TECHNISCHE
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Exploring the hypernuclear landscape

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Fondazione Bruno Kessler, ECT*

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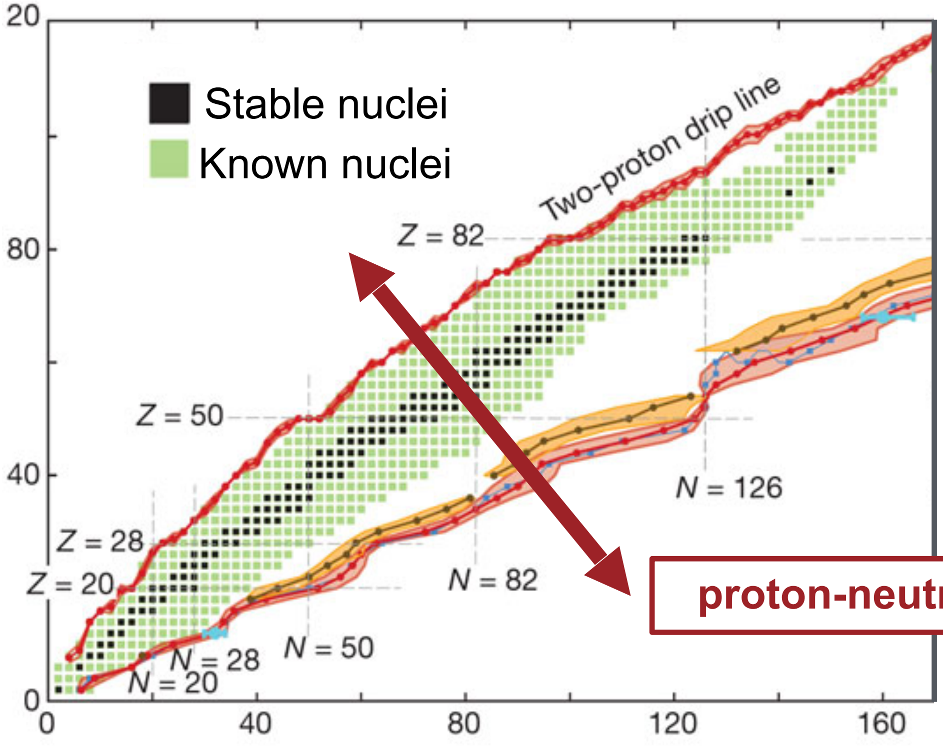
EL EM EN TS

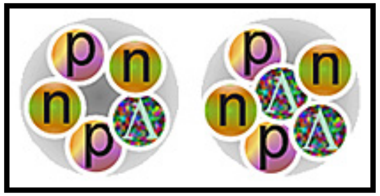
Isospin and strangeness degree of freedom

- Proton-neutron asymmetry: nuclear structure and in-medium forces
- Hypernuclei open the strangeness sector [*e.g.* A. Gal et al., Rev. Mod. Phys. 88 (2016)]
- **Information about single-Λ hypernuclei is difficult to access**



proton-neutron asymmetry

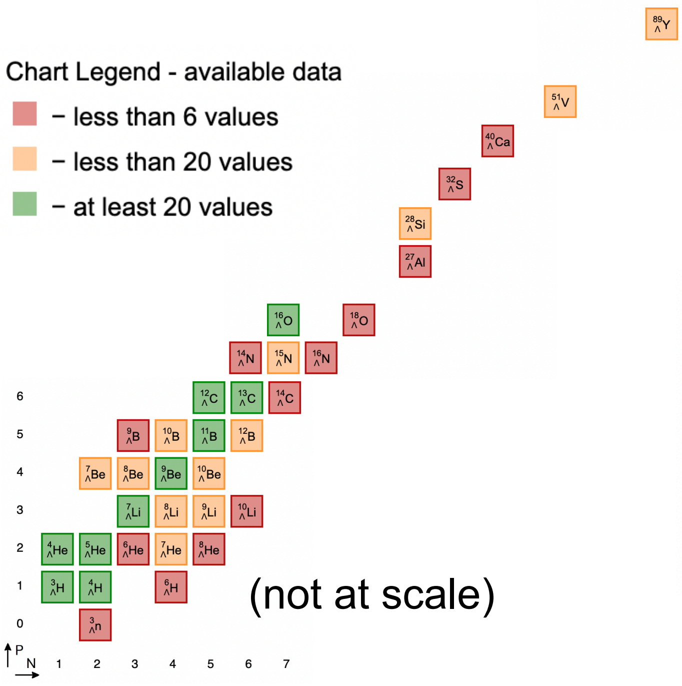
hypernuclei



Λ (usd) lightest hyperon
lifetime 263 ps (weak decay)

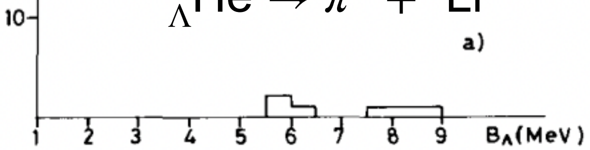
The hypernuclear landscape today

- Only 37 single-Λ hypernuclei known so far, often with scarce information
- https://hypernuclei.kph.uni-mainz.de
- Most recent data from KEK, Jlab, Mainz



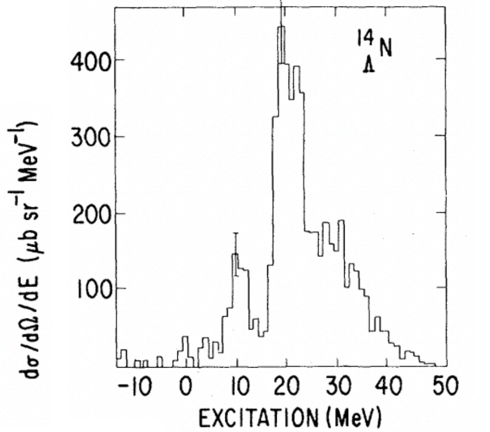
(not at scale)

$$^{8}_{\Lambda}\text{He} \rightarrow \pi^{-} + ^{8}\text{Li}$$



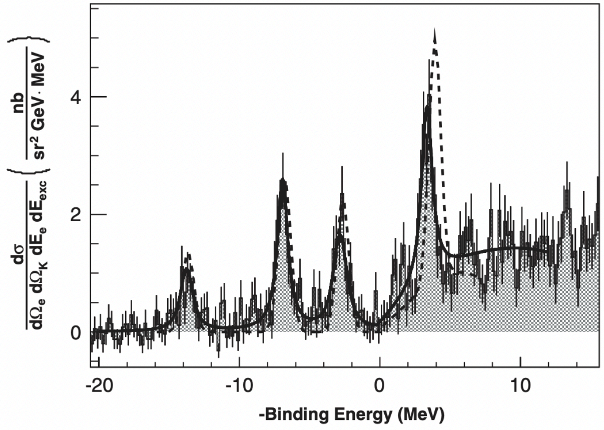
M. Juric et al., NPB 52 (1973)
(K-, emulsion)

$$^{14}\text{N}(K^{-},\pi^{-})^{14}_{\Lambda}\text{N}$$



M. May et al., PRL 47 (1981)
(Brookhaven)

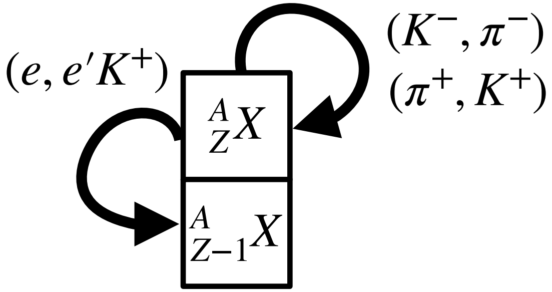
$$^{16}\text{O}(e,e'K^{+})^{16}_{\Lambda}\text{N}$$

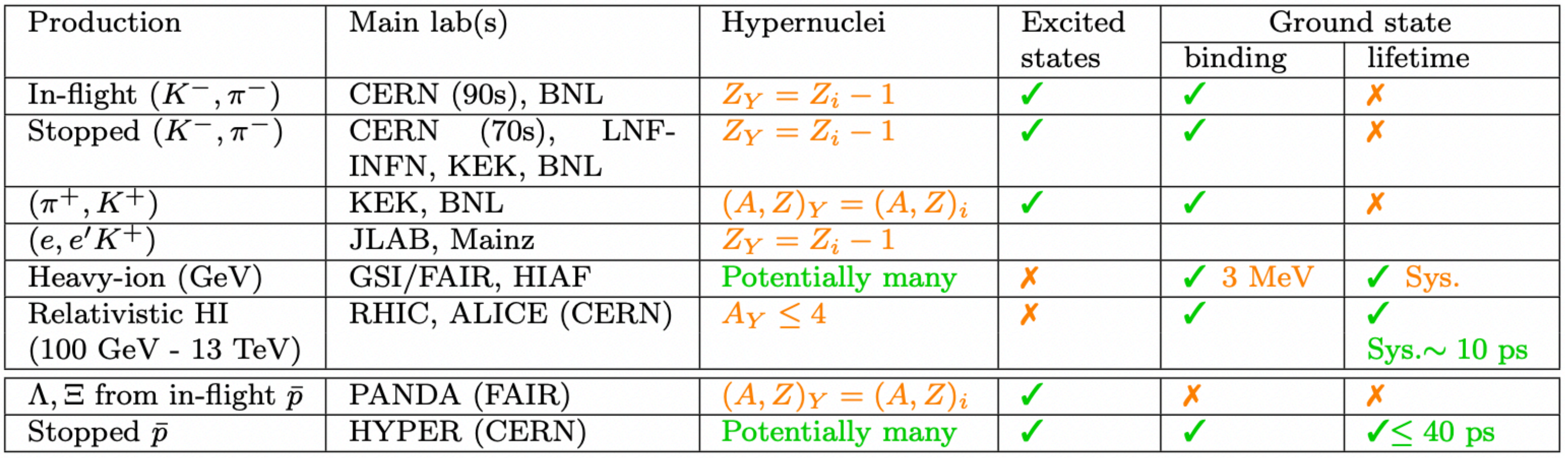


JLab Hall A, PRL 103 (2009)

Production methods and limitations

- **Challenges**: low production rates, short lifetime (200 ps)
- Missing mass and pion spectroscopy restricted to few hypernuclei
- Ultra-relativistic heavy-ion collision cannot reach more than A=4-5





Production	Main lab(s)	Hypernuclei	Excited states	Ground state	
				binding	lifetime
In-flight (K^-, π^-)	CERN (90s), BNL	$Z_Y = Z_i - 1$	✓	✓	✗
Stopped (K^-, π^-)	CERN (70s), LNF-INFN, KEK, BNL	$Z_Y = Z_i - 1$	✓	✓	✗
(π^+, K^+)	KEK, BNL	$(A, Z)_Y = (A, Z)_i$	✓	✓	✗
$(e, e'K^+)$	JLAB, Mainz	$Z_Y = Z_i - 1$			
Heavy-ion (GeV)	GSI/FAIR, HIAF	Potentially many	✗	✓ 3 MeV	✓ Sys.
Relativistic HI (100 GeV - 13 TeV)	RHIC, ALICE (CERN)	$A_Y \leq 4$	✗	✓	✓ Sys.$\sim$ 10 ps
Λ, Ξ from in-flight $\bar{p}$	PANDA (FAIR)	$(A, Z)_Y = (A, Z)_i$	✓	✗	✗
Stopped $\bar{p}$	HYPER (CERN)	Potentially many	✓	✓	✓$\leq$ 40 ps

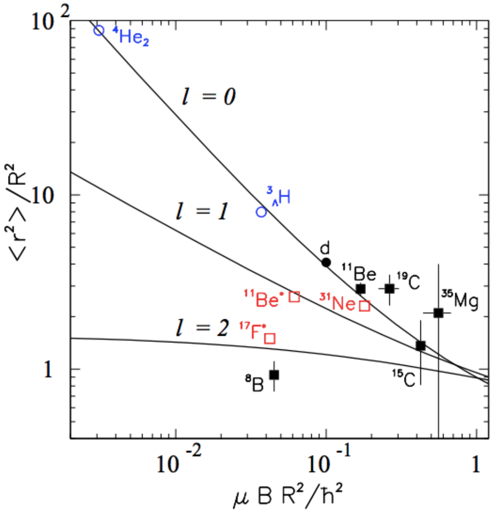
This talk focuses on the potential of **heavy-ion collisions** and **antiproton capture** to produce neutron-rich and neutron-defficient hypernuclei

Hypernuclear halos

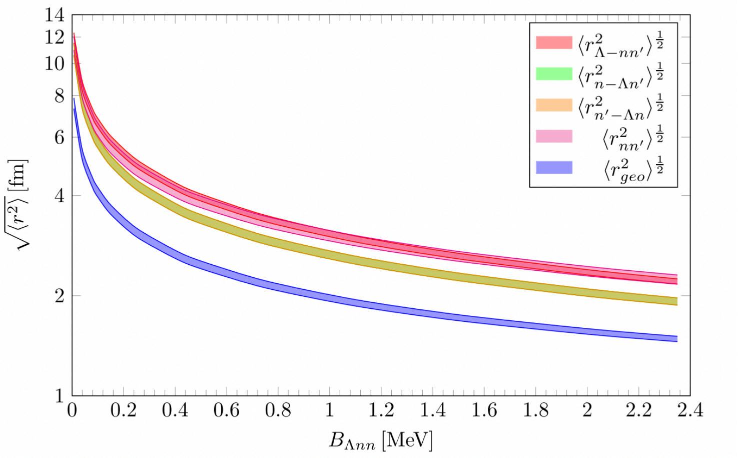
- Universality of halos: several loosely bound hypernuclei are candidates
- $\Lambda - d$ rms distance in **hypertriton** (${}^{3}_{\Lambda}$H) predicted at 10.8 fm

  F. Hildenbrand, H.-W. Hammer, PRC 100 (2019)
- ${}^{7}_{\Lambda}$**Be** is a candidate for a two-proton halo

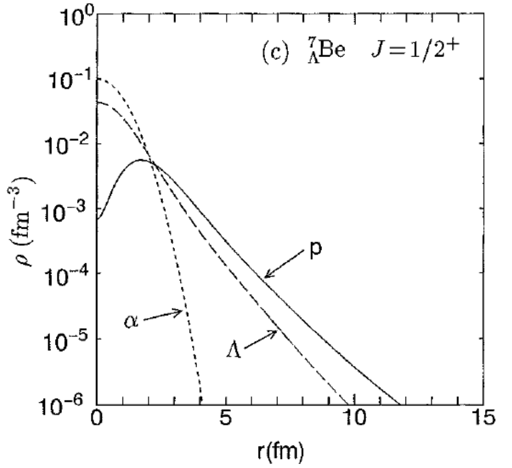
K. Riisager, Phys. Scr. T 152 (2012)



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

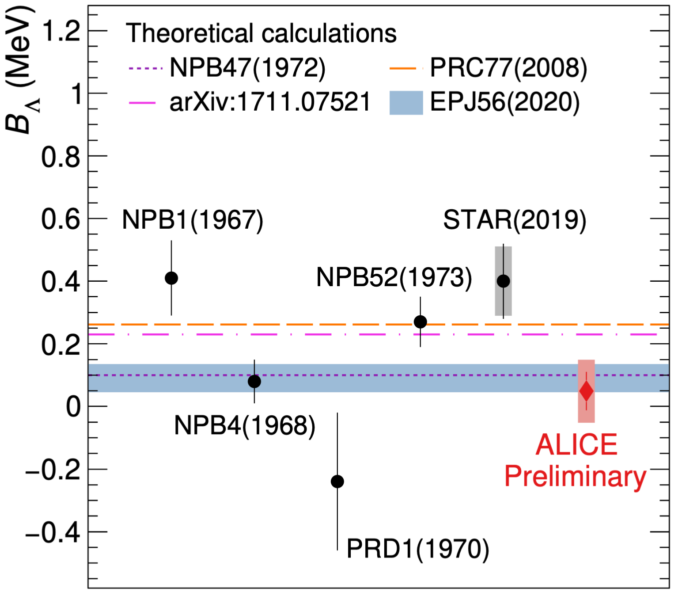


E. Hiyama et al., PRC 53 (1996)

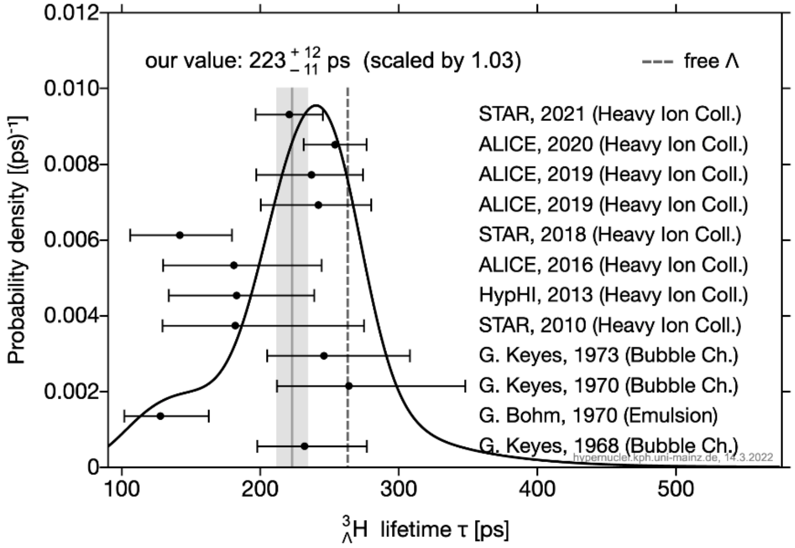


The hypertriton puzzle in a nutshell

- Low binding energy (average 2022: 162(44) 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
  Average 2022: 223(12) ps lower than free Λ lifetime (263 ps)



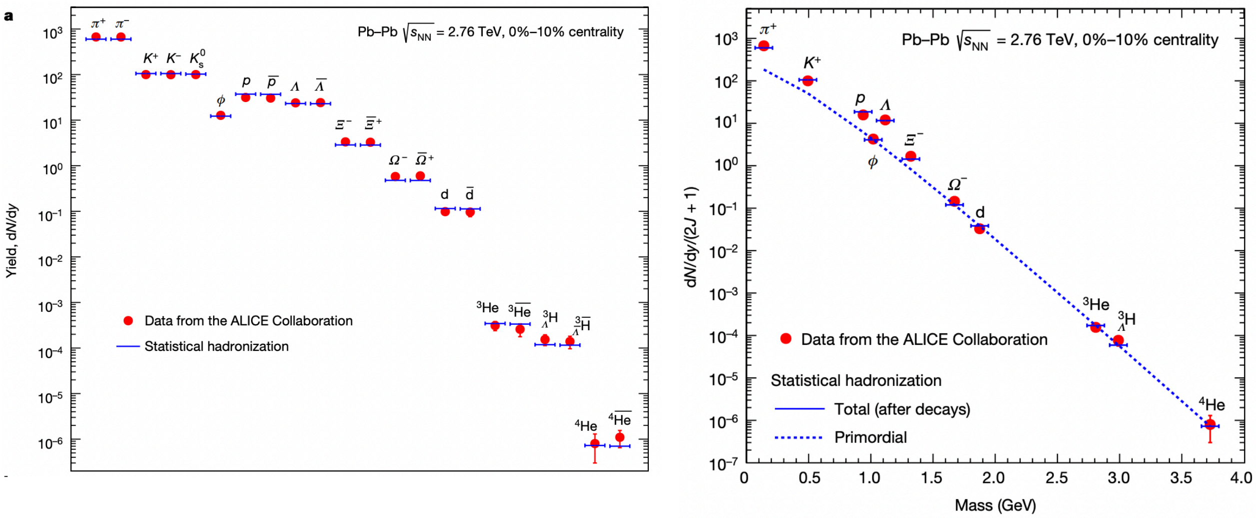
B. Dönigus, EPJA 56 (2020)



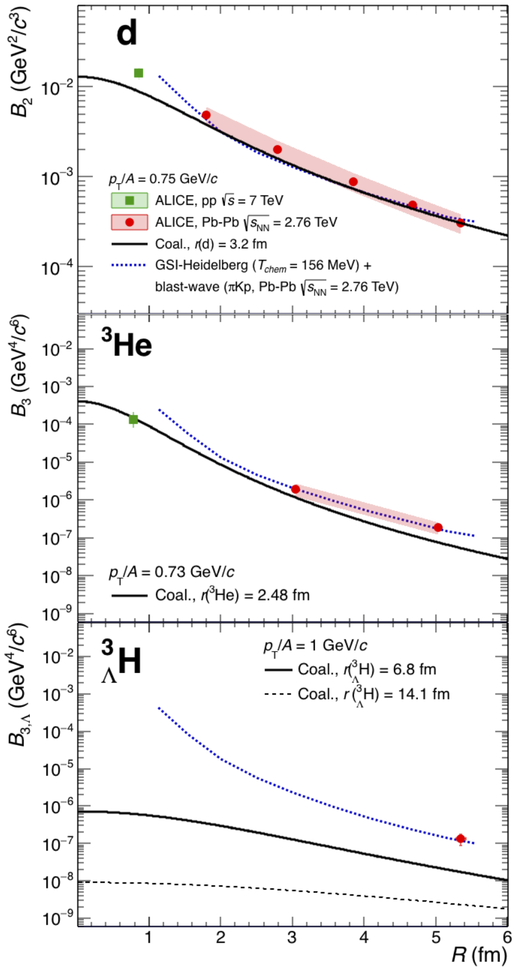
Mainz's database: https://hypernuclei.kph.uni-mainz.de/

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

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 one of the models**

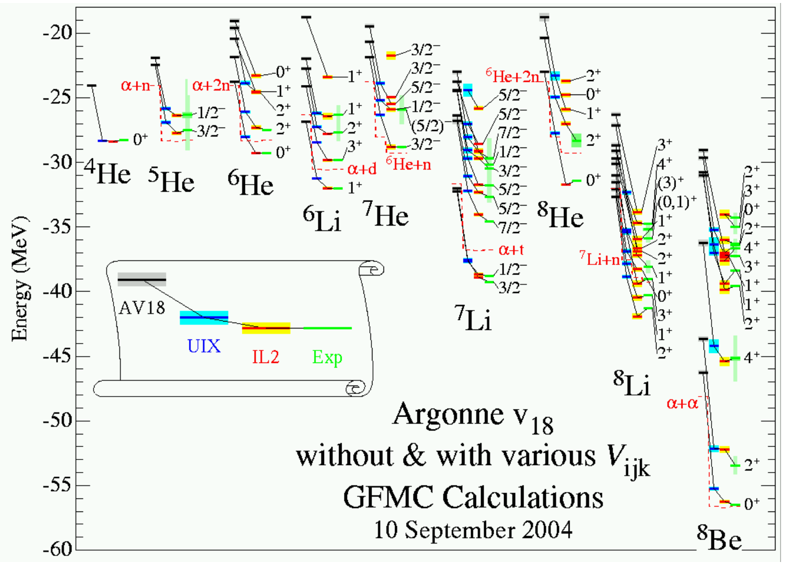
  F. Bellini et al., PRC 103 (2021), ALICE-PUBLIC-2020-005
- **Size of $^{3}_{\Lambda}$H** is central for coalescence predictions
- Recent p-Pb work favors coalescence assuming a halo

  arXiv:2107.10627, accepted in PRL (2022)

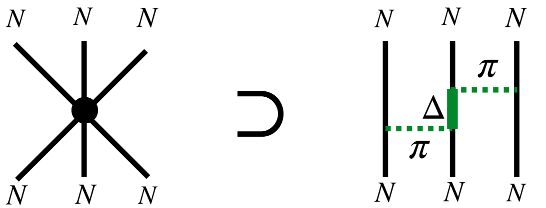
Three-body forces and nuclear structure

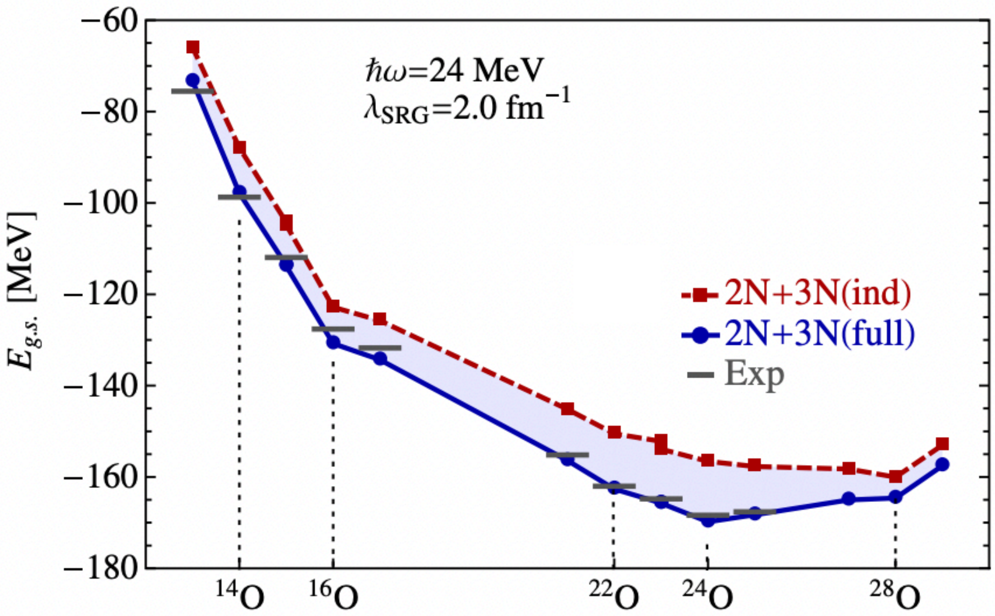
Nuclei

(first nucleonic excited state: +300 MeV)



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





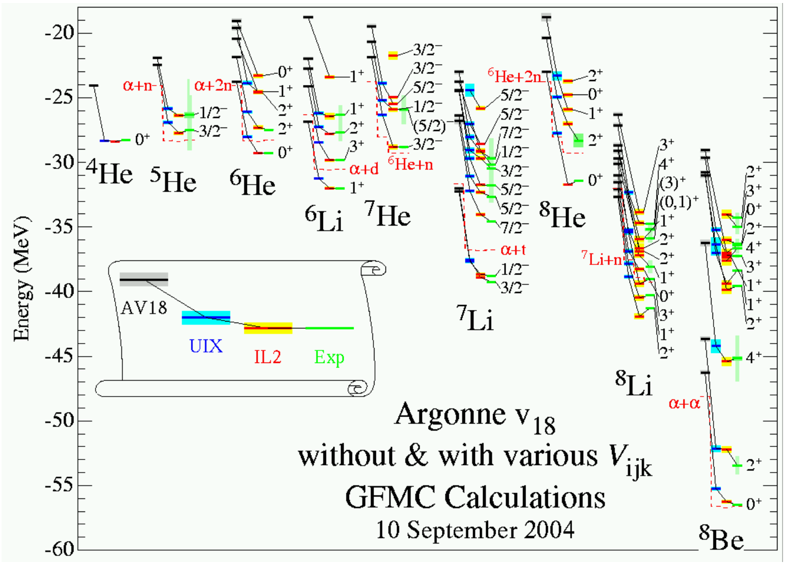
A. Cipollone, C. Barbieri, P. Navratil, PRL 111 (2013)

The first excited state of the Λ hyperon is 70 MeV (to be compared to 300 MeV for N)

Ab initio description of light (hyper)nuclei

Nuclei

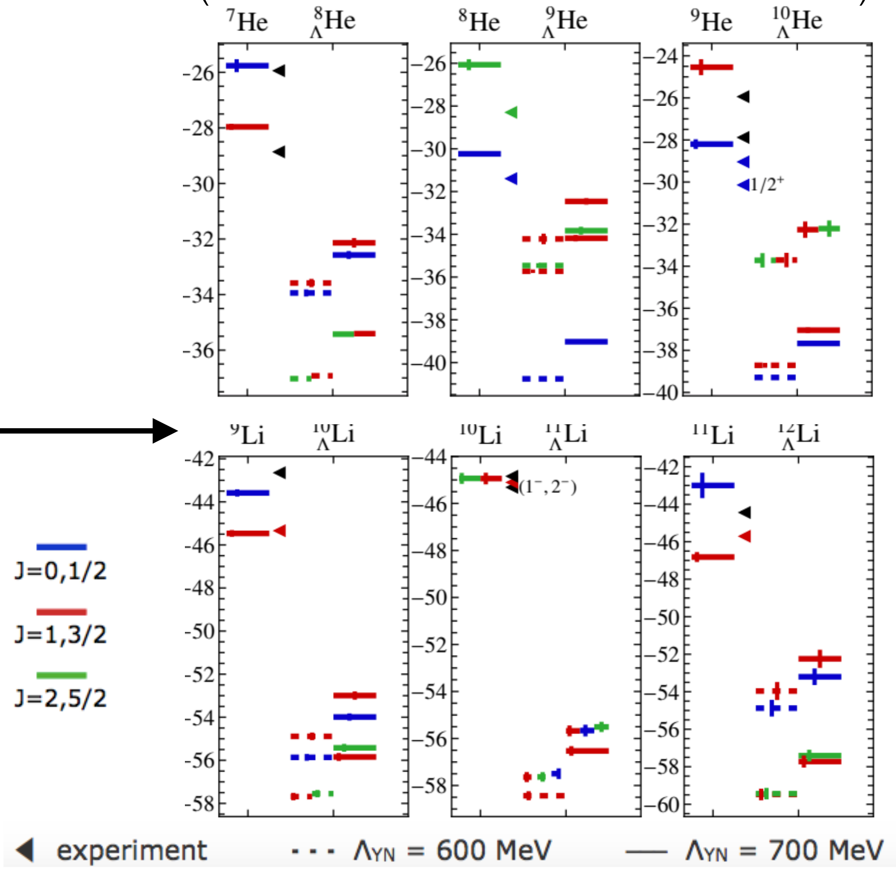
(first nucleonic excited state: +300 MeV)



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

Hypernuclei

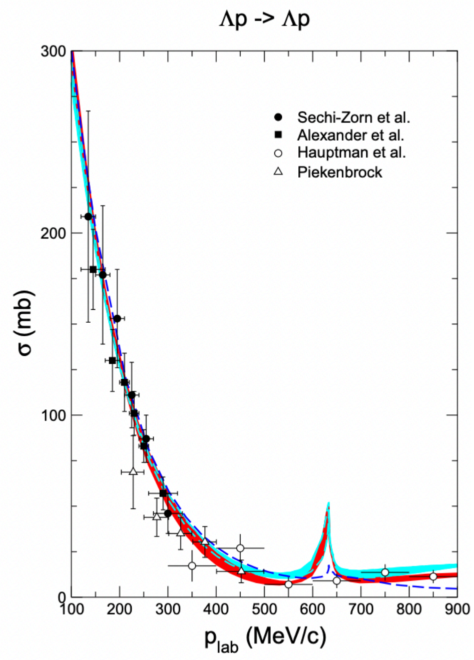
(first excited state of Lambda: +70 MeV)

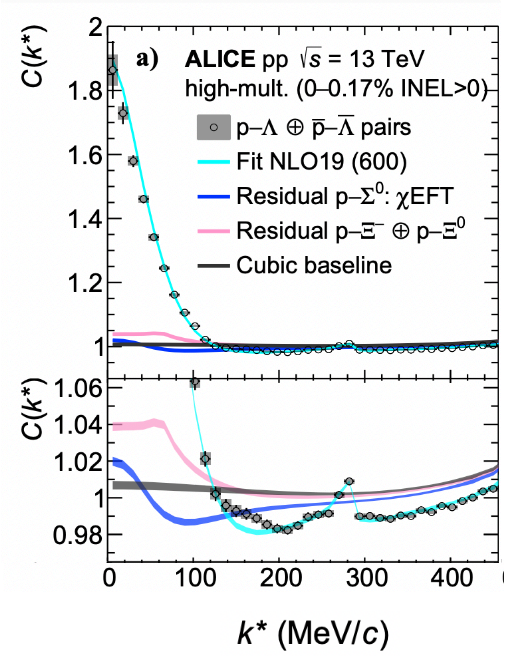


NCSM with explicit Λ excitation: R. Wirth, R. Roth, PLB 779 (2018)

YN and YNN forces

- Direct $\Lambda - p$ scattering : 27 data points only
- Femtoscopy and relativistic *pp* collisions : new laboratory for YN and YY interactions
- Hypernuclei data necessary to pin-down in-medium and many-body forces
- YN and YNN relevant to neutron star and EOS at several ρ_0





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

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

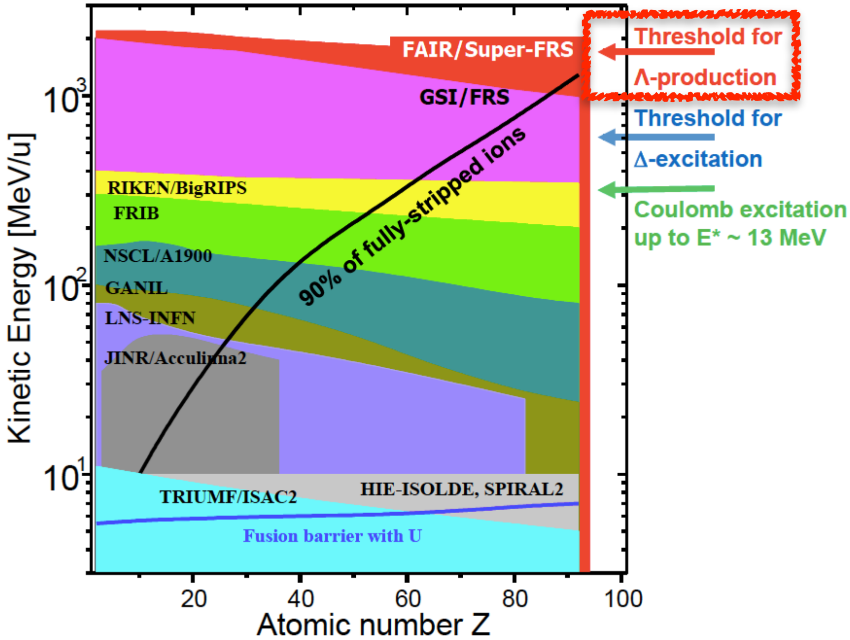
Producing exotic hypernuclei

- **Heavy-ion collision at GeV energies**

  $Np \rightarrow N\Lambda + K^+$: production threshold at 1.6 GeV

  $p\pi^- \rightarrow \Lambda + K^+$: production threshold at 0.76 GeV

- **Antiproton - nucleon annihilation**: ~3% branching ratio of kaon production

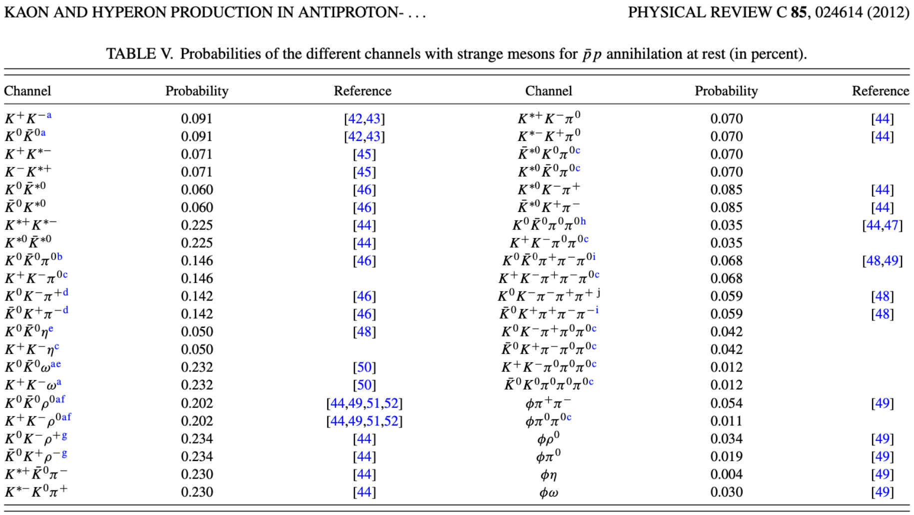


Threshold for Λ-production

Threshold for Δ-excitation

Coulomb excitation up to E* ~ 13 MeV

Strangeness production in $p\bar{p}$ annihilations at rest



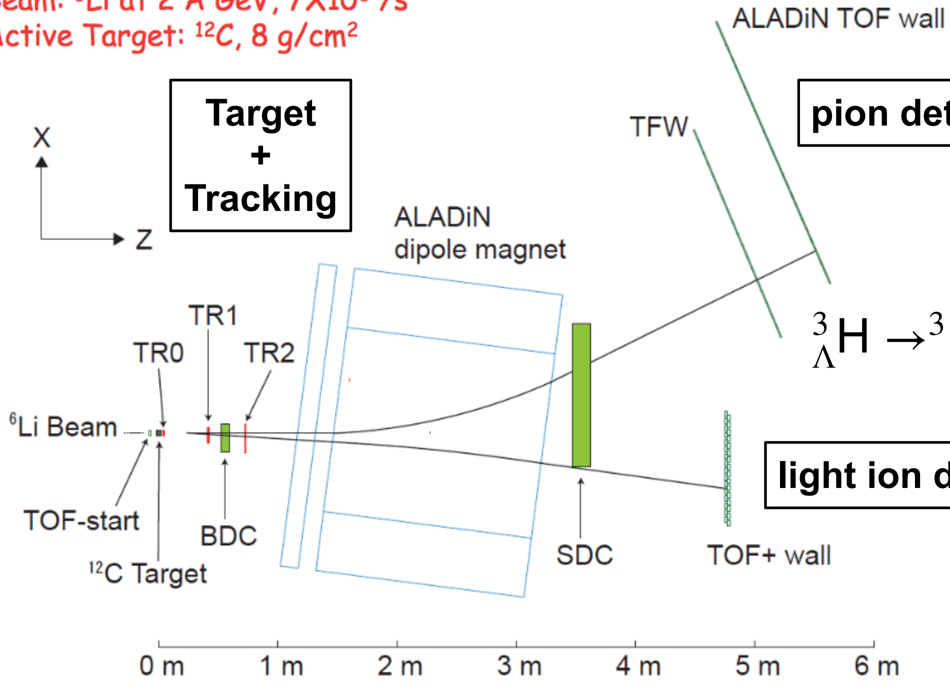
KAON AND HYPERON PRODUCTION IN ANTIPROTON- . . . PHYSICAL REVIEW C **85**, 024614 (2012)

TABLE V. Probabilities of the different channels with strange mesons for $\bar{p}p$ annihilation at rest (in percent).

Channel	Probability	Reference	Channel	Probability	Reference
K^+K^-[a]	0.091	[42,43]	$K^{*+}K^-\pi^0$	0.070	[44]
$K^0\bar{K}^0$[a]	0.091	[42,43]	$K^{*-}K^+\pi^0$	0.070	[44]
K^+K^{*-}	0.071	[45]	$\bar{K}^{*0}K^0\pi^0$[c]	0.070	
K^-K^{*+}	0.071	[45]	$K^{*0}\bar{K}^0\pi^0$[c]	0.070	
$K^0\bar{K}^{*0}$	0.060	[46]	$K^{*0}K^-\pi^+$	0.085	[44]
$\bar{K}^0K^{*0}$	0.060	[46]	$\bar{K}^{*0}K^+\pi^-$	0.085	[44]
$K^{*+}K^{*-}$	0.225	[44]	$K^0\bar{K}^0\pi^0\pi^0$[h]	0.035	[44,47]
$K^{*0}\bar{K}^{*0}$	0.225	[44]	$K^+K^-\pi^0\pi^0$[c]	0.035	
$K^0\bar{K}^0\pi^0$[b]	0.146	[46]	$K^0\bar{K}^0\pi^+\pi^-\pi^0$[i]	0.068	[48,49]
$K^+K^-\pi^0$[c]	0.146		$K^+K^-\pi^+\pi^-\pi^0$[c]	0.068	
$K^0K^-\pi^+$[d]	0.142	[46]	$K^0K^-\pi^-\pi^+\pi^+$[j]	0.059	[48]
$\bar{K}^0K^+\pi^-$[d]	0.142	[46]	$\bar{K}^0K^+\pi^+\pi^-\pi^-$[i]	0.059	[48]
$K^0\bar{K}^0\eta$[e]	0.050	[48]	$K^0K^-\pi^+\pi^0\pi^0$[c]	0.042	
$K^+K^-\eta$[c]	0.050		$\bar{K}^0K^+\pi^-\pi^0\pi^0$[c]	0.042	
$K^0\bar{K}^0\omega$[ae]	0.232	[50]	$K^+K^-\pi^0\pi^0\pi^0$[c]	0.012	
$K^+K^-\omega$[a]	0.232	[50]	$\bar{K}^0K^0\pi^0\pi^0\pi^0$[c]	0.012	
$K^0\bar{K}^0\rho^0$[af]	0.202	[44,49,51,52]	$\phi\pi^+\pi^-$	0.054	[49]
$K^+K^-\rho^0$[af]	0.202	[44,49,51,52]	$\phi\pi^0\pi^0$[c]	0.011	
$K^0K^-\rho^+$[g]	0.234	[44]	$\phi\rho^0$	0.034	[49]
$\bar{K}^0K^+\rho^-$[g]	0.234	[44]	$\phi\pi^0$	0.019	[49]
$K^{*+}\bar{K}^0\pi^-$	0.230	[44]	$\phi\eta$	0.004	[49]
$K^{*-}K^0\pi^+$	0.230	[44]	$\phi\omega$	0.030	[49]

The HyPHI0 experiment at GSI

Beam: ^{6}Li at 2 A GeV, 7X10^6 /s
Active Target: ^{12}C, 8 g/cm^2

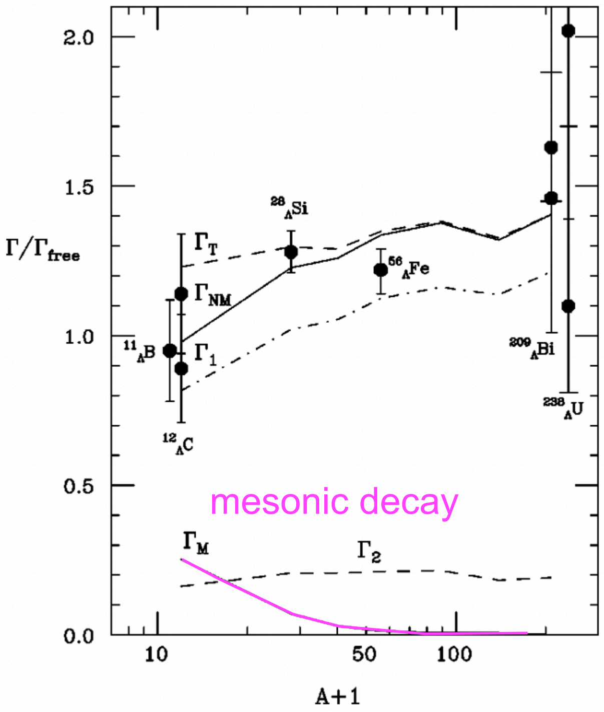


Target
+
Tracking

pion detection

light ion detection

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



From T. Saito (GSI, now RIKEN)

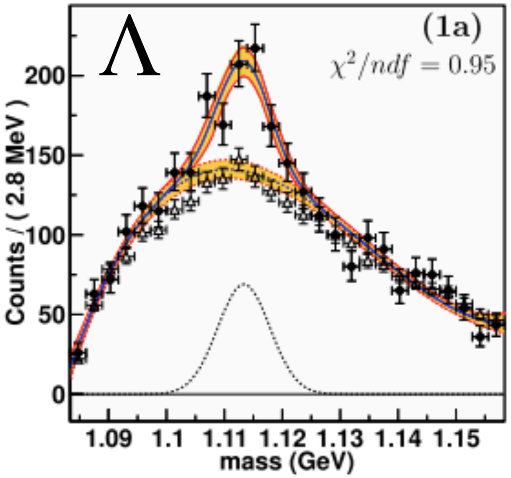
C. Rappold et al., Nucl. Phys. A 913 (2013)

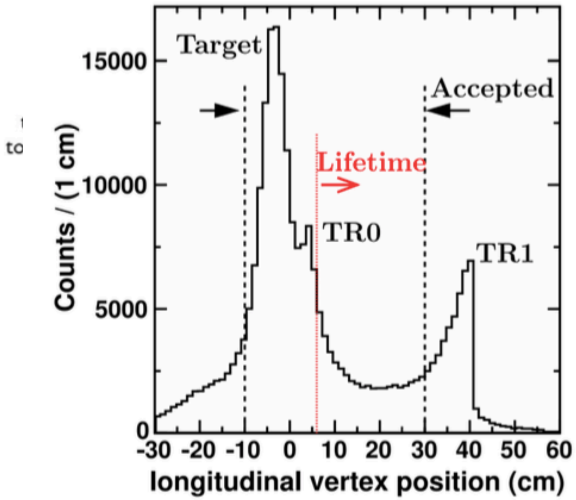
W. M. Alberico et al., PRC 61 (2000)

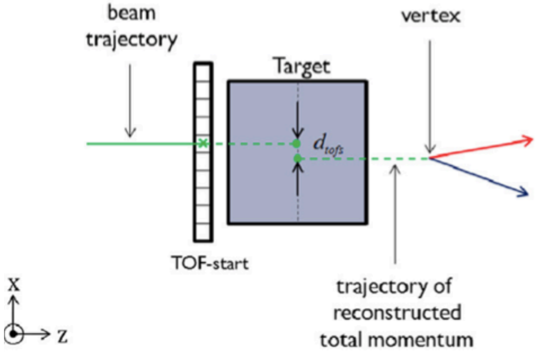
The HyPHI0 experiment at GSI

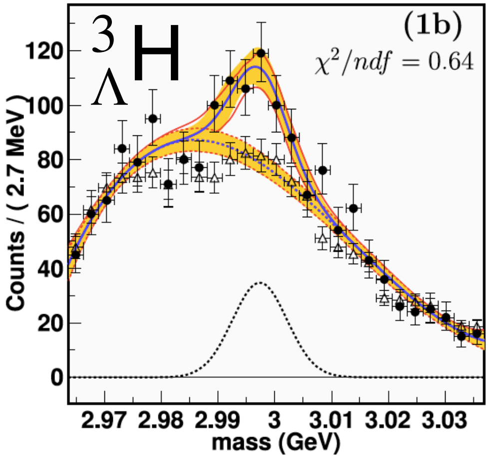
Heavy-ion collisions: ^{6}Li + ^{12}C at 2 GeV/nucleon
1 week of beam time, 7. 10^{6} pps

- Strangeness production ($\sigma(^{3}_{\Lambda}\mathrm{H}) \sim 3.9 \pm 1.4\,\mu$b)
- Invariant mass from weak mesonic decays: $\pi^{-} +$ recoil
- Excellent resolutions required for background rejection









C. Rappold et al., Nucl. Phys. A 913 (2013)

Production of hypernuclei from HI collisions at few GeV / nucleon

- Strangeness production in heavy-ion collisions:

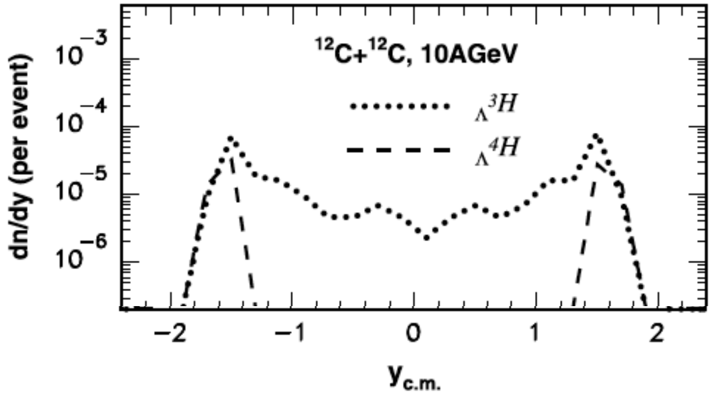
$$p + p \rightarrow p + \Lambda + K^+ \quad (E_{lab} > 1.58\,GeV)$$

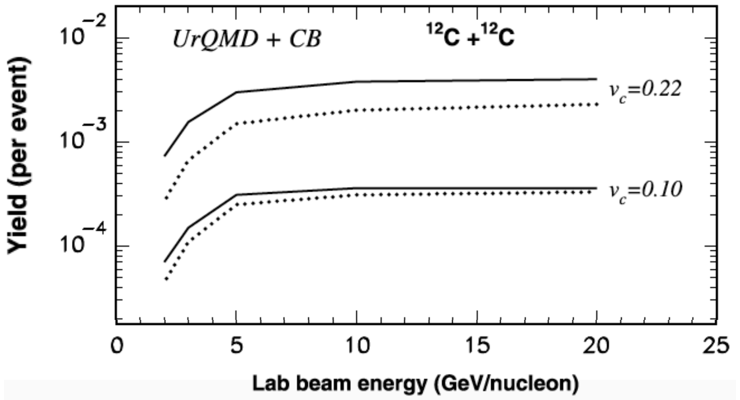
$$\pi^+ + n \rightarrow \Lambda + K^+ \quad (E_{lab} > 0.76\,GeV)$$

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

- Momentum matching leads to small capture probability
- Production saturates from ~5 GeV/nucleon

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

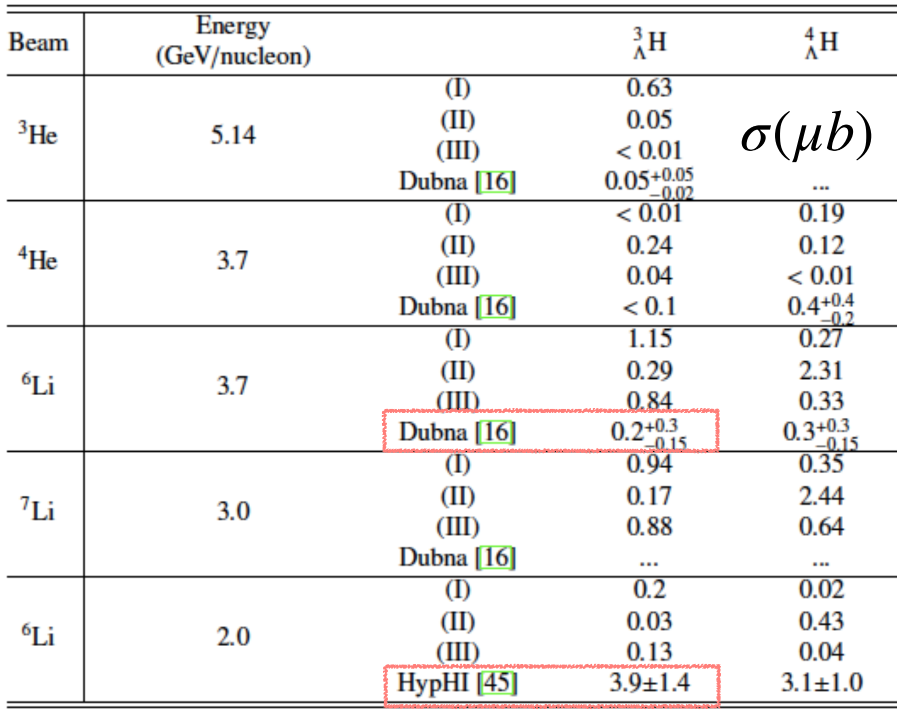




Hyper-residue formation

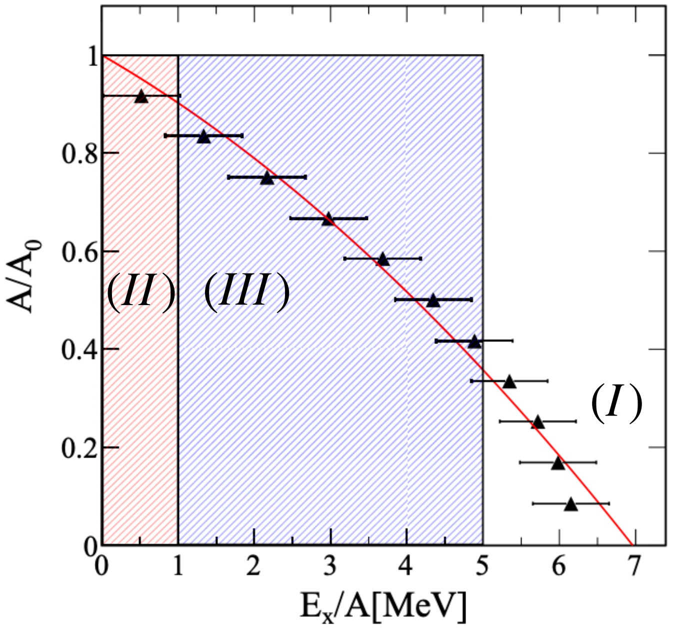
Production cross sections

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



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

Production cross sections

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

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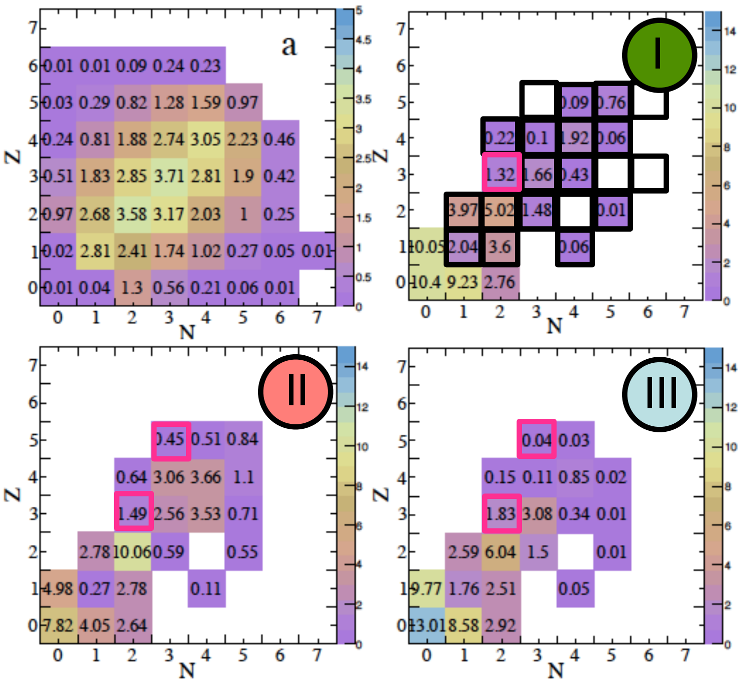
$\sigma(\mu b)$



a

Z \ N	0	1	2	3	4	5	6	7
6	0.01	0.01	0.09	0.24	0.23			
5	0.03	0.29	0.82	1.28	1.59	0.97		
4	0.24	0.81	1.88	2.74	3.05	2.23	0.46	
3	0.51	1.83	2.85	3.71	2.81	1.9	0.42	
2	0.97	2.68	3.58	3.17	2.03	1	0.25	
1	0.02	2.81	2.41	1.74	1.02	0.27	0.05	0.01
0	0.01	0.04	1.3	0.56	0.21	0.06	0.01	

I

Z \ N	0	1	2	3	4	5	6	7
5					0.09	0.76		
4			0.22	0.1	1.92	0.06		
3			1.32	1.66	0.43			
2		3.97	5.02	1.48		0.01		
1	10.05	2.04	3.6		0.06			
0	10.4	9.23	2.76					

II

Z \ N	0	1	2	3	4	5	6	7
5				0.45	0.51	0.84		
4			0.64	3.06	3.66	1.1		
3			1.49	2.56	3.53	0.71		
2		2.78	10.06	0.59		0.55		
1	4.98	0.27	2.78		0.11			
0	7.82	4.05	2.64					

III

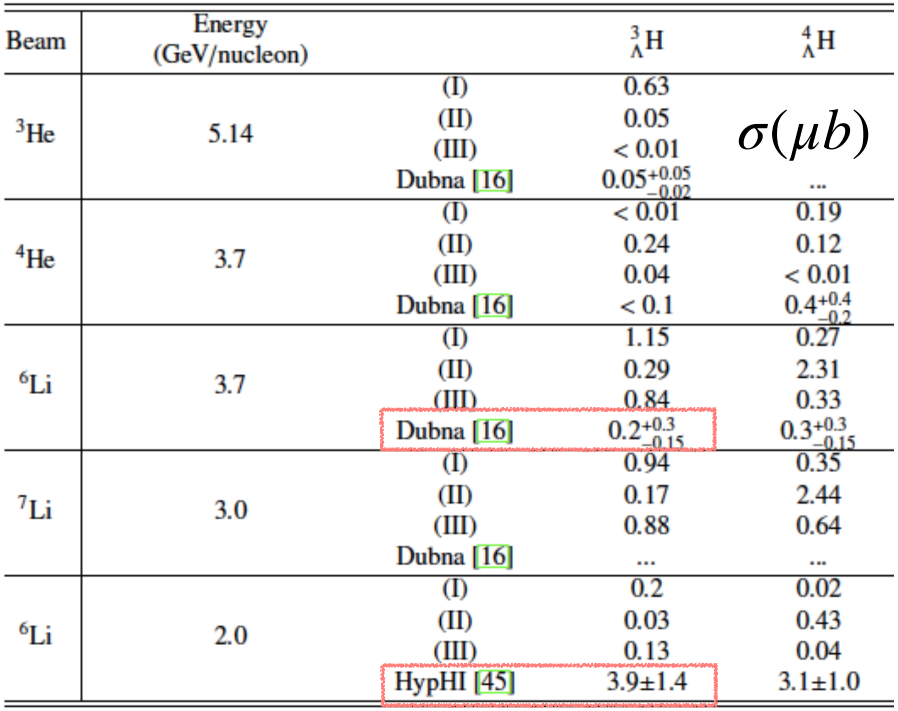
Z \ N	0	1	2	3	4	5	6	7
5				0.04	0.03			
4			0.15	0.11	0.85	0.02		
3			1.83	3.08	0.34	0.01		
2		2.59	6.04	1.5		0.01		
1	9.77	1.76	2.51		0.05			
0	13.01	8.58	2.92					

^{12}C+^{12}C at 2 A GeV

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)

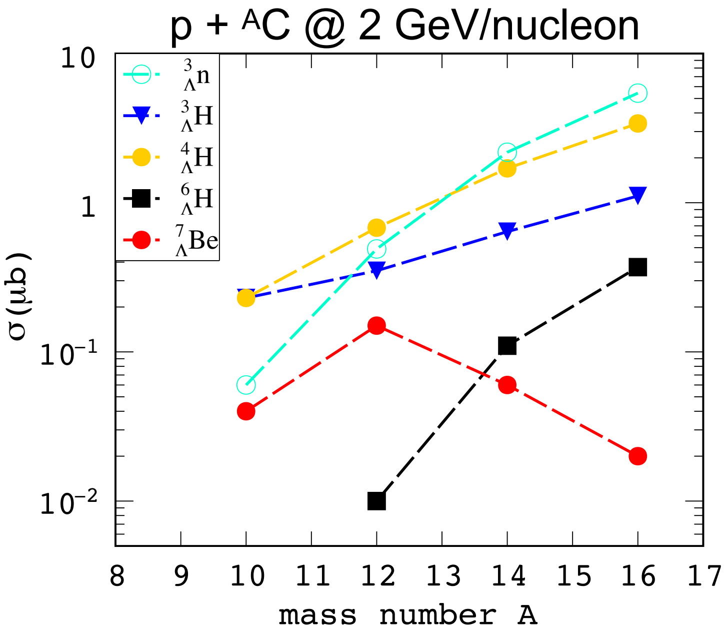
Production cross sections

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

$\sigma(\mu b)$

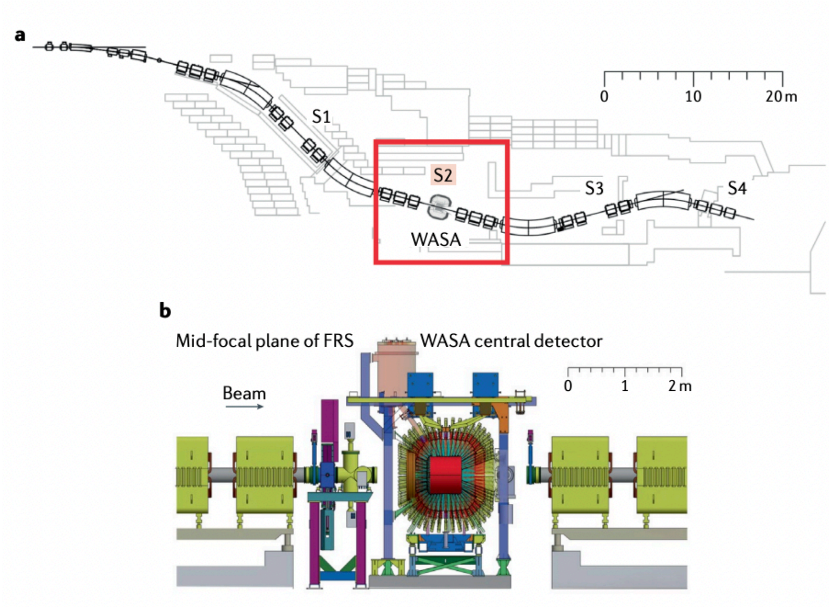


Model predictions: A. S. Botvina *et al.*, PRC 95 (2017); Y. Sun, A. S. Botvina et al., PRC 98 (2018);
See also recent reference: A. S. Botvina *et al.*, PRC 103 (2021)

Hypernuclei programs at GSI/FAIR

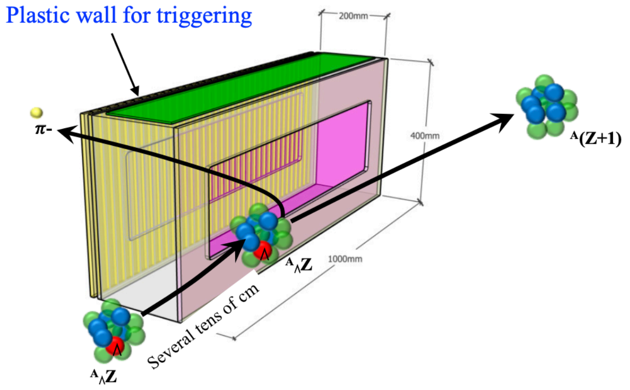
WASA at FRS
- pion tracker in solenoid
- first experiment performed in 2022

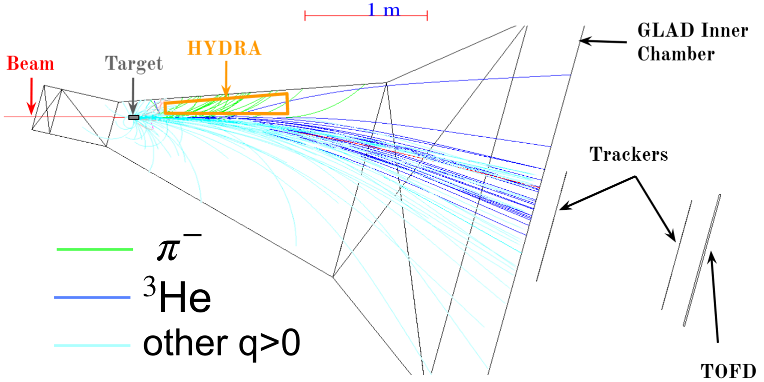
  ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{3}_{\Lambda}n$
- spokesperson: T. Saito, RIKEN



T. R. Saito et al., Nat. Rev. 803 (2021)

HYDRA at R3B
- TPC pion tracker under construction
- first proposal submitted (2022)

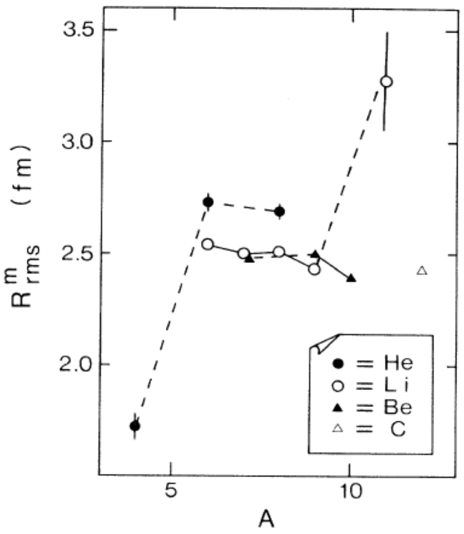




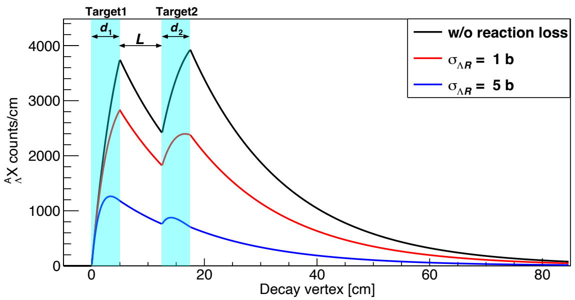
Size of the hyperhalo candidate $^{3}_{\Lambda}$H

Method

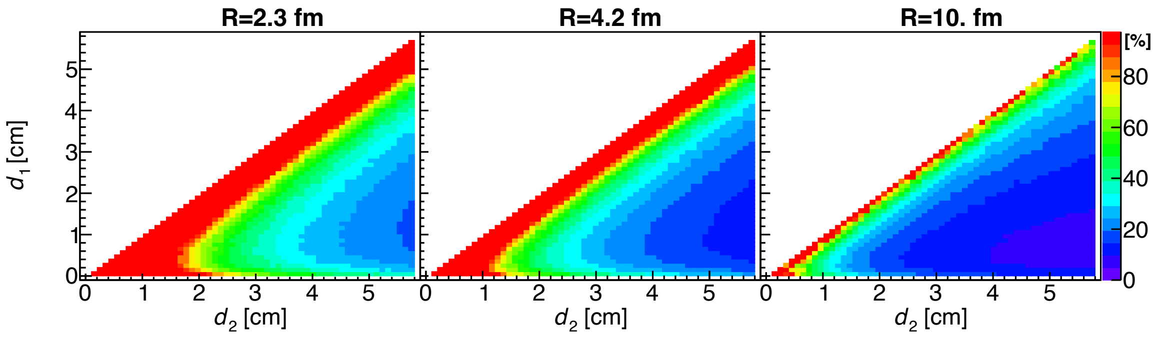
- ^{12}C+^{12}C @ 1.9 GeV/nucleon
- two unknowns (interaction and production cross sections) = two measurements
- hypernucleus **interaction cross section** precision of 15 % to be reached



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



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



The HYDRA team at R3B and collaborators

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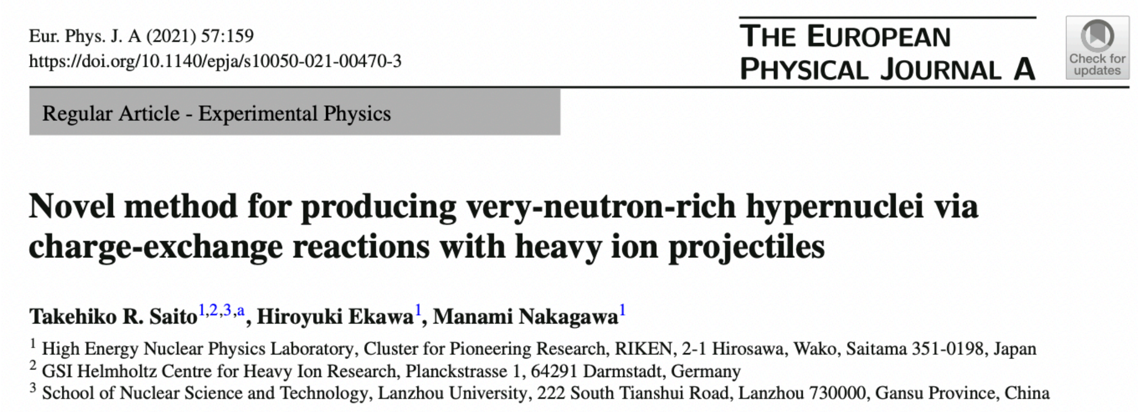
Neutron-rich from double-charge exchange



Eur. Phys. J. A (2021) 57:159
https://doi.org/10.1140/epja/s10050-021-00470-3

THE EUROPEAN
PHYSICAL JOURNAL A

Regular Article - Experimental Physics

Novel method for producing very-neutron-rich hypernuclei via charge-exchange reactions with heavy ion projectiles

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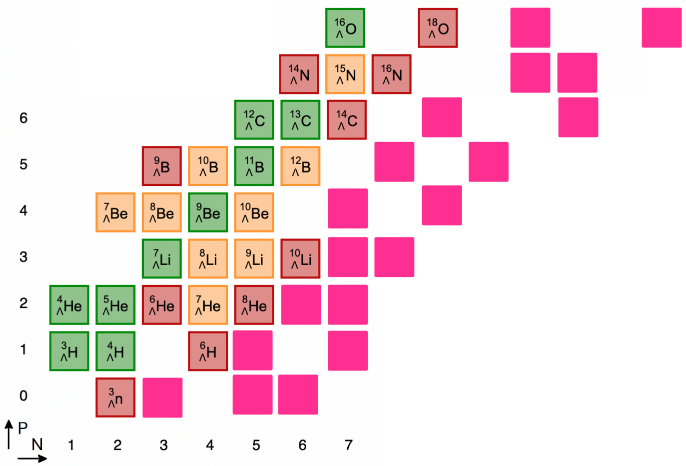
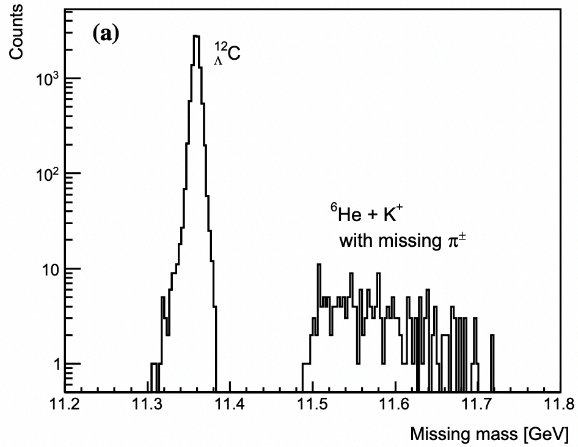


- single and double charge exchange
  $p \rightarrow n, pp \rightarrow nn$ in target-like residue

- simultaneous capture of Λ from $pN \rightarrow \Lambda N + K^+$

- Ex. $^{6}\text{Li} + ^{12}\text{C} \rightarrow ^{6}\text{He} + K^+ + ^{12}_{\Lambda}\text{C}$
  Missing mass from ^{6}He and K detection

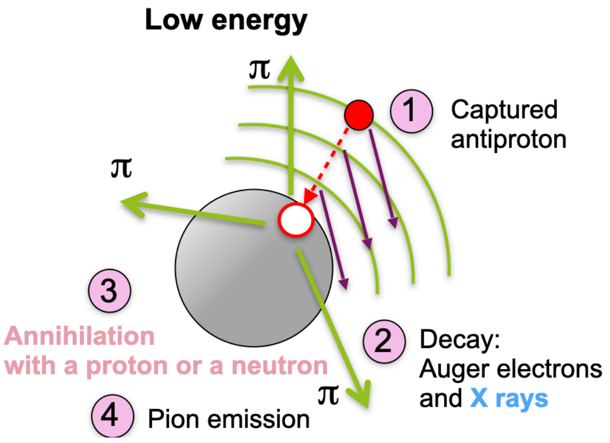
- typical cross sections estimated to 1 nb (UrQMD cal.)

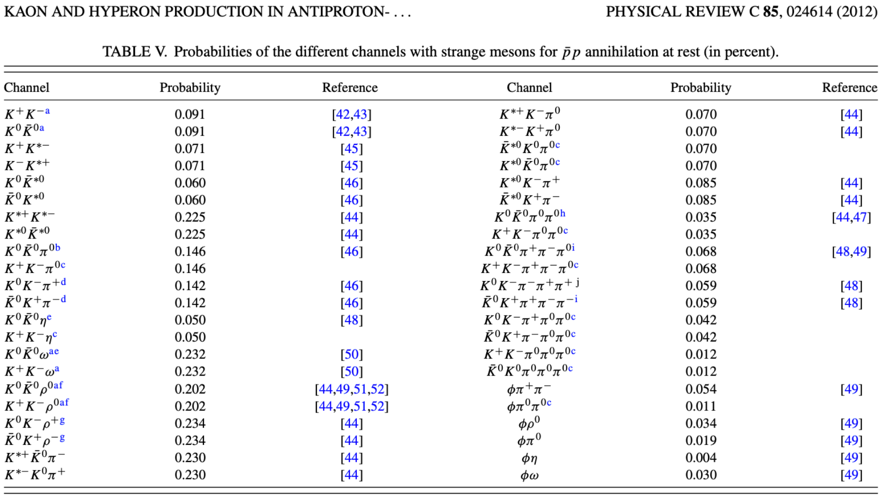


Hypernuclei from low-energy antiprotons

- low-energy antiproton capture forms antiprotonic atoms (100 Mb at ∼100 eV)
- antiproton "decays" towards the nucleus
- antiproton annihilate at the nuclear surface with a proton or a neutron
- most of annihilations (97%) results in the creation of pions
- **3% of annihilations create strangeness (K)**
- $K^-(s\bar{u}) + n \rightarrow \pi^- + \Lambda$, etc... can occur
- If Λ is capture, a hypernucleus is formed

G. T. Condo et al., PRC 29 (1984)





KAON AND HYPERON PRODUCTION IN ANTIPROTON- . . . PHYSICAL REVIEW C **85**, 024614 (2012)

TABLE V. Probabilities of the different channels with strange mesons for $\bar{p}p$ annihilation at rest (in percent).

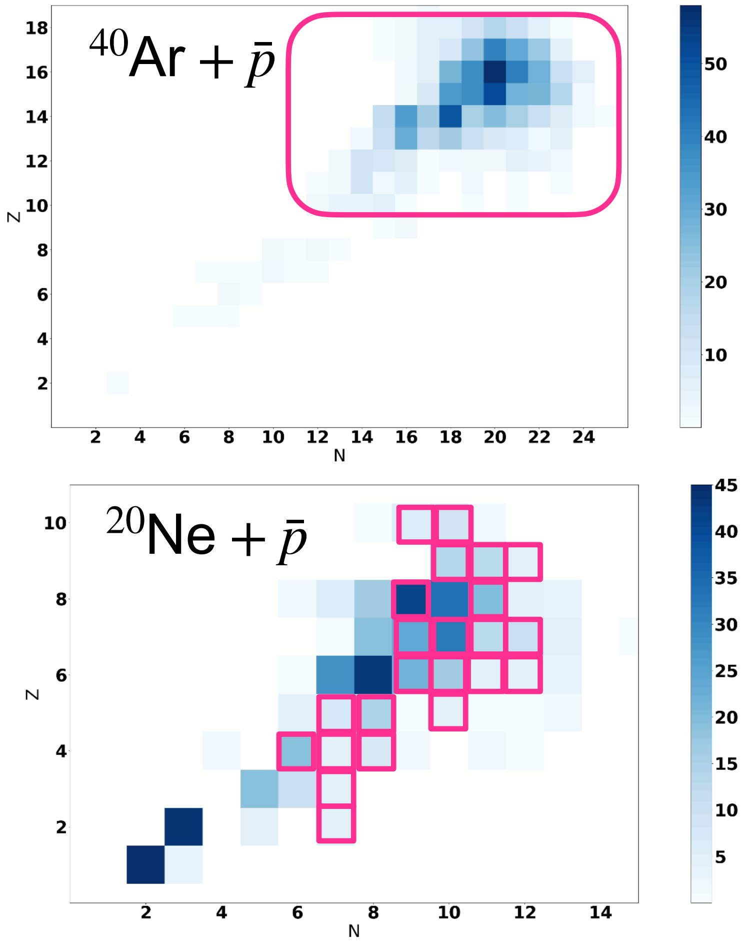
Channel	Probability	Reference	Channel	Probability	Reference
K^+K^-[a]	0.091	[42,43]	$K^{*+}K^-\pi^0$	0.070	[44]
$K^0\bar{K}^0$[a]	0.091	[42,43]	$K^{*-}K^+\pi^0$	0.070	[44]
K^+K^{*-}	0.071	[45]	$\bar{K}^{*0}K^0\pi^0$[c]	0.070	
K^-K^{*+}	0.071	[45]	$K^{*0}\bar{K}^0\pi^0$[c]	0.070	
$K^0\bar{K}^{*0}$	0.060	[46]	$K^{*0}K^-\pi^+$	0.085	[44]
$\bar{K}^0K^{*0}$	0.060	[46]	$\bar{K}^{*0}K^+\pi^-$	0.085	[44]
$K^{*+}K^{*-}$	0.225	[44]	$K^0\bar{K}^0\pi^0\pi^0$[h]	0.035	[44,47]
$K^{*0}\bar{K}^{*0}$	0.225	[44]	$K^+K^-\pi^0\pi^0$[c]	0.035	
$K^0\bar{K}^0\pi^0$[b]	0.146	[46]	$K^0\bar{K}^0\pi^+\pi^-\pi^0$[i]	0.068	[48,49]
$K^+K^-\pi^0$[c]	0.146		$K^+K^-\pi^+\pi^-\pi^0$[c]	0.068	
$K^0K^-\pi^+$[d]	0.142	[46]	$K^0K^-\pi^-\pi^+\pi^+$[j]	0.059	[48]
$\bar{K}^0K^+\pi^-$[d]	0.142	[46]	$\bar{K}^0K^+\pi^+\pi^-\pi^-$[i]	0.059	[48]
$K^0\bar{K}^0\eta$[e]	0.050	[48]	$K^0K^-\pi^+\pi^0\pi^0$[c]	0.042	
$K^+K^-\eta$[c]	0.050		$\bar{K}^0K^+\pi^-\pi^0\pi^0$[c]	0.042	
$K^0\bar{K}^0\omega$[ae]	0.232	[50]	$K^+K^-\pi^0\pi^0\pi^0$[c]	0.012	
$K^+K^-\omega$[a]	0.232	[50]	$\bar{K}^0K^0\pi^0\pi^0\pi^0$[c]	0.012	
$K^0\bar{K}^0\rho^0$[af]	0.202	[44,49,51,52]	$\phi\pi^+\pi^-$	0.054	[49]
$K^+K^-\rho^0$[af]	0.202	[44,49,51,52]	$\phi\pi^0\pi^0$[c]	0.011	
$K^0K^-\rho^+$[g]	0.234	[44]	$\phi\rho^0$	0.034	[49]
$\bar{K}^0K^+\rho^-$[g]	0.234	[44]	$\phi\pi^0$	0.019	[49]
$K^{*+}\bar{K}^0\pi^-$	0.230	[44]	$\phi\eta$	0.004	[49]
$K^{*-}K^0\pi^+$	0.230	[44]	$\phi\omega$	0.030	[49]

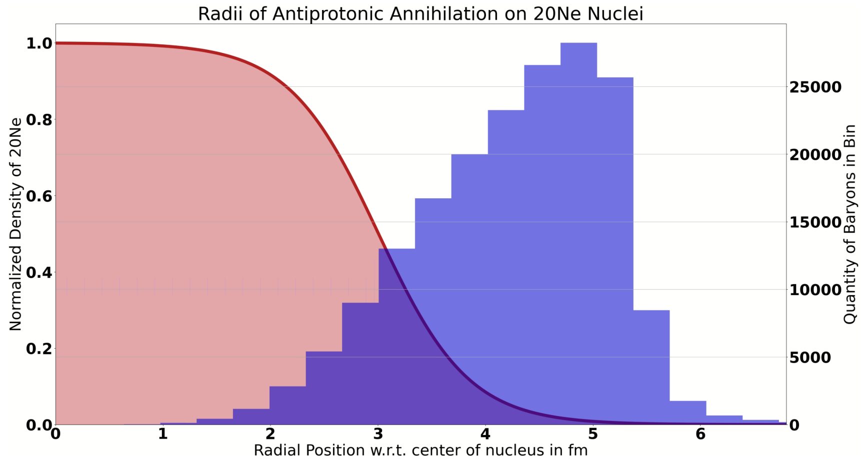
Hypernuclei from low-energy antiprotons: yields

- GiBUU estimates
  O. Buss et al., PR 512 (2012)
- adjusted radial annihilation probability
- realistic annihilation branching ratios
- $K^- + n \rightarrow \pi^- + \Lambda$, ...
- potential criterium for Λ capture
- de-excitation (modified ABLA)
  J. L. Sanchez et al., PRC 105 (2022)

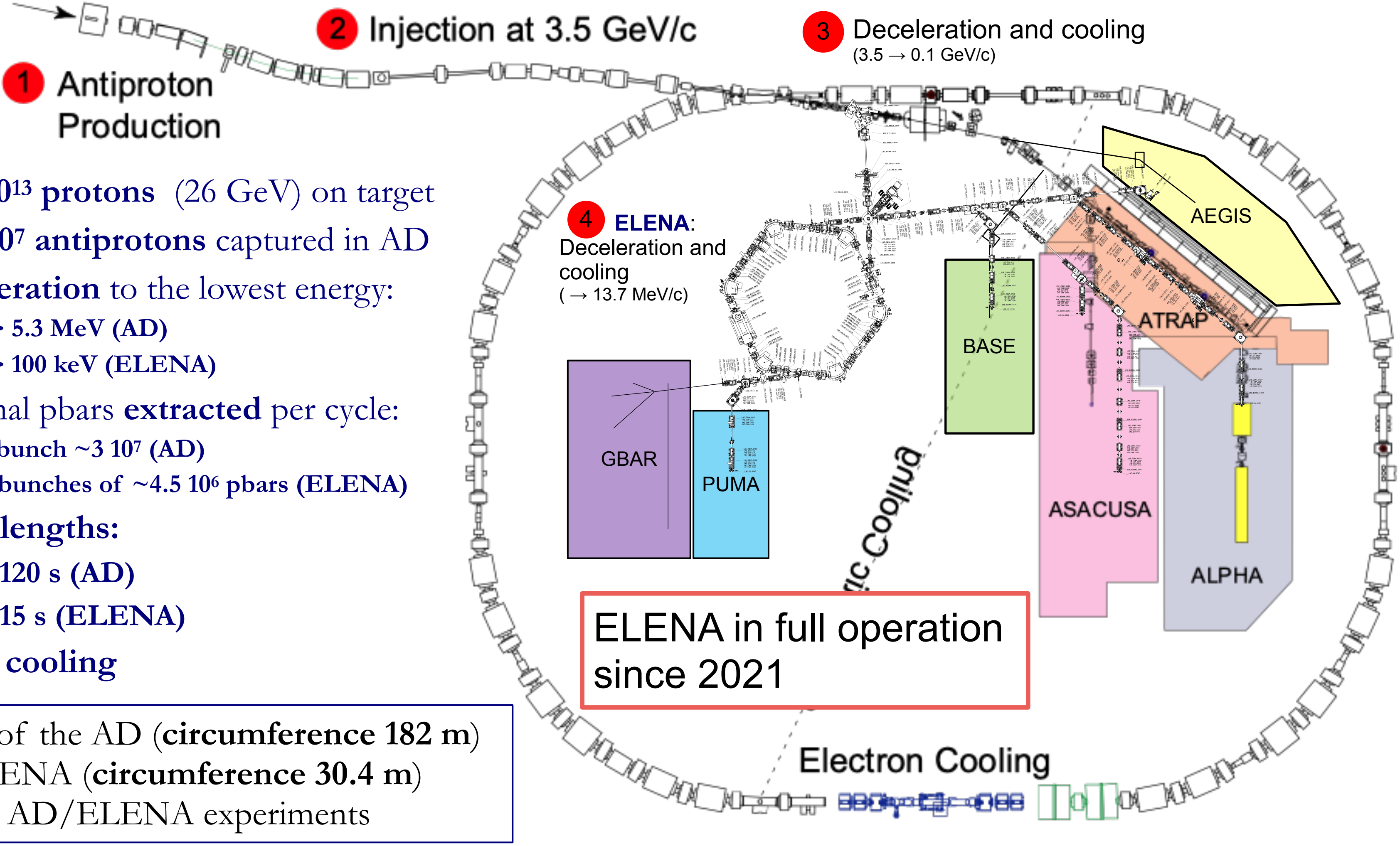
Preliminary work by A. Schmidt, T. Gaitanos, J. L. Sanchez

Hypernuclei yield for 10^6 annihilations





The antimatter factory at CERN



ELENA in full operation since 2021

- **~1.5 10^{13} protons** (26 GeV) on target
- **~3.5 10^{7} antiprotons** captured in AD
- **Deceleration** to the lowest energy:
    - **→ 5.3 MeV (AD)**
    - **→ 100 keV (ELENA)**
- Nominal pbars **extracted** per cycle:
    - **1 bunch ~3 10^{7} (AD)**
    - **4 bunches of ~4.5 10^{6} pbars (ELENA)**
- **Cycle lengths:**
    - **~120 s (AD)**
    - **~15 s (ELENA)**
- **Beam cooling**

Sketch of the AD (**circumference 182 m**)
ELENA (**circumference 30.4 m**)
AD/ELENA experiments

Summary

- The hypernuclei landscape remains rather unexplored
- **Exotic hypernuclei** can be produced from **heavy-ion collisions** and **low-energy antiprotons**

- Programs / projects at **GSI/FAIR, HIAF (China)** and **ELENA, CERN** for ground state properties and spectroscopy for A<50 hypernuclei

Heavy-ion collision

- Production cross sections of $\sim$ **1 μb** at 2 GeV/nucleon
- Current experiments limited to 10^6 - 10^7 pps
- Momentum and vertex resolution essential for S/B reduction (WASA, HYDRA)
- Energy threshold limits possibilities to symmetric and proton-rich nuclei
- Single and double charge exchange reactions ($\sim$ **1 nb**) proposed to produce neutron-rich nuclei

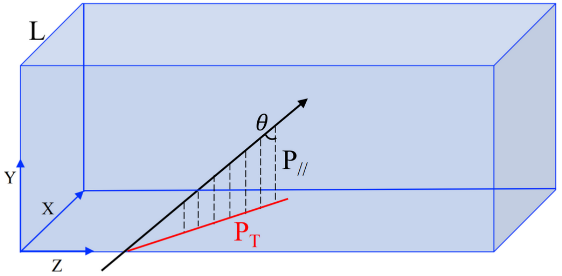
Low energy antiprotons

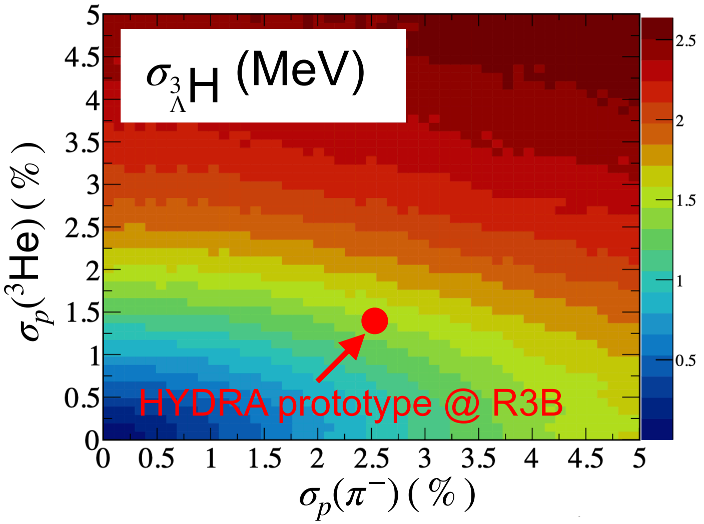
- Yield of hypernuclei estimated to $\sim$ **10^{-3} / annihilation**
- New oportunity to produce neutron-rich hypernuclei at the Antimatter Factory, CERN
- Requires picosecond timing and tracking + particle identification of MeV-recoils

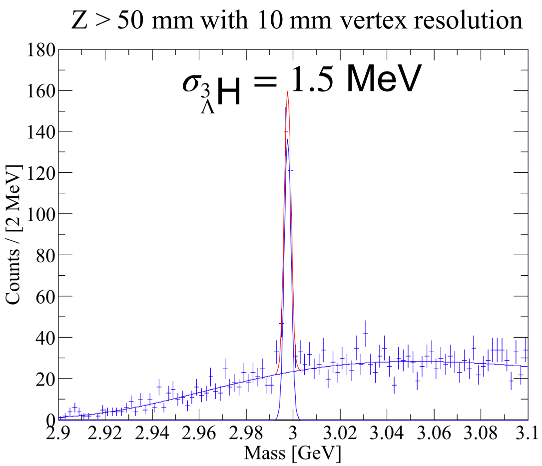
Pion detection and invariant-mass resolution

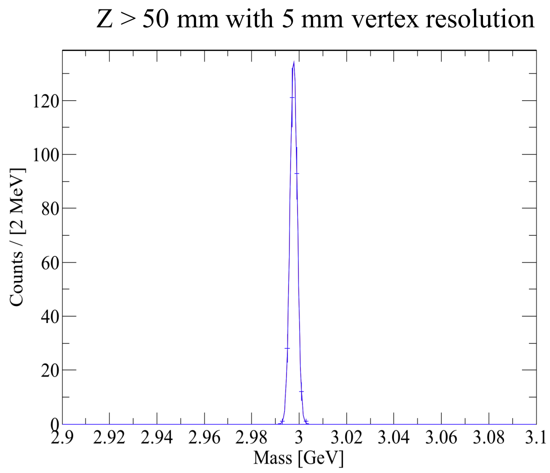
- Targeting an invariant-mass resolution of 1.5 MeV (σ) with low background

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







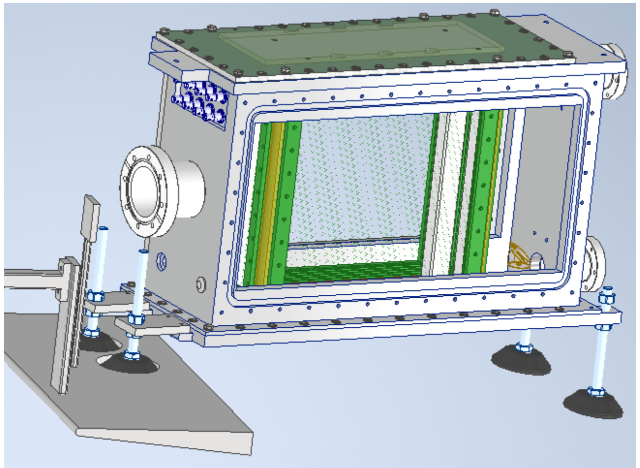


Simulations: Y. Sun and S. Velardita, TUDa

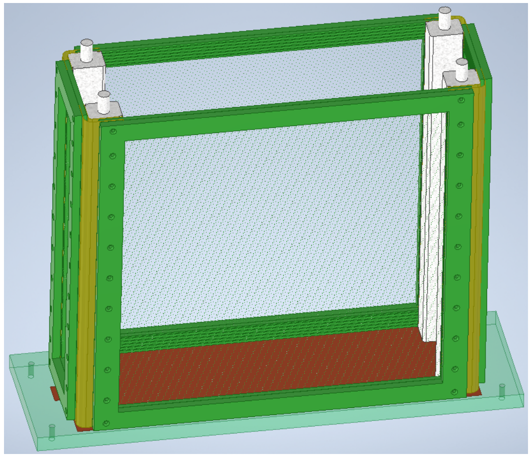
The HYDRA prototype

1/3 HYDRA prototype (29% detection efficiency)

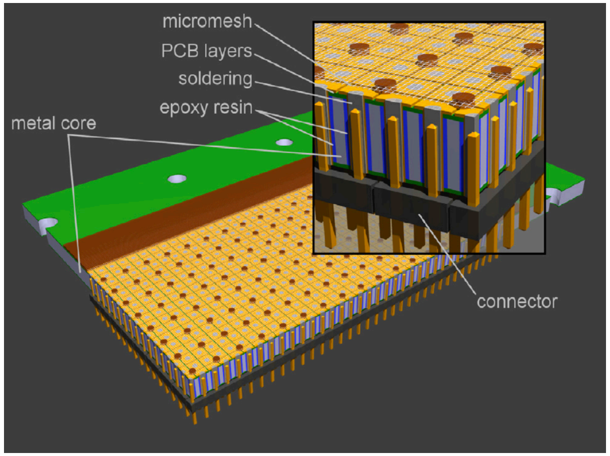
- under completion
- field cage and amplification stages built at CERN
- wiring of field cage at GSI
- laser and in-beam validation in Q3/2022
- continuous readout in operation in Q4/2022
- Full system ready from beginning of 2023



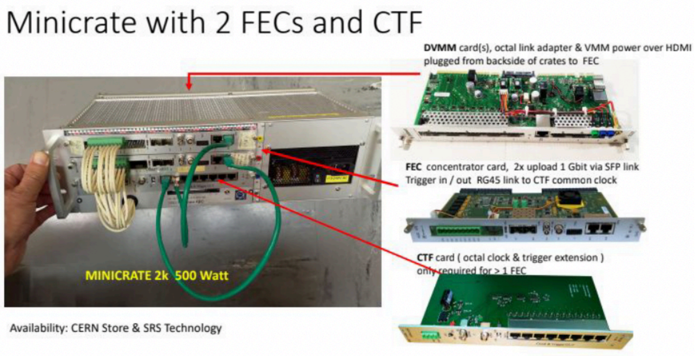
double wire-plane field cage



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



VMM3 chips and SRS readout



Minicrate with 2 FECs and CTF

DVMM card(s), octal link adapter & VMM power over HDMI plugged from backside of crates to FEC

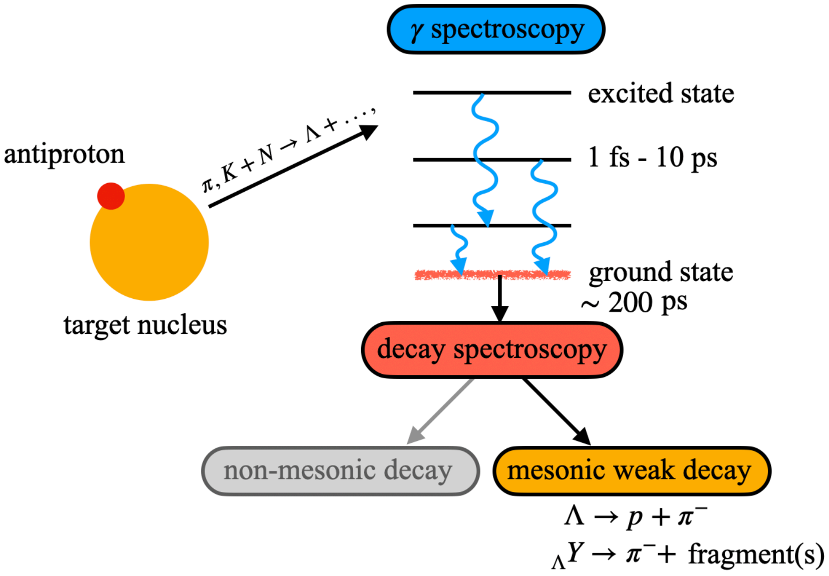
FEC concentrator card, 2x upload 1 Gbit via SFP link Trigger in / out RG45 link to CTF common clock

CTF card (octal clock & trigger extension) only required for > 1 FEC

Availability: CERN Store & SRS Technology

Courtesy L. Ji, TU Darmstadt

Hypernuclei studies at ELENA, CERN



antiproton

$\pi, K + N \to \Lambda + \ldots,$

target nucleus

γ spectroscopy

excited state

1 fs - 10 ps

ground state

$\sim$ 200 ps

decay spectroscopy

non-mesonic decay

mesonic weak decay

$\Lambda \to p + \pi^-$

${}_\Lambda Y \to \pi^- +$ fragment(s)