Future perspective on neutron-rich Hypernuclei

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3rd EMMI workshop: Anti-mater, Hyper-matter and exotic production at the LHC

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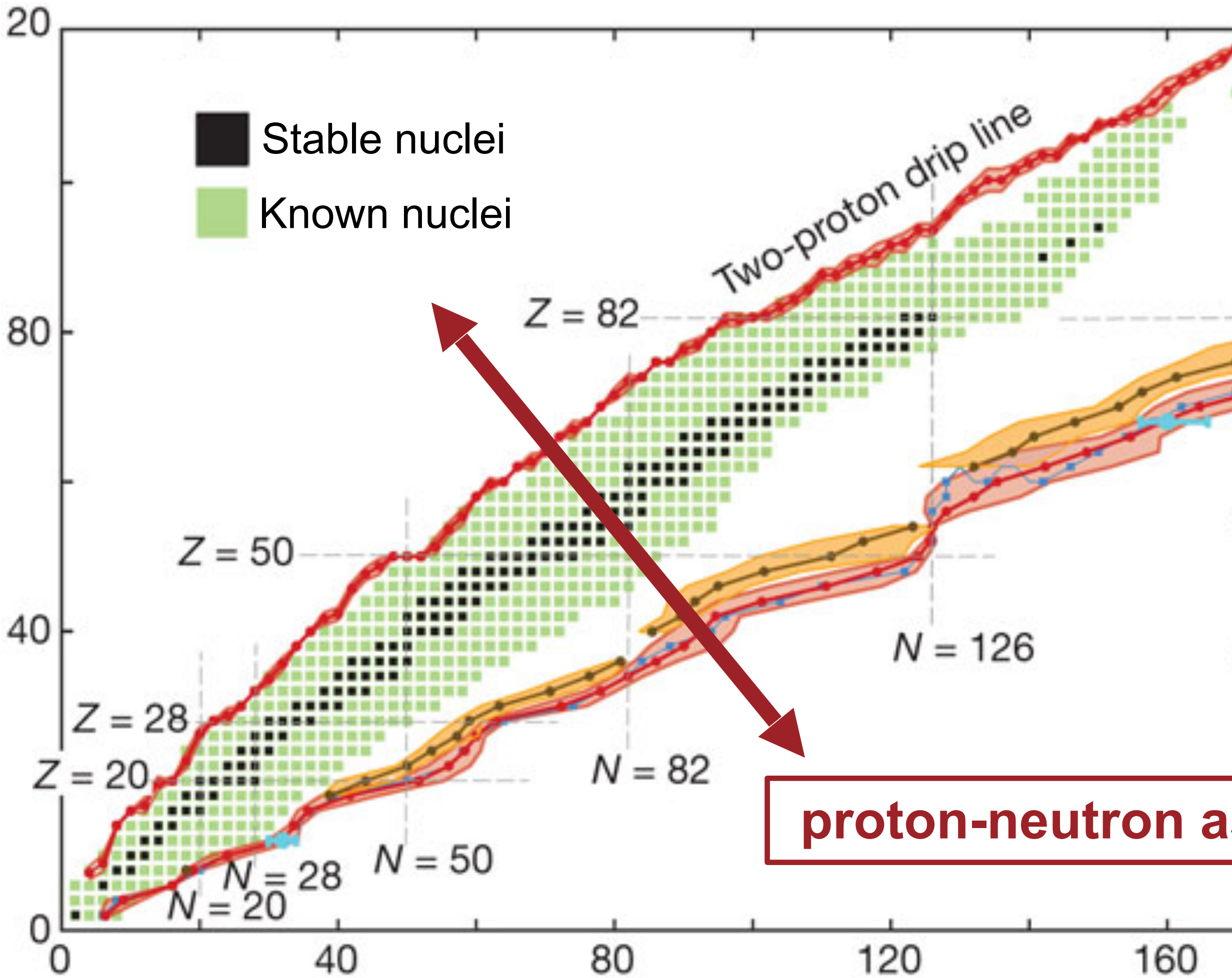
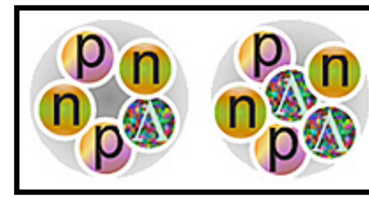
Strangeness, a new degree of freedom



hypernuclei



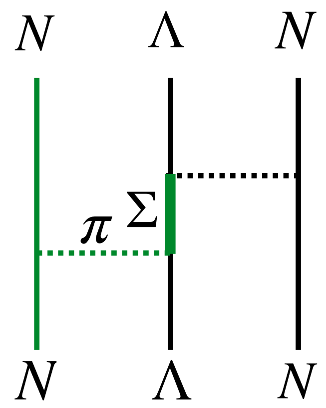
Why studying hypernuclei ?

1) Unified understanding of Baryon-Baryon interactions and baryonic bound systems
   - from *u,d* to *u,s,d* [see talk by H. Tamura]

2) Medium effects
   - Three-body forces
   - in-medium properties of hyperons

3) Many body effects
   - change of size
   - deformation
   - clustering

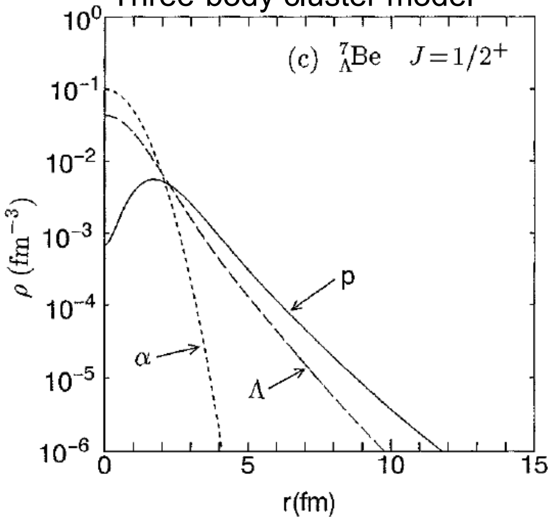
- Λ: lowest mass hyperon (*usd* quarks)
- First excited state (Σ) at only 70 MeV
- Enhanced role of internal degrees of freedom



Hyperhalos

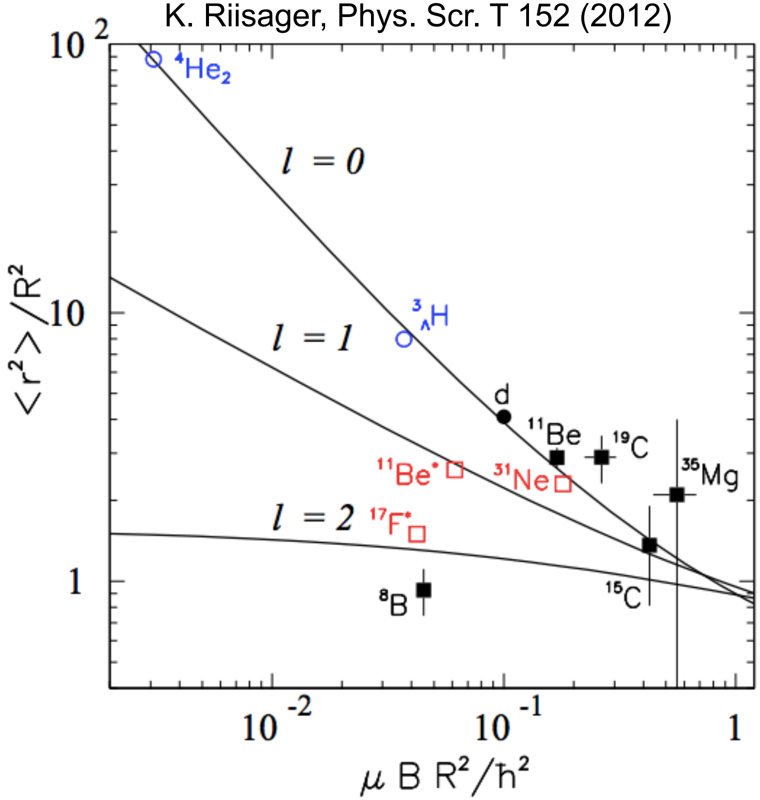
- Several loosely bound (hyper)nuclei predicted to be a halo
- Example of hypertriton
  [talks by M. Puccio, A. Gal]
- ^{7}Be-lambda predicted two-proton halo
  Potential only proton-rich Borromean system

E. Hiyama et al., PRC 53 (1996)
Three-body cluster model



$^5_\Lambda$He + 2p

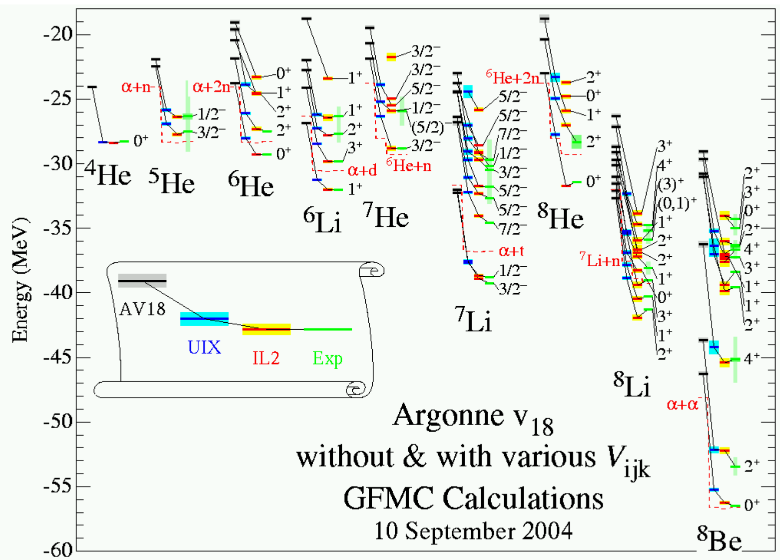
K. Riisager, Phys. Scr. T 152 (2012)



Ab initio description of light (hyper)nuclei

Nuclei

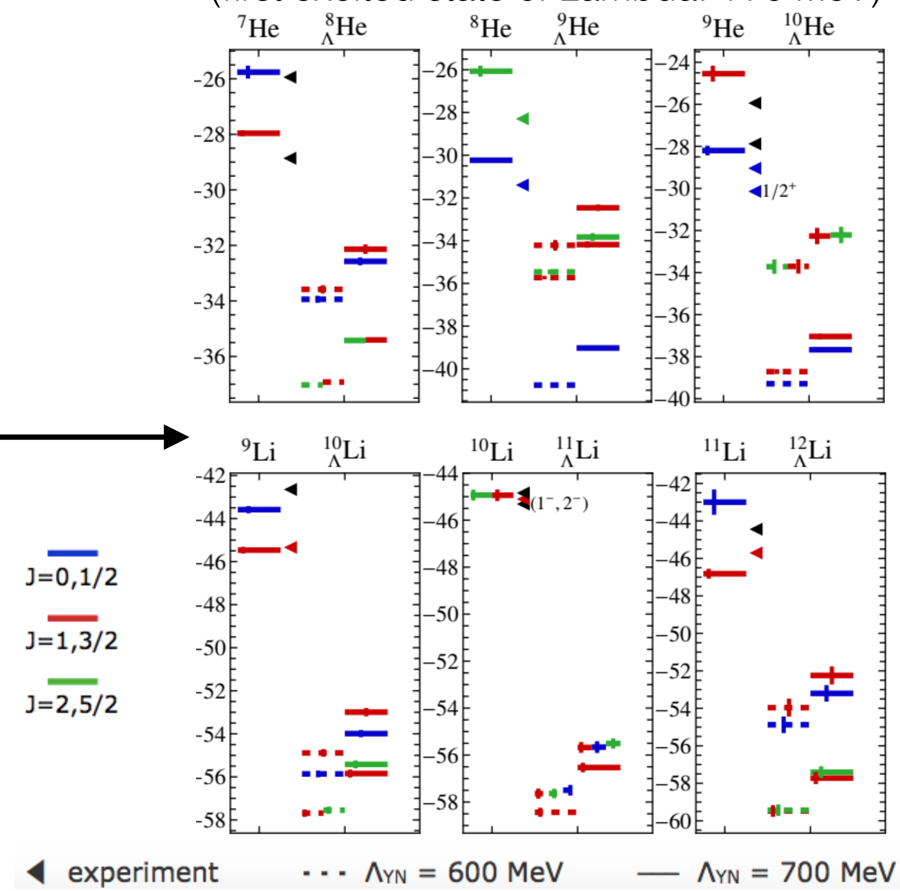
(first nucleonic excited state: +300 MeV)



R.B. Wiringa, S.C. Pieper, PRL 89, 182501 (2004)

Hypernuclei

(first excited state of Lambda: +70 MeV)



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

Ab initio description of light (hyper)nuclei

Hamiltonian from Chiral EFT
Chiral Hamiltonian NN at N3LO, 3N at N2LO
YN: LO chiral interaction
[see talk Haidenbauer (NLO)]

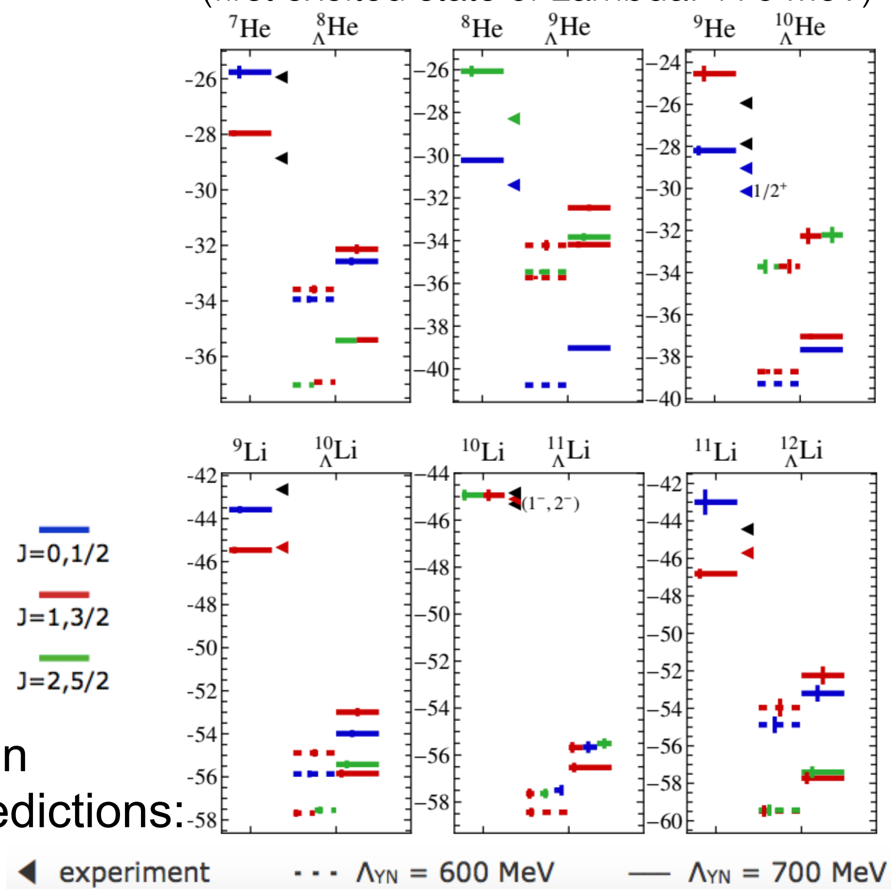
Similarity renormalisation group
Consistent SRG-evolution of NN, 3N, YN

Include explicit $(p, n, \Lambda, \Sigma^0, \Sigma^+, \Sigma^-)$
Wirth et al, PRL 117 (2016)

No core shell model
developed at TU Darmstadt [R. Roth]

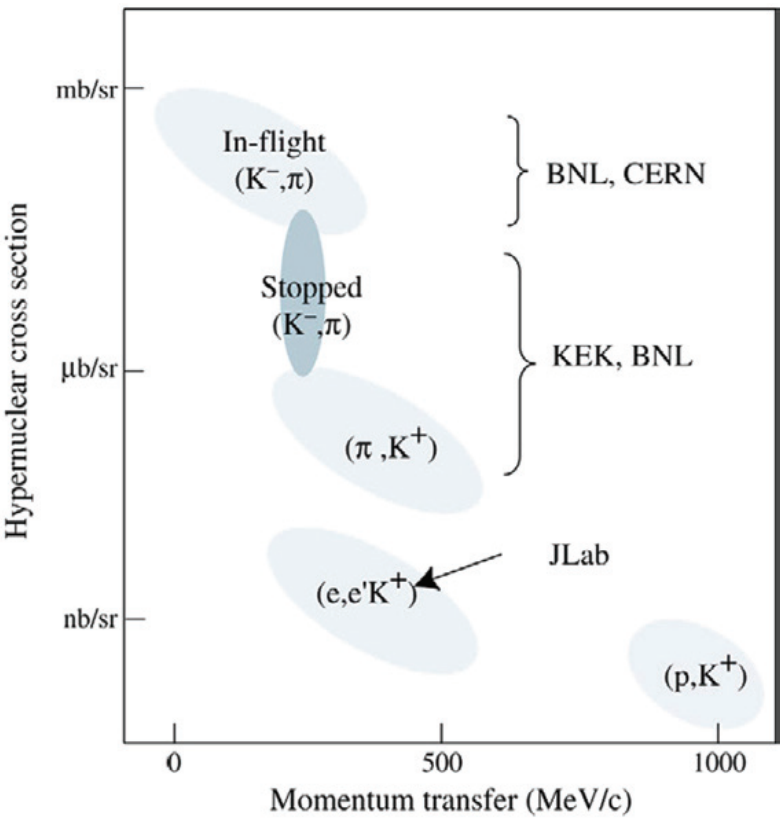
The no core shell model "machinery" has been adapted to hypernuclei. Main limitation for predictions: the YN and YNN interaction.

Hypernuclei
(first excited state of Lambda: +70 MeV)

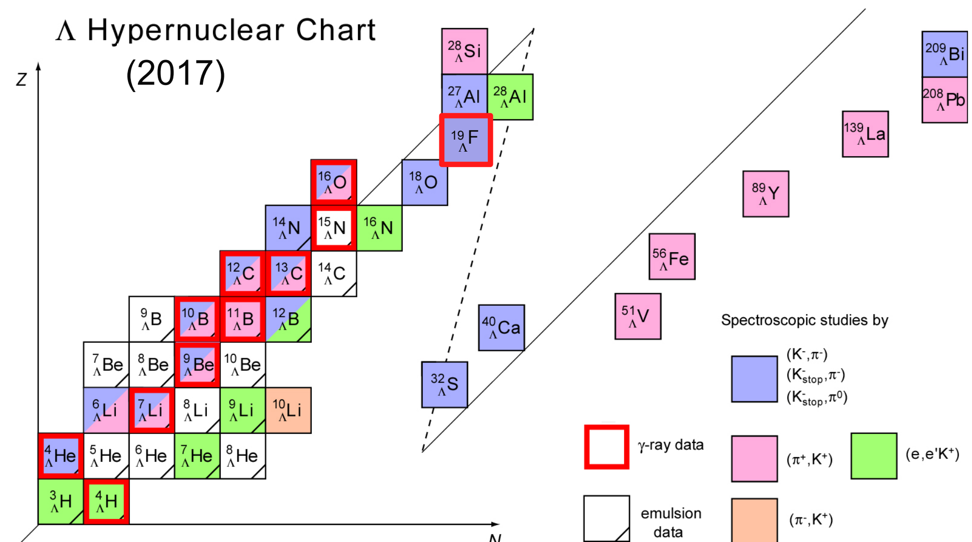


R. Wirth, R. Roth, PLB 779 (2018)

Hypernuclei production at "low energy"



O. Hashimoto, H. Tamura,
Prog. Part. Nucl. Phys. 57 (2006)



H. Tamura, Bormio 2018

Hypernuclei produced from stable nuclei so far from pion, kaon and electrons in direct kinematics… and heavy-ion collisions at GSI

Opportunities at GSI / FAIR

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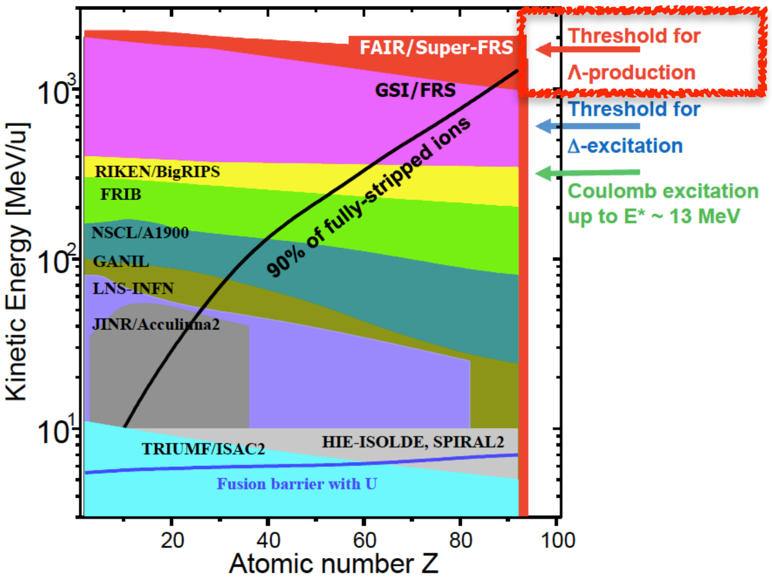
1) **Multi-strangeness hypernuclei** induced by antiprotons (PANDA, CBM) [talk by I. Vassiliev]

2) **Neutron-rich / -deficient** from heavy-ion collisions [talk by Ch. Rappold]



Proof of concept

Experiment **HiPHY0**
(Spokesperson: T. Saito, GSI)

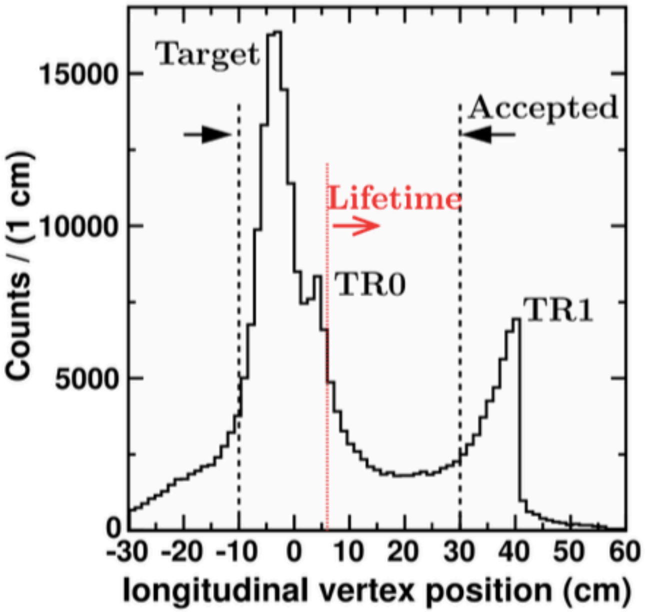
Heavy-ion collisions: $^{6}Li + ^{12}C$ at 2 GeV/nucleon

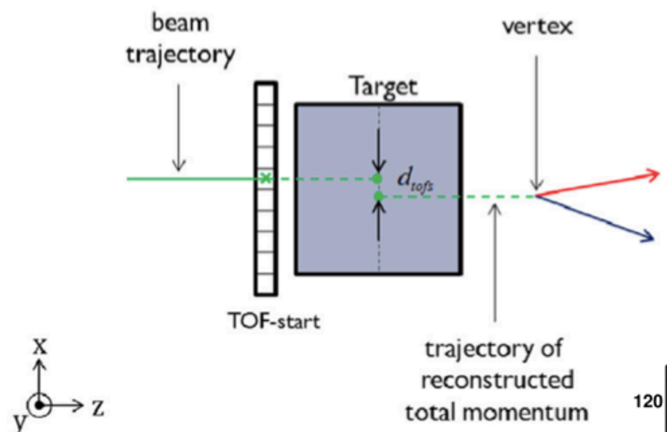
1) Strangeness production (Hyp-N + kaon)
2) Decay of Hyp-N (weak and mesonic decays)

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

Production of hypernuclei from HI collisions at few GeV / nucleon

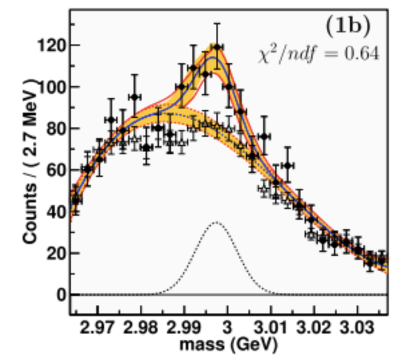
- Trigger: decay vertex + pion + heavy ion residue (spectrometer)





Invariant mass

$^3He + \pi^-$



- Future project : T. Saito, accepted proposal at GSI/FAIR (WASA)

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

Production of hypernuclei from HI collisions at few GeV / nucleon

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- Main source of strangeness production in heavy-ion (HI) collisions:

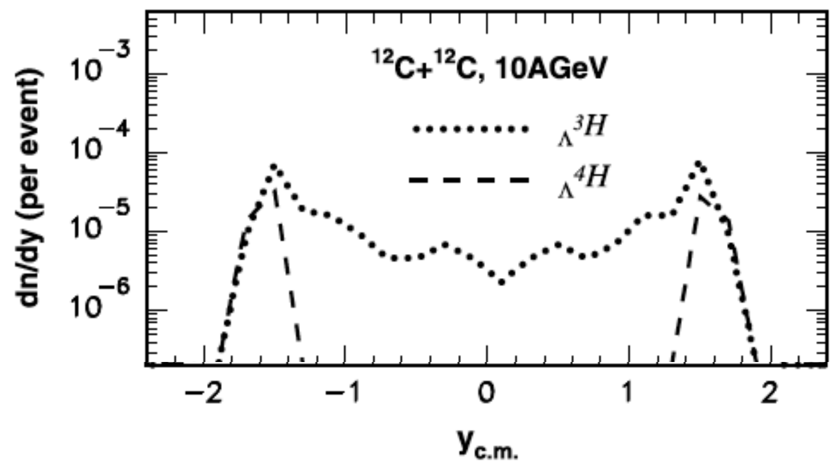
$$p + p \rightarrow p + \Lambda + K^{+} \quad (E_{lab} > 1.58\, GeV)$$

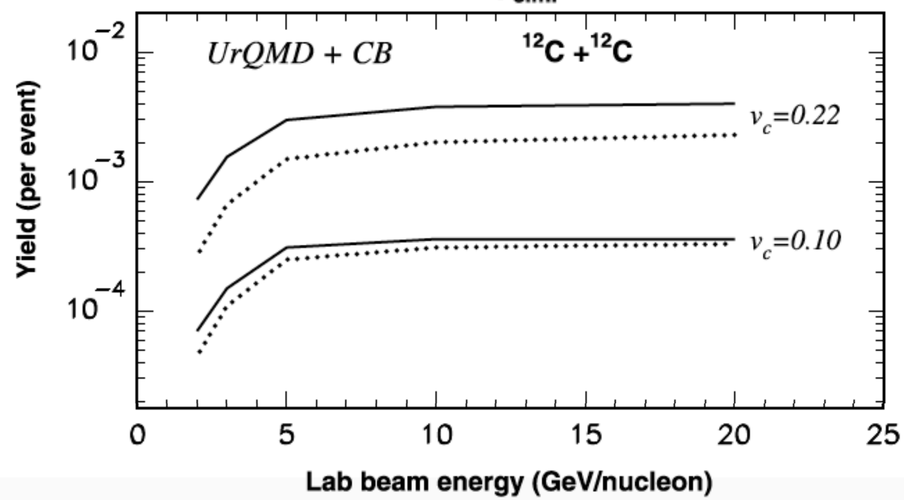
$$\pi^{+} + n \rightarrow \Lambda + K^{+} \quad (E_{lab} > 0.76\, GeV)$$

Models for hypernuclei production from HI collisions [talk by J. Aichelin]

- Evolution of hadrons in space and time using transport model
- Adsorption of lambda (coalescence or potential criteria)
  Coalescence parameter: 0.1c - 0.22c
- De-excitation
- Hyperfragment production saturates from 5-10 A GeV

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





Production of hypernuclei from HI collisions at few GeV / nucleon

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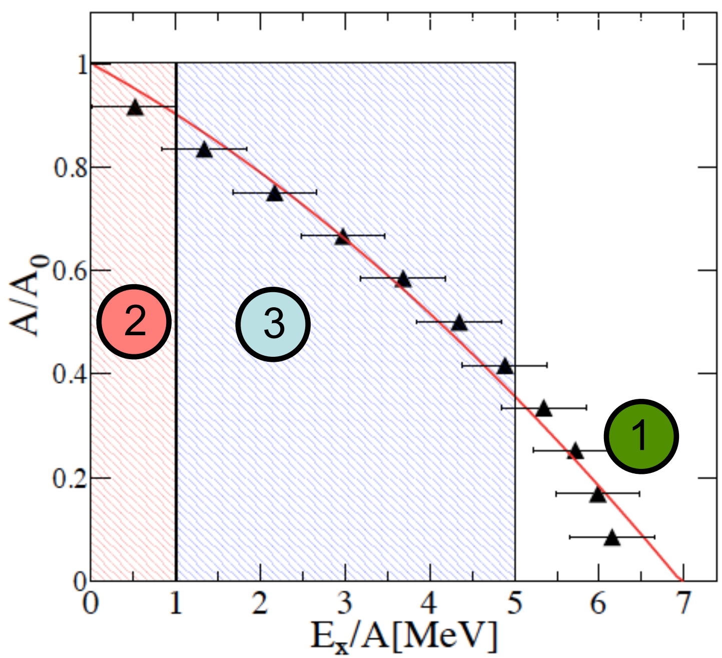
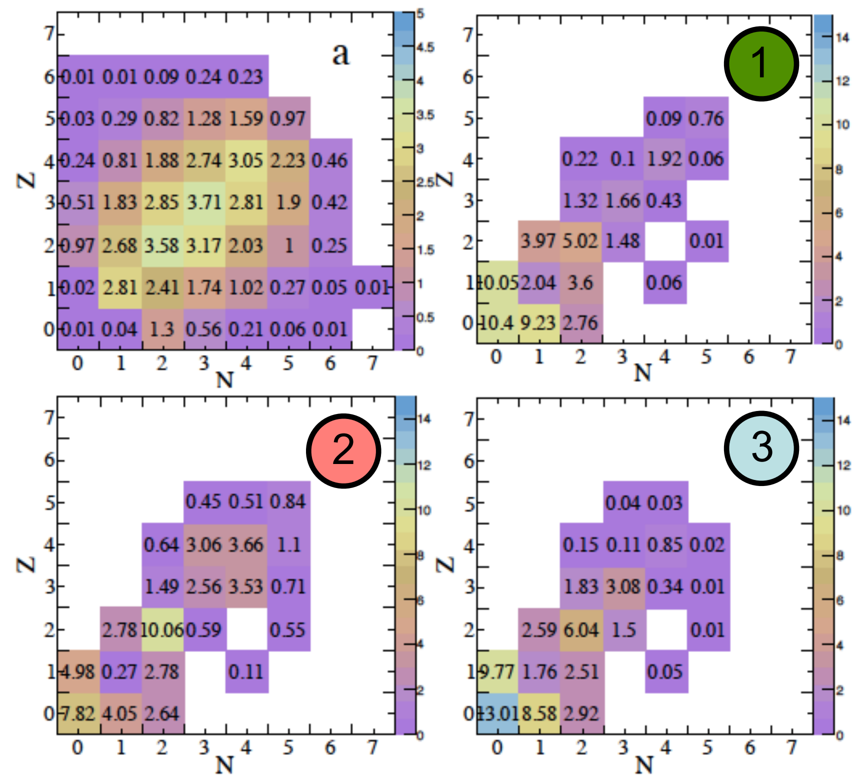
- DCM (Dubna Cascade Model)
  A. S. Botvina, K. K. Giudima, J. Pochodzalla, PRC 88 (2013)
- lambda absorption by potential criterium
- de-excitation by Fermi breakup



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



Y. Sun, A. S. Botvina *et al.,* PRC 98 (2018)

Production of hypernuclei from HI collisions at few GeV / nucleon

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^{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	$^{7}_{\Lambda}$Li	$^{6}_{\Lambda}$He
^{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	< 0.01	0.02
		(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	0.01	< 0.01
		(II)	0.17	2.44	...	...
		(III)	0.88	0.64	...	...
		Dubna [16]	...	...	< 1	< 0.5
^{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	...	...

Cross sections in microbarns

Y. Sun, A. Botvina et al., PRC 98 (2018)
[see also other recent work: A. Le Fèvre et al., PRC 100 (2019)]

Production of hypernuclei from protons at few GeV / nucleon

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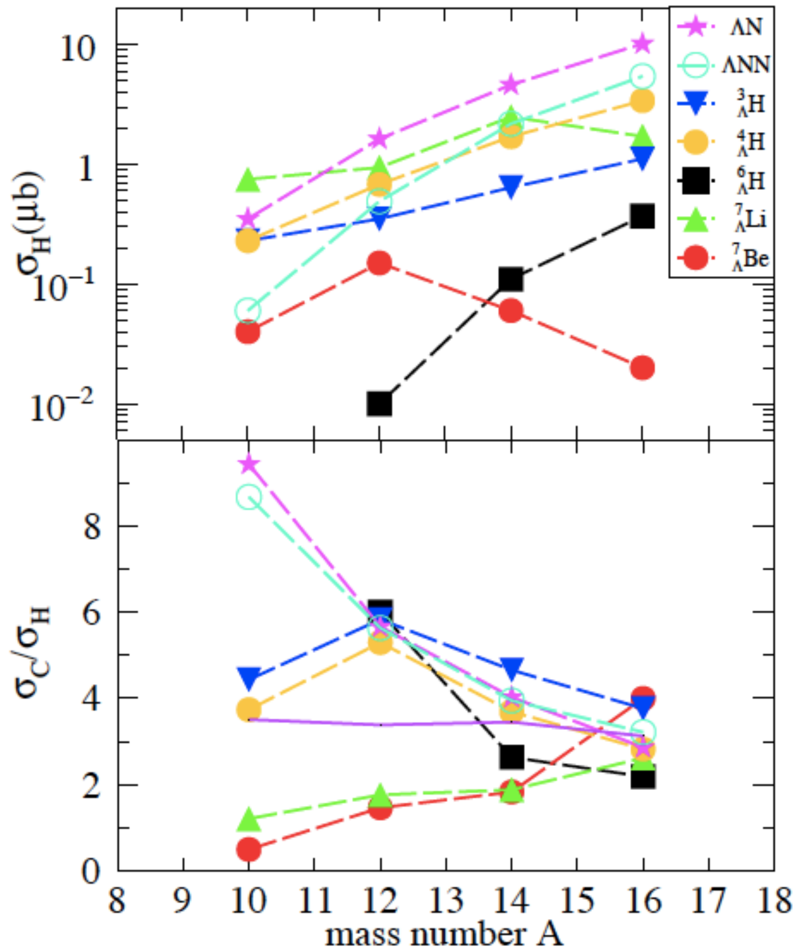
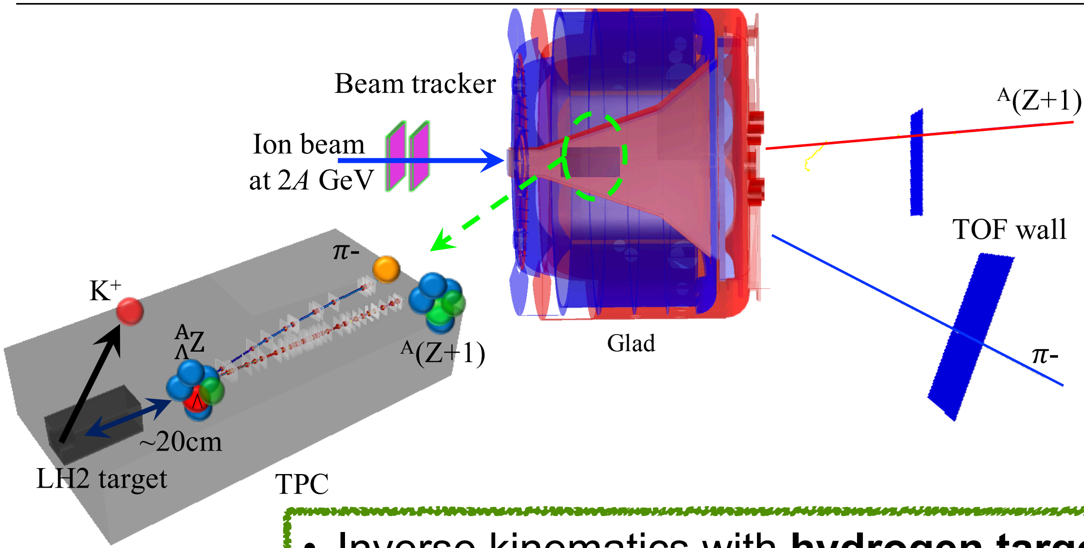
- Comparison of hypernuclei production cross section at 2 A GeV from C and H
- No significant production close to the projectile (momentum matching)
- Beams from ^{10}C to ^{16}C : one order of magnitude can be gained in production
- Potential to produce neutron-rich / defficient hypernuclei by use of radioactive beams
- Current limitation at GSI/FAIR: maximum rigidity of the spectrometer
  FRS : 18 Tm, Super-FRS: 20 Tm

Y. Sun, A. S. Botvina *et al.*, PRC 98 (2018)

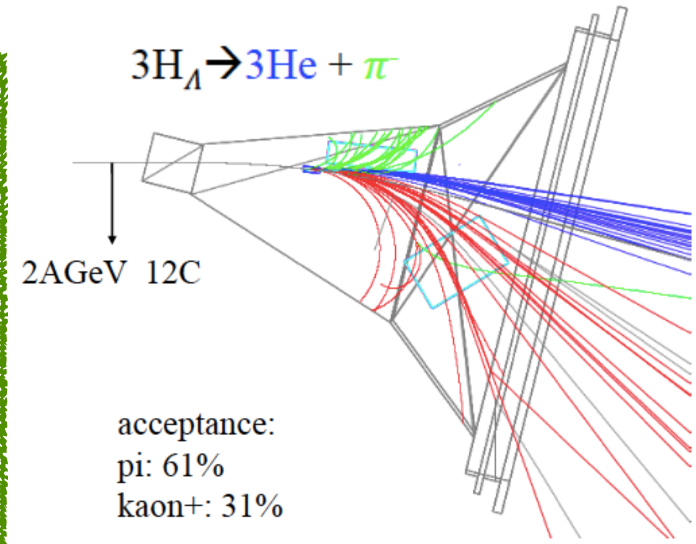


Future plans at R3B, GSI/FAIR



Hypernuclei production in inverse kinematics

- Inverse kinematics with **hydrogen target**
  - increase luminosity
  - reaction mechanism
  - decrease background
- Strangeness production by kaon tagging
- **TPC** inside GLAD dipole (invariant mass)
- Starting project (prototype under design)



Summary

- Hypernuclei are a natural extension to the current state-of-the-art in low-energy nuclear structure studies
- Several experiment efforts at GSI/FAIR towards (i) double-strangeness and (ii) exotic hypernuclei
- Heavy ion collisions at few A GeV are considered as a promising tool to produce neutron-rich and neutron-defficient hypernuclei
- To come at GSI/FAIR in the near future: WASA @ FRS, R3B
- Ab initio frameworks have been developed to hypernuclei (A<15). Predictions available. Main limitation are now the YN interactions.
- Production of hypernuclei at these energies lacks data. Various statistical and dynamical models exist.