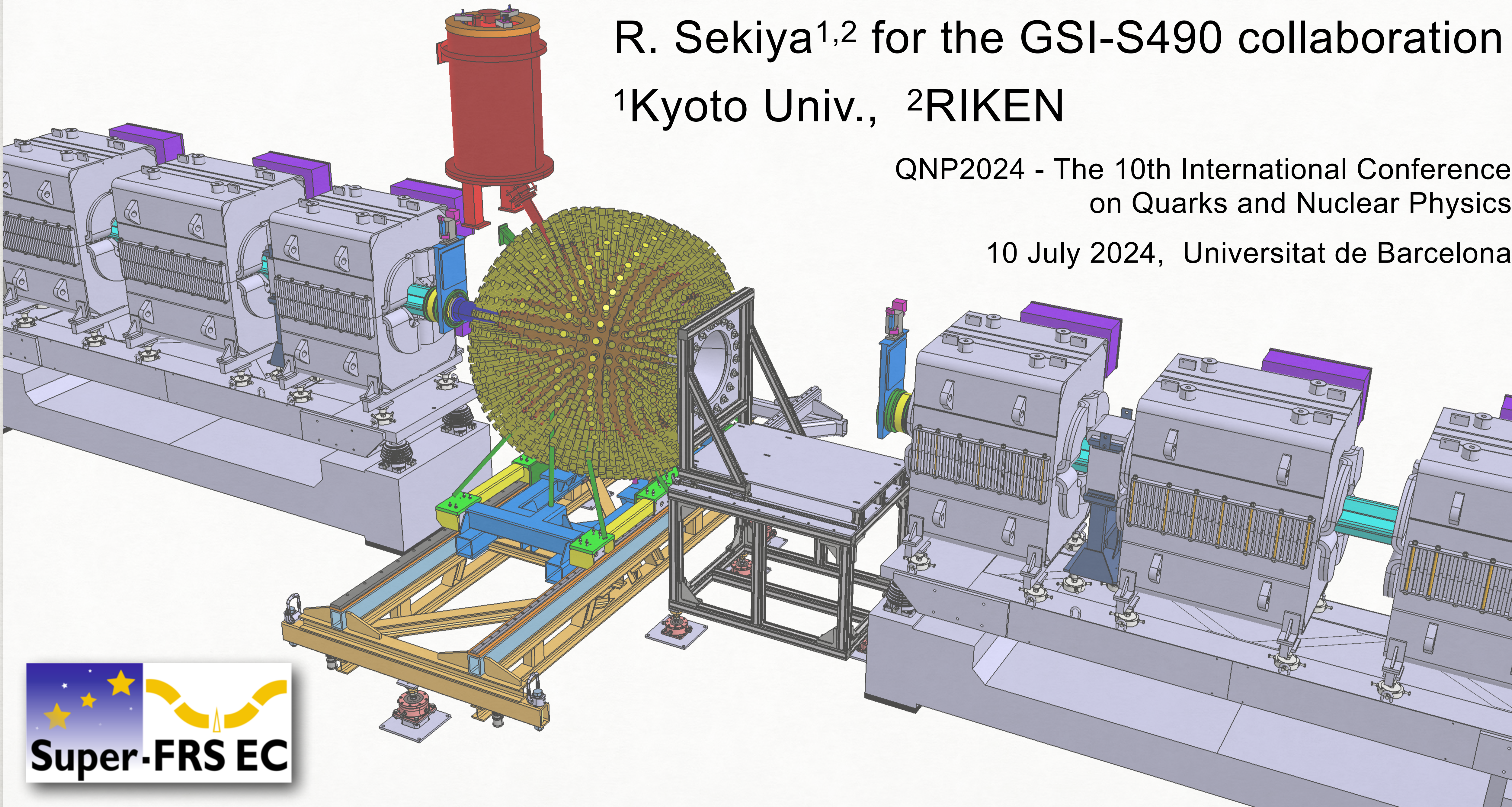
Search for η'- mesic nuclei with the WASA detector at GSI-FRS

R. Sekiya[1,2] for the GSI-S490 collaboration

[1]Kyoto Univ., [2]RIKEN

QNP2024 - The 10th International Conference on Quarks and Nuclear Physics

10 July 2024, Universitat de Barcelona



Super-FRS EC

Meson mass and symmetry in QCD

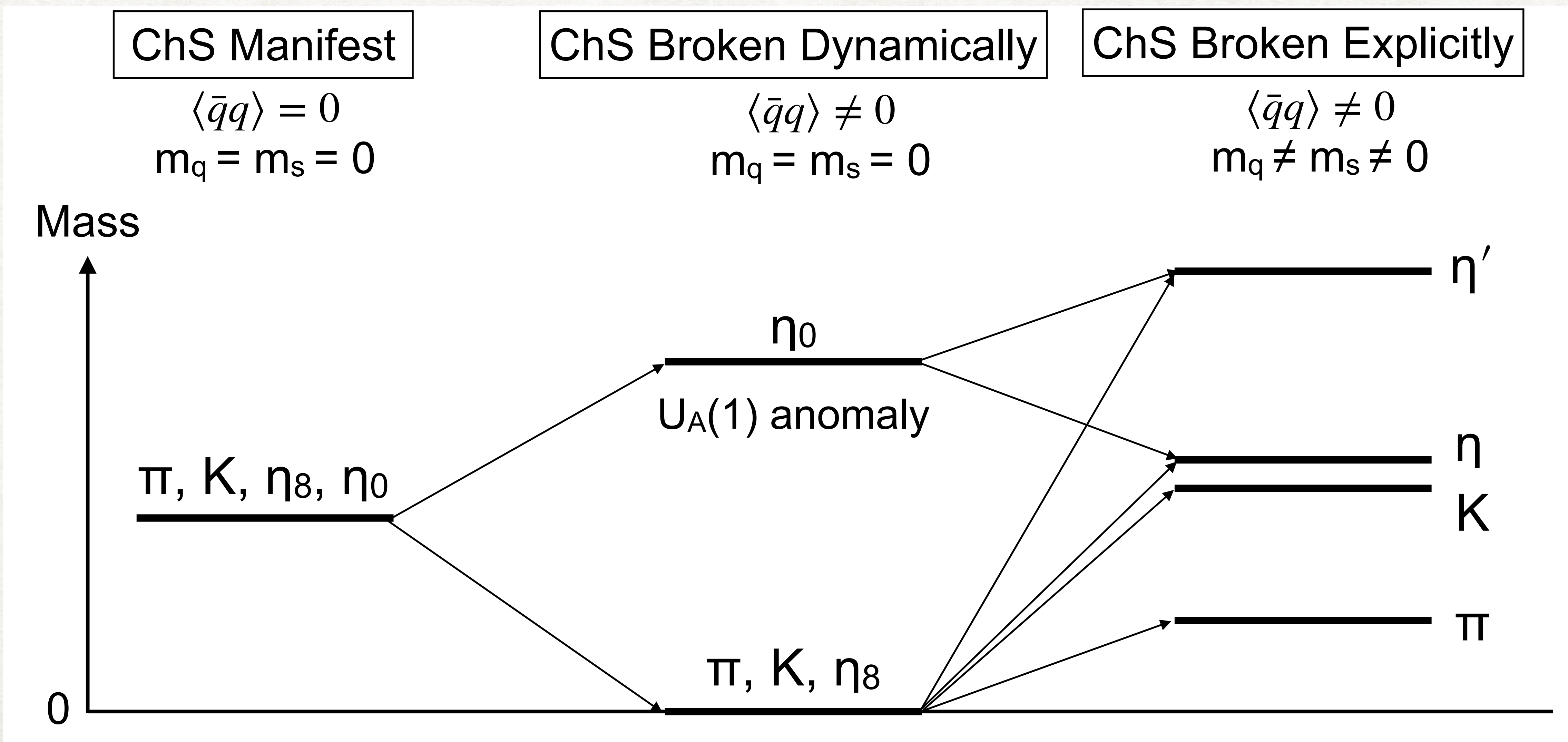
Quark

q $\bar{q}$ $M_q \sim 3$ — 100 MeV

Meson

q $\bar{q}$ $M_m \sim 100$ — 1000 MeV

Dynamical mass generation by symmetry breaking in QCD

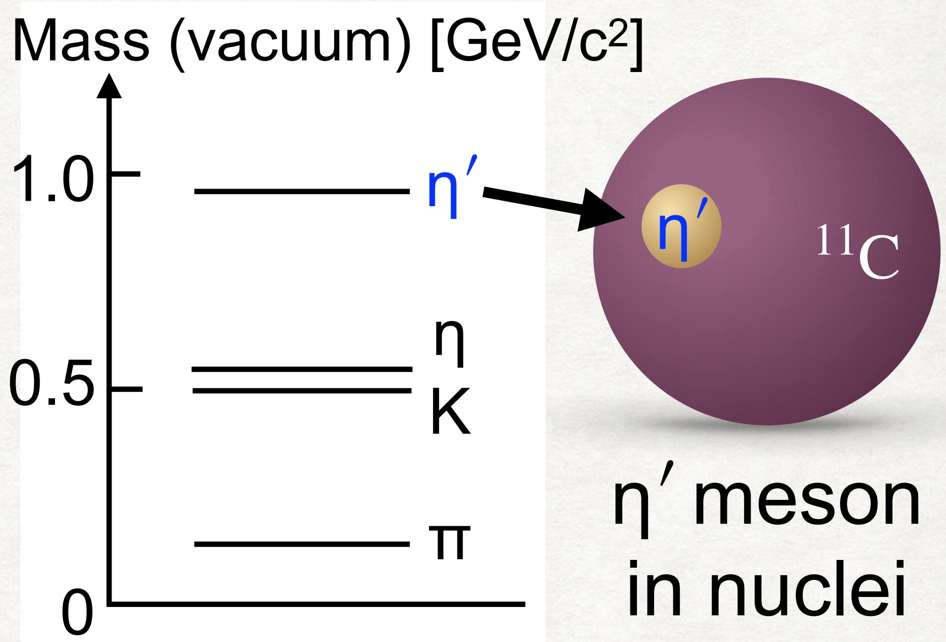


H. Nagahiro et al., PRC 87, 045201 (2013)

η′ meson in-medium

η′-meson in vacuum

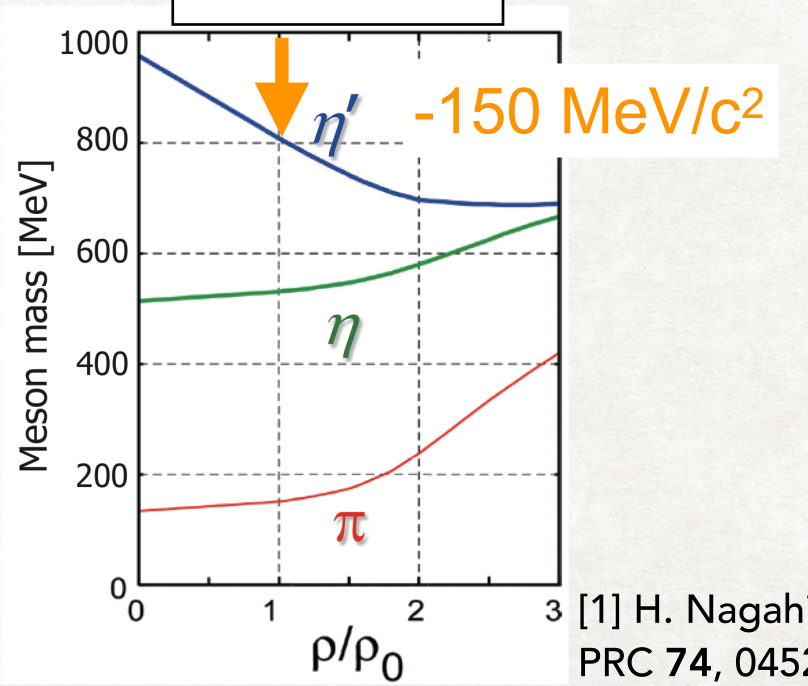
- $M_{\eta'}$ = 958 MeV/c² (especially large) due to
  - Chiral symmetry breaking.
  - $U_A(1)$ anomaly.



η′-meson in nuclei

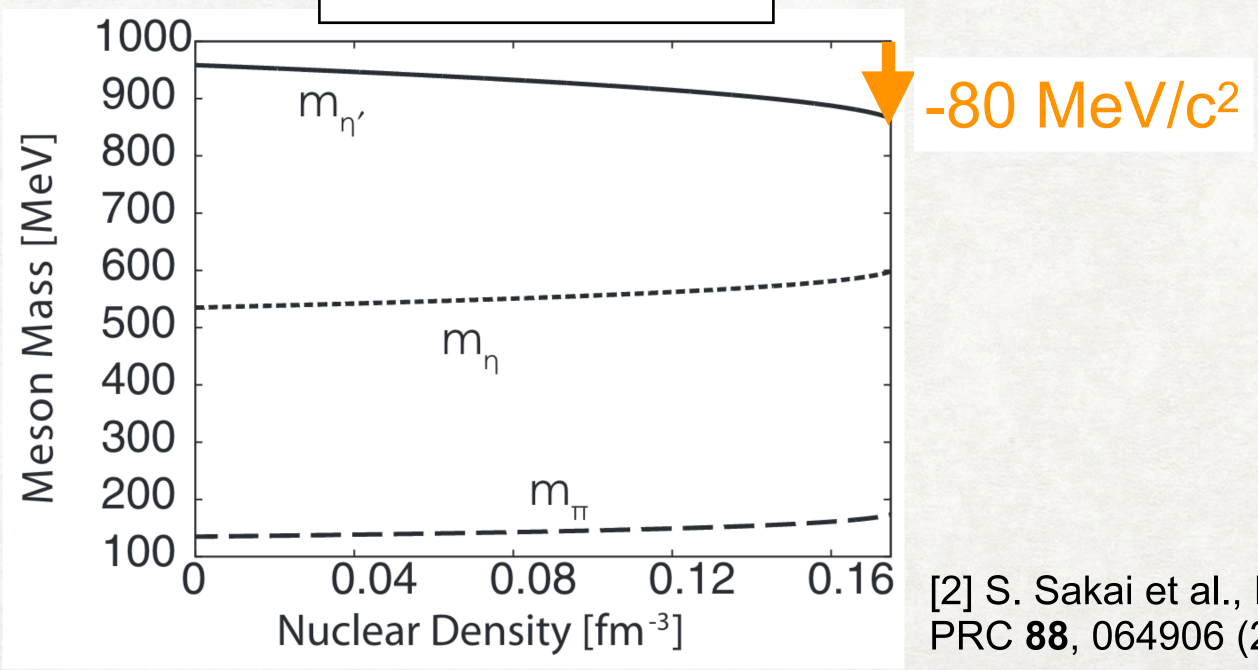
- Partial restoration of chiral symmetry.
- Reduction of $M_{\eta'}$ is predicted.

NJL model



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

Linear σ model



[2] S. Sakai et al., D. Jido, PRC **88**, 064906 (2013)

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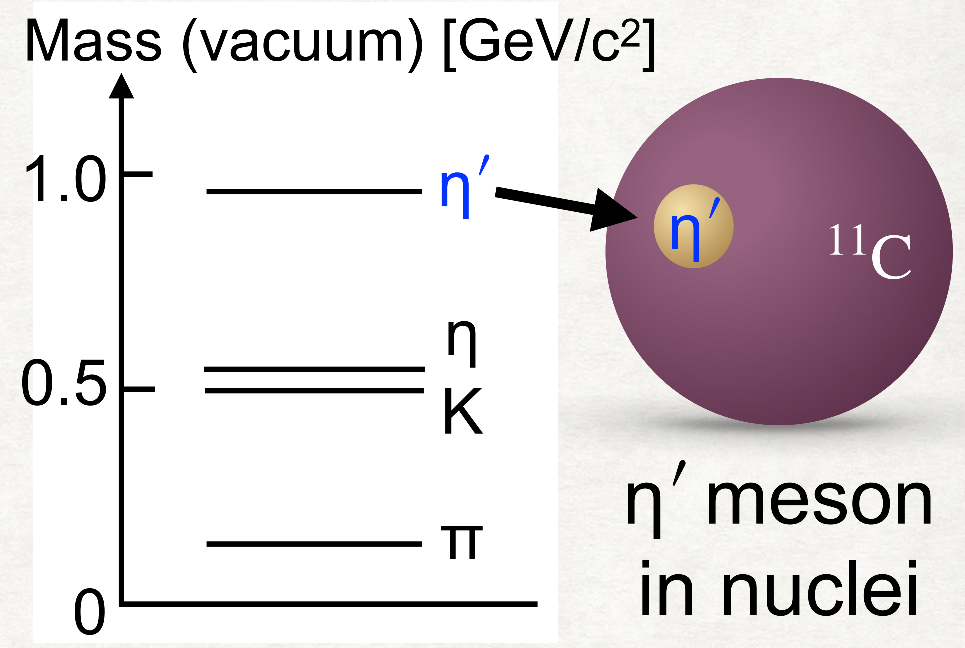
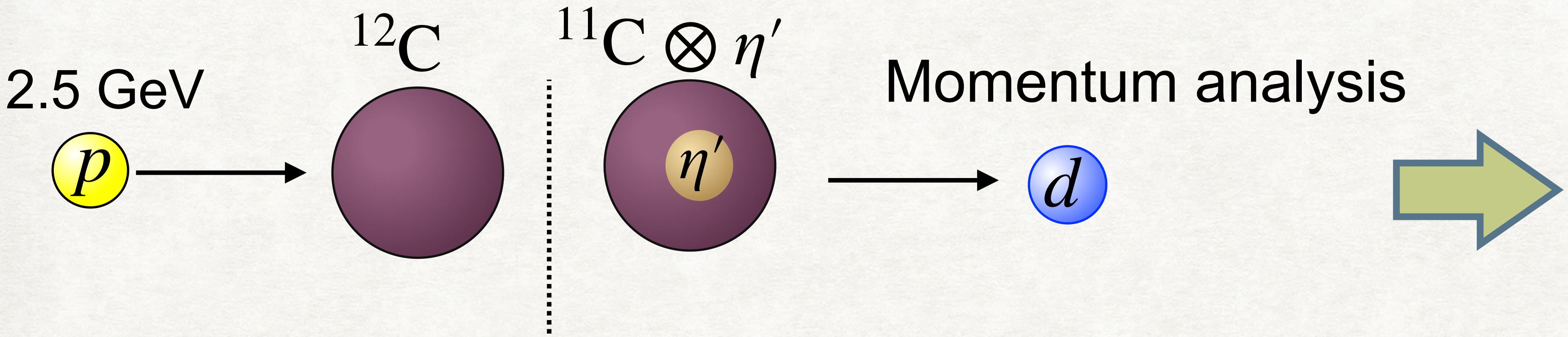


→ Attractive potential : $V_{\eta' A}(r) = \Delta M_{\eta'}(\rho_0)\,(\rho(r)/\rho_0)$

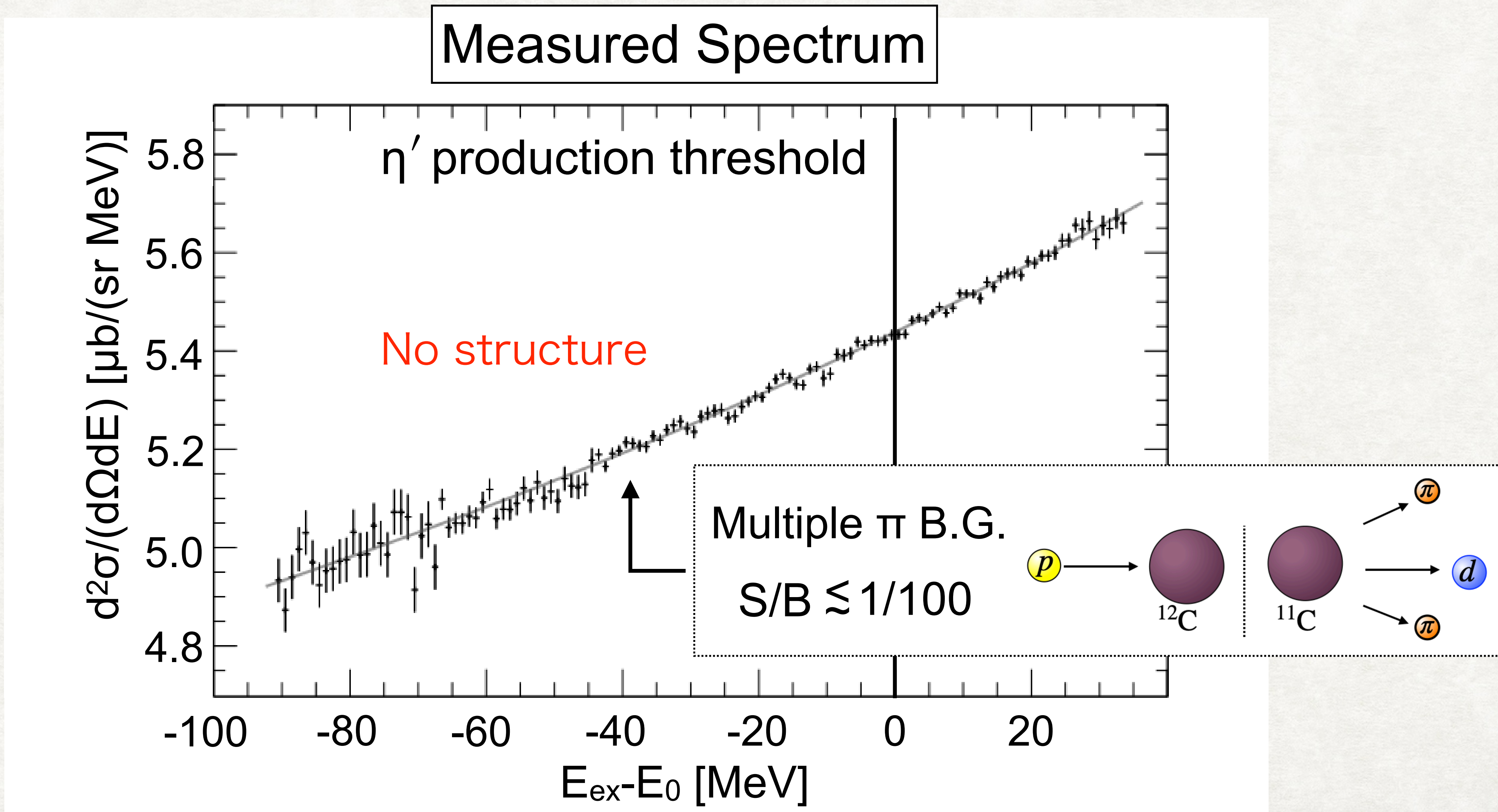
→ Bound states are expected (η'-mesic nuclei)

→ Study of in-medium properties

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

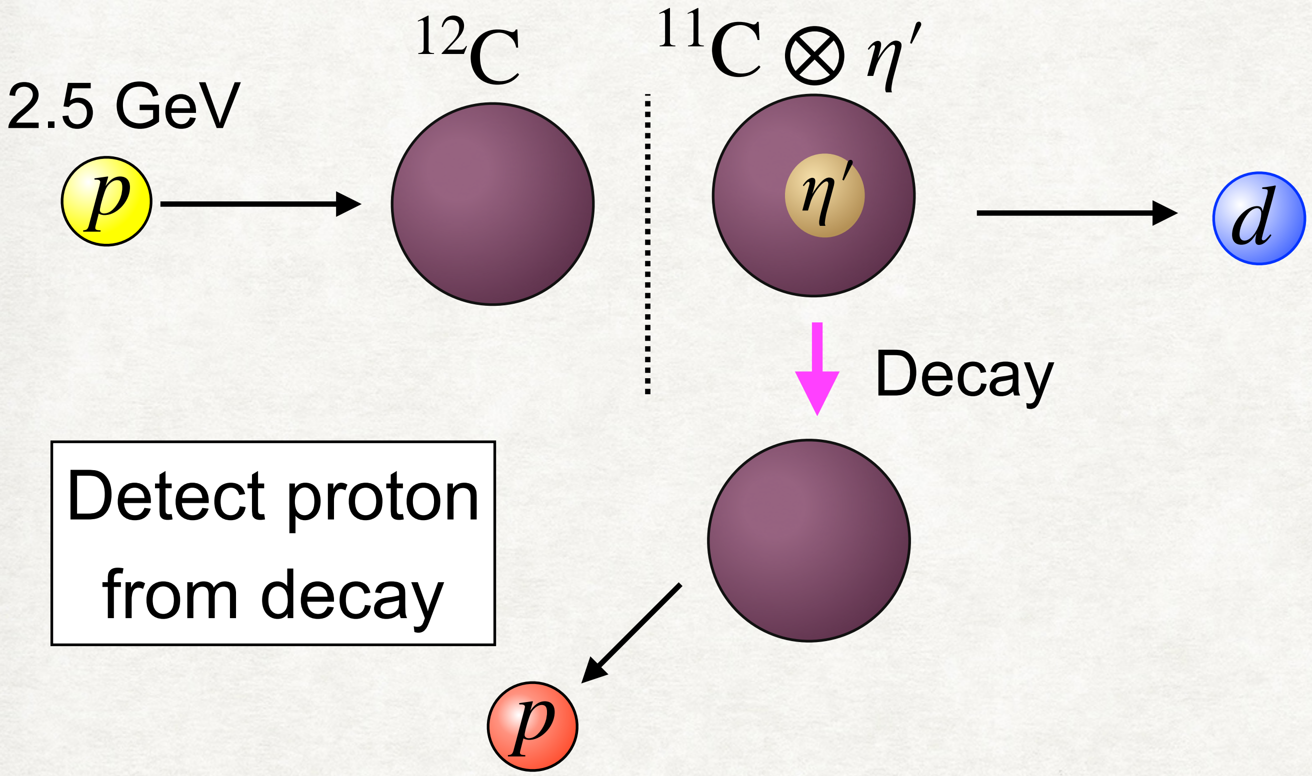


Missing mass spectroscopy



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

Direct search for η′-mesic nuclei in 2022 (GSI-S490)



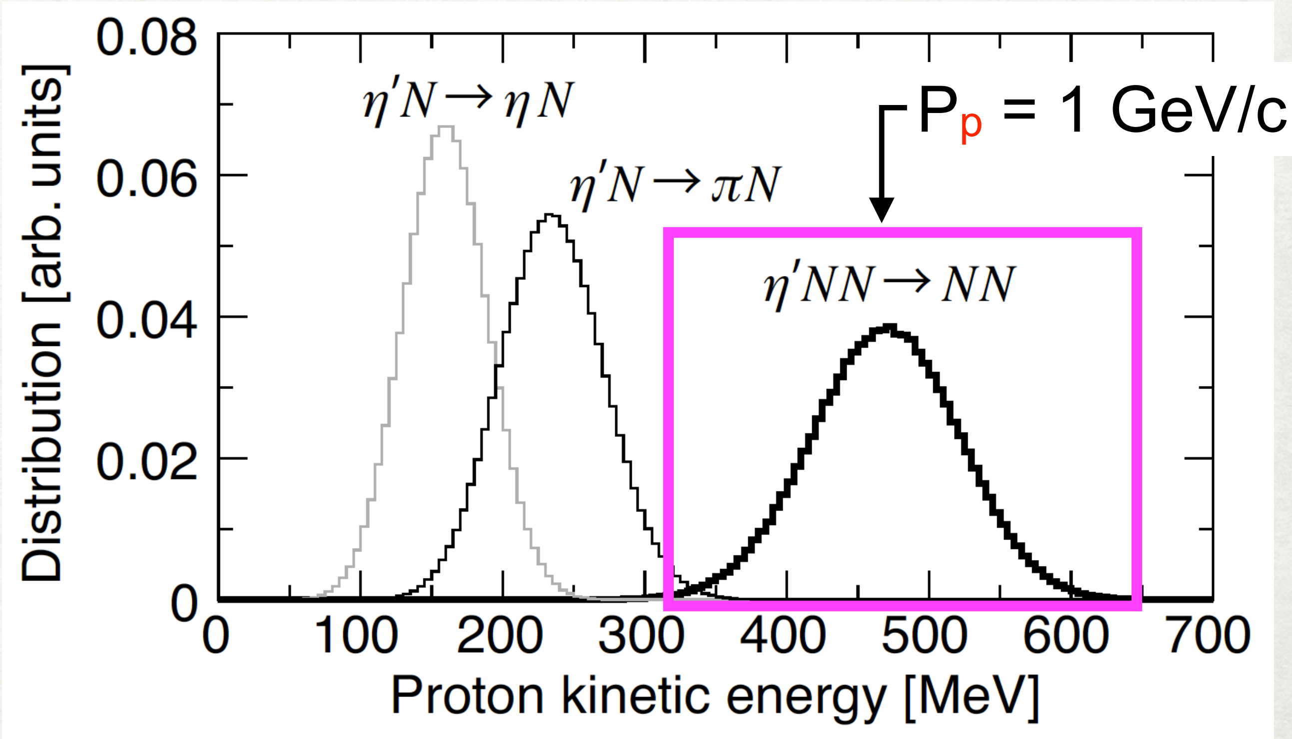
Detect proton from decay

Major decay modes

- η′N → ηN
- η′N → πN
- η′NN → NN

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

- Coincident measurement of p and d
- Detect p backward
- Expected ~100 times better S/B.



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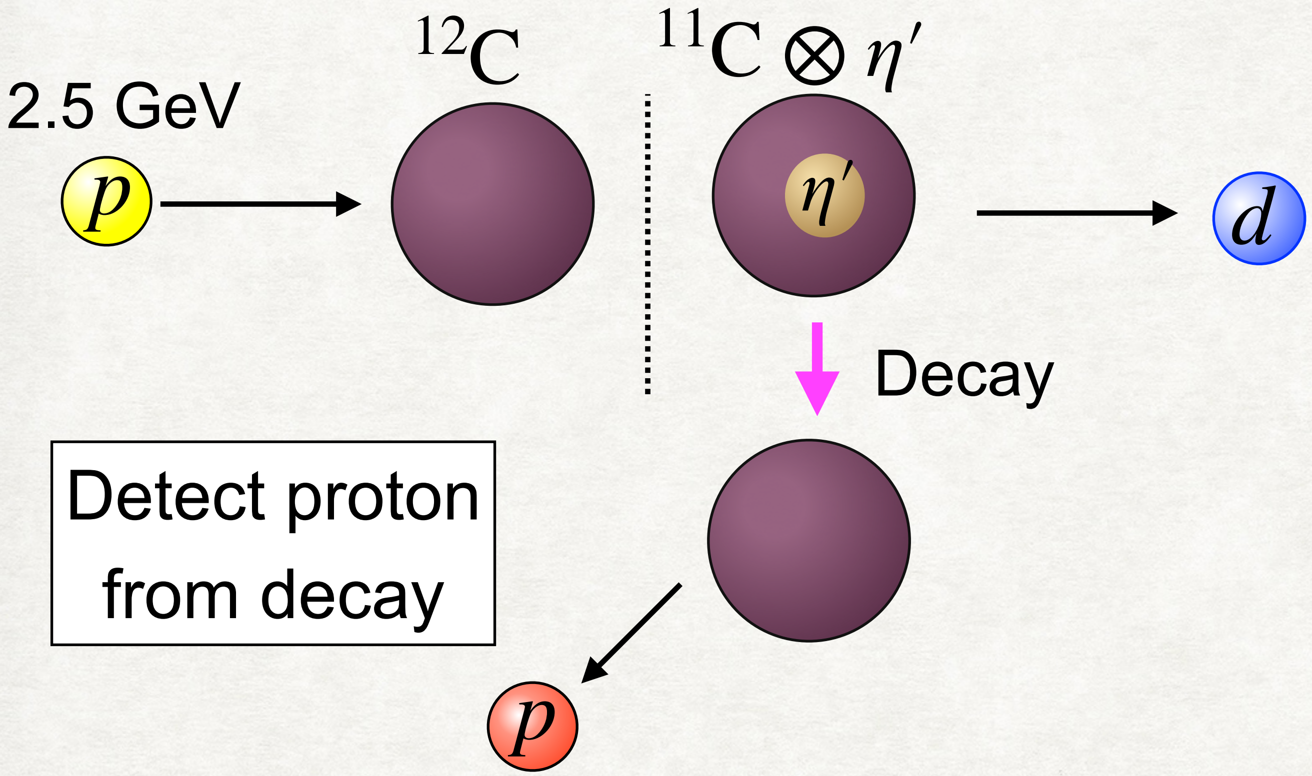

- Coincident measurement of p and d
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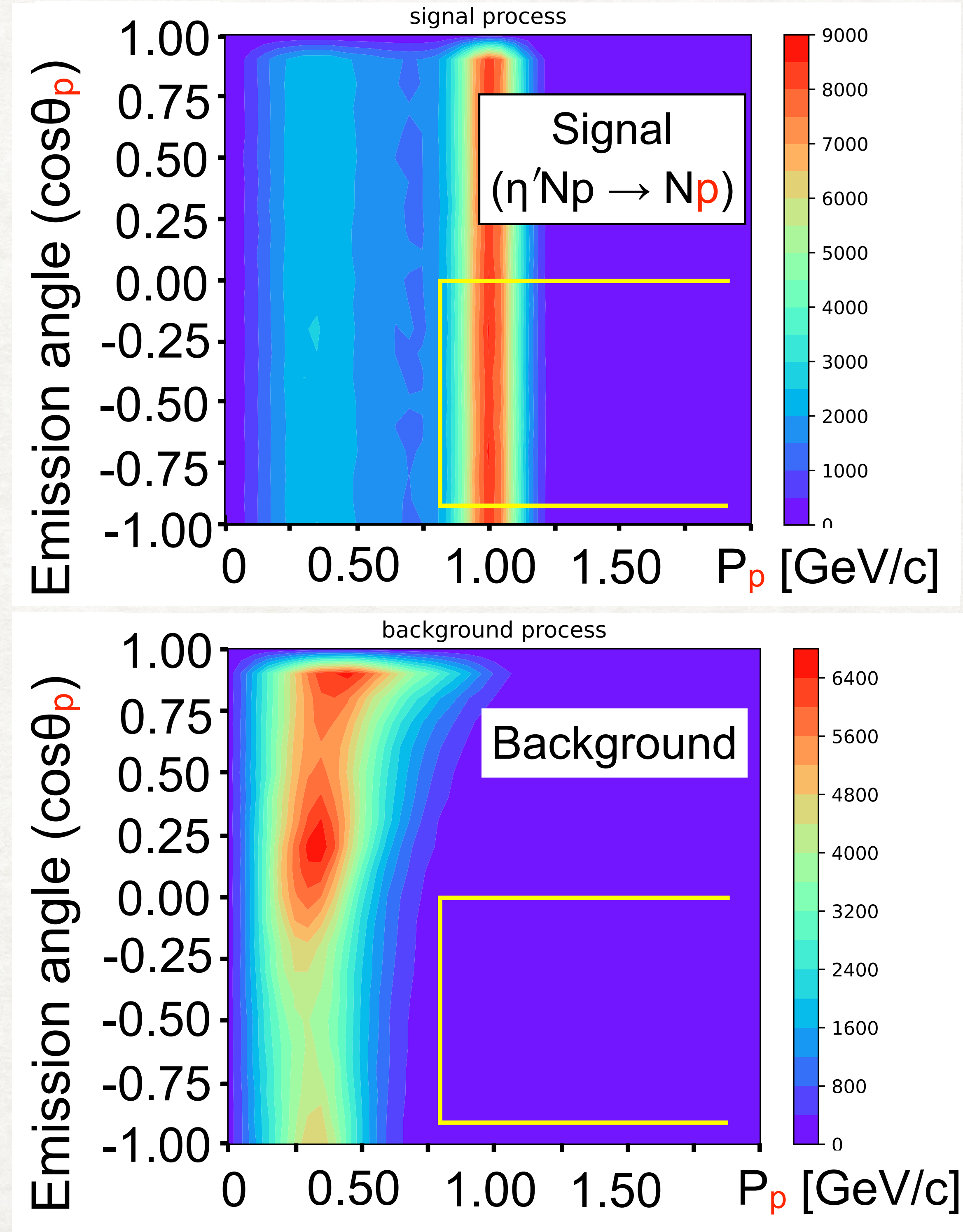
Simulated p distribution
(intra-nuclear cascade simulation)



N. Ikeno et al., arXiv:2406.06058

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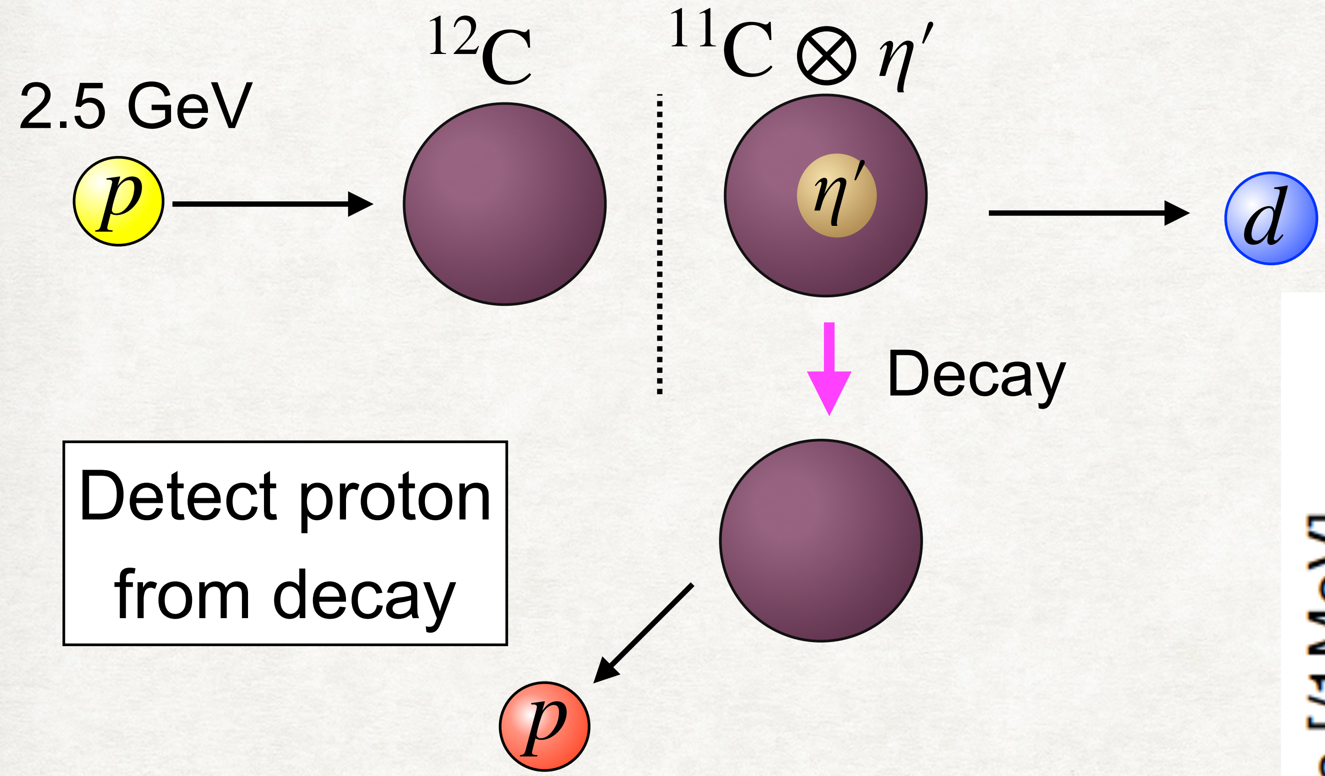
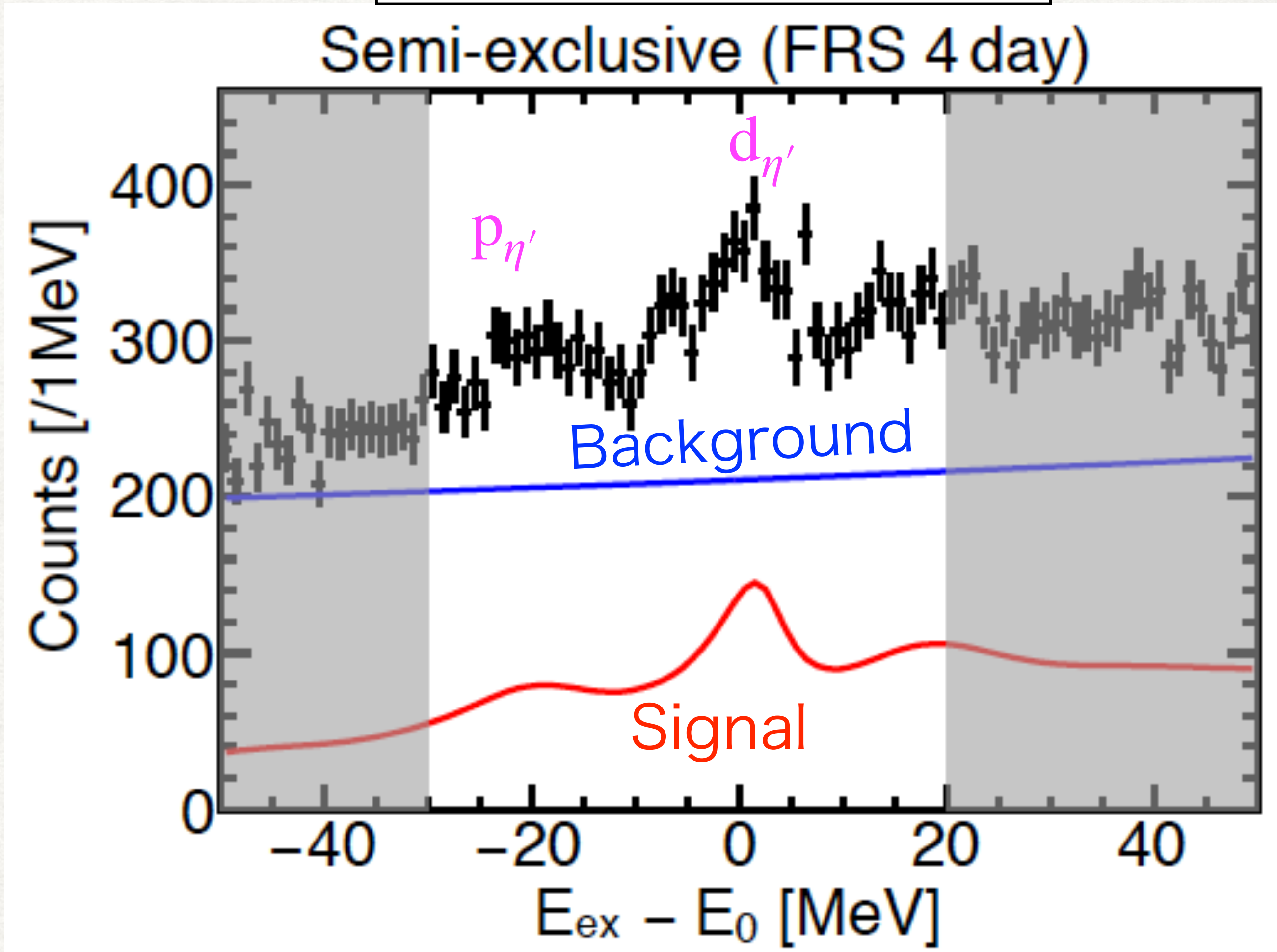


Detect proton from decay

- Coincident measurement of p and d
- Detect p backward
- Expected ~100 times better S/B.

Simulated spectrum

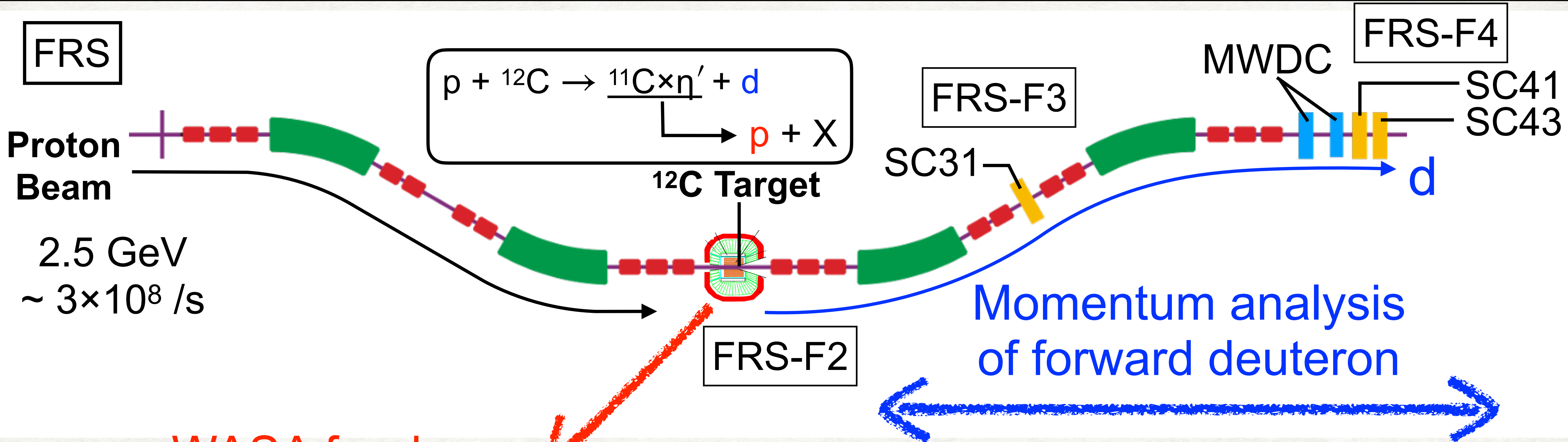


$(V_0, W_0) = (-90, -17)$ [MeV]

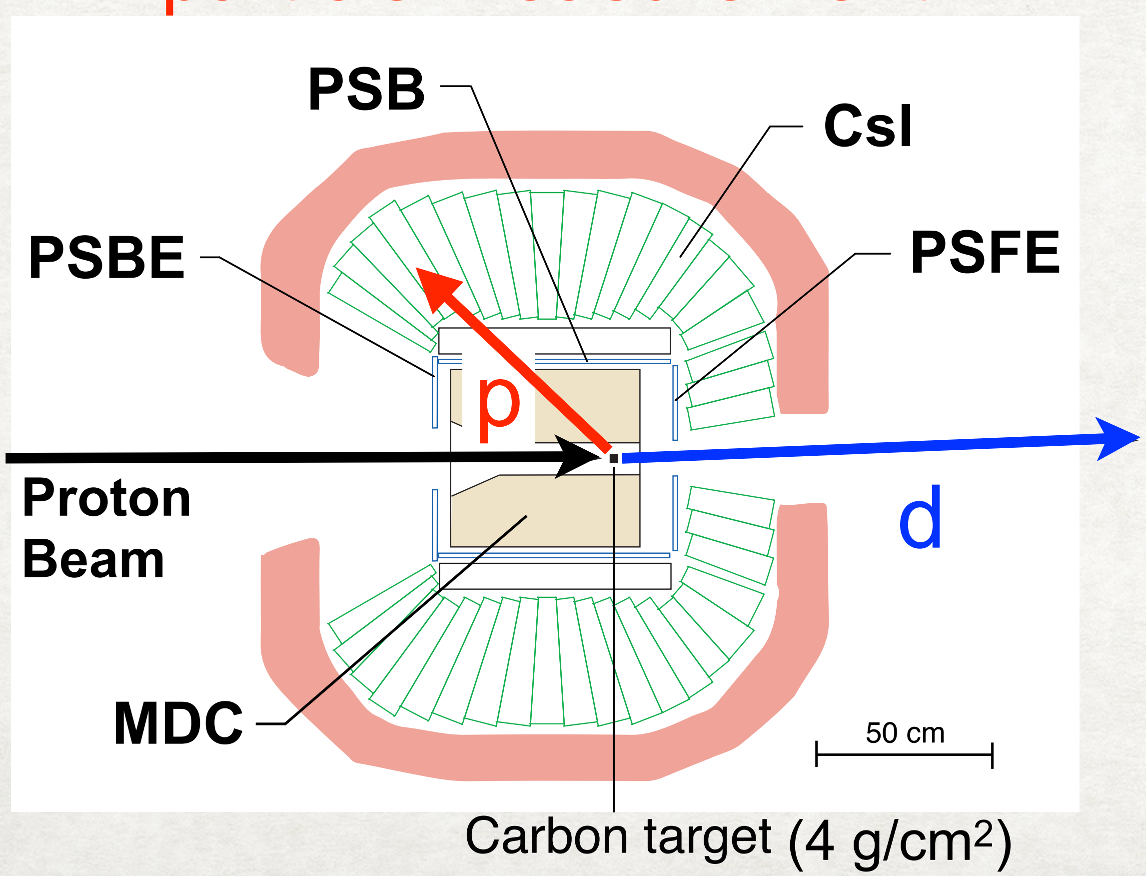
η′-nucleus optical potential

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

Experimental setup for η’-mesic nuclei spectroscopy in 2022

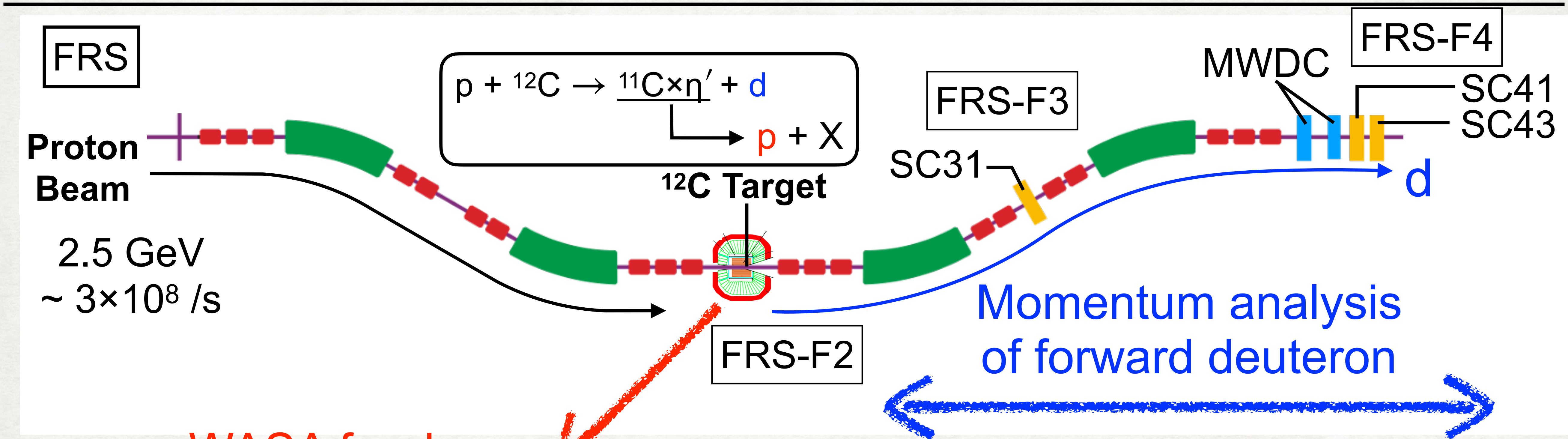


WASA for decay particle measurement



- 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-at-FRS experiment conducted in 2022 Feb



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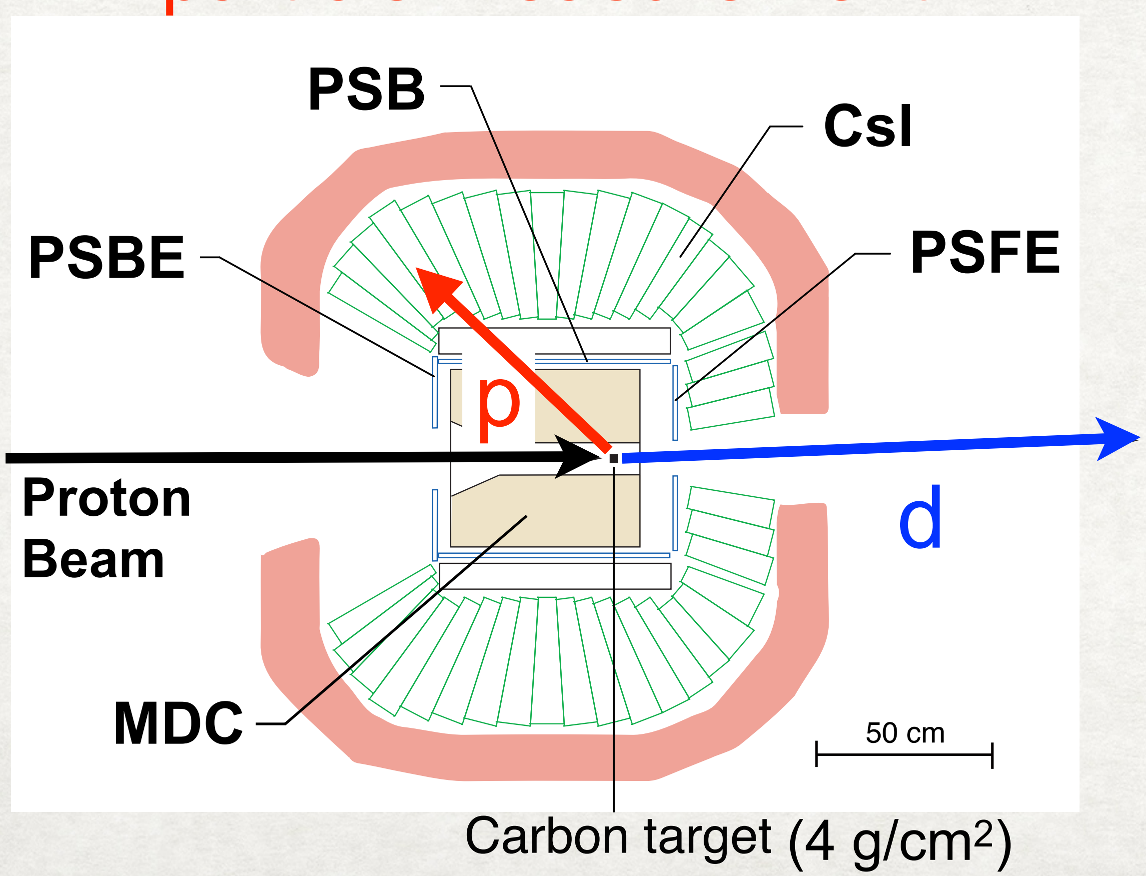
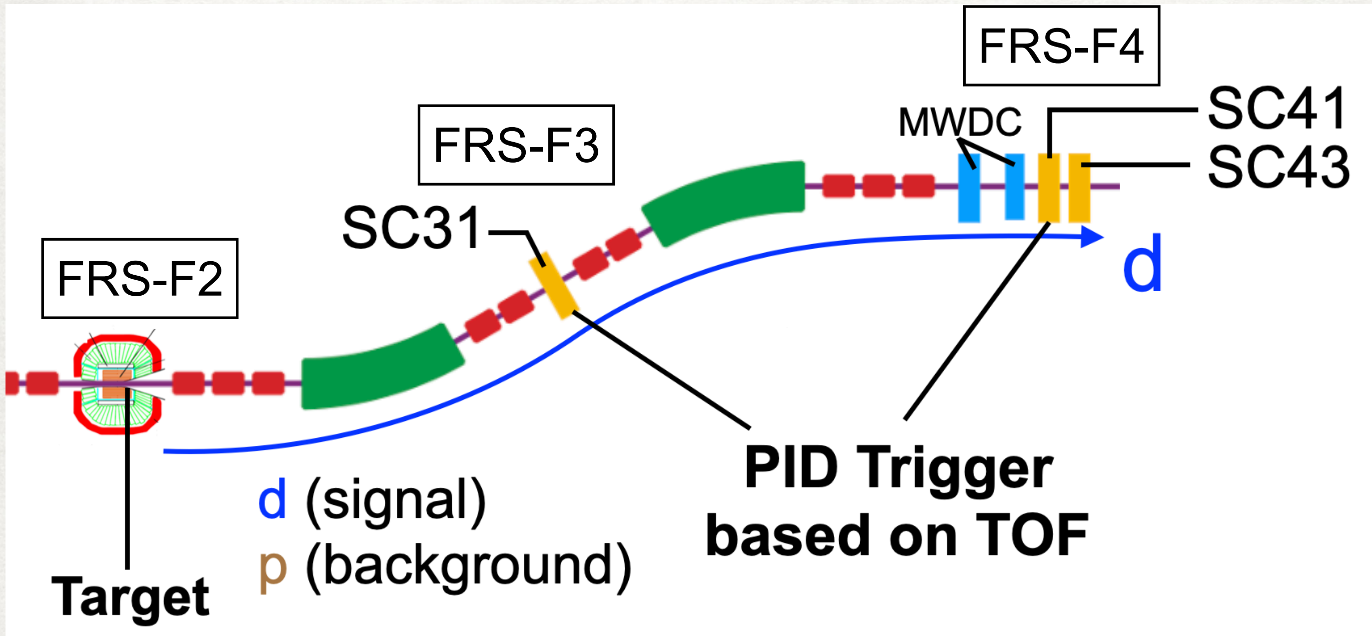


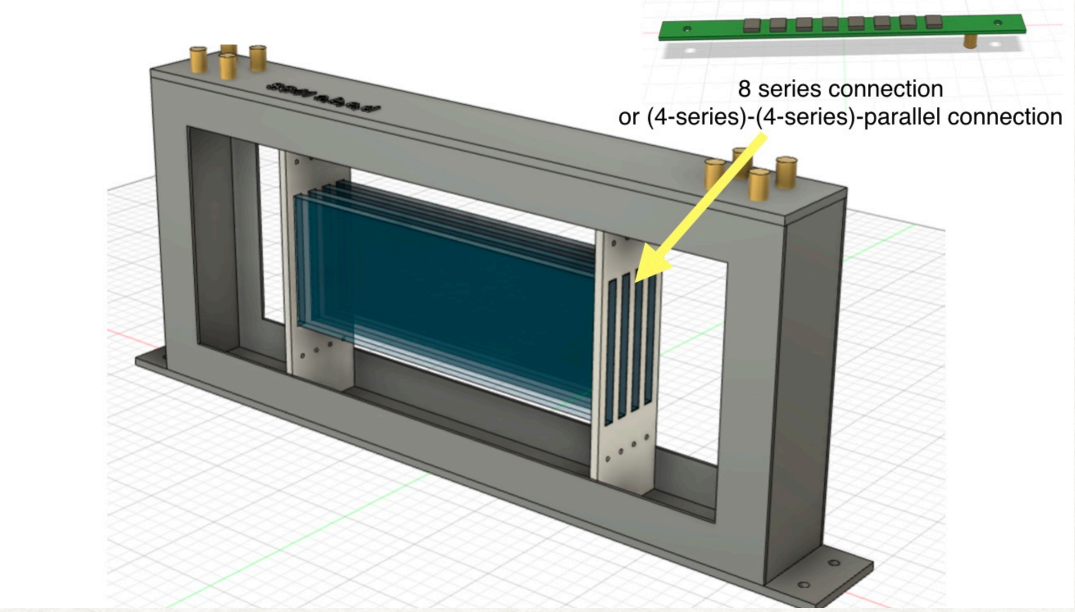
Beam-time in 2022 Feb

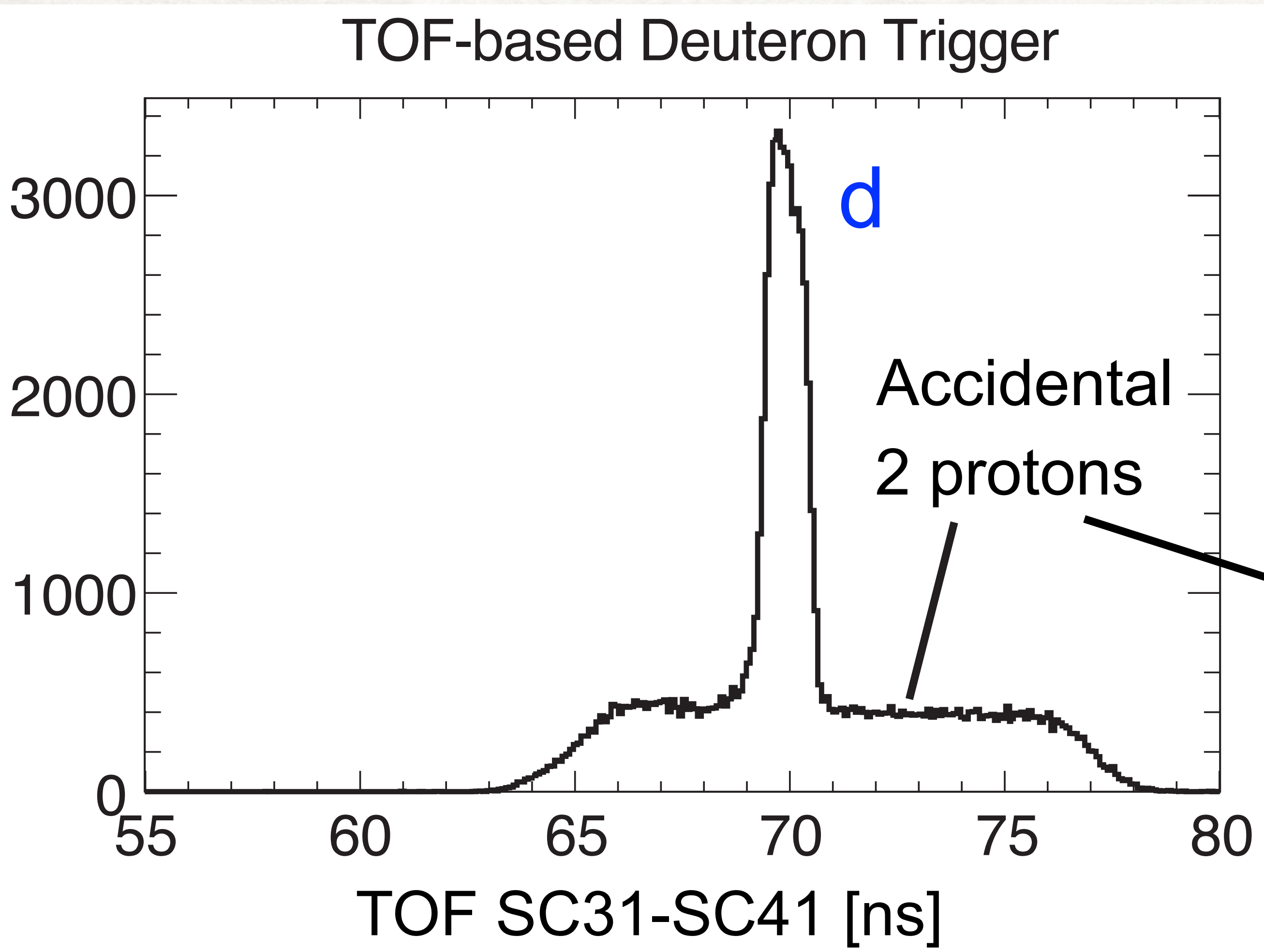
- 3.5 days data accumulation
- $\sim 1.1 \times 10^7$ d is registered

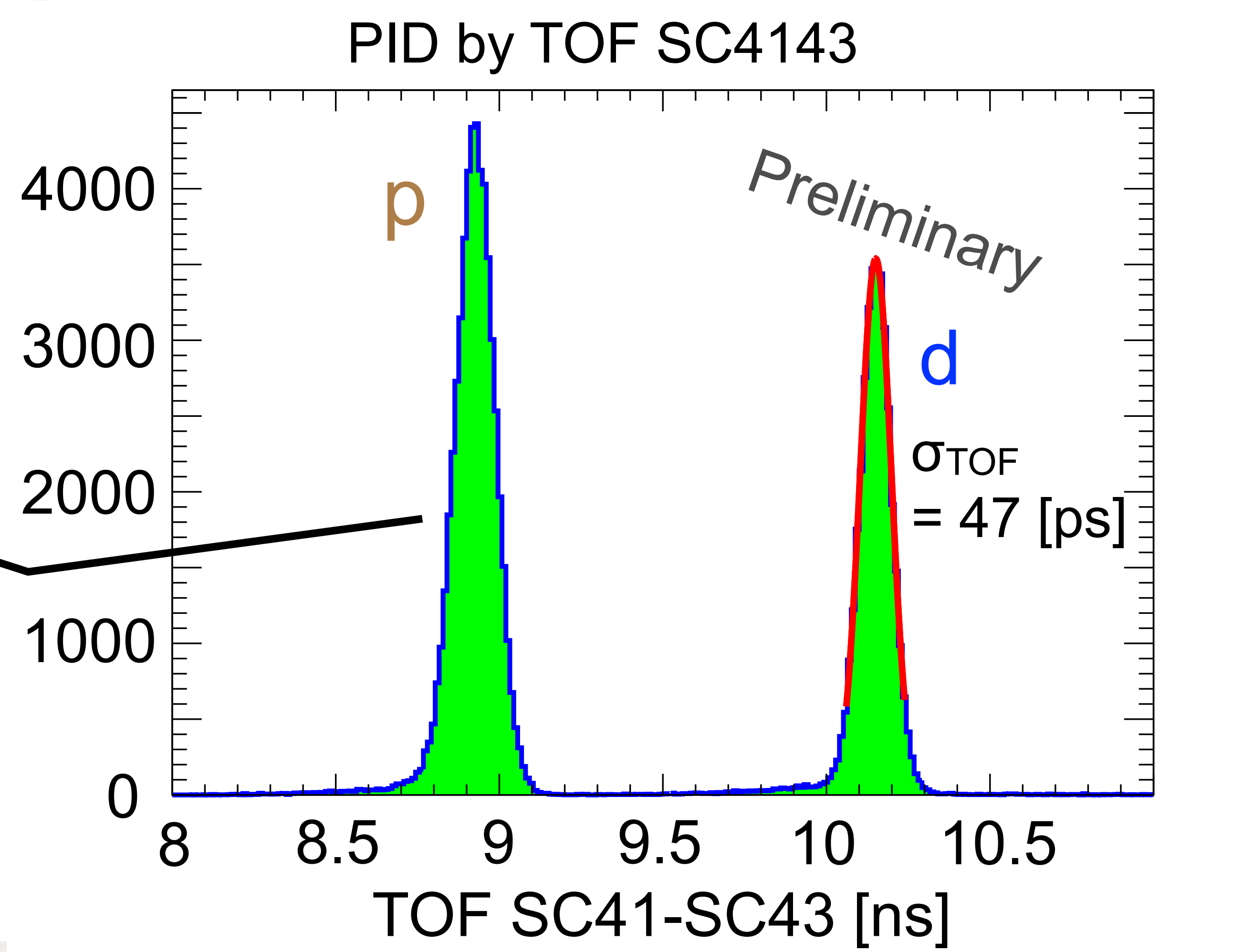
Forward deuteron PID



SC41+SC43 (stacked scintillator)







Inclusive excitation-energy spectrum

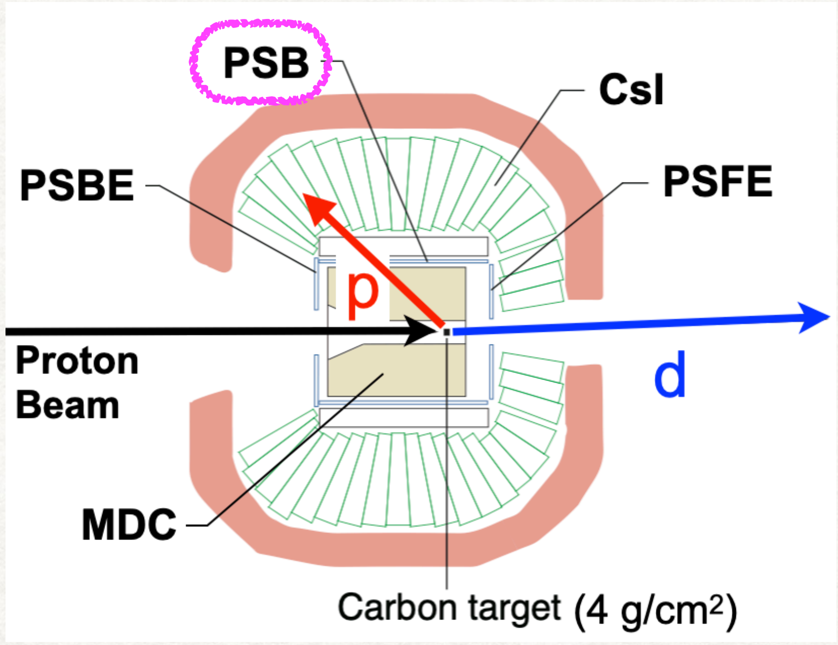
Evaluated excitation-energy from d momentum.

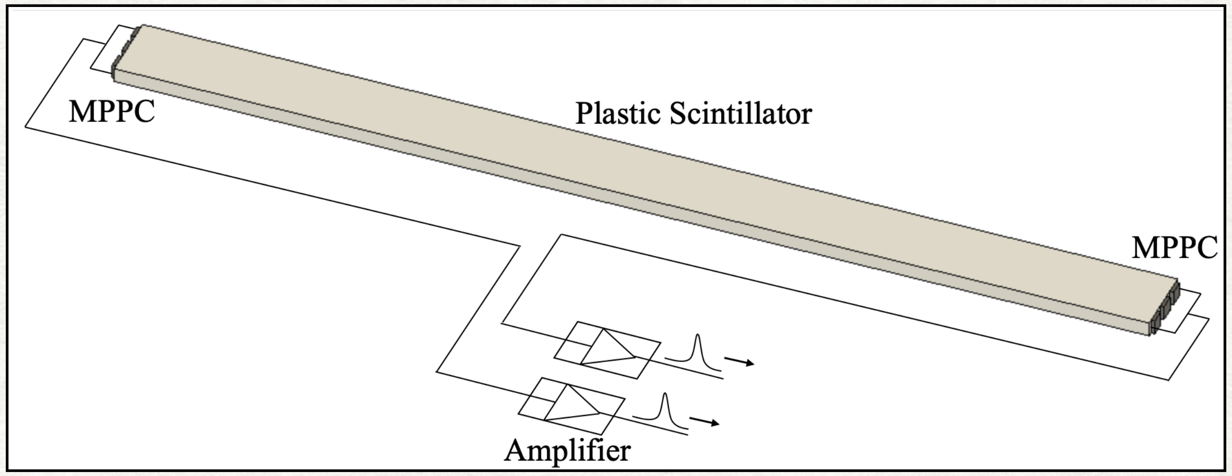
Only for on-site audiences

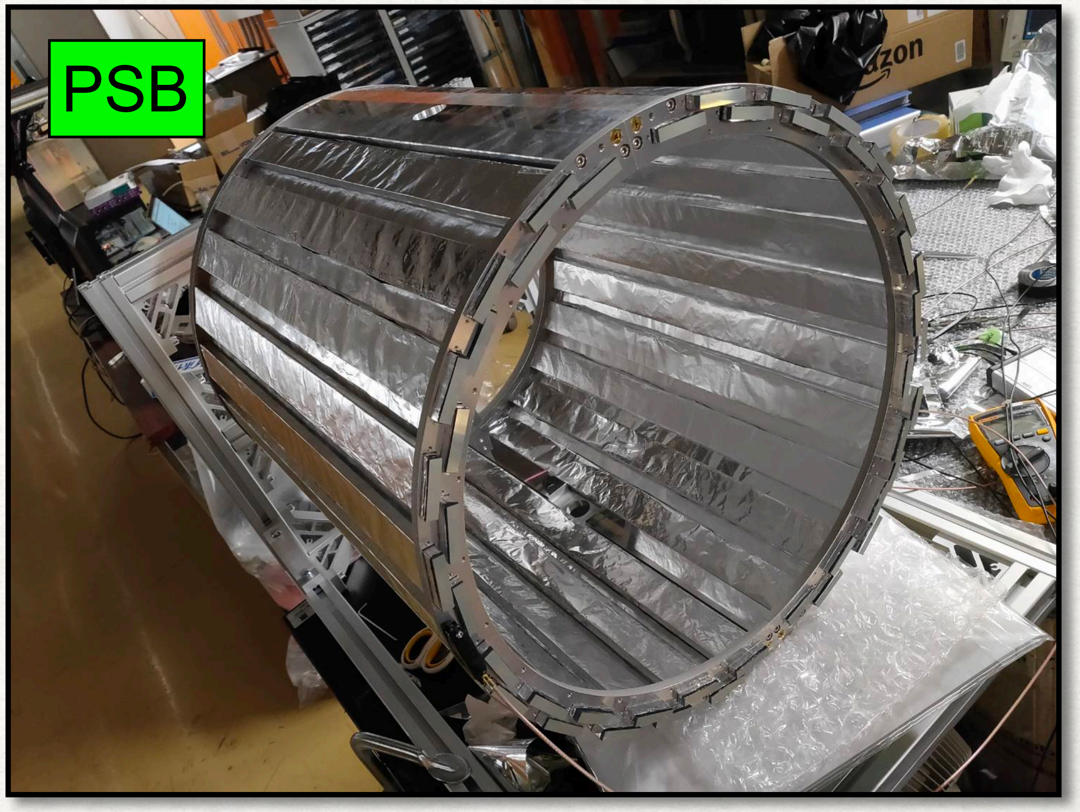
Consistent result with the previous experiment in 2014.

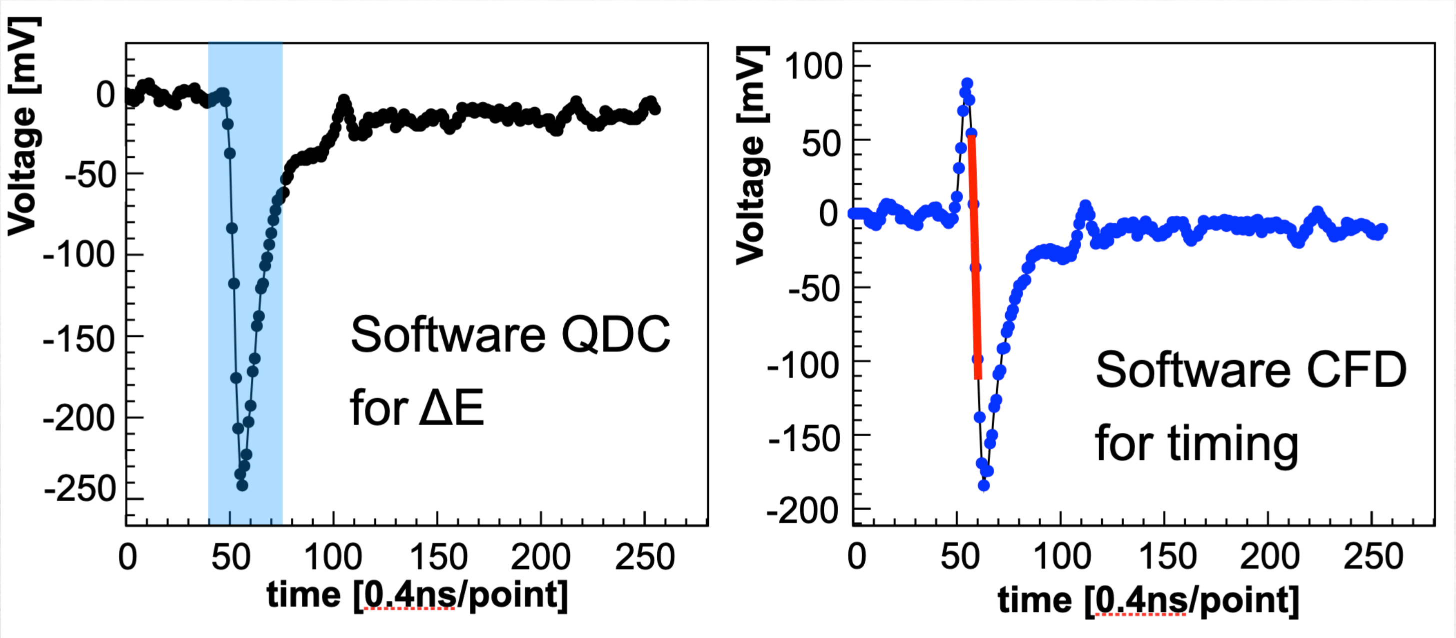
WASA detectors analysis (PSB)

- PSB analysis for ΔE and hit timing.
  - 2.5 GHz waveform data analysis.
  - Software QDC and CFD analysis.









Newly Developed PSB

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

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  - 2.5 GHz waveform data analysis.
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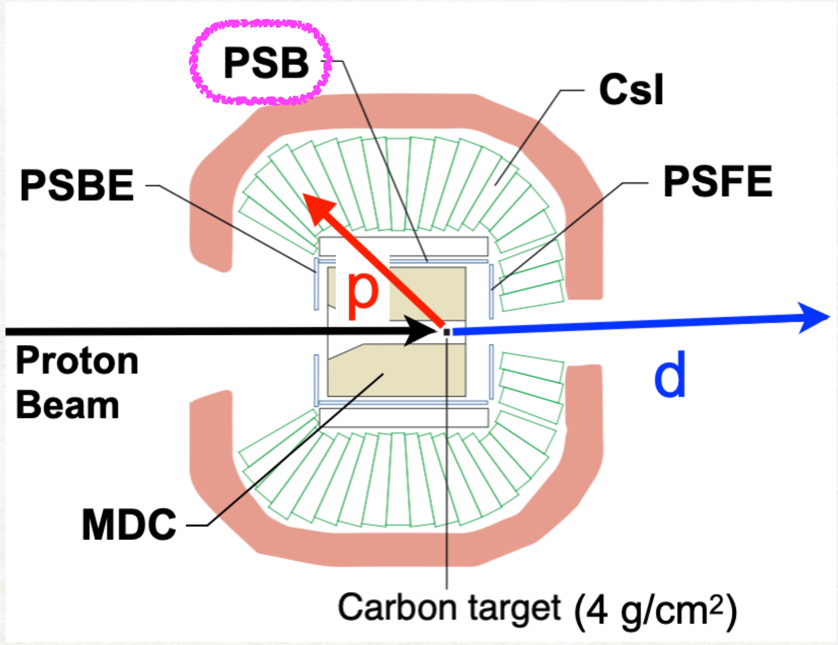
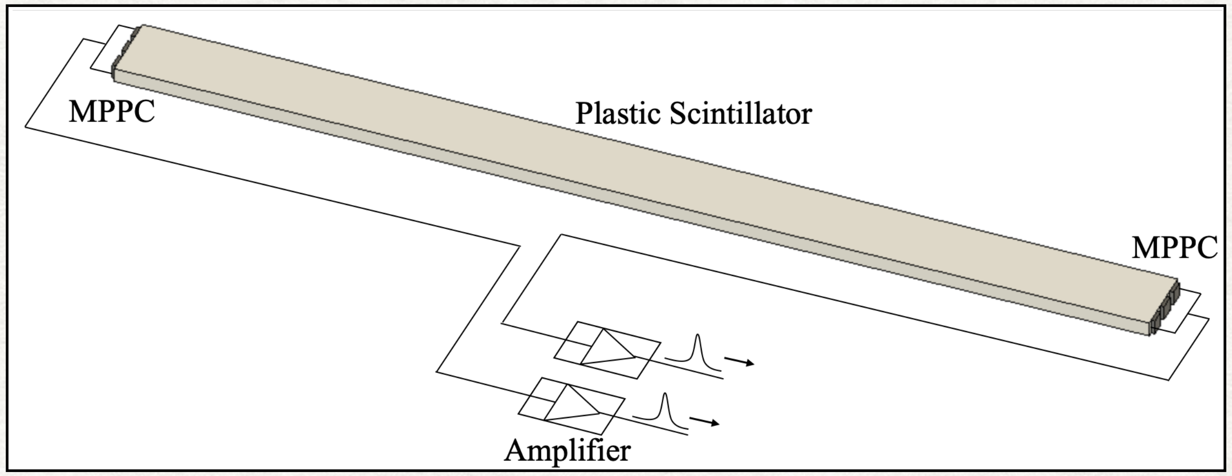
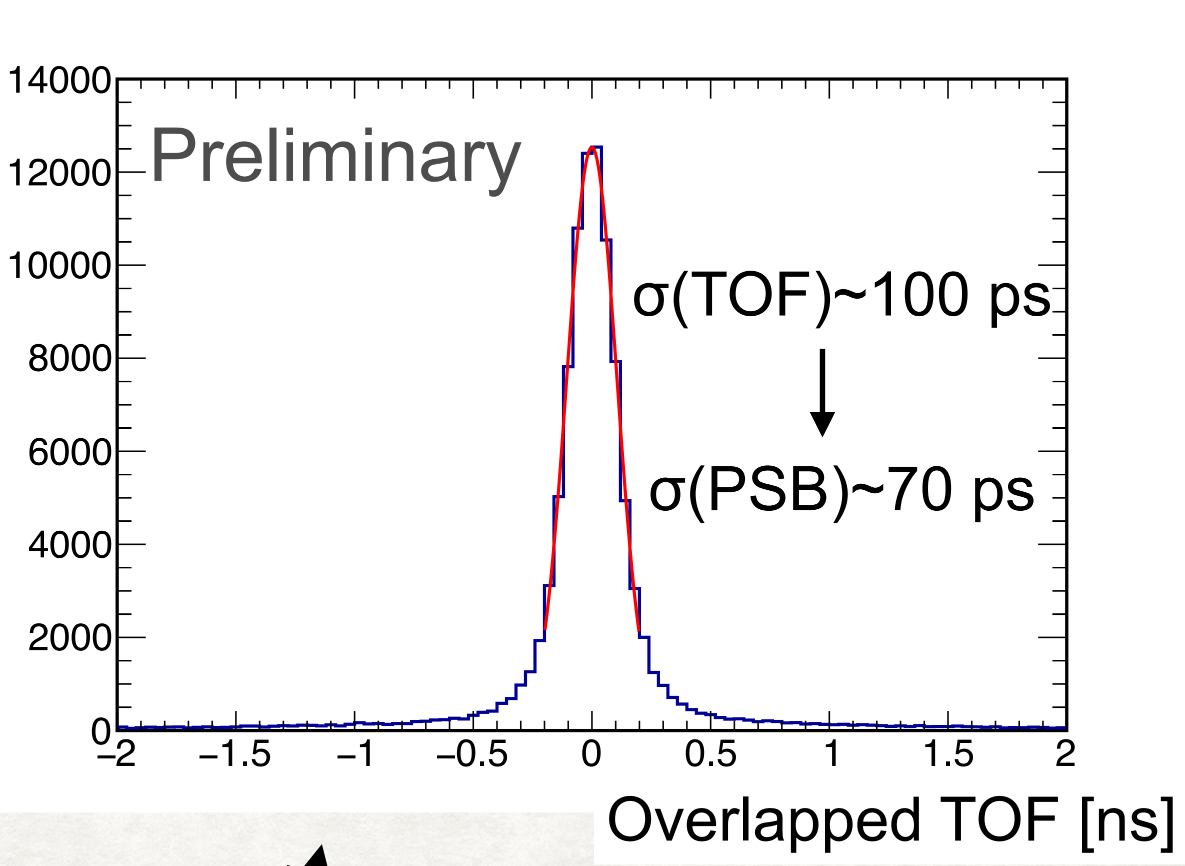
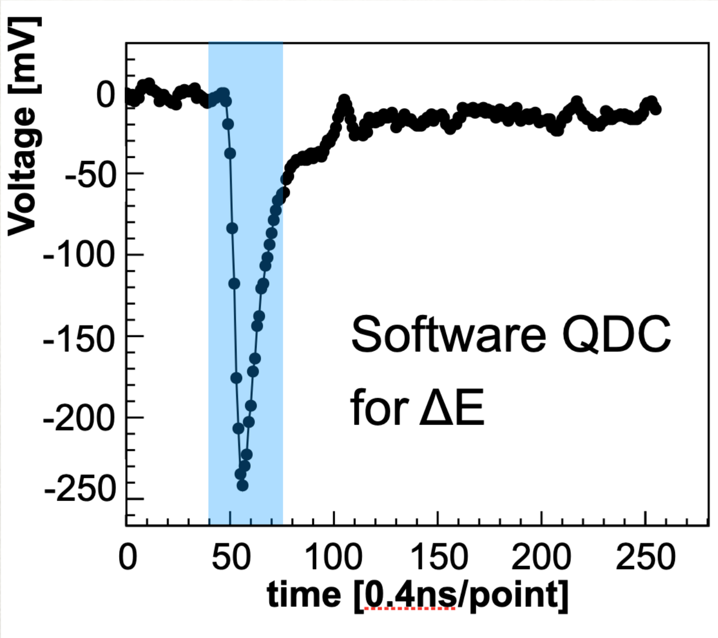
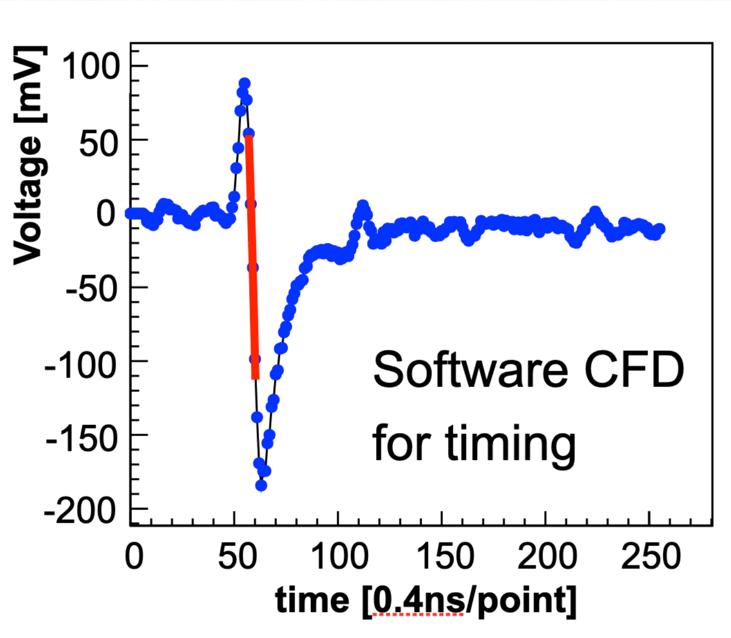
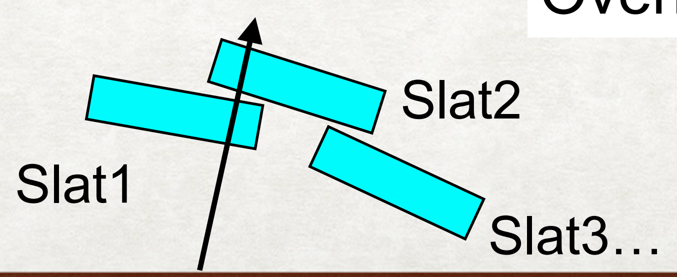






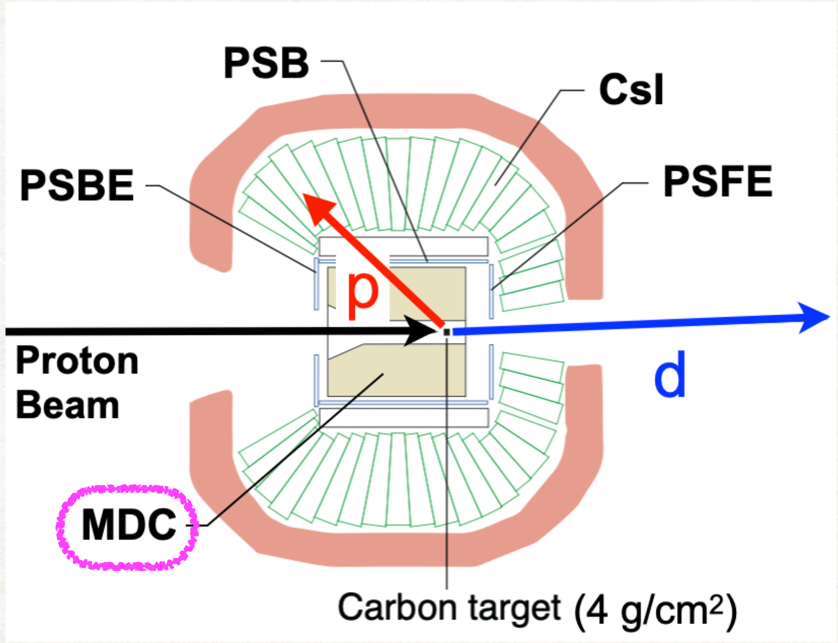




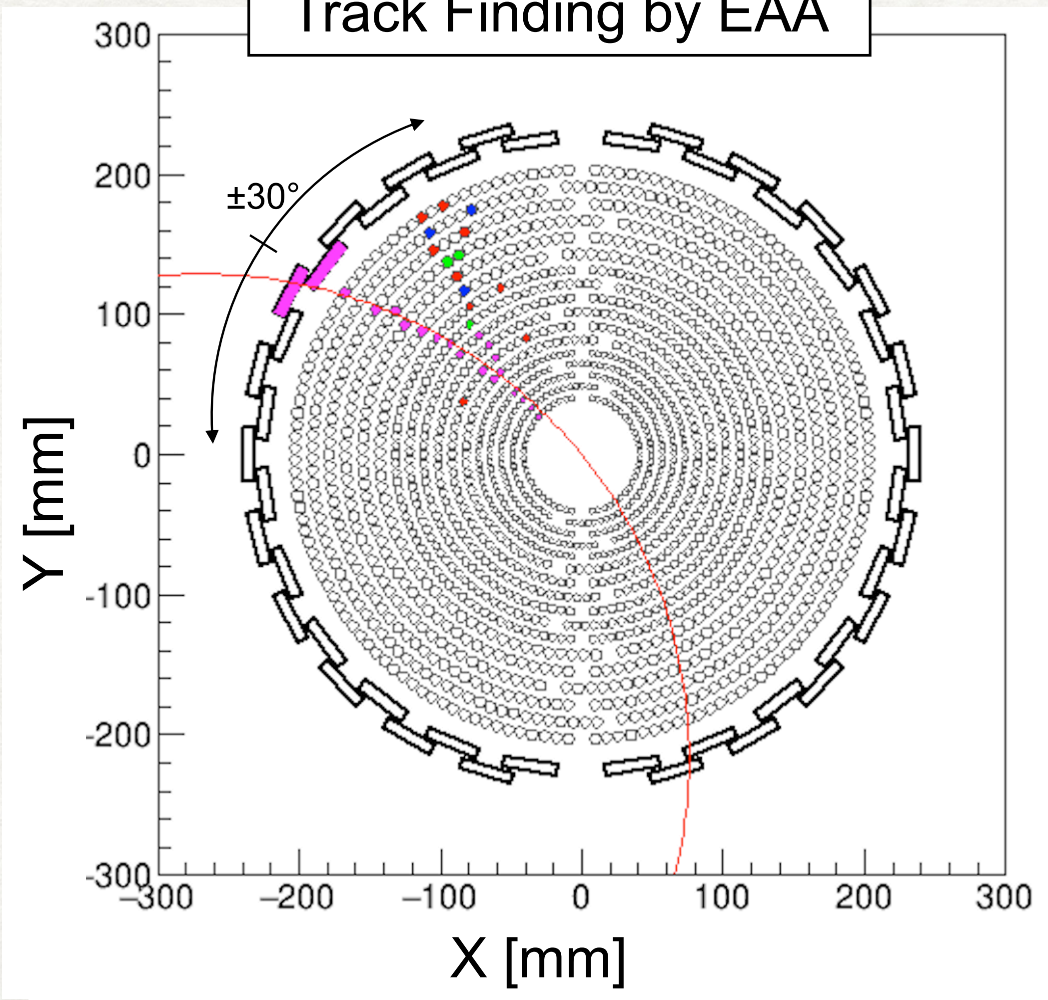


WASA detectors analysis (MDC)

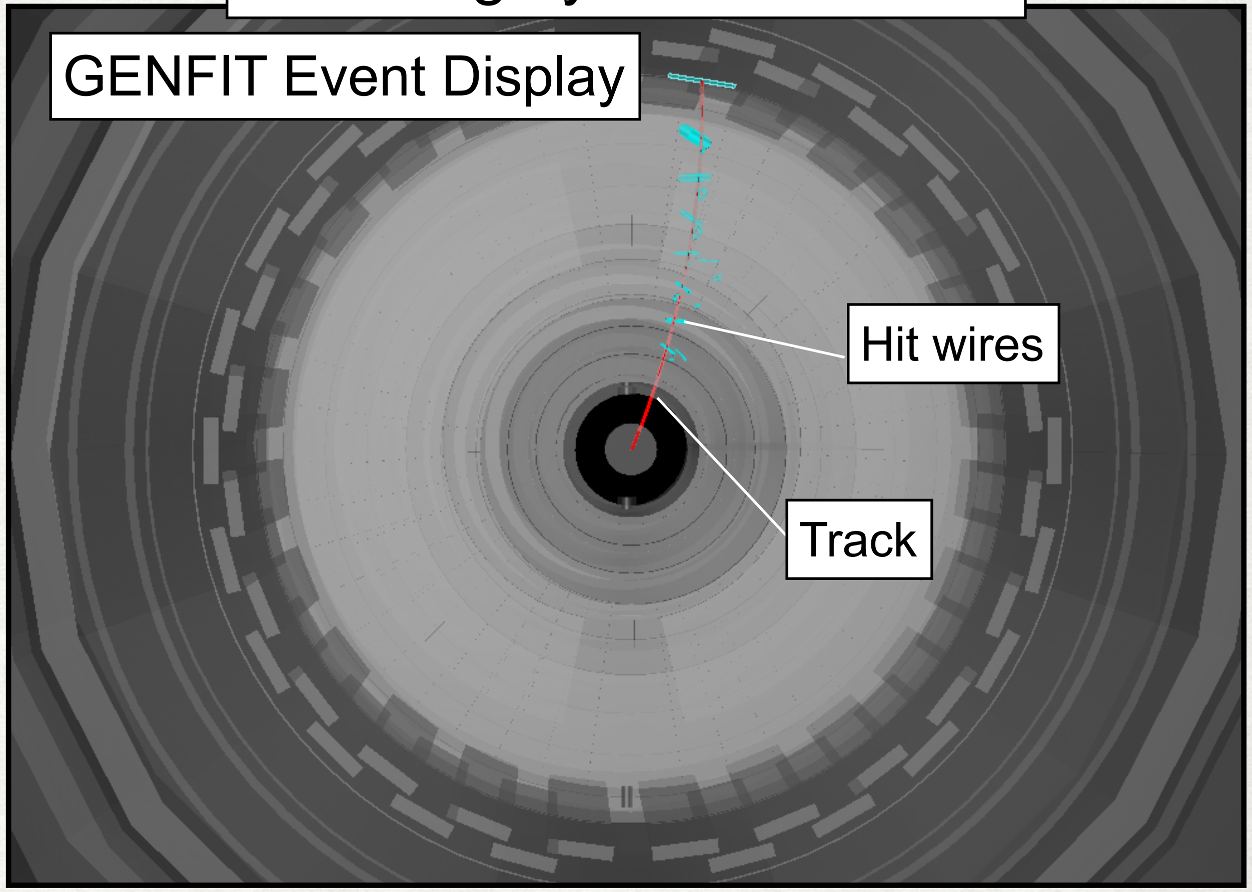
- MDC Tracking for momentum measurement.
  - Track Finding in X-Y plane with Elastic Arm Algorithm.
    - Hit wires selection with given PSB hits.
  - Tracking with Kalman Filter.
    - σ (residual) ~ 200 [um]



Track Finding by EAA

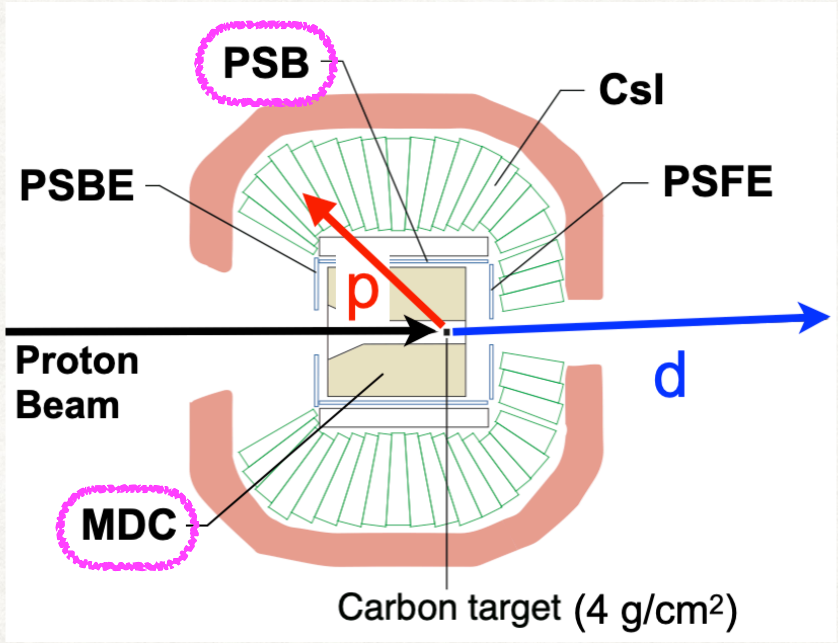


Tracking by Kalman Filter

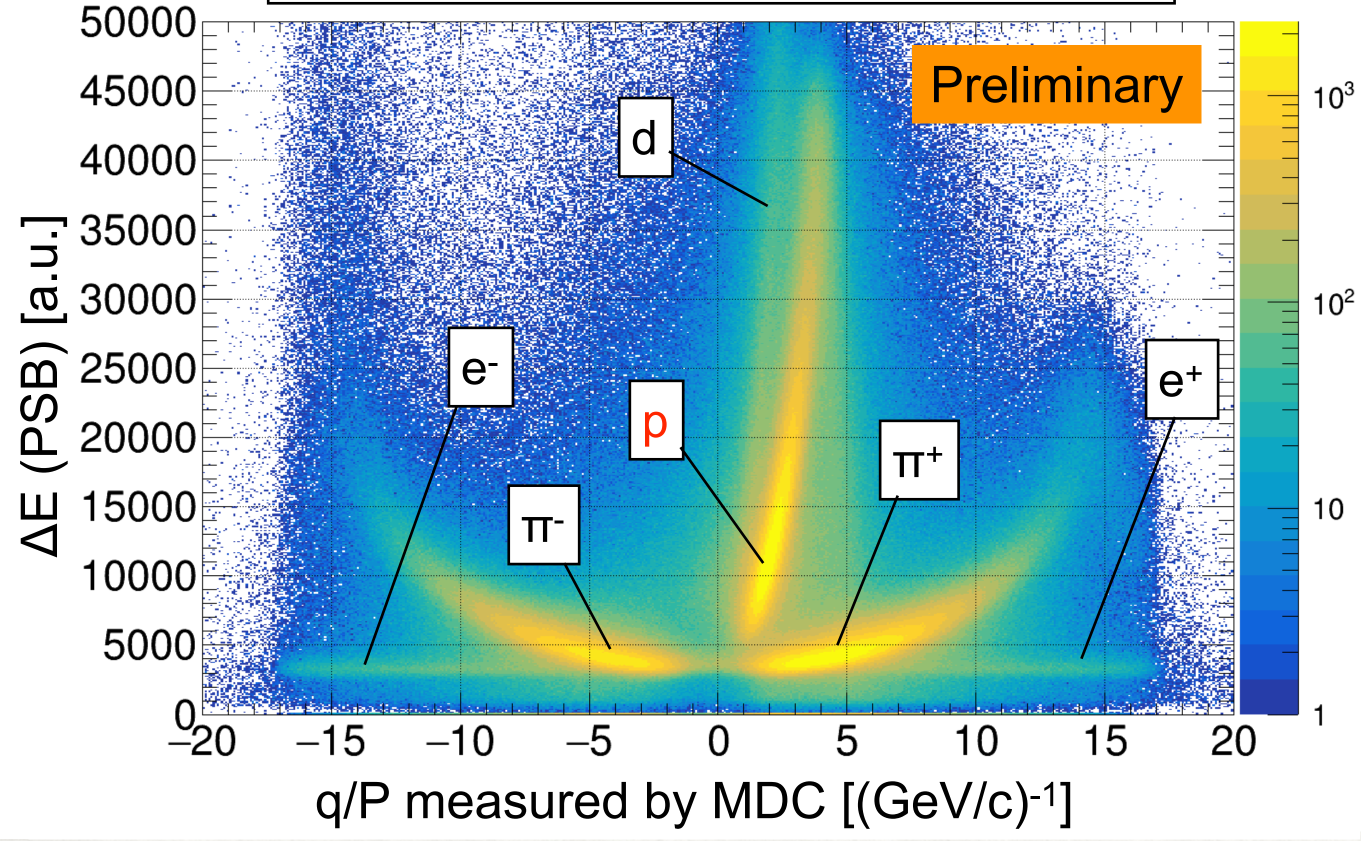


PID by WASA detector (ΔE-P)

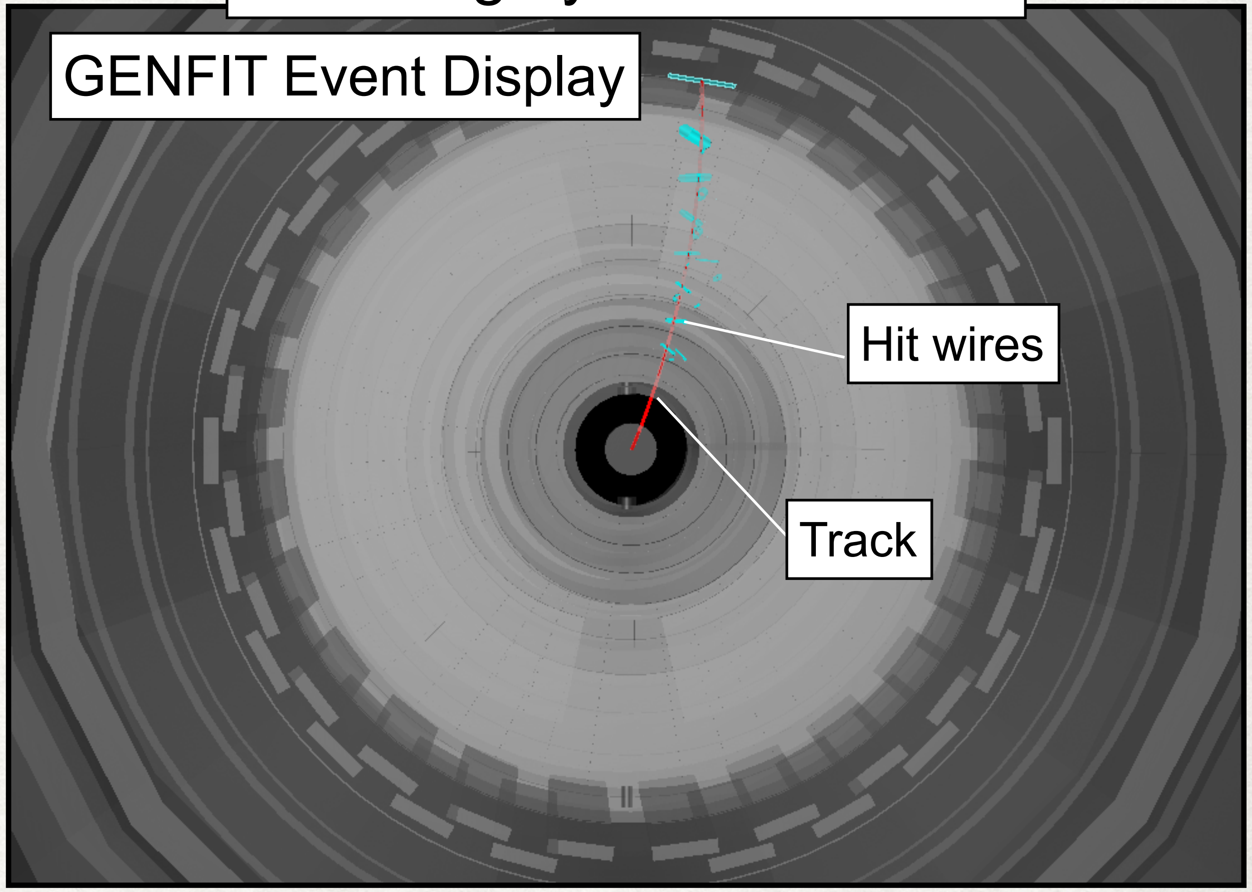
- MDC Tracking for momentum measurement.
  - Track Finding in X-Y plane with Elastic Arm Algorithm.
    - Hit wires selection with given PSB hits.
  - Tracking with Kalman Filter.
    - σ (residual) ~ 200 [um]



PID by WASA (S4 d tagged)

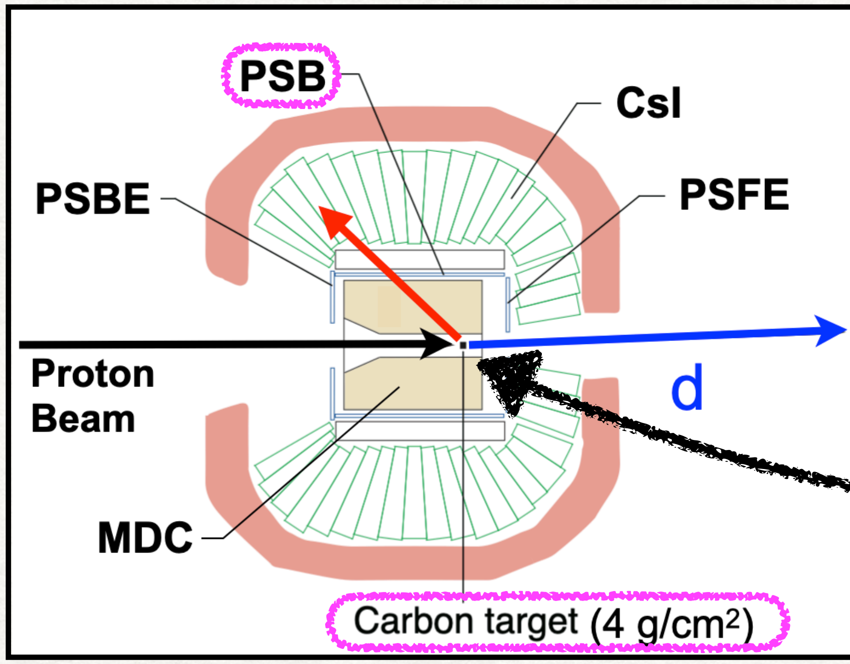


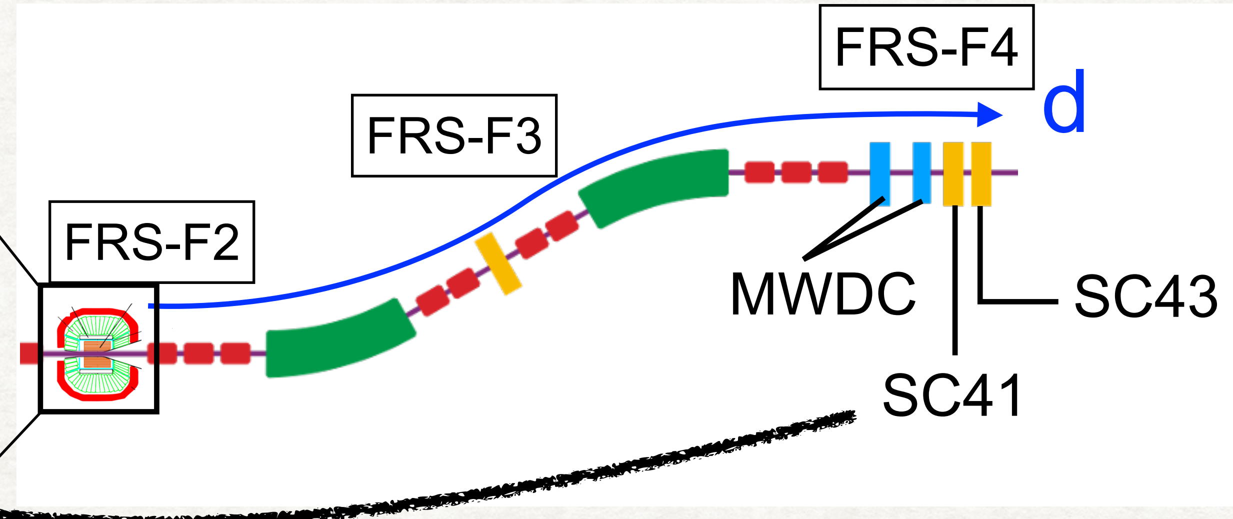
Tracking by Kalman Filter



PID with WASA detector is nicely achieved

PID by TOF inside WASA

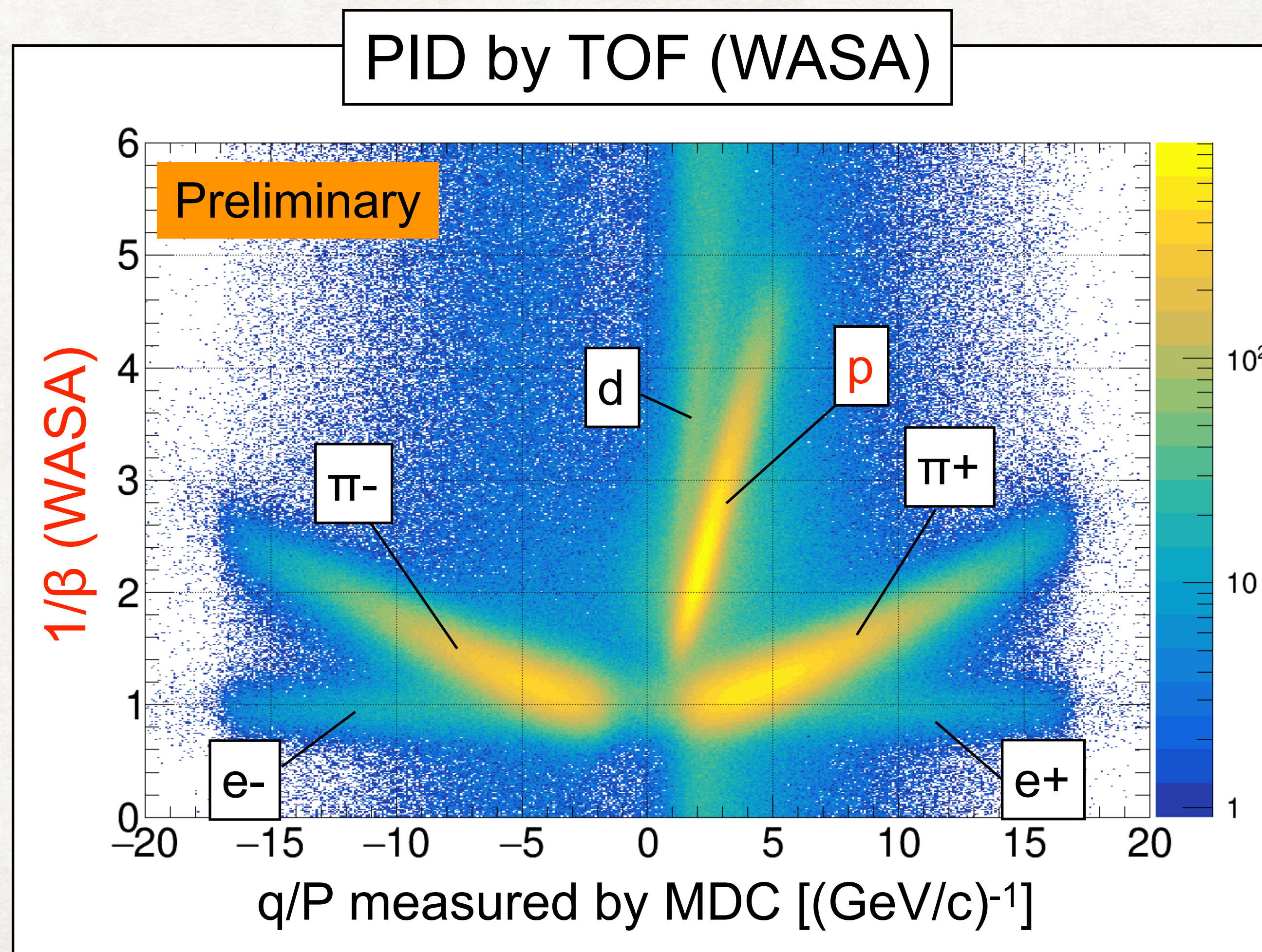




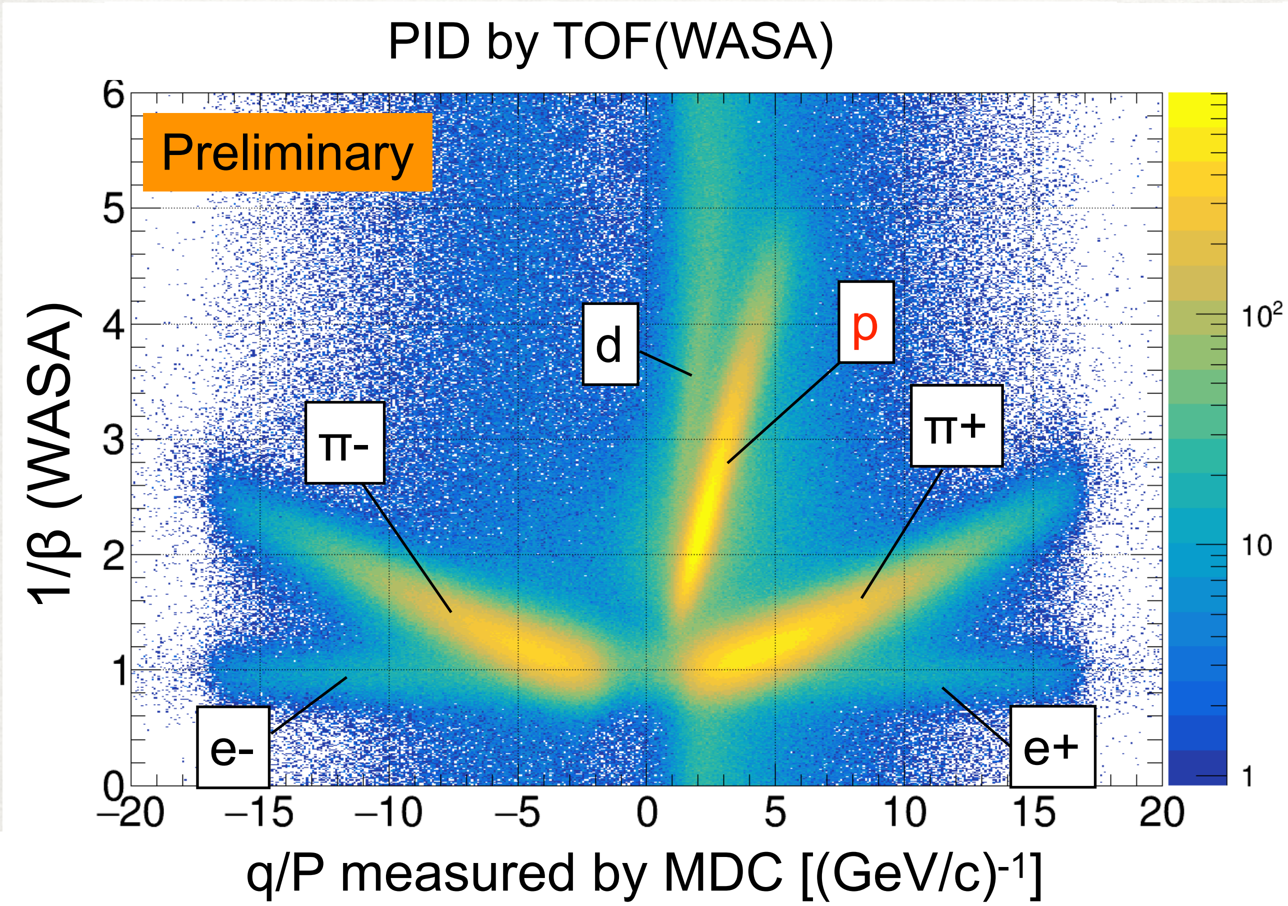
$T_{TARGET}(START) = T_{SC41} - TOF(d \text{ in F2} \rightarrow \text{F4})$

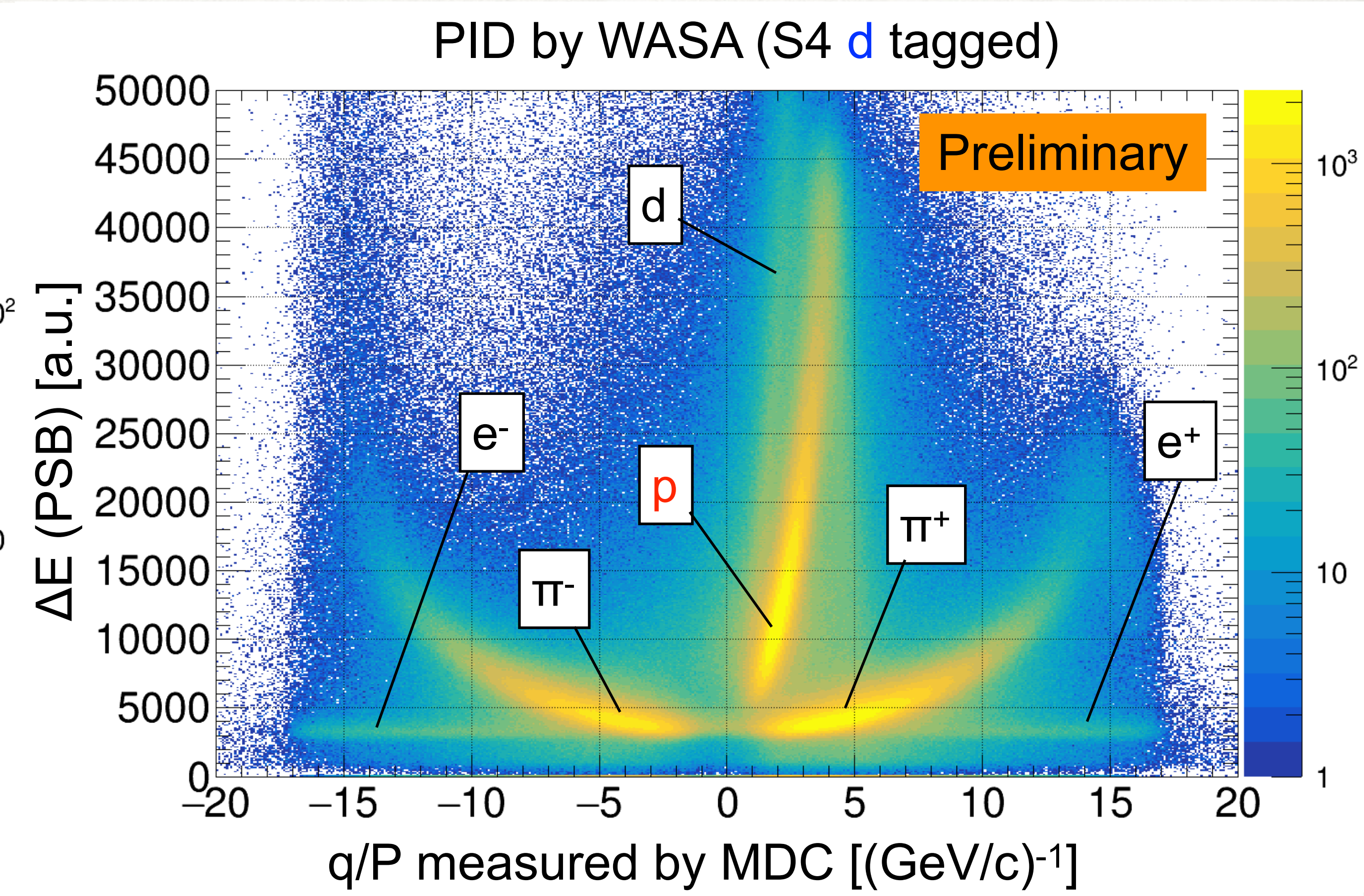
$TOF(WASA) = T_{PSB} - T_{TARGET}(START)$

$$\beta(WASA) = \frac{(\text{Track Length})}{cTOF(WASA)}$$



PID Summary





- Particle identification with the WASA is nicely achieved.
- Evaluation of (β, P, ΔE) resolution are ongoing for reasonable p selection.
- Averaged momentum from (β, P, ΔE) will give much better p-π separation at P ~ 1 GeV/c.

Summary

- We performed missing-mass spectroscopy in $^{12}C(p,dp)$ reaction to search for η′-mesic nuclei at the FRS in GSI in 2022.
  - d momentum measurement with the FRS.
  - p selection with the WASA detector.
  - 3.5 days physics run and 1.1×10^{7} d events are accumulated.

- The forward d identification and evaluation of excitation energy have been done.
  - The inclusive spectra is consistent with the previous experiment in 2014.
- PID in the WASA detector is nicely working with measured P, ΔE and β.
  - Evaluation of (P, ΔE, β) resolution is ongoing for reasonable p selection.
  - Averaged momentum with (P, ΔE, β) will give better p-π separation in our region of interest (P ~ 1 GeV/c).

- Discussion on the semi-exclusive spectrum and physics interpretation in our collaboration group.
- Final semi-exclusive spectrum will be coming soon.

Backup

Theoretical spectra with Green's function methods

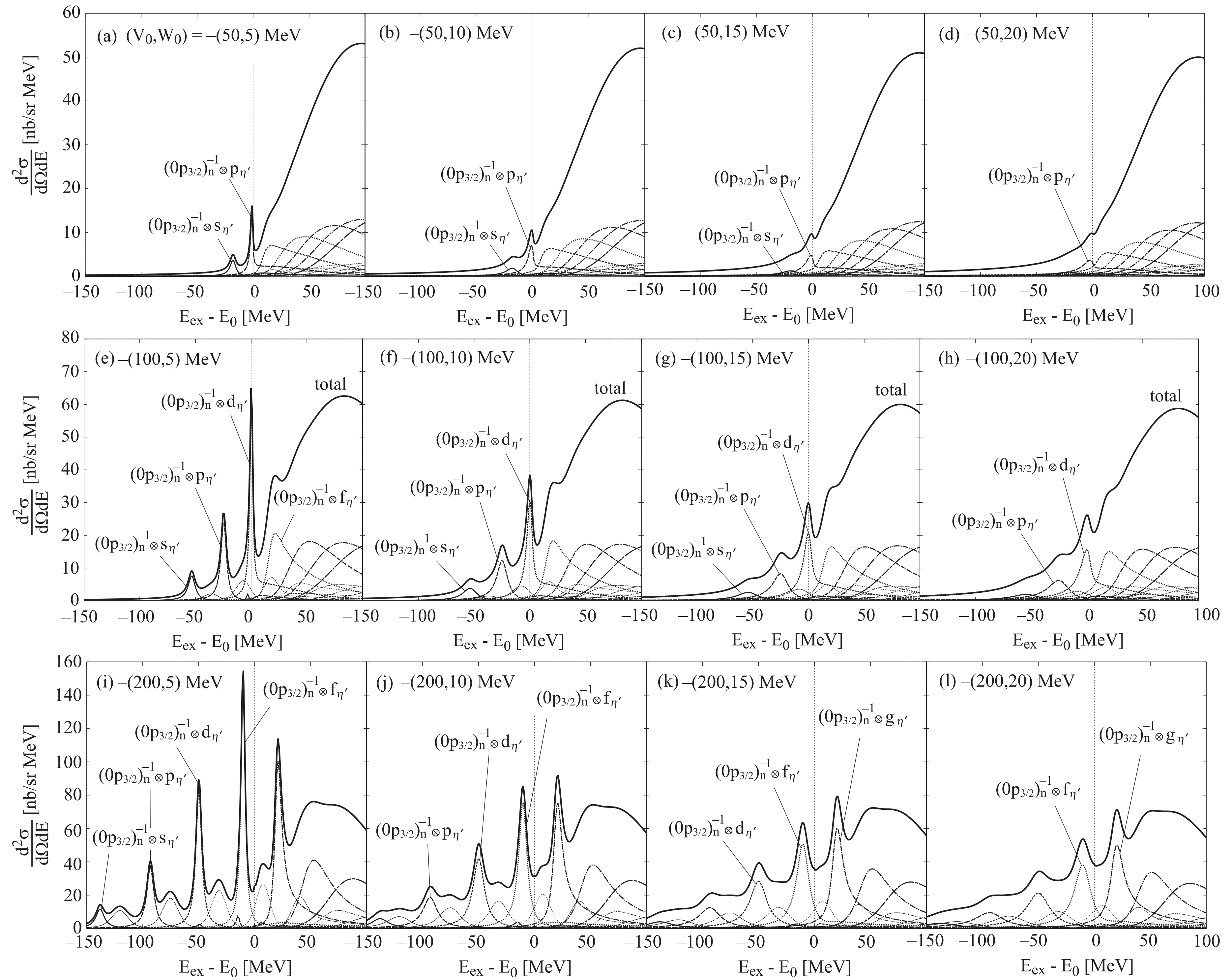
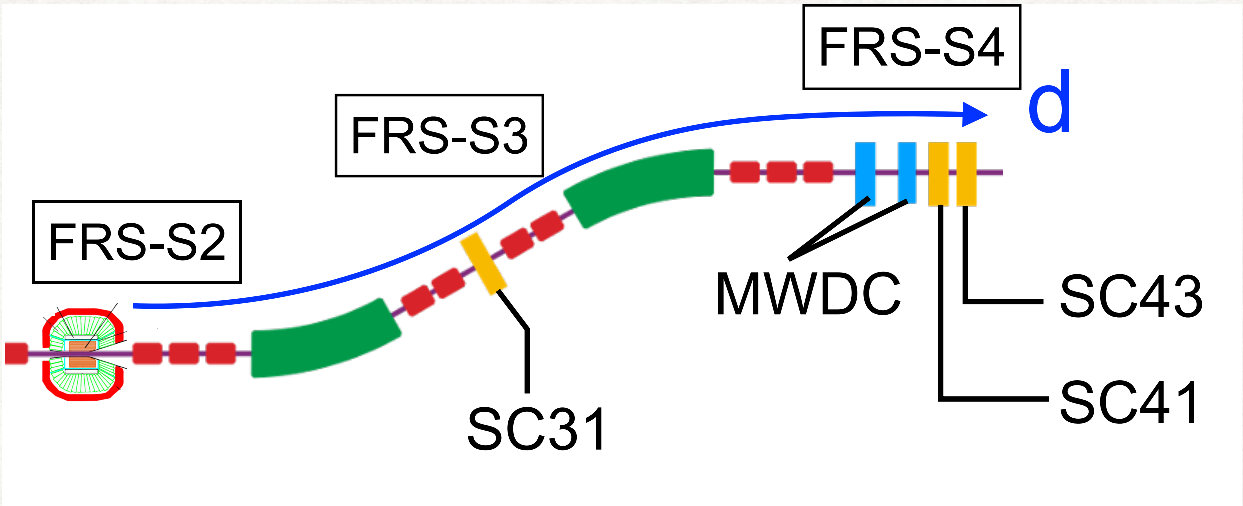


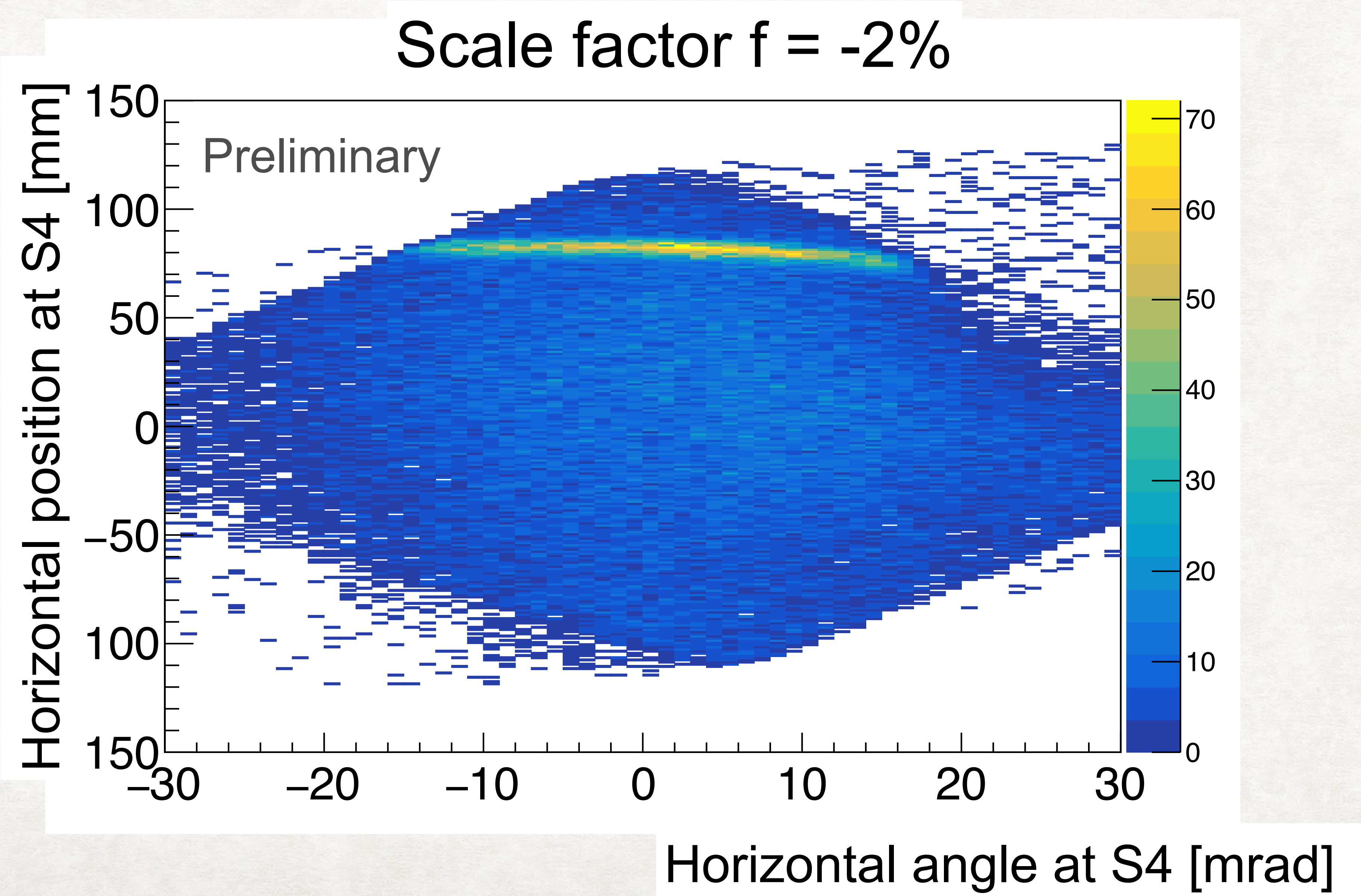
FIG. 8. Calculated spectra of the ${}^{12}\mathrm{C}(p,d){}^{11}\mathrm{C} \otimes \eta'$ reaction for the formation of η'-nucleus systems with proton kinetic energy $T_p = 2.5$ GeV and deuteron angle $\theta_d = 0^\circ$ as functions of the excited energy E_{ex}. E_0 is the η' production threshold. Various combinations of the potential strength are considered within the range of $V_0 = -50$–200 MeV and $W_0 = -5$–20 MeV as indicated in the figure. The thick solid lines show the total spectra and dashed lines indicate subcomponents. The neutron-hole states are indicated as $(n\ell_j)_n^{-1}$ and the η' states as $\ell_{\eta'}$.

H. Nagahiro et al., PRC 87, 045201 (2013)

FRS optics calibaration

- **FRS optics analysis**
  - Elastic d(p,d)p reaction with different FRS scaling factors.





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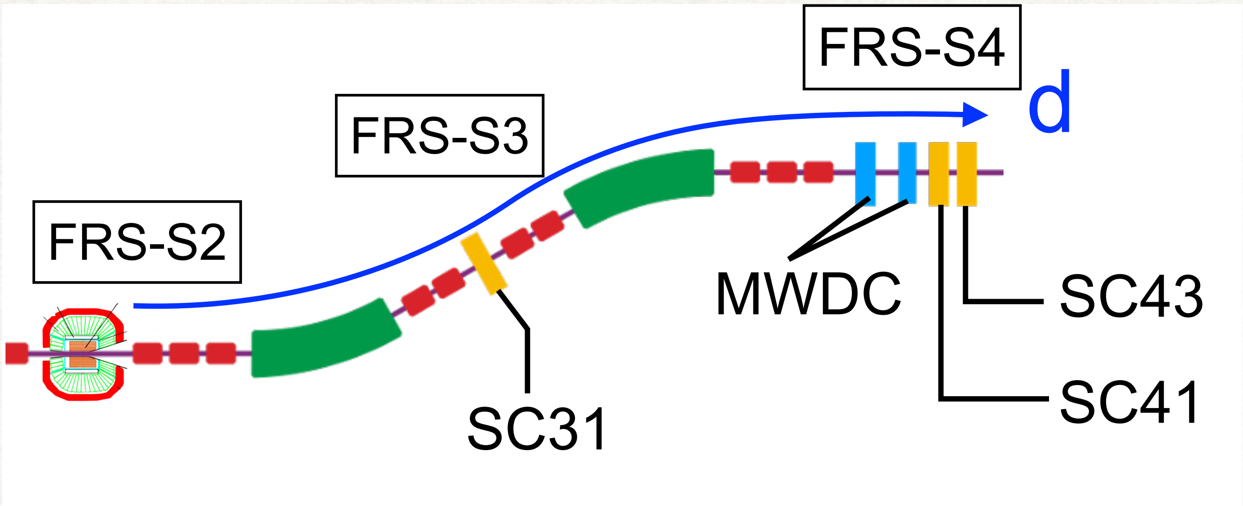

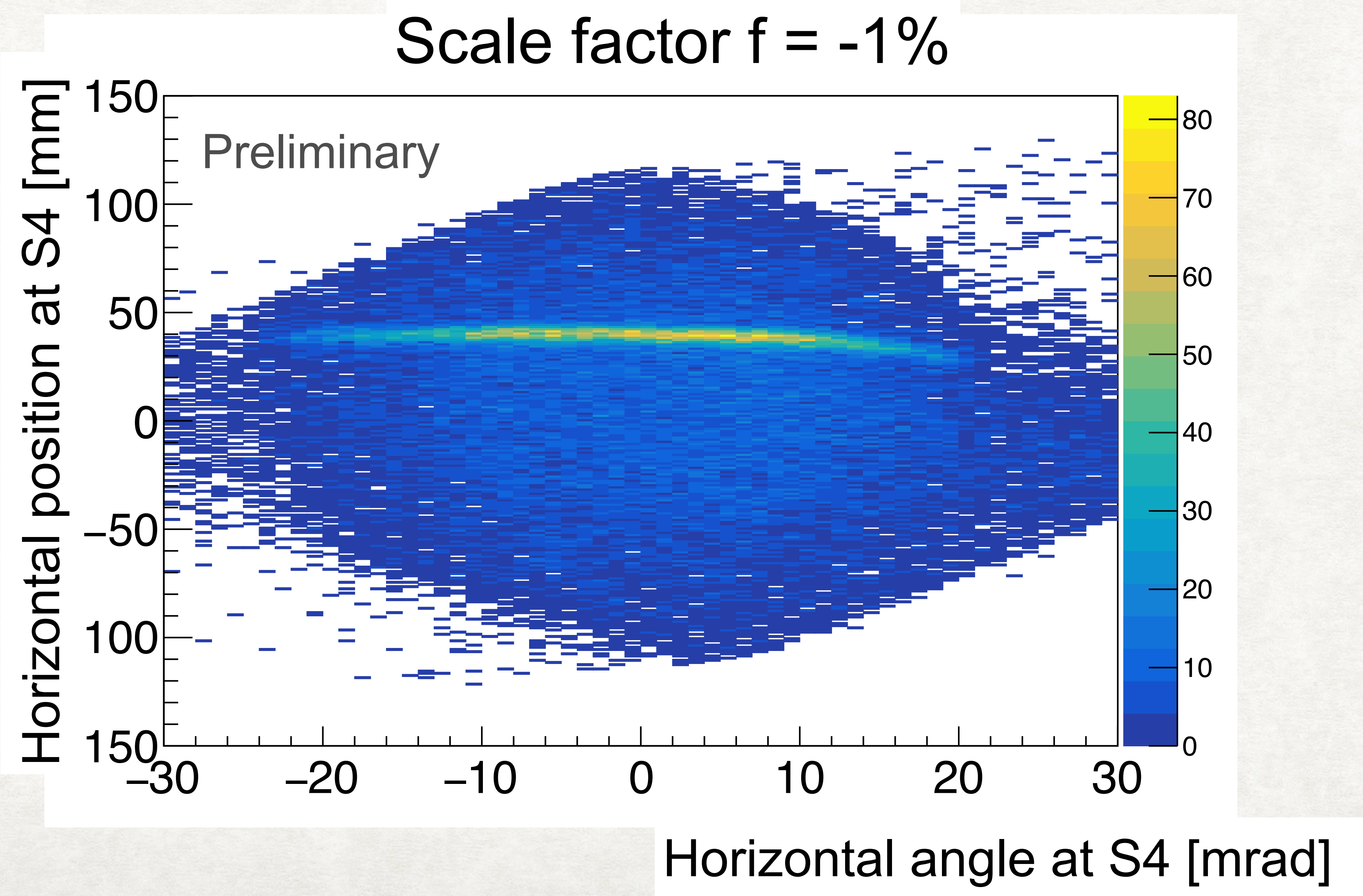

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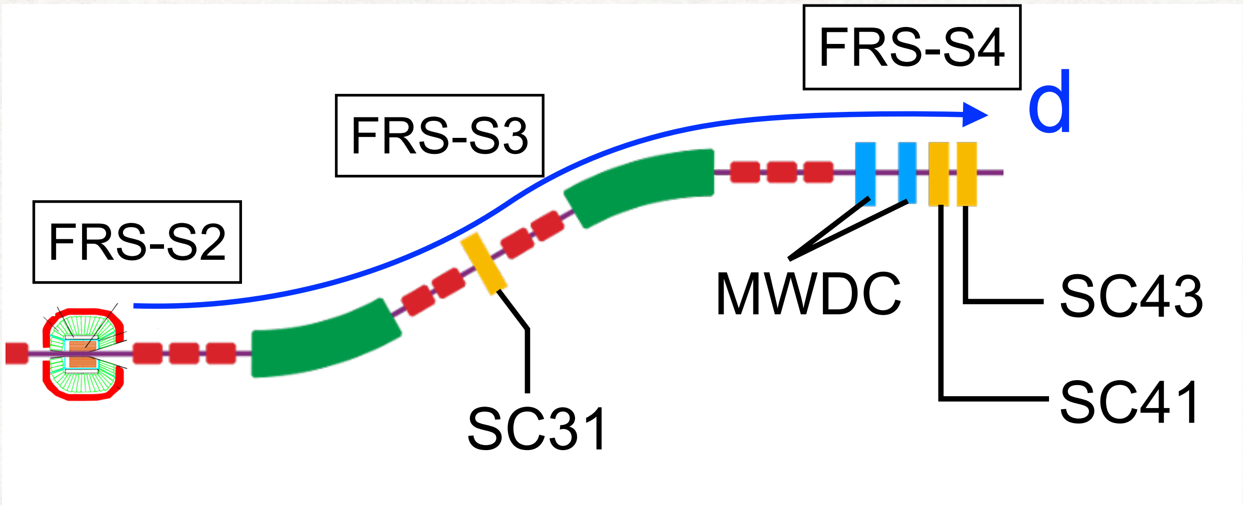

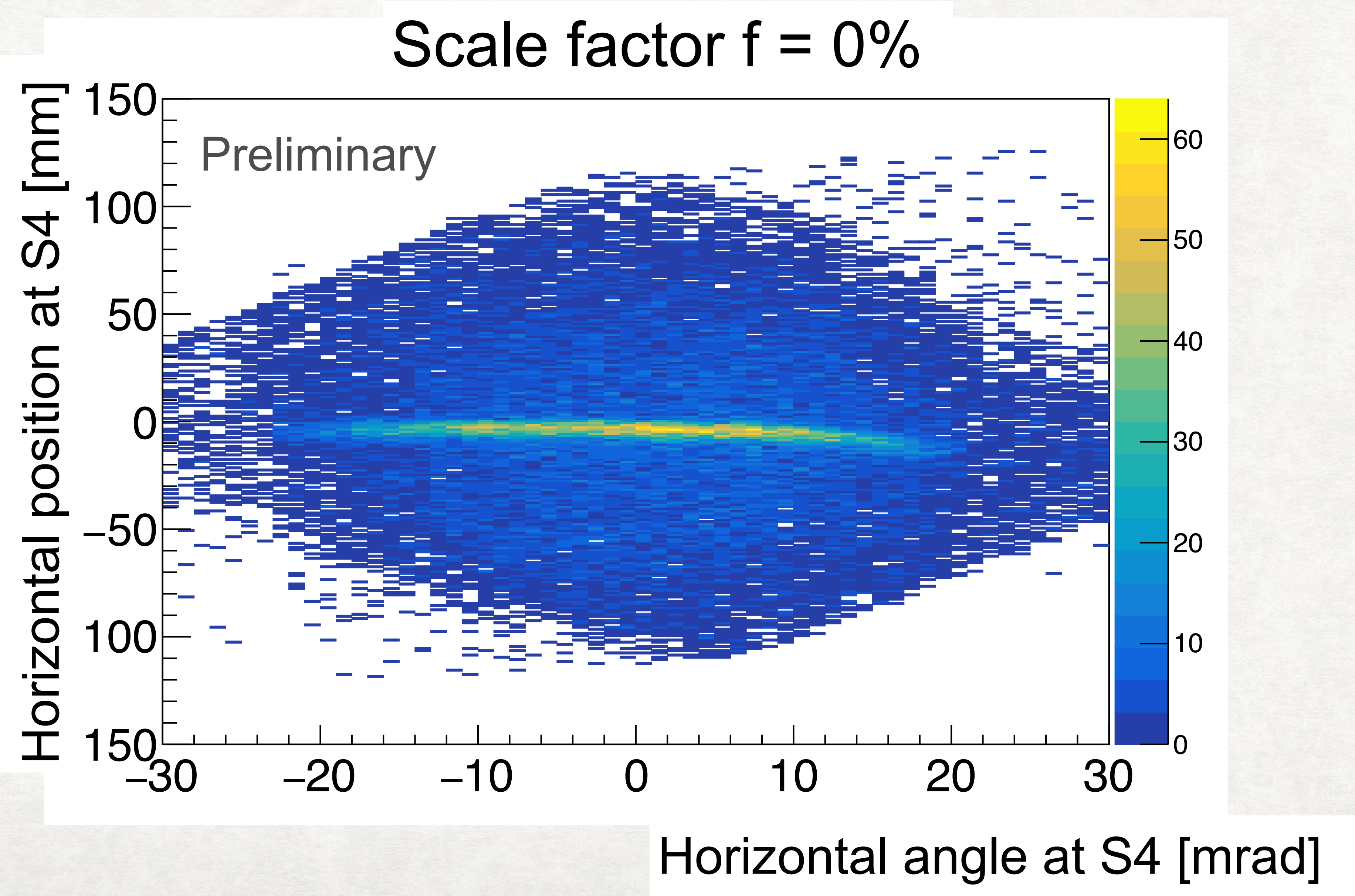

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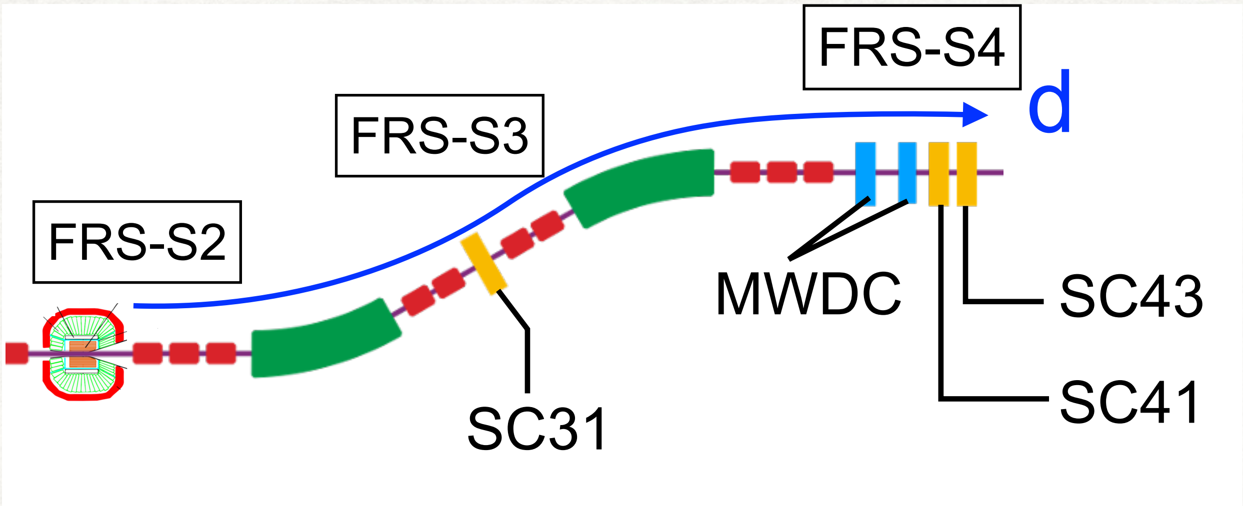

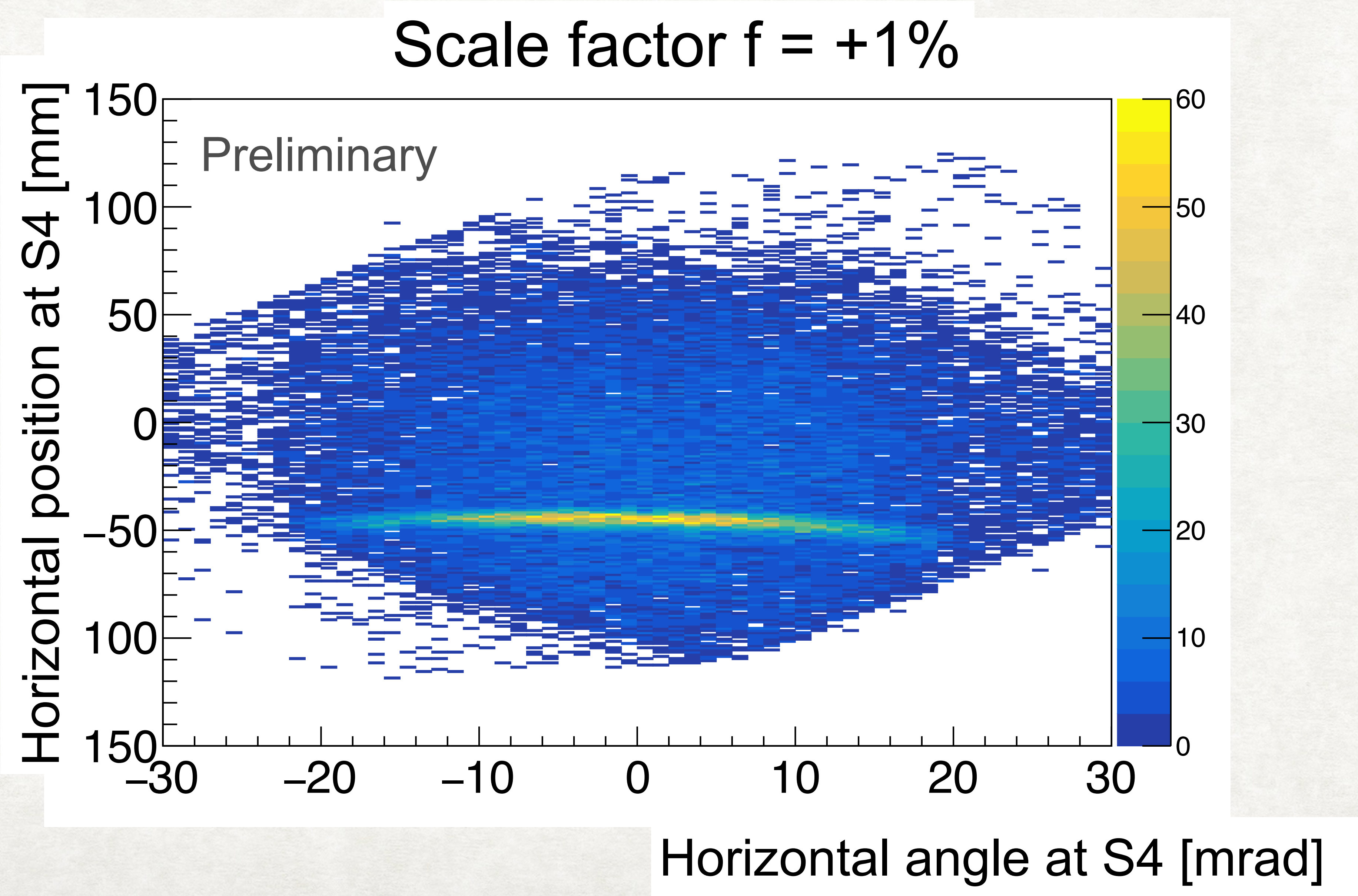

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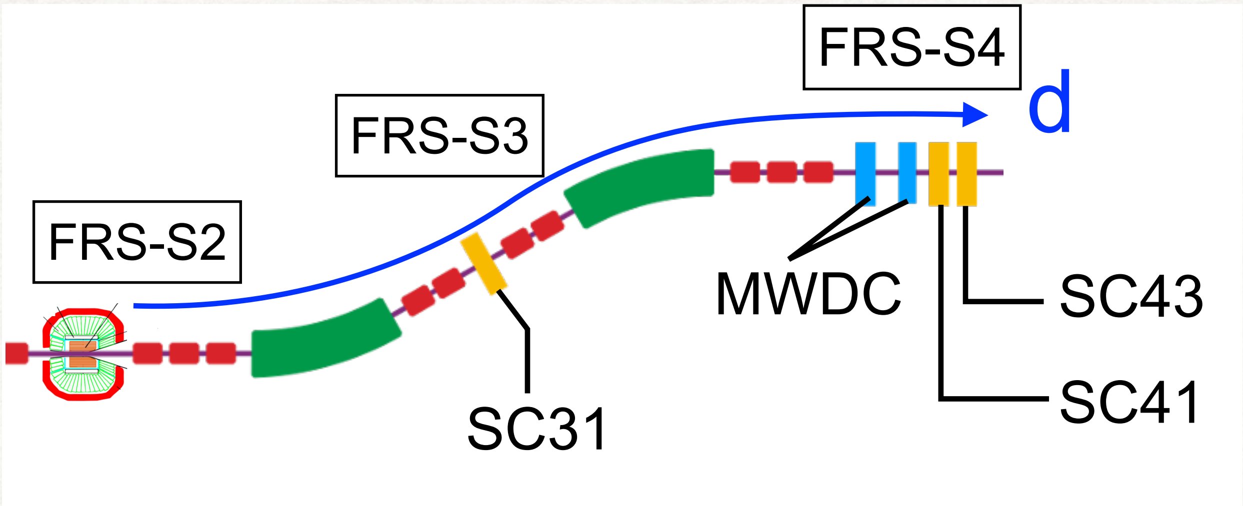
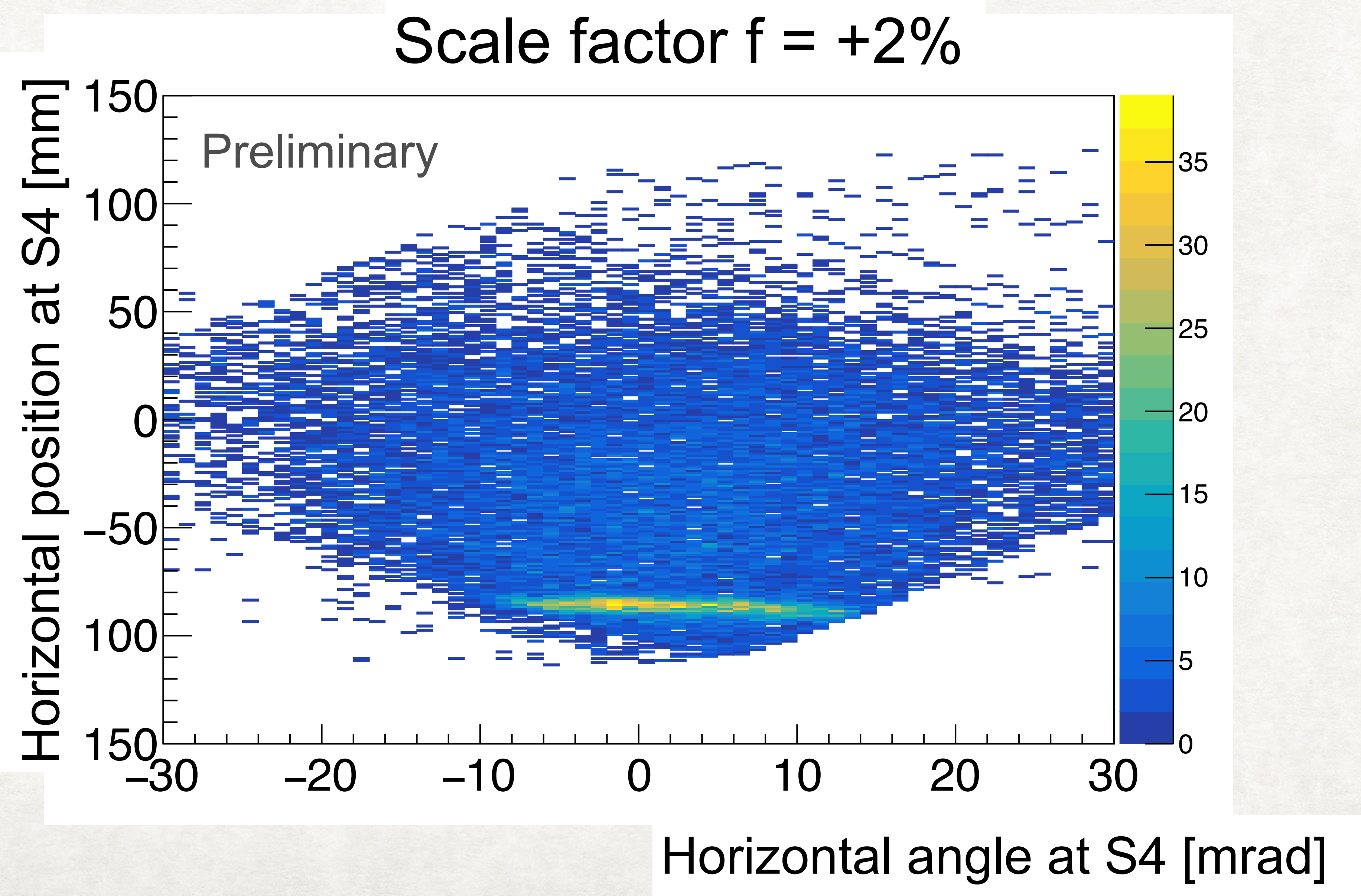




η′- nucleus optical potential

Experimental values

η′-nucleus optical potential

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

$V_0 = \Delta m(\rho_0)$ $W_0 = -\Gamma(\rho_0)/2$

CBELSA / TAPS

$V_0 = -39 \pm 7_{stat} \pm 15_{syst}$ MeV [1,2]

$W_0 = -13 \pm 3_{stat} \pm 3_{syst}$ MeV [3,4]

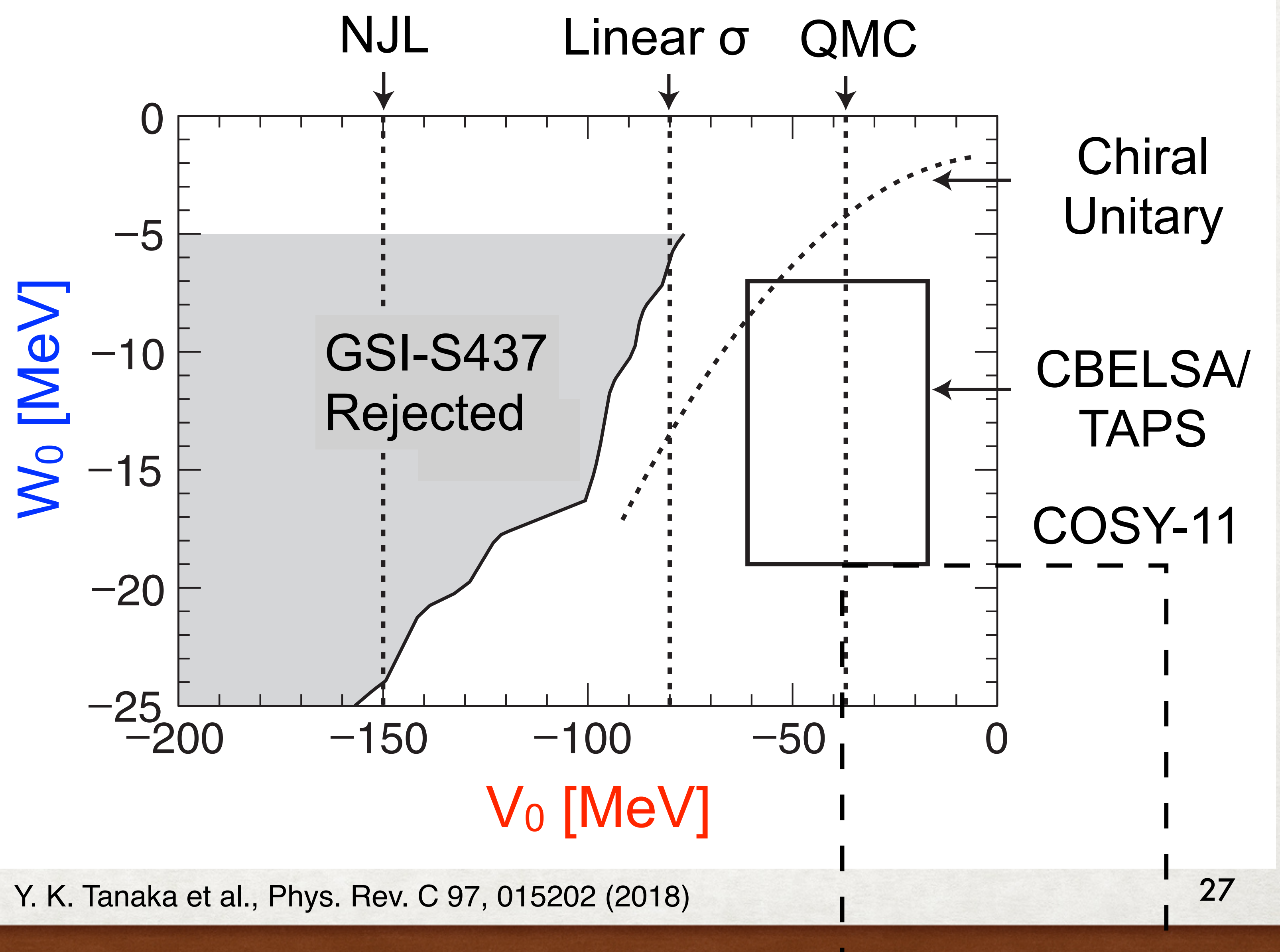
COSY-11 [5]

$Re(a_{\eta' p}) = 0 \pm 0.43$ fm

$Im(a_{\eta' p}) = 0.37$ fm

→ $|V_0| < 38$ MeV

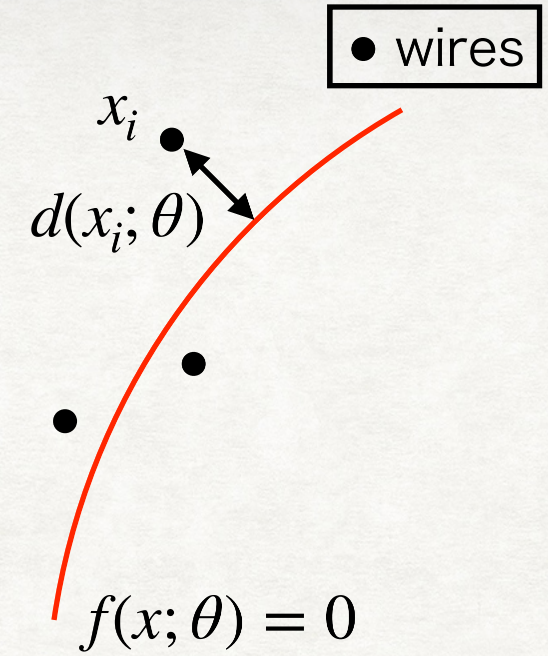
$W_0 = -(33^{+40}_{-14})$ MeV



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

[1] M. Nanova et. al., PLB **727**, 417 (2013)
[2] M. Nanova et al., PRC 94 025205 (2016)
[3] M. Nanova et al., PLB **710**, 600 (2012)
[4] S. Friedrich et al., EPJ A **52**, 297 (2016)
[5] E. Czerwiński et al., PRL 113, 062004 (2014)

Elastic arm algorithm[1]



Function to be minimized

In order to search for the circle with excluding outlier hits, we consider to minimize the following function:

$$E(\boldsymbol{w};\boldsymbol{\theta}) = \sum_{i=1}^{N}\left(w_i \frac{d_i(x_i;\boldsymbol{\theta})}{\lambda_i} + (1-w_i) \right) + V(\boldsymbol{\theta})$$

- w_i = 0 or 1 for i = 1, 2, … N.
- λ_i … threshold to judge the wire is signal or outlier.
- **θ** … fitting parameters
- V(**θ**) … constraint on **θ**. In the present analysis, constraint to make the circle pass through PSB.

In the present case,
$f(x,y;a,b) = (x-a)^2+(y-b)^2-a^2-b^2$

Minimization of E(w;θ)

We do not minimize E(w;θ) directly, but instead we minimize Helmholtz free energy F(**θ**) as decreasing the temperature T.

Partition function: $Z = \sum_{\boldsymbol{w}} \exp(-\beta E(w;\theta)) = e^{-\beta V(\theta)} \prod_{i=1}^{N} \left(e^{-\beta \frac{d_i}{\lambda_i}} + 1 \right)$

Free energy: $F(\boldsymbol{\theta}) = -\frac{1}{\beta}\log Z = -\frac{1}{\beta}\sum_{i=1}^{N} \log\left(1 + e^{-\beta(\frac{d_i}{\lambda_i}-1)}\right) + V(\boldsymbol{\theta})$

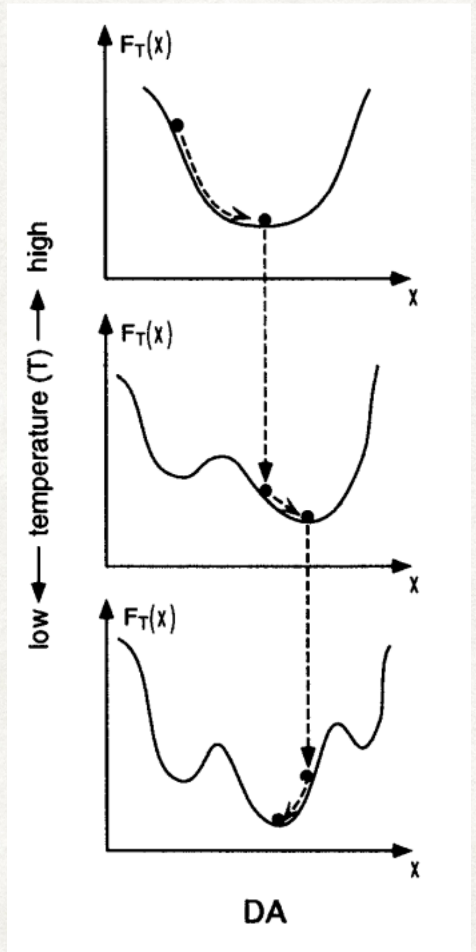


Fig. 1 in ref. [2]

Reference:
[1] R. Frtihwirth, A. Strandlie, Computer Physics Communications 120 (1999) 197-214, https://www.sciencedirect.com/science/article/pii/S0010465599002313
[2] N. Ueda, R. Nakano, “Deterministic Annealing -Another Type of Annealing-”, (7/7/1997), https://www.jstage.jst.go.jp/article/jjsai/12/5/12_689/_pdf