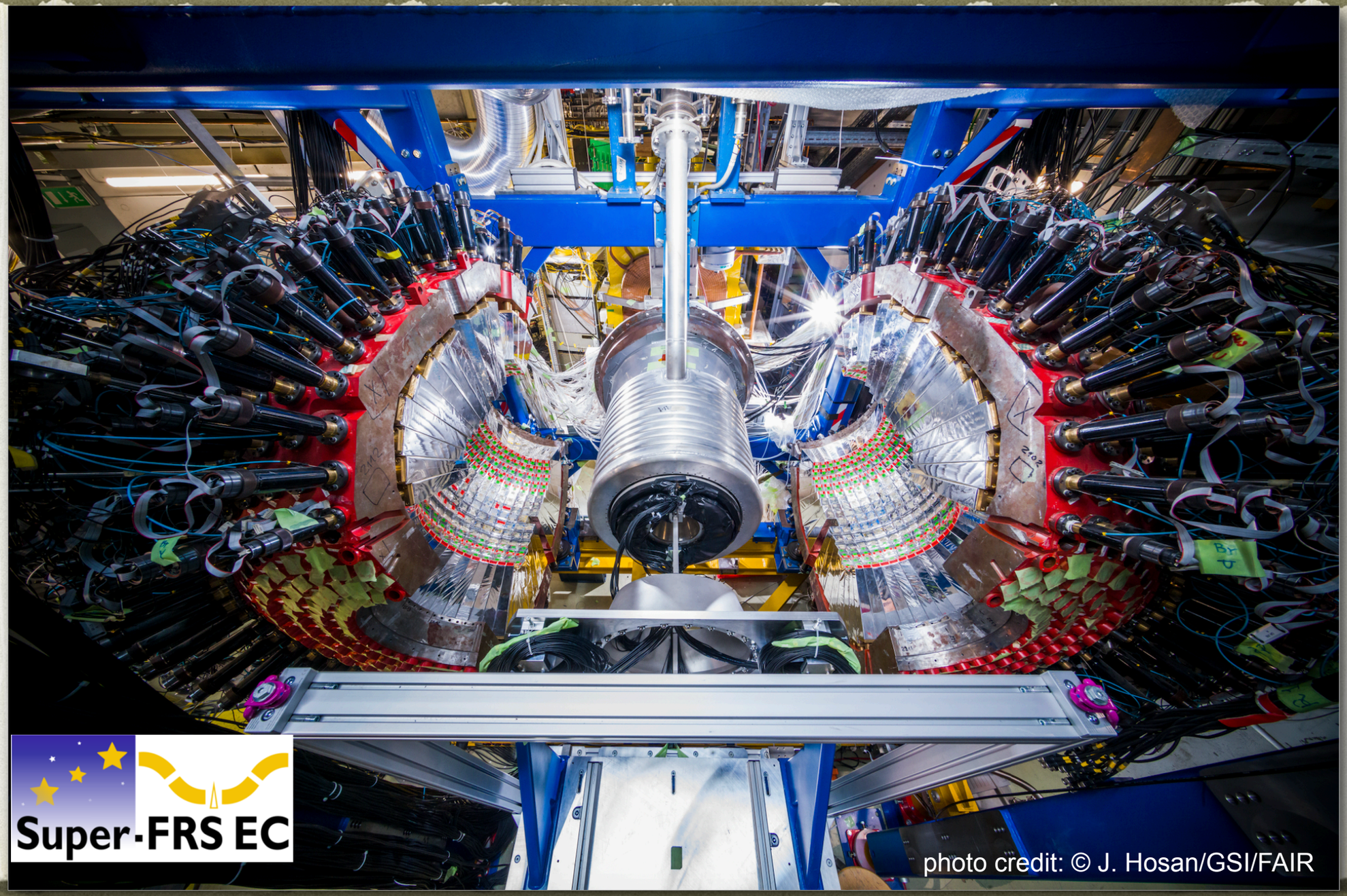


Search for η′-mesic nuclei in ^{12}C(p,dp) reaction using WASA detector at GSI-FRS

R. Sekiya[1,2] for the GSI-s490 collaboration
[1]Kyoto Univ., [2]RIKEN

Workshop: ハドロン分光に迫る反応と構造の物理
@ ELPH on 6-7 Dec. 2022.

η′-mesic nuclei

η′-meson in vacuum

- $M_{\eta'}$ = 958 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.

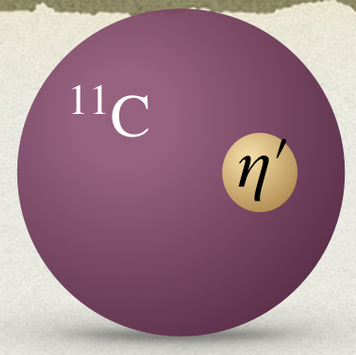
↓

Attractive potential

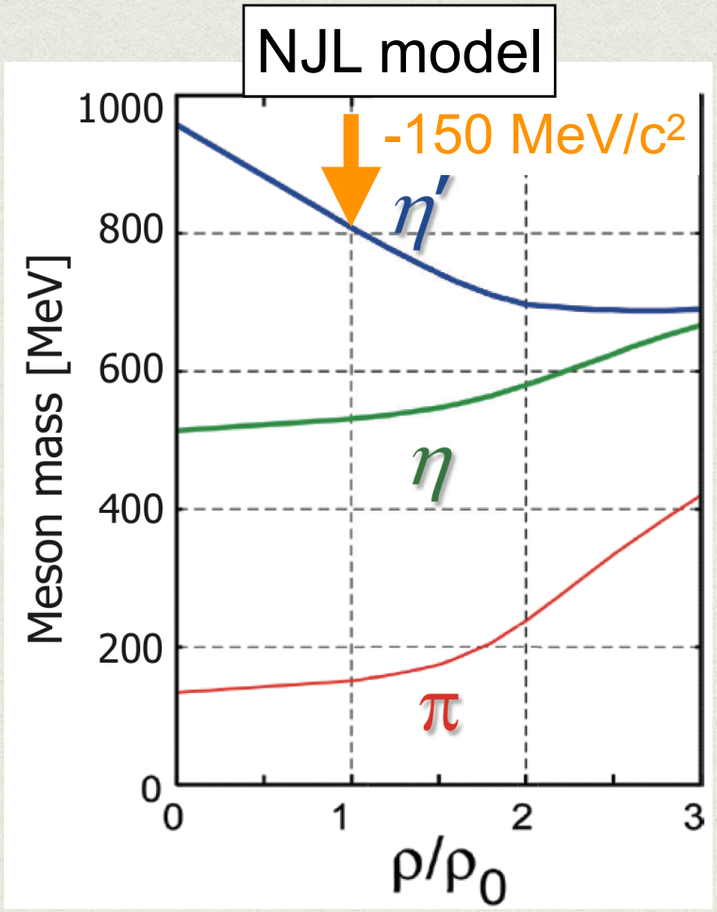
↓

Bound state is expected (η′-mesic nuclei)

Study of in-medium property

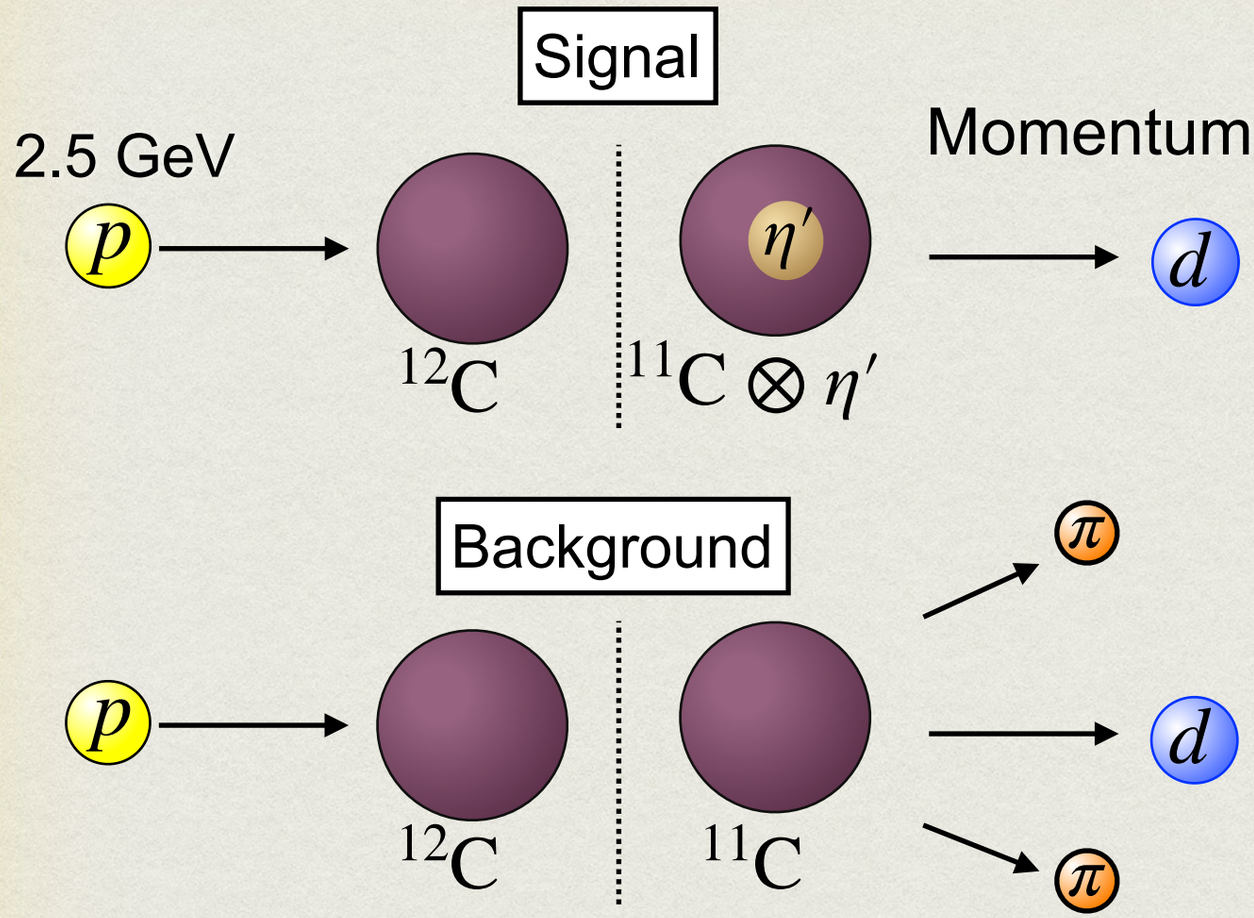


η′-mesic nuclei



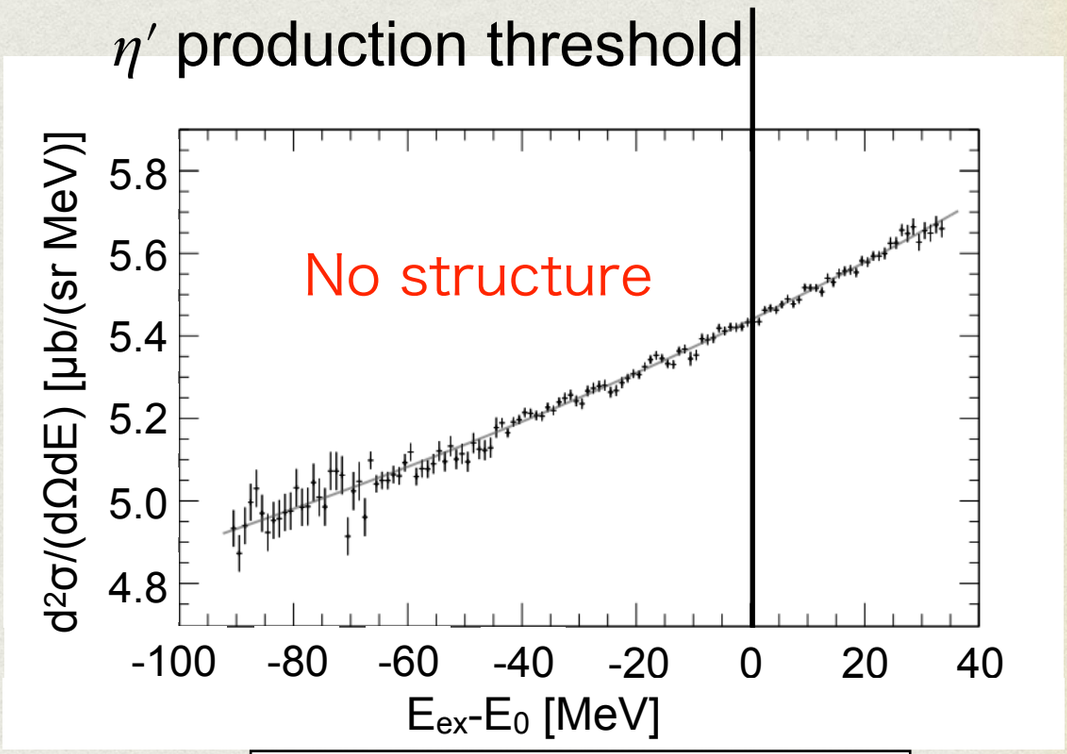
H. Nagahiro et. al., PRC **74**, 045203 (2006)

Inclusive measurement of ^{12}C(p,d) reaction in 2014



- S/B ≲ 1/100
- Multiple pion was a major background.

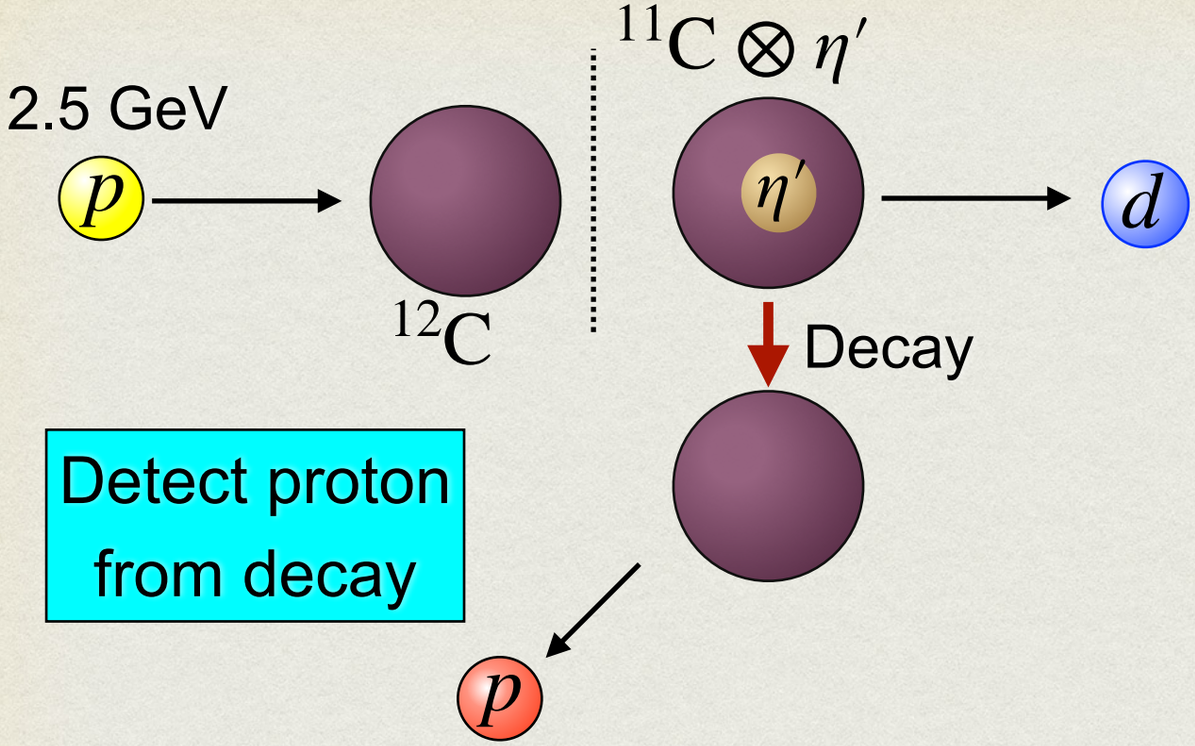
Missing mass spectroscopy



Measured Spectrum

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

Semi-Exclusive measurement of ^{12}C(p,dp) reaction



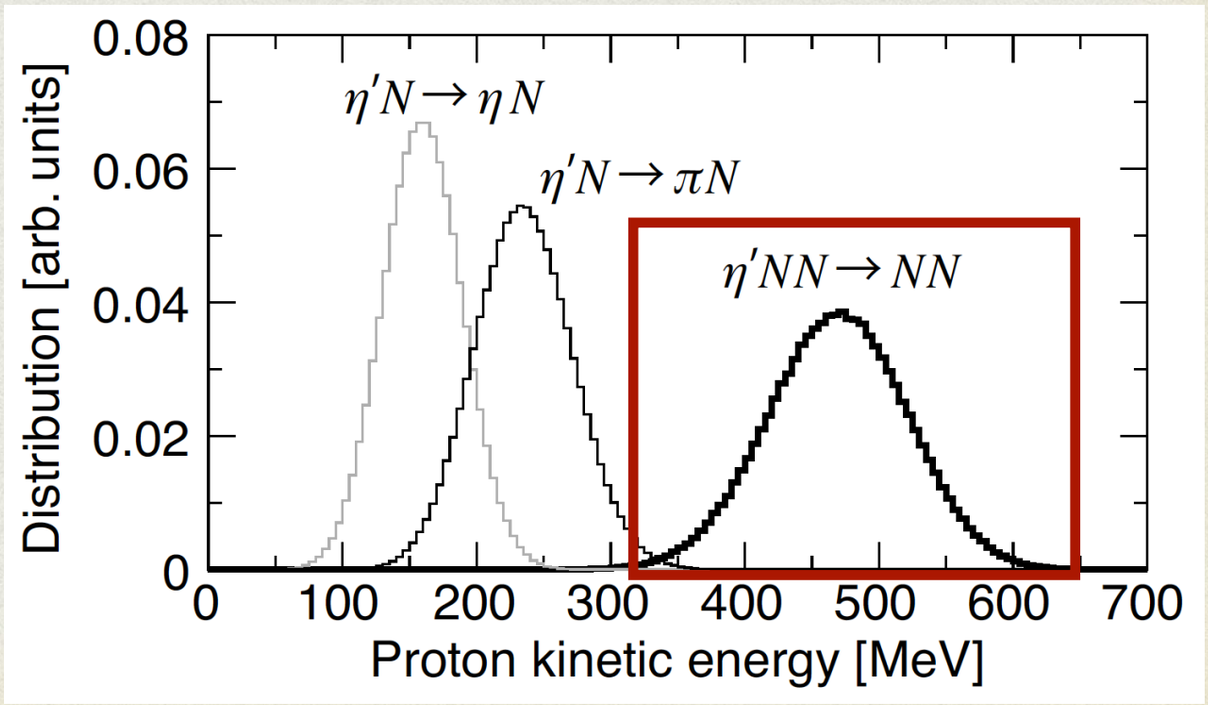
Detect proton from decay

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

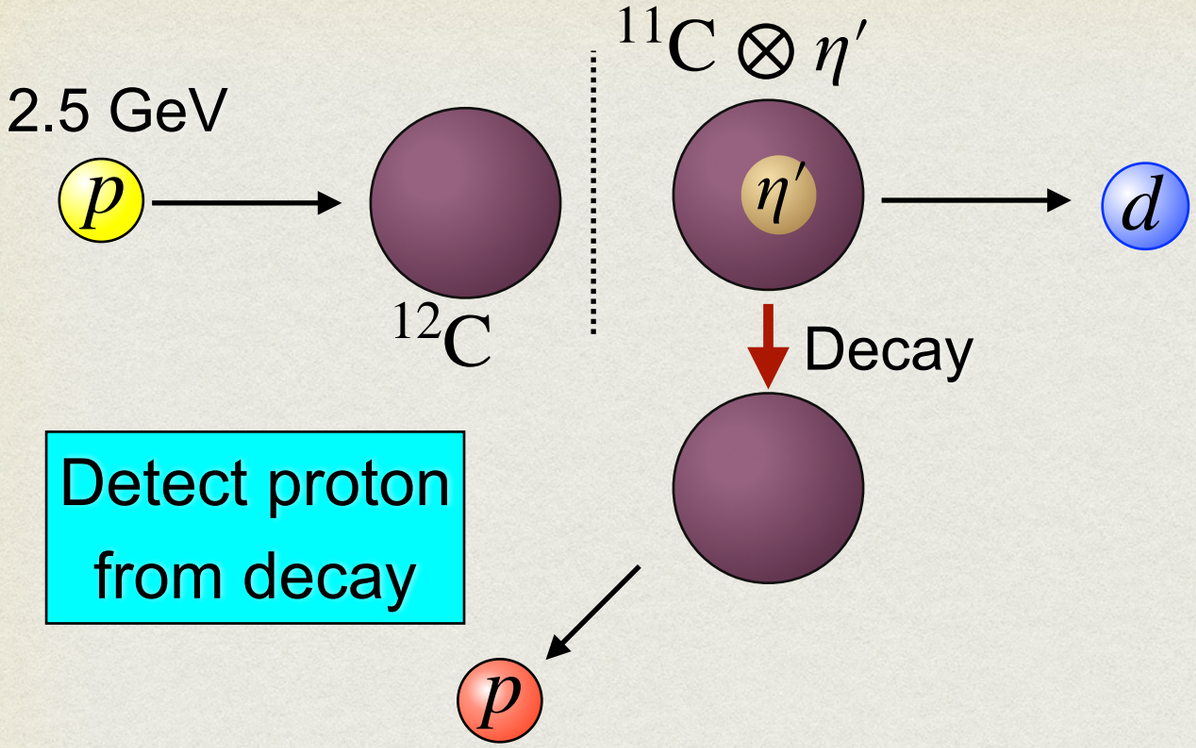
Major decay modes

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

H. Nagahiro, Nucl. Phys. A 914, 360 (2013).



Semi-Exclusive measurement of ^{12}C(p,dp) reaction

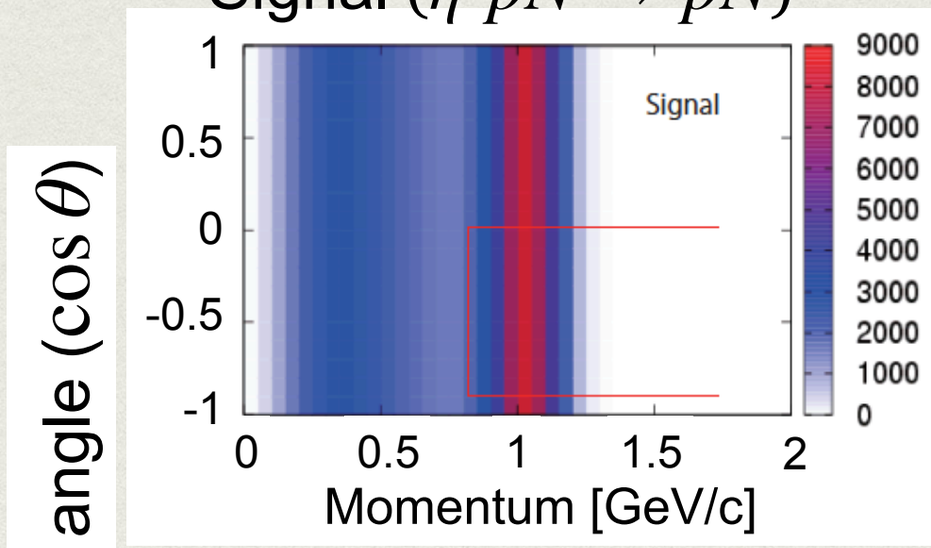


Detect proton from decay

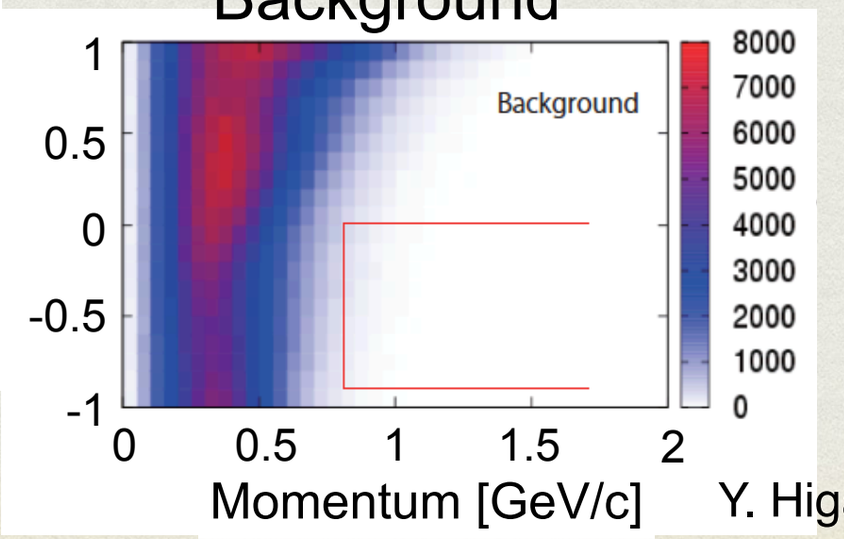
- Coincident measurement of d and p
- Detect p backward
- S/B ~ 1 is expected.

Expected proton distribution by intra-nuclear cascade simulation

Signal ($\eta' pN \rightarrow pN$)

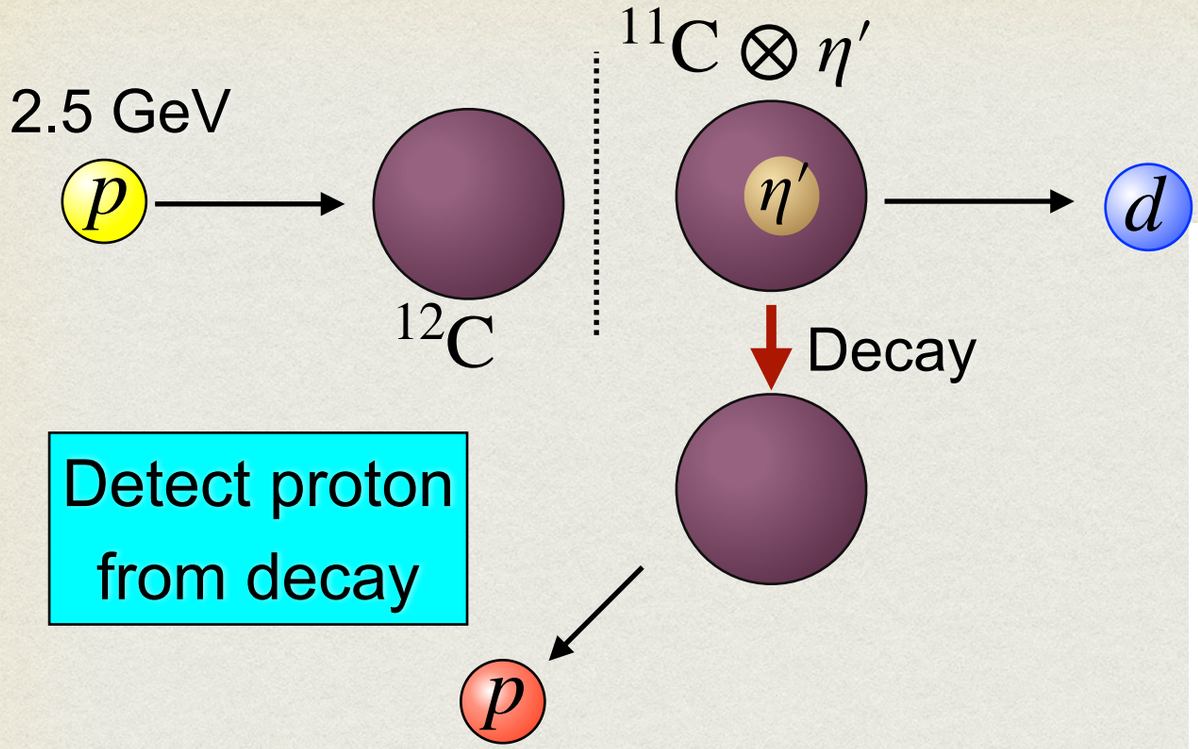


Background



Y. Higashi

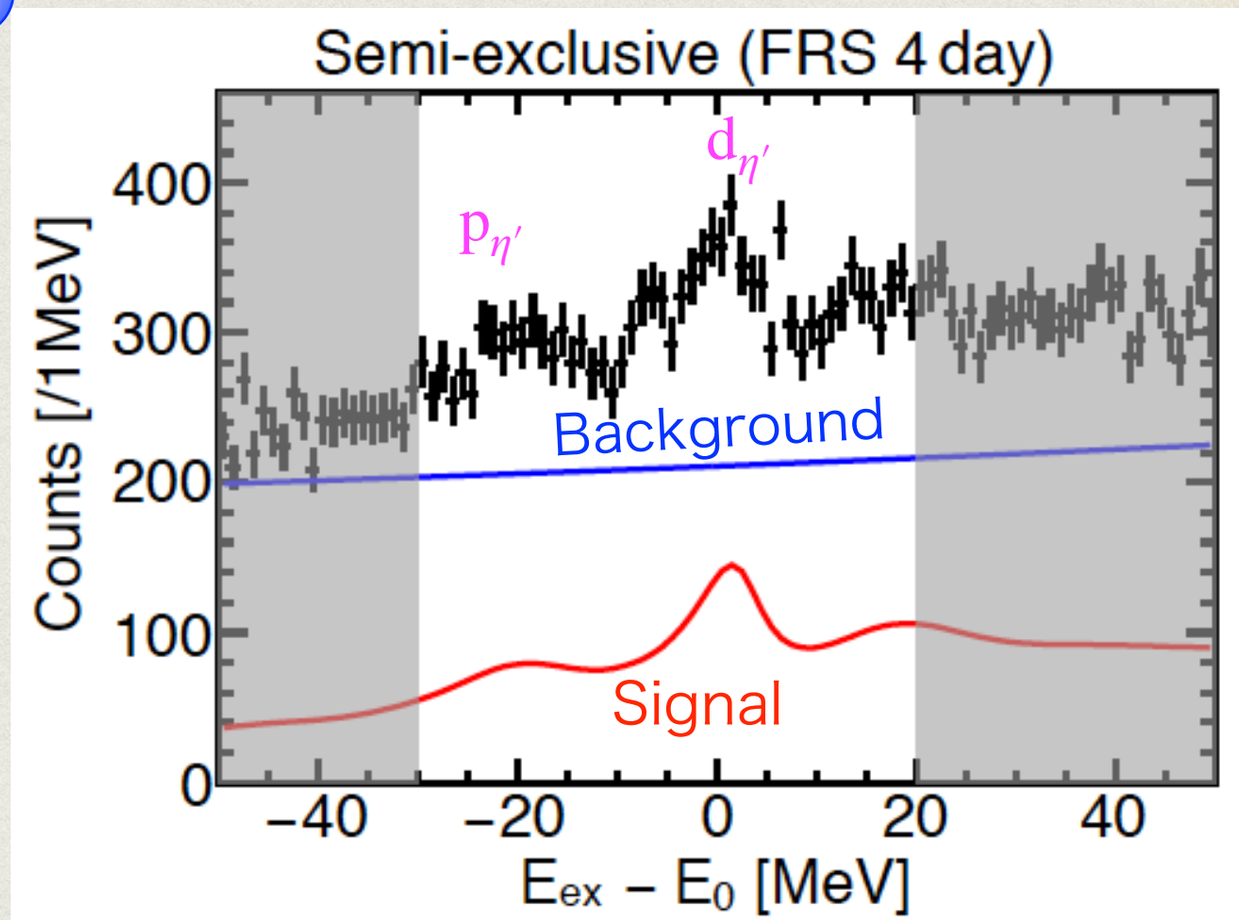
Semi-Exclusive measurement of ^{12}C(p,dp) reaction



Detect proton from decay

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

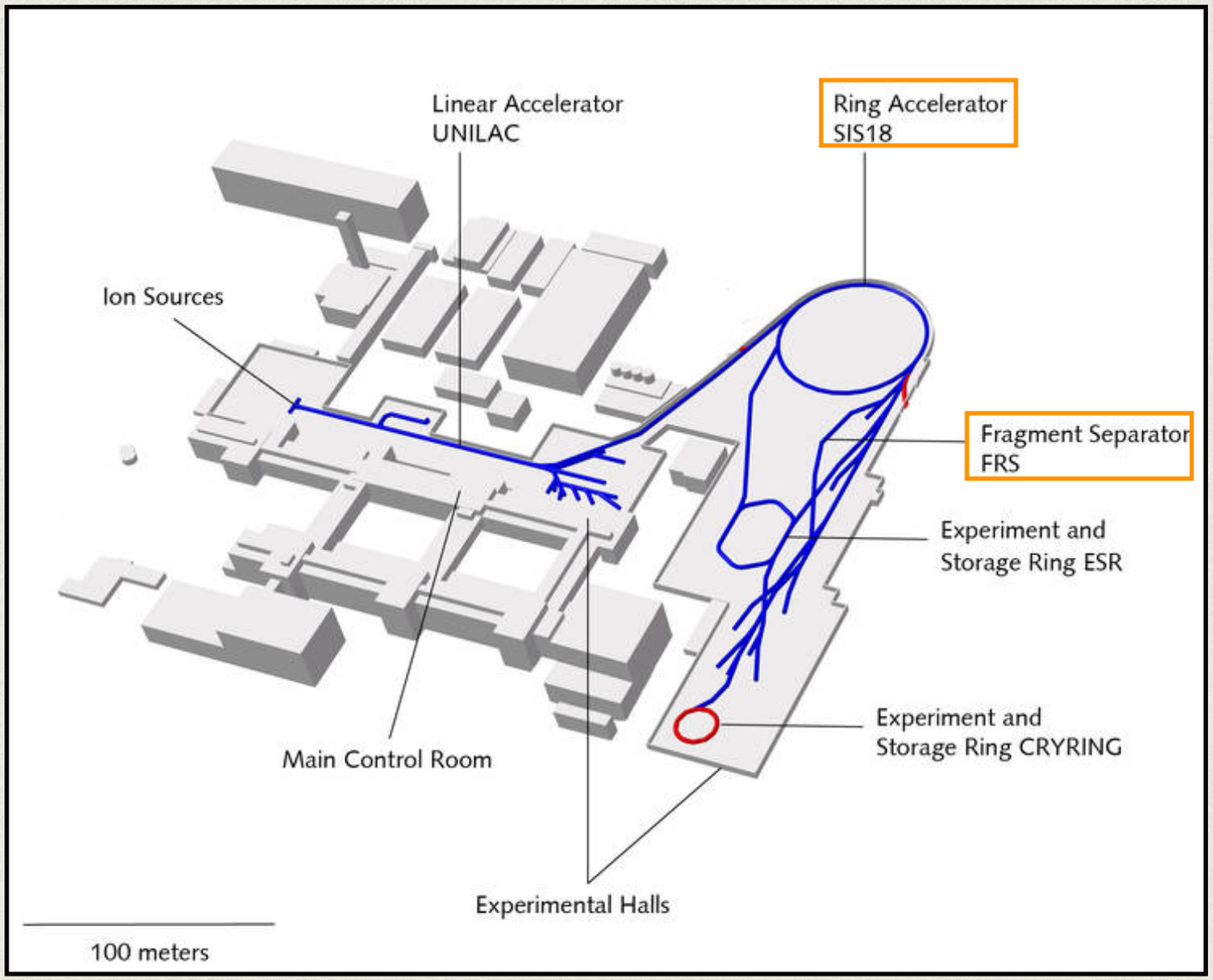
$(V_0, W_0) = (-90, -17)$



Simulated spectrum

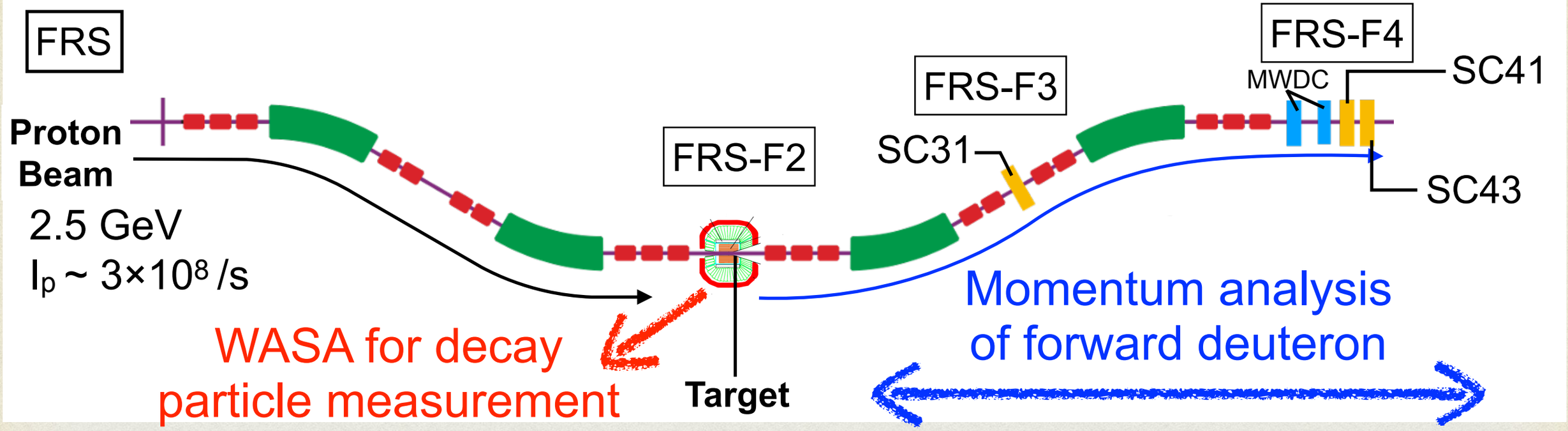
GSI Facility

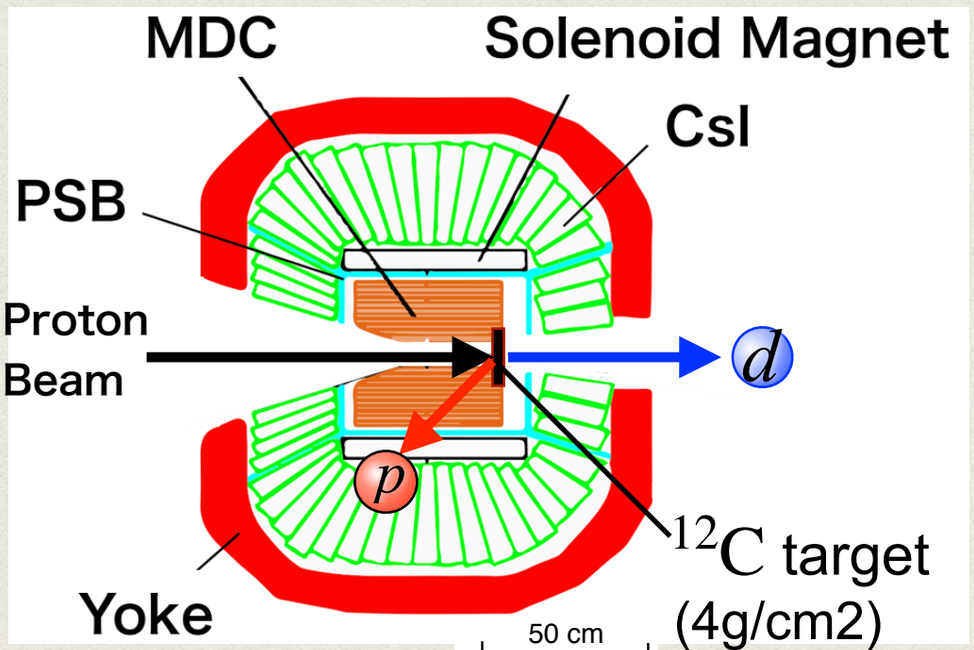
- SIS-18 : Capable of providing 2.5 GeV proton beams.
- FRS : High resolution spectrometer.



https://www.gsi.de/en/researchaccelerators/accelerator_facility.htm

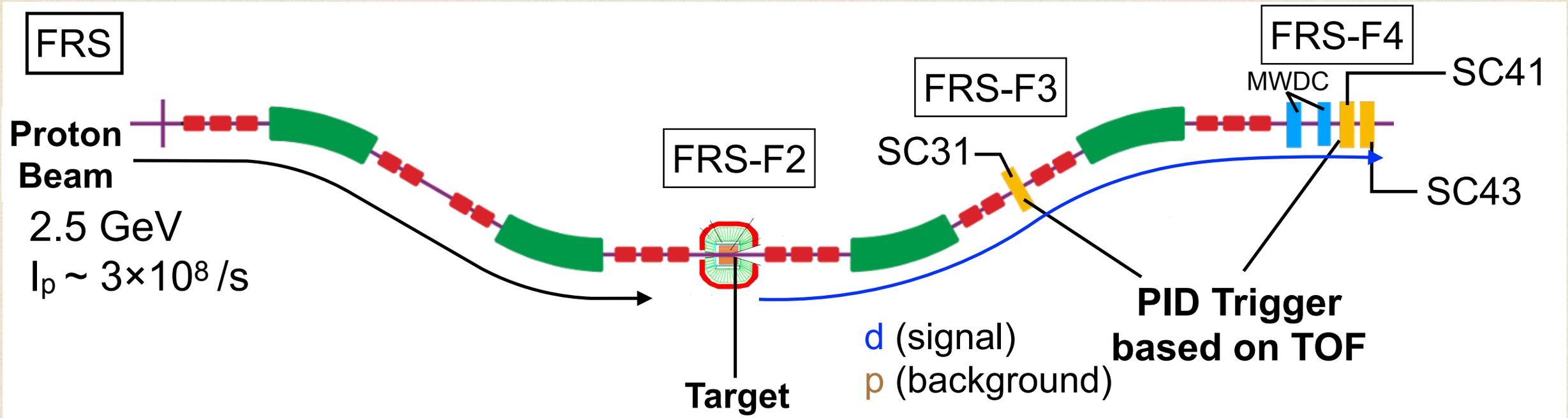
WASA-at-FRS experiment conducted in 2022 Feb.





$$p + {}^{12}C \rightarrow \underline{{}^{11}C \times n'} + d$$
$$\hookrightarrow p + X$$

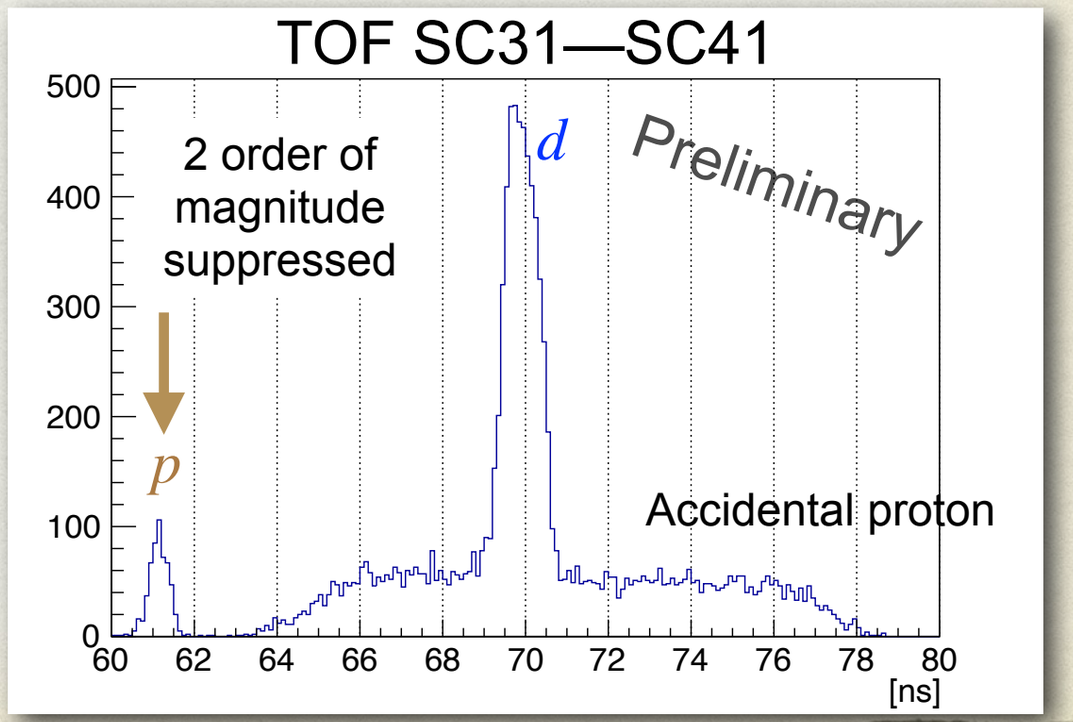
Hardware deuteron PID trigger



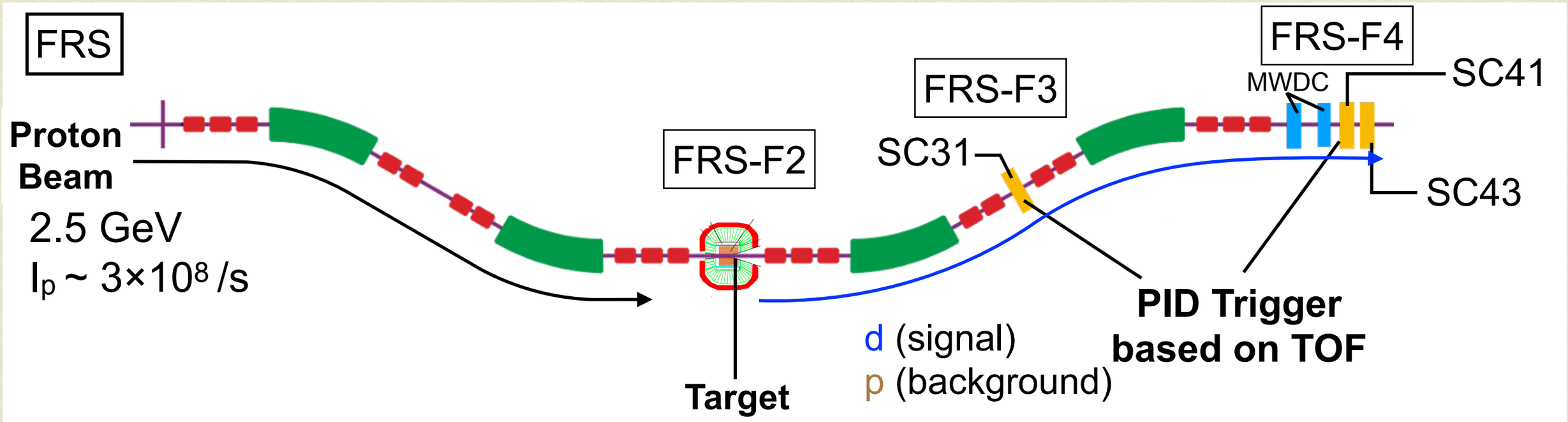
Production Run

- ^{12}C target (4 g/cm^2)
- 3.5 days data collection

  → ~10^7 forward deuteron events



Hardware deuteron PID trigger



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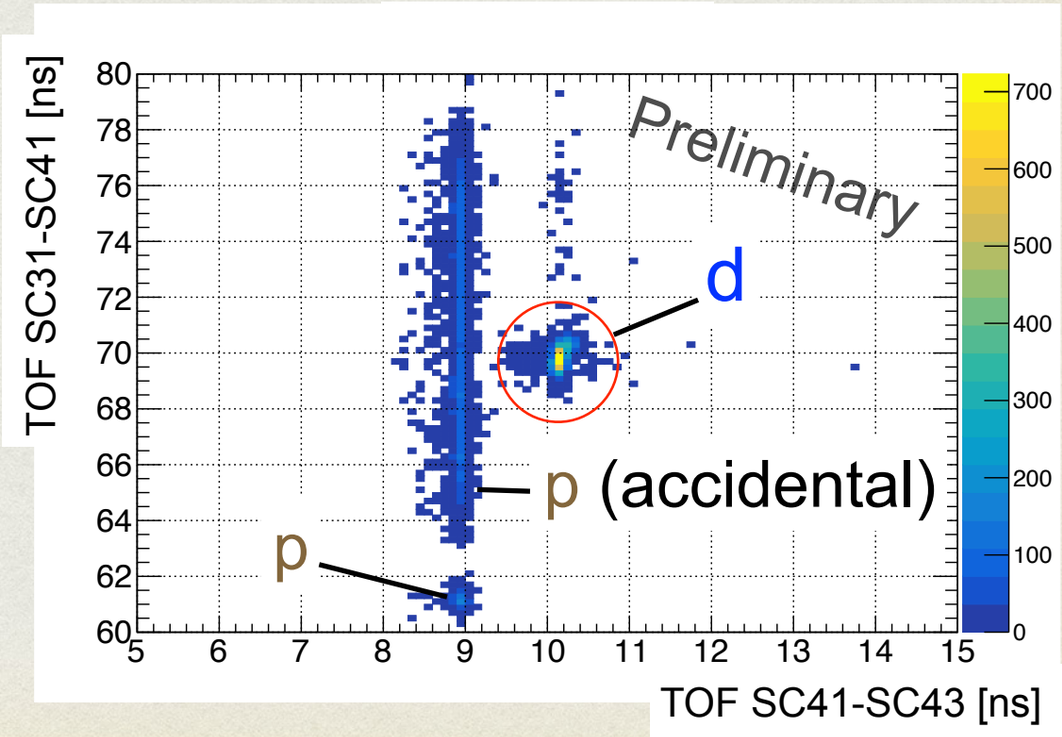
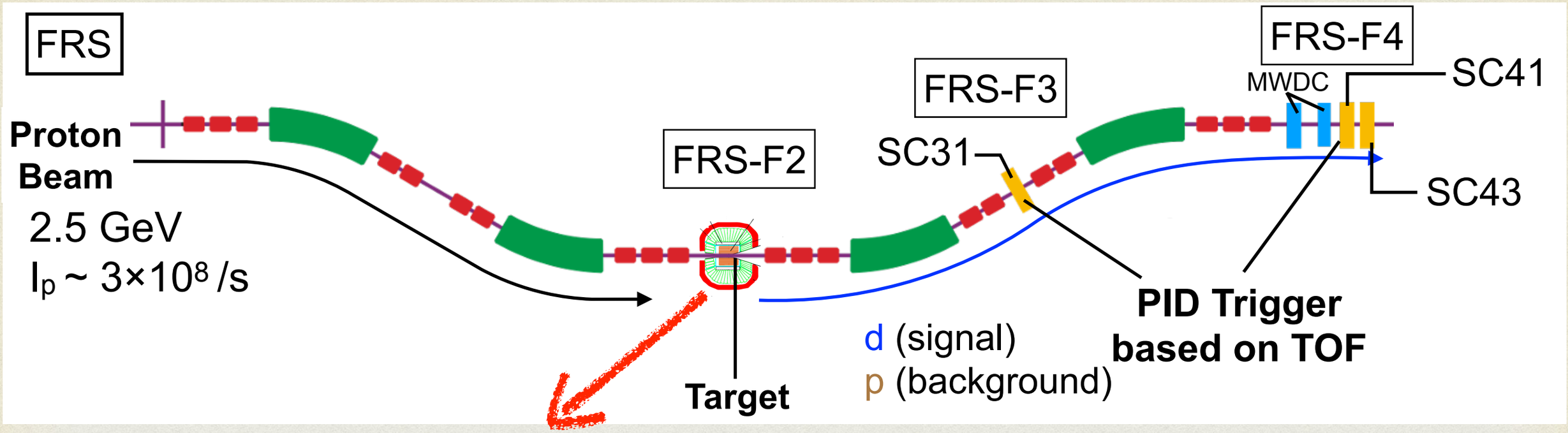
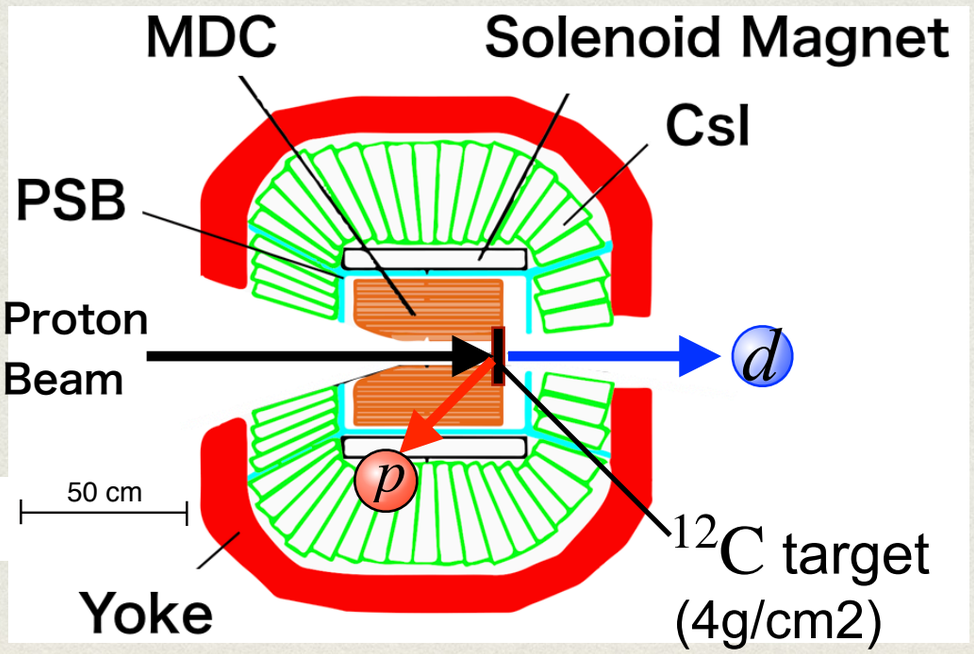


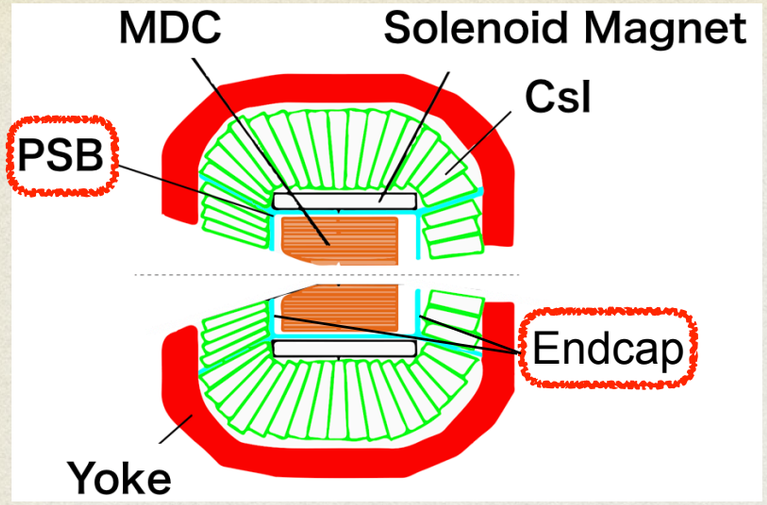
WASA Detector

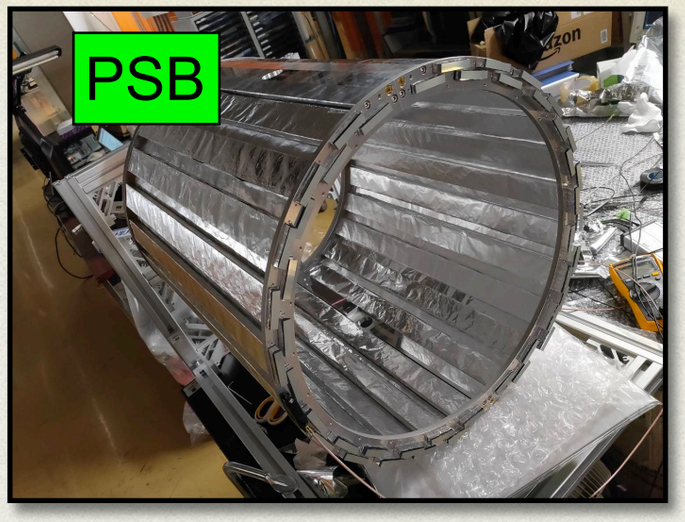


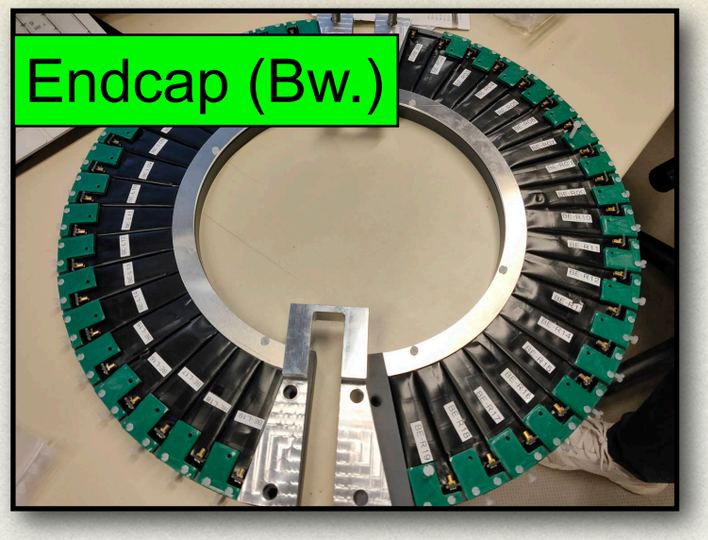


- Superconducting Solenoid Magnet.
- Mini-Drift Chamber (MDC).
- Plastic Scintillators (PSB/Endcap).
- CsI Electromagnetic Calorimeter.

Plastic Scintillator Barrel (PSB) and Endcap







PSB

- 46 plastics (550×38×8 mm^3)
- MPPCs readout from both ends
- σ ~ 55—80 ps

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

MPPC board connected in series

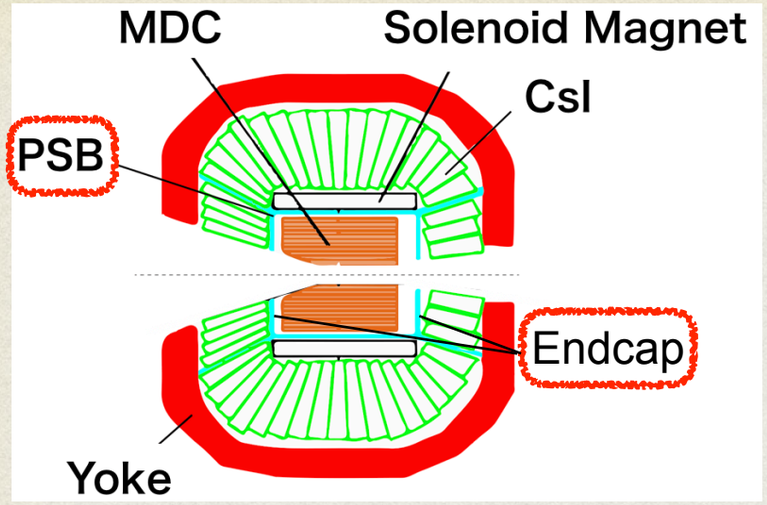
Endcap (Forward/Backward)

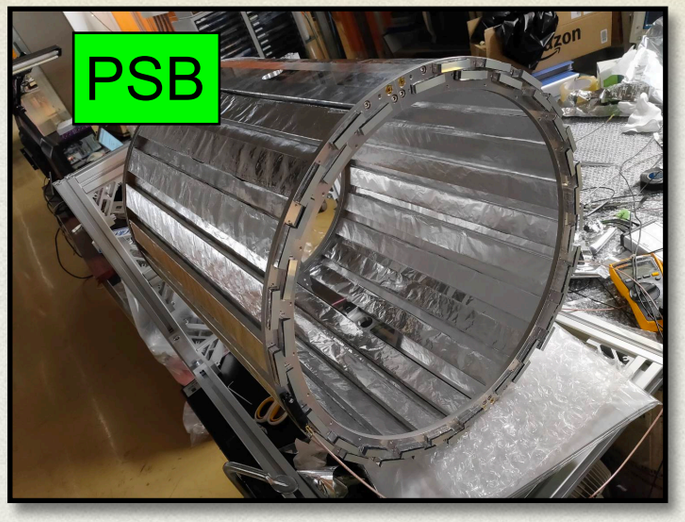
- 44 (Fw.) / 38 (Bw.) plastics
- MPPCs readout from one side

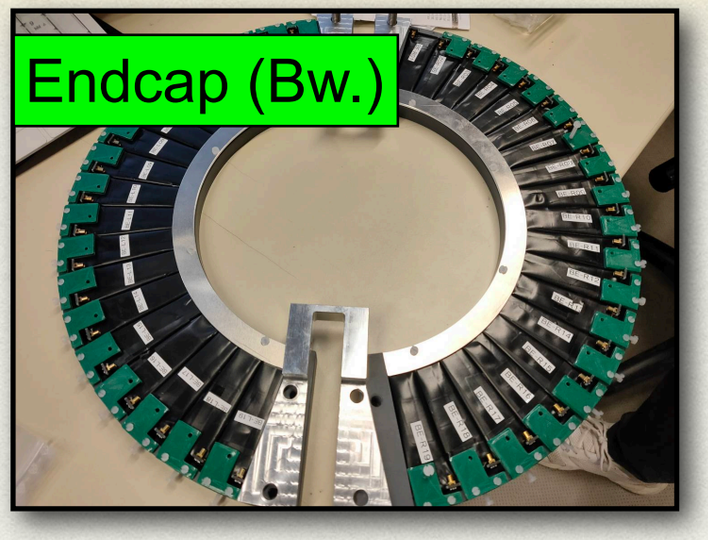
Data acquisition

- TDC (V1290) & QDC (V792)
- 2.5 GHz sampling waveform digitizer (V1742)

Plastic Scintillator Barrel (PSB) and Endcap







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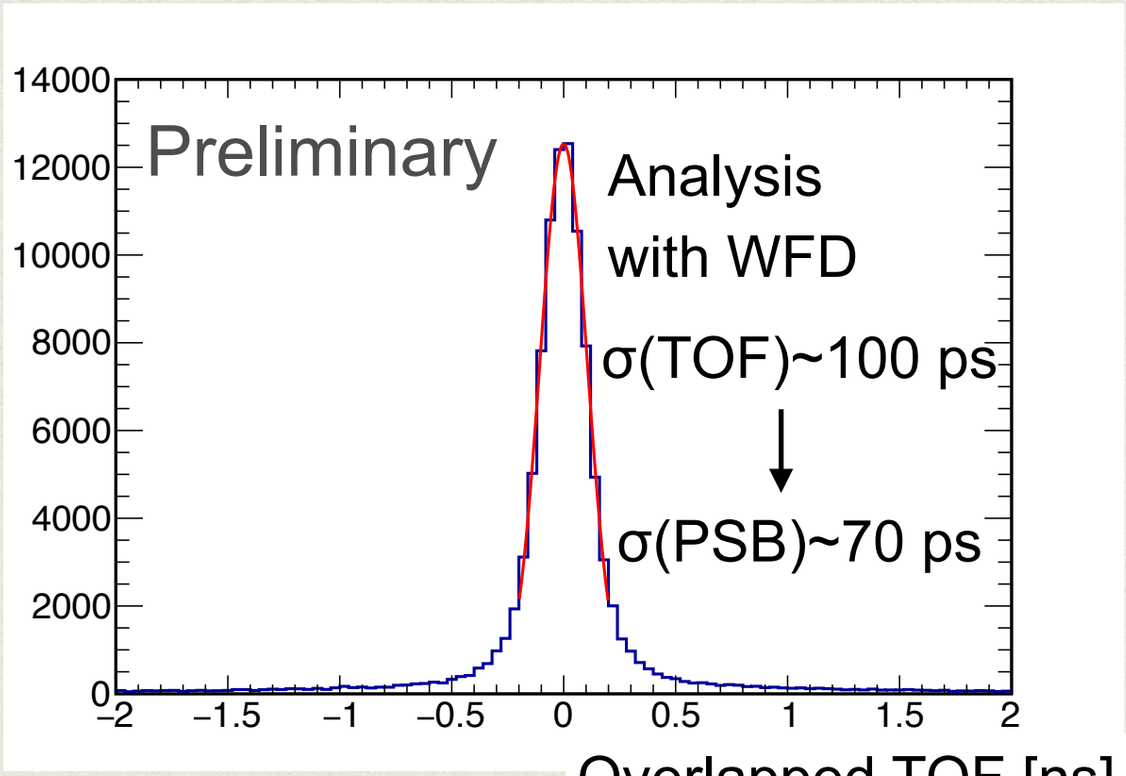
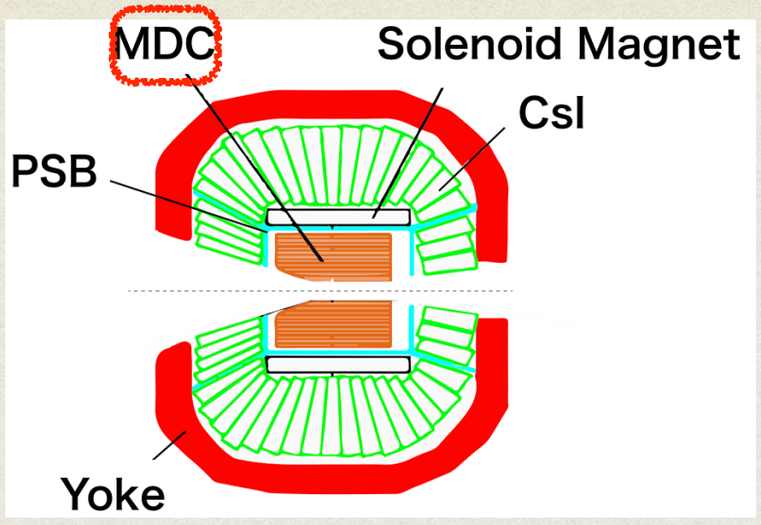


Mini-Drift Chamber



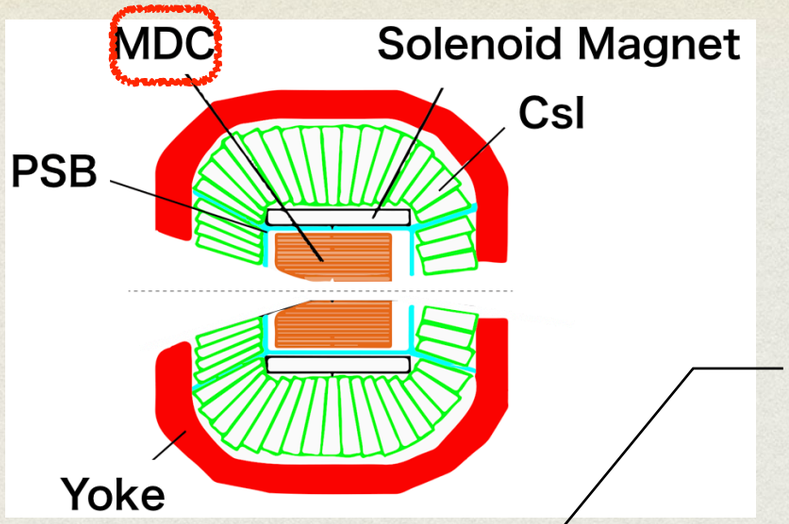
Design & Readout

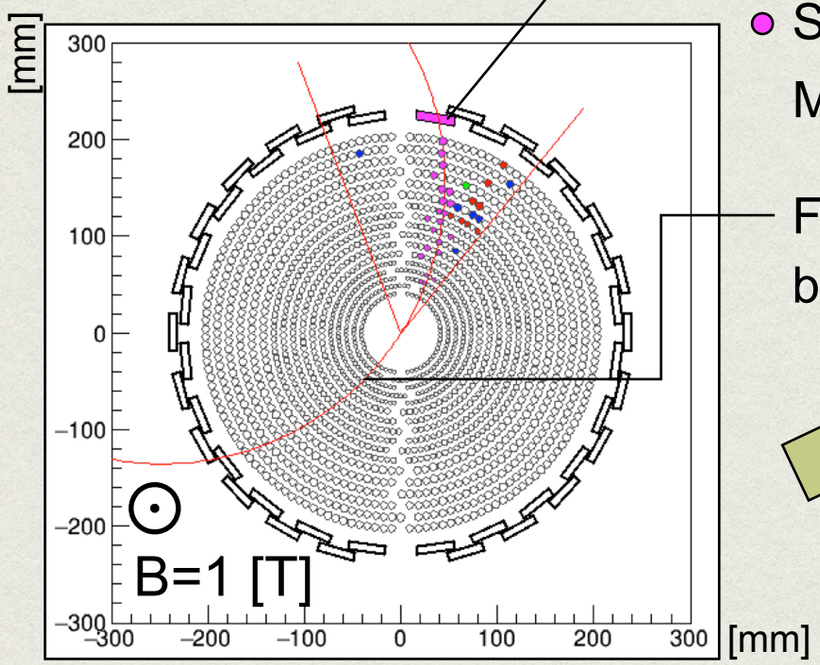
- 1738 straw tubes (17 layers)
- Stereo wires for z-measurement
- Signals processed by ASD (CMP-16).

Data acquisition

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

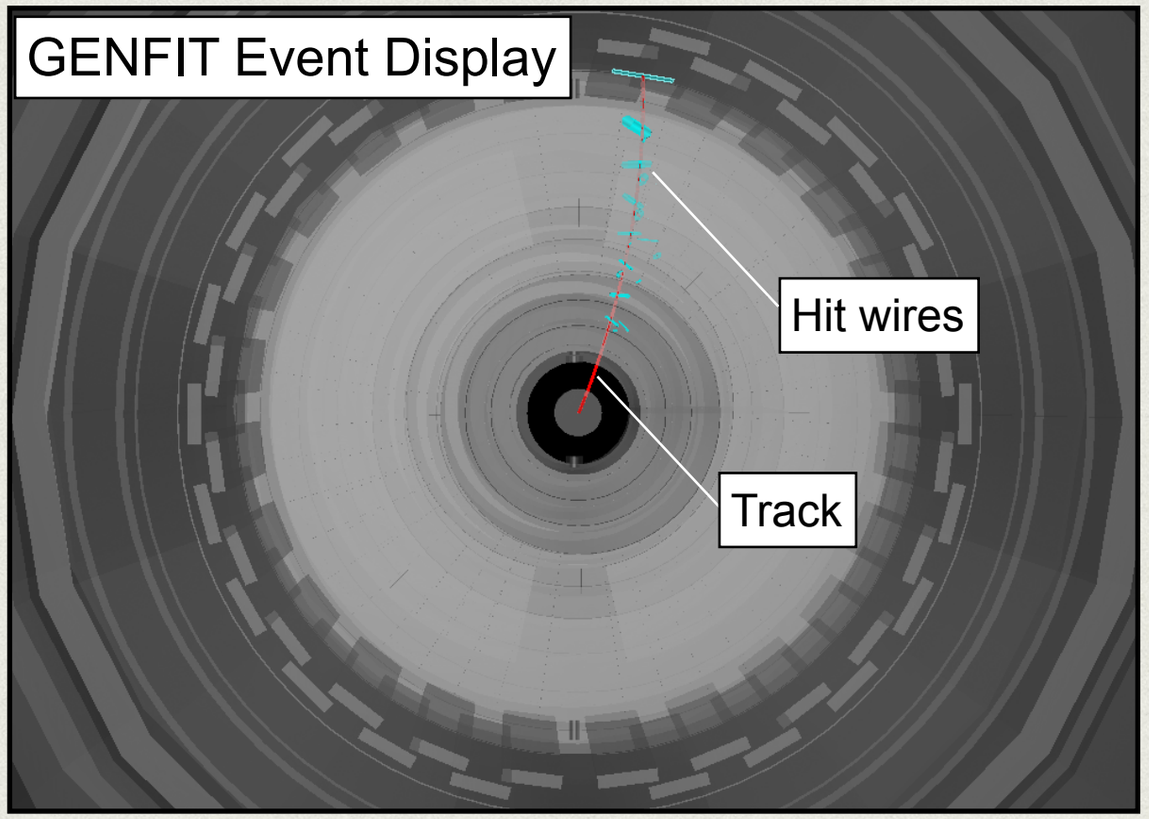
MDC Tracking





- Required PSB hits.
- Selected MDC wires.
- Fitted line by EAA.

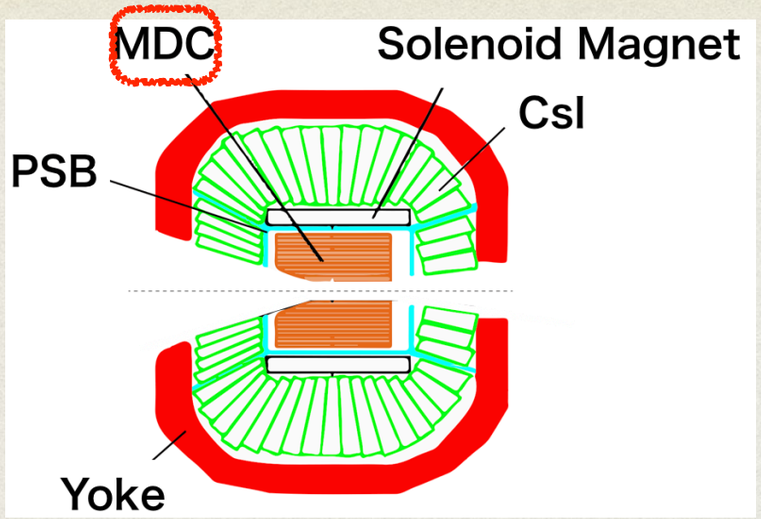
Hit selection by Elastic Arm Algorithm [1].



Fitting track points with GENFIT, a toolkit for tracking based on Kalman Filter [2,3].

[1] R. Frtihwirth, A. Strandlie, Computer Physics Communications 120 (1999) 197-214
[2] C. Höppner et al., Nucl. Instrum. Methods Phys. Res. A 620, 518 (2010).
[3] T. Bilka et al., arXiv 1902.04405 (2019).

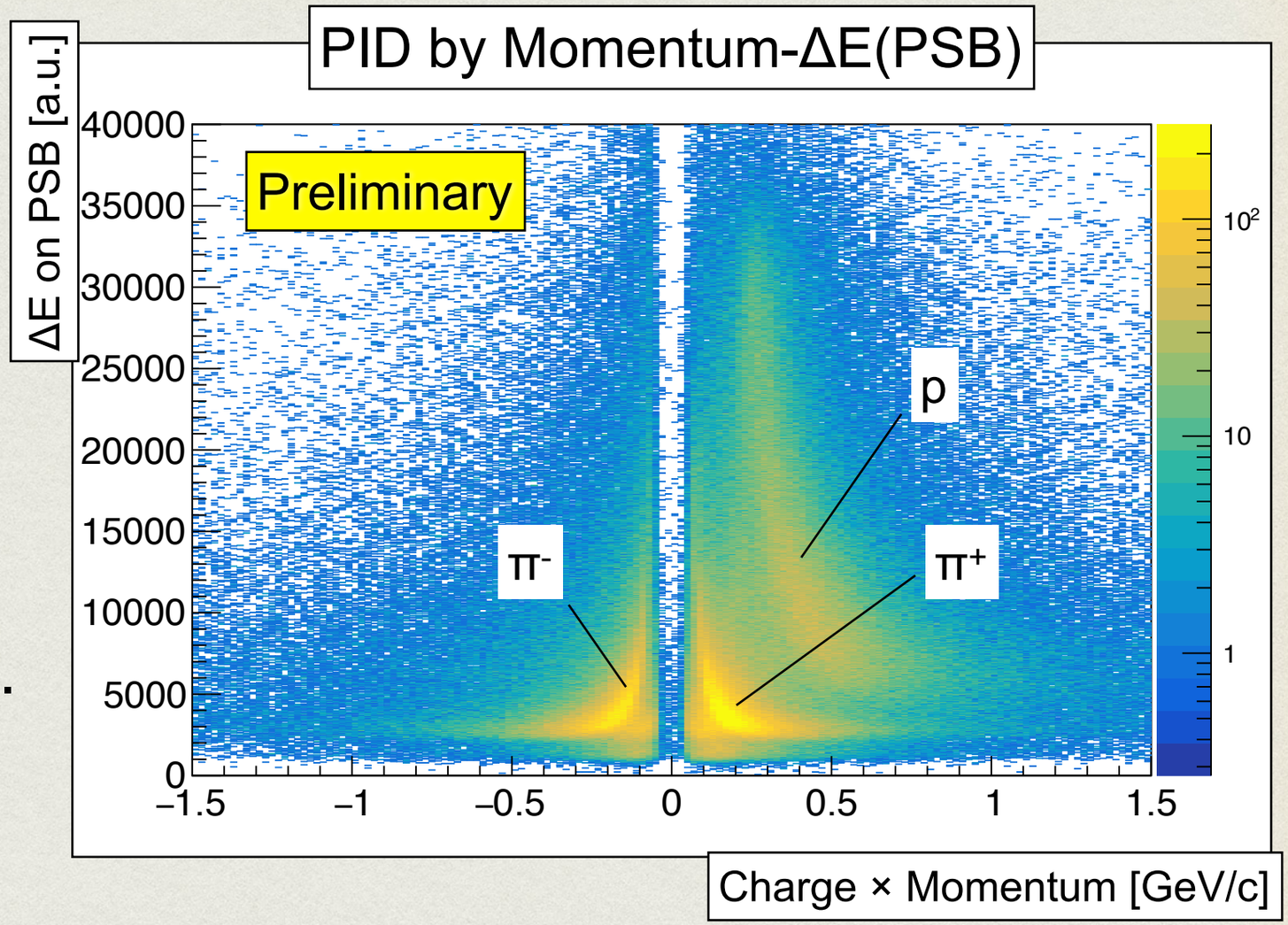
MDC Tracking



Trigger:

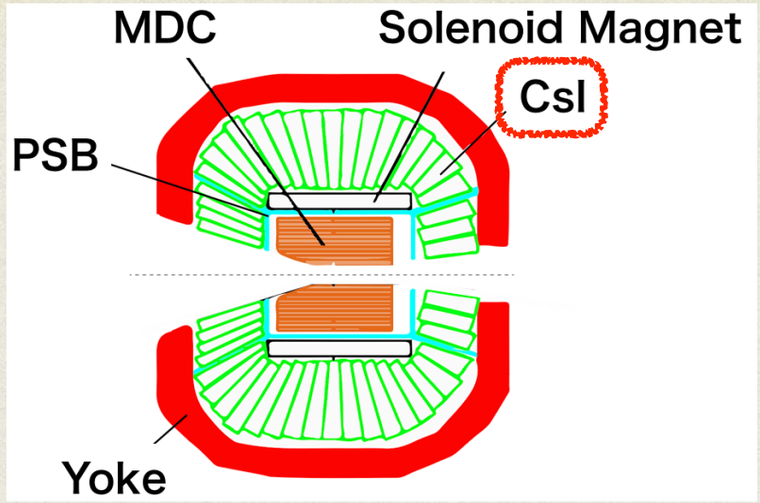
- Hardware TOF
- Downscaled SC41 and PSB.

1% of the data are analyzed.

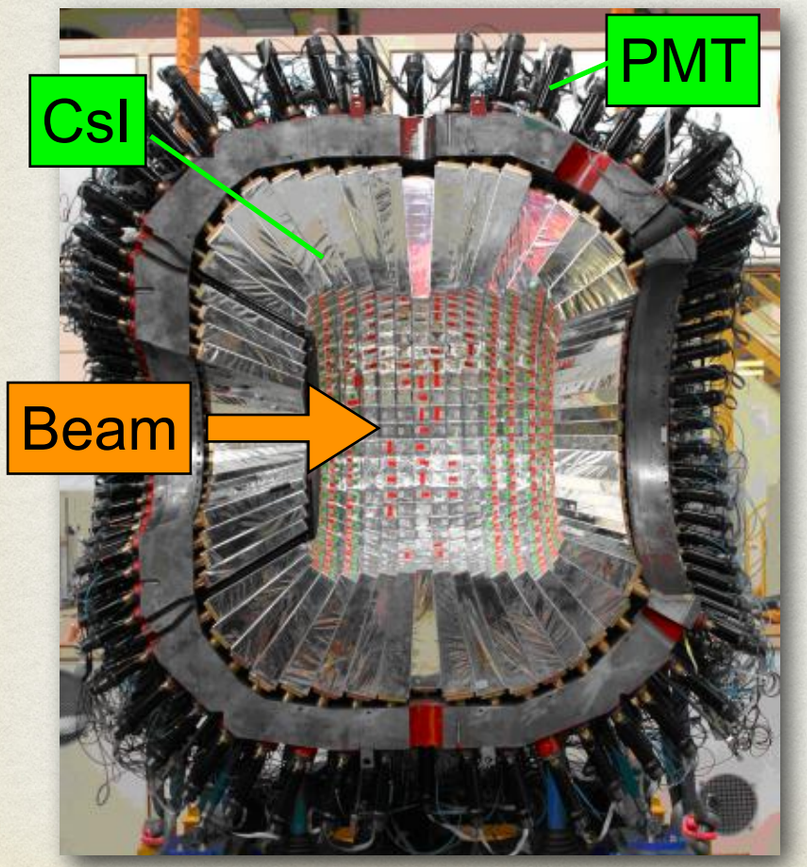


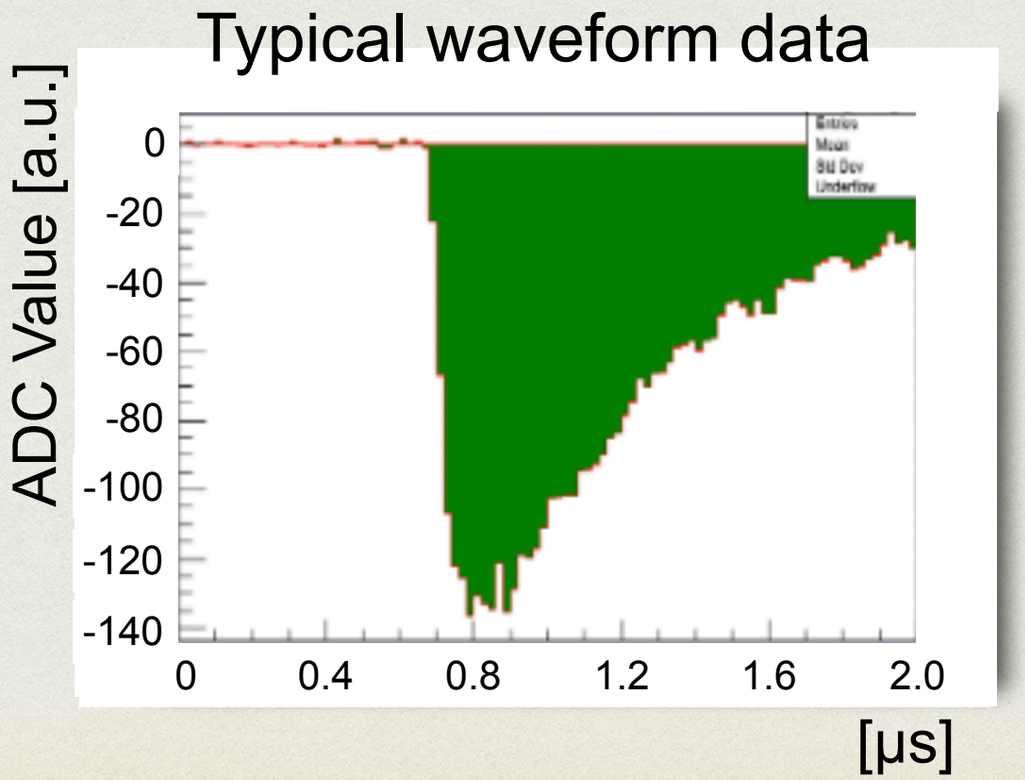
More precise analysis is ongoing for better p-π separation

CsI Electromagnetic Calorimeter

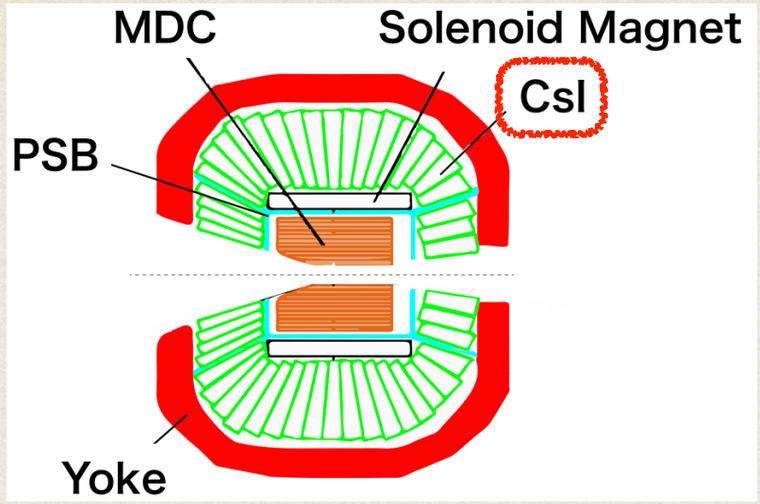


- 1012 CsI(Na) calorimeters with PMT readout
- 50 MHz waveform digitizer (GSI FEBEX3 module)





PID by PSB-CSI ΔE



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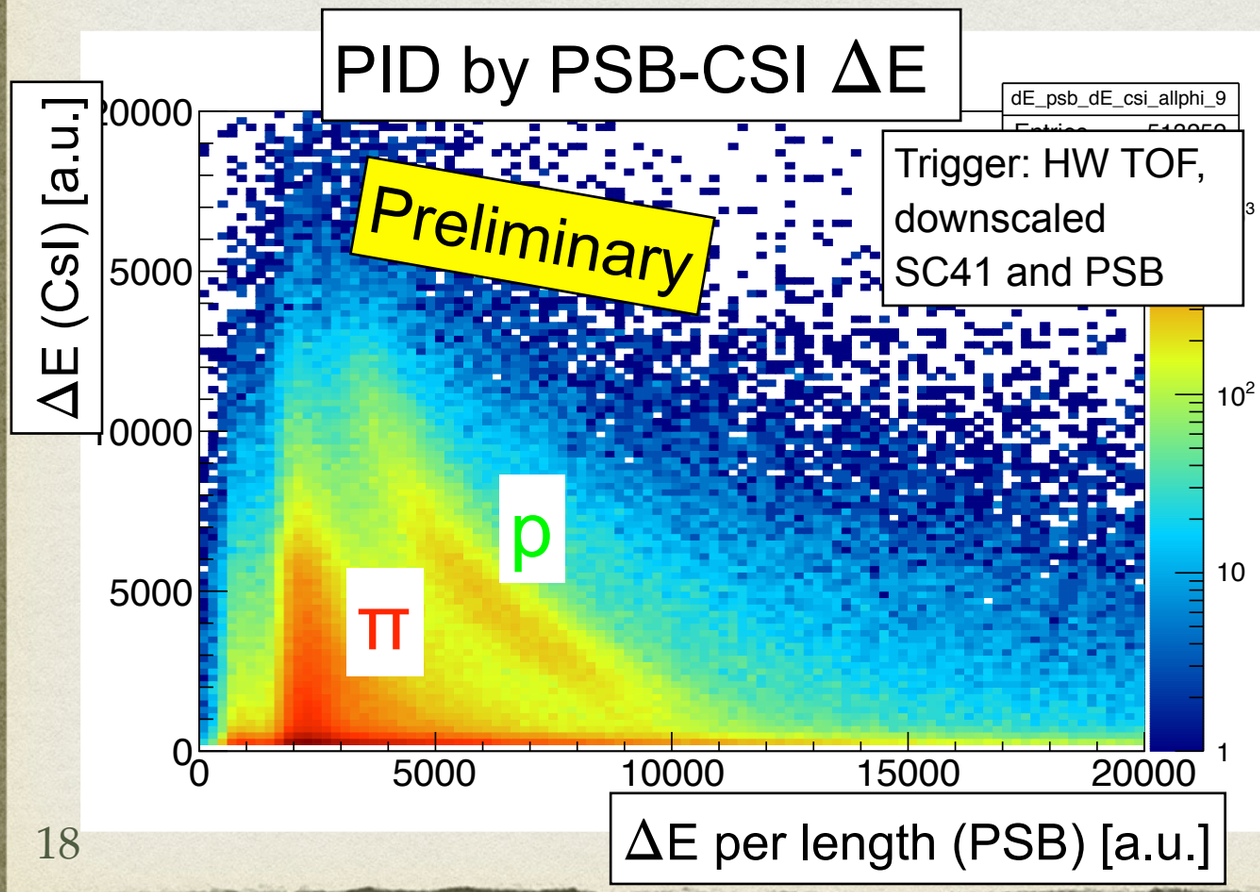
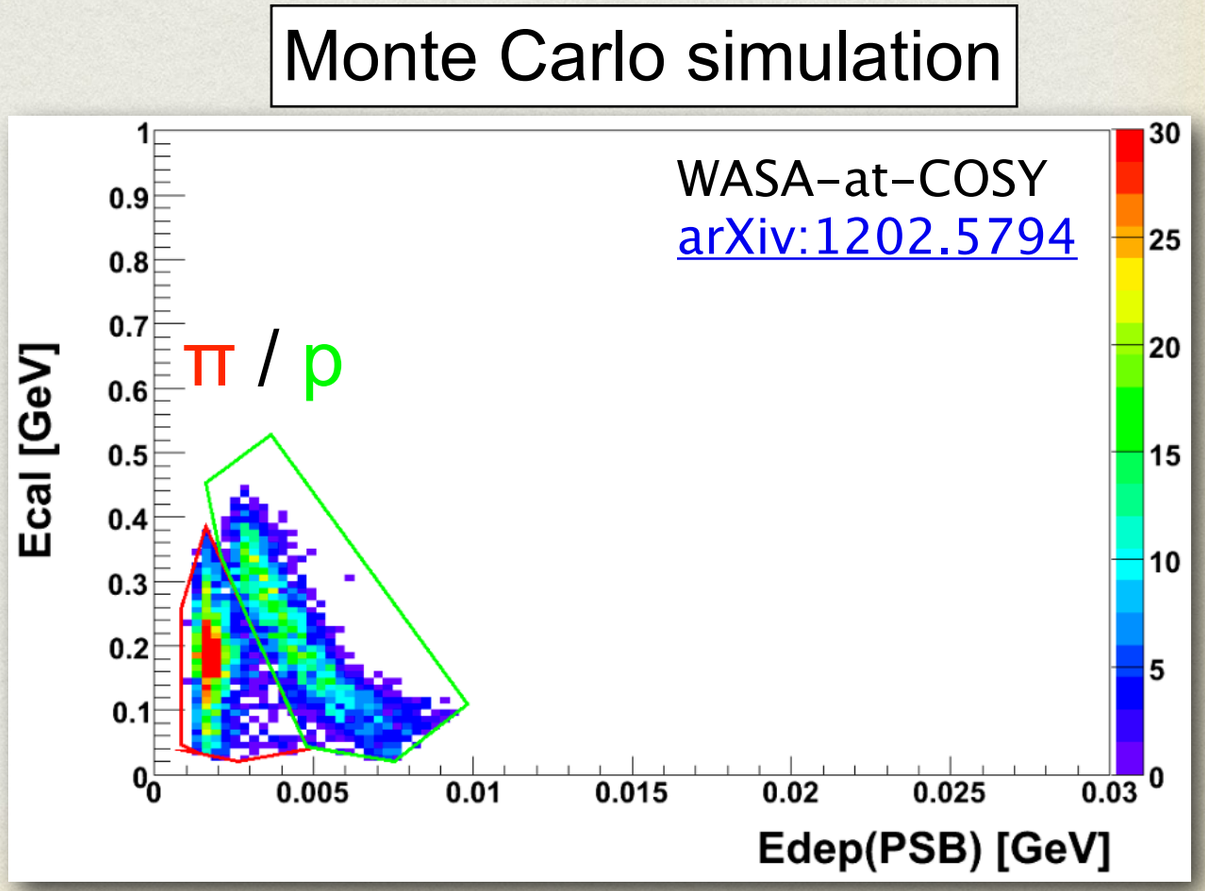




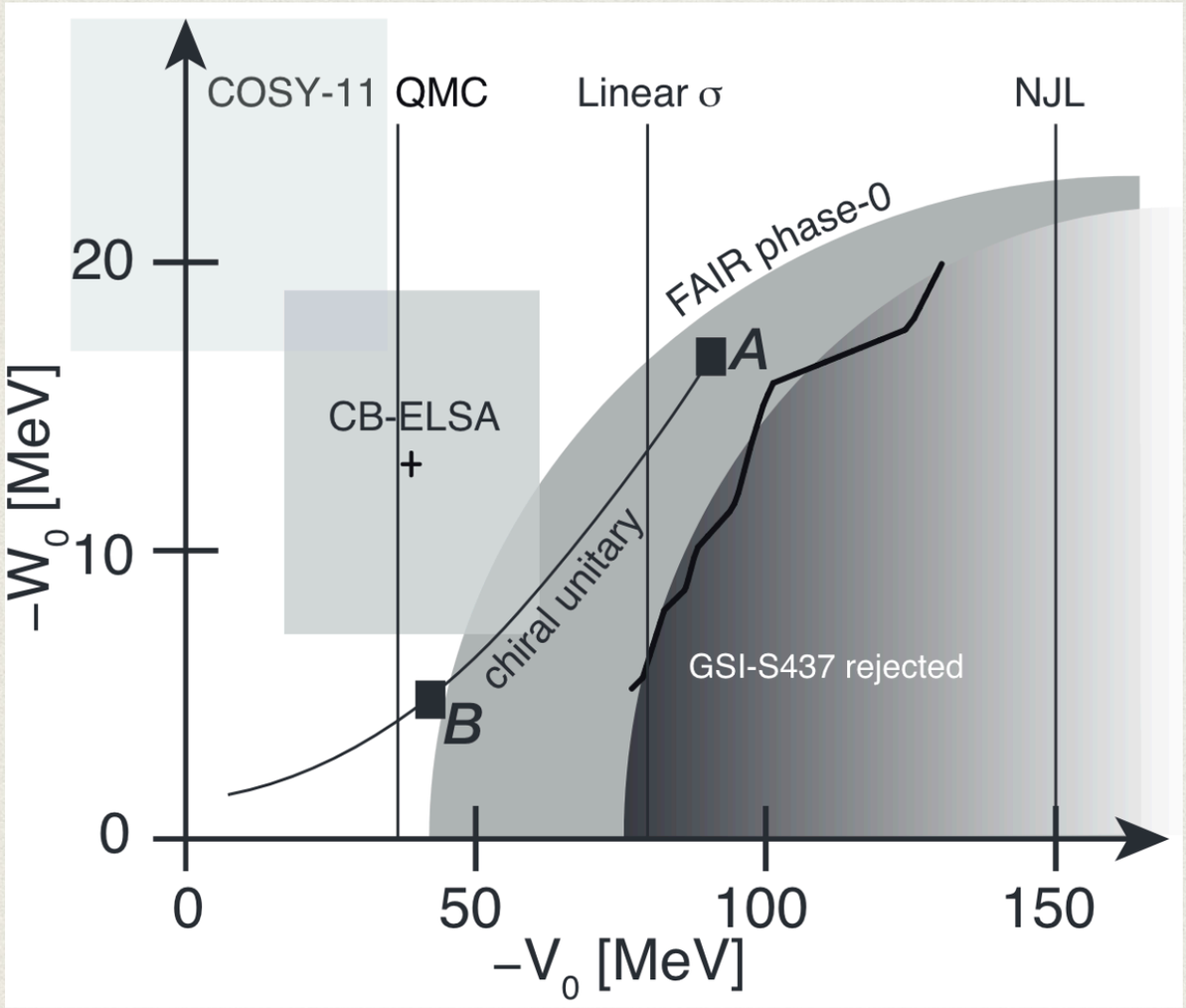
Summary

- We search for η′-mesic nuclei to study in-medium property of η′ meson.
- We have performed missing mass spectroscopy of $^{12}C(p,dp)$ reaction using the WASA detector in GSI-FRS in 2022 Feb.
  - Measured forward deuterons with FRS.
  - Measured protons from decay of η′-mesic nuclei with WASA detector.
  - 3.5 days data accumulation with hardware deuteron PID trigger.
- The analysis is on going.

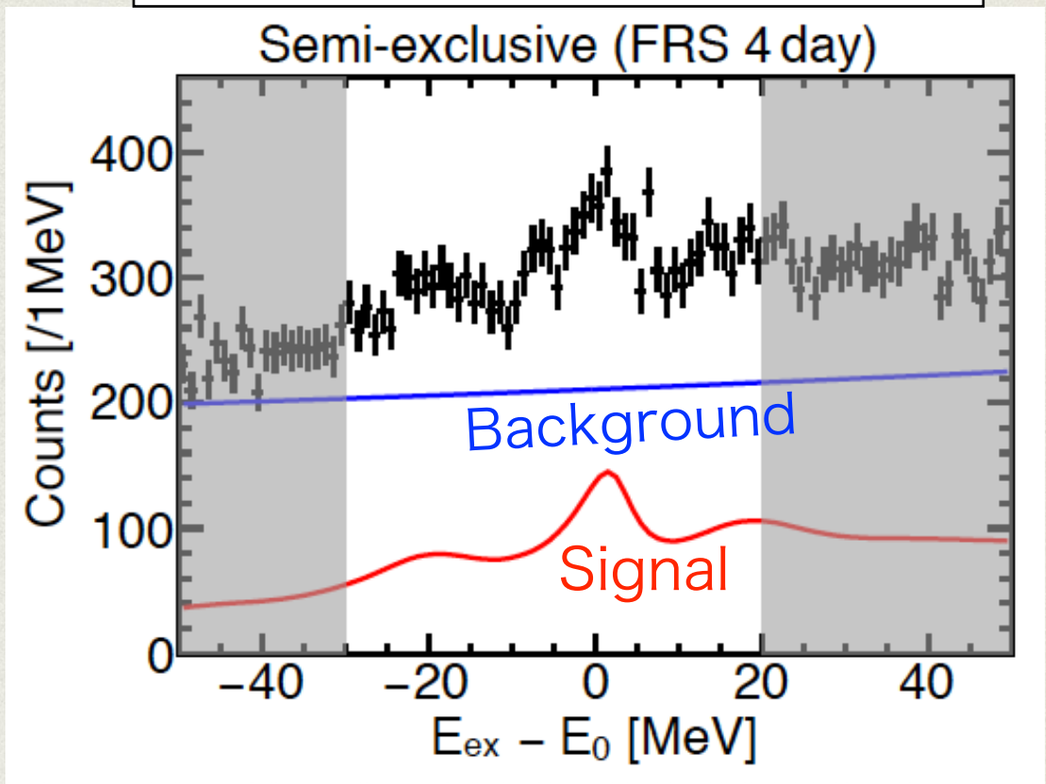
η'-nucleus optical potential

$$U(r) = (V_0 + iW_0)\rho(r)/\rho_0$$

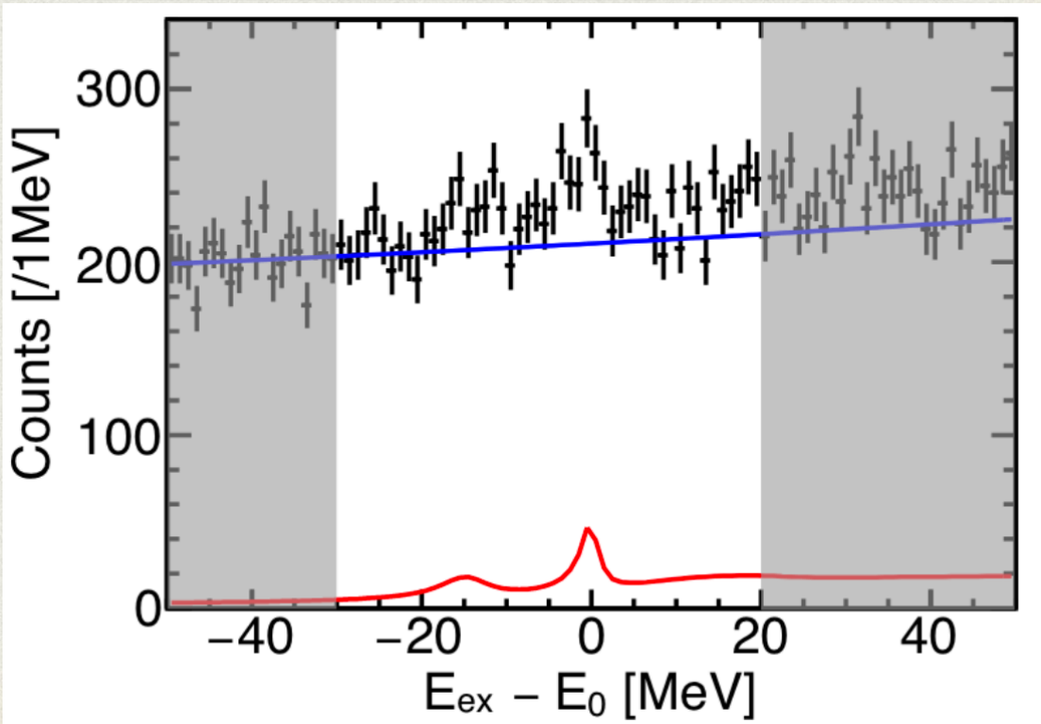
$$V_0 = \underbrace{\Delta m(\rho_0)}_{\eta' \text{ mass reduction}}, \qquad W_0 = -\underbrace{\Gamma(\rho_0)/2}_{\text{Width}}$$



Case A: (V_0, W_0) = (-90, -17)



Case B: (V_0, W_0) = (-45, -5.5)



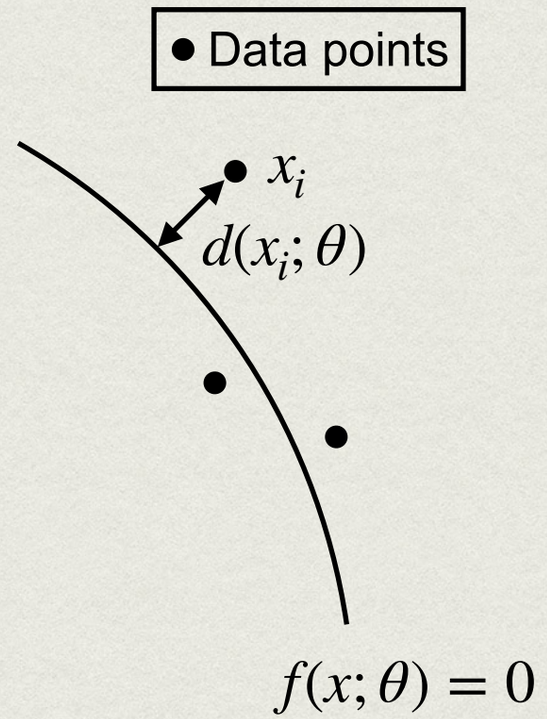
Elastic Arm Algorithm

Super-FRS EC

Consider minimizing the following “Energy” function.

$$E(w;\theta) = \sum_{i=1}^{N} \left(w_i d_i + \lambda (1 - w_i)^2 \right) + V(\theta)$$

- $d_i = d(x_i;\theta)$: distance between x_i and $f(x;\theta) = 0$.
- w_i = 0 or 1 (for i = 1, 2, 3, … N)
- λ: penalty term
- V(θ): Constraint on parameters θ.



The partition function:

$$Z = \sum_{w} \exp \left\{ -\beta \sum_{i=1}^{N} w_i d_i - \beta\lambda \sum_{i=1}^{N} (1 - w_i)^2 \right\} = \Pi_{i=1}^{N} \left(e^{-\beta\lambda} + e^{-\beta d_i} \right)$$

We get the equilibrium state by minimizing the Helmholtz free energy.

$$F(\theta) = -\frac{1}{\beta} \sum_{i=1}^{N} \log \left(e^{-\beta\lambda} + e^{-\beta d_i} \right)$$

By decreasing T to 0 as taking θ which realize equilibrium, we obtain the θ which minimize the energy function.

R. Frtihwirth, A. Strandlie, Computer Physics Communications 120 (1999) 197-214