S447
Hypernuclear spectroscopy with heavy ion beams

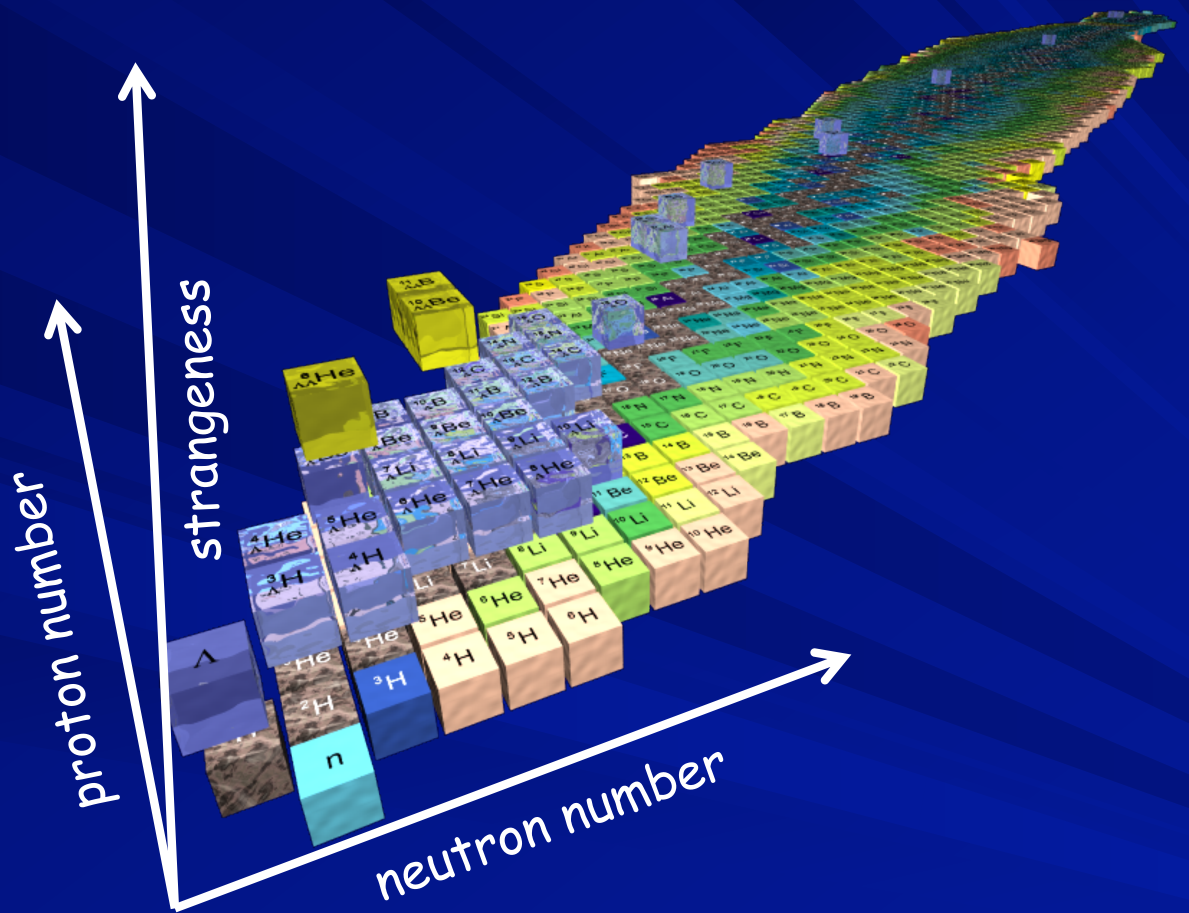
Three-body hypernuclear puzzles: the hypertriton lifetime and signals indicating n-n-Λ

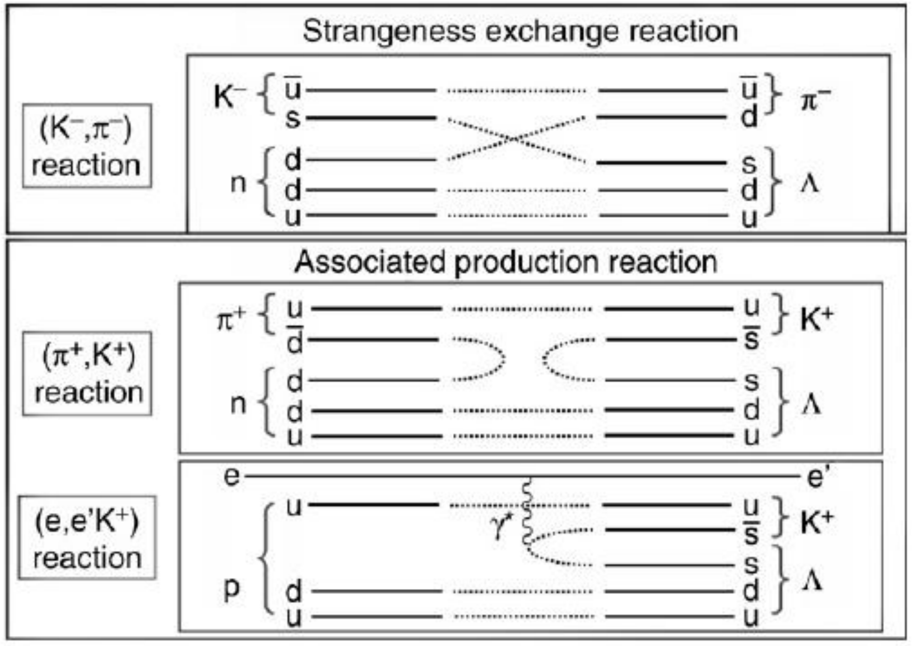
Take R. Saito

GSI Helmholtz Center for Heavy Ion Research, Germany
and
Helmholtz Institute Mainz, Germany

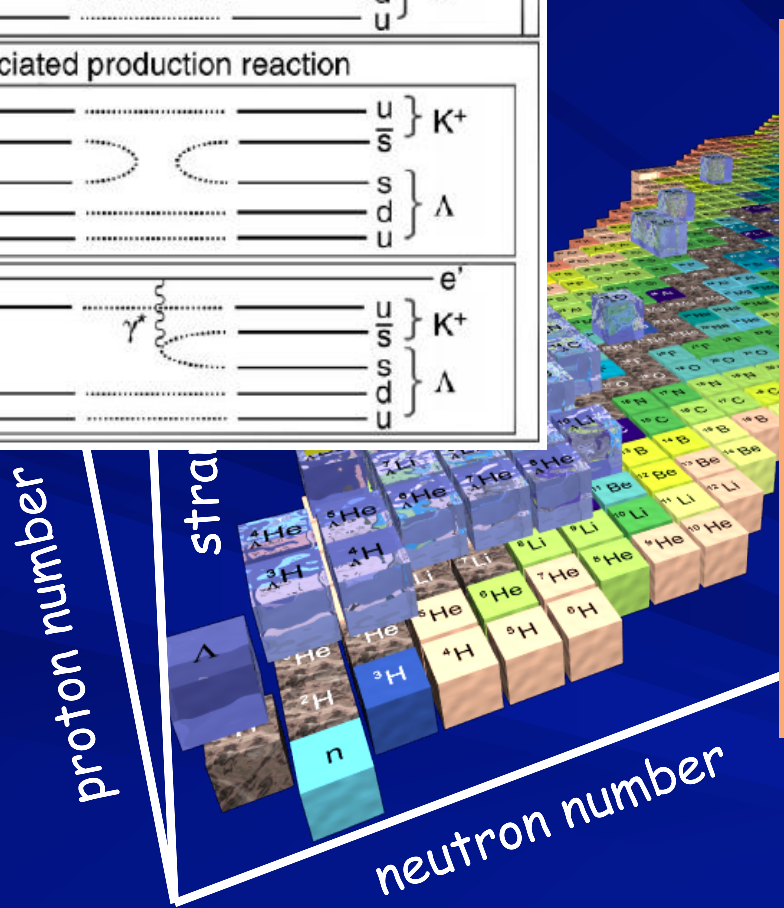
Workshop on WASA at GSI/FAIR,
November 27th – 28th, 2017, GSI, Germany

3D nuclear chart





clear chart



Advantage

- Precise spectroscopy
  - Structure in detail
- Clean experiment

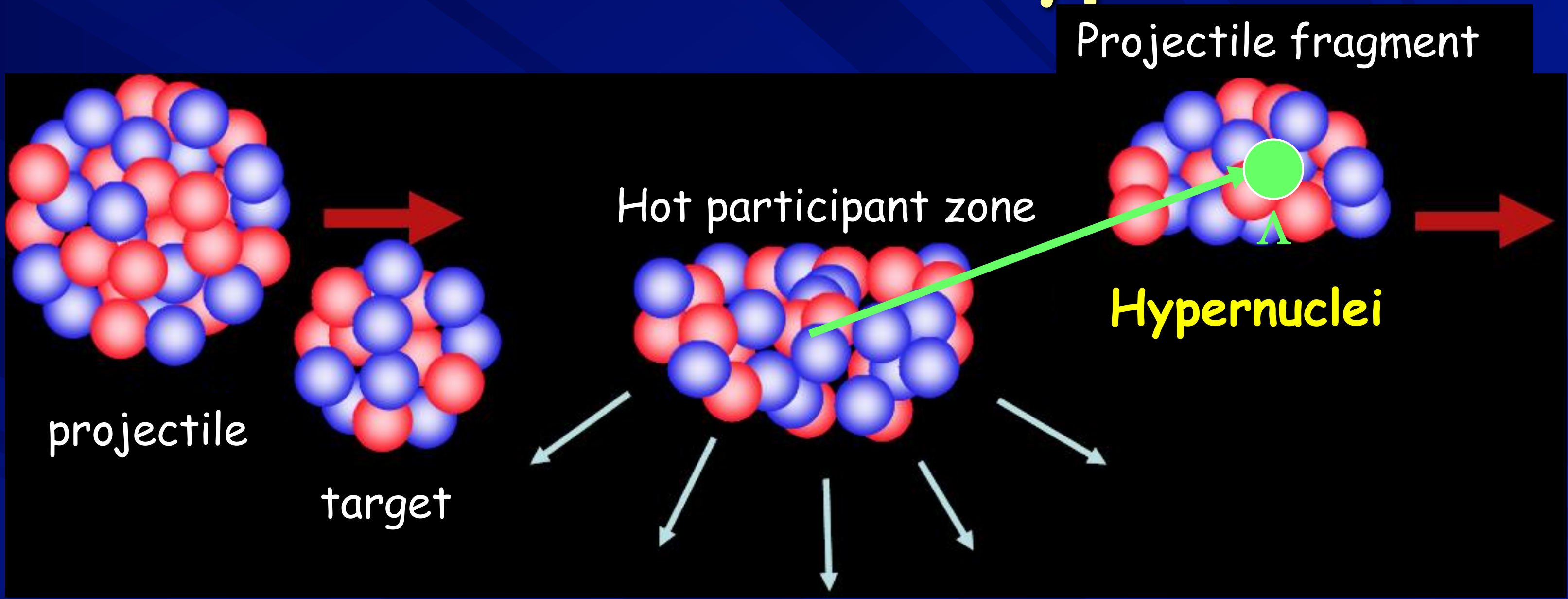
Difficulties

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

Hypernuclear spectroscopy with heavy ion beams

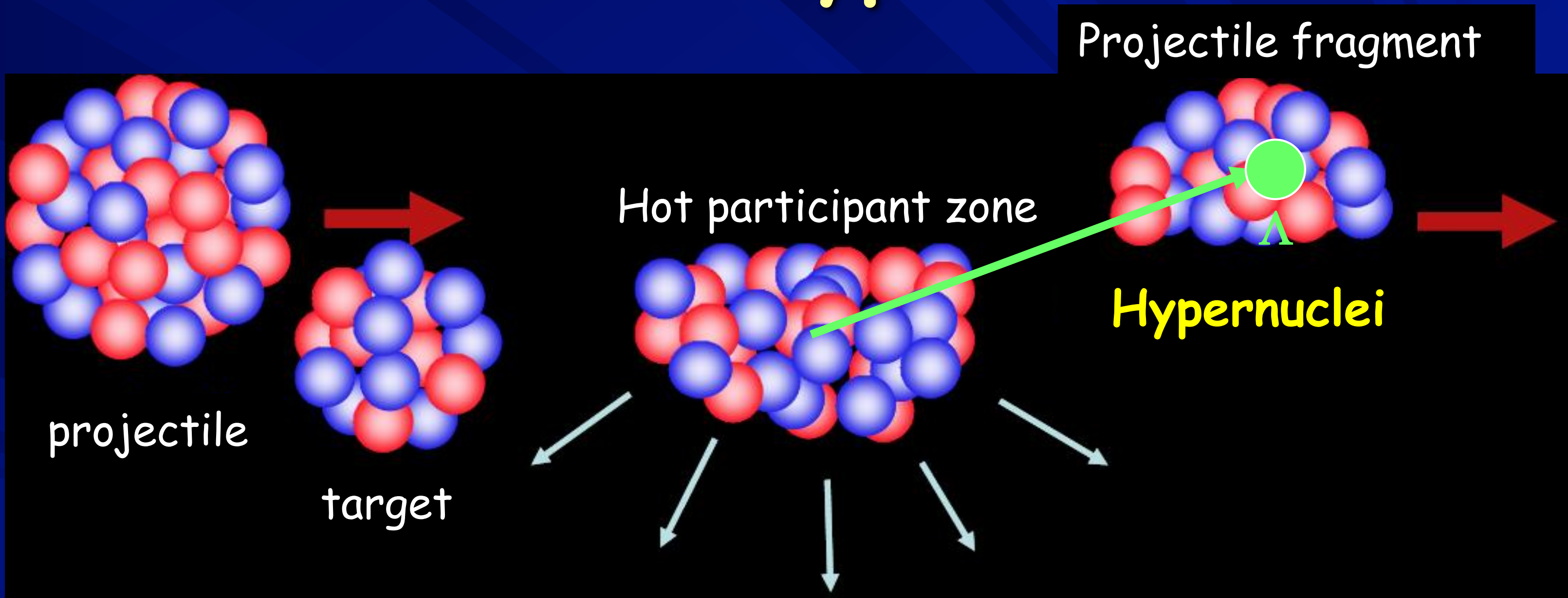
HypHI project, started in 2005

Violent Production of Hypernuclei



- **Coalescence of Λ in projectile fragments**

Relativistic hypernuclei



- **Large Lorentz factor** γ (>3)
  - Effective lifetime : Longer by the Lorentz factor

    200 ps -> 600 ps at GSI (ct ~ 20 cm)

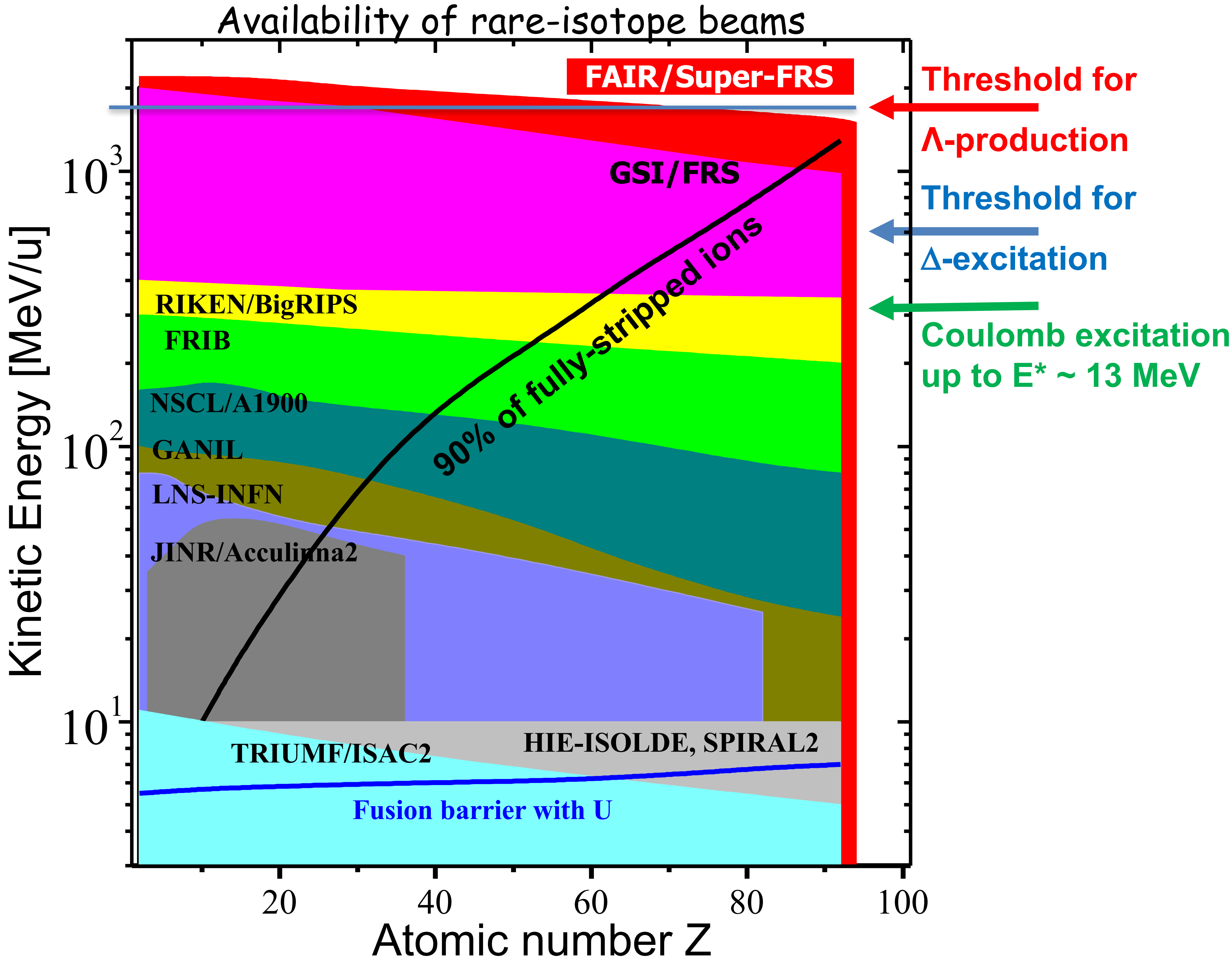
    200 ps -> 4 ns at FAIR (ct ~ 120 cm)

- **Hypernuclear separation and spin precession**

Nuclear matter with multiple-strangeness

Why hypernuclei with heavy ion beams?

- **Projectile fragmentation + Λ capture**
  - Neutron- and proton-rich hypernuclei
  - Unexpected exotics and phenomenon
- **Hypernuclei at projectile rapidity (β ~ 0.94)**
  - Invariant mass spectroscopy in flight
  - Vertex information -> Lifetime
- **Hypernuclear production with RI-beams**
  - **Very unique only at FRS/GSI and Super-FRS/FAIR**



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

Why hypernuclei with heavy ion beams?

- **Projectile fragmentation + Λ capture**
  - Neutron- and proton-rich hypernuclei
  - Unexpected exotics and phenomenon

HypHI Phase 0

- **Hypernuclei at projectile rapidity (β ~ 0.94)**
  - Invariant mass spectroscopy in flight
  - Vertex information -> Lifetime

- **Hypernuclear production with RI-beams**
  - **Very unique only at FRS/GSI and Super-FRS/FAIR**

HypHI: Hypernuclear spectroscopy with Heavy Ion beams

Started in 2005

HypHI at GSI/FAIR: Concept of Experiments

Produced hypernucleus close to projectile velocity

- Large Lorents factor $\gamma > 3$
- $c\tau \sim 20$ cm at 2 A GeV

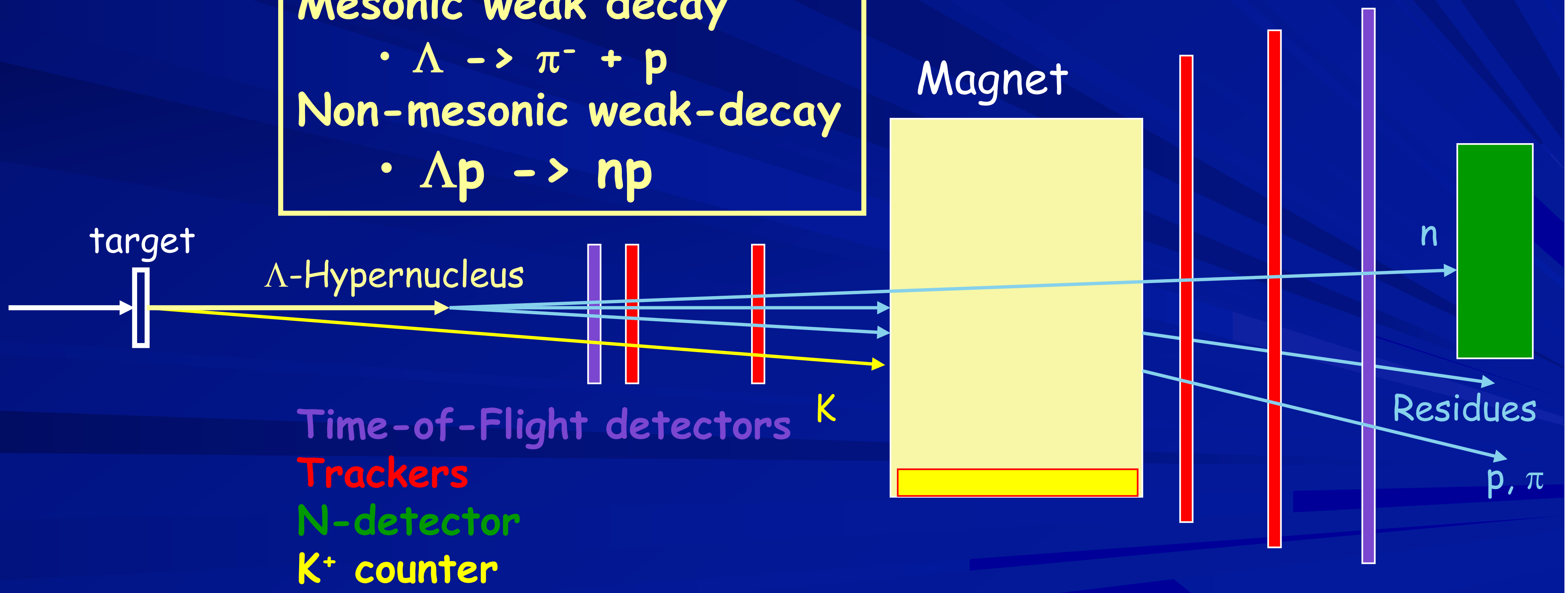
Example : $^{12}C + {}^{12}C \rightarrow {}^{A}_{\Lambda}Z + K^{+,0} + X$

Mesonic weak decay

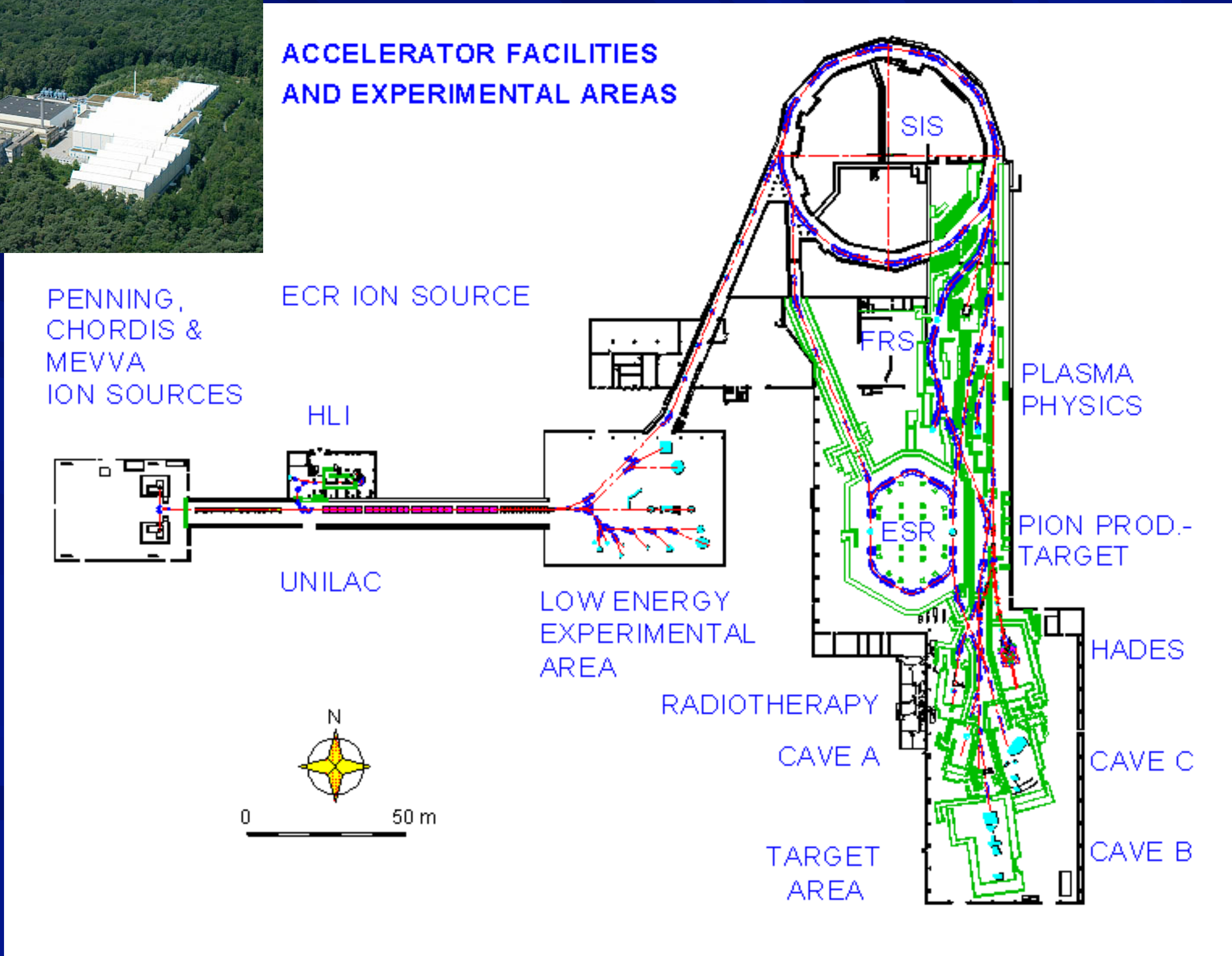
- $\Lambda \rightarrow \pi^- + p$

Non-mesonic weak-decay

- $\Lambda p \rightarrow np$



GSI Helmholtz Center for Heavy Ion Research

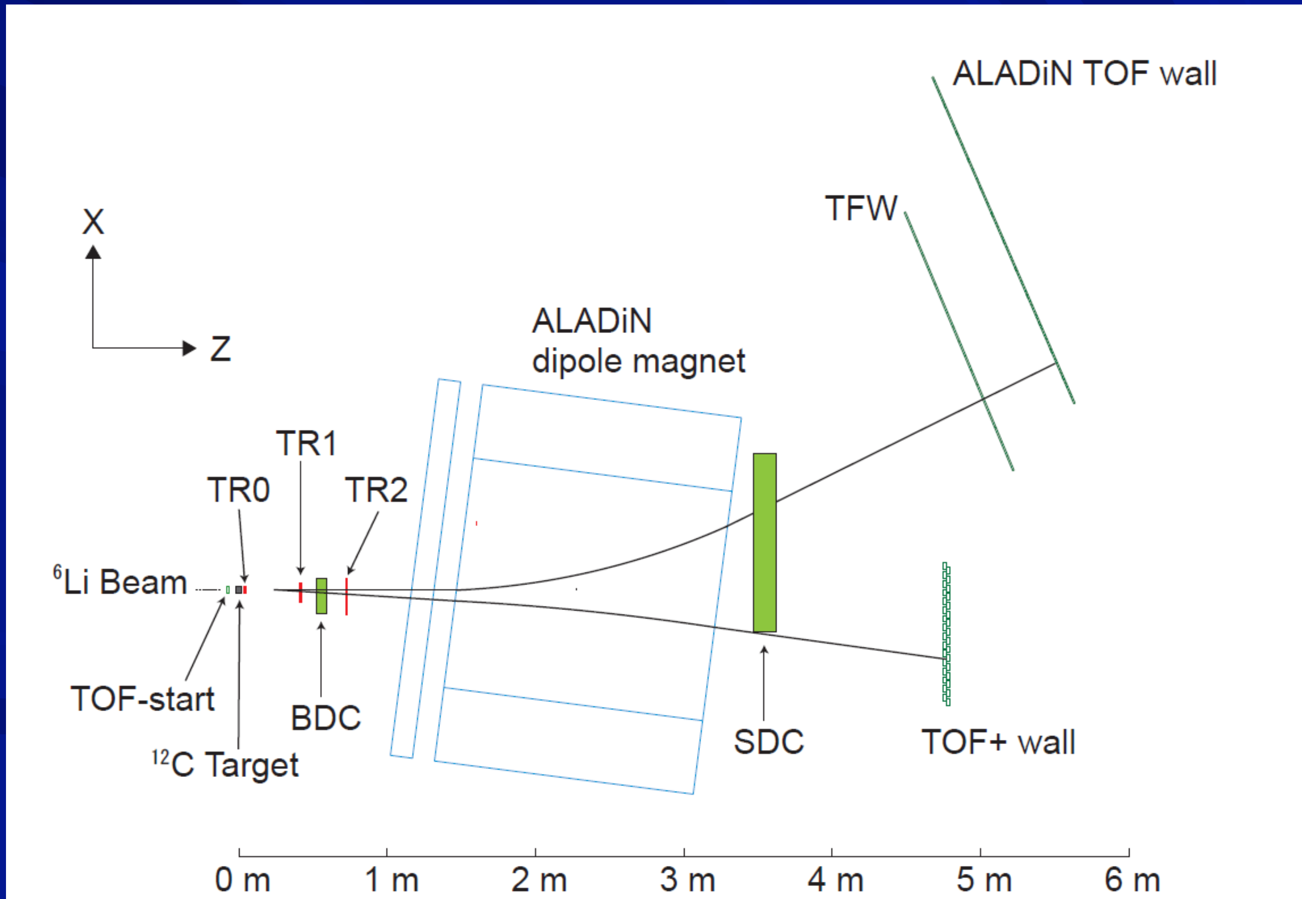


HypHI Phase 0 in October 2009

- 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 $\Lambda \rightarrow \pi^{-} + p$

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

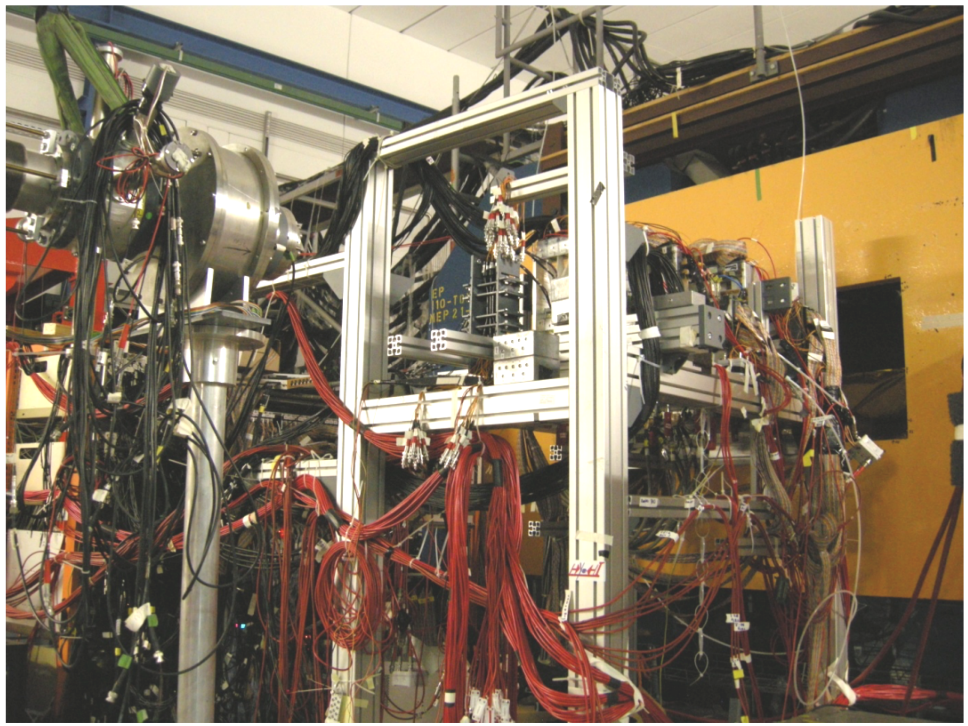
$^{4}_{\Lambda}H \rightarrow \pi^{-} + {}^{4}He$

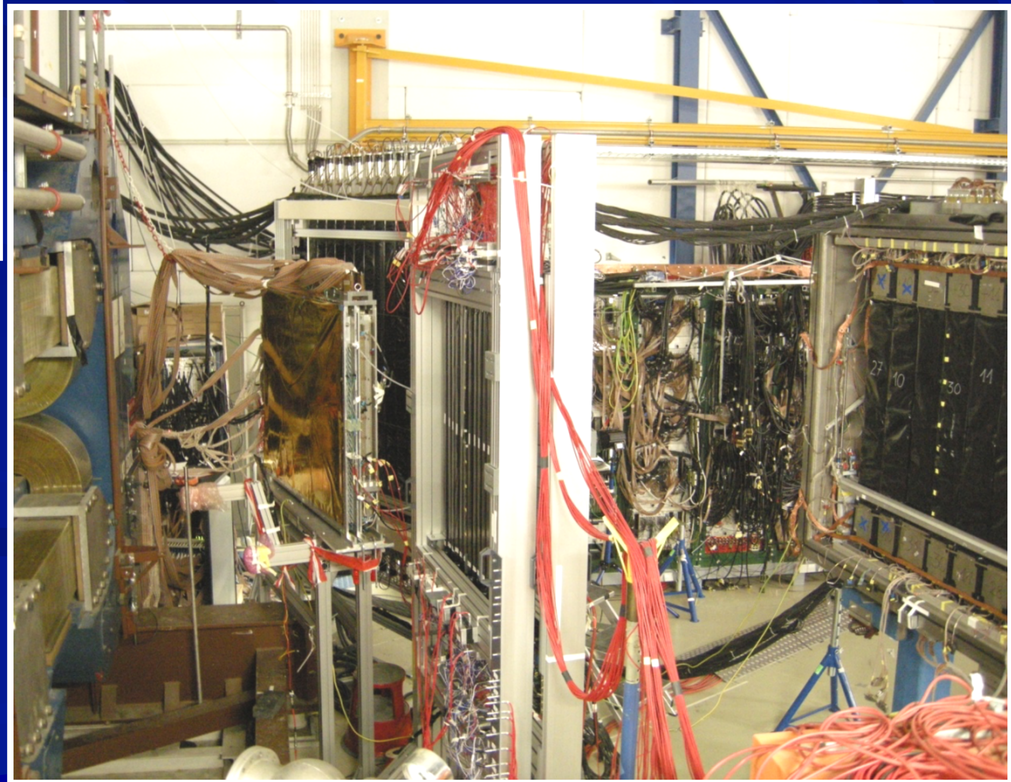


Funding

- Helmholtz-University Young Investigators Group VH-NG-239, 2006-2012
- DFG grant SA1696/1-1 2007-2009, TOF detectors

HypHI setup in 2009

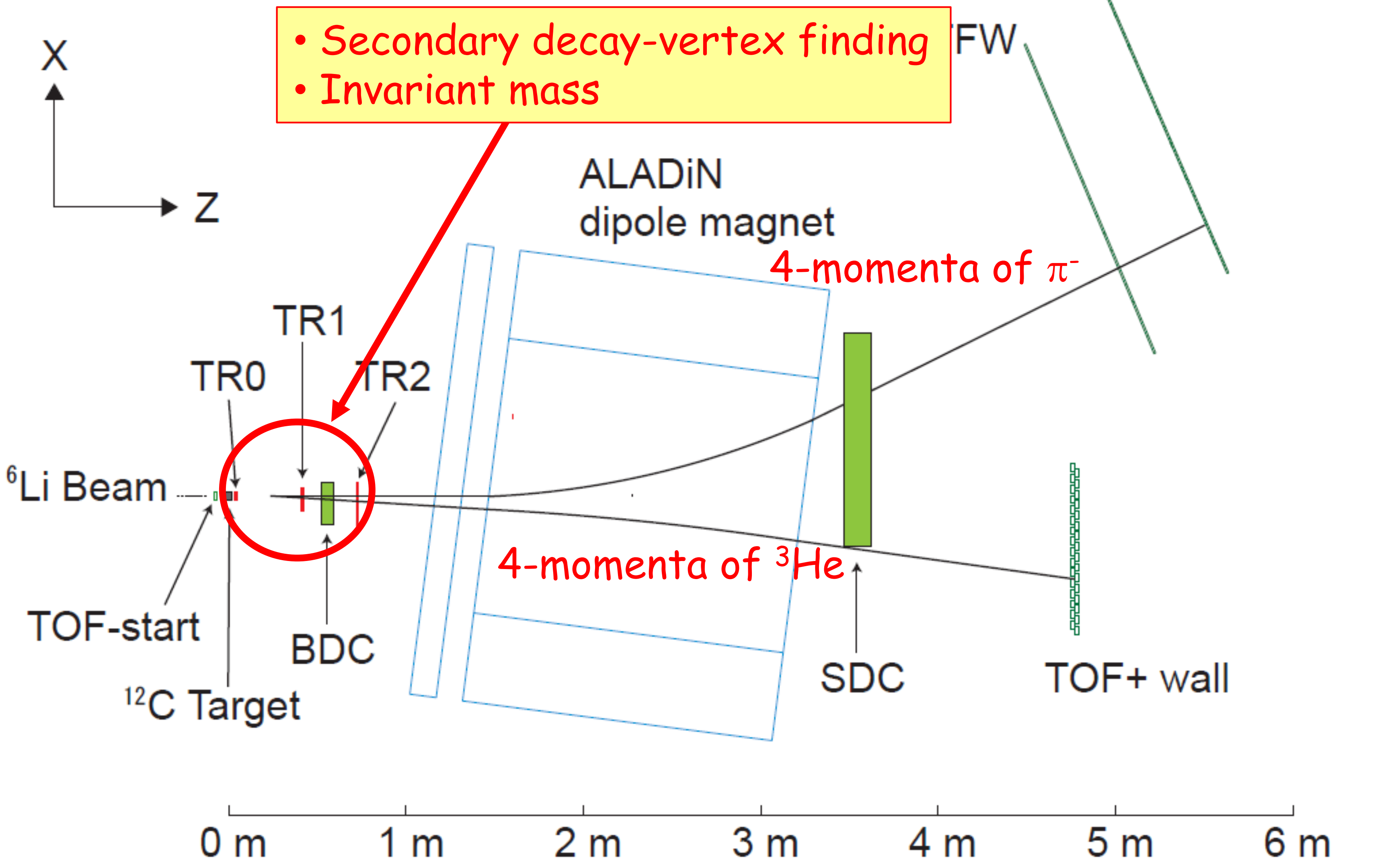




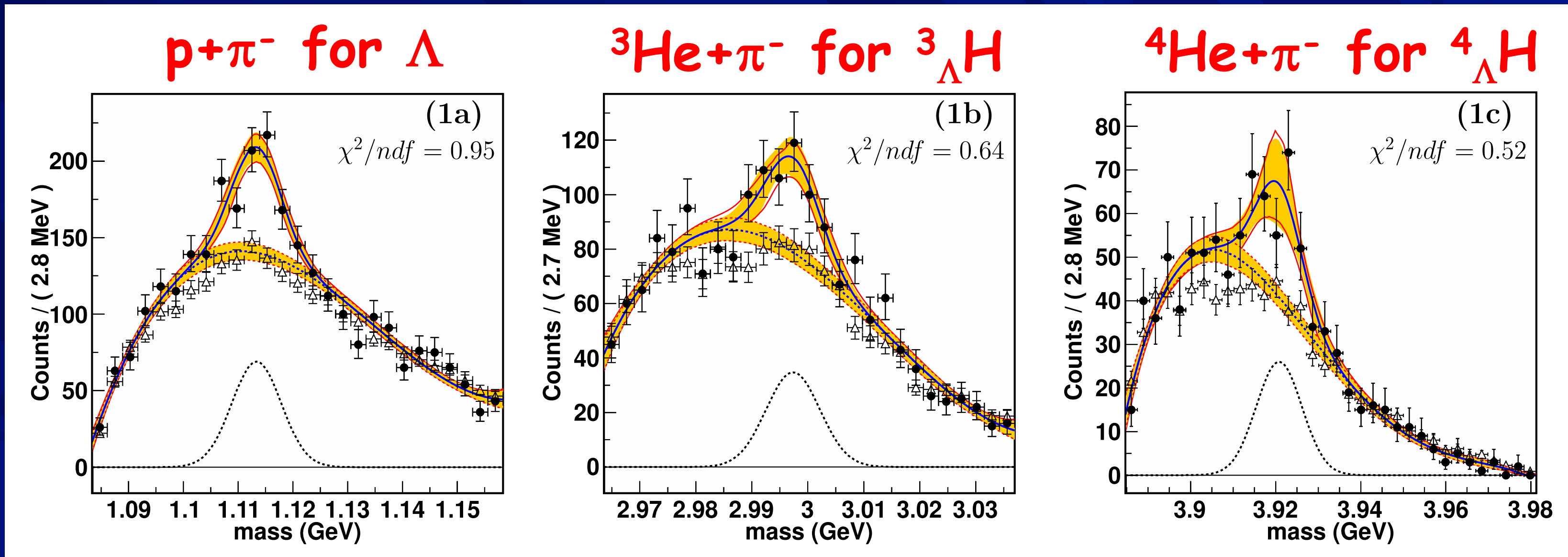
HypHI Phase 0 (2009), $^{6}Li+^{12}C$ at 2 A GeV

Example:

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



HypHI Phase 0 (2009), $^{6}Li+^{12}C$ at 2 A GeV



	Λ	$^{3}_{\Lambda}H$	$^{4}_{\Lambda}H$
Observed counts	280 ± 63	154 ± 49	123 ± 33
Peak width [MeV]	4.5 ± 1.9	4.8 ± 1.3	5.4 ± 1.2
Peak significance	6.7σ	4.7σ	4.9σ
Lifetime value [ps]	262^{+56}_{-43}	183^{+42}_{-32}	140^{+48}_{-33}
Cross section	1.7 mb	3.9 μb	3.1 μb

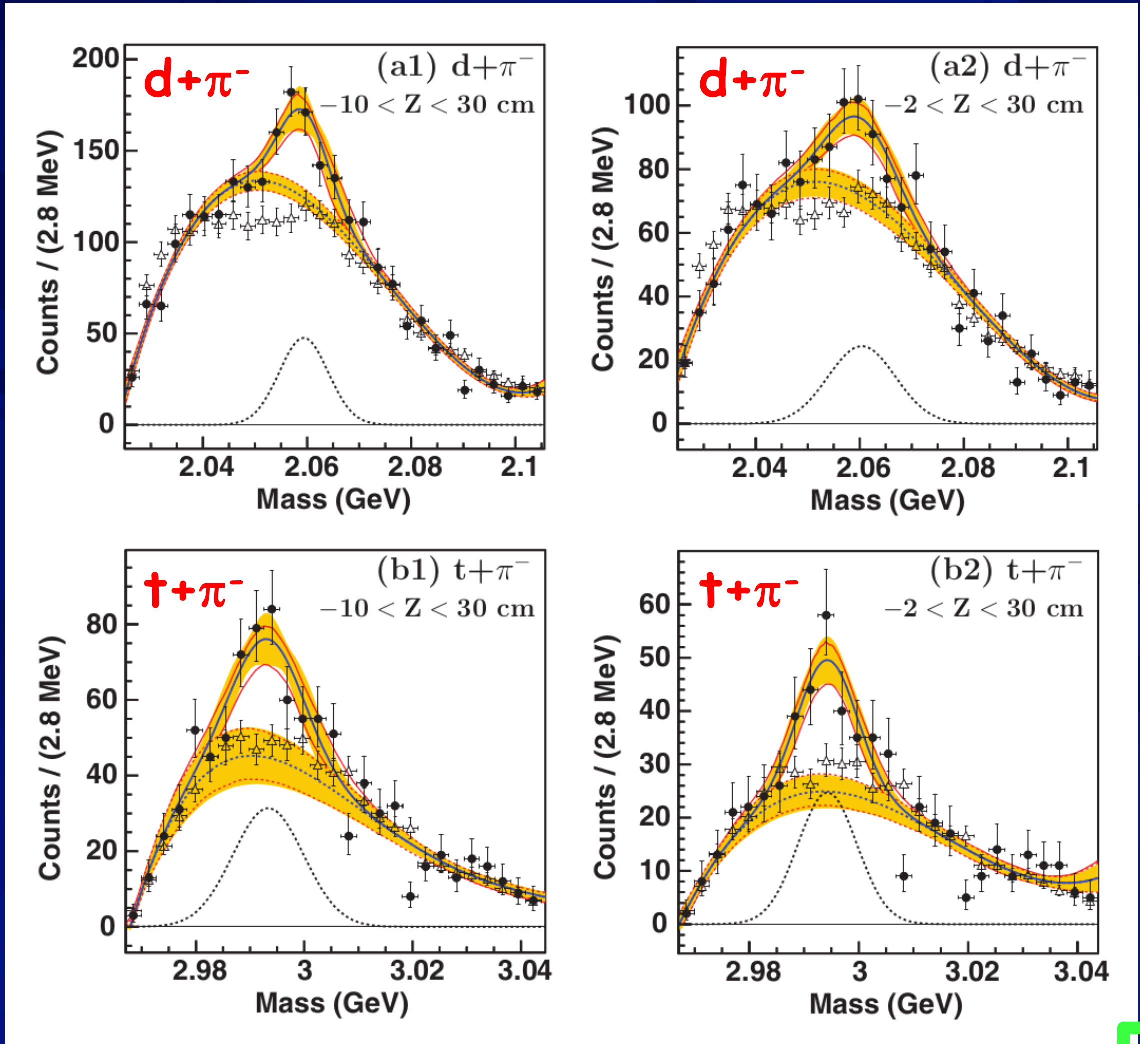
NPA 913 (2013) 170

PLB 747 (2015) 129

The feasibility demonstrated

Two puzzles from HypHI Phase 0

Puzzle 1: d+π^- and t+π^- signals



PRC 88 (2013) 041001(R)

τ ~ 190 ps

?

Neutral nucleus with Λ, nnΛ ??

$^3_\Lambda n \to t + \pi^-$

$^3_\Lambda n \to t^* + \pi^- \to n + d + \pi^-$

Theoretical calculations for nnΛ

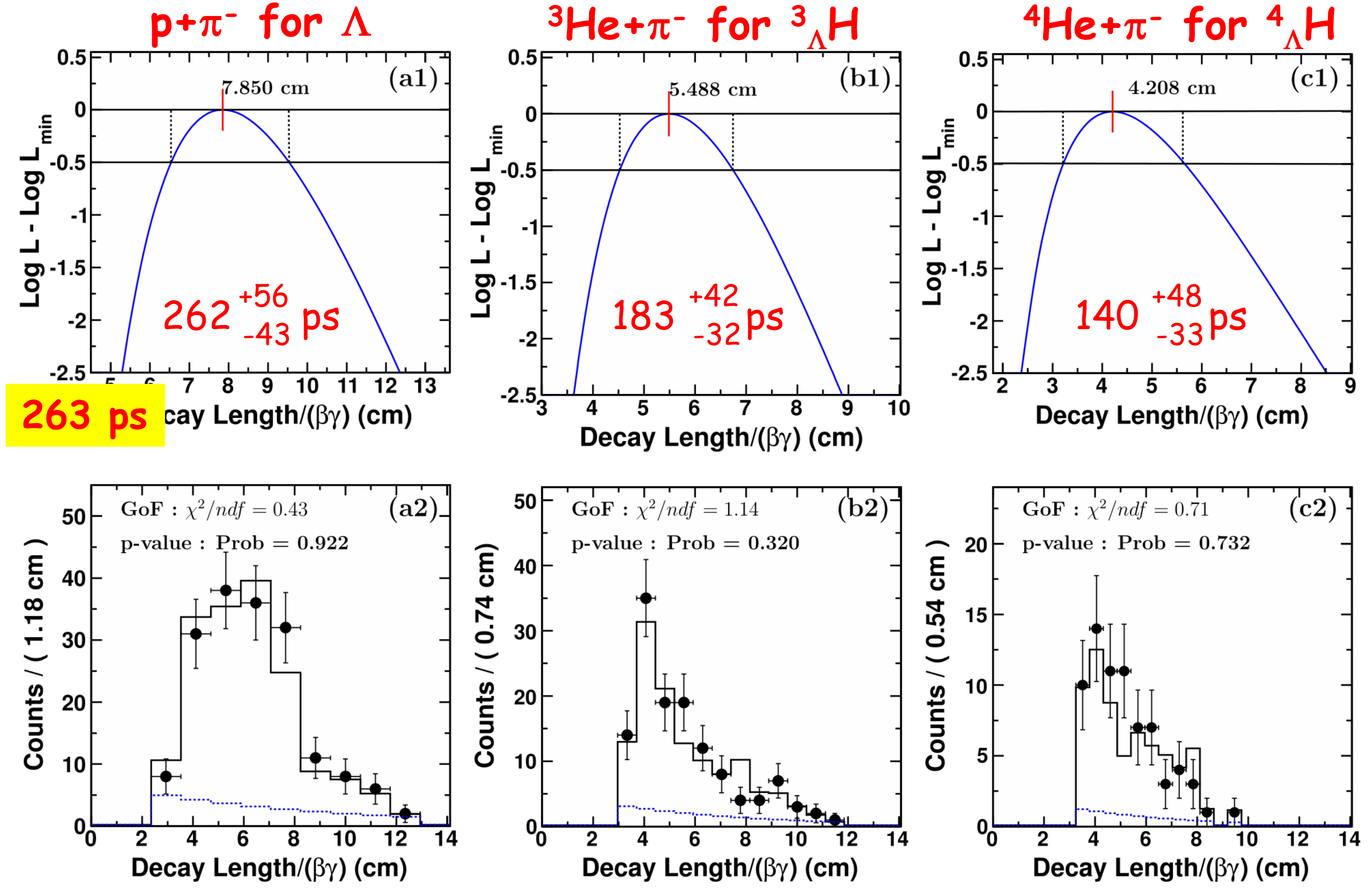
- E. Hiyama et al., Phys. Rev. C89 (2014) 061302(R)
- A. Gal et al., Phys. Lett. B736 (2014) 93
- H. Garcilazo et al., Phys. Rev. C89 (2014) 057001

nnΛ can not be bound

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

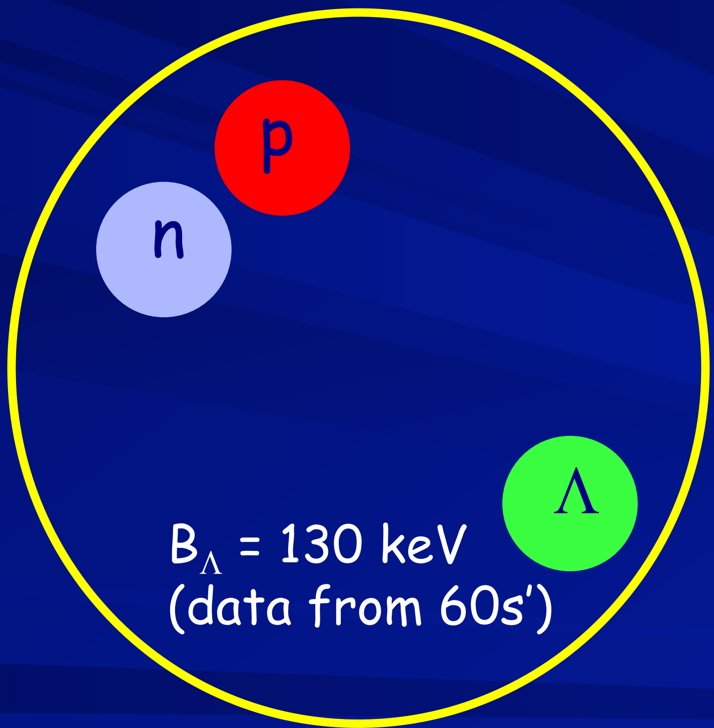
Lifetime: Unbineed maximum likelihood fitting

C. Rappold et al. / Nuclear Physics A 913 (2013) 170–184 181



Puzzle 2: Short lifetime of $^{3}_{\Lambda}H$

$^{3}_{\Lambda}H$: Benchmark in hypernuclear physics



HypHI Phase 0

$$183^{+42}_{-32}\ \text{ps}$$

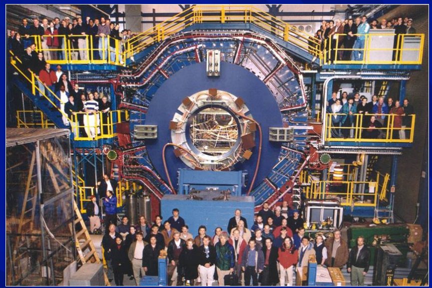
NPA 913 (2013) 170

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

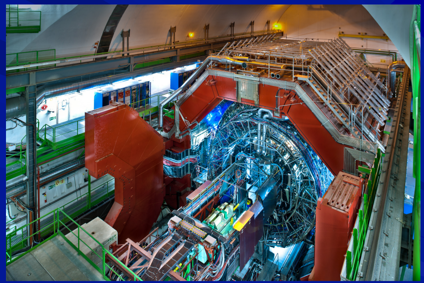
Recent status of lifetime values of $^{3}_{\Lambda}H$ (a few months ago)

- HypHI
  - $^{6}Li+^{12}C$ and $^{20}Ne+^{12}C$ at 2 A GeV at GSI
  - Phase 0 ($^{6}Li+^{12}C$), 183^{+42}_{-32} ps (Λ: 263 ps)

- STAR at BNL RHIC
  - $^{197}Au+^{197}Au$
  - Observation of short lifetime of $^{3}_{\Lambda}H$
  - Two/three-body decays combined: 155^{+25}_{-22} ps



- ALICE at LHC CERN
  - $^{208}Pb+^{208}Pb$
  - 181^{+54}_{-39} ps



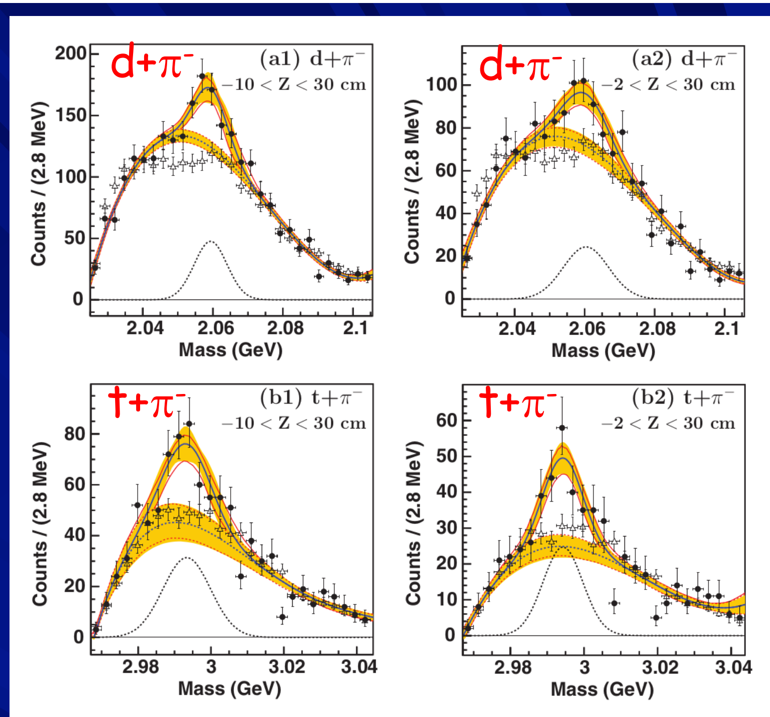
No theories to explain the short lifetime of $^{3}_{\Lambda}H$

Solving two puzzles

Signals indicating nnΛ bound state

All theoretical calculations are negative

- 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



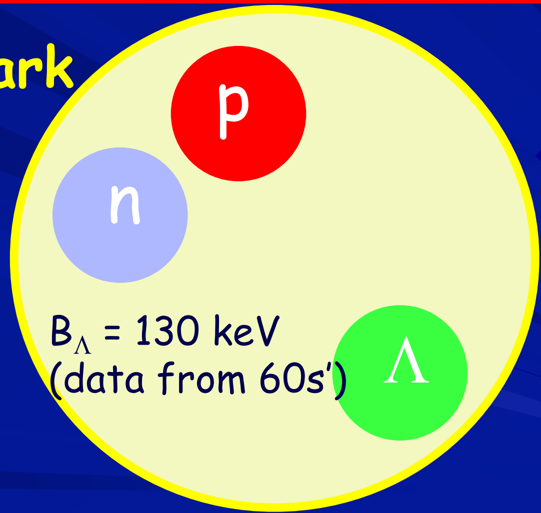
C. Rappold et al., PRC 88 (2013) 041001

Short lifetime of $^3_\Lambda$H

- HypHI Phase 0: 183^{+42}_{-32} ps
- STAR at RHIC: $\cancel{155^{+25}_{-22}\text{ ps}}$ 142^{+24}_{-21}
- ALICE at LHC: $\cancel{181^{+54}_{-39}\text{ ps}}$ 237^{+33}_{-36}

No theories to reproduce the short lifetime

Benchmark



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

Two puzzles from HypHI Phase 0

- Indication of ${}^{3}_{\Lambda}n$ ($nn\Lambda$) bound state

  Heavy ion beams (GSI/FAIR, STAR, ALICE)
  $(e,e'k^{+})$ with a tritium target

- Short lifetime of ${}^{3}_{\Lambda}H$

  Heavy ion beams (GSI/FAIR, STAR, ALICE)
  MAMI (binding energy)

- No theories to reproduce the both

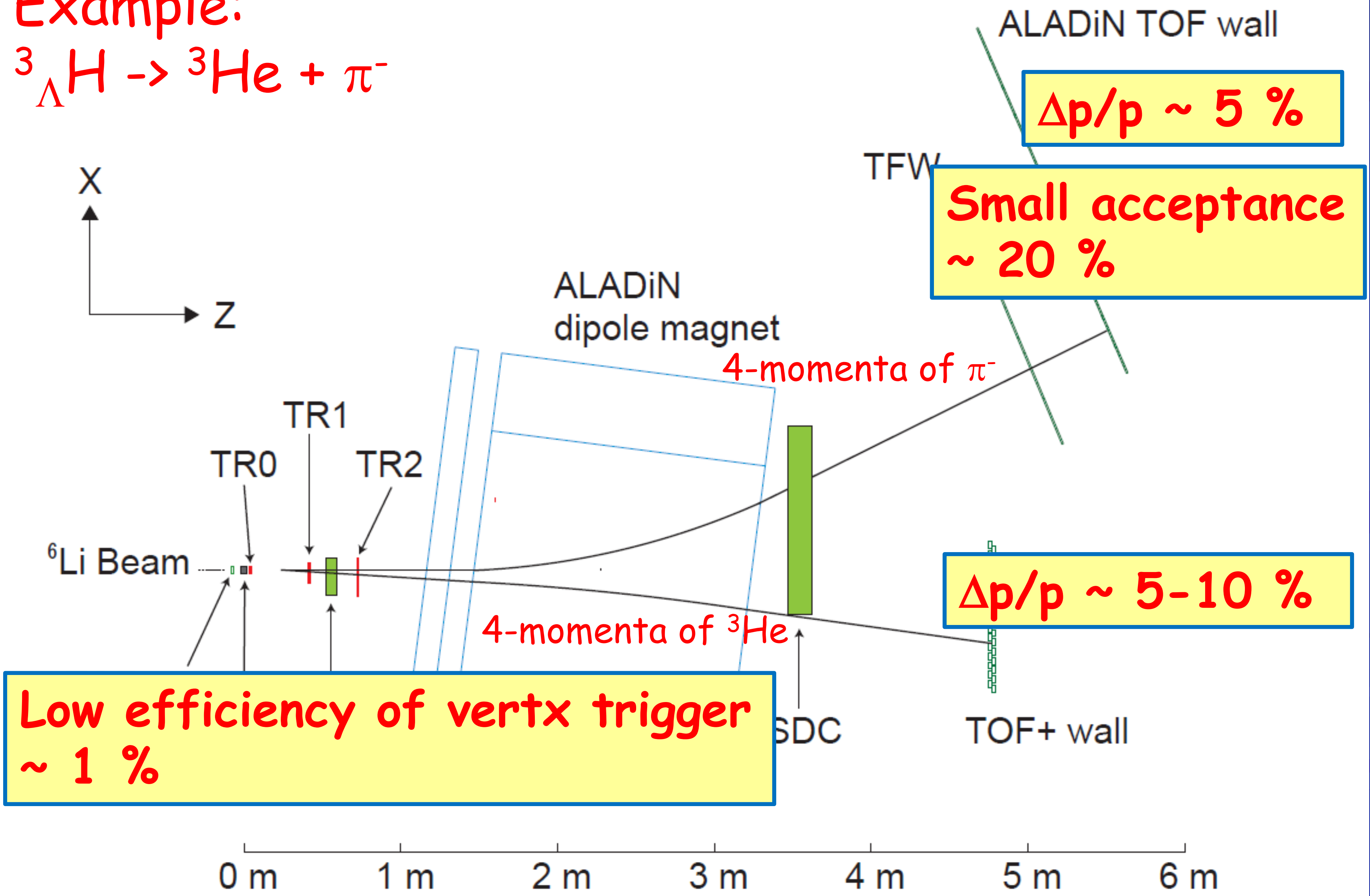
Very urgent issues to be solved

With one experimental setup at GSI/FAIR

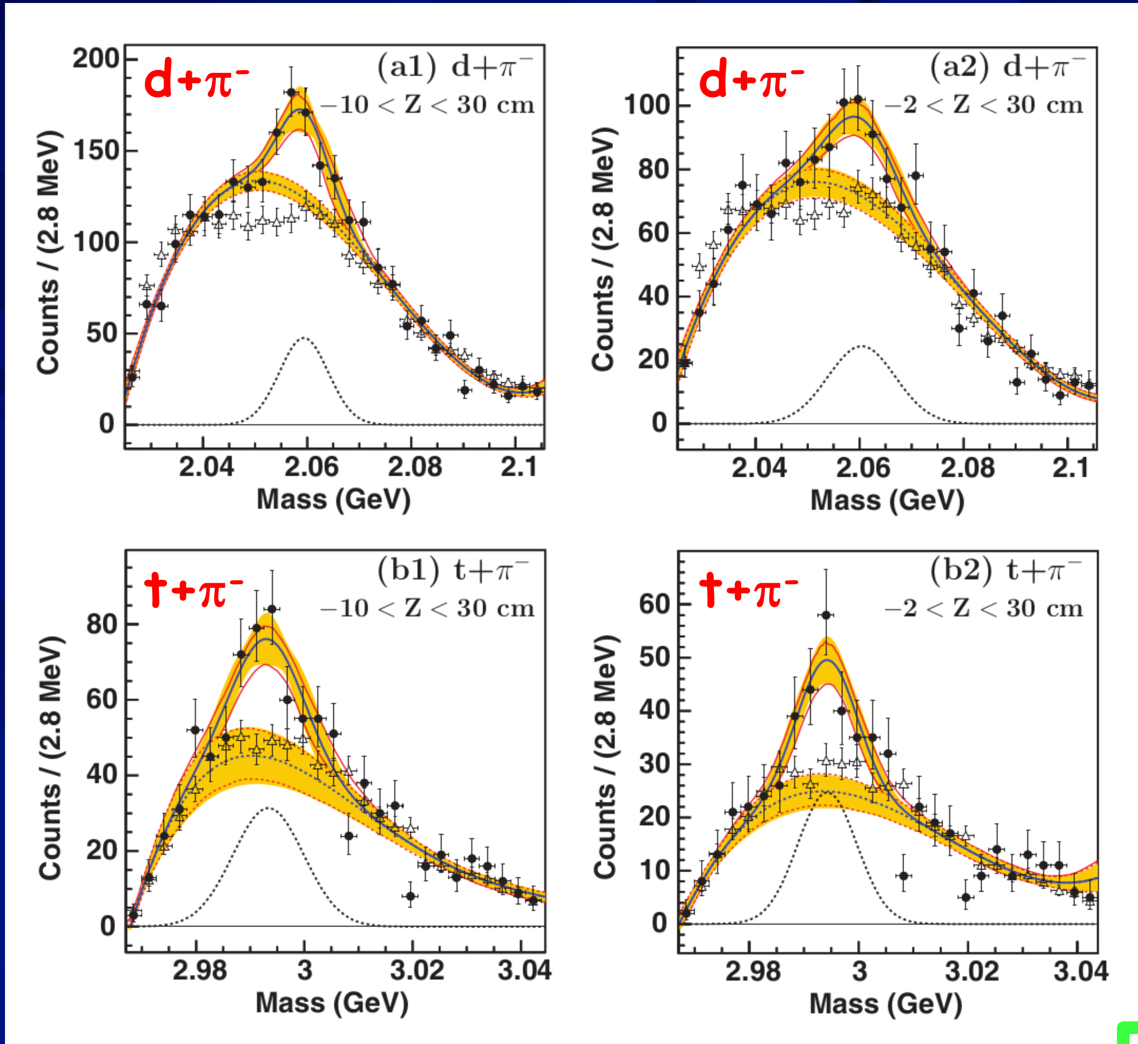
HypHI Phase 0 (2009), $^{6}Li+^{12}C$ at 2 A GeV

Example:

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



Invariant mass signals of HypHI Phase 0



- Poor mass resolution
- Poor S/B ratio
- Signals on top of the bump of the background

PRC 88 (2013) 041001(R)

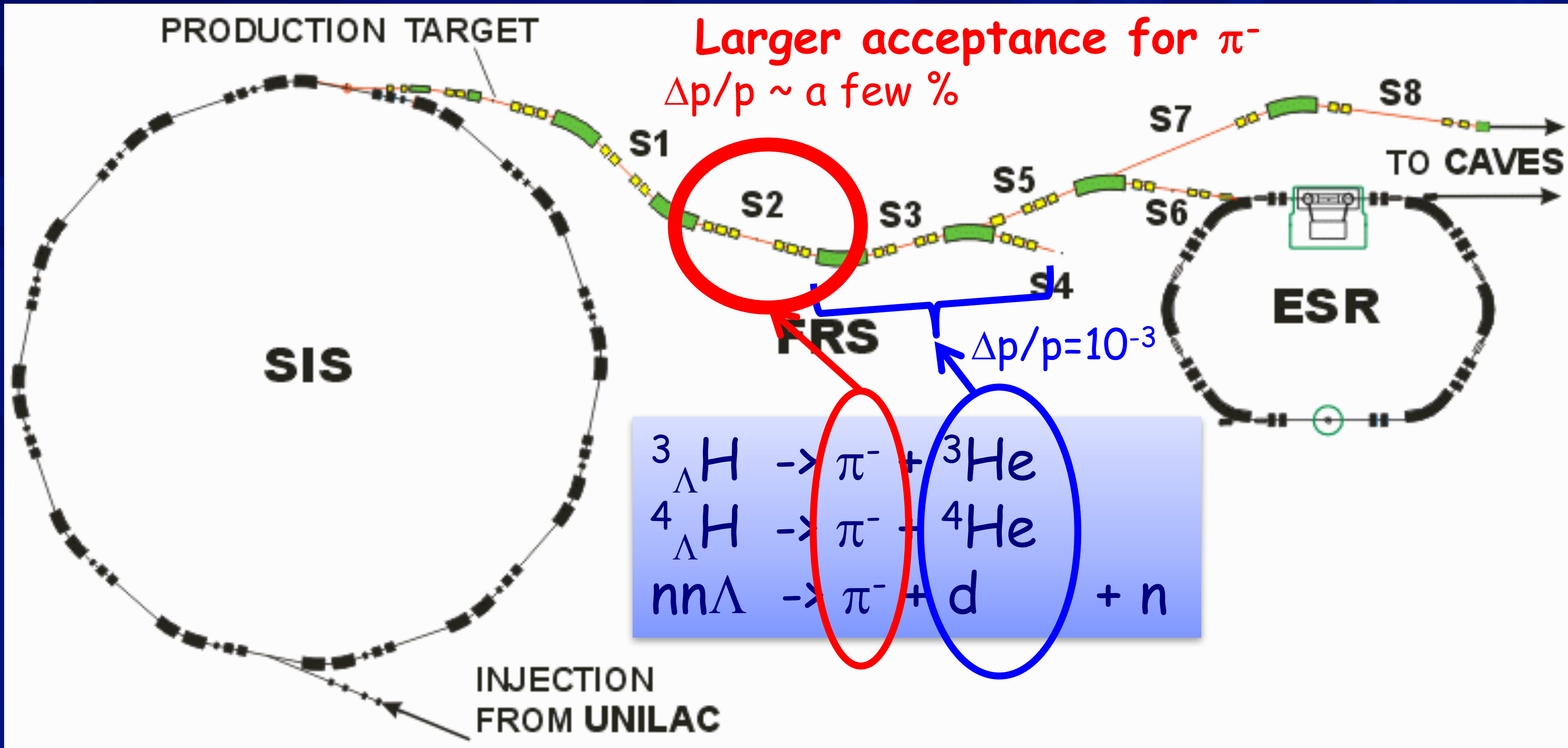
Neutral nucleus with Λ, nnΛ ??

$^{3}{}_{\Lambda}$n -> t + π^-

$^{3}{}_{\Lambda}$n -> t* + π^- -> n + d + π^-

New novel technique with FRS at FAIR Phase 0 (GSI)

Accelerator complex and FRS at GSI



WASA at COSY in Juelich

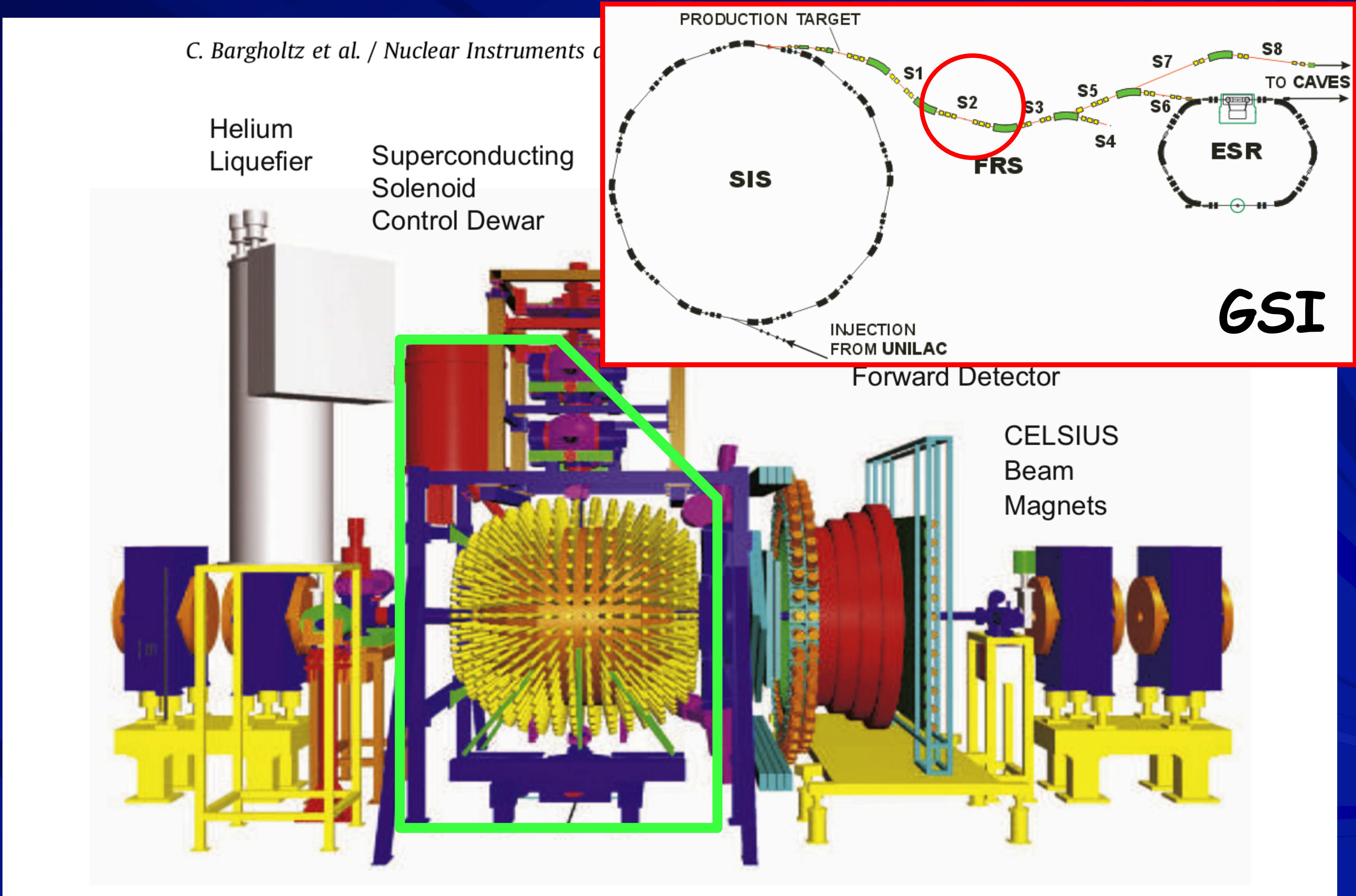
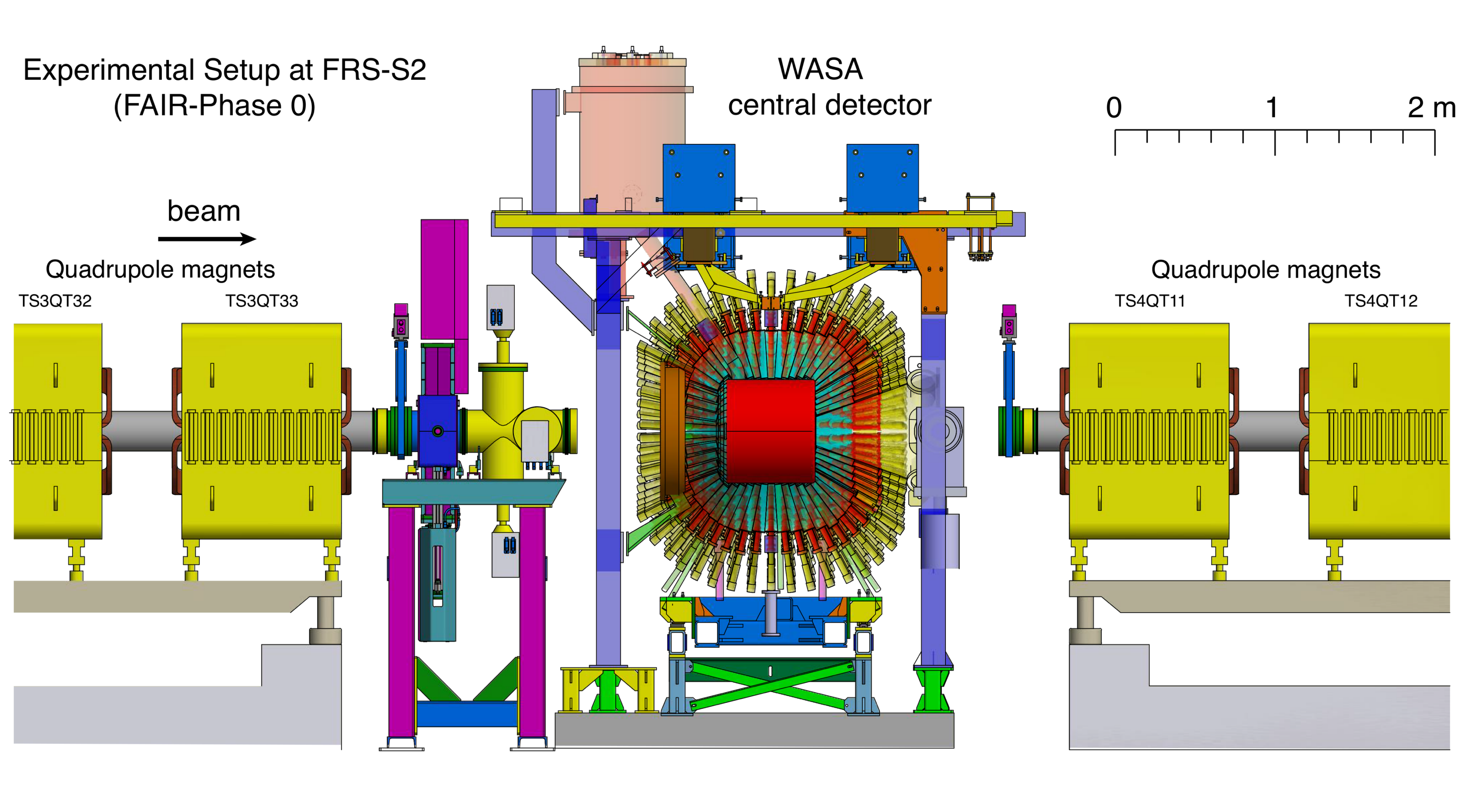


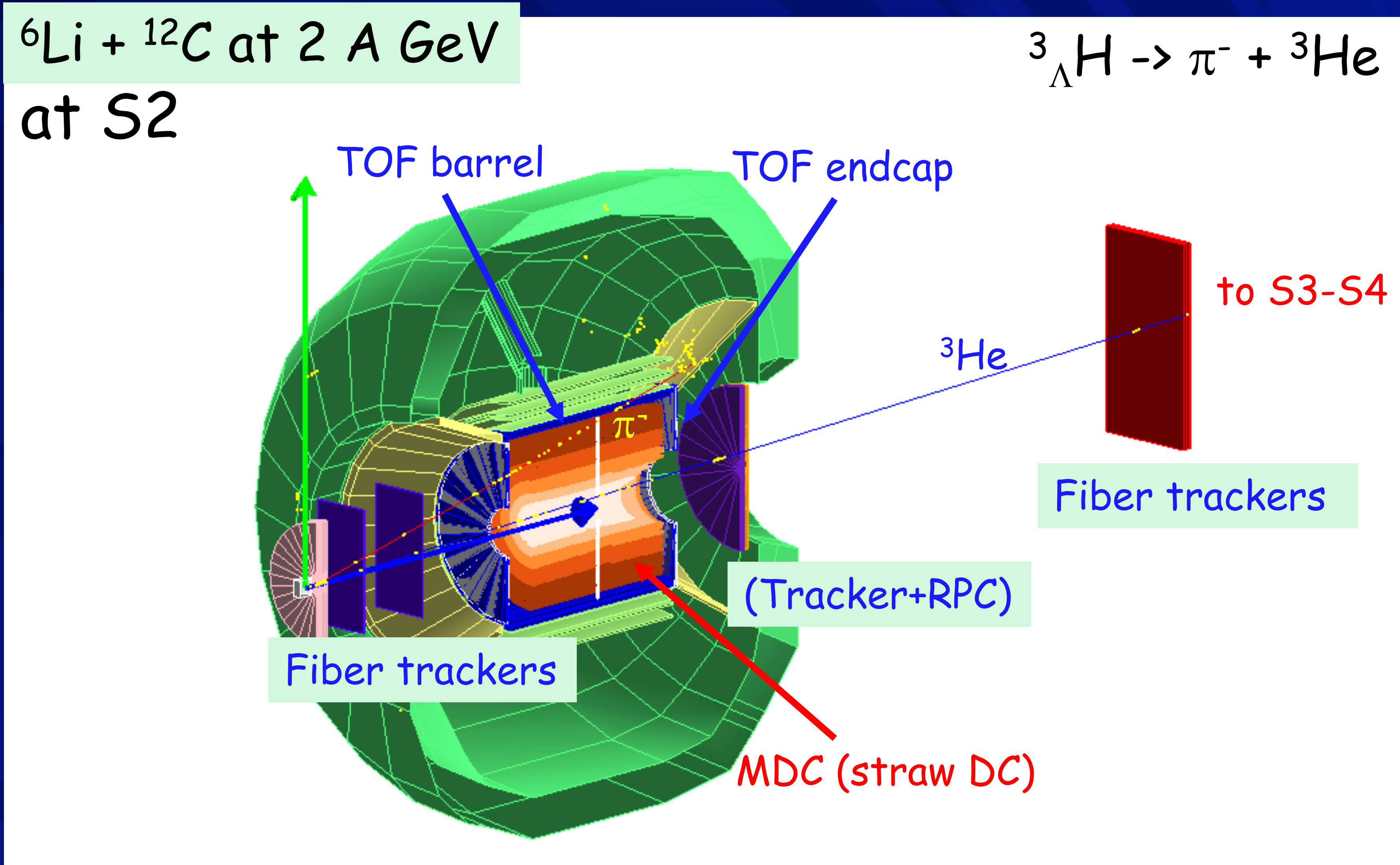
Fig. 1. CAD view of the WASA detector facility. The zero-degree spectrometer is located further downstream to the right.

WASA to S2 of FRS at GSI



Experiment planed in 2019

Monte Carlo simulations with WASA at S2 and FRS



GEANT 4, Kalman filter reconstruction and MOCADI,

Rate estimation and Simulated invariant mass distribution

Different Bρ from beams/fragments
- Small background
- Simple triggers

Table … of FRS, requested shifts for each setup and corre- spondi…

Channel of interest	FRS rigidity [Tm]	Duration of beams on target	Estimated signal integral
$d+\pi^-$	16.675	24 shifts (8 days)	4.0×10^3
${}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He}+\pi^-$	12.623	9 shifts (3 days)	1.5×10^3
${}^4_\Lambda\mathrm{H} \to {}^4\mathrm{He}+\pi^-$	16.675	together with $d+\pi^-$	5.0×10^3

10 ~ 40 times more

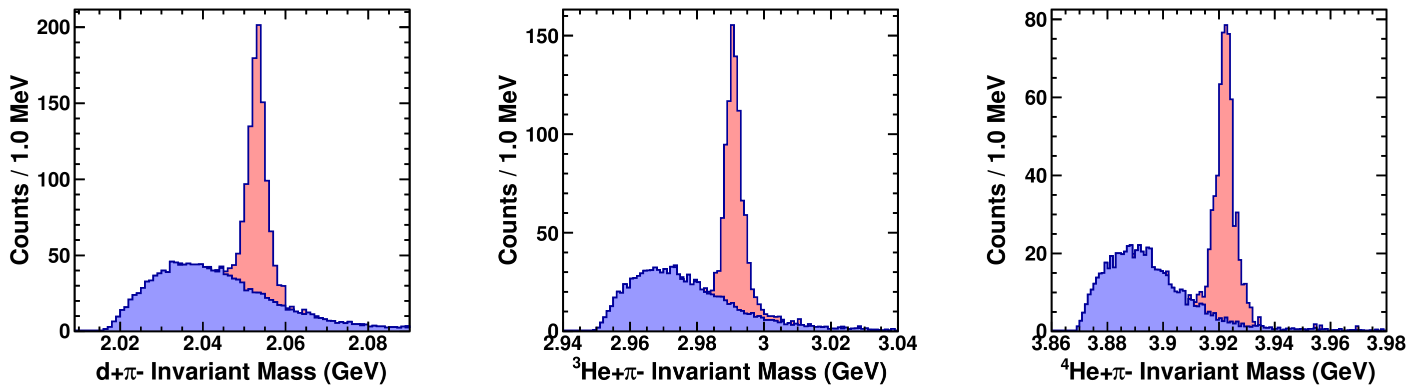
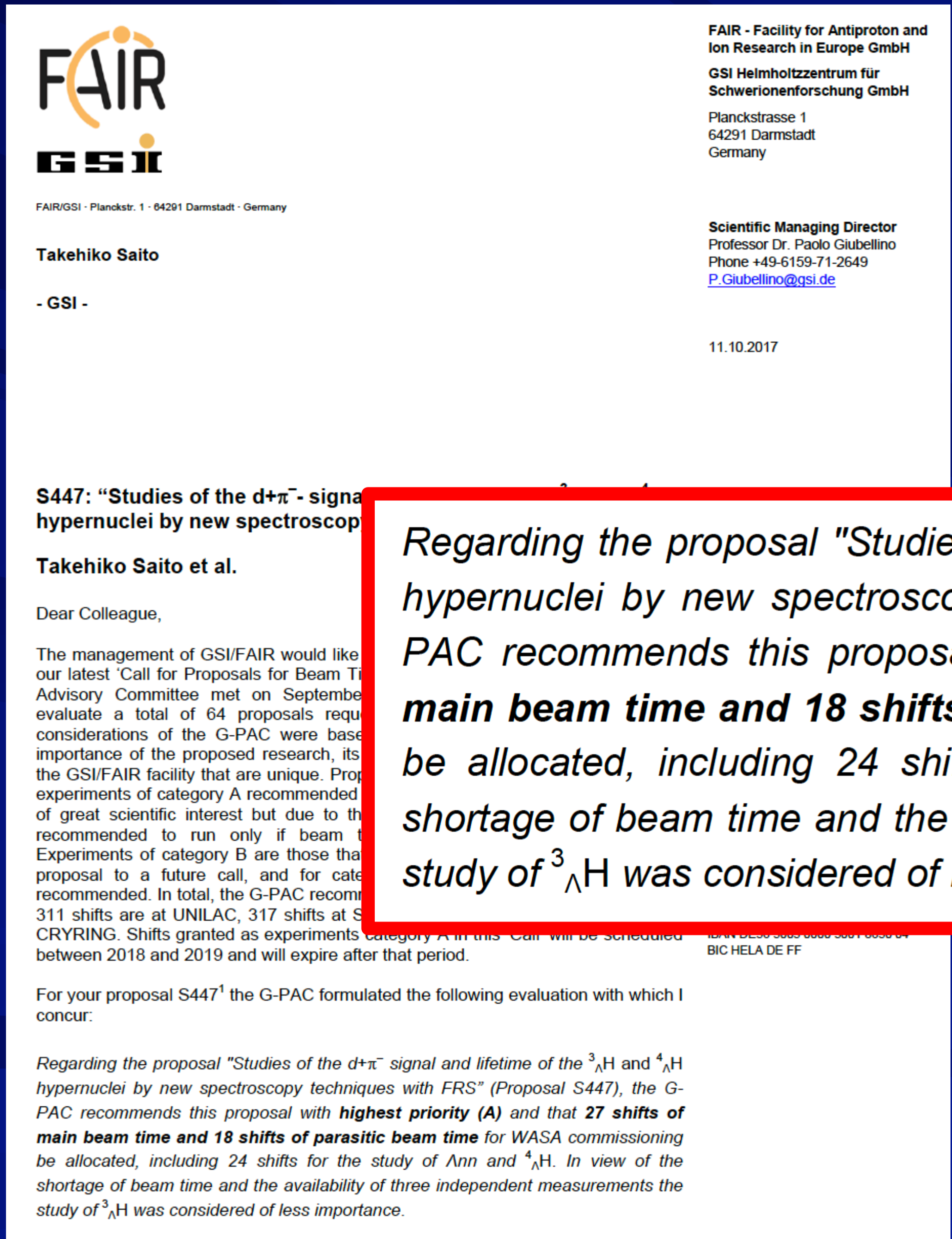


Figure 8: Expected invariant mass distributions of d+π^- from ${}^3_\Lambda$n, 3He+π^- from ${}^3_\Lambda$H and 4He+π^- from ${}^4_\Lambda$H, together with signals (red) and backgrounds (blue)

5 times better resolution

Approval by the GSI G-PAC in 2017


FAIR - Facility for Antiproton and Ion Research in Europe GmbH

GSI Helmholtzzentrum für Schwerionenforschung GmbH

Planckstrasse 1
64291 Darmstadt
Germany

FAIR/GSI · Planckstr. 1 · 64291 Darmstadt · Germany

Takehiko Saito

- GSI -

Scientific Managing Director
Professor Dr. Paolo Giubellino
Phone +49-6159-71-2649
P.Giubellino@gsi.de

11.10.2017

S447: "Studies of the d+π⁻- signa
hypernuclei by new spectroscop

Takehiko Saito et al.

Dear Colleague,

The management of GSI/FAIR would like
our latest 'Call for Proposals for Beam Ti
Advisory Committee met on Septembe
evaluate a total of 64 proposals requ
considerations of the G-PAC were base
importance of the proposed research, its
the GSI/FAIR facility that are unique. Prop
experiments of category A recommended
of great scientific interest but due to th
recommended to run only if beam t
Experiments of category B are those tha
proposal to a future call, and for cate
recommended. In total, the G-PAC recom
311 shifts are at UNILAC, 317 shifts at S
CRYRING. Shifts granted as experiments category A in this Call will be scheduled
between 2018 and 2019 and will expire after that period.

BIC HELA DE FF

For your proposal S447[1] the G-PAC formulated the following evaluation with which I concur:

*Regarding the proposal "Studies of the d+π⁻ signal and lifetime of the $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H hypernuclei by new spectroscopy techniques with FRS" (Proposal S447), the G-PAC recommends this proposal with **highest priority (A)** and that **27 shifts of main beam time and 18 shifts of parasitic beam time** for WASA commissioning be allocated, including 24 shifts for the study of Λnn and $^{4}_{\Lambda}$H. In view of the shortage of beam time and the availability of three independent measurements the study of $^{3}_{\Lambda}$H was considered of less importance.*

*Regarding the proposal "Studies of the d+π⁻ signal and lifetime of the $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H hypernuclei by new spectroscopy techniques with FRS" (Proposal S447), the G-PAC recommends this proposal with **highest priority (A)** and that **27 shifts of main beam time and 18 shifts of parasitic beam time** for WASA commissioning be allocated, including 24 shifts for the study of Λnn and $^{4}_{\Lambda}$H. In view of the shortage of beam time and the availability of three independent measurements the study of $^{3}_{\Lambda}$H was considered of less importance.*

In 2019

NuPECC Long Range Plan

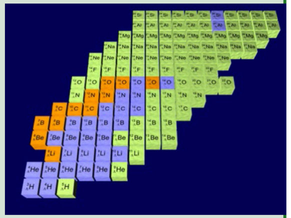
Hadron physics

Nuclear structure and reaction dynamics

Page 65

Box 5: Hypernuclei

Recently, hypernuclear spectroscopy with heavy ion induced reactions has been successfully performed by the HypHI collaboration at GSI. They have shown that the lifetime of the lightest hypernucleus, $^{3}_{\Lambda}$H, is significantly shorter than the Λ-hyperon, also reported by hadron-collider collaborations. A short $^{3}_{\Lambda}$H lifetime has not yet been explained by any theory so far and remains as a puzzle. A signal indicating the existing a neutral strange nucleus, $^{3}_{\Lambda}$n (nnΛ), has been reported, which is still under debate and it requires experimental confirmation. By solving these puzzles with more data on exotic hypernuclei toward nucleon drip-lines, one can deduce essential information on the baryon-baryon interaction under SU(3) including three-body forces. Exotic hypernuclei can only be studied with heavy ions at GSI and FAIR. With these experiments, Europe will play an essential role in nuclear physics with strangeness.



Hypernuclear chart expected to be synthesized and studied at GSI and FAIR. Blue boxes indicate known hypernuclei while orange and green coloured boxes show cases to be populated with 10^4 and 10^3 reconstructed events per week, respectively.

Generalised Parton Distributions (GPDs) and Transverse Spin and Momentum-Dependent Distributions (TMDs)

Our knowledge of nucleon structure has drastically improved in the last few years thanks to the vigorous activity revolving around Generalised Parton Distributions (GPDs) and Transverse

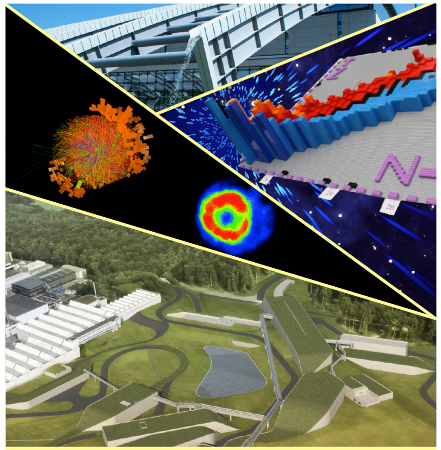
increased the energy of its electron beam from 6 to 12 GeV. Accurate cross-section measurements have shown indications of leading-twist dominance in the accessible kinematic regions. The high precision of the data has stimulated further theoretical analyses to understand the fine details. A variety of beam and target spin asymmetries has been used to constrain models

continuum degrees of freedom are required.

Focused research on constructing improved nuclear EDF that would allow for a precise description of nuclear properties across the nuclear chart, including the spin and isospin channels, restored symmetries, and spectroscopic data is required.

Hypernuclei

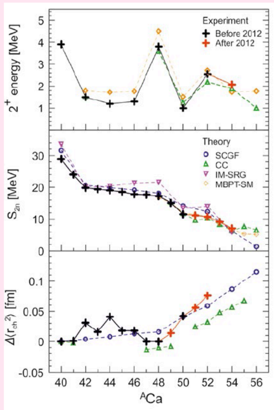
Understanding of the nuclear force can be extended to the flavoured-SU(3) symmetry by studying hypernuclei, nuclei with bound hyperon(s) (baryons with strange quarks where Λ (usd) is the lightest). Hyperons in hypernuclei can



NuPECC
Long Range Plan 2017
Perspectives
in Nuclear Physics

Box 3. Structure of Ca isotopes

Standard magic numbers, well established for stable nuclei, fade away in neutron-rich systems where new ones may appear. How do we determine their location? A shell closure cannot be established from a single experimental signature but rather has to emerge from the concurrence of several features, e.g. in energies of the lowest 2^+ excited state, two-nucleon separation energies and charge radii isotopic shifts. Hence, different experiments are typically necessary to assess the evolution of magic numbers, as testified by recent studies of neutron-rich calcium isotopes. Penning-trap measurements at TRIUMF and ISOLDE have extended our knowledge of nuclear masses up to ^{54}Ca (central panel) and pointed to the appearance of a new magic number at N=32. More recently, charge radii obtained via laser spectroscopy at ISOLDE (lower panel) weakened this conclusion. In parallel, the measurement of the lowest 2^+ excited state in ^{54}Ca at RIKEN (upper panel) has opened the same debate on N=34. Ab initio calculations (coloured curves) have started to access medium-mass isotopic chains systematically. Comparisons between these calculations and current and future experiments in the region, e.g. up to ^{56}Ca, will help unveil how such magic numbers emerge from underlying complex nucleon dynamics.



be used as probes of the inside core of nuclei since the hyperon is not subject to the Pauli principle. Hypernuclei close to stability were studied mainly using reactions of meson- and electron-beams. A recent hypernuclei spectroscopic study of $^3_\Lambda$H is discussed in chapter 1. These studies open a new degree of freedom related to strangeness, which could be combined with exotic nuclei. For instance few-body systems such as 2n+Λ remain to be explained by first principles. These studies are also appealing for future developments.

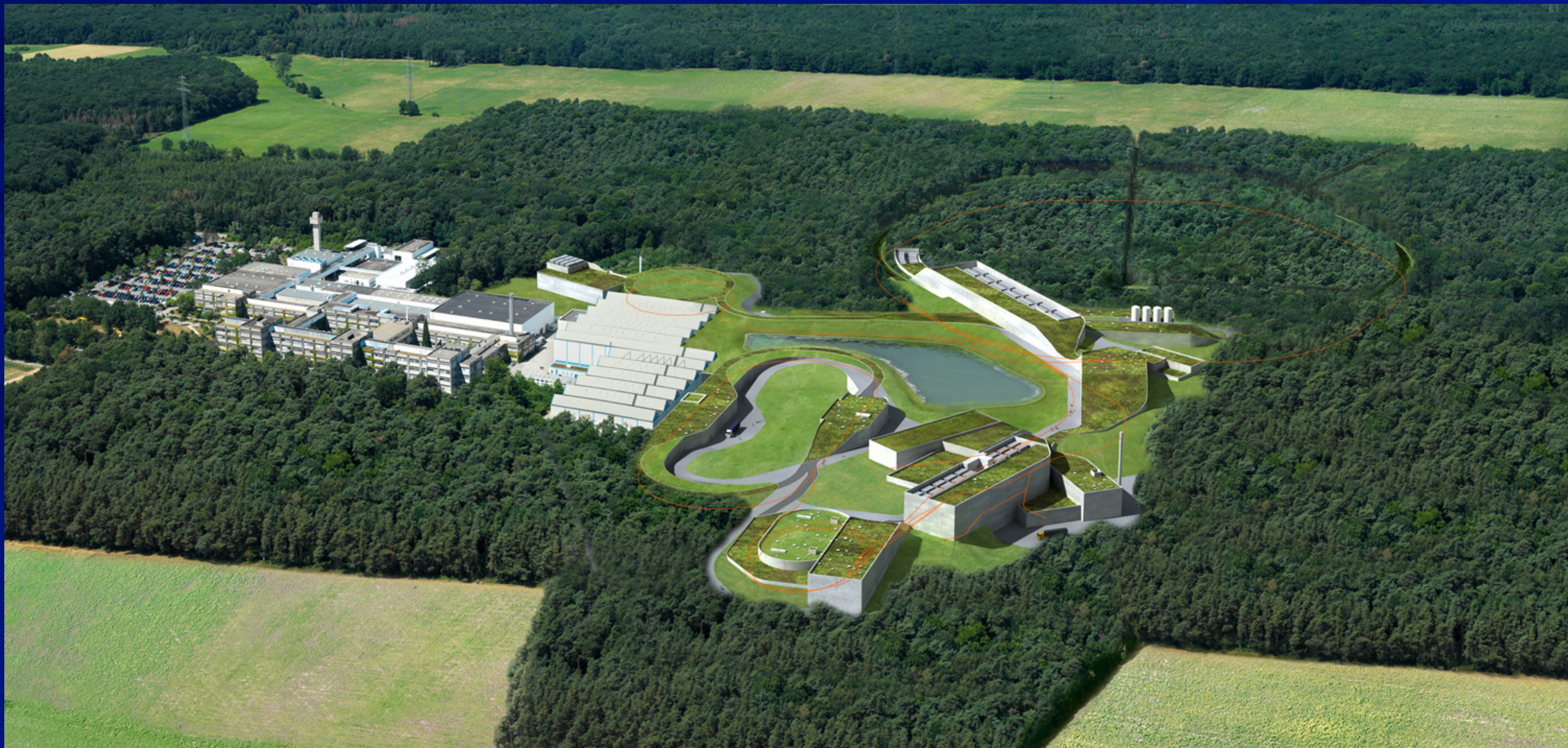
Testing and constraining three-neutron forces is in turn crucial for neutron-rich nuclei and the equation of state of neutron-rich matter, which is key for understanding and predicting properties of neutron stars. In addition, few-neutron resonances are also considered a milestone calculation in lattice QCD.

Electroweak reactions

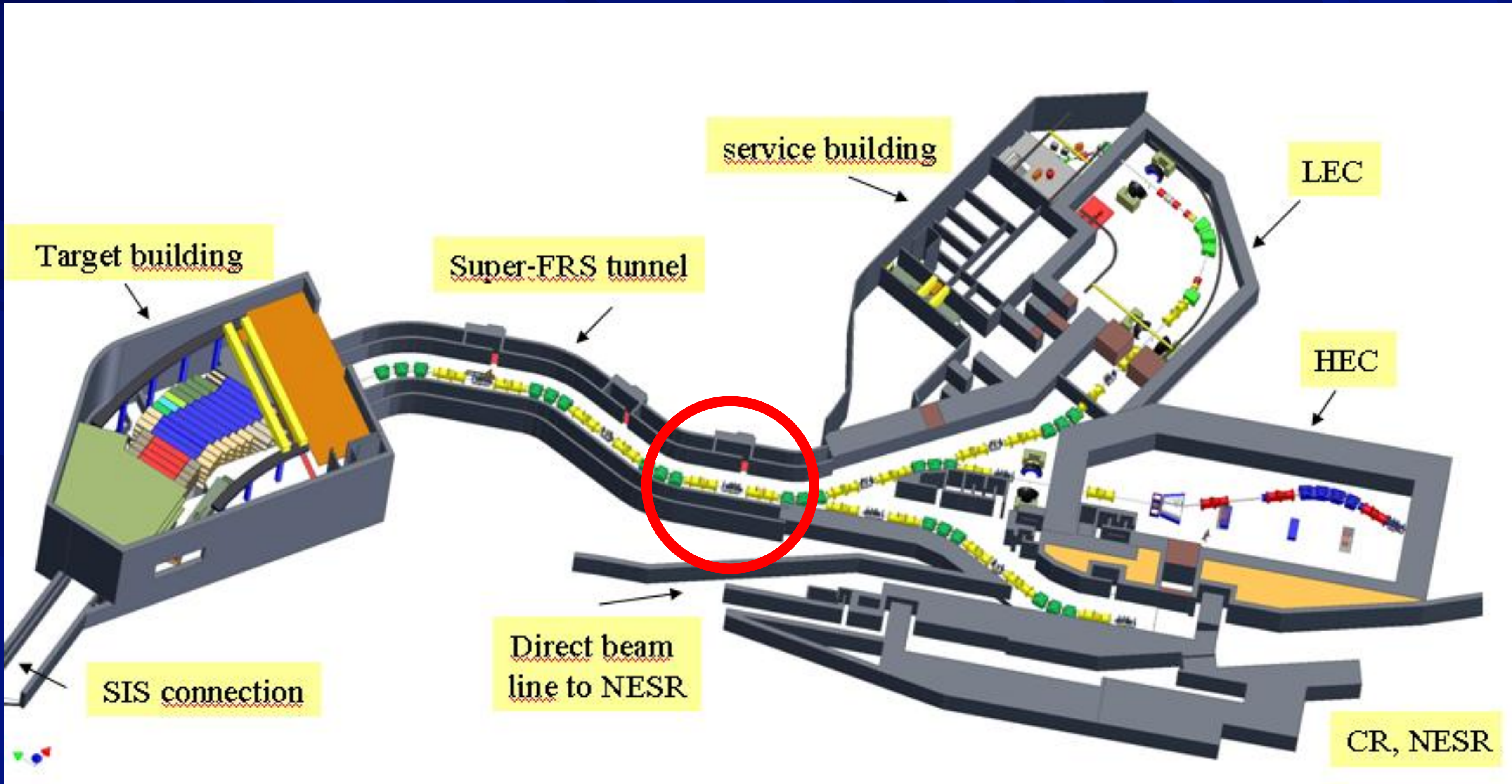
Electromagnetic and weak interactions play a crucial role in nuclear physics. On the theoretical

One of day-1 experiments of NuSTAR at FAIR

FAIR in Germany



Super-FRS at FAIR



Precise hypernuclear spectroscopy with RI-beams

Summary

- Hypernuclear spectroscopy with heavy ion beams
- Two puzzles by HypHI Phase 0
  - Signals indicating nnΛ
  - Short hypertriton lifetime

- Near future project
  - FRS + WASA at GSI (FAIR Phase 0) in Germany, 2019
    - nnΛ and hypertriton lifetime
  - Super-FRS at FAIR in Germany, 2023+X
    - Exotic hypernuclei with RI beams

Take Saito
t.saito@gsi.de