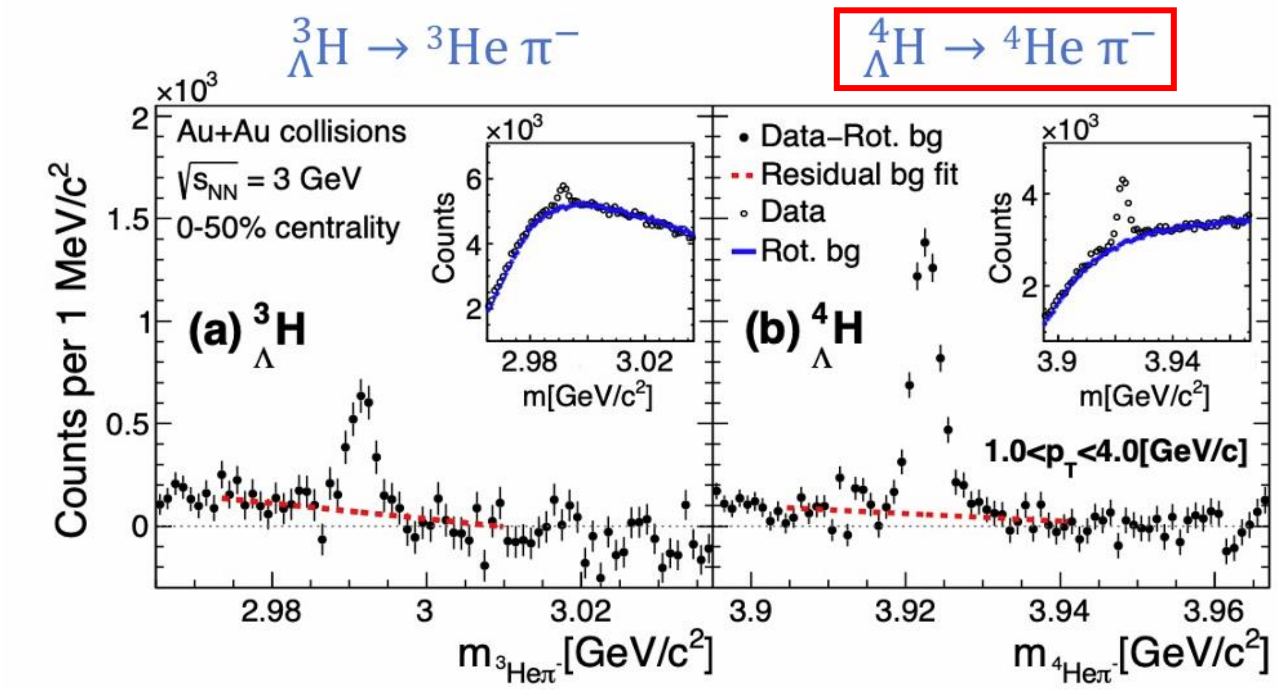
3 GeV Au+Au

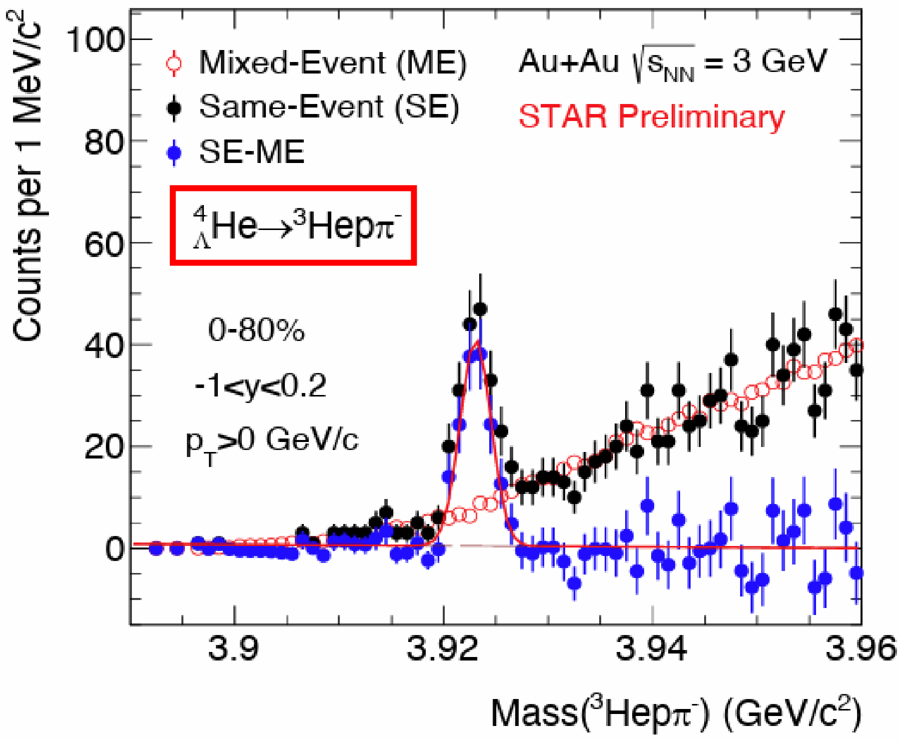


[Dönigus, EPJ Web of Conferences 276, 04002 (2023)]

A = 4 hypernuclei at RHIC

- **Abundance of A = 4 hypernuclei from RHIC at 3 GeV**



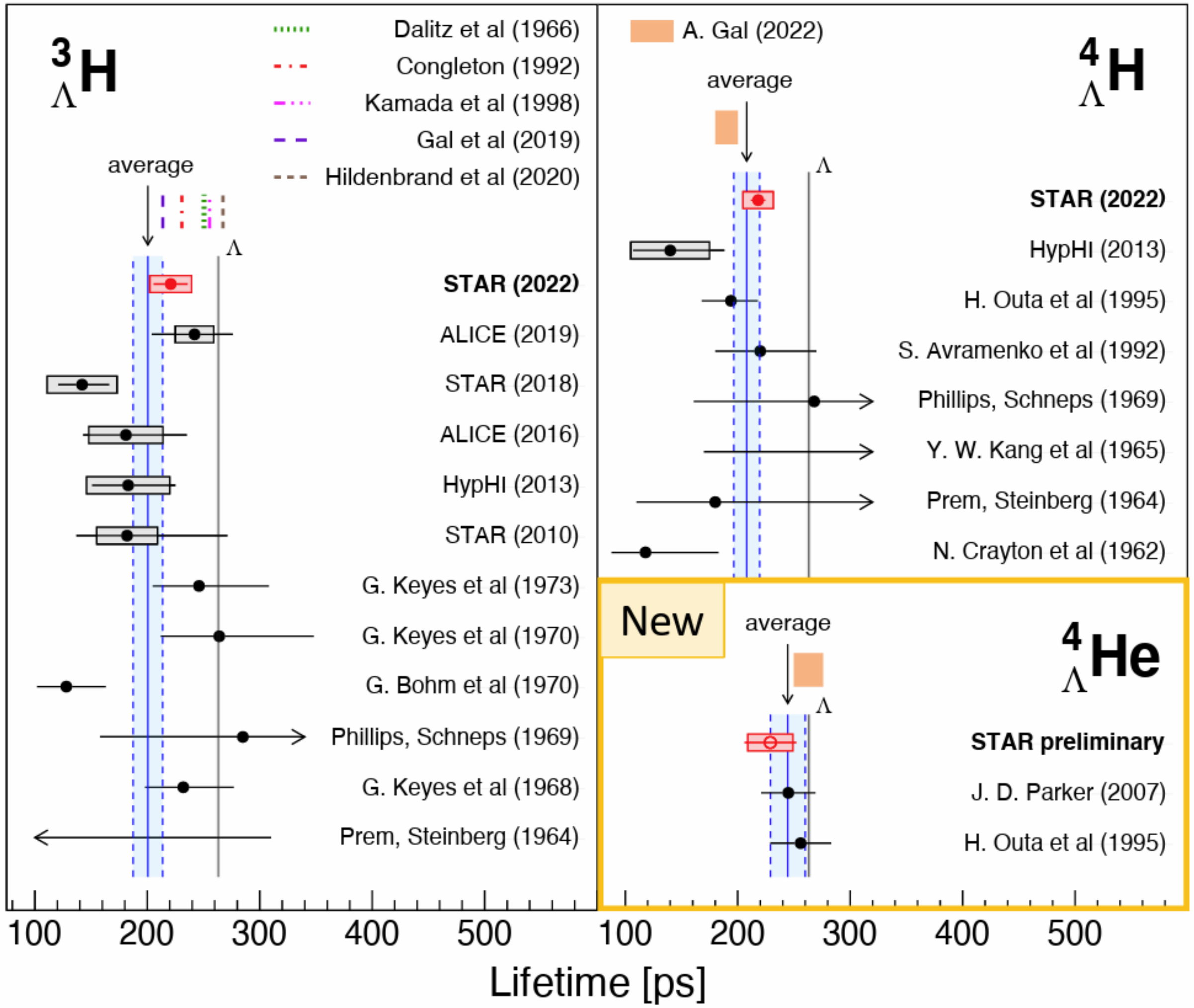


Taken from SQM2022, Yuangjing Ji

A = 4 hypernuclei at RHIC

- Abundance of A = 4 hypernuclei from RHIC at 3 GeV

- **Used to obtain their lifetime**
  (STAR, PRL128, 202301 (2022))



A = 4 hypernuclei at RHIC

- Abundance of A = 4 hypernuclei from RHIC at 3 GeV
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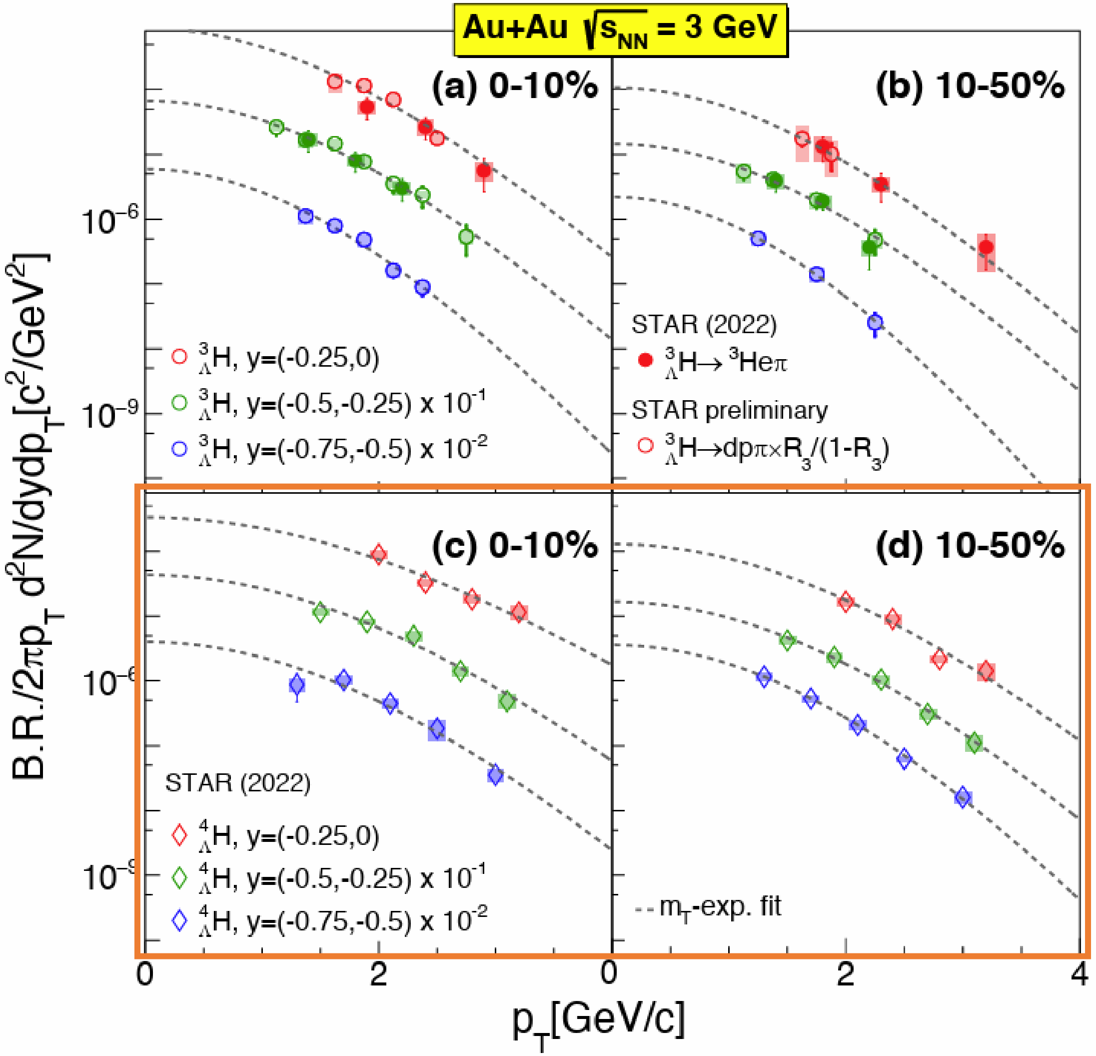
- **Used to obtain their (differential) production (STAR, PRL128, 202301 (2022))**



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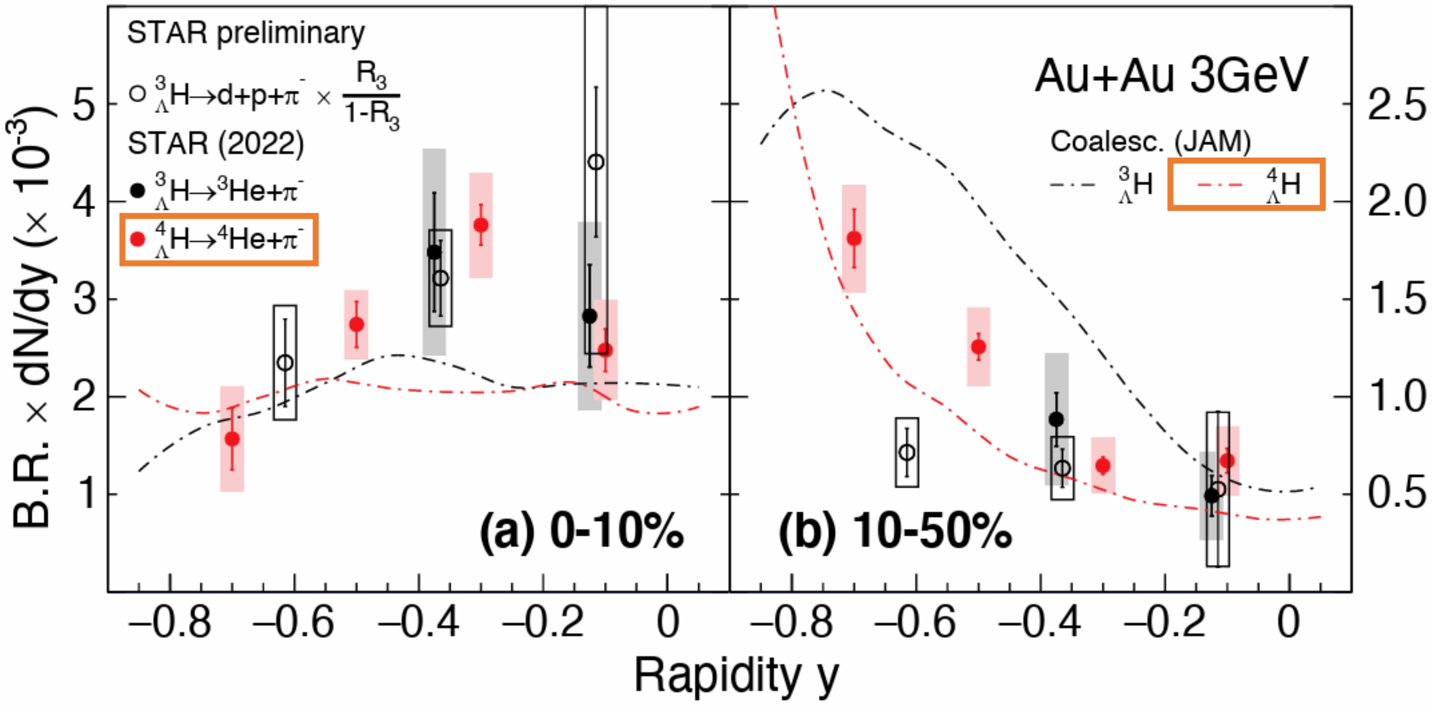

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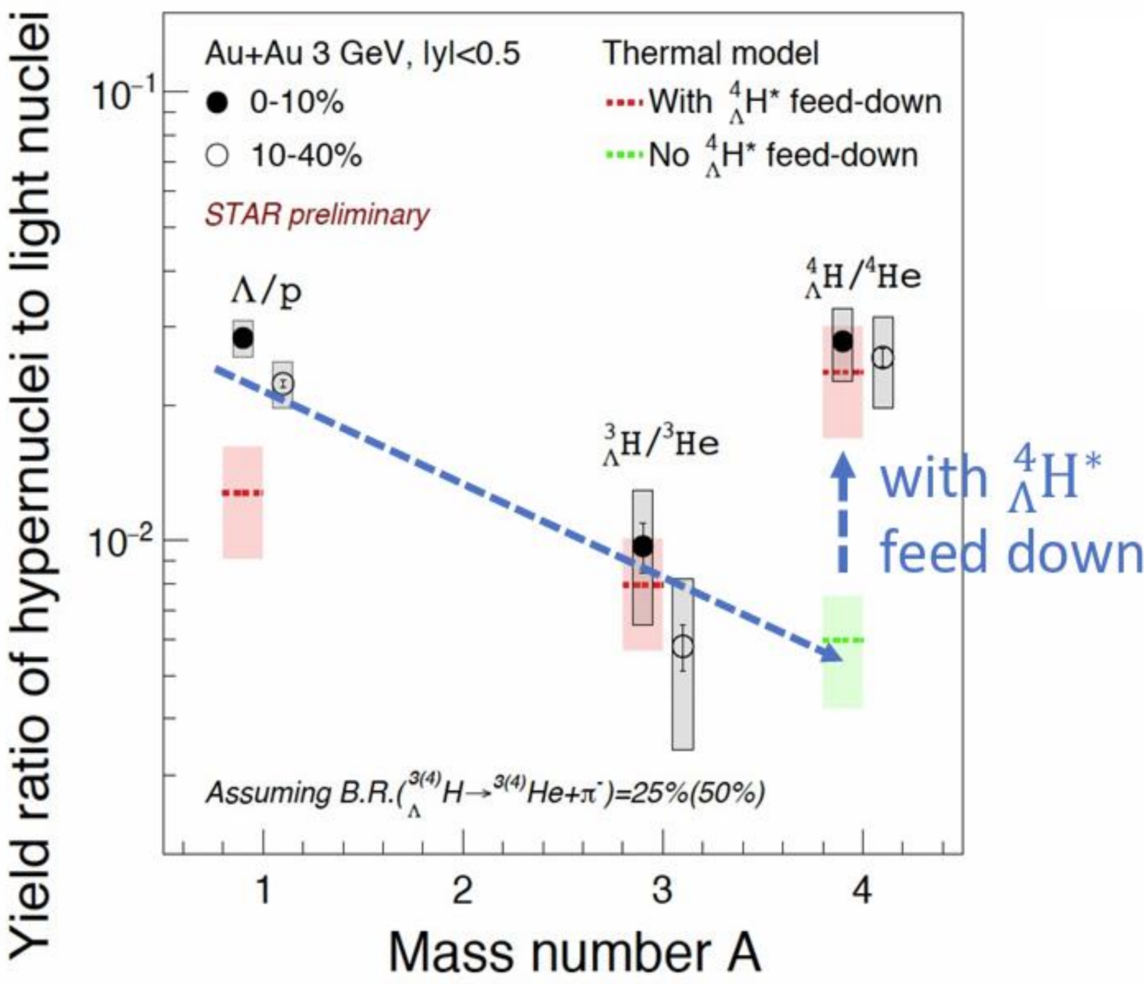
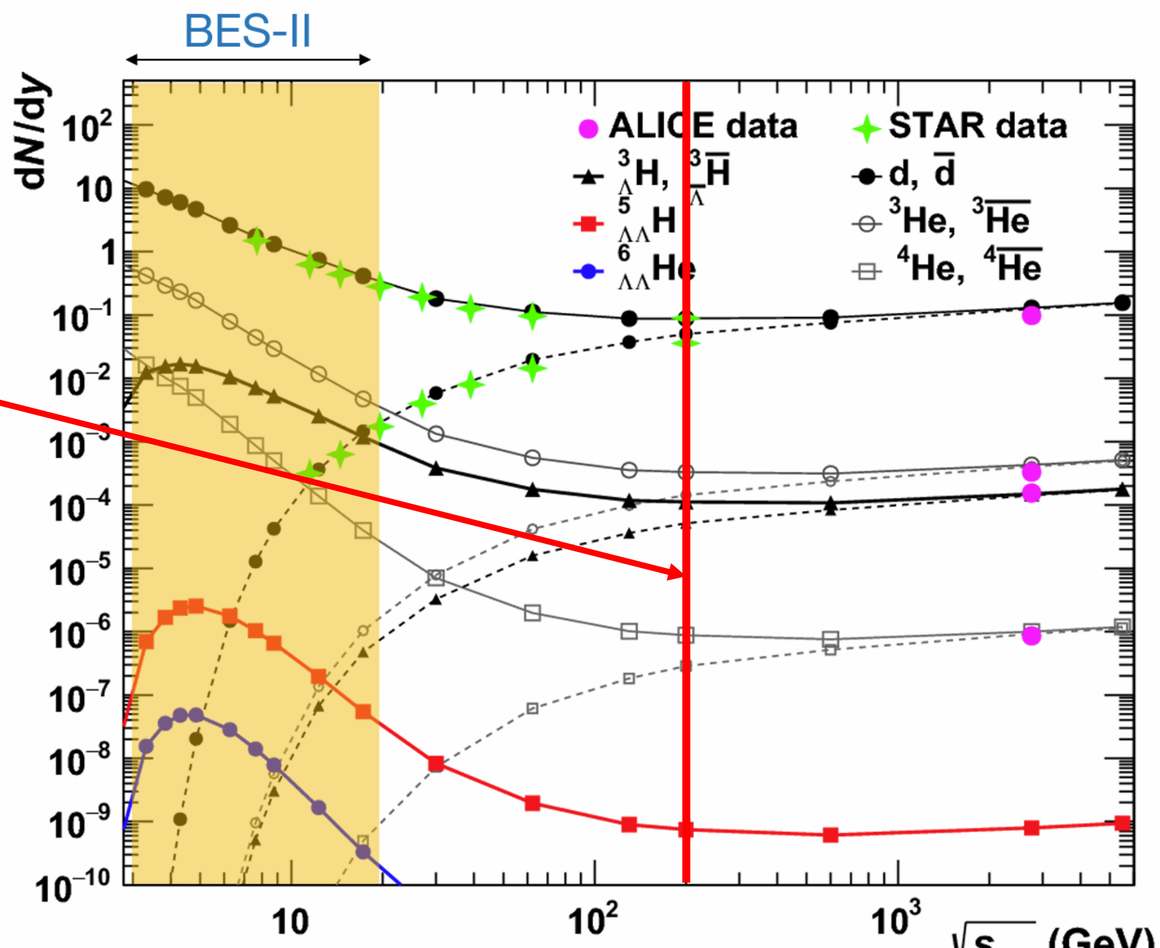


A = 4 hypernuclei at RHIC

200 GeV Au+Au
193 GeV U+U
200 GeV Zr+Zr (Ru+Ru)

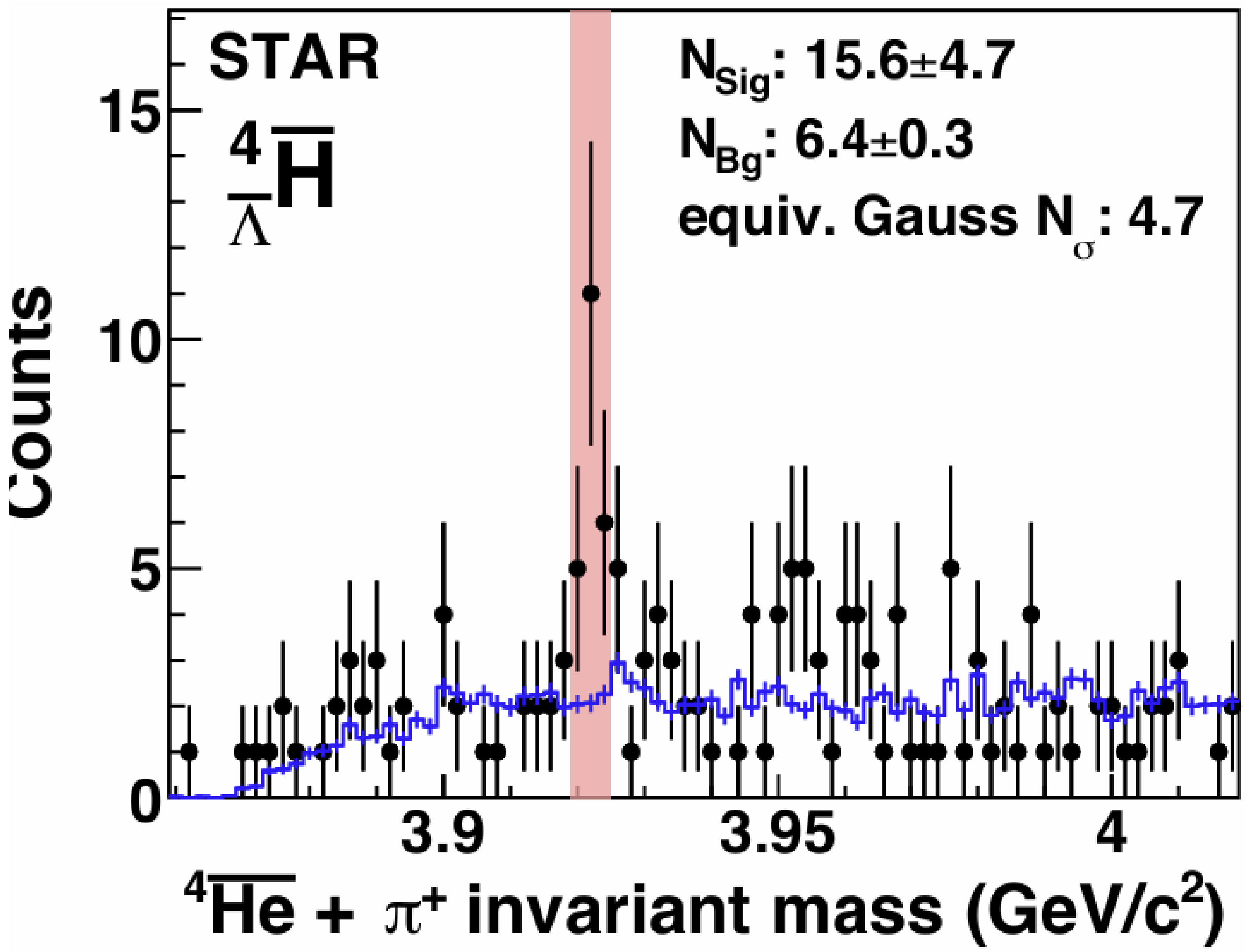


Dönigus, EPJ Web of Conferences 276, 04002 (2023)

A = 4 hypernuclei at RHIC

- **First observation of the antihyperhydrogen-4 from RHIC at 200 GeV**

STAR, arXiv:2310.12674



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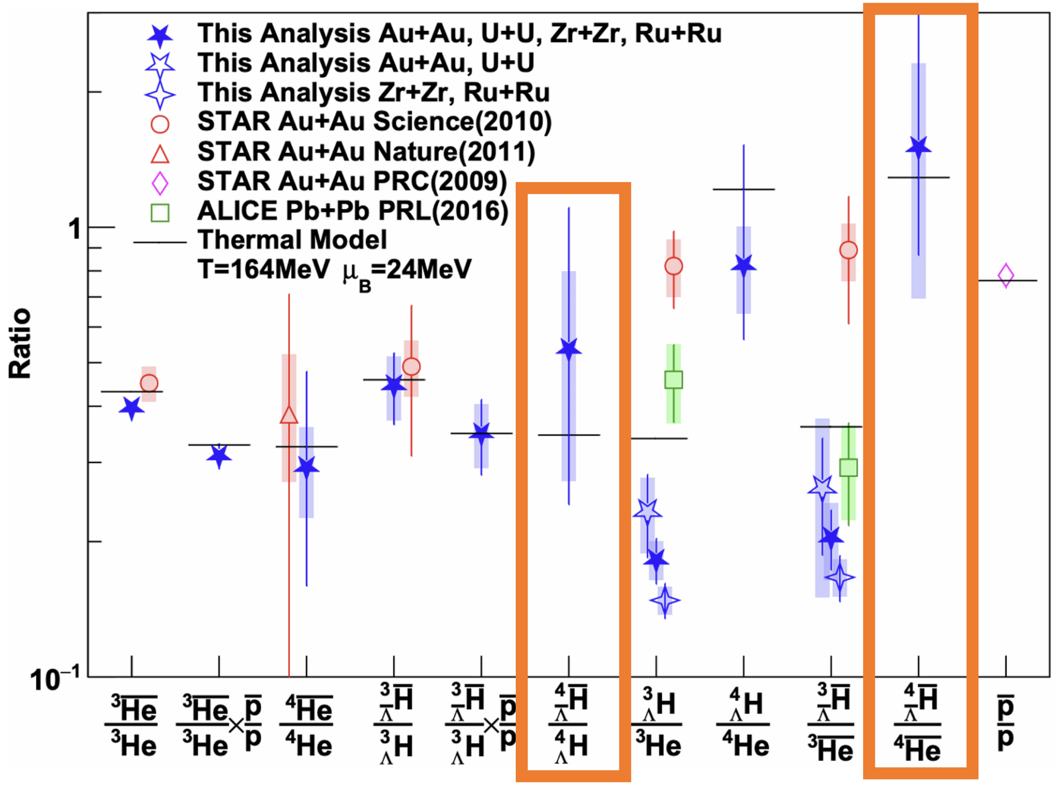
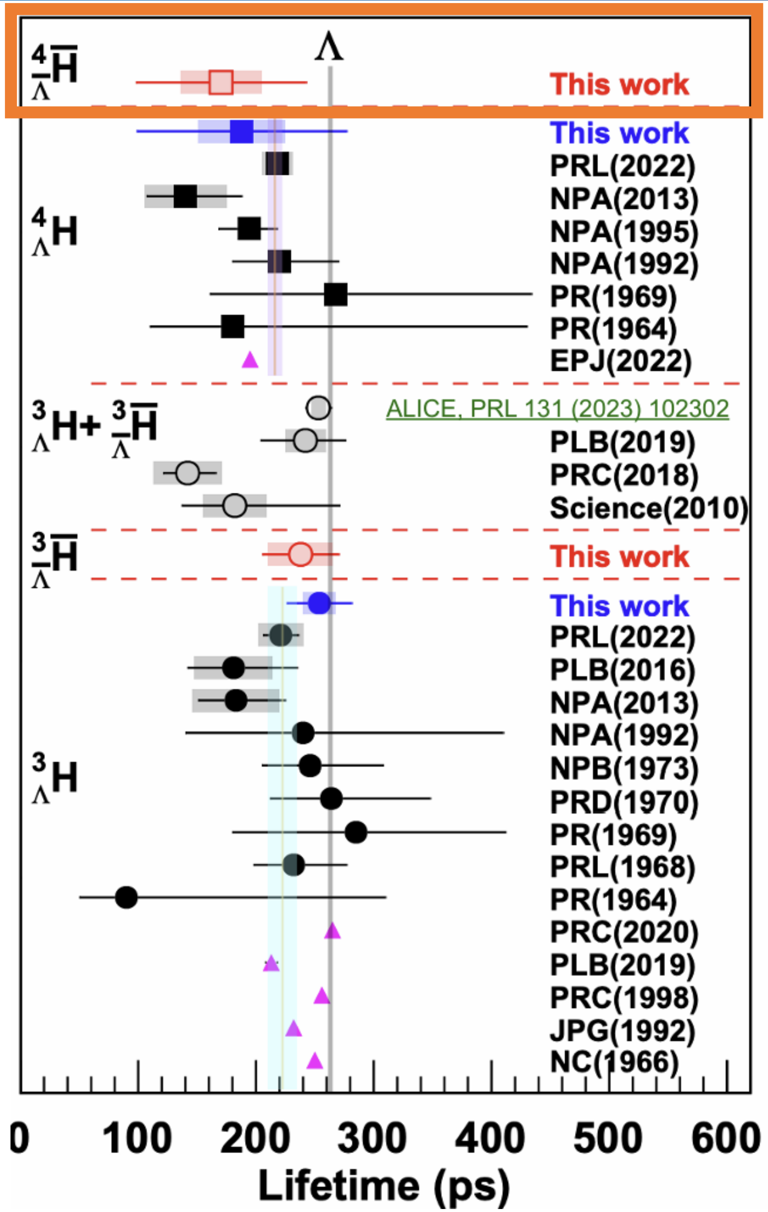
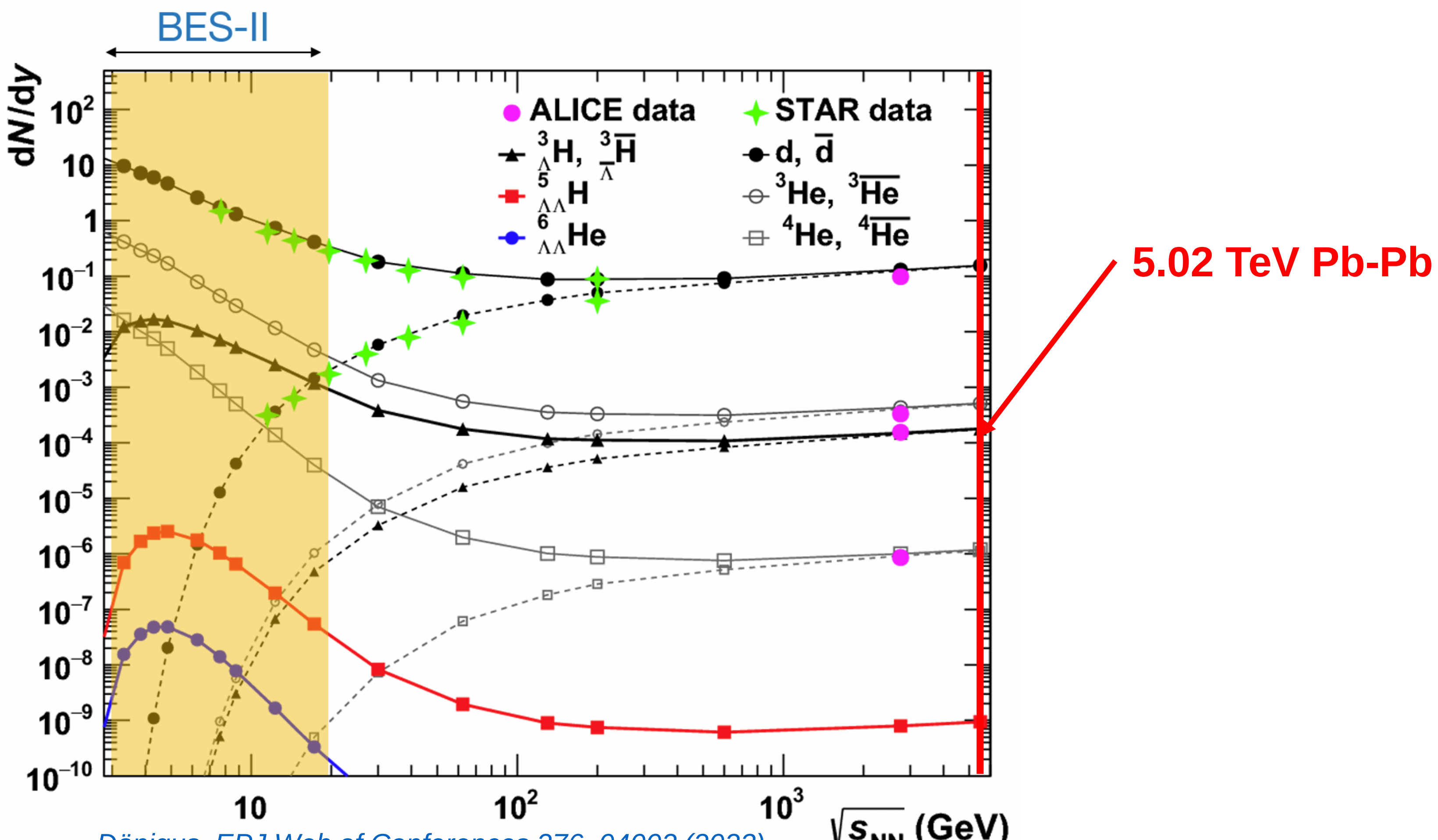




A = 4 hypernuclei at the LHC



Dönigus, EPJ Web of Conferences 276, 04002 (2023)

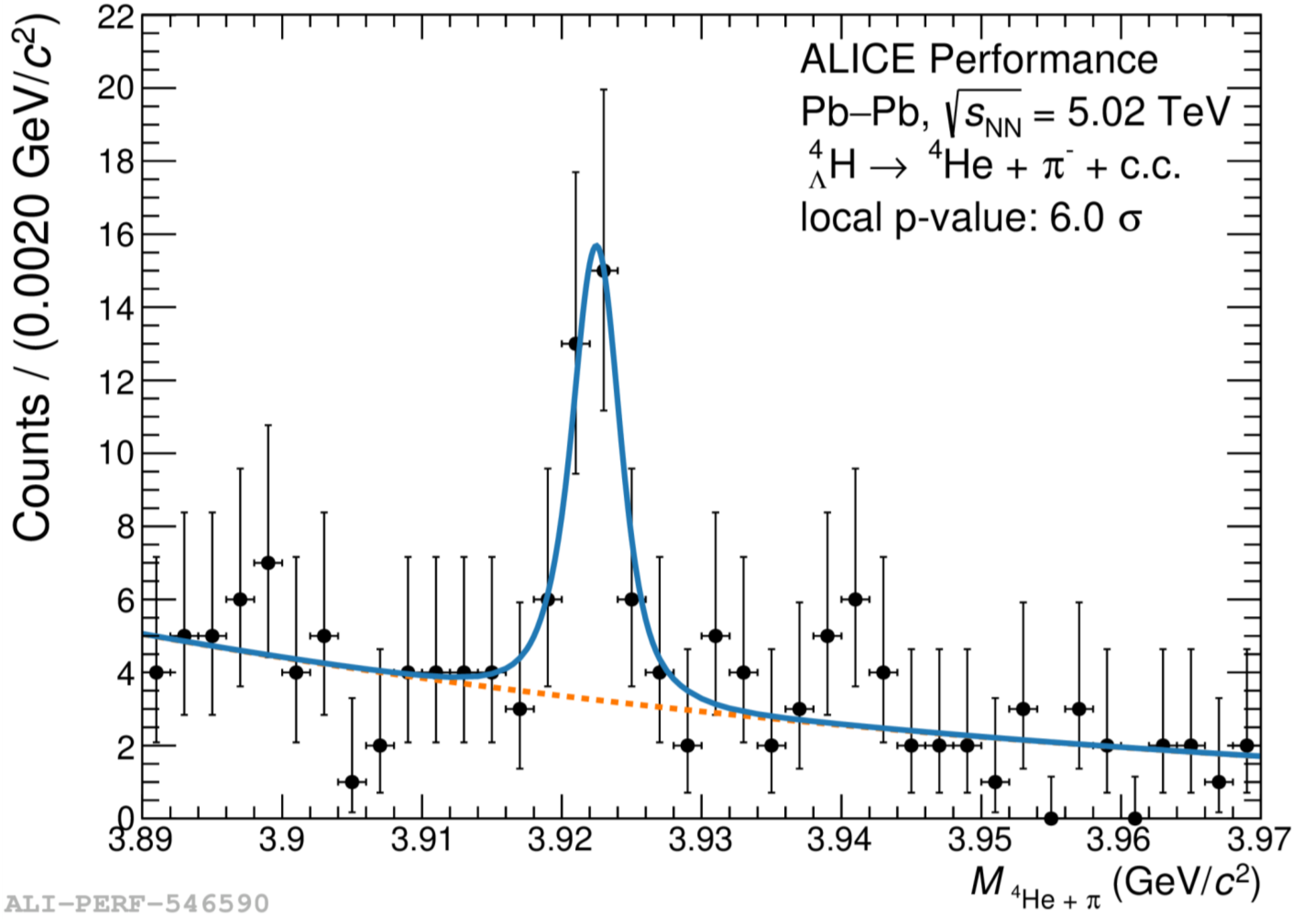
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

A = 4 hypernuclei at the LHC

- For the first time, we are able to reconstruct A = 4 (anti)hypernuclei at the LHC and determine their production yield
- **(Anti)hyperhydrogen-4** invariant-mass spectrum in Run 2 Pb-Pb collisions at 5.02 TeV
- Examined in the two-body decay:

$$^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-} + \mathrm{c.c.}$$

- Reaching a local p-value of **6.0σ**



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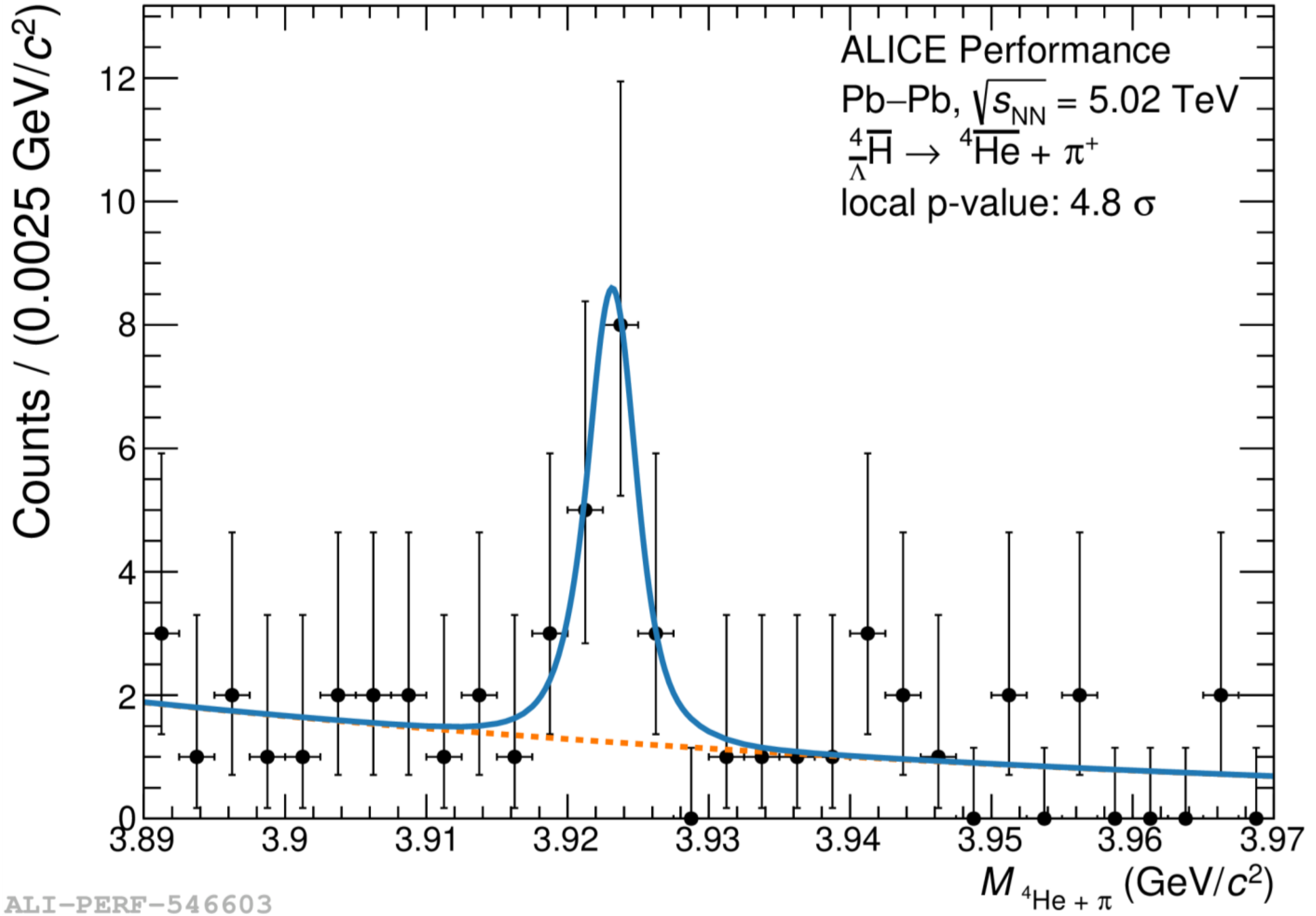
- **Antihyperhydrogen-4**
  in Run 2 Pb-Pb collisions
  at 5.02 TeV

- Reaching a local p-value of **4.8σ**



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A = 4 hypernuclei at the LHC

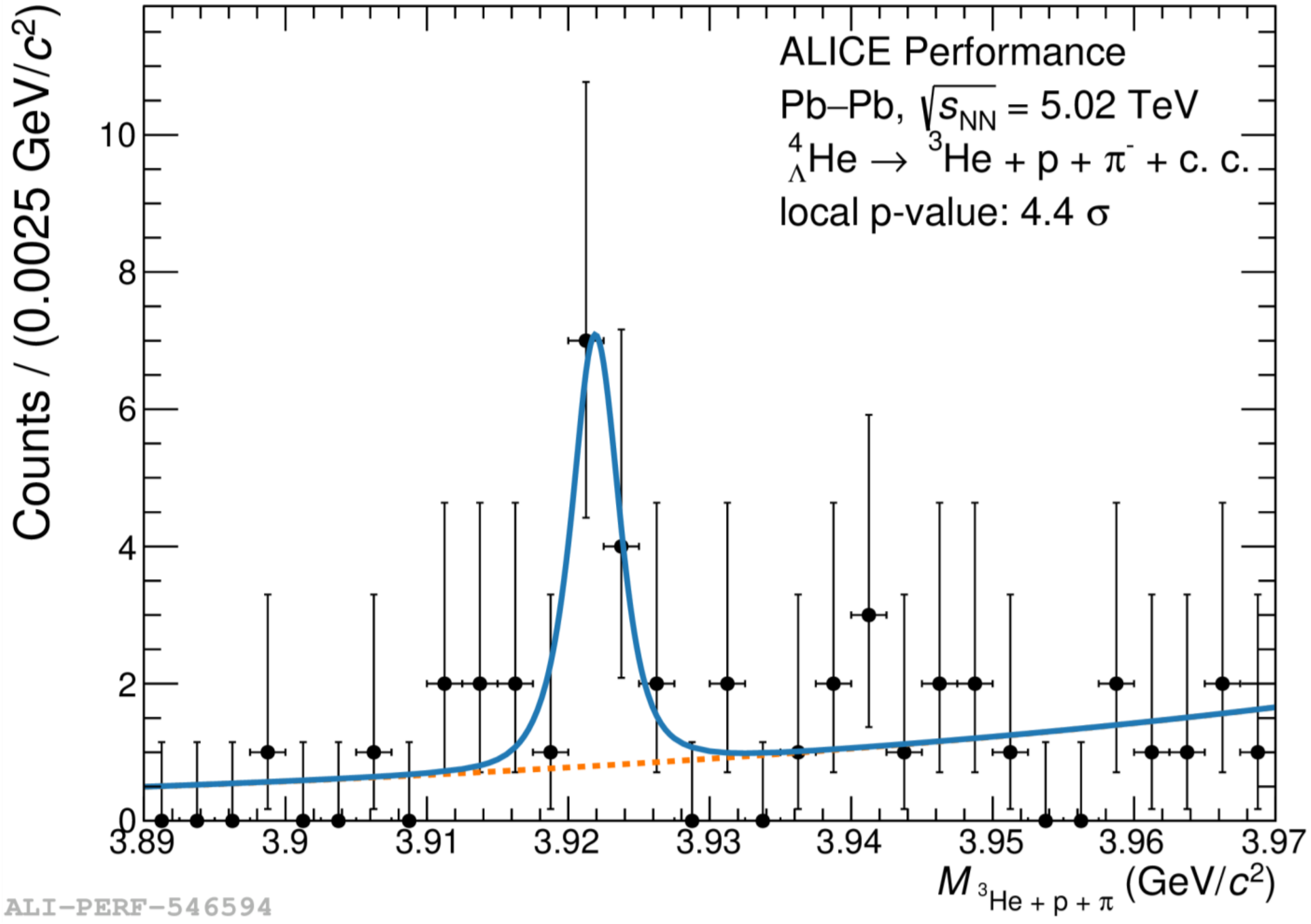
- For the first time, we are able to reconstruct A = 4 (anti)hypernuclei at the LHC and determine their production yield

- **(Anti)hyperhelium-4** invariant-mass spectrum in Run 2 Pb-Pb collisions at 5.02 TeV

- Examined in the three-body decay:

$$^{4}_{\Lambda}\mathrm{He} \rightarrow \, ^{3}\mathrm{He} + p + \pi^{-} + \mathrm{c.c.}$$

- Reaching a local p-value of **4.4σ**

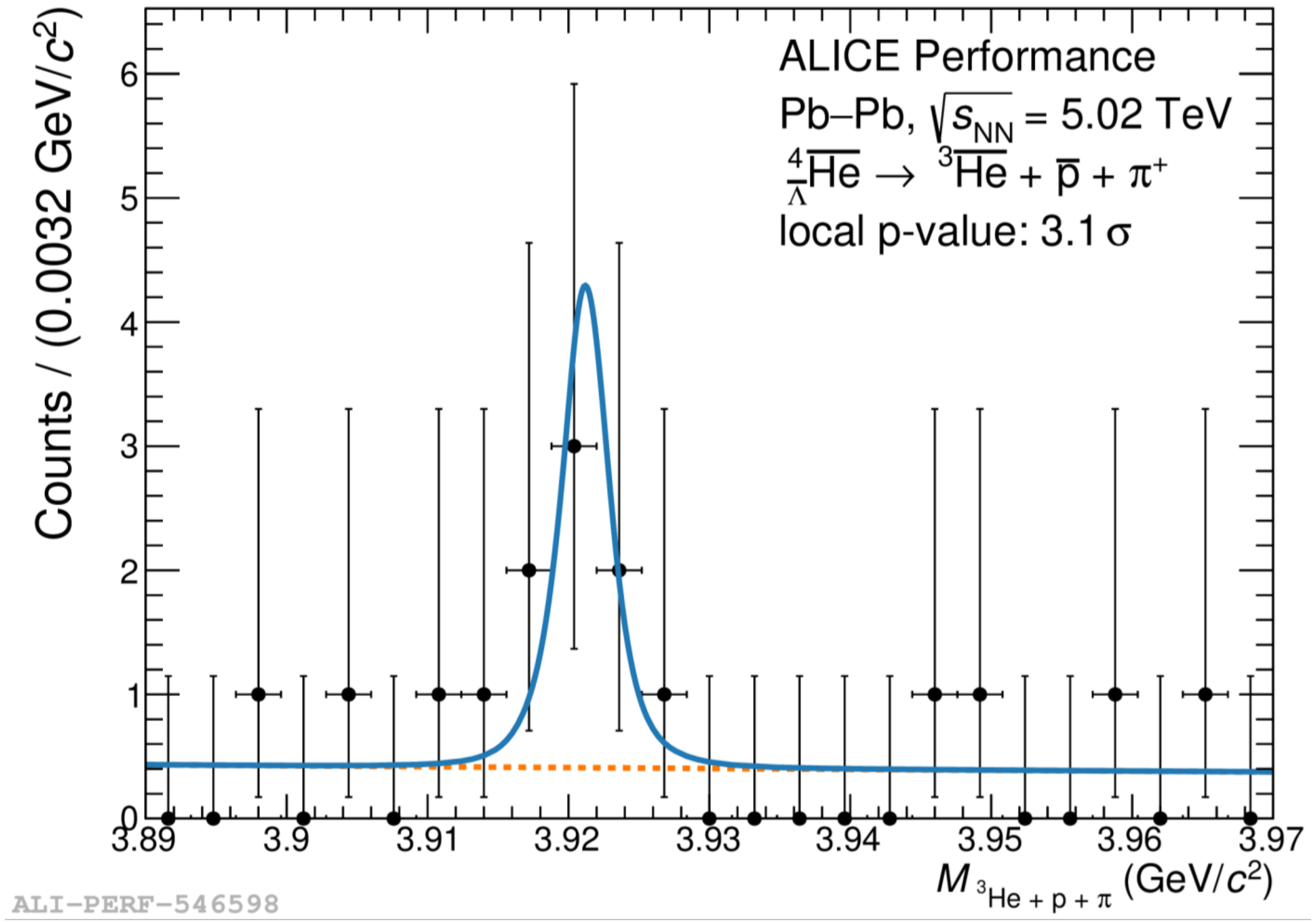


A = 4 hypernuclei at the LHC

- For the first time, we are able to reconstruct A = 4 (anti)hypernuclei at the LHC and determine their production yield

- **First observation of the antihyperhelium-4** in Run 2 Pb-Pb collisions at 5.02 TeV

- Reaching a local p-value of **3.1σ**



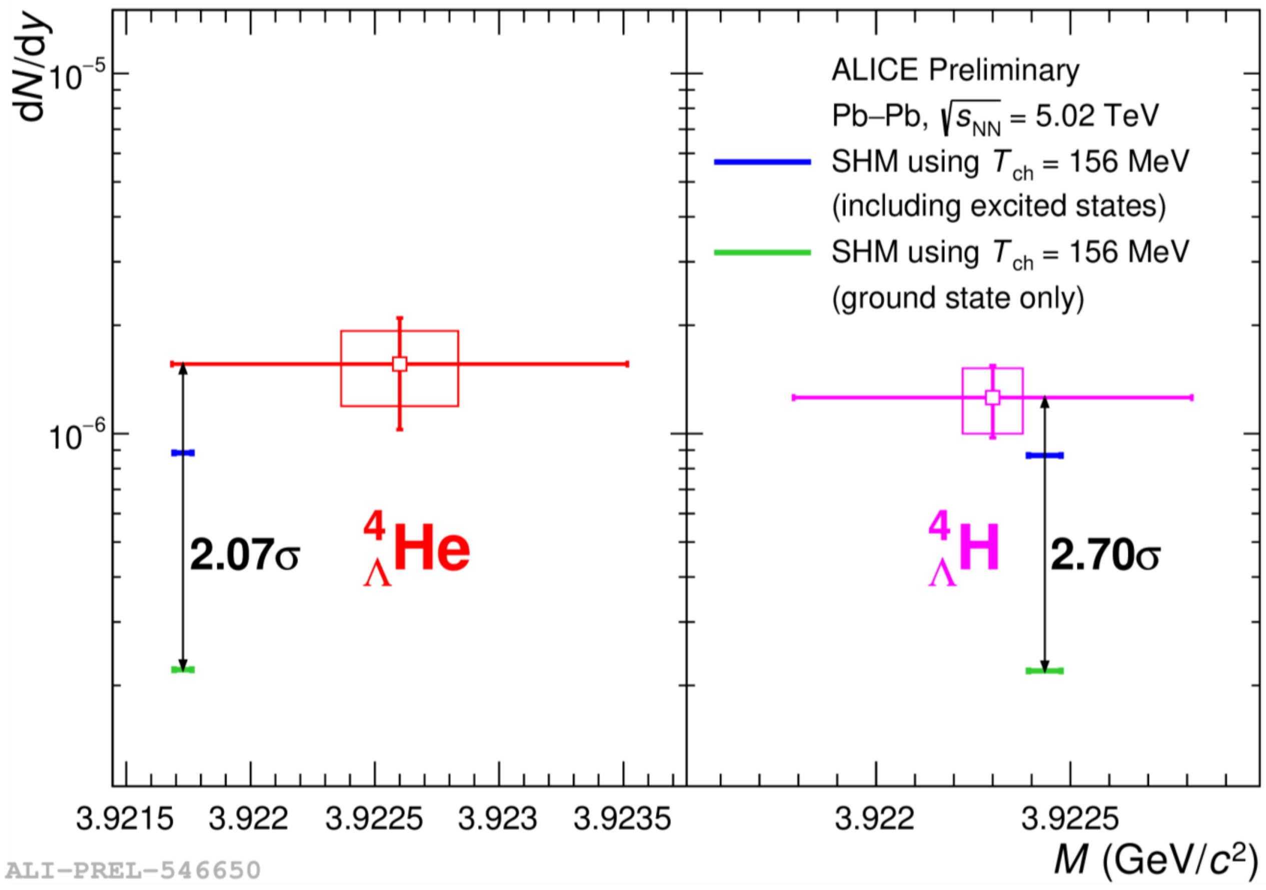
A = 4 hypernuclei at the LHC

- First measurement of the (anti)hyperhelium-4 production yield

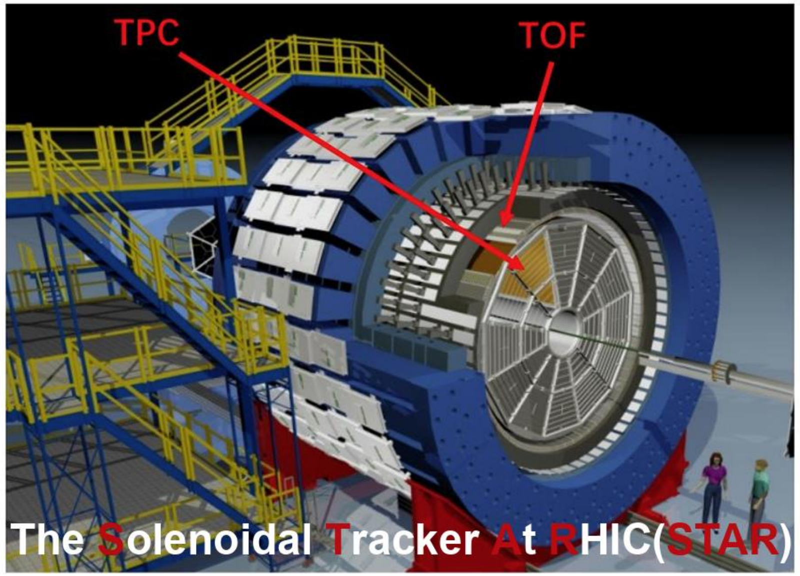
- Our yields are compatible with the SHM and the presence of excited states with J=1

- Mass measurement compared to world average from Hypernuclei Database

- Currently dominated by statistical uncertainties



Perspectives for the (near) future



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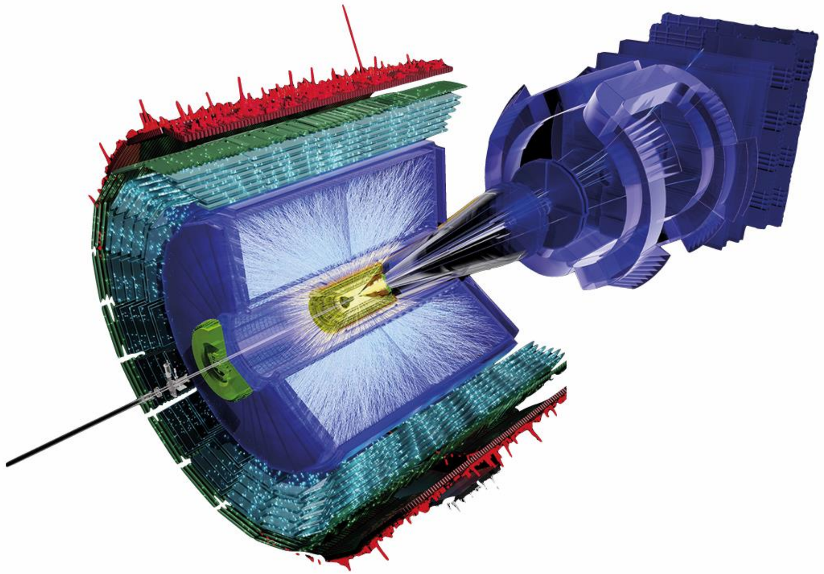
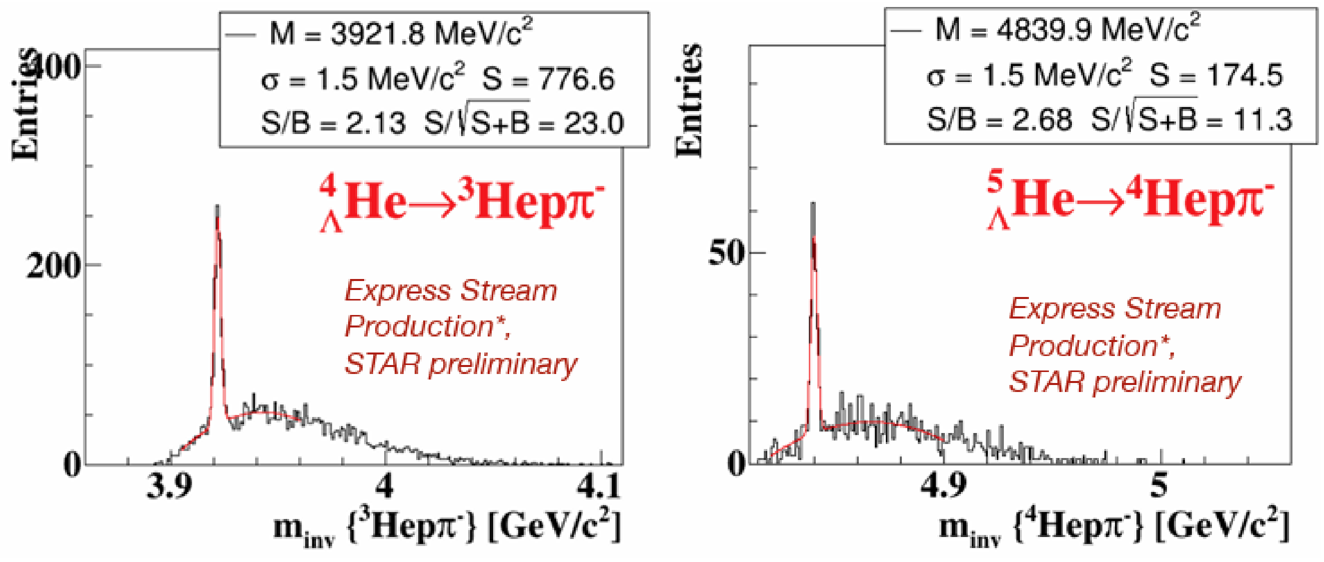


ALICE

A = 5 hypernuclei

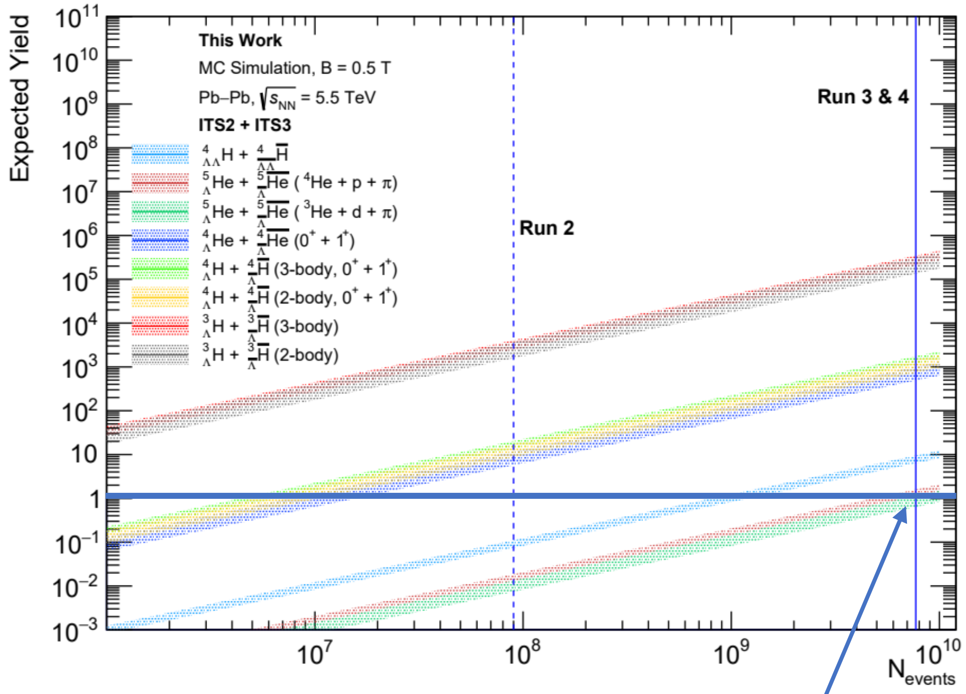


*Data from express stream (Au+Au $\sqrt{s_{NN}}$=3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV) are not with the final calibrations

Taken from QM2022, Yue Hang Leung

We are looking forward to the final results!

Taken from the master thesis, Janik Ditzel



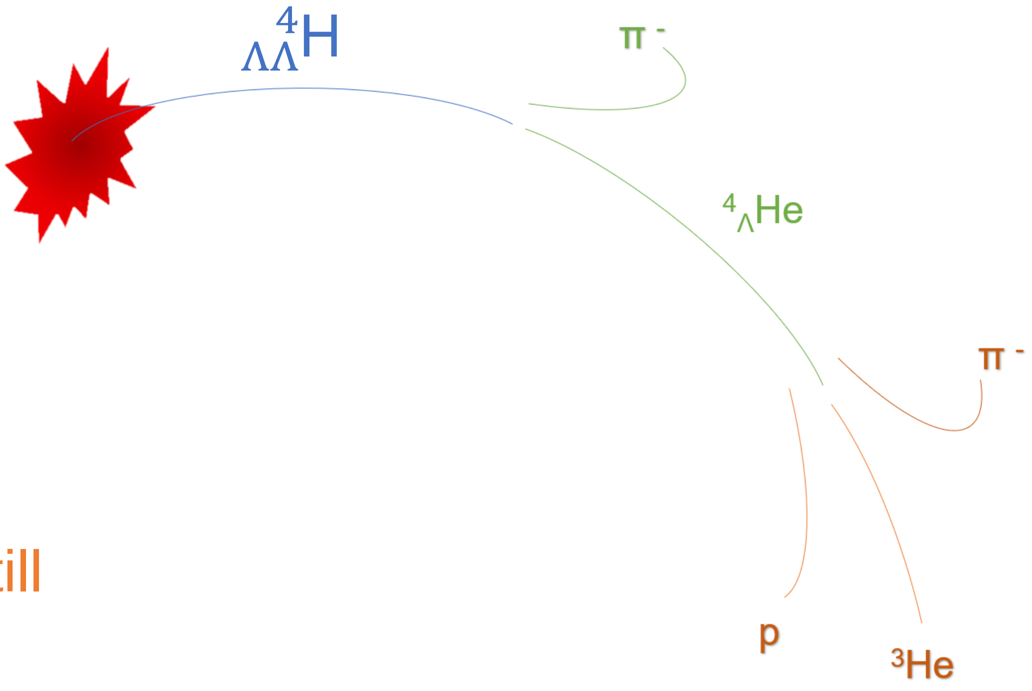
At the LHC, these objects probably remain unreachable with the statistics of Run 3 & 4

Multi-strange A=4 hypernuclei

- What about multi-strange hypernuclei?
- More difficult to reconstruct due to cascading decays
- Lightest possible double hypernucleus:
- Decay mode:

$$ {}^{4}_{\Lambda\Lambda}\mathrm{H} \rightarrow {}^{4}_{\Lambda}\mathrm{He} + \pi_{sec} $$
$$ \rightarrow {}^{3}\mathrm{He} + p + \pi $$

- Mass expected to be 4.106 GeV/c^2
- Existence of ${}^{4}_{\Lambda\Lambda}\mathrm{H}$ bound state theoretically still unclear and experimentally not found yet

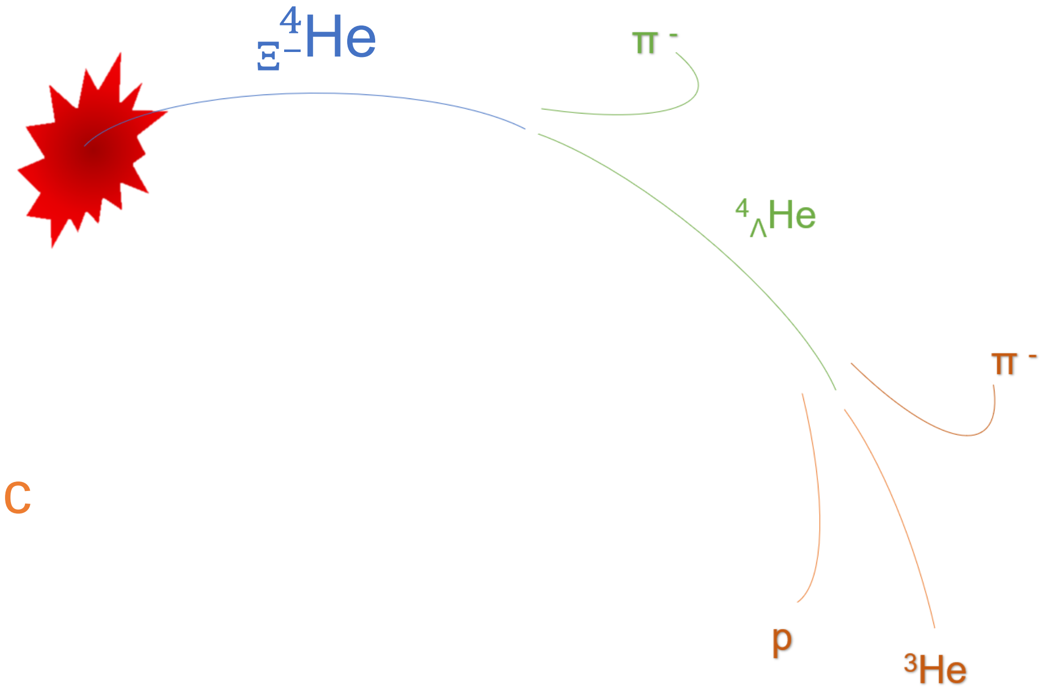


Multi-strange A=4 hypernuclei

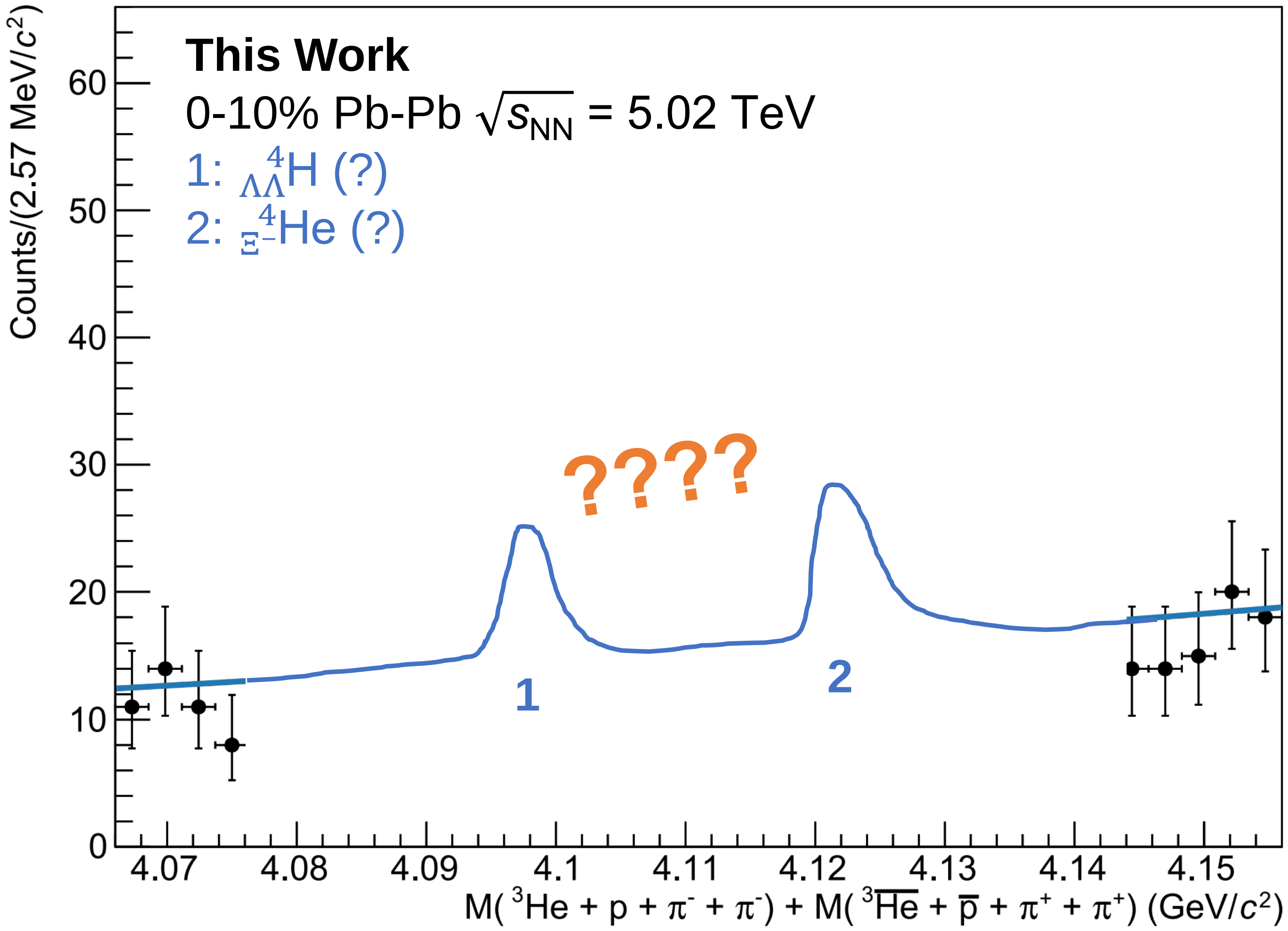
- Possibly also: ${}^{4}_{\Xi^-}\mathrm{He}$
- Decays in the same way as ${}^{4}_{\Lambda\Lambda}\mathrm{H}$

$${}^{4}_{\Xi^-}\mathrm{He} \rightarrow {}^{4}_{\Lambda}\mathrm{He} + \pi_{sec}\ (\Xi^- \rightarrow \Lambda + \pi^-)$$
$$\rightarrow {}^{3}\mathrm{He} + p + \pi$$

- Mass expected to be 4.126 GeV/c^2 by calculations using recent information from the Ξ^- potential Phys.Lett.B 820 (2021) 136555
- Special features: Possibility to create atomic structures; excited states? arxiv:2308.12041
- Experimentally not found yet

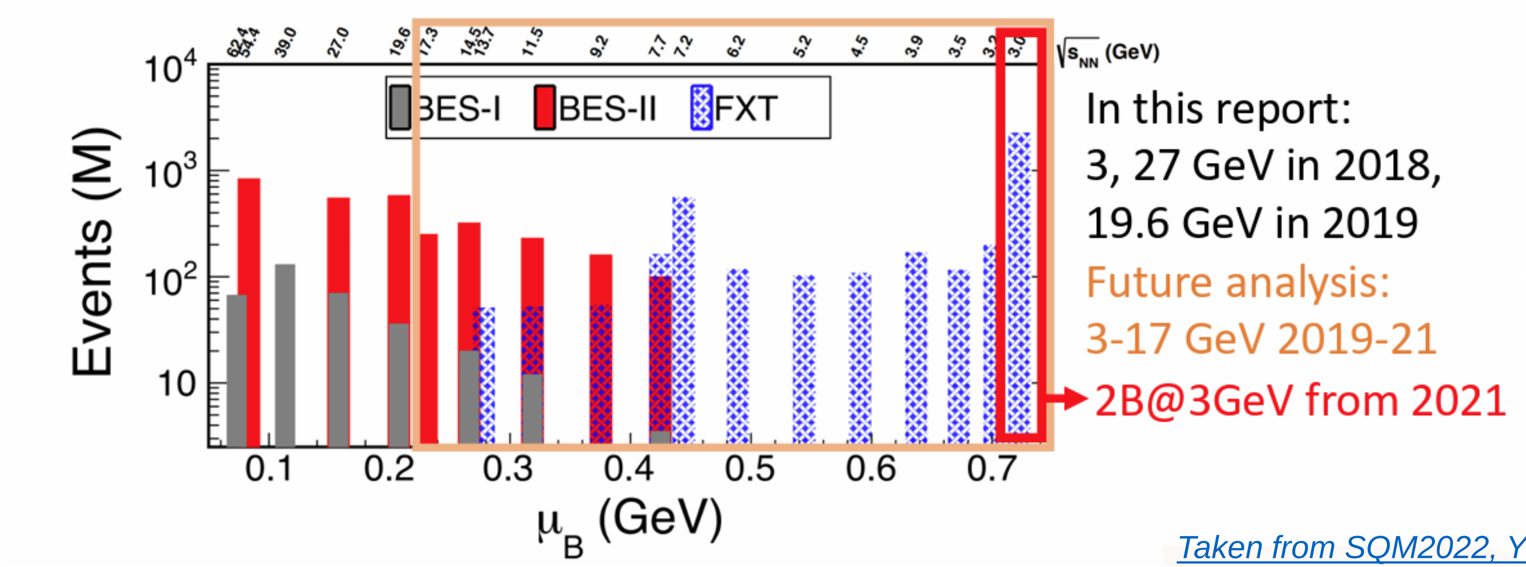


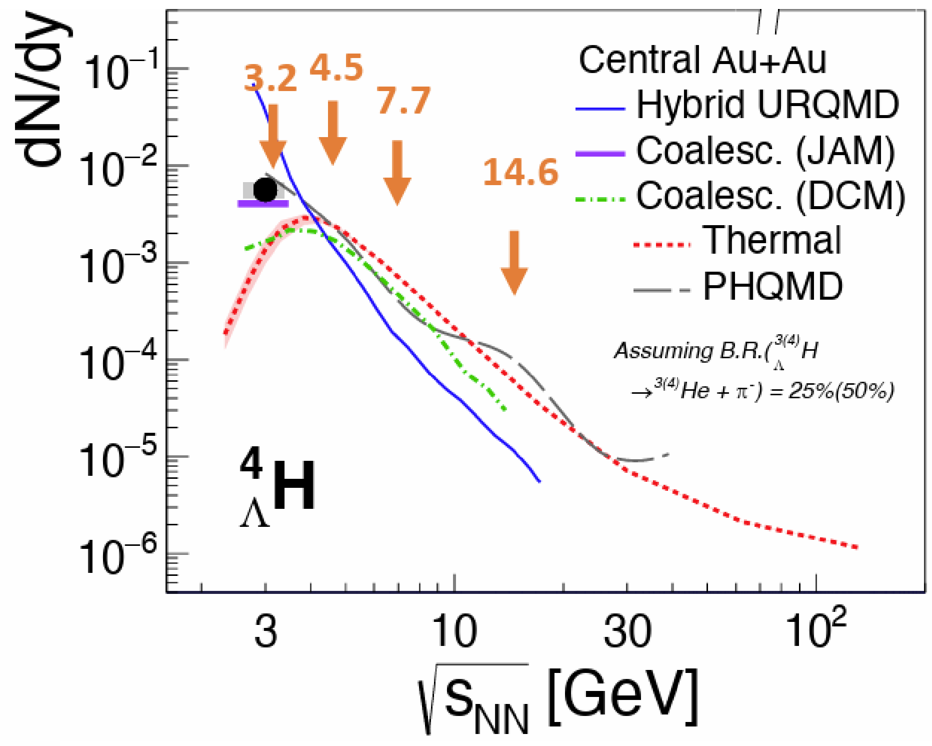
How would the spectrum look like?



Scanning more data

- At RHIC, data sets with different energies are available
- The analysis of those data sets may provide further statistics for measurements of hypernuclei

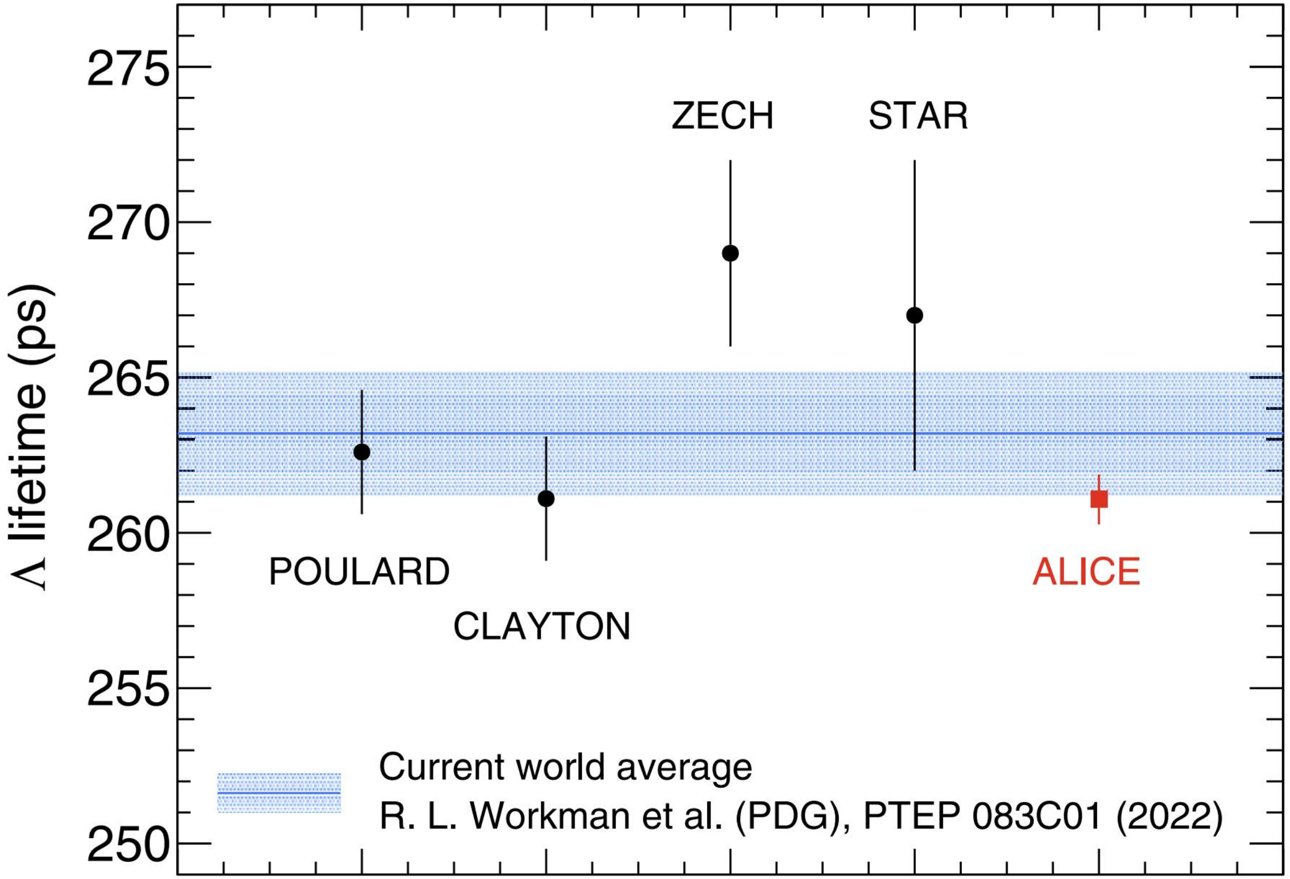




Taken from SQM2022, Yuangjing Ji

Scanning more data

- Also at the LHC, more data is available soon with the ongoing Run 3
- High precision measurements for hypernuclei will be possible as for the Λ hyperon for example

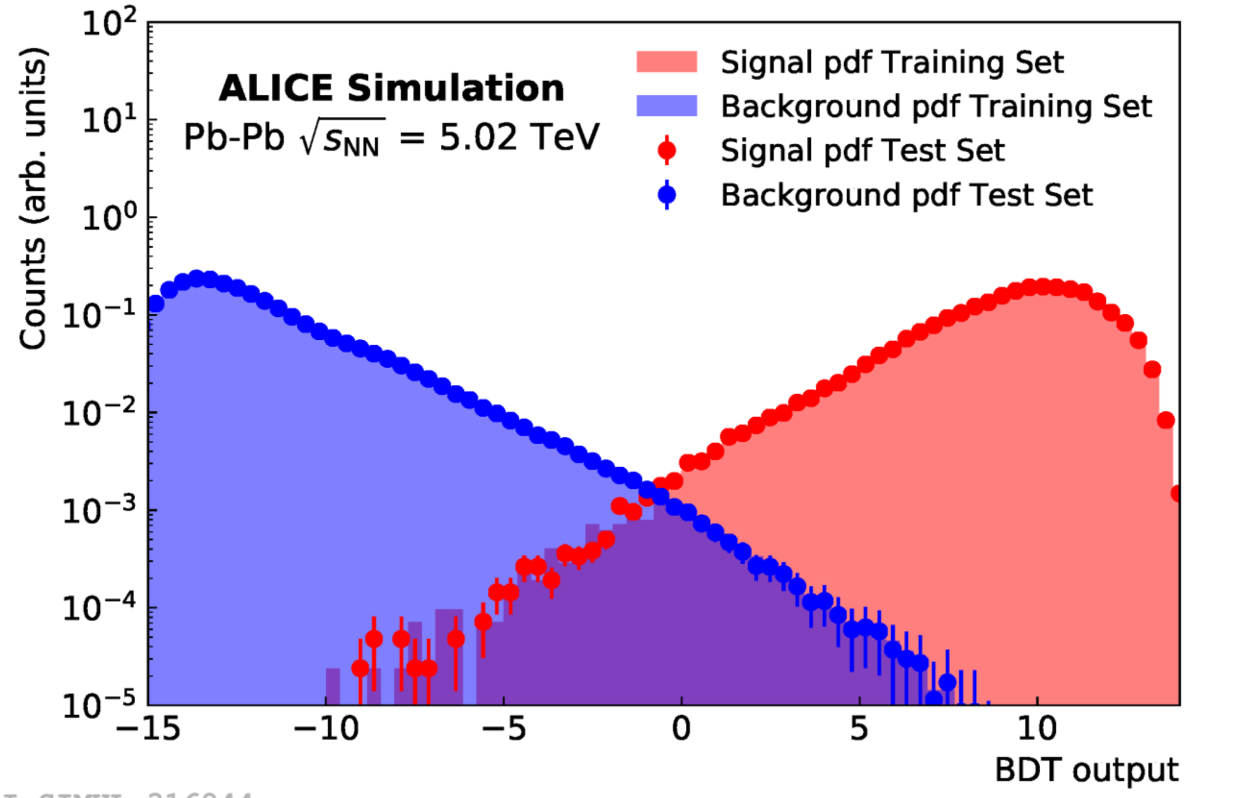


Improvements on methods

- Using machine learning techniques for the signal extraction allows to find correlations among selection criteria
- This can restore a significant fraction of the efficiency and allows to extract more candidates of these rarely produced objects

- Strangeness trackers (implemented in ALICE for Run 3) allow to also track the hypernucleus itself

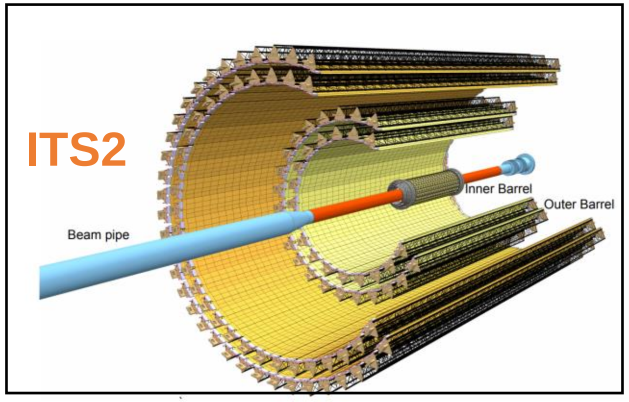
hipe4ML
https://hipe4ml.github.io/

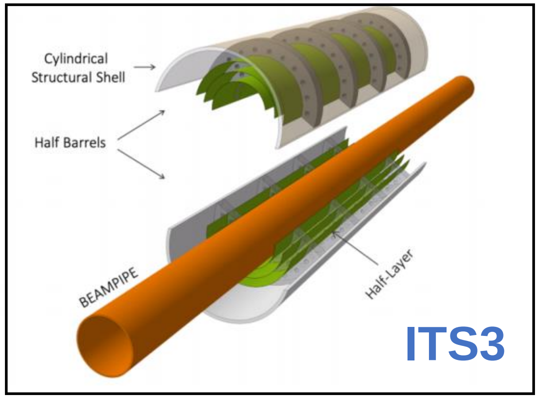


ALI-SIMUL-316844

Detector upgrades

- ITS and TPC of the ALICE setup were upgraded for Run 3
- ITS2 is now a fully pixel detector → results in a higher resolution for primary and secondary vertices
- ITS3 (waver-like foils for the inner barrell; to be installed in 2028) will even improve the resolution





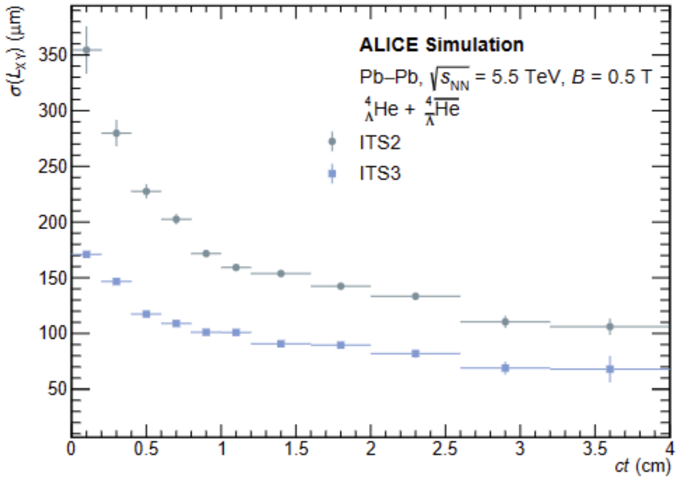


Fig. 17: Resolution on the ${}^{4}_{\Lambda}$He-candidate decay length in the xy plane for ITS2 (green circles) and ITS3 (blue squares) as a function of p_T.

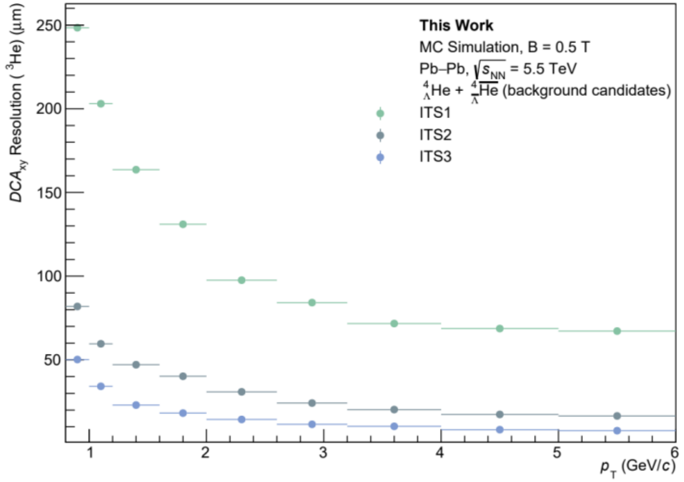
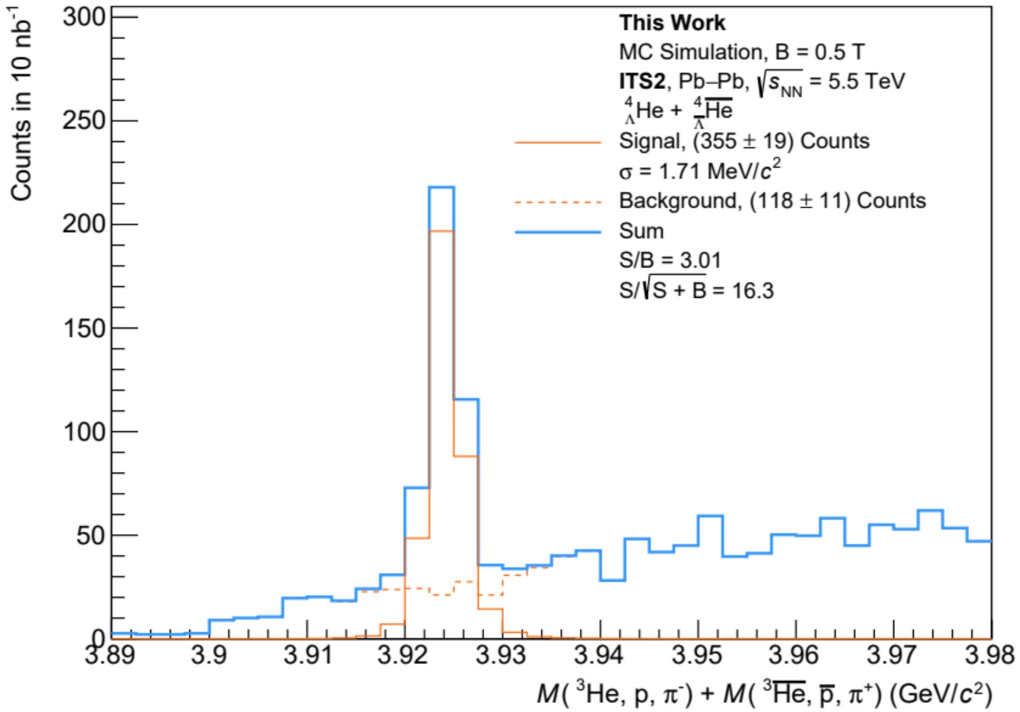


Fig. 16: Transverse-plane impact-parameter resolution for primary (background) ^{3}He particles from ${}^{4}_{\Lambda}$He decays for ITS2 (green circles) and ITS3 (blue squares) as a function of p_T.

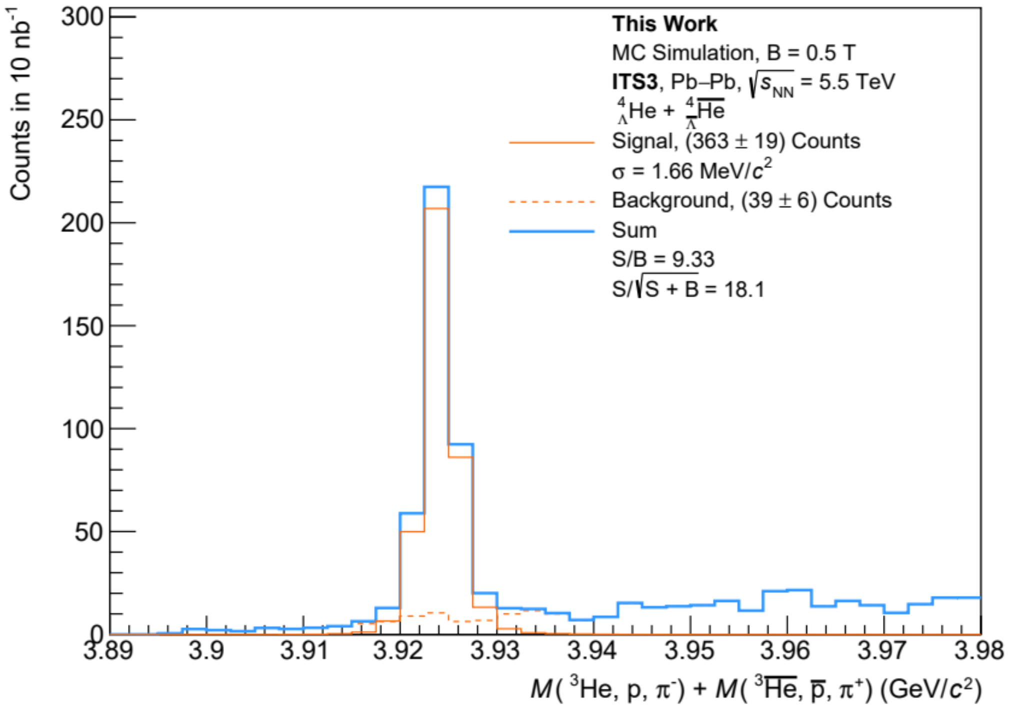
Taken from the master thesis, Janik Ditzel and *ITS3 public note*

Detector upgrades

ITS2

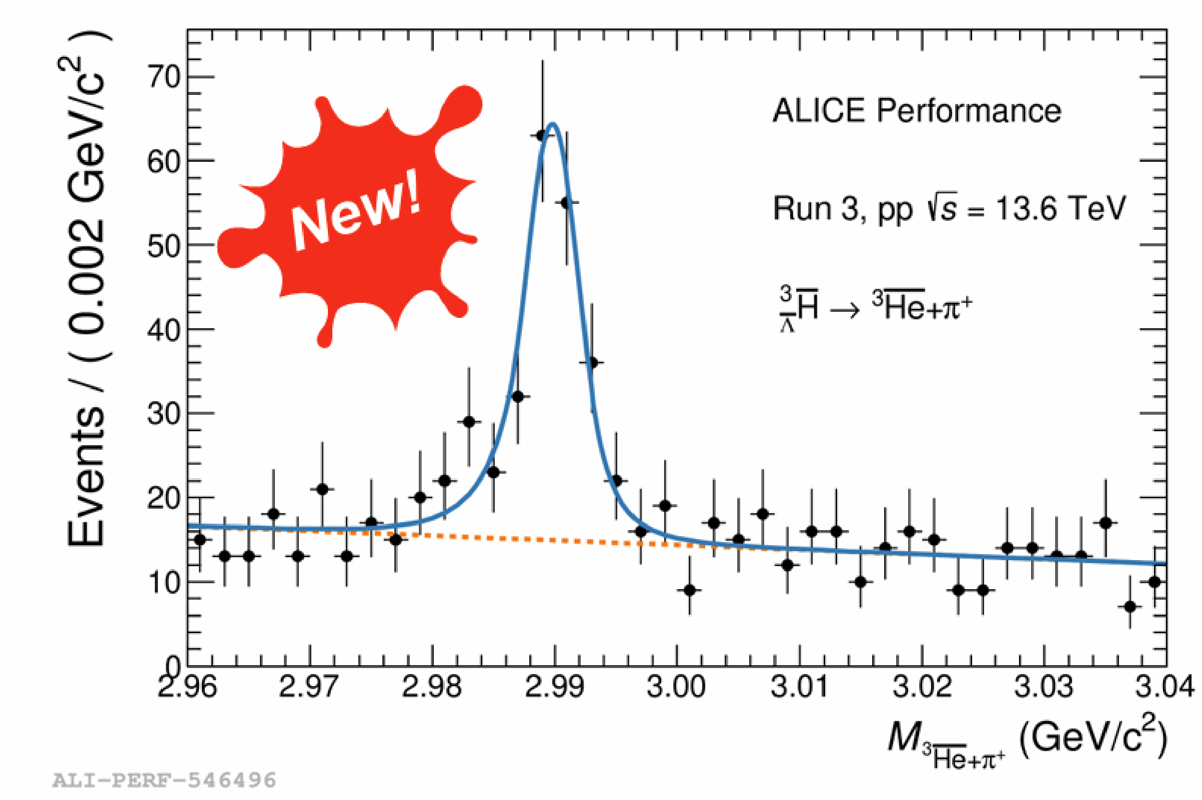


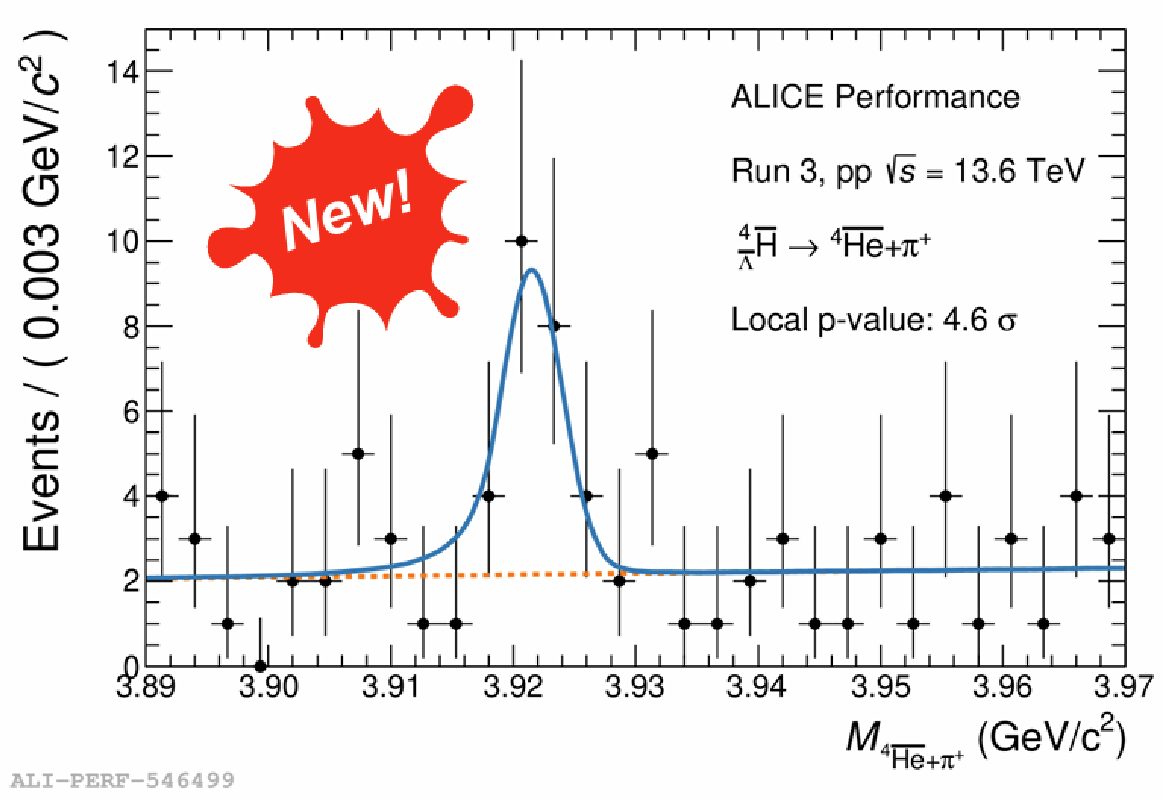
ITS3



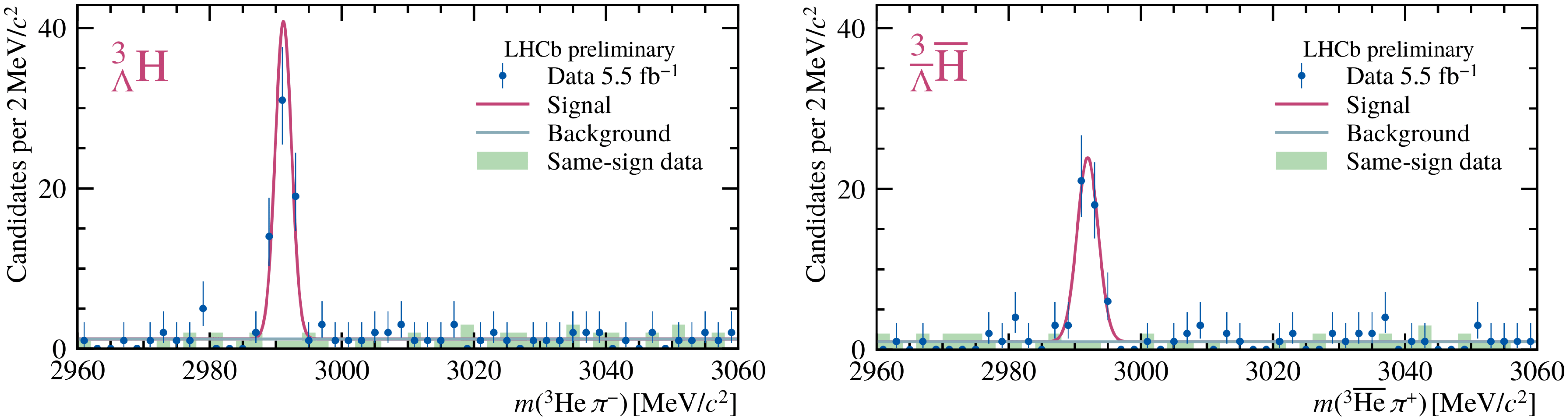
Taken from the master thesis, Janik Ditzel

First results on the ongoing Run 3





New player in the game: LHCb

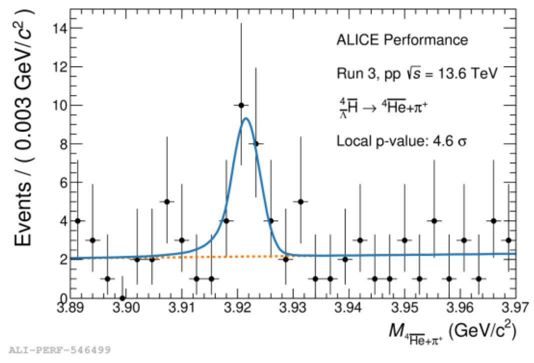


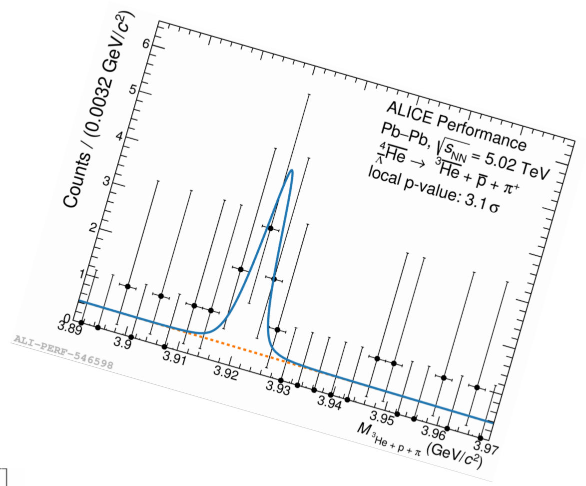
New method for the helium-3 identification allows for the (anti)hypertriton reconstruction

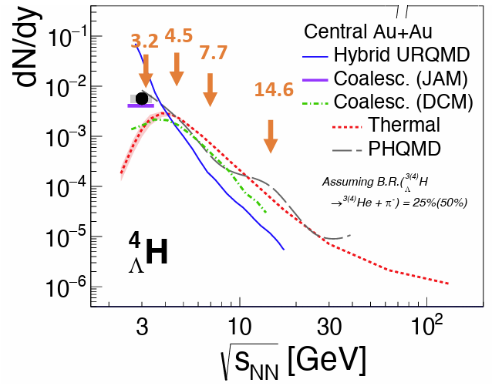
Taken from EPS2023, Hendrik Jage

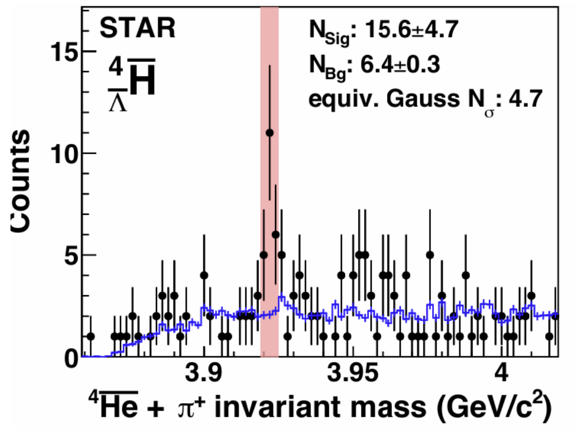
Summary

- The future is bright for the study of the production and properties of light (anti)(hyper)nuclei
- The latest results show small uncertainties and a good agreement with the theoretical predictions
- Using machine learning techniques allows for the study of rarely produced objects
- Studies on different energies at RHIC will provide more differential measurements
- The ongoing Run 3 and upcoming Run 4 at the LHC will add large statistics for the measurement of those particles and provide high precision data





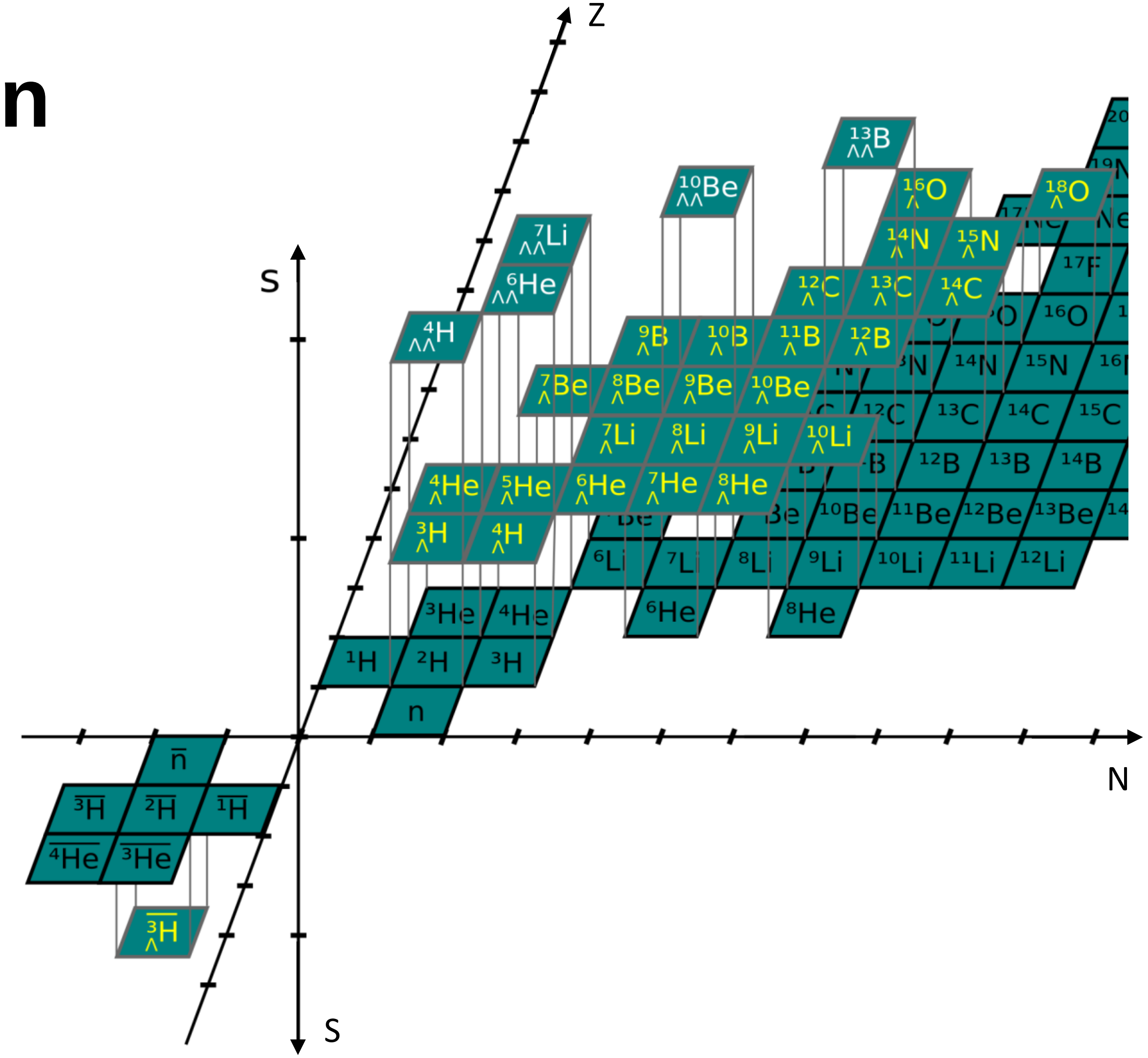




Backup

Hypernuclei: Introduction

- Hypernuclei consist of nucleons and hyperons
- Hyperons are baryons containing at least one strange quark
- Λ hyperon
  - Composition: uds
  - Mass: 1115.6 MeV/c^2
  - Lifetime: [261.07 ± 0.37 (stat.) ± 0.72 (syst.)] ps
    [Phys. Rev. D 108, 032009 (2023)]
- Decay weakly after a few cm
- Only the (anti)hypertriton has been measured by ALICE so far



N. Löher, 2014

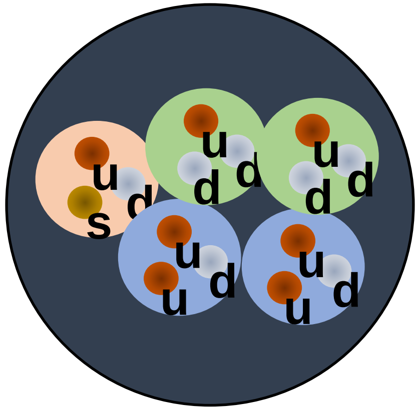
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

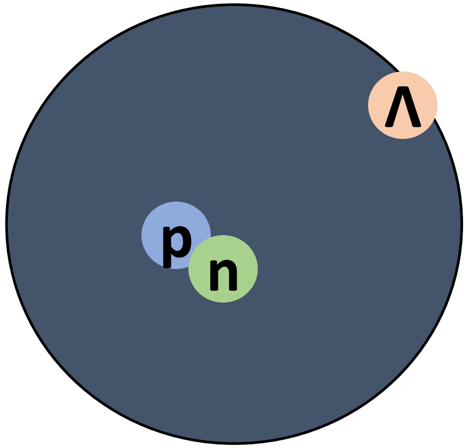
Hypernuclei: Motivation

But why hypernuclei?
What are they good for?

1) Λ hyperons in a system of nucleons allow for the formation of interesting bound states, e.g. the hyperhelium-5 or the hypertriton

A. Gal, E.V. Hungerford, D.J. Millener, Rev.Mod.Phys. 88 (2016) 3, 035004





Hypernuclei: Motivation

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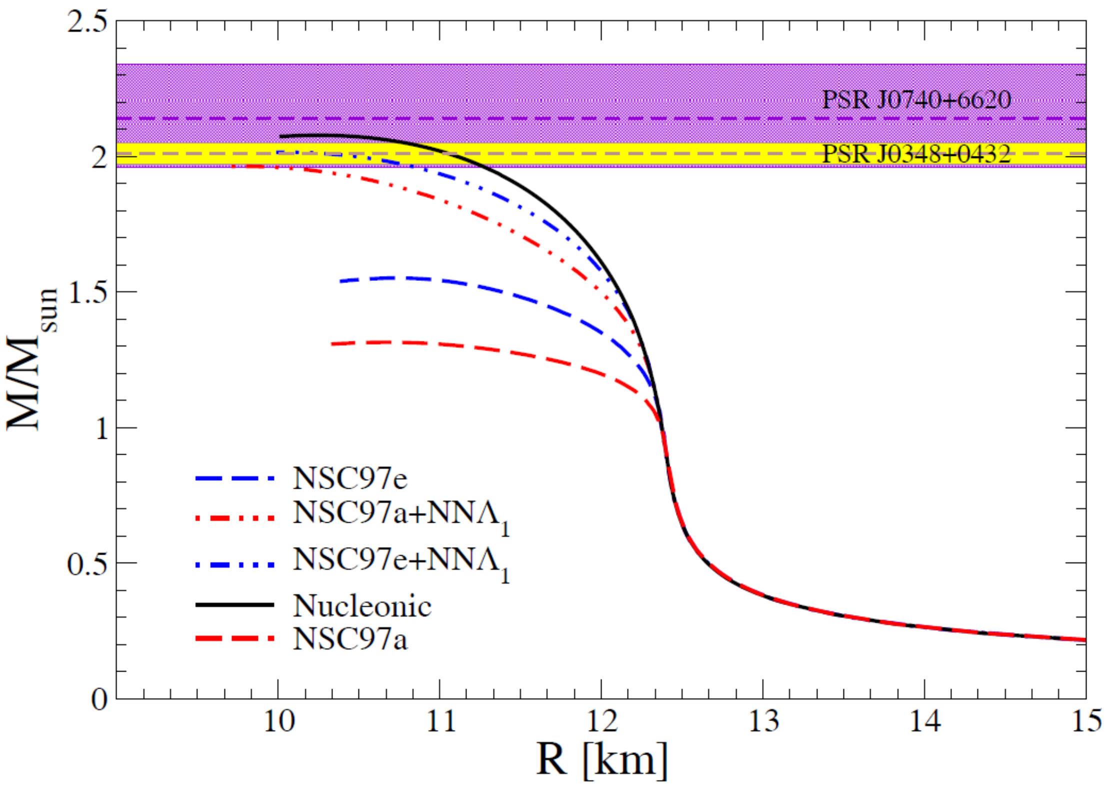
2) Hyperons in neutron stars? Very dense objects (mass > 2 solar masses while having a radius of a few km)

→ understanding of the Λ-N and Λ-Λ interaction



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

Hypernuclei: Motivation

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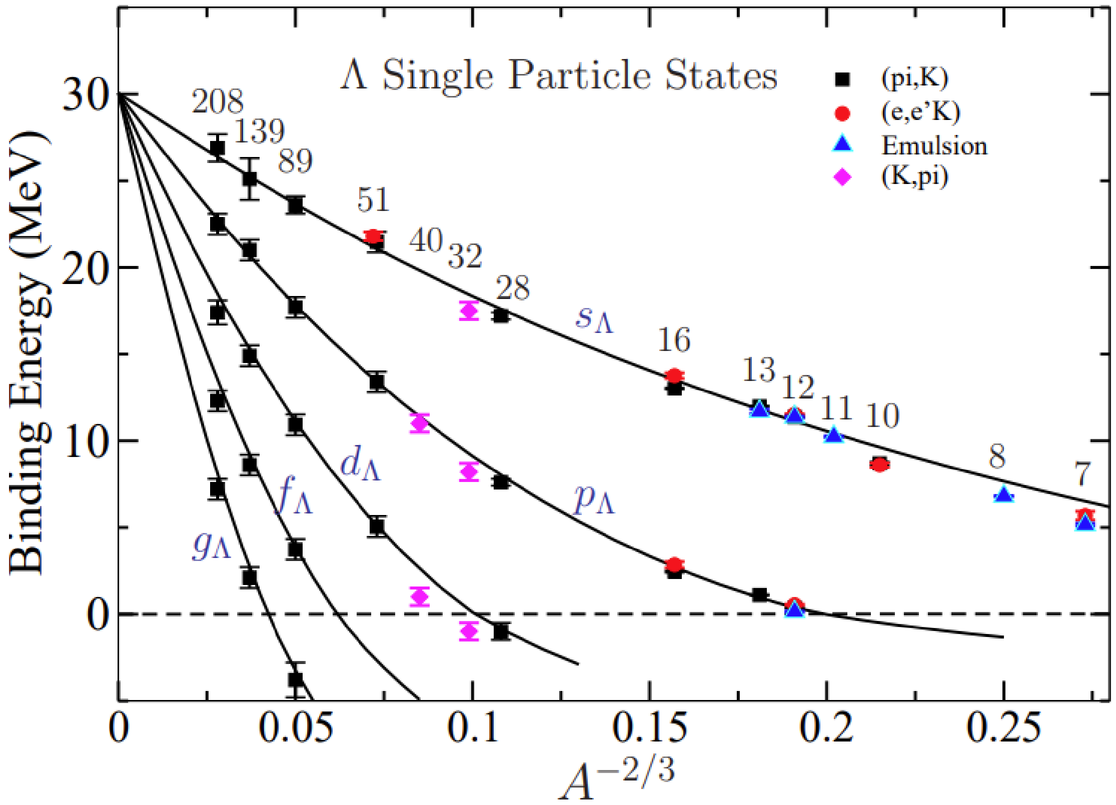
3) Testing the nuclear shell model with the Λ hyperon

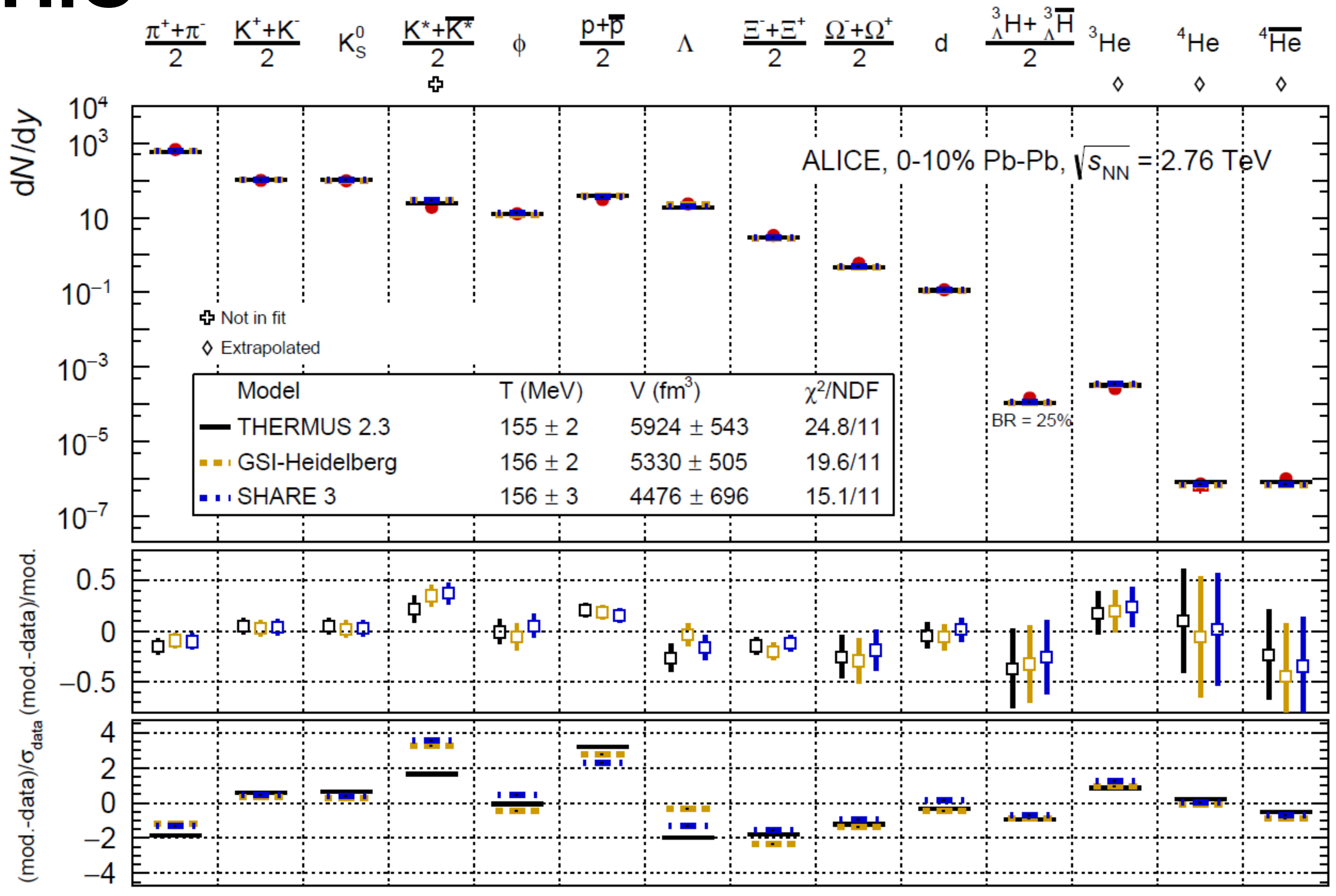


A. Gal, E.V. Hungerford, D.J. Millener, Rev.Mod.Phys. 88 (2016) 3, 035004

Particle production in HIC

- In large hadronizing systems, the integrated yield of several particle species is well described over orders of magnitude by the Statistical Hadronization Model (SHM)

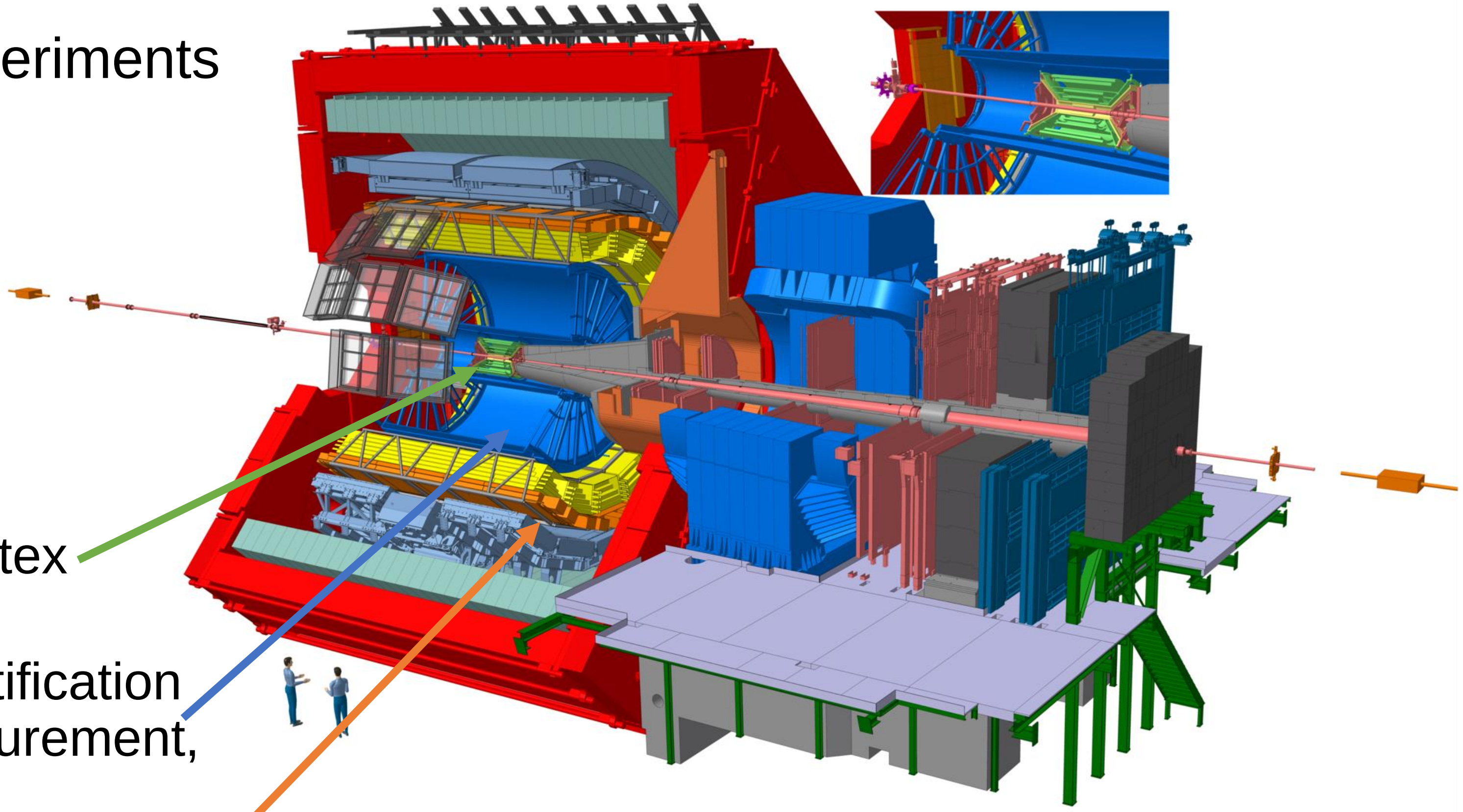
- SHM assumes hadron abundances from statistical equilibrium at the common chemical freeze-out temperature T_{ch} = 156 MeV



Nucl. Phys. A 971 (2018) 1–20, arXiv:1710.07531 [nucl-ex]

ALICE detector

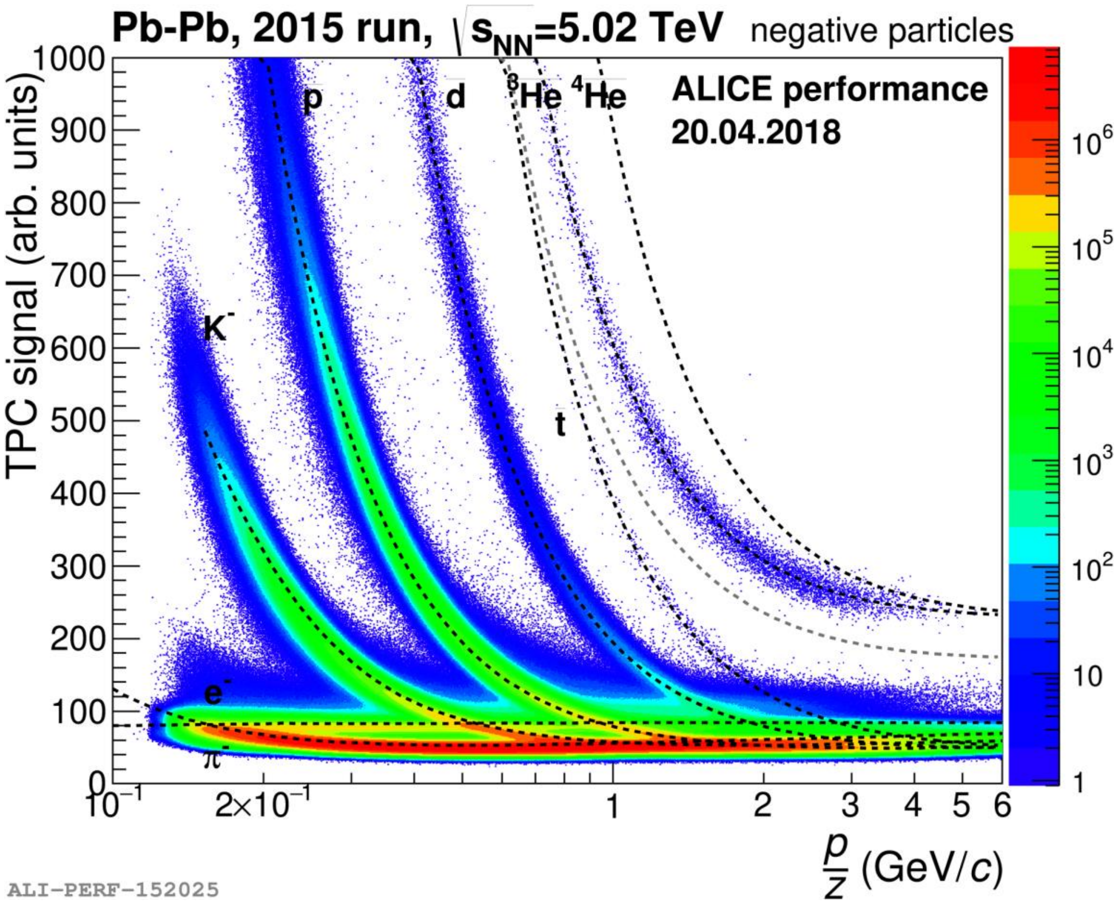
- One of the four major LHC experiments
- Specialized in tracking and particle identification from low to high momenta using different detector technologies



- Main features for this purpose:
  - ITS for primary and decay vertex reconstruction, tracking
  - TPC for charged particle identification via specific energy-loss measurement, tracking
  - TOF for time-of-flight measurement, tracking

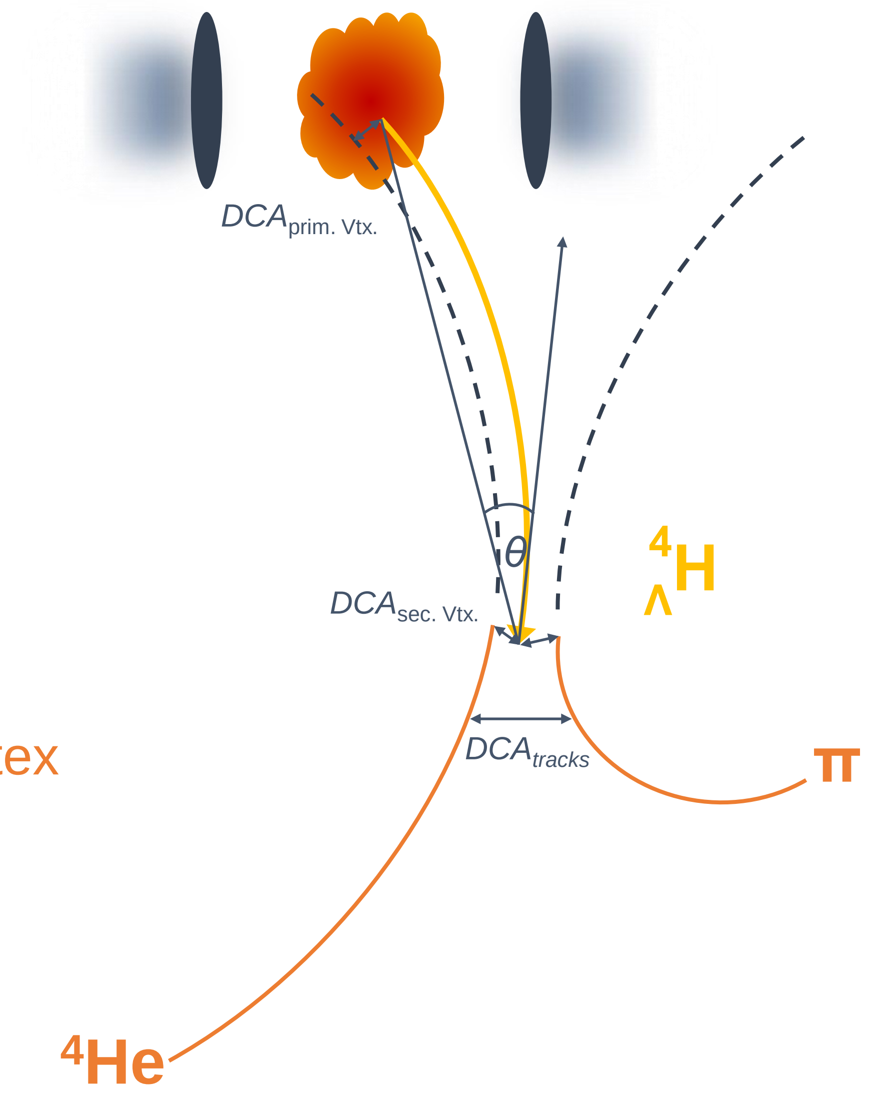
Hypernuclei reconstruction

- **Step 1**: find and identify the daughter particle tracks
  - Using TPC PID via the specific energy loss
  - Excellent separation of different particle species



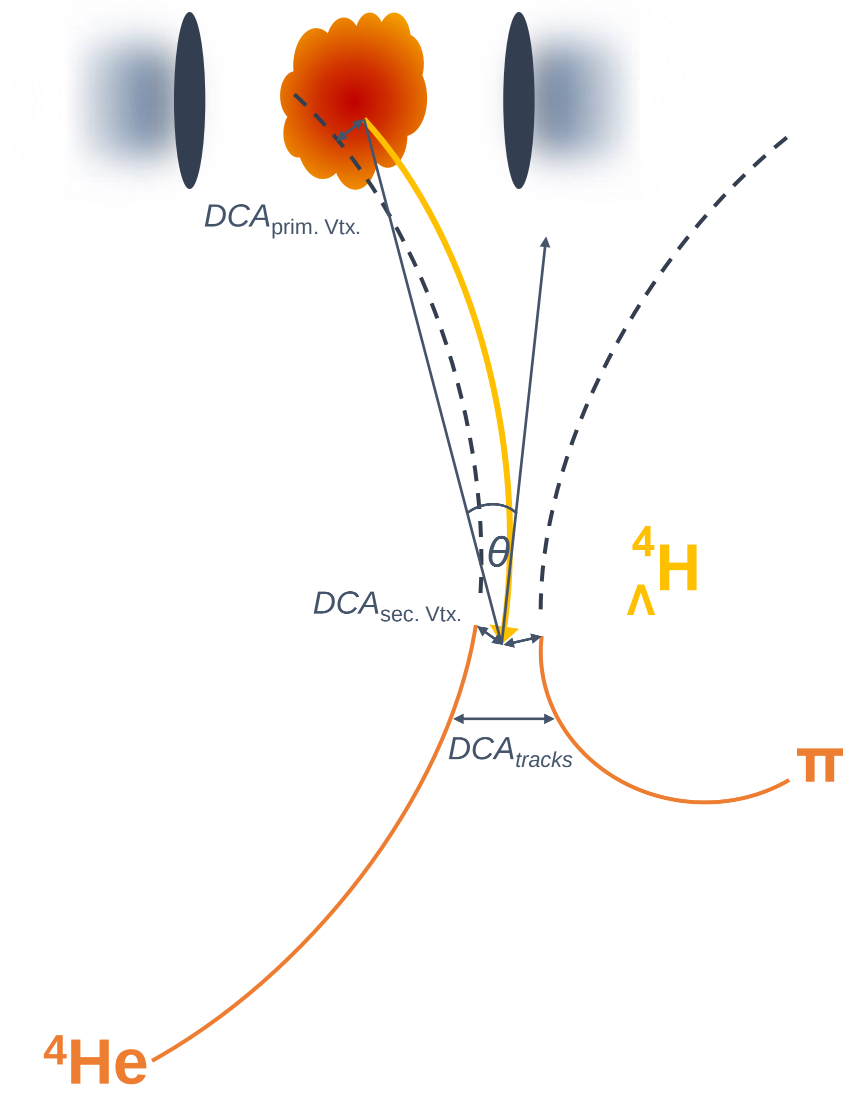
Hypernuclei reconstruction

- **Step 1**: find and identify the daughter particle tracks
- **Step 2**: reconstruct the decay vertex of the hypernucleus
  - The identified daughters are assumed to come from a common vertex
  - Their tracks are matched by a Kalman Filter approach to find the best possible decay vertex
  - Problem: huge combinatorial background
  - Solution: topological and kinematical cuts



Hypernuclei reconstruction

- **Step 1**: find and identify the daughter particle tracks
- **Step 2**: reconstruct the decay vertex of the hypernucleus
- **Step 3**: apply corrections
  - Tracking efficiency and detector acceptance
  - Branching ratio and absorption



Signal extraction

- Using a machine learning approach (Boosted Decision Tree) for the signal extraction
- A machine is trained and tested using a dedicated MC sample with injected hypernuclei and a background sample
- In this case we use like-sign candidates for the background sample
- The result is a model that is applied on the data and allows a selection via the BDT output value

https://hipe4ml.github.io/