TECHNISCHE UNIVERSITÄT DARMSTADT

Hypernuclei at R3B

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Mini-symposium « hyperons @ FAIR », online

October 25, 2021

Alexander von Humboldt Stiftung / Foundation

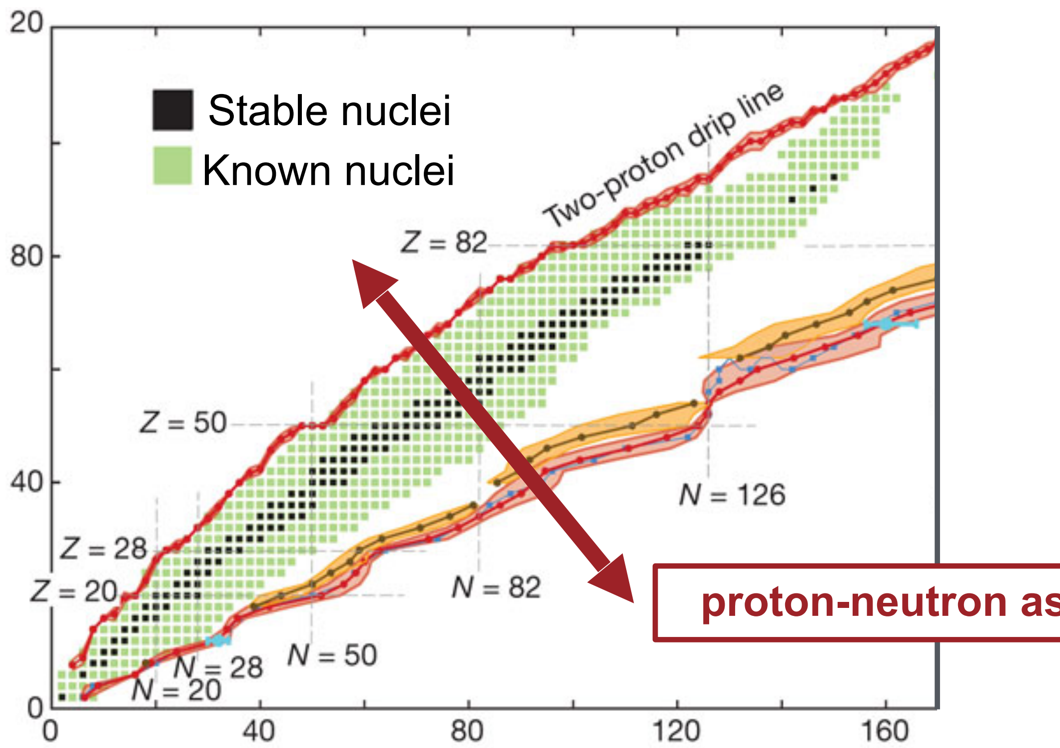
Bundesministerium für Bildung und Forschung

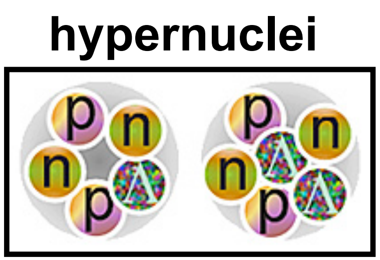
HFHF

HESSEN Hessisches Ministerium für Wissenschaft und Kunst

Isospin and strangeness degree of freedom

- Proton-neutron asymmetry ⇒ nuclear structure and in-medium forces
- Hypernuclei open the strangeness sector
- In the next years, we aim at investigating weekly-bound hypernuclei at R3B



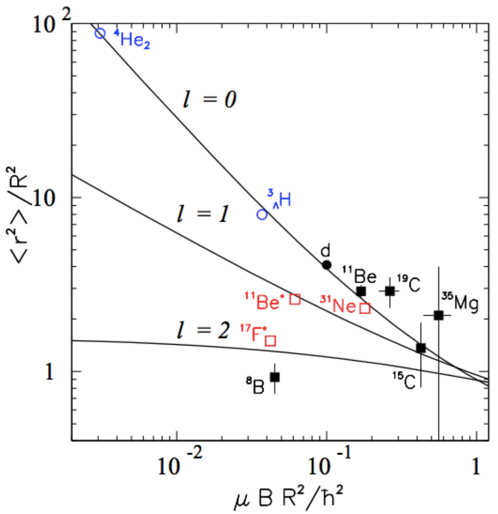


Hypernuclear halos

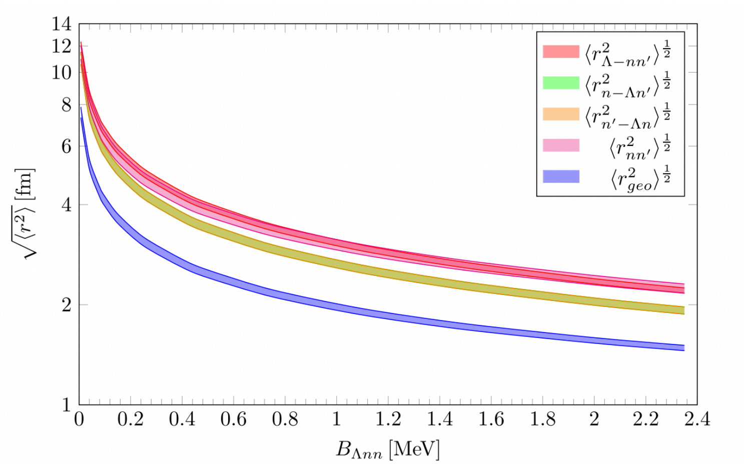
- Universality of halos: several loosely bound (hyper)nuclei are candidates
- $\Lambda - d$ distance in **hypertriton** ($^3_\Lambda$H) predicted at 10.8 fm

  F. Hildenbrand, H.-W. Hammer, PRC 100 (2019)
- $^7_\Lambda$**Be** predicted as a two-proton halo

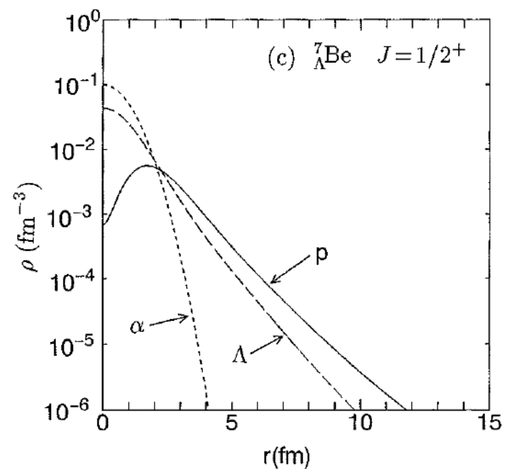
K. Riisager, Phys. Scr. T 152 (2012)



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

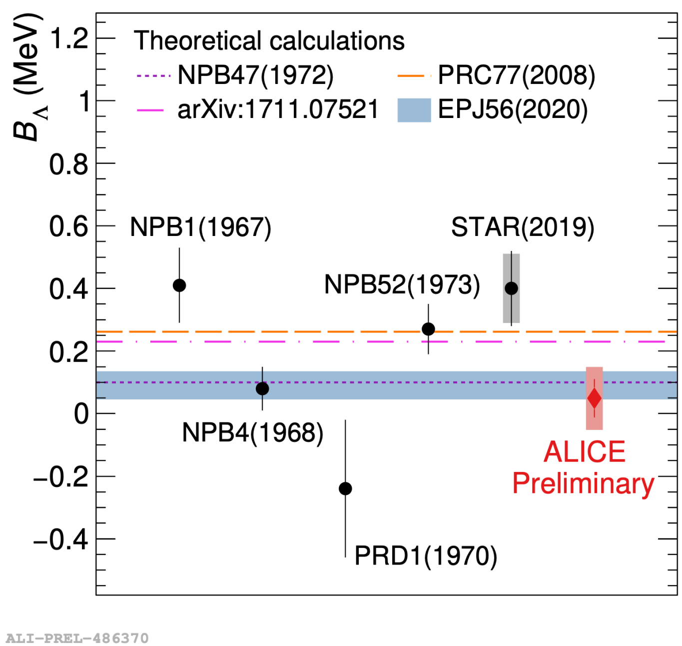


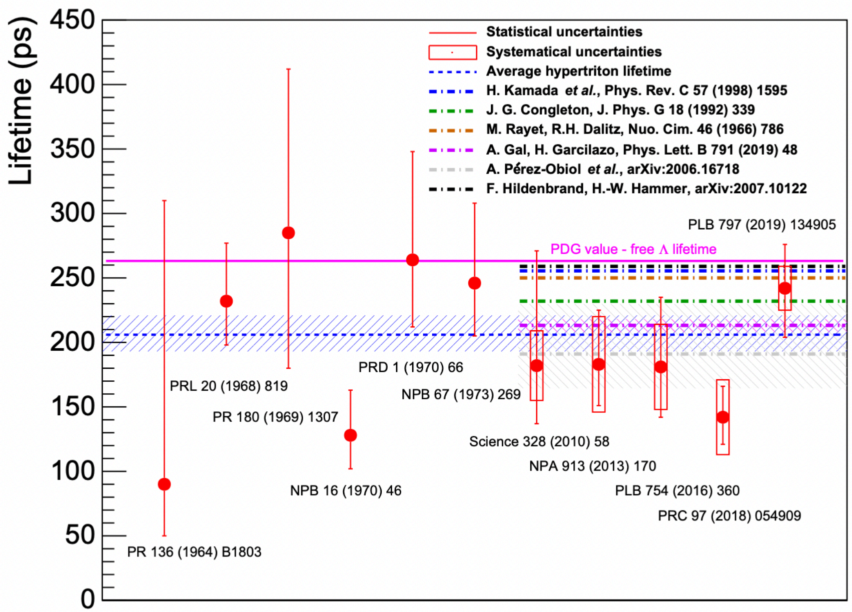
E. Hiyama et al., PRC 53 (1996)



The hypertriton puzzle in a nutshell

- Low binding energy (average 2020: 130(50) keV, STAR 2020: 410(120) keV)
- Large spatial extension predicted (***unmeasured***)
- Inconsistency between several lifetime analyses
(STAR, HyPHI0, ALICE), see presentation by T. Saito





B. Dönigus, EPJA 56 (2020)

$^{3}_{\Lambda}$H:cluster formation in relativistic HI collisions

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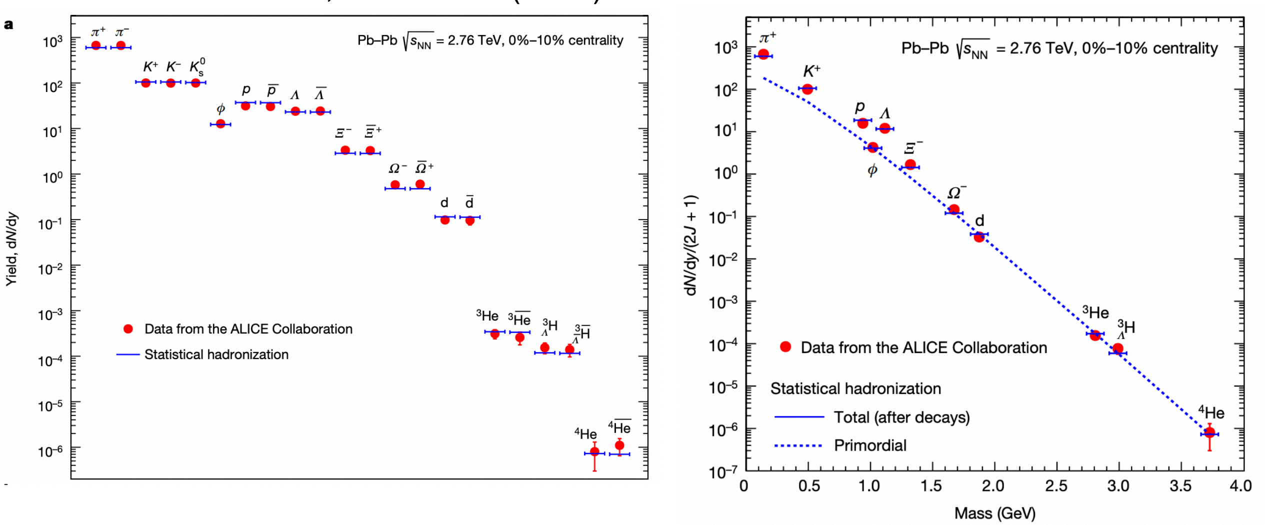
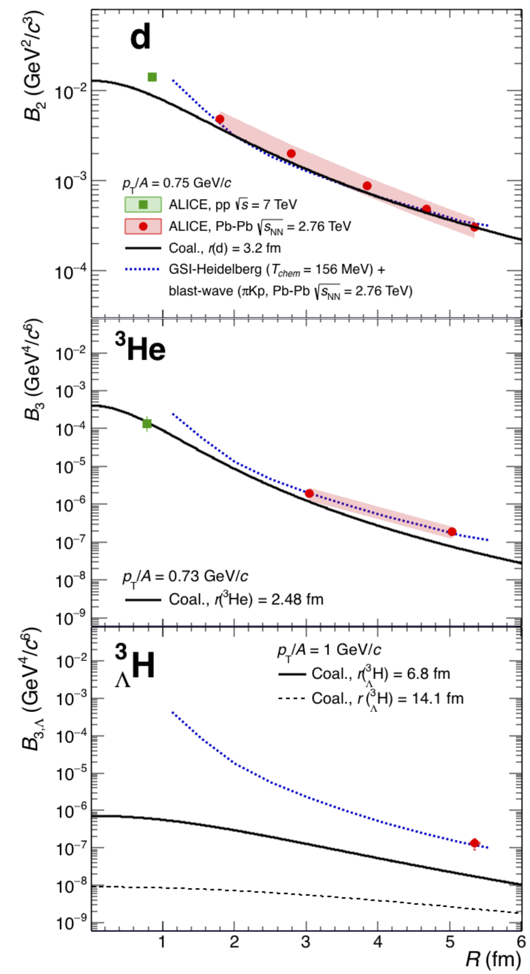
A. Andronic et al., Nature 561 (2018)



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



- Statistical hadronization or coalescence?
- $^{3}_{\Lambda}$H has the **potential to rule out coalescence models** for cluster (nuclei) production in HI collisions

  F. Bellini et al., PRC 103 (2021), ALICE-PUBLIC-2020-005
- **Size of $^{3}_{\Lambda}$H** is central for coalescence predictions

Three-body forces and nuclear structure

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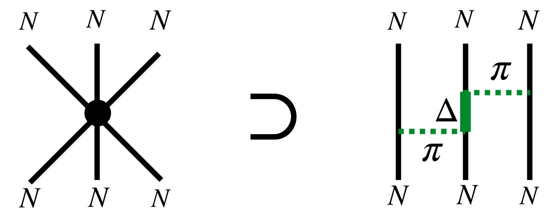
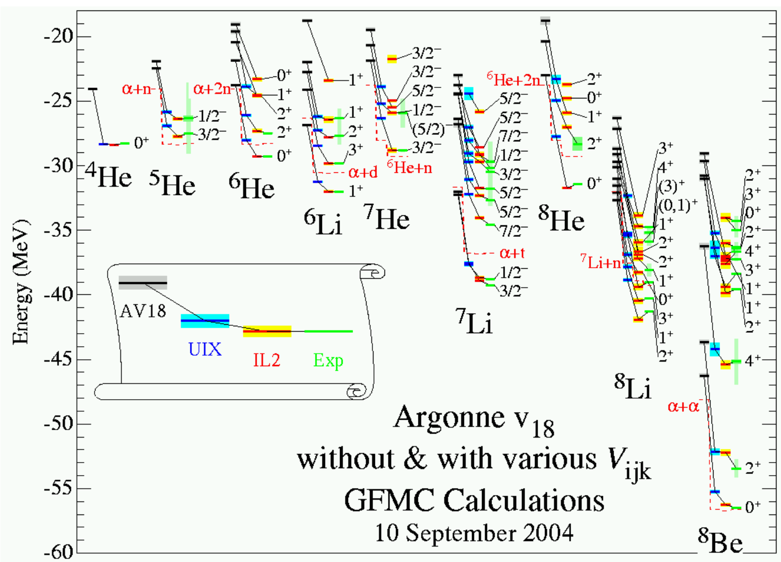
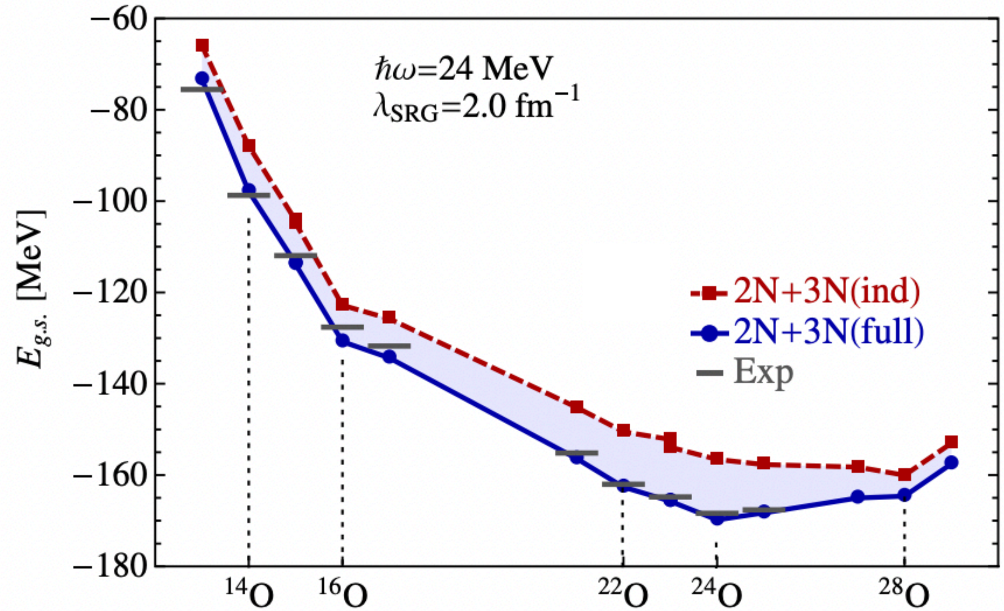


Nuclei

(first nucleonic excited state: +300 MeV)





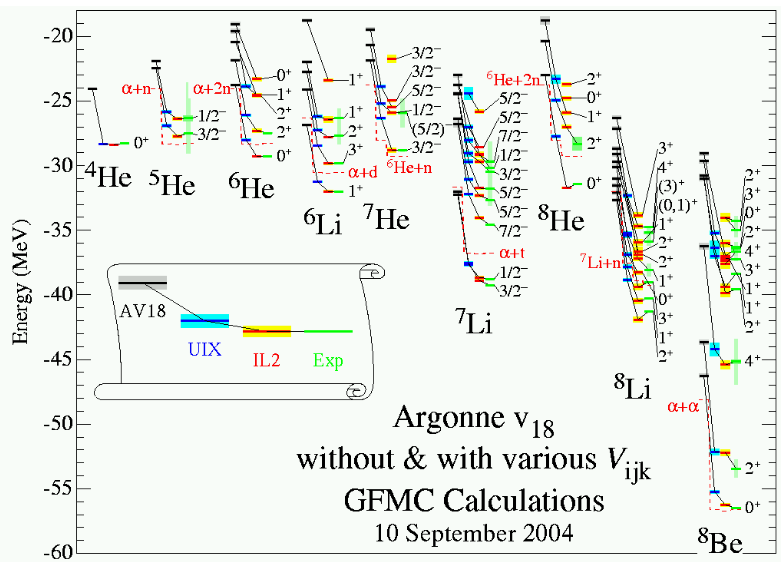
R.B. Wiringa and S.C. Pieper, PRL 89 (2004)

A. Cipollone, C. Barbieri, P. Navratil, PRL 111 (2013)

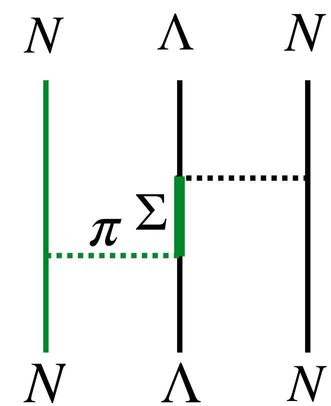
Three-body forces and nuclear structure

Nuclei

(first nucleonic excited state: +300 MeV)



- Λ: lowest mass hyperon (*usd* quarks)
- First excited state (Σ) at only 70 MeV
- Enhanced role of internal degrees of freedom

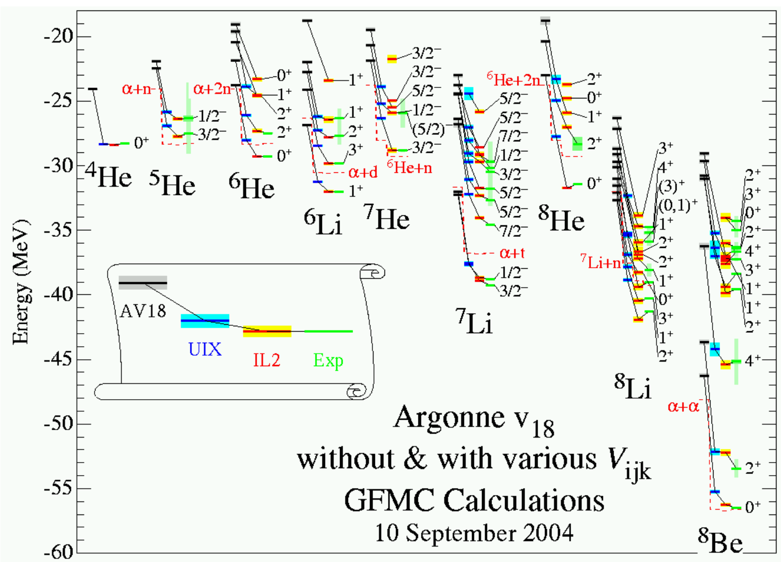


R.B. Wiringa and S.C. Pieper, PRL 89 (2004)

Ab initio description of light (hyper)nuclei

Nuclei

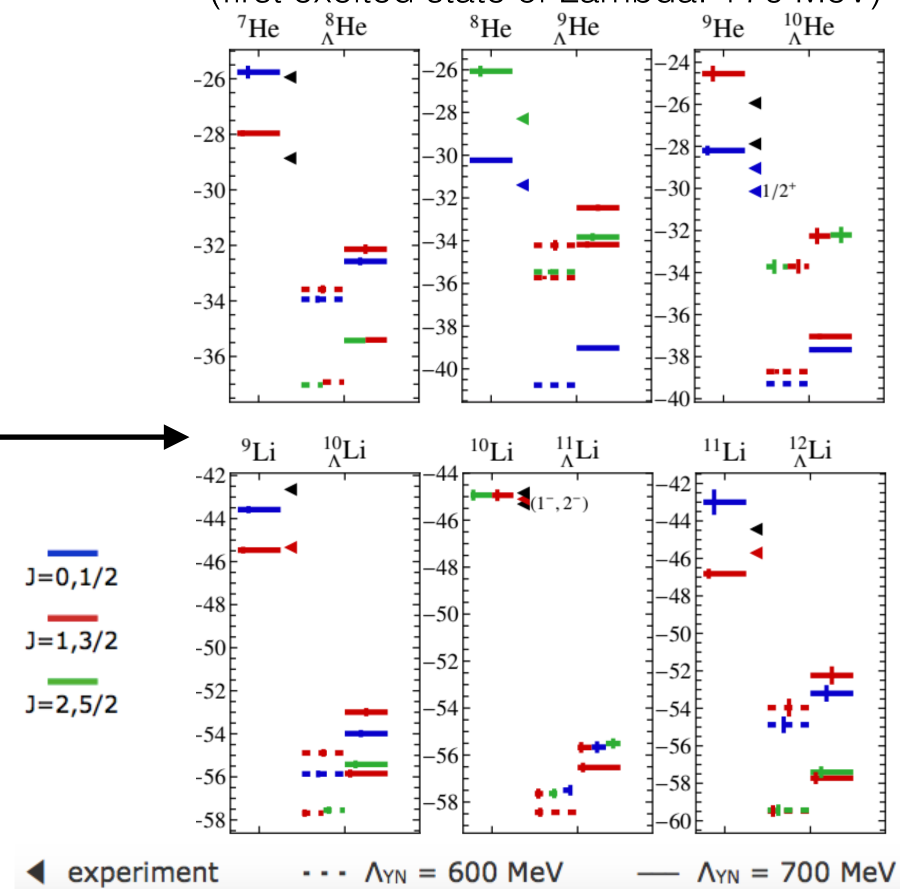
(first nucleonic excited state: +300 MeV)



R.B. Wiringa and S.C. Pieper, PRL 89 (2004)

Hypernuclei

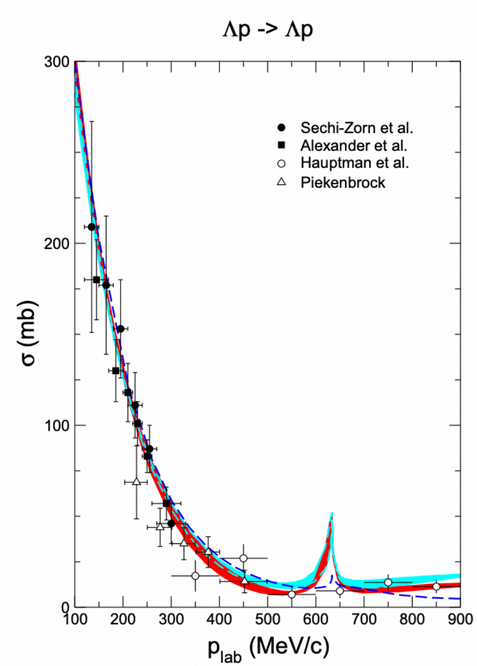
(first excited state of Lambda: +70 MeV)



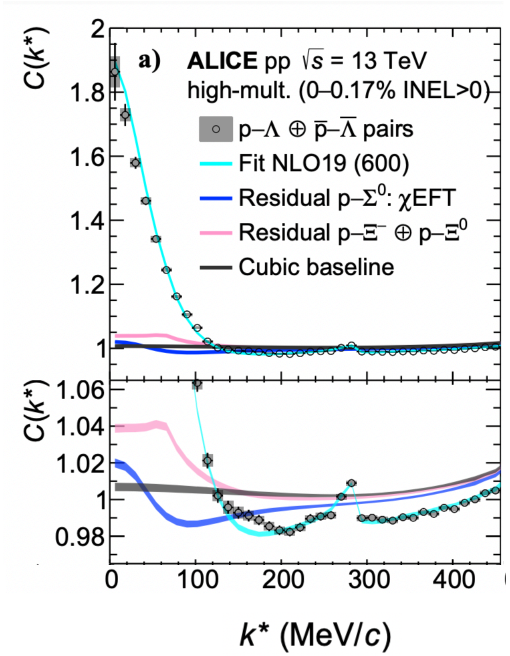
R. Wirth, R. Roth, PLB 779 (2018)

YN and YNN forces

- Direct $\Lambda - p$ scattering : 27 data points only
- Femtoscopy and *pp* collisions : new laboratory for YN and YY interactions
- Hypernuclei data necessary to pin-down in-medium and many-body forces



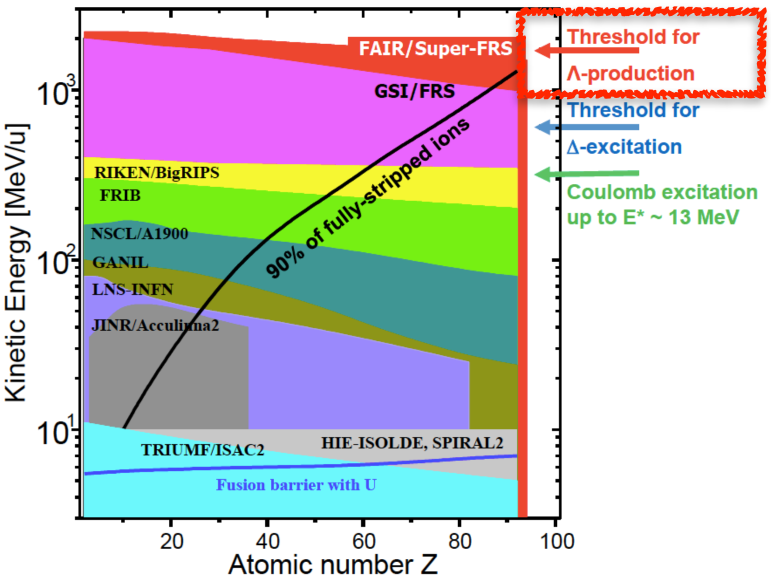
J. Haidenbauer, U.-G. Meißner, A. Nogga, EPJA 56 (2020) and references therein



ALICE collaboration, arXiv:2104.04427
ALICE collaboration, Nature 588 (2020)

Multi-GeV/n ions : opportunities at FAIR

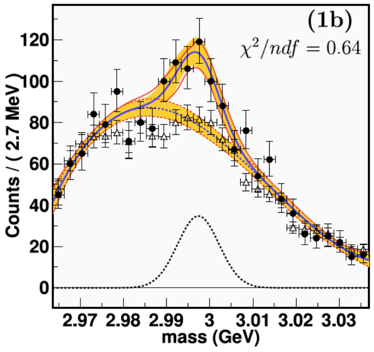
- Heavy-ion collisions at FAIR energies competitive to produce hypernuclei (HyPHI0)
- Strangeness production threshold requires > 1.6 GeV/nucleon



Proof of concept experiment **HypHI0**
(Spokesperson: T. Saito, GSI)

Heavy-ion collisions: ^{7}Li + ^{12}C at 2 GeV/nucleon

1) Strangeness production ($\sigma \sim 1\ \mu$b*)
2) Decay of Hyp-N (weak mesonic decays)



Invariant mass spectrum of $^{3}_{\Lambda}$H from decay products ^{3}He and π^{-}

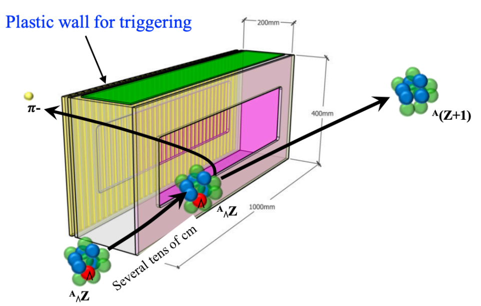
C. Rappold *et al.*, NPA 913 (2013)

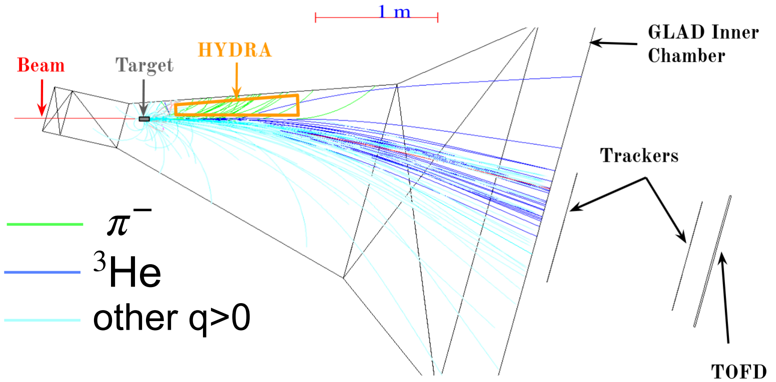
* ***Ex. model predictions:*** A. S. Botvina *et al.*, PRC 95 (2017); Y. Sun, A. S. Botvina et al., PRC 98 (2018); See also recent reference: A. S. Botvina *et al.*, PRC 103 (2021)

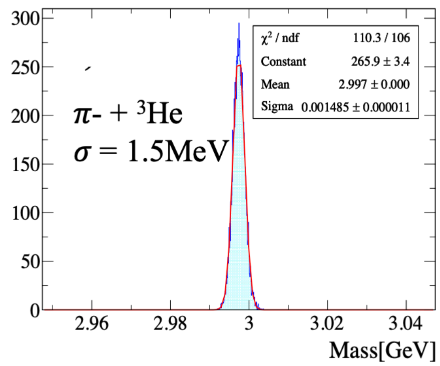
HYDRA at R3B

- **Concept: high-resolution invariant-mass with high efficiency**
  - off-beam 1-meter long TPC inside GLAD magnet (2 T)
  - selective trigger
  - large detection efficiency for pionic decays (55 %)
  - minimum straggling, high position resolution (<200 μm)
  - high vertex position resolution (< 5 mm)

- **Objectives:** >10^6 pps, and invariant mass resolution < 2 MeV (σ)







Courtesy S. Velardita, TU Darmstadt

Beam-rate limitations

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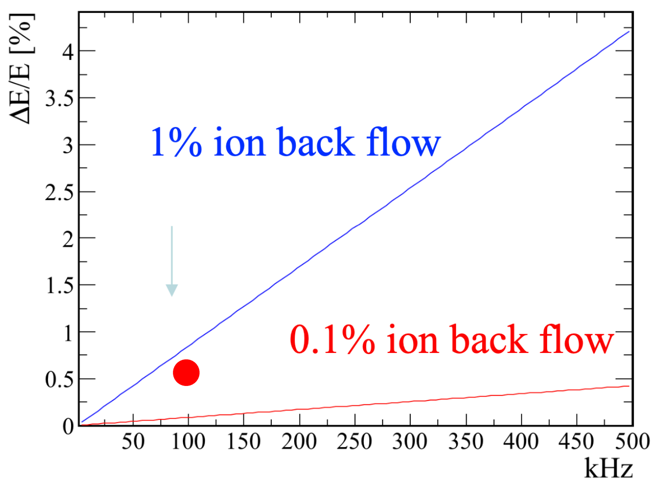
- **few 10^4 Hz trigger rate limit**
  - Beam of 10^6 pps: < 1 % of events from pion - ion coincidences
  - Continuous TPC readout (VMM3 FEE)

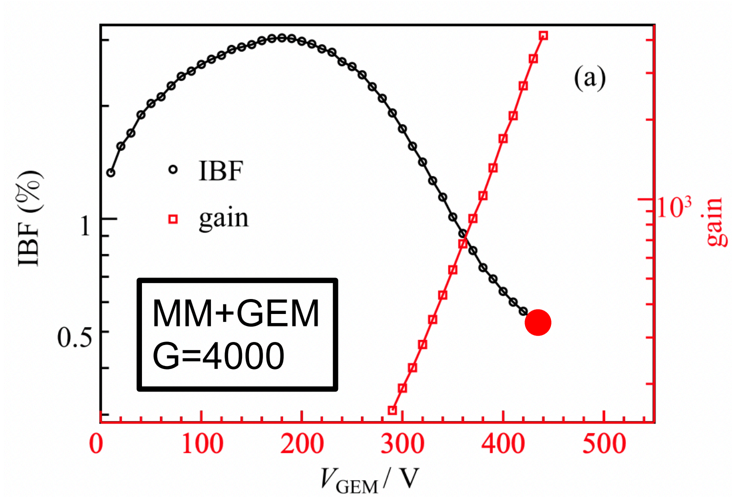
- **Space charge distorsion** of drift field $\Delta E/E < 0.5\,\%$
  - < 100 kHz tracks in TPC
  - Ion back flow reduced to IBF < 0.5% by combined Micromegas + GEM
  - Additional software drift corrections possible

$$\rho = \frac{nG\varepsilon Te}{V}$$

G: gain of the amplification
ε: ion backflow fraction
V: volume of the TPC



Courtesy Y. L. Sun, TU Darmstadt



Y.-L. Zhang et al, CPC 41 (2017)

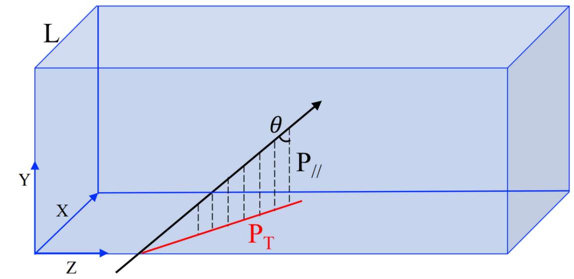
Pion detection and invariant-mass resolution

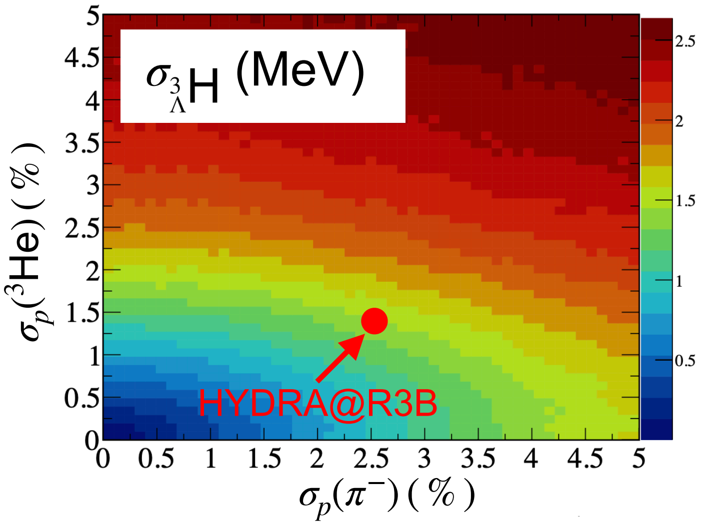
- Targeting an invariant-mass resolution of 1.5 MeV (σ) with low background

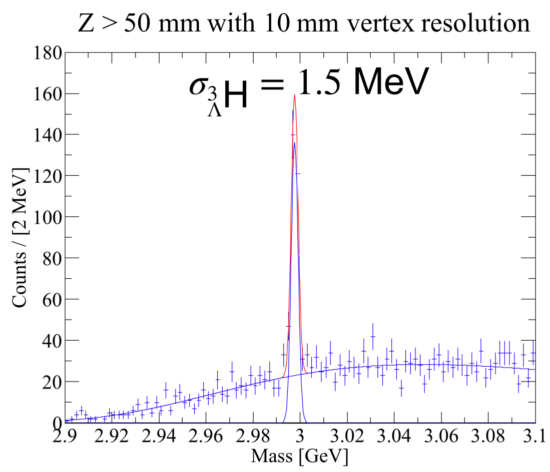
$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\sqrt{\frac{720}{N+4}}\,\frac{\sigma_x p\,\sin\theta}{0.3\,B\,L^2}\right)^2 + \left(\frac{0.2}{\beta B\sqrt{L\,X_0}}\left[1+0.038\ln\left(\frac{L}{X_0}\right)\right]\right)^2 + (\cot\theta\sigma_\theta)^2$$

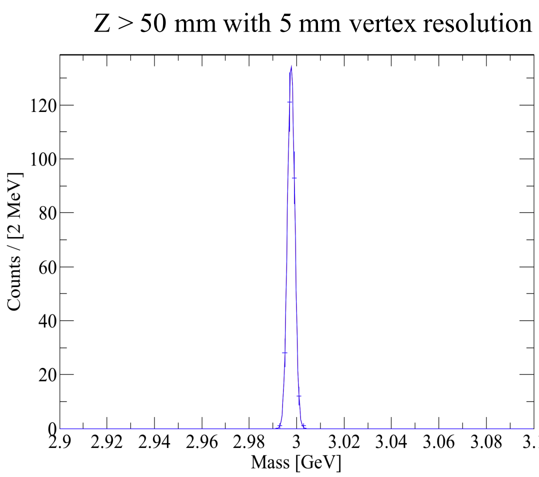
Pad size

Multiple scattering









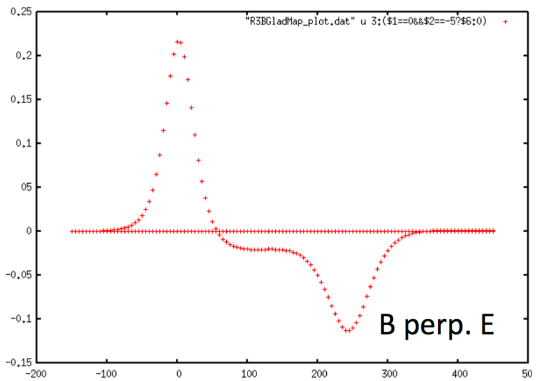
Simulations: Y. Sun and S. Velardita, TUDa

Tracking in non-homogenous B field

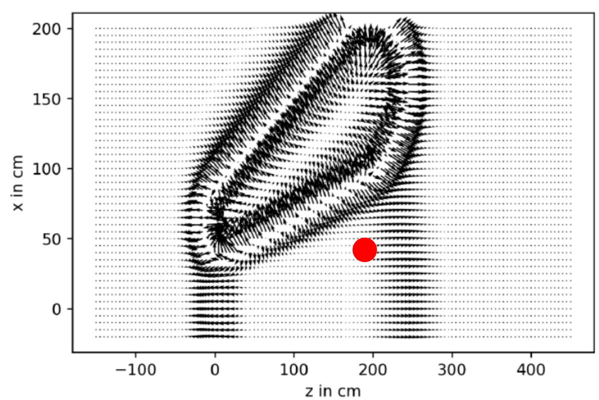
- Non vertical magnetic field components in B field of GLAD
- ExB drift: millimeter displacement compared to vertical drift
- Laser-induced reference tracks to benchmark B-field mapping

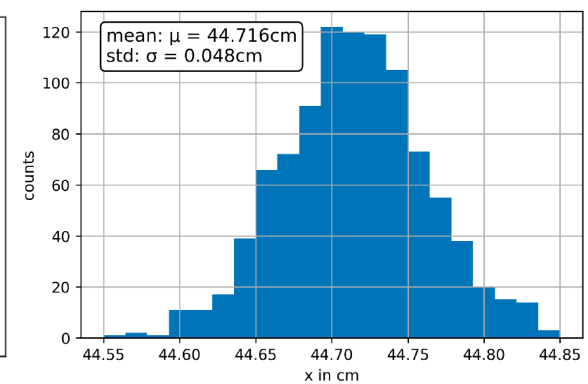
Electrons (Garfield simulation) drifting 100 mm lead to an offset < 3 mm compared to the vertical projection

Bz (T)



Z (cm)





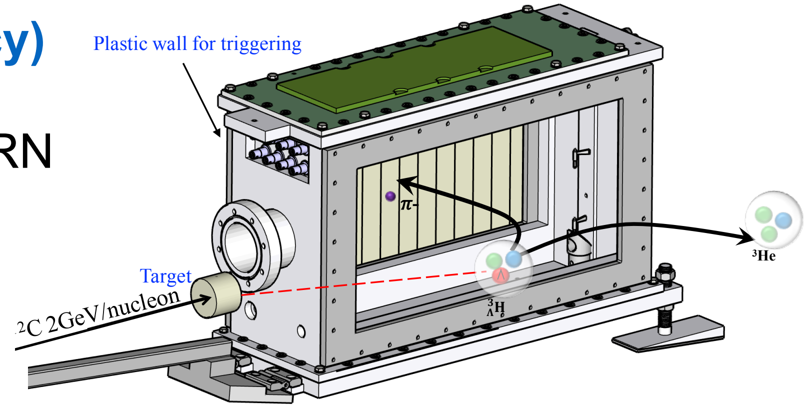
at point (45, 10, 190)

Courtesy D. Wassmer, TU Darmstadt

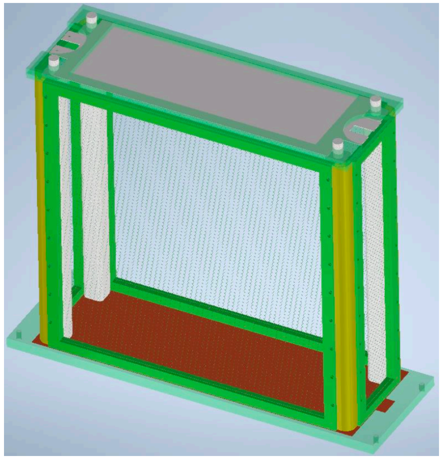
The HYDRA prototype

1/3 HYDRA prototype (7% detection efficiency)

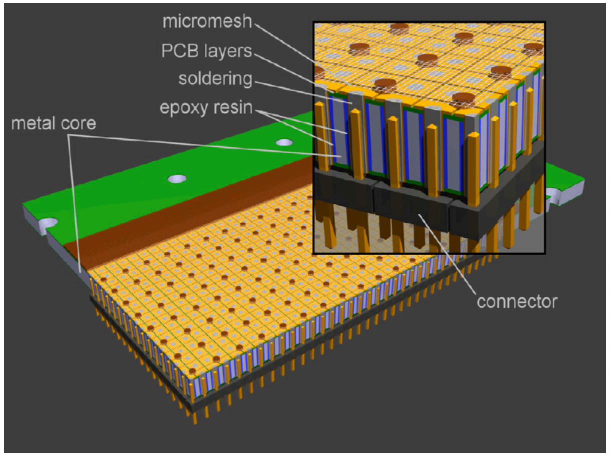
- under completion
- field cage and amplification stages built at CERN
- laser and in-beam validation in Q1/2022
- continuous readout in operation in Q3/2022
- Full system ready from beginning of 2023



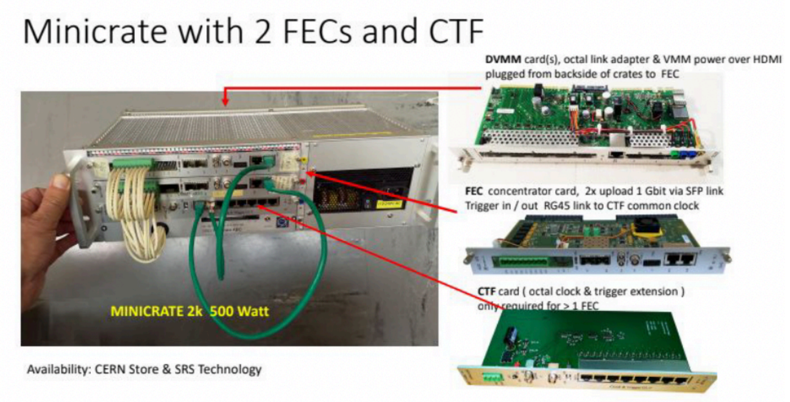
double wire-plane field cage



metal-core Micromegas pad plane
J. Giovinazzo et al., NIMA 892 (2018)



VMM3 chips and SRS readout



Courtesy L. Ji, TU Darmstadt

Proposal to NEXT G-PAC : size of ${}^{3}_{\Lambda}$H and ${}^{6}_{\Lambda}$He

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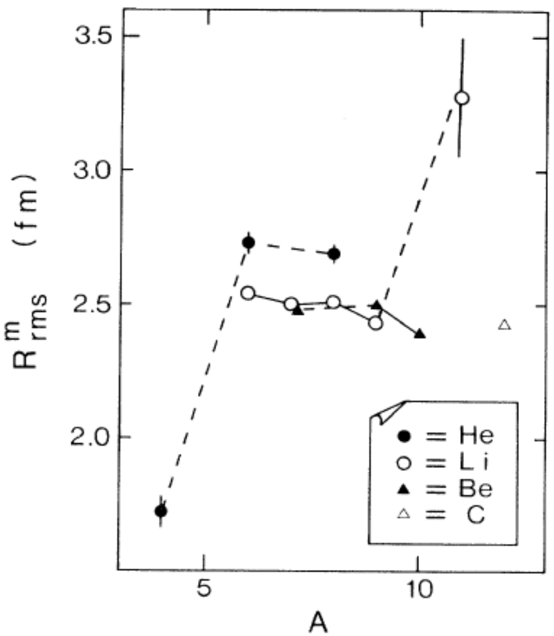
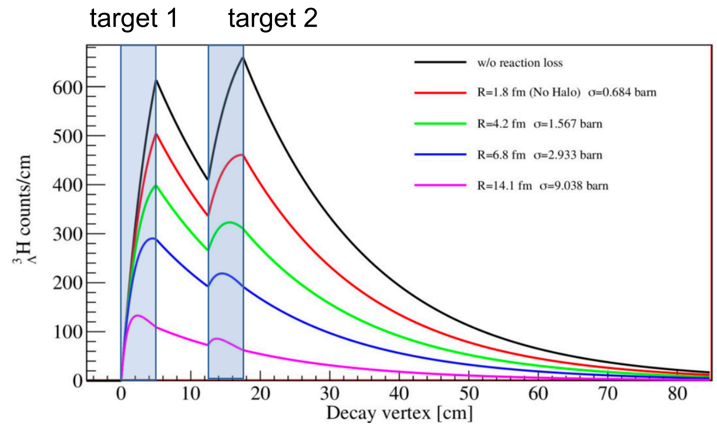
Method

- production target and **secondary** target inside GLAD
- Two unknowns (interaction and production cross sections) = two measurements

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



I. Tanihata et al., PLB 160 (1985)
I. Tanihata et al., PRL 55 (1985)



Matter radius (fm)	Measured statistics ${}^{3}_{\Lambda}$H	Measured statistics ${}^{6}_{\Lambda}$He
$R = 1.25\times A^{1/3}$	1438(37)	950(30)
R + 1.0	1105(33)	714(26)
4.2	683(26)	–
6.8	243(15)	–
14.1	3(1)	–

HYDRA LoI, A. Obertelli, Y. L. Sun et al., G-PAC 2020

The HYDRA team at R3B and collaborators

HYDRA core team:
T. Aumann, M. Duer (YI group leader), L. Ji (PhD), A. Obertelli, D. Rossi, Y. L. Sun (PD), S. Velardita (PhD) + **open postdoc position** *TU Darmstadt, Germany*
D. Körper, H. Simon *GSI/FAIR, Germany*
H. Alvarez-Pol, Y. Ayyad, J. L. Rodriguez *Universidade de Santiago de Compostela, Spain*
L. Fabbietti, R. Gernhaüser *TU Munich, Germany*
S. Ota *Center for Nuclear Studies (CNS), University of Tokyo, Japan*

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J. Stroth *University of Frankfurt, Germany*
J. Benlliure, D. Cortina-Gil *Universidade de Santiago de Compostela, Spain*
T. R. Saito *RIKEN, Japan; Lanzhou University, China; GSI, Germany*
C. Rappold, O. Tengblad *Instituto de Estructura de la Materia, CSIC, Spain*
A. Corsi, E. C. Pollacco *CEA, France*

Theory support:
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R. Wirth *FRIB, USA*
M. Bleicher, A. Botvina, H. Elfner *J.W. Goethe Universität, Frankfurt am Mainz, Germany*

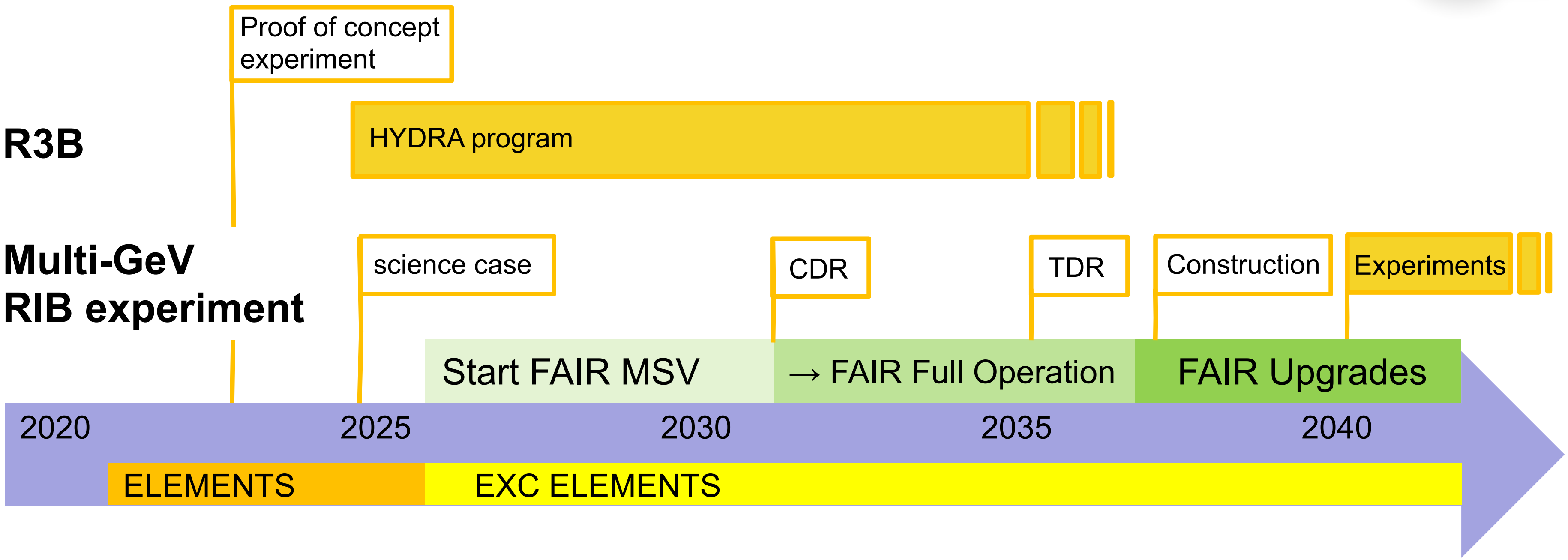
Summary

- **HYDRA** @ R3B: high-resolution tracker (TPC) for hypernuclei invariant mass
- HYDRA prototype under construction (ready 2023 with continuous readout)
- First proposal to determine the **size of $^{3}_{\Lambda}$H and $^{6}_{\Lambda}$He** at G-PAC (2022)
- Study of the **two-proton halo candidate $^{7}_{\Lambda}$Be**
- **binding energies along C,O isotopic chains**
- Concept and design program towards a multi-GeV RI facility for FAIR upgrades (horizon 2040)

Beyond FAIR phase 0: Multi-GeV RIB at FAIR

- **Multi-GeV Radioactive Isotope Beams** at FAIR
- A future world-unique fixed-target experiment at HESR rooted into GSI expertise
- Opens up the nuclear chart for hypernuclei studies and other new opportunities

- Key project for coming Excellent Cluster proposal (2024) covering 2025-2039
- First steps in the ELEMENTS initiative between Frankfurt, Gießen, GSI, TUDa



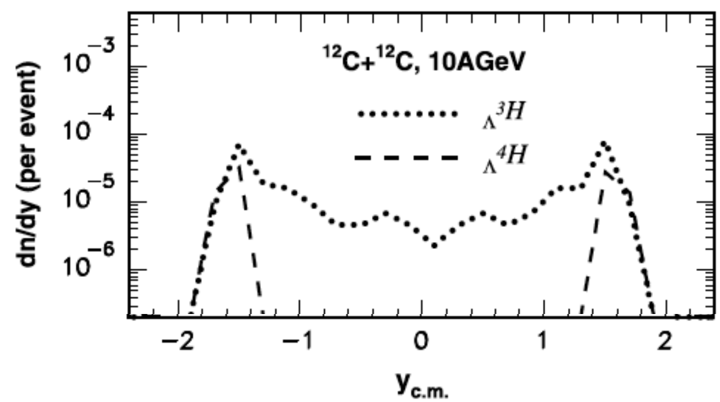
Production of hypernuclei from HI collisions at few GeV / nucleon

A. S. Botvina et al., PLB 742 (2015)

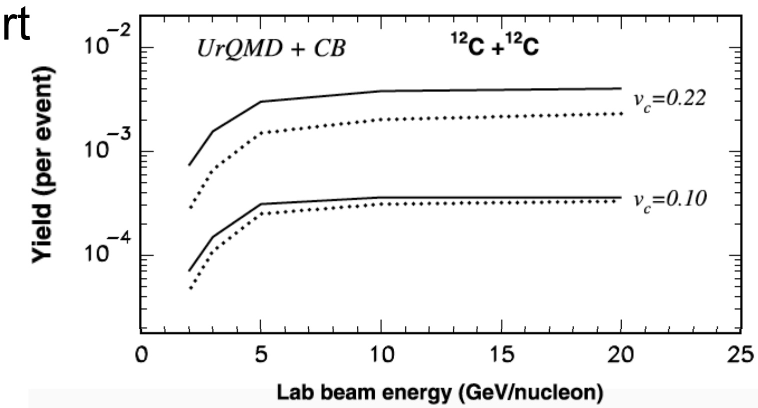
- Strangeness production in heavy-ion collisions:

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

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



- **Hypernuclei production from HI collisions**
  - Evolution of hadrons in space-time from transport
  - Adsorption of Λ (coalescence or potential criteria)
  - De-excitation
  - Saturation from 5-10 A GeV



Production of hypernuclei from HI collisions at few GeV / nucleon (S-FRS, R3B energies)

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Expt with ^{12}C target, DUBNA: S. Avramenko et al., NPA 547 (1992), HyPHI: C. Rappold et al., NPA 913 (2013)

Beam	Energy (GeV/nucleon)		$^{3}_{\Lambda}$H	$^{4}_{\Lambda}$H
^{3}He	5.14	(I)	0.63	...
		(II)	0.05	...
		(III)	< 0.01	...
		Dubna [16]	$0.05^{+0.05}_{-0.02}$	...
^{4}He	3.7	(I)	< 0.01	0.19
		(II)	0.24	0.12
		(III)	0.04	< 0.01
		Dubna [16]	< 0.1	$0.4^{+0.4}_{-0.2}$
^{6}Li	3.7	(I)	1.15	0.27
		(II)	0.29	2.31
		(III)	0.84	0.33
		Dubna [16]	$0.2^{+0.3}_{-0.15}$	$0.3^{+0.3}_{-0.15}$
^{7}Li	3.0	(I)	0.94	0.35
		(II)	0.17	2.44
		(III)	0.88	0.64
		Dubna [16]	...	...
^{6}Li	2.0	(I)	0.2	0.02
		(II)	0.03	0.43
		(III)	0.13	0.04
		HypHI [45]	3.9±1.4	3.1±1.0

$\sigma(\mu b)$

Model: A. S. Botvina *et al.,* PRC 95 (2017), ***Calculations:*** Y. Sun, A. S. Botvina et al., PRC 98 (2018)
See also recent reference: A. S. Botvina *et al.*, PRC 103 (2021)

Hypertriton binding energy