Recent results and perspectives from HypHI

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2nd EMMI Workshop:
Antimatter, hypermatter and exotica production at the LHC
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Outline

The HypHI project

Results on ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H

Result on d+π^- and t+π^-

Result on hypernuclear cross section

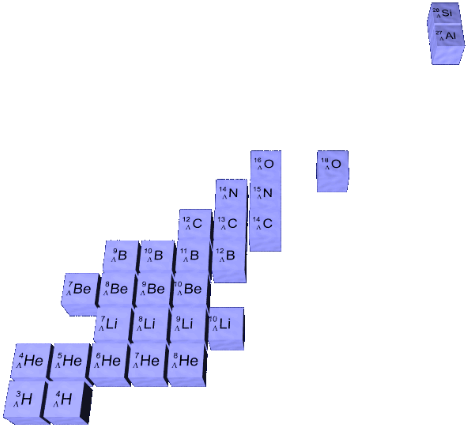
Next at FRS and SuperFRS

Summary & Perspectives

Outline

Several phases

Current knowledge:

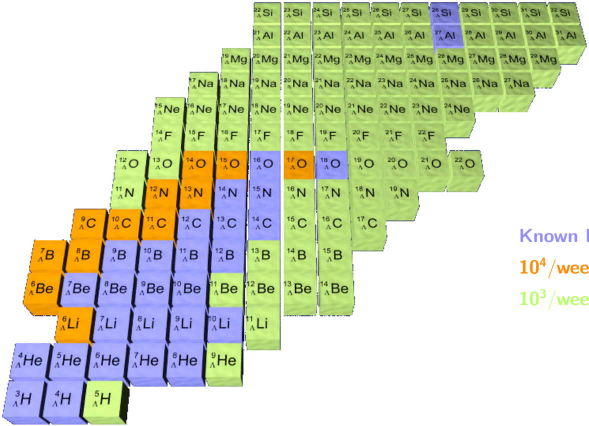


Known Hypernuclei

Several phases

Ideal outcome of the HypHI[1] project started in 2006:

(1) **Hyp**ernuclei with **H**eavy **I**on



Known Hypernuclei

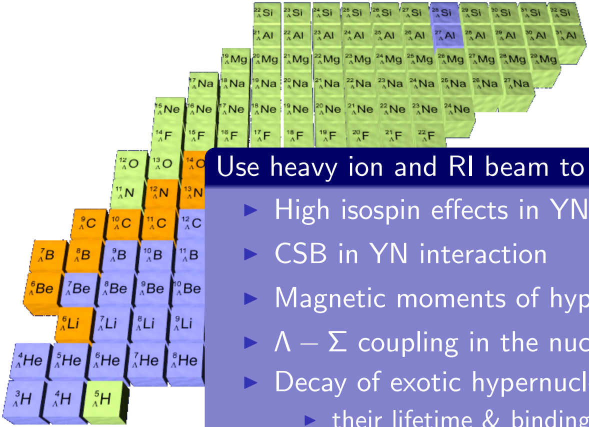
10^4/week

10^3/week

Several phases

Ideal outcome of the HypHI[1] project started in 2006:

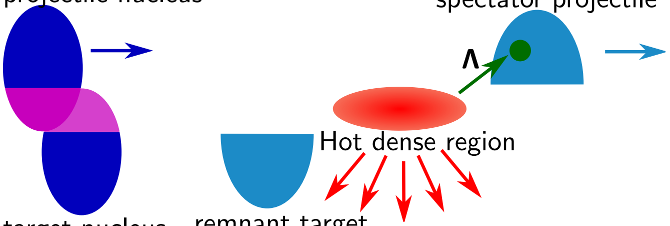
(1) **Hyp**ernuclei with **H**eavy **I**on



Use heavy ion and RI beam to study

- High isospin effects in YN interaction
- CSB in YN interaction
- Magnetic moments of hypernuclei
- $\Lambda - \Sigma$ coupling in the nuclear matter
- Decay of exotic hypernuclei
  - their lifetime & binding energy
- Multistrangeness hypernuclei

Heavy Ion : Properties of the production mechanism



- $NN \to \Lambda KN$ Energy threshold ~ 1.6 GeV.
- Beam energy $> E_{th}$: available at GSI (2 A GeV)
- Coalescence of Λ or (π^+, K^+) reaction in spectator fragment.

  $\Rightarrow$ same velocity than projectile: Lorentz Boosted
- Effective lifetime longer:
  - 200 ps $\to$ 600 ps ($\gamma \sim 3$) at GSI: $c\tau \sim 15$ to 20 cm.

  $\Longrightarrow$ study Hypernuclei in flight
  - Lifetime measurement via decay vertex reconstruction.

Goals of the HypHI phase 0 experiment

The phase 0 experiment:

- aimed to demonstrate the feasibility of hypernuclear spectroscopy by means of heavy ion collisions.
- focused on the study of ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, ${}^{5}_{\Lambda}$He
- via a reaction ^{6}Li beam at 2 AGeV on a ^{12}C target.

Experiment performed in October 2009

To measure:

- the production cross section.
- hypernuclear lifetime.

By identifying them:

1. Invariant mass spectroscopy :
   $$M_{hyp} = \sqrt{(\sum E_{decay})^2 - \| \sum \vec{p}_{decay} \|^2}$$
2. Secondary vertex selection.

Results from HypHI experiment: Phase 0 @ GSI

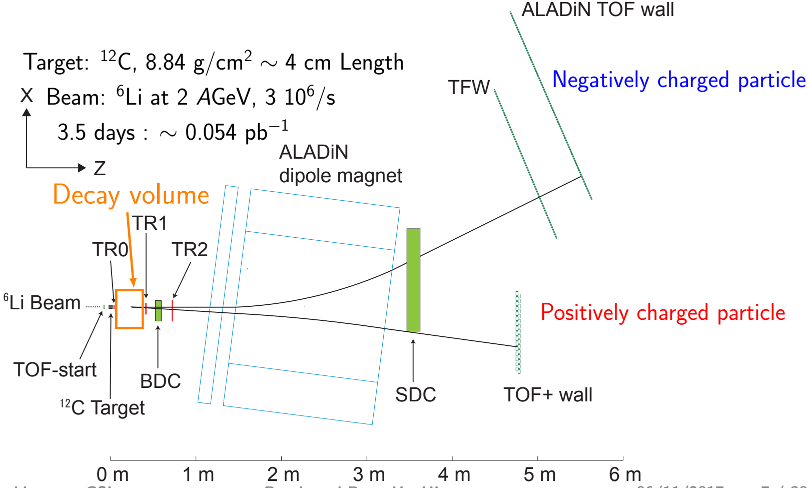
Fixed target, Reaction : $^{6}Li + ^{12}C$ @ 2 AGeV or $\sqrt{s_{NN}} = 2.7$ GeV

$^{3}_{\Lambda}H \rightarrow \pi^{-} + ^{3}He$ $^{4}_{\Lambda}H \rightarrow \pi^{-} + ^{4}He$ $^{5}_{\Lambda}He \rightarrow \pi^{-} + ^{4}He + p$

Target: ^{12}C, 8.84 g/cm^2 $\sim$ 4 cm Length

Beam: ^{6}Li at 2 AGeV, 3 10^6/s

3.5 days : ~ 0.054 pb^{-1}



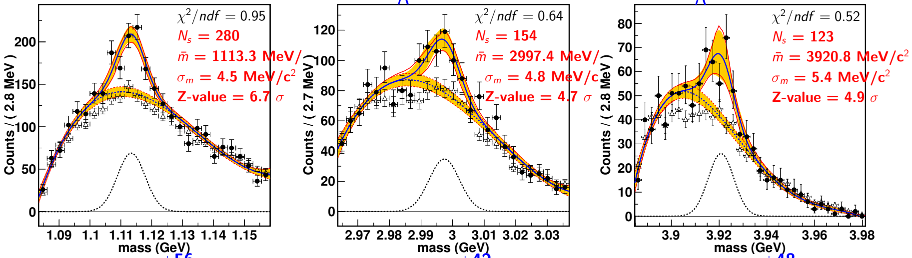
Outline

Hypernuclear spectroscopy from ^{6}Li+^{12}C @ 2 *A* GeV

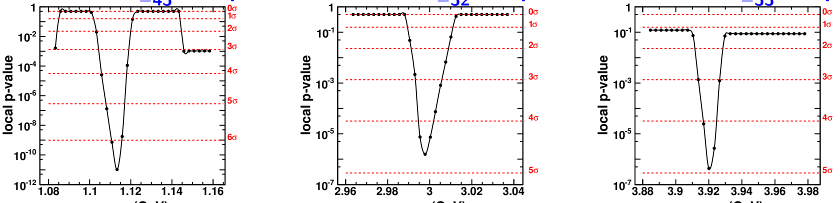
[C. Rappold *et al.*, Nucl. Phys. A. **913**, 170 (2013)]

Evidence of Λ, $^{3}_{\Lambda}$H et $^{4}_{\Lambda}$H & Lifetime measurements

$\Lambda \rightarrow p+\pi^-$ | $^{3}_{\Lambda}H \rightarrow {}^{3}He+\pi^-$ | $^{4}_{\Lambda}H \rightarrow {}^{4}He+\pi^-$



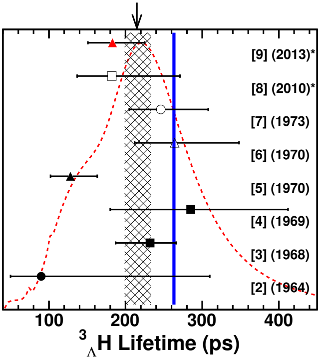
$\tau = 262^{+56}_{-43} \pm 45$ ps | $\tau = 183^{+42}_{-32} \pm 37$ps | $\tau = 140^{+48}_{-33} \pm 35$ps

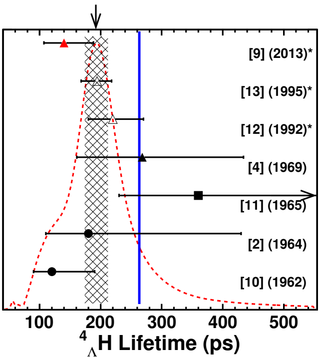


On the measured lifetime of light hypernuclei ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H

[C. Rappold *et al.*, Phys. Lett. B **728**, 543 (2014)]

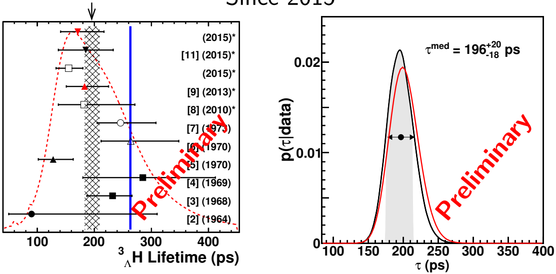
- Average combined lifetime in 2013:
  ${}^{3}_{\Lambda}$H : 216^{+19}_{-16} ps & ${}^{4}_{\Lambda}$H : 192^{+20}_{-18} ps
- Upper Limit 95 CL% at : ${}^{3}_{\Lambda}$H : 250 ps & ${}^{4}_{\Lambda}$H : 227 ps
- Theory: ${}^{3}_{\Lambda}$H [H. Kamada *et al.* PRC 57 1595 (1998)]: 256 ps
- Theory: ${}^{4}_{\Lambda}$H [T. Motoba *et al.* NPA 534 597 (1991)]: 233 or 244 ps





Combination with the most recent available lifetime results:

Since 2015

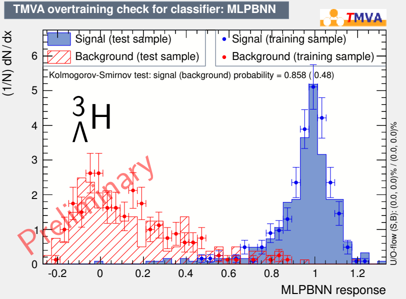


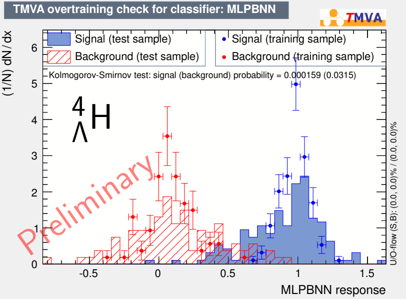
- PDG says need to rescale errors if $\chi^2 > 1$
  - initial χ^2=1.18, $197.5^{+12.4}_{-11.2}$ ps
  - scaled χ^2=0.98, $195.9^{+13.8}_{-12.5}$ ps
- Upper Limit at 95% : 223.9 ps & at 99% : 234.0 ps
- Bayesian :
  - $195.9^{+19.7}_{-18}$ ps & Upper Limit 95% : 229 ps
  - Bayes Factor : $B_{10} = 3.0$

New perspective: ML for hypernuclear discrimination

Increase trading influence of machine learning / AI in society:

- In 2011/2012: Use of machine learning for hypernuclear discrimination
- Training and testing data set: directly the experimental data

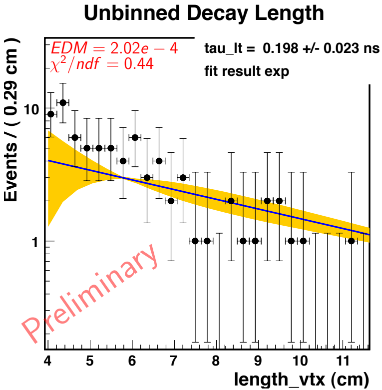


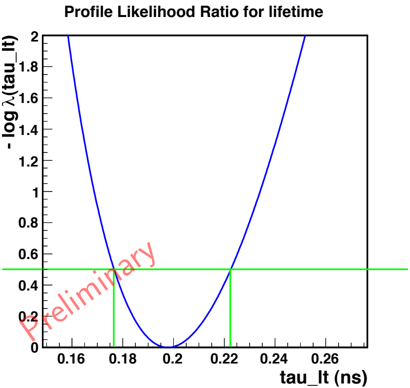


New perspective: ML for hypernuclear discrimination

Applying ML discrimination for ${}^{3}_{\Lambda}H$ lifetime :

- Statistical error: 198 $^{+25}_{-21}$ ps
- published HypHI lifetime : $\tau = \mathbf{183^{+42}_{-32}} \pm \mathbf{37}$ ps
- World average of 2015 : 196^{+14}_{-13} ps

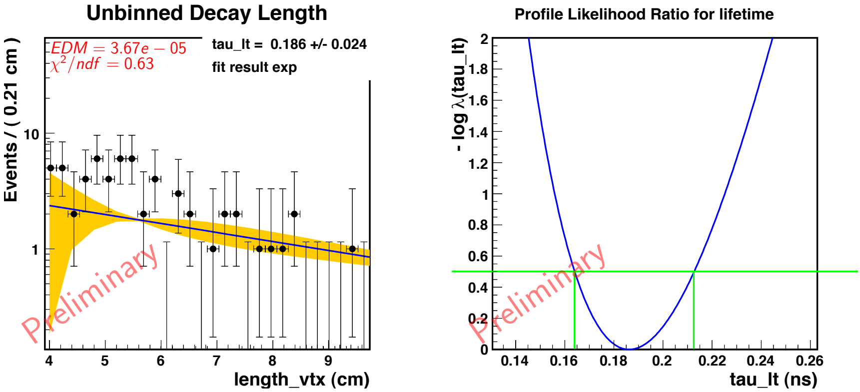




New perspective: ML for hypernuclear discrimination

Applying ML discrimination for $^{4}_{\Lambda}H$ lifetime :

- Statistical error: 186 $^{+27}_{-22}$ ps
- published HypHI lifetime : $\tau = \mathbf{140^{+48}_{-33} \pm 35}$ ps
- World average of 2013 : 192^{+20}_{-18} ps



Hypernuclear spectroscopy from ^{6}Li+^{12}C @ 2 A GeV

Important Conclusion

- Demonstration of the hypernuclear spectroscopy via heavy ion induced reaction
- Evidence of identification of Λ, ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H via invariant mass
- Estimation of the lifetime of Λ, ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H
- Estimated ${}^{3}_{\Lambda}$H lifetime more precise ($183^{+42}_{-32} \pm 37$ ps)
- Combined lifetime analysis excludes all current models of ${}^{3}_{\Lambda}$H
- Upper Limit:
  - at 95% CL : ${}^{3}_{\Lambda}$H : 223.9 ps & at 99% : 234.0 ps & ${}^{4}_{\Lambda}$H : 227 ps
- No theoretical model can explain the shorten ${}^{3}_{\Lambda}$H lifetime:
  - ${}^{3}_{\Lambda}$H [H. Kamada *et al.* PRC 57 1595 (1998)]: 256 ps
  - ${}^{4}_{\Lambda}$H [T. Motoba *et al.* NPA 534 597 (1991)]: 233 ps / 244 ps
- ${}^{3}_{\Lambda}$H may not be as weakly bound as considered

Outline

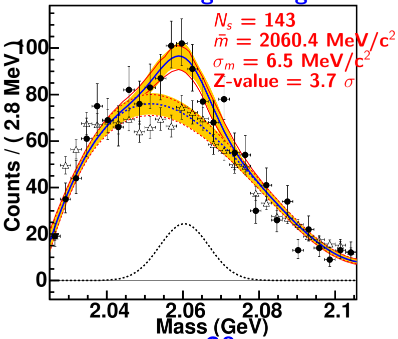
Search for evidence of ${}^3_\Lambda$n by observing d+π^- and t+π^-

[C. Rappold *et al.*, Phys. Rev. C (Rapid Comm.) **88**, 041001 (2013)]

Possible bound state ${}^3_\Lambda$n (nnΛ) ?

${}^3_\Lambda$n → d+π^-

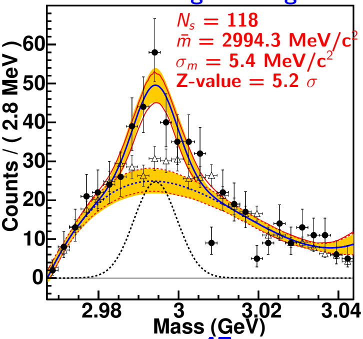
Excluding the target



$\tau = 181^{+30}_{-24} \pm 25$ps

${}^3_\Lambda$n → t+π^-

Excluding the target

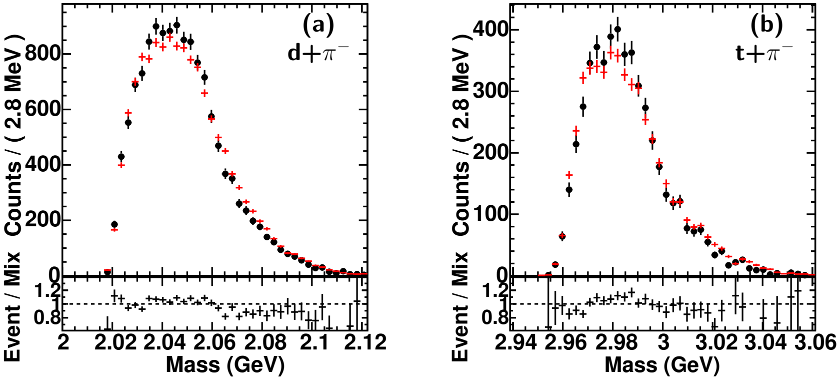


$\tau = 190^{+47}_{-35} \pm 36$ps

Search for evidence of ${}^{3}_{\Lambda}$n by observing d+π^- and t+π^-

[C. Rappold *et al.*, Phys. Rev. C (Rapid Comm.) **88**, 041001 (2013)]

- Study of possible sources : GEANT4 Monte Carlo simulations
- d and t from ^{6}Li+^{12}C reaction & π^- from the primary vertex and from the weak decay of hyperons and hypernuclei.



Search for evidence of ${}^{3}_{\Lambda}$n by observing d+π^- and t+π^-

Important Points

- Evidence of signals in the invariant mass of d+π^- and t+π^-
- the decay attributed to strangeness-changing weak interaction
- A possible interpretation : ${}^{3}_{\Lambda}$n
  - t+π^- : two-body decay via ${}^{3}_{\Lambda}n \rightarrow t + \pi^-$
  - d+π^- : three-body decay via ${}^{3}_{\Lambda}n \rightarrow t^* + \pi^- \rightarrow d + n + \pi^-$

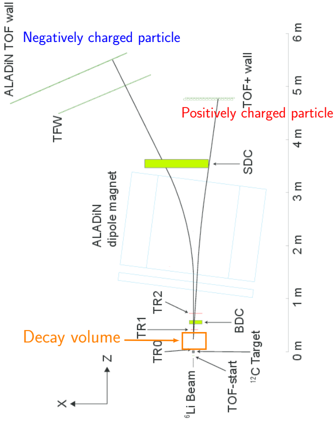
However:

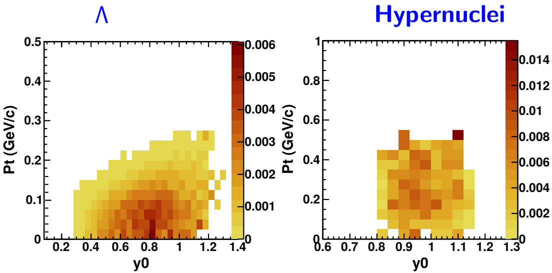
- theoretical studies show ${}^{3}_{\Lambda}$n not bound
  - No explanation within the current understanding of the ΛN interaction (by A. Gal (arxiv :1404.5855), E. Hiyama (PRC 89, 061302) and H. Garcilazo (PRC 89, 057001))
- Model core-Λ: no viable (n-n not bound) ? borromean state ? Effimov state ?

Outline

Hypernuclear production cross section in spectator region

Fixed target, Reaction : ^{6}Li+^{12}C @ 2 AGeV or $\sqrt{s_{NN}} = 2.7$ GeV



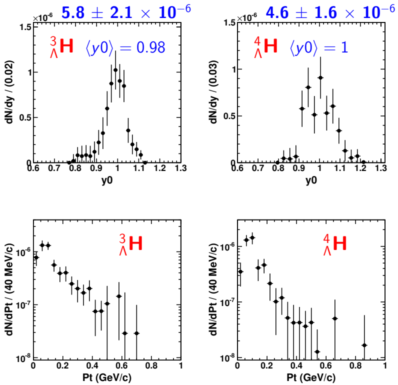


[C. Rappold *et al.*, Phys. Lett. B**747** (2015) 129]

Hypernuclear production cross section in spectator region

Production cross section & multiplicity :

	CS
Λ	1.7 ± 0.8 mb
${}^{3}_{\Lambda}\mathrm{H}$	3.9 ± 1.4 μb
${}^{4}_{\Lambda}\mathrm{H}$	3.1 ± 1.0 μb
${}^{3}_{\Lambda}\mathrm{H}/{}^{4}_{\Lambda}\mathrm{H}$	1.4 ± 0.8
${}^{3}_{\Lambda}\mathrm{H}/\Lambda$	$2.6 \pm 1.4 \times 10^{-3}$
${}^{4}_{\Lambda}\mathrm{H}/\Lambda$	$2.1 \pm 1.1 \times 10^{-3}$
${}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He} \cdot \mathrm{p}/\Lambda$	0.28 ± 0.14
${}^{4}_{\Lambda}\mathrm{H}/{}^{4}\mathrm{He} \cdot \mathrm{p}/\Lambda$	0.08 ± 0.04

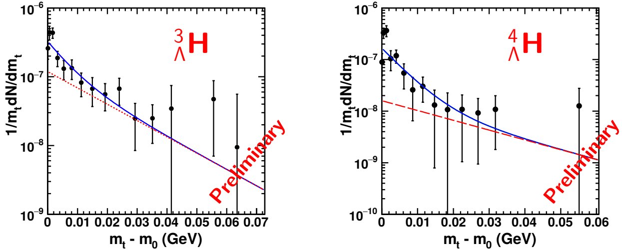


[C. Rappold *et al.*, Phys.Lett. B**747** (2015) 129]

Inverse slope / Temperature

Inverse slope T, m_t spectrum :

$$f(m_t - m_0) = K_1/T_1 \; e^{-(m_t-m_0)/T_1} + K_2/T_2 \; e^{-(m_t-m_0)/T_2}$$

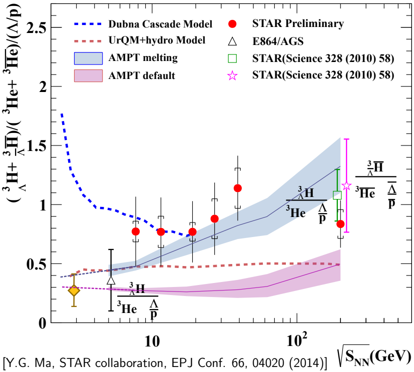


- for $^{3}_{\Lambda}$H : $T_1 \sim 7 \pm 2$ MeV & $T_2 \sim 18 \pm 7$ MeV
- for $^{4}_{\Lambda}$H : $T_1 \sim 6 \pm 2$ MeV & $T_2 \sim 13 \pm 6$ MeV
- very similar to multi-fragmentation ALADIN results

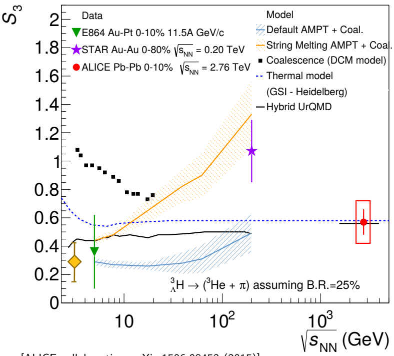
  [T. Odeh et al., Phys. Rev. Lett. 84 (2000) 4557]
- and Goldhaber model :[A.S. Goldhaber, Phys. Lett. B 53 (1974) 306]

Comparison S3 factor : HypHI results

$$S_3 = {}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}\cdot \mathrm{p}/\Lambda = 0.28 \pm 0.14 \;/\; S_4 = {}^{4}_{\Lambda}\mathrm{H}/{}^{4}\mathrm{He}\cdot \mathrm{p}/\Lambda = 0.08 \pm 0.04$$



[Y.G. Ma, STAR collaboration, EPJ Conf. 66, 04020 (2014)]



[ALICE collaboration, arXiv:1506.08453 (2015)]

[T.A. Armstrong et al., Phys. Rev. C70, 024902 (2004)]
[C. Rappold et al., Phys.Lett. B747, 129 (2015)]
[STAR collaboration, EPJ Conf. 66, 04020 (2014)]
[STAR Collaboration, Science 328, 58 (2010)]
[ALICE collaboration, arXiv:1506.08453 (2015)]

AMPT + Coal. : S. Zhang et al., Phys.Lett.B684 (2010) 224.
DCM model : J. Steinheimer et al., Phys.Lett.B714 (2012) 85.
Thermal model : A. Andronic et al., Phys.Lett.B697 (2011) 203.
Hybrid UrQMD : J. Steinheimer et al., Phys.Lett.B714 (2012) 85

Outline

Prospects in Hypernuclear Physics for FRS/SuperFRS

Future of HypHI project : Exotic hypernuclei / strangeness cluster

Use heavy ion and RI beam to study @ FRS & SuperFRS :

- Hypernuclei toward the proton and neutron drip-lines with Exotic beam ⇒ **SuperFRS**
- $\Lambda - \Sigma$ coupling in the nuclear matter ⇒ **SuperFRS**
- Lifetime of exotic hypernuclei. ⇒ **FRS / SuperFRS**
- Most urgent : Confirmation of $^{3}_{\Lambda}n$ ⇒ **FRS**

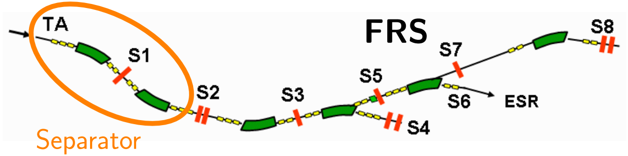
Prospects in Hypernuclear Physics for FRS/SuperFRS

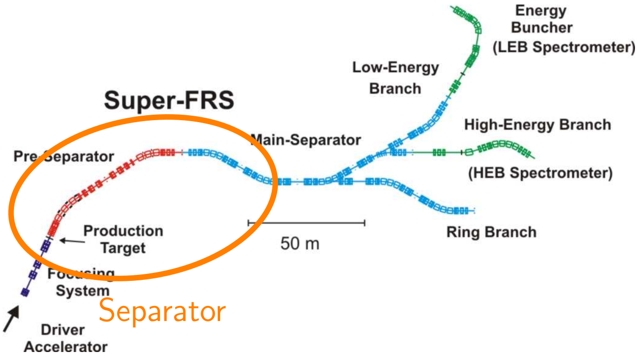
Why at FRS / Super FRS ?

- high momentum resolution for forward fragments : $10^{-4}\delta p/p$ optimal
  - to be compared with previous experimental apparatus : $\sim 10^{-2}\delta p/p$
- Exotic hypernuclei : Need RI beam
  - With high energy ~ 2 AGeV (min 1.6AGeV)
  - With high intensity : small cross section ($\sim \mu$b)
- Optimizing each experiment to one decay / species

$\Rightarrow$ **Only possible at GSI/FAIR and FRS / SuperFRS**

The concept & Layouts: Exclusive experiment





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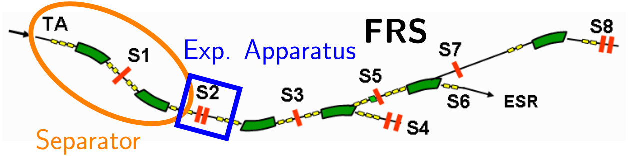

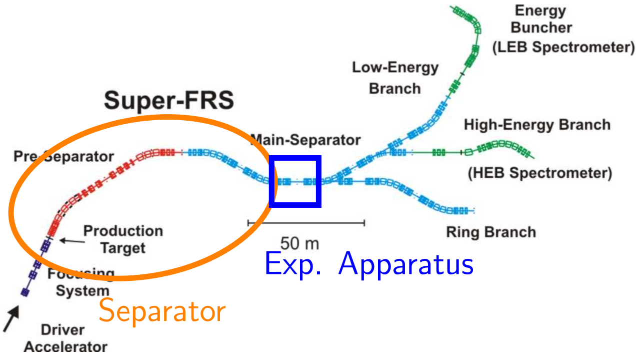

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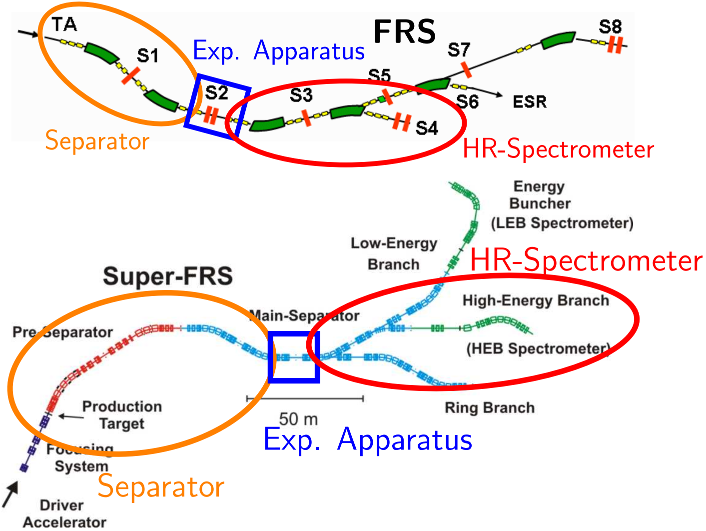

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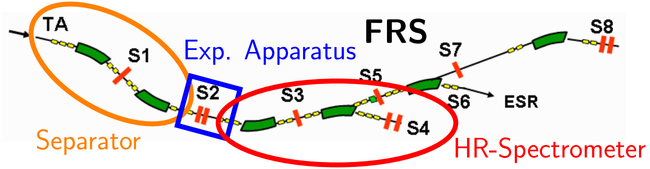
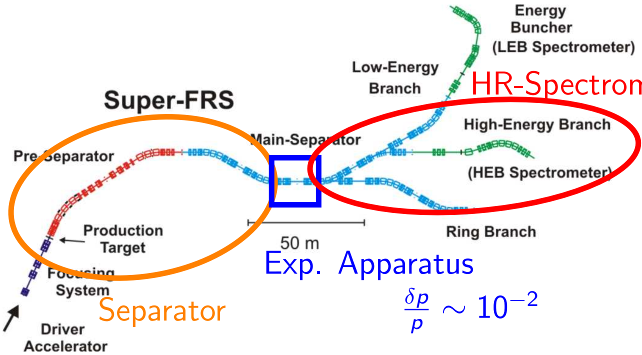




$\frac{\delta p}{p} \sim 10^{-3}$

$\frac{\delta p}{p} \sim 10^{-2}$

Transport optimization: Final step of optimal search

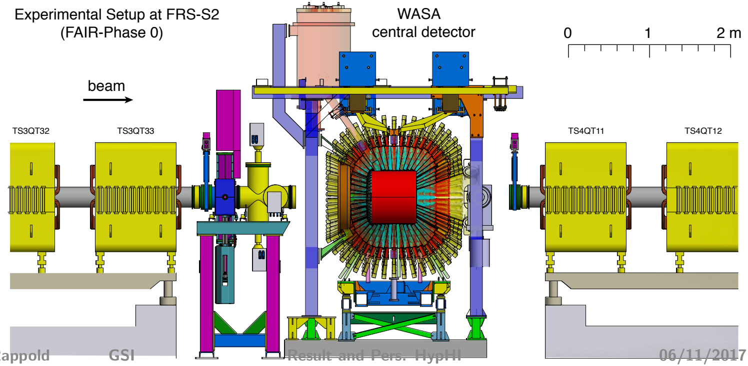
- MOCADI sim. for exotic beam transport within separator part
- Variables: Beam energy, transmission, survival rate, target thickness, contamination
- + EPAX and QGSM: RI beam & hypernuclear cross section
  - QGSM model compared to ^{6}Li+^{12}C results is ×4 smaller
- Multivariate dataset → optimization to find the optimum

	Reaction	Target (cm)	2^{nd} beam	E_k ($AGeV$)	I (10^6/s)	Yield (/s)
$^{9}_{\Lambda}$C	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	0.3
$^{11}_{\Lambda}$B	^{20}Ne+^{9}Be	2	^{17}F	1.97	5.7	0.4
$^{9}_{\Lambda}$Be	stable beam		^{16}O	2.	10.	1.5
$^{5}_{\Lambda}$Li	^{12}C+^{9}Be	6	^{10}C	1.94	5.1	0.8
$^{6}_{\Lambda}$Li	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	1.4
$^{9}_{\Lambda}$Li	^{16}O+^{9}Be	5.5	^{14}O	1.93	5.5	0.7
$^{7}_{\Lambda}$He	^{20}Ne+^{9}Be	2	^{17}F	1.97	5.7	0.9

[C. Rappold and J. López-Fidalgo PRC 94 (2016) 044616]

Wasa at S2: Solenoid magnet scenario

- Generic setup that can be used for different experiments:
- Large angular coverage :
  - close to 4π acceptance in mid-rapidity, projectile and/or target rapidity region.
- Good momentum (P_t and $P_{//}$) and vertex resolution.
- High rate & granularity for multiplicity.



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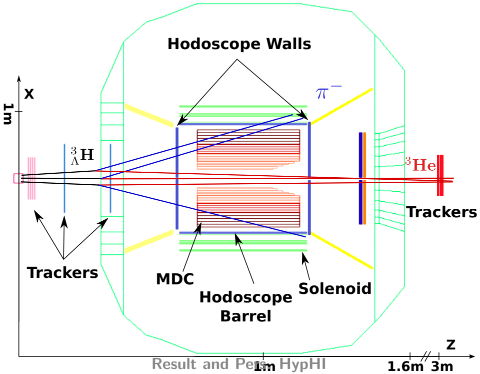
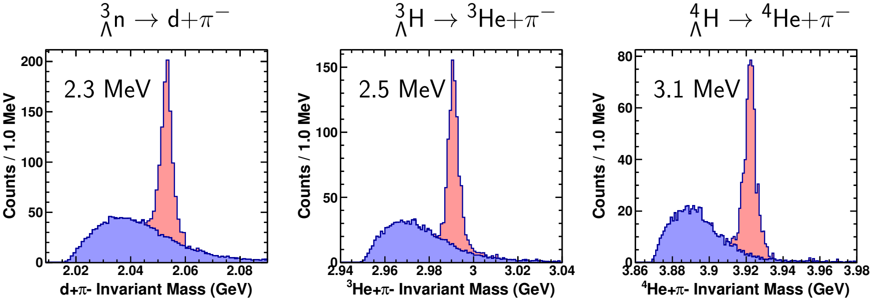


Invariant masses and yield estimation



Channel of Interest	FRS regidity (Tm)	Estimated signal Int.
$d+\pi^-$	16.675	4.0×10^3 (8 days)
${}^{3}_{\Lambda}H$	12.623	1.5×10^3 (3 days)
${}^{4}_{\Lambda}H$	16.675	5.0×10^3 (8 days)

Experiment approved by G-PAC to run (2019): 45 shifts (27 main)

Outline

Summary

- Hypernuclear physics: meeting point between particle physics and nuclear physics.
- The Phase 0 of the project was completed in October 2009
  $\Rightarrow$ Milestone of the phase 0.
  - Demonstrated the feasibility of HypHI by observing the MWD of Λ, ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$
  - Evidence of ${}^{3}_{\Lambda}n$ possible existence
  - Shorten lifetime of ${}^{3}_{\Lambda}H$: More theoretical study needed.
  - Cross sections and yield ratios will constrain hyper-matter production models.
- A second experience took place in March 2010:
  Same setup for 7 days of ${}^{20}Ne+{}^{12}C$ @ 2 AGeV
  - Promising results from the on-going data analysis.

Summary

- hypernuclear study @ FRS and SuperFRS as high resolution forward spectrometer
  - More precise hypernuclear spectroscopy, Sub MeV
  - FRS & SuperFRS as:
    - Separator to provide exotic beam
    - High resolution spectrometer for decayed fragment
  - Exclusive measurements : hypernuclear structure only.
- in near future at FRS (FAIR Phase 0):
  - $\Rightarrow$ Possibility to confirm the existence of ${}^{3}_{\Lambda}$n via d+π^- : ^{6}Li+^{12}C @ 2AGeV
  - Improve ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H mass resolution + Lifetime
- in future at SuperFRS:
  - Study proton and neutron-rich hypernuclei possible
    Unknown: ${}^{8}_{\Lambda}$Be, ${}^{16}_{\Lambda}$C, ${}^{9}_{\Lambda}$Li, ${}^{11}_{\Lambda}$Be, ${}^{13}_{\Lambda}$B
- Unique opportunity with SuperFRS for exotic hypernuclei & multi-hypernuclear object