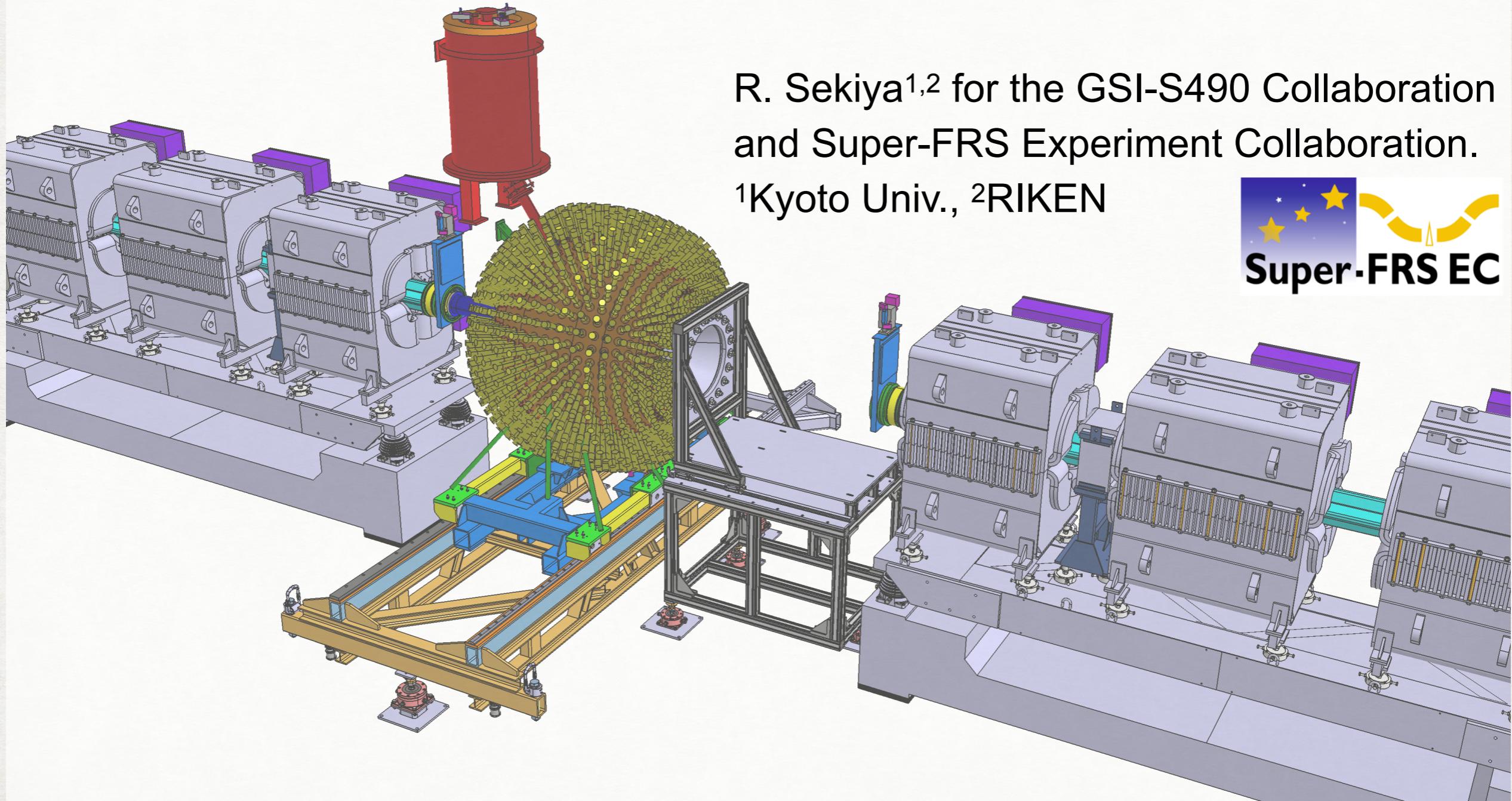


Search for η' -mesic nuclei in $^{12}\text{C}(\text{p},\text{dp})$ reaction with the WASA detector at GSI-FRS

R. Sekiya^{1,2} for the GSI-S490 Collaboration
and Super-FRS Experiment Collaboration.
¹Kyoto Univ., ²RIKEN



Meson mass and symmetry in QCD

Quark



$M_q \sim 3 - 100 \text{ MeV}$

Meson



$M_m \sim 100 - 1000 \text{ MeV}$

Dynamical mass generation by symmetry breaking in QCD

ChS Manifest

$$\langle \bar{q}q \rangle = 0$$
$$m_q = m_s = 0$$

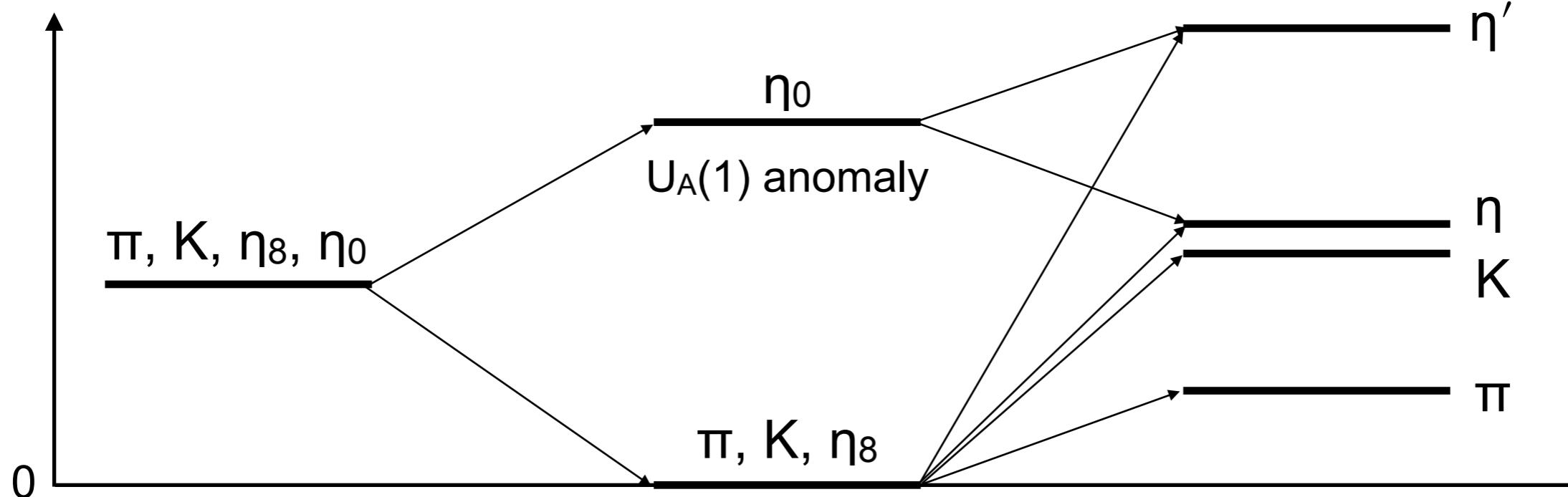
ChS Broken Dynamically

$$\langle \bar{q}q \rangle \neq 0$$
$$m_q = m_s = 0$$

ChS Broken Explicitly

$$\langle \bar{q}q \rangle \neq 0$$
$$m_q \neq m_s \neq 0$$

Mass



η' -mesic in-medium

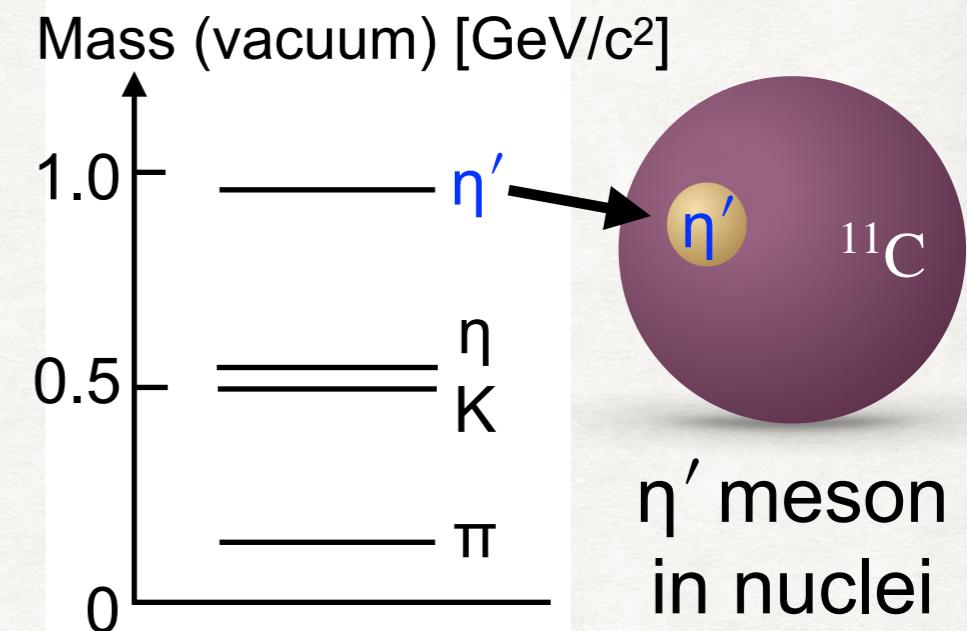
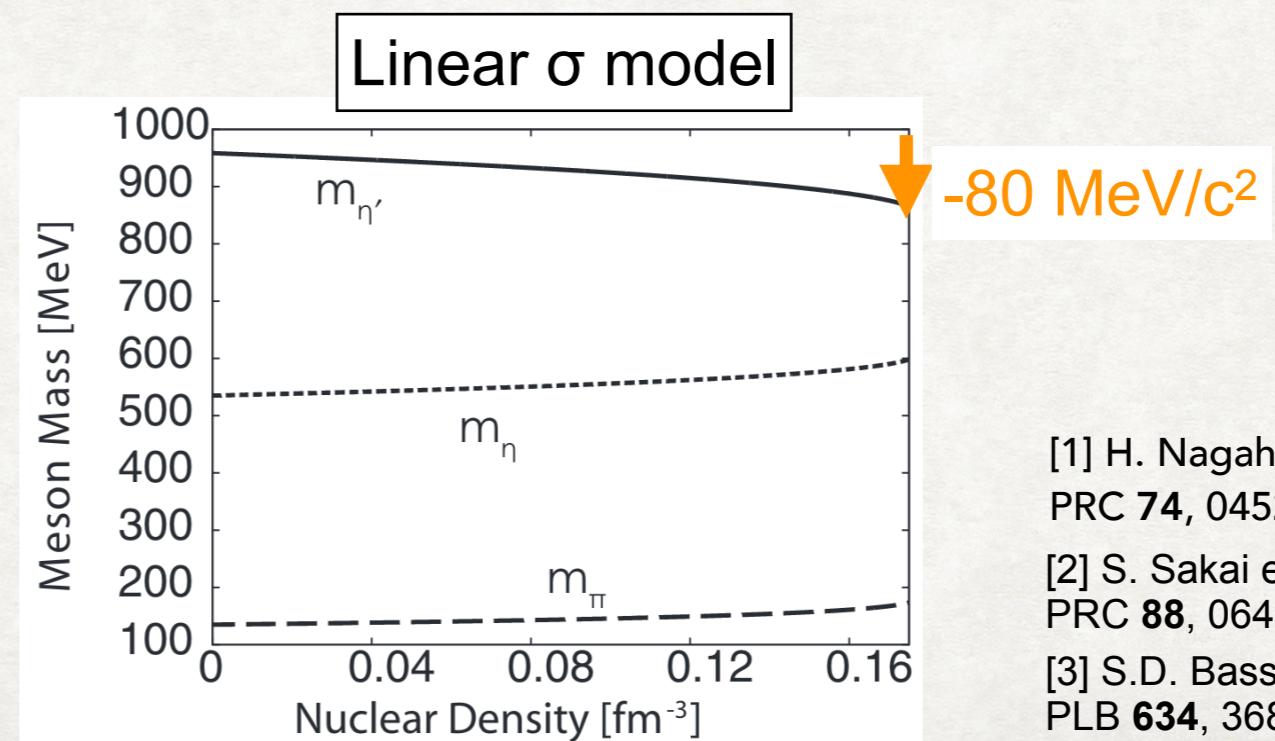
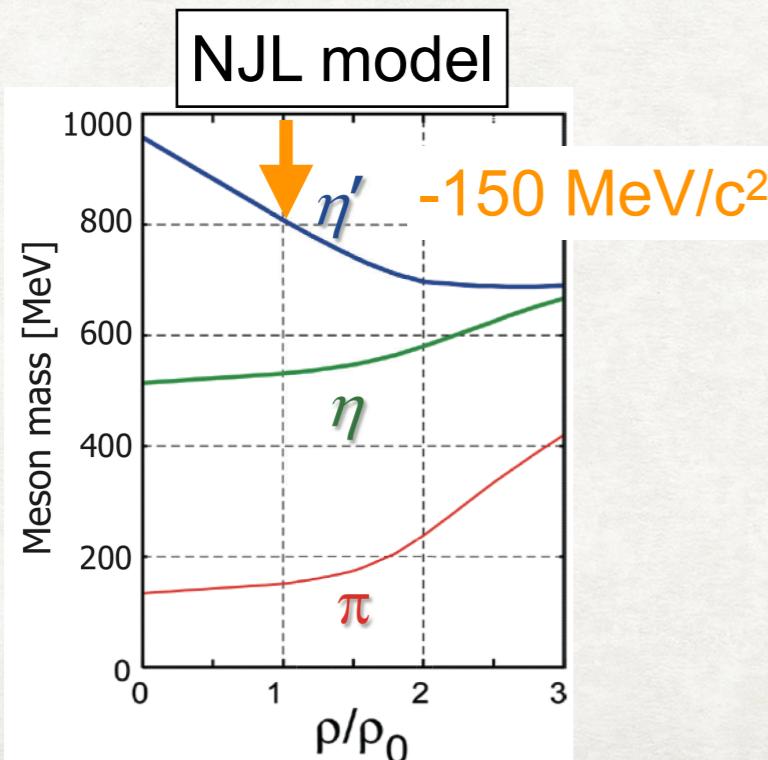
η' -meson in vacuum

- $M_{\eta'} = 958 \text{ MeV}/c^2$ (especially large) due to
 - Chiral symmetry breaking.
 - $U_A(1)$ anomaly.

η' -meson in nuclei

- Partial restoration of chiral symmetry.
- Reduction of $M_{\eta'}$ is predicted.

$$\Delta m(\rho_0) = -150 \text{ MeV} \text{ (NJL)}^{[1]}, -80 \text{ MeV} \text{ (Linear } \sigma)^{[2]}, -38 \text{ MeV} \text{ (QMC)}^{[3]}$$



- [1] H. Nagahiro et. al., PRC **74**, 045203 (2006)
 [2] S. Sakai et al., D. Jido, PRC **88**, 064906 (2013)
 [3] S.D. Bass, A.W.Thomas, PLB **634**, 368 (2006)

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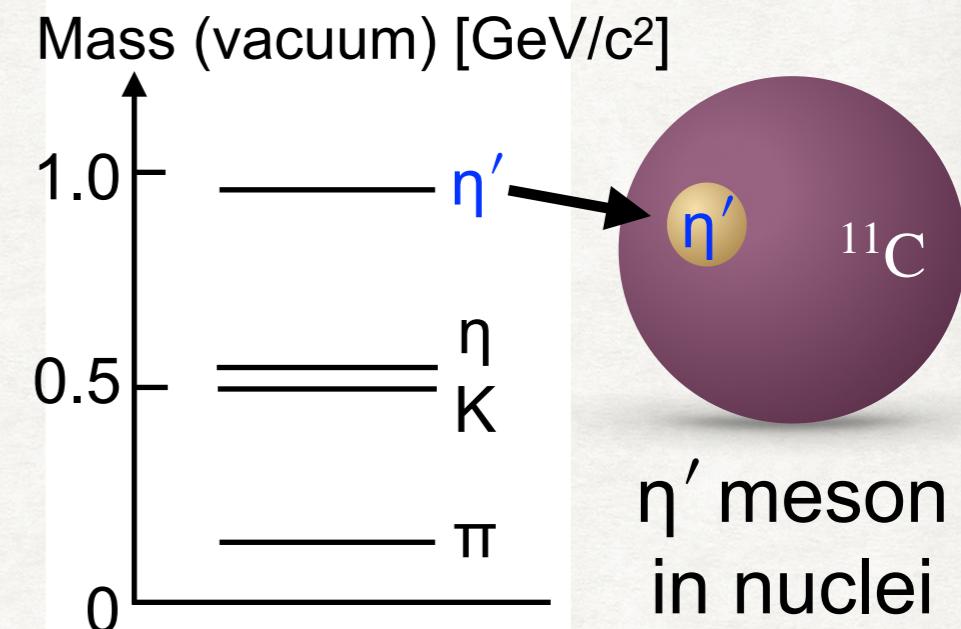
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↓
Attractive potential

↓
Bound state is expected (η' -mesic nuclei)



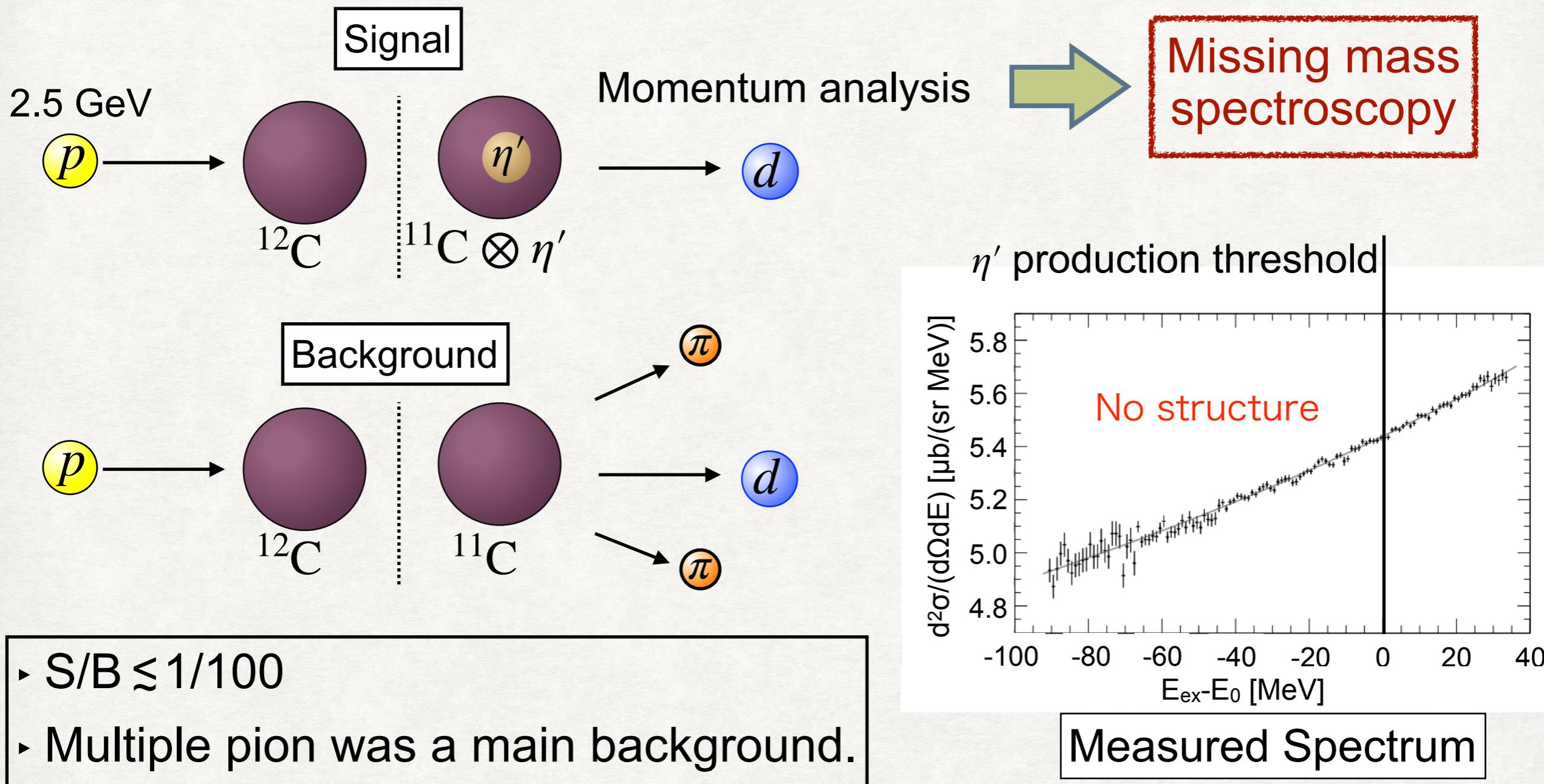
$$V_{\eta'A}(r) = \Delta m_{\eta'}(\rho_0) \frac{\rho(r)}{\rho_0}$$

[1] H. Nagahiro et. al.,
PRC **74**, 045203 (2006)

[2] S. Sakai et al., D. Jido,
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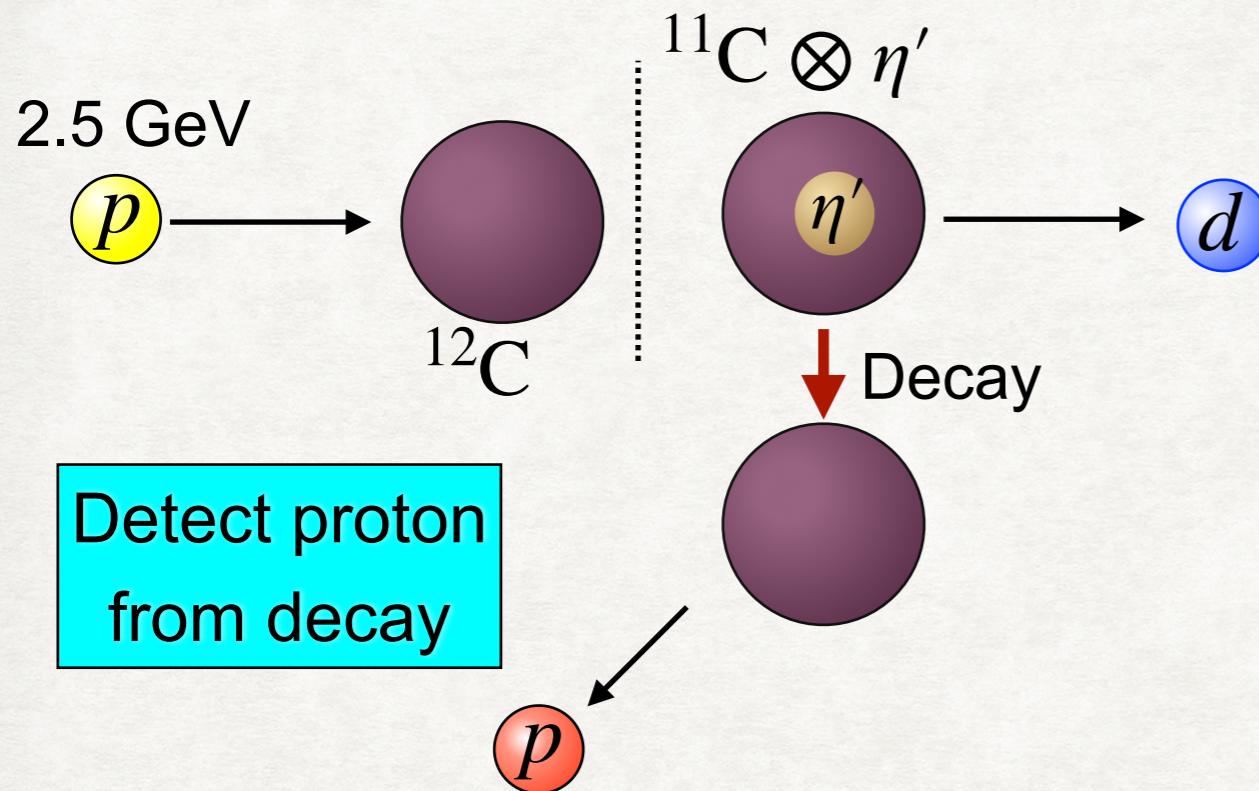
[3] S.D. Bass, A.W.Thomas,
PLB **634**, 368 (2006)

Direct search for η' -mesic nuclei in 2014 (GSI-S437)



Y. K. Tanaka et al., Phys. Rev. C 97, 015202 (2018)

Direct search for η' -mesic nuclei (present experiment)



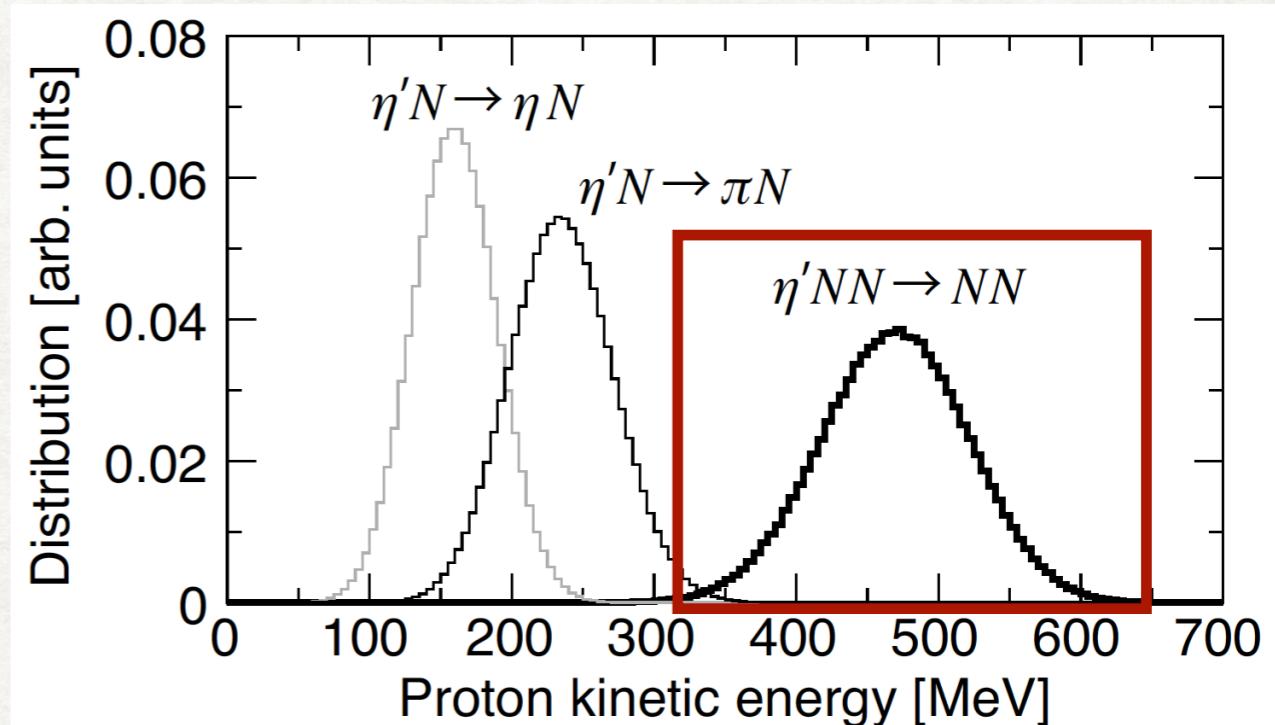
- Coincident measurement of d and p
- Detect p backward
- S/B ~ 1 is expected *

* JAM simulation by Y. Higashi

Major decay modes

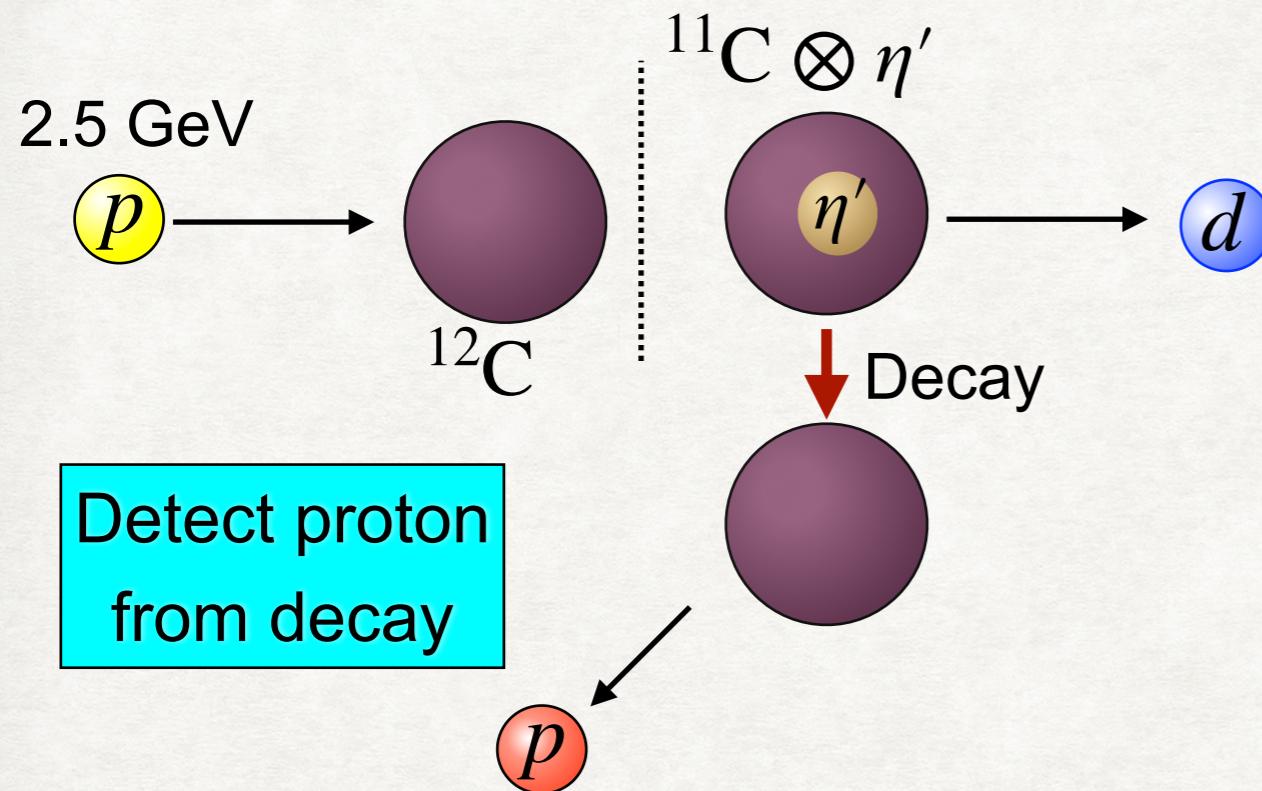
- $\eta' p \rightarrow \eta p$
- $\eta' N \rightarrow \pi p$
- $\eta' pN \rightarrow pN$

H. Nagahiro, [Nucl. Phys. A 914, 360 \(2013\)](#).



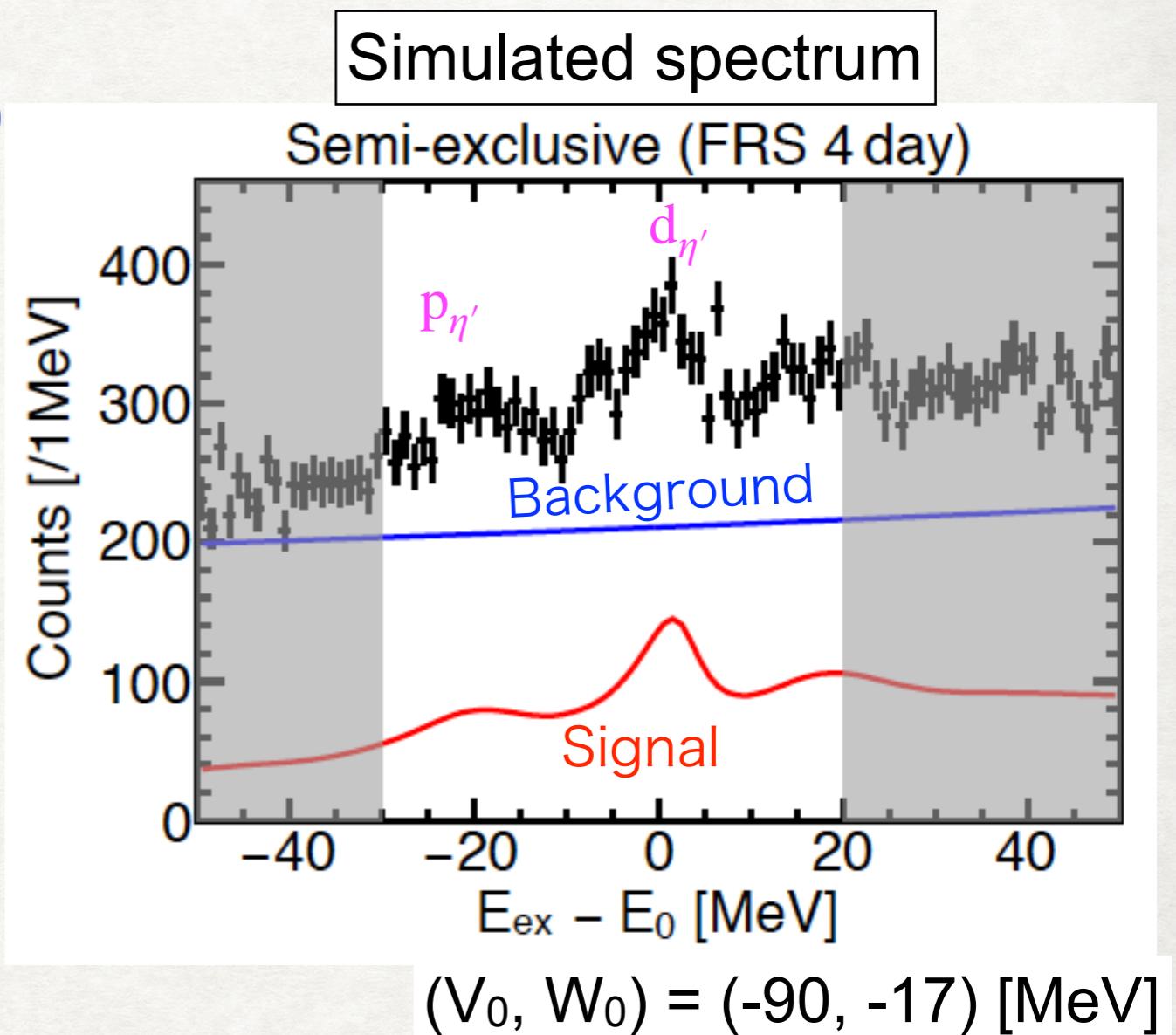
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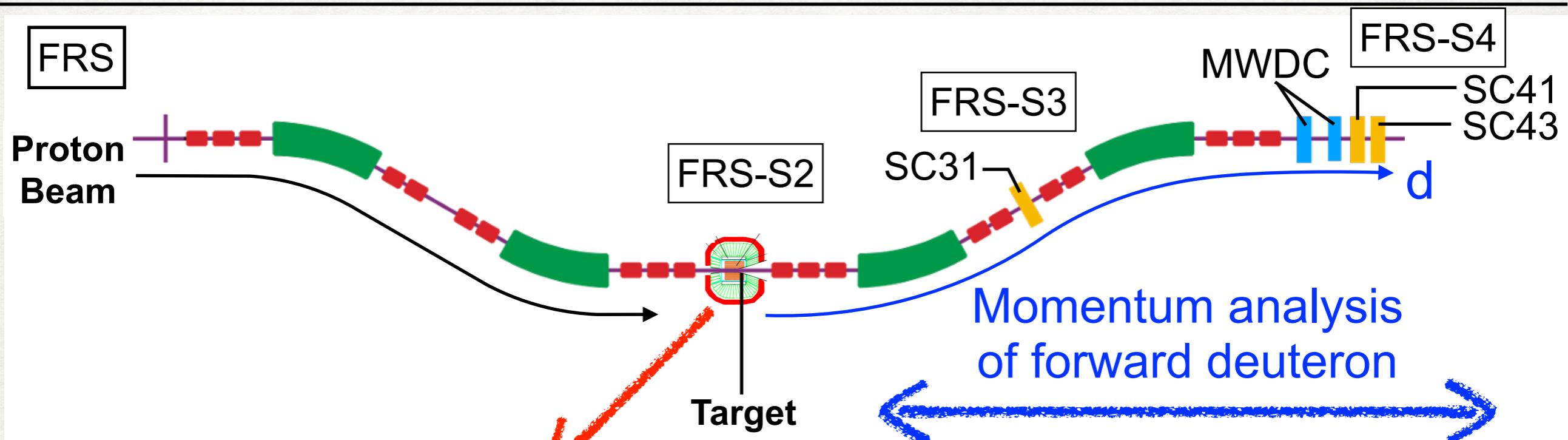
* JAM simulation by Y. Higashi



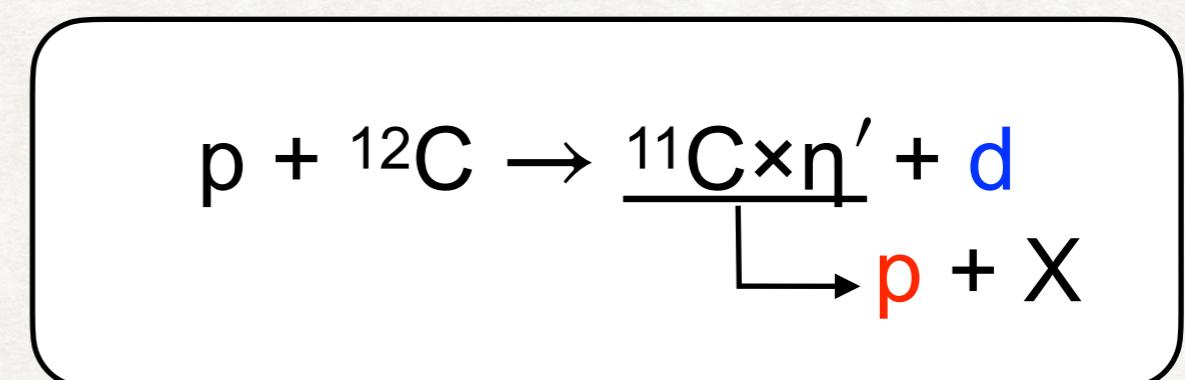
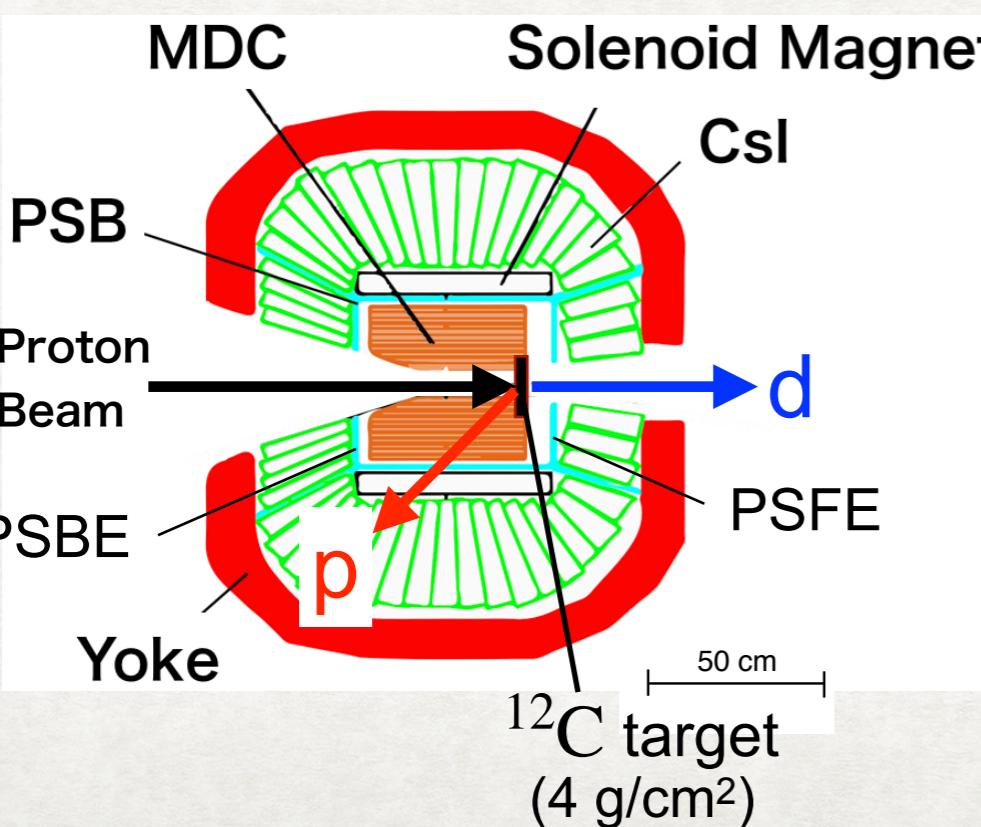
η' -nucleus optical potential

$$V_{\eta'}(r) = (V_0 + iW_0) \rho(r)/\rho_0$$

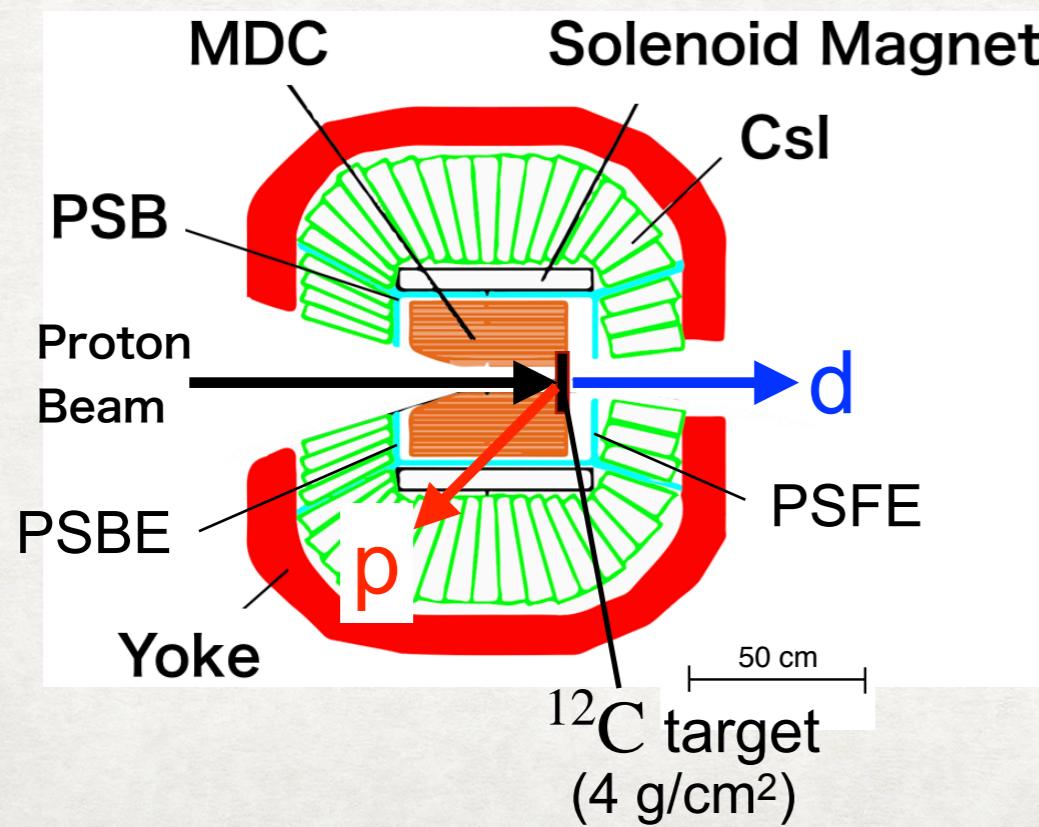
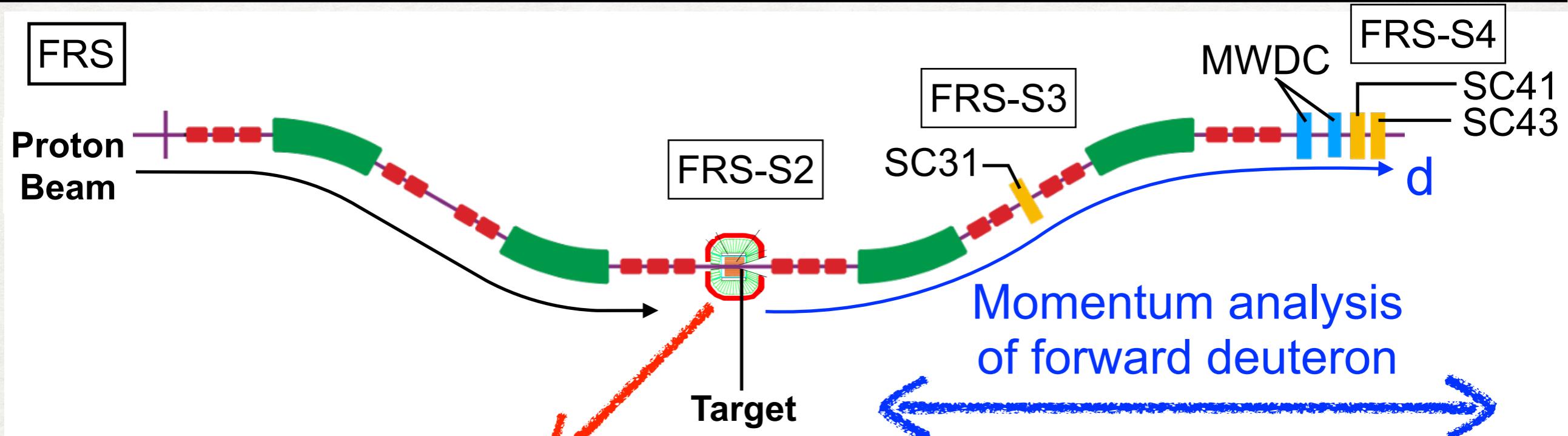
WASA-at-FRS experiment conducted in 2022 Feb



WASA for decay
particle measurement

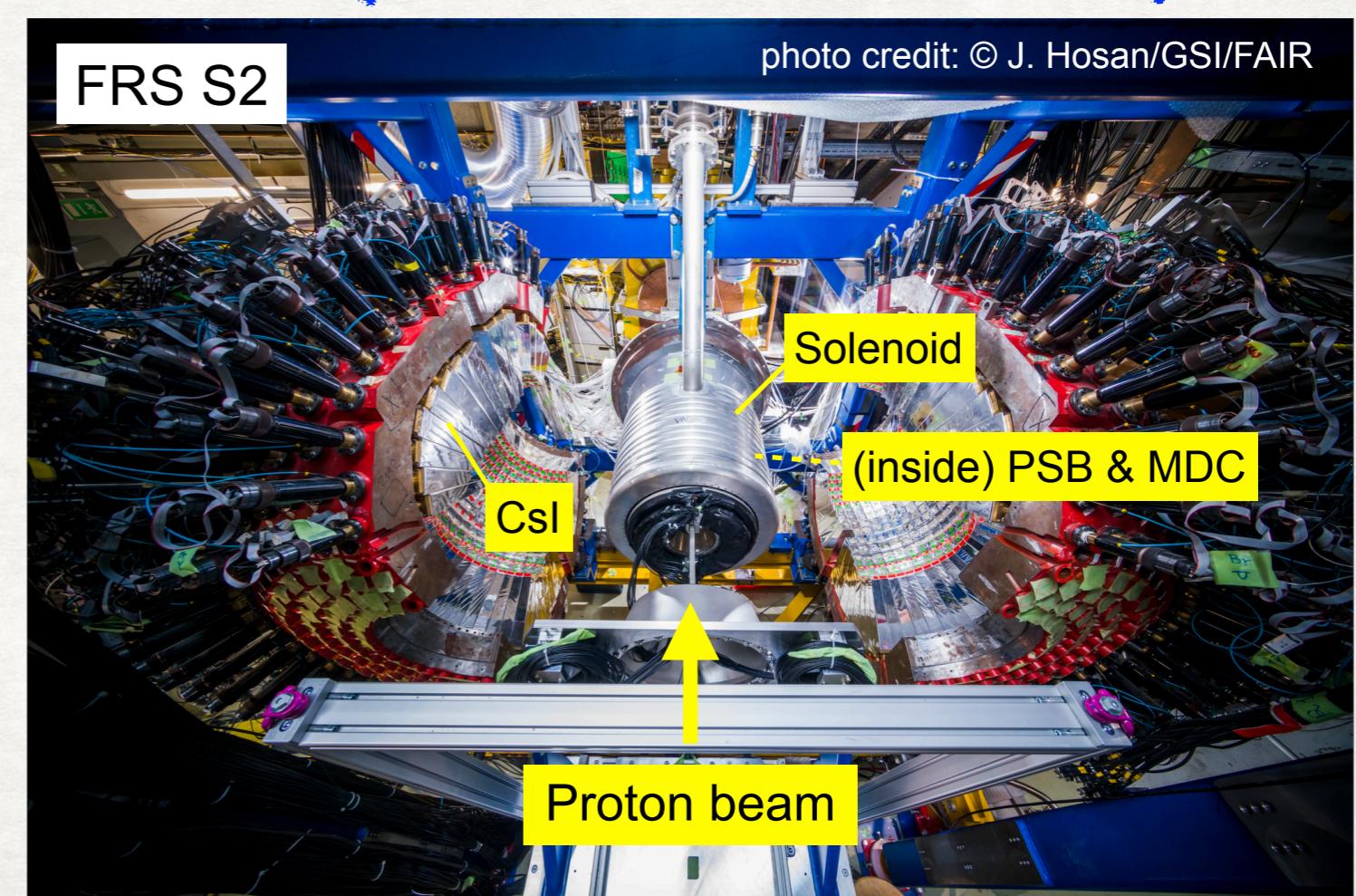
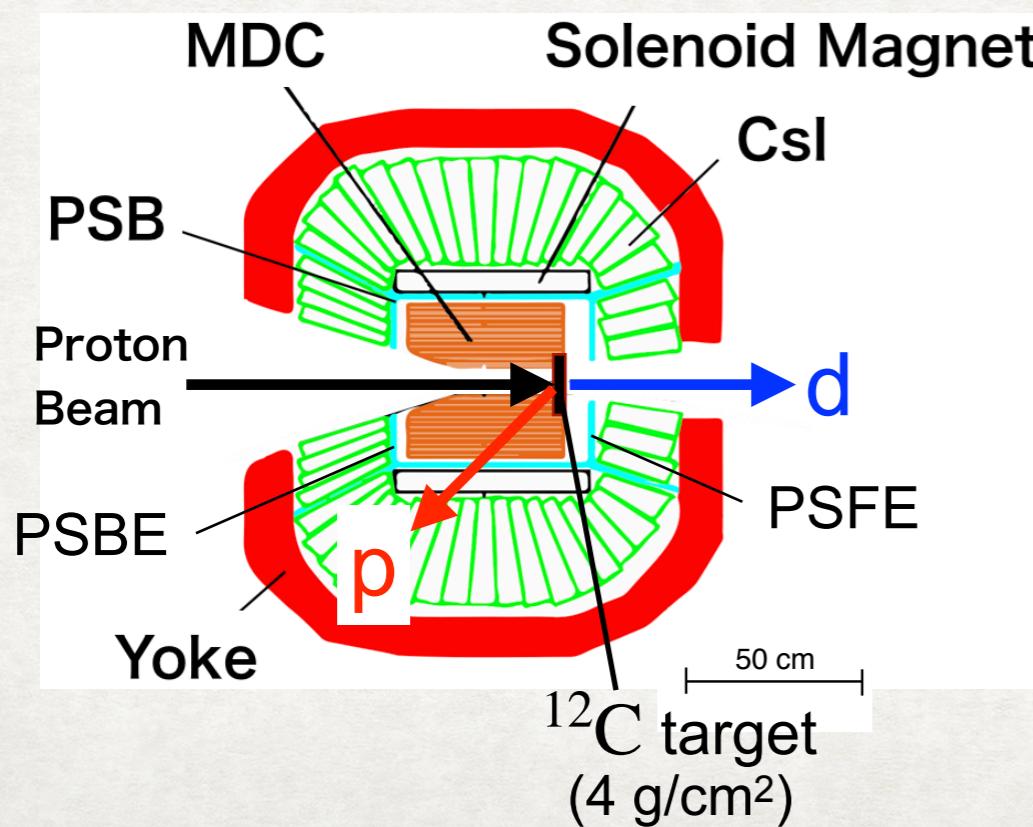
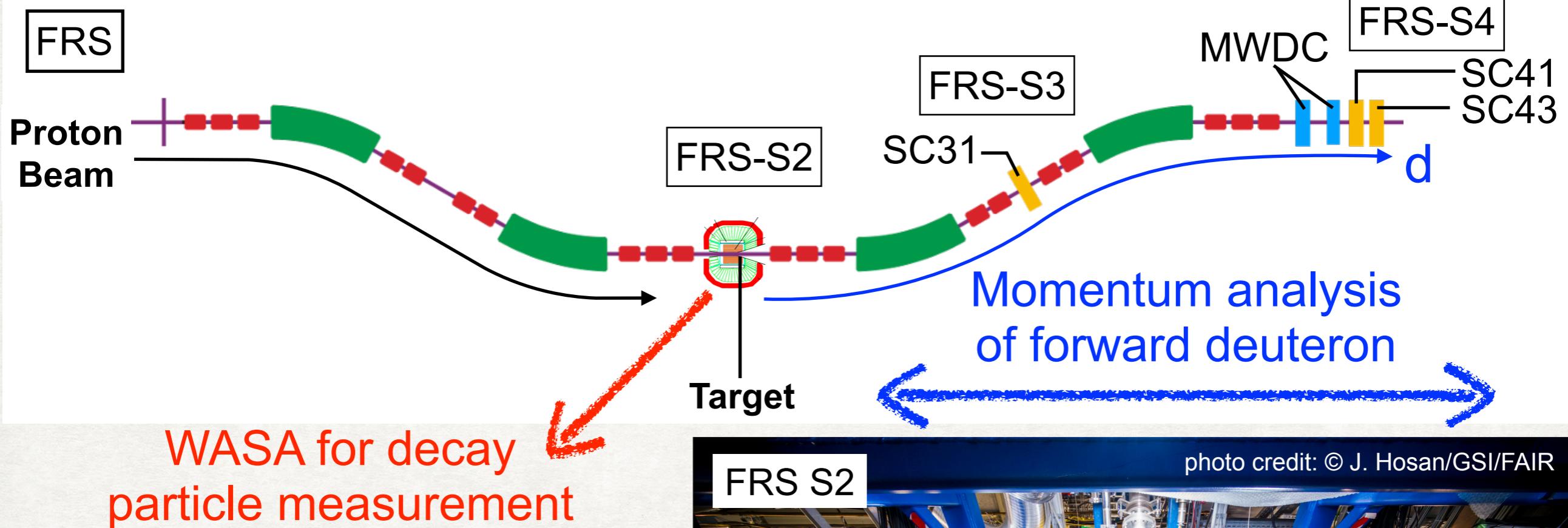


WASA detector

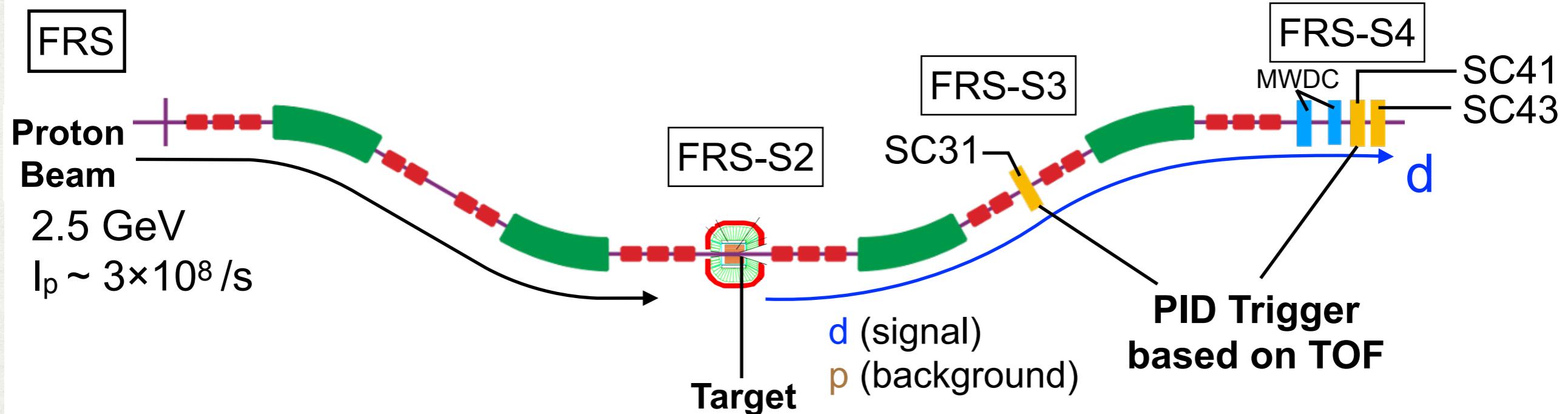


- ▶ Superconducting Solenoid Magnet.
 - ▶ 1T Magnetic Field.
- ▶ Mini-Drift Chamber (MDC).
 - ▶ Charged particle tracking.
- ▶ Plastic Scintillators (PSB/PSBE/PSFE).
 - ▶ Timing & ΔE Measurement.
- ▶ CsI Electromagnetic Calorimeter.
 - ▶ Charged particle & γ Energy.

WASA detector

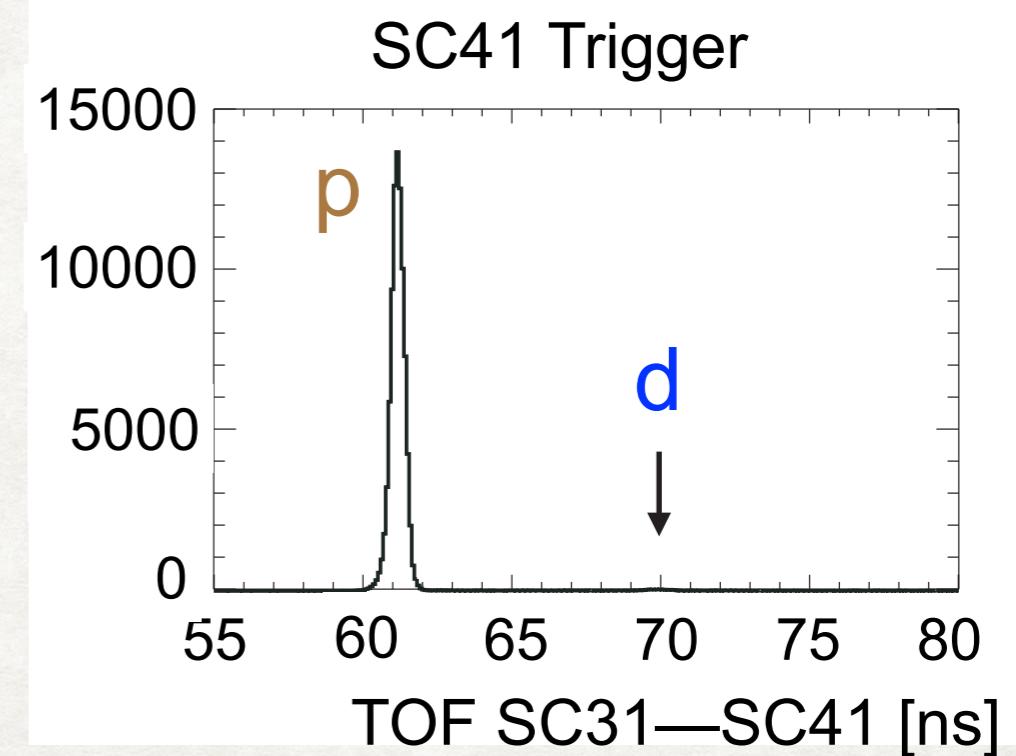


Beamtime in 2022 Feb

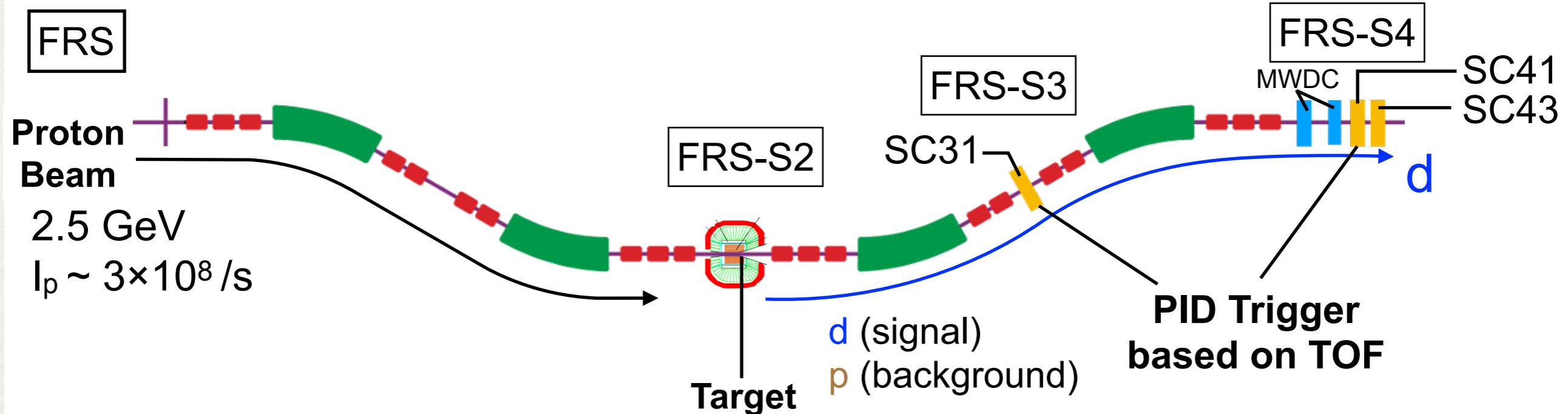


Production Run

- ▶ 2.5 GeV proton beam with $I_p \sim 3 \times 10^8 / s$.
- ▶ ^{12}C target (4 g/cm^2).
- ▶ 3.5 days data collection with hardware deuteron trigger.
→ $\sim 10^7$ forward deuteron events

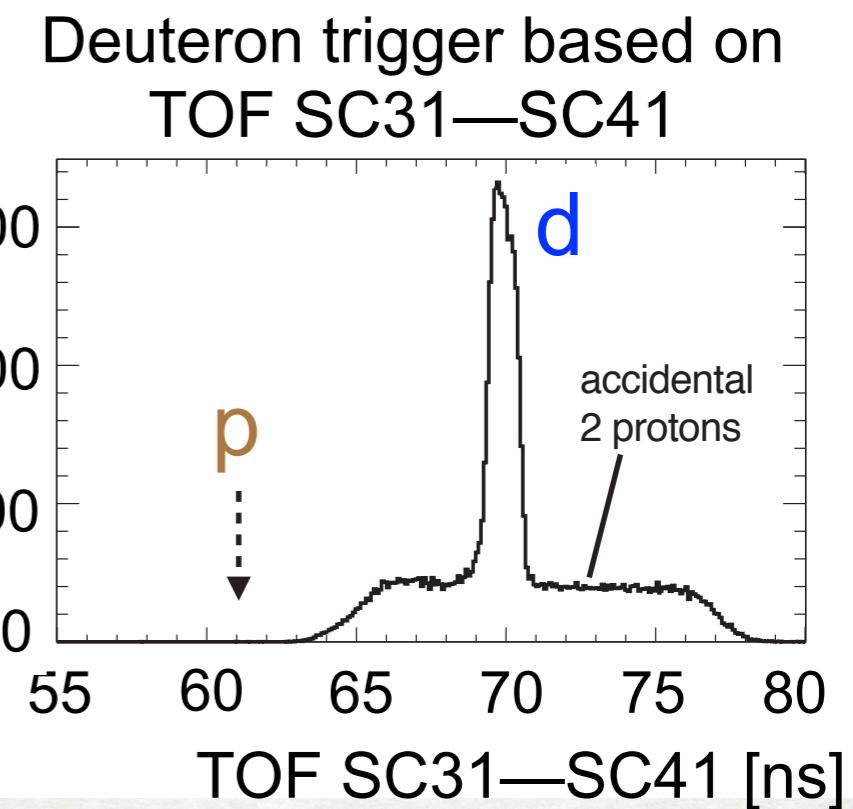


Beamtime in 2022 Feb



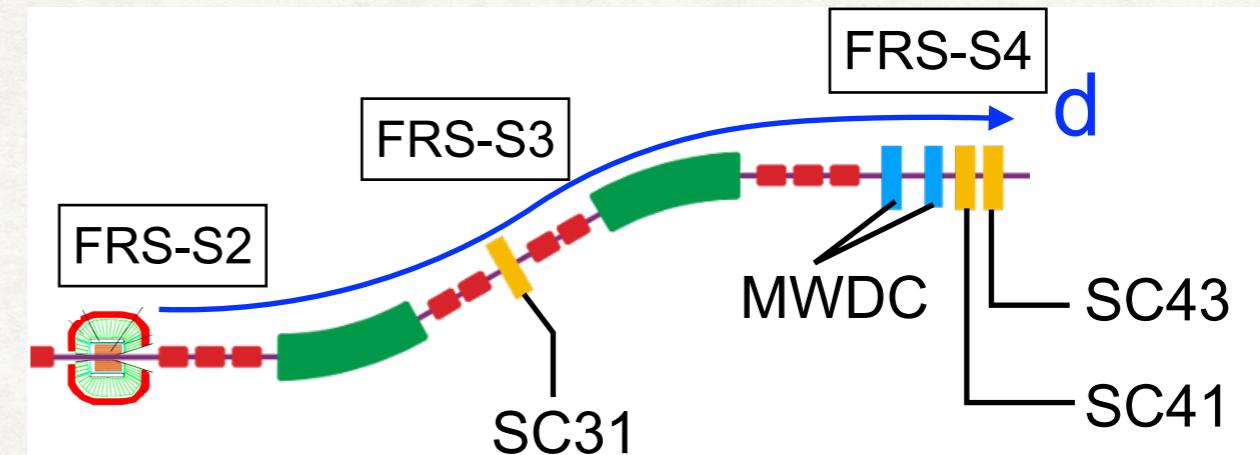
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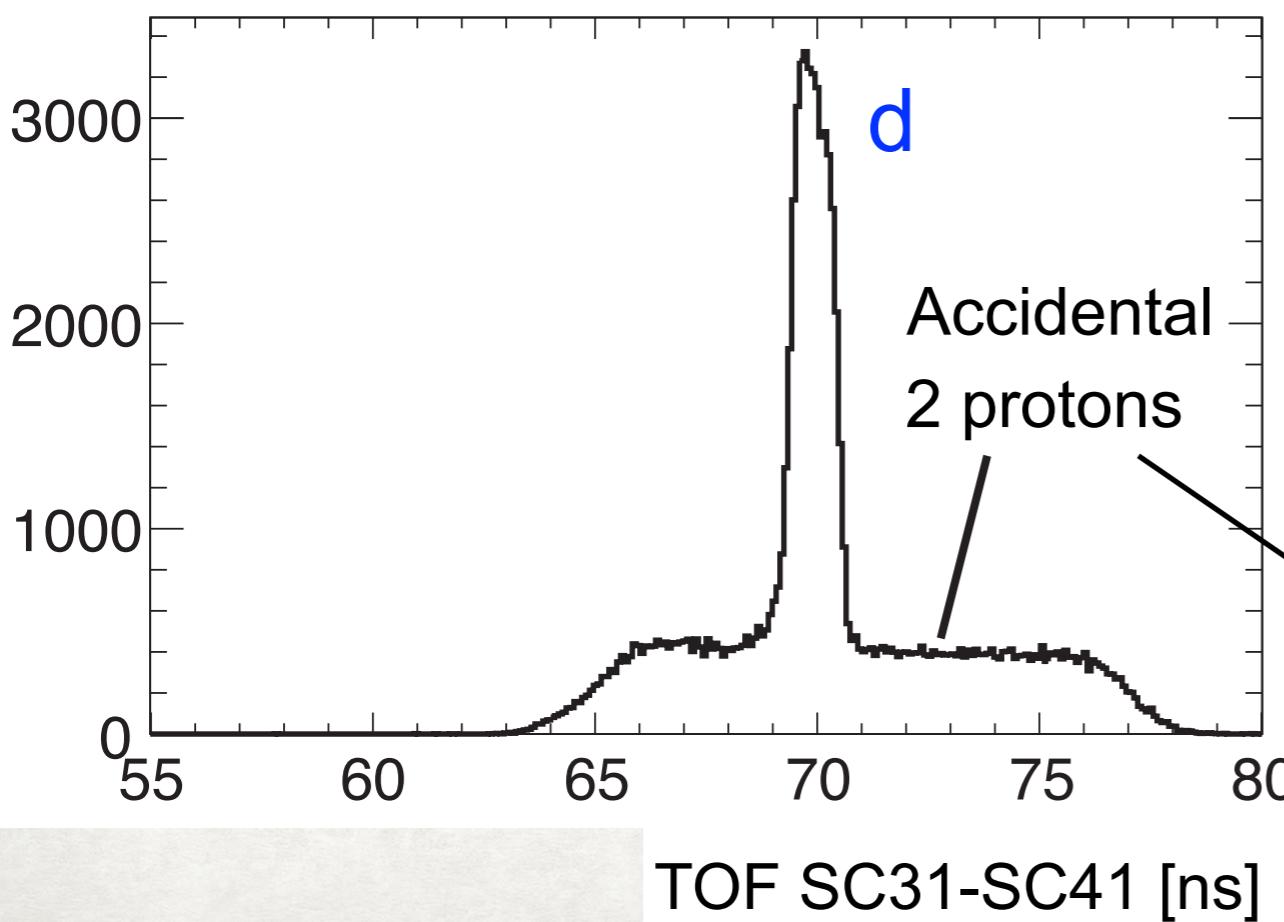


Forward deuteron PID

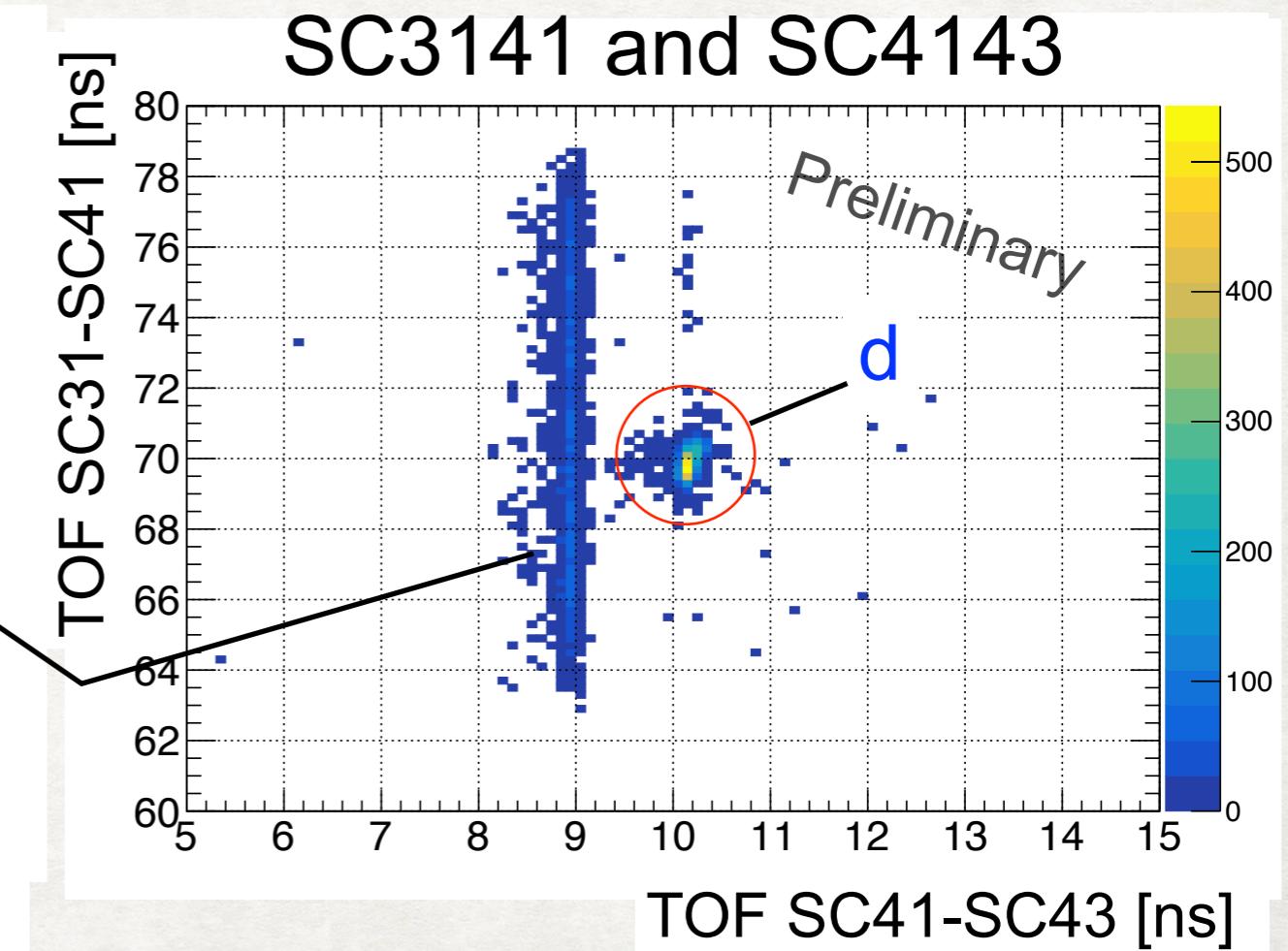
- TOF analysis for **d** PID.
 - Clear separation between p and **d**.



TOF-based Deuteron Trigger



PID by TOF
SC3141 and SC4143



Inclusive excitation-energy spectrum

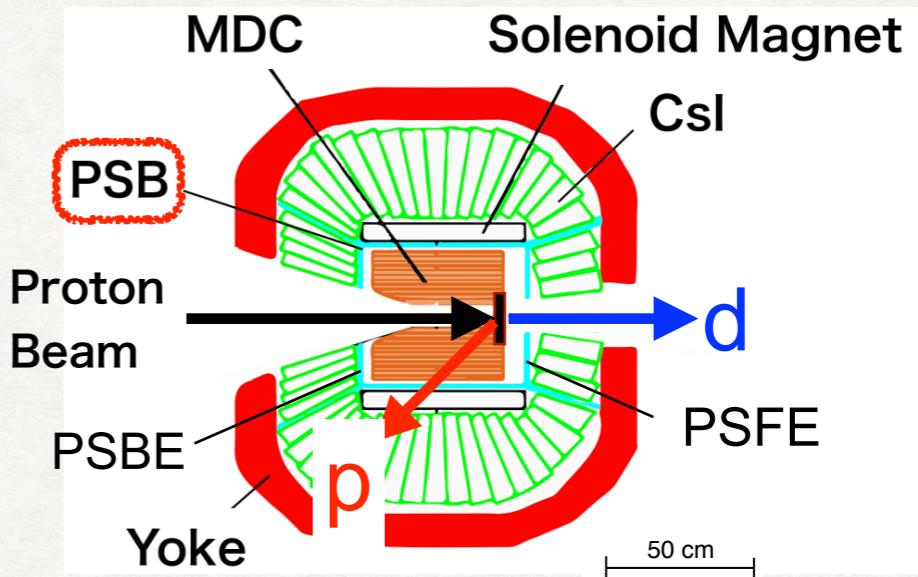
Evaluated excitation-energy from \mathbf{d} momentum.

Preliminary

Achieved statistics we aimed for over $E_{\text{ex}}-E_0$ region of interest.

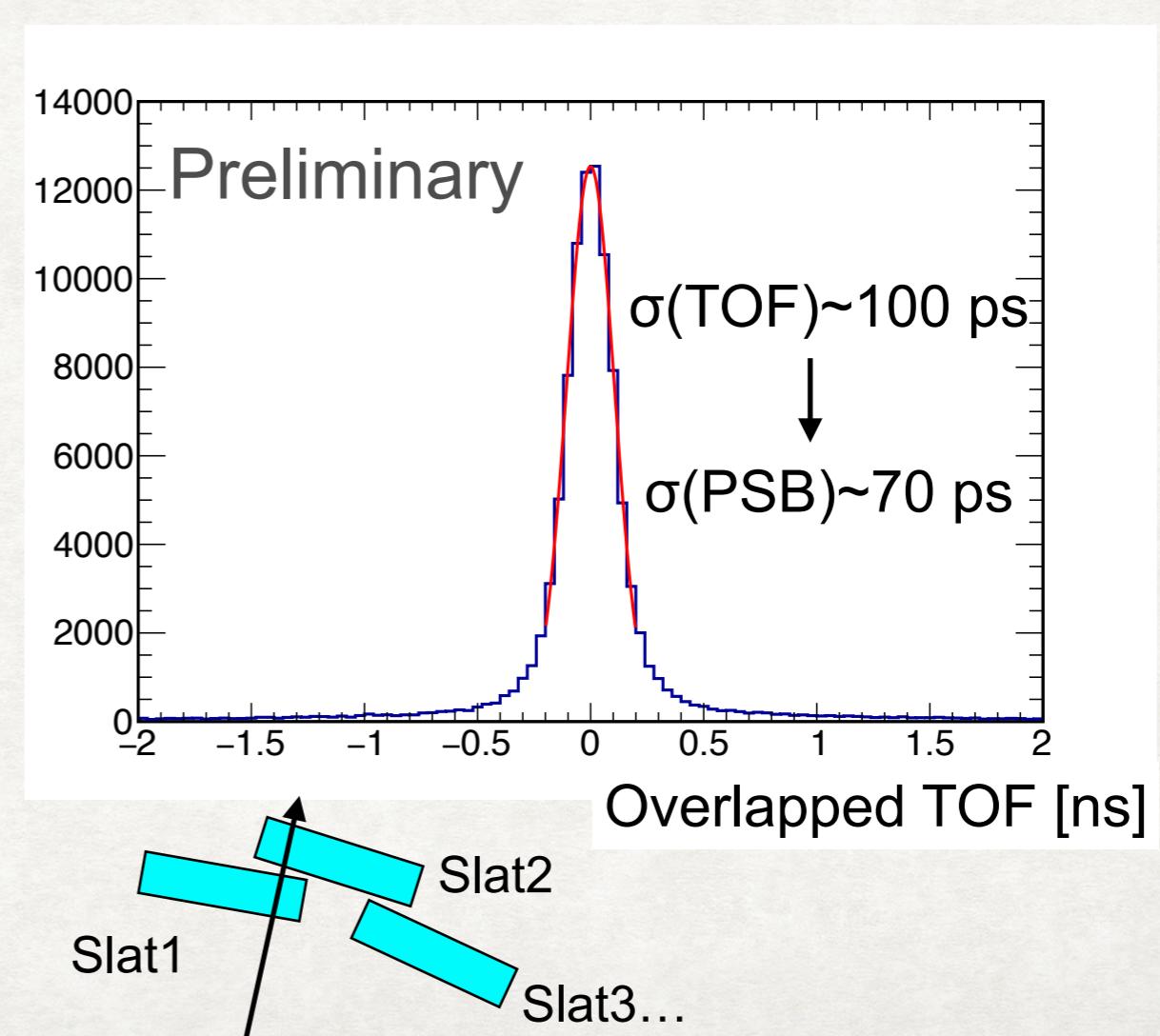
WASA detectors analysis

- PSB analysis for ΔE and hit timing.



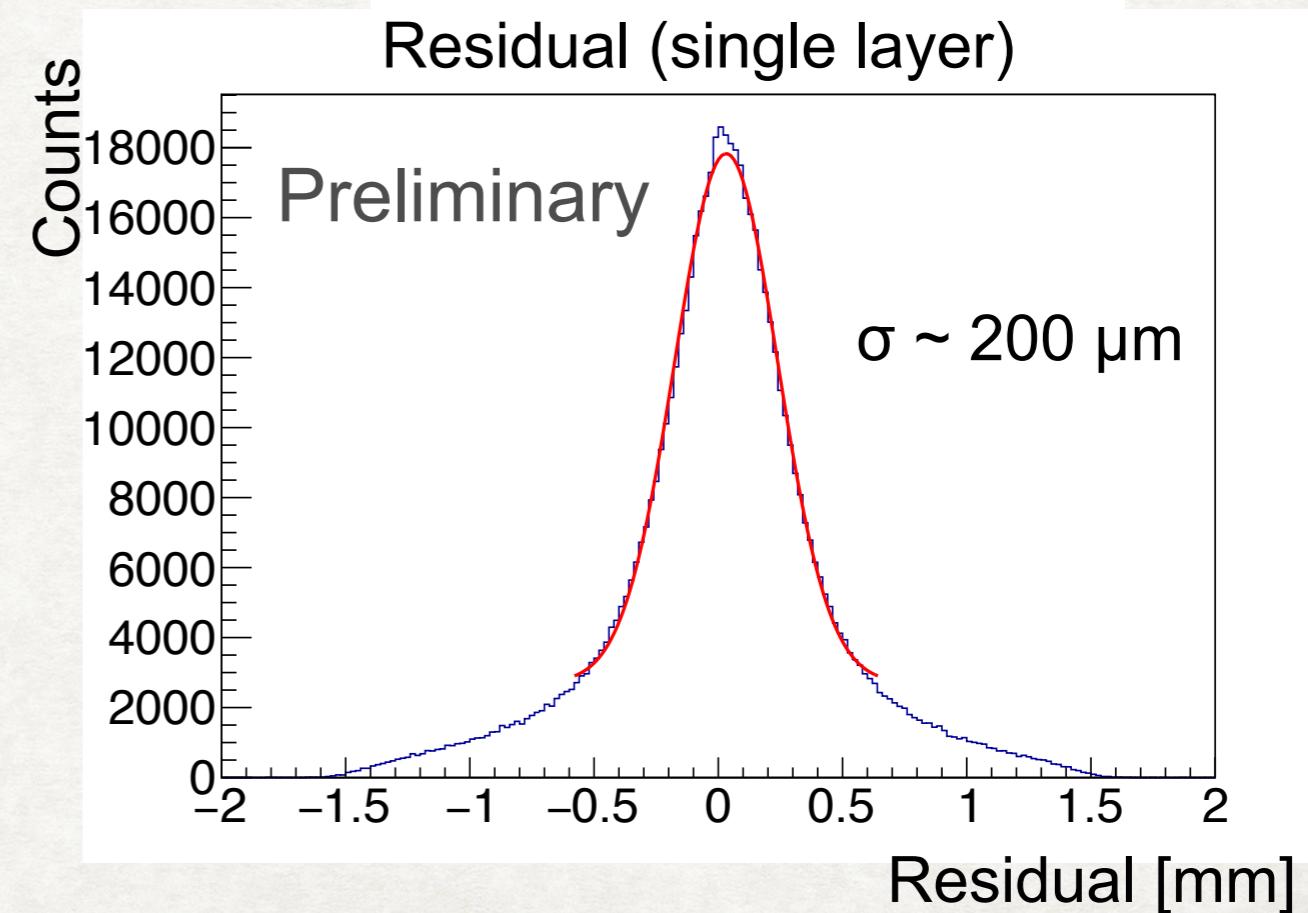
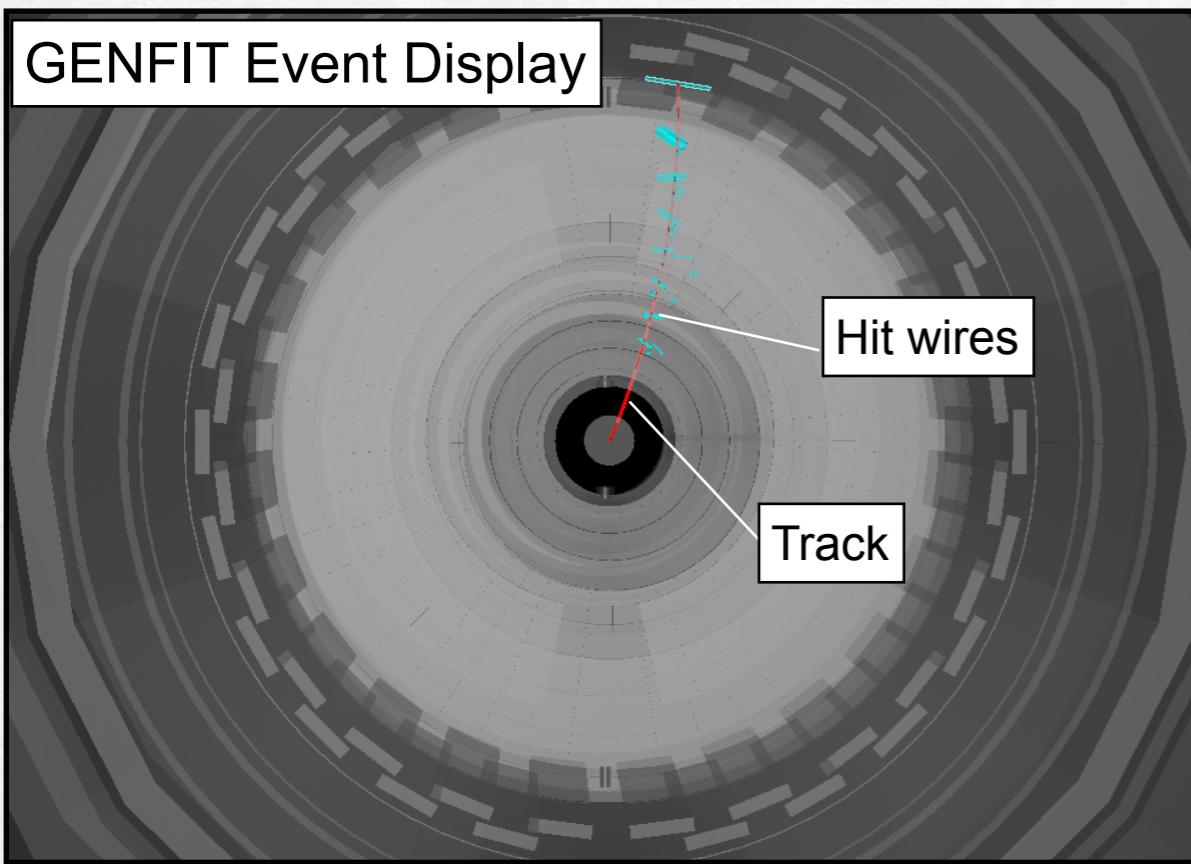
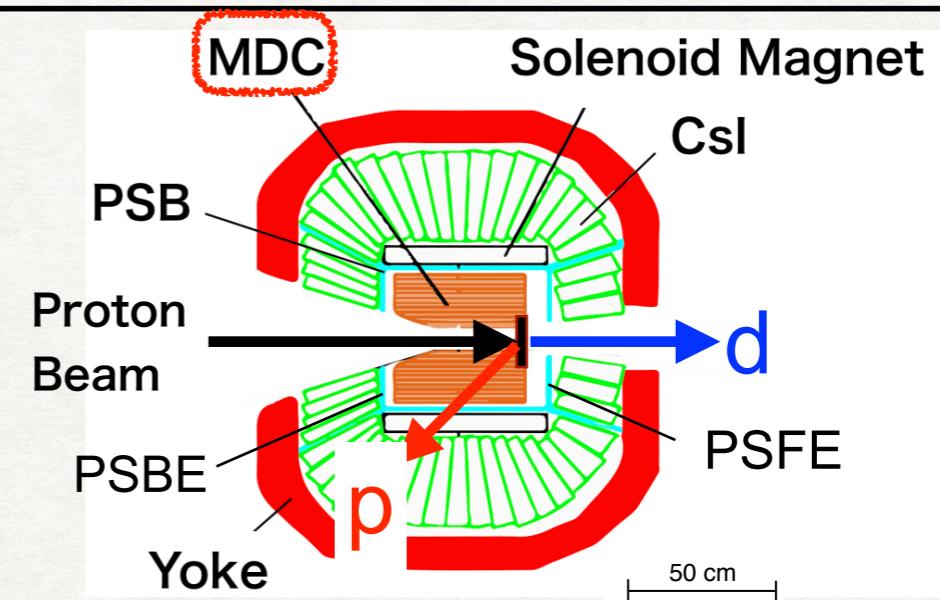
Newly Developed PSB

(R.Sekiya et.al., NIM A 1034 (2022) 166745)



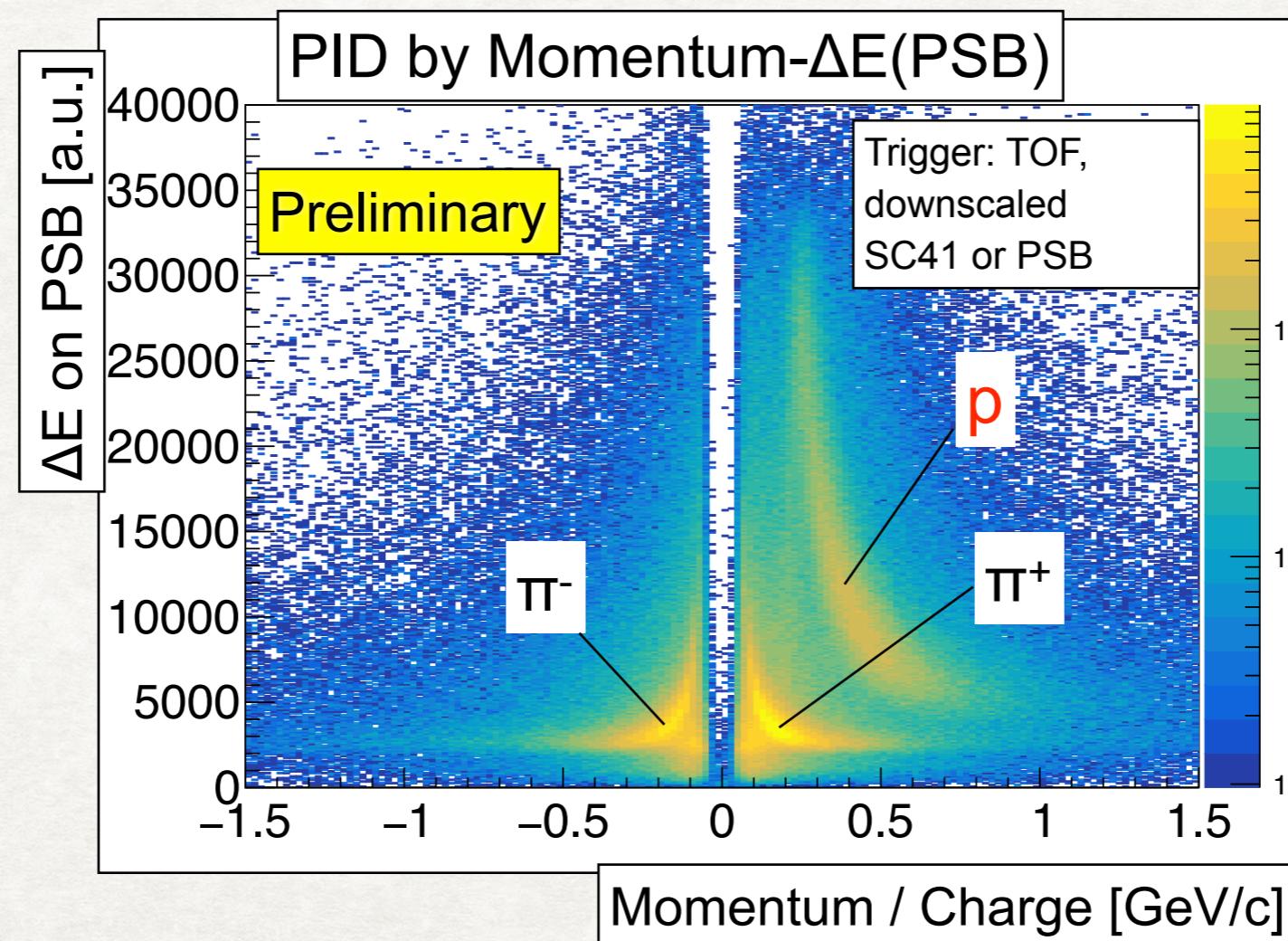
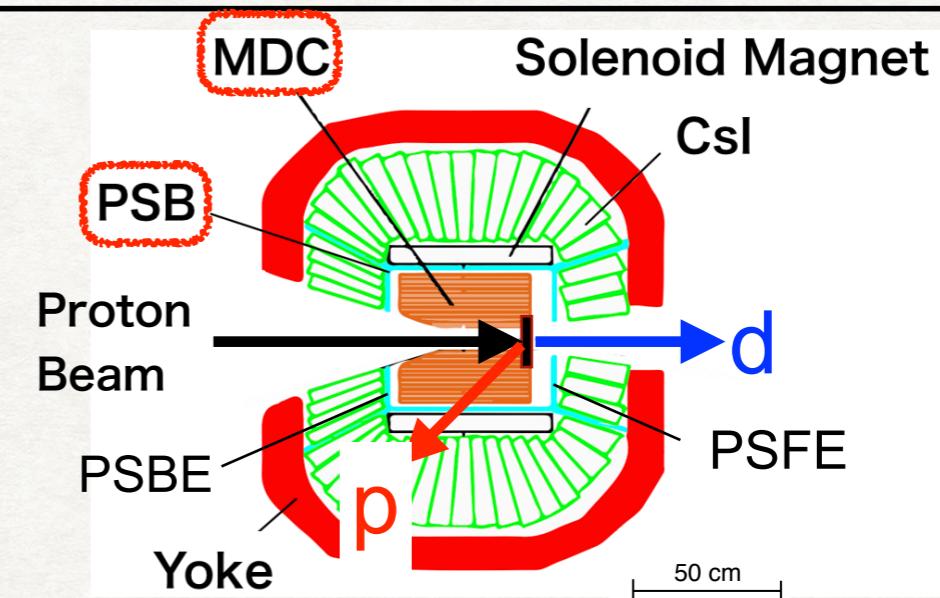
WASA detectors analysis

- PSB analysis for ΔE and hit timing.
- MDC Tracking for momentum.
 - Tracking with Kalman Filter.



WASA detectors analysis (PID by momentum- ΔE)

- PSB analysis for ΔE and hit timing.
- MDC Tracking for momentum.
 - Tracking with Kalman Filter.



$p-\pi^\pm$ are separated!!

Summary

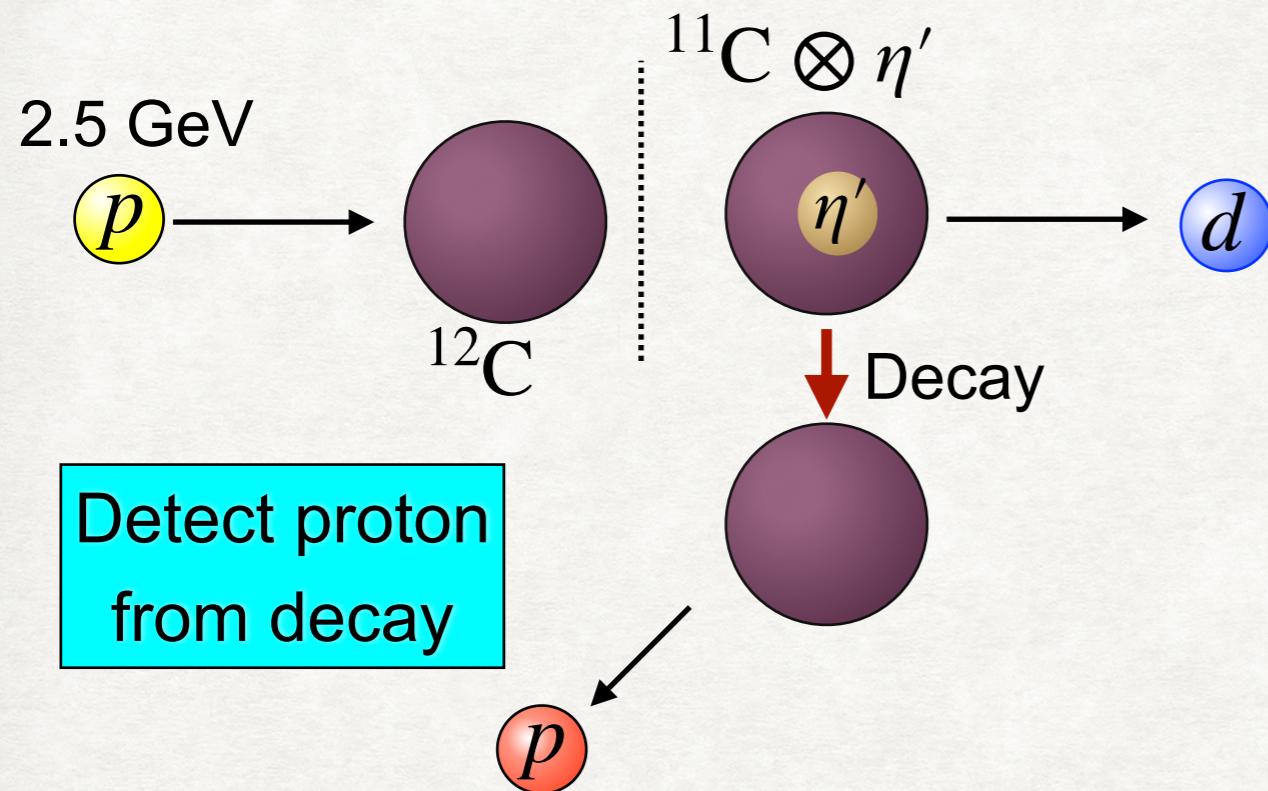
- We search for η' -mesic nuclei to study in-medium property of η' meson.
- We performed missing-mass spectroscopy in $^{12}\text{C}(\text{p},\text{d})$ reaction with p tagging.
 - We measured forward d with FRS.
 - We measured p from η' -mesic nuclei decay with WASA.
 - 10^7 d events are accumulated in 3.5 days.
- The analysis is on going.
 - $\text{p}-\pi$ identification with WASA is achieved.
 - Forward d identification is done with TOF SC41—43.
 - Sufficient statistics are obtained in inclusive excitation-energy spectrum.

Next Step

- We finalize WASA analysis.
- We will obtain missing-mass spectrum with p selection in WASA.

Backup

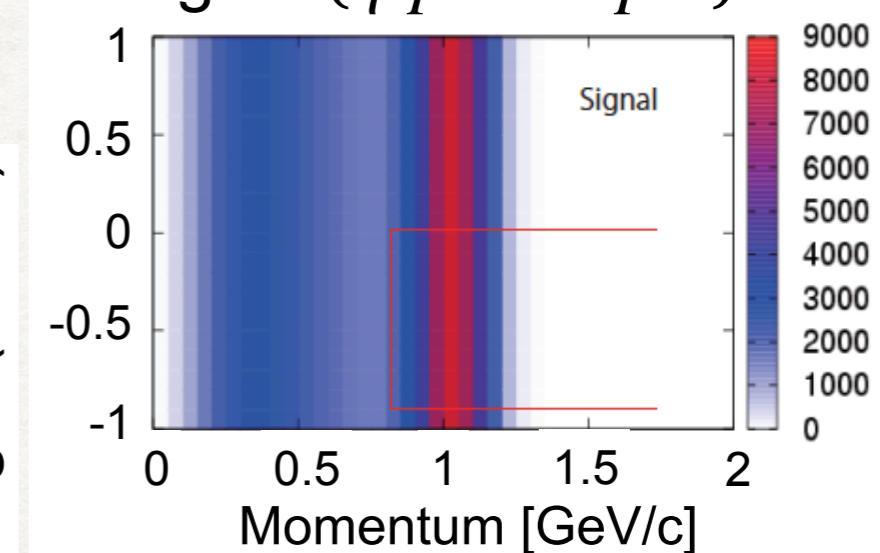
Background estimation by simulation



- Coincident measurement of d and p
- Detect p backward
- S/B ~ 1 is expected.

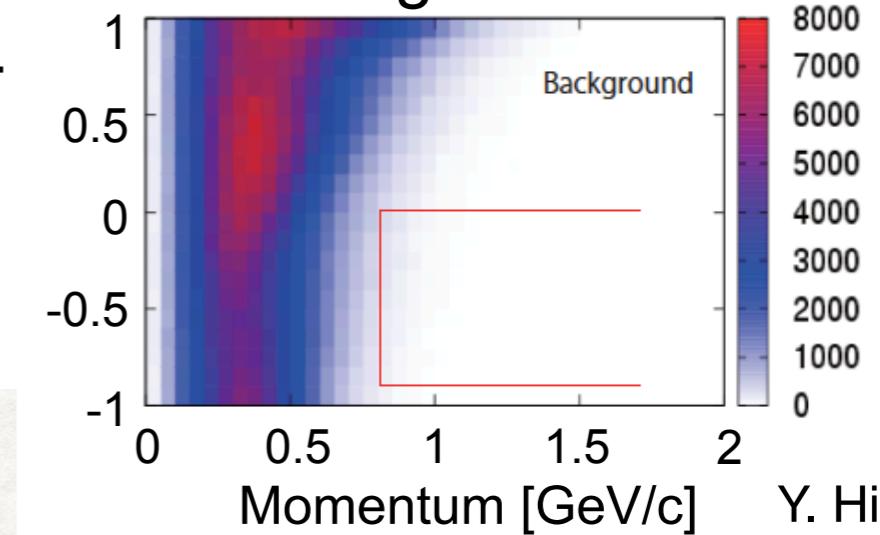
Expected proton distribution
by intra-nuclear cascade simulation

Signal ($\eta' p N \rightarrow p N$)



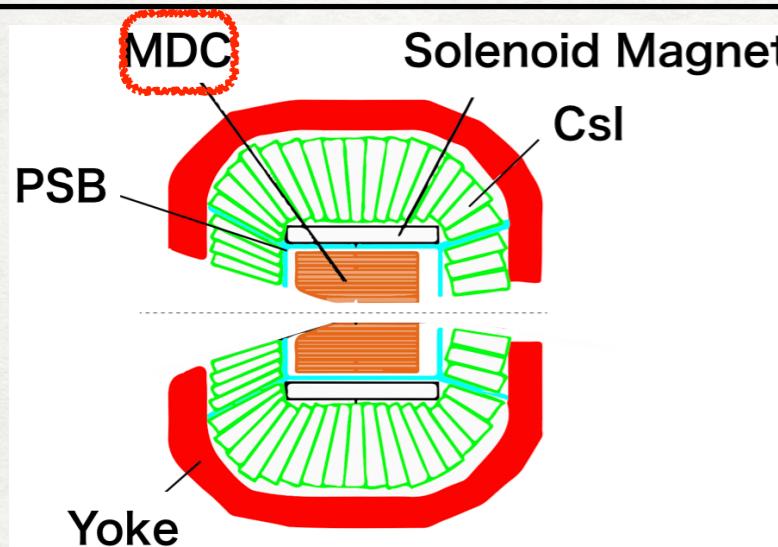
Emission polar angle ($\cos \theta$)

Background



Y. Higashi

Mini-Drift Chamber



Design & Readout

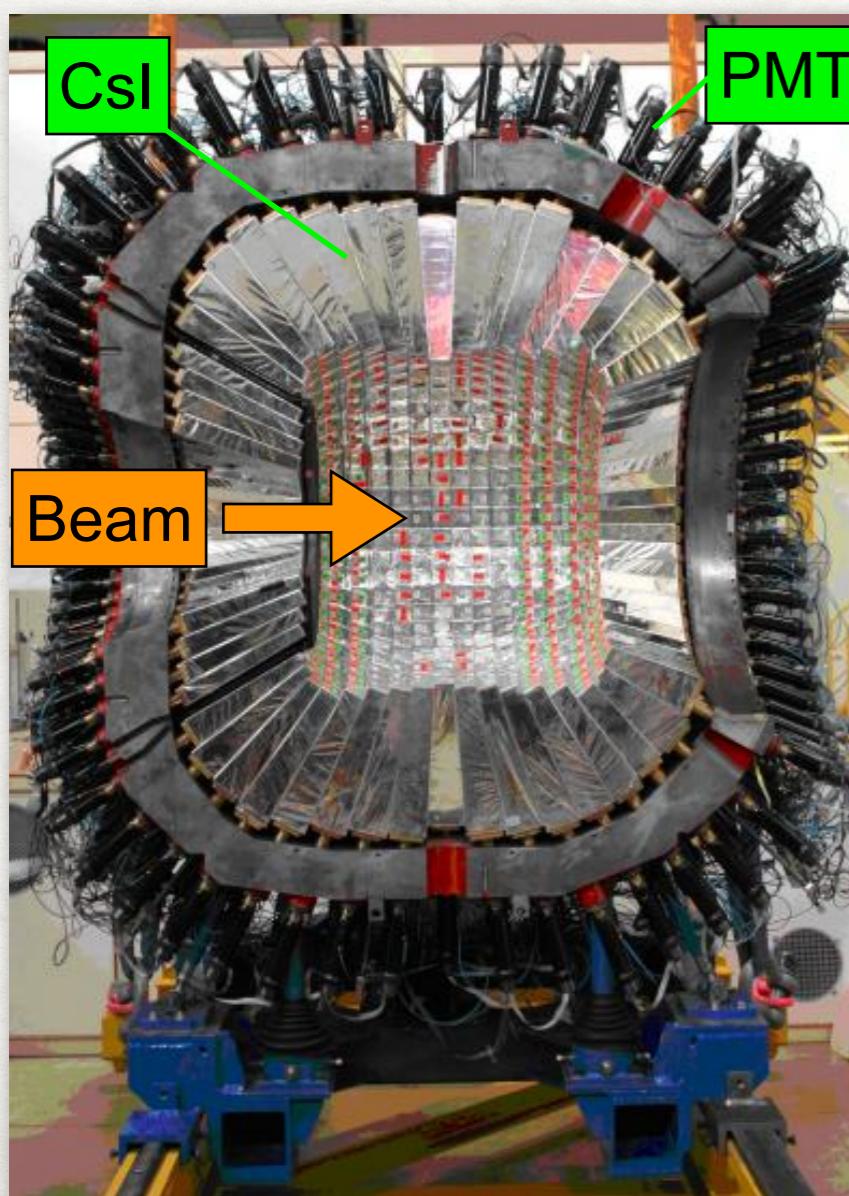
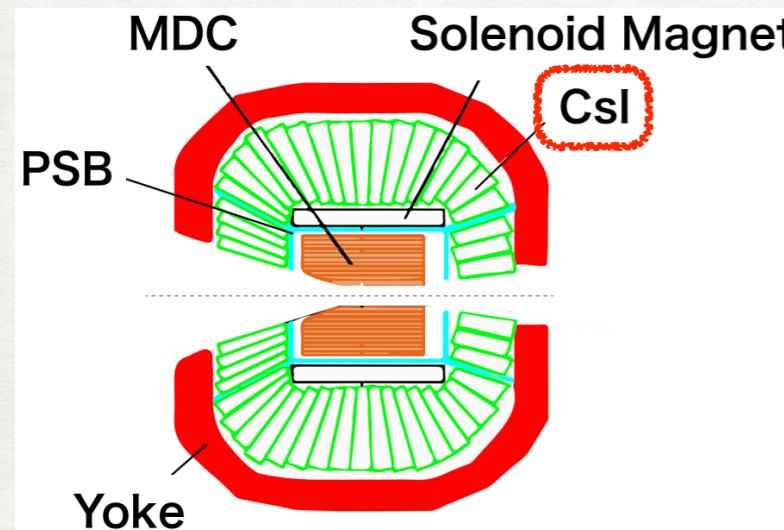
- ▶ 1738 straw tubes (17 layers)
- ▶ Stereo wires for z-measurement
- ▶ Signals processed by ASD (CMP-16).

Data acquisition

- ▶ Leading/Trailing TDC
(GSI Clock-TDC module)



CsI Electromagnetic Calorimeter

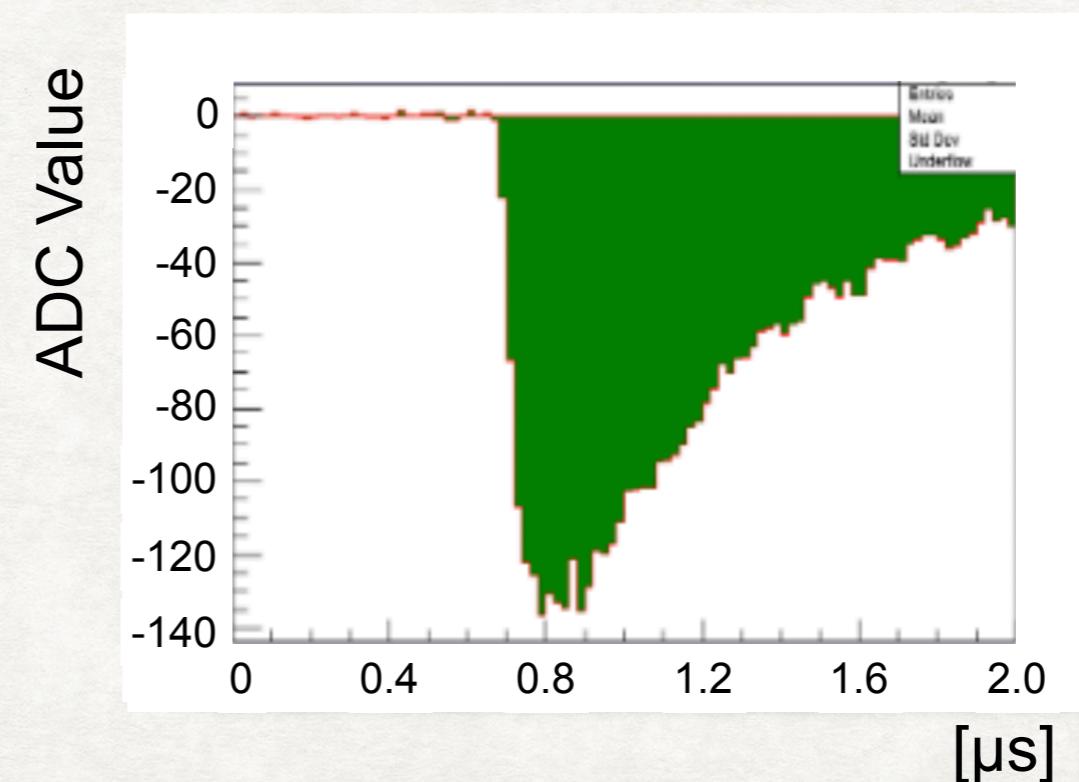


Design & Readout

- ▶ 1012 CsI(Na) calorimeters with PMT readout

Data acquisition

- ▶ 50 MHz waveform digitizer (GSI FEBEX3 module)



WASA detectors analysis (PID by PSB-CsI ΔE)

- CsI ΔE analysis.
 - Analysis of waveform (50 MS/s)
 - Charged π -p are identified.
 - Now trying analysis for γ from neutral meson decay.

