Hypernuclear production on HI Collisions

and more

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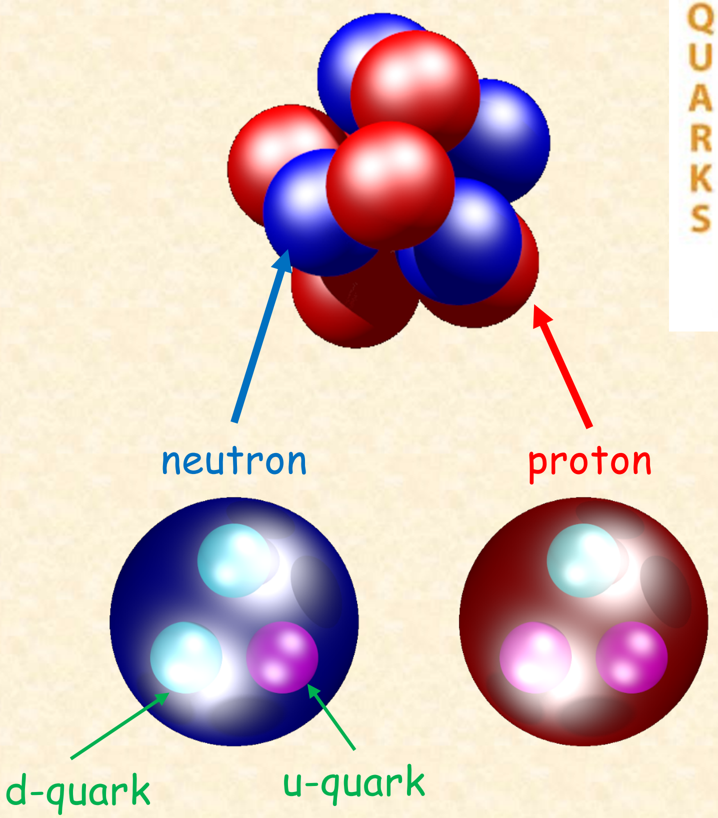
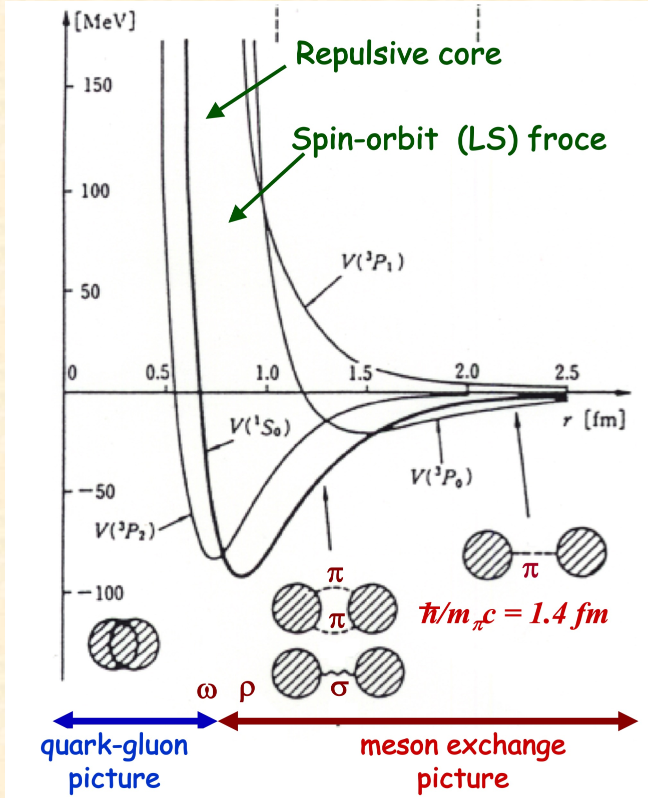
Professor and group leader,
School of Nuclear Science and Technology,
Lanzhou University,
China

Quarks and sub-atomic nuclei

Sub-atomic nucleus

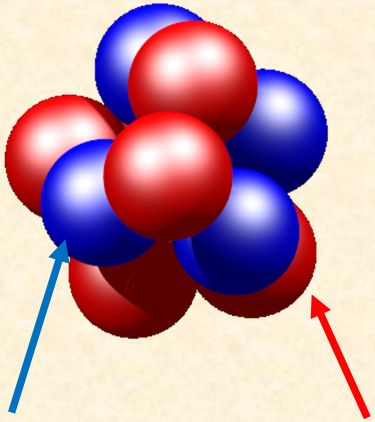




There are many identical quarks

Quarks and sub-atomic nuclei

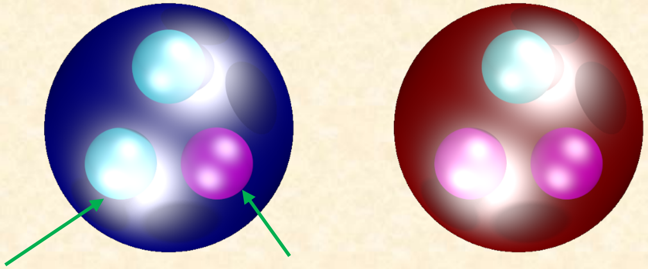
Sub-atomic nucleus



Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

neutron

proton

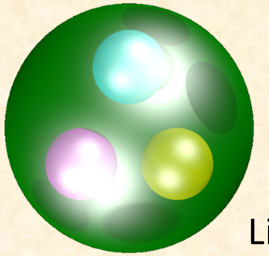


d-quark

u-quark

There are many identical quarks

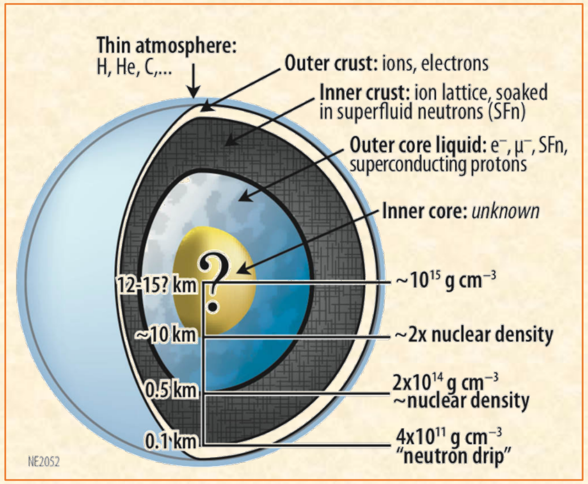
hyperon (Λ)



Lifetime: 10^{-10} ps

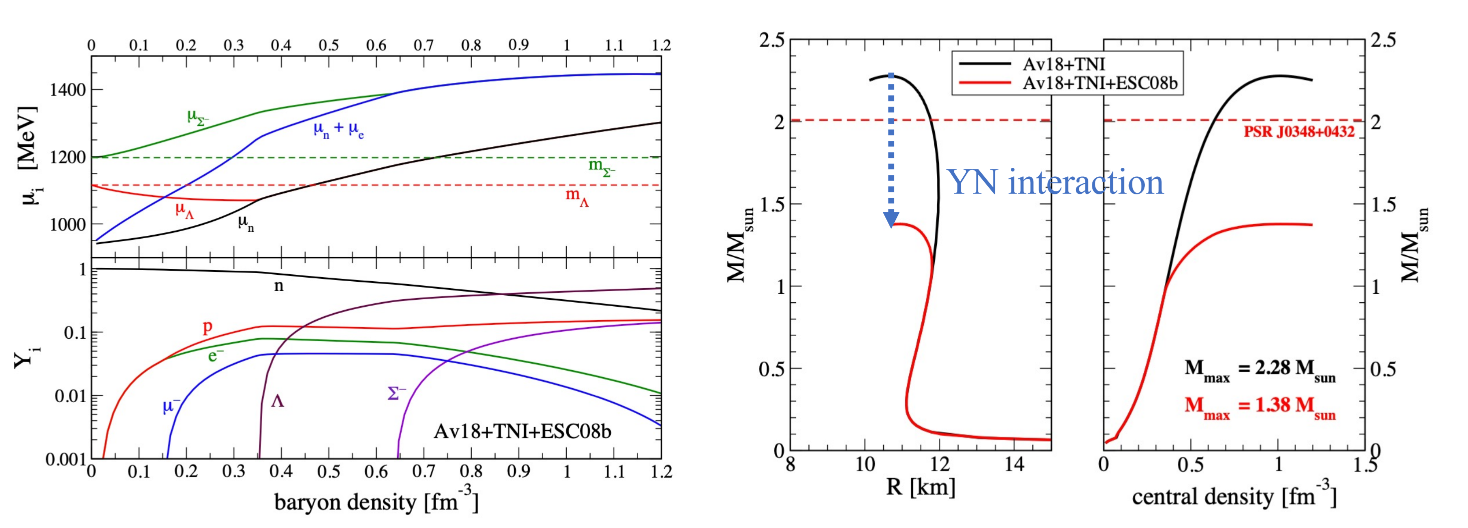
s-quark: distinguishable from u- and d-quarks

Neutron stars and dense nuclear matter

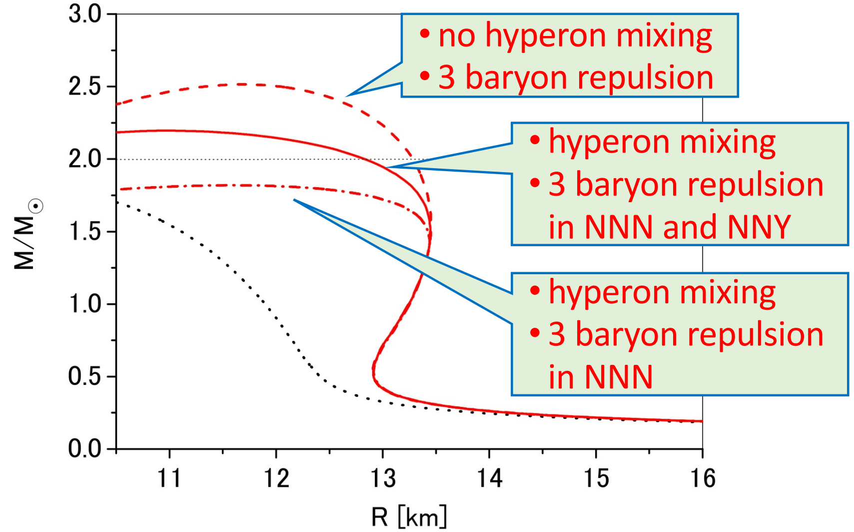


Baryon interaction

- N−N
- Λ−N
- **Σ−N**
- **Λ−Λ, Σ−Σ, Λ−Σ**
- **Ξ−N**
- **Ξ−Λ, Ξ−Σ**
- **Ξ−Ξ**

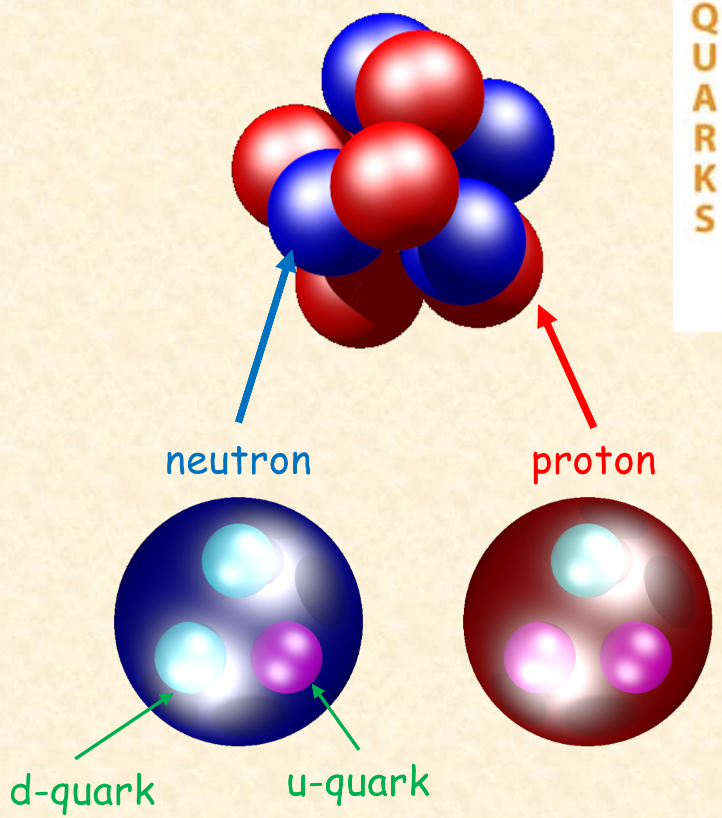


Y. Yamamoto, T. Furumoto, N. Yasutake, Th.A. Rijken, Phys. Rev. C90 045805 (2014)



Quarks and sub-atomic nuclei

Sub-atomic nucleus



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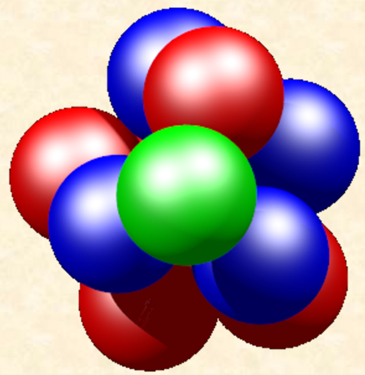
hyperon (Λ)

Lifetime: 10^{-10} ps

s-quark: distinguishable from u- and d-quarks

hypernucleus

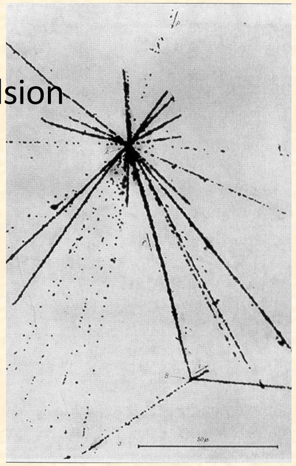


Micro-laboratory to study baryonic-interactions

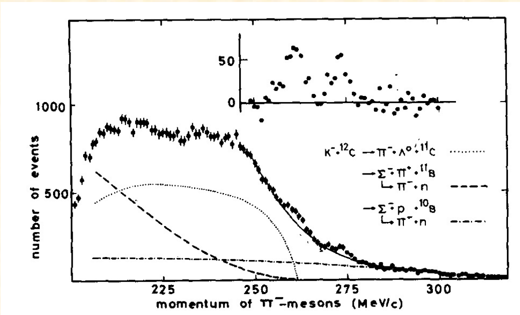
History of hypernuclear Experiments before HI (only a major part)

1953 – 1970
With nuclear emulsion

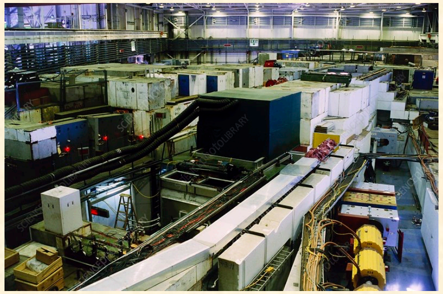
Marian Danysz (left) and Jerzy Pniewski, who first observed a hypernucleus.

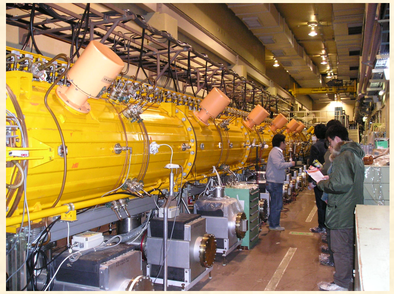


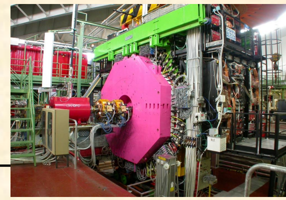
1970 - 1985
Kaon beams at CERN



1985 - 2005
Kaon and pion beams at AGS/BNL and PS/KEK







FINUDA

From 21st century
Kaon beams at J-PARC and electron beams at JLab

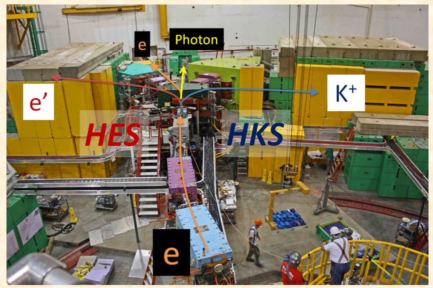


Chart of ordinary nuclei

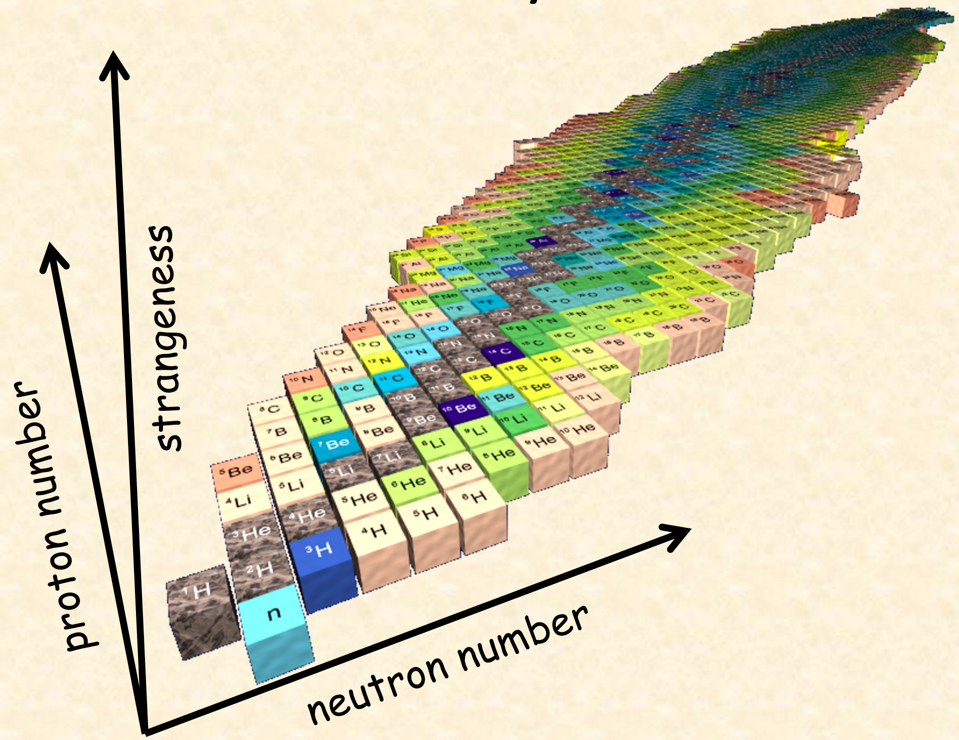


Chart of single-strangeness hypernuclei

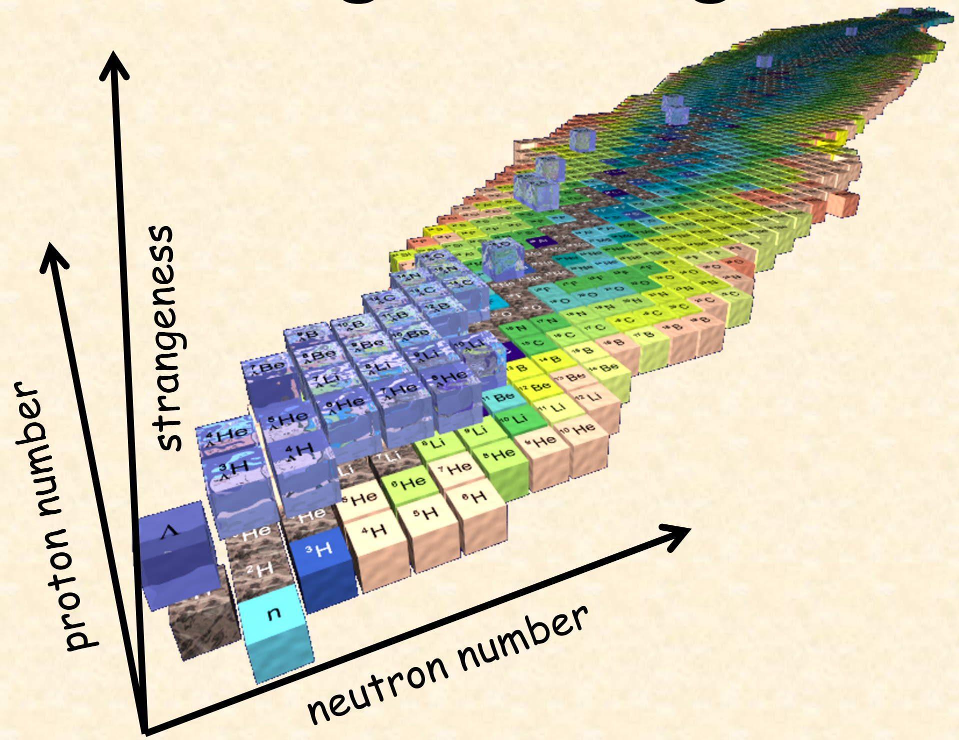


Chart of double-strangeness hypernuclei

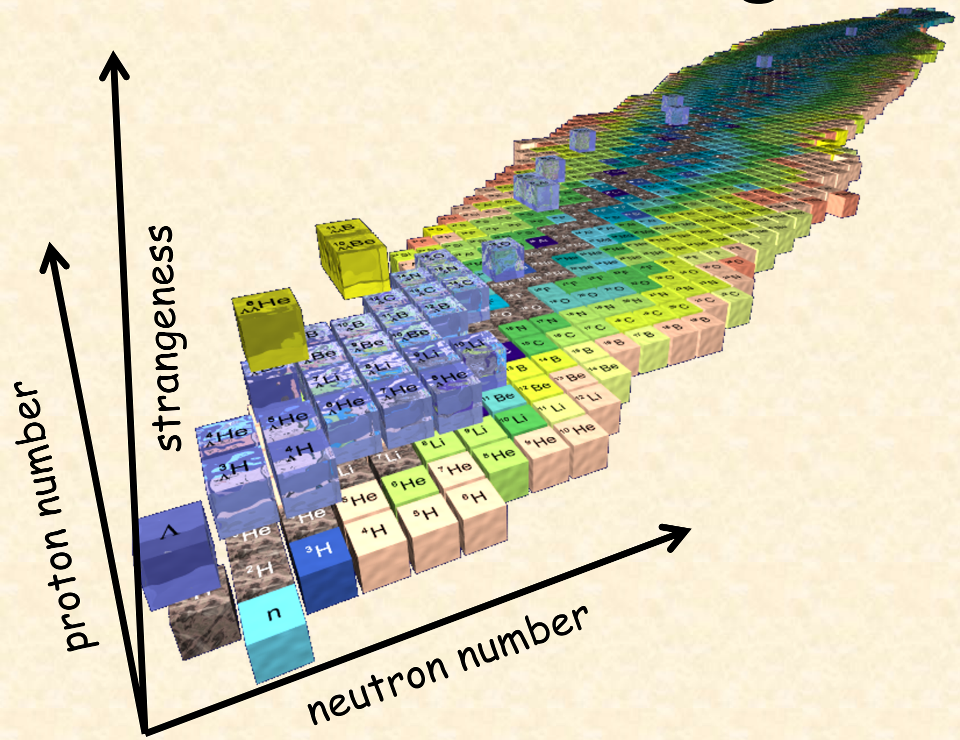
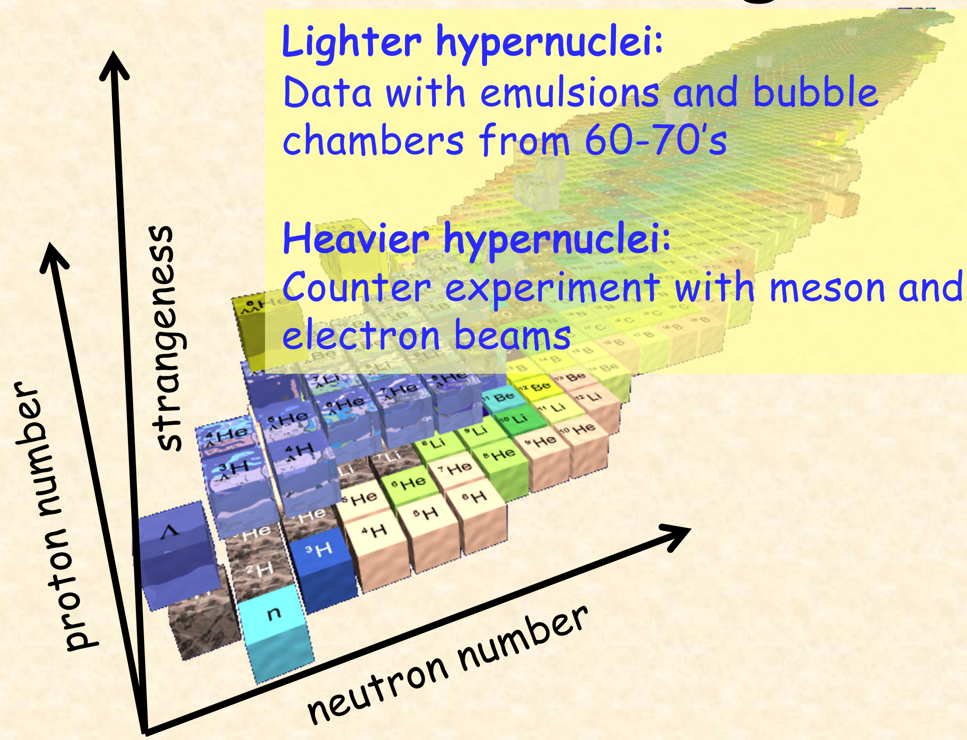


Chart of double-strangeness hypernuclei



Lighter hypernuclei:
Data with emulsions and bubble chambers from 60-70's

Heavier hypernuclei:
Counter experiment with meson and electron beams

Hypernuclear spectroscoy with Heavy Ion Beam

Advantage
- Precise spectroscopy
  - Structure in detail
- Clean experiment

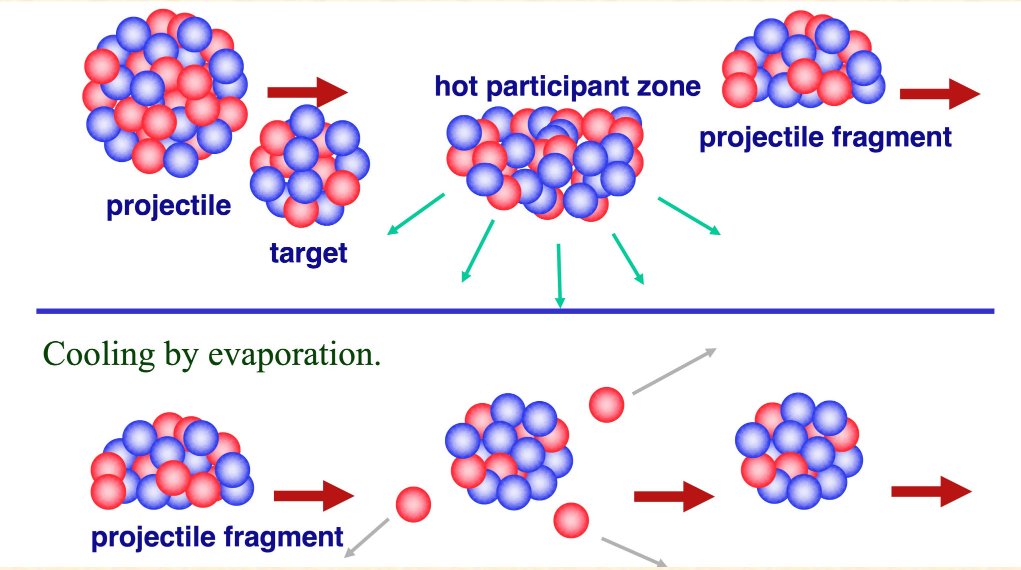
Difficulties
- Limited isospin
- Small momentum transfer to separate hypernuclei
- Difficulties on decay studies
- Only up to double-strangeness

Hypernuclear spectroscopy with heavy ion beams

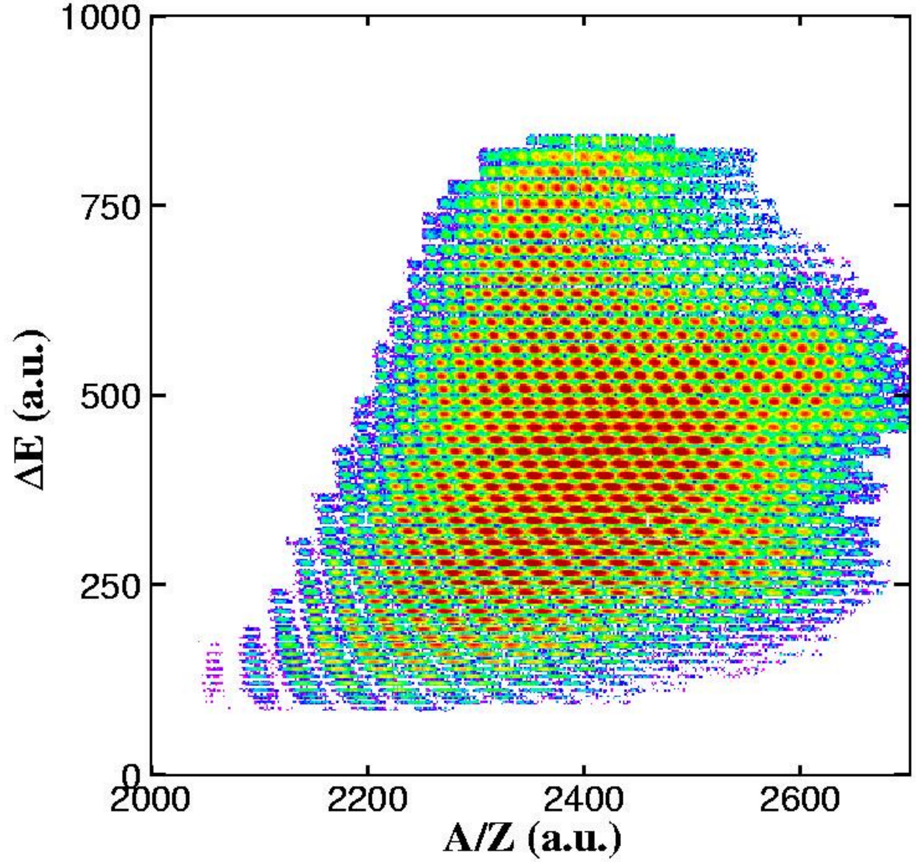
HypHI project, started in 2005

The way to produce hypernuclei with HypHI

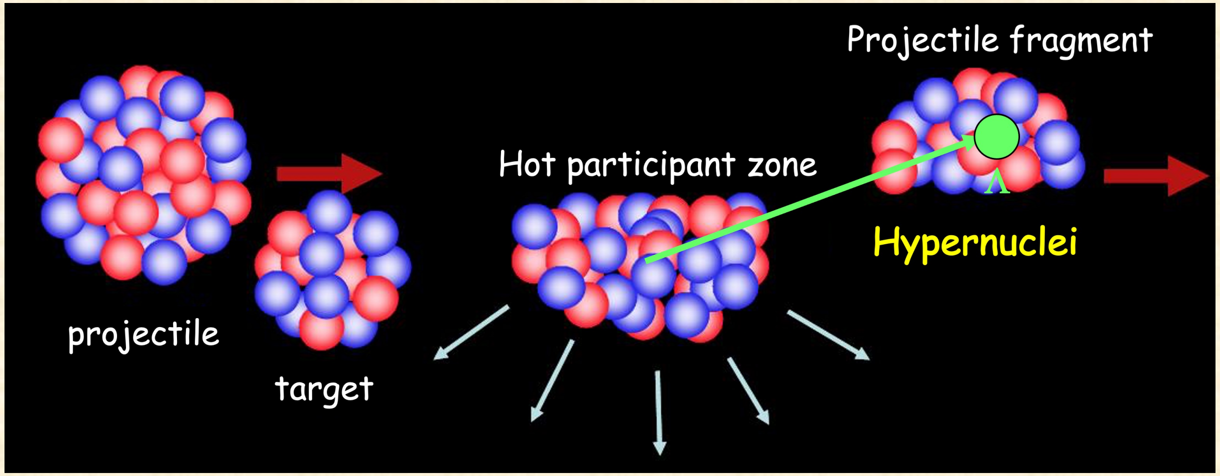
Projectile fragmentation reaction

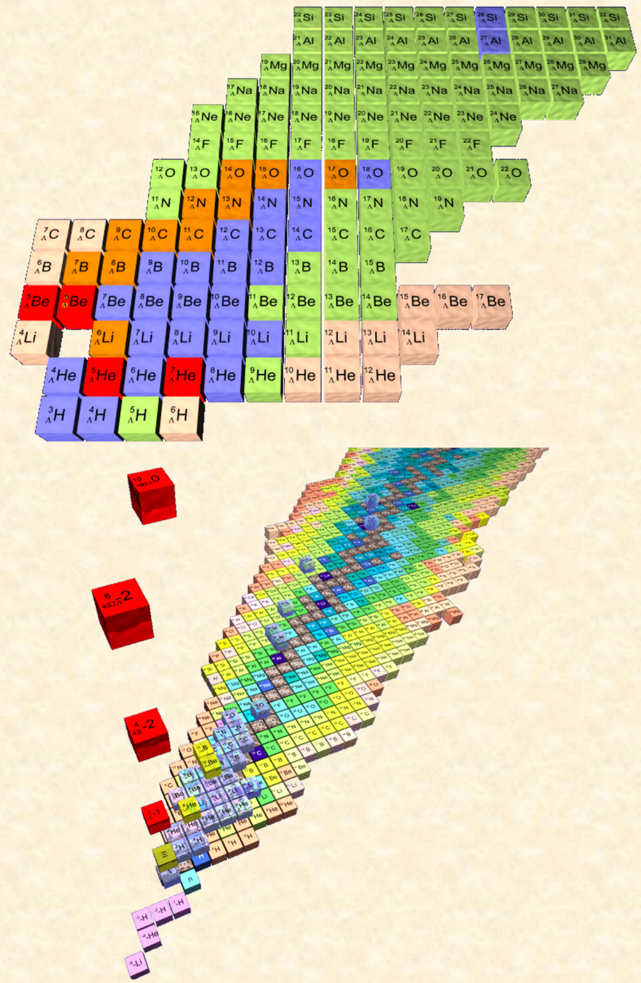


U + H at 1 A GeV



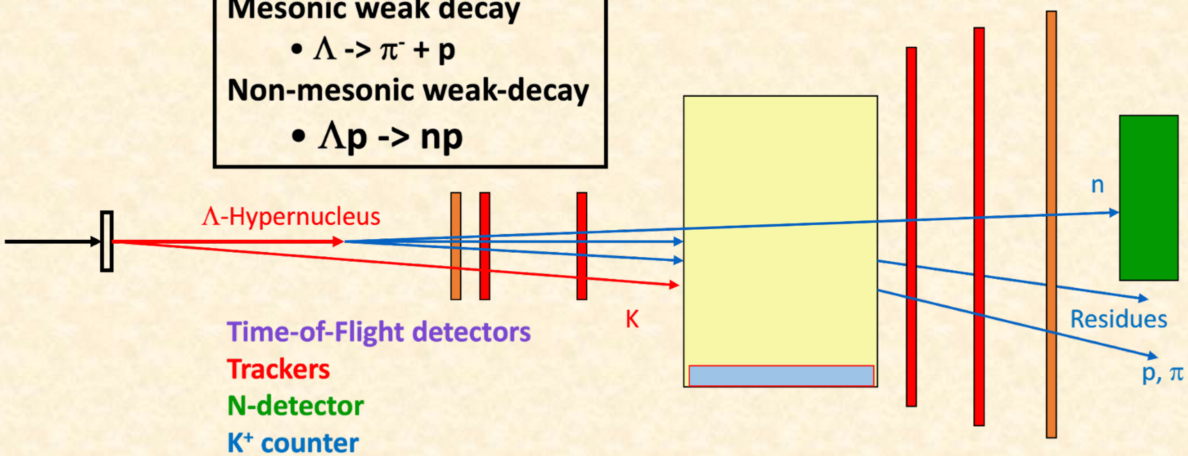
The way to produce hypernuclei with HypHI





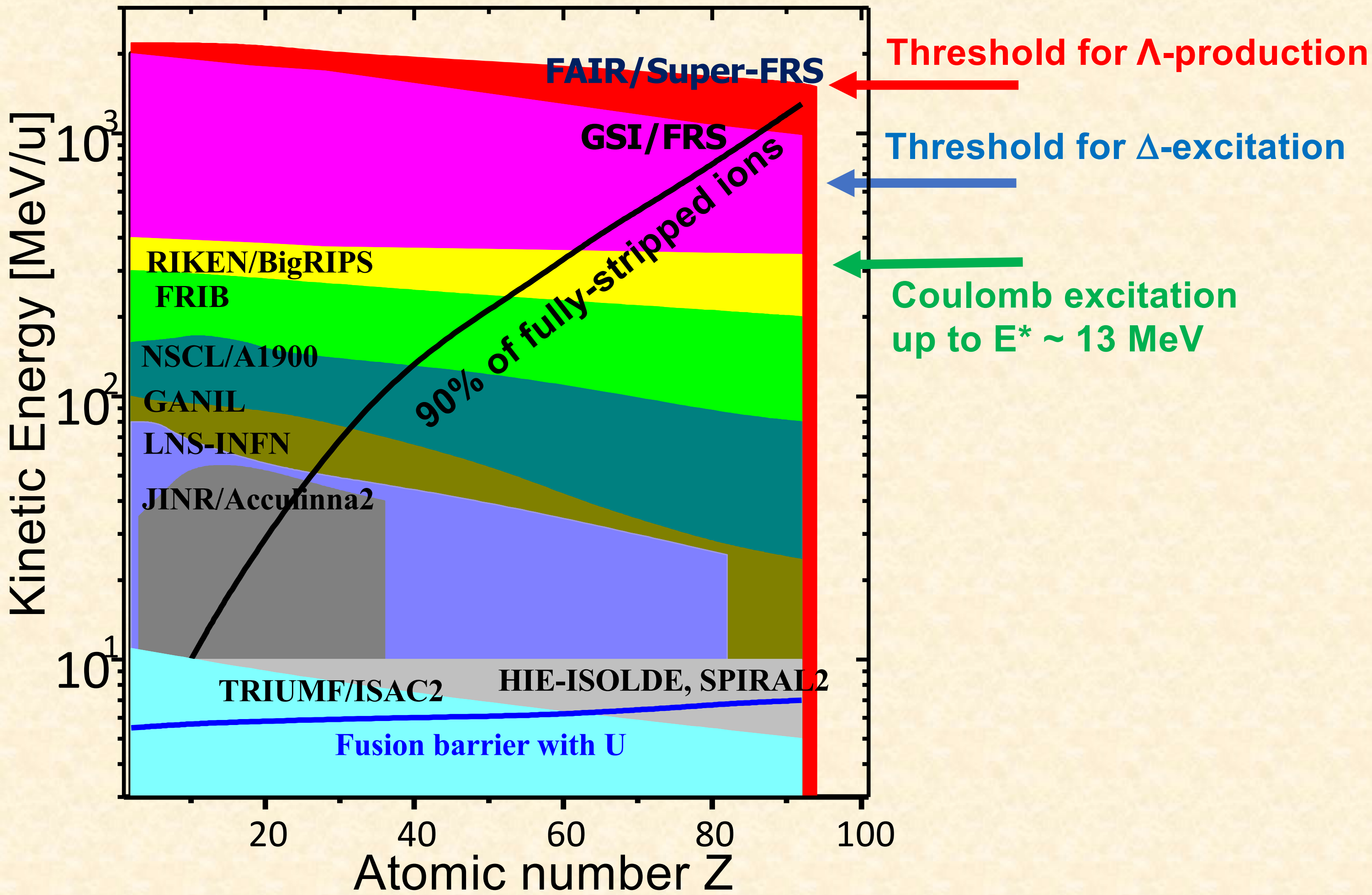
Mesonic weak decay
- **Λ -> π⁻ + p**

Non-mesonic weak-decay
- **Λp -> np**



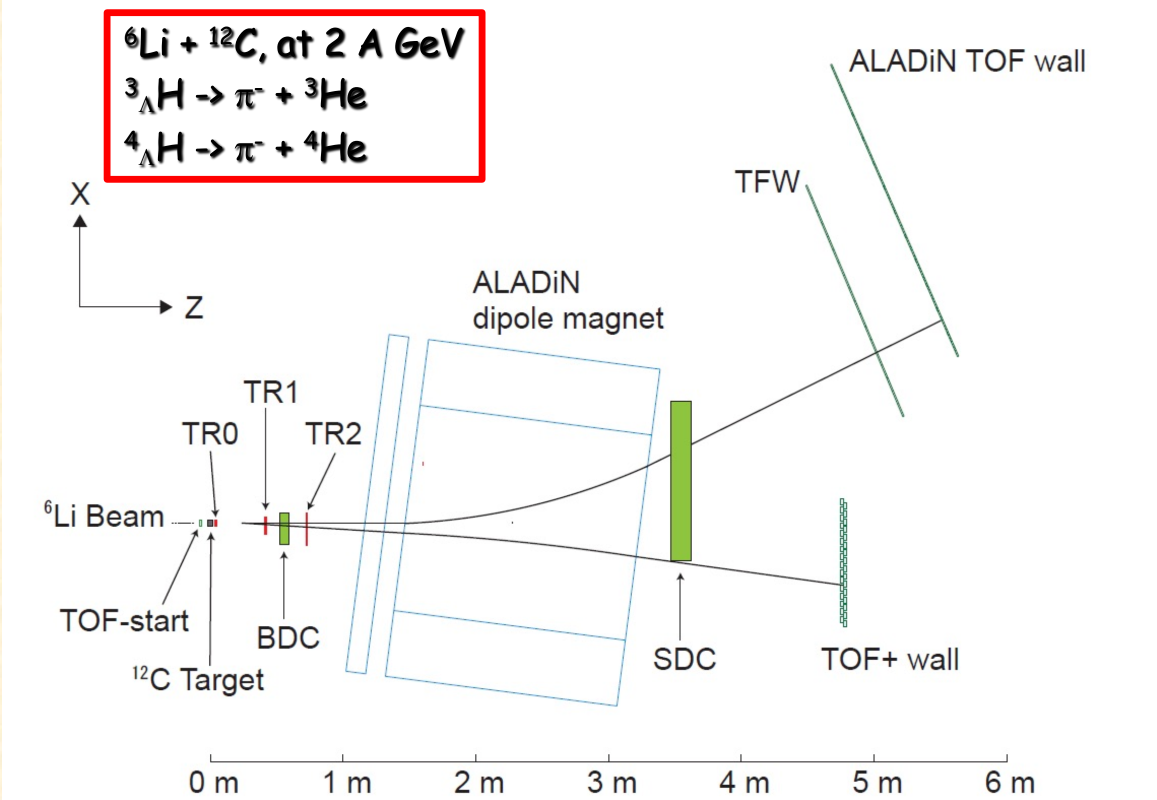
Time-of-Flight detectors
Trackers
N-detector
K⁺ counter

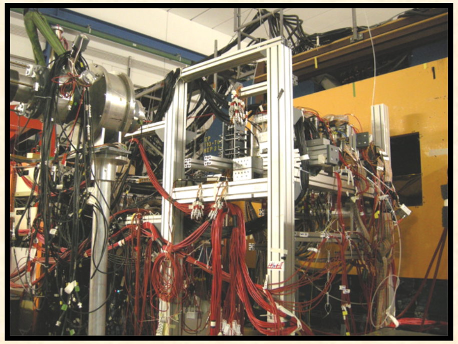
Hypernuclear production with Rare-Isotope beams

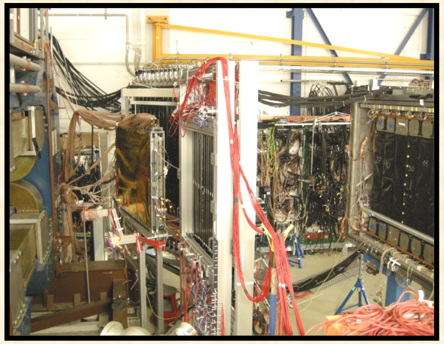


HypHI Phase 0 experiment (2006 – 2012)

- To demonstrate the feasibility of precise hypernuclear spectroscopy with ^{6}Li primary beams at 2 A GeV on a carbon target







Results of HypHI Phase 0 (2009)

- **Observations of $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ and Λ-hyperon**
  - Nucl. Phys. A 913 (2013) 170
- **Short lifetime of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$**
  - Nucl. Phys. A 913 (2013) 170
  - Phys. Lett. B 728 (2014) 543
- **Indications of the nnΛ bound state**
  - Phys. Rev. C 88 (2013) 041001-1-6(R)
- **Production cross section of $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ and Λ-hyperon with $^{6}Li+^{12}C$ at 2 A GeV**
  - Phys. Lett. B 747 (2014) 129
- **Summary paper**
  - Nucl. Phys. A 954 (2016) 199

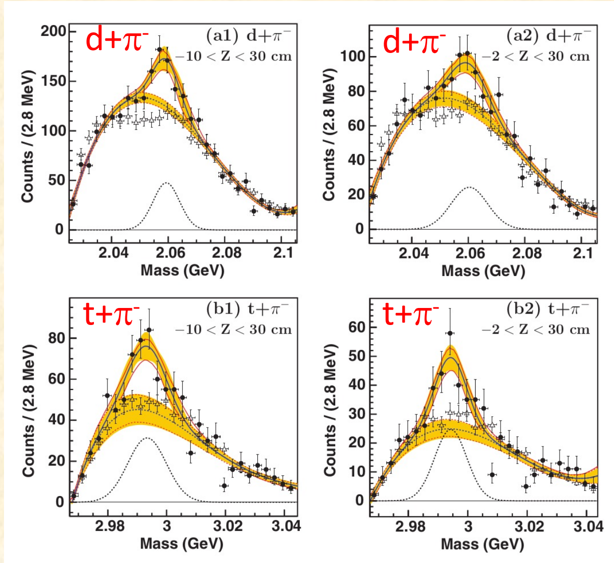
Two puzzles from HypHI

Signals indicating nnΛ bound state

<u>All theoretical calculations are negative</u>

- 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

and much more publication



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

Short lifetime of $^{3}_{\Lambda}$H C. Rappold et al., Nucl. Phys. A 913 (2013) 170

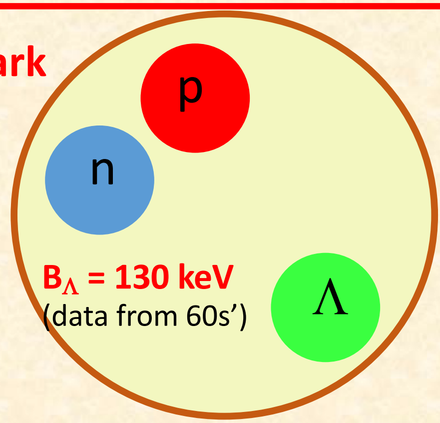
- HypHI Phase 0: 183^{+42}_{-32} ps
- STAR at RHIC: ~~155^{+25}_{-22} ps~~ **142^{+24}_{-21}**
- ALICE at LHC: ~~181^{+54}_{-39} ps~~ **237^{+33}_{-36}**

STAR Collaboration, Phys. Rev. C 97 (2018) 054909

ALICE Collaboration, Phys. Lett. B 797 (2019) 134905

<u>No theories to reproduce the short lifetime</u>

Benchmark

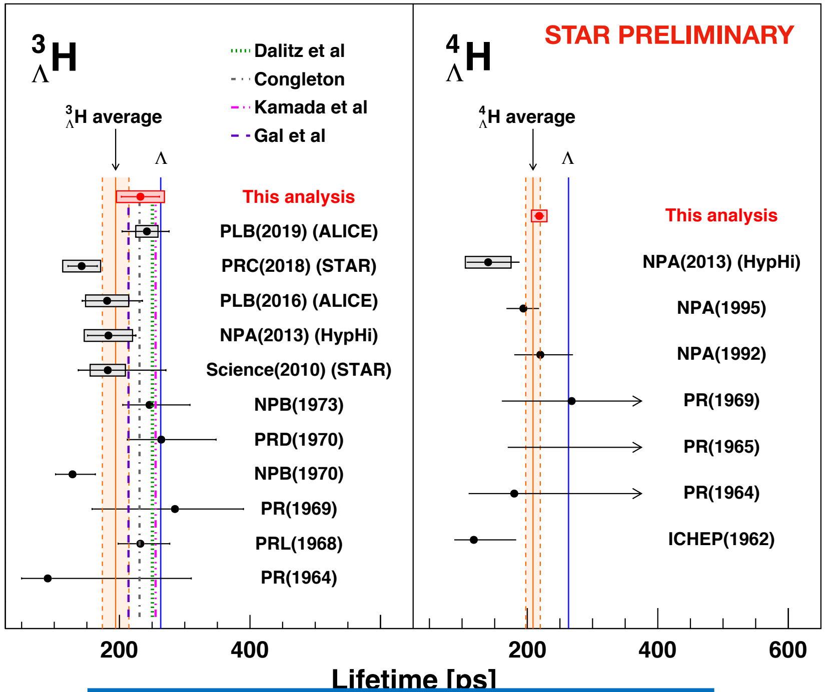


$\tau(^{3}_{\Lambda}$H) should be equal to $\tau(\Lambda$, 263 ps)

Hot topics in hypernuclear and few-body physics

Remarks on the most recent STAR result on $\tau({}^3_\Lambda H)$

New results on ${}^3_\Lambda H$ and ${}^4_\Lambda H$ lifetime



${}^3_\Lambda H : \tau = 232.1 \pm 29.2(\text{stat}) \pm 36.7(\text{syst})[\text{ps}]$

${}^4_\Lambda H : \tau = 218.3 \pm 7.5(\text{stat}) \pm 11.8(\text{syst})[\text{ps}]$

- ${}^4_\Lambda H$:
  - **Most precise measurement to date.**
  - **Consistent with previous measurements.**
- ${}^3_\Lambda H$:
  - **Consistent with theoretical calculations including pion FSI.**

NC46(1966)786 (Dalitz et al)

JPG NPP 18(1992)339 (Congleton)

PRC57(1998)1595 (Kamada et al)

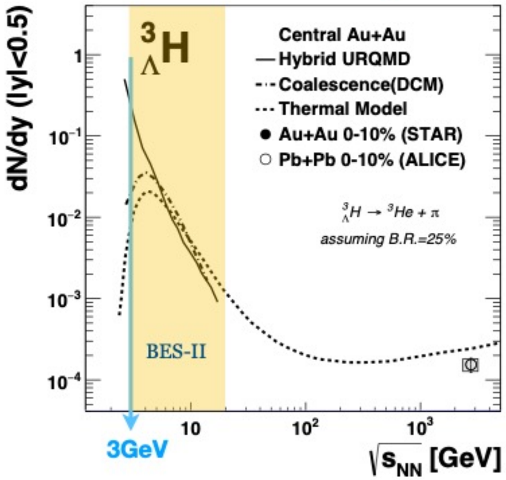
PLB791(2019)48 (Gal et al)

Yue-Hang Leung
Presented in the Reimei-THEIA Web-seminar,
April 22nd, 2021

Remarks on the most recent STAR result on $\tau({}^{3}_{\Lambda}H)$

STAR BES-II

- Higher baryon density at lower beam energies
    - STAR BES-II -> great opportunity to study hypernuclei production

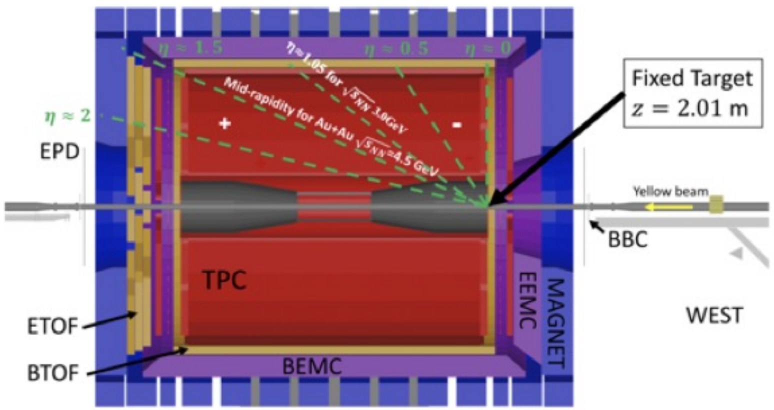


PLB714(2012),85 (Hybrid URQMD, Coalescence(DCM))

PLB 697 (2011)203 (Thermal Model)

PLB 754 (2016)360 (ALICE)

STAR Fixed-target Experiment Setup



- 250M events at $\sqrt{s_{NN}} = 3$ GeV with STAR fixed target mode

Yue-Hang Leung
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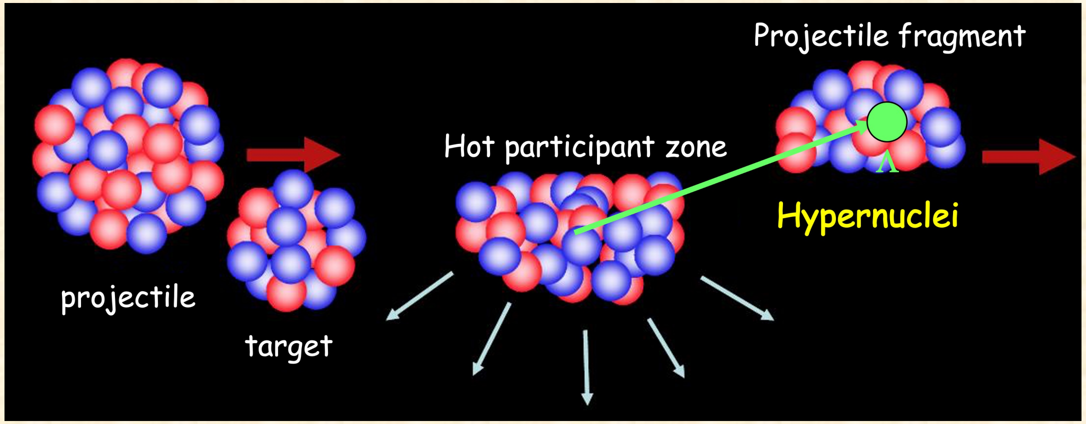
Remarks on the most recent STAR result on $\tau({}^{3}_{\Lambda}H)$

Relativistic HI collision

- Penalty factor for forming heavier fragments/clusters
- Ex.: Yield of ${}^{4}_{\Lambda}H$ is much smaller than the hypertriton with STAR and ALICE

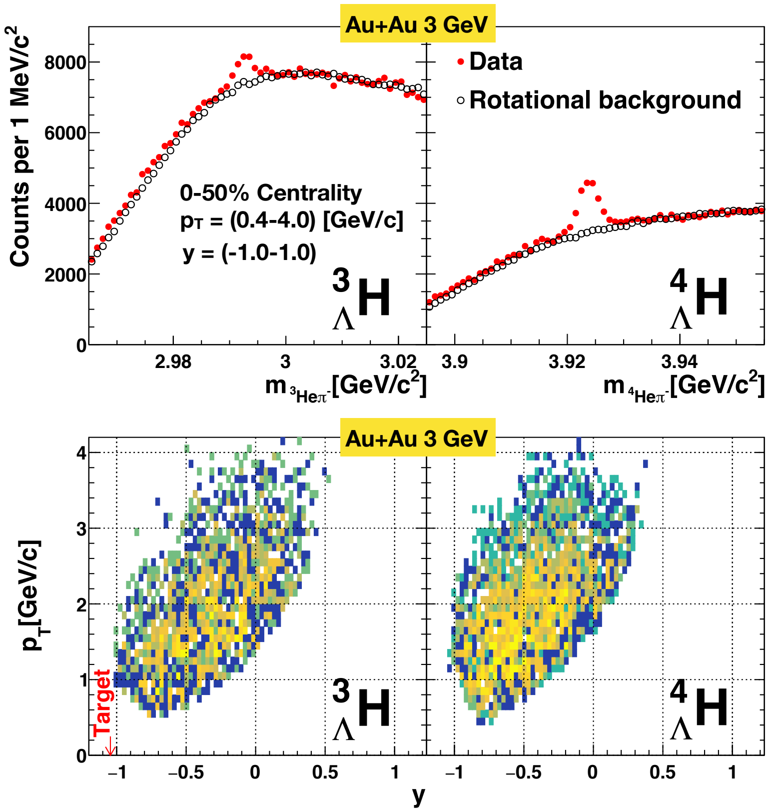
Fixed-target HI collision

- Variety of fragments/clusters up to the mass of the projectile
- Ex. HypHI, 3.9 μb for hypertriton and 3.1 μb for ${}^{4}_{\Lambda}H$ with ${}^{6}Li + {}^{12}C$ at 2 A GeV



Remarks on the most recent STAR result on $\tau(^{3}_{\Lambda}H)$

Hypernuclei reconstruction and acceptance



- Decay channels

$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi \quad (B.R. \approx 25\%)$

PRC57(1998)1595

~2900 candidates

$^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi \quad (B.R. \approx 50\%)$

~6300 candidates

NPA585(1995) 365c

NPA639(1998) 251c

$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi \quad (B.R. \approx 40\%)$

PRC57(1998)1595

~7000 candidates

- Good mid-rapidity coverage at 3 GeV

**KFParticle package used for reconstruction*

*M. Zyzak, "Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR", thesis, urn:nbn:de:hebis:30:3-414288

STRONG 2020 STAR

Yue-Hang Leung
Presented in the Reimei-THEIA Web-seminar,
April 22nd, 2021

$^{4}_{\Lambda}$He should be produced

Contaminants from
$^{4}_{\Lambda}\mathrm{He} \rightarrow \pi^{-} + {}^{3}\mathrm{He} + \mathrm{p}$

Remarks on the most recent STAR result on $\tau({}^{3}_{\Lambda}H)$

Three-body decays of light hypernuclei: example, ${}^{5}_{\Lambda}He$

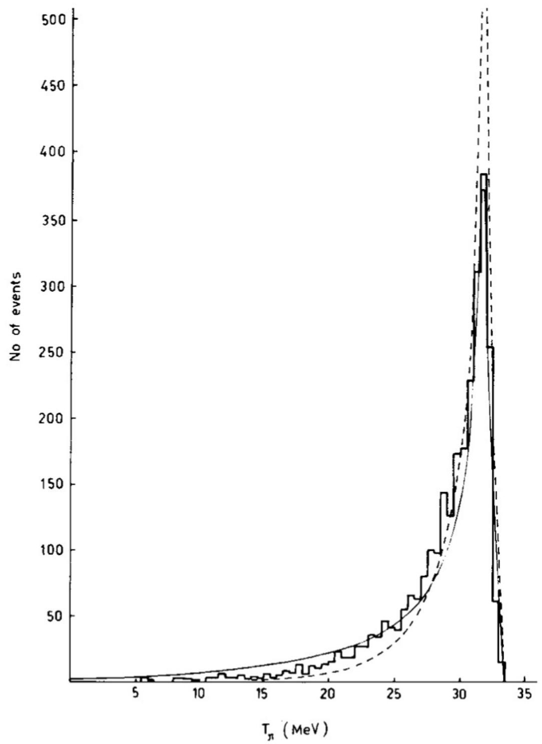


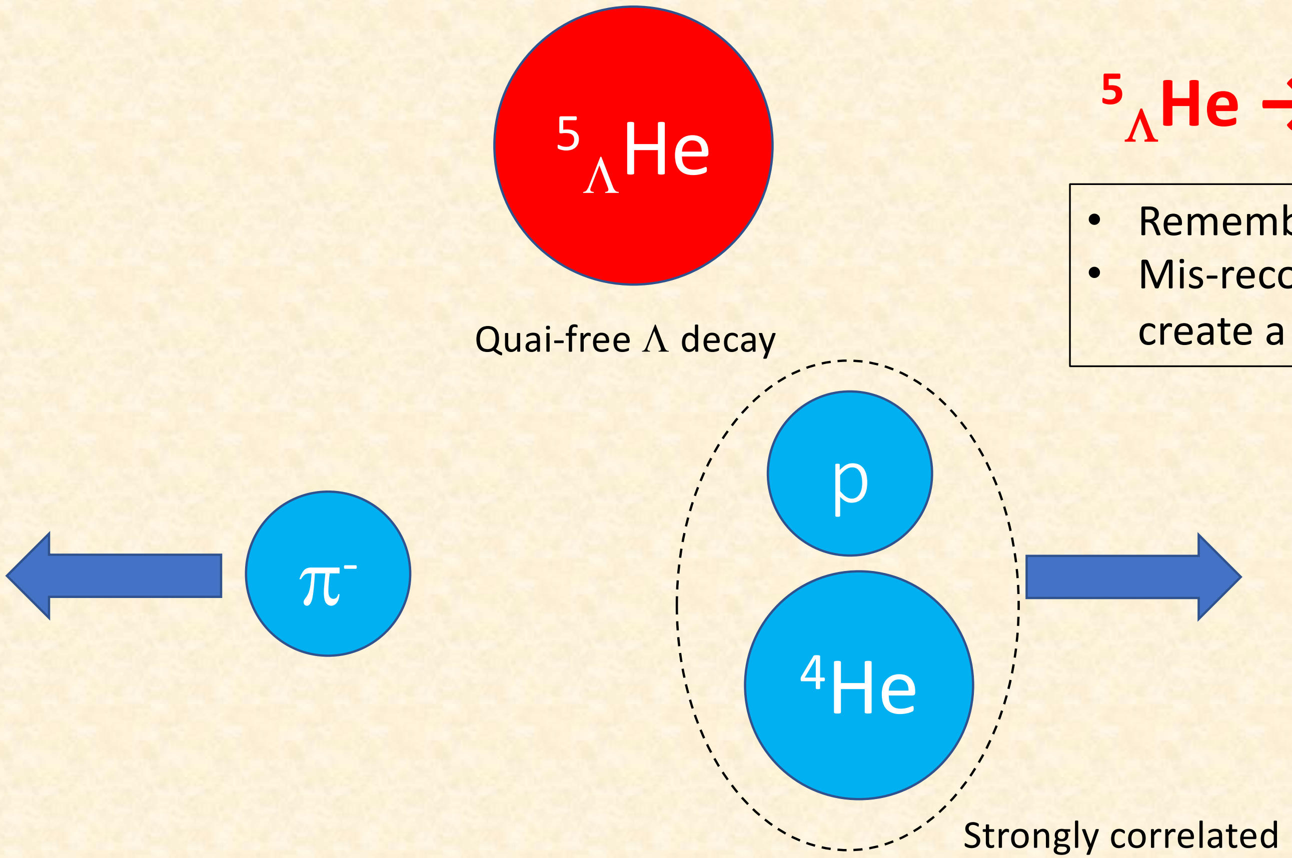
Fig. 2. Experimental π^- meson kinetic energy distribution. Solid curve: theoretical distribution with hard-core potential for the s-state p-^{4}He interaction; dotted curve: theoretical distribution with attractive potential for the s-state p-^{4}He interaction.

Kinematic energy distribution of π^- from the three-body decay of ${}^{5}_{\Lambda}He \rightarrow \pi^- + {}^{4}He + p$

Nuclear Physics B 14 (1969) 11-27

Remarks on the most recent STAR result on $\tau({}^{3}_{\Lambda}H)$

Three-body decays of light hypernuclei: example, ${}^{5}_{\Lambda}He$

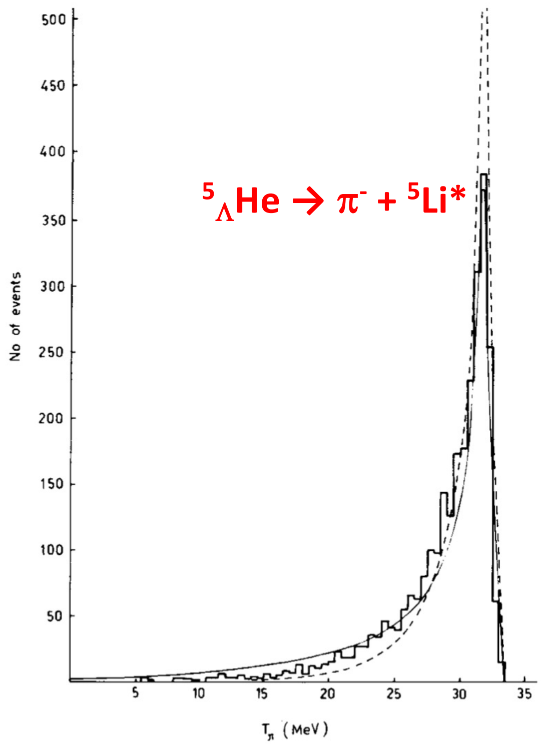


${}^{5}_{\Lambda}He \rightarrow \pi^- + {}^{5}Li^* \rightarrow \pi^- + {}^{4}He + p$

- Remembering the two-body decay kinematics
- Mis-reconstruction with π^- + ${}^{4}He$ from ${}^{5}_{\Lambda}He$ will create a peak like ${}^{4}_{\Lambda}H \rightarrow \pi$- + ${}^{4}He$

Remarks on the most recent STAR result on $\tau({}^{3}_{\Lambda}H)$

Three-body decays of light hypernuclei: example, ${}^{5}_{\Lambda}He$



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Nuclear Physics B 14 (1969) 11-27

Remarks on the most recent STAR result on $\tau({}^{3}_{\Lambda}H)$

For the case of ${}^{4}_{\Lambda}He$

${}^{4}_{\Lambda}He \rightarrow \pi^- + {}^{4}Li^* \rightarrow \pi^- + {}^{3}He + p$

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

Lifetime of ${}^{4}_{\Lambda}He$:
254 ± 24 ps
Phys. Rev. C 76 (2007) 035501

All the channels involving $\pi^- + {}^{3}He$ from heavier hypernuclei should be considered

- ${}^{4}_{\Lambda}He \rightarrow \pi^- + {}^{3}He + p$
- ${}^{4}_{\Lambda}H \rightarrow \pi^- + {}^{3}He + n$
- ${}^{5}_{\Lambda}He \rightarrow \pi^- + {}^{3}He + n + p$
- ${}^{6}_{\Lambda}He \rightarrow \pi^- + {}^{3}He + n + n + p$
- ${}^{6}_{\Lambda}Li \rightarrow \pi^- + {}^{3}He + n + p + p$
- ${}^{7}_{\Lambda}Li \rightarrow \pi^- + {}^{3}He + n + n + p + p$

and much more

HypHI and WASA-FRS:
Using ${}^{6}Li$ beams to minimize contamination from heavier hypernuclei

Strongly correlated

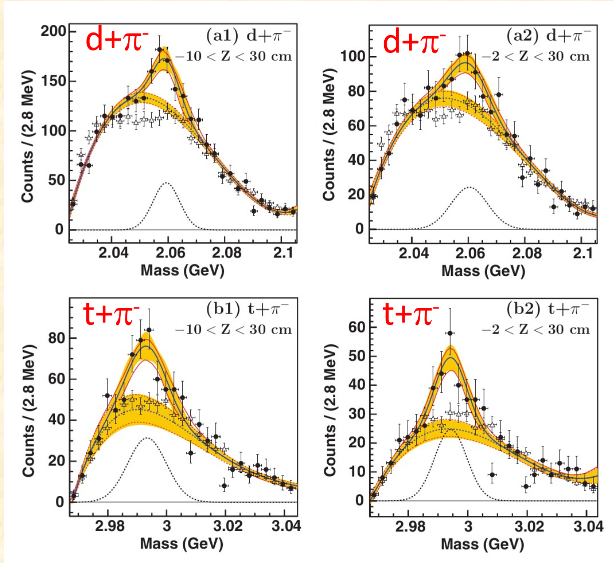
Two puzzles from HypHI

Signals indicating nnΛ bound state

<u>All theoretical calculations are negative</u>

- 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

and much more publication



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

Short lifetime of $^3_\Lambda$

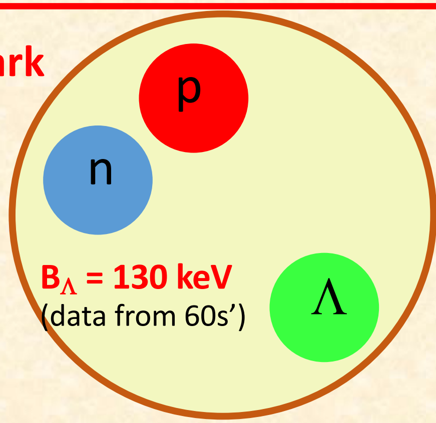
No such contamination

- HypHI Phase 0: 183 ... ps Phys. Rev. C 97 (2018) 054909
- STAR at RHIC: ~~155^{+25}_{-22} ps~~ **142^{+24}_{-21}**
- ALICE at LHC: ~~181^{+54}_{-39} ps~~ **237^{+33}_{-36}**

ALICE Collaboration, Phys. Lett. B 797 (2019) 134905

<u>No theories to reproduce the short lifetime</u>

mark



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

Hot topics in hypernuclear and few-body physics

New results on hypertriton

NATURE PHYSICS | VOL 16 | APRIL 2020 | 409–412 | www.nature.com/naturephysics

nature physics

LETTERS

https://doi.org/10.1038/s41567-020-0799-7

Check for updates

Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton

The STAR Collaboration*

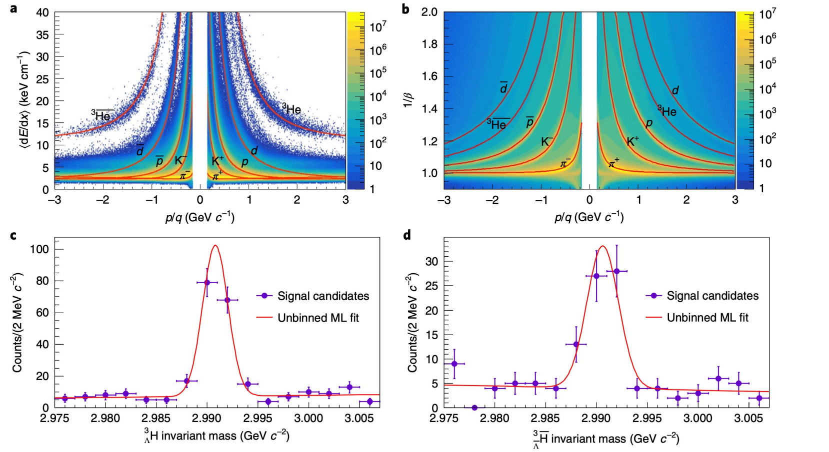


Fig. 2 | Particle identification and the invariant mass distributions for $^{3}_{\Lambda}$H and $^{3}_{\Lambda}\overline{\text{H}}$ reconstruction. a,b, ⟨d*E*/dx⟩ (mean energy loss per unit track length in the gas of the TPC) versus p/q (where p is the momentum and q is the electric charge in units of the elementary charge e) (**a**) and $1/\beta$ (where β is the speed of a particle in units of the speed of light) versus p/q (**b**). ⟨d*E*/dx⟩ is measured by the TPC and $1/\beta$ is measured by the TOF detector in conjunction with the TPC. In both cases, the coloured bands show the measured data for each species of charged particle, while the red curves show the expected values. Charged particles are identified by comparing the observed ⟨d*E*/dx⟩ and $1/\beta$ with the expected values. **c,d**, Utilizing both 2-body and 3-body decay channels, the invariant mass distributions of $^{3}_{\Lambda}$H (**c**) and $^{3}_{\Lambda}\overline{\text{H}}$ (**d**) are shown. The error bars represent statistical uncertainties (s.d.). The red curves represent a fit with a Gaussian function plus a linear background, using the unbinned maximum likelihood (ML) method.

The Λ binding energy, B_Λ, for $^{3}_{\Lambda}$H and $^{3}_{\Lambda}\overline{\text{H}}$ is calculated using the mass measurement shown in equation (1). We obtain

$$B_\Lambda = 0.41 \pm 0.12(\text{stat.}) \pm 0.11(\text{syst.})\ \text{MeV} \qquad (3)$$

Former value by emulsion (data from 60's)

0.13 ± 0.05 MeV

average value of 0.13 ± 0.05(stat.) MeV. When applied to our value of 0.41 ± 0.12(stat.) MeV it yields a significantly smaller value of $7.90^{+1.71}_{-0.93}$ fm. The larger B_Λ and shorter effective scattering length suggest a stronger YN interaction between the Λ and the relatively low-density nuclear core of the $^{3}_{\Lambda}$H (ref. [36]). This, in certain models, requires SU(3) symmetry breaking and a more repulsive YN interaction at high density, consistent with implications from the range of masses observed for neutron stars[5].

Recent theoretical calculation

Revisiting the hypertriton lifetime puzzle

A. Pérez-Obiol,[1] D. Gazda,[2] E. Friedman,[3] and A. Gal[3,*]
[1]*Laboratory of Physics, Kochi University of Technology, Kami, Kochi 782-8502, Japan*
[2]*Nuclear Physics Institute, 25068 Řež, Czech Republic*
[3]*Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*
(Dated: July 9, 2020)

arXiv:2006.16718v2 [nucl-th] 8 Jul 2020

Concluding remarks. Reported in this work is a new microscopic three-body calculation of the ${}^3_\Lambda$H pionic two-body decay rate $\Gamma({}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He}+\pi^-)$. Using the $\Delta I = \frac{1}{2}$ rule and a branching ratio taken from experiment to connect to additional pionic decay rates, the lifetime $\tau({}^3_\Lambda\mathrm{H})$ was deduced. As emphasized here $\tau({}^3_\Lambda\mathrm{H})$ varies strongly with the small, rather poorly known Λ separation energy $B_\Lambda({}^3_\Lambda\mathrm{H})$; it proves possible then to correlate each one of the three distinct RHI experimentally reported values $\tau_{\mathrm{exp}}({}^3_\Lambda\mathrm{H})$ with a theoretical value $\tau_{\mathrm{th}}({}^3_\Lambda\mathrm{H})$ that corresponds to its own underlying $B_\Lambda({}^3_\Lambda\mathrm{H})$ value. The $B_\Lambda({}^3_\Lambda\mathrm{H})$ intervals thereby correlated with these experiments are roughly $B_\Lambda \lesssim 0.1$ MeV, $0.1 \lesssim B_\Lambda \lesssim 0.2$ MeV and $B_\Lambda \gtrsim 0.2$ MeV for ALICE, HypHI and STAR, respectively. New experiments proposed at MAMI on Li target [39] and at JLab, J-PARC and ELPH on ^{3}He target [40] will hopefully pin down precisely $B_\Lambda({}^3_\Lambda\mathrm{H})$ to better than perhaps 50 keV, thereby leading to a unique resolution of the 'hypertriton lifetime puzzle'.

STAR, HypHI, ALICE: **from 121 to 270 ps**

Other recent theoretical works

For hypertriton:
<u>Effective field theory</u>
F. Hildenbrand et al., Phys. Rev. C 102, 064002 (2020)

- $R = \Gamma_{3He} / (\Gamma_{3He} + \Gamma_{pd})$ is sensitive to the binding energy

For nnΛ:
<u>Pionless effective field theory</u>
S.-I. Ando et al., Phys. Rev. C 92, 024325 (2015)
F. Hildenbrand et al., Phys. Rev. C 100 034002 (2019)
Not yet excluding the bound state

Urgent issues

Hypertriton
Lifetime (HypHI,STAR,ALICE): **121 ~ 270 ps**
Binding Energy: **130 ± 50 keV (Very old emulsion)**
410 ± 120 ± 110 keV (STAR 2020)

nnΛ
Does it exist?

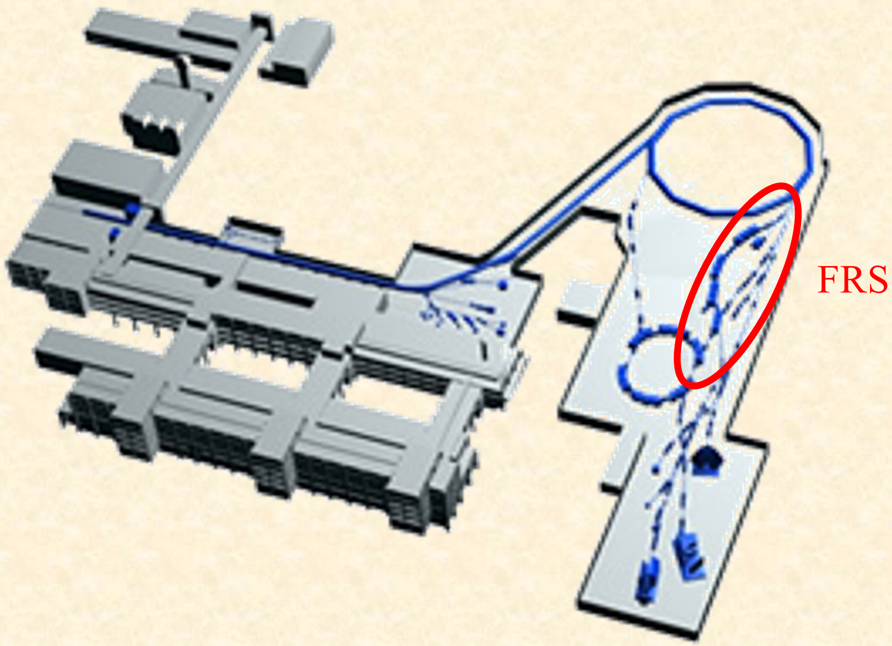
Very precise measurements for hypertriton on

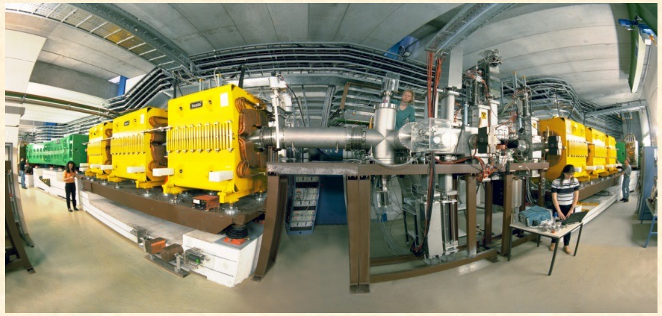
- **Lifetime**
- **Binding energy**

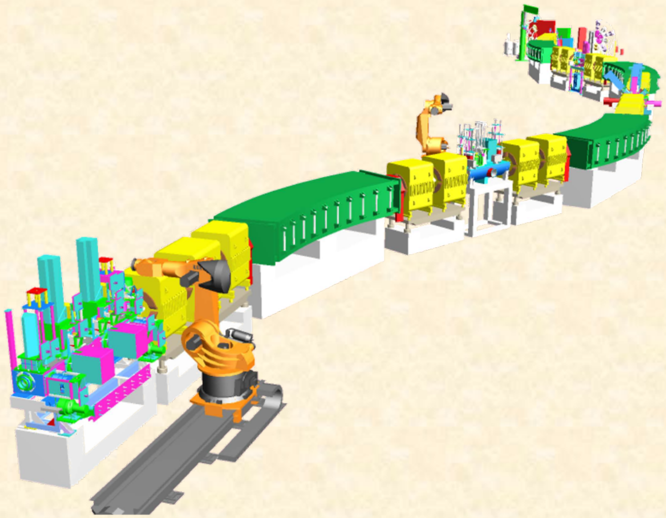
Confirmation of nnΛ with large statistics

And, much more information for double-strangeness hypernuclei

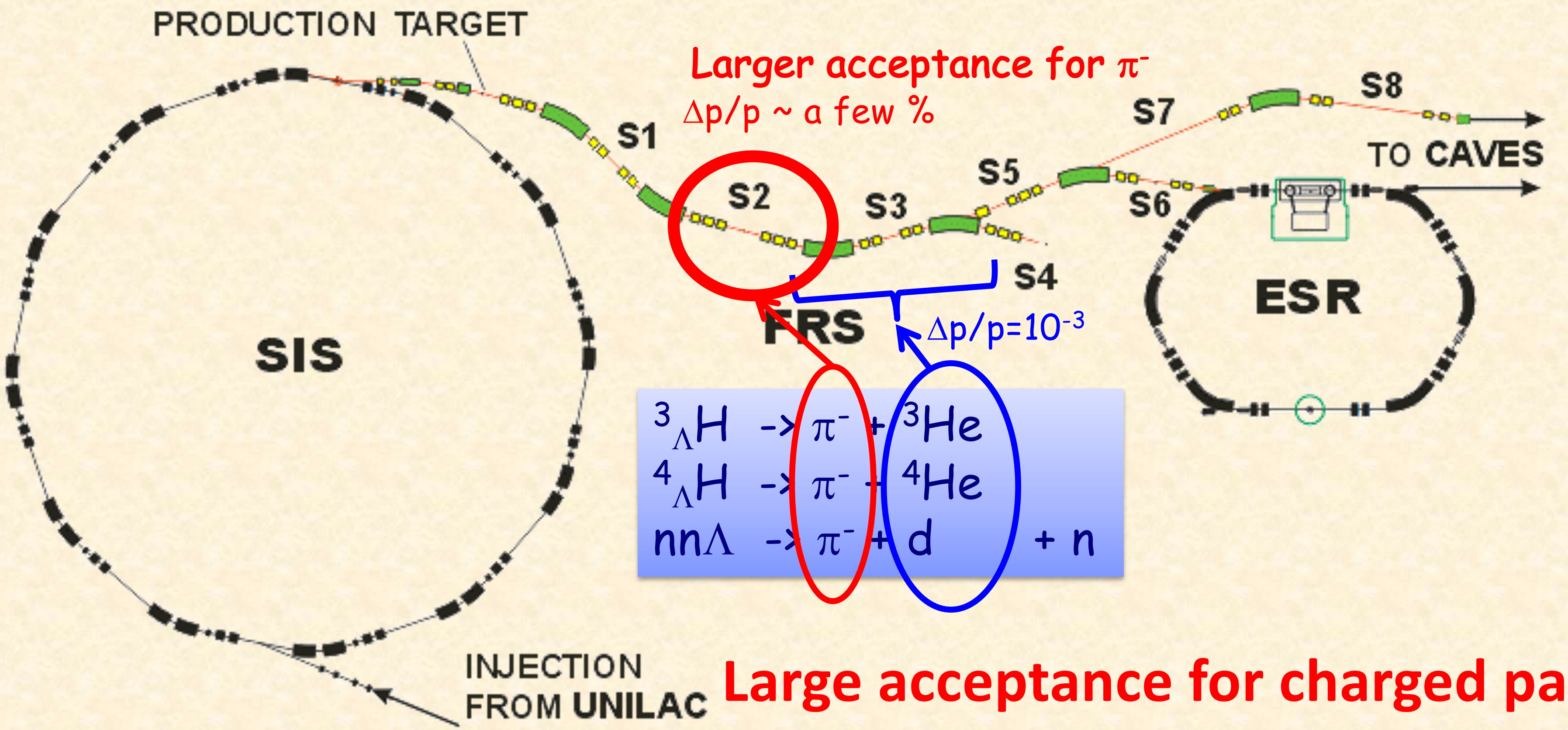
The WASA-FRS experiment at GSI in Germany







The WASA-FRS experiment at FAIR Phase 0 (GSI)



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

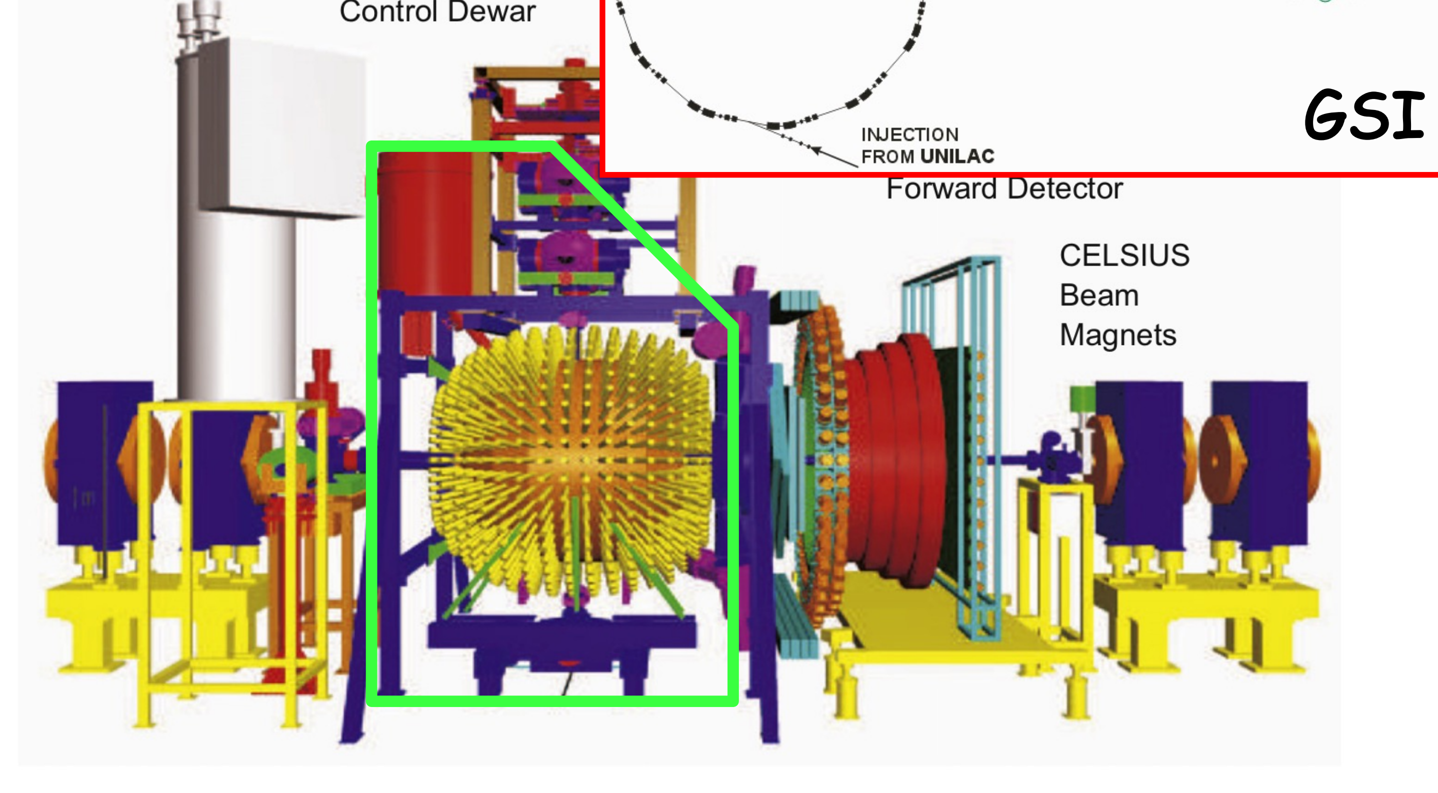
$^{4}_{\Lambda}H \rightarrow \pi^{-} + {}^{4}He$

$nn\Lambda \rightarrow \pi^{-} + d + n$

Large acceptance for charged particles including protons

The WASA-FRS experiment at FAIR Phase 0 (GSI)

C. Bargholtz et al. / Nuclear Instruments o



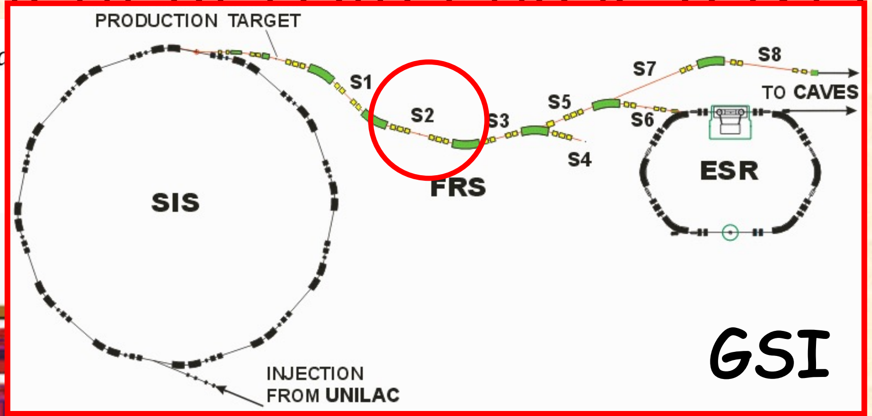
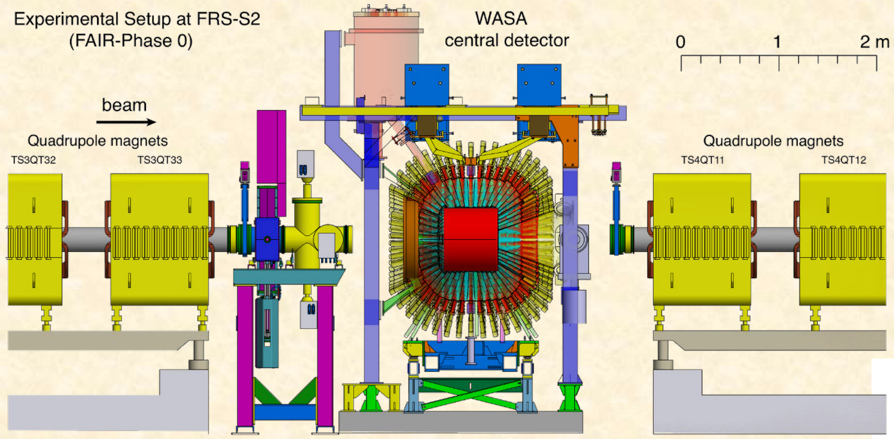


Fig. 1. CAD view of the WASA detector facility. The zero-degree spectrometer is located further downstream to the right.

The WASA-FRS experiment at FAIR Phase 0 (GSI)



WASA-FRS collaboration
with Super-FRS Experiment Collaboration

- **hypernuclei**
- **η'-nucleus**

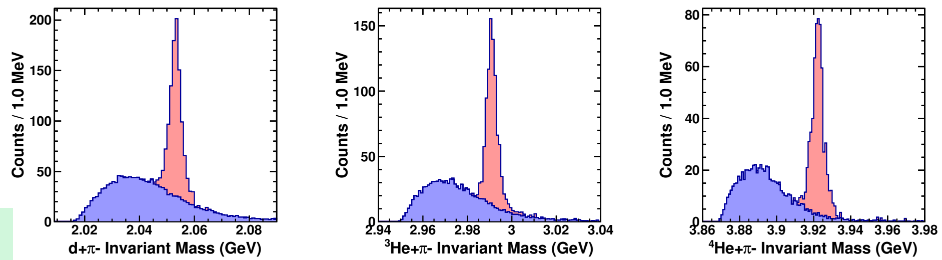
Table 2: Summary of the channels of interest, magnetic rigidity setup of FRS, requested shifts for each setup and corresponding expected signal integrals after the event reconstructions.

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
${}^3_\Lambda$H→^{3}He+π^-	12.623	9 shifts (3 days)	1.5×10^3
${}^4_\Lambda$H→^{4}He+π^-	16.675	together with $d+\pi^-$	5.0×10^3

10 ~ 40 times more

Already approved by the GSI PAC (highest priority)
2017 and 2020

- **6 days commissioning**
- **9 days for hypernuclear physics run**



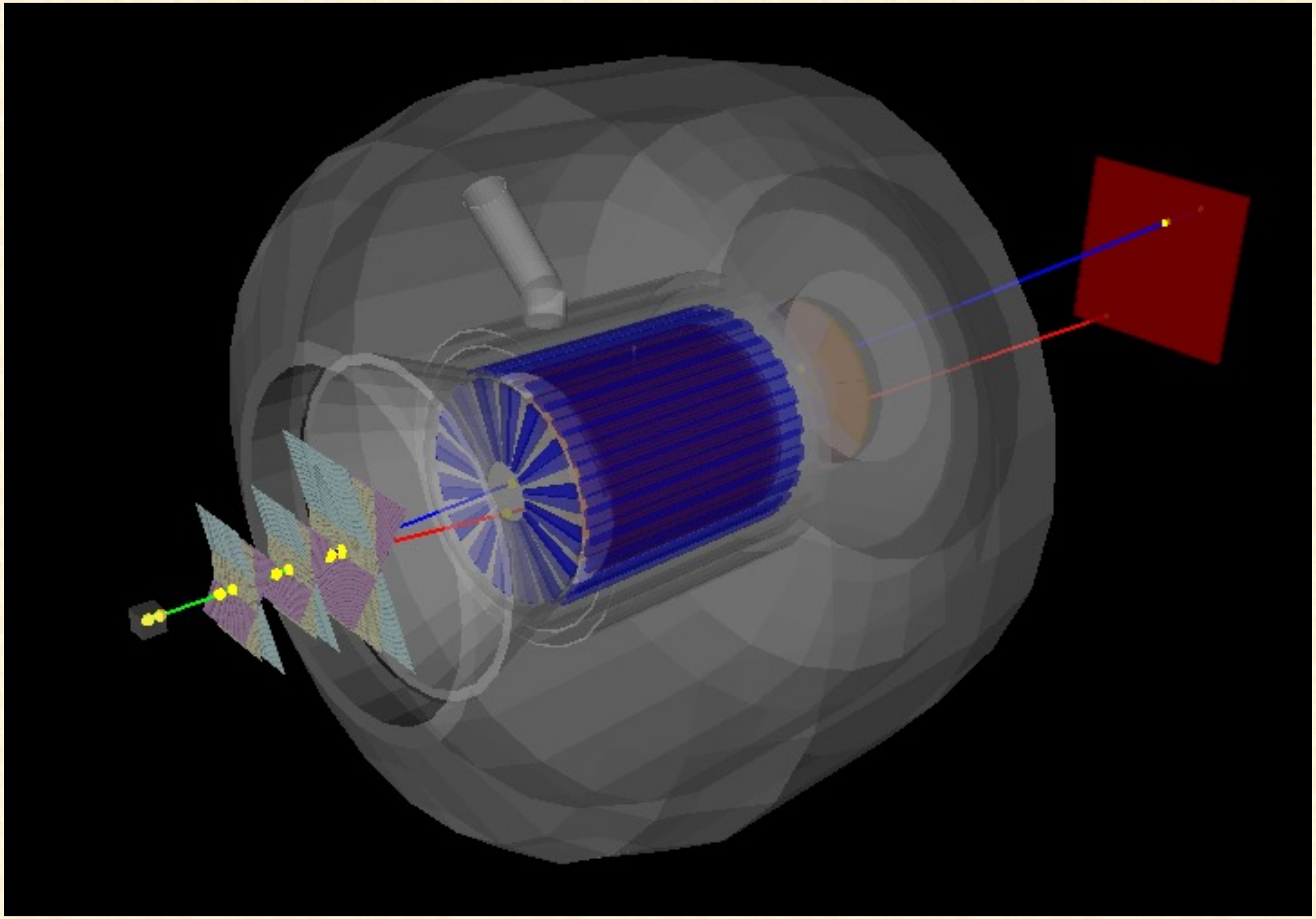
At least 2 times better resolution

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).

The WASA-FRS experiment at FAIR Phase 0 (GSI)

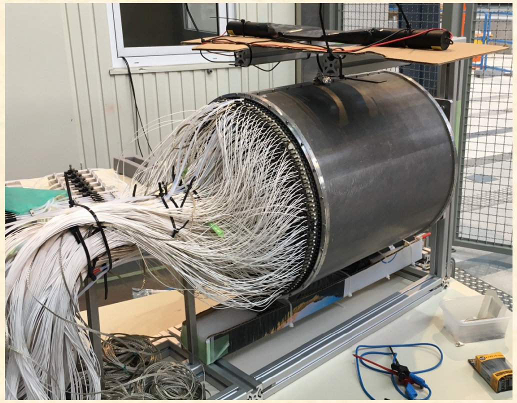
WASA already at GSI since March 2019

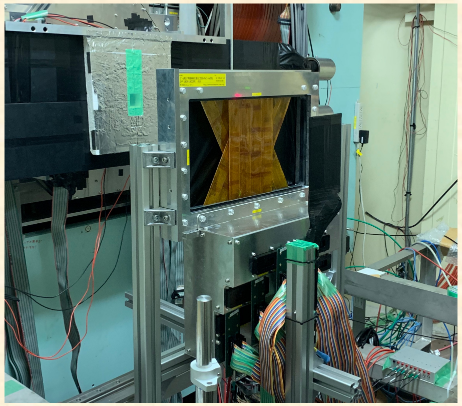
The WASA-FRS experiment at FAIR Phase 0 (GSI)

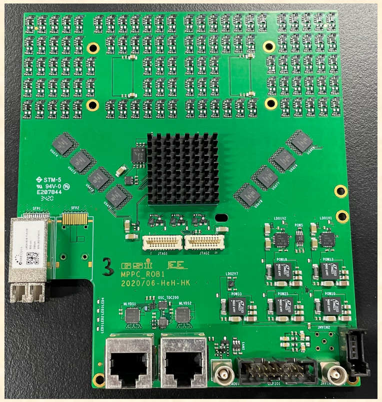


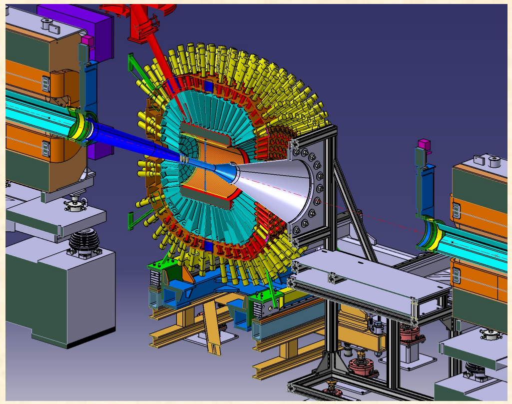
The WASA-FRS experiment at FAIR Phase 0 (GSI)

- Commissioning of
  - Mini drift chamber: **DONE**
  - Superconducting magnet: **already at 4K**
- Upgrading of
  - Time-of-Flight Barrel: in progress, **by summer of 2021**
- Development and construction of
  - Large Scintillating fiber detectors: **DONE**
  - Mini fiber detector inside the iron yoke: **DONE**
  - Electronics for fiber detectors: in progress, **Almost DONE**
  - New holding structures: in progress, **by summer 2020**



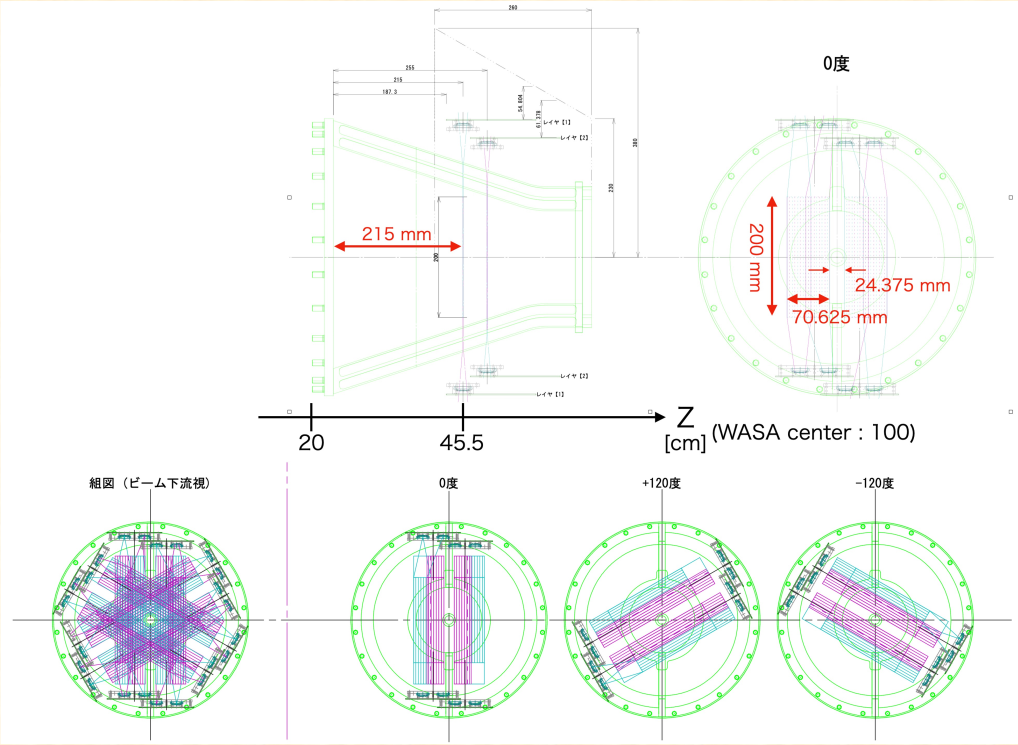


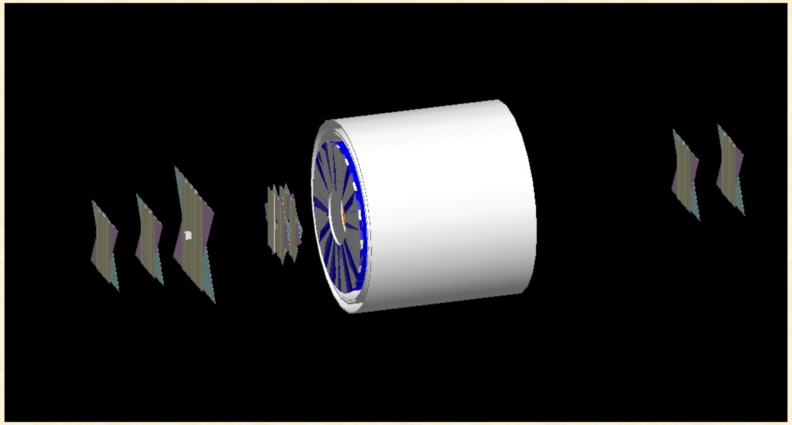


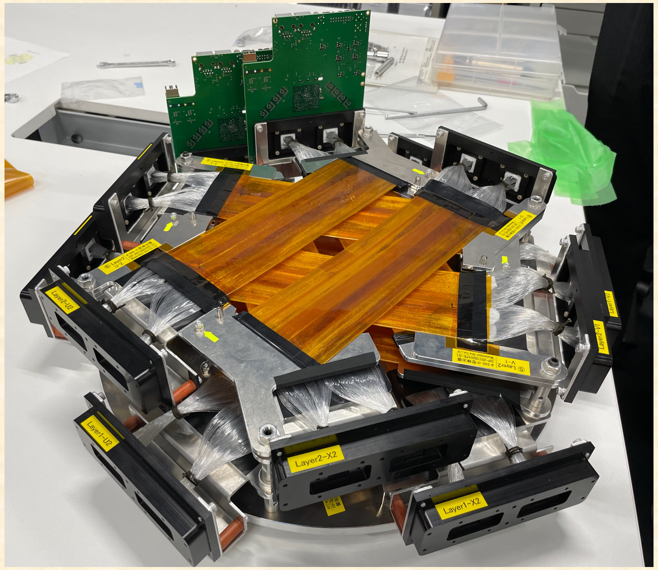


The WASA-FRS experiment at FAIR Phase 0 (GSI)

Mini fiber detector

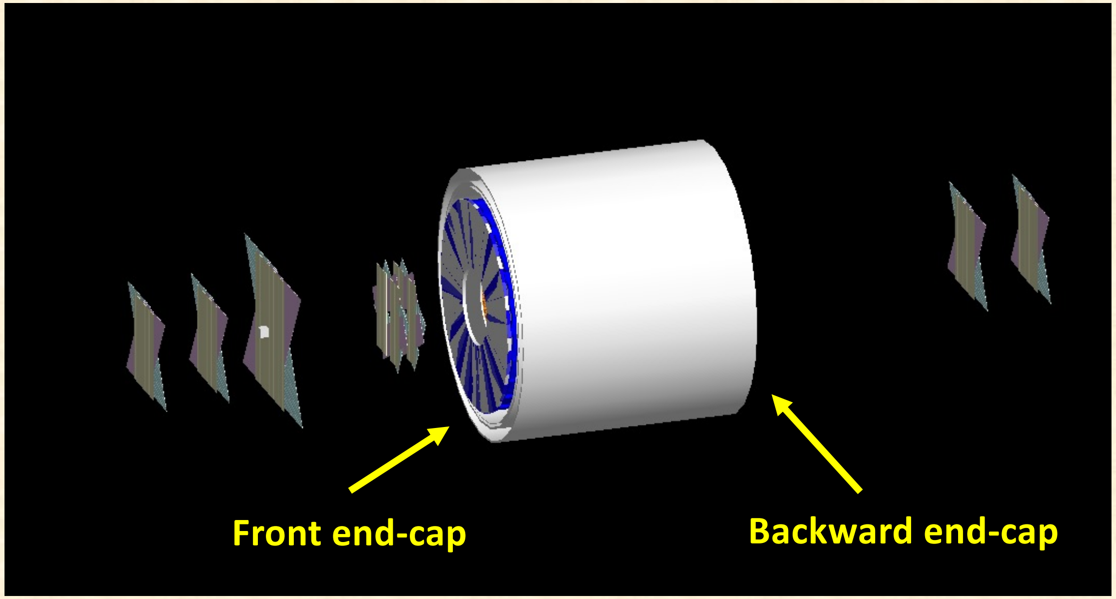


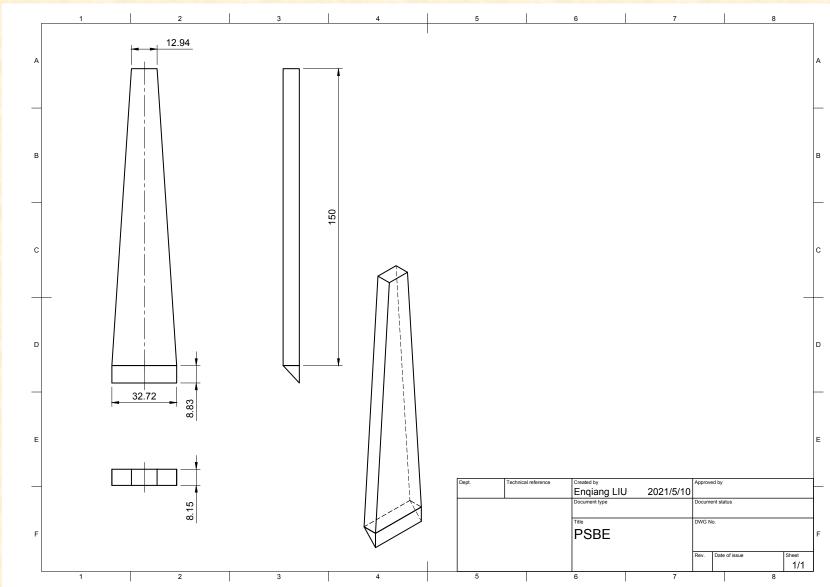


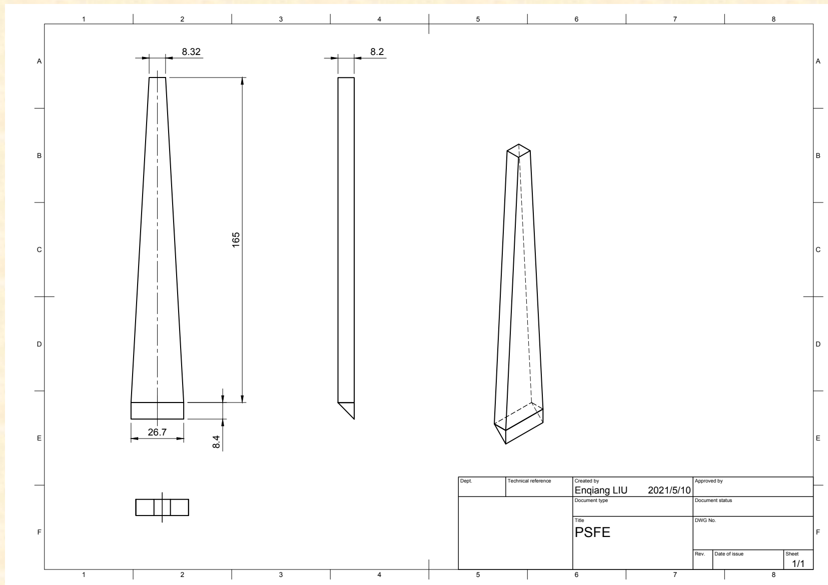


Upgrading the endcap detectors

Lanzhou University
Institute of Modern Physics
RIKEN



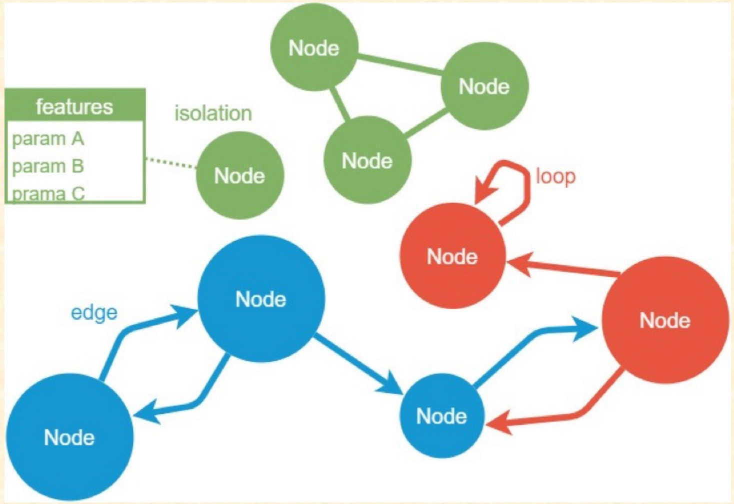




The WASA-FRS experiment at FAIR Phase 0 (GSI)

Development of the machine learning model for data analyses

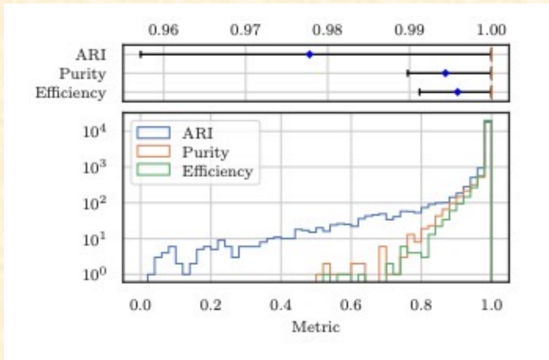
Graph Neural Network (GNN)

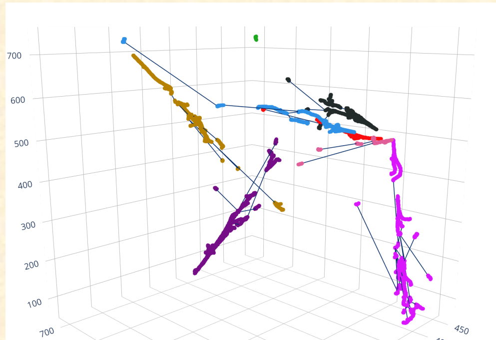


Graph
node : data point
edge : relation between nodes

node and edge can have features and a label

Clustering of Electromagnetic Showers and Particle Interactions with Graph Neural Networks in Liquid Argon Time Projection Chambers Data





arXiv:2007.01335v2 [physics.ins-det] 22 Sep 2020

The WASA-FRS experiment at FAIR Phase 0 (GSI)

Development of the machine learning model for data analyses

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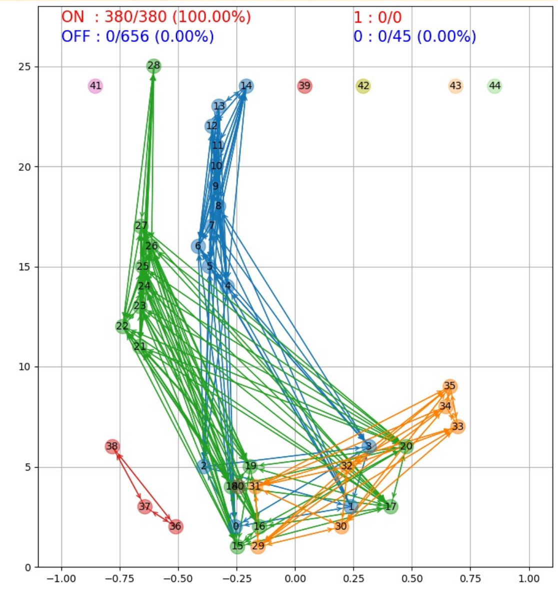
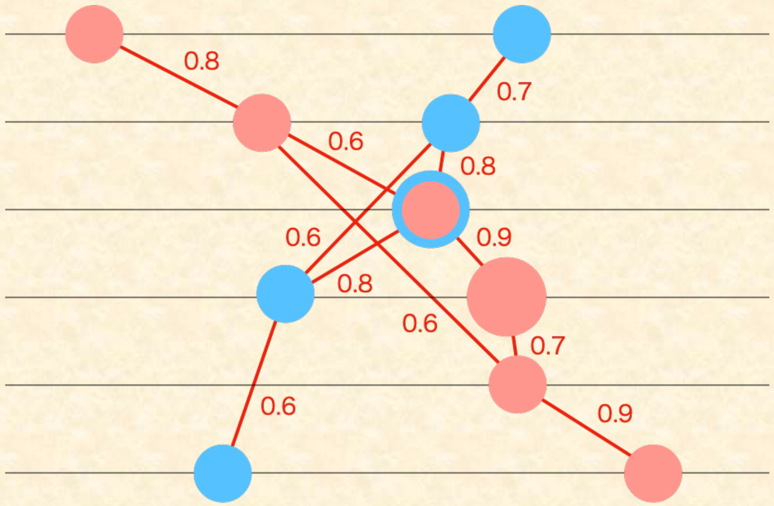


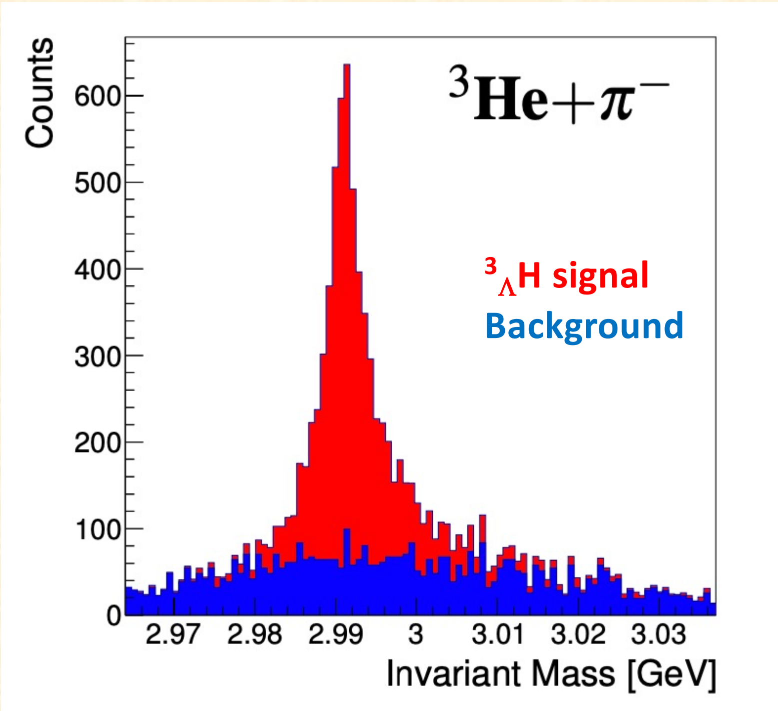


Dataset	π^- (perfect)	π^- (valid)	Other (perfect)	Other (valid)	Node AP(test)	Edge AP(test)
100k	96.31 %	99.77 %	95.12 %	98.66 %	0,94924	0,99932
300k	97.35 %	99.79 %	96.21 %	98.75 %	0,95876	0,99964
1M	98.09 %	99.92 %	97.05 %	99.07 %	0,97219	0,99980

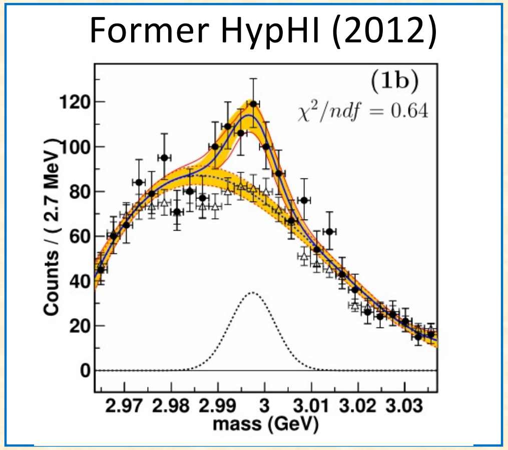
H. Ekawa et al., To be submitted to Journal of Computational Physics

The WASA-FRS experiment at FAIR Phase 0 (GSI)

Updated Monte Carlo simulations



4 days measurement



target position: z=25 cm
vertex z cut: 35 – 50 cm
#layer(MDC): > 6
cldst cut: < 0.3 cm

Mass resolution:

- 3.2 MeV/c^2 (1 T field)
- 1.5 times better than HypHI

Statistics

- About 5800 in the peak for 4 days
- 38 times more than HypHI
- 120 σ significance

Expected Lifetime accuracy

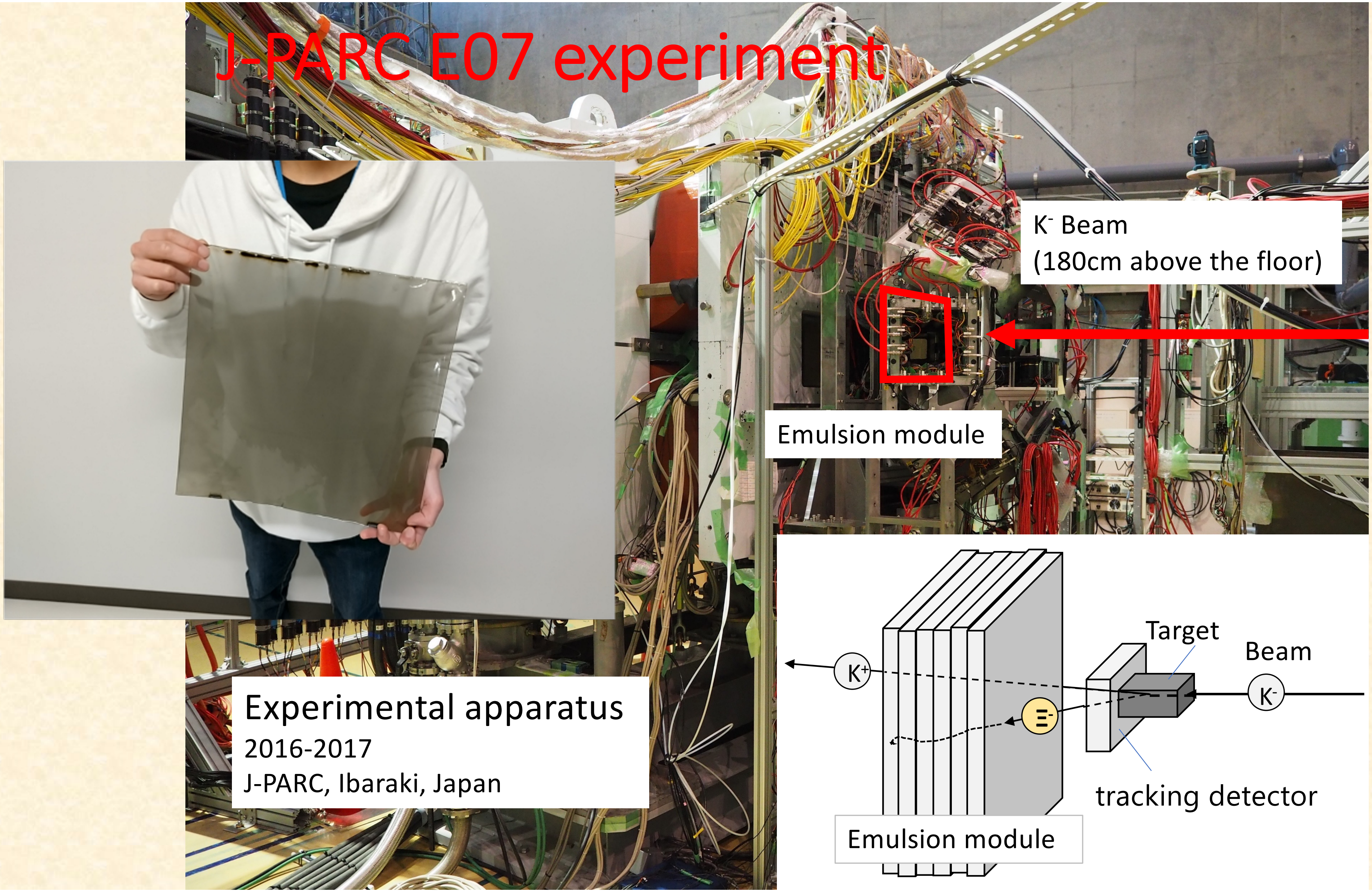
- **8 ps**
- 5 times better than HypHI

The existence or not of nnL will be confirmed with large confidence level

To be performed in February – March, 2022

J-PARC accelerator facility

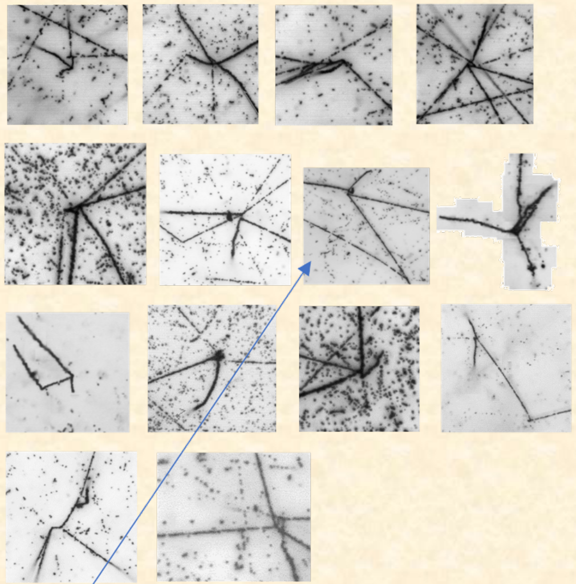
J-PARC E07 experiment



Analysis of J-PARC E07 data with Machine Learning at RIKEN

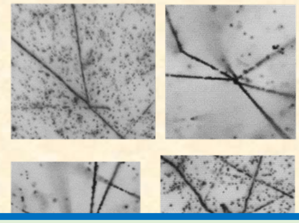
Outcome of the E07 experiments

$\Lambda\Lambda$ candidates: 14



Twin Λ events: 13

Others: 6



Non-triggered events recorded in 1000 emulsions sheets

- 1000 double-strangeness hypernuclear events
- Millions of single-strangeness hypernuclear events

Overall scanning of all emulsion sheets

(35 X 35 cm^2 X 1000)

$_{\Lambda\Lambda}$Be

H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02

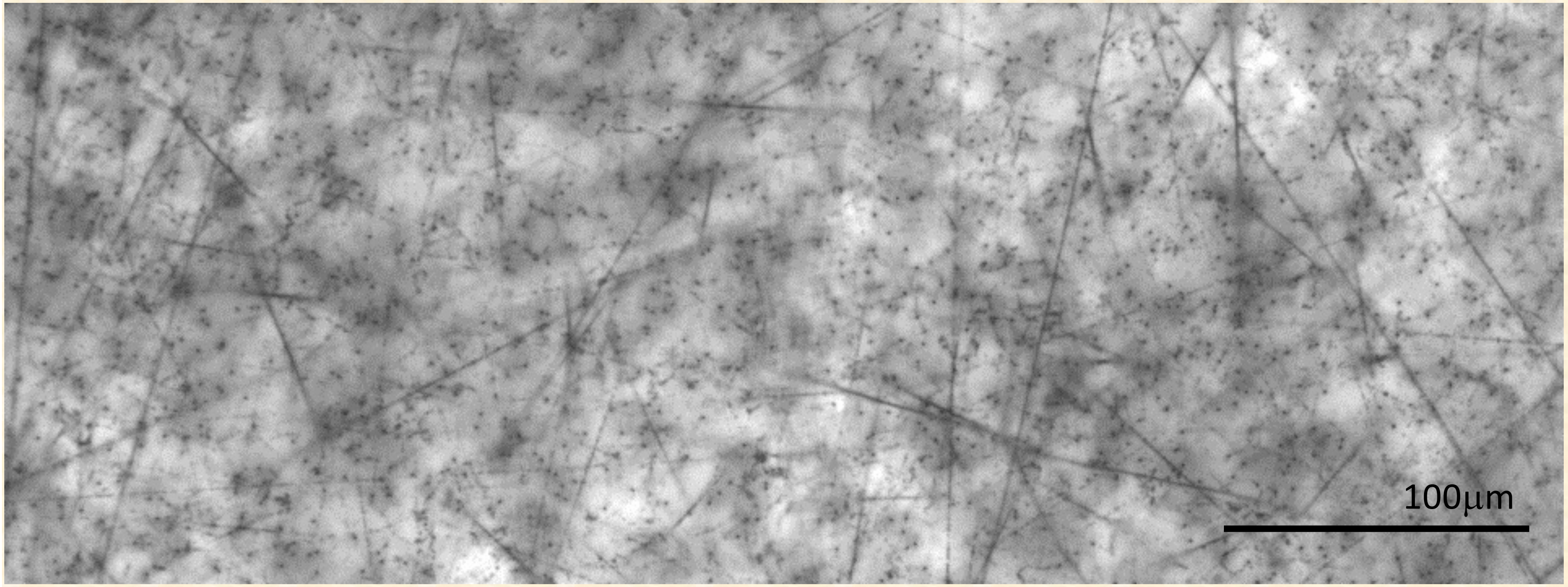
$^{15}_{\Xi}$C

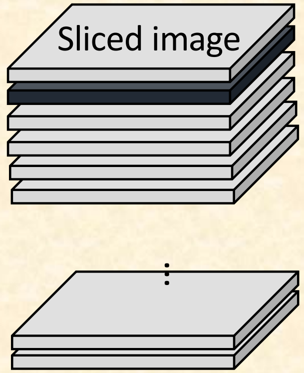
S. H. Hayakawa et al.,

Physical Review Letters, 126, 062501 (2021)

Analysis of J-PARC E07 data with Machine Learning at RIKEN

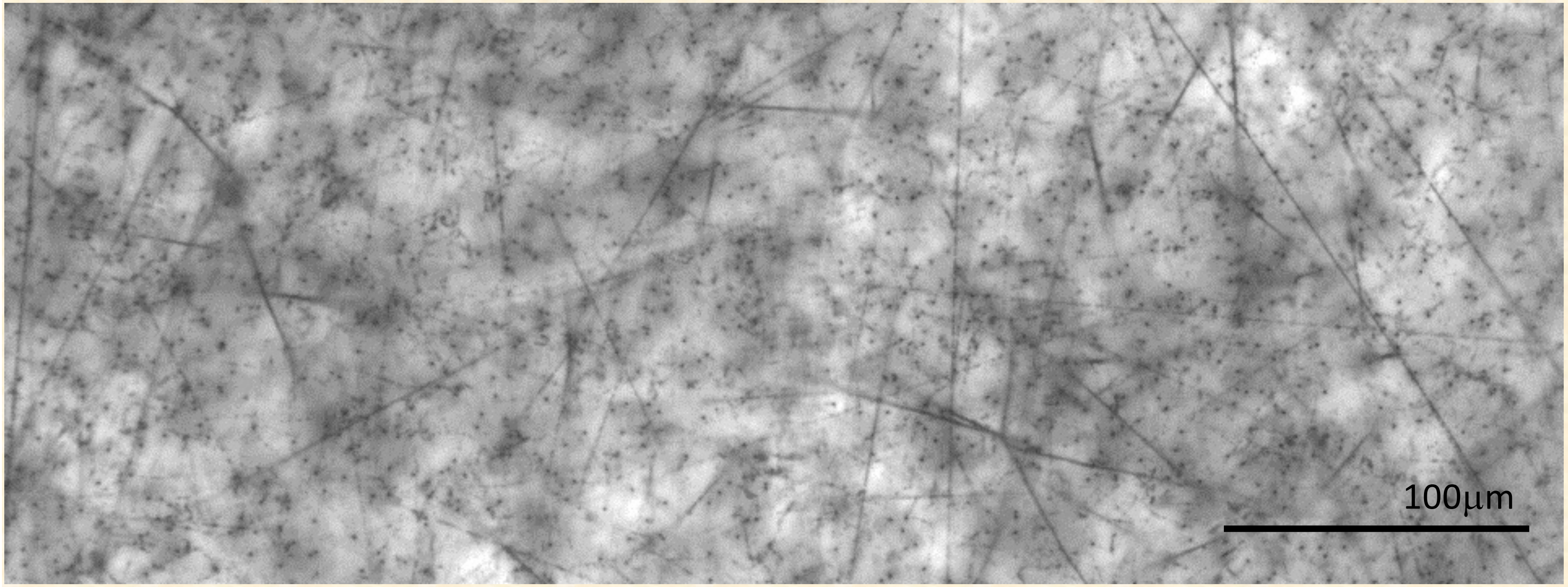
Overall scanning for E07 emulsions

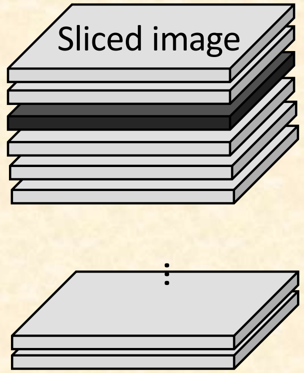




Analysis of J-PARC E07 data with Machine Learning at RIKEN

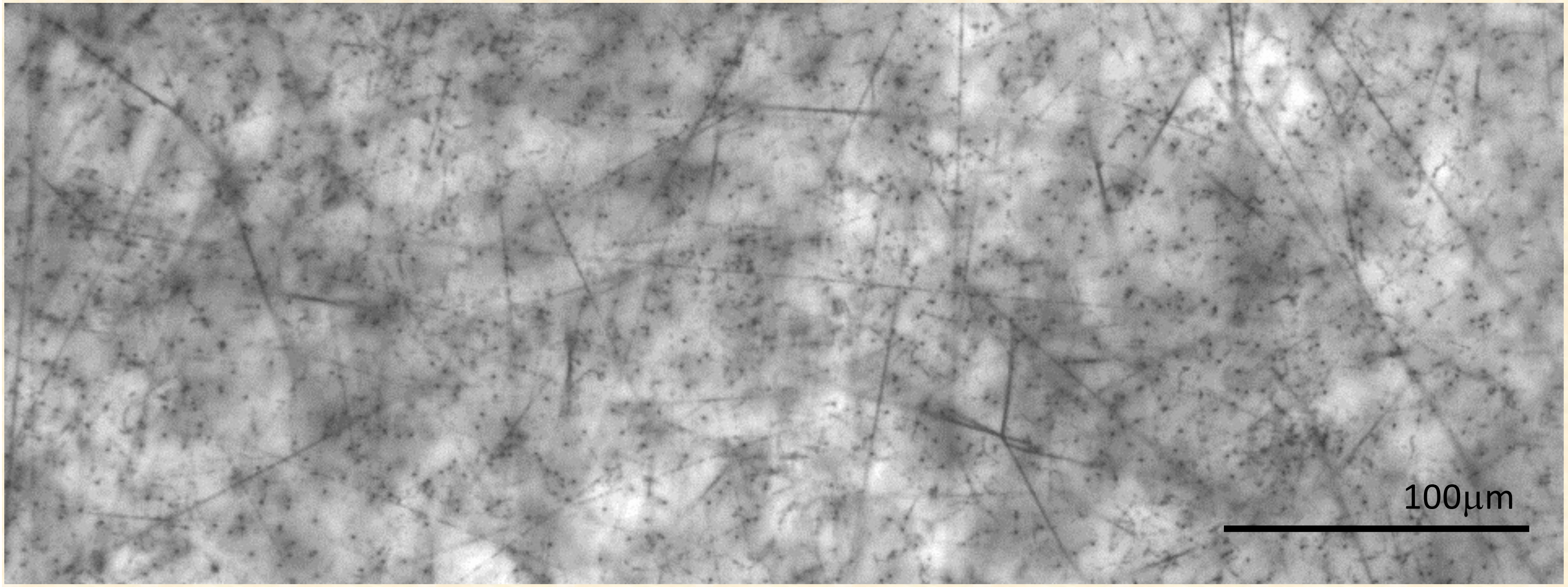
Overall scanning for E07 emulsions

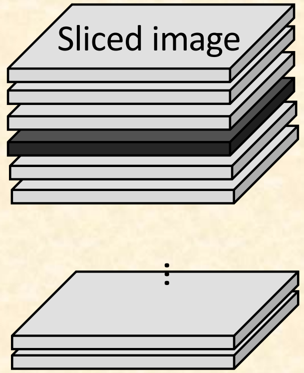




Analysis of J-PARC E07 data with Machine Learning at RIKEN

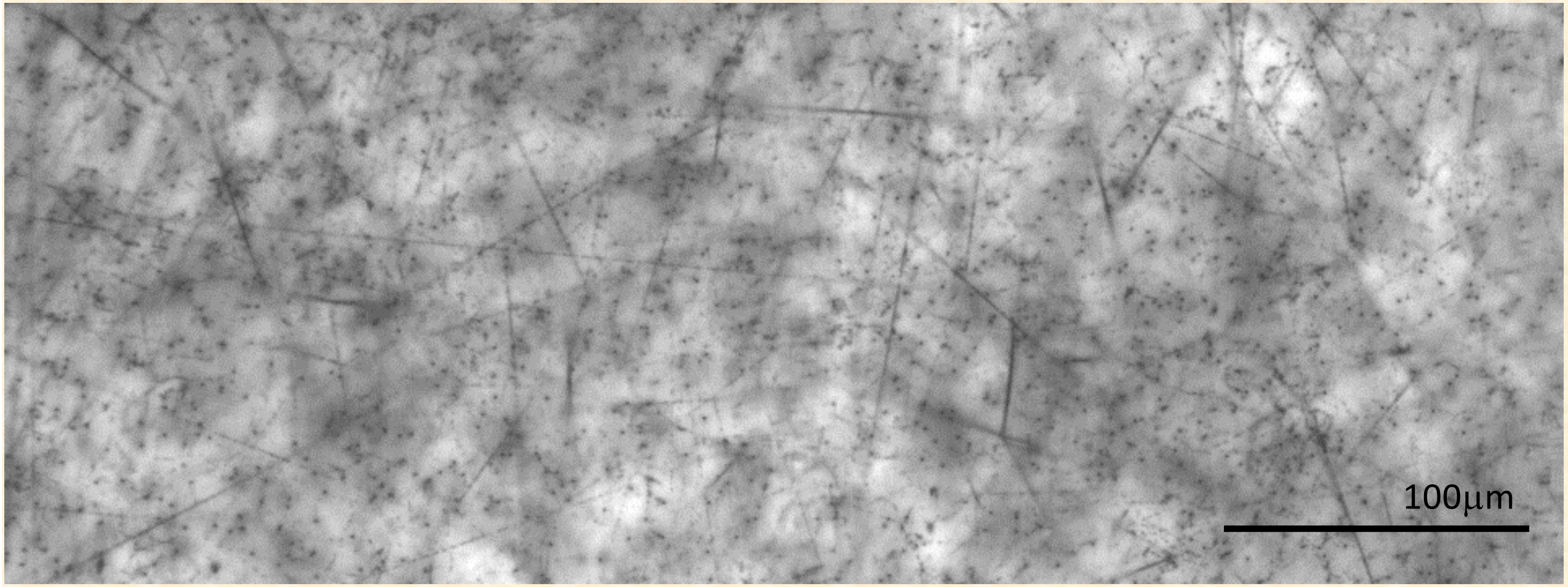
Overall scanning for E07 emulsions

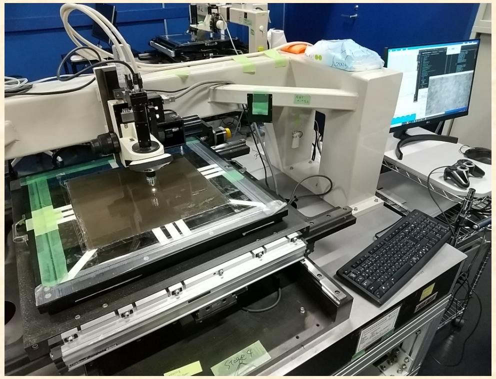


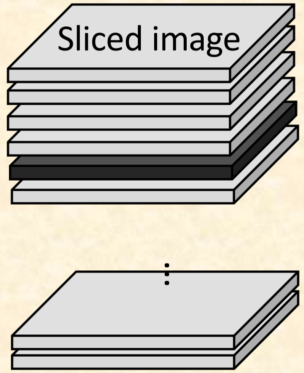


Analysis of J-PARC E07 data with Machine Learning at RIKEN

Overall scanning for E07 emulsions







Analysis of J-PARC E07 data with Machine Learning at RIKEN

Overall scanning for E07 emulsions

Data size:
- 10^7 images per emulsion (100 T Byte)
- 10^{10} images per 1000 emulsions (100 P Byte)

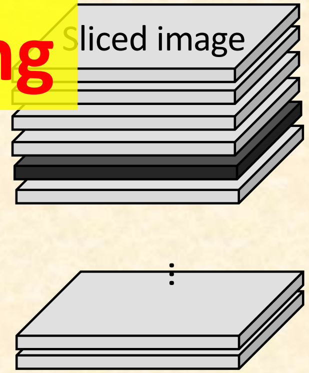
Number of background tracks:
- Beam tracks: $10^4/mm^2$
- Nuclear fragmentations: $10^3/mm^2$

Current equipments/techniques with visual inspections

560 years

→ **3 years**

Machine Learning



100µm

1000 double strangeness hypernuclei (formerly 5)

Analysis of J-PARC E07 data with Machine Learning

1000 double-strangeness hypernuclear candidates

↑

Starting in April 2020

New results on hypertriton

NATURE PHYSICS | VOL 16 | APRIL 2020 | 409–412 | www.nature.com/naturephysics

nature physics
LETTERS
https://doi.org/10.1038/s41567-020-0799-7
Check for updates

Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton

The STAR Collaboration*

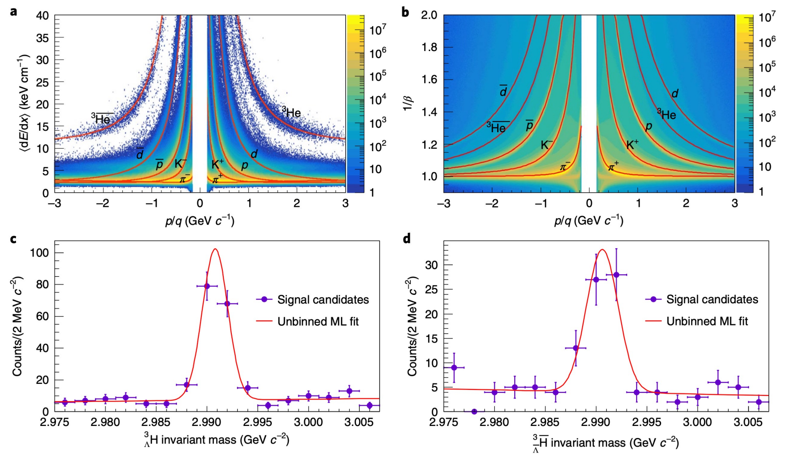


Fig. 2 | Particle identification and the invariant mass distributions for $^{3}_{\Lambda}$H and $^{3}_{\bar{\Lambda}}\overline{\text{H}}$ reconstruction. **a**,**b**, $\langle dE/dx \rangle$ (mean energy loss per unit track length in the gas of the TPC) versus p/q (where p is the momentum and q is the electric charge in units of the elementary charge e) (**a**) and $1/\beta$ (where β is the speed of a particle in units of the speed of light) versus p/q (**b**). $\langle dE/dx \rangle$ is measured by the TPC and $1/\beta$ is measured by the TOF detector in conjunction with the TPC. In both cases, the coloured bands show the measured data for each species of charged particle, while the red curves show the expected values. Charged particles are identified by comparing the observed $\langle dE/dx \rangle$ and $1/\beta$ with the expected values. **c**,**d**, Utilizing both 2-body and 3-body decay channels, the invariant mass distributions of $^{3}_{\Lambda}$H (**c**) and $^{3}_{\bar{\Lambda}}\overline{\text{H}}$ (**d**) are shown. The error bars represent statistical uncertainties (s.d.). The red curves represent a fit with a Gaussian function plus a linear background, using the unbinned maximum likelihood (ML) method.

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Former value by emulsion (data from 60's)
0.13 ± 0.05 MeV

average value of 0.13 ± 0.05(stat.) MeV. When applied to our value of 0.41 ± 0.12(stat.) MeV it yields a significantly smaller value of $7.90^{+1.71}_{-0.93}$ fm. The larger B_Λ and shorter effective scattering length suggest a stronger YN interaction between the Λ and the relatively low-density nuclear core of the $^{3}_{\Lambda}$H (ref. [36]). This, in certain models, requires SU(3) symmetry breaking and a more repulsive YN interaction at high density, consistent with implications from the range of masses observed for neutron stars[5].

Analysis of J-PARC E07 data with Machine Learning

Hypertriton detection and binding energy

↑

Starting in April 2020

Analysis of J-PARC E07 data with Machine Learning

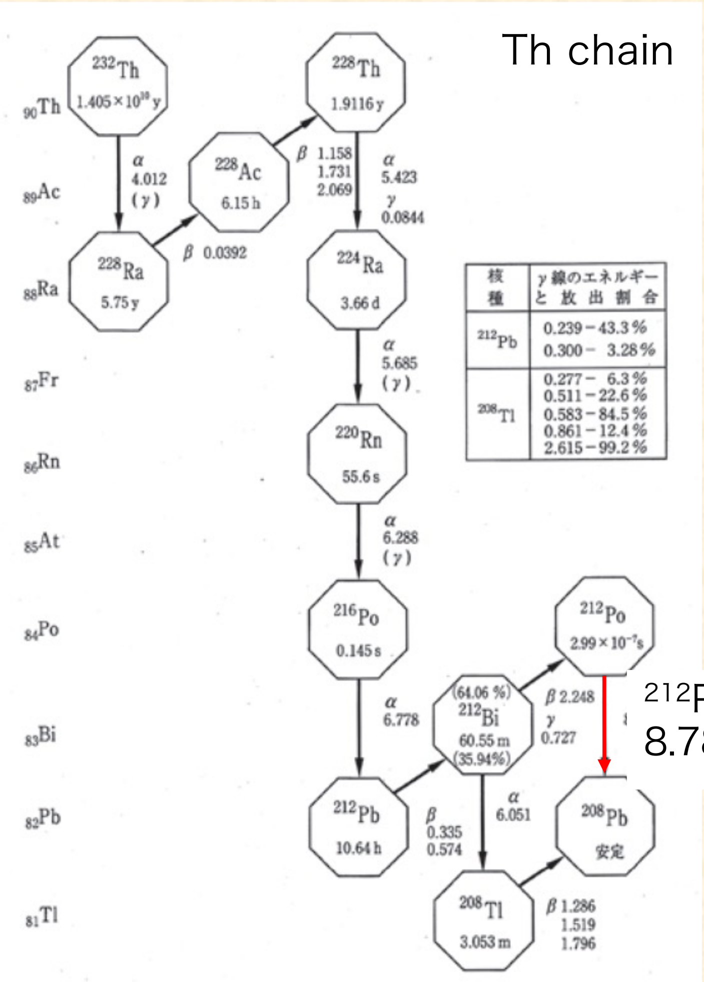
Hypertriton detection and binding energy

Development of the Machine Learning model with Convolutional Neural Network (CNN)

Detecting α-decay events for calibrating the emulsion sheet (density, shrinkage, …)

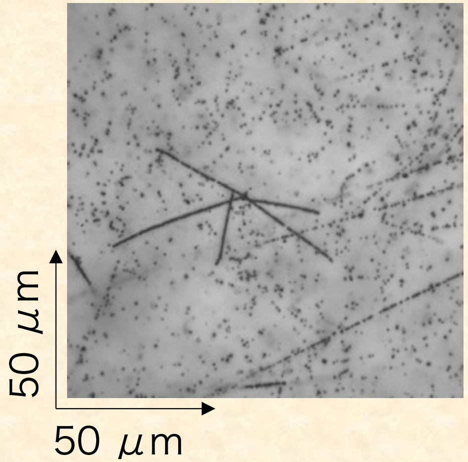
Starting in April 2020

Alpha decay chains in the nuclear emulsion



^{212}Po -> ^{208}Pb
8.785 MeV

Th chain α decay
in emulsion



・Energy calibration source.
・Randomly recorded.
・Decay process is unique.
→ ML with MC simulation.

Image classifier using a Convolutional Neural Network

J. Yoshida, et al., Nuclear Instrument and Method A, 989 (2021) 164930

"Deep Learning"

- Multistage convolutional networks
- Effective to detect various features

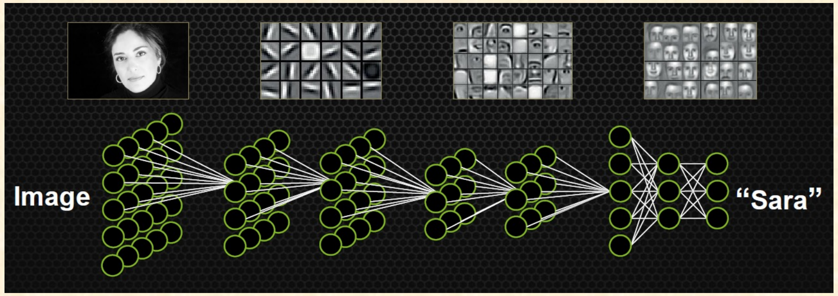
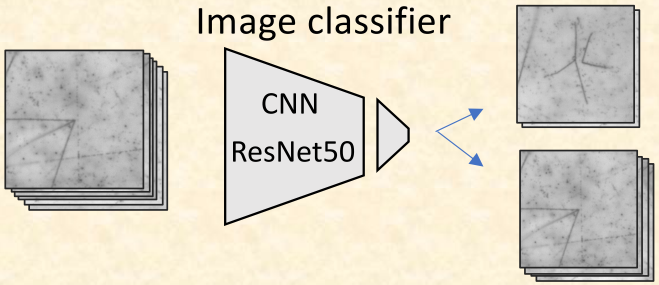


Image classifier

Dataset
46948 images



Alpha candidates
~350 images

others

201
are correctly
Alpha decays

	Precision (Purity)	Recall (Efficiency)	# of Candidates
Conventional (line information)	0.081 +- 0.006	0.788 +- 0.056	2489
This method	0.571 +- 0.017	0.788	350 +- 10

- Machine learning reduced the load of visual inspection by approximately 1/7.
- We acquired basic techniques for modern machine learning.

Analysis of J-PARC E07 data with Machine Learning

Hypertriton detection and binding energy

Development of the machine learning model (mask-R CNN) with training data produced by Monte Carlo simulations and GAN technique

Development of the Machine Learning model with Convolutional Neural Network (CNN)

Detecting α-decay events for calibrating the emulsion sheet (density, shrinkage, …)

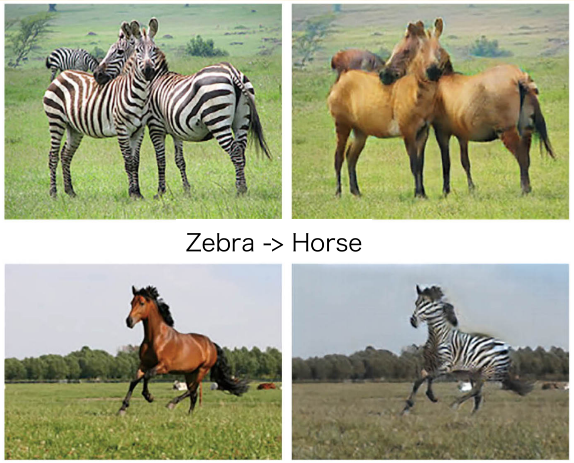
Completed
J. Yoshida et al.,
Nuclear Instrument and Method A,
989 (2021) 164930

Starting in April 2020

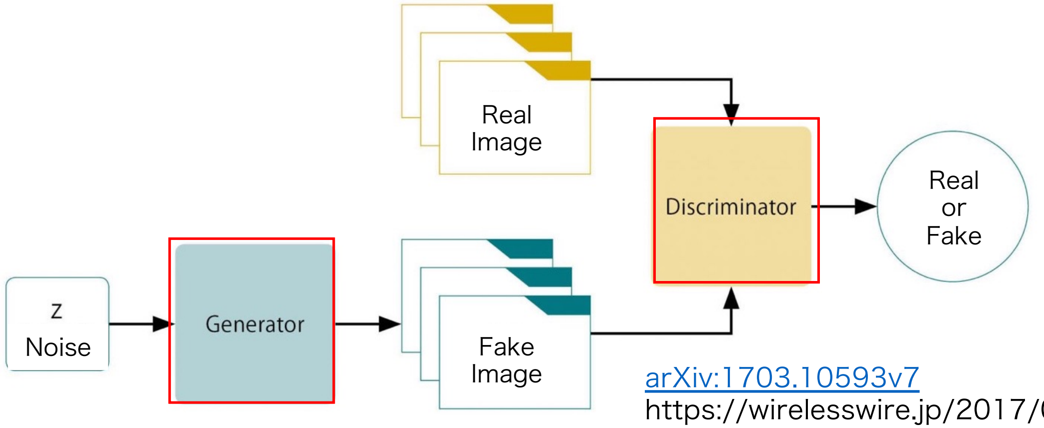
Challenge:
Training data produced with Monte Carlo simulations

Generating training data

pix2pix: Image transformation by ML.

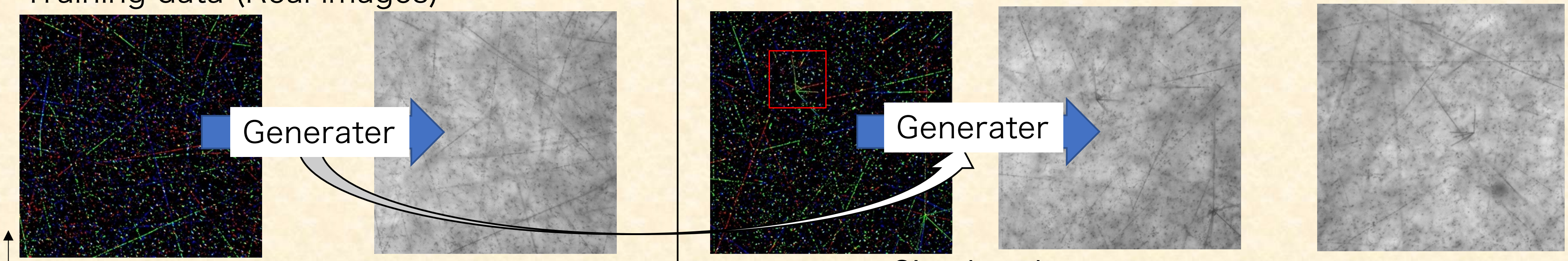


GAN(Generative Adversarial Networks)



arXiv:1703.10593v7
https://wirelesswire.jp/2017/01/58467/

Training data (Real images)



Processed

Original

50 μm

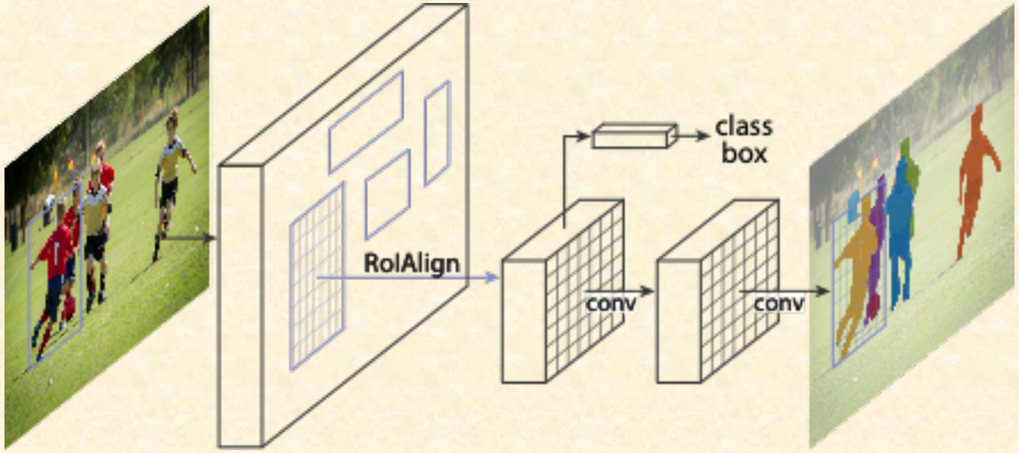
Simulated

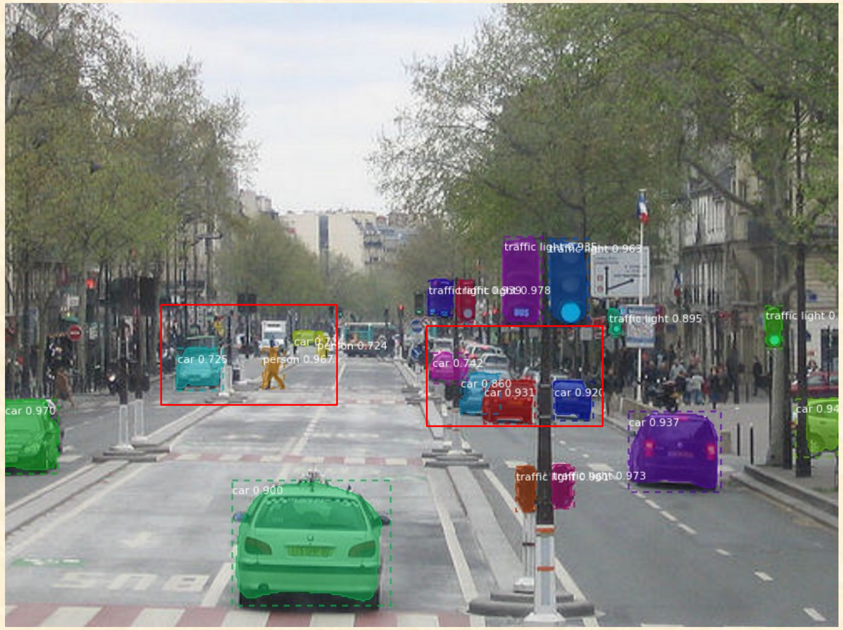
Real

A. Kasagi, E. Liu, M. Nakagawa, J. Yoshida et al, to be published

Object detection (Mask R-CNN)

- Convolutional operation on the region of interest (ROI)
- Determine the category and banding box for each object.





https://arxiv.org/abs/1703.06870
https://github.com/matterport/Mask_RCNN

- Direct detection of objects in images.
- Can be adapted to regions crowded with multiple objects.

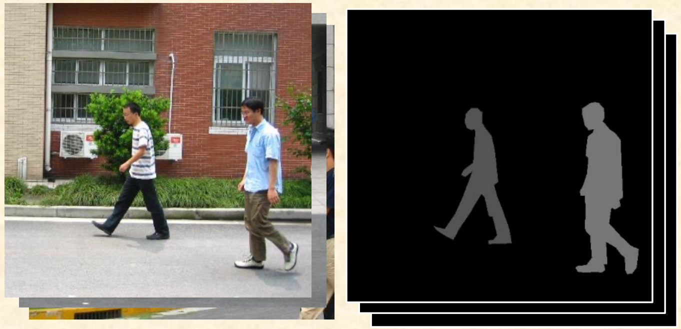
Can we adapt to events in nuclear emulsion?

Classification of each object

For crowded region.

Training & result of Mask R-CNN

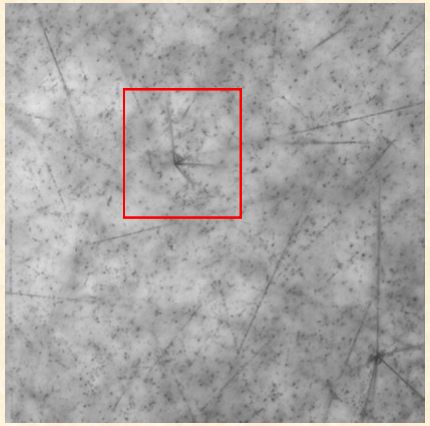
Mask R-CNN



A Pedestrian dataset

https://www.cis.upenn.edu/~jshi/ped_html/

Training data (Simulated image)



50 μm

Simulated image
Positional information available

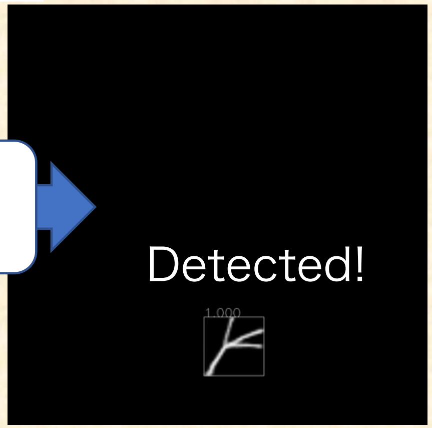
Training

Network

Real image

50 μm

Trained Network



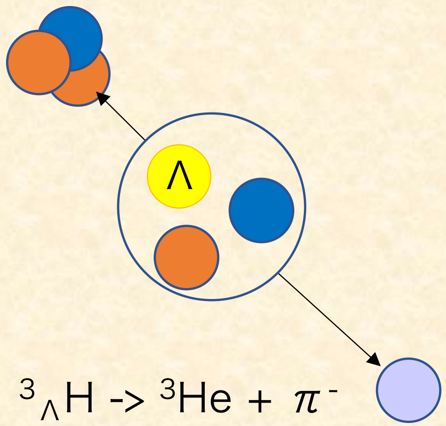
- Models trained with Simulation data can be used to detect real events.
- High detection efficiency(～90%)

A. Kasagi, E. Liu, M. Nakagawa, J. Yoshida et al, to be published

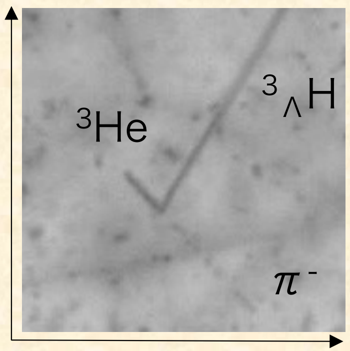
Hypertriton search by Mask R-CNN

Rare event detection

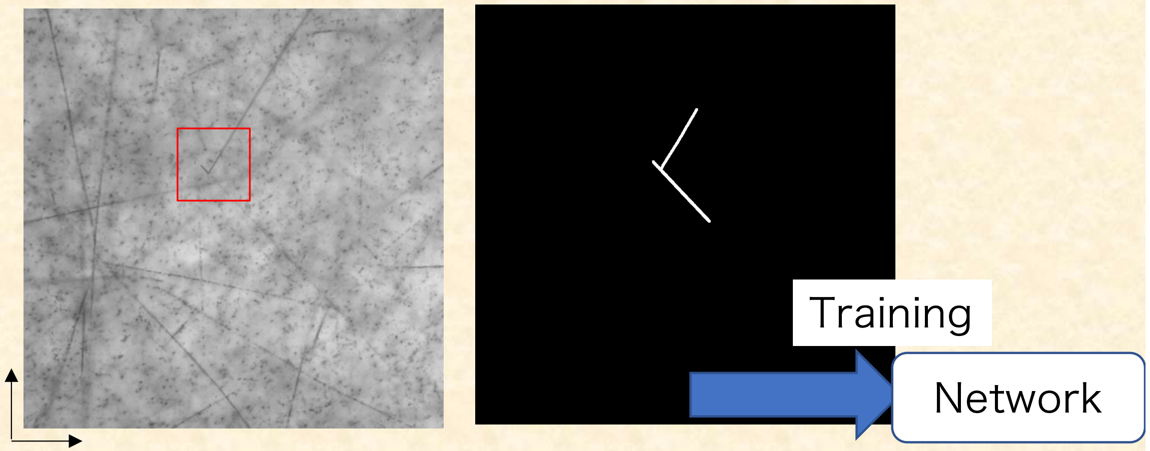
・2 body decay of $^{3}_{\Lambda}H$



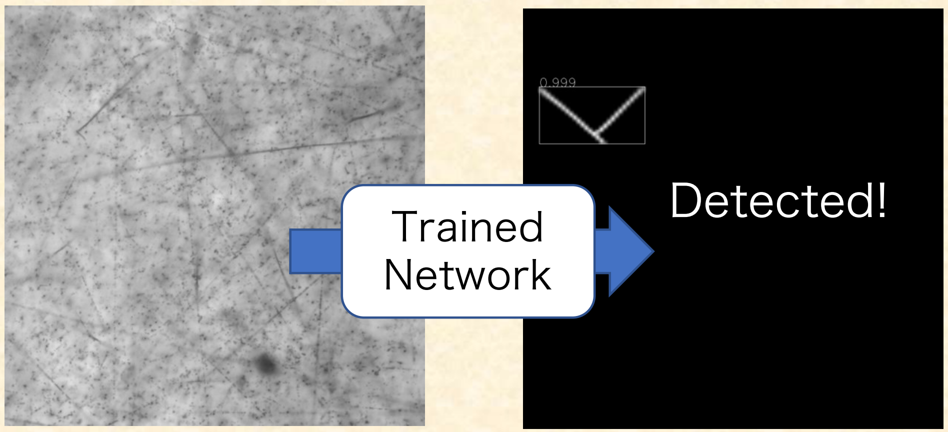
Simulated image



Training data



Real image



・Rare events can be detected by machine learning using simulation data.
・Number of images to check: 2000k -> 5k

・Development and Analysis is in progress.

A. Kasagi, E. Liu, M. Nakagawa, J. Yoshida et al, to be published

Analysis of J-PARC E07 data with Machine Learning

Hypertriton detection and binding energy

In progress

Development of the machine learning model (mask-R CNN) with training data produced by Monte Carlo simulations and GAN technique

Completed. A. Kasagi, to be published soon.

Development of the Machine Learning model with Convolutional Neural Network (CNN)

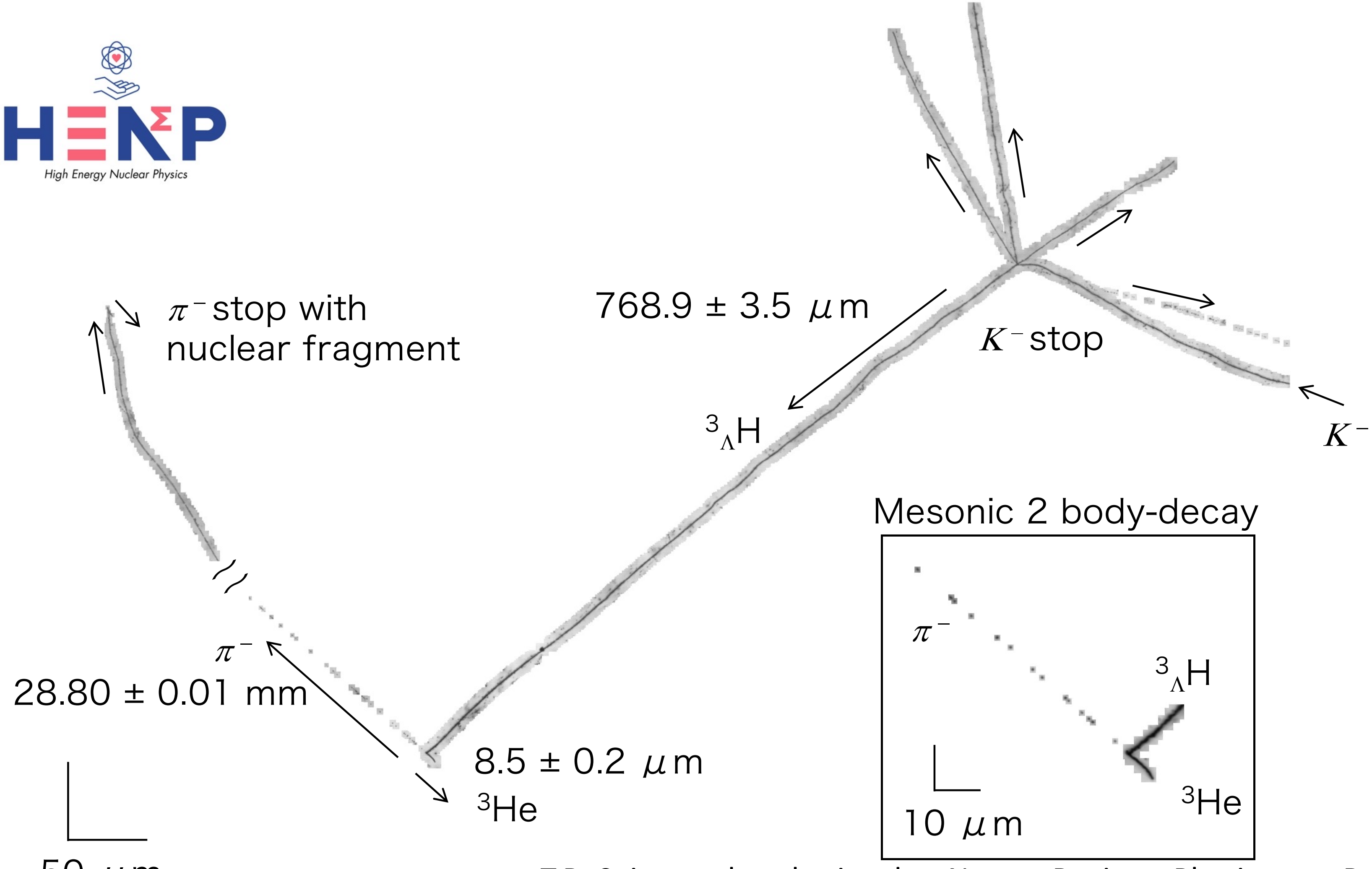
Detecting α-decay events for calibrating the emulsion sheet (density, shrinkage, …)

Completed
J. Yoshida et al.,
Nuclear Instrument and Method A,
989 (2021) 164930

Starting in April 2020

Challenge:
Training data produced with Monte Carlo simulations

The First Discovered Hypertriton ($^{3}_{\Lambda}H$) in the J-PARC E07 Nuclear Emulsion
February 2nd,15:23 HENP, RIKEN



T.R. Saito et al, submitted to Nature Reviews Physics as a Roadmap article

Status of the analysis of the emulsion

Analyzed data: 0.03 % of the entire data (as of May 3rd 2021)

Identified

- Hypertriton: 4 events
  The local emulsion density has been determined event-by-event and B_Λ has been deduced
- $^4_\Lambda H$: 16 events
  For seven events, the local emulsion density has been determined event-by-event and B_Λ has been deduced

For 100 events achieving an accuracy of 50 keV for the binding energy

- 0.75 % of the whole data for hypertriton (in 2022)
- 0.19 % of the whole data for $^4_\Lambda H$ (in this year)

Systematic error: better than 25 keV

E. Liu et al., to be published

With all data

- 5 keV accuracy

Systematic error:
around a few keV with event-by-event density calibration

Analysis of J-PARC E07 data with Machine Learning

Hypertriton detection and binding energy

In progress

$^{4}{}_{\Lambda}$He binding energy

Charge-symmetry breaking

1000 double hypernuclear candidates

New experiments at J-PARC

Huge binding energy data for Λ–, Σ–, $\Lambda\Lambda$–, $\Lambda\Sigma$–, $\Sigma\Sigma$– and Ξ–hypernuclei

Development of the machine learning model (mask-R CNN) with training data produced by Monte Carlo simulations and GAN technique

Completed. A. Kasagi, to be published soon.

Development of the Machine Learning model with Convolutional Neural Network (CNN)

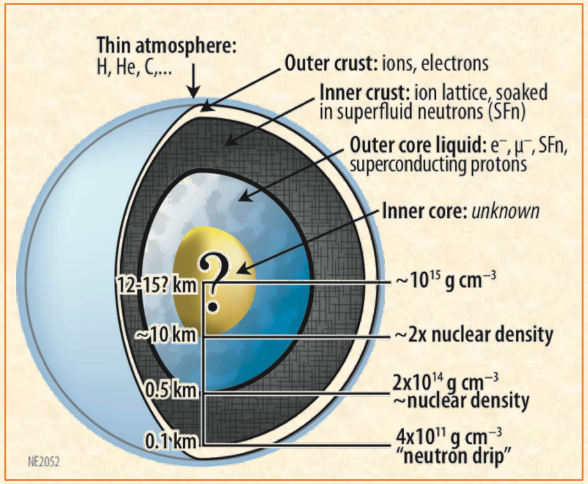
Detecting α-decay events for calibrating the emulsion sheet (density, shrinkage, …)

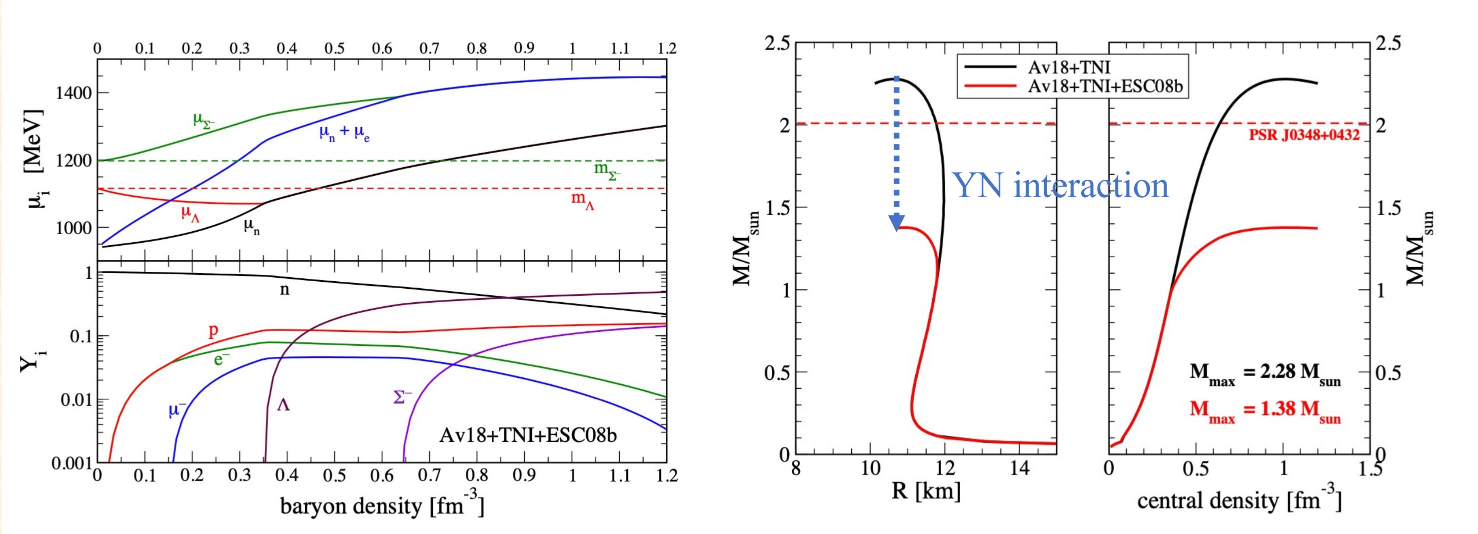
Completed
J. Yoshida et al.,
Nuclear Instrument and Method A,
989 (2021) 164930

Starting in April 2020

Challenge:
Training data produced with Monte Carlo simulations

Neutron stars and dense nuclear matter

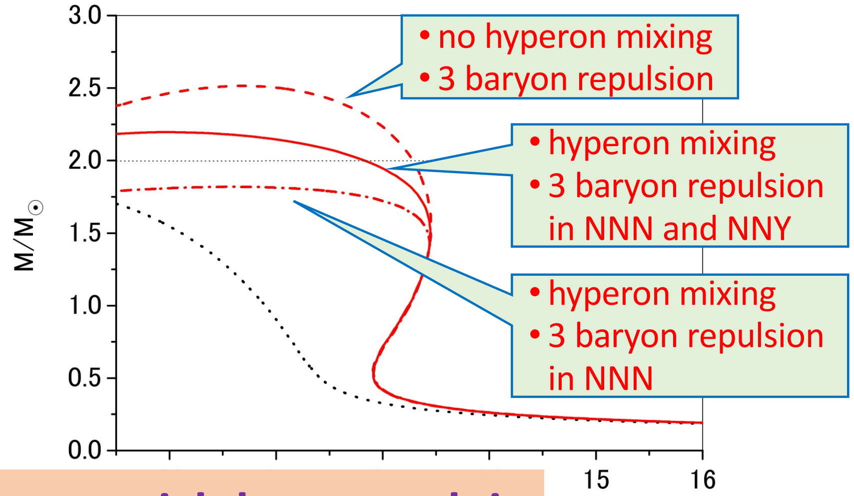




Baryon interaction

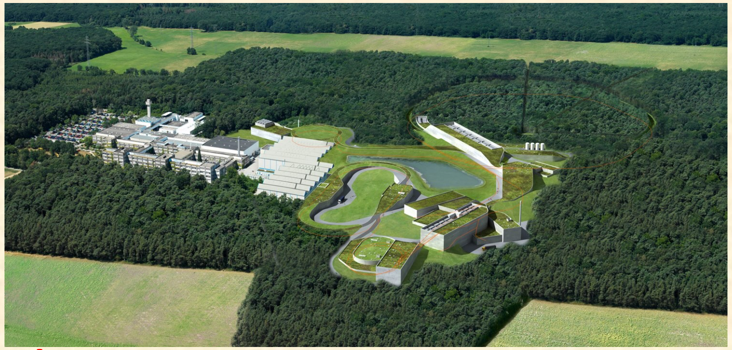
- N−N
- Λ−N
- **Σ−N**
- **Λ−Λ, Σ−Σ, Λ−Σ**
- **Ξ−N**
- **Ξ−Λ, Ξ−Σ**
- **Ξ−Ξ**

Y. Yamamoto, T. Furumoto, N. Yasutake, Th.A. Rijken, Phys. Rev. C90 045805 (2014)



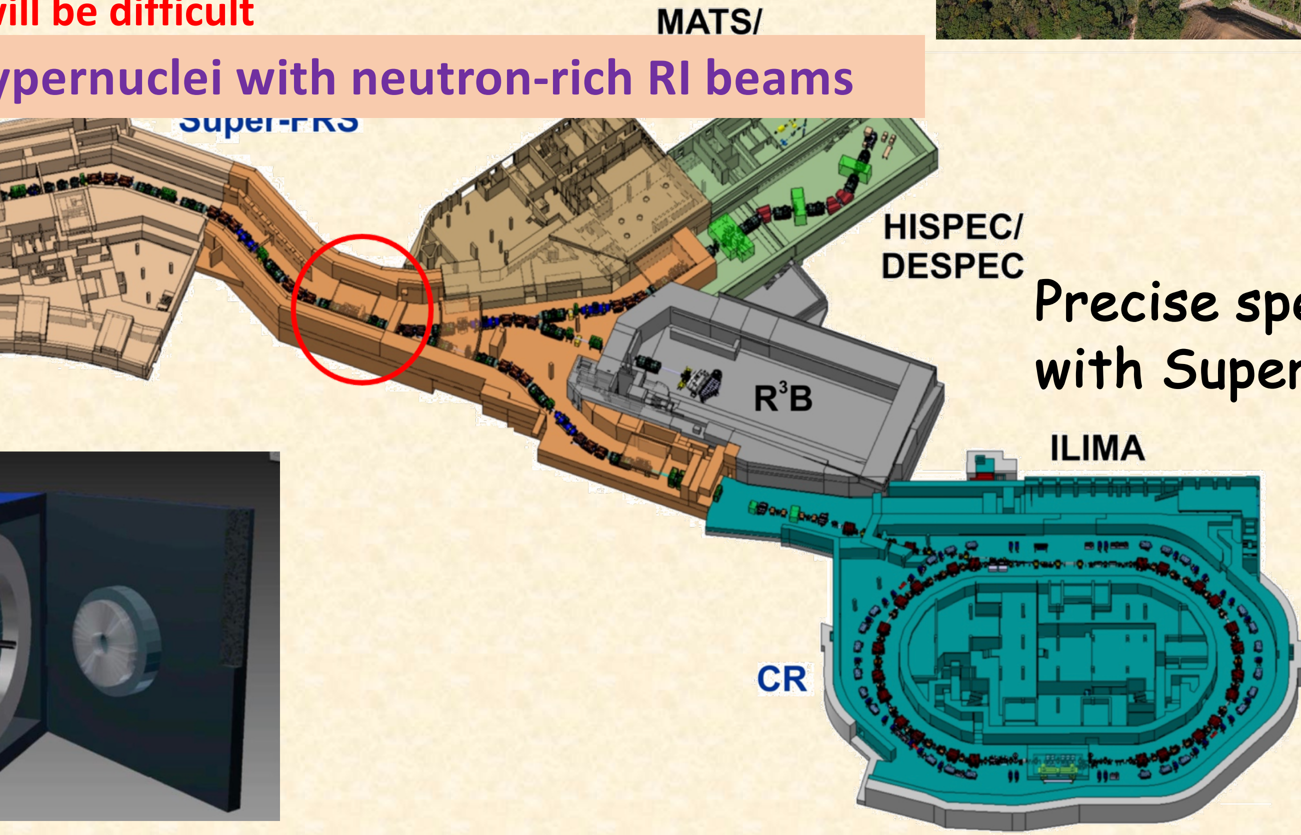
Neutron rich nuclear matter: Very-neutron-rich hypernuclei

Further steps at FAIR in Germany

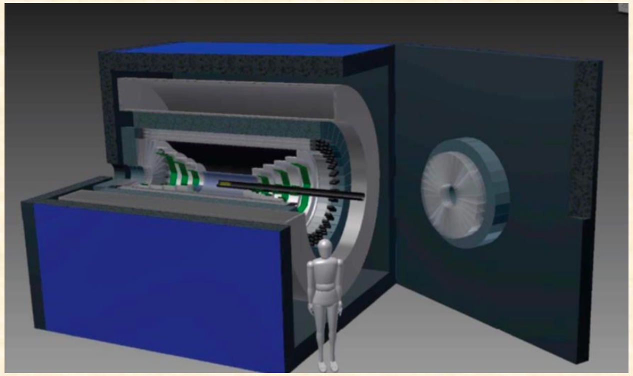


Neutron measurement will be difficult

Neutron-rich hypernuclei with neutron-rich RI beams



Precise spectroscopy with Super-FRS



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

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

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

Takehiko R. Saito[1,2,3,a], **Hiroyuki Ekawa**[1], **Manami Nakagawa**[1]

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[2] GSI Helmholtz Centre for Heavy Ion Research, Planckstrasse 1, 64291 Darmstadt, Germany
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Received: 20 February 2021 / Accepted: 18 April 2021

Communicated by Alexandre Obertelli

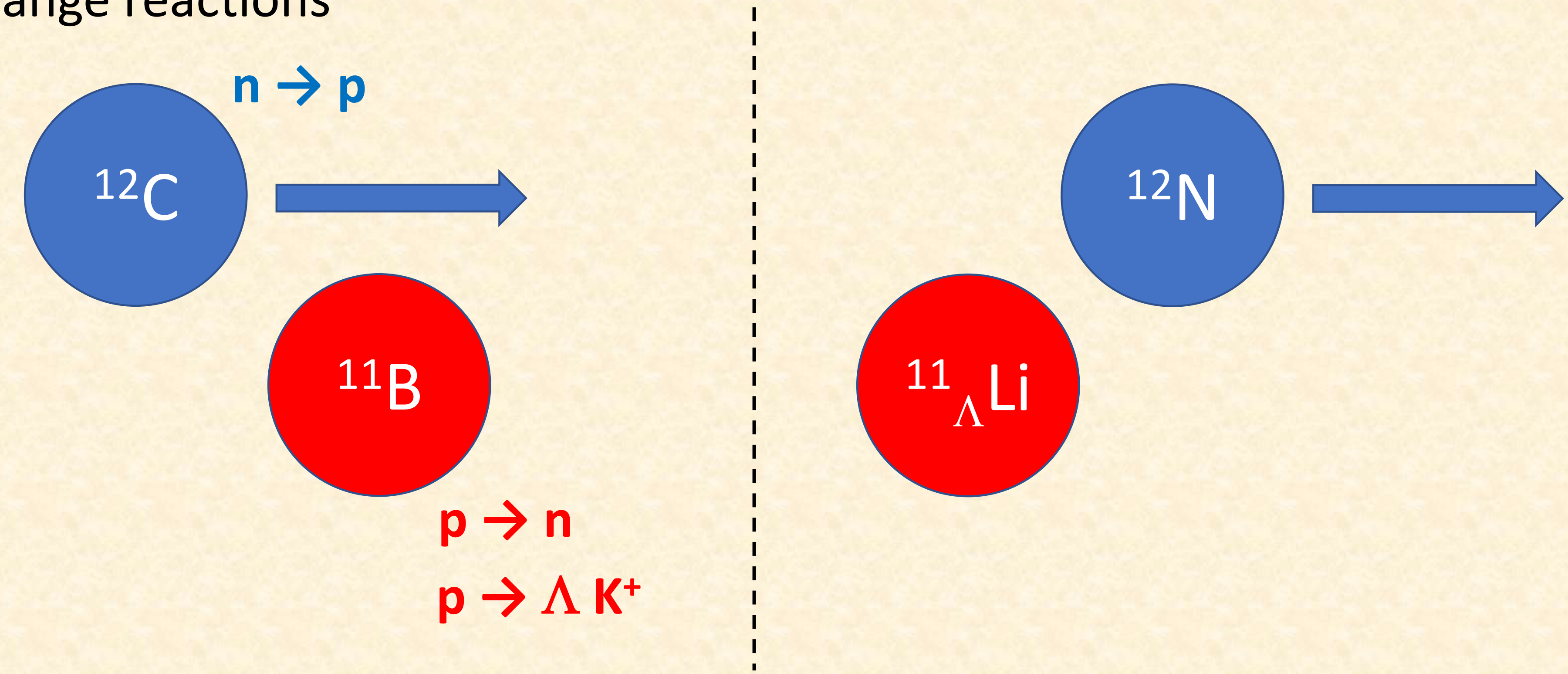
Abstract We propose a novel method for producing very-neutron-rich hypernuclei and corresponding resonance states by employing charge-exchange reactions via pp(^{12}C, ^{12}N K^+)nΛ with single-charge-exchange and ppp(^{9}Be, ^{9}C K^+)nnΛ with double-charge-exchange, both of which produce ΛK^+ in a target nucleus. The feasibility of producing very-neutron-rich hypernuclei using the proposed method was analysed by applying an ultra-relativistic quantum molecular dynamics model to a ^{6}Li + ^{12}C reaction at 2 A GeV. The yields of very-neutron-rich hypernuclei, signal-to-background ratios, and background contributions were investigated. The proposed method is a powerful tool for studying very-neutron-rich hypernuclei and resonance states with a hyperon for experiments employing the Super-FRS facility at FAIR and HFRS facility at HIAF.

the nature of fragmentation reactions of heavy ion beams, the isospin values of the produced hypernuclei were widely distributed. Therefore, neutron-rich and proton-rich hypernuclei could be studied.

One of the problems revealed by the results of the HypHI Phase 0 experiment is the possible existence of an unprecedented bound state of a Λ-hyperon with two neutrons, denoted as Λnn ($^3_\Lambda$n) [3]. Neutral nuclear states with neutrons and Λ-hyperons are of particular interest because the natures of these states should have an impact on our understanding of the deep cores of neutron stars. However, theoretical calculations have shown negative results for the existence of Λnn bound states [4–7]. Although there is disagreement between the results of the HypHI Phase 0 experiment and theoretical calculations, whether or not the Λnn state can exist has recently become a hot topic in experimental and theoretical

Novel method to produce exotic hypernuclei

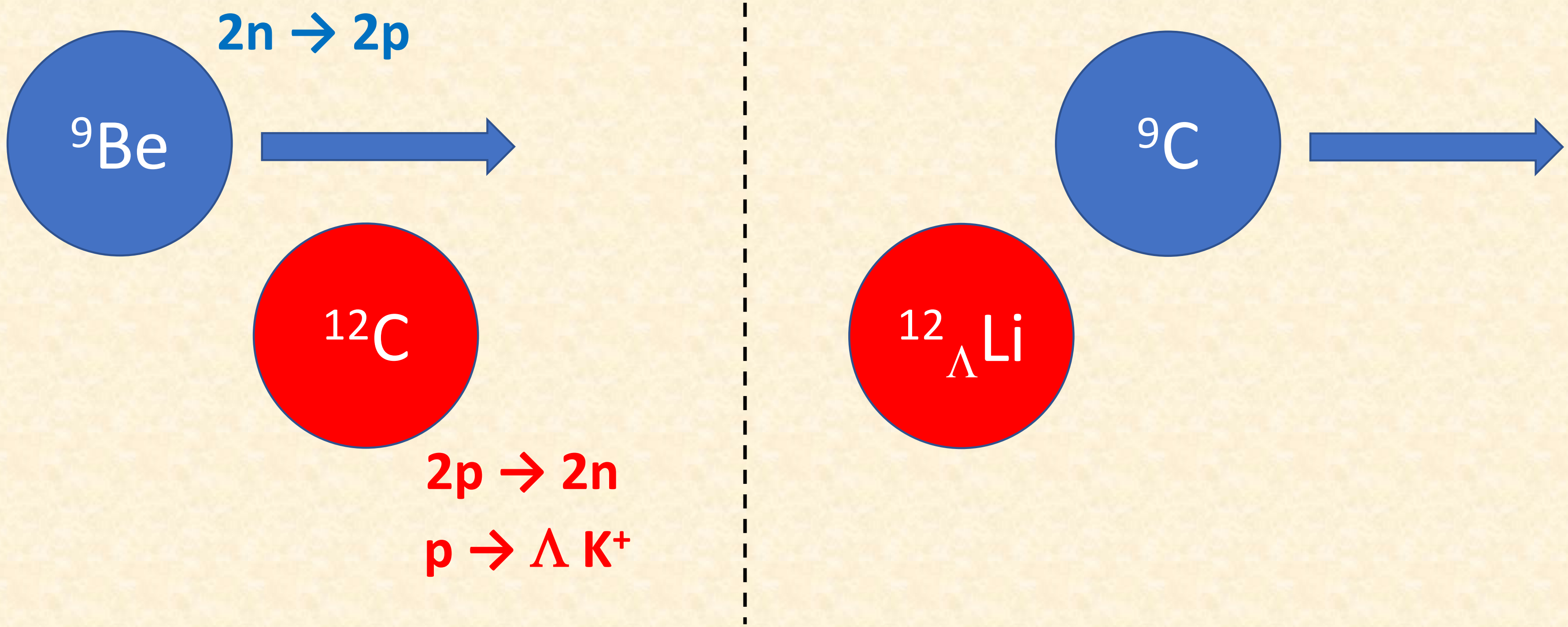
Production of neutral and very-neutron-rich hypernuclei with charge exchange reactions



T. R. Saito et al., European Physical Journal A 57 (2021) 159.

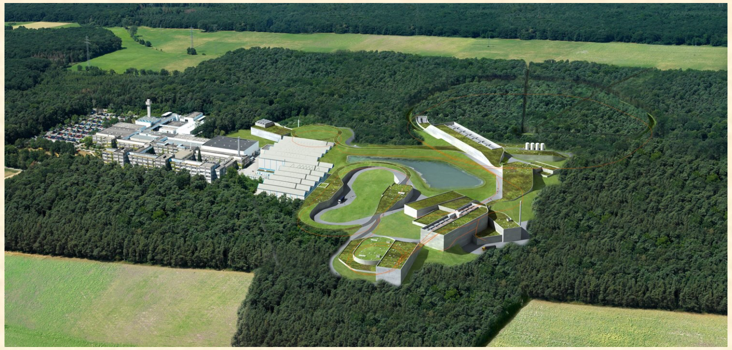
Novel method to produce exotic hypernuclei

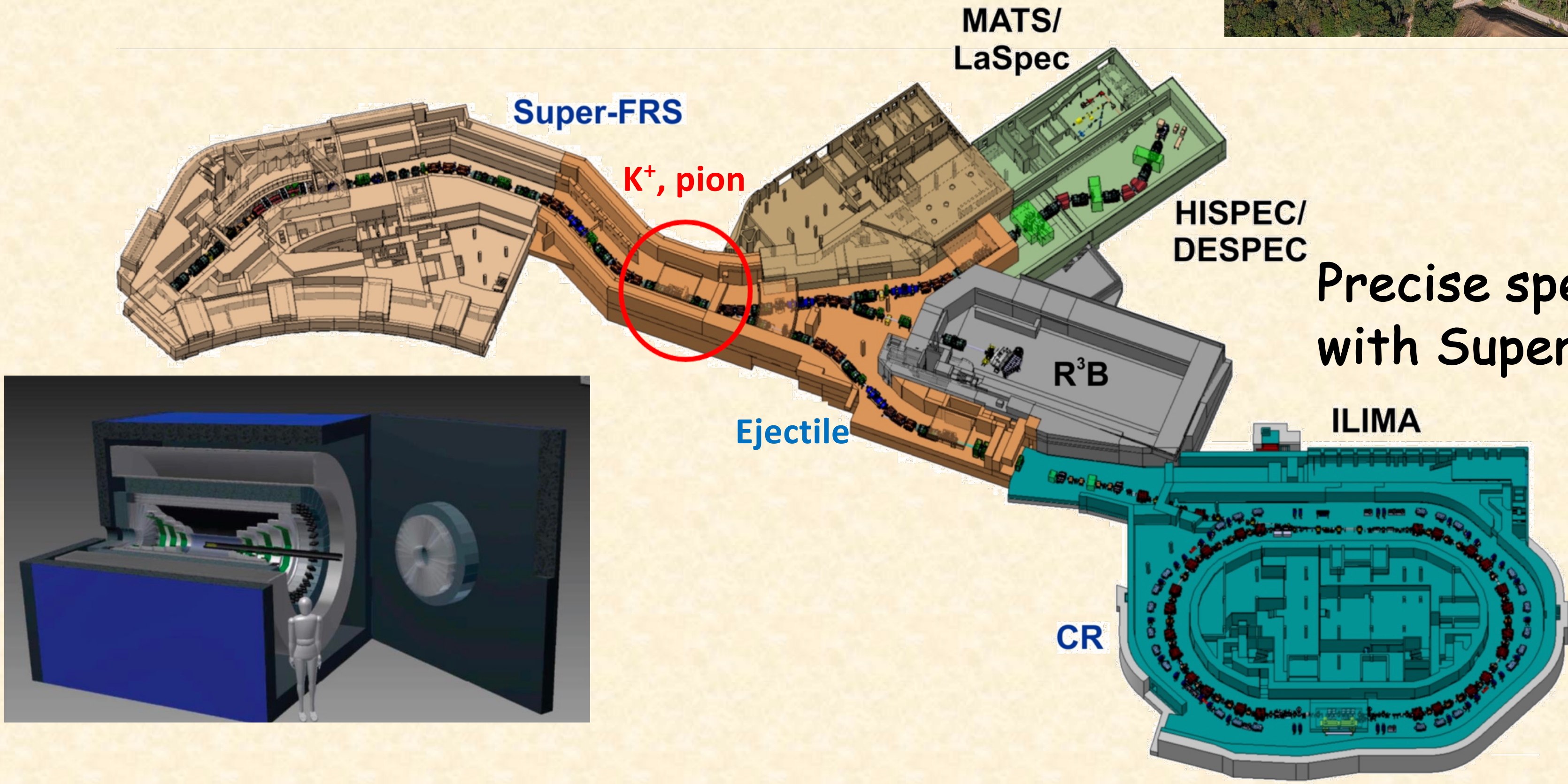
Production of neutral and very-neutron-rich hypernuclei with charge exchange reactions



T. R. Saito et al., European Physical Journal A 57 (2021) 159.

Further steps at FAIR in Germany





Precise spectroscopy with Super-FRS

Novel method to produce exotic hypernuclei

Production of neutral and very-neutron-rich hypernuclei with charge exchange reactions

Single charge exchange
pp (^{12}C, ^{12}N) np
with $K^+\Lambda$ production from proton
pp (^{12}C, ^{12}N K+) nΛ

Double charge exchange
ppp (^{9}Be, ^{9}C) nnp
with $K^+\Lambda$ production from proton
ppp (^{9}Be, ^{9}C K+) nnΛ

Table 1 Summary of hypernuclei/resonances and proposed charge-exchange reactions for $Z = 0 \sim 8$.

Target	Single-charge exchange (^{12}C, ^{12}N K^+)	Double-charge exchange (^{9}Be, ^{9}C K^+)	Produced hypernuclei or resonance	Former observation
^{3}He	✓		$^{3}_{\Lambda}$n (Λnn)	[3]
^{4}He	✓		$^{4}_{\Lambda}$n	
^{6}Li		✓	$^{6}_{\Lambda}$n	
^{7}Li		✓	$^{7}_{\Lambda}$n	
^{6}Li	✓		$^{6}_{\Lambda}$H	[12]
^{7}Li	✓		$^{7}_{\Lambda}$H	
^{9}Be		✓	$^{9}_{\Lambda}$H	
^{9}Be	✓		$^{9}_{\Lambda}$He	
^{10}B		✓	$^{10}_{\Lambda}$He	
^{10}B	✓		$^{10}_{\Lambda}$Li	[14]
^{11}B	✓		$^{11}_{\Lambda}$Li	
^{12}C		✓	$^{12}_{\Lambda}$Li	
^{12}C	✓		$^{12}_{\Lambda}$Be	
^{14}N		✓	$^{14}_{\Lambda}$Be	
^{14}N	✓		$^{14}_{\Lambda}$B	
^{16}O		✓	$^{16}_{\Lambda}$B	
^{16}O	✓		$^{16}_{\Lambda}$C	
^{19}F		✓	$^{19}_{\Lambda}$C	
^{19}F	✓		$^{19}_{\Lambda}$N	
^{20}Ne		✓	$^{20}_{\Lambda}$N	
^{20}Ne	✓		$^{20}_{\Lambda}$O	
^{23}Na		✓	$^{23}_{\Lambda}$O	

T. R. Saito et al., European Physical Journal A 57 (2021) 159.

30 – 50 pb

Both bound and resonance states

Possibility on γ–ray spectroscopy

Novel method to produce exotic hypernuclei

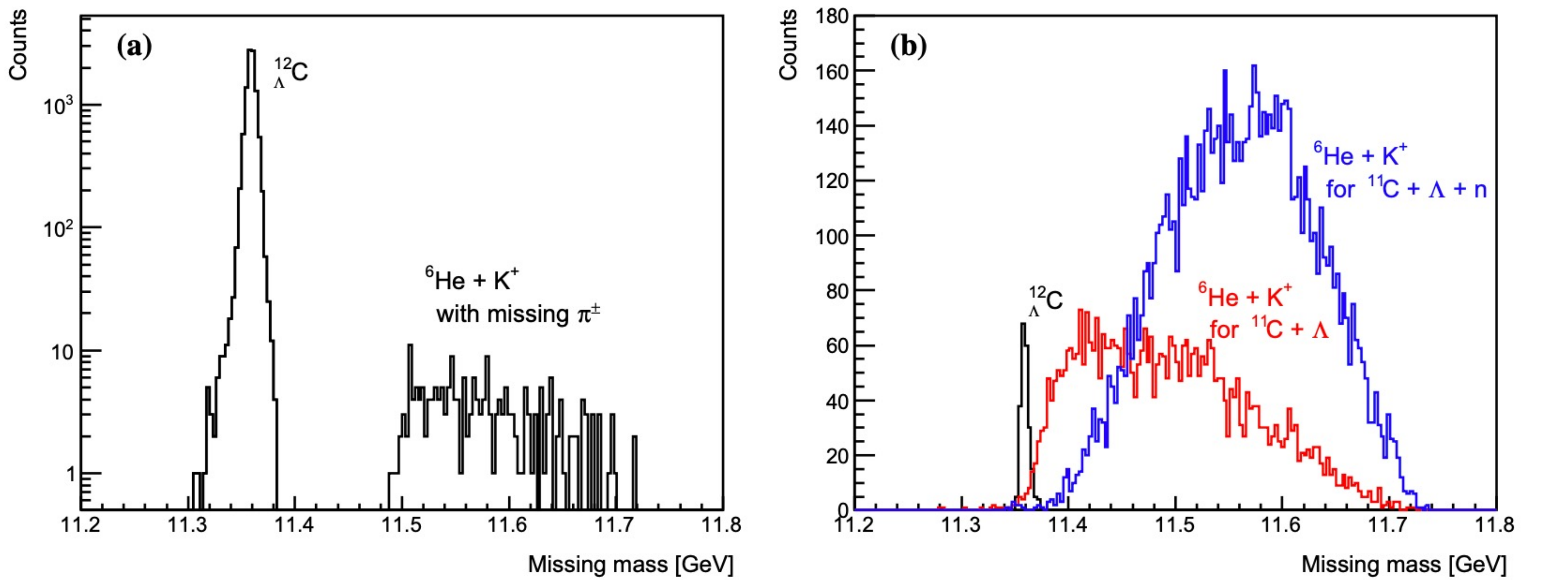


Fig. 5 Left panel **a** missing mass distributions reconstructed by measurements of ^{6}He and K^+ for the perfect case, ^{6}Li + ^{12}C at 2 *A* GeV → ^{6}He + K^+ + $^{12}_{\Lambda}$C, and an incomplete case with missing π^+, ^{6}Li + ^{12}C at 2 *A* GeV → ^{6}He + K^+ + $^{12}_{\Lambda}$B + π^+. Right panel **b** Missing mass distributions based on observing ^{6}He and K^+ for the case of ^{6}Li + ^{12}C at 2 *A* GeV → ^{6}He + K^+ + ^{11}C + Λ (red colour) and ^{6}Li + ^{12}C at 2 *A* GeV → ^{6}He + K^+ + ^{10}C + n + Λ (blue colour) with the $^{12}_{\Lambda}$C peak. The width of the $^{12}_{\Lambda}$C peak is approximately 4.5 MeV in σ

T. R. Saito et al., European Physical Journal A 57 (2021) 159.

With the proposed setup at NUSTAR/FAIR

Projectile fragmentation reaction (like HypHI and WASA-FRS)

- Precise measurements for light hypernuclei
- Proton-rich hypernuclei with proton-rich RI beams
- Binding energy, decay branches
- Production cross section

Charge exchange reactions

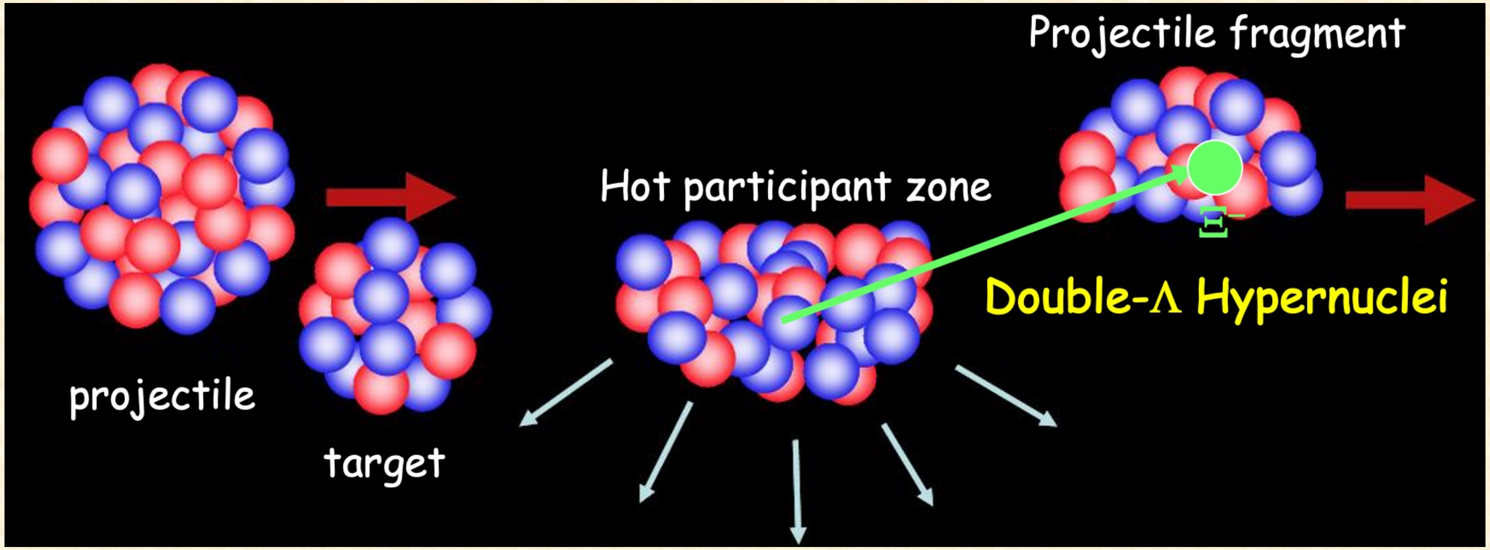
- Neutral hypernuclei
- Very-neutron-rich hypernuclei
- Associated resonance states
- γ-ray spectroscopy

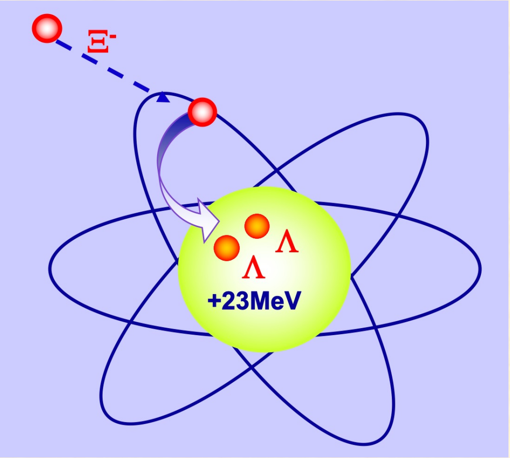
Others

- Mesic-nuclei such as η'-nuclei
- Nucleon resonances in exotic nuclei
- Charged pion production: as a source of muon productions for nuclear transmutation
- Complete measurement for nuclear reaction studies

Hypernuclear project at HIAF in China

Towards double-strangeness hypernuclei: E > 3.75 A GeV





Huge variety of

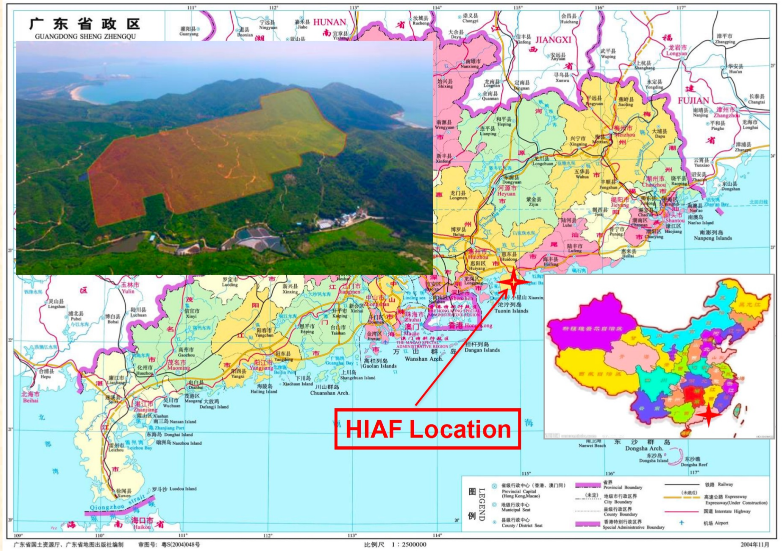
- Λ hypernuclei
- Σ hypernuclei
- Ξ hypernuclei
- Double-Λ hypernuclei

Hypernuclear project at HIAF in China

HIAF (High Intensity heavy ion Accelerator Facility)

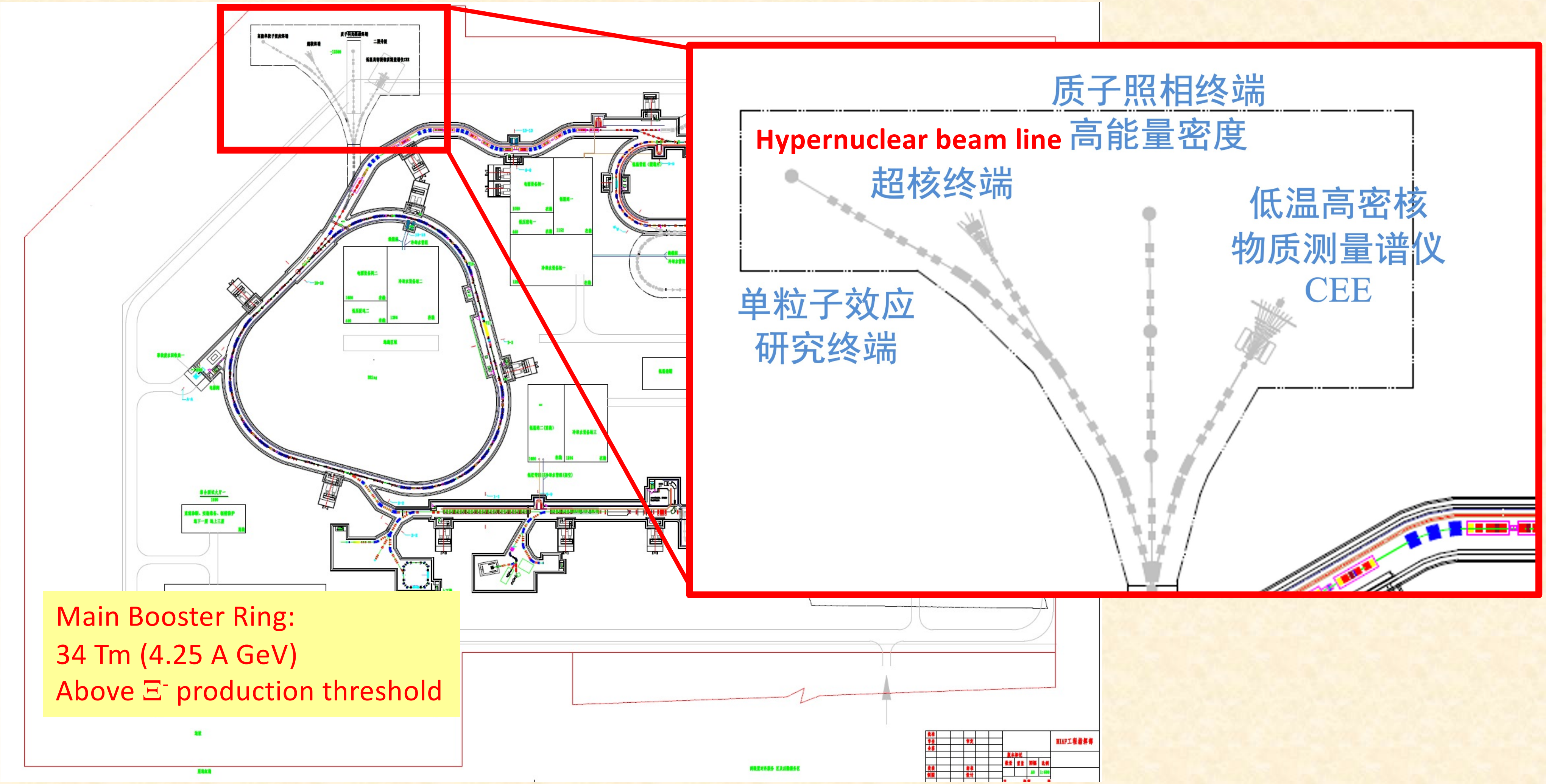
- To be operational in 2025

T.S. is leading the new hypernuclear project since 2016



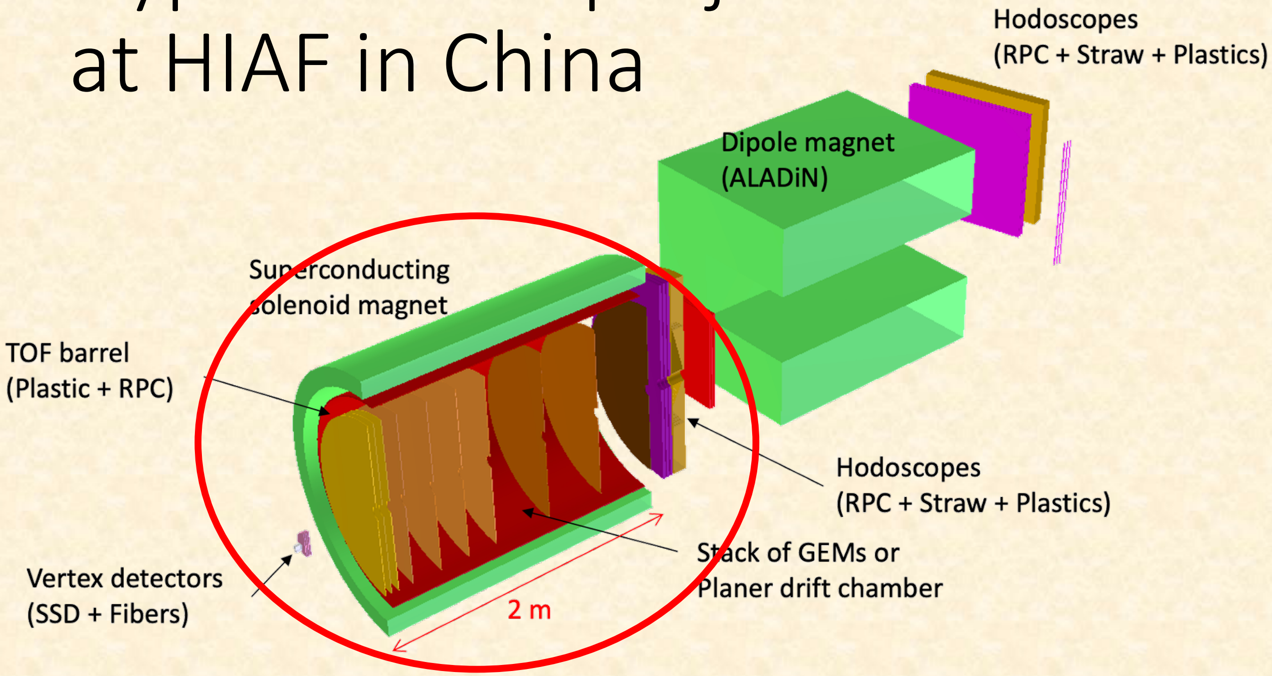
New institute to be built in Huizhou

Hypernuclear project at HIAF in China



Main Booster Ring:
34 Tm (4.25 A GeV)
Above Ξ^- production threshold

Hypernuclear project at HIAF in China

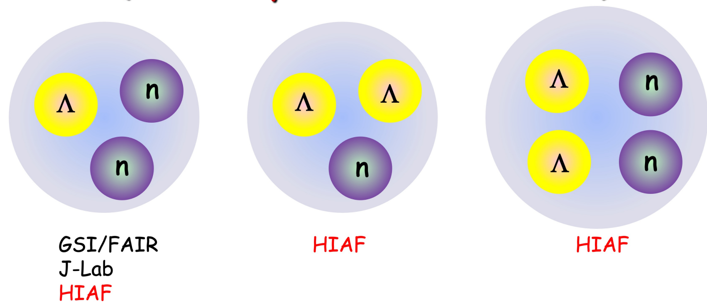


d + Ξ^- -> $^{3}_{\Xi^-}$n -> n$\Lambda\Lambda$
t + Ξ^- -> $^{4}_{\Xi^-}$n -> nn$\Lambda\Lambda$
^{3}He + Ξ^- -> $^{4}_{\Xi^-}$H -> $^{4}_{\Lambda\Lambda}$H
^{4}He + Ξ^- -> $^{5}_{\Xi^-}$H -> $^{5}_{\Lambda\Lambda}$H
^{6}Li + Ξ^- -> $^{7}_{\Xi^-}$He -> $^{7}_{\Lambda\Lambda}$He
^{6}Li + Ξ^- -> $^{7}_{\Xi^-}$He -> $^{6}_{\Lambda\Lambda}$He +n
^{7}Li + Ξ^- -> $^{8}_{\Xi^-}$He -> $^{8}_{\Lambda\Lambda}$He
^{9}Be + Ξ^- -> $^{10}_{\Xi^-}$Li -> $^{10}_{\Lambda\Lambda}$Li
^{10}Be + Ξ^- -> $^{11}_{\Xi^-}$Li -> $^{11}_{\Lambda\Lambda}$Li
^{10}B + Ξ^- -> $^{11}_{\Xi^-}$Be -> $^{11}_{\Lambda\Lambda}$Be
^{11}B + Ξ^- -> $^{12}_{\Xi^-}$Be -> $^{12}_{\Lambda\Lambda}$Be

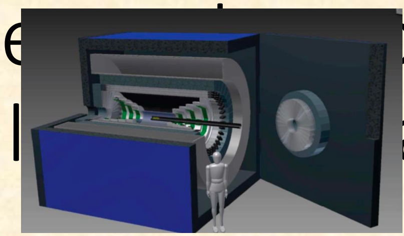
	Single-strangeness hypernuclei	Double-strangeness hypernuclei
Observation per week	6 X 10^6	6 X 10^2
Lifetime accuracy	**~ 1 ps**	**~ 10 ps**
Binding energy accuracy	~ 100 keV	Sub MeV

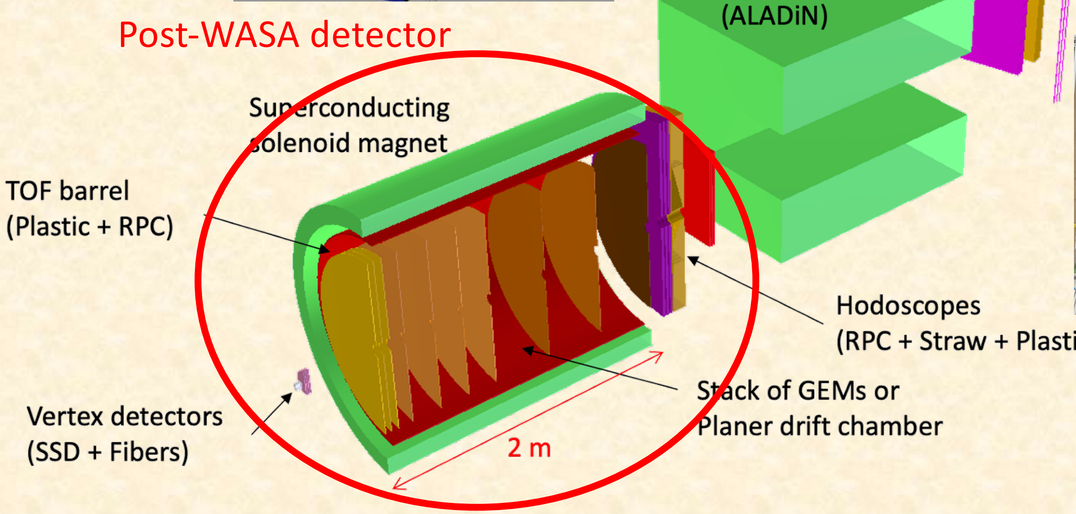
Hypernuclear scattering experiment feasible

Femto Neutron Stars
(named by Josef Pochodzalla)



Hype roject
at HI a





d $+ \Xi^- \to {}^{3}_{\Xi^-}n \to n\Lambda\Lambda$

t $+ \Xi^- \to {}^{4}_{\Xi^-}n \to nn\Lambda\Lambda$

$^{3}He + \Xi^- \to {}^{4}_{\Xi^-}H \to {}^{4}_{\Lambda\Lambda}H$

$^{4}He + \Xi^- \to {}^{5}_{\Xi^-}H \to {}^{5}_{\Lambda\Lambda}H$

$^{6}Li + \Xi^- \to {}^{7}_{\Xi^-}He \to {}^{7}_{\Lambda\Lambda}He$

$^{6}Li + \Xi^- \to {}^{7}_{\Xi^-}He \to {}^{6}_{\Lambda\Lambda}He + n$

$^{7}Li + \Xi^- \to {}^{8}_{\Xi^-}He \to {}^{8}_{\Lambda\Lambda}He$

$^{9}Be + \Xi^- \to {}^{10}_{\Xi^-}Li \to {}^{10}_{\Lambda\Lambda}Li$

$^{10}Be + \Xi^- \to {}^{11}_{\Xi^-}Li \to {}^{11}_{\Lambda\Lambda}Li$

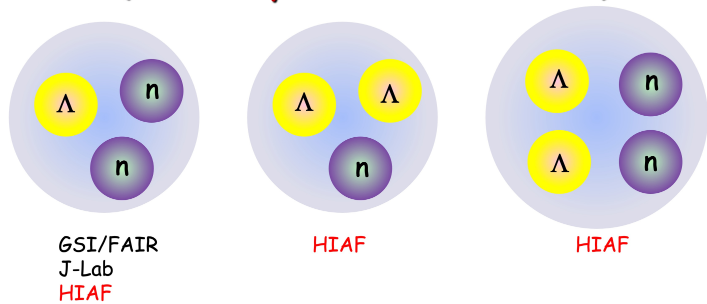
$^{10}B + \Xi^- \to {}^{11}_{\Xi^-}Be \to {}^{11}_{\Lambda\Lambda}Be$

$^{11}B + \Xi^- \to {}^{12}_{\Xi^-}Be \to {}^{12}_{\Lambda\Lambda}Be$

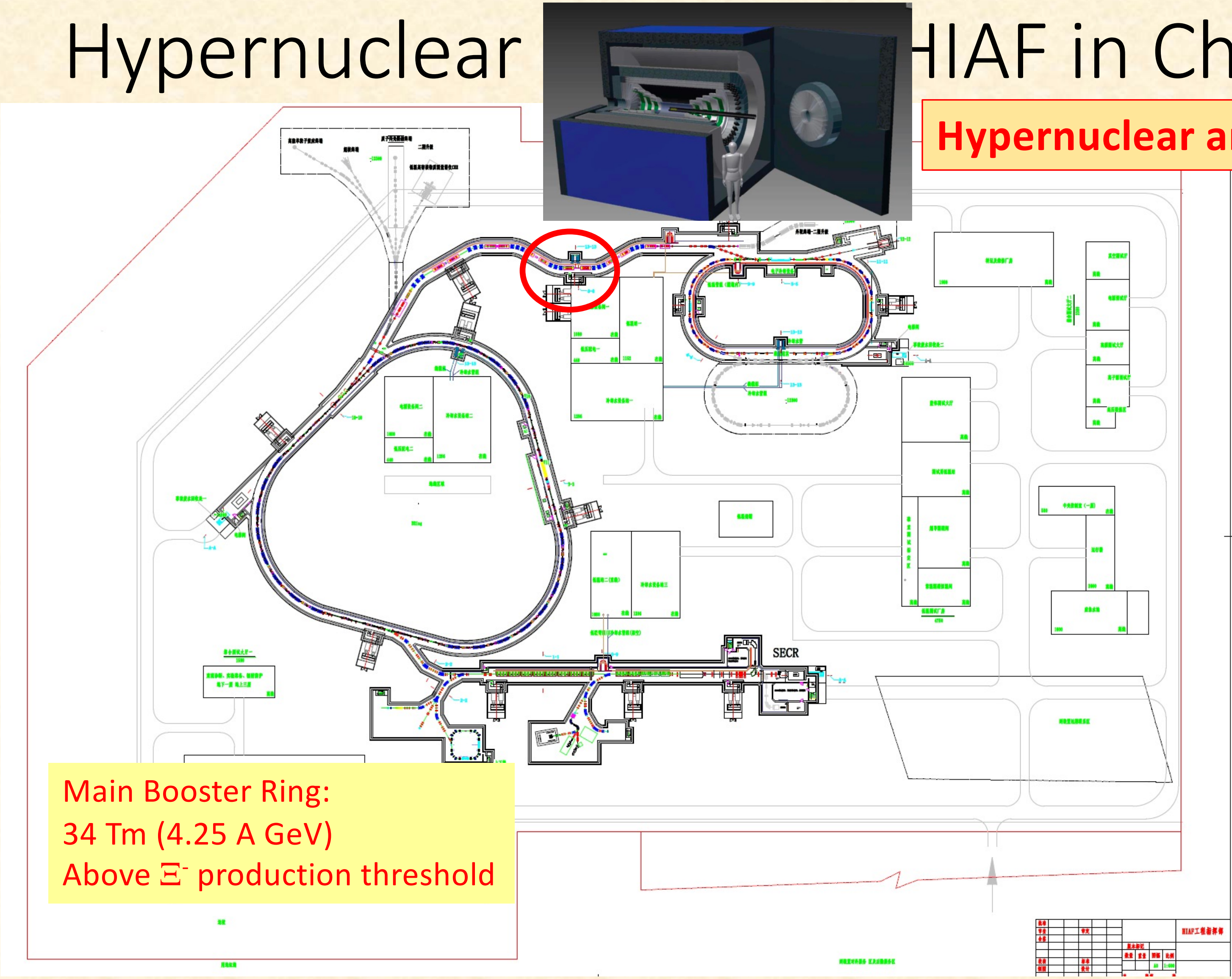
	Single-strangeness hypernuclei	Double-strangeness hypernuclei
Observation per week	6 X 10^6	6 X 10^2
Lifetime accuracy	**~ 1 ps**	**~ 10 ps**
Binding energy accuracy	~ 100 keV	Sub MeV

Hypernuclear scattering experiment feasible

Femto Neutron Stars
(named by Josef Pochodzalla)



Hypernuclear HIAF in China



Hypernuclear and nuclear physics

Main Booster Ring:
34 Tm (4.25 A GeV)
Above Ξ^- production threshold

Summary

Our approach for hypertriton and nnΛ

- The WASA-FRS experiment
  - Lifetime of hypertriton: ~ 8ps accuracy
  - To confirm whether or not the nnL bound state can exist
- J-PARC E07 nuclear emulsion + Machine learning
  - Binding energy of hypertriton: 50 keV accuracy within a year, 5 keV accuracy within a few years

Perspective

- Post-WASA-FRS experiment at FAIR
  - Proton rich hypernuclei with projectile fragmentation reaction
  - Neutral and very-neutron-rich hypernuclei/resonances with charge exchange reactions
- J-PARC E07 nuclear emulsion + Machine learning
  - Binding energy of ${}^{4}_{\Lambda}He$ and other light hypernuclei
  - 1000 double-strangeness hypernuclear candidates
- HIAF in China
  - Double-strangeness hypernuclei
  - Hypernuclear scattering measurement
  - With HFRS
- J-PARC Heavy Ion program
  - Hypernuclear separator

Collaborations

Hypernuclear studies with heavy ion beams

CSIC-Madrid: S. Escrig, C. Rappold

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