CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

HENP High Energy Nuclear Physics

NiSHiNA CENTER

GSI

Super-FRS EC

WASA @ FRS: from past to current status of nuclear and hadron physics at FRS

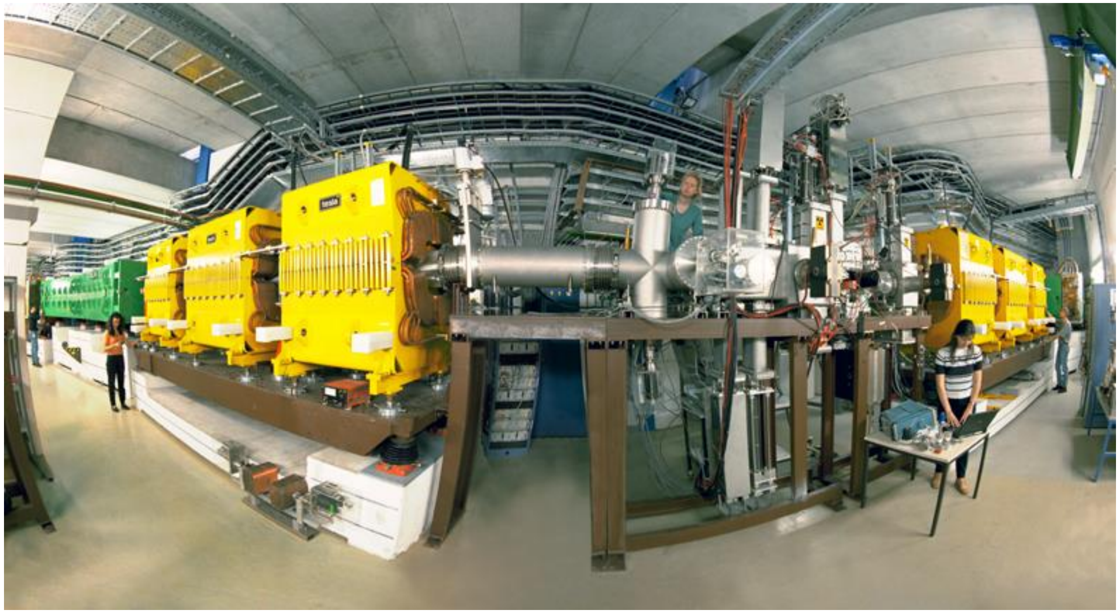
QCD at FAIR workshop 2024

13/11/2024

Christoph Scheidenberger
GSI & Justus-Liebig-Universität Giessen
&
Christophe Rappold
IEM – CSIC, Madrid - Spain

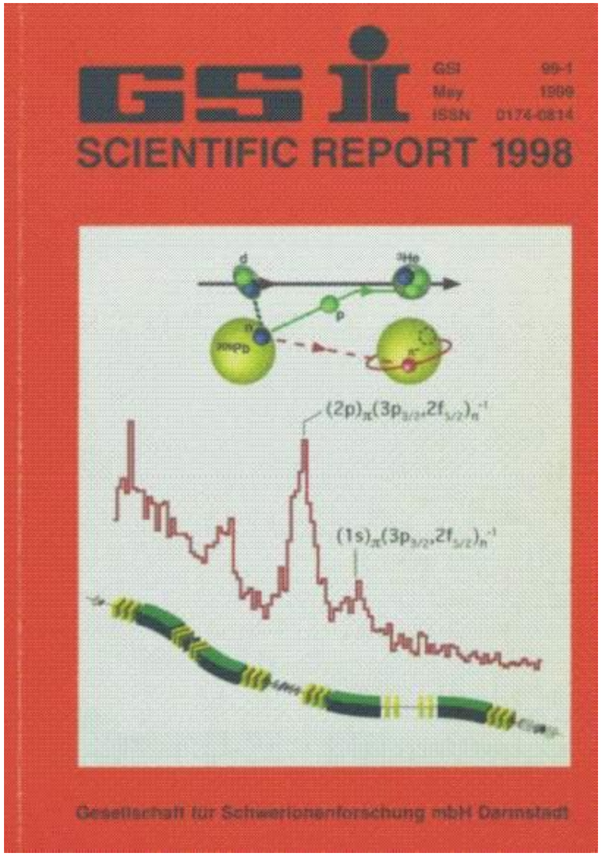
FRS – a versatile instrument for experiments with relativistic beams

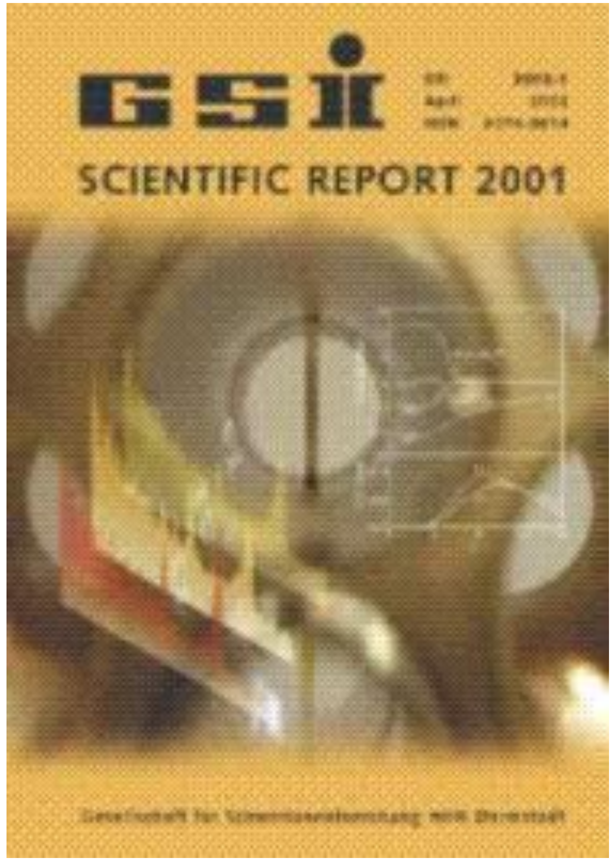
- Production of exotic nuclei and identification (Bρ-ΔE-ToF)
- Separator (cocktail beams, mono-isotopic beams)
- Momentum slit → selective trigger
- Spectrometer (high momentum resolution)
- Different ion-optical modes: analyzer-spectrometer, dispersion matching



- **Anti-proton production**
- **Hadron physics**
- Atomic physics
- Nuclear physics
- Applications

Hadron physics experiments at FRS: a long history

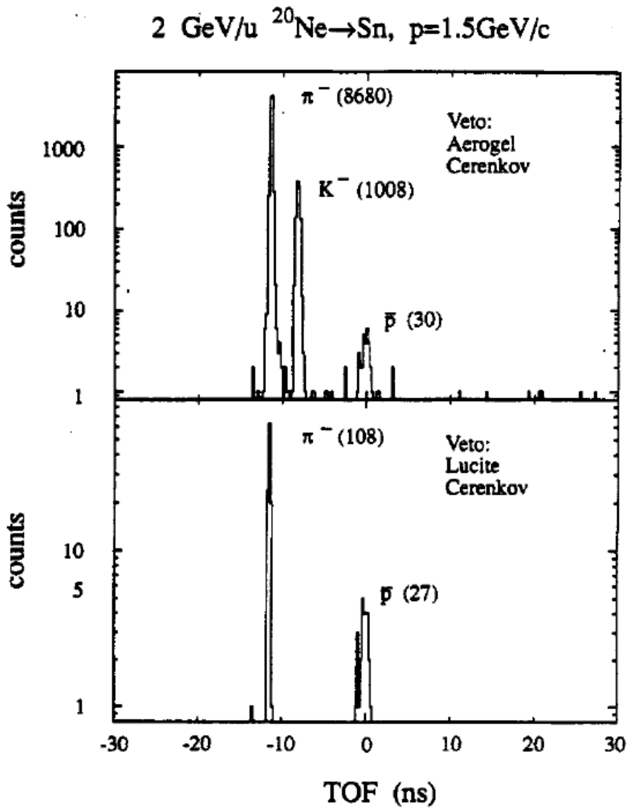


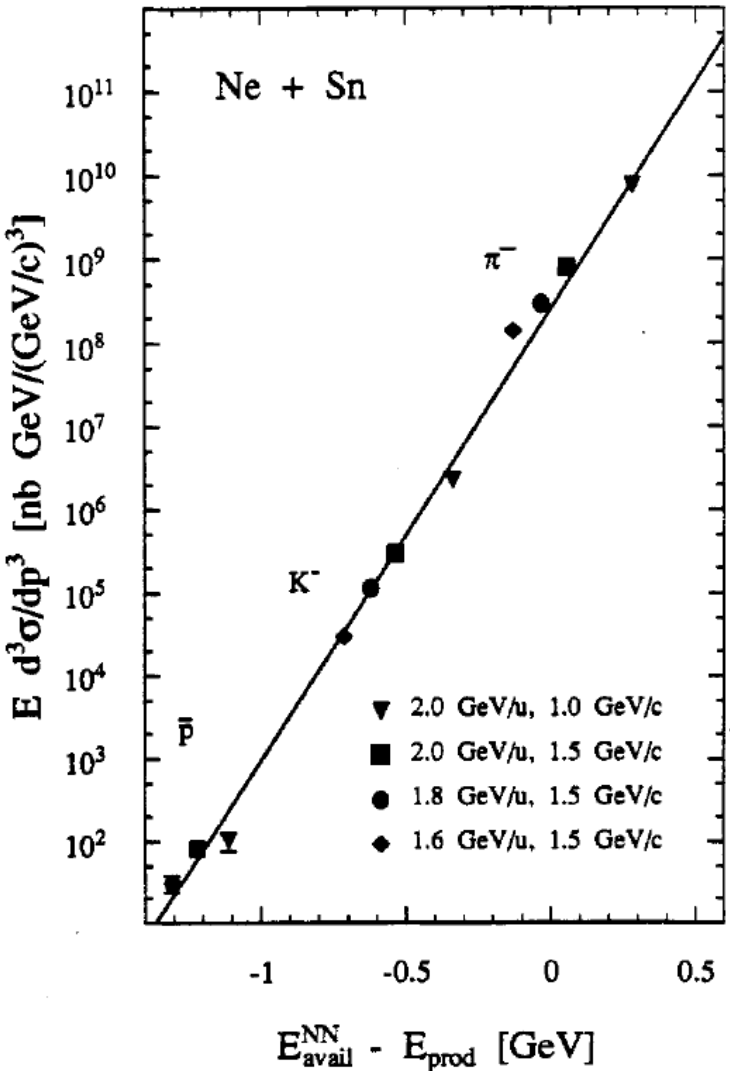


Sub-threshold anti-proton production at FRS

Deeper insight to sub-threshold particle production process:

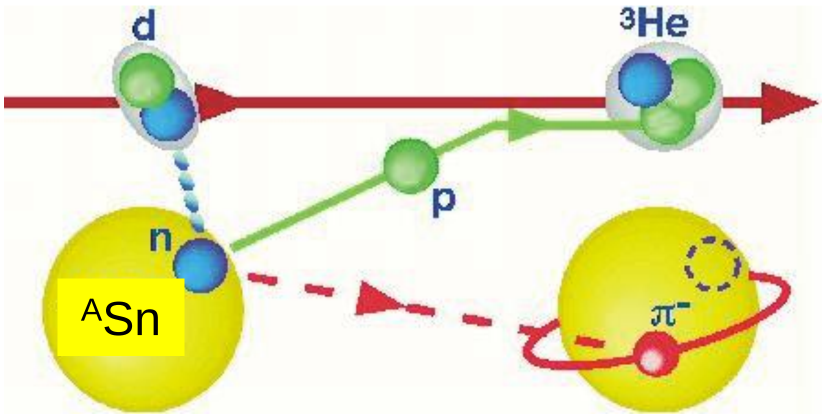
- Energy dependence
- Size and asymmetry dependence
- Momenta of created particles

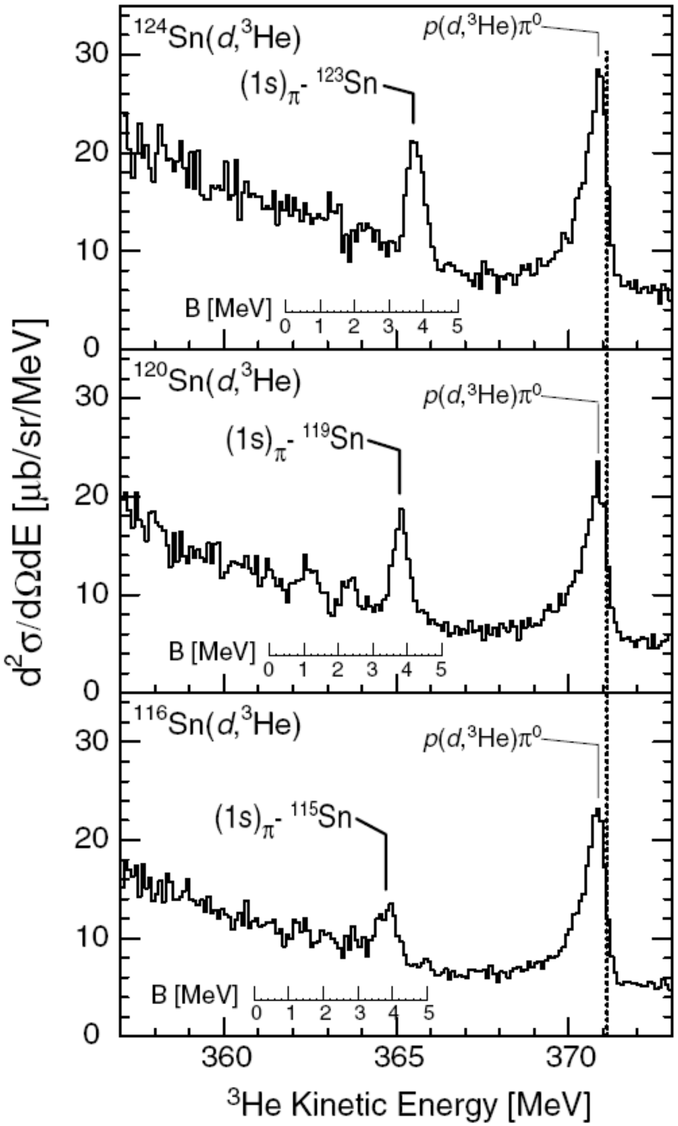




A. Gillitzer et al., Prog. Part. Nucl. Phys. 30 (1993) 97
A. Schröter et al., Physica Scripta 48 (193) 184

Discovery and study of deeply-bound pionic states with FRS



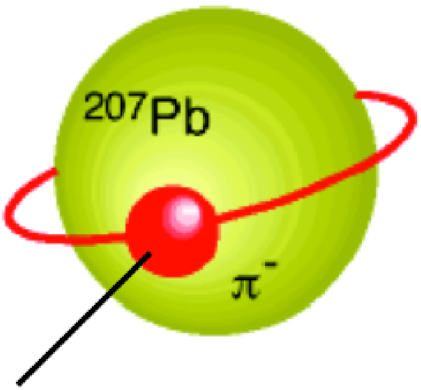


- Pion-nucleus interaction
  → binding energy, width, mass shift
- Difference of s-wave potential
  → restoration of chiral symmetry?
  → reduction of chiral order parameter f_π ?
- Partial chiral restoration in nuclear medium
  → well-defined quantum states
  → saturation density

H. Geissel et al., Phys. Rev. Lett. 88 (2002) 122301
K. Suzuki et al., Phys. Rev. Lett. 92 (2004) 072302

Meson-nucleus bound states

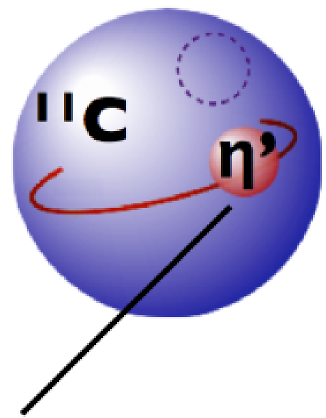
mesic atom



negatively-charged
meson (π^-, K^-, etc.)

electromagnetic
+ strong interaction

mesic nucleus

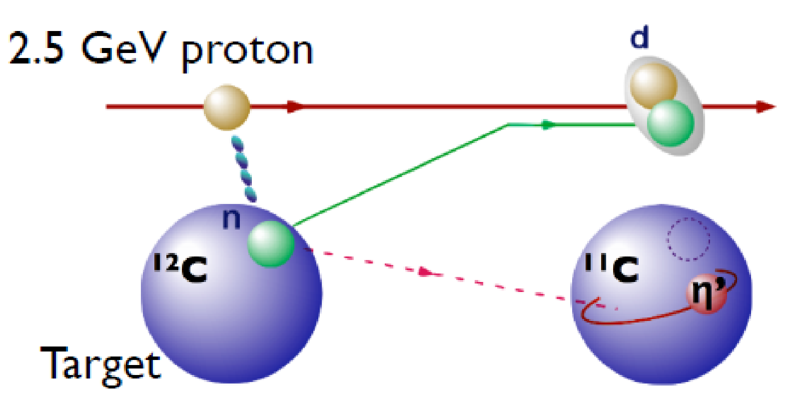


neutral meson (η, η', ω, etc.)

strong interaction only

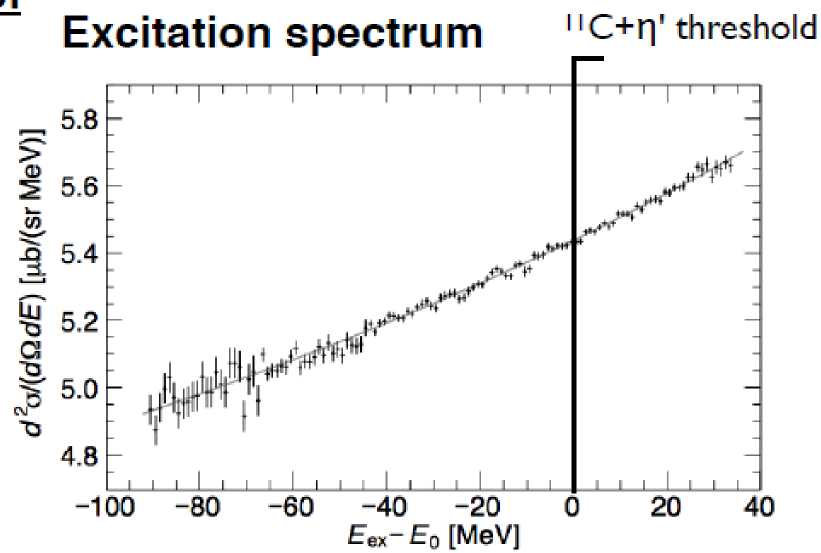
Probe for strong interaction effect
in finite nuclear density

$^{12}C(p,d)$ missing-mass spectroscopy at GSI

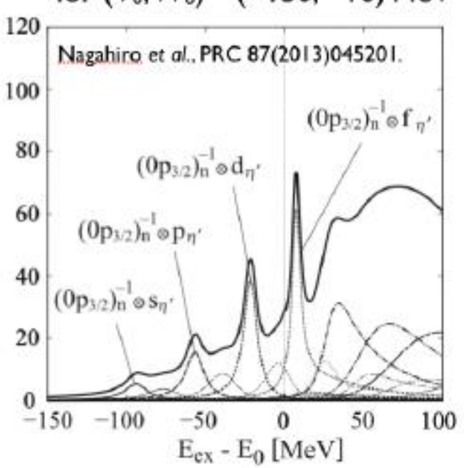


Y.K. Tanaka, K. Itahashi, H. Fujioka et al.
Phys. Rev. Lett. 117 (2016) 202501

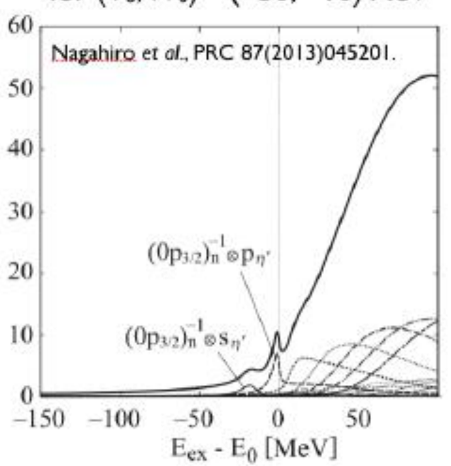
Excitation spectrum



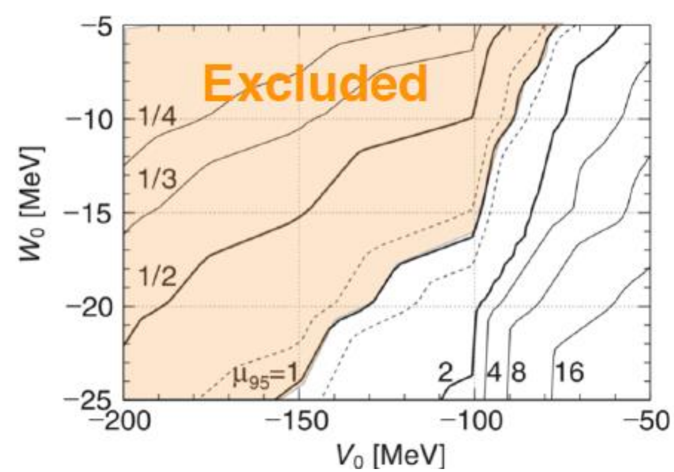
Theoretically expected spectrum for $(V_0, W_0) = (-150, -10)$ MeV



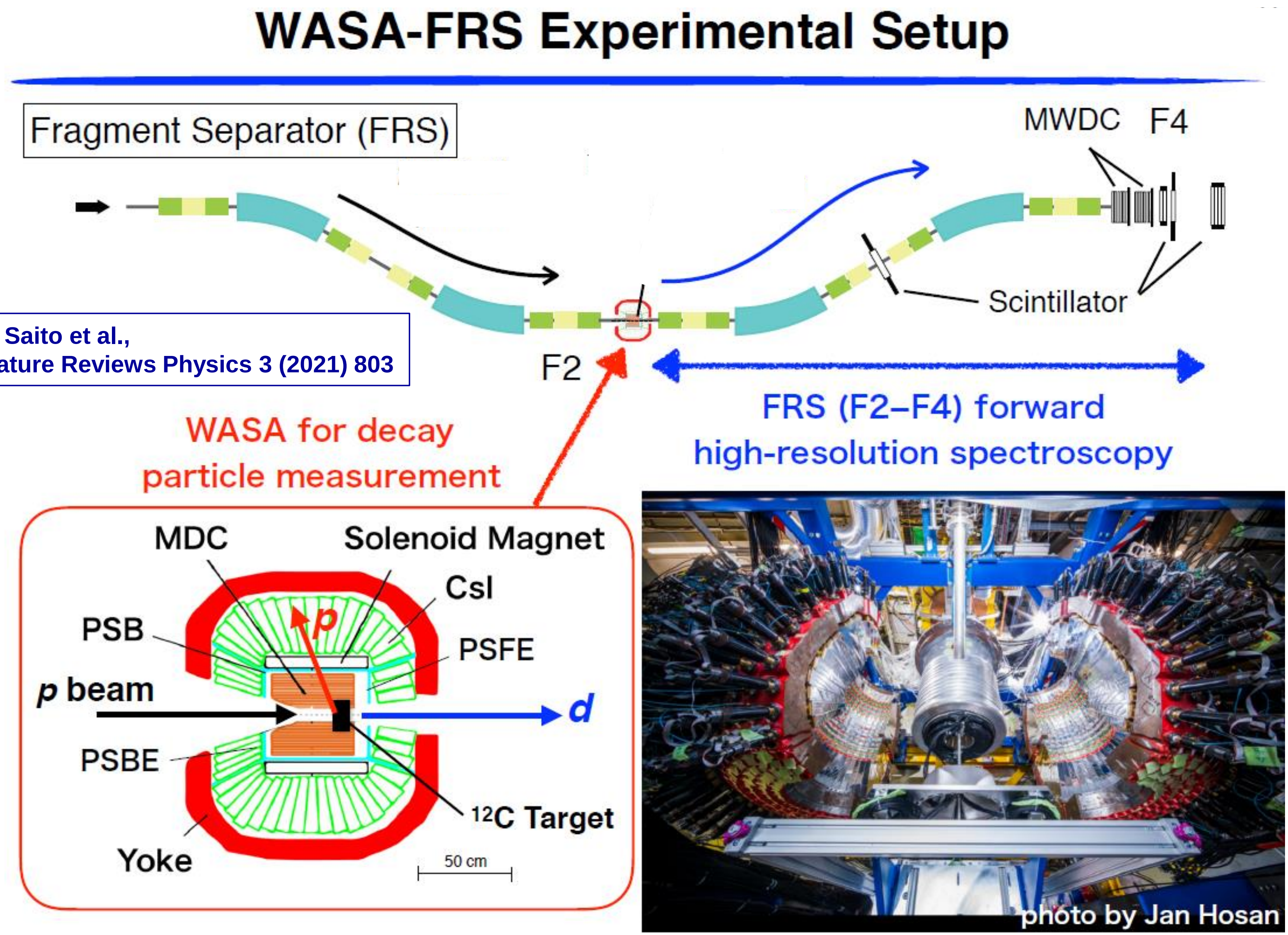
Theoretically expected spectrum for $(V_0, W_0) = (-50, -10)$ MeV



Upper limit of cross section, constraint on potential (V_0, W_0)

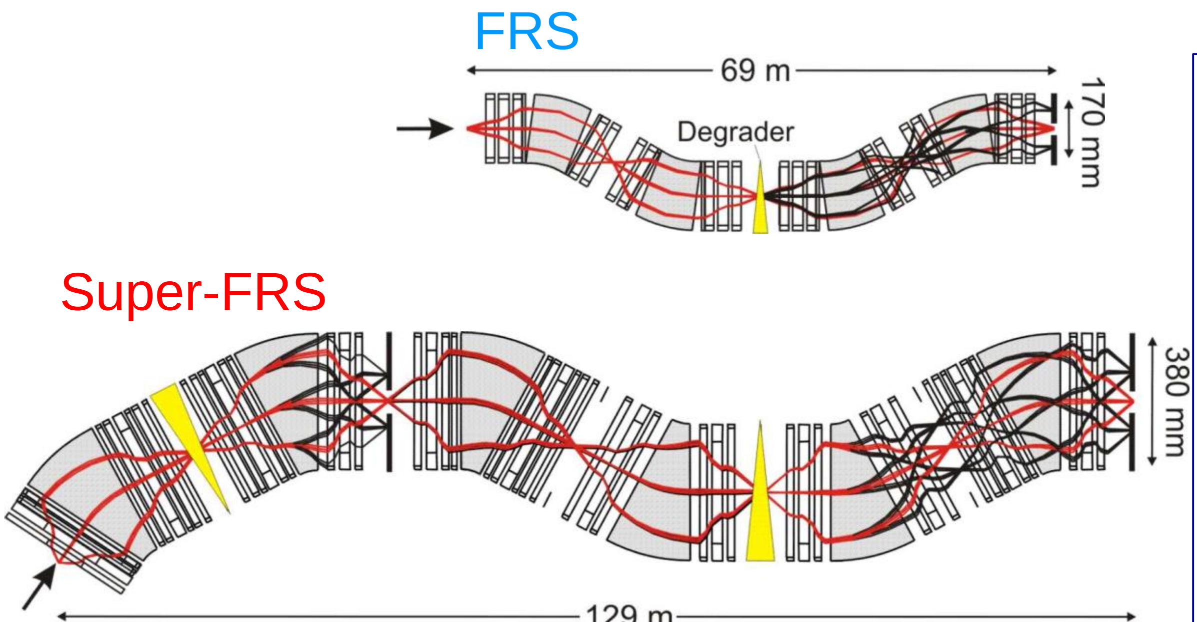


A new era: combination of WASA@FRS (and soon: Super-WASA@Super-FRS)



T. Saito et al.,
Nature Reviews Physics 3 (2021) 803

Opportunities at FRS and Super-FRS



	$B\rho_{max}$	$\Delta p/p$	$\Delta\Phi_x$, $\Delta\Phi_y$	resolving power	gain factor ^{19}C	gain factor ^{132}Sn
FRS	18 Tm	1.0 %	±13, ±13 mrad	1500	1	1
Super-FRS	20 Tm	2.5 %	±40, ±20 mrad	1500	5	10
				including primary rate	250	20 000

H. Geissel et al. Nucl. Instr. Meth. B70 (1992) 247
H. Geissel et al. Nucl. Instr. Meth. B204 (2003) 71

Special features (FRS & Super-FRS):

- **p … U, exotic nuclei, $\pi^{+/-}$, pbar**
- **Dispersion matching**
- **Momentum spectroscopy (dp ≈ 10^{-4}) → missing mass**
- **Selectivity for certain channels**

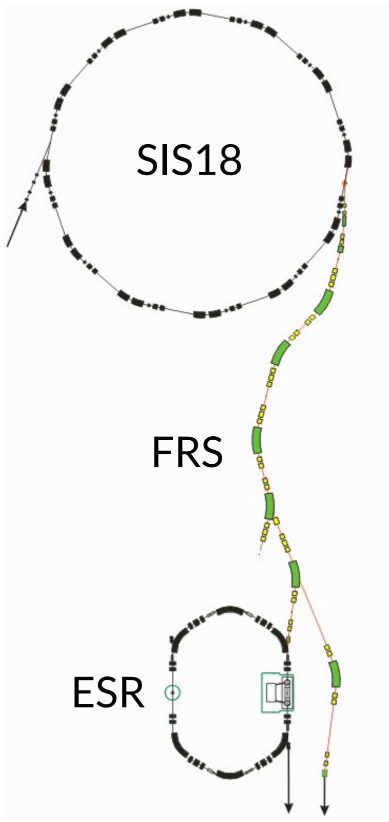
New features (Super-FRS):

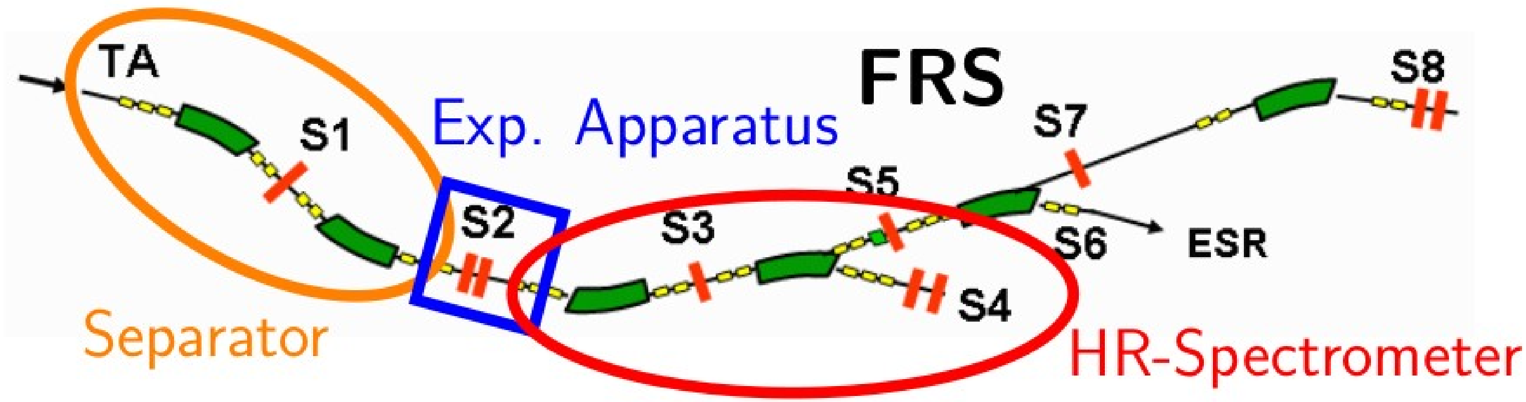
- **SIS-100 energy domain**
- **Pre-separation of secondary beams**
- **Multiple-stage operation**
- **Larger apertures & acceptance**

see contribution by Kenta Itahashi in
"Parallel Session II on white paper's chapter 9"
(today afternoon)

WASA-FRS Experiment : Concept & Layout

GSI facility





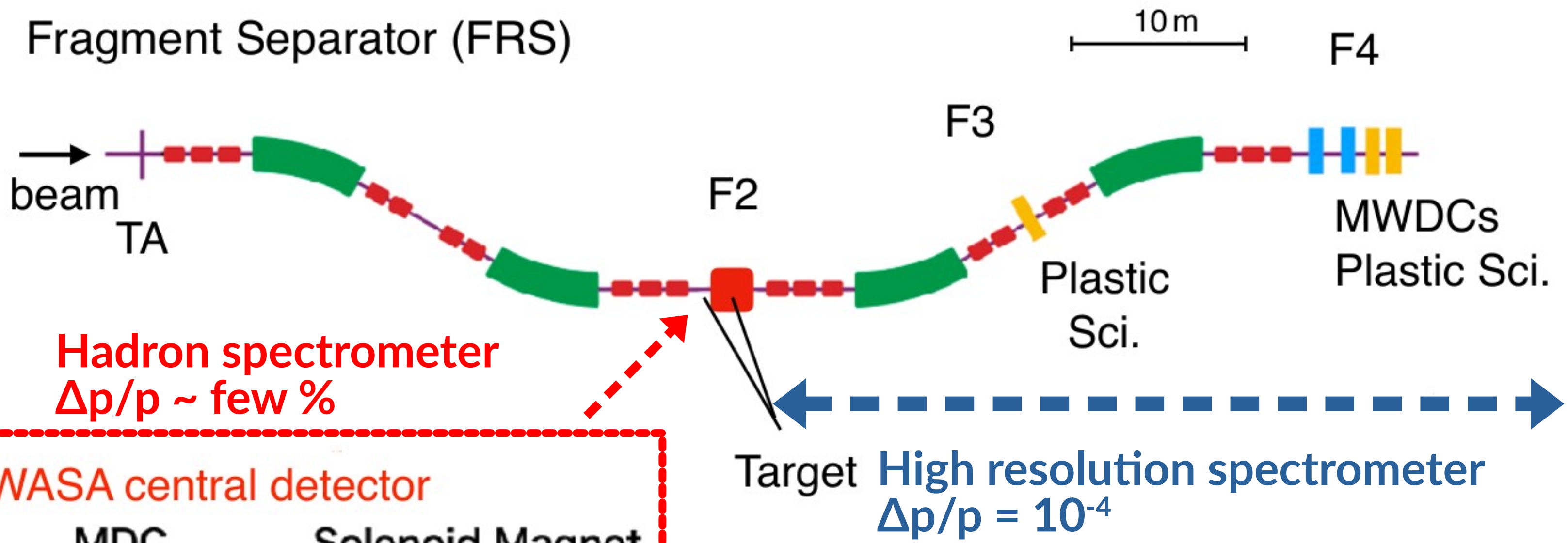
- **We had the opportunity to use WASA central system:**

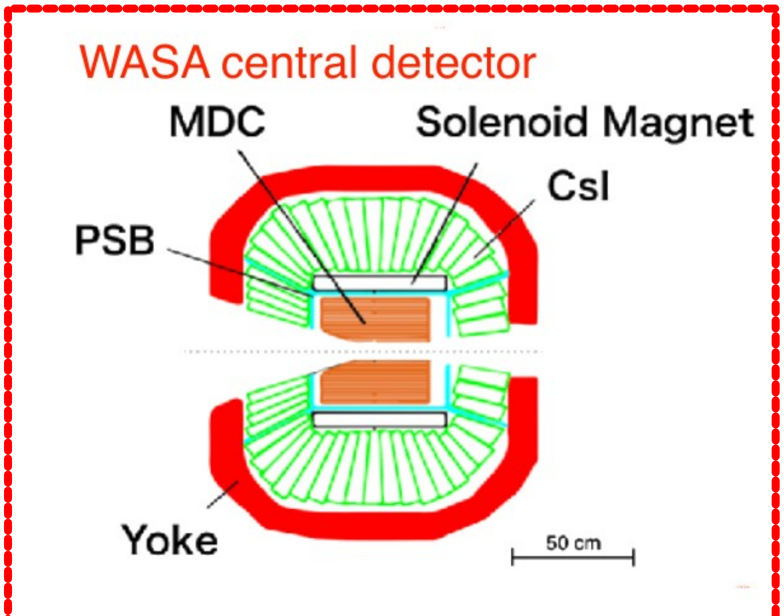
  → Moved to GSI in 2019 from COSY - Jülich

  → Placed in S2 in 2021

- Since 2019, preparation work of the WASA setup with: new detectors & new electronics readouts & cryogenics system & new holding structures
- From original WASA: solenoid & return yoke (with CsI)

WASA-FRS Experimental campaign: Jan. – March 2022





Two experiments took place:

- η'-mesonic nuclei spectroscopy
- Hypernuclei spectroscopy

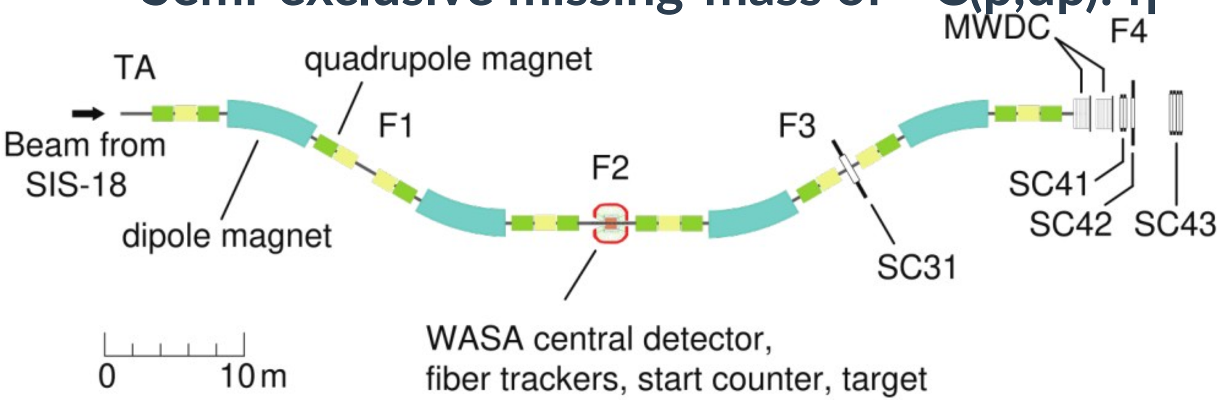
2 of 10 key topic of SuperFRS EC

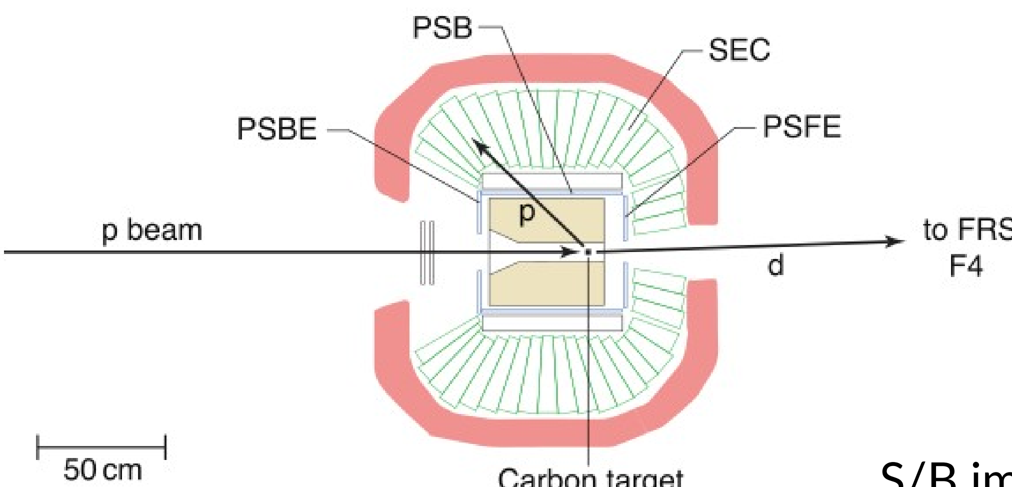
Super-FRS EC

WASA-FRS: Study of η′-mesic Nuclei

- **Study of axial U(1) anomaly & chiral condensate in medium:**

  Semi-exclusive missing-mass of $^{12}C(p,dp)$: η'-^{11}C



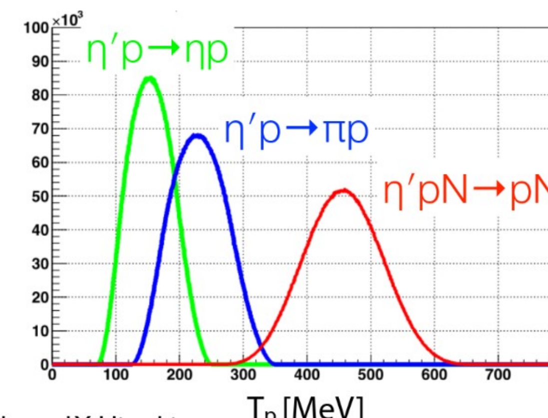


3 decay modes η'-nuclei:

η' p → η p

η' N → π p

η' pN → p N



Y.K.Tanaka and Y. Higashi

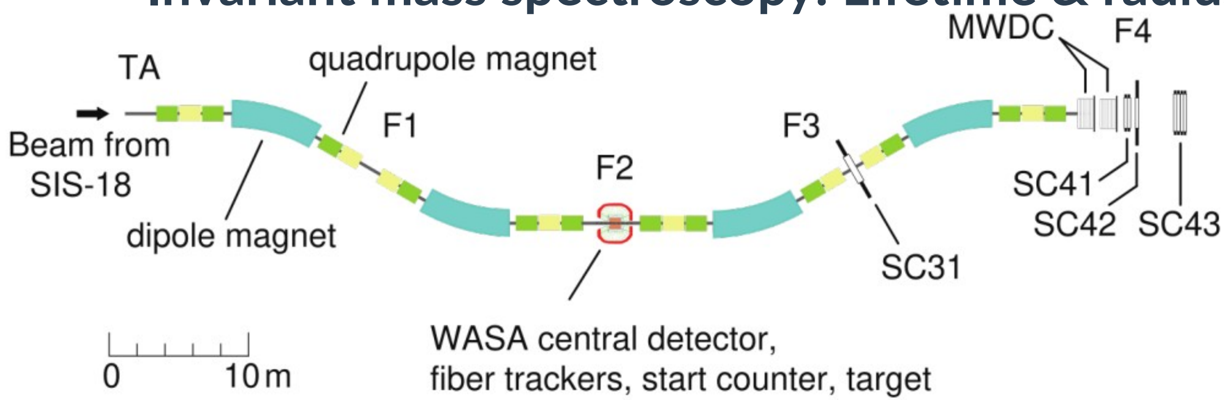
Focus on detection:

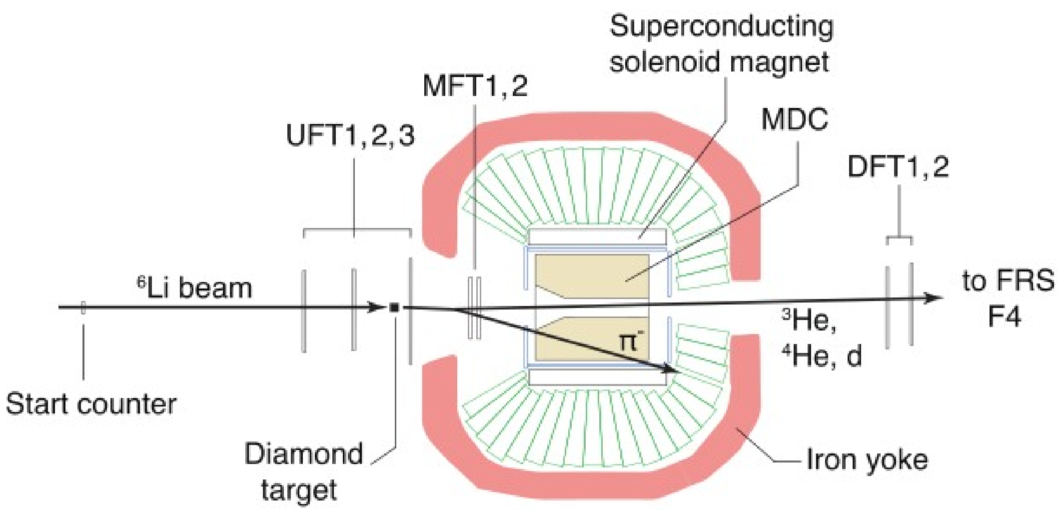
p [300 - 600 MeV] in WASA & d in FRS

S/B improve by 100 in semi-exclusive measurement

WASA-FRS: Study of hypernuclei

- **2 puzzles: possible signal of nnΛ & structure of $^{3}_{\Lambda}H$:**
  Invariant mass spectroscopy: Lifetime & radius





Hypernuclei in nuclei-nuclei collision:

Coalescence of Λ or (π+ , K+) reaction in spectator fragment

→ ~ velocity as projectile (boosted)

→ In-flight study

Focus on mesonic weak decay of:

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

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

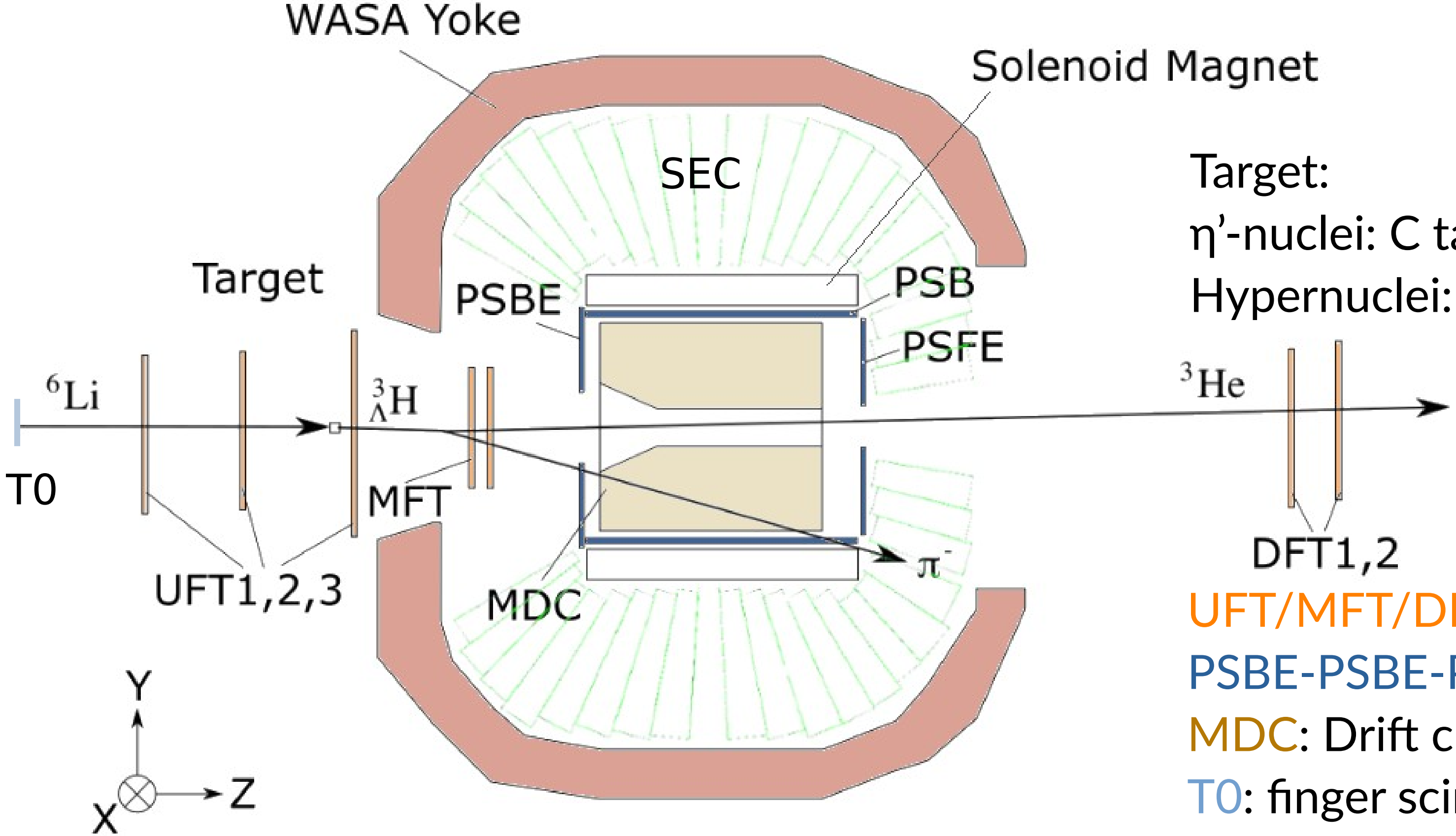
π- measured in WASA
^{3}He, ^{4}He, d measured in FRS

→ Vertex reconstruction behind target

Experimental apparatus: WASA-FRS

- **At the middle focal plane of FRS:**

Fixed target, Reaction : η'-nuclei: p + 12C @ 2.5 GeV, 2.5 10^8/s
Hypernuclei: ^{6}Li+ ^{12}C @ 1.96 GeV/u, 2 10^7/s

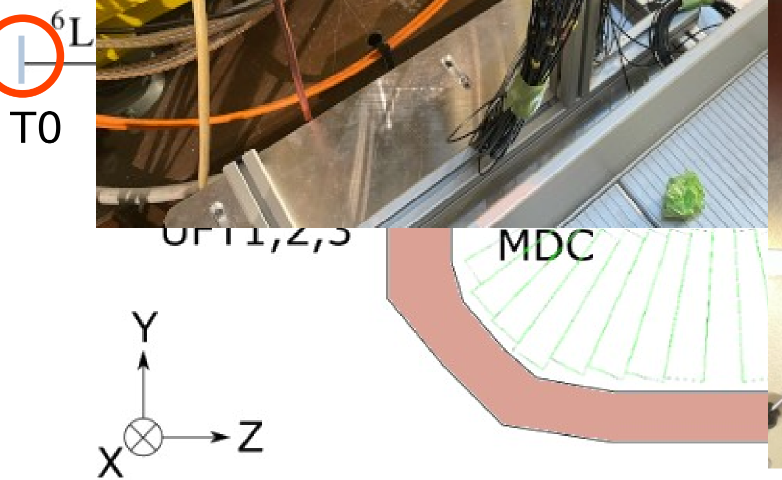


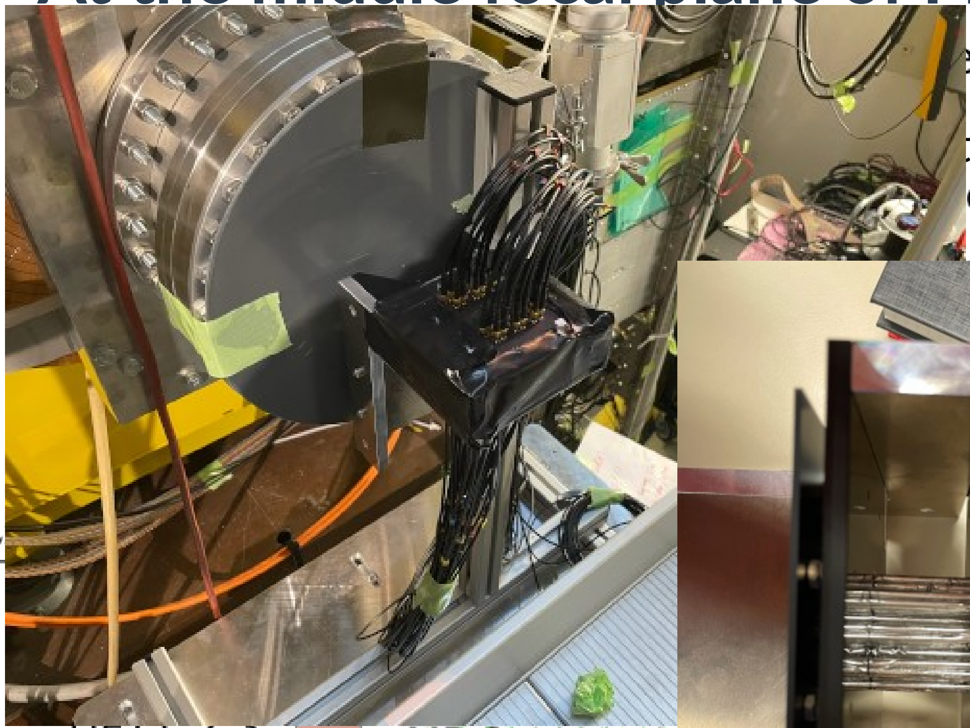
Target:
η'-nuclei: C target: 8 g/cm^2
Hypernuclei: C target: 9.87 g/cm^2

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:





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

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

enoid Magnet

T0 detector:

- 28 segments 1.5 x 1.5 mm² x 4.5 cm
- Total size 3.4 x 4.5 cm²
- Start timing of the Time-of-Flight
- Time resolution: σ ~ 40 ps
- < 2MHz per segment → 2 10^7 total beam intensity
- E. Liu et al., NIM A **1064**, 169384 (2024)

/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:**

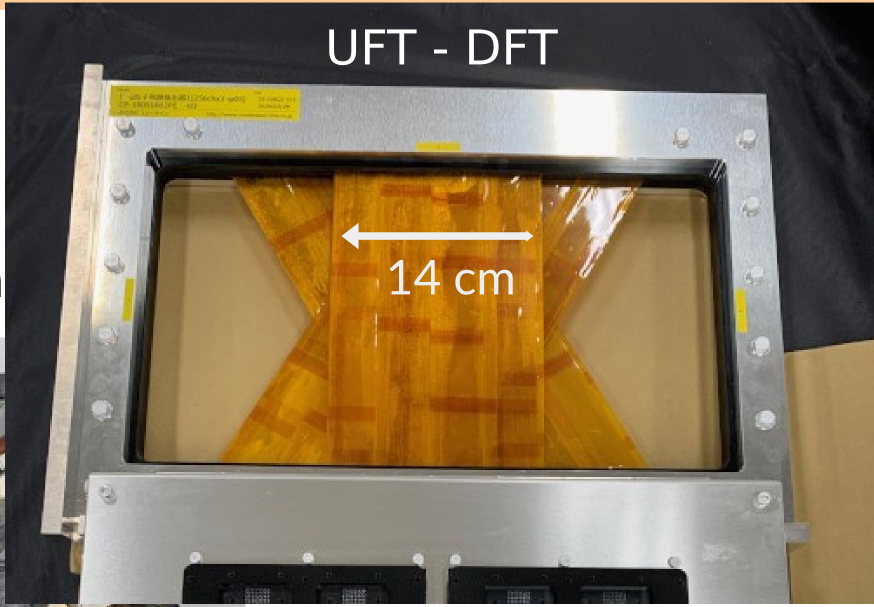
3n → d+π⁻ … 3H → 3He+π⁻

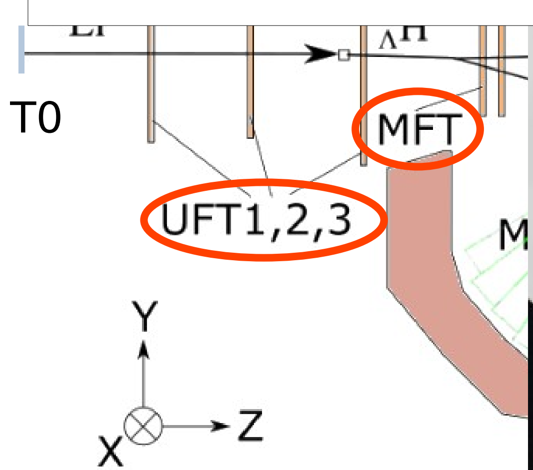
…ction : 6Li+

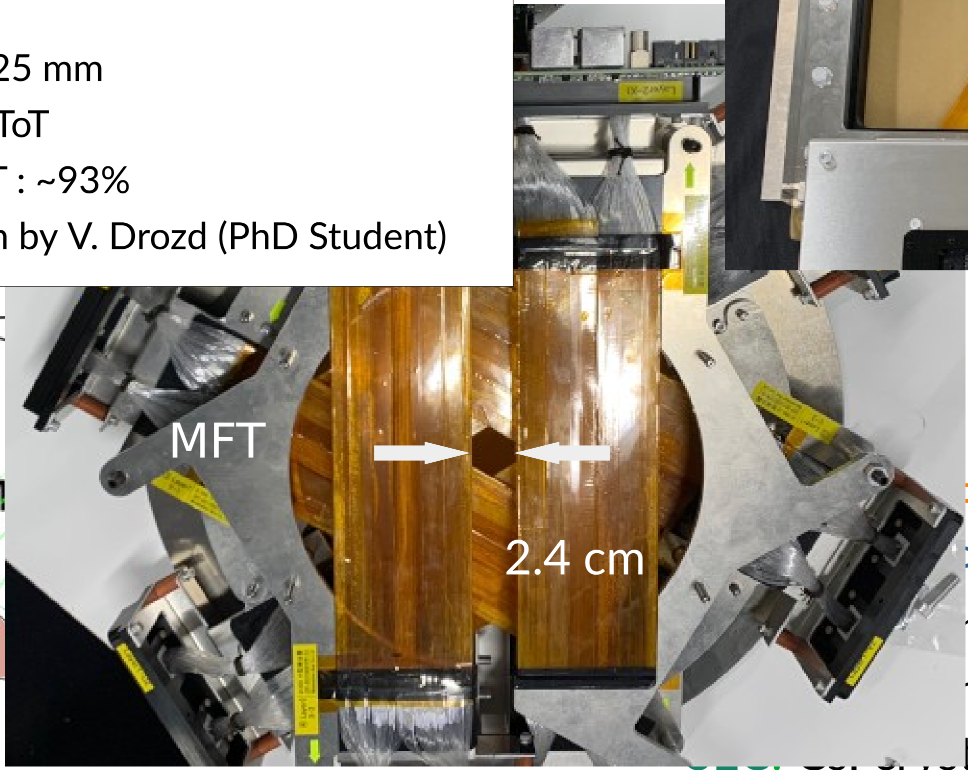
…lenoid Ma…

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%
- NIMA paper in preparation by V. Drozd (PhD Student)







…FT: Fiber Trackers

…PSFE: Plastic scintillators

…hambers base on straw tubes

…ntillators

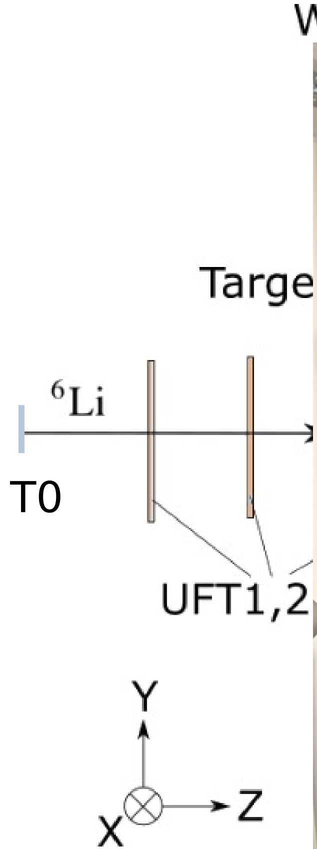
…tal calorimeter

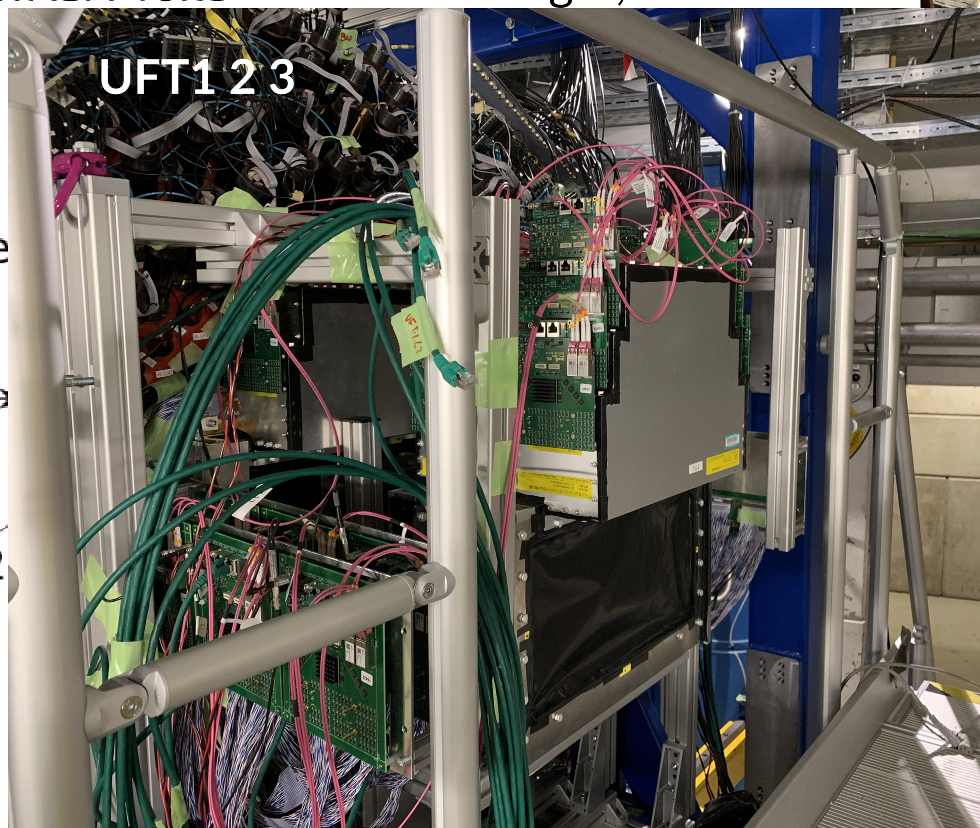
Experimental apparatus: WASA-FRS HypHI

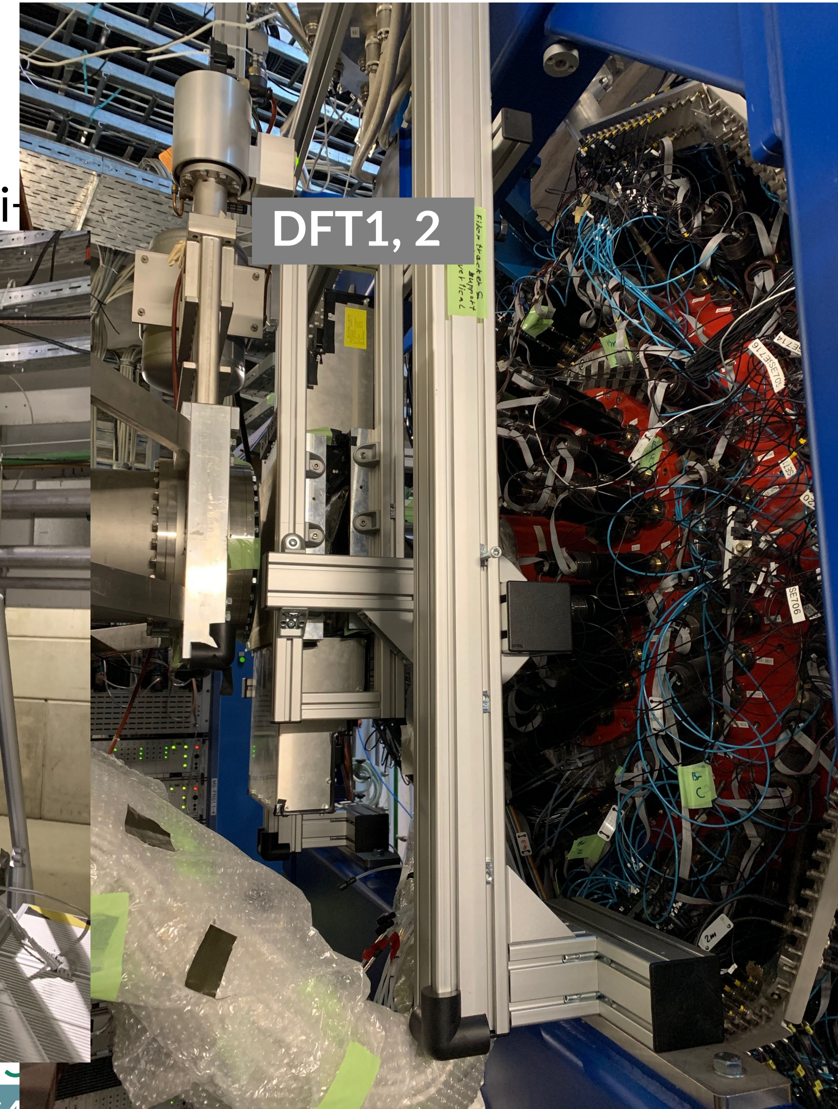
- **At the middle focal plane of FRS:**

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

Fixed target, Reaction : ^{6}Li-







Experimental apparatus: WASA-FRS HypHI

- **At the middle focal plan**

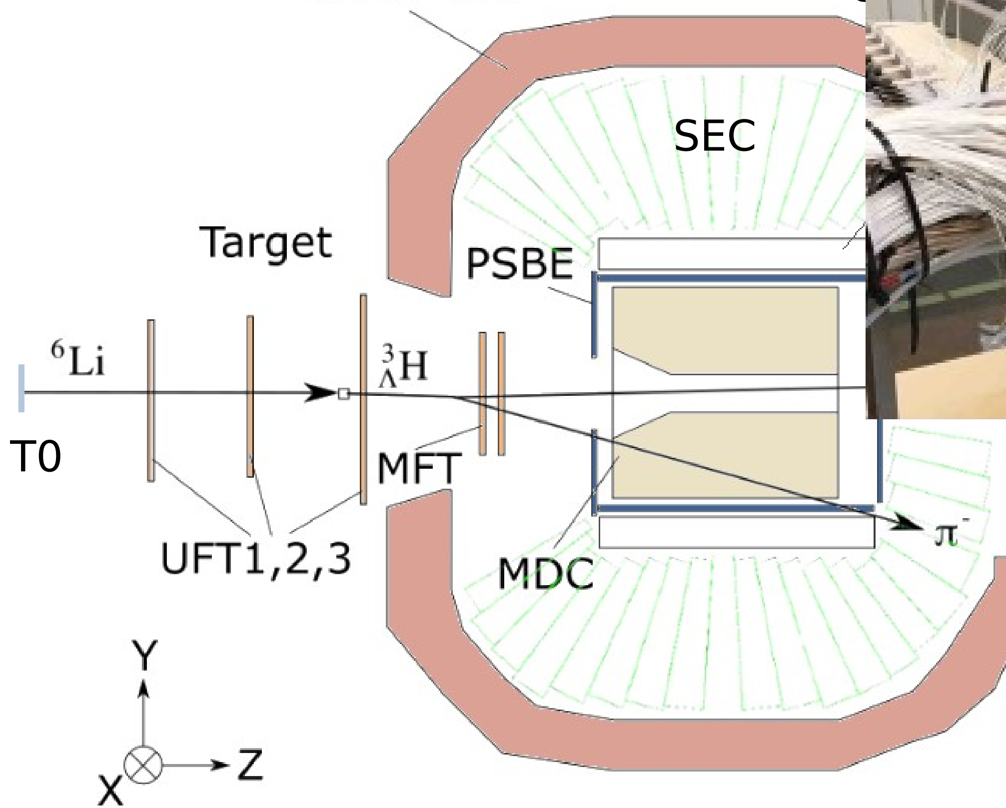
$^{3}_{\Lambda}\mathrm{n} \rightarrow \mathrm{d} + \pi^{-} + (\mathrm{n})$ $^{3}_{\Lambda}$

Fixed targ

2.7 GeV

10^{7}/s

es



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

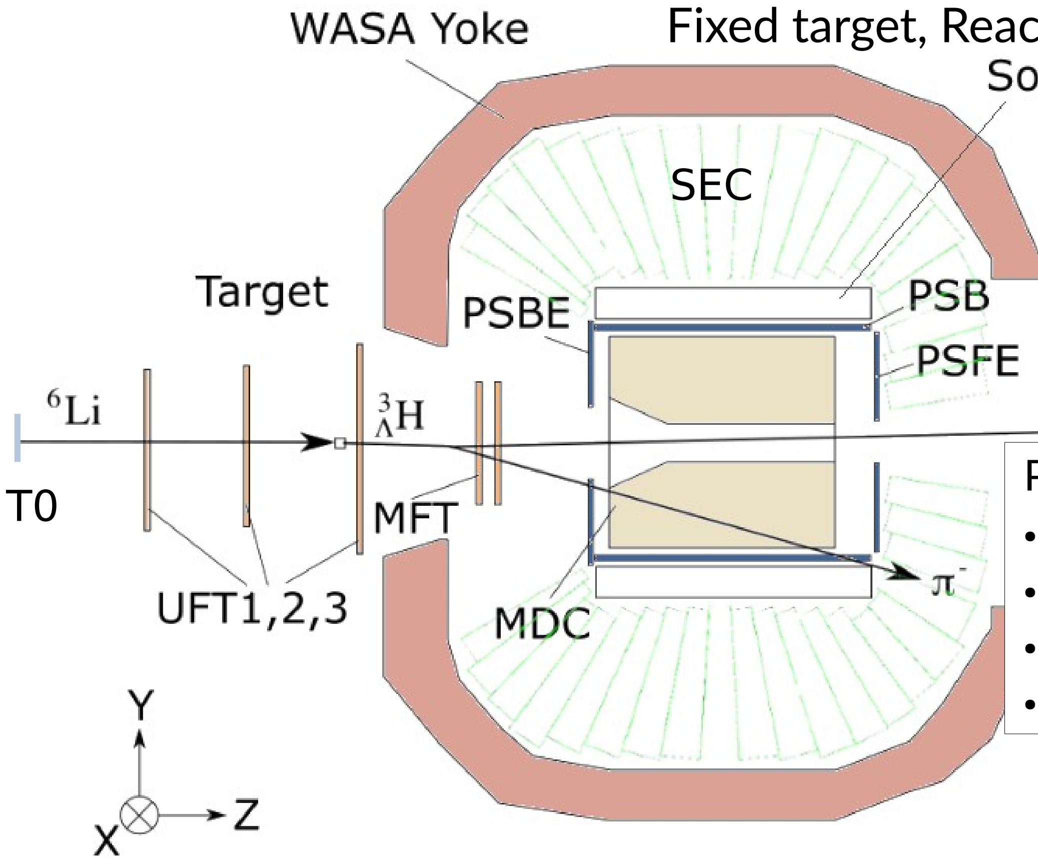
- At the middle focal plane of F

$^{3}_{\Lambda}n \rightarrow d + \pi^{-} + (n)$ $^{3}_{\Lambda}H \rightarrow {}^{3}He$ … π^{-}

Fixed target, Reac… $_{NN}$ = 2.7 GeV

cm²

~ 2 x 10⁷/s



PSB: Plastic scintillator barrel

- 48 bars, size : 55 x 3.8 x 0.8 cm³
- Stop ToF & final positions of charged hadrons
- Time & Position resolution: σ_t ~ 85 ps & σ_z ~ 1 cm
- R. Sekiya et al. NIMA **1034** (2022) 166745

…tors

MDC: Drift chambers base on straw tubes

T0: finger scintillators

SEC: CsI crystal calorimeter

Experimental apparatus: WASA-FRS HypHI

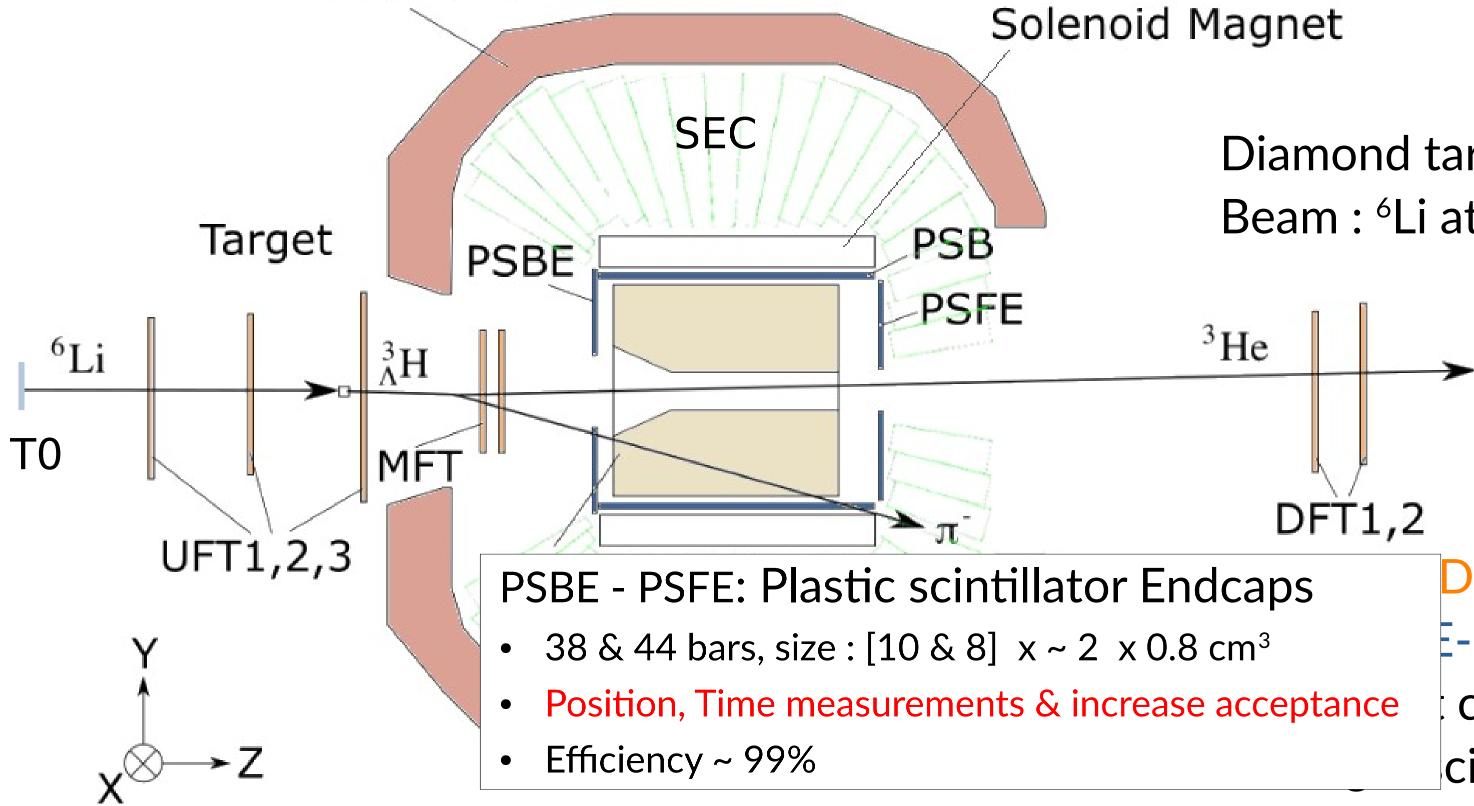
- **At the middle focal plane of FRS:**

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

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

c ubes

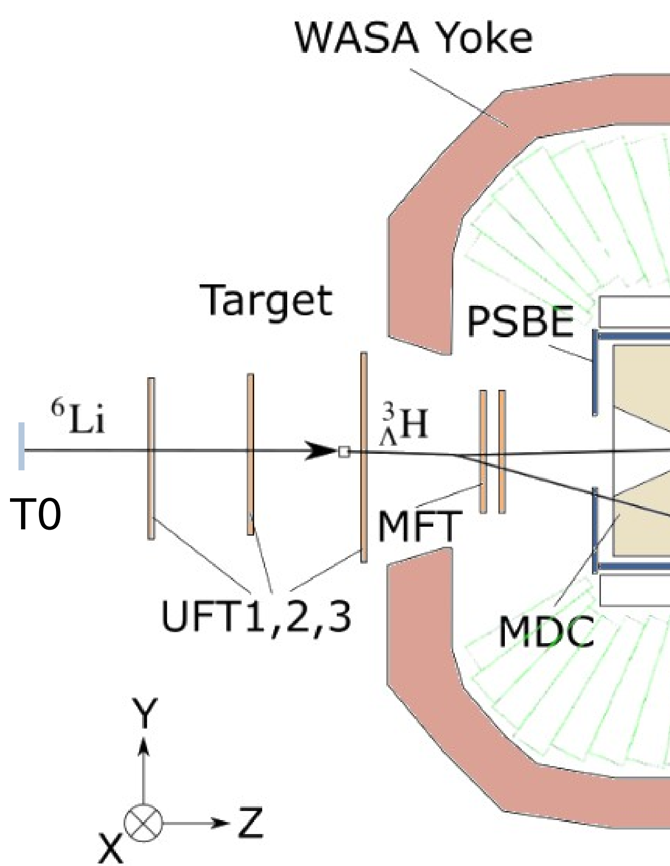
cintillators

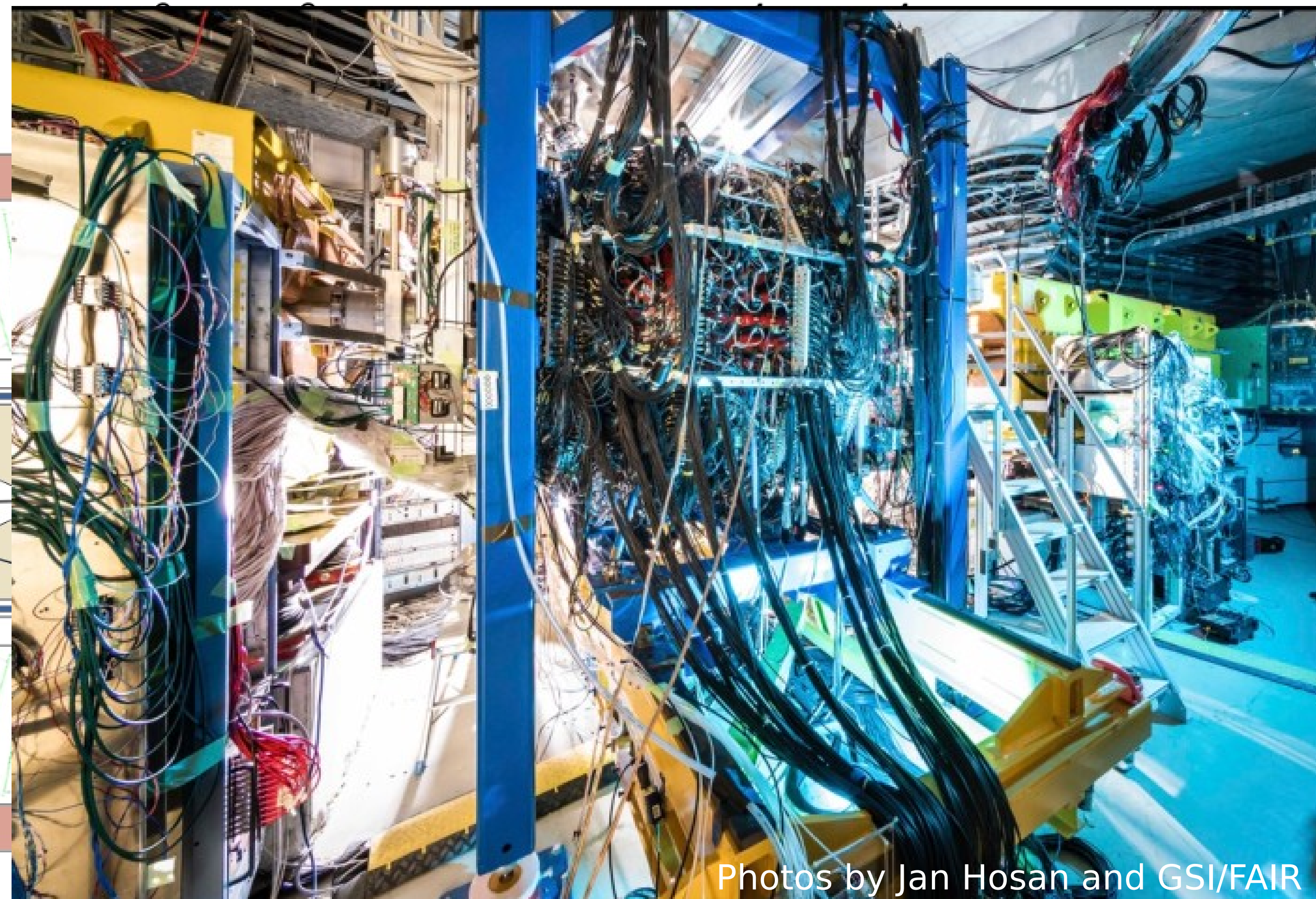
SEC: CsI crystal calorimeter

Experimental apparatus: WASA-FRS HypHI

- **At the middle focal plane of FRS:**

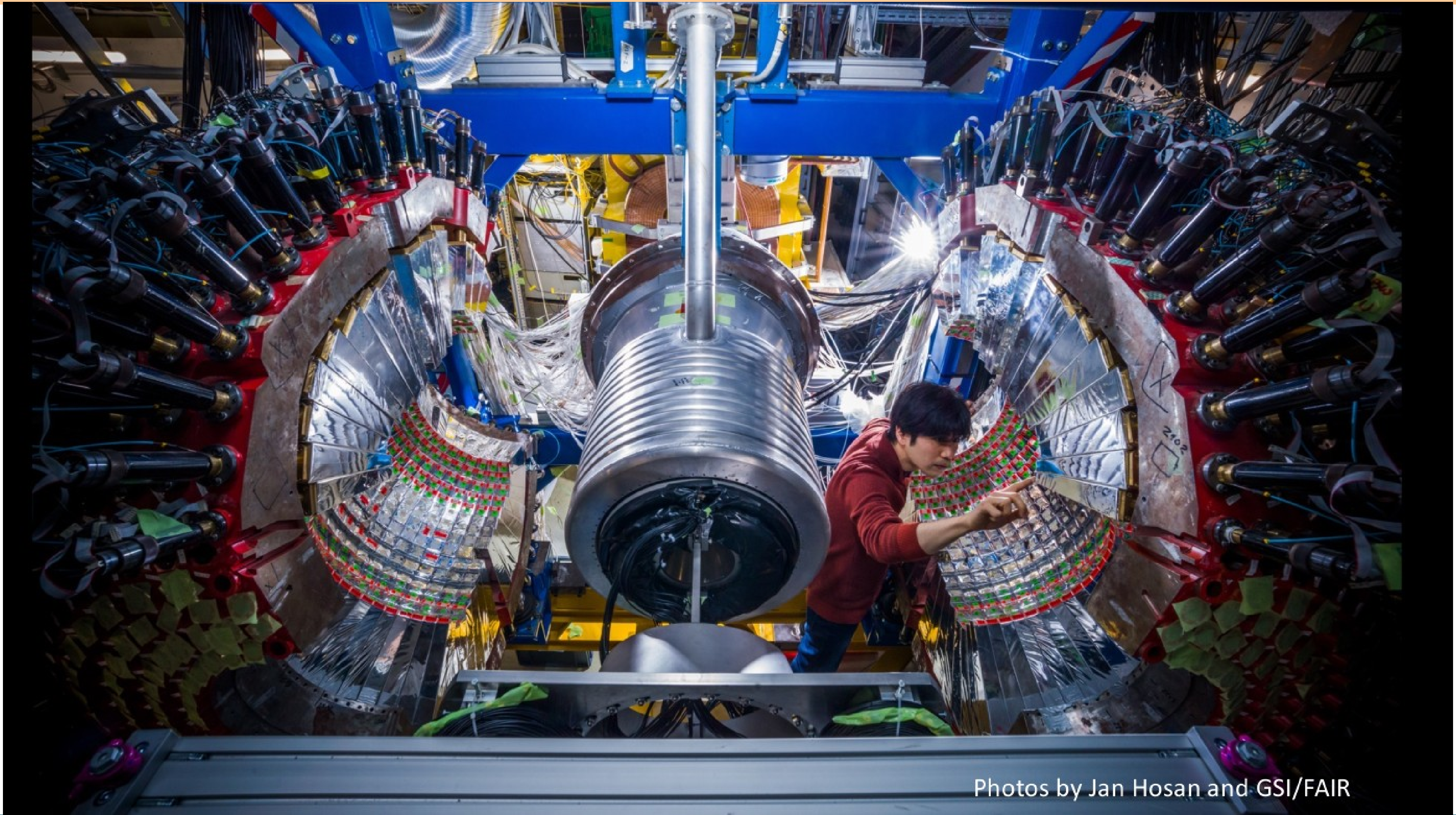
$^{3}_{\Lambda}n \rightarrow d + \pi^{-} + (n)$





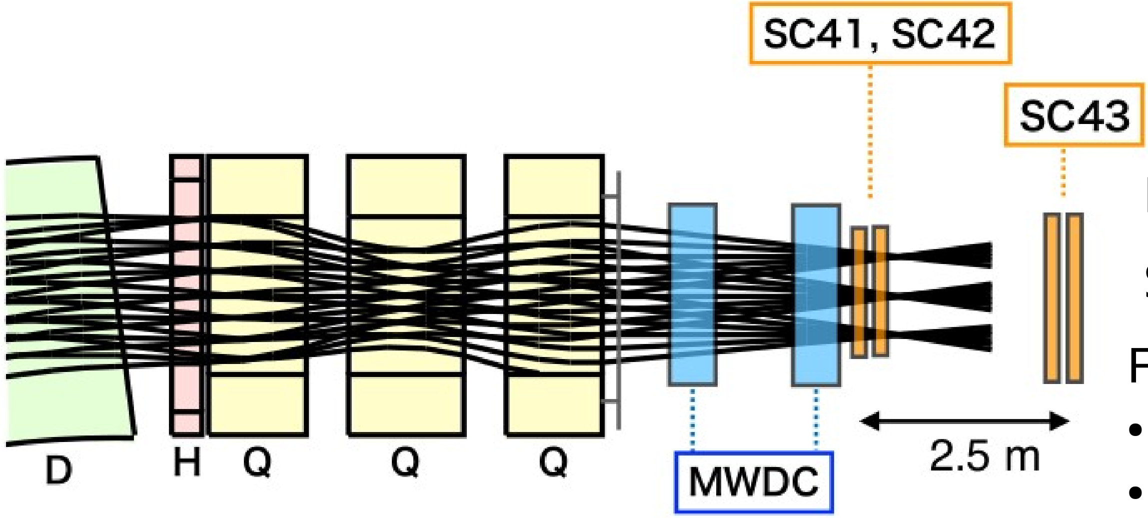
SEC: CsI crystal calorimeter

Experimental apparatus: WASA-FRS HypHI



Experimental apparatus: WASA-FRS HypHI

- At the final focal plane of FRS:

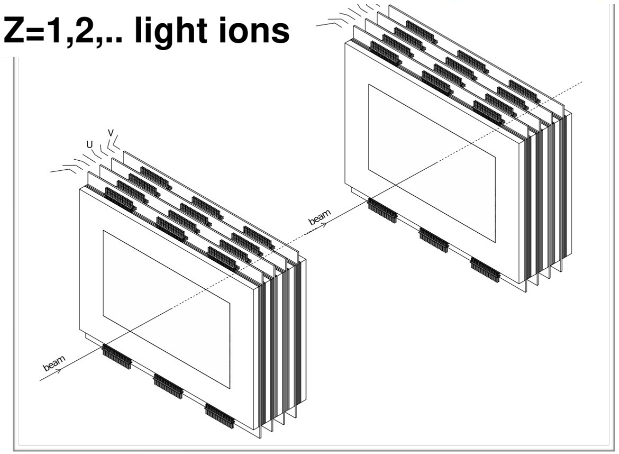


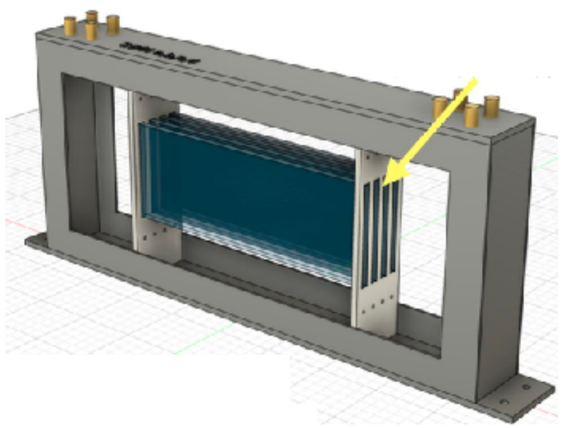
MWDC: Multi-Wire Drift Chamber

SC: stacked scintillator

For Z=1 and Z=2 ion measurements:

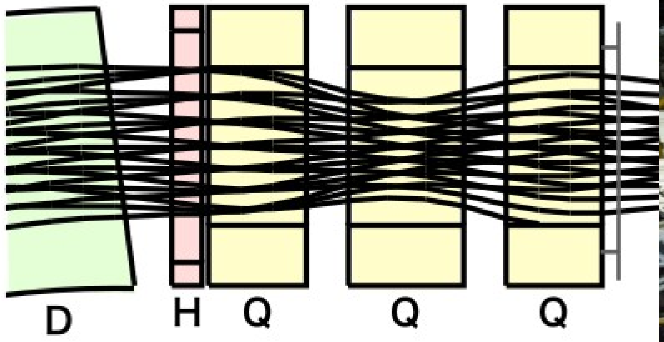
- Tracking of focal plan → Bρ
- TOF

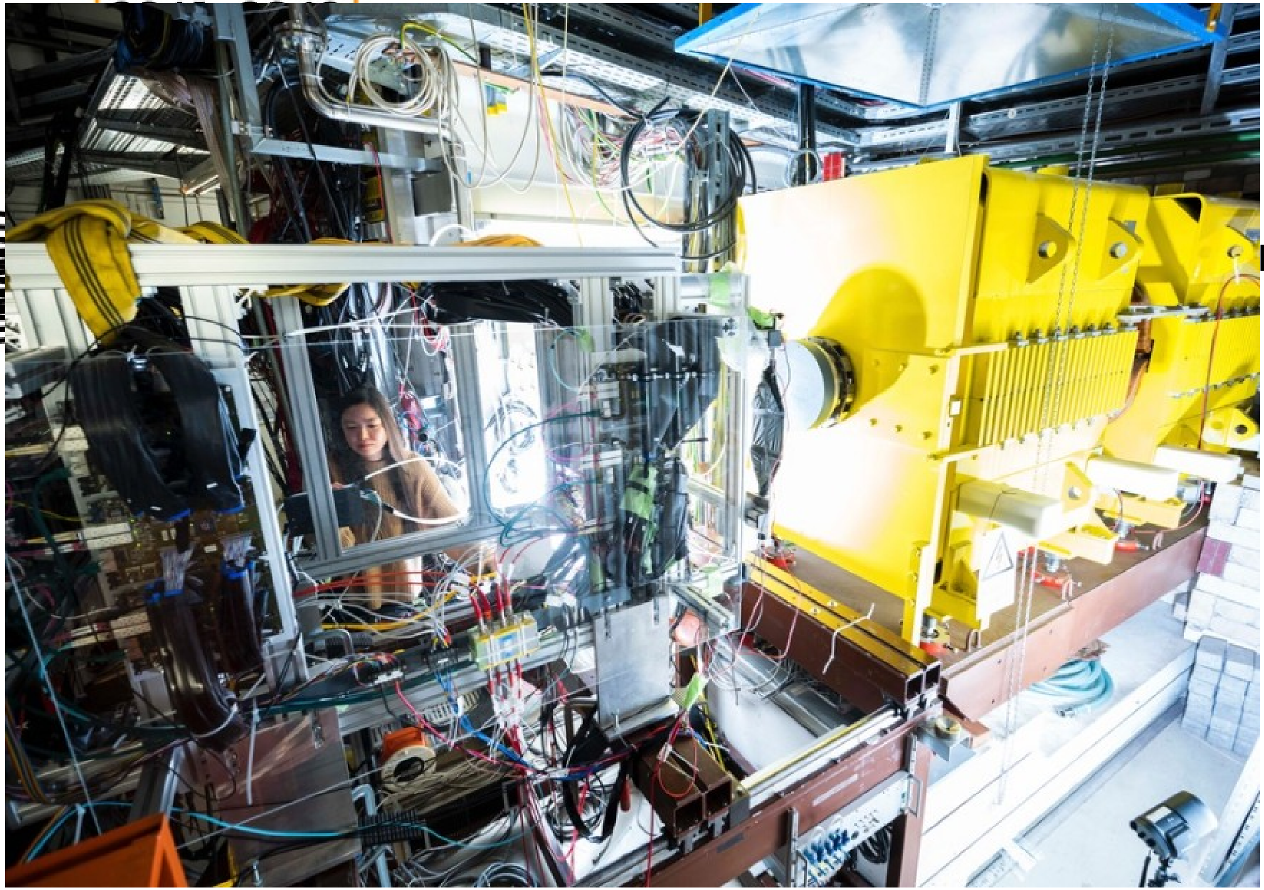




Experimental apparatus: WASA-FRS HypHI

- At the final focal plane of FRS:



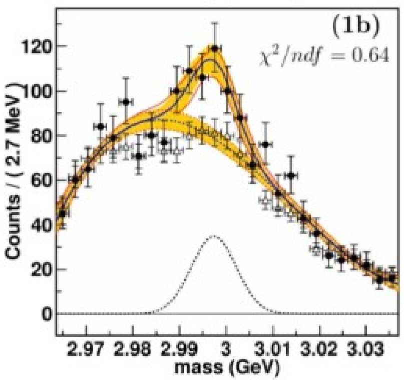


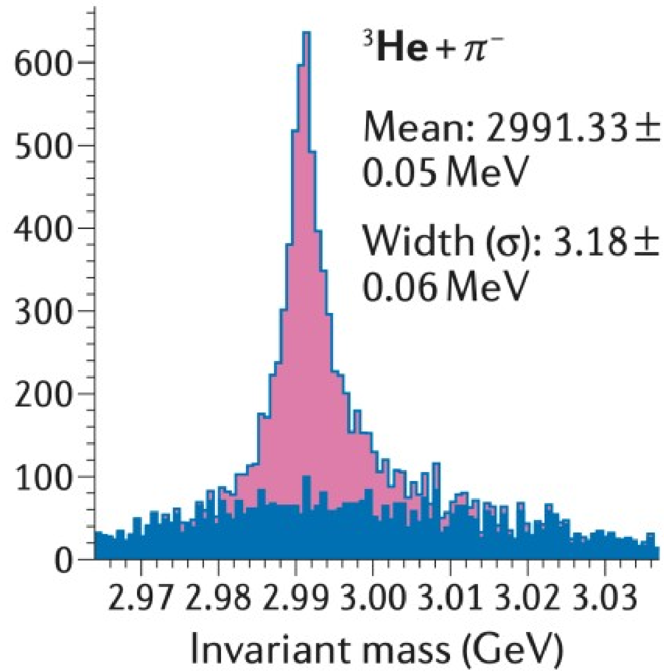
Photos by Jan Hosan and GSI/FAIR

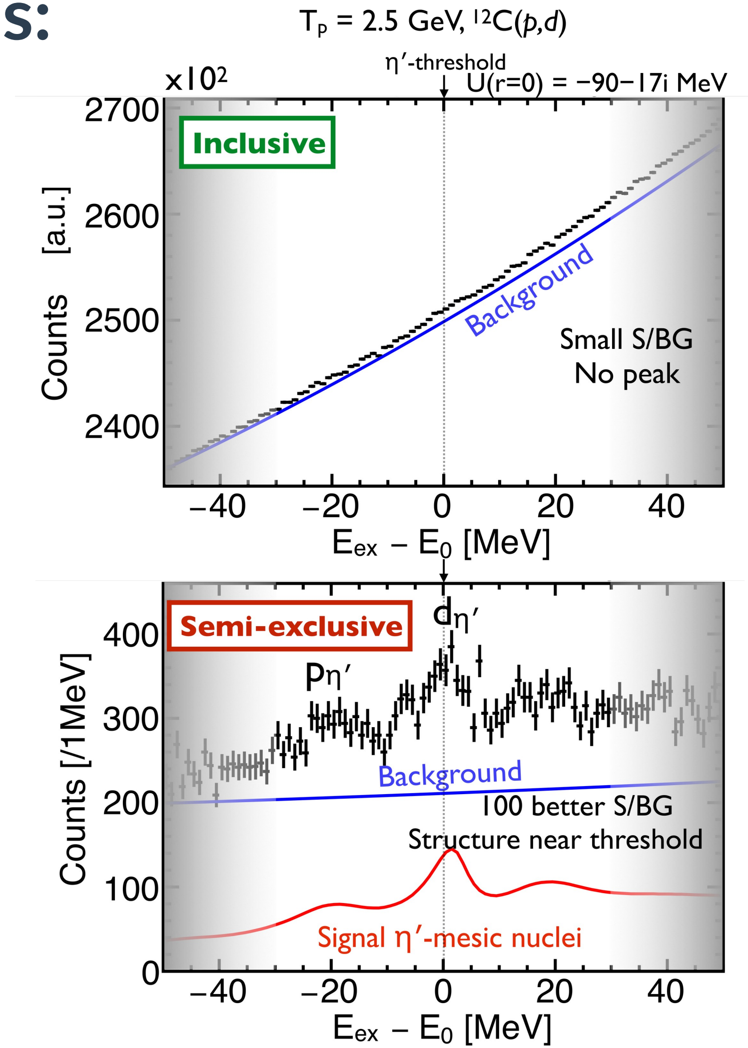
Expected performances

- **Expected results by MC simulations:**

Former HypHI (2012)







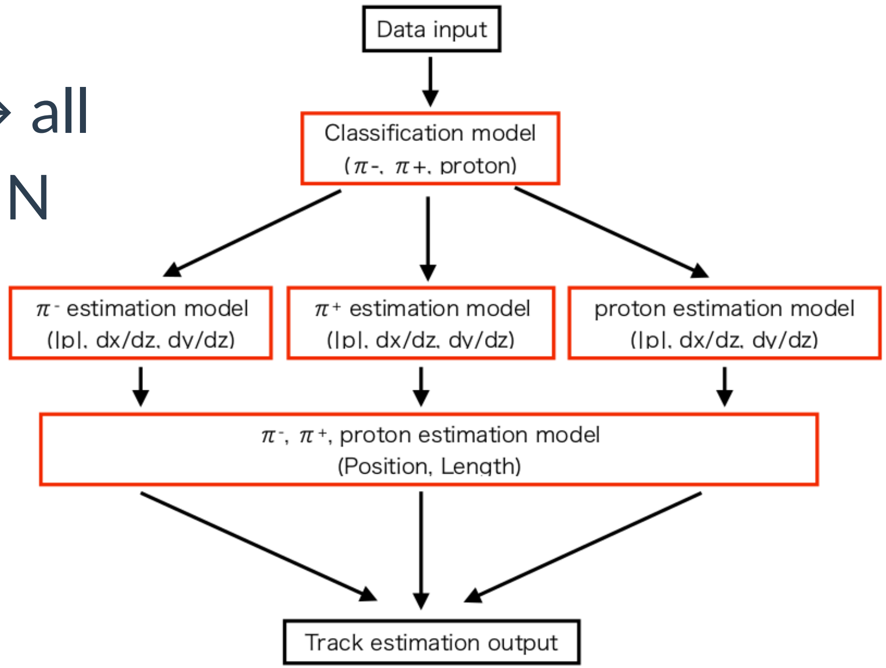
Mass resolution: 3.2 MeV/c^2

Expected Lifetime accuracy: 8 ps

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

WASA Tracking: new development with GNN

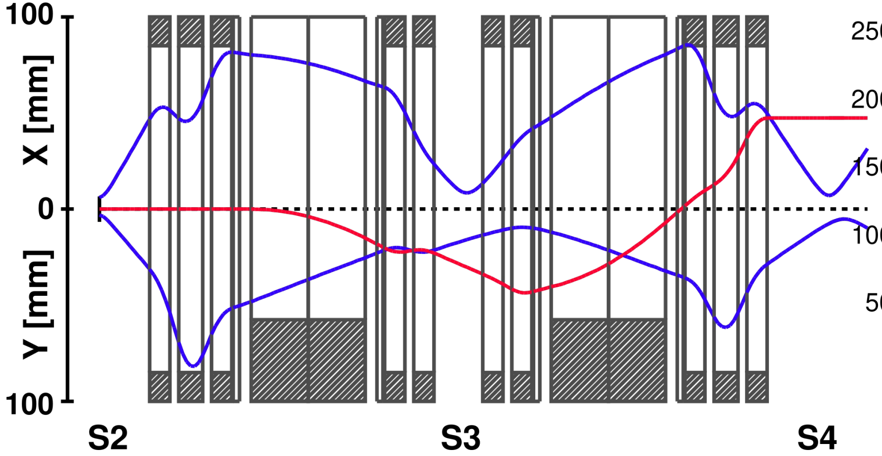
- **From published work:** [H. Ekawa et al., Eur. Phys. J. A 59, 103 (2023)]
  - Excellent track finder for π− (98%) & others / Ghosts 0.04%
  - Also track parameters estimation only for π−
- **New R&D: More complex GNN models → 5 models**
  - Excellent track finder → all particles
  - Good track parameters estimators → all
  - Allow Particle Identification with GNN
- **Improvement in KF fitter:**
  - Optimized setting: High efficiency

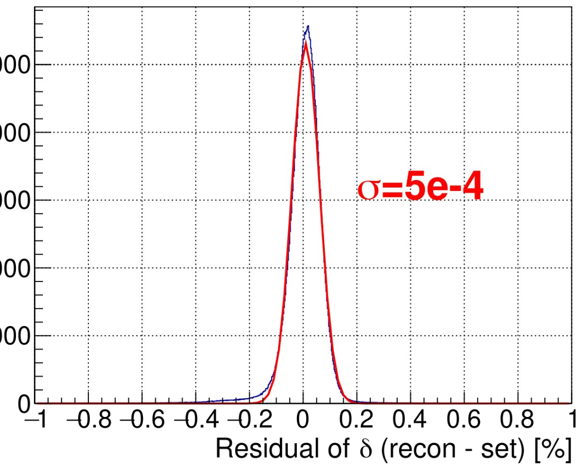


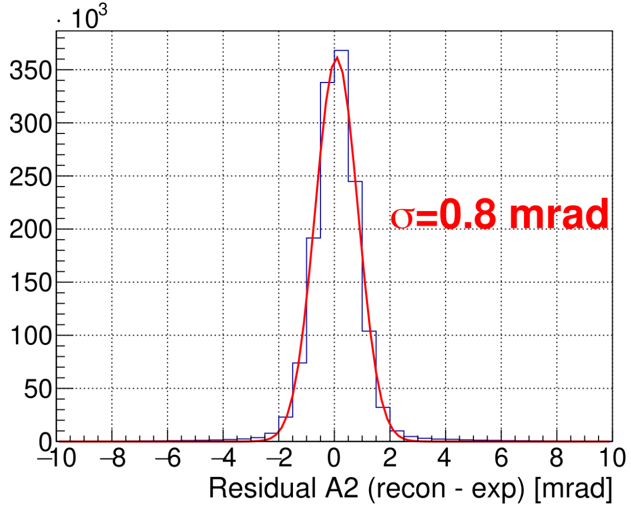
FRS: Ion-optics from experimental data

- **Analysis of high resolution spectrometer for fragments:**
  - Momentum analysis : High acceptance & high resolution

    → Needs ion-optics calibration: Several datasets with fixed parameters







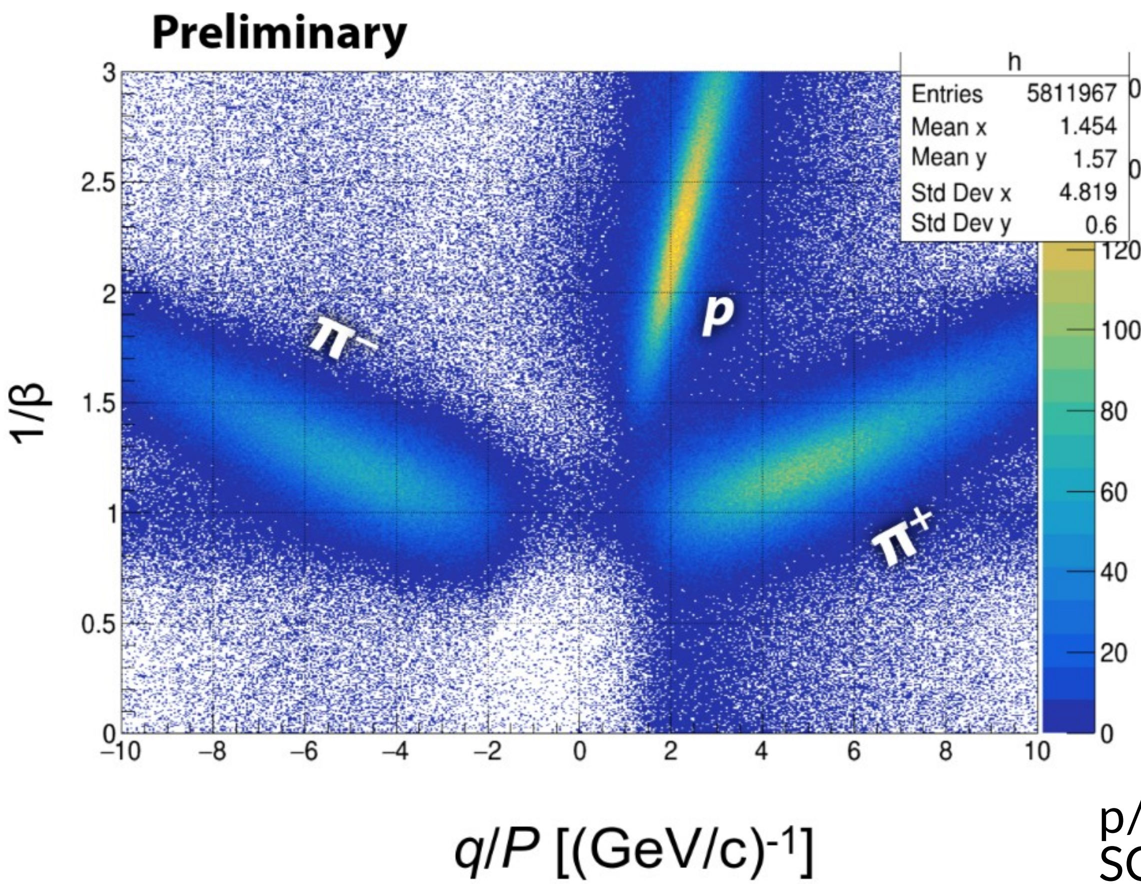
E. Liu's PhD thesis

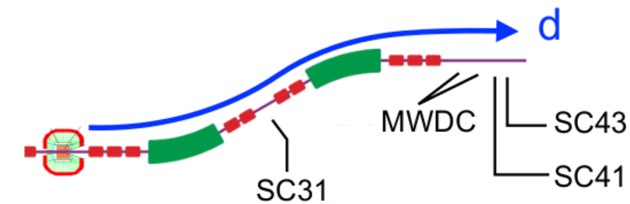
After correction and ion-optics up to second order :

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

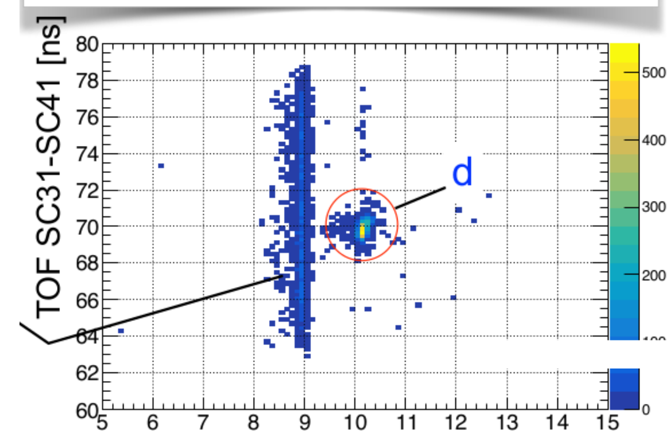
Particle identification: η′-mesic Nuclei

- **WASA Combined PID with TOF, ΔE and q/p :**
  - TOF start ~ 200 ps computed based on S4 + track info. in FRS





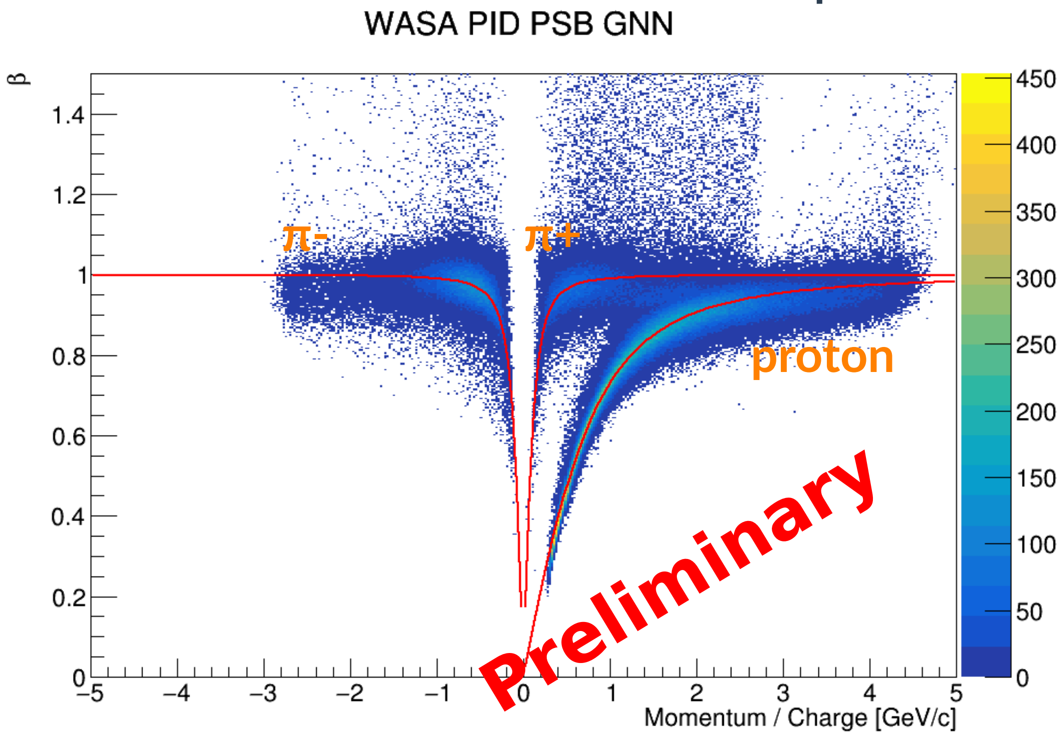
SC31-SC41-SC43 TOF made perfect offline PID

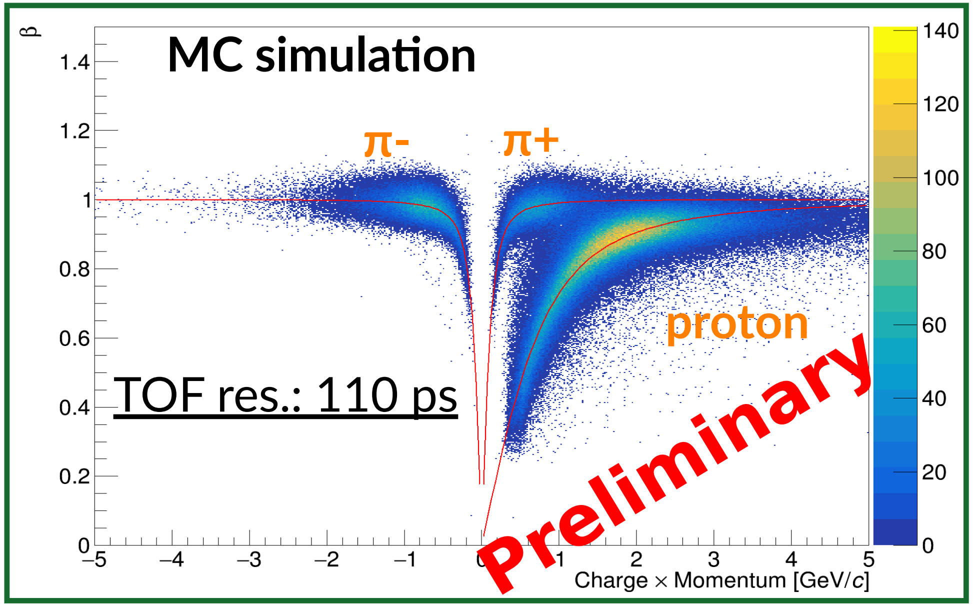


p/d ratio at S4 >1000
SC31-SC41 TOF trigger → p/d ratio ~ 10

Particle identification: Hypernuclei

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





→Improved the track finding with Graph Neural Network:
Estimator resolutions: momentum 8.8%, angular 2.3 mrad

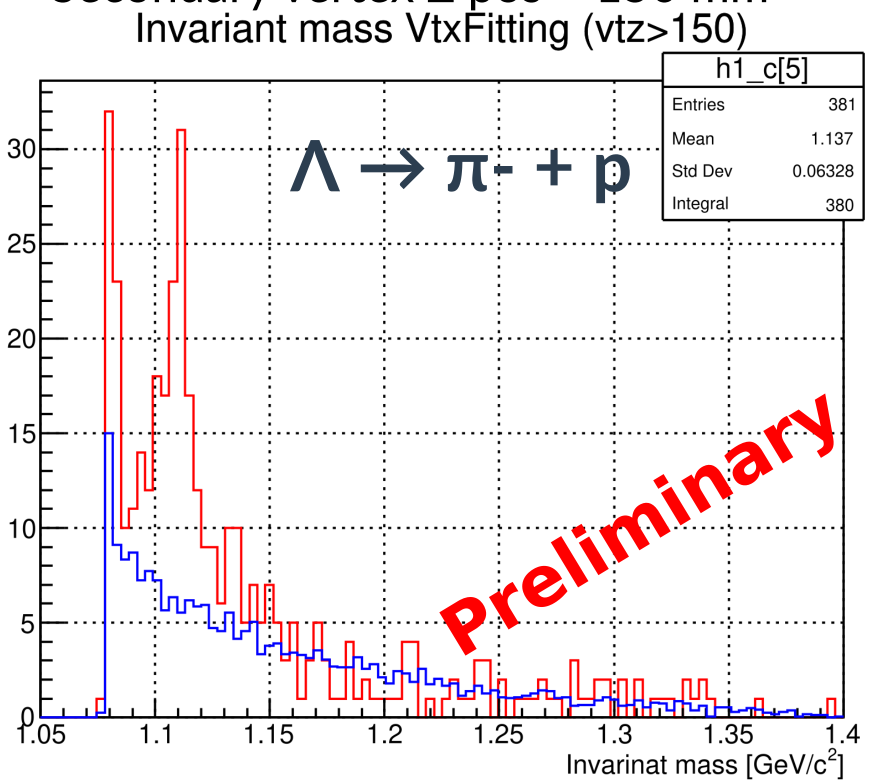
[H. Ekawa et al., Eur. Phys. J. A 59, 103 (2023)]

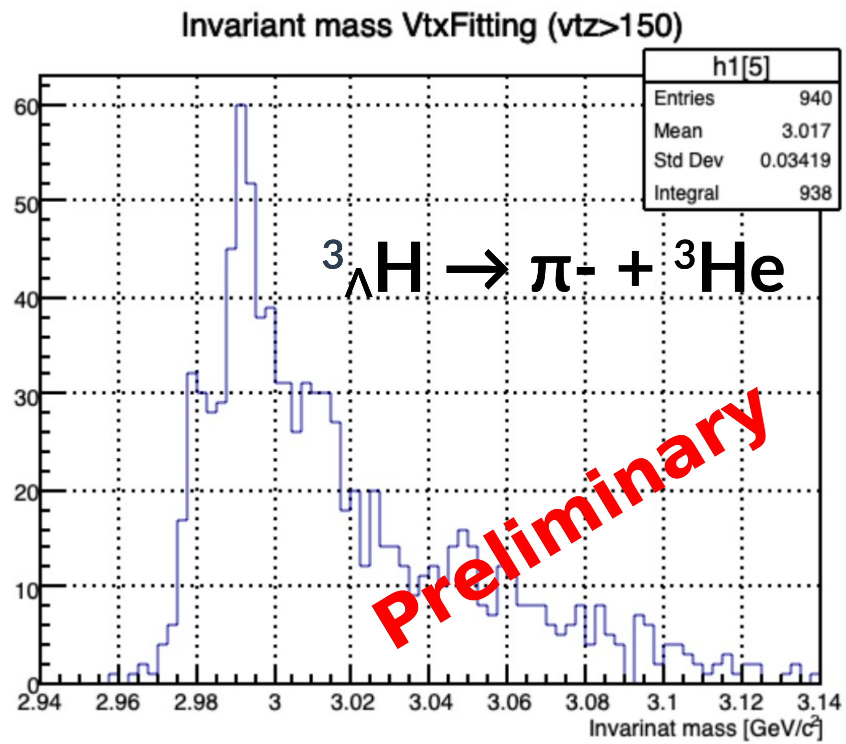
Preliminary invariant masses

- **Invariant mass of Λ → π- + p & $^{3}_{\Lambda}H$ → π- + ^{3}He:**

Red → real event | Blue → mixed event: π- Event #n + p Event #n+1

Secondary vertex Z pos > 150 mm





~ S-B = 85 events

Summary

- **WASA-FRS:**
  - The experiment took place 2022, it was very successfully !
  - **S490: η′-mesic Nuclei:**
    - η′NN→NN : WASA worked nicely for tagging the protons
    - p (WASA)+d (FRS) detection: BG suppression of ~1/200
    - Missing mass spectra under detail analysis !
  - **S447: $^{3}_{\Lambda}H$ and nnΛ puzzles:**
    - → Λ + hypertriton events are observed
    - Lifetime & radius measurement soon !
    - More data:
      - mid-rapidity Λ dataset from proton measured in FRS
      - 12C beam : $^{9}_{\Lambda}B \rightarrow {}^{9}C + \pi^-$ & $^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^-$

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