Hypernuclear halos with HYDRA at R3B

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THEIA seminar

March 16, 2022

Isospin and strangeness degree of freedom

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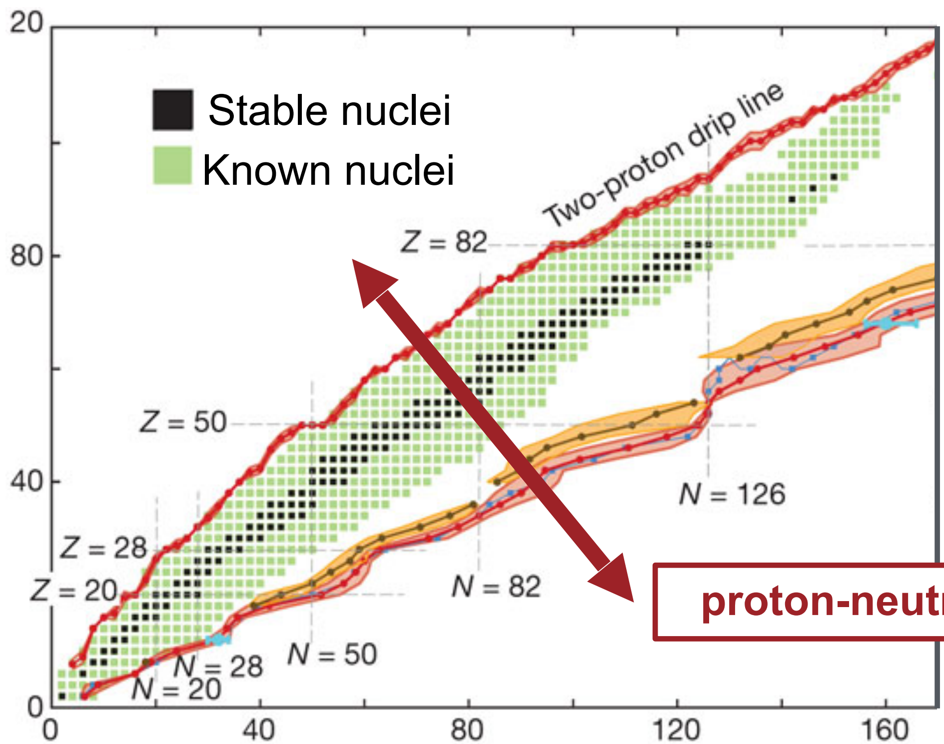
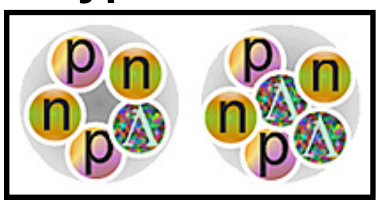
- Proton-neutron asymmetry: nuclear structure and in-medium forces
- Hypernuclei open the strangeness sector
- With HYDRA, we aim at **weekly-bound single-Λ hypernuclei at R3B (FAIR)**

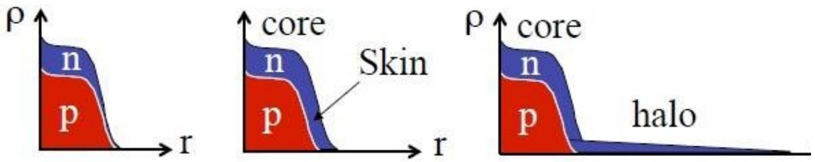


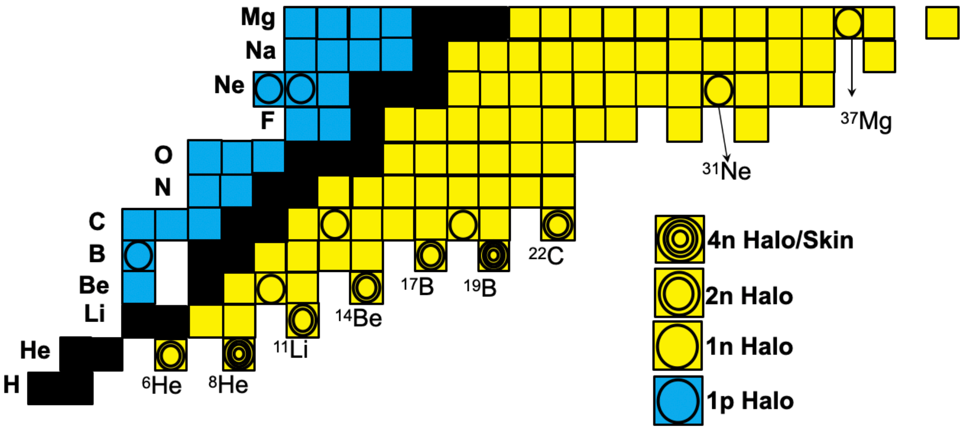
proton-neutron asymmetry

hypernuclei



Non-strange halo nuclei





- First observation of **neutron halos** in Berkeley and interpretation from ISOLDE
  I. Tanihata et al., PRL 55 (1985), P.G. Hansen and B. Jonson, EPL 4 (1987)

- Quantum tunnelling: low binding energy and low angular momentum (l=0,1)

- **Proton halos** investigated (ex. ^{17}Ne)
  W. Geithner et al., PRL 101 (2008), C. Lehr et al., PLB 827 (2022)

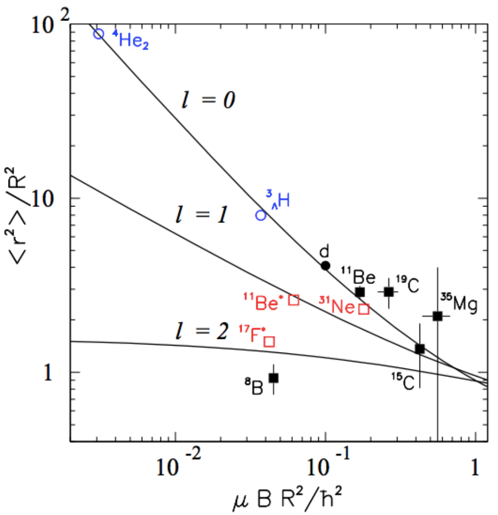
- **Medium mass halos** (p-wave) suggested for the ^{31}Ne and ^{37}Mg
  T. Nakamura et al., PRL 112 (2014), N. Kobayashi et al., PRL 112 (2014)

Hypernuclear halos

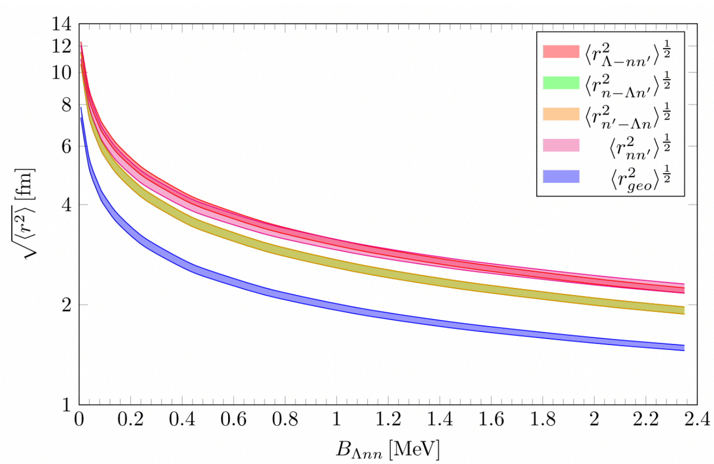
- Universality of halos: several loosely bound hypernuclei are candidates
- $\Lambda - d$ rms distance in **hypertriton** ($^3_\Lambda$H) predicted at 10.8 fm

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

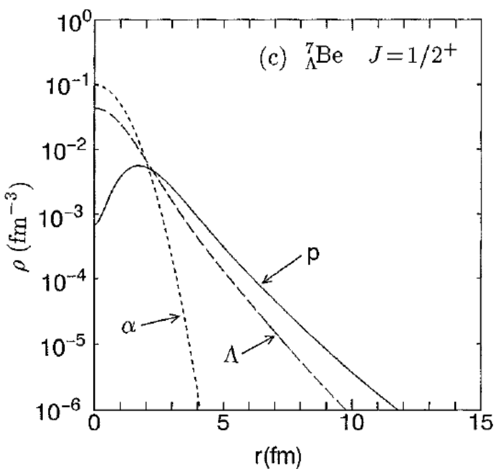
K. Riisager, Phys. Scr. T 152 (2012)



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



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



The hypertriton puzzle in a nutshell

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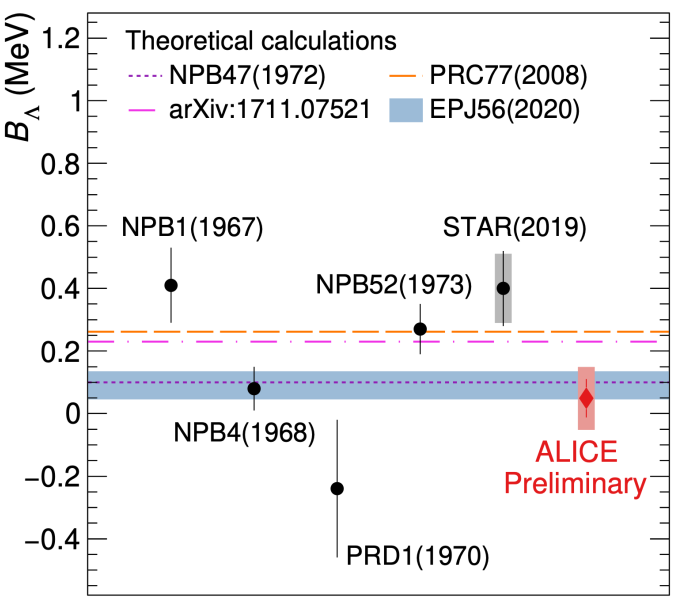
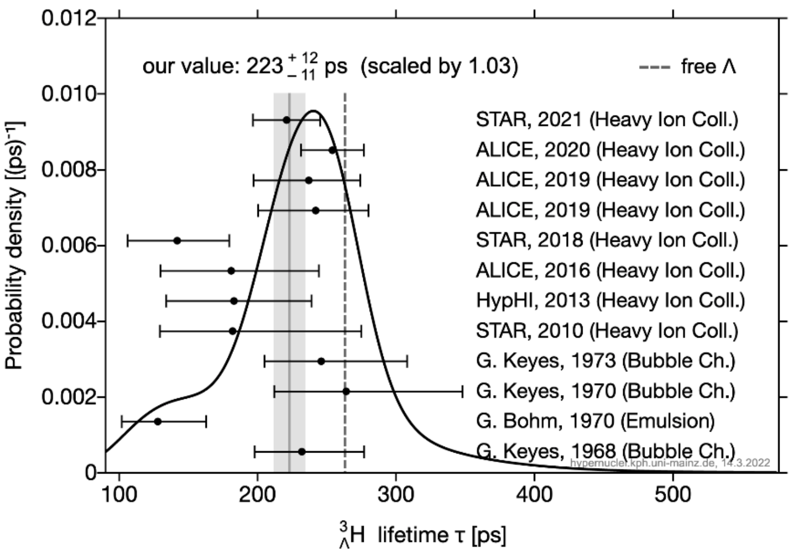
- Low binding energy (average 2020: 130(50) keV, STAR 2020: 410(120) keV)
- Large spatial extension predicted (*unmeasured*)
- Inconsistency between several lifetime analyses (STAR, HyPHI0, ALICE)
  Latest ALICE value: $254 \pm 15\,(stat.) \pm 17\,(sys.)$ ps



B. Dönigus, EPJA 56 (2020)



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

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

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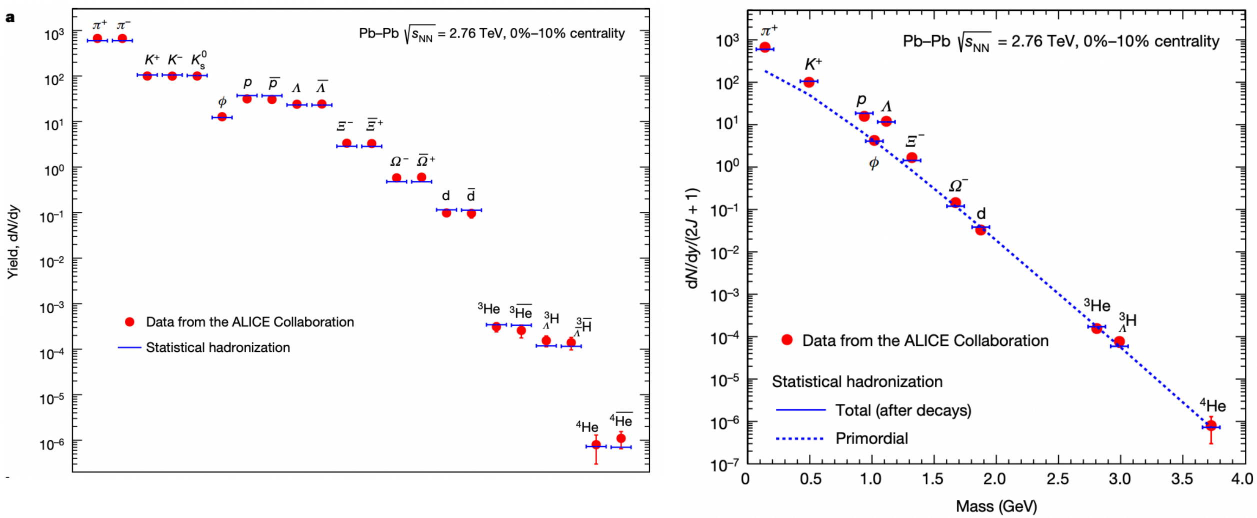
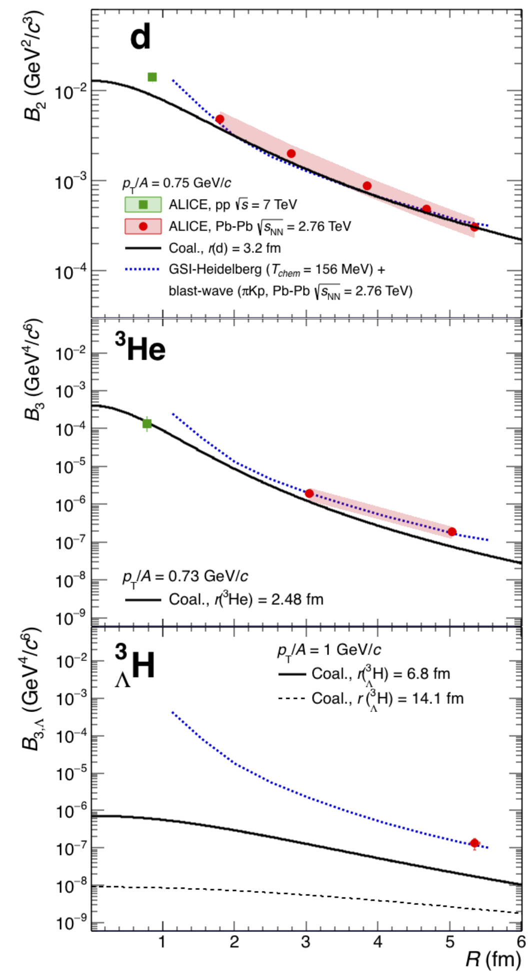
A. Andronic et al., Nature 561 (2018)



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

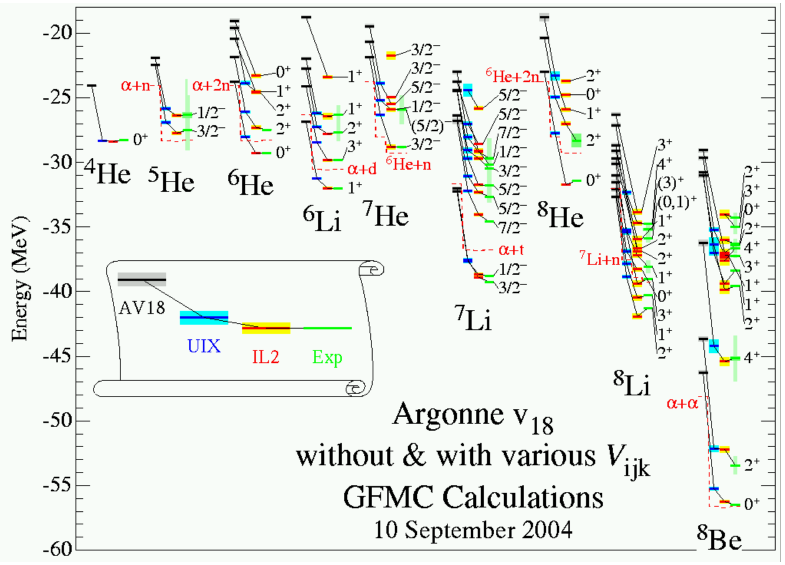


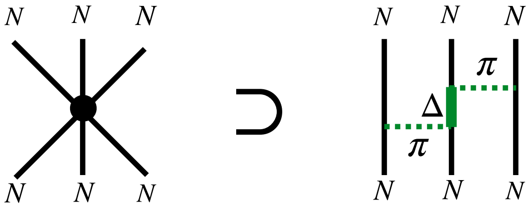
- Statistical hadronization or coalescence?
- ${}^{3}_{\Lambda}$H has the **potential to rule out coalescence models** for cluster (nuclei) production in HI collisions
  F. Bellini et al., PRC 103 (2021), ALICE-PUBLIC-2020-005
- **Size of ${}^{3}_{\Lambda}$H** is central for coalescence predictions

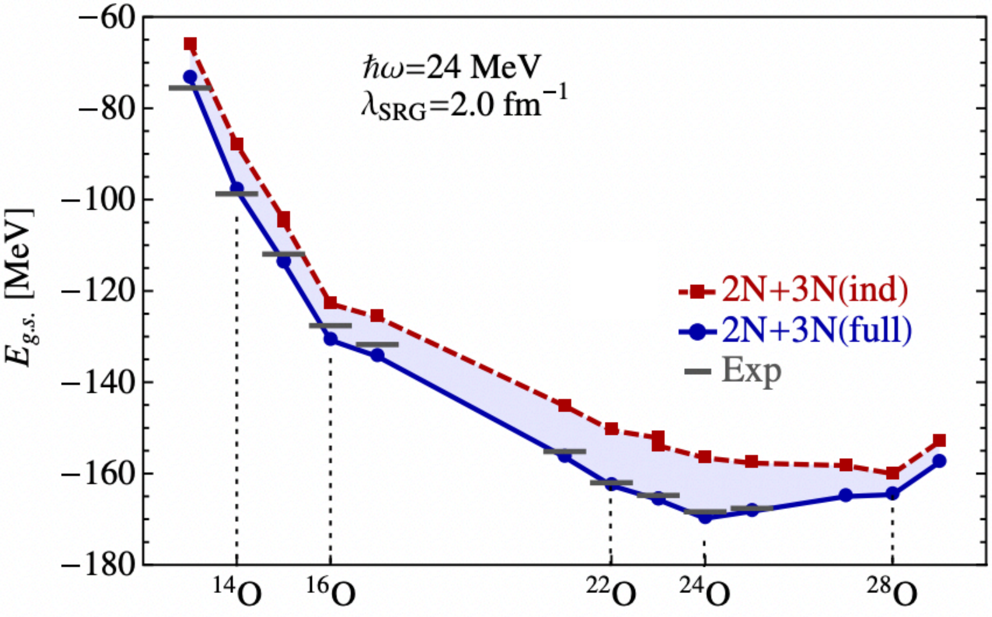
Three-body forces and nuclear structure

Nuclei

(first nucleonic excited state: +300 MeV)







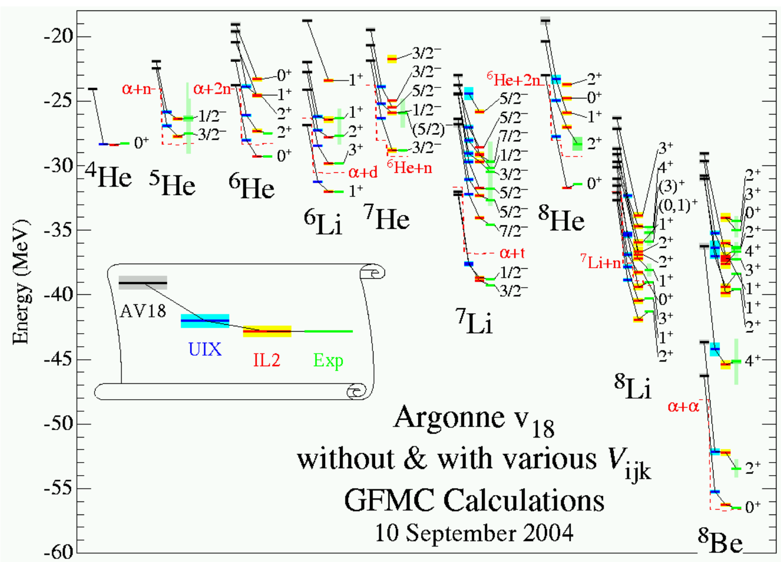
R.B. Wiringa and S.C. Pieper, PRL 89 (2004)

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

Ab initio description of light (hyper)nuclei

Nuclei

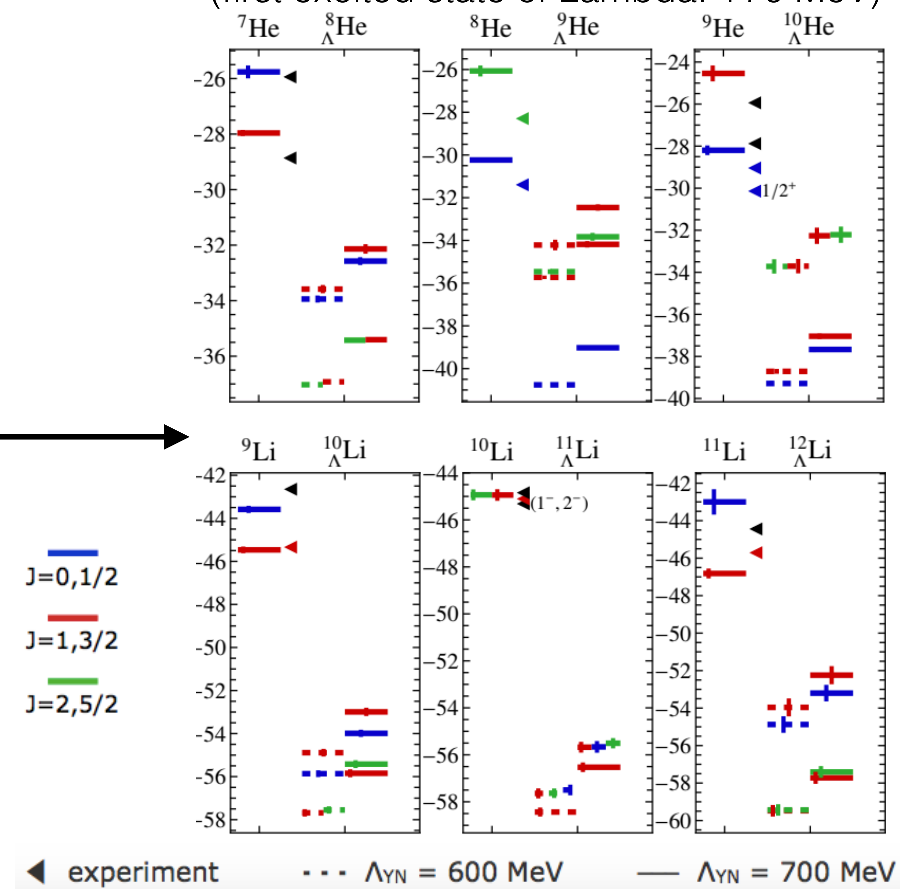
(first nucleonic excited state: +300 MeV)



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

Hypernuclei

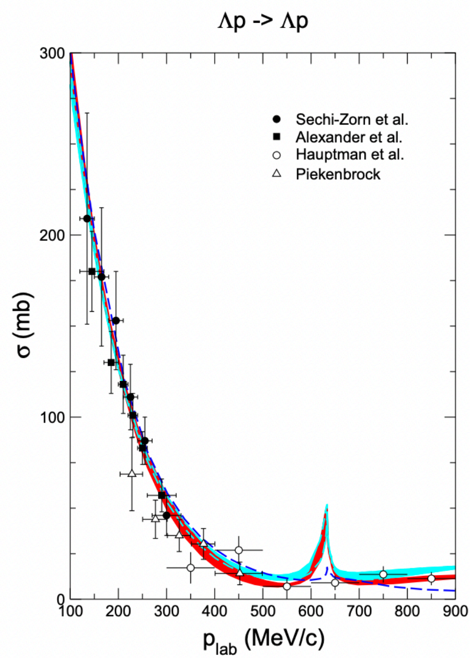
(first excited state of Lambda: +70 MeV)



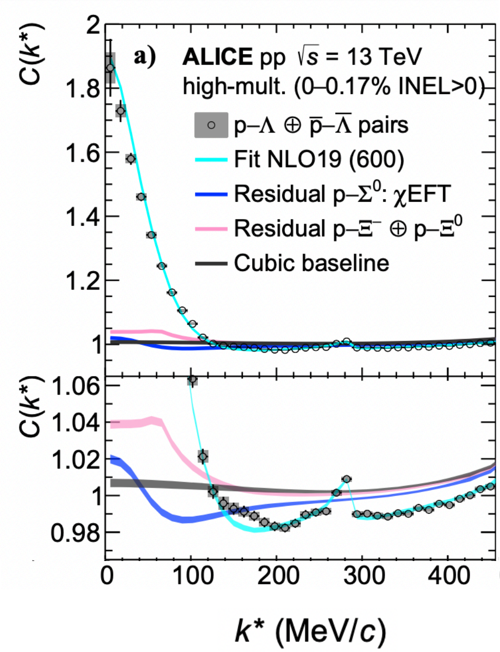
R. Wirth, R. Roth, PLB 779 (2018)

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

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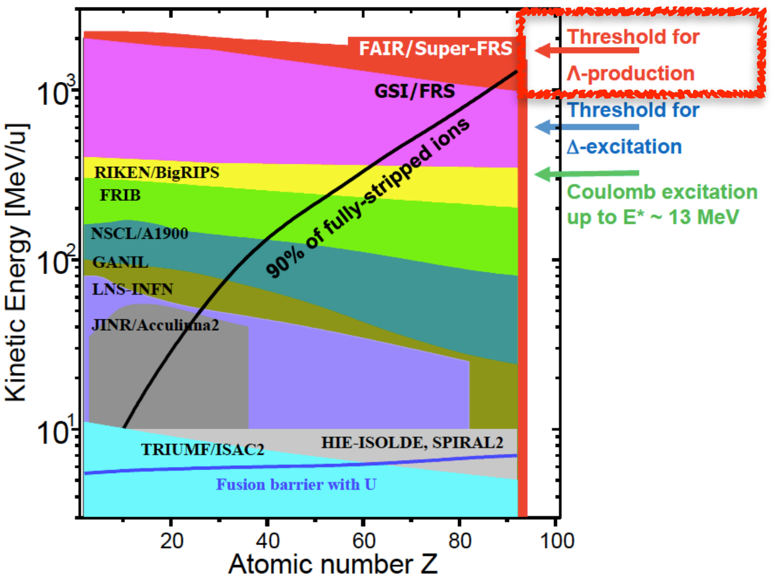
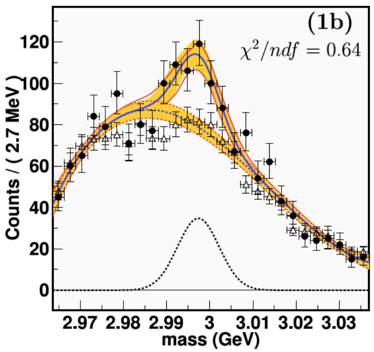
- Heavy-ion collisions at FAIR energies competitive to produce hypernuclei (HyPHI0)
- Strangeness production threshold requires > 1.6 GeV/nucleon



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)

Ongoing WASA experiment at FRS
(Spokesperson: T. Saito, RIKEN, Lanzhou, GSI)

Production of hypernuclei from HI collisions at few GeV / nucleon

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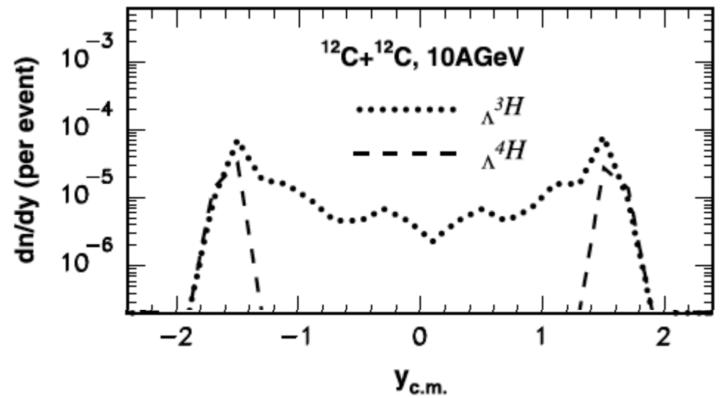
A. S. Botvina et al., PLB 742 (2015)

- Strangeness production in heavy-ion collisions:

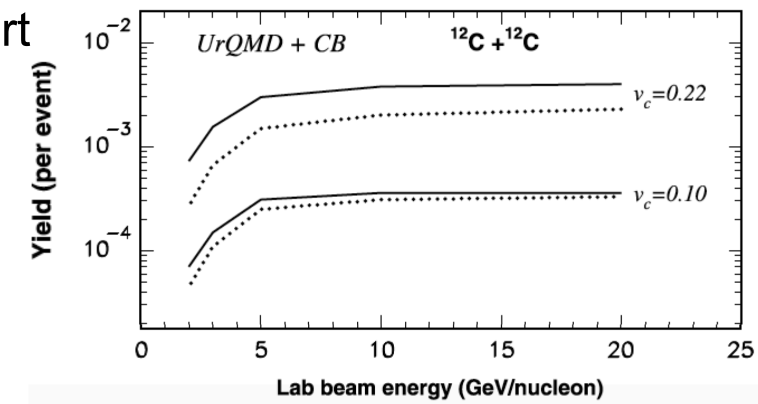
$$p + p \rightarrow p + \Lambda + K^{+} \quad (E_{lab} > 1.58\,GeV)$$

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



- **Hypernuclei production from HI collisions**
  - Evolution of hadrons in space-time from transport
  - Adsorption of Λ (coalescence or potential)
  - De-excitation

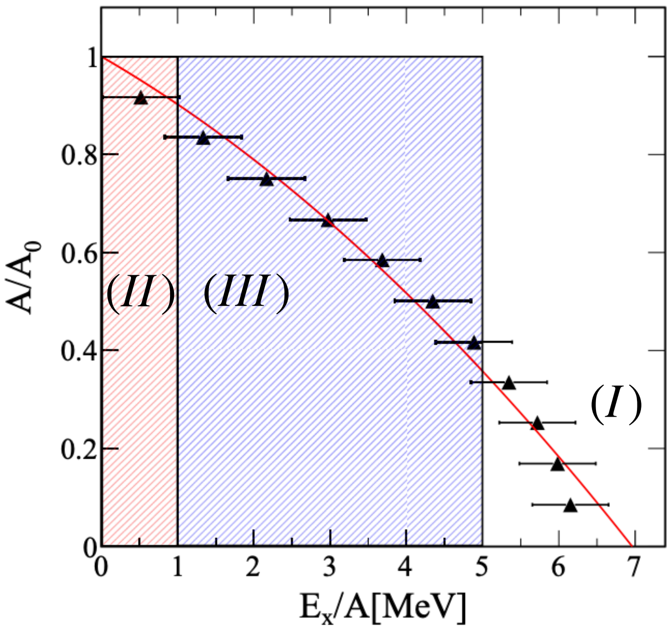
- Production saturation from 5-10 A GeV



Production cross sections

Expt with ¹²C 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	$\sigma(\mu b)$
		(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



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)

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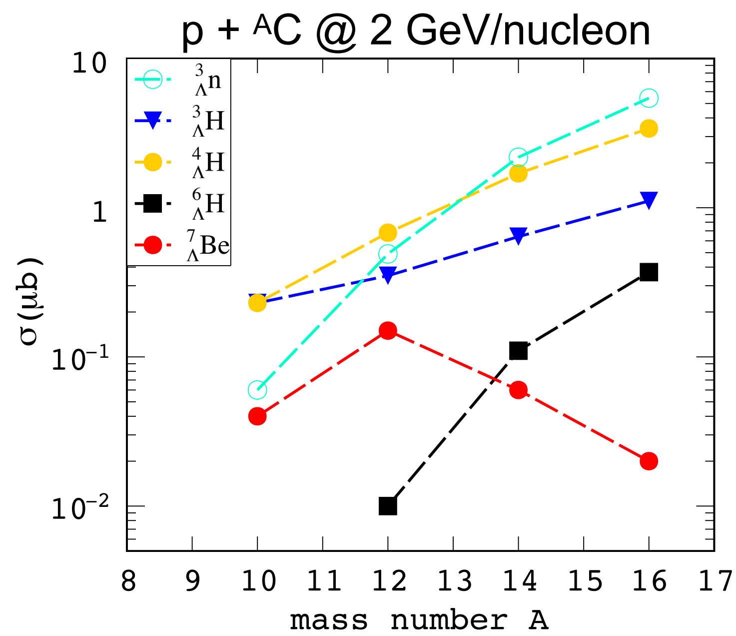

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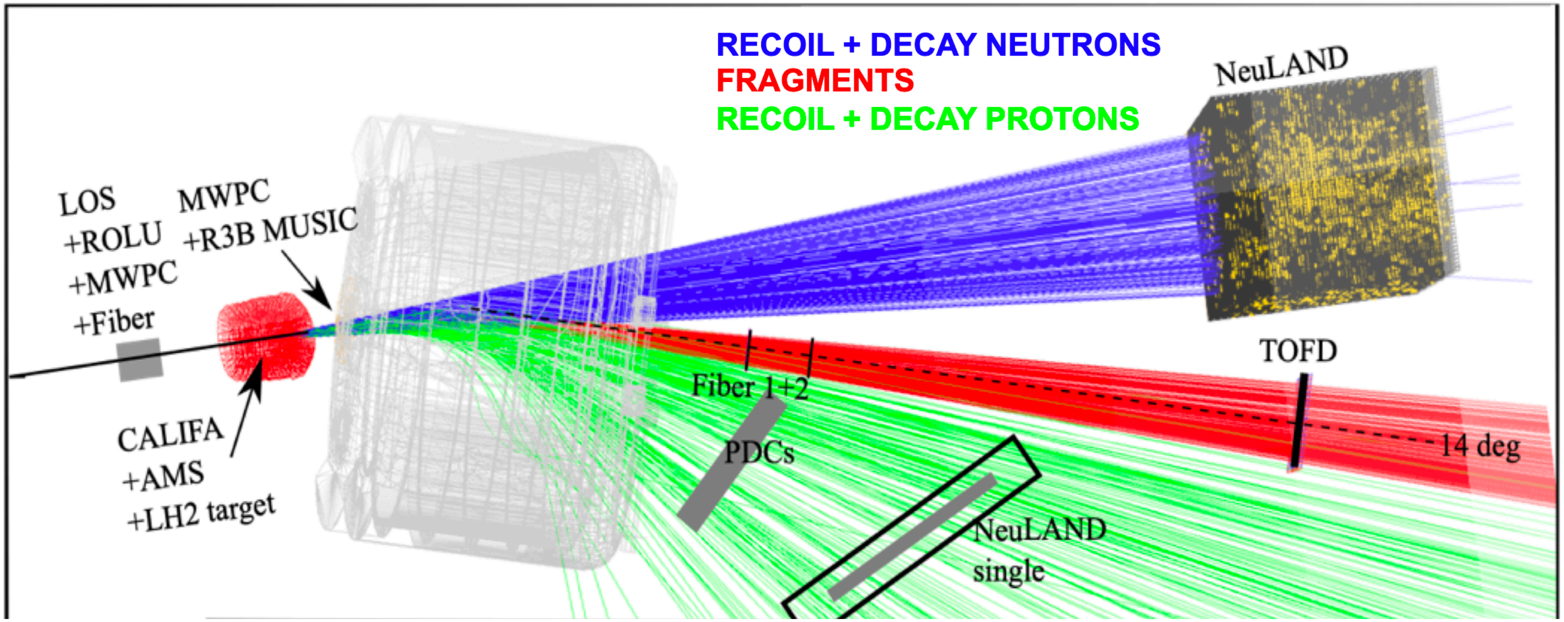
See also recent reference: A. S. Botvina *et al.*, PRC 103 (2021)

The R3B experiment

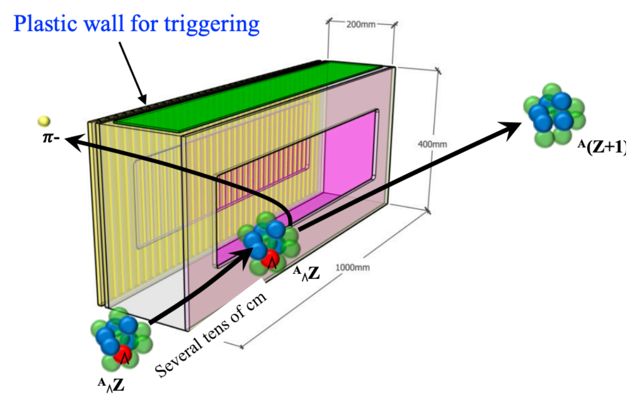
- R3B is a complete setup dedicated to kinematically complete measurements
- Not suited for all high-resolution invariant mass (ex. pion decay from hypernuclei)
- With HYDRA, we propose a new detection system for R3B: a TPC inside the GLAD dipole
  - ❑ Tracking inside B field gives access to full momentum
  - ❑ TPC: (1) minimum material budget, (2) large active volume with minimal cost

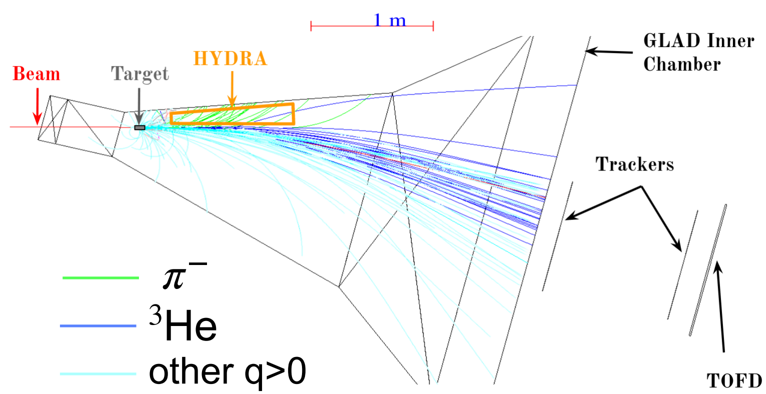


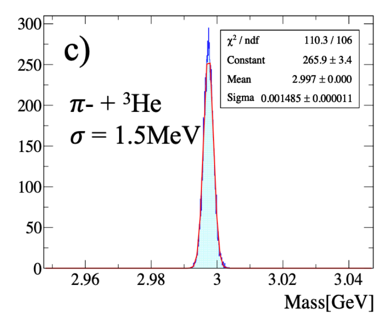
HYDRA at R3B

- **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 beam, and invariant mass resolution ~ 1.5 MeV (σ)







Courtesy S. Velardita, TU Darmstadt

Beam-rate limitations

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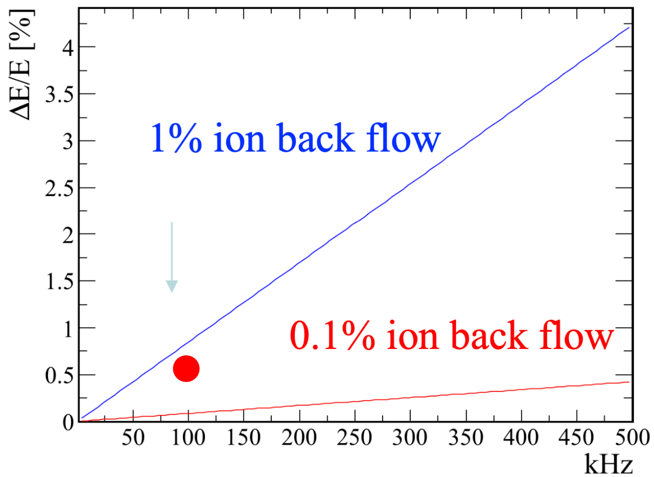
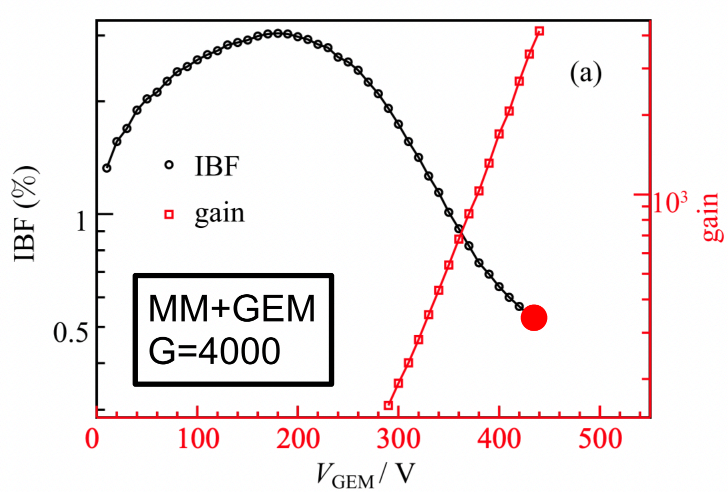
- **few 10^4 Hz trigger rate limit**
  - Beam of 10^6 pps: < 1 % of events from pion - ion coincidences
  - Continuous TPC readout (VMM3 FEE foreseen)

- **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)

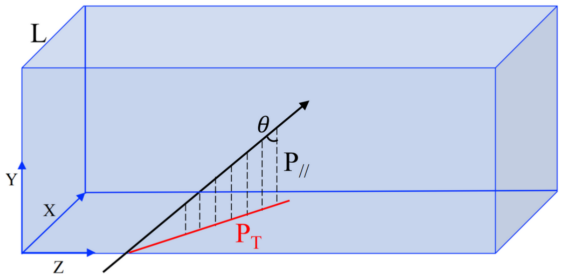
Pion detection and invariant-mass resolution

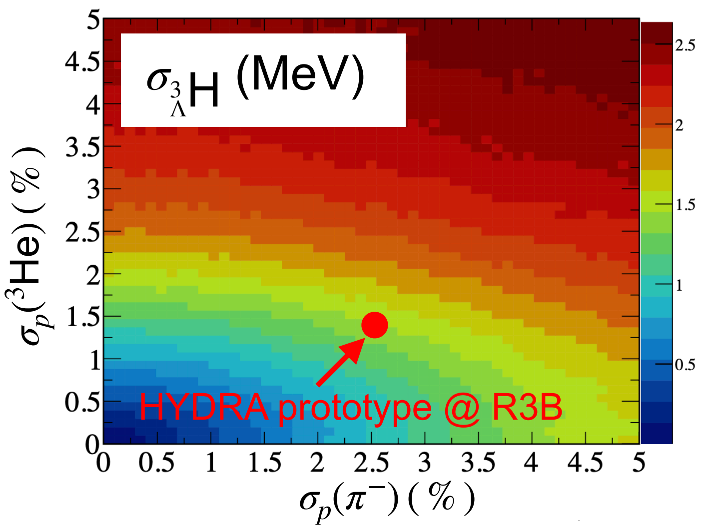
- Targeting an invariant-mass resolution of 1.5 MeV (σ) with low background

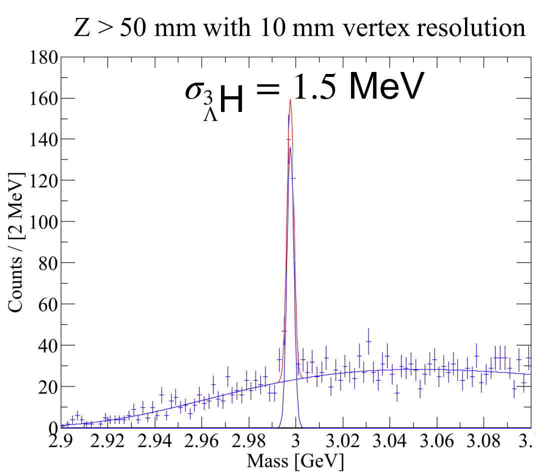
$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\sqrt{\frac{720}{N+4}}\,\frac{\sigma_x p\,\sin\theta}{0.3\,B\,L^2}\right)^2 + \left(\frac{0.2}{\beta B\sqrt{L\,X_0}}\left[1+0.038\ln\left(\frac{L}{X_0}\right)\right]\right)^2 + (\cot\theta\sigma_\theta)^2$$

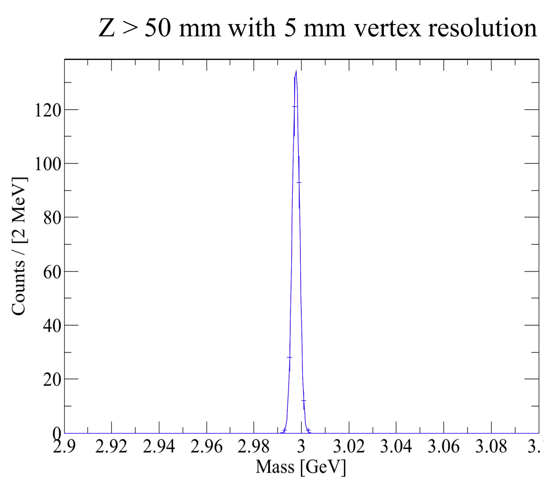
Pad size

Multiple scattering









Simulations: Y. Sun and S. Velardita, TUDa

Tracking in non-homogenous B field

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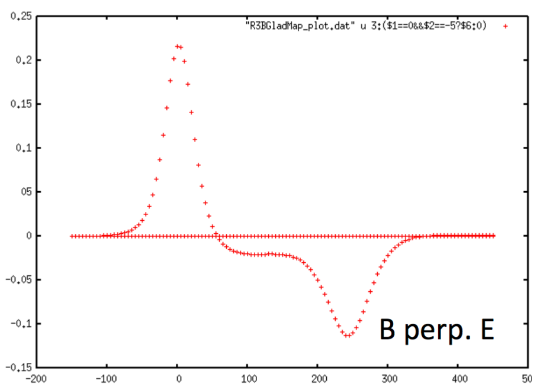
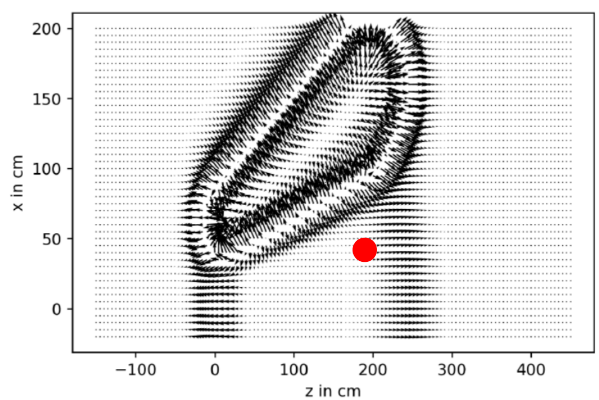
- transverse magnetic field components in B field of GLAD
- ExB drift: millimeter displacement compared to vertical drift
- Laser-induced reference tracks to benchmark B-field mapping

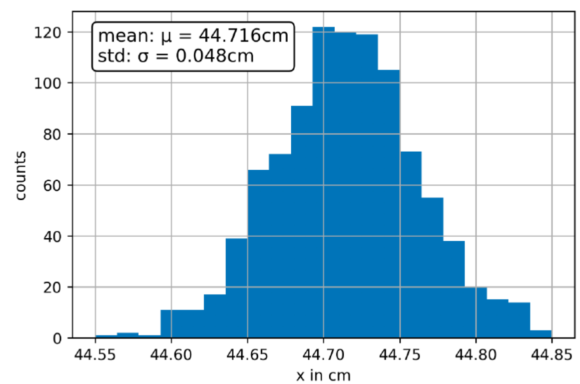
Electrons (Garfield simulation) drifting 100 mm lead to an offset < 3 mm compared to the vertical projection

Bz (T)



Z (cm)





at point (45, 10, 190)

Courtesy D. Wassmer, TU Darmstadt

The HYDRA prototype

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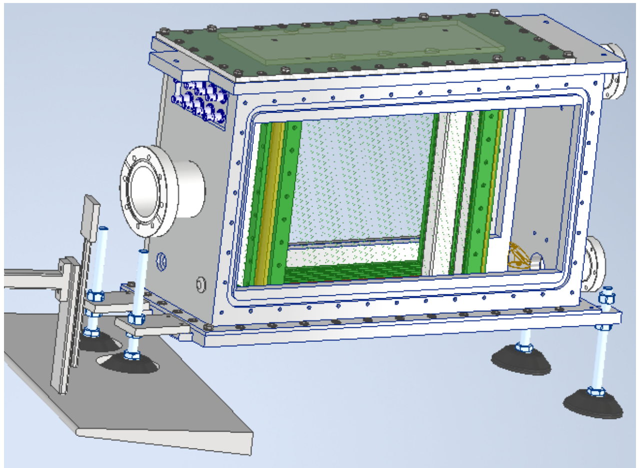
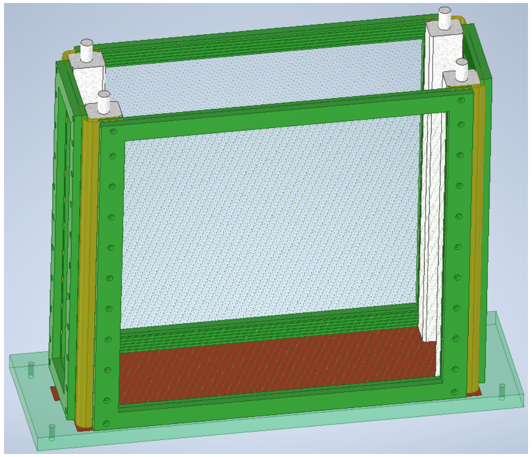
1/3 HYDRA prototype (7% detection efficiency)

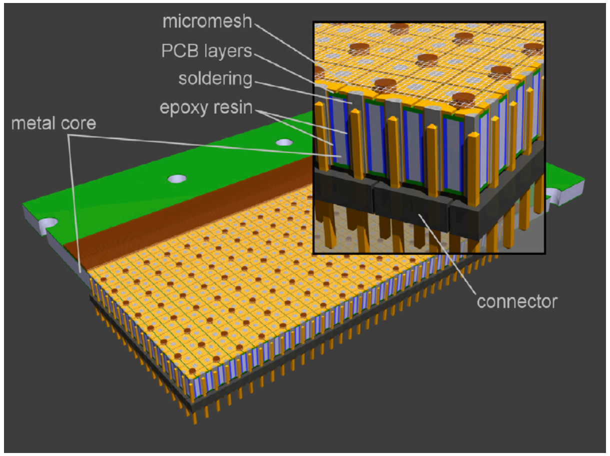
- under completion
- field cage and amplification stages built at CERN
- wiring of field cage at GSI
- laser and in-beam validation in Q3/2022
- continuous readout in operation in Q4/2022
- Full system ready from beginning of 2023



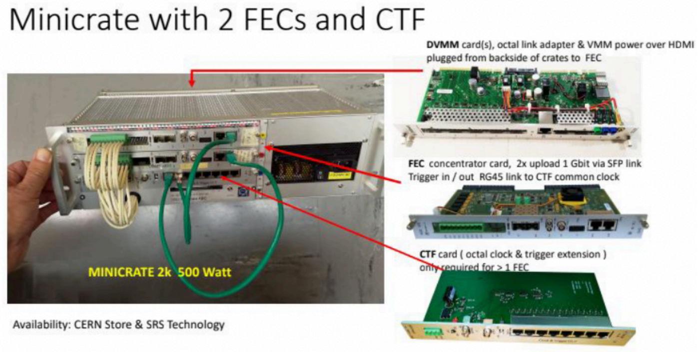
double wire-plane field cage



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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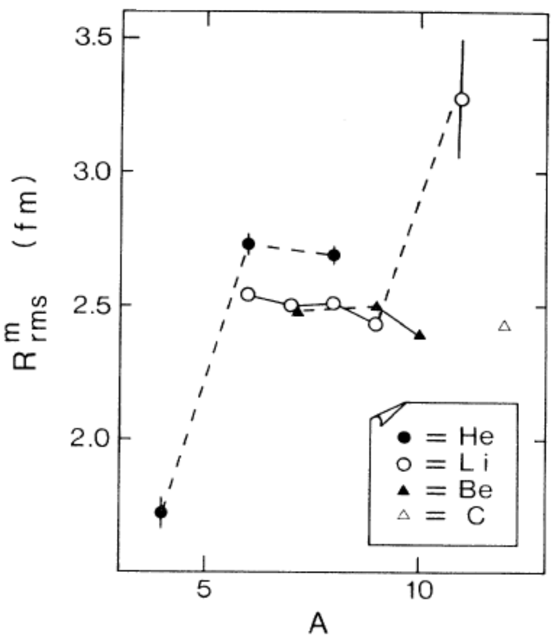
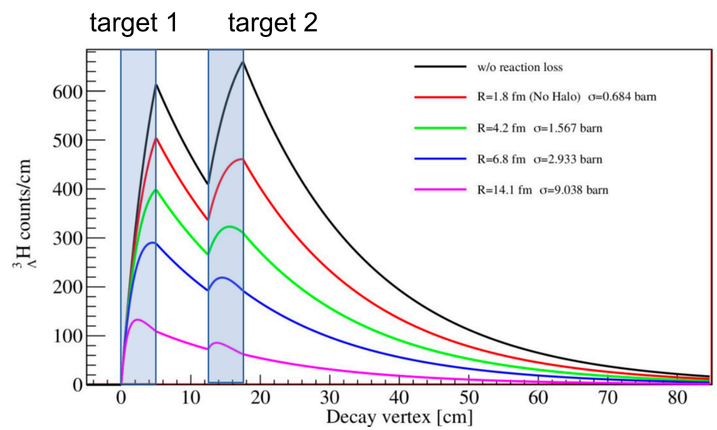
Method

- 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	${}^{6}_{\Lambda}$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)	–

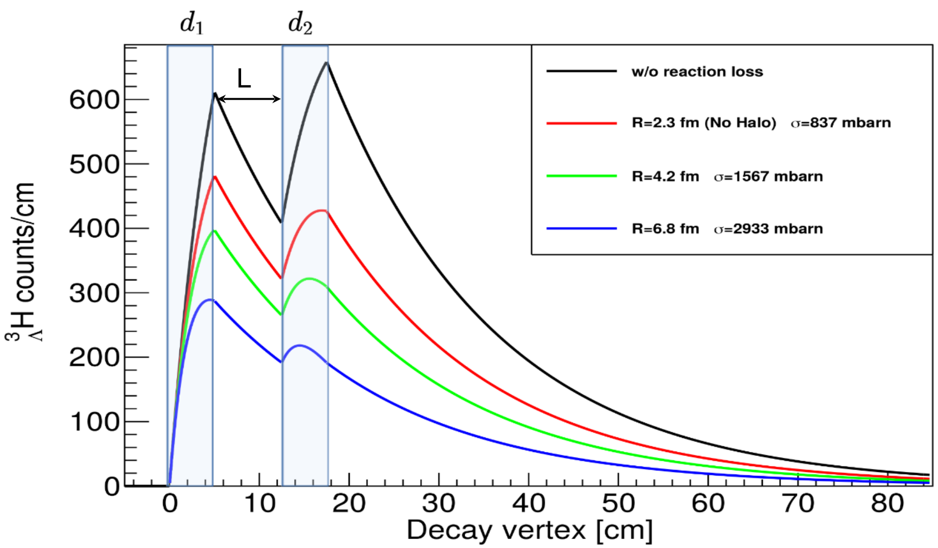
HYDRA LoI, A. Obertelli, Y. L. Sun et al., G-PAC 2020

Sensitivity of measurement

- Analytical model with 3 physical parameters, 2 targets

σ_Λ: hypernucleus production, $\sigma_{\Lambda R}$: hypernucleus interaction, σ_R: beam interaction

$$f(\sigma_{\Lambda R}) = A\,(1 - e^{-B(\sigma_{\Lambda R})d_1})e^{-\left(\frac{L}{\gamma\beta\tau c} + B(\sigma_{\Lambda R})\,d_2\right)} - A\,e^{-B(\sigma_{\Lambda R})d_2} + e^{-B(\sigma_{\Lambda R})d_1} + A - 1 = 0$$



where:

$$A = \frac{N_\Lambda(d_1)\;N_{0,d_2}}{N_\Lambda(d_1 + L + d_2)\;N_{0,d_1}} \cdot e^{-n\sigma_R\,d_2}$$

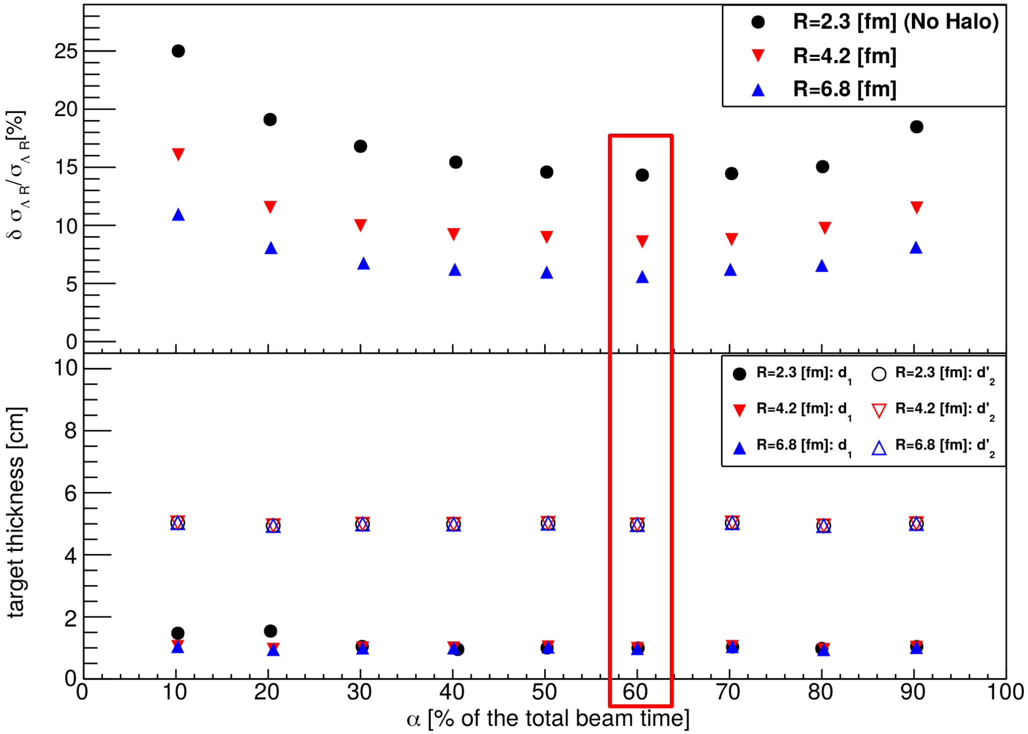
$$B(\sigma_{\Lambda R}) = n\sigma_{\Lambda R} + \frac{1}{\gamma\beta c\tau} - n\sigma_R$$

$$N_{0,d_1} = I \cdot \alpha\, t;$$

$$N_{0,d_2} = I \cdot (1 - \alpha)\, t.$$

S. Velardita et al., in preparation (2022)

Sensitivity of measurement



Proposal (next FAIR G-PAC):

- ^{12}C beam @2GeV/A
- ^{12}C targets max thickness 5 cm
- Total beam time, t=5 days
- Beam intensity, $I=2\cdot10^6$ pps
- Efficiency HYDRA prototype 5%

Radius [fm]	$\sigma_{\Lambda R}$ [mb]	$\delta\sigma_{\Lambda R}/\sigma_{\Lambda R}[\%]$
2.3 (No halo)	837 ± 119	14
4.2	1567 ± 134	9
6.8	2933 ± 175	6

Ongoing realistic simulations to take into account (i) vertex resolution, (ii) feeding from other channels, (iii) realistic efficiency

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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 FAIR G-PAC (2022)
- Future cases: study of the **two-proton halo candidate $^{7}_{\Lambda}$Be, binding energies along C,O isotopic chains**