Recent results from the GSI heavy-ion program on hypernuclei

4th Workshop on anti-matter, hyper-matter and exotica production at the LHC

14/02/2023

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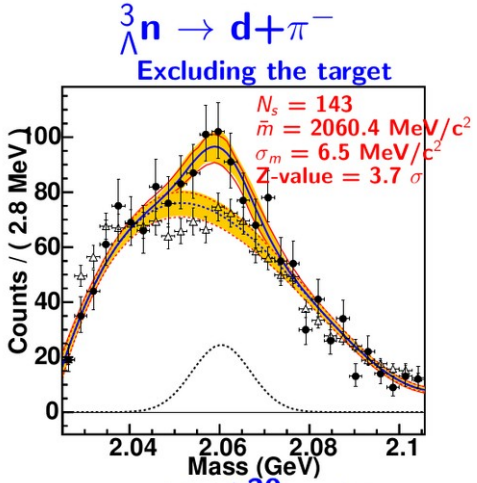
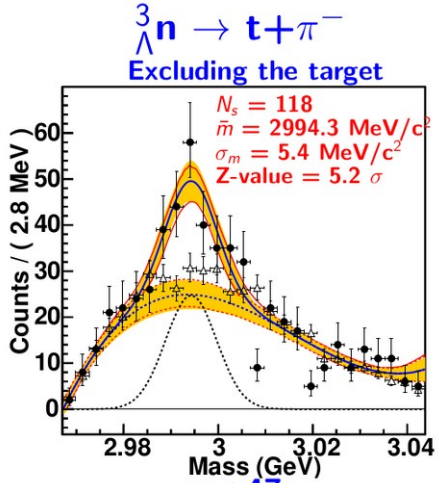
For WASA-FRS and Super-FRS Experiment collaborations

Current puzzles for light hypernuclei: $^{3}_{\Lambda}$H & $^{3}_{\Lambda}$n

- **In our first experiment, HypHI Phase 0:**
  Two puzzling observations were made: [C. Rappold et al., PRC 88 (2013) 041001]
  - Possible signal of nnΛ bound state
    - <u>All theoretical calculations show negative results</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





  - Short lifetime of $^{3}_{\Lambda}$H :
    - Our published value : 183 $^{+43}_{-32}$ ps [C. Rappold et al., Nucl. Phys. A 913 (2013) 170]
    - Plus other recent measurements : Combined lifetime analysis excludes all current models of $^{3}_{\Lambda}$H [C. Rappold et al., Phys. Lett. B 728, 543 (2014)]

Current puzzles for light hypernuclei: $^{3}_{\Lambda}H$ & $^{3}_{\Lambda}n$

- **Yet the puzzles deepen :**
  - Over the years more data from ALICE and STAR experiments :

    More tension on the combined lifetime measurements
    - ALICE : 181^{+54}_{-39} ps → 237^{+34}_{-38} ps [PLB 128 (2019) 134905]
    - STAR : 155 $^{+25}_{-22}$ ps → 142 $^{+24}_{-21}$ ps → 221 +- 15 ps [PRL 128 (2022) 202301]
    - HypHI : 183^{+42}_{-32} ps

      We will provide one very precise data point with our new WASA-FRS experiment

  - Hot topics in nuclear experiments:
    - STAR, ALICE, J-PARC, ELPH, HADES, HYDRA and WASA-FRS

  - Still no clear theoretical explanation for the short lifetime, is it ?

Current puzzles for light hypernuclei: $^{3}_{\Lambda}$H & $^{3}_{\Lambda}$n

- **Yet the puzzles deepen :**
  - Binding energy of hypertriton :

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*

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

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

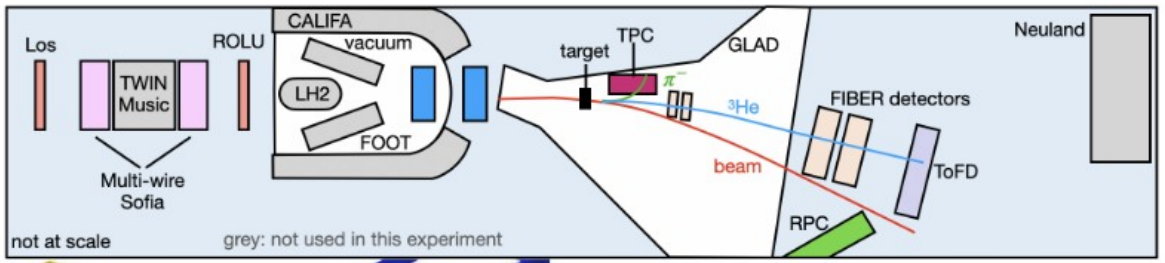
  - Previously accepted value: $B_\Lambda = 0.13 \pm 0.05$ MeV
  - And still : ALICE measured a Λ binding energy of :
    - $B_\Lambda = 0.050 \pm 0.060 \pm 0.100$ MeV

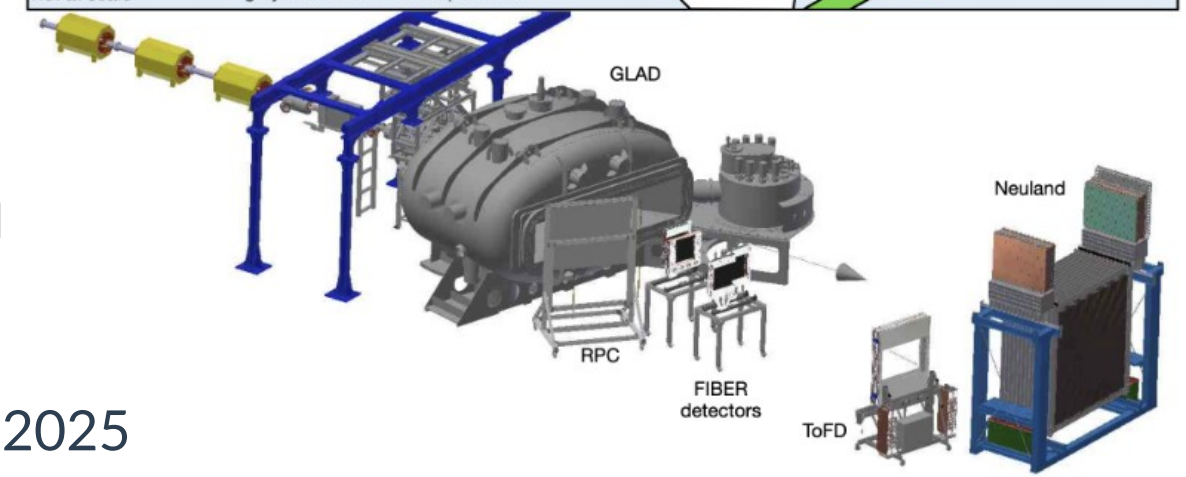
GSI-FAIR programs on hypernuclei

- **Currently several collaborations on the study of hypernuclei:**
  - WASA-FRS collaboration :
    - in ^{6}Li + ^{12}C & ^{12}C + ^{12}C @ 1.98 *A*GeV → 2022
    - Lifetime and reaction mechanism in spectator rapidity region
      - Study of light hypernuclei : $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, nnΛ
      - Study of heavier hypernuclei : $^{9}_{\Lambda}$B
  - HADES collaboration :
    - in Ag+Ag 1.58*A*GeV → 2019 & Au+Au 1.23*A*GeV → 2012
    - Lifetime and reaction mechanism in mid-rapidity region
      - Study of light hypernuclei $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H
  - HYDRA - R3B collaboration :
    - in ^{12}C + ^{12}C 1.9 AGeV → approved for 2024-2025 beamtime schedule
    - Lifetime and radius :
      - Study of light hypernuclei $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, $^{4,5,6}_{\Lambda}$He, $^{7}_{\Lambda}$Li, $^{9}_{\Lambda}$Be, $^{11}_{\Lambda}$B

HYDRA experiment – R3B collaboration

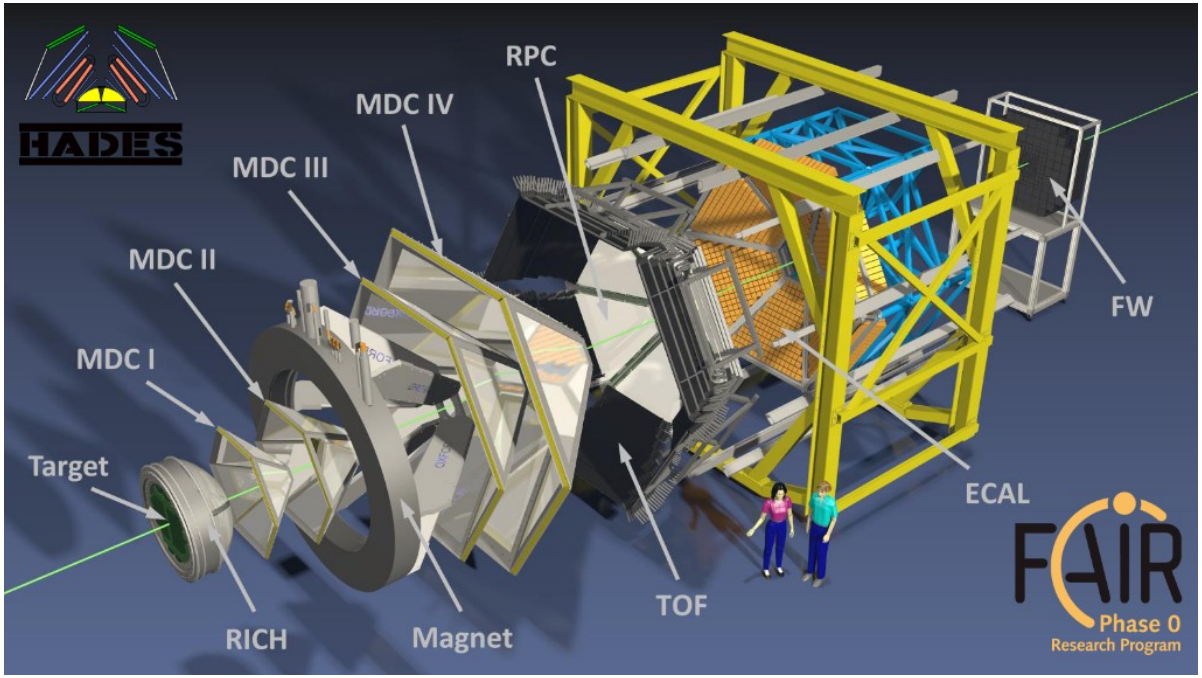
- **HYDRA : ^{12}C + ^{12}C @ 1.9 *A*GeV**
  - Study of the radius of $^{3}_{\Lambda}H$ as a super halo hypernuclei:
    - Related to the lifetime puzzle of the hypertriton
    - Plan to observe $^{3}_{\Lambda}H$ → halo and $^{4}_{\Lambda}H$ → non halo
  - Possibility for observing :
    - $^{4,5,6}_{\Lambda}He$, $^{7}_{\Lambda}Li$, $^{9}_{\Lambda}Be$, $^{11}_{\Lambda}B$
  - Experimental approach :
    - At R3B in GLAD : new TPC
      → for pi- mesonic decay
    - Interaction cross section :
      2-target measurement method
  - Experiment approved in the
    last G-PAC : to run in 2024 – 2025





HADES collaboration

- **HADES Heavy-ion experiments:**
  - 2012 dataset :
    - Au+Au @ 1.23 *A*GeV
  - 2019 dataset:
    - Ag+Ag @ 1.58 *A*GeV
  - Had observed $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H
    - In mid-rapidity region of the collisions → first time
  - Lifetimes extracted & dynamics of the hypernuclear production
    → Talk from Manuel Lorenz on Wednesday

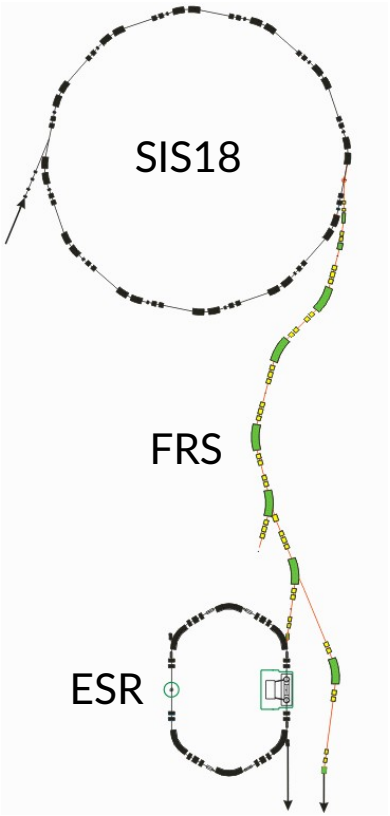


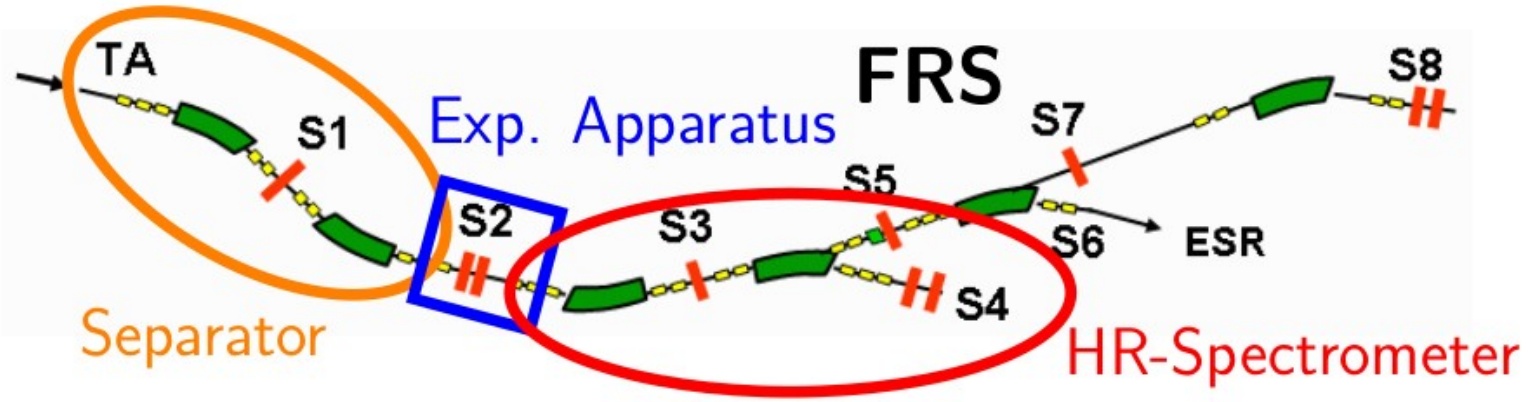
WASA-FRS experiment

- **Future of HypHI project : Exotic hypernuclei / strangeness cluster**
  - Use of heavy ion and RI beam to study hypernuclei at FRS & SuperFRS
    - Hypernuclei toward the proton and neutron drip lines with Exotic beam
    - Λ – Σ coupling in the nuclear matter
    - Lifetime of exotic hypernuclei
    - Chance to repeat the observation of nnΛ
  - Why @ FRS / SuperFRS ?
    - High momentum resolution for forward fragments :
      - 10^-4 δp / p optimal
    - Exotic hypernuclei ; Need RI beam
      - With high energy ~ 2 AGeV
      - With high intensity
    - Can optimize each data taking for one decay / species

WASA-FRS experiment : Concept & Layout

GSI facility





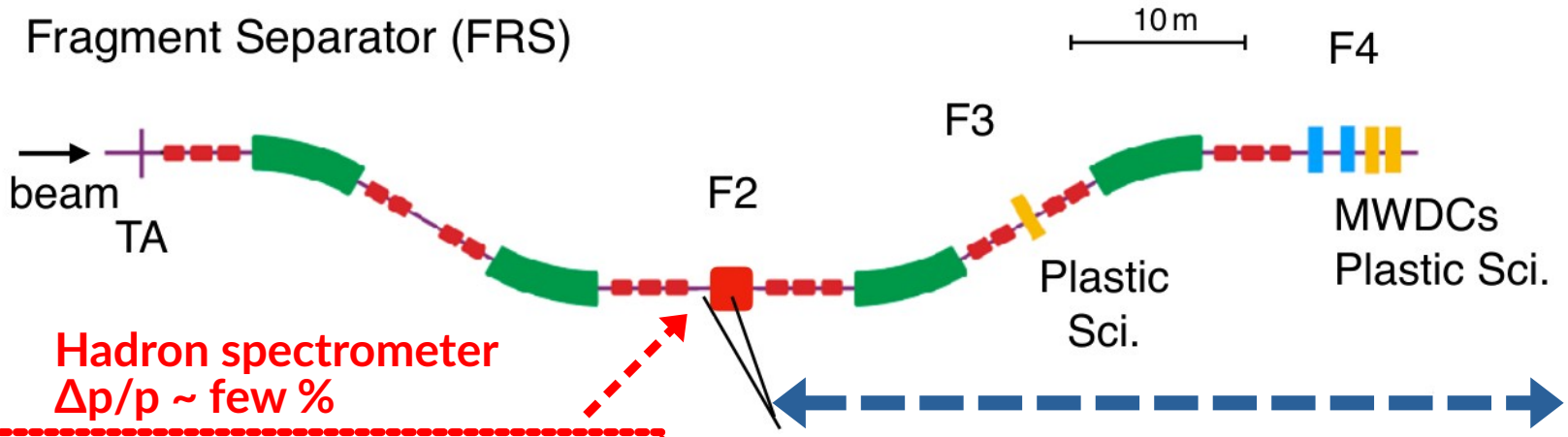
- **We had the opportunity to use WASA central detectors :**

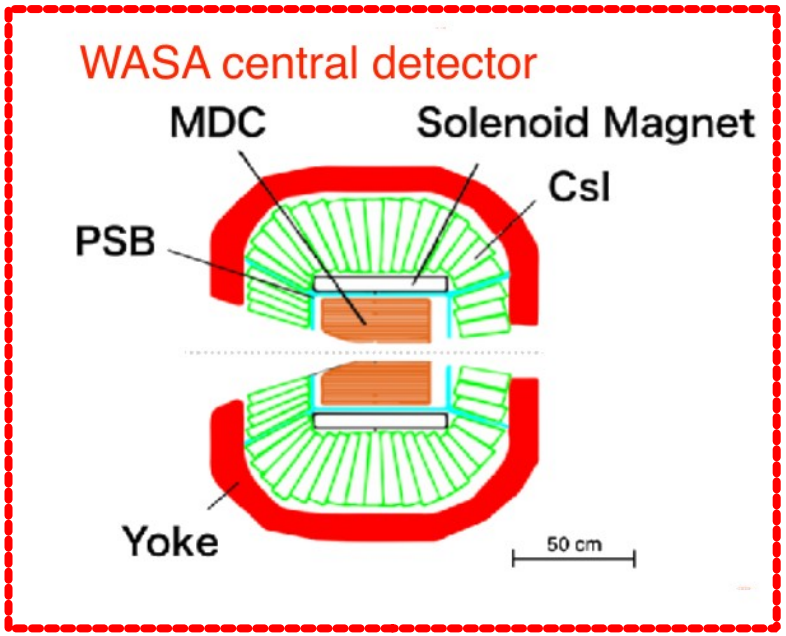
  → Moved to GSI in 2019

  → Placed in S2 in 2021

- Since 2019, preparation work of the WASA setup with new detectors & new readouts & cryogenics system

WASA-FRS Experimental campaign: Jan. – March 2022





Two experiments took place:

- η'-mesonic nuclei spectroscopy
- Hypernuclei spectroscopy

2 of 10 key topic of SuperFRS EC

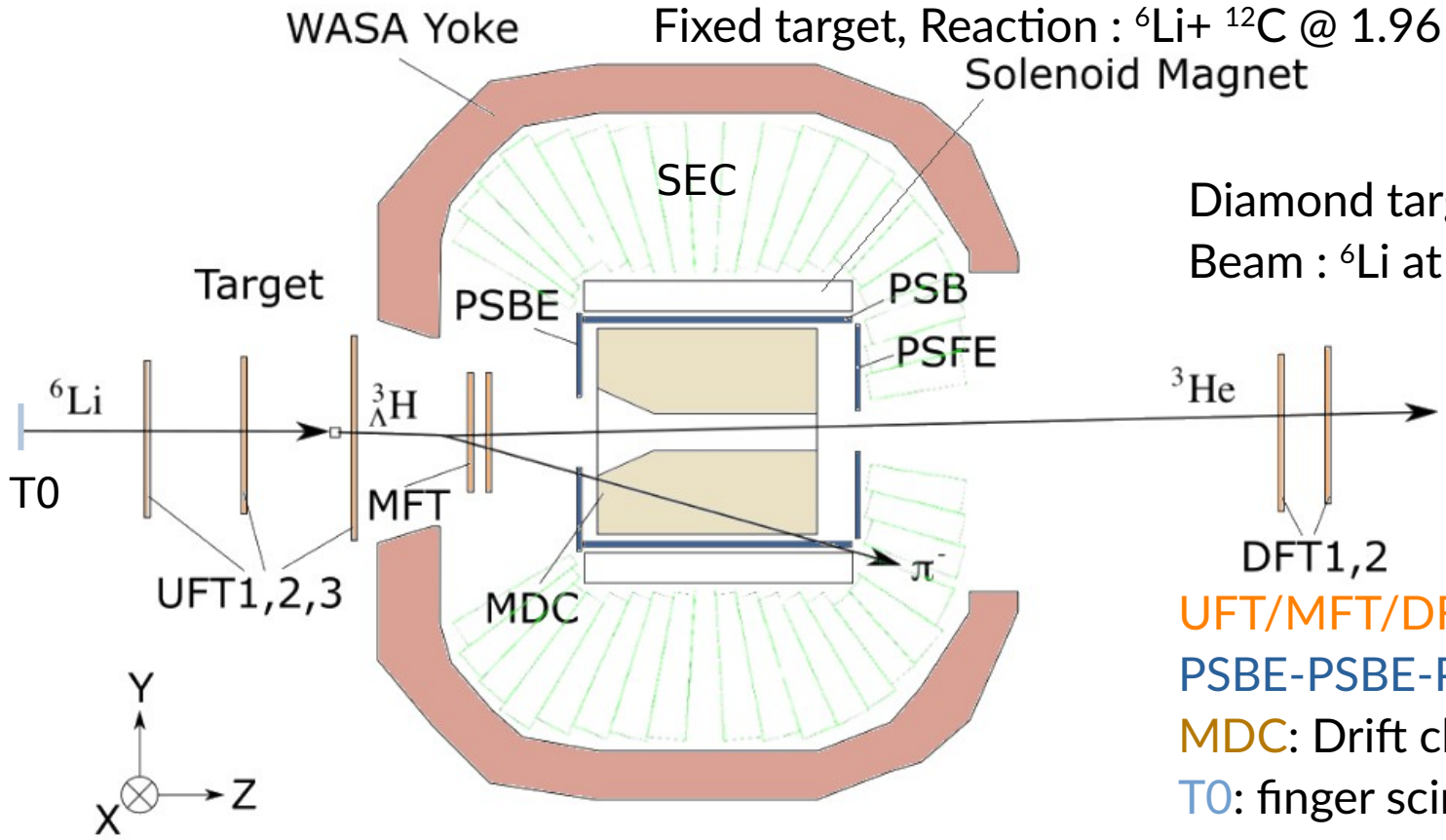
Super-FRS EC

Experimental apparatus: WASA-FRS HypHI

- At the middle focal plane of FRS:

$^{3}_{\Lambda}n \rightarrow d+\pi^{-}$ $^{3}_{\Lambda}H \rightarrow {}^{3}He+\pi^{-}$ $^{4}_{\Lambda}H \rightarrow {}^{4}He+\pi^{-}$

Fixed target, Reaction : $^{6}Li+ {}^{12}C$ @ 1.96 AGeV or $\sqrt{s_{NN}}$ = 2.7 GeV



Diamond target: 9.87 g/cm²

Beam : ^{6}Li at 1.96 AGeV ~ 2 x 10^{7}/s

UFT/MFT/DFT: Fiber Trackers

PSBE-PSBE-PSFE: Plastic scintillators

MDC: Drift chambers base on straw tubes

T0: finger scintillators

SEC: CsI crystal calorimeter

Experimental apparatus: WASA-FRS HypHI

- At the middle focal plane of FRS:

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

ion : ^{6}Li+ ^{12}C @ 1.96 AGeV or $\sqrt{s_{NN}}$ = 2.7 GeV

enoid Magnet

T0 detector:

- 28 segments 1.5 x 1.5 mm^2 x 4.5 cm
- Total size 3.4 x 4.5 cm^2
- Start timing of the Time-of-Flight
- Time resolution: σ ~ 60 ps
- < 2MHz per segment → 2 10^7 total beam intensity

FT1,2

/MFT/DFT: Fiber Trackers

E-PSBE-PSFE: Plastic scintillators

C: Drift chambers base on straw tubes

finger scintillators

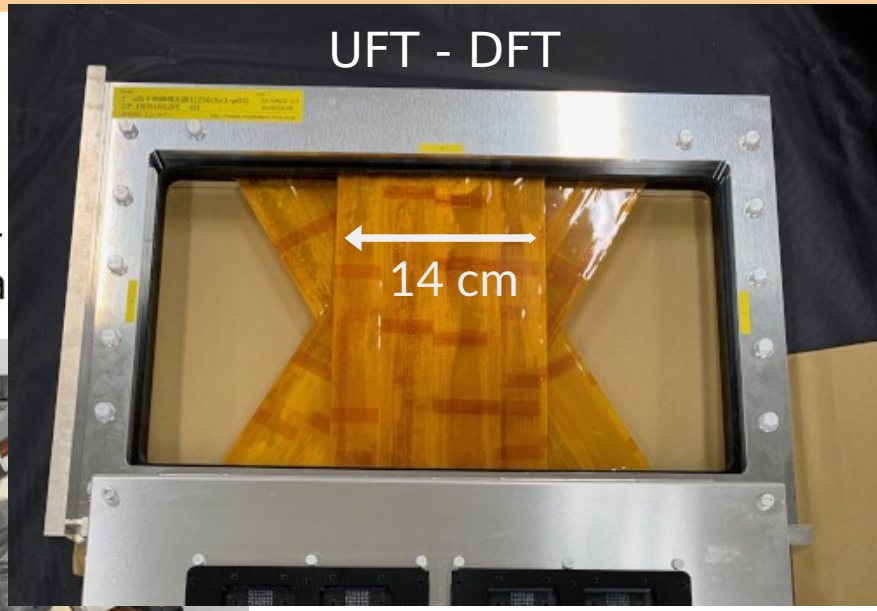
SEC: CsI crystal calorimeter

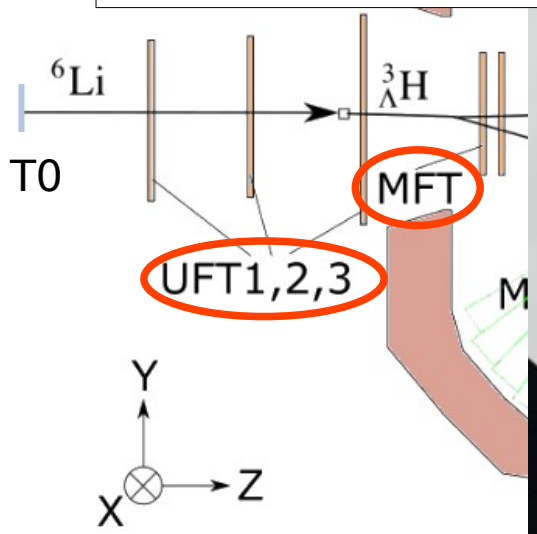
Experimental apparatus: WASA-FRS HypHI

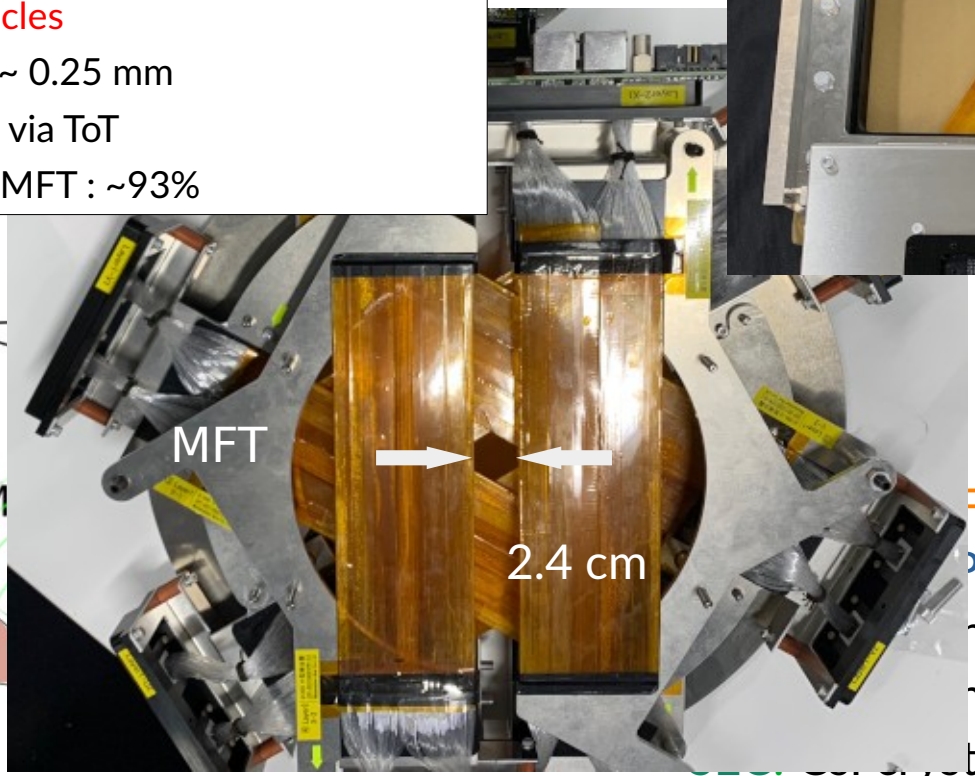
- At the middle focal plane of FRS:

Fiber trackers: XUV layouts

- 512 or 768 fiber / layer : Fiber of 0.5 mm Xsection
- In total: 5760 channel readout
- Tracking charged particles
- Position resolution: σ ~ 0.25 mm
- Charge also measured via ToT
- UFT=DFT Eff : ~ 95% MFT : ~93%







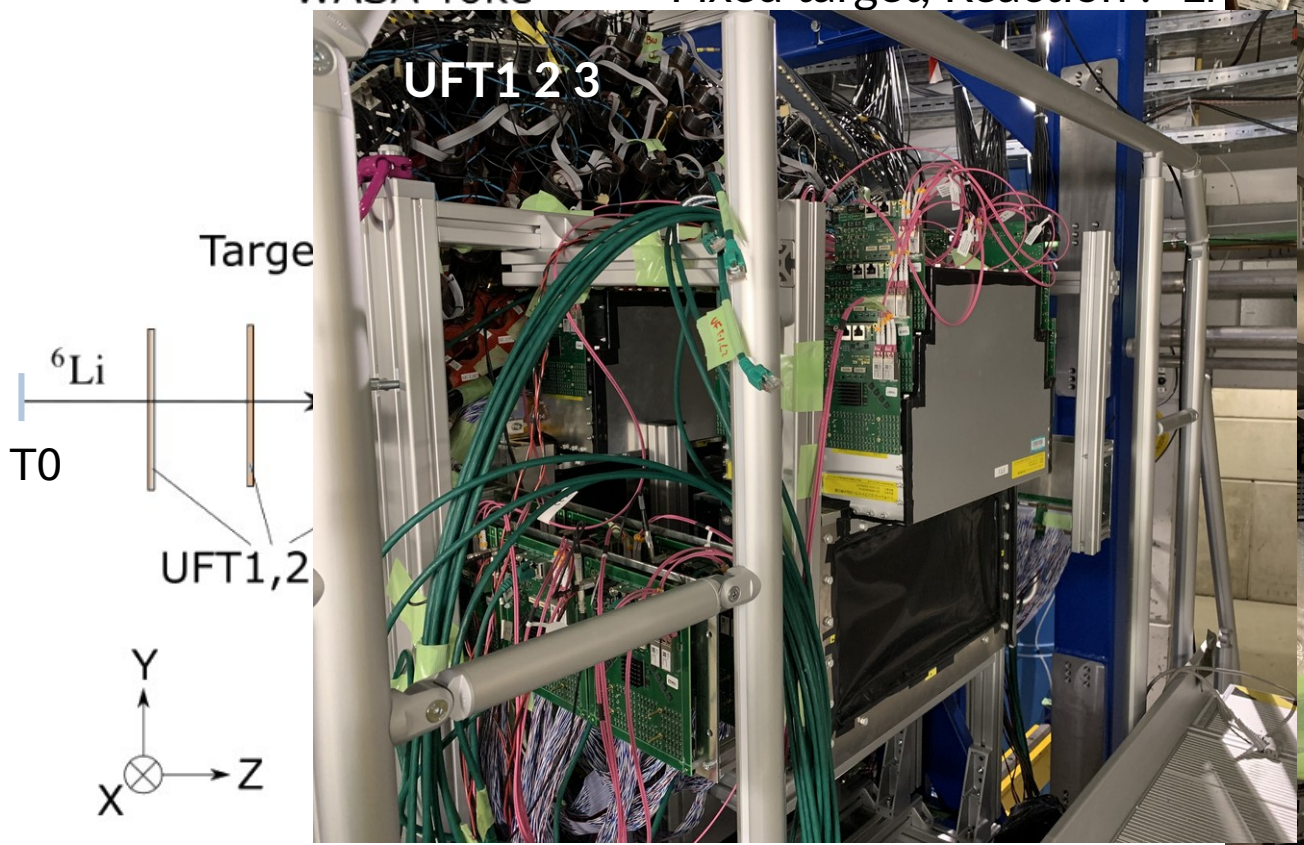
FT: Fiber Trackers
PSFE: Plastic scintillators
hambers base on straw tubes
ntillators
tal calorimeter

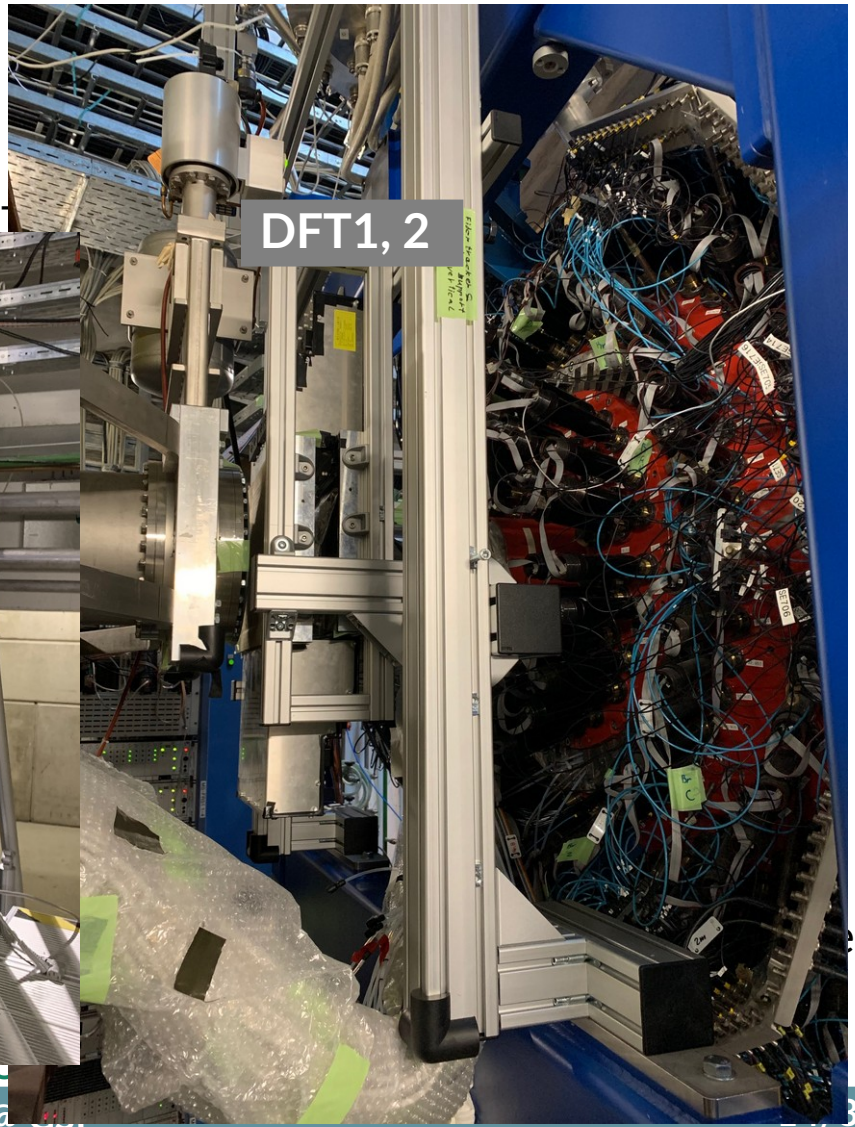
Experimental apparatus: WASA-FRS HypHI

- At the middle focal plane of FRS:

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

WASA Yoke Fixed target, Reaction : ^{6}Li-

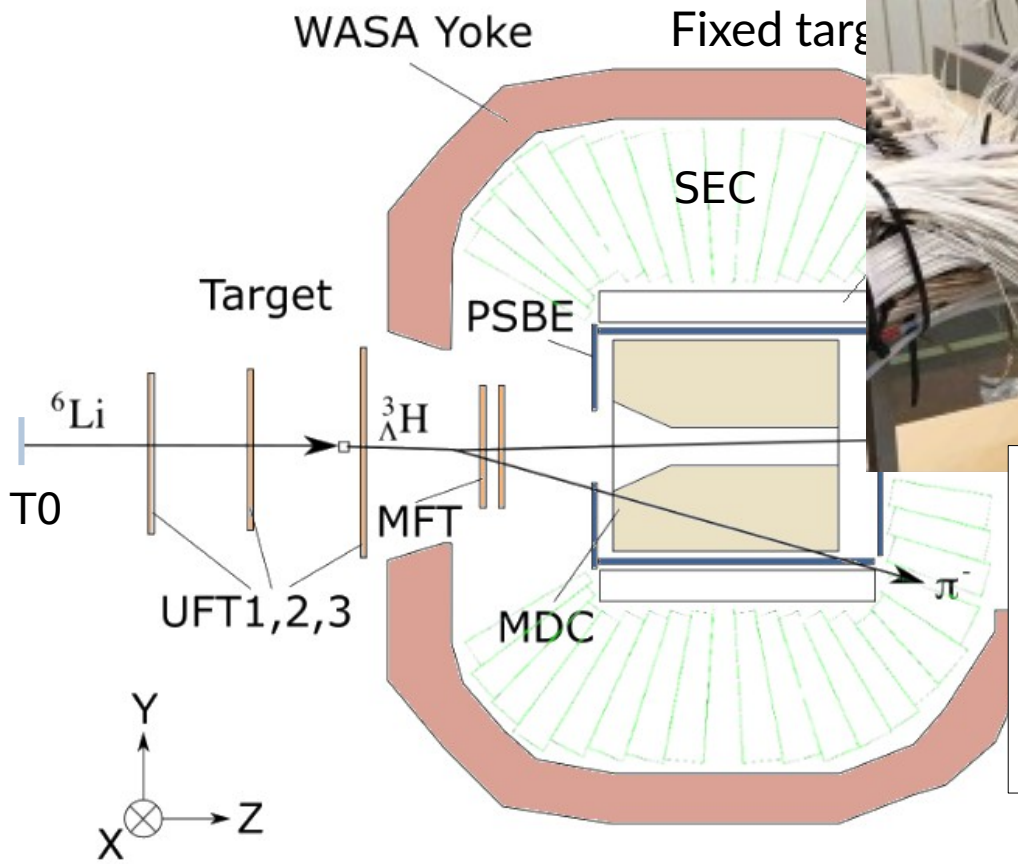




Experimental apparatus: WASA-FRS HypHI

- At the middle focal plan

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



2.7 GeV

x 10^7/s

MDC: Strawtubes drift chamber

- 17 layers : Diameters : 4, 6 & 8 mm 9 // z axis + 8 stereos
- In total: 1738 channel readout
- Tracking charged hadrons : Momentum analysis
- Position resolution: σ ~ 0.3 – 0. 5 mm
- Inner to outer layer eff. ~ 92% → 96%

T0: finger scintillators

SEC: CsI crystal calorimeter

Experimental apparatus: WASA-FRS HypHI

- At the middle focal plane of F

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

$\sqrt{s_{NN}}$ = 2.7 GeV

cm²

~ 2 x 10^{7}/s

PSB: Plastic scintillator barrel

- 48 bars, size : 55 x 3.8 x 0.8 cm^3
- Stop ToF & final positions of charged hadrons
- Time & Position resolution: σ_t ~ 85 ps & σ_z ~ 1 cm

PSBE-PSBE-PSFE: Plastic scintillators

MDC: Drift chambers base on straw tubes

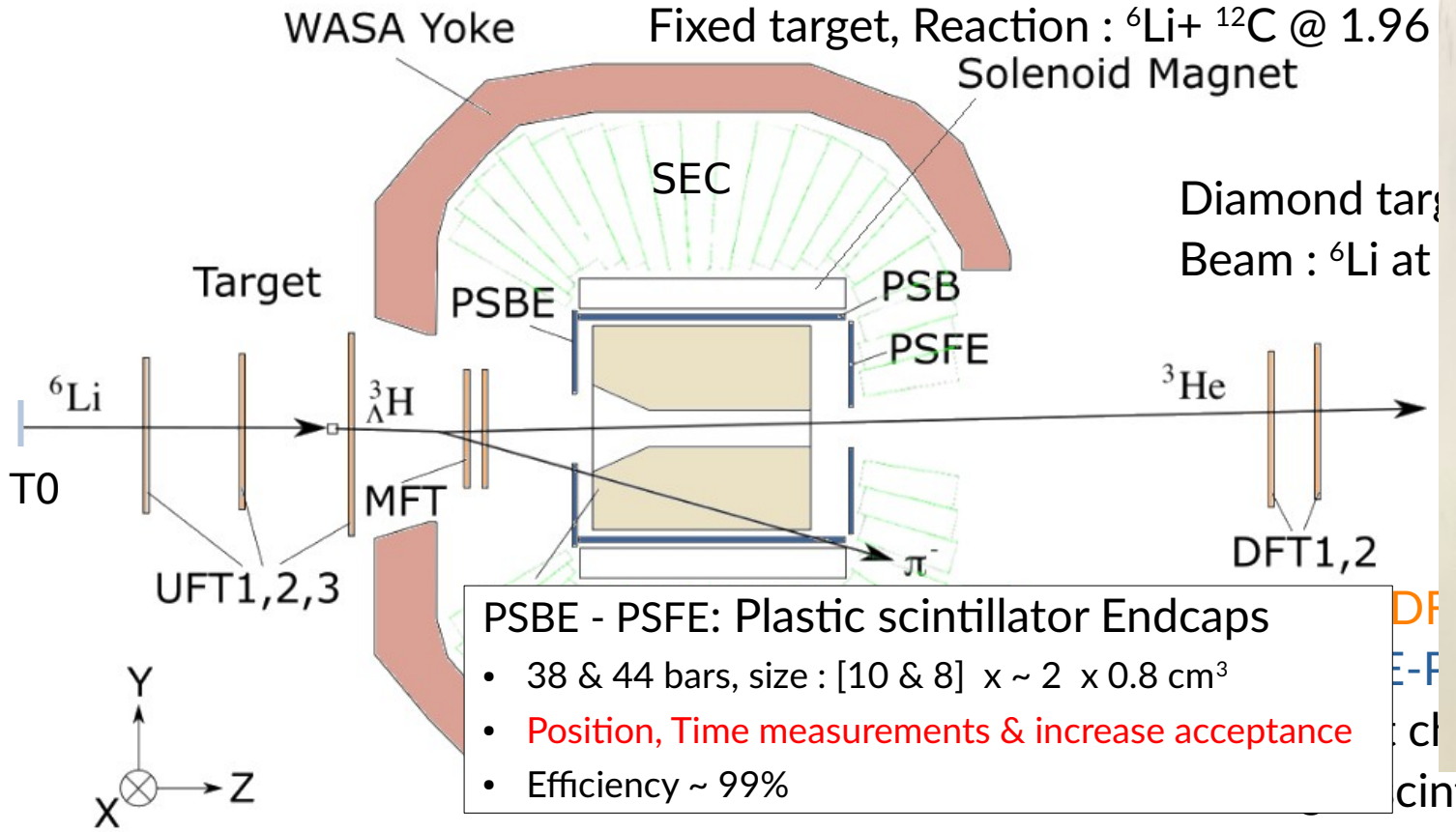
T0: finger scintillators

SEC: CsI crystal calorimeter

Experimental apparatus: WASA-FRS HypHI

- At the middle focal plane of FRS:

$^{3}_{\Lambda}n \rightarrow d+\pi^{-}$ $^{3}_{\Lambda}H \rightarrow {}^{3}He+\pi^{-}$ $^{4}_{\Lambda}$



Fixed target, Reaction : ^{6}Li+ ^{12}C @ 1.96

Diamond targ

Beam : ^{6}Li at

PSBE - PSFE: Plastic scintillator Endcaps

- 38 & 44 bars, size : [10 & 8] x ~ 2 x 0.8 cm^{3}
- Position, Time measurements & increase acceptance
- Efficiency ~ 99%

DF

E-F

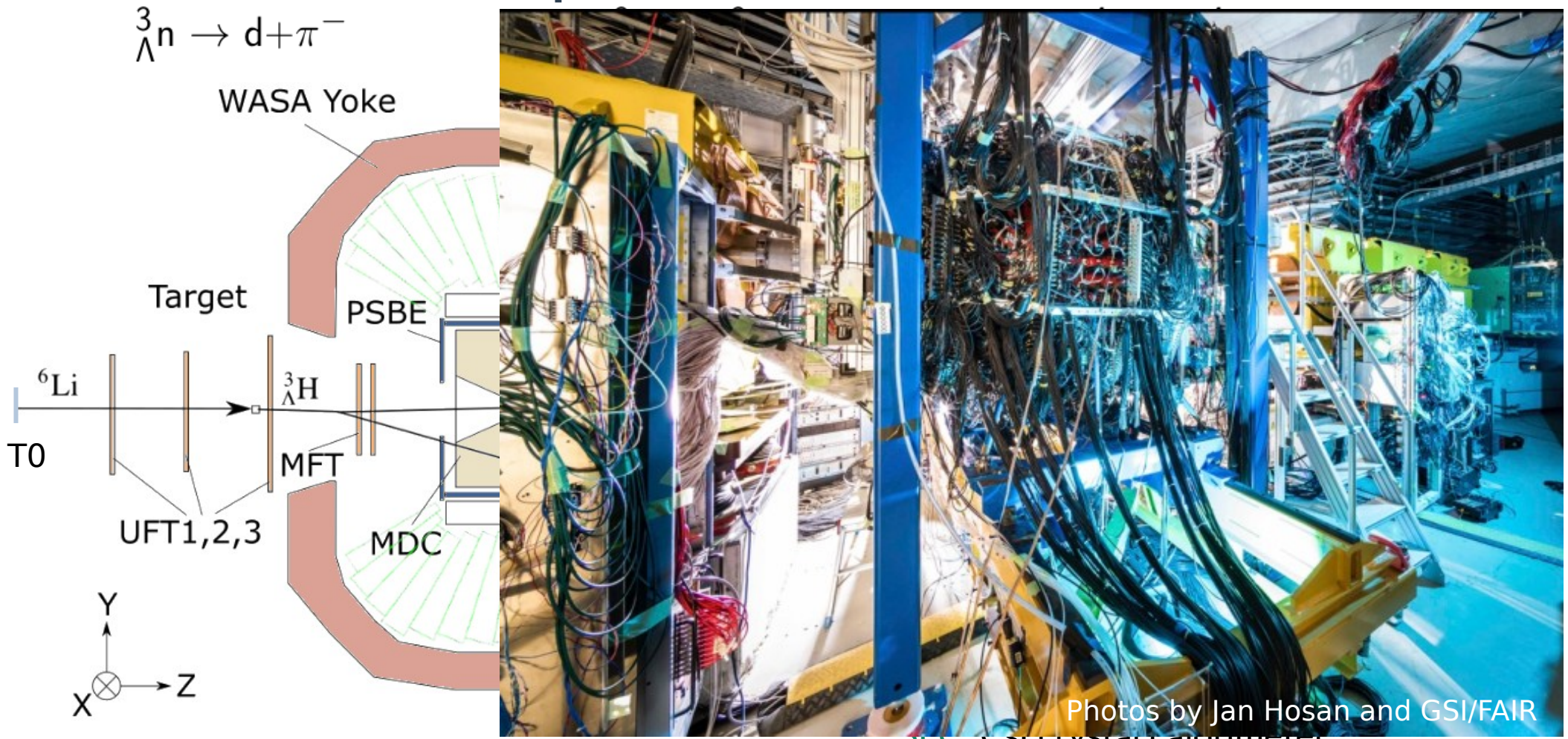
ch ubes

cintillators

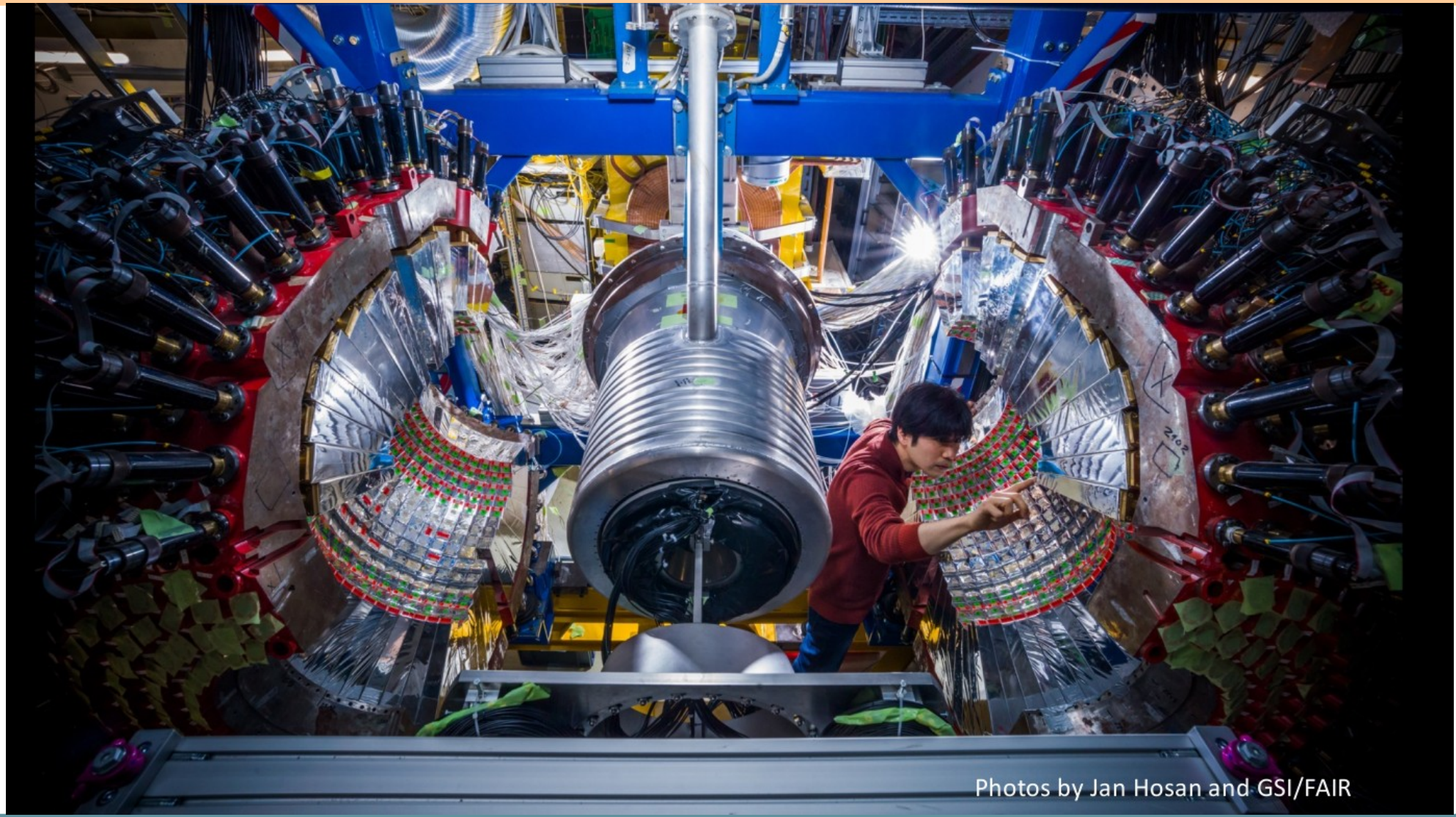
SEC: CsI crystal calorimeter

Experimental apparatus: WASA-FRS HypHI

- At the middle focal plane of FRS:

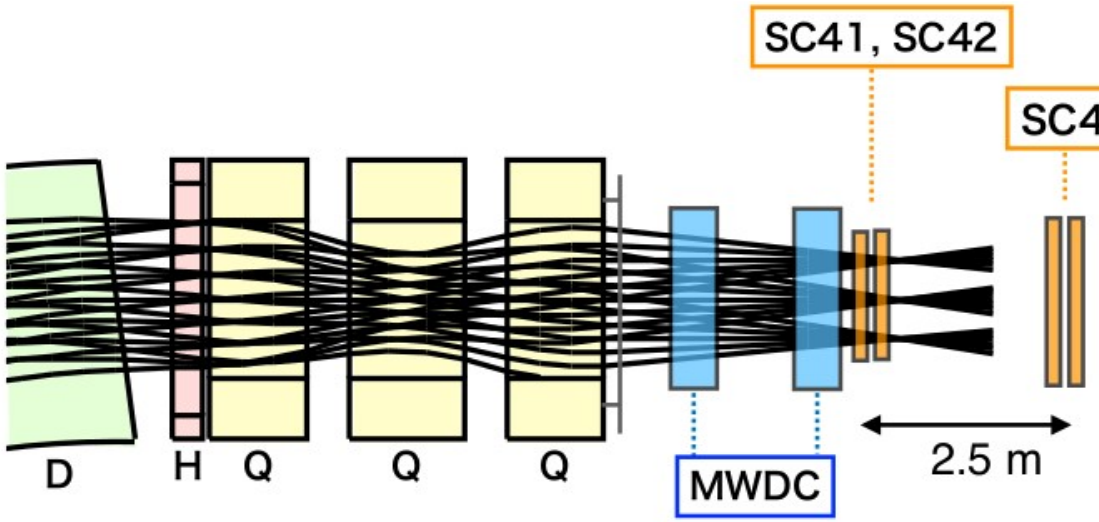


Experimental apparatus: WASA-FRS HypHI



Experimental apparatus: WASA-FRS HypHI

- At the final focal plane of FRS:

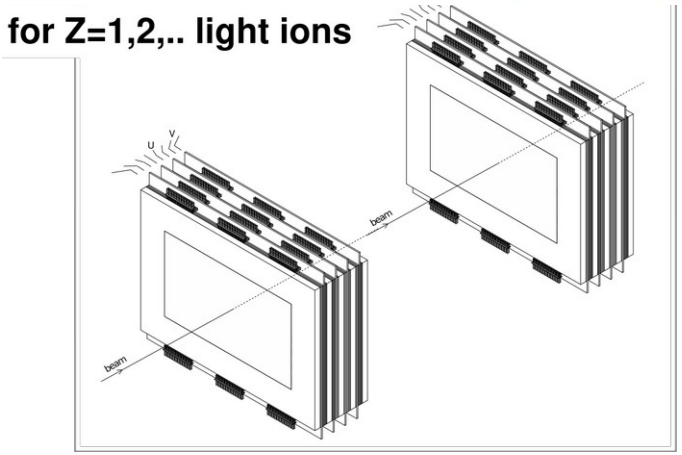


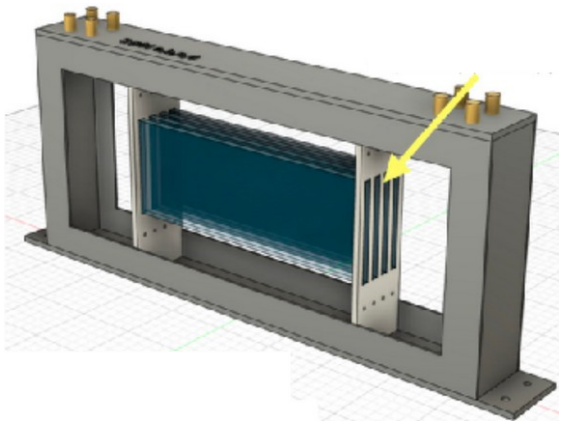
MWDC: Multi-Wire Drift Chamber

SC: stacked scintillator

For Z=1 and Z=2 ion measurements:

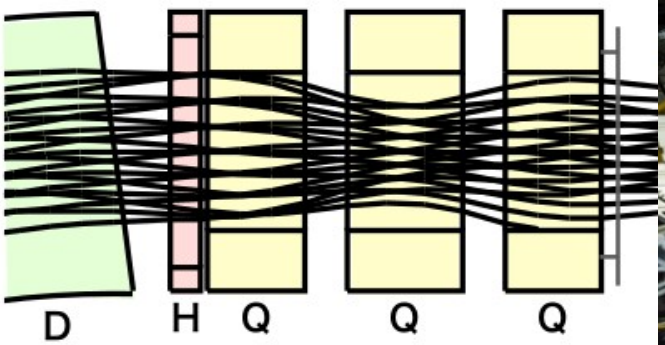
- Tracking of focal plan → Bρ
- TOF

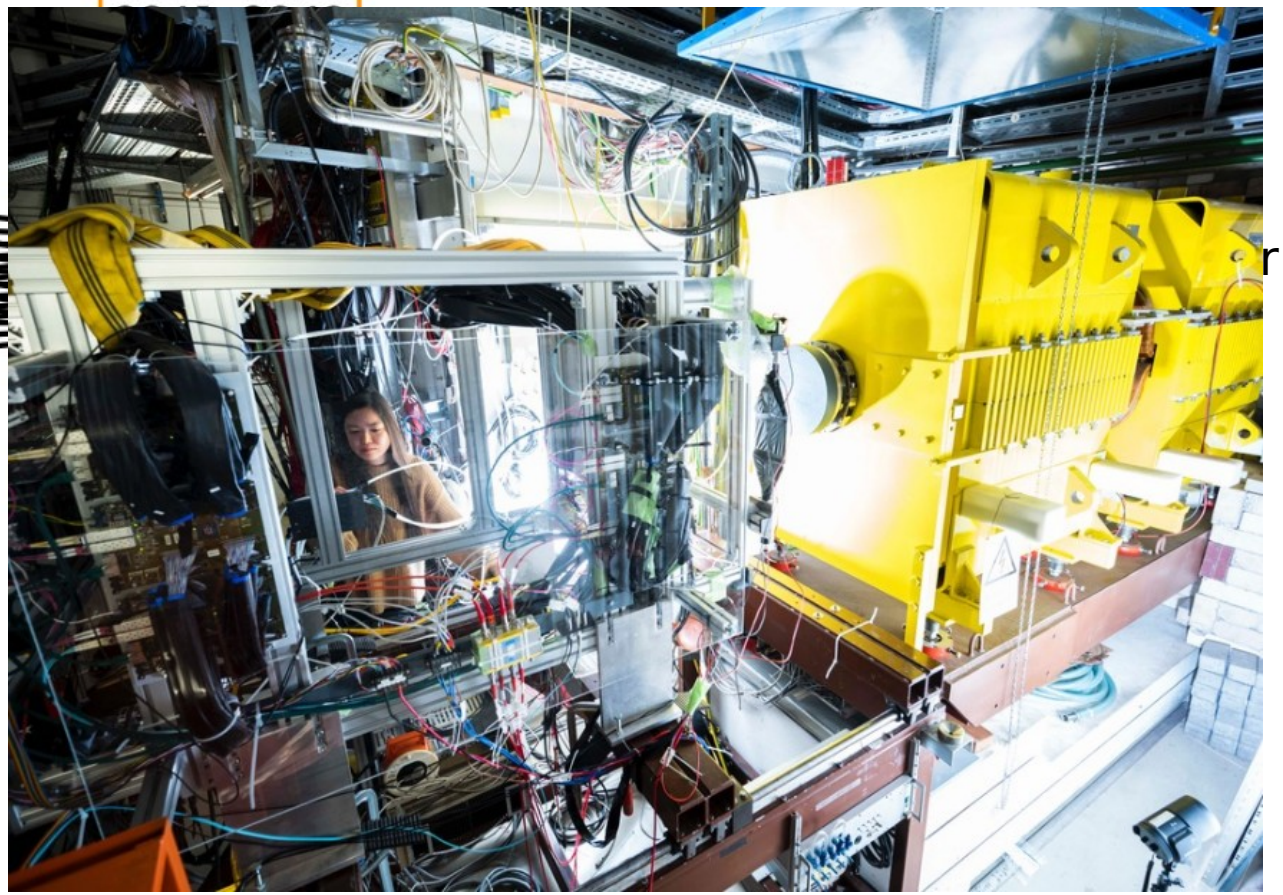




Experimental apparatus: WASA-FRS HypHI

- At the final focal plane of FRS:

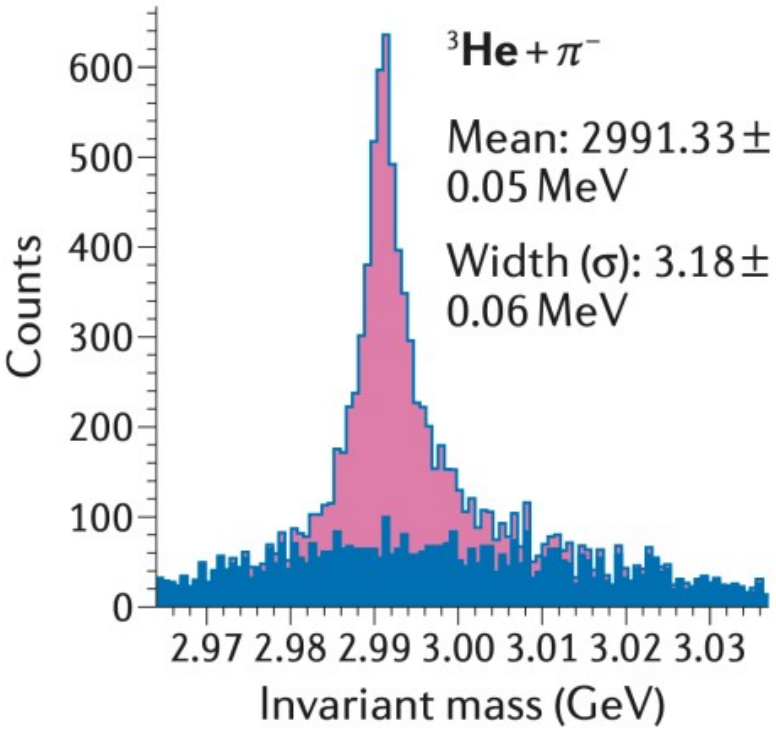




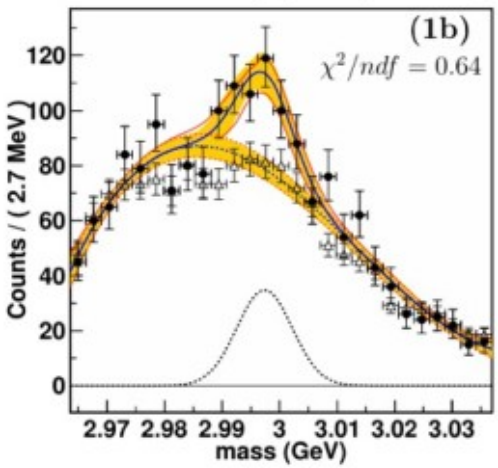
Photos by Jan Hosan and GSI/FAIR

Expected performances

- **Expected results by updated MC simulations:**



Former HypHI (2012)



- 4 days measurement

[T.R,Saito et al., Nature Reviews Physics 3, 803-813 (2021)]

- **Mass resolution**
  - 3.2 MeV/c^2 (1 T field)
  - 1.5 times better than HypHI
- **Statistics**
  - ~ 5800 in the peak for 4 days
  - 38 times more than HypHI
- **Expected Lifetime accuracy**
  - 8 ps
  - 5 times better than HypHI

Data taking

Run	Period	Data size
Commissioning run	28th Jan. - 7th Feb.	7 TB
Physics run for HypHI	10th Mar. - 19th Mar.	48 TB

Acquired data:

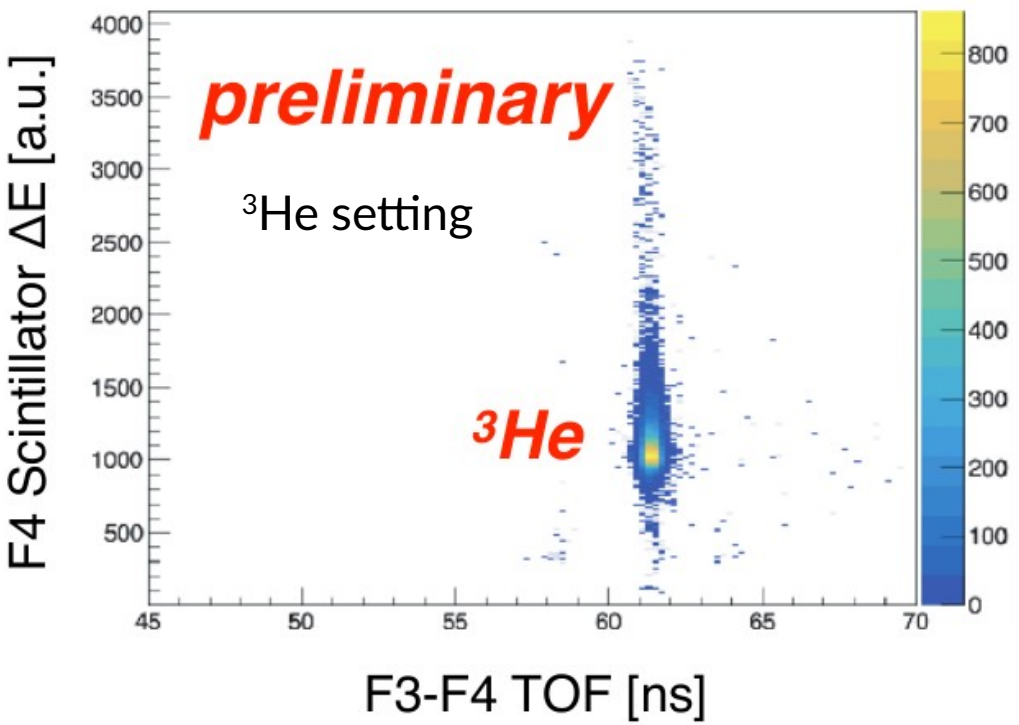
DAQ & Trigger system: Hybrid event triggered based on timestamp system

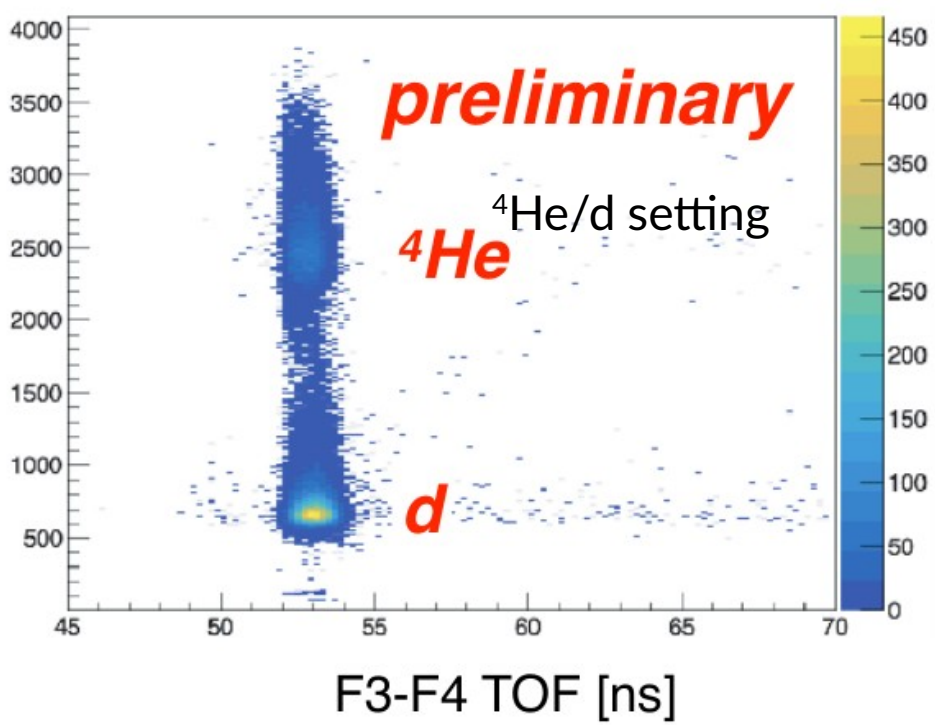
→ Bρ acceptance S2-S4 at 2% Δp/p & TOF S3-S4 & ΔE selection at S4

Beam	Fragment at S4	Amount	Time	Accepted trigger rate	
6Li beam	^{3}He	3.3×10^{8}	40.9 hours	2.6 kHz	$^{3}_{\Lambda}$H
	^{4}He	0.9×10^{8}	43.9 hours	1.8 kHz	$^{4}_{\Lambda}$H
	d	1.8×10^{8}			nnΛ
	p (mid-rap.)	5.3×10^{6}	3.2 hours	0.68 kHz	Λ
12C beam	^{3}He	1.0×10^{8}	13.5 hours	2.4k Hz	$^{3}_{\Lambda}$H
	^{9}C	2.4×10^{5}			$^{9}_{\Lambda}$B

Preliminary data analysis

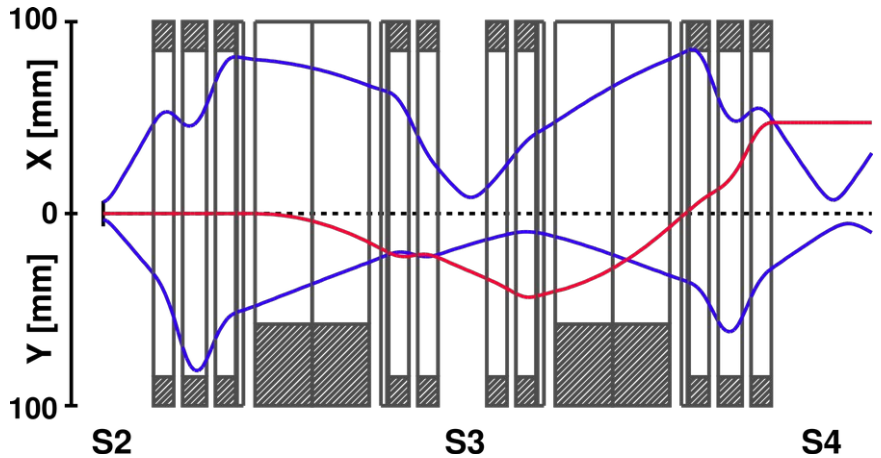
- **Analysis of high resolution spectrometer for fragments:**
  - PID at S4 final focal plane of FRS:

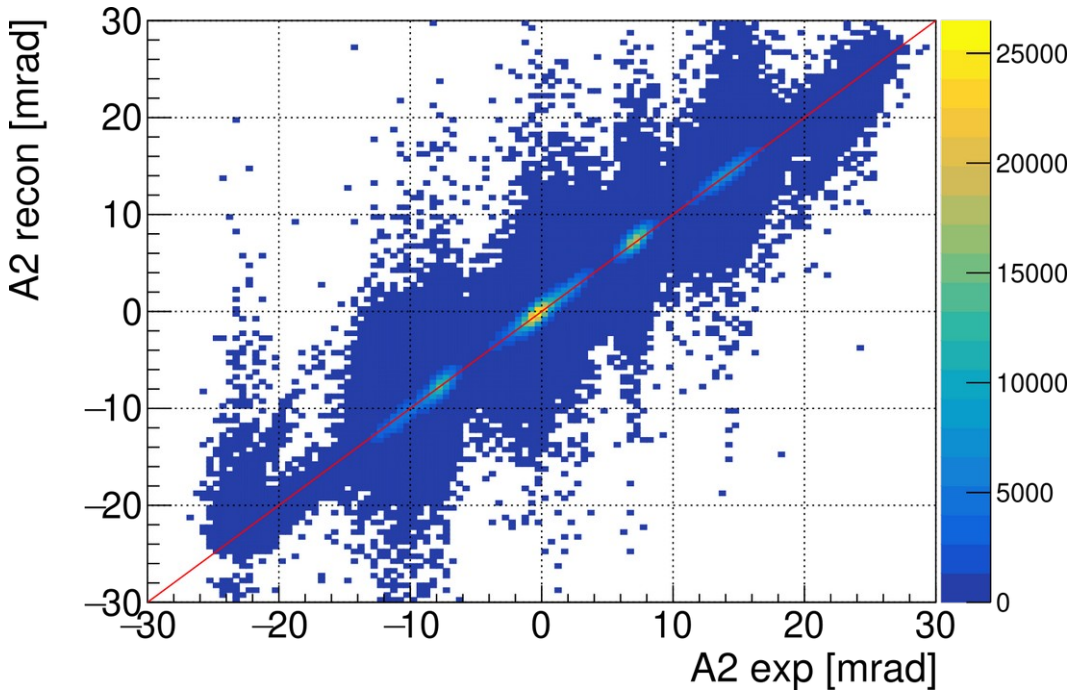




Preliminary data analysis

- **Analysis of high resolution spectrometer for fragments:**
  - Momentum analysis : High acceptance & high resolution
    → Needs ion-optics calibration: Several datasets with fixed parameters





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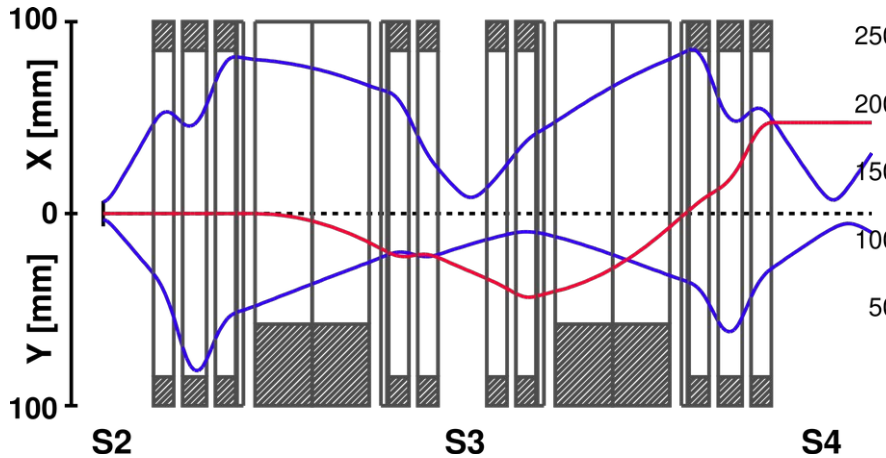
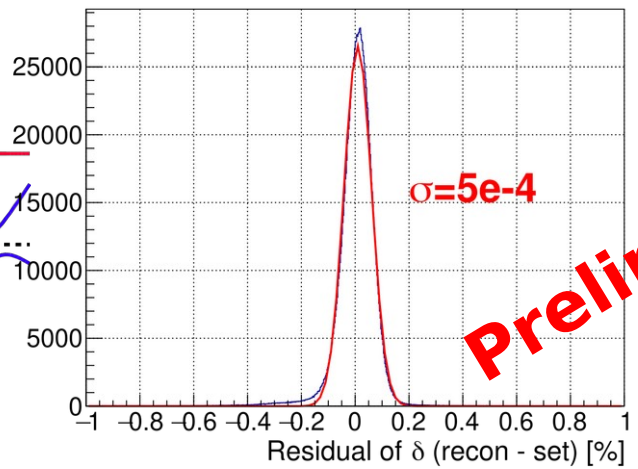
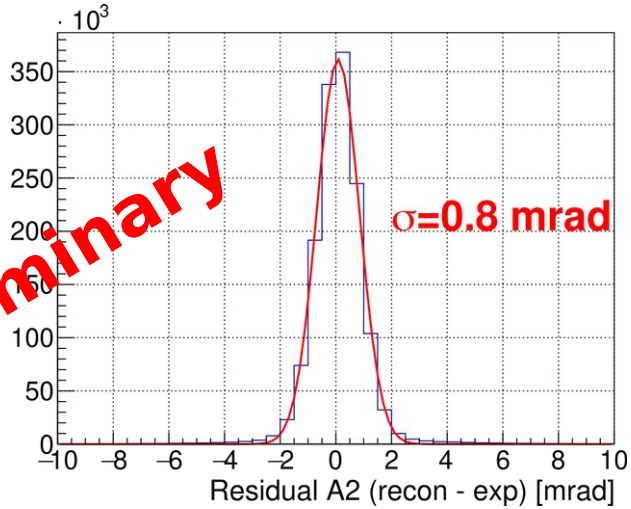






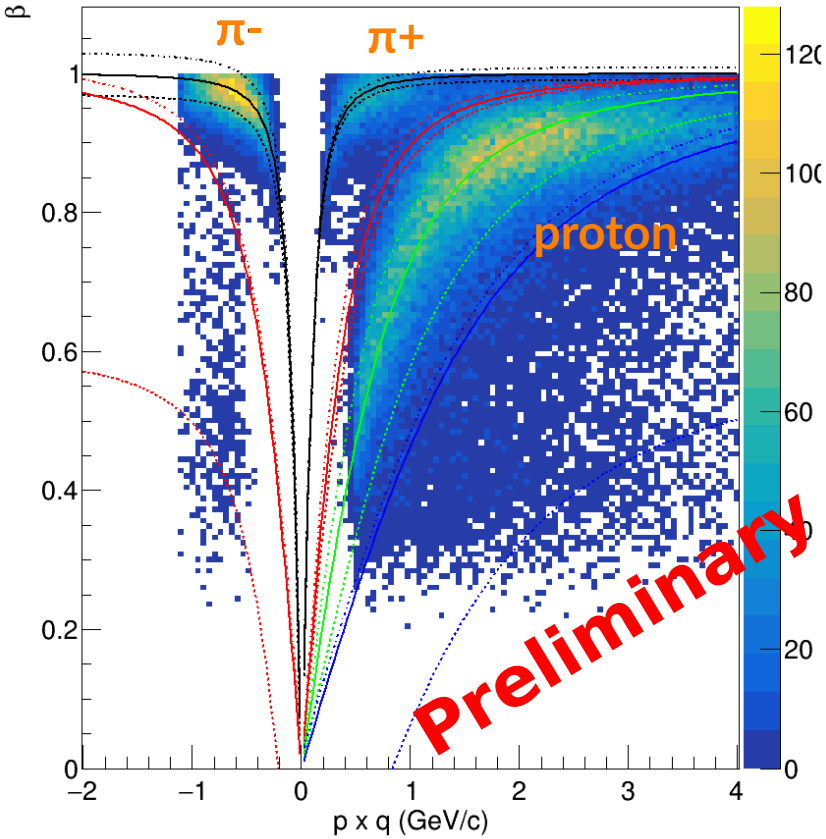
Preliminary

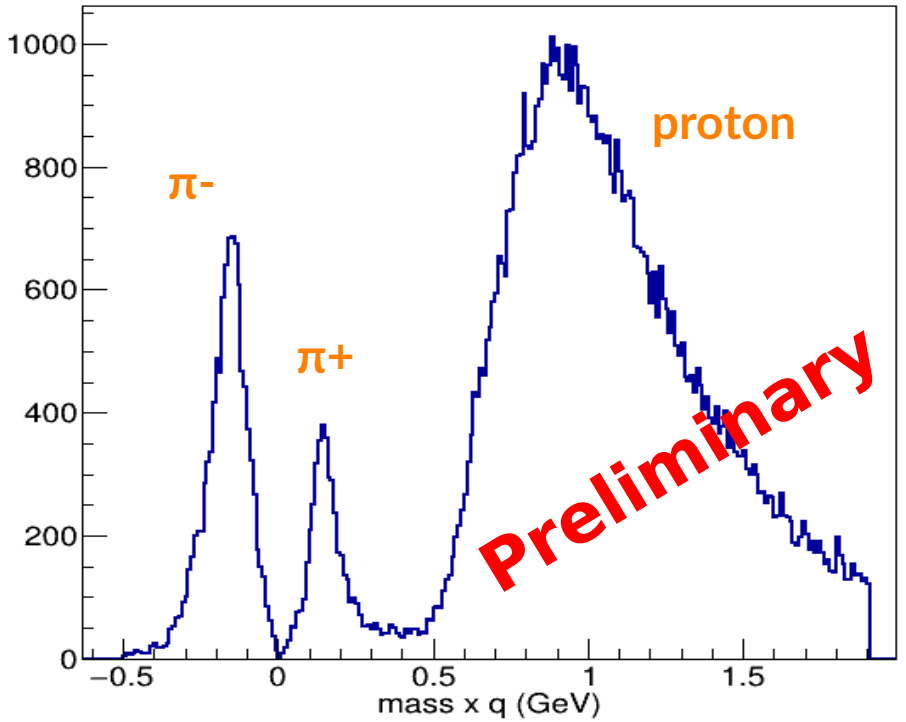
After correction and ion-optics up to second order :

- A momentum resolution for fragments : 5 10^{-4}
- Position & angular resolutions : [x,y] ~ 0.2 mm & [a, b] ~ 0.8 and 0.7 mrad

Preliminary data analysis

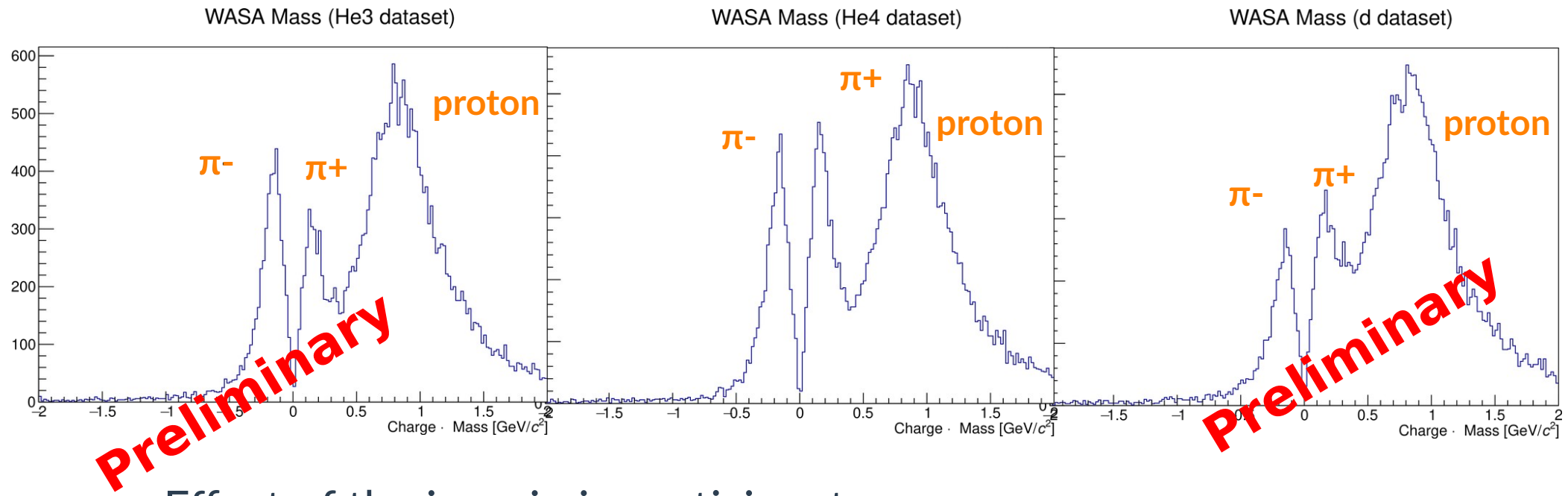
- **Analysis of WASA central system for hadron measurements :**
  - PID at S2 middle focal plane of FRS:





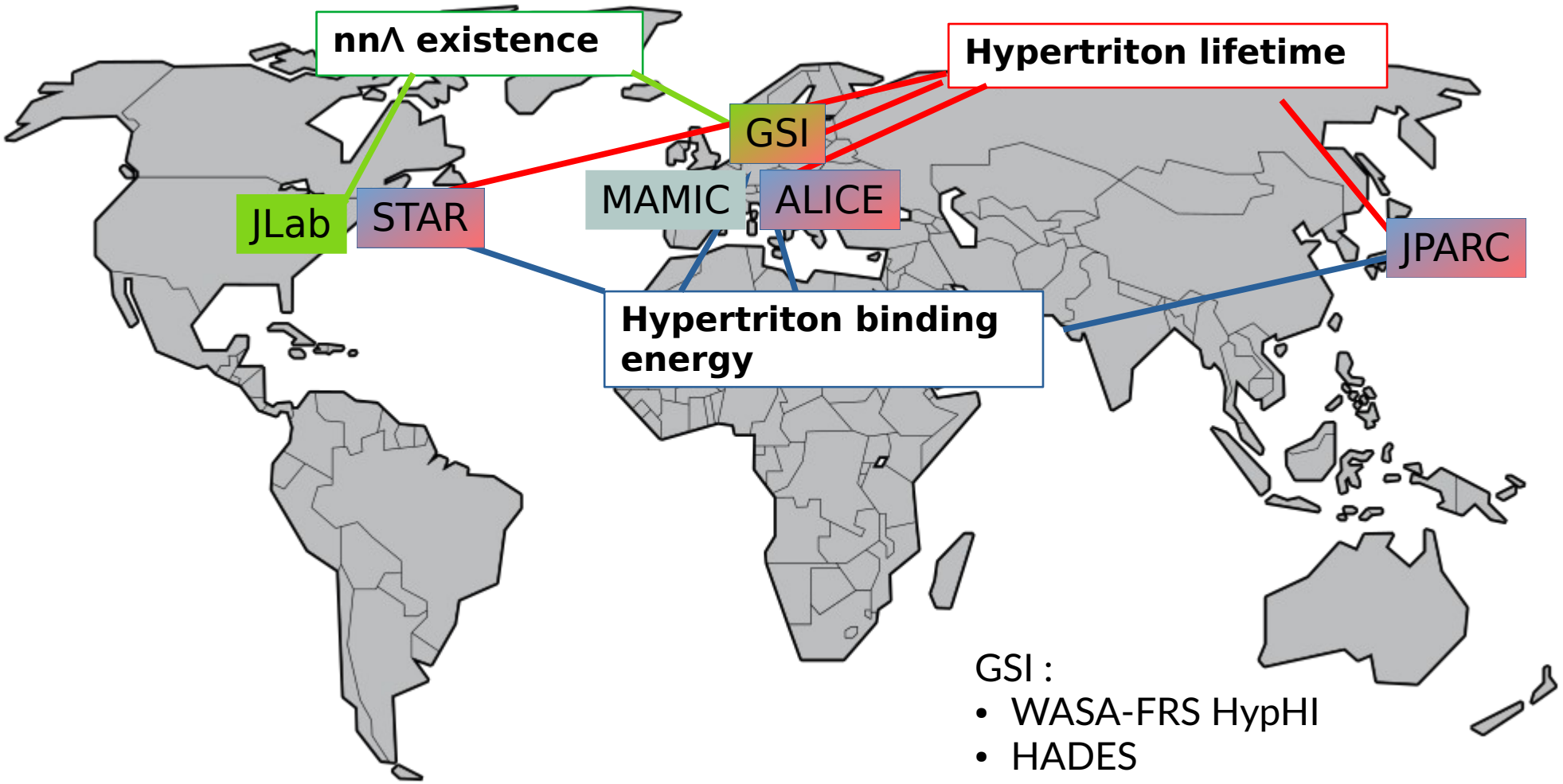
Preliminary data analysis

- **Analysis of WASA central system for hadron measurements :**
  - PID at S2 middle focal plane of FRS:



  - Effect of the isospin in participant zone

World efforts for tackling those puzzles



GSI :

- WASA-FRS HypHI
- HADES
- HYDRA

Summary

- **2 current puzzles in hypernuclear physics: Hypertriton & nnΛ**
  - Many efforts all around the world to tackle them
  - In particular at GSI at lower energy regime:

    HADES, HYDRA, WASA-FRS HypHI
- **In the WASA-FRS collaboration: for the lifetime of $^{3}_{\Lambda}$H and for the existence of nnΛ**
  - The experiment took place beginning 2022, it was very successfully !
  - Currently, the analysis is advancing:

    Calibrations carrying-on & PIDs

    → Hypernuclear event are under reconstruction

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