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Hypernuclear halos with HYDRA at R^3B- GSI/FAIR

Simone Velardita

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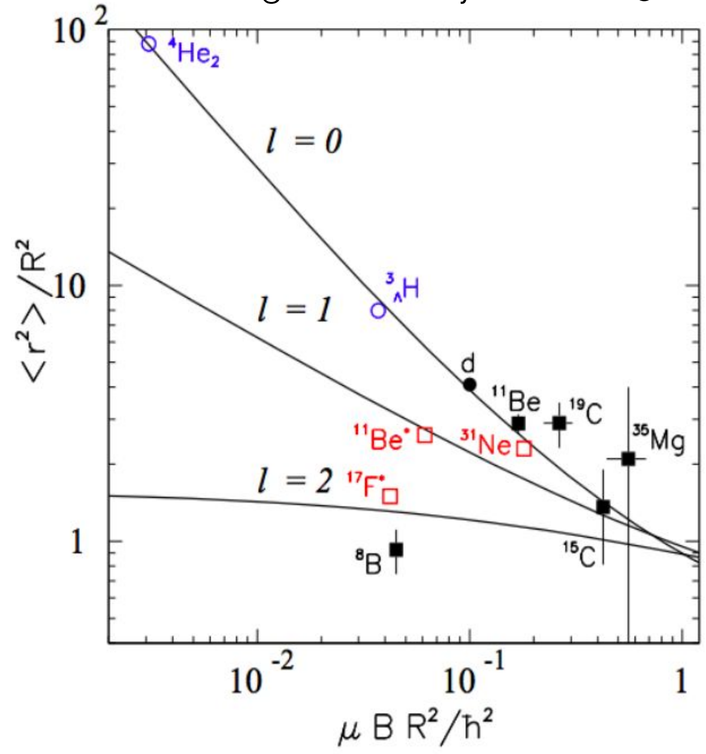
Nuclear halo

- ➔ Loosely bound system at the dripline
- ➔ Nucleon(s) wave function extends into classically forbidden region
  - ◆ large nuclear size
- ➔ **Evidenced** in exotic nuclei:
  - ◆ historically discovered in ^{11}Li (S_{2n}=0.378 MeV)
- ➔ **Predicted** for hypernuclei:
  - ◆ $^{3}_{\Lambda}$H ($S_{\Lambda d}$=0.13 MeV) [1], $^{6}_{\Lambda}$He (S_n=0.17 MeV) [2]
  - ◆ no experimental observation of hypernuclei halo

K. Riisager et al., Phys. Scr. (2013)



[1] A Cobis et al. J. Phys. G: Nucl. Part. Phys. 23 (1997) [2] E. Hiyama et al., Prog. Part. Nucl. Phys. 63 (2009)

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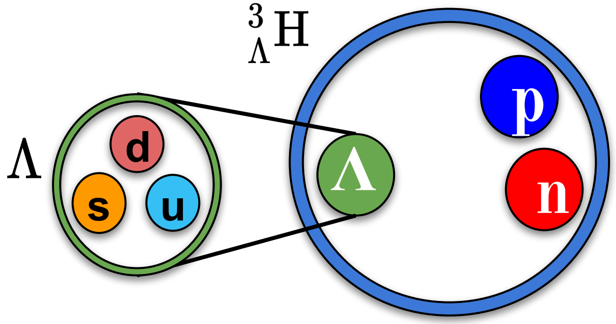
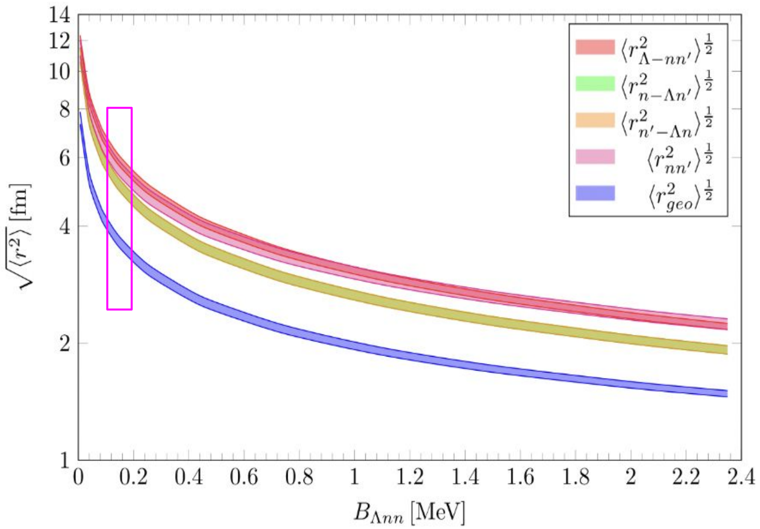
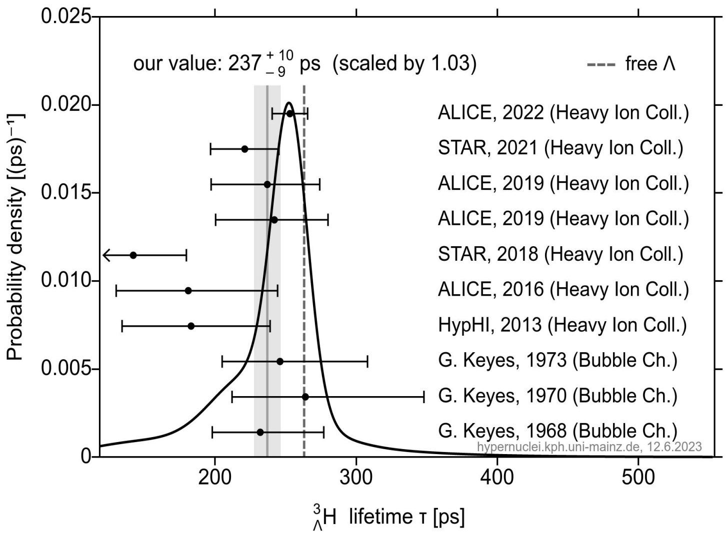
Hypertriton in a nutshell



- ➔ **Loosely** bound system: Λ binding energy 148(40) keV (average 2023)
- ➔ Large spatial extension predicted (**unmeasured**)→ “hyper”-halo nucleus
- ➔ Lifetime expected to be compatible with the free Λ (263 ps)
  - ◆ Latest ALICE value (2022) [arXiv:2209.07360v2]: 253 ± 11 (stat.) ± 6 (syst.) ps



F. Hildenbrand, H.-W. Hammer, PRC 100 (2019)



Mainz’s database: https://hypernuclei.kph.uni-mainz.de/

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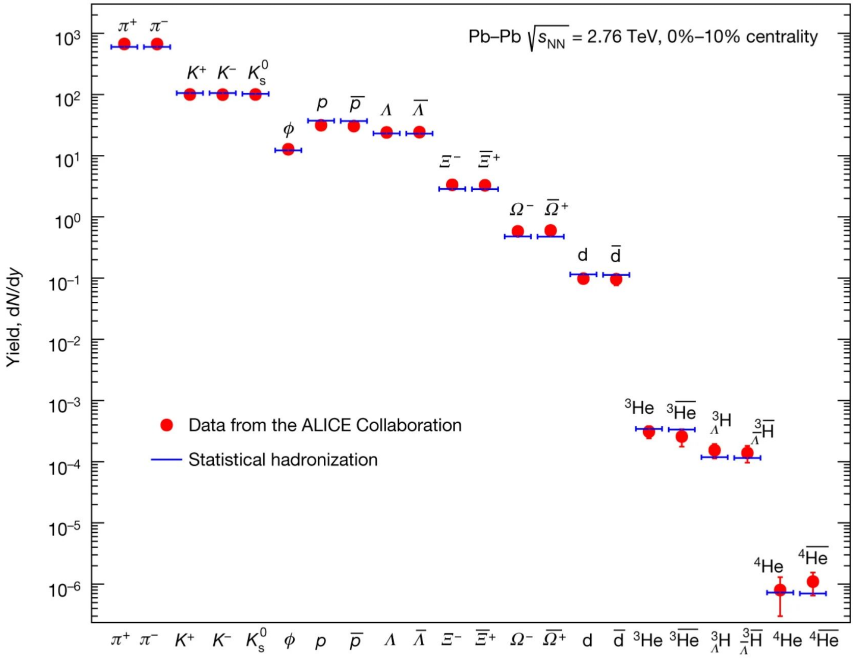
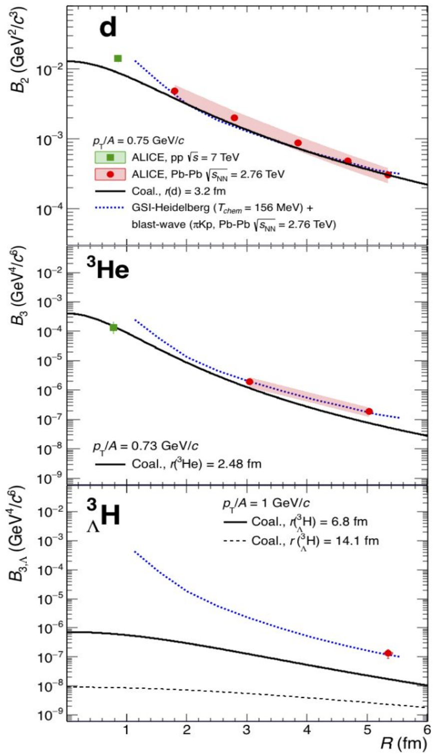
Nature of nucleosynthesis in HIC

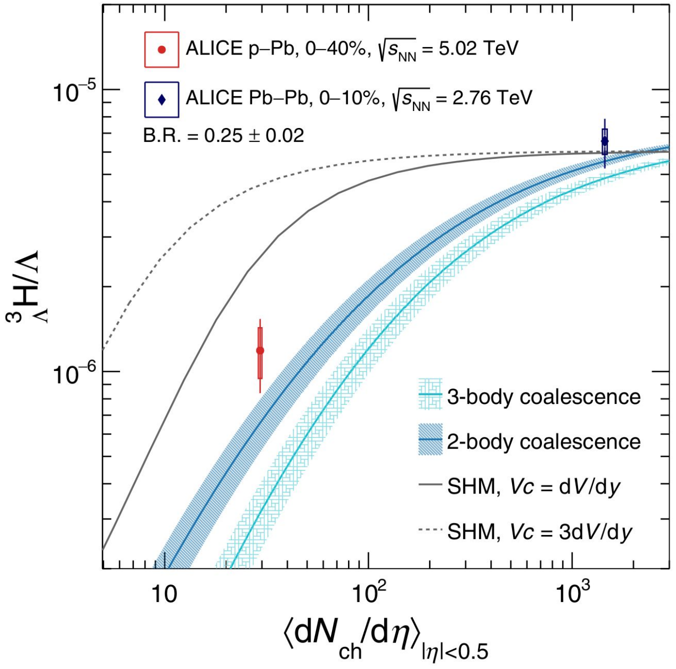
- ➔ **Statistical hadronization** or **coalescence model**?
- ➔ $^{3}_{\Lambda}$H is suggested to be a conclusive test for nucleosynthesis in Heavy Ion Collision (HIC)
- ➔ **Size of $^{3}_{\Lambda}$H** is central for coalescence predictions



A. Andronic et al., Nature 561 (2018)



F. Bellini et al., PRC 99 (2019)



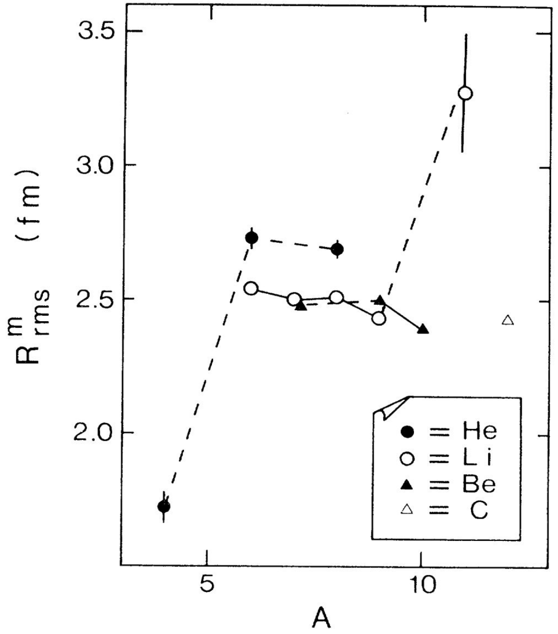
S. Acharya et al., PRL 128 (2022)

Estimation of the hypertriton size

➔ Measure hypernuclei interaction cross sections and from these deduce the matter radii:

$$\sigma_I(p,t) = \pi[R_I(p) + R_I(t)]^2$$

➔ Hypernuclear version of I. Tanihata et al. experiment [I. Tanihata et al. PLB 160 (1985)]



τ(^{11}Li)= 12.62(8) ms ≫ τ(Λ)=263 ps

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Production in HIC at GSI/FAIR energies

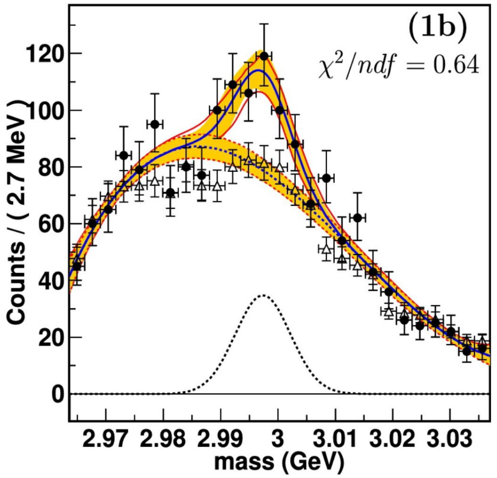
- ➔ Hypernuclei so far mainly produced using pions, kaons and electrons beams in direct kinematics
  - ◆ limited to hypernuclei **close to stability**
- ➔ Relativistic **HICs** can potentially extend the hypernuclei studies **far from stability**
  - ◆ main strangeness production mechanisms

$$p + p \rightarrow p + \Lambda + K^+ \quad (E_{lab} > 1.58\, GeV)$$

$$\pi^+ + n \rightarrow \Lambda + K^+ \quad (E_{lab} > 0.76\, GeV)$$

  - ◆ The HypHI0 experiment at GSI demonstrate the feasibility of the method using ^{6}Li+^{12}C at 2 AGeV [3]
    - light hypernuclear systems reconstructed by the invariant mass from weak decay products, e.g. $^3_\Lambda$H → π^-+^{3}He

$^3_\Lambda$H candidates



[3] C. Rappold et al., NPA 913 (2013)

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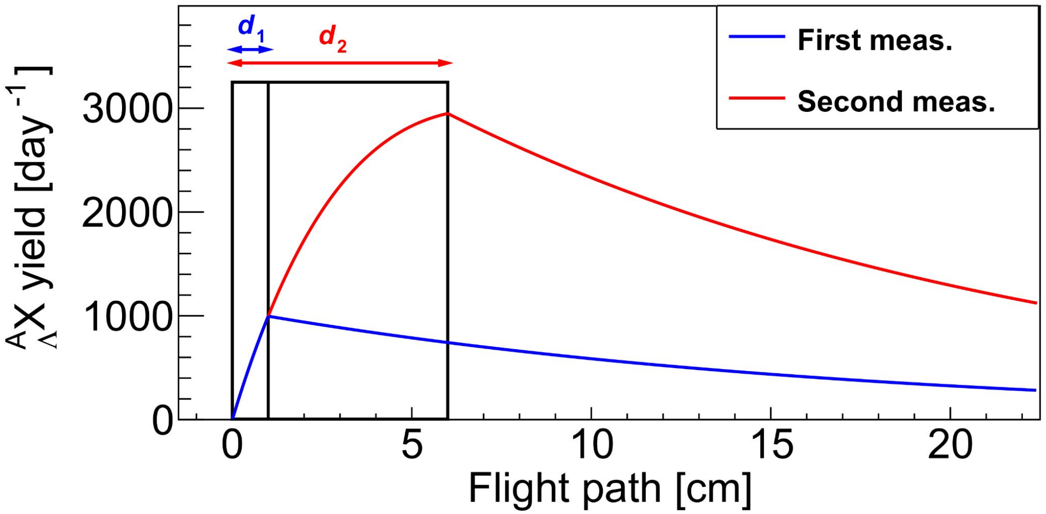
The two-target method

➔ extract the **interaction cross section** by measuring the mesonic **decay vertex distribution**

➔ the yield of the hypernuclei depends on 3 physical cross sections: σ_R beam interaction, σ_Λ production (**unknown**), $\sigma_{\Lambda R}$ interaction (**unknown**)

- ◆ two measurements with two targets of thicknesses, d_1 and d_2



$$\frac{N_\Lambda(d_1)}{N_\Lambda(d_2)} \cdot \frac{N_{0,d_2}}{N_{0,d_1}} \cdot \left(1 - e^{B\,d_2}\right) \cdot e^{-n\sigma_R(d_2-d_1)} - 1 + e^{-B\,d_1} = 0$$

where

$$B = n\,\sigma_{\Lambda R} + \frac{1}{\gamma\beta c\,\tau} - n\,\sigma_R$$

$$N_{0,d_1} = I\,t\,\alpha \quad \text{and} \quad N_{0,d_2} = I\,t\,(1-\alpha)$$

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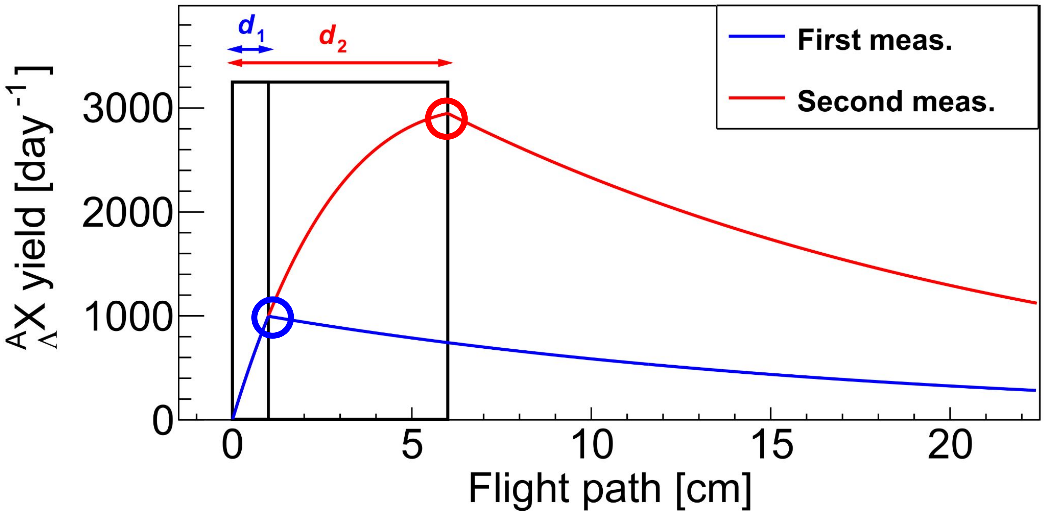

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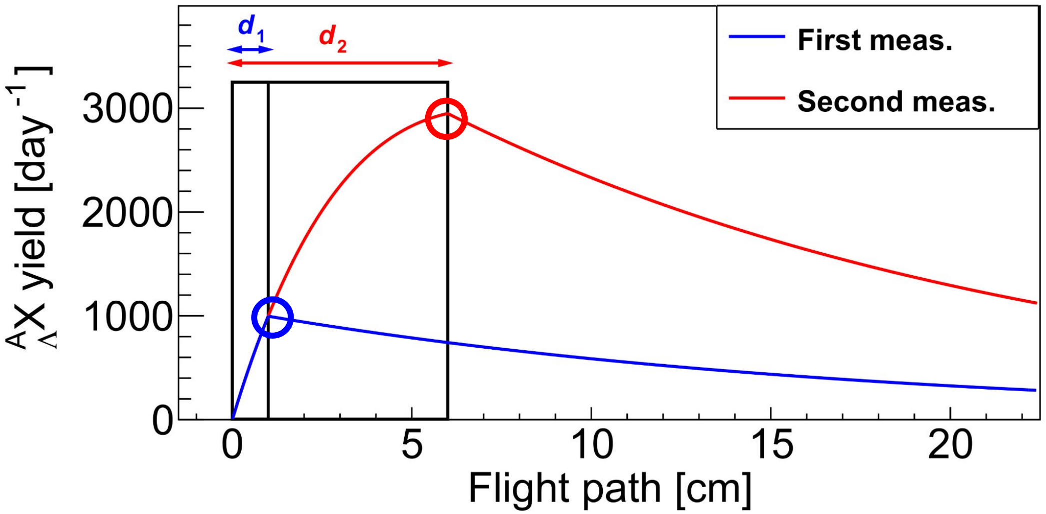

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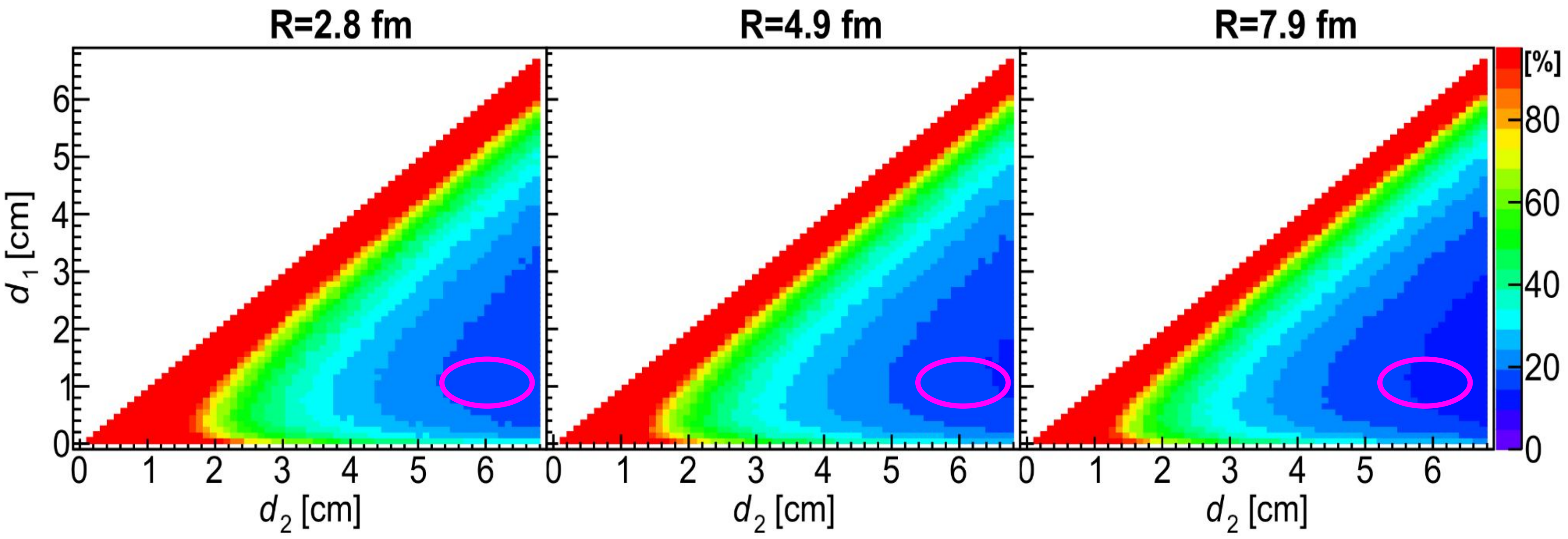
Accepted experiment

- ^{12}C beam @1.9 GeV/A
- 1- and 6 cm thick ^{12}C target
- Total beam time t=8 days
- Beam intensity I=(1-5) · 10^6 pps

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

Radius (rms) [fm]	$\sigma_{\Lambda R}$ [mb]	$\delta\sigma_{\Lambda R}/\sigma_{\Lambda R}$[%]
2.8 (no halo)	645 ± 106	17
4.9	861 ± 129	15
7.9	1062 ± 134	13

Sensitivity of measurement



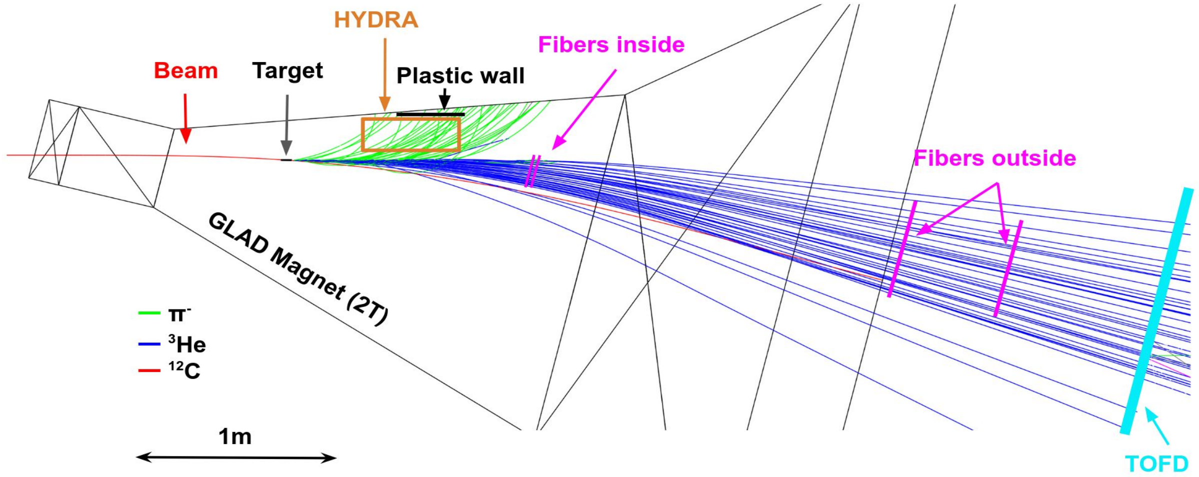
➔ Minimal uncertainty is reached for a large difference in the thickness of the two targets

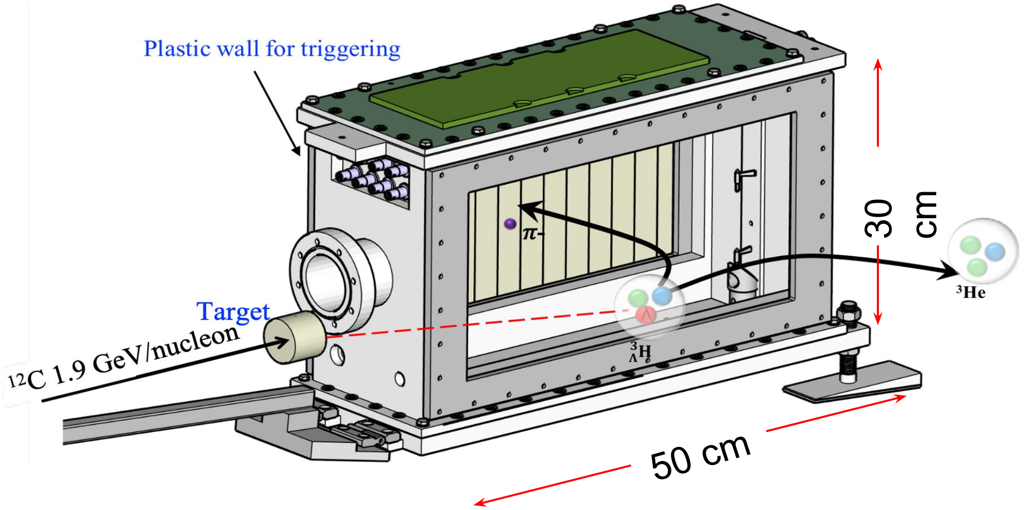
- optimal values are **d_1~1 cm** and **d_2~6 cm**

S. Velardita et al., EPJA 59 (2023)

Experiment at R^{3}B-GSI/FAIR (2025)

- ➔ **Hypertriton interaction cross section** from $^{12}C+^{12}C \rightarrow X + {}^3_\Lambda H \rightarrow X + \pi^- + {}^3He$
- ➔ Large acceptance → **Time Projection Chamber** (TPC) inside GLAD dipole
- ➔ ${}^3_\Lambda$H low production cross section 1.8 µb (predicted) [4]→ Off beam position to allow high intensity beam
- ➔ High momentum and position resolution→ Mylar entrance window and double-wire field-cage
- ➔ B field inhomogeneities of GLAD dipole corrected by reference tracks→ Built-in laser with micro-bundle mirrors [5]





[4] Y. Sun et al. PRC 98 (2018) [5] J. Abele et al. NIM A 499 (2003)

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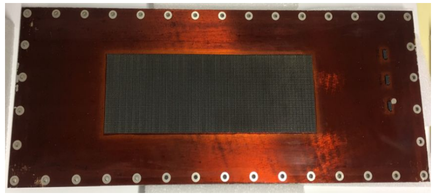
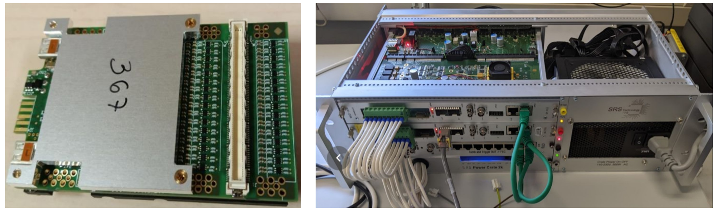
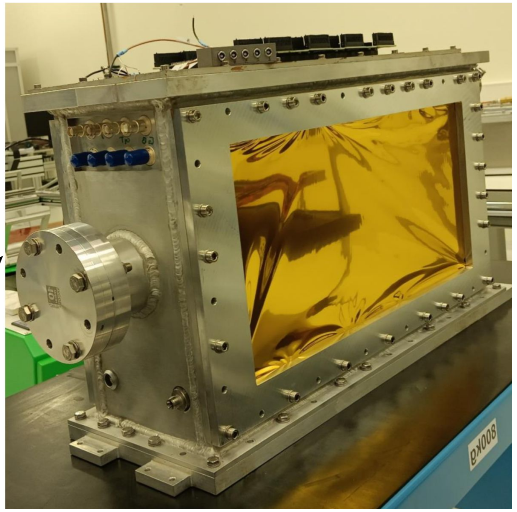
mini-HYDRA TPC



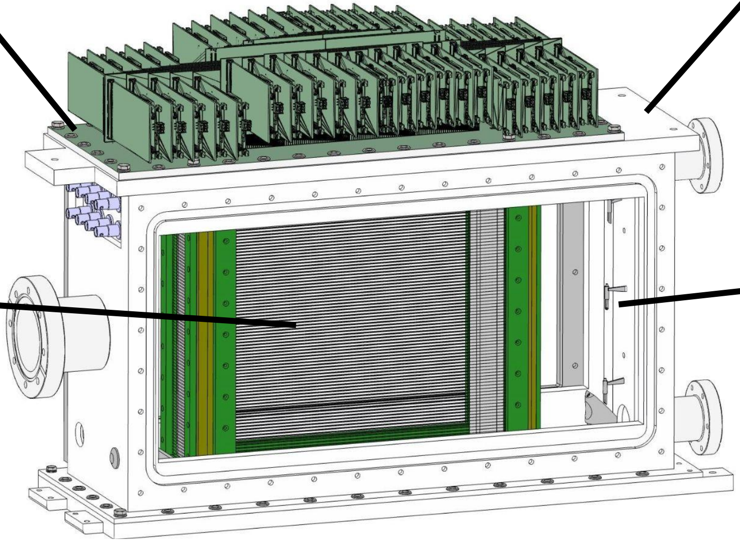
b) Metal core pad-plane MicroMegas amplification [6] plus GEM to reduce the ion back flow <1%

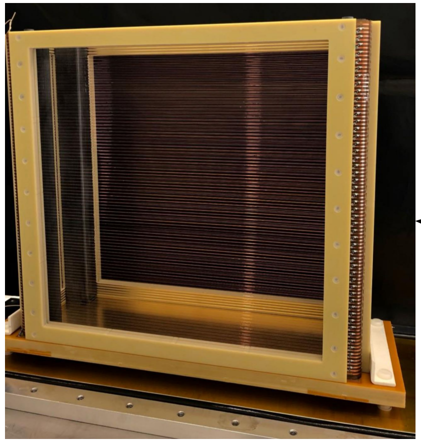


c) VMM3 front-end card and SRS backend for continuous readout [7]

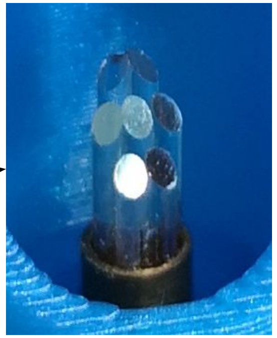


d) TPC assembled and currently under test





a) Double-wire field cage



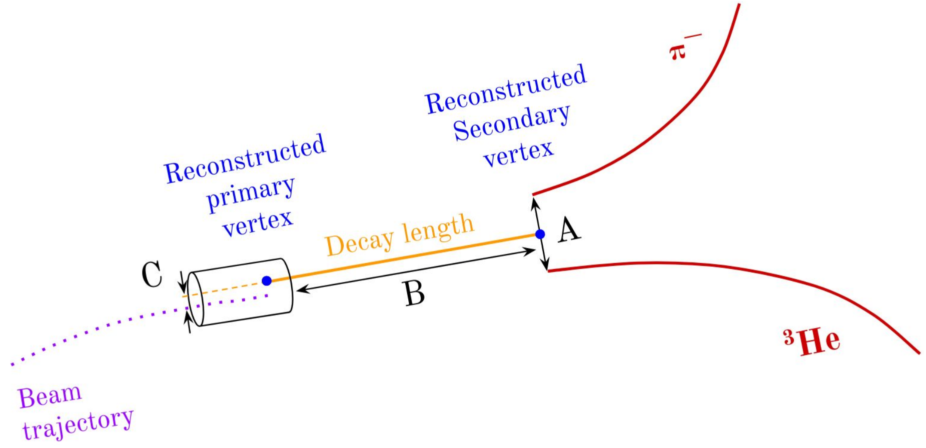
e) Laser (266 nm, 9 mJ and 20 Hz) coupled with micro-mirrors bundle

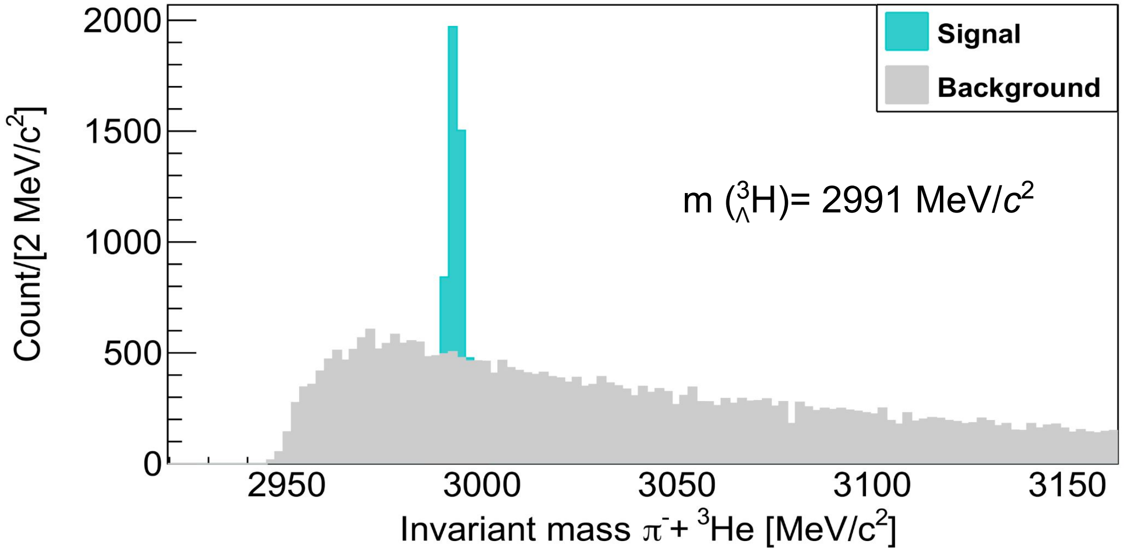
[6] J. Giovinazzo et al., NIM A. 892 (2018) [7] D. Pfeiffer et al., NIM A. 1031 (2022)

Monte Carlo simulations

Geant4:

- ➔ Total detection efficiency 12%
- ➔ Vertex position resolution < 10 mm
- ➔ Momentum resolution < 2%
- ➔ Rejection of background events with a signal over background ~3
- ➔ Invariant mass resolution of 2 MeV/c^2 (σ)





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Conclusions

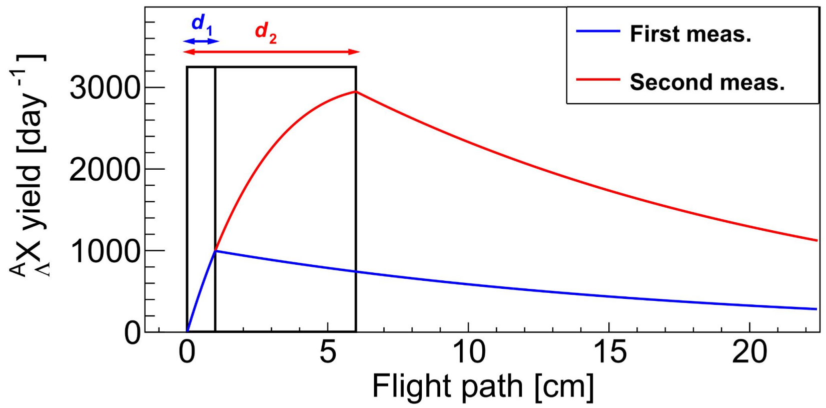
➔ Hypernuclear program initiated at R^{3}B- GSI/FAIR

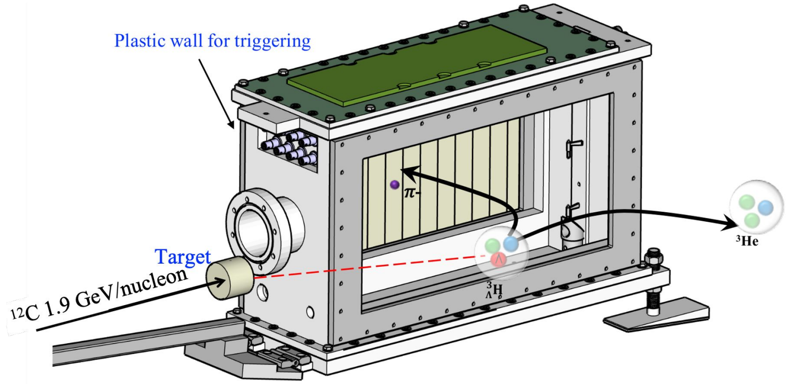
➔ $^3_\Lambda$H interaction cross section (experiment foreseen for 2025)

- new method developed [S. Velardita et al., EPJA 59 (2023)]
- validated with GEANT4 simulations
- expected relative uncertainty interaction cross section ~15%
- deduce the matter radius of $^3_\Lambda$H to assess on its halo or non-halo nature

➔ Hydra pion tracker built, under test measurements

- hybrid MicroMegas/GEM
- built-in laser system for reference tracks
- VMM3 electronics for continuous readout





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Collaborators

The R^{3}B collaboration.

The HYDRA team:
M. Duer, A. Enciu, L. Ji, A. Obertelli, D. Rossi, Y. L. Sun, S. Velardita, F. Wienholtz TU Darmstadt, Germany
P. Gasik, J. Hehner, B. Löher, C. Schmidt, M. Träger GSI/FAIR, Germany
H. Alvarez-Pol, Y. Ayyad Universidade de Santiago de Compostela, Spain
S. Ota University of Osaka, Japan
J. Taieb CEA, France

Theory support:
H.-W. Hammer, R. Roth IKP, TU Darmstadt, Germany
M. Bleicher, A. Botvina, H. Elfner J.W. Goethe Universität, Frankfurt am Mainz, Germany
C. Bertulani Texas A&M Commerce, USA

ELEMENTS HFHF Bundesministerium für Bildung und Forschung GSI FAIR Alexander von Humboldt Stiftung/Foundation

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BACKGROUND (1)

4 possible sources of background:

1. the coincidence of π^- and ^3He both produced from the fragmentation of ^{12}C
   a. it's mostly removed by selecting the decay vertex position upstream the target
2. the decay of an heavier hypernucleus which decay via π^- emission together with a multi-ion final state that includes ^3He
   a. The relative kinetic energy between π^- and ^3He will be always < 43 MeV (Q-value for the decay of the hypertriton)
3. a π^- from the decay of a free Λ, K^0_{short} and heavier hypernuclei, and ^3He produced in coincidence from the fragmentation of the ^{12}C projectile
   a. Reduced by applying topological cuts
4. Two-step strangeness production, i.e., the production of hypertriton from fragments with A≥3 and E_{kin} >1.6 GeV/A formed in the primary collision
   a. Neglected because it contributes for <2% on the total number of hypertriton produced in the primary reaction

BACKGROUND (2)