Recent progress of the HypHI project at GSI and its perspective at FAIR

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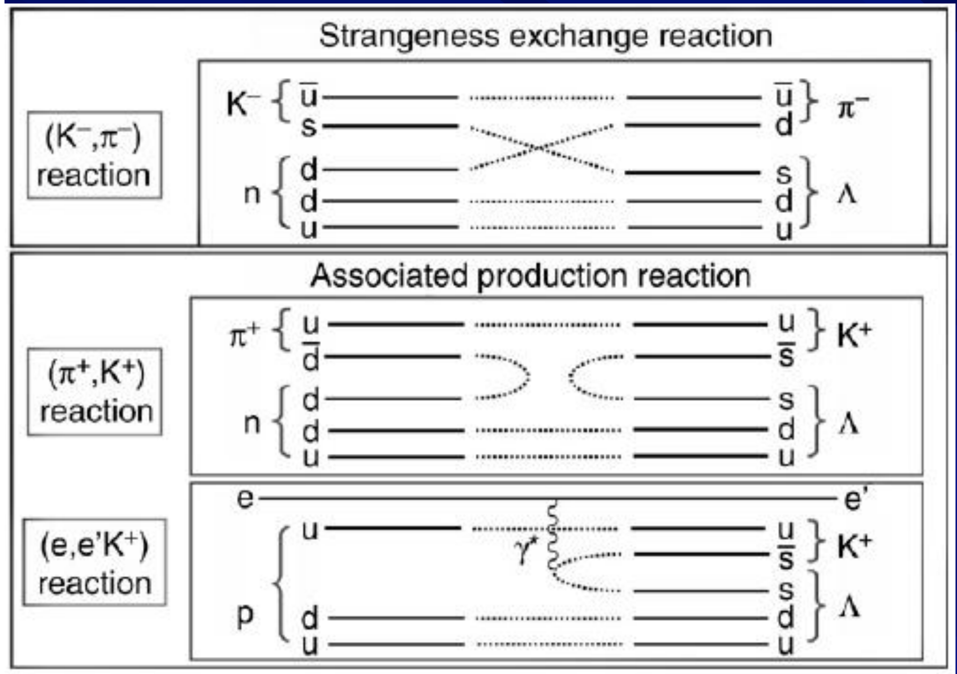
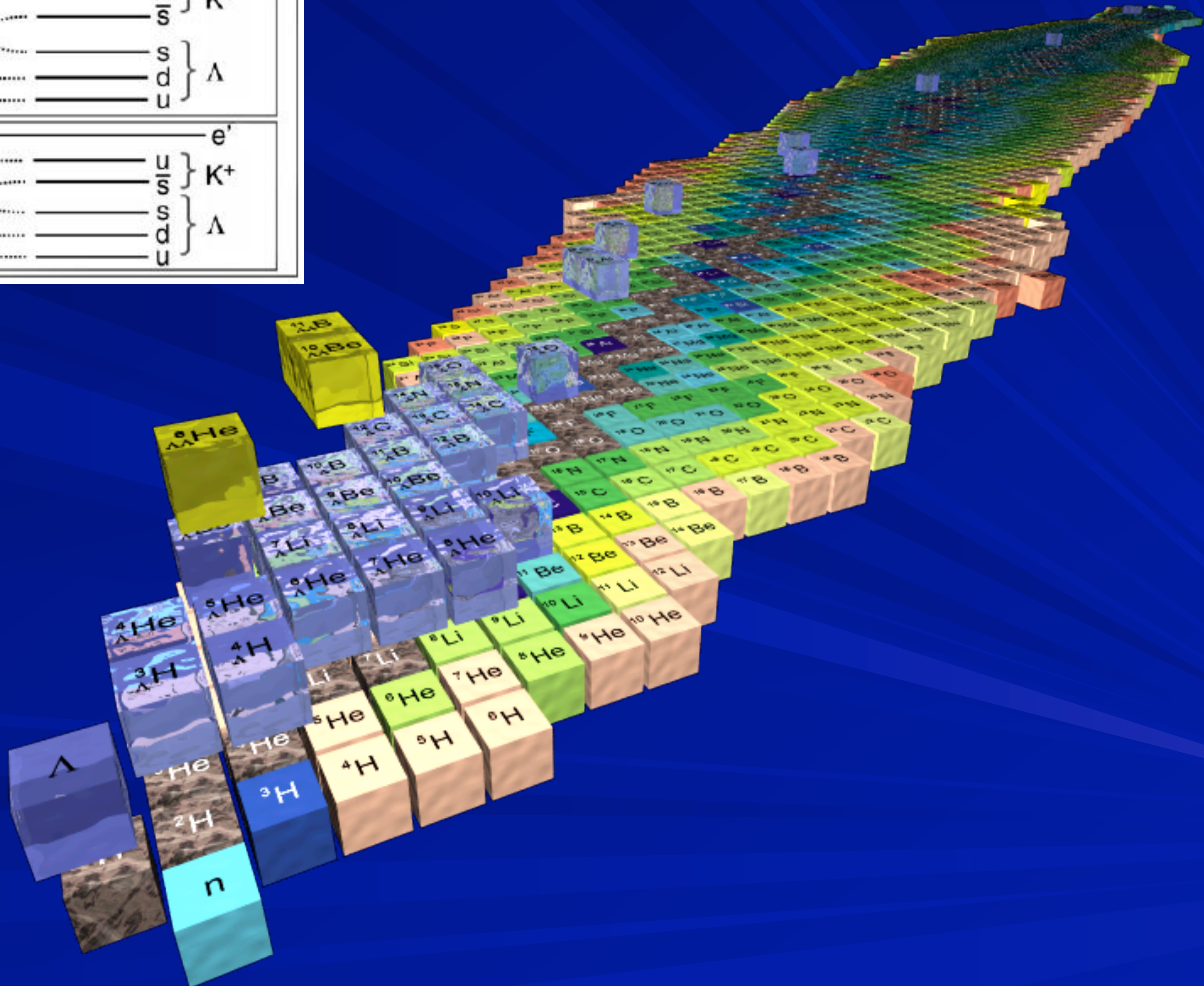
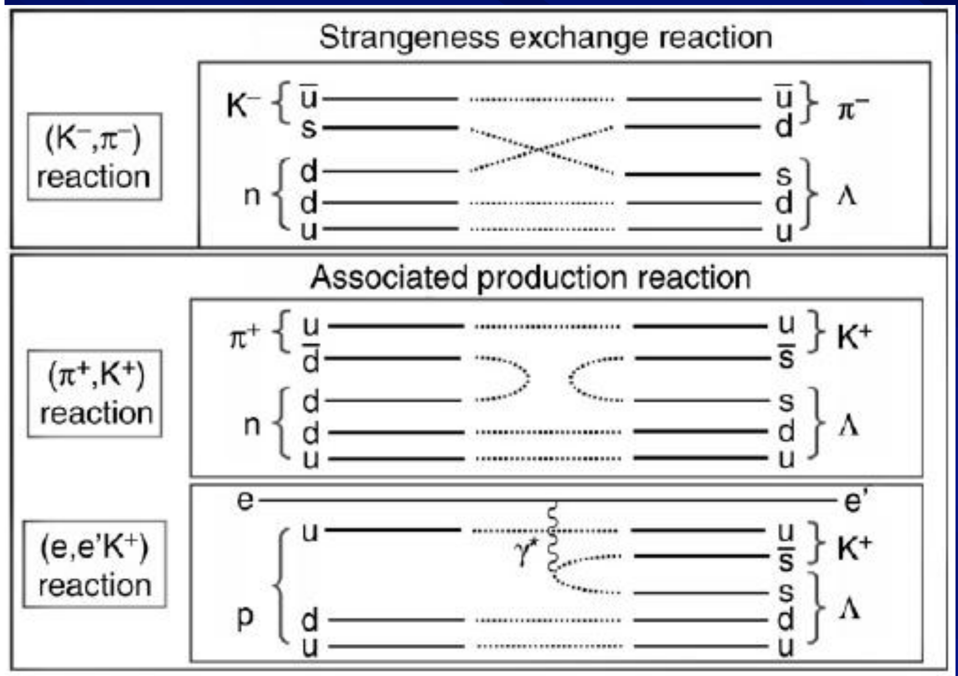
September 7th – 12th 2015, HYP2015, Sendai/Japan

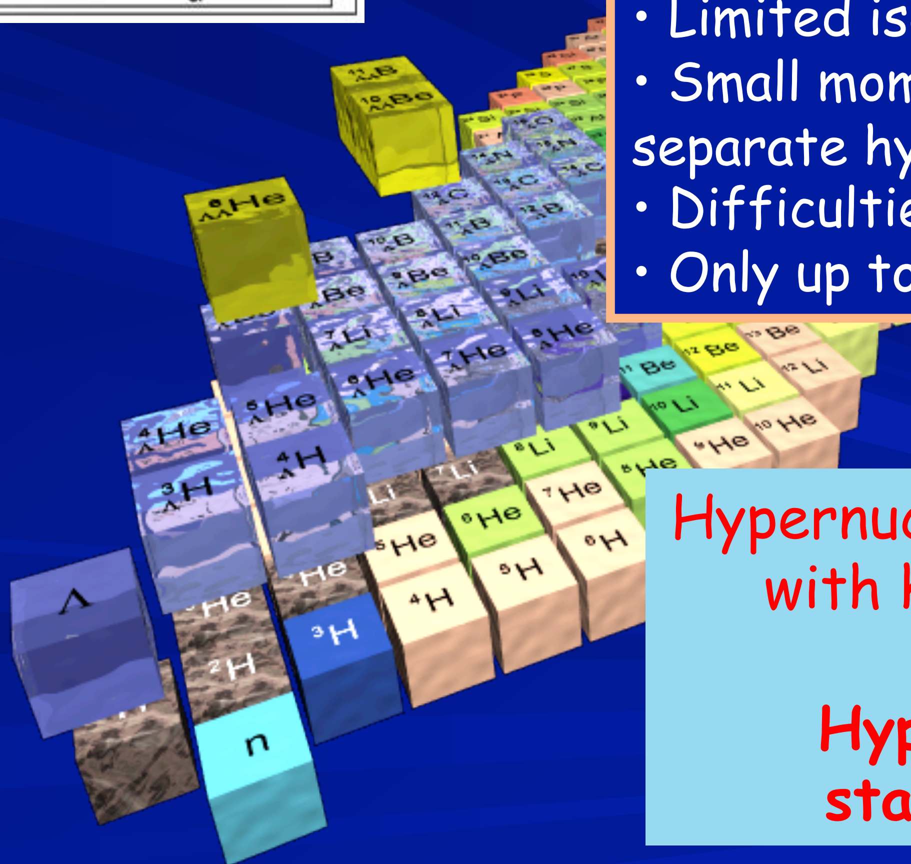
3D nuclear landscape







3D nuclear landscape



Advantage

- Precise spectroscopy
  - Structure in detail
- Clean experiment

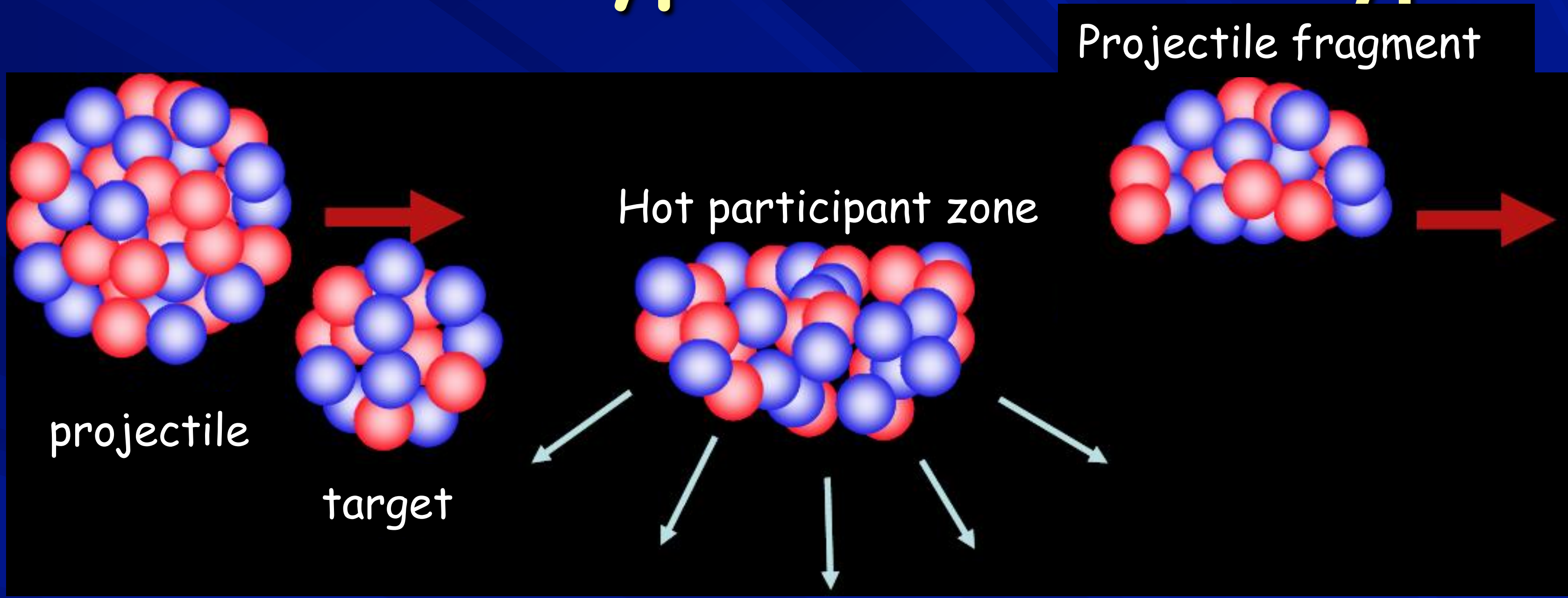
Difficulties

- Limited isospin
- Small momentum transfer to separate hypernuclei
- Difficulties on decay studies
- Only up to double-strangeness

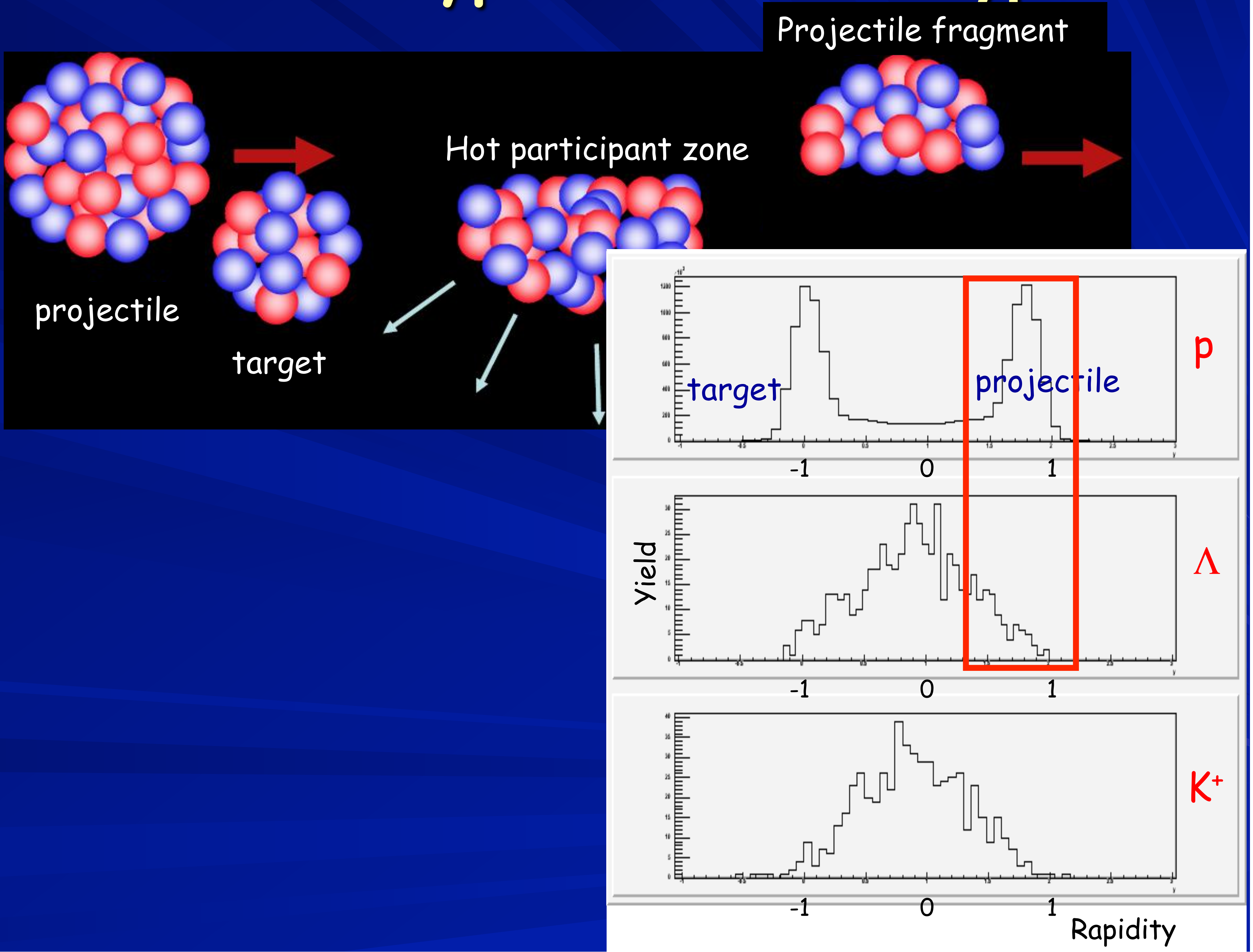
Hypernuclear spectroscopy with heavy ion beams

HypHI project, started in 2015

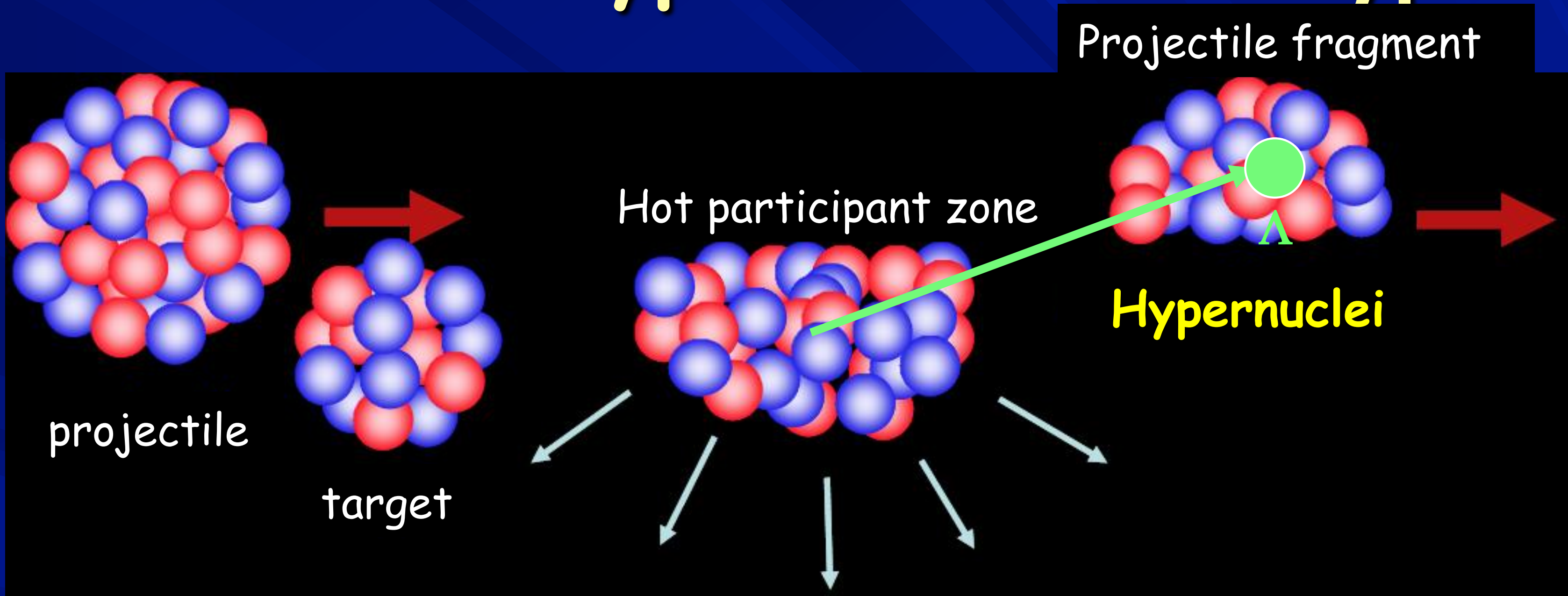
Production of Hypernuclei with HypHI



Production of Hypernuclei with HypHI

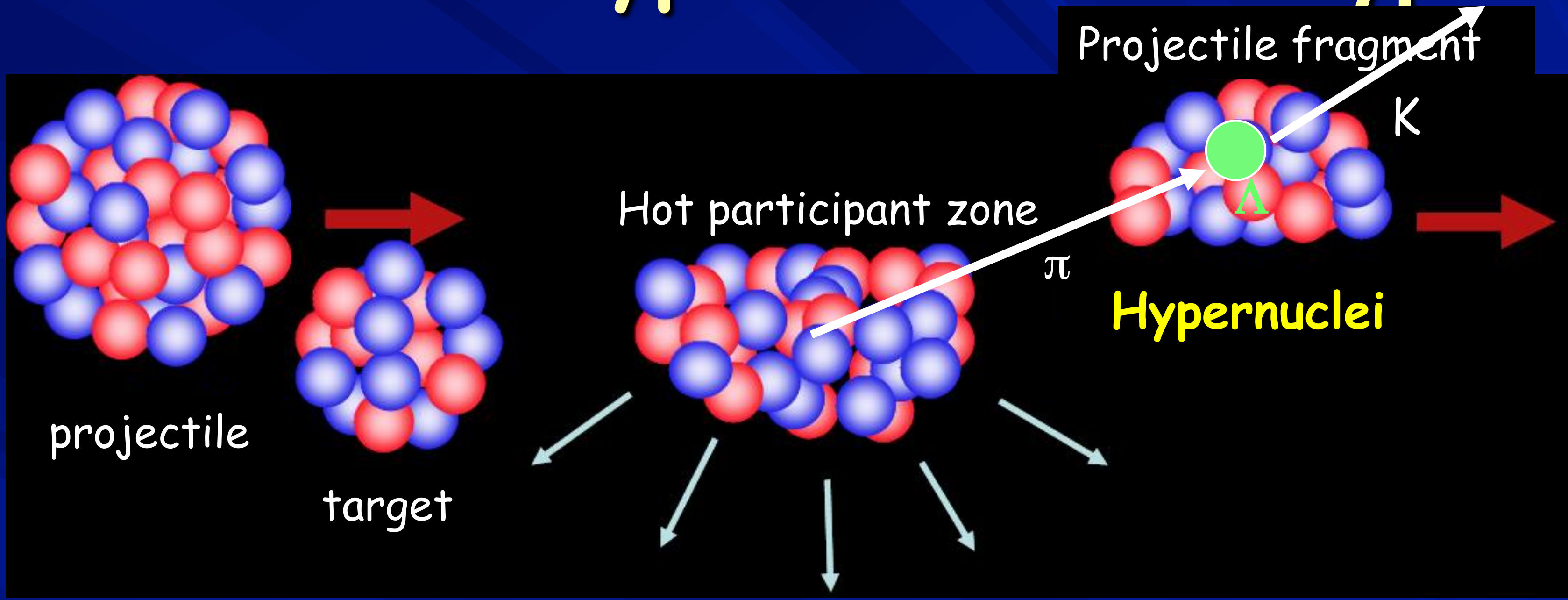


Production of Hypernuclei with HypHI



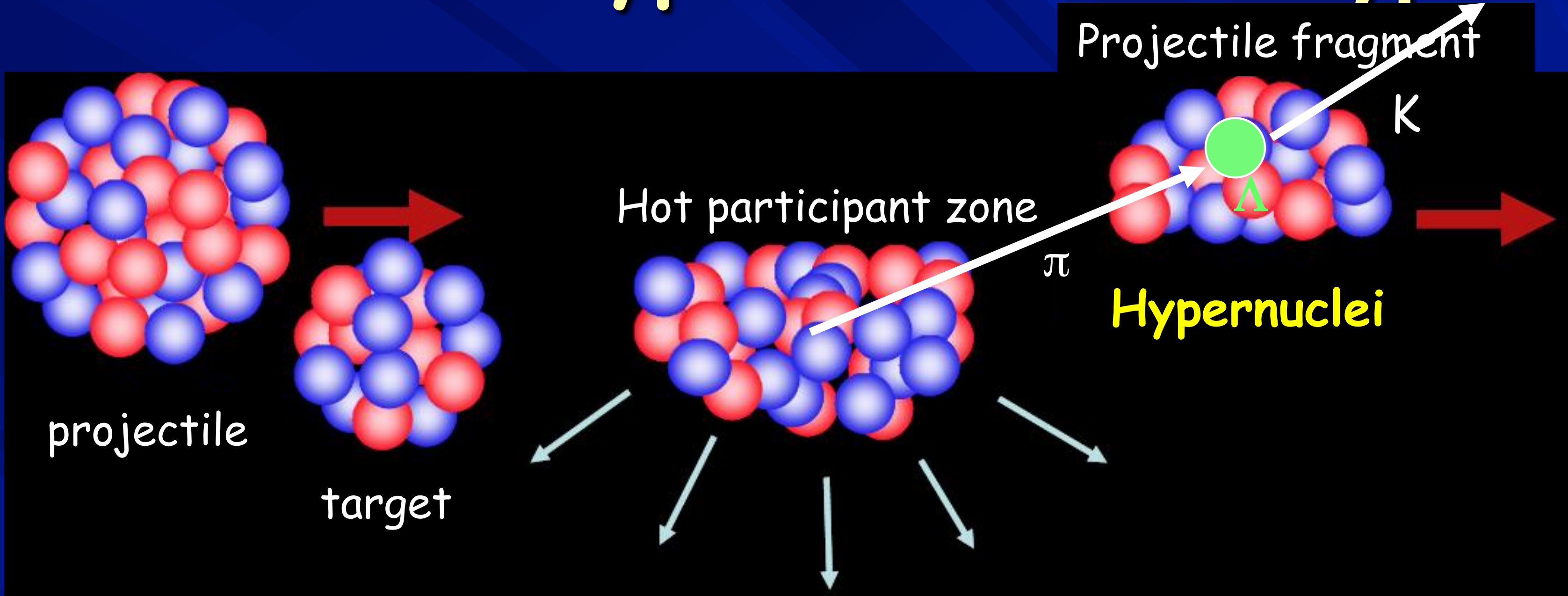
- Coalescence of Λ in projectile fragments

Production of Hypernuclei with HypHI



- Coalescence of Λ in projectile fragments
- (π^+, K^+) reactions in projectile fragments

Production of Hypernuclei with HypHI



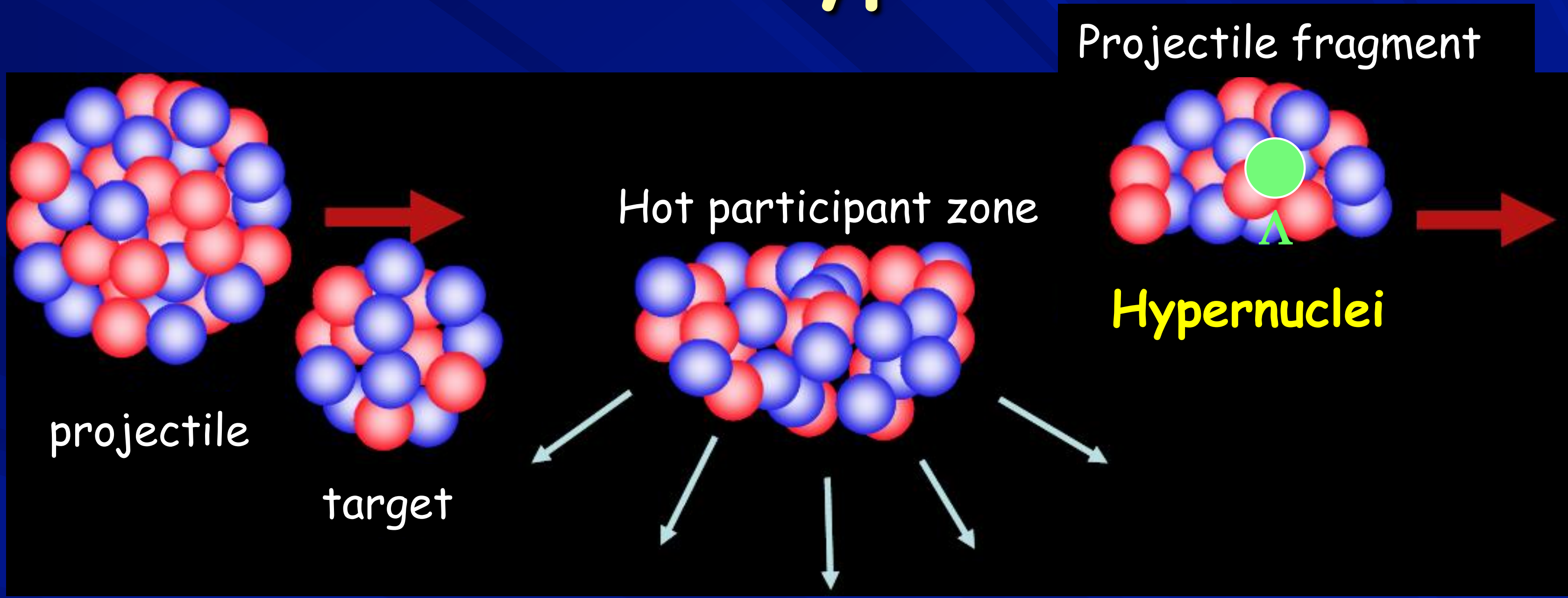
- Coalescence of Λ in projectile fragments
- (π^+,K^+) reactions in projectile fragments

- NN -> ΛKN : Energy threshold ~ 1.6 GeV
  - Heavy ion beams with E > 1.6 A GeV needed
    - Stable heavy ion beam at GSI
    - Stable heavy ion beam at FAIR
    - RI-beam from FRS and super-FRS

Accessible to neutron- and proton rich hypernuclei

Heavy hypernuclei: A > 4

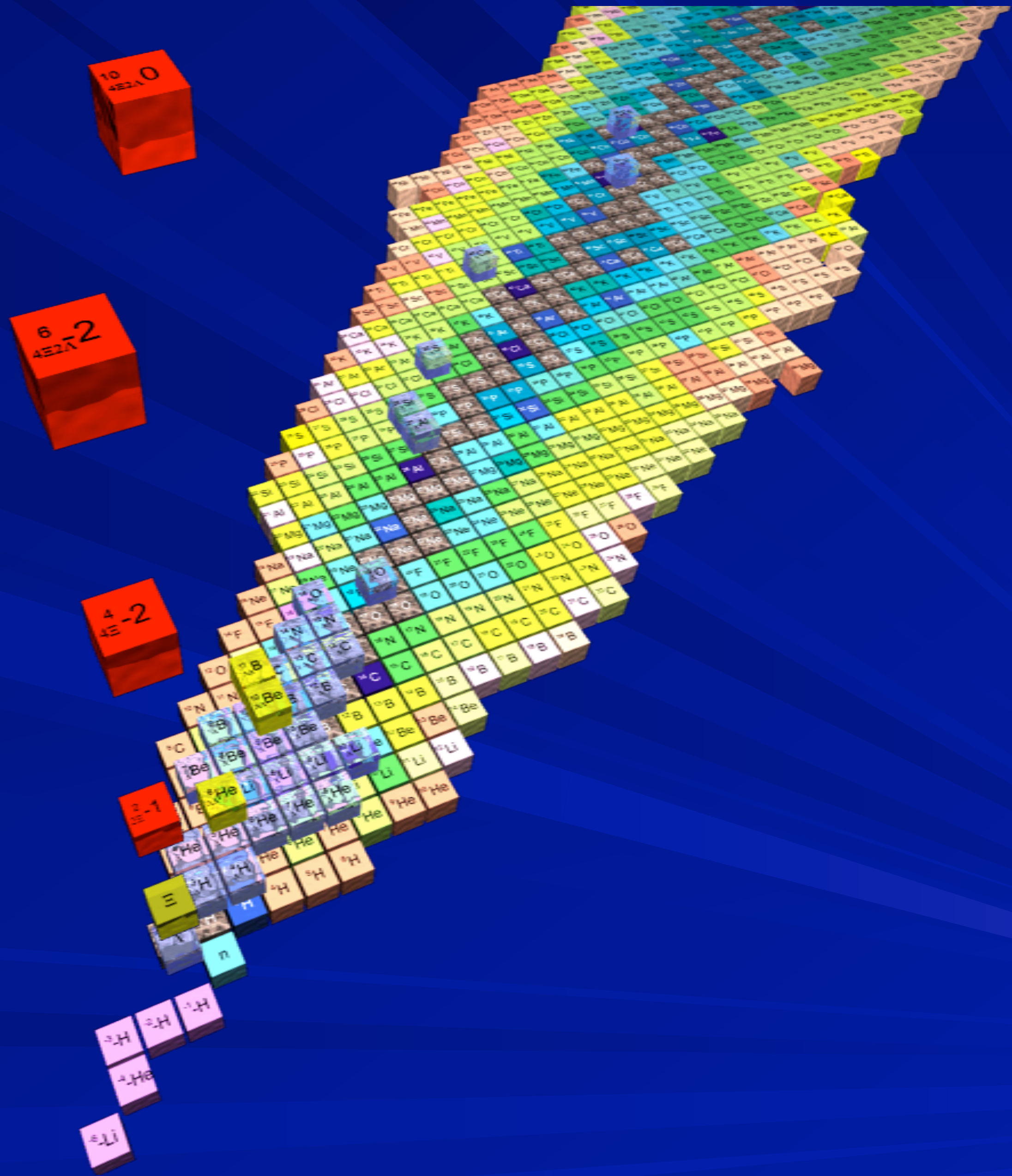
Relativistic hypernuclei



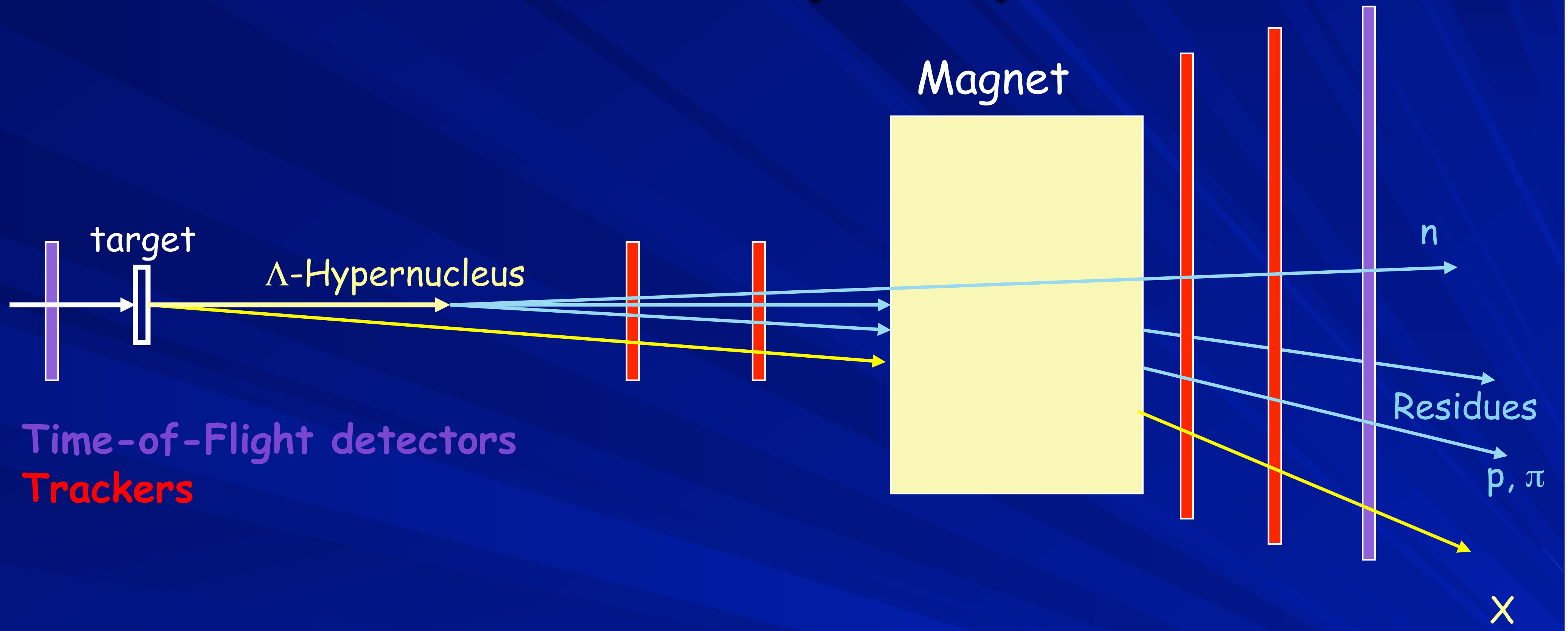
- **Large Lorentz factor** γ (>3)
  - Effective lifetime : Longer by the Lorentz factor
    200 ps -> 600 ps at GSI (ct ~ 20 cm)
    200 ps -> 4 ns at FAIR (ct ~ 120 cm)

- **Hypernuclear separation and spin precession**
  - Can be feasible with 20 Tm at 20 A GeV
  - Large spin precession in magnetic fields
    - 225 degrees with free-Λ magnetic moment

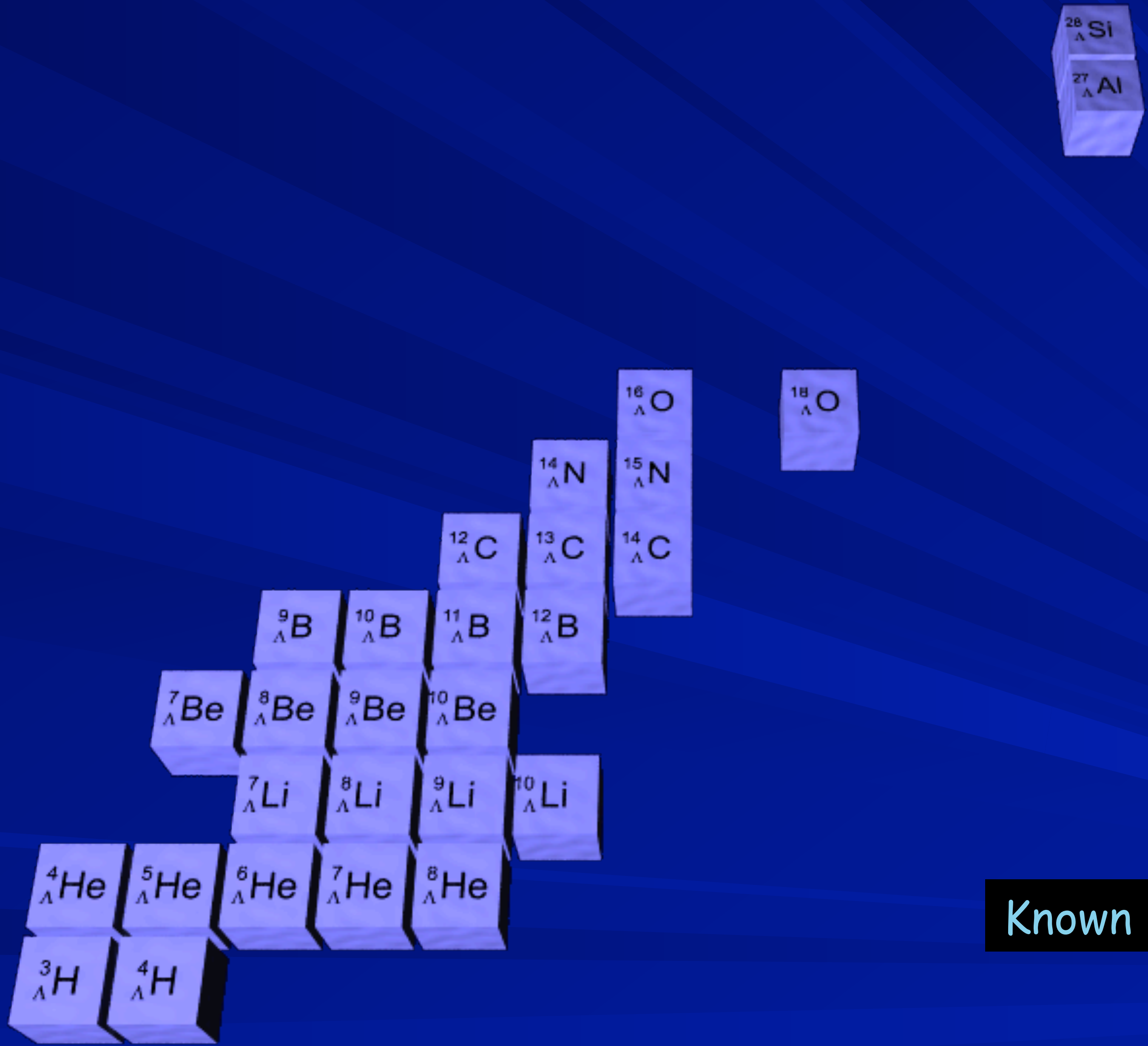
Nuclear matter with multiple-strangeness



Detection principle



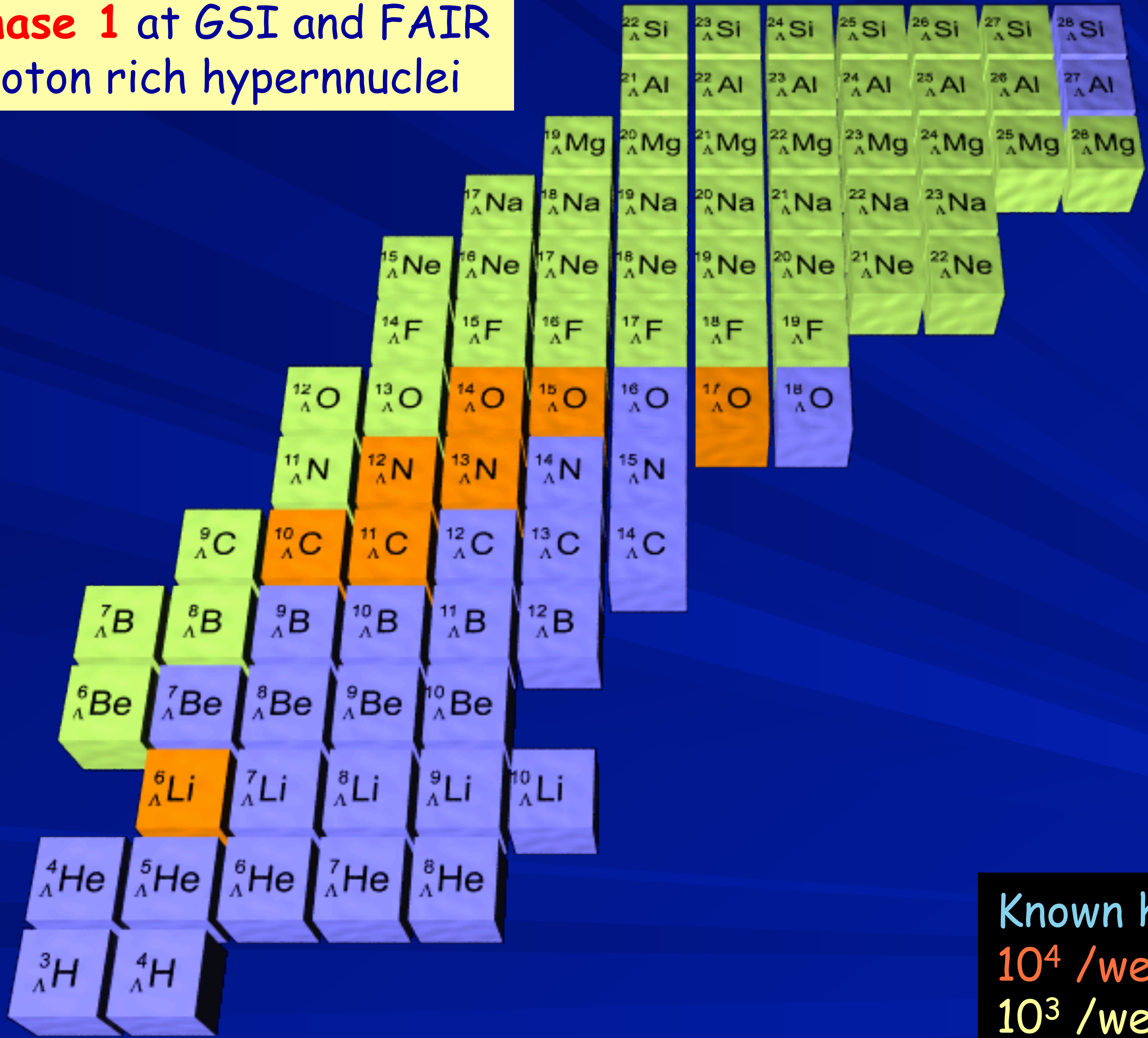
Present hypernuclear landscape



Known hypernuclei

Hypernuclear landscape with HypHI

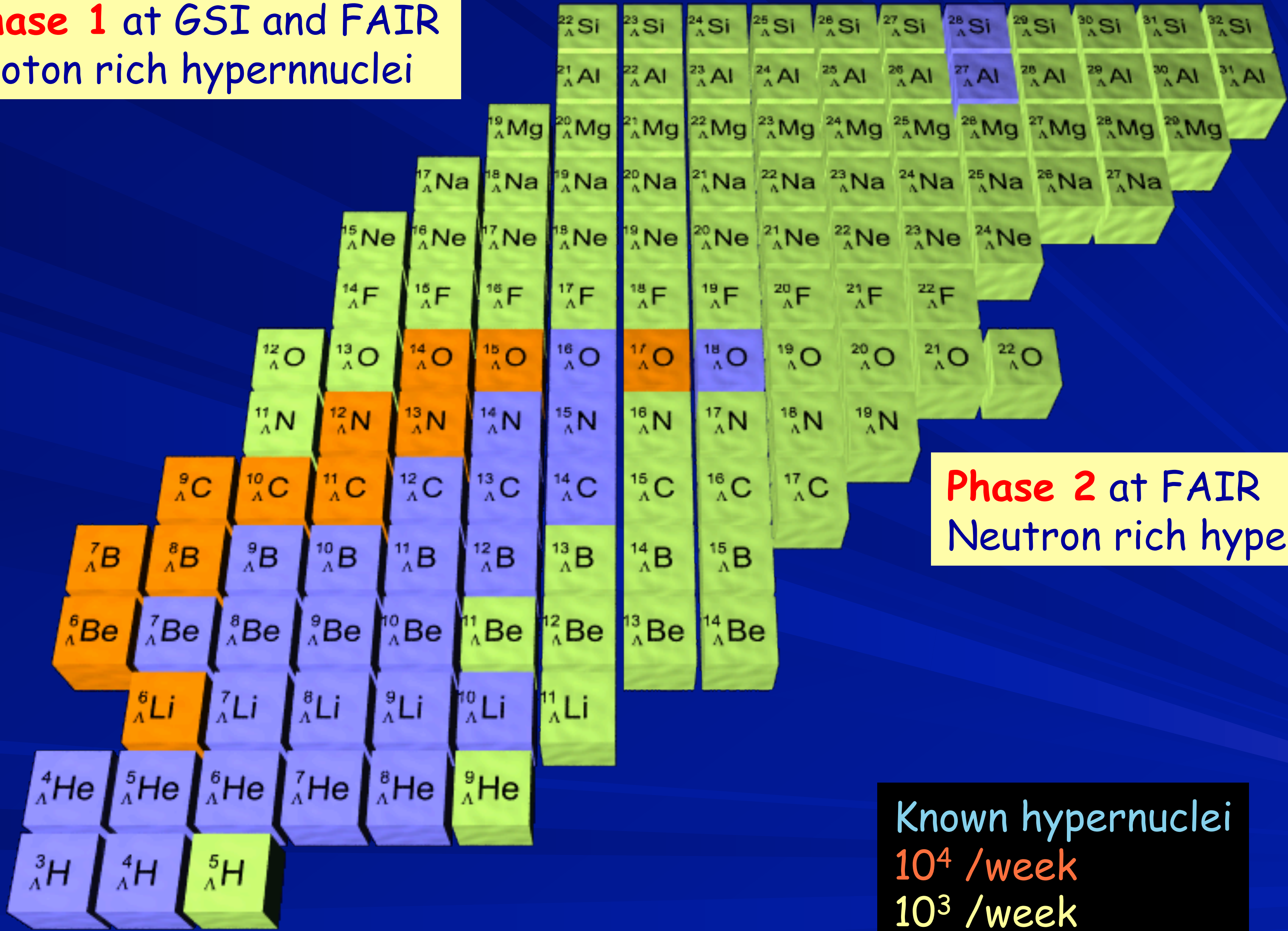
Phase 1 at GSI and FAIR
Proton rich hypernnuclei



Known hypernuclei
10^4 /week
10^3 /week

Hypernuclear landscape with HypHI

Phase 1 at GSI and FAIR
Proton rich hypernnuclei

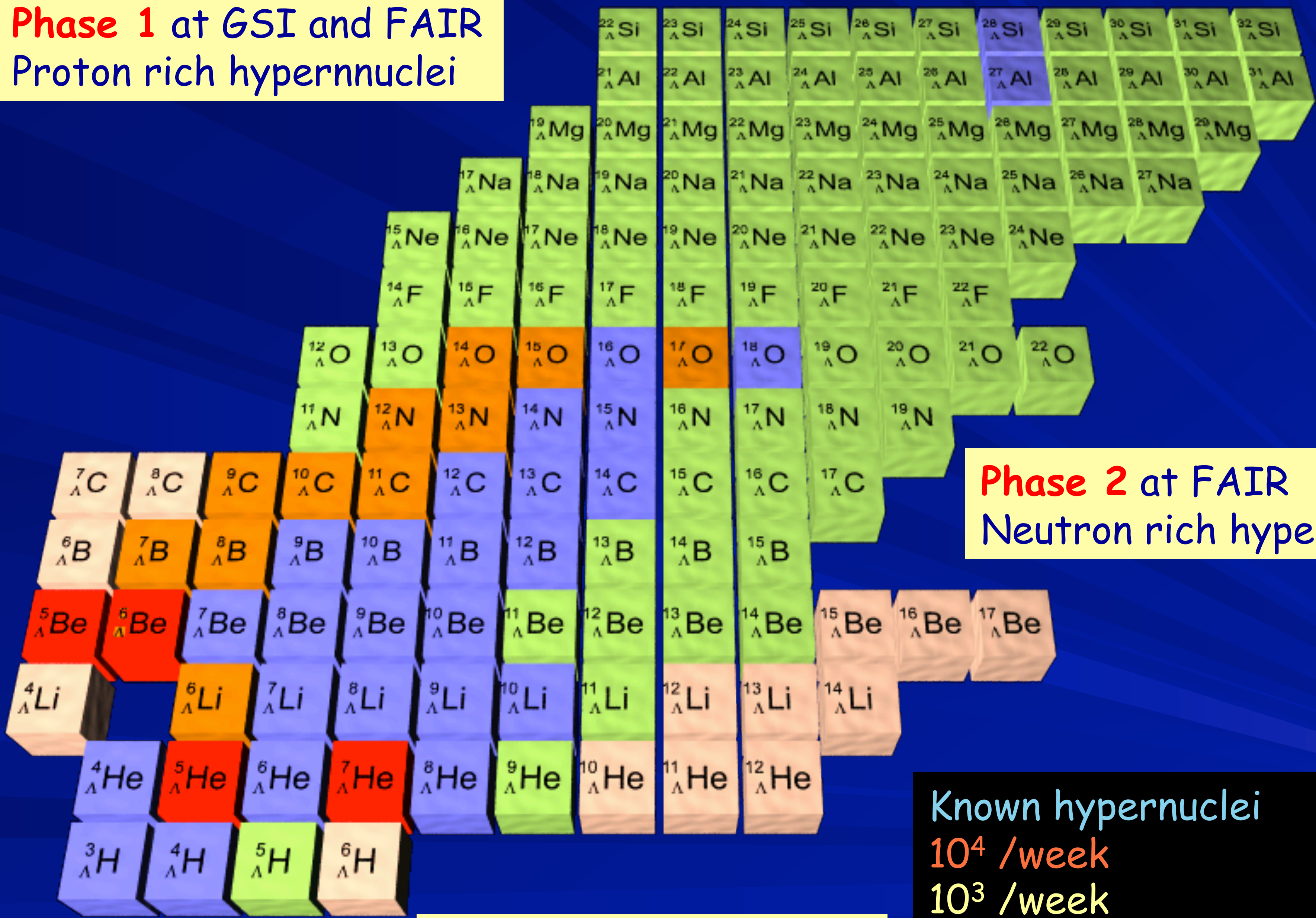


Phase 2 at FAIR
Neutron rich hypernuclei

Known hypernuclei
10^4 /week
10^3 /week

Hypernuclear landscape with HypHI

Phase 1 at GSI and FAIR
Proton rich hypernnuclei



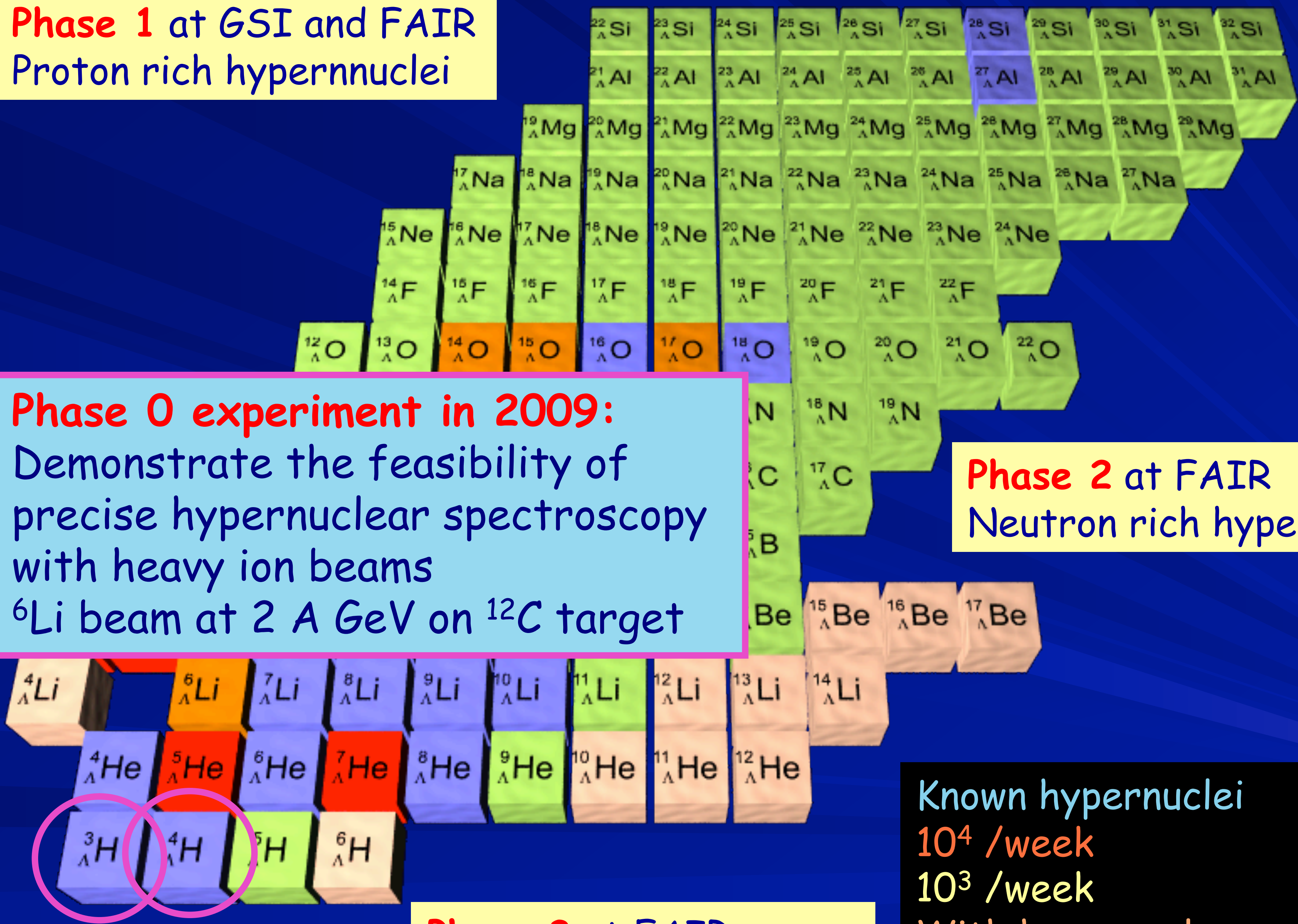
Phase 2 at FAIR
Neutron rich hypernuclei

Phase 3 at FAIR
Hypernuclear separator

Known hypernuclei
10^4 /week
10^3 /week
With hypernuclear separator
Magnetic moments

Hypernuclear landscape with HypHI

Phase 1 at GSI and FAIR
Proton rich hypernnuclei



Phase 0 experiment in 2009:
Demonstrate the feasibility of precise hypernuclear spectroscopy with heavy ion beams
^{6}Li beam at 2 A GeV on ^{12}C target

Phase 2 at FAIR
Neutron rich hypernuclei

Phase 3 at FAIR
Hypernuclear separator

Known hypernuclei
10^4 /week
10^3 /week
With hypernuclear separator
Magnetic moments

Presentations in the HYP series

- **2006, Mainz/Germany**
  - Ideas of the HypHI project and its Phase 0 (^{6}Li + ^{12}C)
- **2009, Tokai/Japan**
  - During the Phase 0 experiment
  - Progress on the Phase 0 experiment
- **2012, Barcelona/Spain**
  - Preliminary results of Phase 0

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  - Preliminary results of Phase 0

C. Rappold et al., NPA 913 (2013) 170
C. Rappold et al., PRC 88 (2013) 041001(R)
C. Rappold et al., PLB 728 (2014) 543
C. Rappold et al., PLB 747 (2015) 129

- **2015, Sendai/Japan**
  - Published results on Phase 0 in 2013-2015
  - More results on Phase 0
  - Preliminary results on Phase 0.5 (^{20}Ne + ^{12}C)
  - New ideas with HypHI + FRS/super-FRS at GSI/FAIR

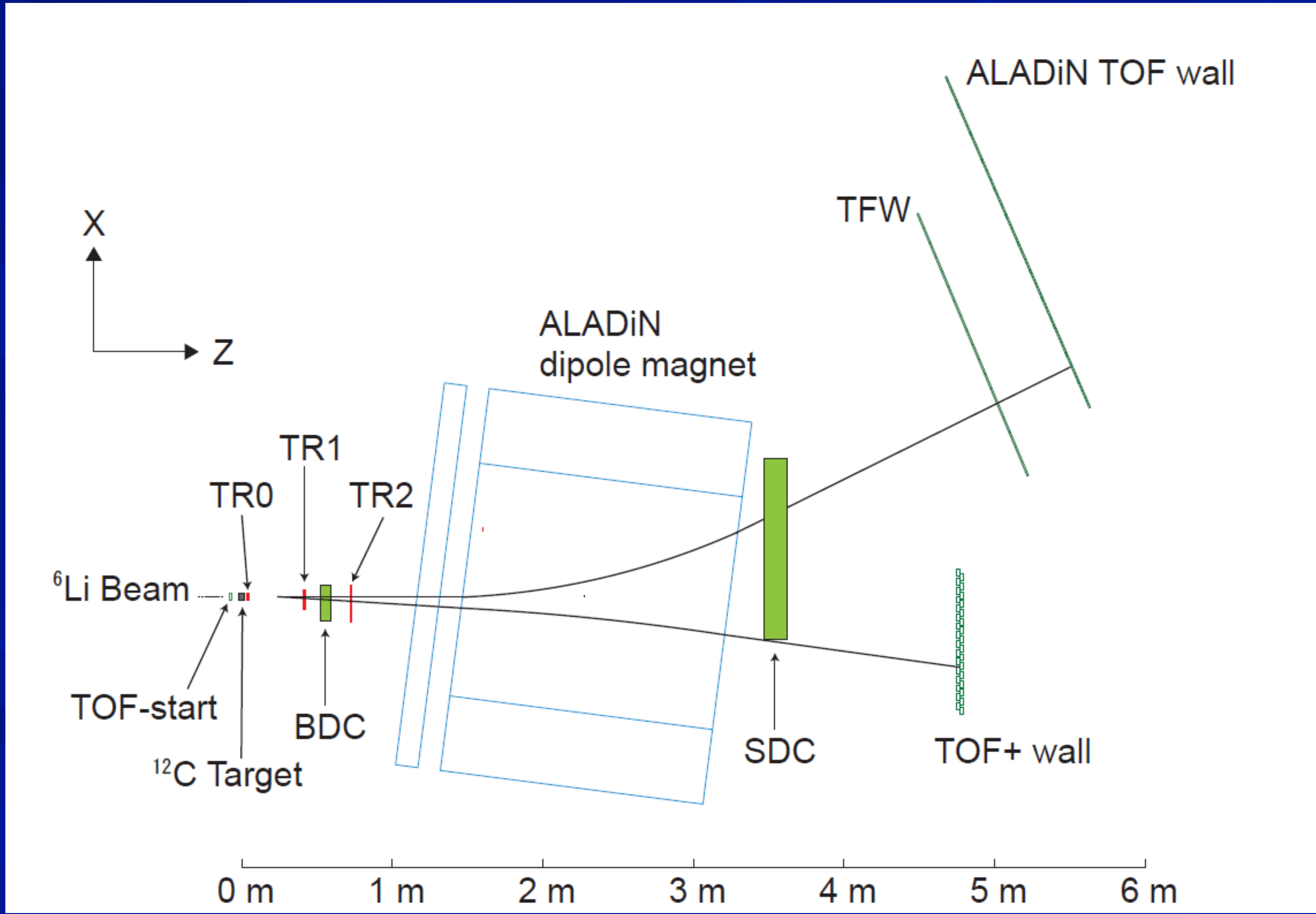
Topical session for the hypertriton lifetime, on Tuesday
• talk by Christophe Rappold for the HypHI results

HypHI Phase 0 in October 2009

- The goal of the Phase 0 experiments
  - To demonstrate the feasibility of precise hypernuclear spectroscopy with ^{6}Li primary beams at 2 A GeV : Mesonic decay $\Lambda \rightarrow \pi^- + p$

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

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



Funding

• Helmholtz-University Young Investigators Group VH-NG-239, 2006-2012

• DFG grant SA1696/1-1 2007-2009, TOF detectors

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Nuclear Physics A 913 (2013) 170–184

NUCLEAR PHYSICS A

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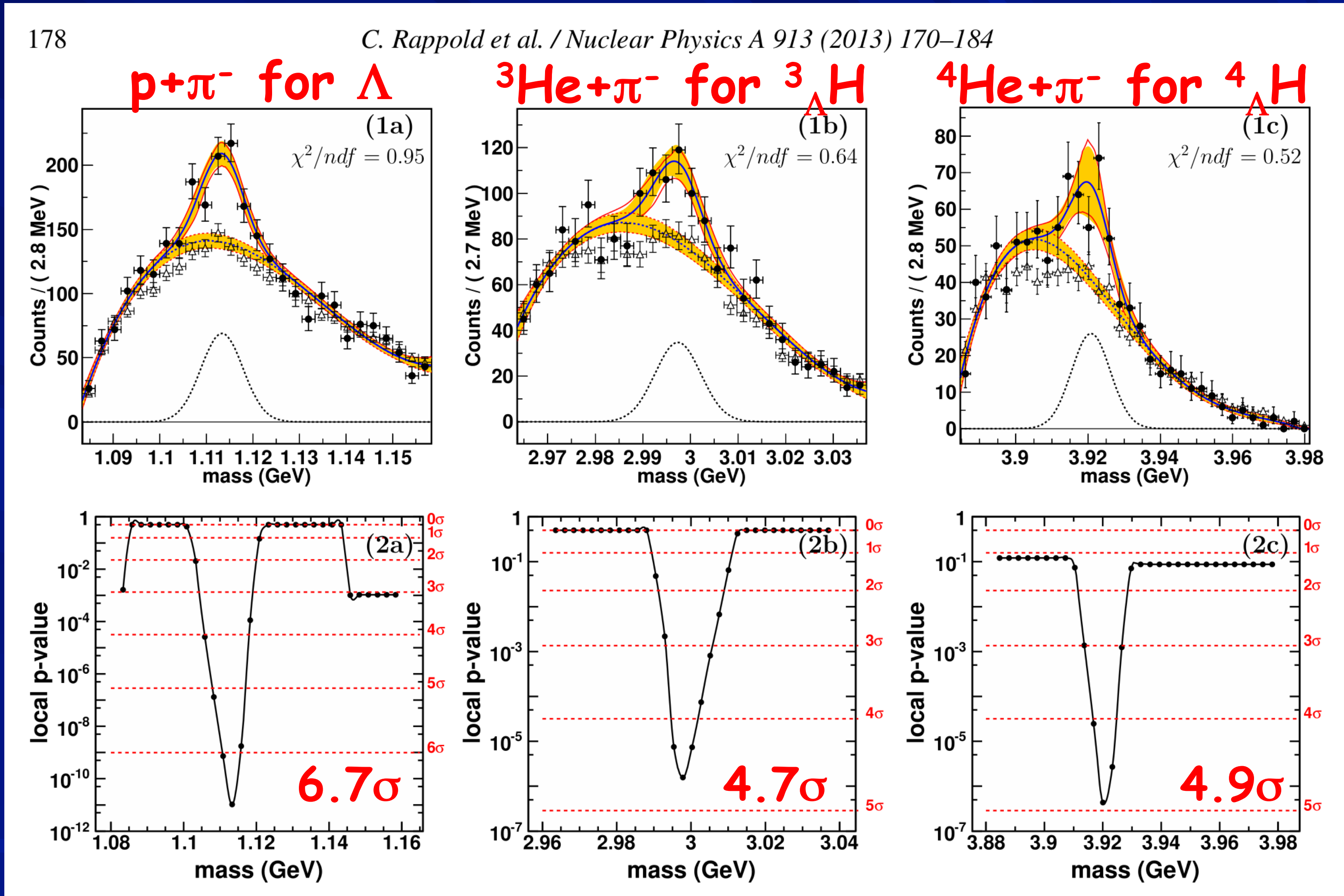
Hypernuclear spectroscopy of products from ^{6}Li projectiles on a carbon target at 2 *A* GeV

C. Rappold [a,b,∗], E. Kim [b,c], D. Nakajima [b,d], T.R. Saito [b,e,f,∗], O. Bertini [b,e], S. Bianchin [b], V. Bozkurt [b,g], M. Kavatsyuk [h], Y. Ma [b,e], F. Maas [b,e,f], S. Minami [b], B. Özel-Tashenov [b], K. Yoshida [b,f,i], P. Achenbach [e], S. Ajimura [j], T. Aumann [k,b], C. Ayerbe Gayoso [e], H.C. Bhang [c], C. Caesar [k], S. Erturk [g], T. Fukuda [l], B. Göküzüm [b,g], E. Guliev [h], T. Hiraiwa [m], J. Hoffmann [b], G. Ickert [b], Z.S. Ketenci [g], D. Khaneft [b,e], M. Kim [c], S. Kim [c], K. Koch [b], N. Kurz [b], A. Le Fèvre [b,n], Y. Mizoi [l], M. Moritsu [m], T. Nagae [m], L. Nungesser [e], A. Okamura [m], W. Ott [b], J. Pochodzalla [e], A. Sakaguchi [i], M. Sako [m], C.J. Schmidt [b], M. Sekimoto [o], H. Simon [b], H. Sugimura [m], T. Takahashi [o], G.J. Tambave [h], H. Tamura [p], W. Trautmann [b], S. Voltz [b], N. Yokota [m], C.J. Yoon [c]

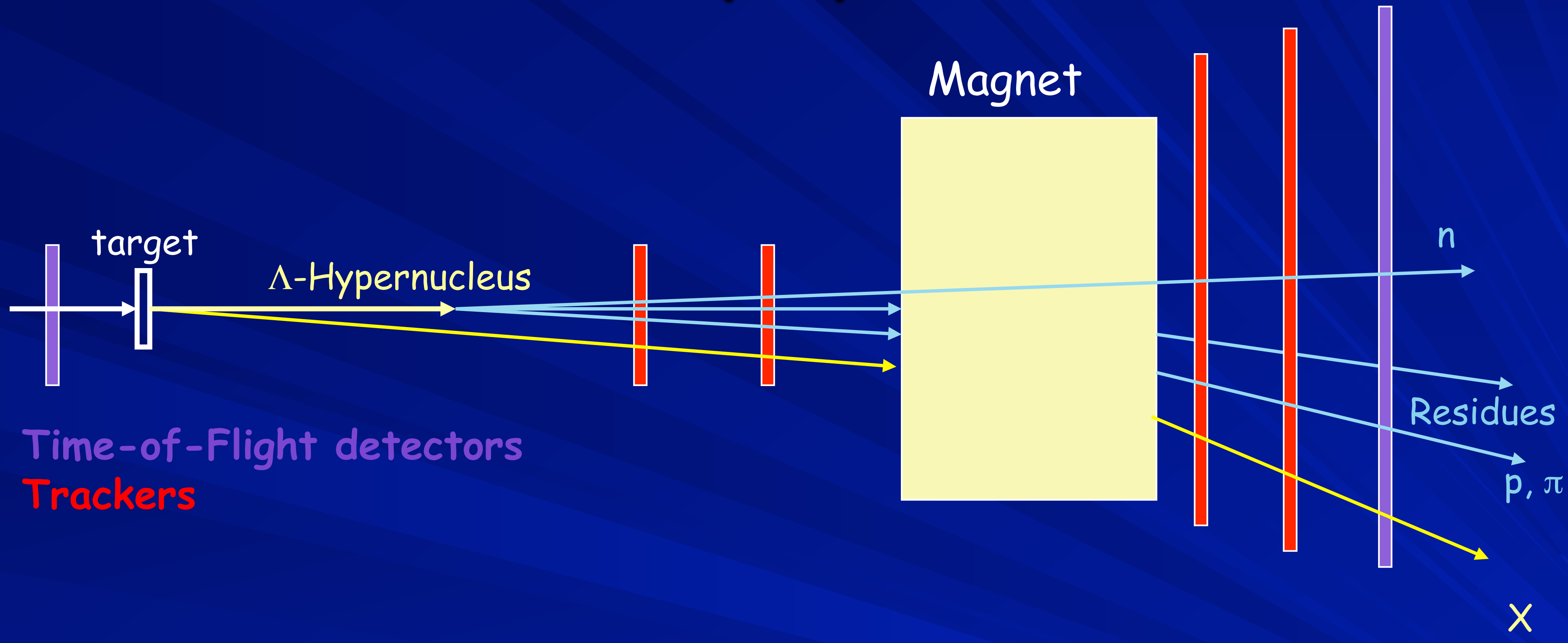
Invariant mass distribution



a

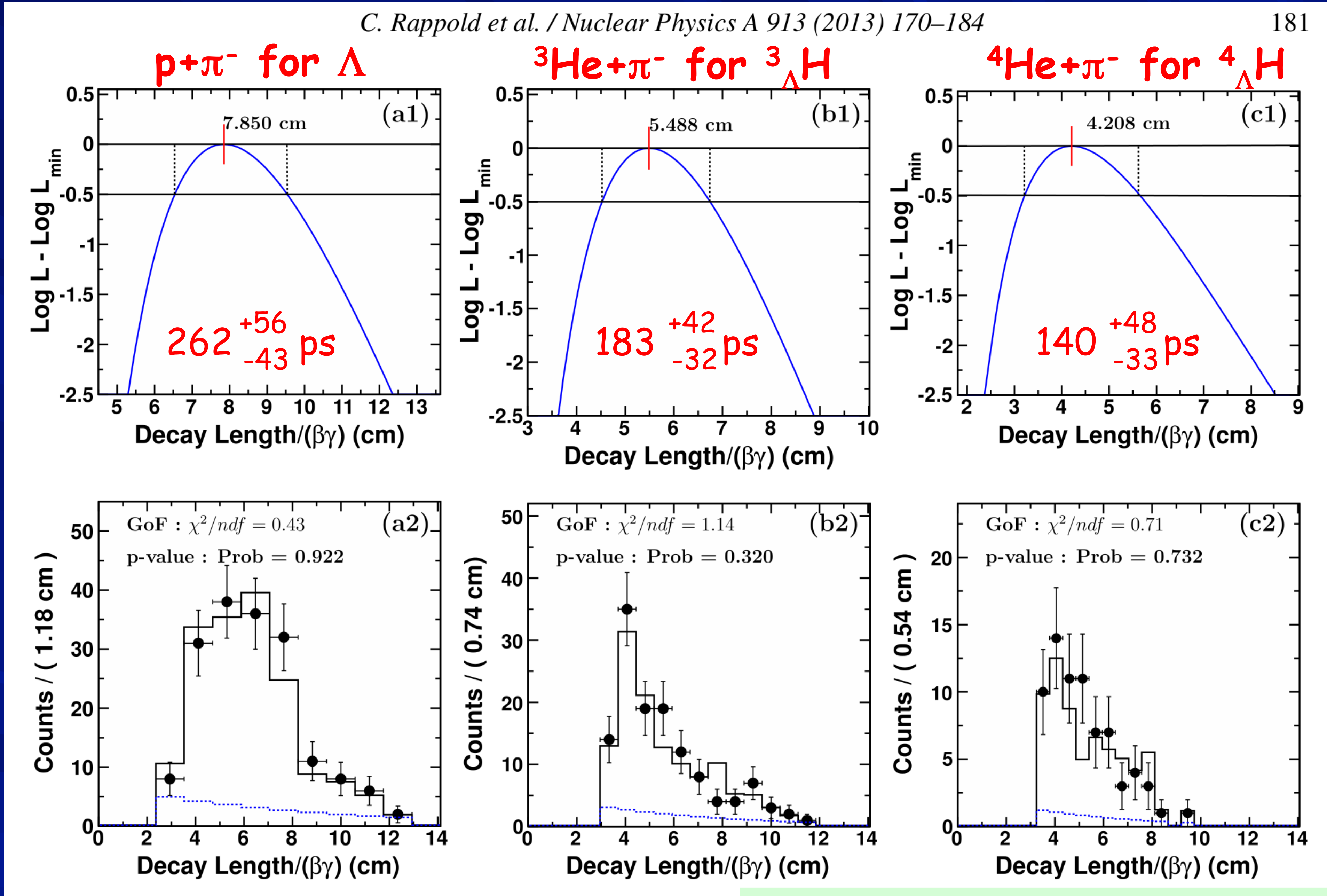
- Statistical analysis of Λ invariant mass (-100 mm < Vertex Z < 300 mm) with RooStats and RooFit package
- Fitting model = n_s *(Gaus: sig_m, sig_s)* + n_b *(Chebychev: a0, a1, a2)*

Vertex -> proper time $c\tau$



➡ talk by C. Rappold on Tuesday

Lifetime: Unbinned maximum likelihood fitting



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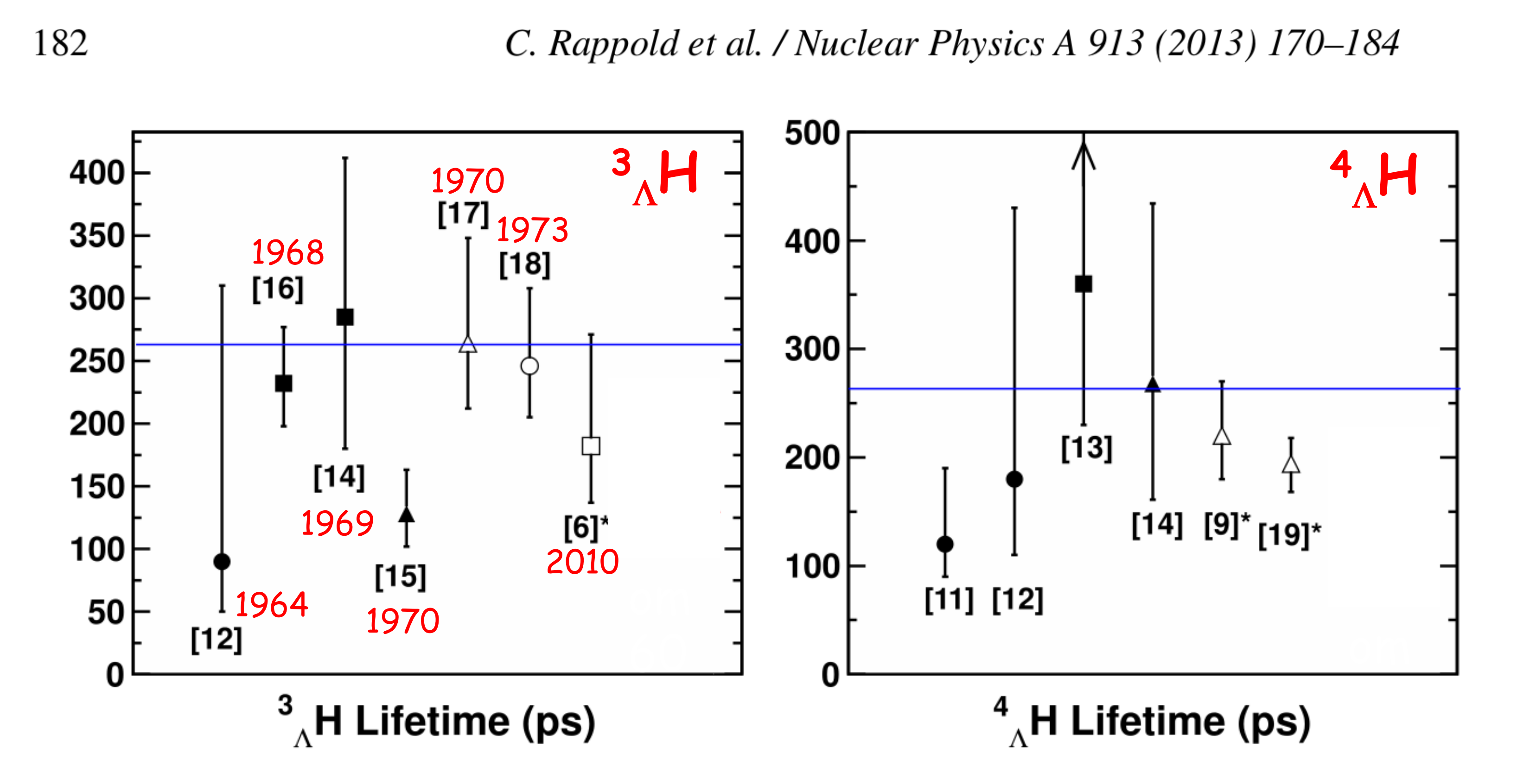
Comparison to the world data



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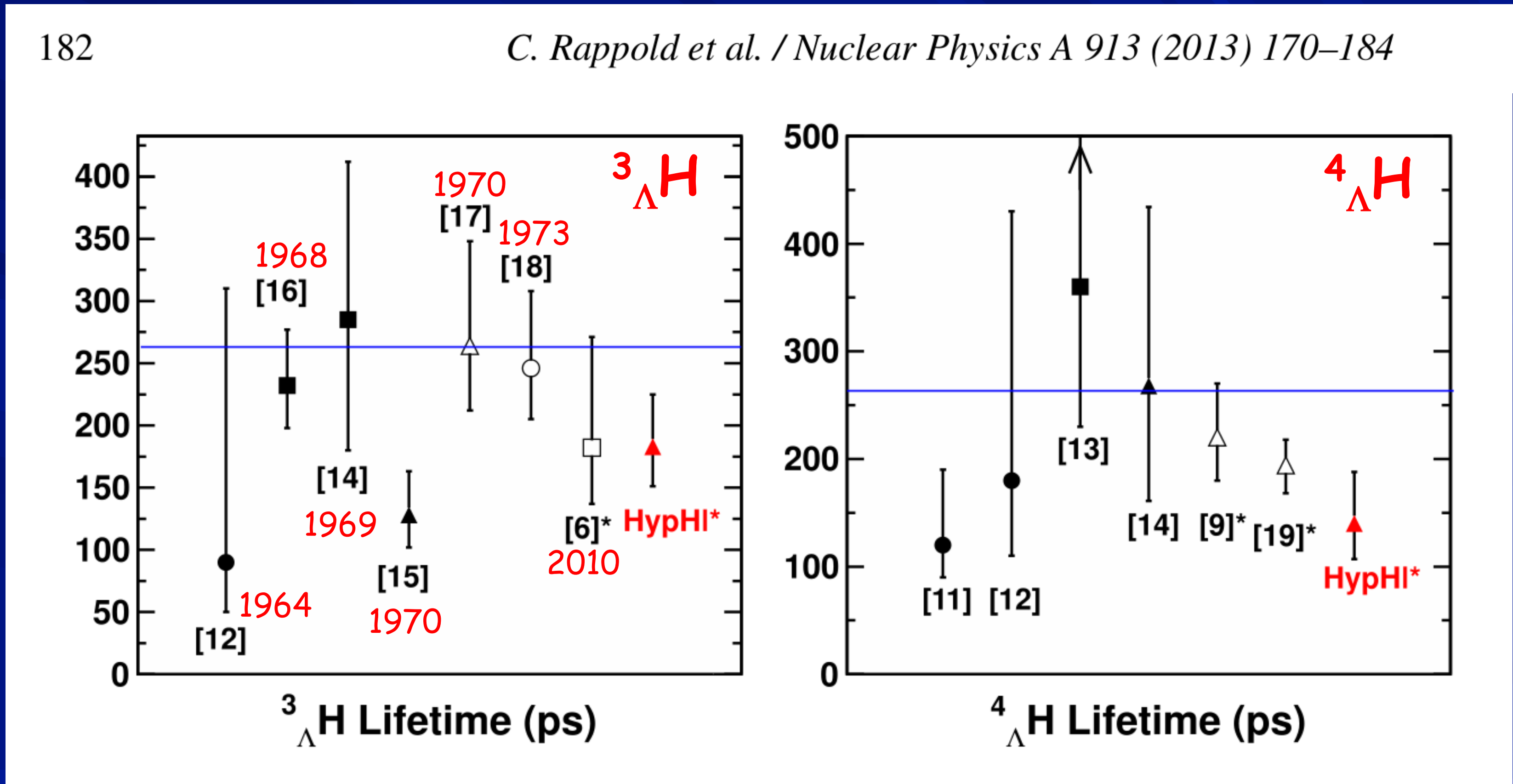
Comparison to the world data



FIRST evidence of the short hypertriton lifetime with the counter experiment technique (~2σ)

➡ talk by C. Rappold on Tuesday

Lifetime: Analysis on the existing data

Physics Letters B 728 (2014) 543–548

Contents lists available at ScienceDirect

Physics Letters B

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

C. Rappold [a,b,*], T.R. Saito [a,c,d], O. Bertini [a,c], S. Bianchin [a], V. Bozkurt [a,e], M. Kavatsyuk [f], E. Kim [a,g], Y. Ma [a,c], F. Maas [a,c,d], S. Minami [a], D. Nakajima [a,h], B. Özel-Tashenov [a], K. Yoshida [a,d,i]

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- Combined analyses with calculated likelihood functions
- Bayesian analysis

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Averaged combination
Bayesian approach

A B S T R A C T

A statistical combination of the experimental lifetime estimations available in the literatures is performed for ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$, including several recent measurements. The combined average values of the lifetime for ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ are respectively 216^{+19}_{-16} ps and 192^{+20}_{-18} ps with a reduced χ^2 of 0.89 and 0.48. A new insight into the lifetime estimation of the HypHI Phase 0 experiment by a Bayesian approach is also presented. In this approach, several different prior distributions including the combination of previous lifetime data and a Jeffrey prior are used. The principal mode and the smallest credible interval at 68% of the posterior distribution, given by the prior belief of the previous measurements, are 217^{+19}_{-16} ps and 194^{+20}_{-18} ps respectively for ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$. The two employed approaches have revealed that the lifetime of hypernuclei ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ can be shor

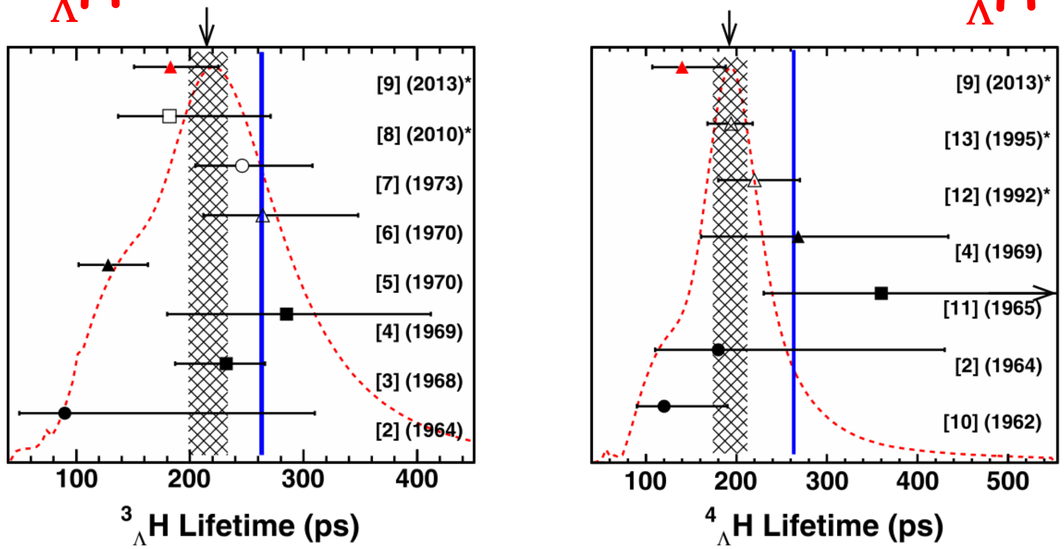
→ talk by C. Rappold on Tuesday

Lifetime: Analysis on the existing data

C. Rappold et al. / Physics Letters B 728 (2014) 543–548 545

$^{3}_{\Lambda}H$ $\quad$ $^{4}_{\Lambda}H$

216^{+19}_{-16} ps



192^{+20}_{-18} ps

Fig. 2. (Color online.) World data comparison of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ lifetimes. The combined average is represented by the arrow at the top, while the width of the hatched band corresponds to the one standard deviation of the average. The vertical line at 263.2 ps with width of ±2 ps shows the known lifetime of Λ hyperon. References to counter experiments is marked by an asterisk.

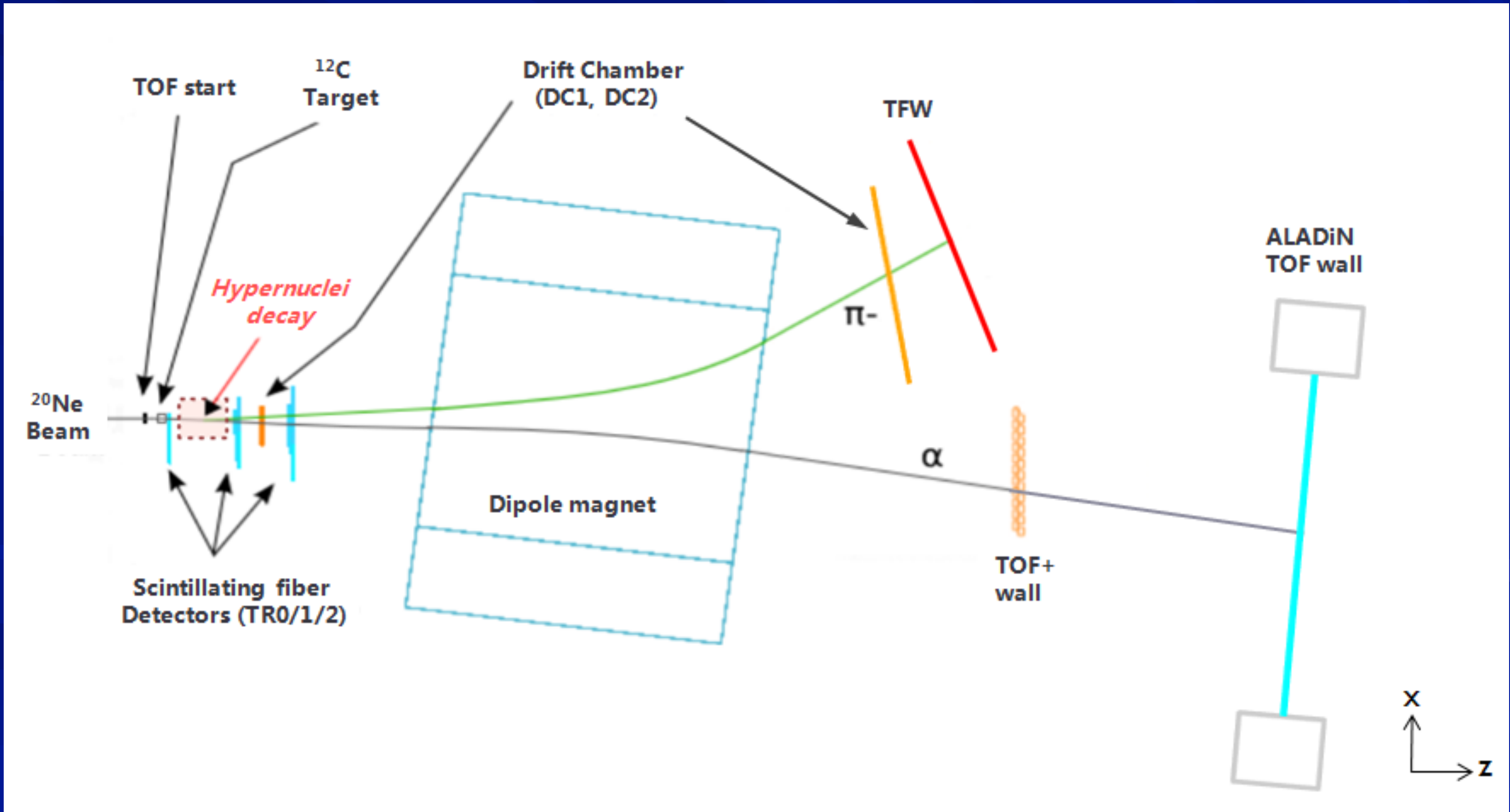
Bayesian analyses:

- Upper limit with 95 % confidence level
  - $^{3}_{\Lambda}H$: 250 ps (B_{10} = 2.7)
  - $^{4}_{\Lambda}H$: 227 ps (B_{10} = 3.8)

→ talk by C. Rappold on Tuesday

Phase 0.5 experiment in March 2010

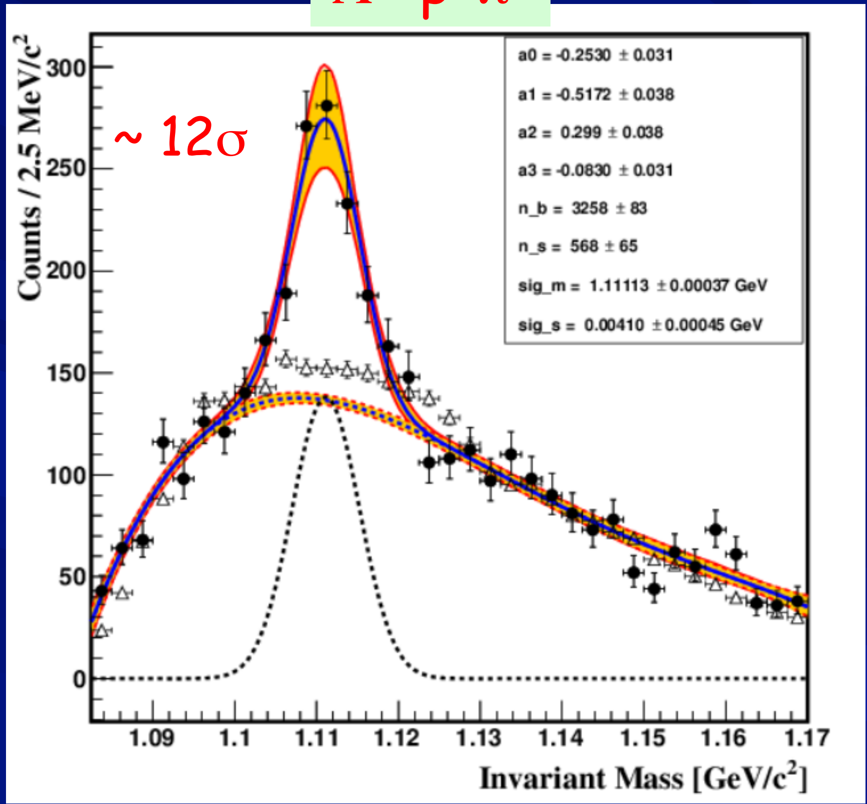
- Hypernuclear spectroscopy with heavier projectiles: ^{20}Ne
- H and He hypernuclei
- Li, Be, B and C hypernuclei
- Analyses in progress



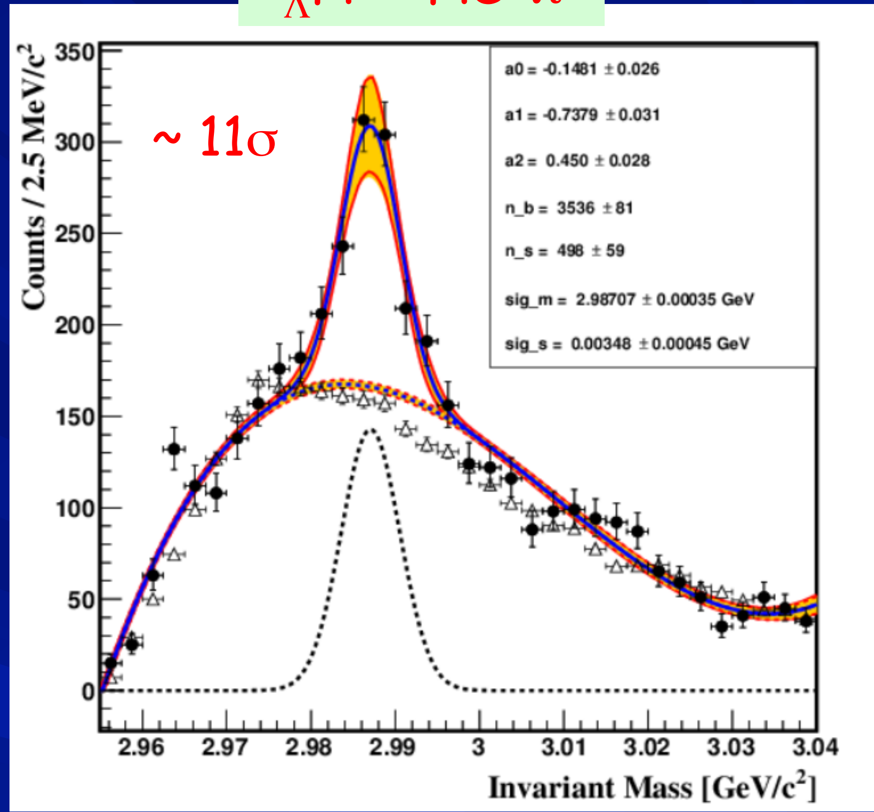
V. Bozkurt and K. Yoshida, PhD thesis

$^{20}Ne+^{12}C$: $\Lambda \to p+\pi^-$ and $^{3}_{\Lambda}He \to {}^{3}He+\pi^-$

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

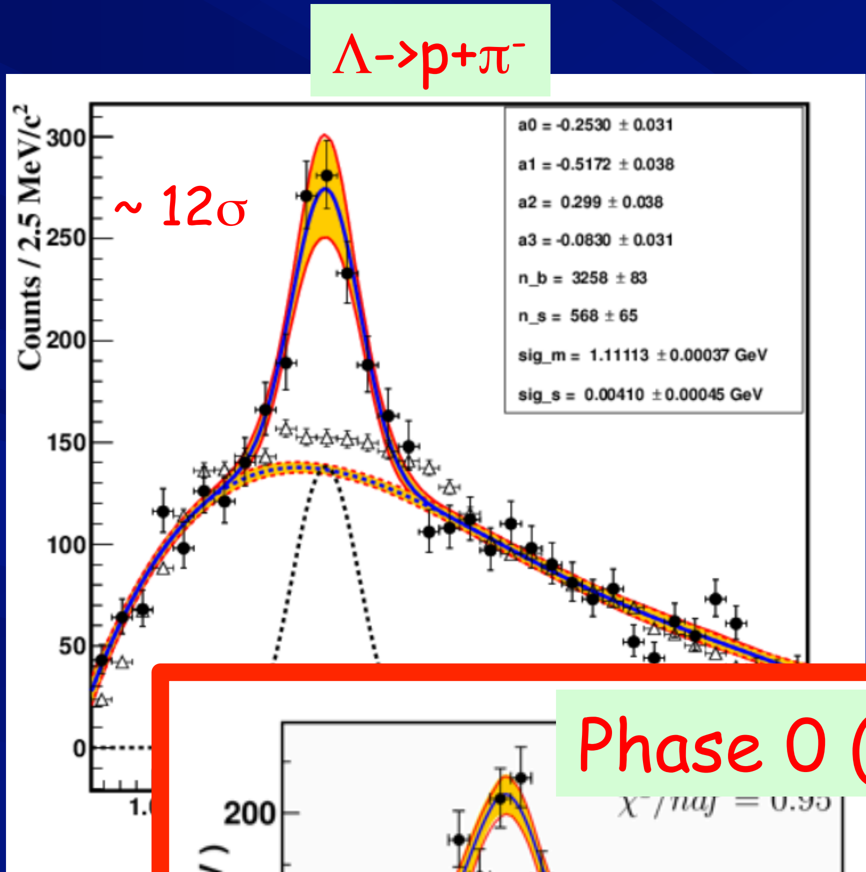


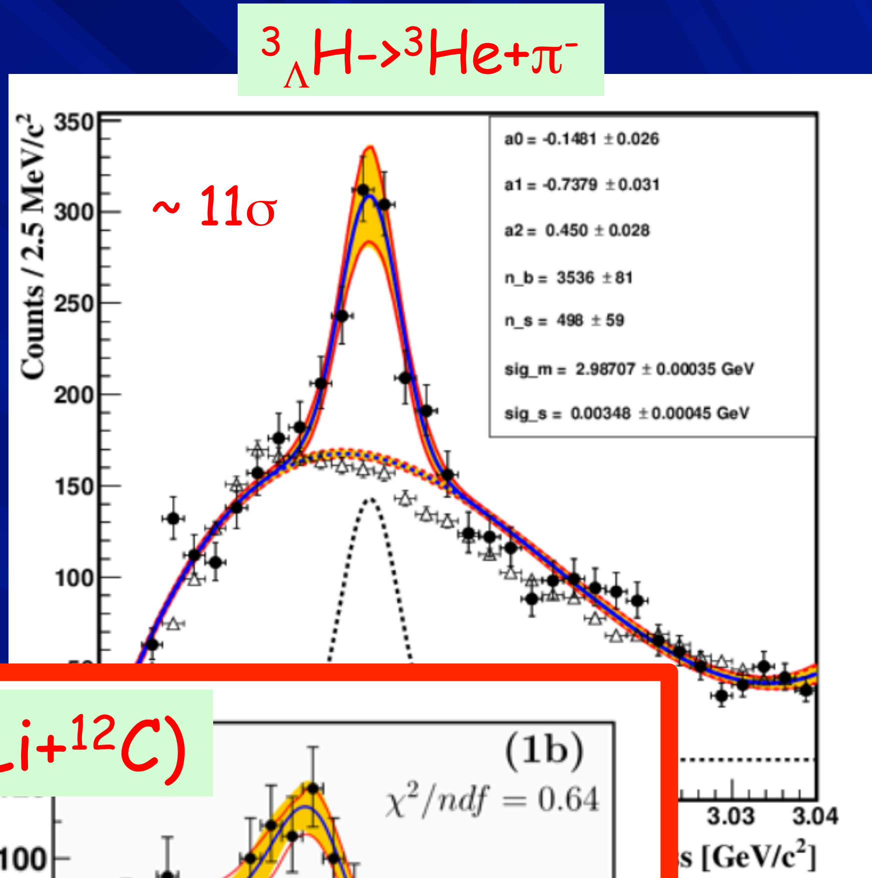
$^{3}_{\Lambda}H \to {}^{3}He+\pi^-$

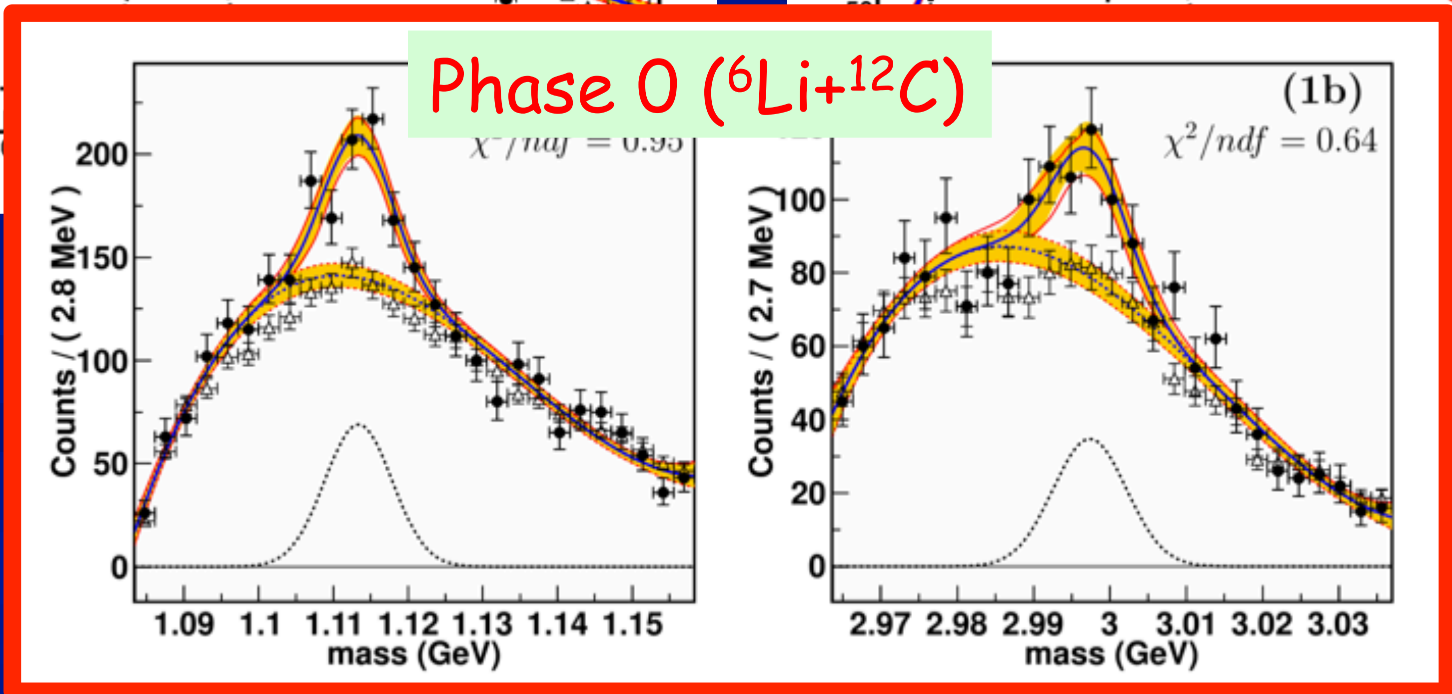


V. Bozkurt, Ph.D. thesis, to be published

$^{20}Ne+^{12}C$: $\Lambda \to p+\pi^-$ and $^{3}_{\Lambda}He \to {}^{3}He+\pi^-$



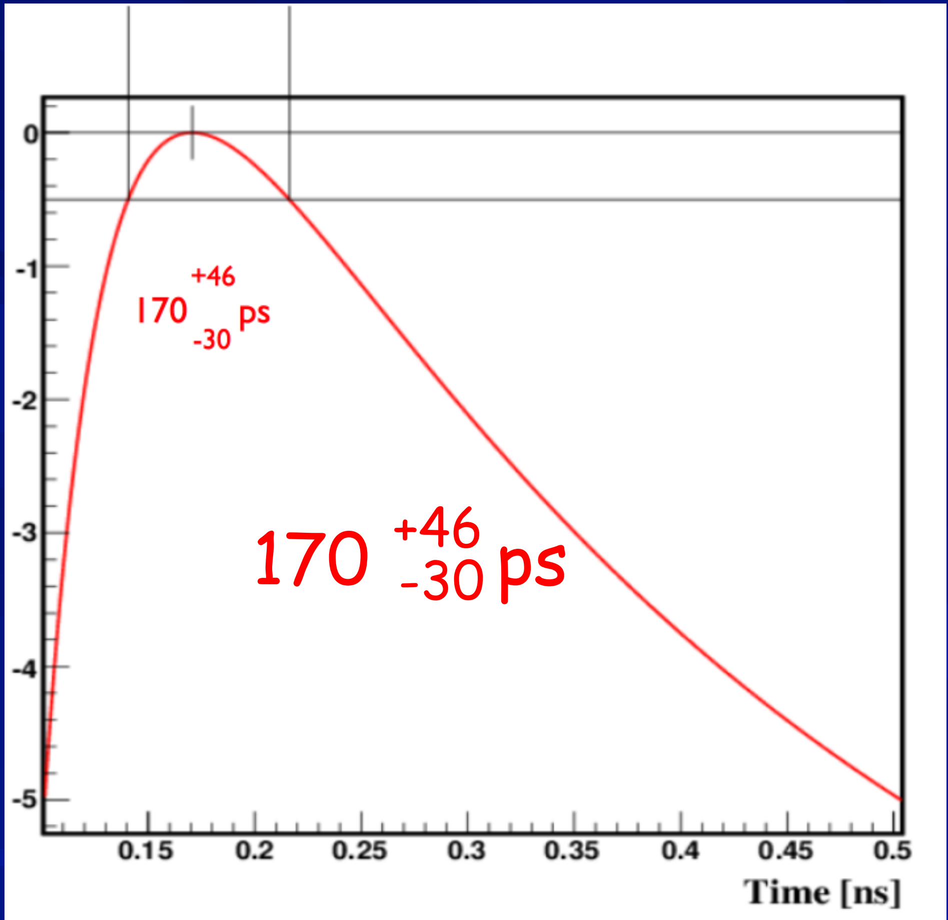


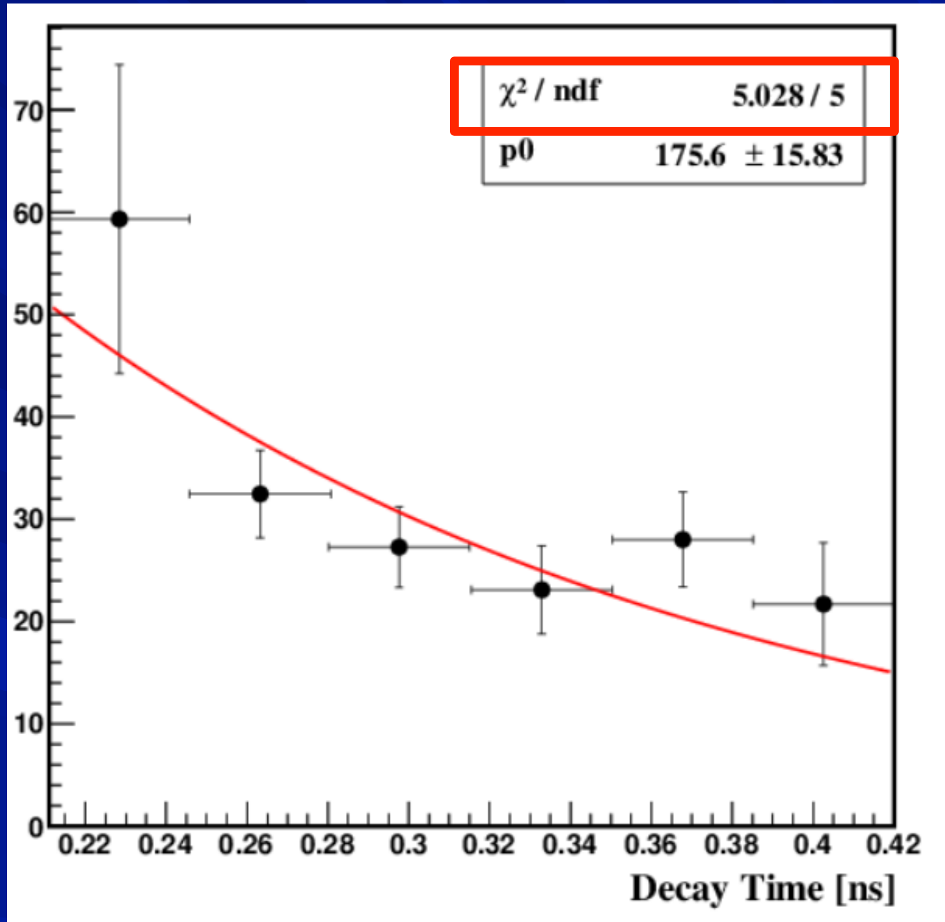


be published

$^{20}Ne+^{12}C$: Lifetime of $^{3}_{\Lambda}H$

Unbinned maximum likelihood fitting





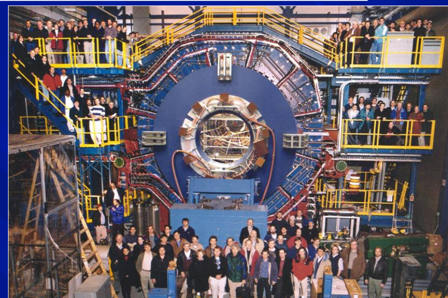
c.f.: Phase 0, 183 $^{+42}_{-32}$ ps

V. Bozkurt, Ph.D. thesis, to be published

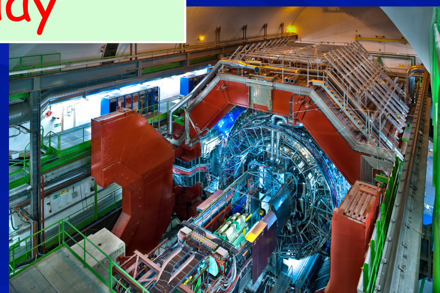
→ talk by C. Rappold on Tuesday

Recent status of lifetime values of $^{3}_{\Lambda}H$

- **HypHI** ➡ talk by C. Rappold on Tuesday
  - $^{6}Li+^{12}C$ and $^{20}Ne+^{12}C$ at 2 A GeV at GSI
  - Phase 0 ($^{6}Li+^{12}C$), 183^{+42}_{-32} ps (Λ: 263 ps)
  - Phase 0 ($^{20}Ne+^{12}C$), 170^{+46}_{-30} ps (Λ: 263 ps)
- **STAR at BNL RHIC** ➡ talks by N. Shah and Y. Xu on Tuesday
  - $^{197}Au+^{197}Au$
  - Observation of short lifetime of $^{3}_{\Lambda}H$
  - Two/three-body decays combined: 155^{+25}_{-22} ps



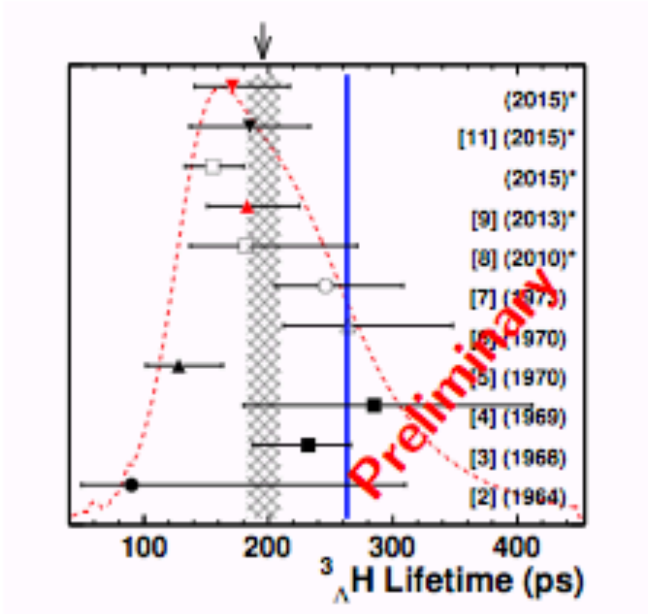
- **ALICE at LHC CERN** ➡ talk by S. Piano on Tuesday
  - $^{208}Pb+^{208}Pb$
  - 181^{+54}_{-39} ps

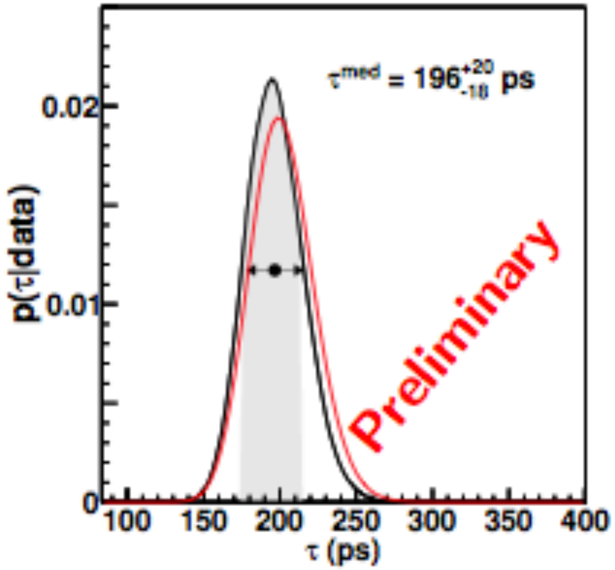


No theories to explain the short lifetime of $^{3}_{\Lambda}H$

Combination with the most recent available lifetime results:

➡ talk by C. Rappold on Tuesday





- 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 : $B_{10} = 3.0$

More results on HypHI Phase 0

$^{6}Li + ^{12}C$ at 2 A GeV

Physics Letters B 747 (2015) 129–134

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Hypernuclear production cross section in the reaction of ^{6}Li + ^{12}C at 2 *A* GeV

C. Rappold[a,b,*], T.R. Saito[a,c,d,e], O. Bertini[a,c], S. Bianchin[a], V. Bozkurt[a,f], E. Kim[a,g], M. Kavatsyuk[h], Y. Ma[a,c], F. Maas[a,c,d], S. Minami[a], D. Nakajima[a,i], B. Özel-Tashenov[a], K. Yoshida[a,d,j], P. Achenbach[c], S. Ajimura[k], T. Aumann[l,a], C. Ayerbe Gayoso[c], H.C. Bhang[g], C. Caesar[l,a], S. Erturk[f], T. Fukuda[n], B. Göküzüm[a,f], E. Guliev[h], J. Hoffmann[a], G. Ickert[a], Z.S. Ketenci[f], D. Khaneft[a,c], M. Kim[g], S. Kim[g], K. Koch[a], N. Kurz[a], A. Le Fèvre[a,m], Y. Mizoi[n], L. Nungesser[c], W. Ott[a], J. Pochodzalla[c,d], A. Sakaguchi[j], C.J. Schmidt[a], M. Sekimoto[o], H. Simon[a], T. Takahashi[o], G.J. Tambave[h], H. Tamura[p], W. Trautmann[a], S. Voltz[a], C.J. Yoon[g]

[a] GSI Helmholtz Centre for Heavy Ion Research, Planckstrasse 1, 64291 Darmstadt, Germany
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[c] Johannes Gutenberg-Universität Mainz, J.J. Becherweg 40, 55099 Mainz, Germany
[d] The Helmholtz Institute Mainz (HIM), J.J. Becherweg 40, 55099 Mainz, Germany
[e] Iwate University, Morioka, Iwate 020-8550, Japan
[f] Nigde University, 51100 Nigde, Turkey
[g] Seoul National University, Gwanakro Sillim-dong, Gwanak-gu, Seoul 151-747, Republic of Korea
[h] KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands
[i] The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[j] Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan
[k] Research Centre for Nuclear Physics (RCNP), 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
[l] Technische Universität Darmstadt, 64289 Darmstadt, Germany
[m] SUBATECH, La Chantrerie, 4 rue Alfred Kastler, BP 20722, 44307 Nantes, France
[n] Osaka Electro-Communication University, Hatsu-cho 18-8, Neyagawa, Osaka 572-8530, Japan
[o] KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
[p] Tohoku University, 6-3 Aoba Aramaki Aoba Sendai, Miyagi 980-7875, Japan

Cross section & kinematics

Table 2

Summary of the estimations of the parameters of interest such as the cross sections and the yield ratios. $\langle x \rangle$ and σ_{stat} correspond to the expected value and the statistical standard deviation of the posterior probability density function. σ_{sys} and σ_{prior} stand for the systematic uncertainties and the prior sensitivity uncertainties.

	$\langle x \rangle$	σ_{stat}	σ_{sys}	σ_{prior}
Λ_{tot} (mb)	1.7	± 0.7 (stat)	± 0.4 (sys)	± 0.2 (prior)
Λ_{obs} (mb)	0.3	± 0.1 (stat)	± 0.06 (sys)	± 0.03 (prior)
${}^{3}_{\Lambda}H$ (μb)	3.9	± 1.3 (stat)	± 0.3 (sys)	± 0.3 (prior)
${}^{4}_{\Lambda}H$ (μb)	3.1	± 1.0 (stat)	± 0.3 (sys)	± 0.1 (prior)
${}^{3}_{\Lambda}H/{}^{4}_{\Lambda}H$	1.4	± 0.7 (stat)	± 0.1 (sys)	± 0.2 (prior)
${}^{3}_{\Lambda}H/\Lambda$ ($\times 10^{-3}$)	2.6	± 1.4 (stat)	± 0.3 (sys)	± 0.2 (prior)
${}^{4}_{\Lambda}H/\Lambda$ ($\times 10^{-3}$)	2.1	± 1.1 (stat)	± 0.1 (sys)	± 0.2 (prior)

C. Rappold et al., PLB 747 (2015) 129

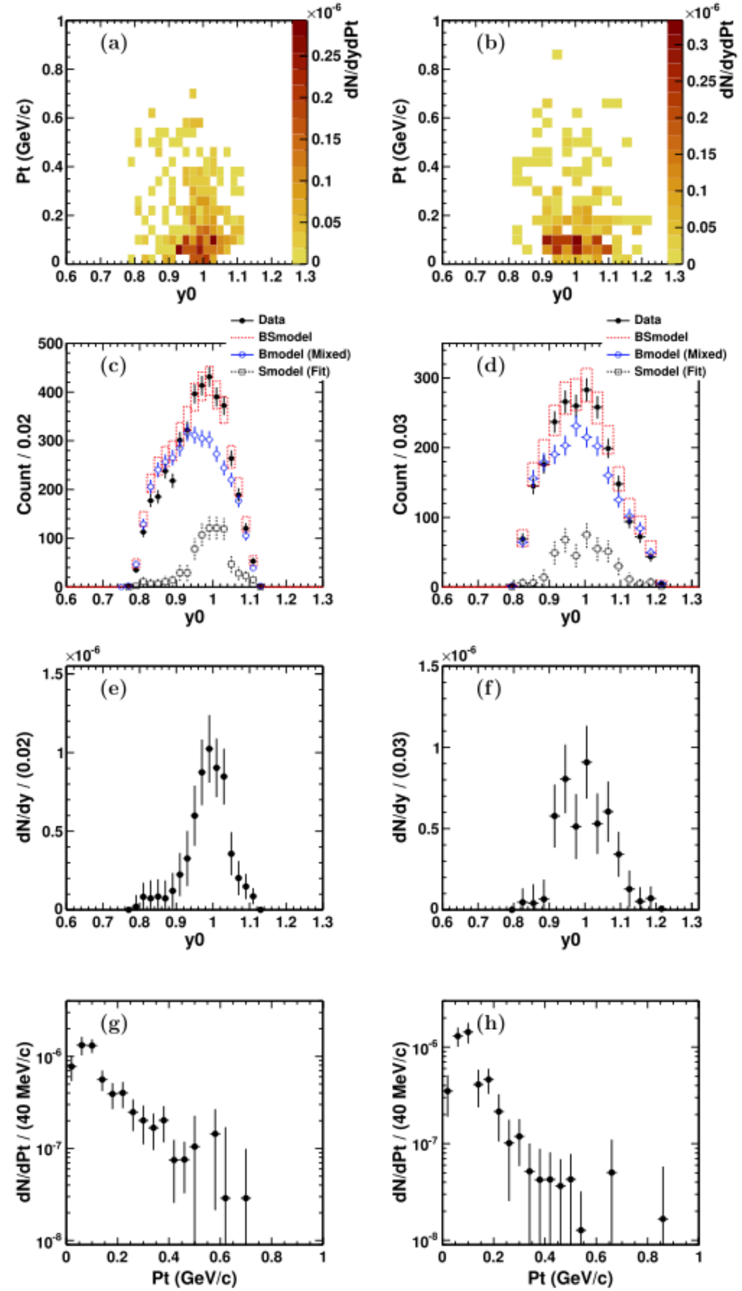
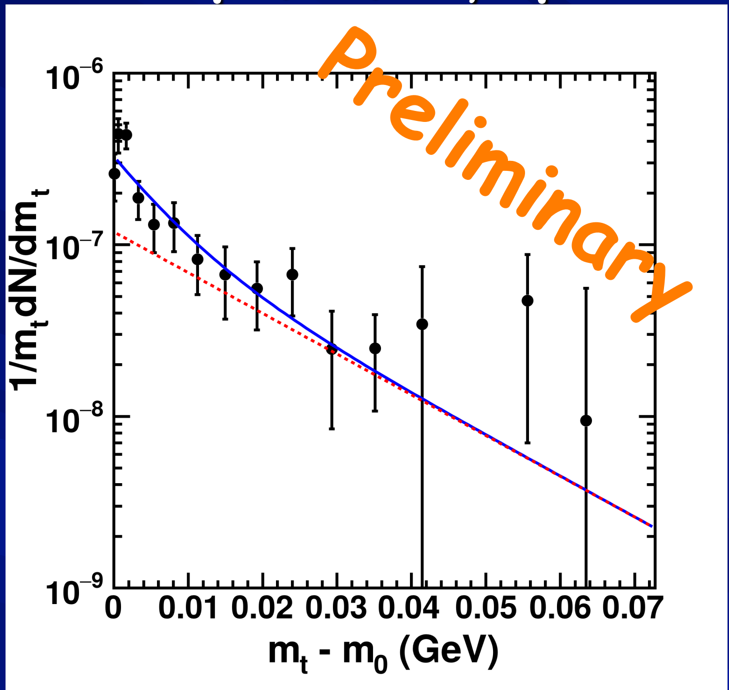
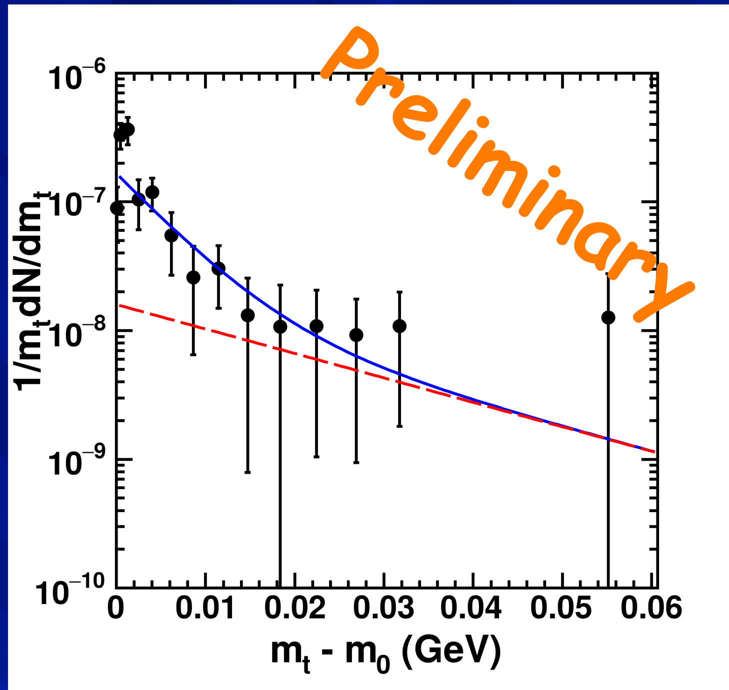


Fig. 3. (Color online.) Multiplicity distribution as a function of the rapidity observable *y0* and of the transversal momentum *Pt* in the center-of-mass system for ${}^{3}_{\Lambda}H$ in panel (a), ${}^{4}_{\Lambda}H$ in panel (b), respectively. In panels (c) and (d) the projected rapidity distributions of the data set ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ respectively are shown in black full circle together with extracted signal contribution *Smodel* (open box), the background-only distribution from the mixed event analysis *Bmodel* (open circle) and the signal-plus-background model *BSmodel* (dash box representing the 1-σ standard deviation interval). Panels (e), (f) and (g), (h) show the rapidity and *Pt* distribution of extracted ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ signal, respectively.

Deducing spectator temperature

- Inverse slope, T, m_t spectrum:





- For ${}^{3}_{\Lambda}H$: T_1 ~ 7 ± 2 MeV, T_2 ~ 18 ± 7 MeV
- For ${}^{4}_{\Lambda}H$: T_1 ~ 6 ± 2 MeV, T_2 ~ 13 ± 6 MeV
- Very similar to multi-fragmentation results by ALADiN

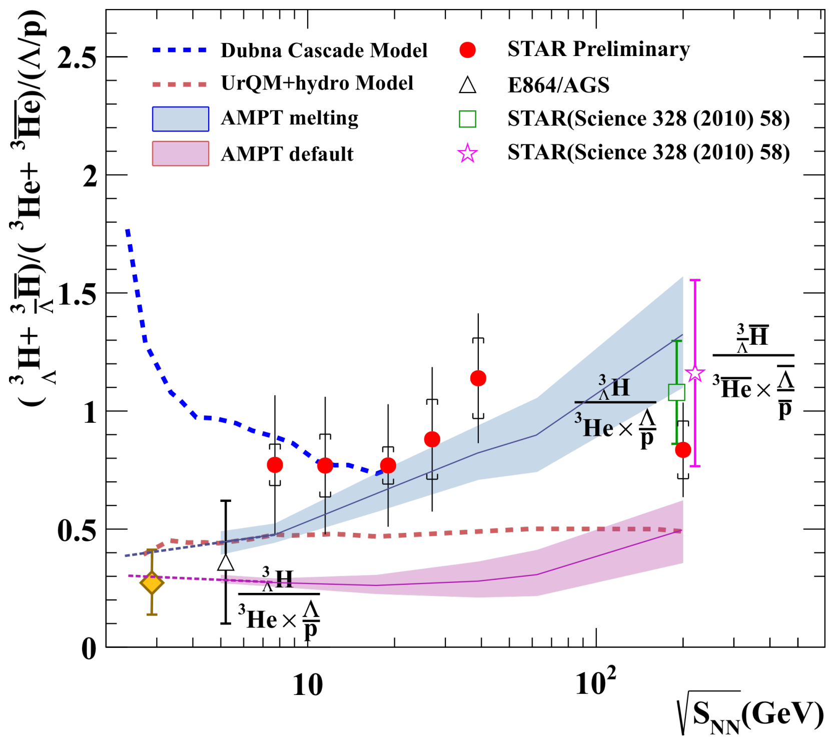
  T. Odeh et al., Phys. Rev. Lett. 84 (2000) 4557
- Also similar to the Goldhaber model

  A.S. Goldhaber, Phys. Lett. B 53 (1974) 306

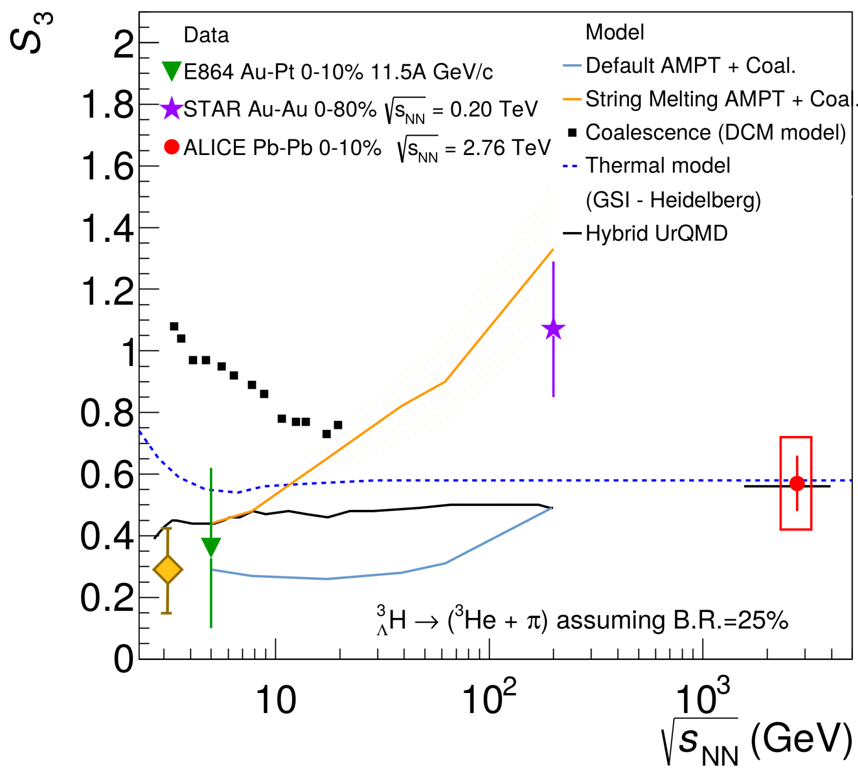
C. Rappold et al. (HypHI coll.), to be published

S3 factor

$$\left(S_3 = {}^3_\Lambda\mathrm{H} / \left({}^3\mathrm{He} \times \frac{\Lambda}{\mathrm{p}}\right)\right)$$



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

Invariant mass reconstructions
Phase 0: $^{6}Li + ^{12}C$

- All final states with charged particles
  - $p + \pi^-$
  - $^{3}He + \pi^-$
  - $^{4}He + \pi^-$

  - $^{6}Li + \pi^-$
  - $^{3}He + p + \pi^-$
  - $^{4}He + p + \pi^-$
  - $d + p + \pi^-$
  - $d + p + \pi^-$

  - $d + \pi^-$
  - $t + \pi^-$

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **88**, 041001(R) (2013)

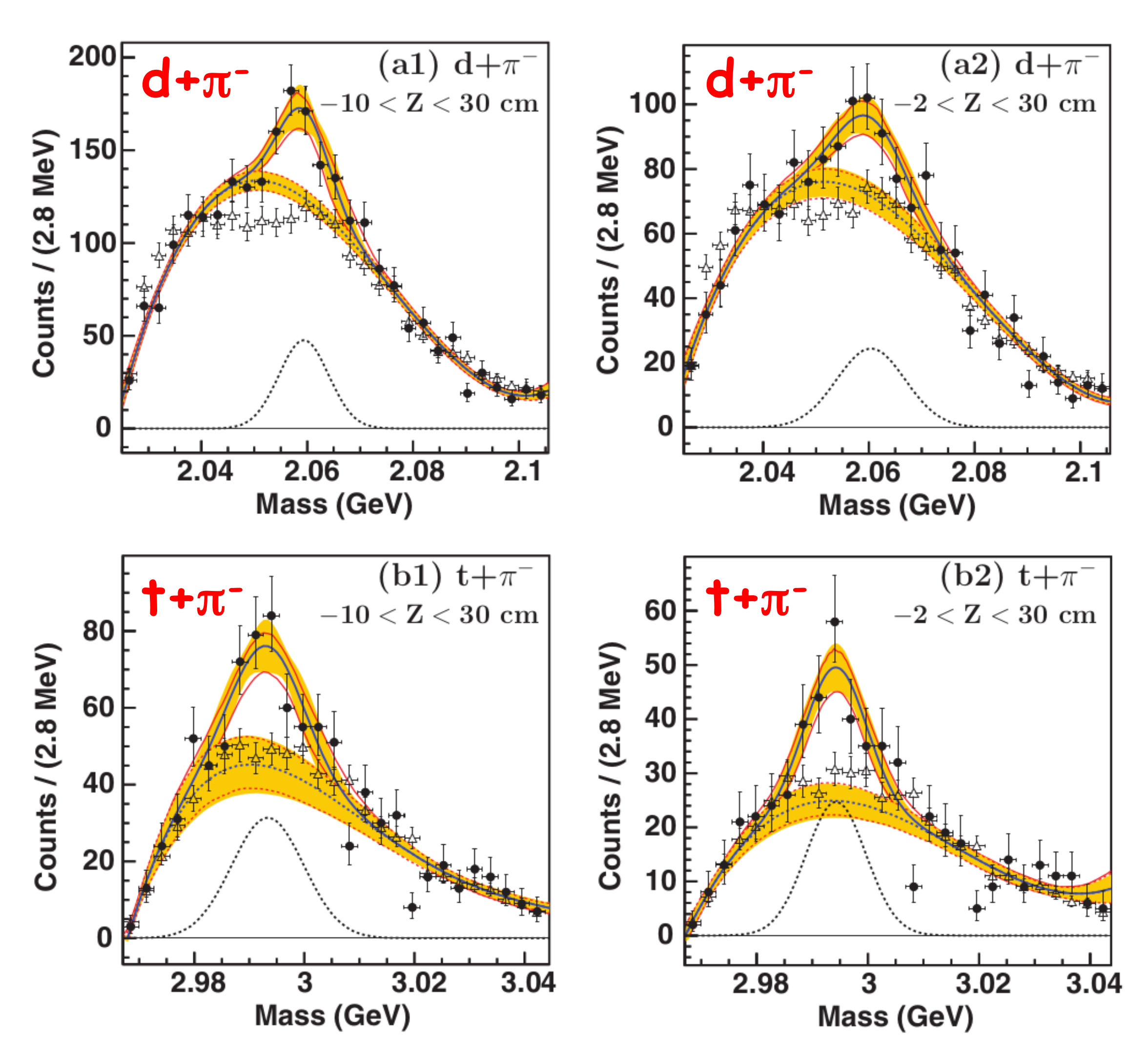
Search for evidence of ${}^{3}_{\Lambda}n$ by observing $d + \pi^-$ and $t + \pi^-$ final states in the reaction of ${}^{6}\mathrm{Li} + {}^{12}\mathrm{C}$ at 2A GeV

C. Rappold,[1,2,*] E. Kim,[1,3] T. R. Saito,[1,4,5,†] O. Bertini,[1,4] S. Bianchin,[1] V. Bozkurt,[1,6] M. Kavatsyuk,[7] Y. Ma,[1,4] F. Maas,[1,4,5] S. Minami,[1] D. Nakajima,[1,8] B. Özel-Tashenov,[1] K. Yoshida,[1,5,9] P. Achenbach,[4] S. Ajimura,[10] T. Aumann,[1,11] C. Ayerbe Gayoso,[4] H. C. Bhang,[3] C. Caesar,[1,11] S. Erturk,[6] T. Fukuda,[12] B. Göküzüm,[1,6] E. Guliev,[7] J. Hoffmann,[1] G. Ickert,[1] Z. S. Ketenci,[6] D. Khaneft,[1,4] M. Kim,[3] S. Kim,[3] K. Koch,[1] N. Kurz,[1] A. Le Fèvre,[1,13] Y. Mizoi,[12] L. Nungesser,[4] W. Ott,[1] J. Pochodzalla,[4] A. Sakaguchi,[9] C. J. Schmidt,[1] M. Sekimoto,[14] H. Simon,[1] T. Takahashi,[14] G. J. Tambave,[7] H. Tamura,[15] W. Trautmann,[1] S. Voltz,[1] and C. J. Yoon[3]
(HypHI Collaboration)

$d+\pi^-$ and $t+\pi^-$: Invariant mass

RAPID COMMUNICATIONS

C. RAPPOLD *et al.* PHYSICAL REVIEW C **88**, 041001(R) (2013)



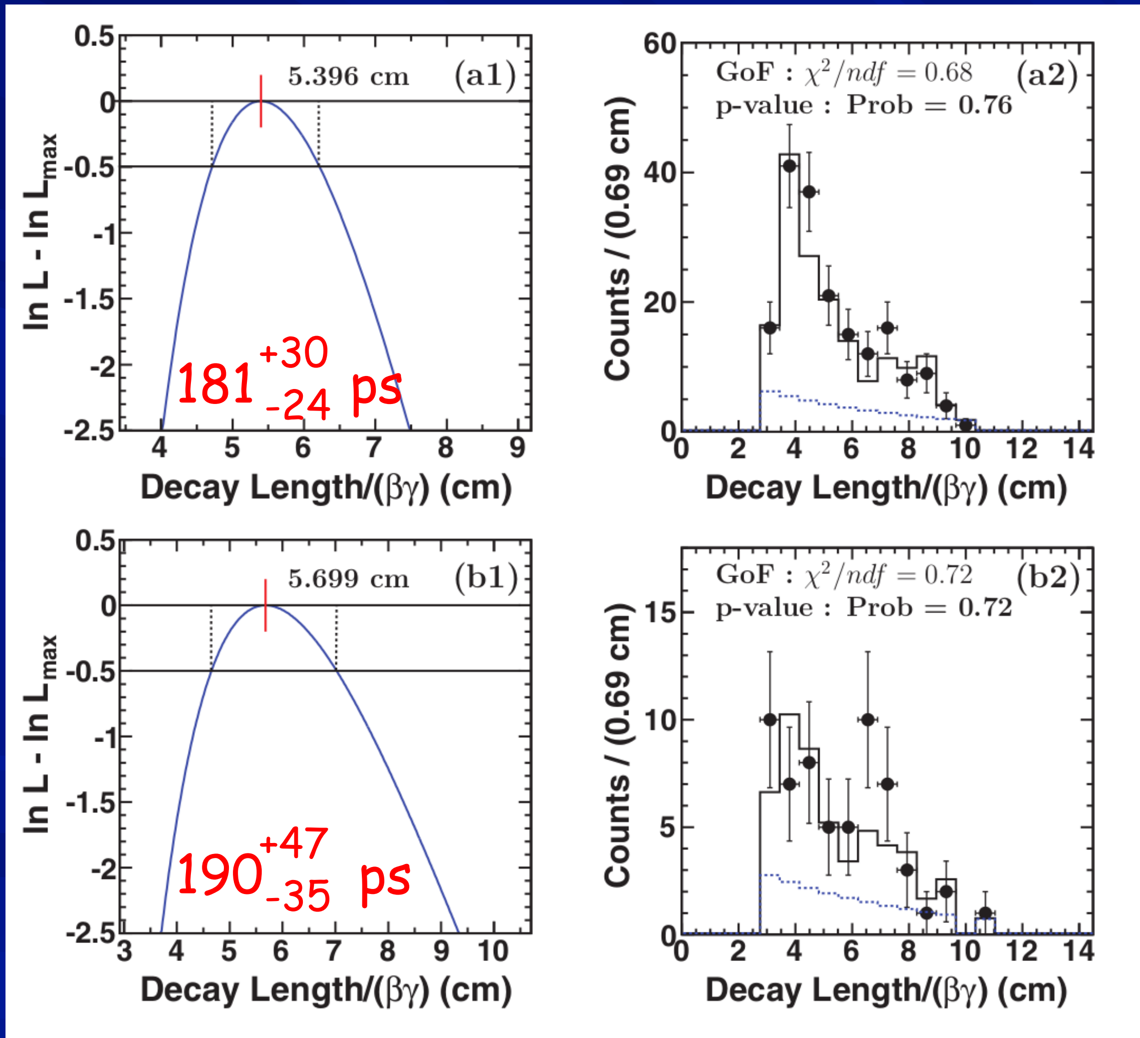
d+π⁻ and t+π⁻ : Lifetime

RAPID COMMUNICATIONS

SEARCH FOR EVIDENCE OF $^{3}_{\Lambda}n$ BY . . . PHYSICAL REVIEW C **88**, 041001(R) (2013)

d+π⁻

t+π⁻



$d+\pi^-$ and $t+\pi^-$:Signals from others

RAPID COMMUNICATIONS

SEARCH FOR EVIDENCE OF ${}^{3}_{\Lambda}n$ BY . . . PHYSICAL REVIEW C **88**, 041001(R) (2013)

Decay channel	Counts
${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{p+d}+\pi^-$	8 to $\mathrm{d}+\pi^-$
${}^{4}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d+d}+\pi^-$	1 to $\mathrm{d}+\pi^-$
${}^{4}_{\Lambda}\mathrm{H} \rightarrow \mathrm{t+p}+\pi^-$	6 to $\mathrm{t}+\pi^-$
${}^{6}_{\Lambda}\mathrm{He} \rightarrow {}^{4}\mathrm{He+d}+\pi^-$	15 to $\mathrm{d}+\pi^-$
${}^{4}_{\Lambda}\mathrm{He} \rightarrow \mathrm{p+p+d}+\pi^-$	8 to $\mathrm{d}+\pi^-$
${}^{5}_{\Lambda}\mathrm{He} \rightarrow \mathrm{d}+{}^{3}\mathrm{He}+\pi^-$	14 to $\mathrm{d}+\pi^-$

Observed $d+\pi^-$: 202
Observed $t+\pi^-$: 181

Neutral nucleus with Λ, $nn\Lambda$??

${}^{3}_{\Lambda}n \rightarrow t + \pi^-$
${}^{3}_{\Lambda}n \rightarrow t^* + \pi^- \rightarrow n + d + \pi^-$

Theoretical calculations for nnΛ

- E. Hiyama et al., Phys. Rev. C89 (2014) 061302(R)
- A. Gal et al., Phys. Lett. B736 (2014) 93
- H. Garcilazo et al., Phys. Rev. C89 (2014) 057001

nnΛ can not be bound

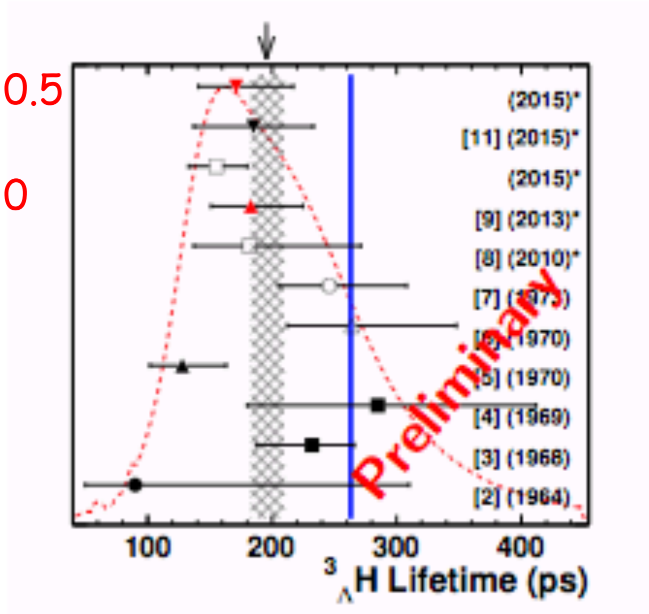
based on the current understanding of $^{3}_{\Lambda}H$

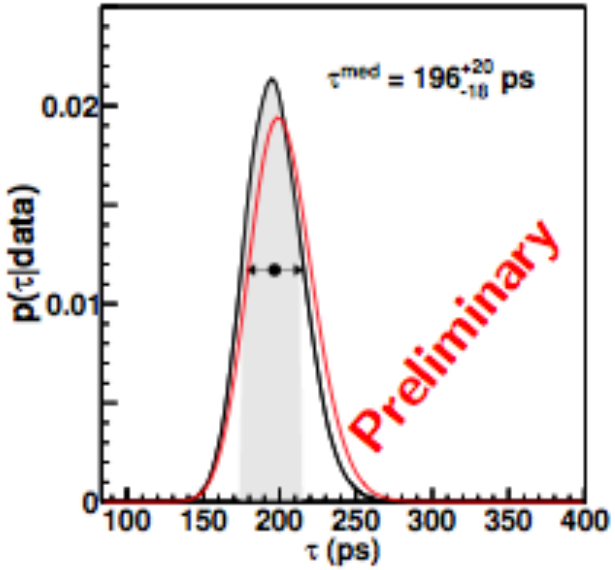
No theories to explain the short lifetime of $^{3}_{\Lambda}H$

Combination with the most recent available lifetime results:

➡ talk by C. Rappold on Tuesday

HypHI Phase 0.5
ALICE
STAR new
HypHI Phase 0

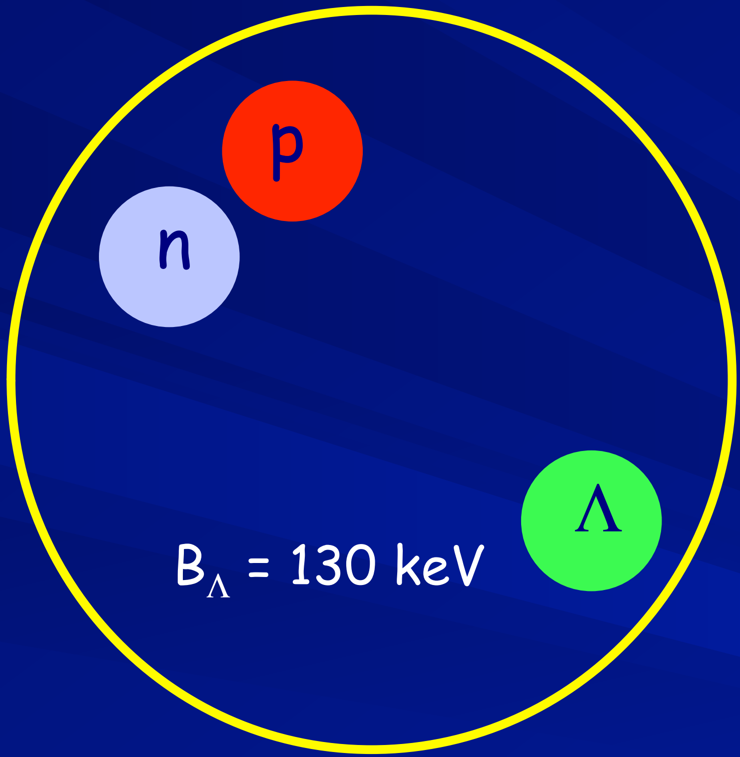




- PDG says need to rescale errors if $\chi^2 > 1$
  - initial χ^2=1.18, $197.5^{+12.4}_{-11.2}$ ps
  - scaled χ^2=0.98, $195.9^{+13.8}_{-12.5}$ ps
- Upper Limit at 95% : 223.9 ps & at 99% : 234.0 ps
- Bayesian :
  - $195.9^{+19.7}_{-18}$ ps & Upper Limit 95% : 229 ps
  - Bayes Factor : $B_{10} = 3.0$

Do we understand the simplest hypernucleus?

${}^{3}_{\Lambda}H$



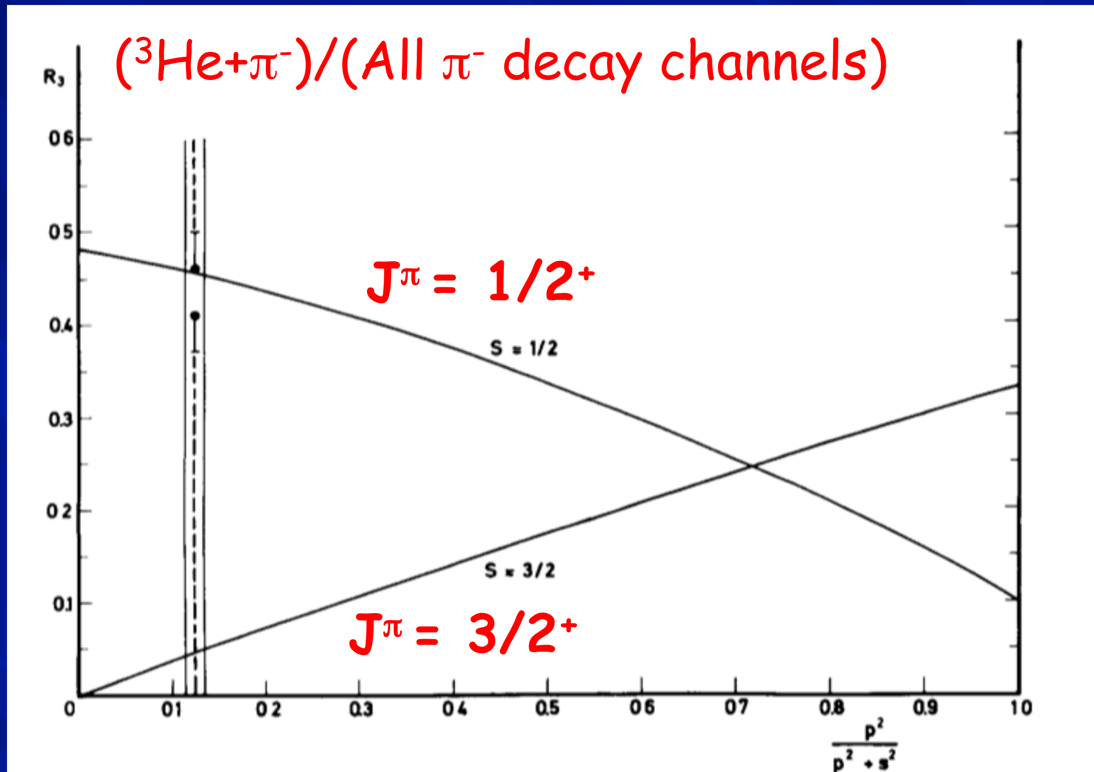


Fig. 4. The ratio $R_3 = ({}^{3}_{\Lambda}H \to \pi^- + {}^{3}He)/(\text{all } \pi^-$ mesonic decays of ${}^{3}_{\Lambda}H$) as a function of $p^2/(p^2+s^2)$. The curves illustrate the results of the calculations made by Dalitz and Liu [4] for $J({}^{3}_{\Lambda}H) = \frac{1}{2}$ and $\frac{3}{2}$.

$R({}^{3}_{\Lambda}H) > R({}^{208}Pb)$

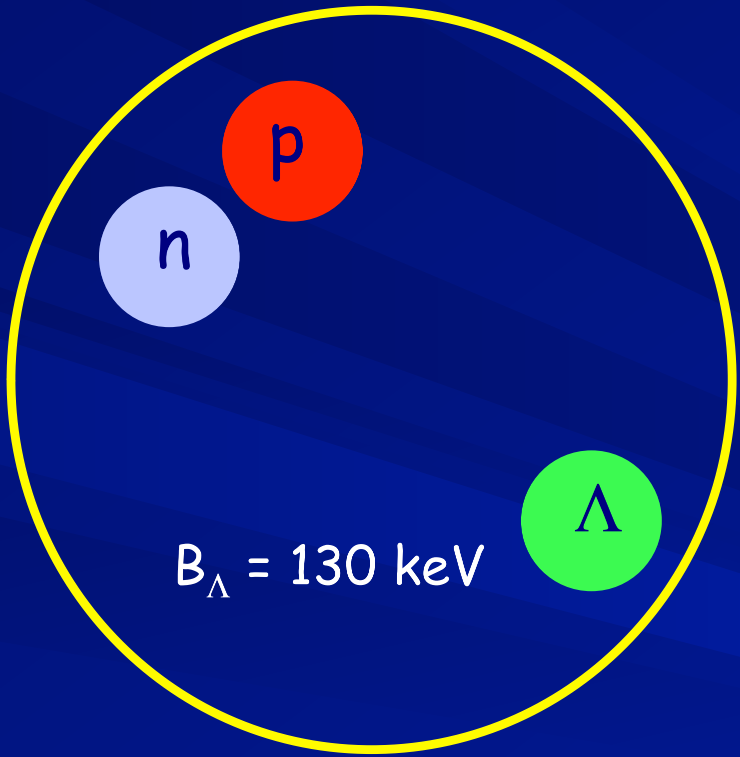
$\tau({}^{3}_{\Lambda}H)$ should be equal to $\tau(\Lambda$, 263 ps)

However,
$\tau({}^{3}_{\Lambda}H)$ = ~ 180 ps

T. Bertrand et al., NPB 16(1970)77

Do we understand the simplest hypernucleus?

$^{3}_{\Lambda}H$



$R(^{3}_{\Lambda}H) > R(^{208}Pb)$

$\tau(^{3}_{\Lambda}H)$ should be equal to $\tau(\Lambda, 263\ ps)$

However,
$\tau(^{3}_{\Lambda}H) = \sim 180\ ps$

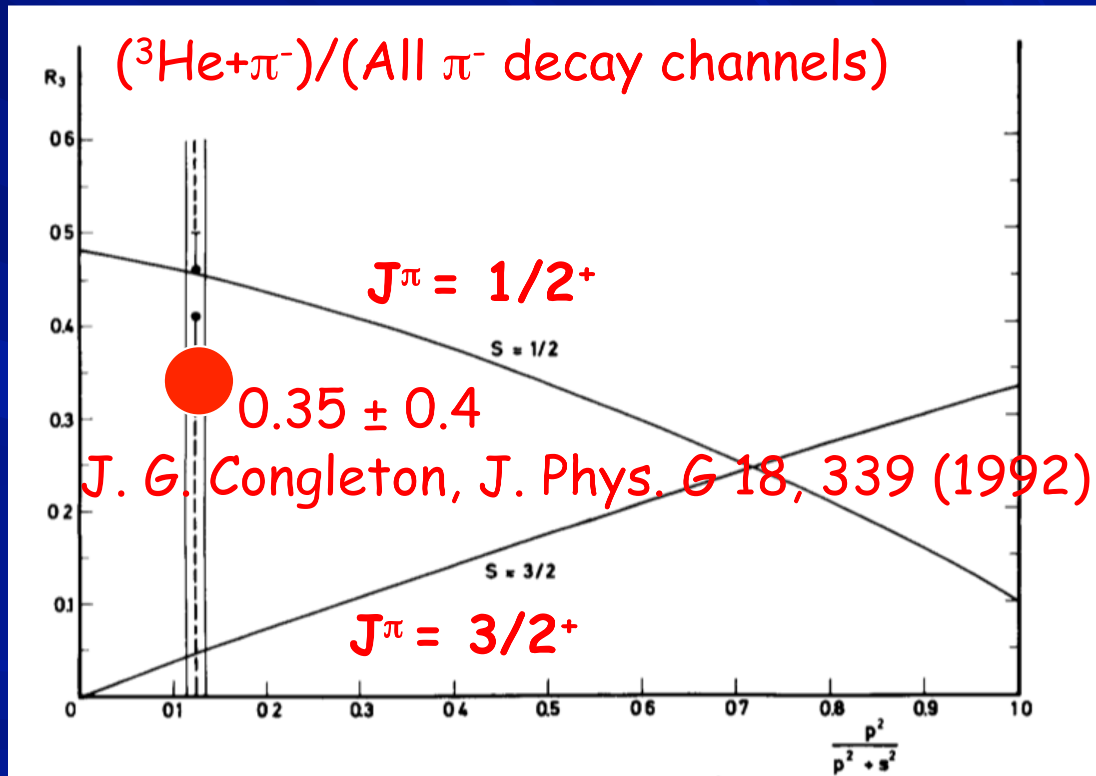
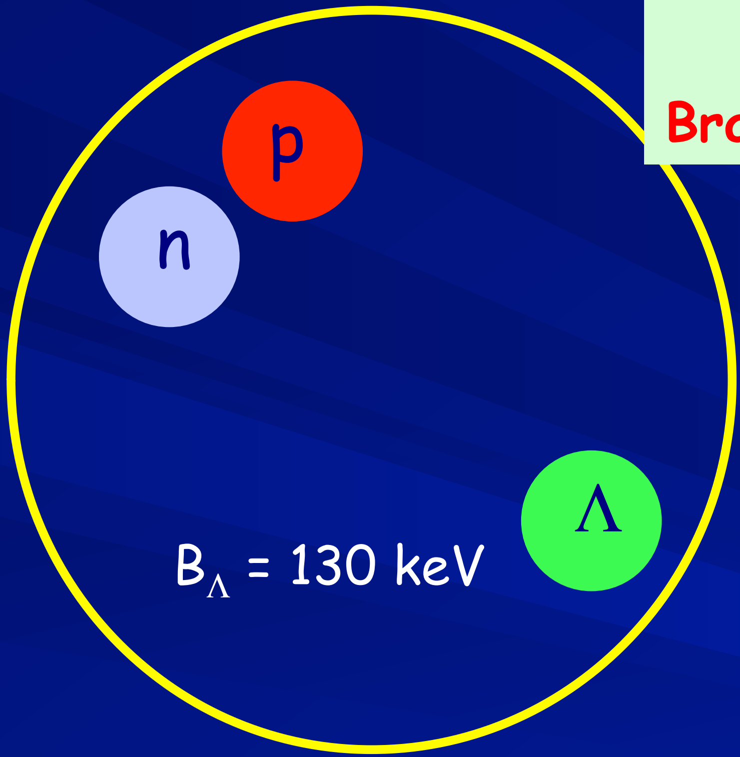


Fig. 4. The ratio $R_3 = (^{3}_{\Lambda}H \rightarrow \pi^- + ^{3}He)/(\text{all } \pi^- \text{ mesonic decays of } ^{3}_{\Lambda}H)$ as a function of $p^2/(p^2+s^2)$. The curves illustrate the results of the calculations made by Dalitz and Liu [4] for $J(^{3}_{\Lambda}H) = \frac{1}{2}$ and $\frac{3}{2}$.

T. Bertrand et al., NPB 16(1970)77

Do we understand the simplest hypernucleus?

$^{3}_{\Lambda}H$



Three body decay observed by STAR
→ talk by Y. Xu on Tuesday

Branching ratio: 3-body/2-body = $2.41^{+0.39}_{-0.34}$

$R(^{3}_{\Lambda}H) > R(^{208}Pb)$

$\tau(^{3}_{\Lambda}H)$ should be equal to $\tau(\Lambda$, 263 ps)

However,
$\tau(^{3}_{\Lambda}H)$ = ~ 180 ps

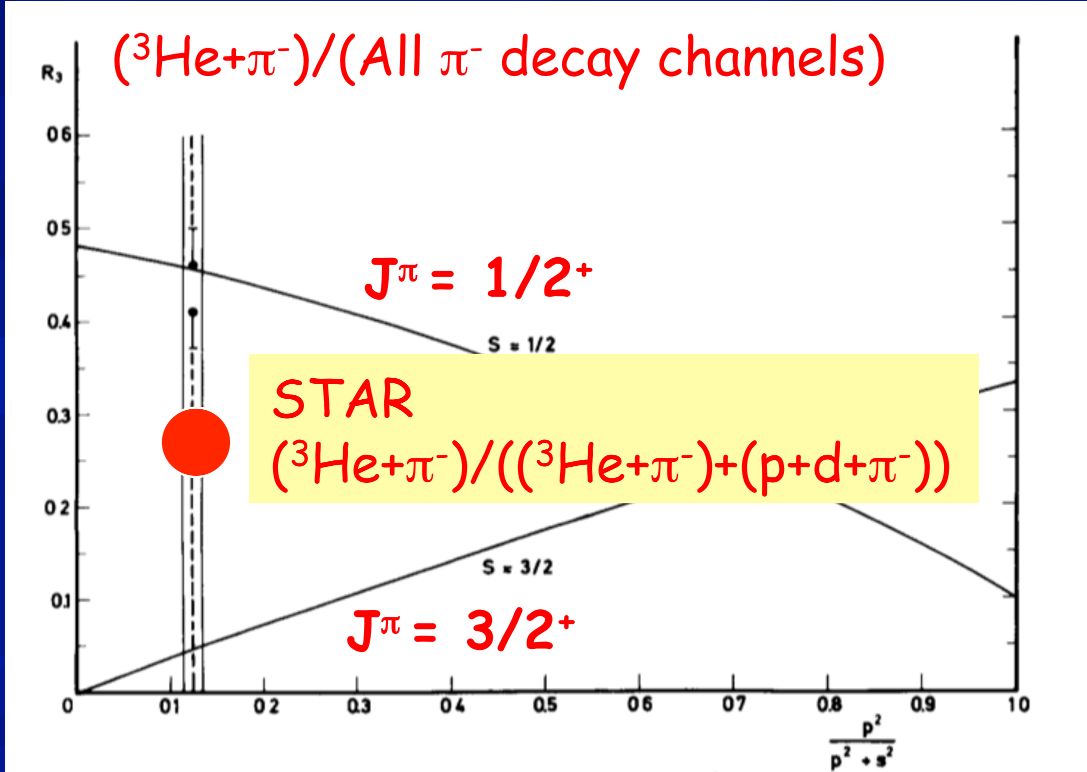
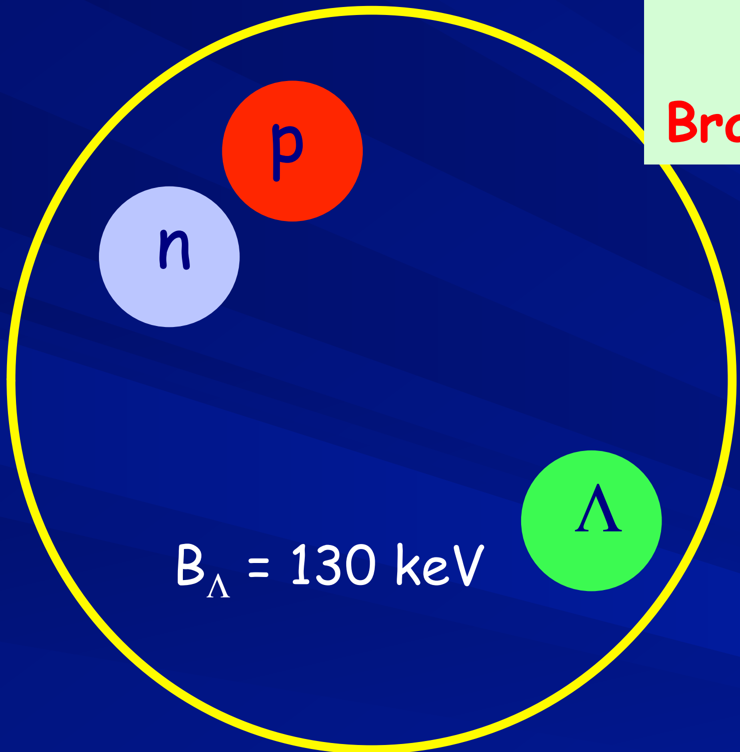


Fig. 4. The ratio $R_3 = (^3_\Lambda H \to \pi^- + ^3He)$/(all π^- mesonic decays of $^3_\Lambda H$) as a function of $p^2/(p^2+s^2)$. The curves illustrate the results of the calculations made by Dalitz and Liu [4] for $J(^3_\Lambda H) = \frac{1}{2}$ and $\frac{3}{2}$.

T. Bertrand et al., NPB 16(1970)77

Do we understand the simplest hypernucleus?

$^{3}_{\Lambda}H$



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$R(^{3}_{\Lambda}H) > R(^{208}Pb)$

$\tau(^{3}_{\Lambda}H)$ should be equal to $\tau(\Lambda$, 263 ps)

However,
$\tau(^{3}_{\Lambda}H)$ = ~ 180 ps

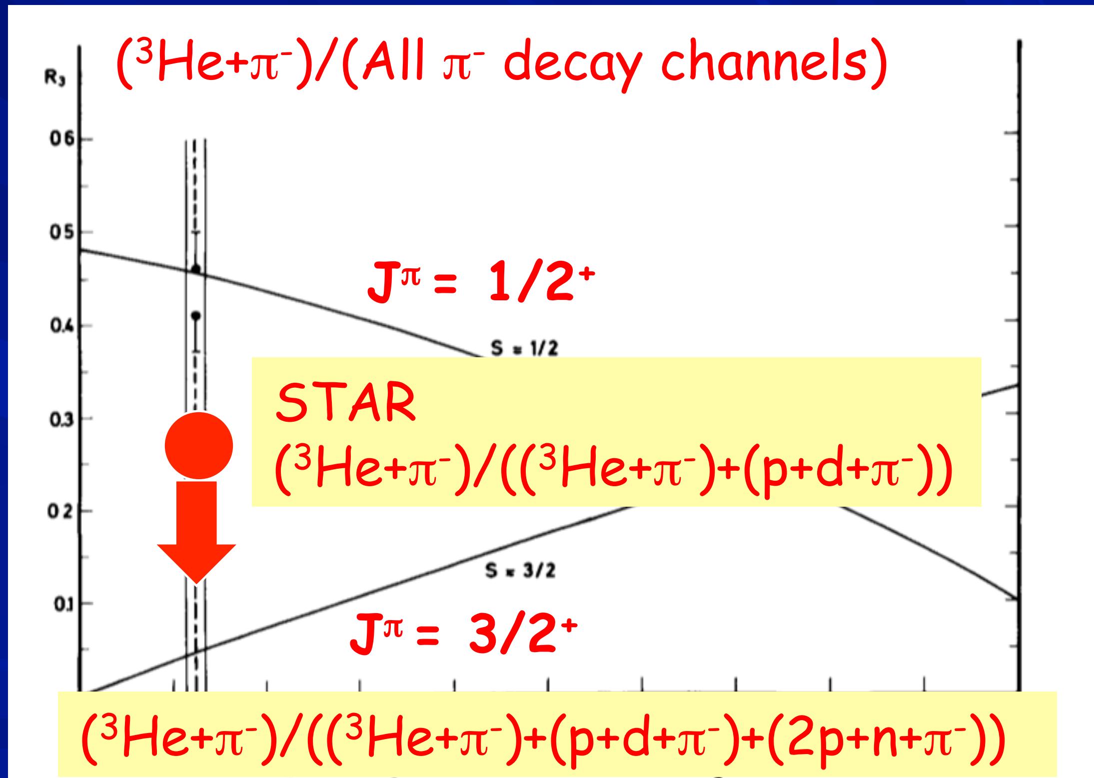


Fig. 4. The ratio $R_3 = (^{3}_{\Lambda}H \rightarrow \pi^- + ^3He)/$(all π^- mesonic decays of $^{3}_{\Lambda}H$) as a function of $p^2/(p^2+s^2)$. The curves illustrate the results of the calculations made by Dalitz and Liu [4] for $J(^{3}_{\Lambda}H) = \frac{1}{2}$ and $\frac{3}{2}$.

T. Bertrand et al., NPB 16(1970)77

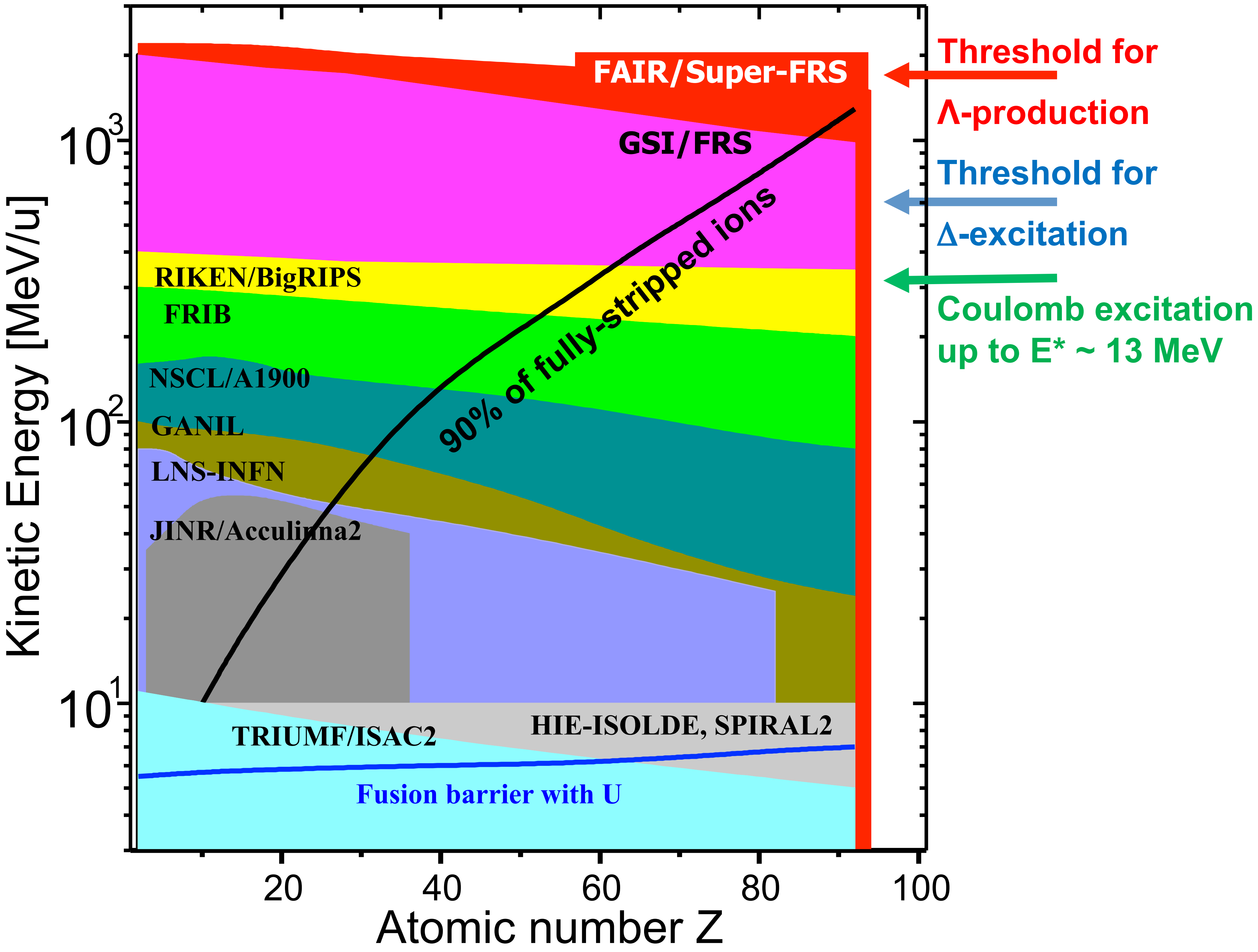
Results from HypHI

- Short lifetime of $^{3}_{\Lambda}H$
  - $^{6}Li + ^{12}C$ and $^{20}Ne + ^{12}C$ at 2 *A* GeV
- Signals on d + π^- and t + π^-
  - $^{6}Li + ^{12}C$ at 2 *A* GeV
  - nnΛ ($^{3}_{\Lambda}n$) ???
- Production cross section
  - $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ and Λ
  - $^{6}Li + ^{12}C$ at 2 *A* GeV

These can be subjects for experiments planed at FAIR Phase 0 and 1

One of Day-1 experiments in NuSTAR/FAIR

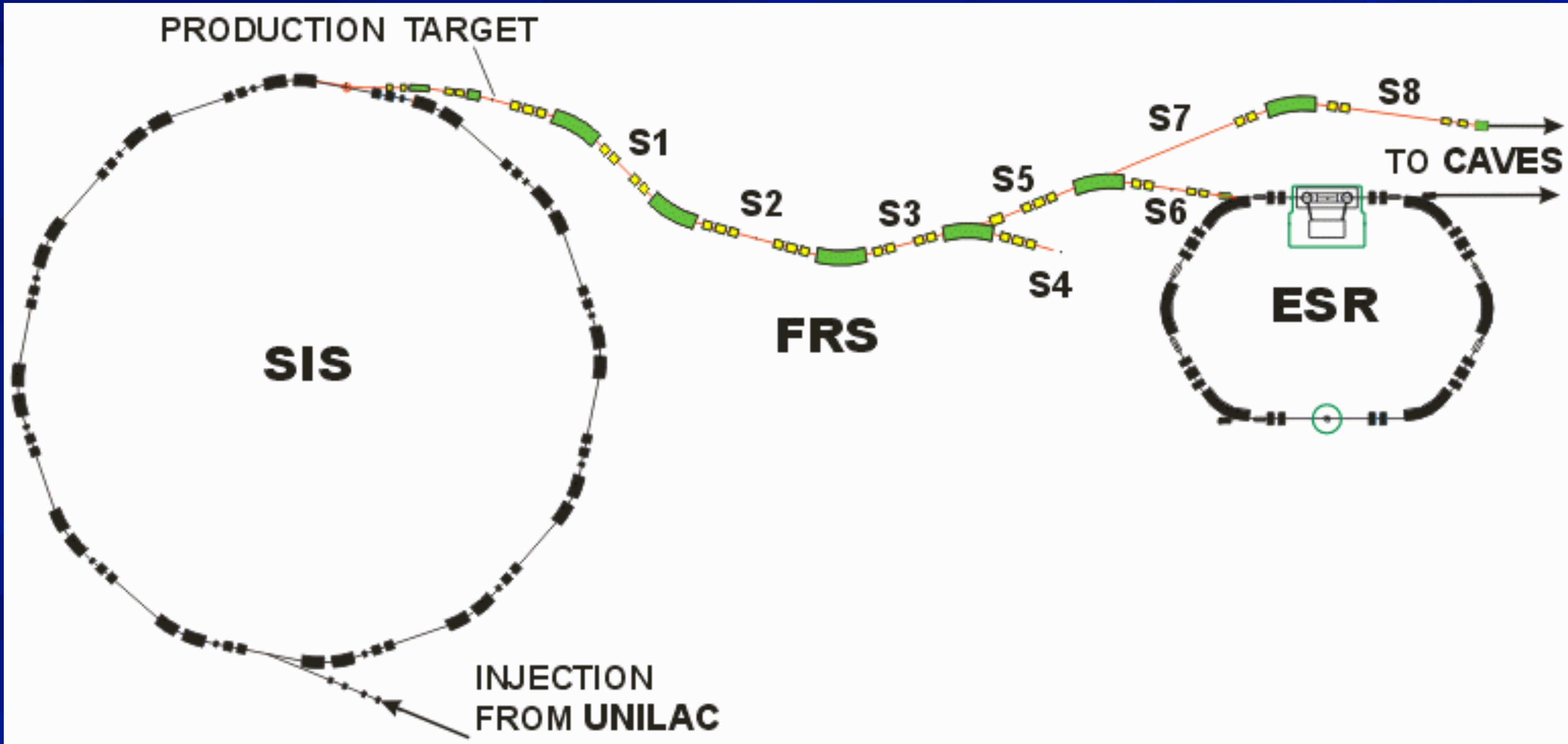
Hypernuclear spectroscopy with excellent exotic beam spectrometers



FAIR/Super-FRS
GSI/FRS
RIKEN/BigRIPS
FRIB
NSCL/A1900
GANIL
LNS-INFN
JINR/Acculinna2
TRIUMF/ISAC2
HIE-ISOLDE, SPIRAL2
Fusion barrier with U
90% of fully-stripped ions
Threshold for
Λ-production
Threshold for
Δ-excitation
Coulomb excitation
up to E* ~ 13 MeV
Kinetic Energy [MeV/u]
Atomic number Z
10^3
10^2
10^1
20
40
60
80
100

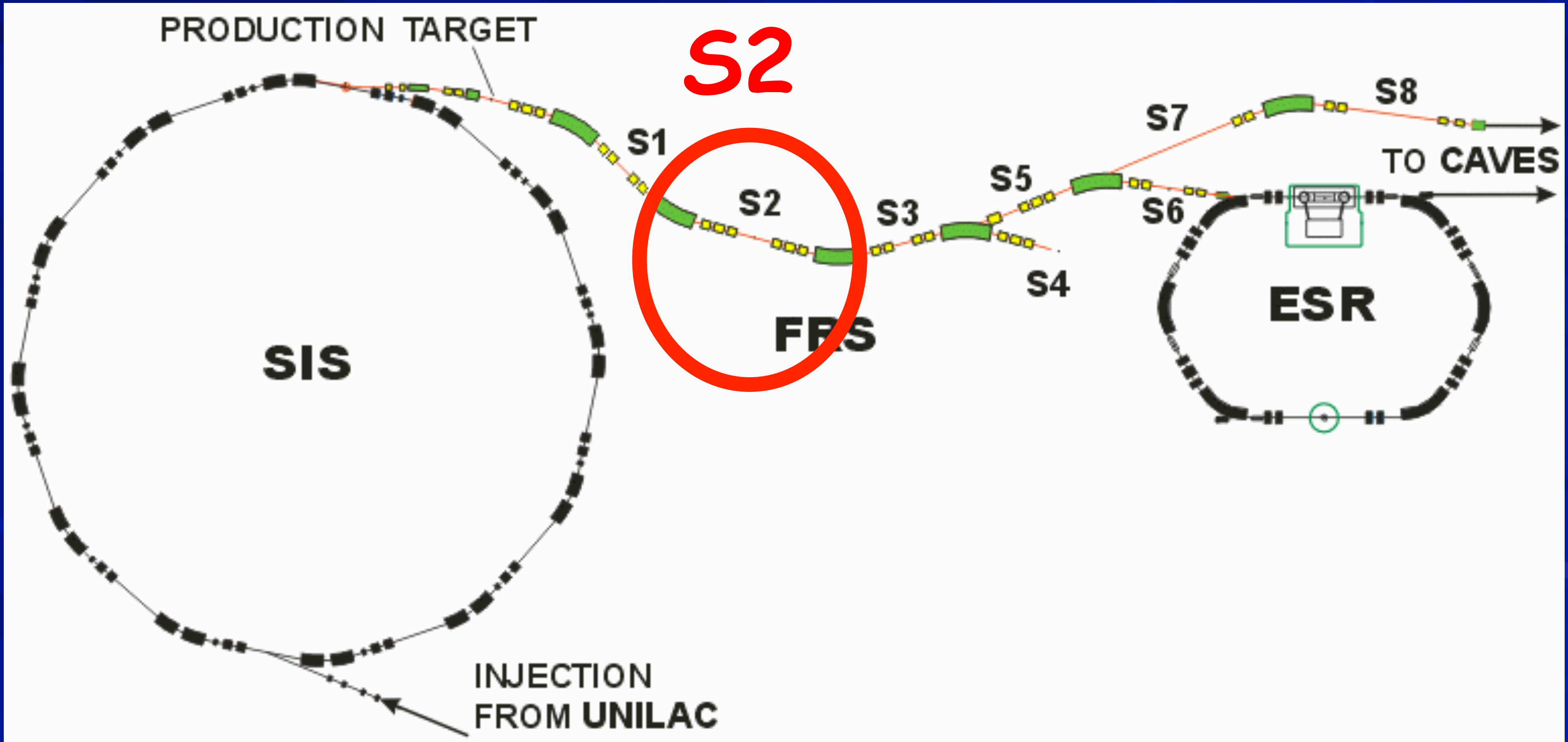
Possibility with FRS

FRS used as the 0 degree forward spectrometer with an excellent momentum resolution

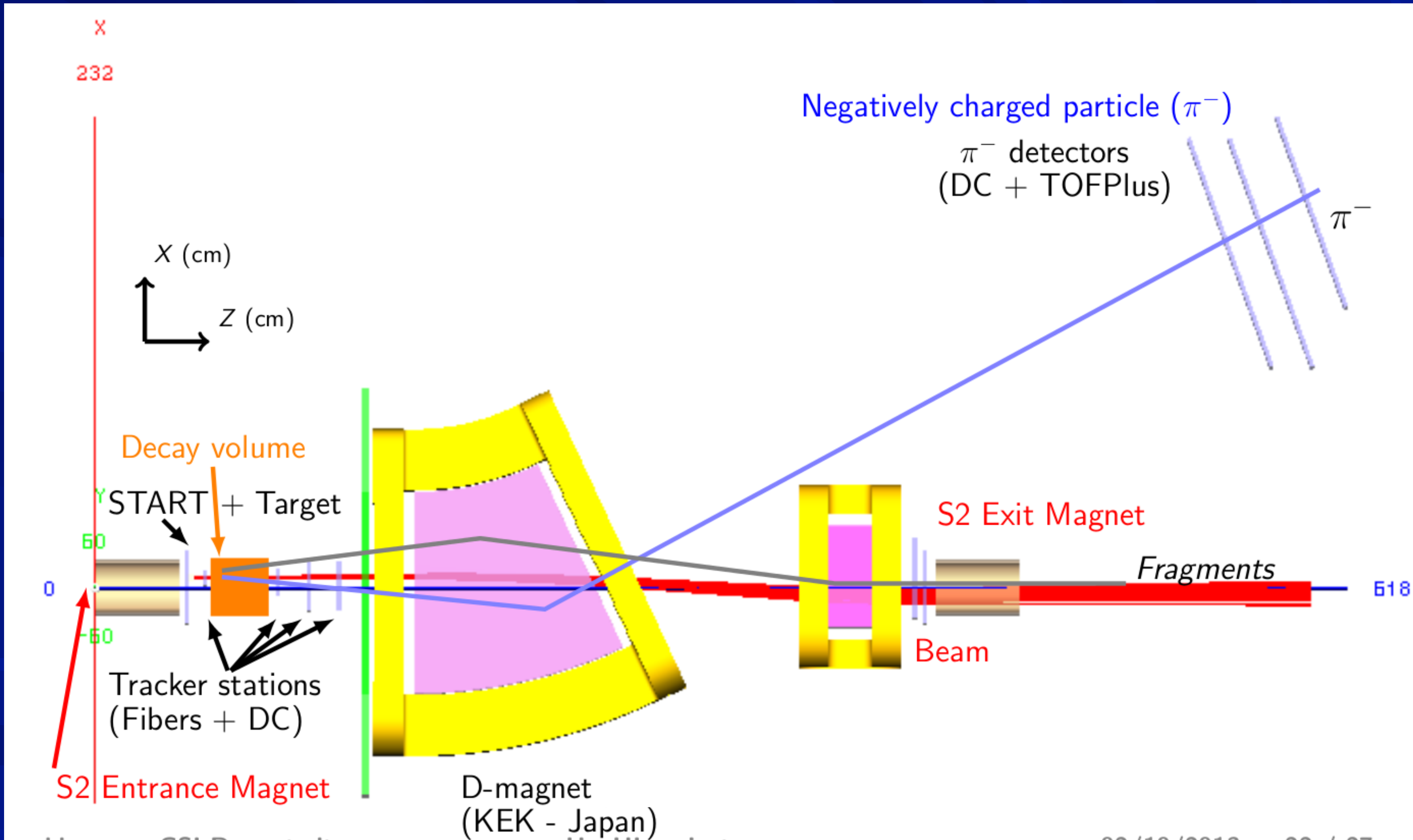


Possibility with FRS

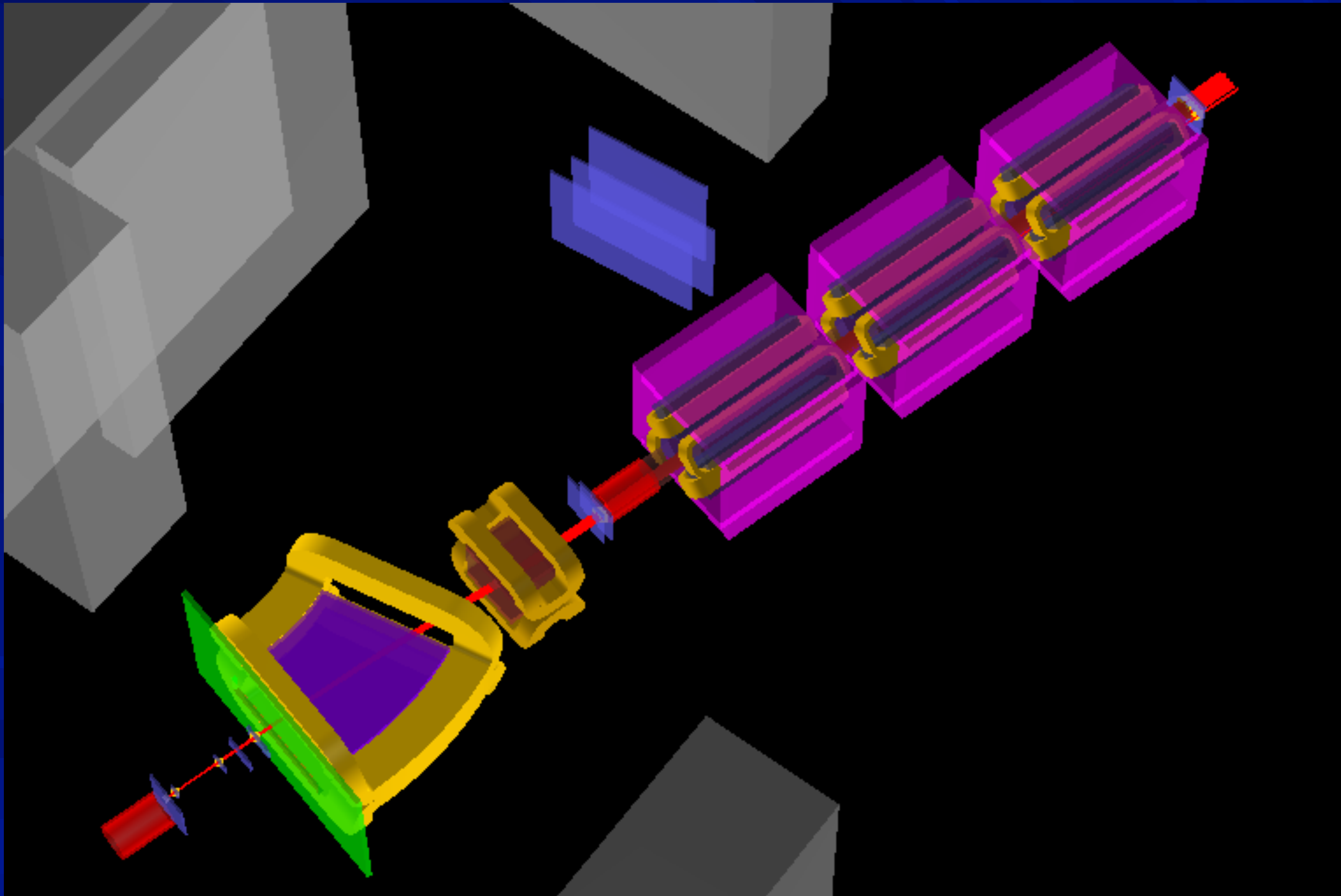
FRS used as the 0 degree forward spectrometer with an excellent momentum resolution



HypHI+FRS at FAIR Phase 0 (GSI)



HypHI+FRS at FAIR Phase 0 (GSI)



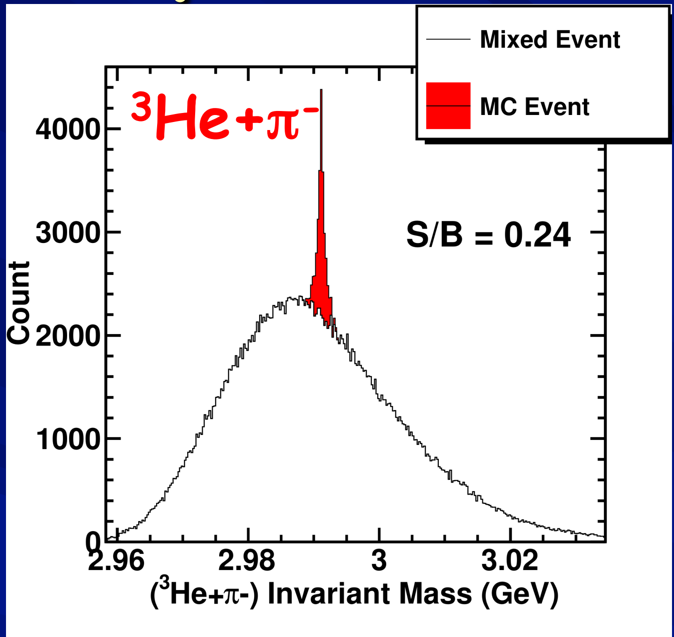
Proposed pilot experiment

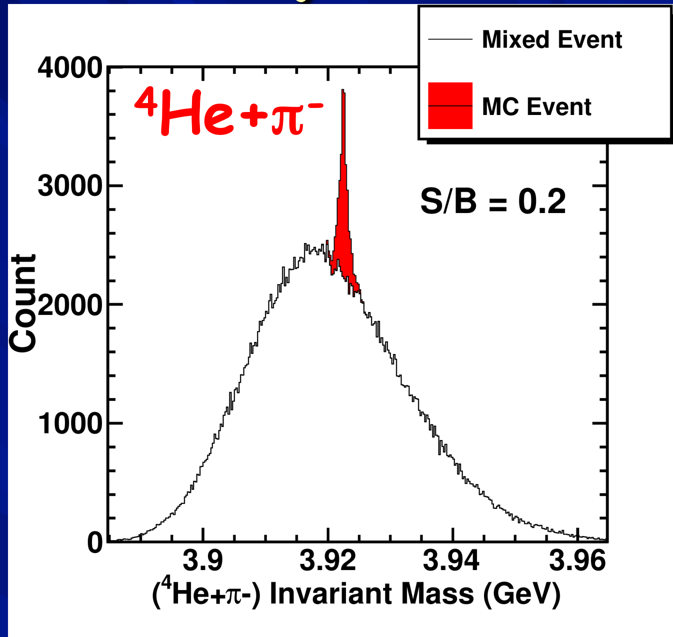
- $^{6}Li + {}^{12}C$ at 2 A GeV, beam intensity ~ 5 X 10^{6} /s

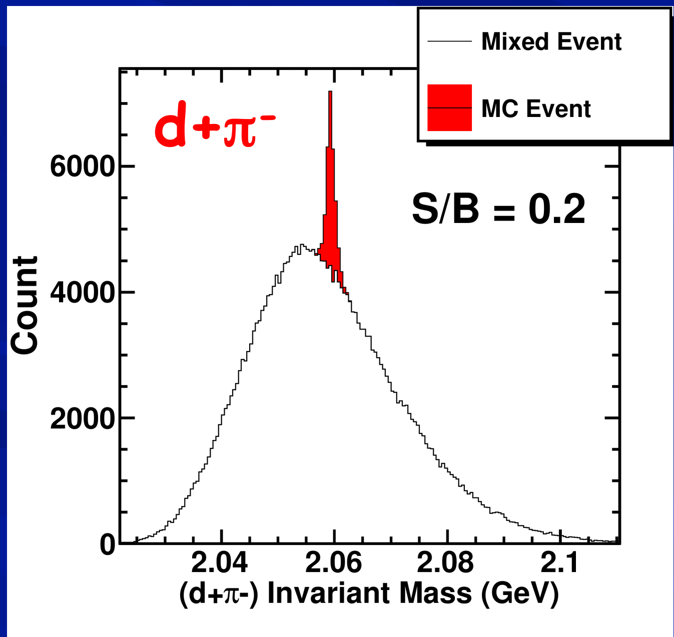
  - RUN 1: $B\rho$ = 12.5 Tm, 4 days
    - For $^{3}_{\Lambda}H$. Invariant mass and lifetime
    - Demonstration of the feasibility
  - RUN2: $B\rho$ = 16.5 Tm, 4 days
    - For $^{4}_{\Lambda}H$ and $d+\pi^{-}$. Invariant mass and lifetime
  - RUN3: $B\rho$ = 11.0 Tm, 1-2 days
    - Cross-checking for $^{3}_{\Lambda}H$
  - RUN4: $B\rho$ = 14.0 Tm, 1-2 days
    - Cross-checking for $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ and $d+\pi^{-}$

- Expected results
  - Showing **the power of hypernuclear spectroscopy with FRS/ super-FRS**
  - **Lifetime of $^{3}_{\Lambda}H$** and $^{4}_{\Lambda}H$
  - **Existence of $nn\Lambda$**

Expected invariant mass by M.C.





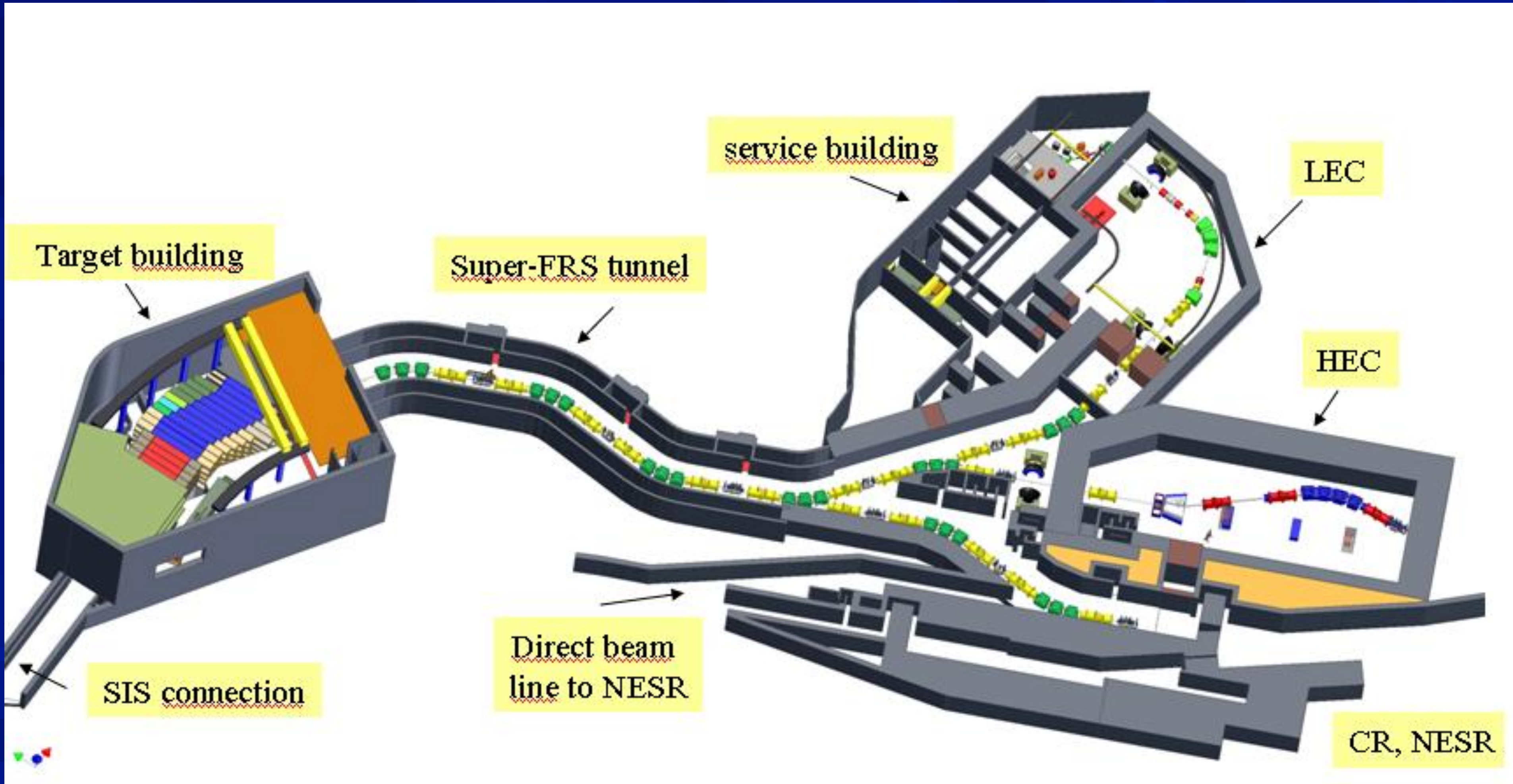


σ : ~ 0.8 MeV

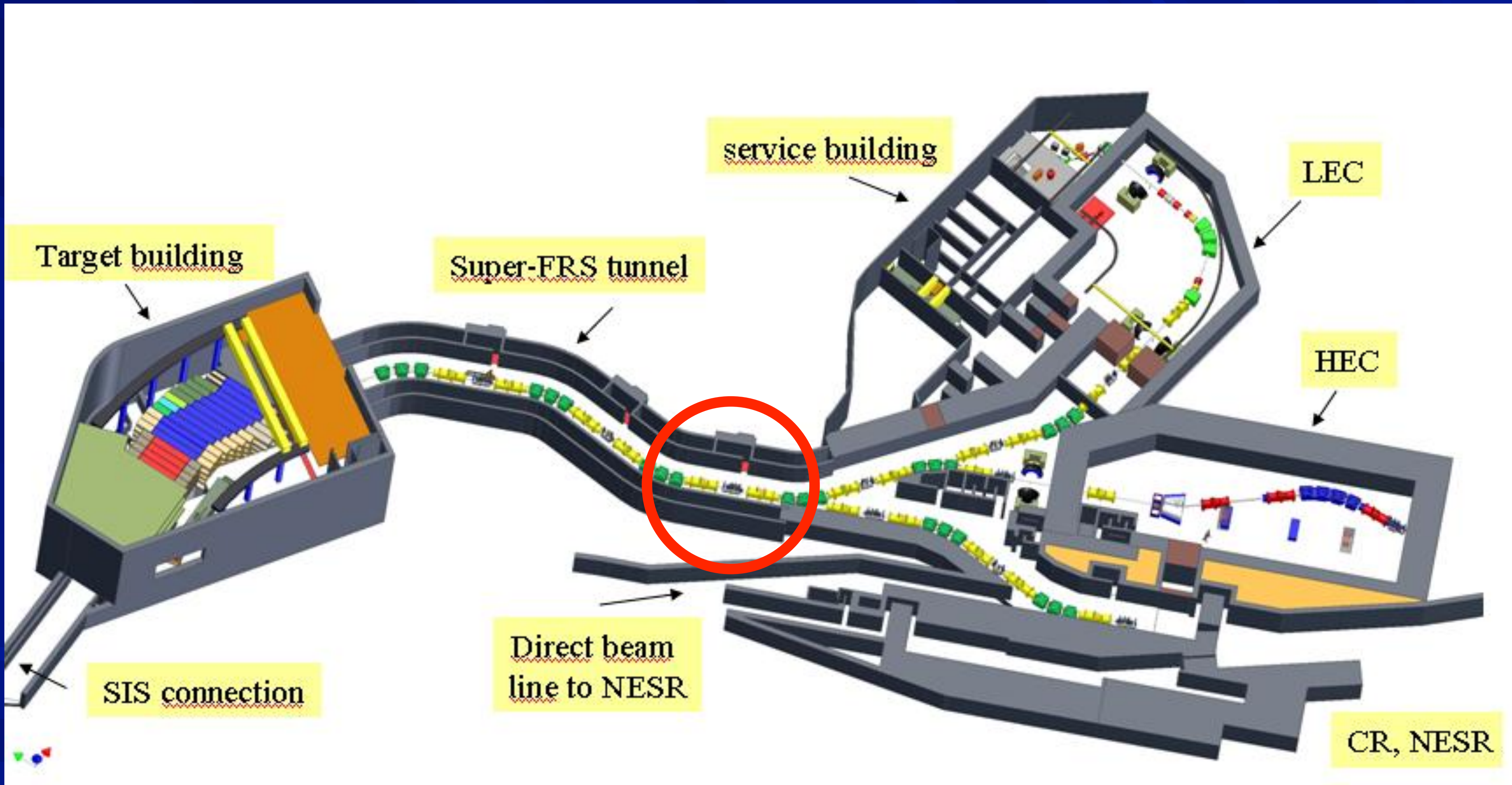
FAIR

FAIR

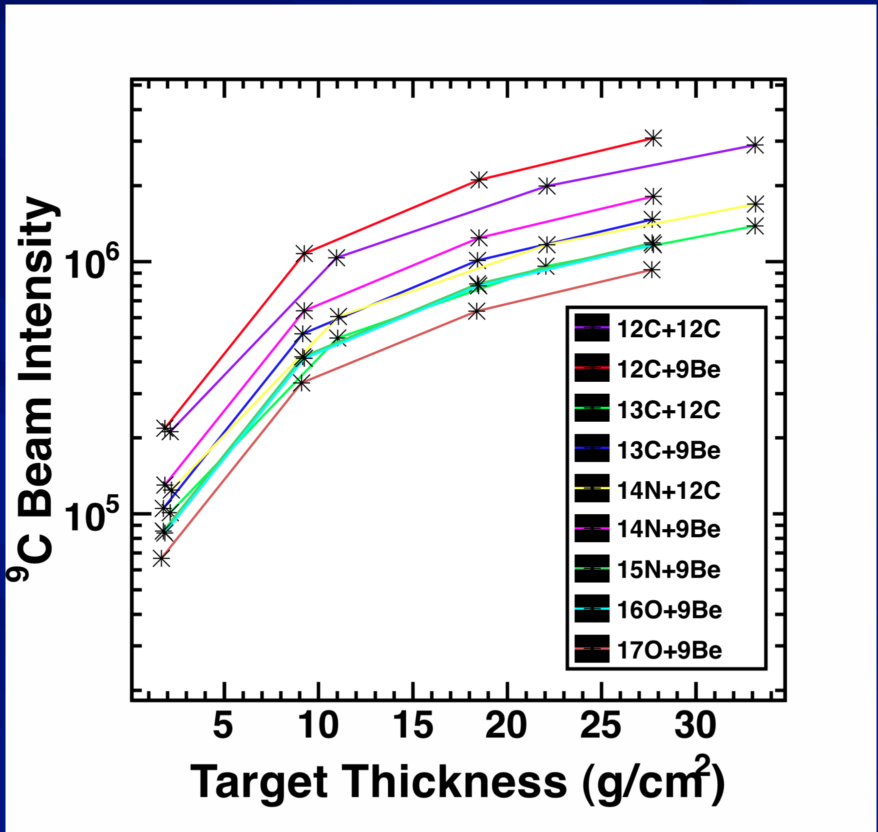
With super-FRS at FAIR



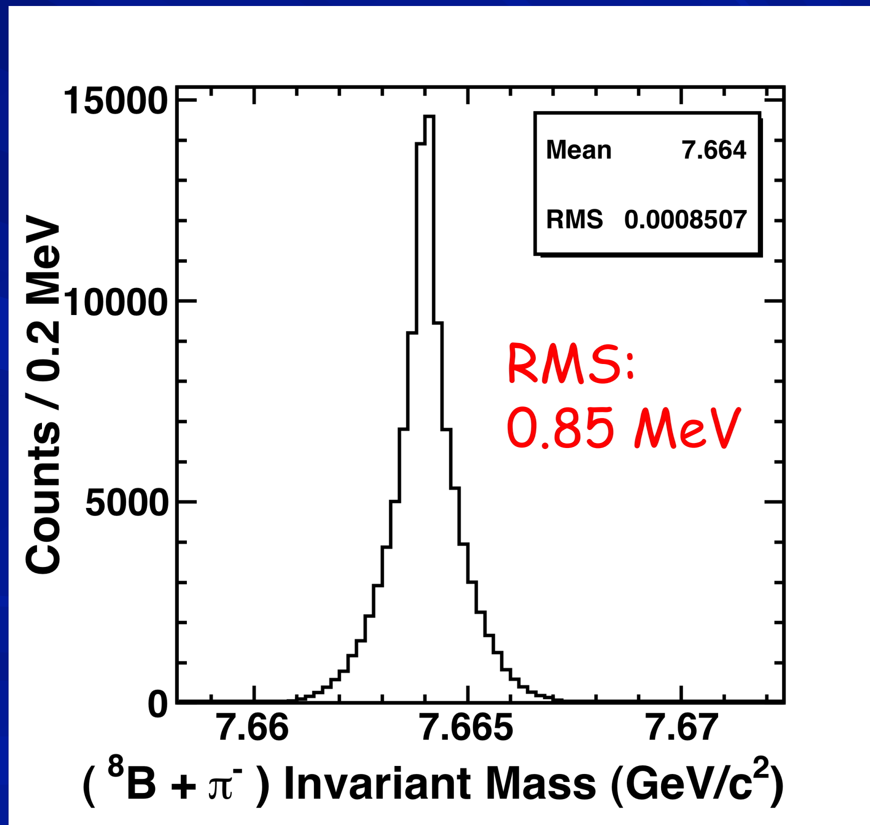
With super-FRS at FAIR



With super-FRS at FAIR



${}^{3}_{\Lambda}$H 2 μb	${}^{4}_{\Lambda}$H 1.2 μb	${}^{3}_{\Lambda}$He 1.2 μb	${}^{4}_{\Lambda}$He 3.4 μb	${}^{5}_{\Lambda}$He 2.6 μb	${}^{6}_{\Lambda}$He 1.4 μb
${}^{4}_{\Lambda}$Li 1.4 μb	${}^{5}_{\Lambda}$Li 1.2 μb	${}^{5}_{\Lambda}$Be 0.4 μb	${}^{6}_{\Lambda}$Be 1.6 μb	${}^{7}_{\Lambda}$Be 0.6 μb	${}^{8}_{\Lambda}$Be 0.8 μb
${}^{6}_{\Lambda}$B 0.4 μb	${}^{7}_{\Lambda}$B 0.2 μb	${}^{8}_{\Lambda}$B 0.6 μb	${}^{8}_{\Lambda}$C 0.2 μb		



Summary

- **HypHI Phase 0 experiment, $^{6}Li+^{12}C$ at 2 A GeV**
  - Nuclear Physics A913 (2013) 170
    - Invariant mass spectroscopy for $^{3}_{\Lambda}H$ and $^{4}{\Lambda}H$
    - Shorter lifetime of $^{3}_{\Lambda}H$ and $^{4}{\Lambda}H$ than Λ
  - Physical Review C88 (2013) 041001(R)
    - Signals on the $d+\pi^{-}$ and $t+\pi^{-}$ invariant mass
  - Physics Letters B747 (2015) 129
    - Production cross section of $^{3}_{\Lambda}H$ and $^{4}{\Lambda}H$ and kinematics
- **Physics Letters B728 (2014) 543**
  - Combined analyses and Bayesian statistic analyses for the existing $^{3}_{\Lambda}H$ and $^{4}{\Lambda}H$ lifetime data
  - Shorter lifetime of $^{3}_{\Lambda}H$ and $^{4}{\Lambda}H$ than Λ
  - Even shorter with new data from ALICE, STAR and HypHI Phase 0.5
- **Phase 0.5 , $^{20}Ne+^{12}C$ at 2 A GeV**
  - Invariant mass spectroscopy
  - Preliminary results on the shorter lifetime of $^{3}_{\Lambda}H$ than Λ

Summary

- **New plans for the precise hypernuclear spectroscopy with FRS at FAIR Phase 0**
  - Confirmation of nnΛ, and lifetime measurements for $^{3}_{\Lambda}H$ and $^{4}\Lambda H$
- **New plans for precise hypernuclear spectroscopy with super-FRS at FAIR Phase 1**
  - Neutron/proton rich hypernuclei with RI-beams

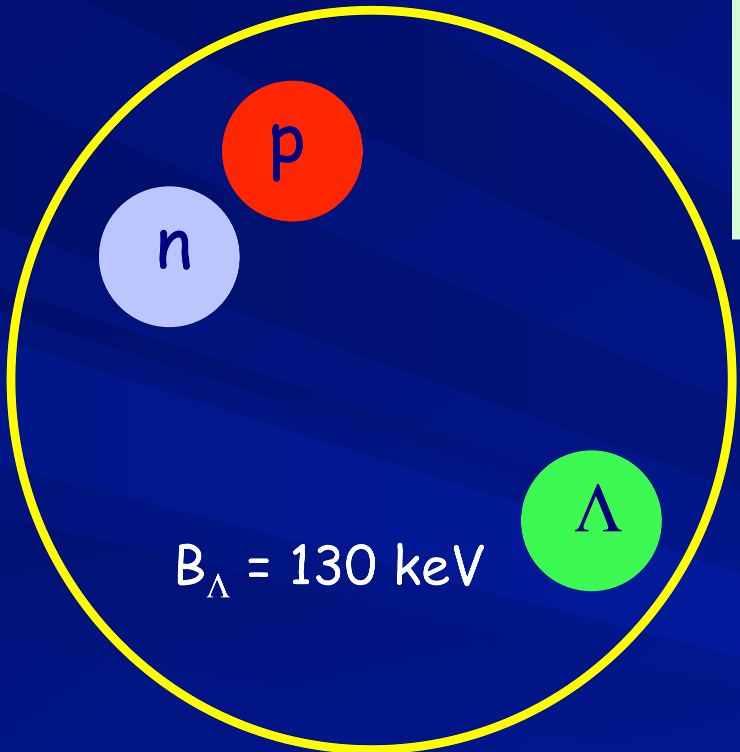
HypHI Phase 0 and 0.5 collaboration

- GSI Helmholtz-University Young Investigators Group VH-NG-239
  - S. Bianchin (GSI -> TRIUMF)
  - O. Borodina (Mainz Univ., GSI)
  - V. Bozkurt (Nigde Univ., GSI)
  - E. Kim (Seoul Univ., GSI)
  - D. Nakajima (Tokyo Univ., GSI)
  - B. Özel-Tashnov (GSI -> Areva)
  - C. Rappold (Giessen, GSI)
  - K. Yoshida (Osaka Univ., GSI)
  - T.R. Saito (Spokes person)
- Mainz University
  - P. Achenbach, J. Pochodzalla
- GSI HP2 and Mainz University
  - D. Khaneft, Y. Ma, F. Maas
- GSI HP1
  - W. Trautmann
- GSI EE department
  - J. Hoffmann, K. Koch, N. Kurz, S. Minami, W. Ott, S. Voltz
- GSI Nuclear reaction
  - T. Aumann, C. Caeser, H. Simon
- GSI Detector Lab.
  - C. Schmidt
- KEK
  - T. Takahashi, Y. Sekimoto
- KVI
  - E. Guliev, M. Kavatsyuk, G.J. Tambave
- Nigde University
  - B. Goekuezuem, Z.S. Ketenci, S. Erturk
- Osaka University
  - S. Ajimura, A. Sakaguchi
- Osaka Electro-Communication University
  - T. Fukuda, Y. Mizoi
- Seoul National University
  - H. Bhang, M. Kim, S. Kim, C.J. Yoon
- Tohoku University
  - H. Tamura

Student
Postdoc

Do we understand the simplest hypernucleus?

$^{3}_{\Lambda}H$



Three body decay observed by STAR
→ talk by Y. Xu on Tuesday

Branching ratio information by STAR will be very IMPORTANT

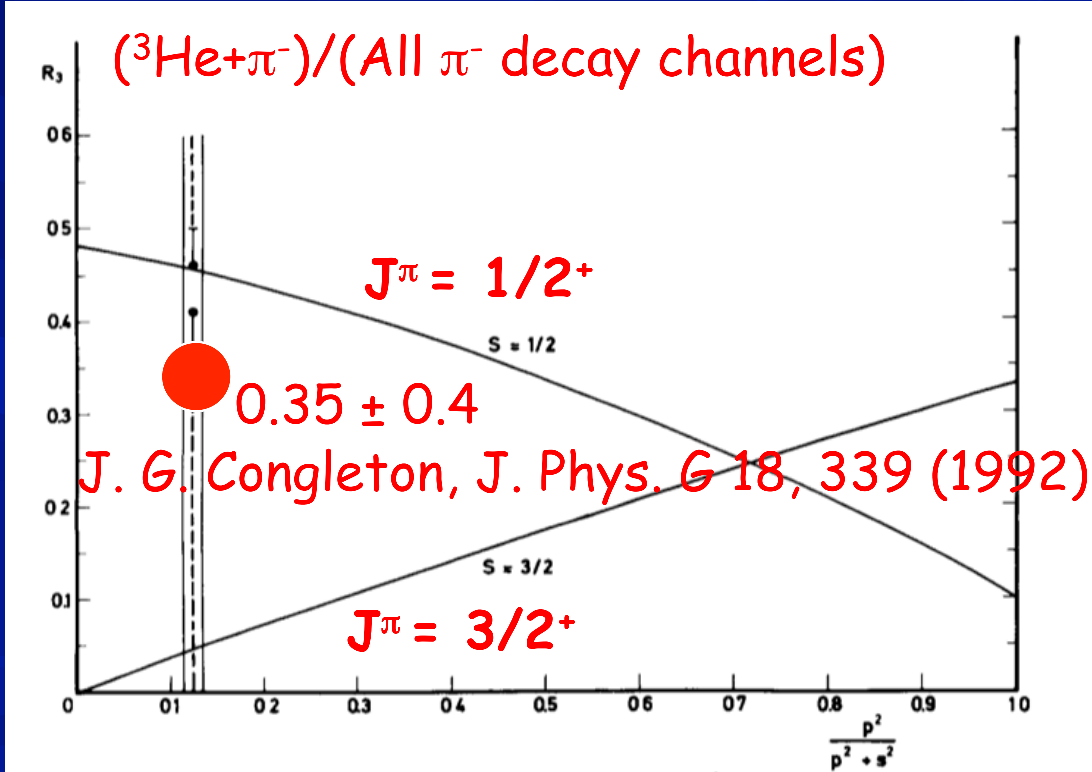


Fig. 4. The ratio $R_3 = (^{3}_{\Lambda}H \to \pi^{-} + {}^{3}He)$/(all π^{-} mesonic decays of $^{3}_{\Lambda}H$) as a function of $p^2/(p^2+s^2)$. The curves illustrate the results of the calculations made by Dalitz and Liu [4] for $J(^{3}_{\Lambda}H) = \frac{1}{2}$ and $\frac{3}{2}$.

T. Bertrand et al., NPB 16(1970)77

$R(^{3}_{\Lambda}H) > R(^{208}Pb)$

$\tau(^{3}_{\Lambda}H)$ should be equal to $\tau(\Lambda$, 263 ps)

However,
$\tau(^{3}_{\Lambda}H)$ = ~ 180 ps

Particle identification

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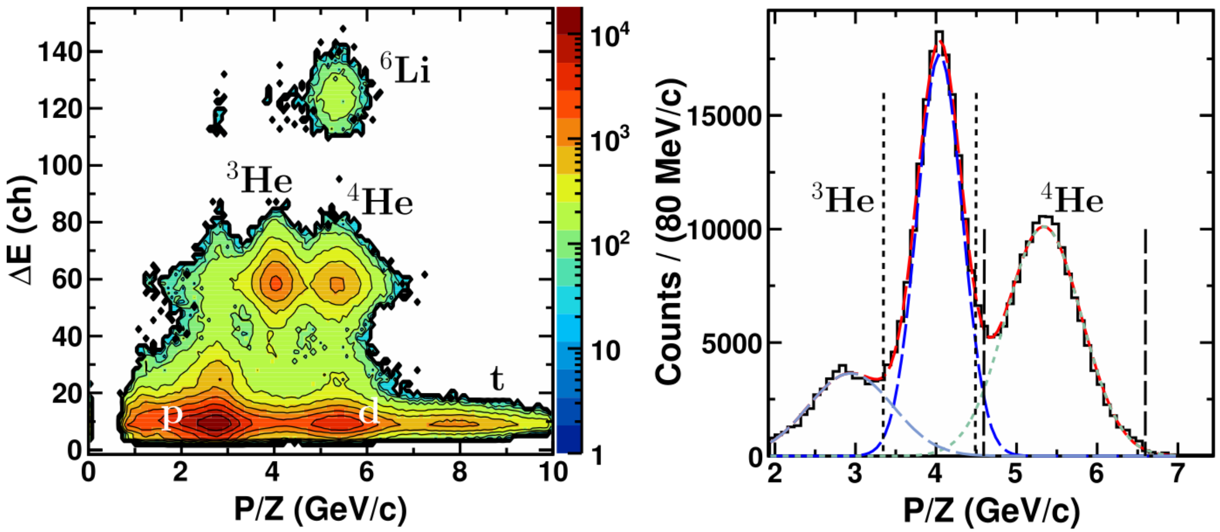
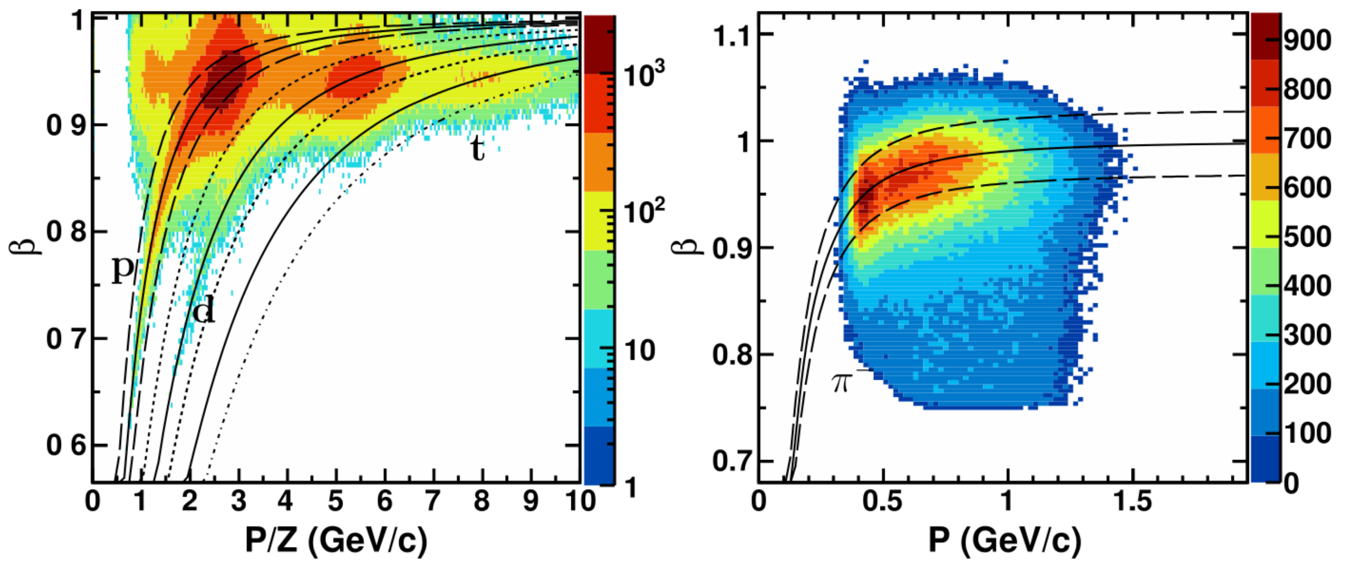
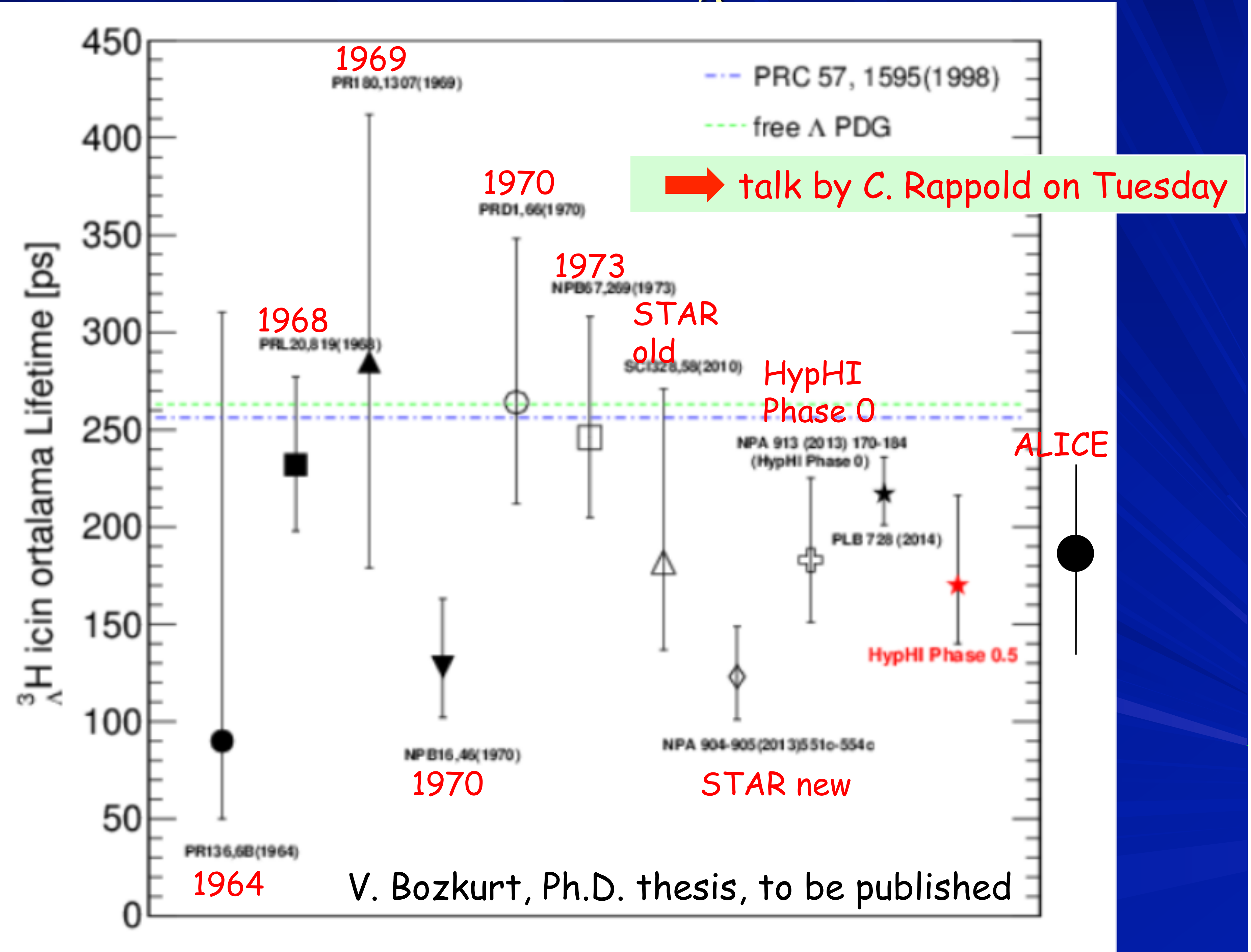


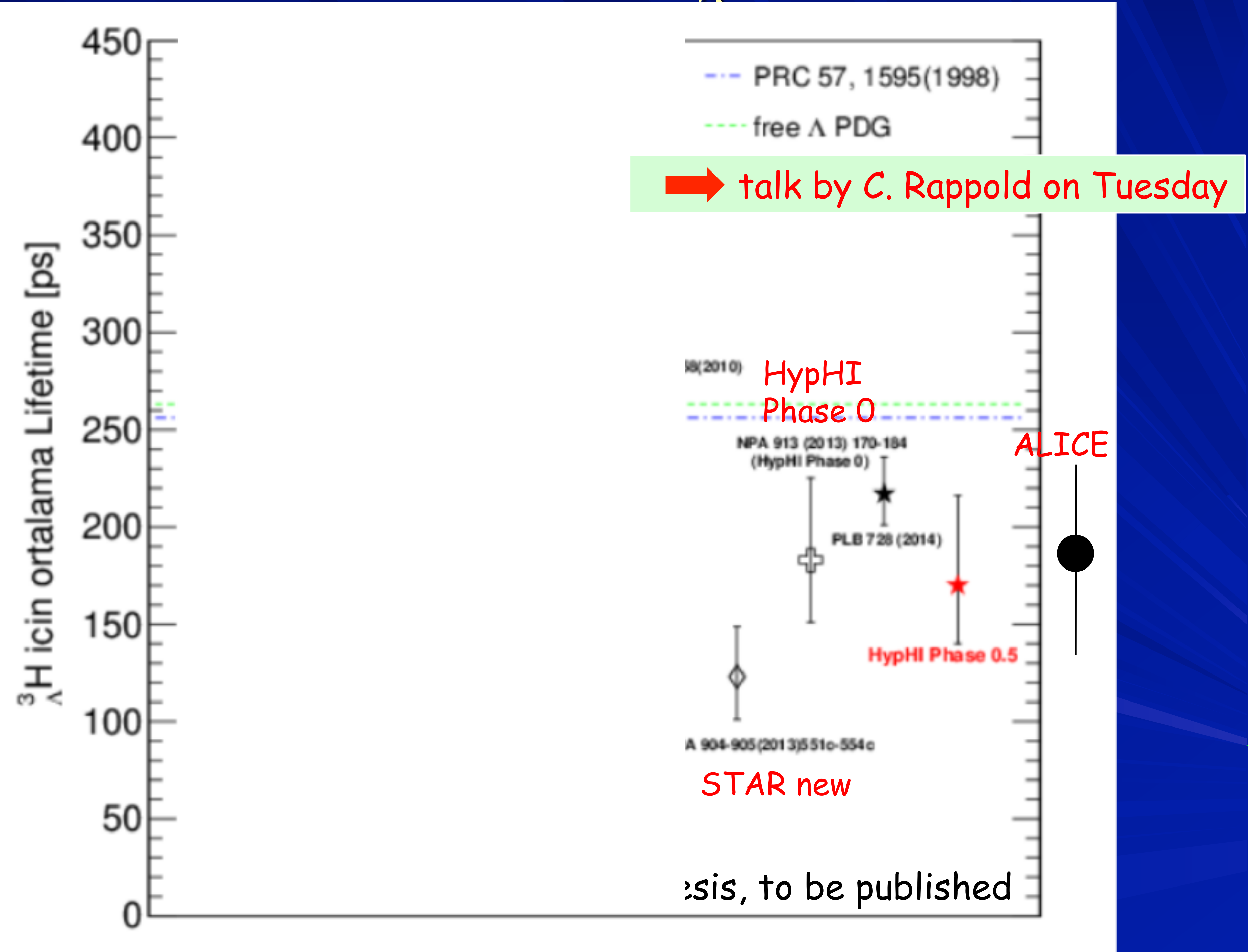
C. Rappold et al. / Nuclear Physics A 913 (2013) 170–184 175



Lifetime of $^{3}_{\Lambda}H$

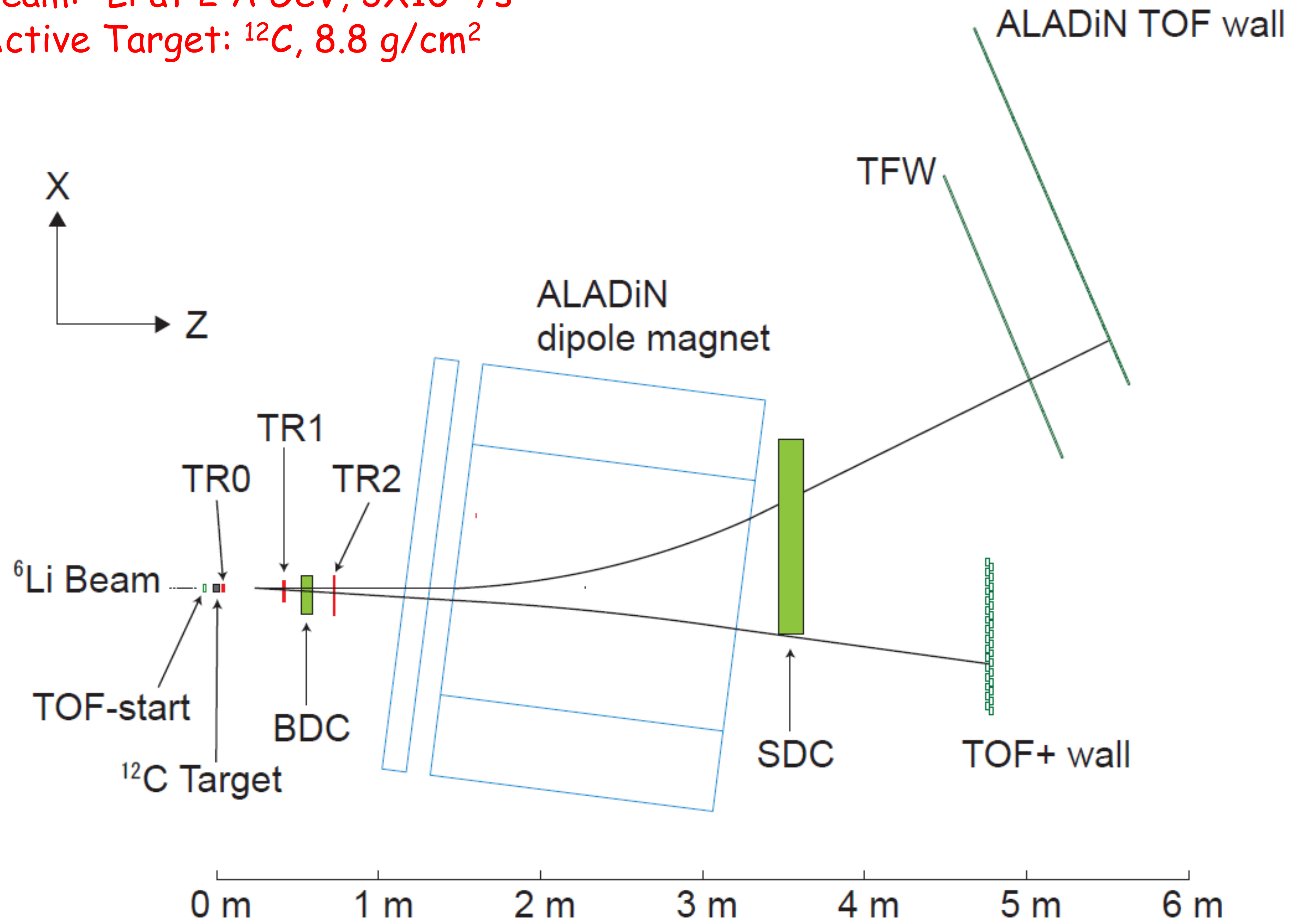


Lifetime of $^3_\Lambda H$



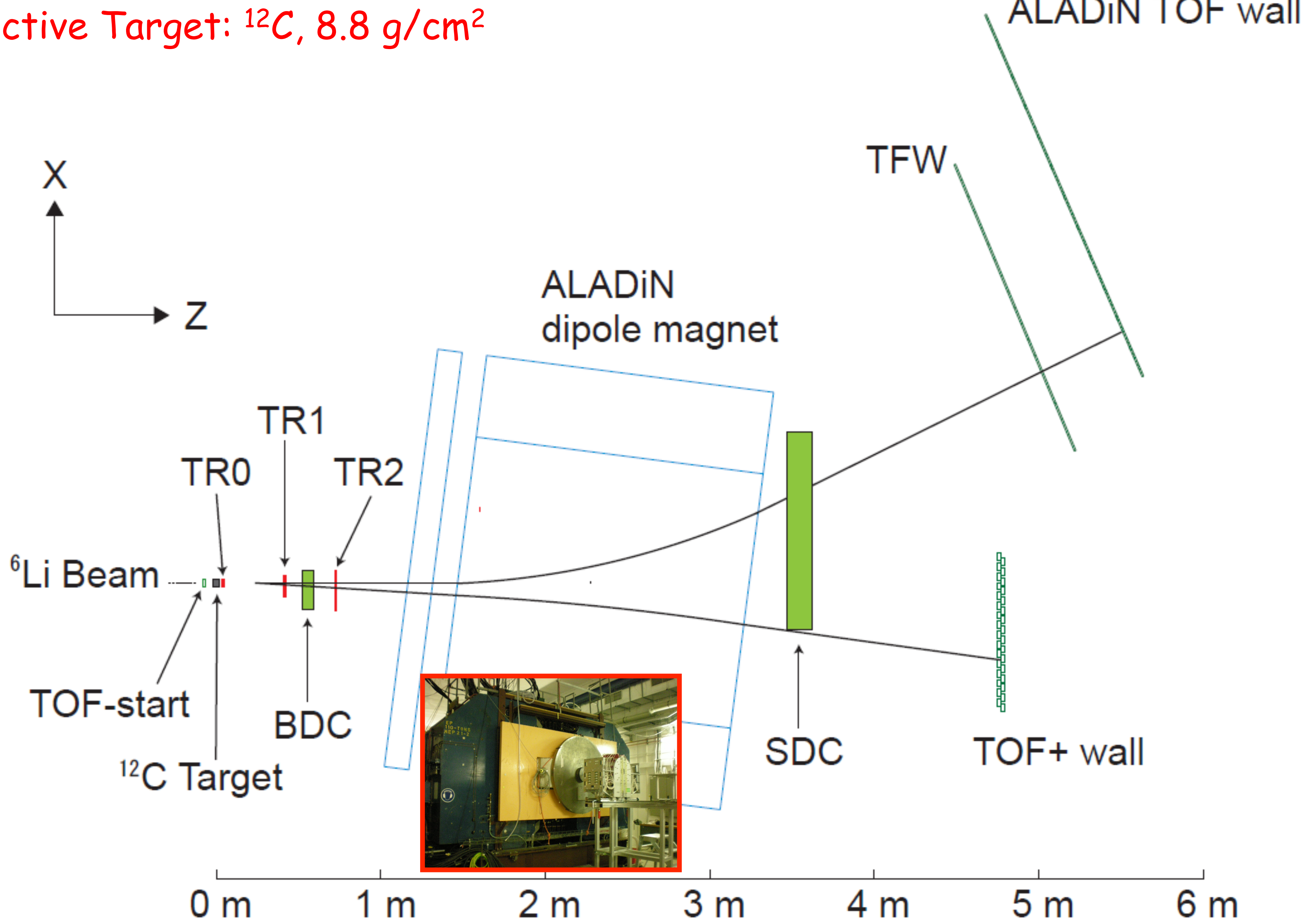
Phase 0 setup

Beam: ^{6}Li at 2 A GeV, 3X10^{6} /s
Active Target: ^{12}C, 8.8 g/cm^{2}



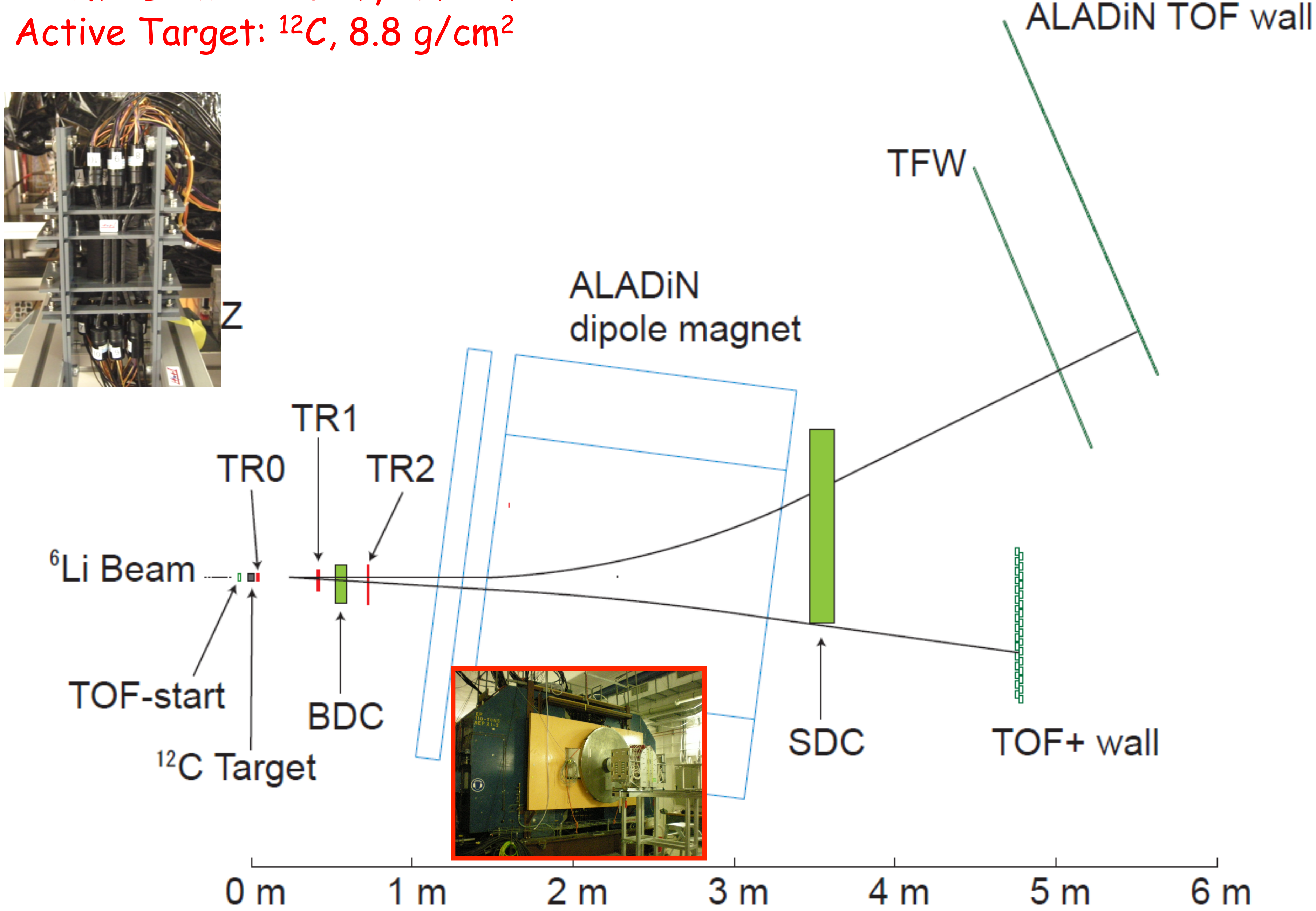
Phase 0 setup

Beam: ^{6}Li at 2 A GeV, $3X10^{6}$ /s
Active Target: ^{12}C, 8.8 g/cm^{2}



Phase 0 setup

Beam: ^{6}Li at 2 A GeV, $3X10^{6}$ /s
Active Target: ^{12}C, 8.8 g/cm^{2}



Phase 0 setup

Beam: ^{6}Li at 2 A GeV, $3X10^{6}$ /s

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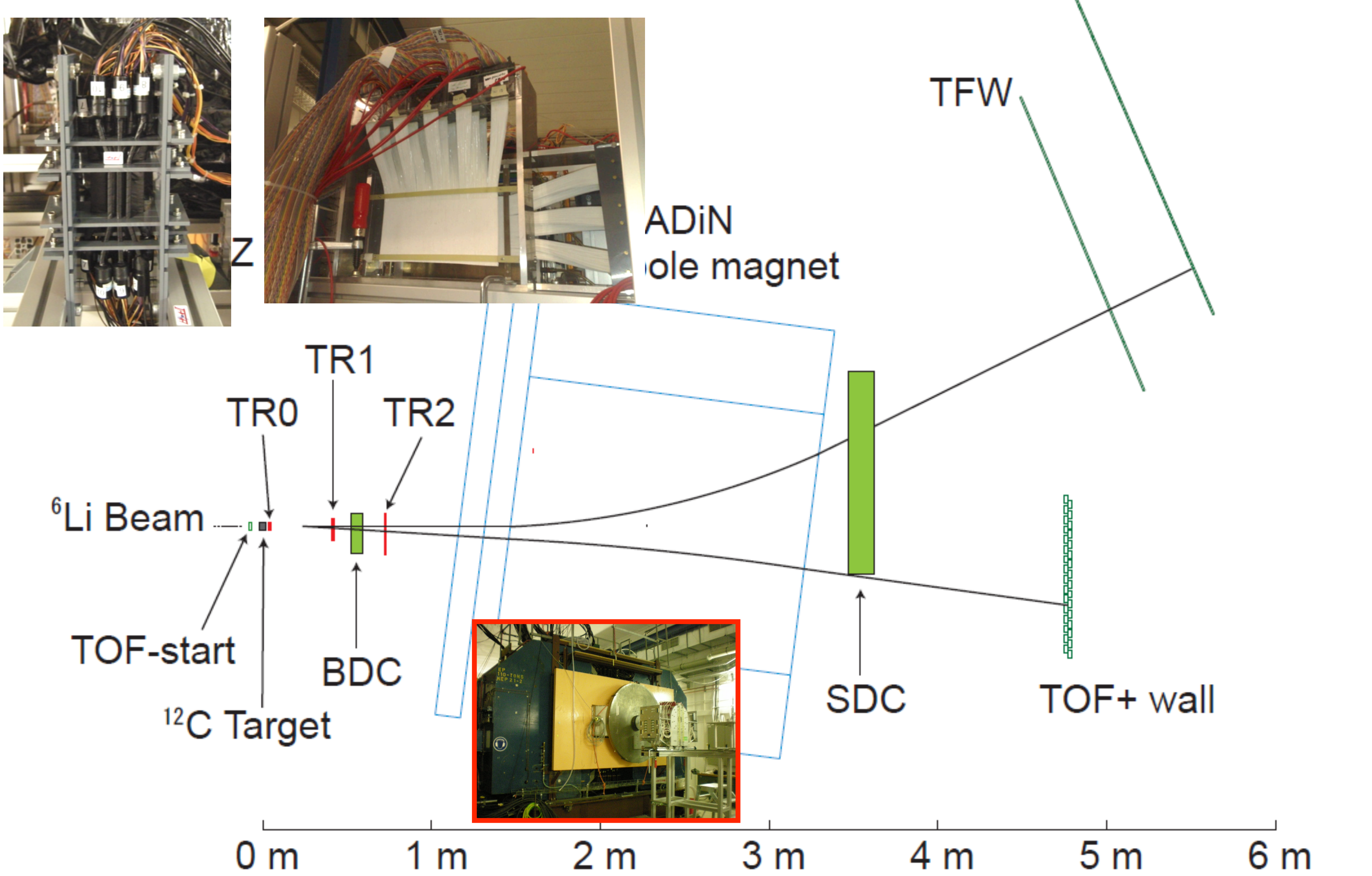

Phase 0 setup

Beam: ^{6}Li at 2 A GeV, $3X10^{6}$ /s
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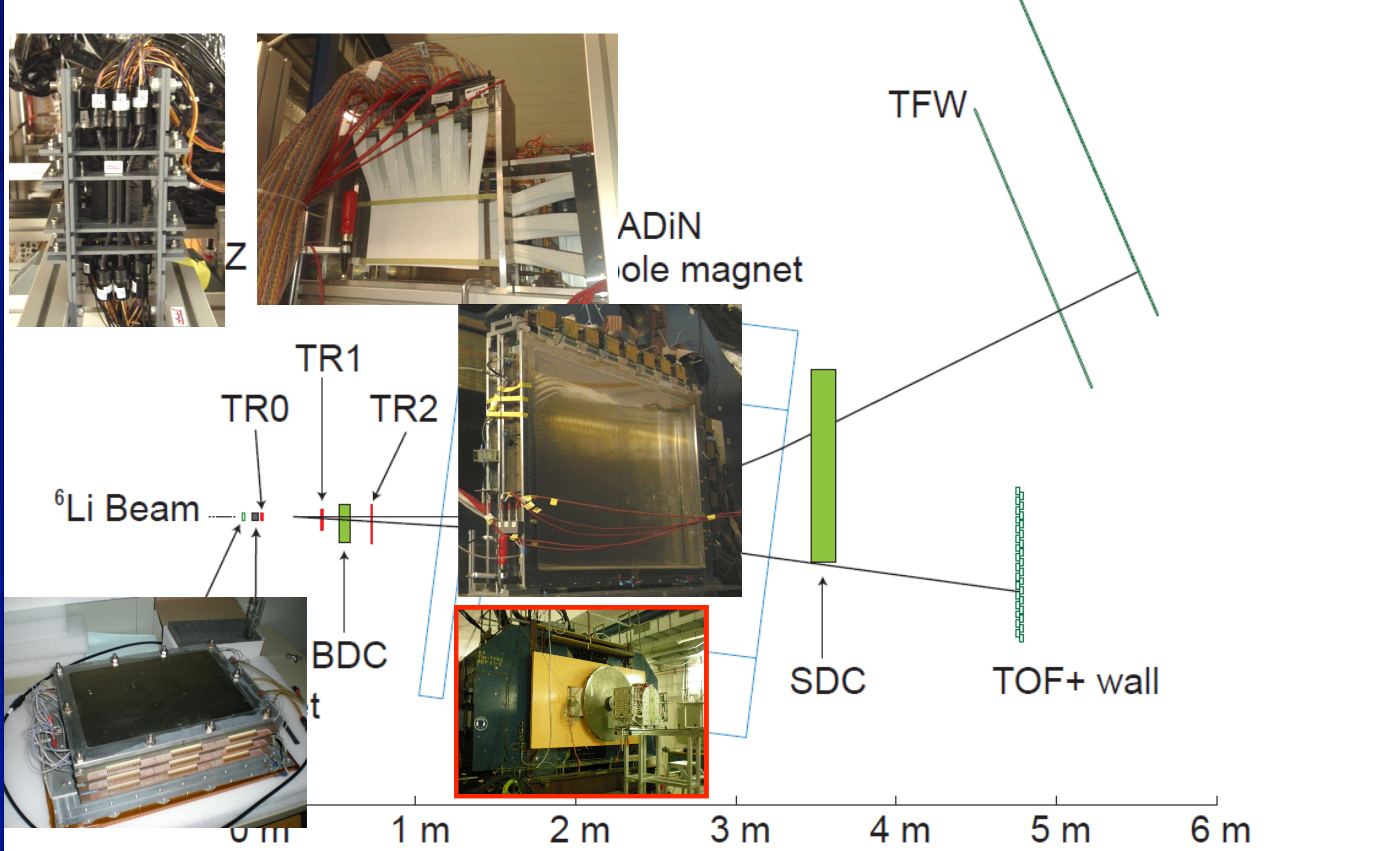
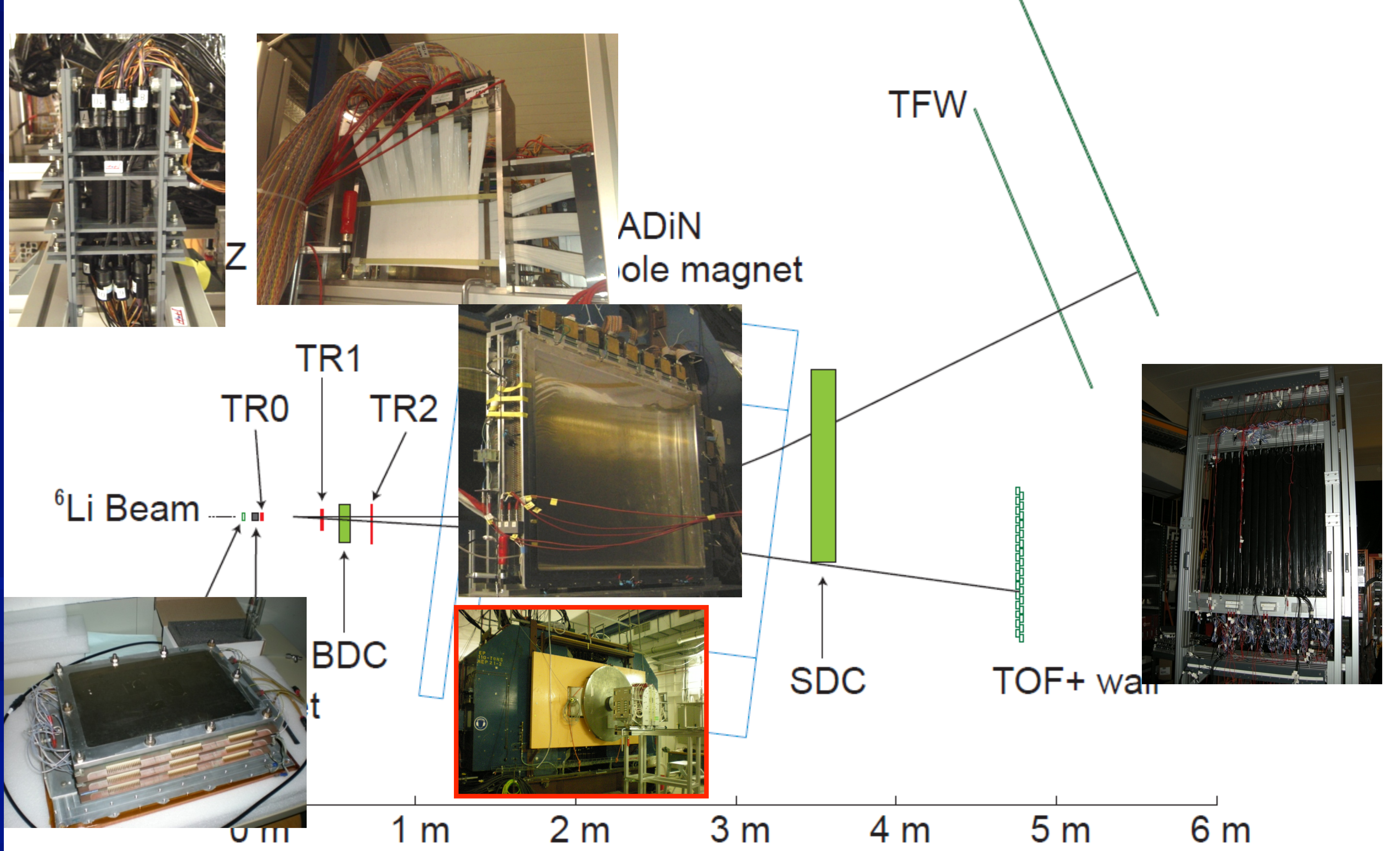


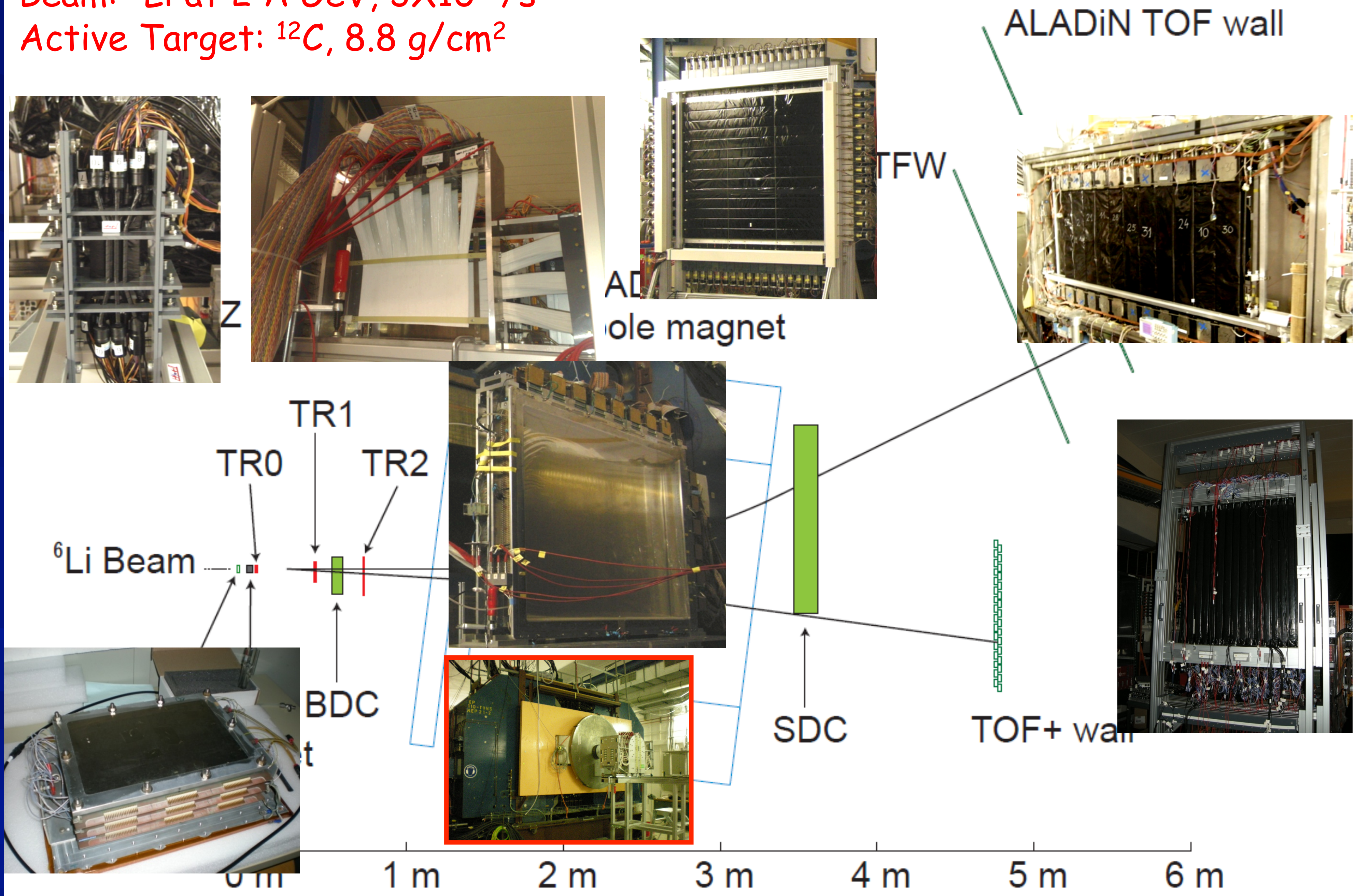
Phase 0 setup

Beam: ^{6}Li at 2 A GeV, $3X10^{6}$ /s
Active Target: ^{12}C, 8.8 g/cm^{2}



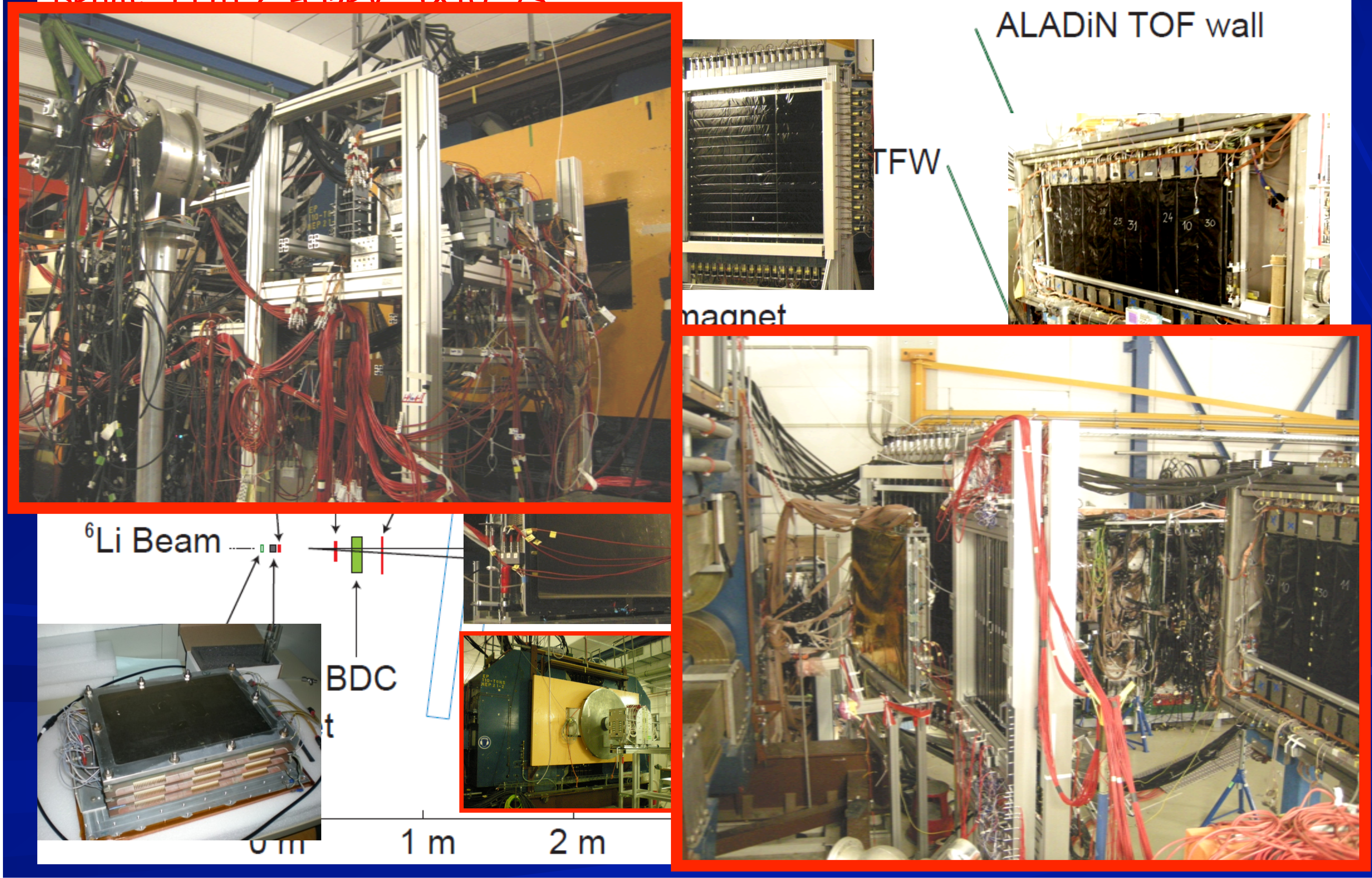
Phase 0 setup

Beam: ^{6}Li at 2 A GeV, 3×10^{6} /s
Active Target: ^{12}C, 8.8 g/cm^2

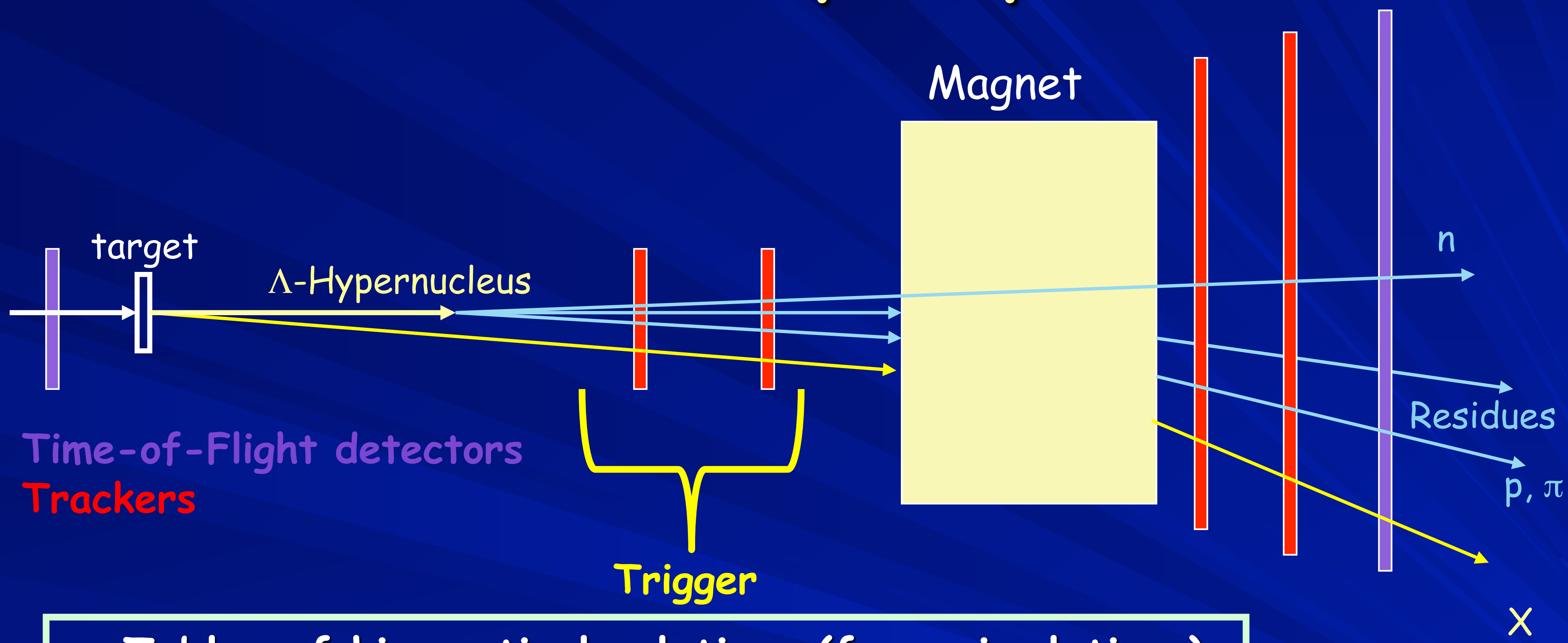


Phase 0 setup

Beam: ^{6}Li at 2 A GeV, 3X10^{6} /s



Detection principle



- Tables of kinematical relations (from simulations)
- Programmed in fast online hardware (FPGA)

→ **Displaced vertex trigger**

C. Rappold, PhD thesis