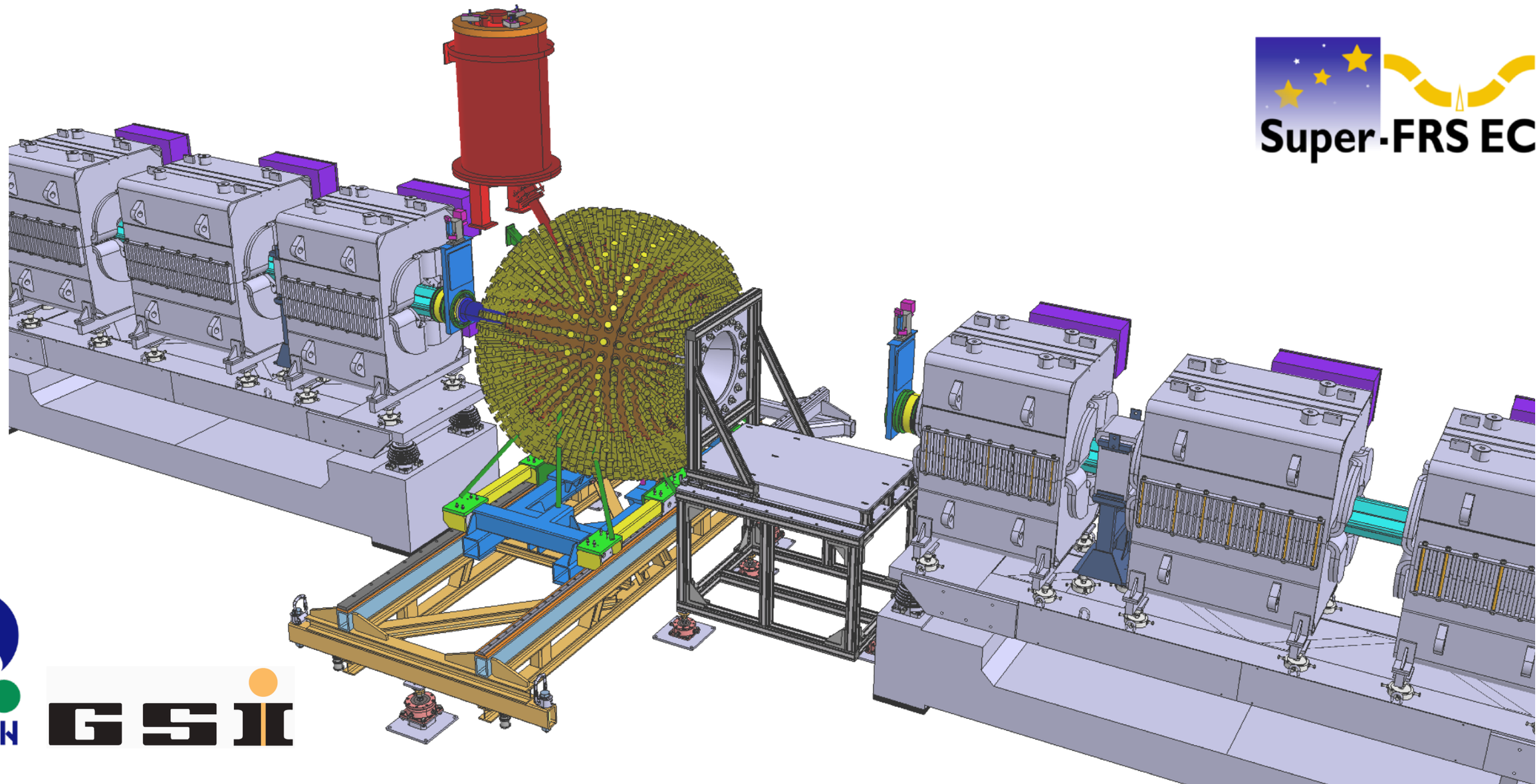
Status of the recent WASA-FRS experiments at GSI/FAIR

Yoshiki Tanaka (RIKEN)

WASA-FRS and Super-FRS Experiment collaborations



Super-FRS EC

RIKEN

GSI

WASA-FRS Experiments at GSI (2022 Jan.-March)

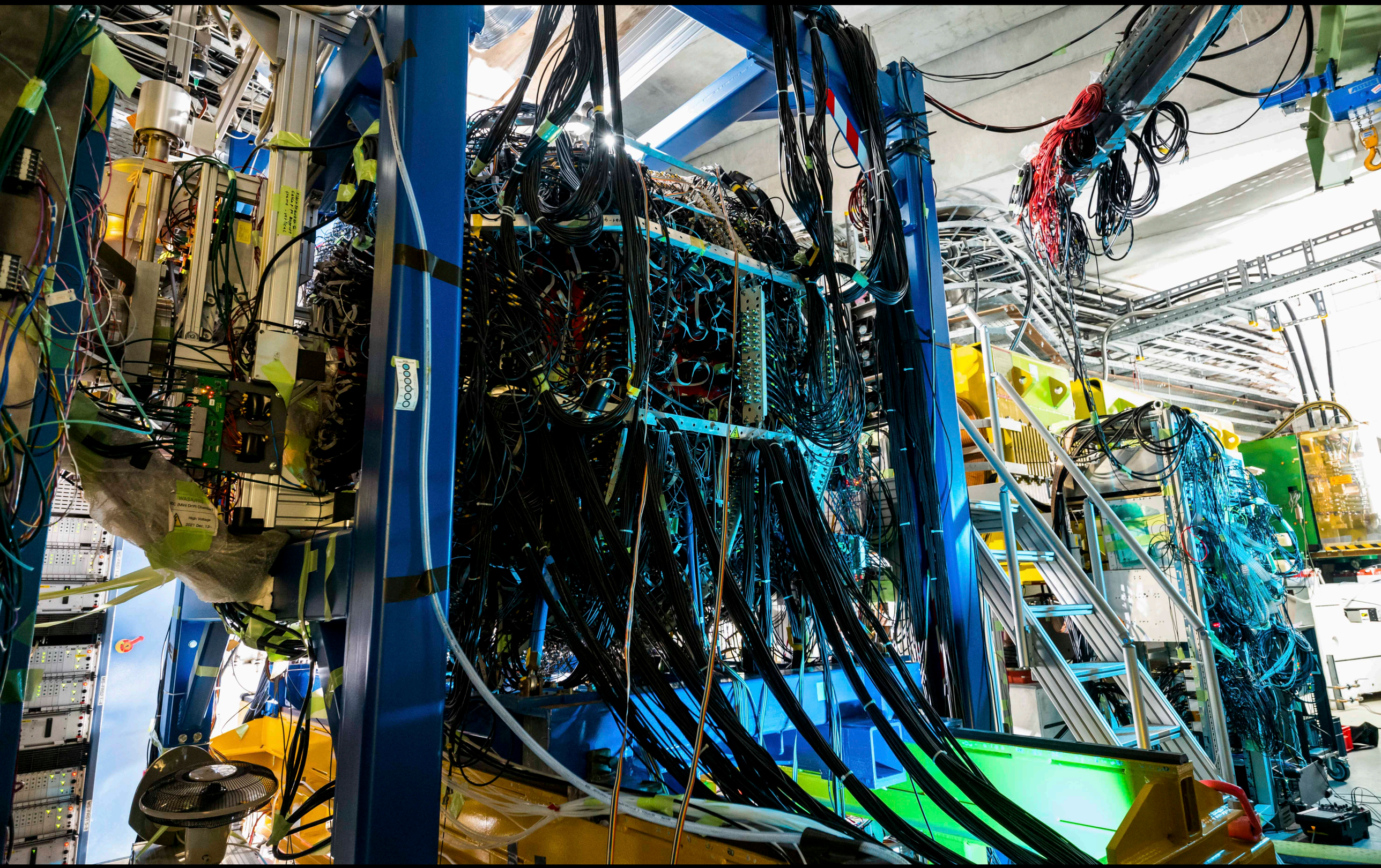


Photo by Jan Hosan

WASA-FRS Experiments at GSI (2022 Jan.-March)

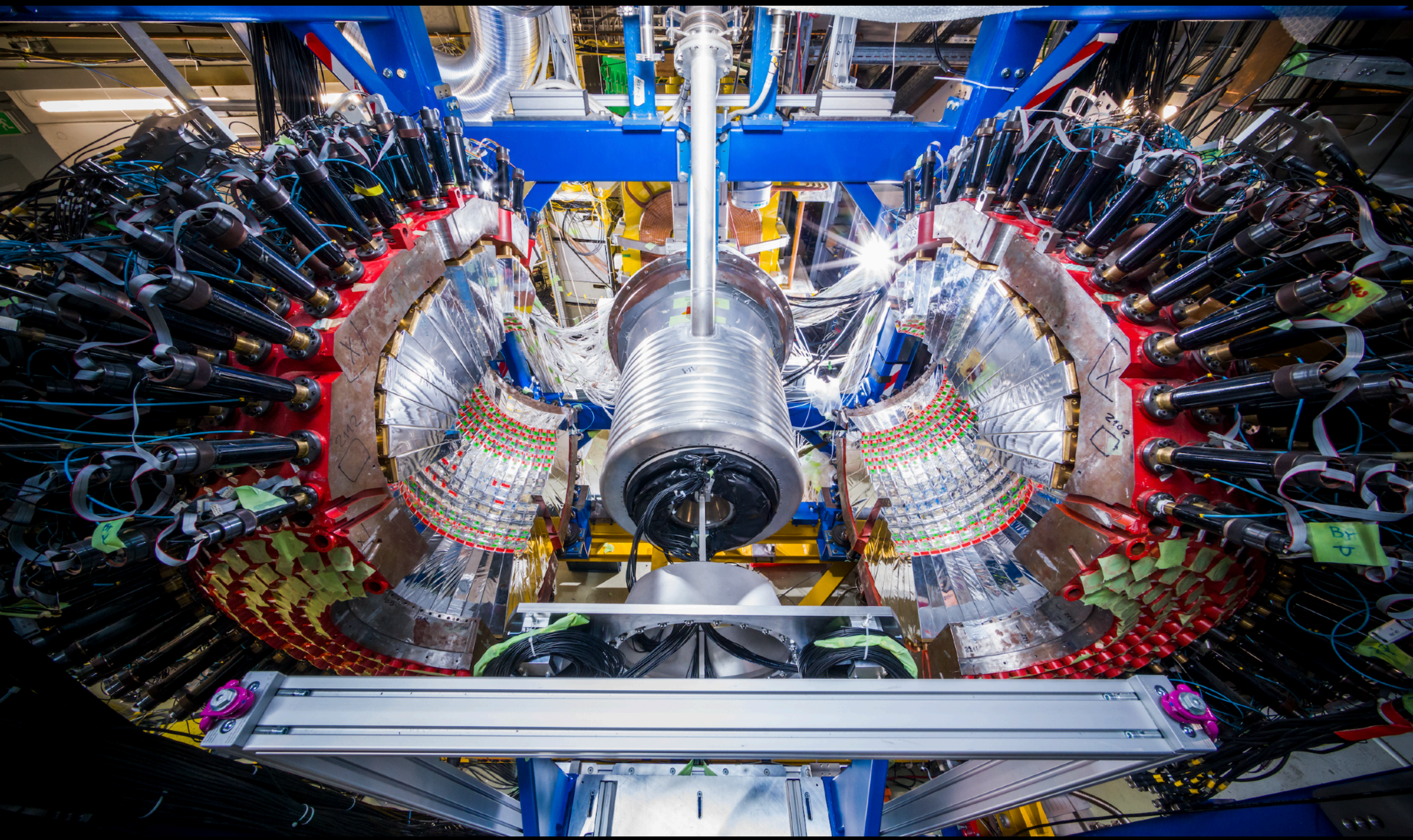
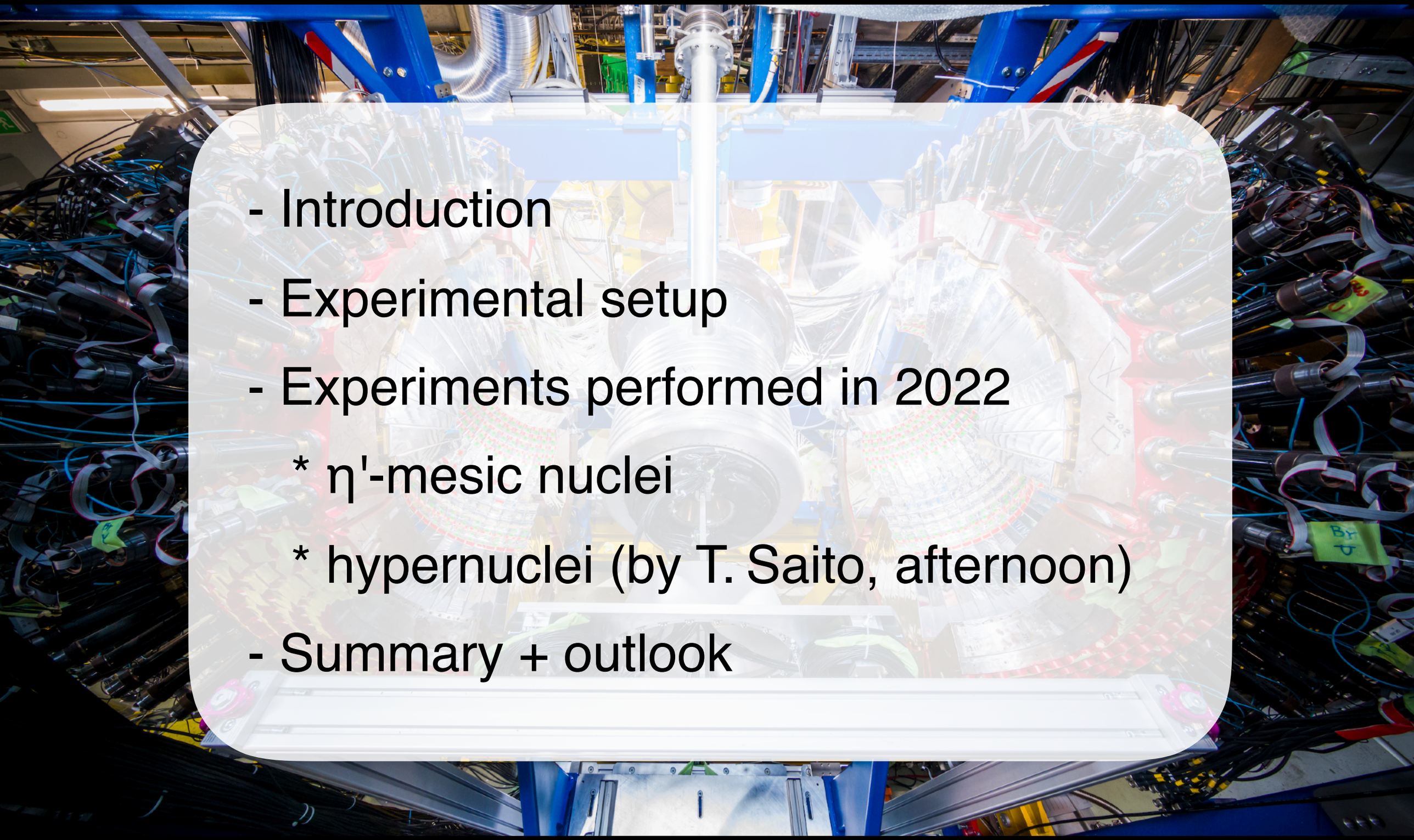


Photo by Jan Hosan

WASA-FRS Experiments at GSI (2022 Jan.-March)



- Introduction
- Experimental setup
- Experiments performed in 2022
  * η'-mesic nuclei
  * hypernuclei (by T. Saito, afternoon)
- Summary + outlook

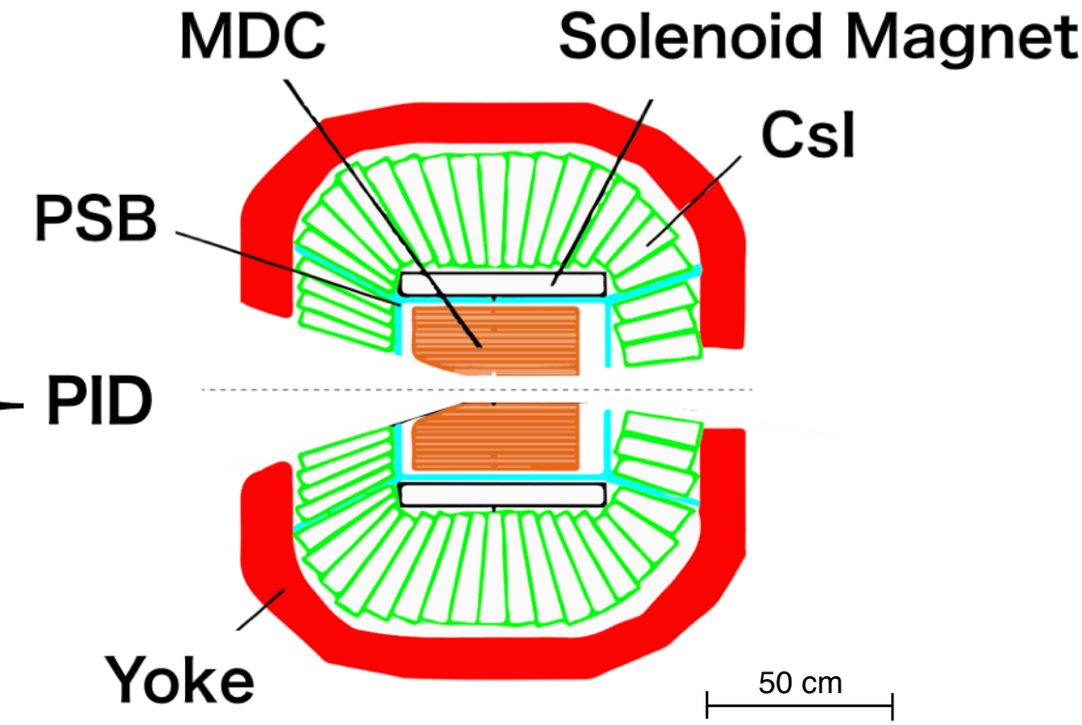
Photo by Jan Hosan

WASA (Wide-Angle Shower Apparatus)

WASA Central Detector

- ◇ Superconducting solenoid magnet (~1.3 T)
- ◇ Mini drift chamber (MDC) for tracking
- ◇ Plastic scintillator barrel (PSB) for ΔE,TOF
- ◇ CsI Electromagnetic calorimeter

PID



Operated at CELSIUS (Uppsala)
in 1999–2005

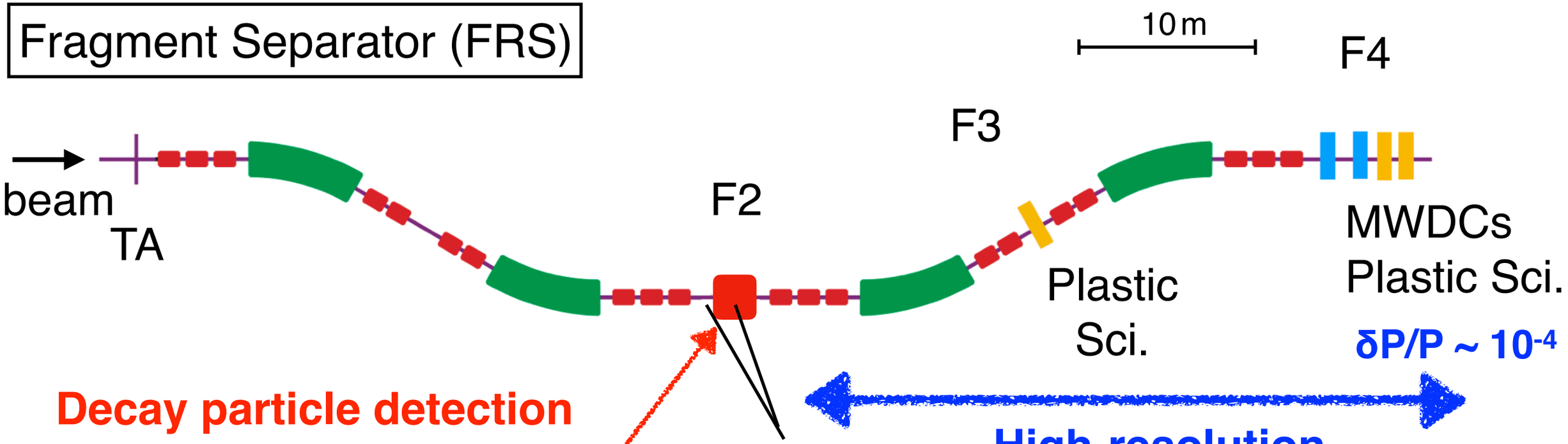
⬇

at COSY (Jülich) in 2006–2014

"internal experiment" with pellet target

WASA + FRS at GSI

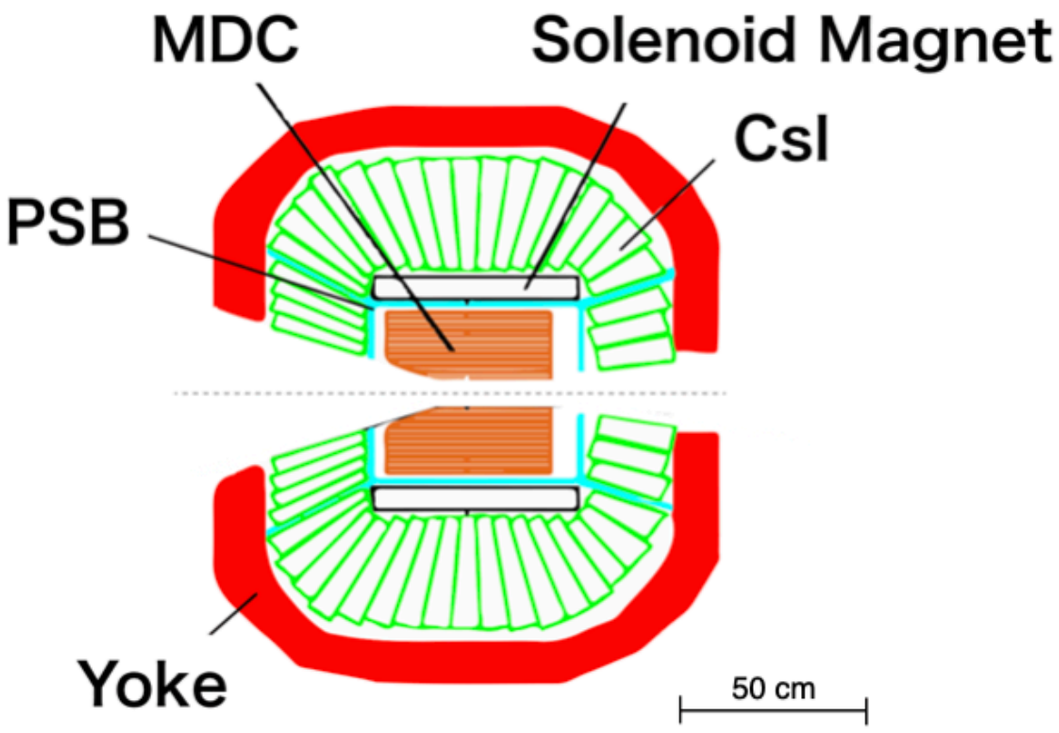
Fragment Separator (FRS)



Decay particle detection

High-resolution momentum analysis at 0°

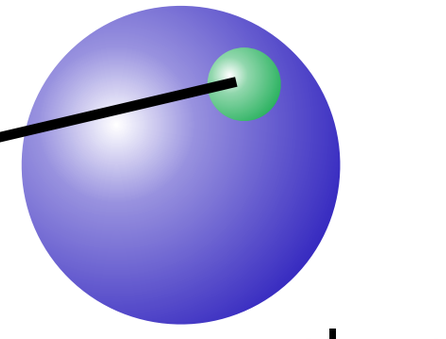
WASA central detector



◇ Meson (π, η, η' ...)
mesic nuclei

◇ Hyperon (Λ, ...)
hypernuclei

◇ Nucleon resonance (Δ, N*)

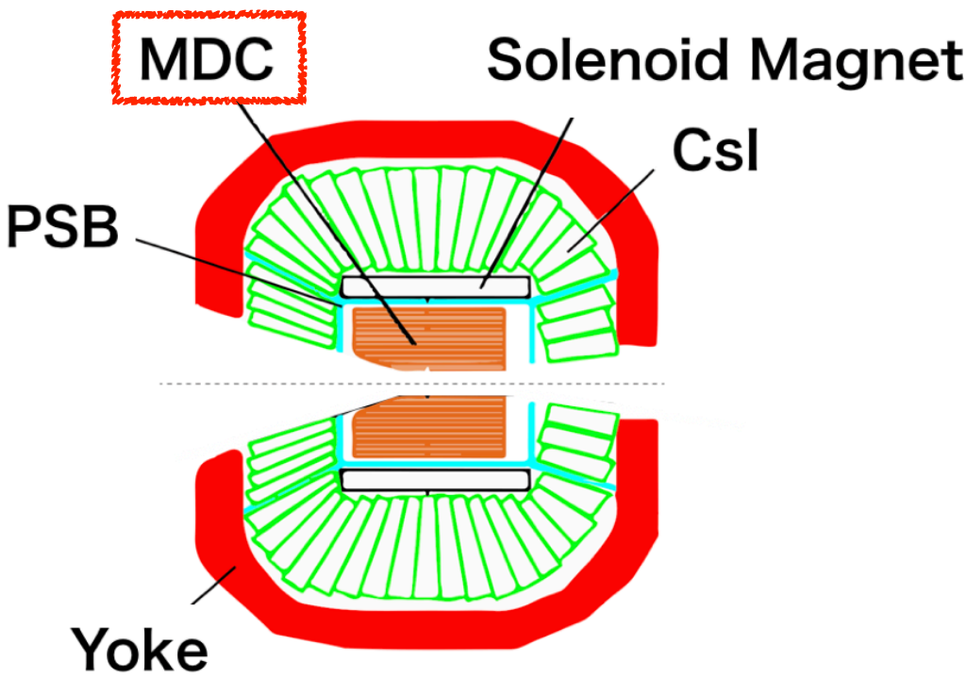


Super-FRS EC

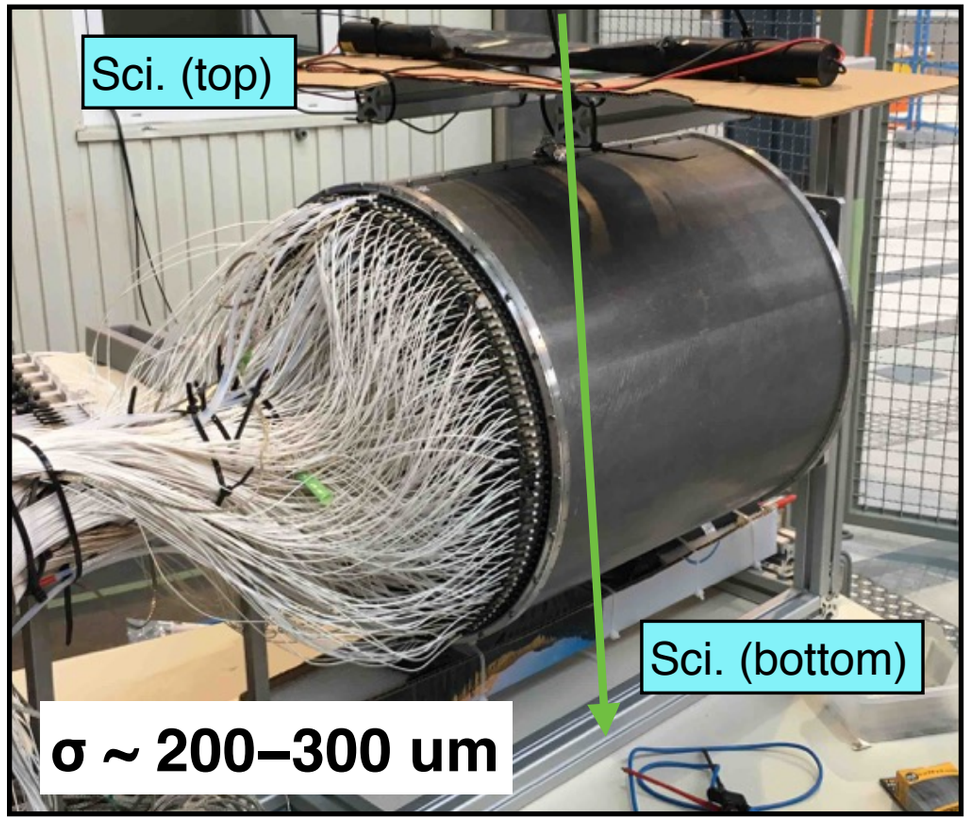
NUSTAR

MDC (Mini-Drift Chamber)

- ◇ Drift chambers base on straw tubes for charged particle tracking
- ◇ 17 cylindrical layers (9 layers parallel to z axis, 8 layers “stereo”), in total 1738 channels
- ◇ New readout electronics with GSI Clock-TDC



Offline test in 2018–2019



Y.K. Tanaka, V. Serdyuk, J.L.Rodiguez Sanchez,
K. Itahashi, S.Y. Matsumoto, T. R. Saito`

DAQ update with GSI Clock-TDC (2021)

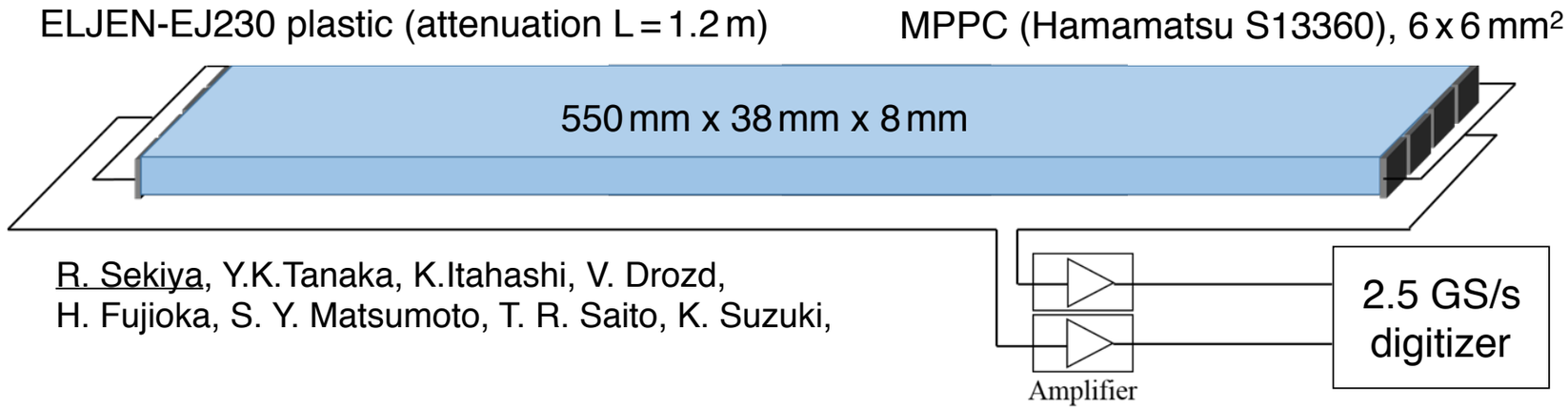
M. Nakagawa, E. Liu, H. Ekawa,
S. Escrig., S. Minami, N. Kurz, Y. Tanaka

PSB (Plastic Scintillator Barrel) + Endcap

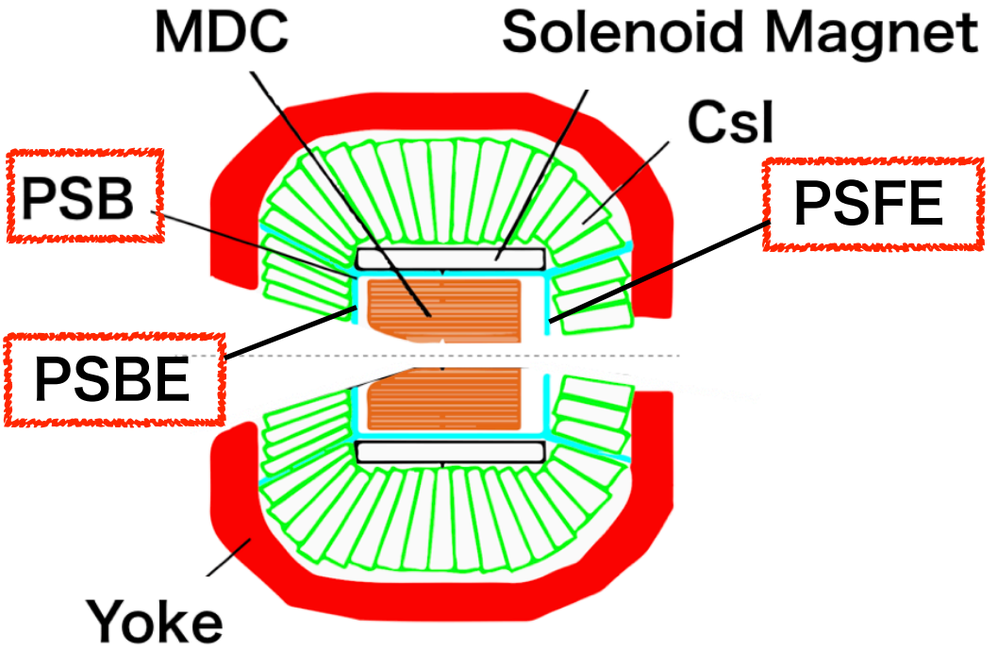
◇ Plastic scintillator for Timing and ΔE measurement

◇ Development of new PSB with MPPC(SiPM) readout for better time resolution σ(t) ~ 55–80 ps

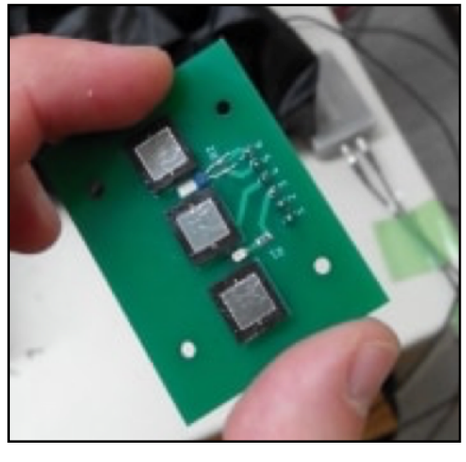
◇ Readout with TDC + QDC + 2.5GHz Waveform digitizer



R. Sekiya, Y.K.Tanaka, K.Itahashi, V. Drozd,
H. Fujioka, S. Y. Matsumoto, T. R. Saito, K. Suzuki,



MPPC board



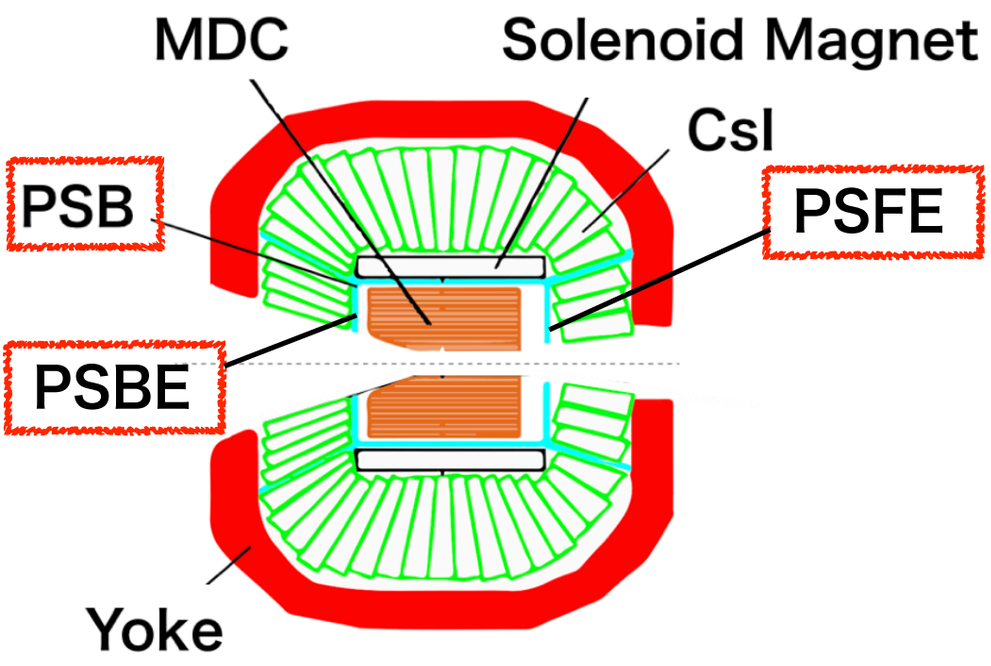
Amplifier

R. Sekiya, V. Drozd, Y.K. Tanaka et al.,
Nucl. Instr. Meth. A1034, 166745 (2022)

JSPS Kakenhi (Itahashi)

PSB (Plastic Scintillator Barrel) + Endcap

- ◇ Plastic scintillator for Timing and ΔE measurement
- ◇ Development of new PSB with MPPC(SiPM) readout for better time resolution σ(t) ~ 55–80 ps
- ◇ Readout with TDC + QDC + 2.5GHz Waveform digitizer

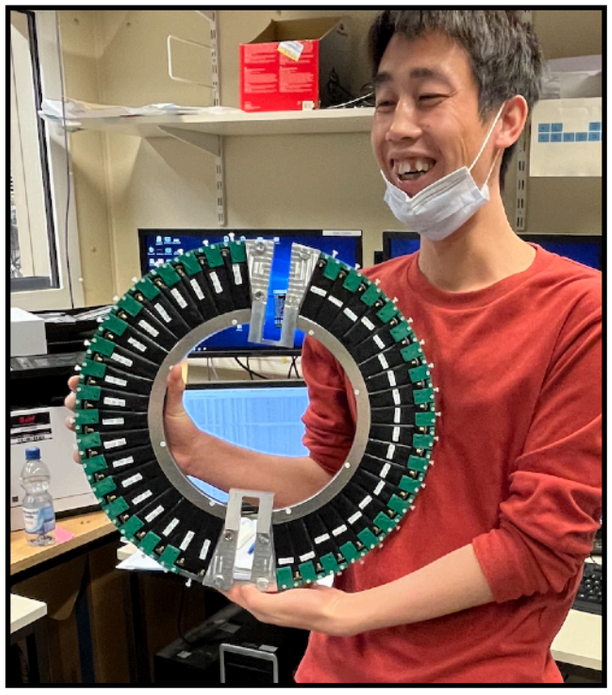


Constructed new PSB at RIKEN (2021)

R. Sekiya, V. Drozd, Y.K. Tanaka et al.,
Nucl. Instr. Meth. A1034, 166745 (2022)

JSPS Kakenhi (Itahashi)

PSFE/BE endcap



E. Liu, H. Ekawa, M. Nakagawa,
T.R. Saito, T. Weber
From HENP/RIKEN

CsI electromagnetic calorimeter

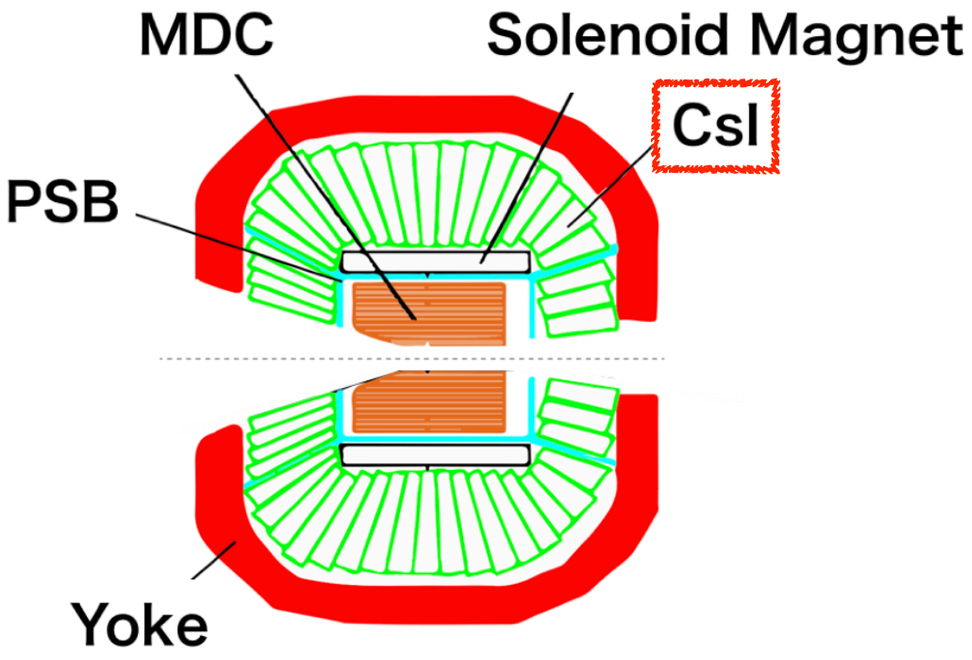
◇ CsI(Na) scintillator for TKE (charged particle) and Eγ measurement

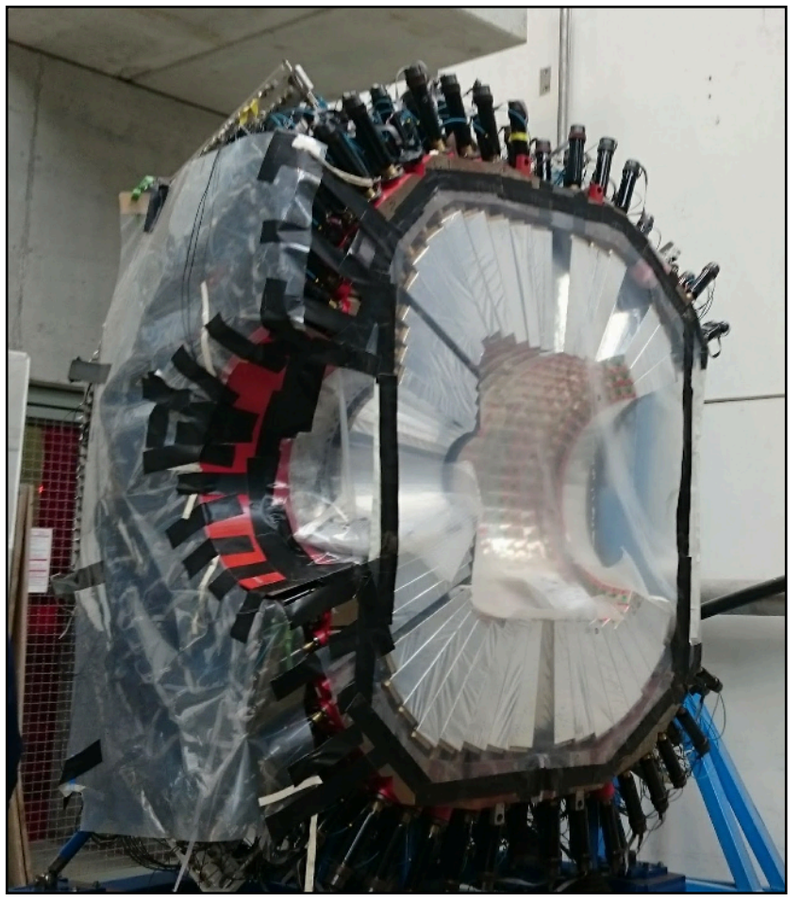
→ additional charged-particle PID
Reconstruction of neutral meson decay (π^0, η, η')

◇ 24 layers in θ and up to 48 segments in ϕ

◇ New readout system with 50MHz FADC (GSI-FEBEX3) for 800 channels

JSPS Kakenhi (Itahashi) + support from EE and NUSTAR collaboration





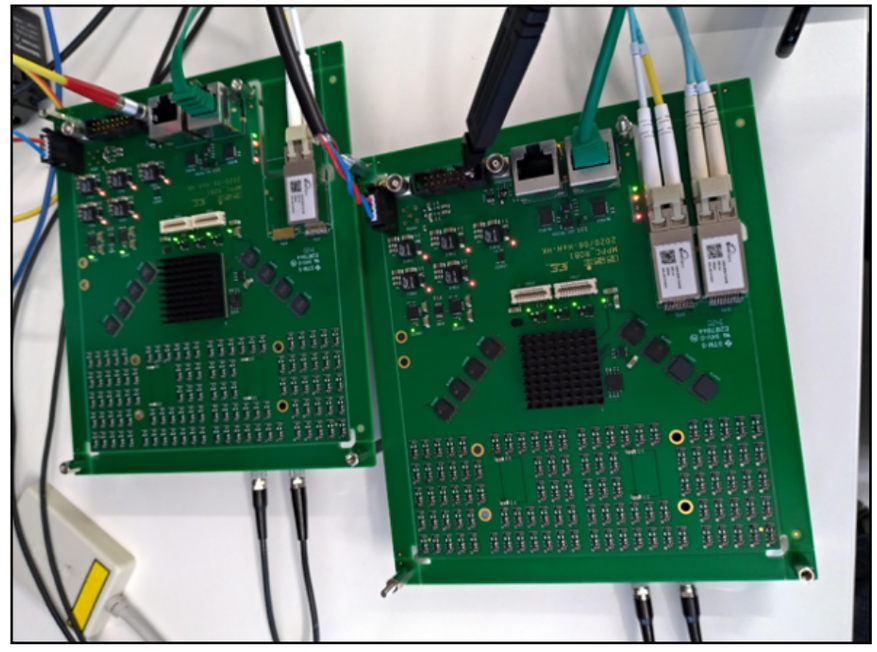
Scintillator Electromagnetic Calorimeter	
Amount of sensitive material	135 g/cm^2
[radiation lengths]	≈ 16
[nuclear interaction length]	≈ 0.8
Geometric acceptance:	96%
polar angle	≈ 20° – 169°
azimuth angle	≈ 0° – 360°
Max kinetic energy for stopping	
$\pi^{\pm}$/proton/deuteron	190/400/500
Scattering angle resolution	≈ 5°(FWHM)
Time resolution	
charged particles	5 ns(FWHM)
photons	≈40 ns(FWHM)
Energy resolution	
charged particles	≈ 3%(FWHM)
photons	≈ 8%(FWHM)

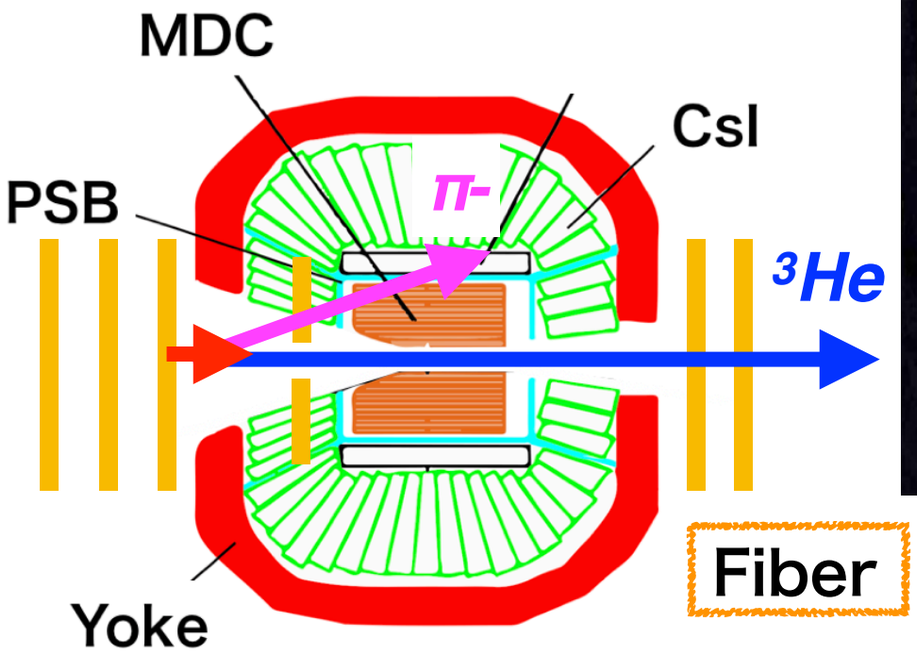
Table from WASA-at-COSY proposal

Fiber tracking detector

◇ Fiber tracker for vertex reconstruction in Hypernuclei experiment (HypHI)
  * 0.5 mm pitch * readout by MPPC array (Hamamtsu S13361)

◇ Newly designed readout board (amplifier + TDC)





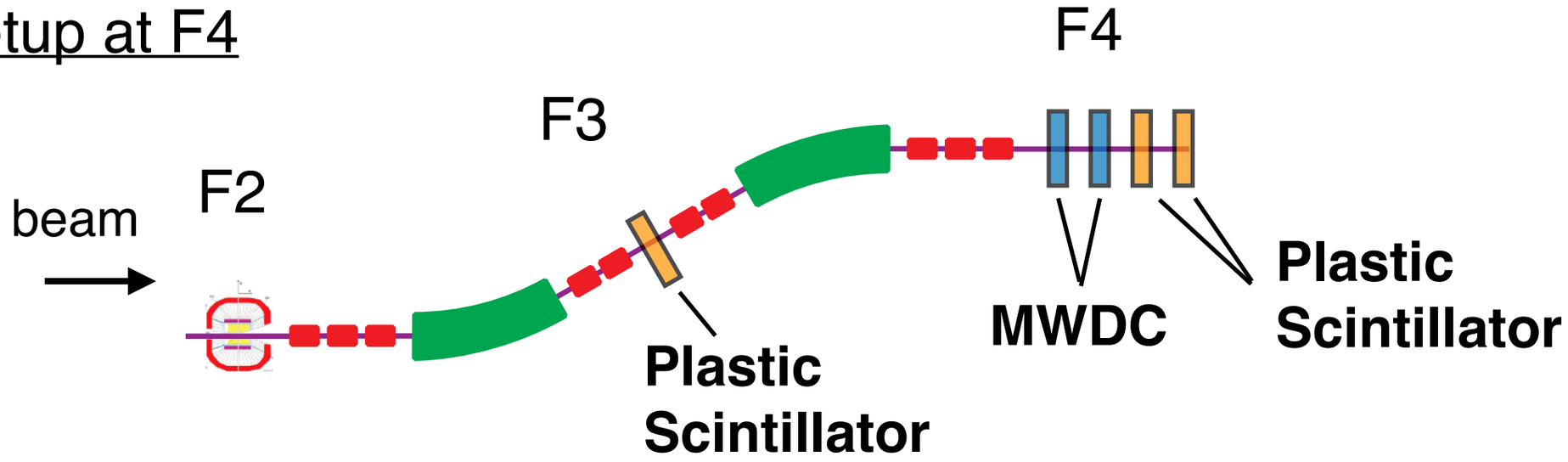
EE Department
N. Kurz, H. Heggen, S. Minami

from RIKEN and Univ. Osaka

H. Ekawa, M. Nakagawa, E. Liu
V. Drozd, S. Escrig, T. Saito,

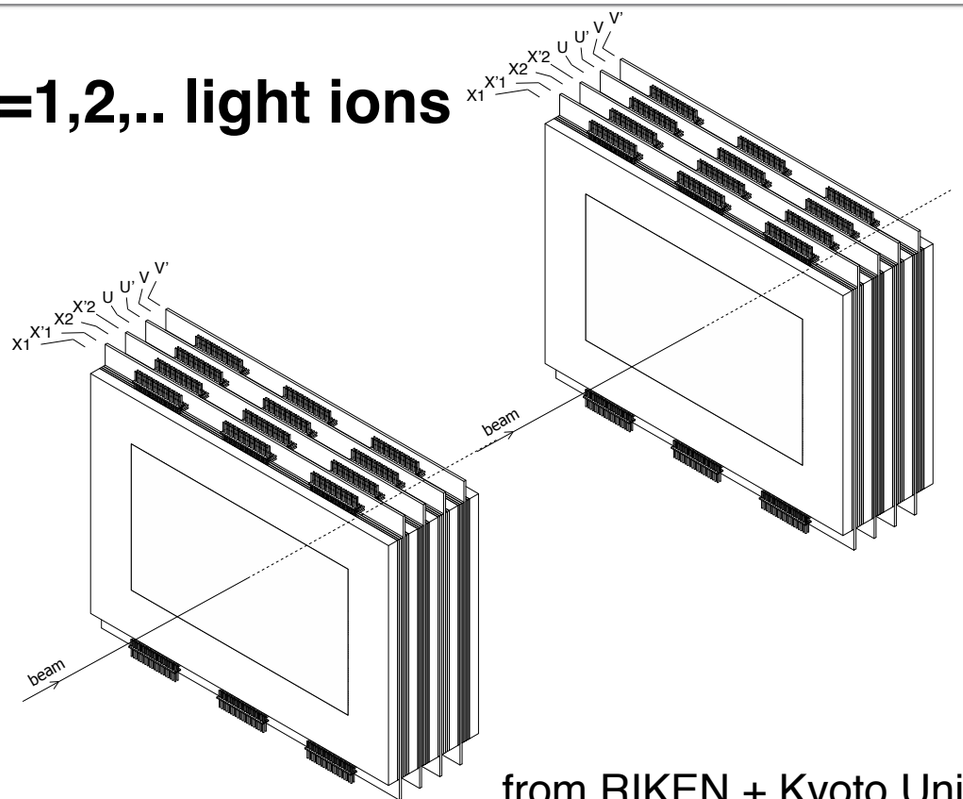
FRS-F4 detectors for WASA experiments

Detector setup at F4



Multi-Wire Drift Chamber (MWDC)

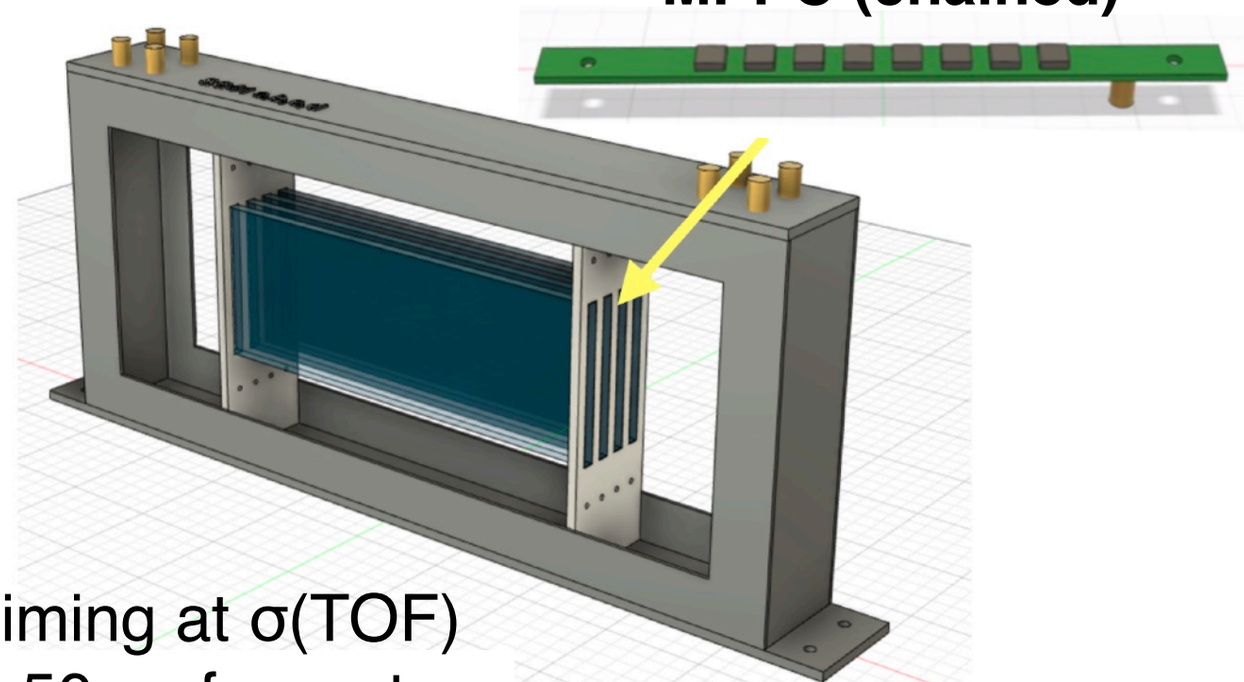
for Z=1,2,.. light ions



from RIKEN + Kyoto Univ.

Plastic at F4 (stacked scintillator)

MPPC (chained)



aiming at σ(TOF)
< 50 ps for proton

JSPS Kakenhi, Tanaka

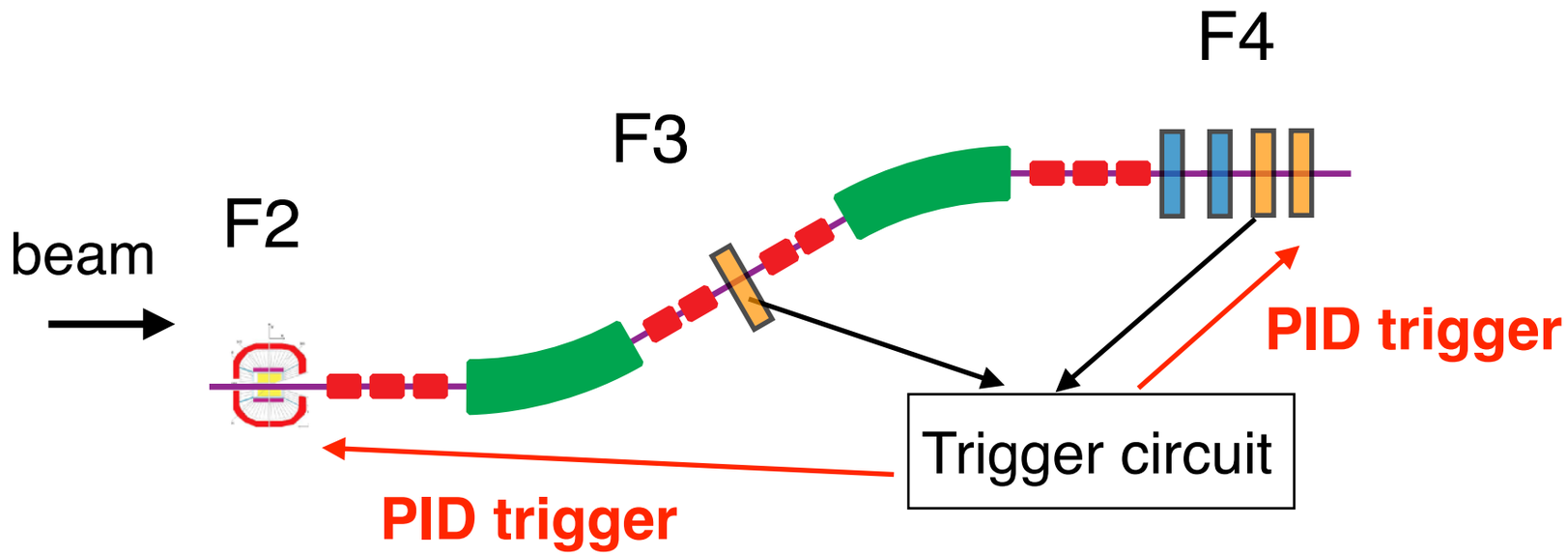
DAQ Trigger for WASA-FRS

Clean PID trigger from FRS-F3/F4

◇ Bρ is selected by FRS within 2% → Bρ selection

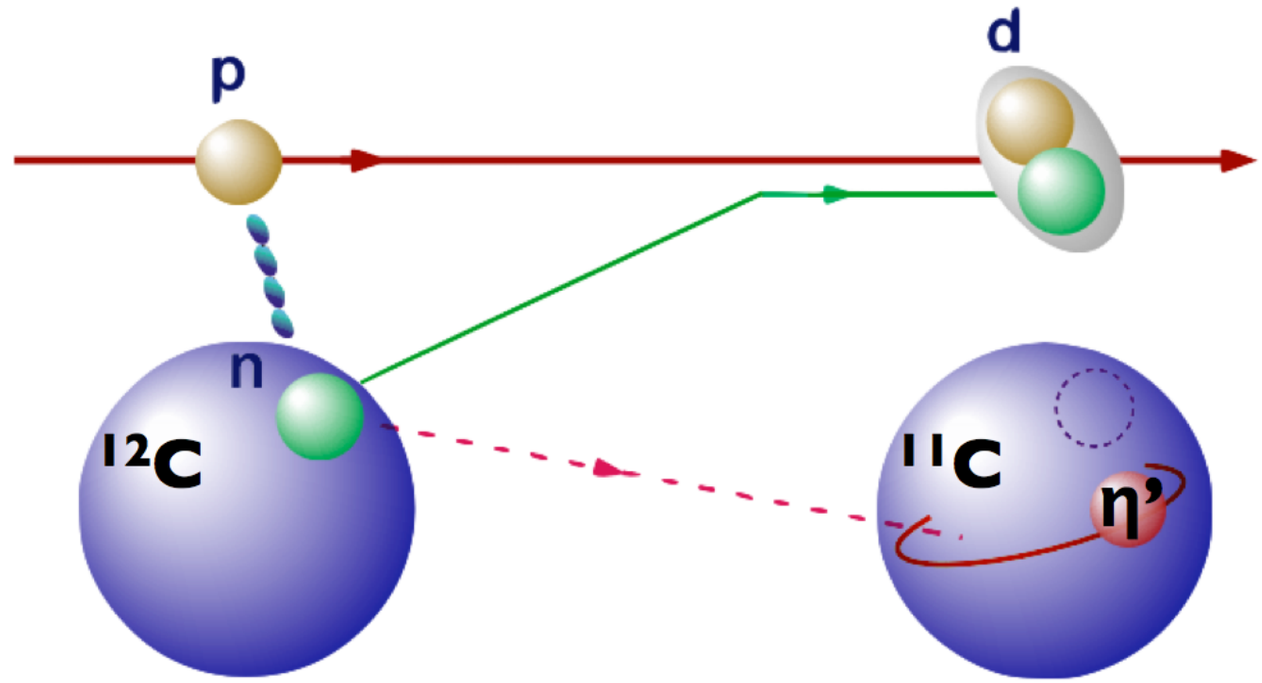
◇ TOF-based F3-F4 coincidence on hardware → A/Q selection

◇ ΔE selection with Plastic scintillators → Z selection



WASA detectors are exposed to very high rate,
but trigger is very clean with well-defined timing

η'-mesic nuclei spectroscopy



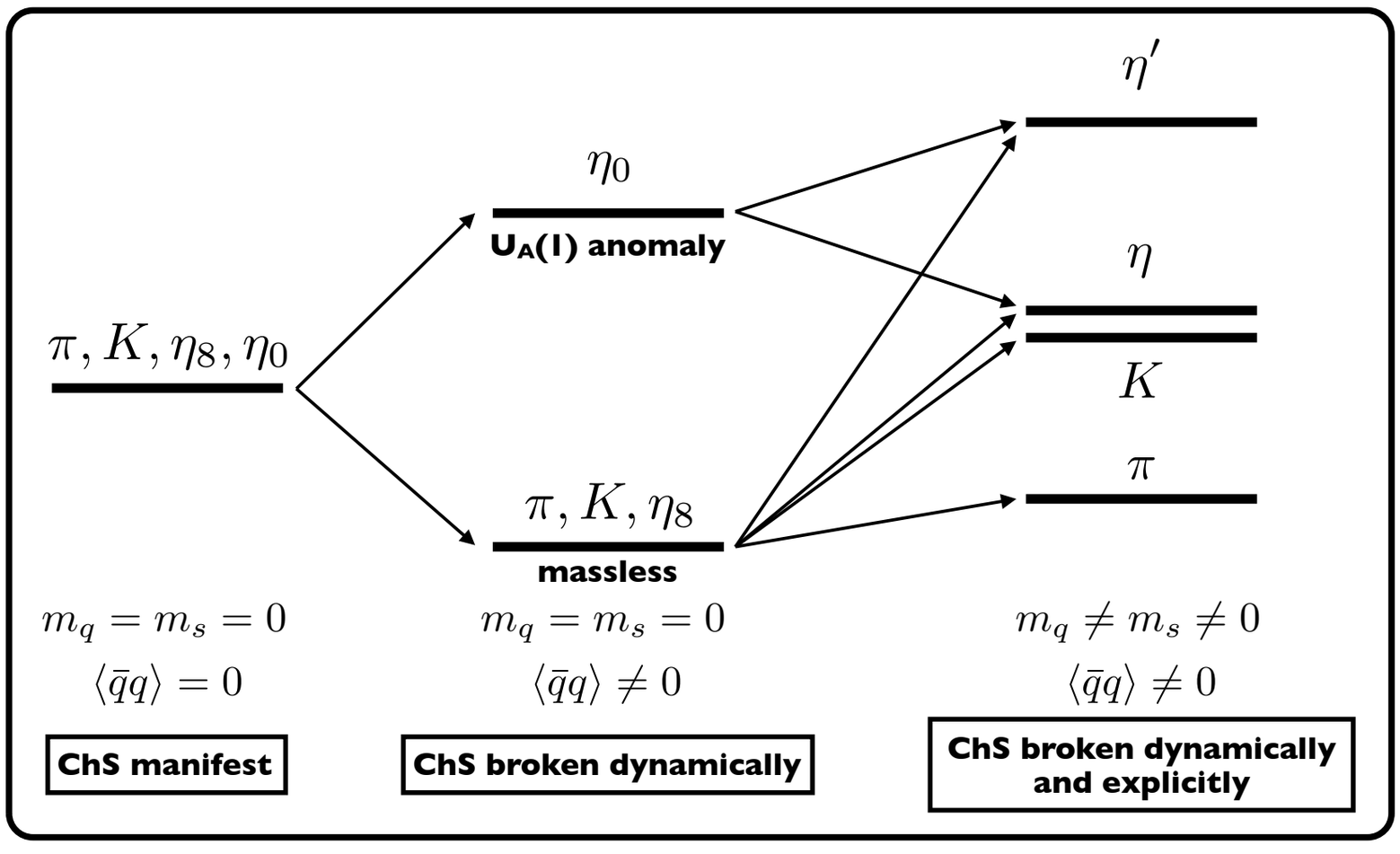
RIKEN GSI PRiME Super-FRS EC

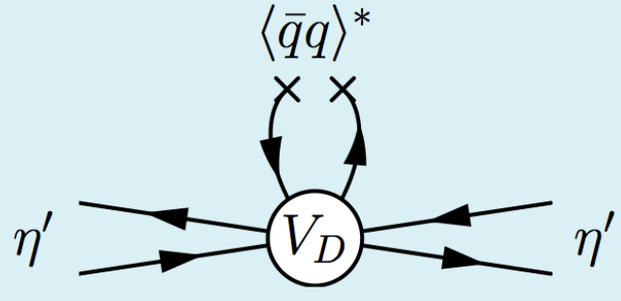
η' meson

η′ meson in vacuum

η'

- Mass = 958 MeV/c^2 (especially large), Width : 0.2 MeV, $J^P = 0^-$
- $U_A(1)$ anomaly and spontaneous breaking of chiral symmetry





$U_A(1)$ anomaly contributes η' mass through ChSB

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

D. Jido, H. Nagahiro, S. Hirenzaki, PRC 85, 032201 (2012).

η' meson

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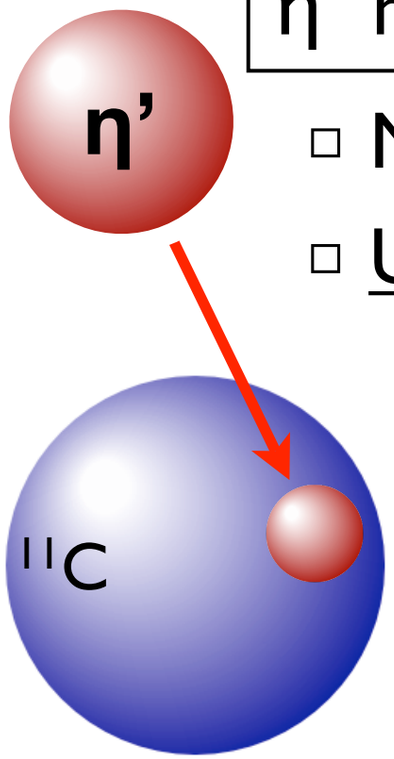
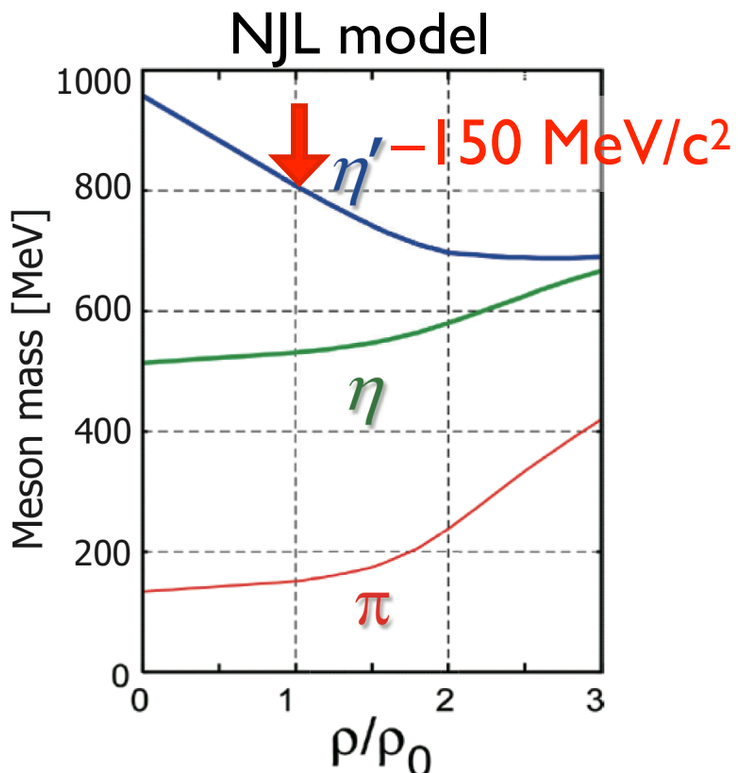
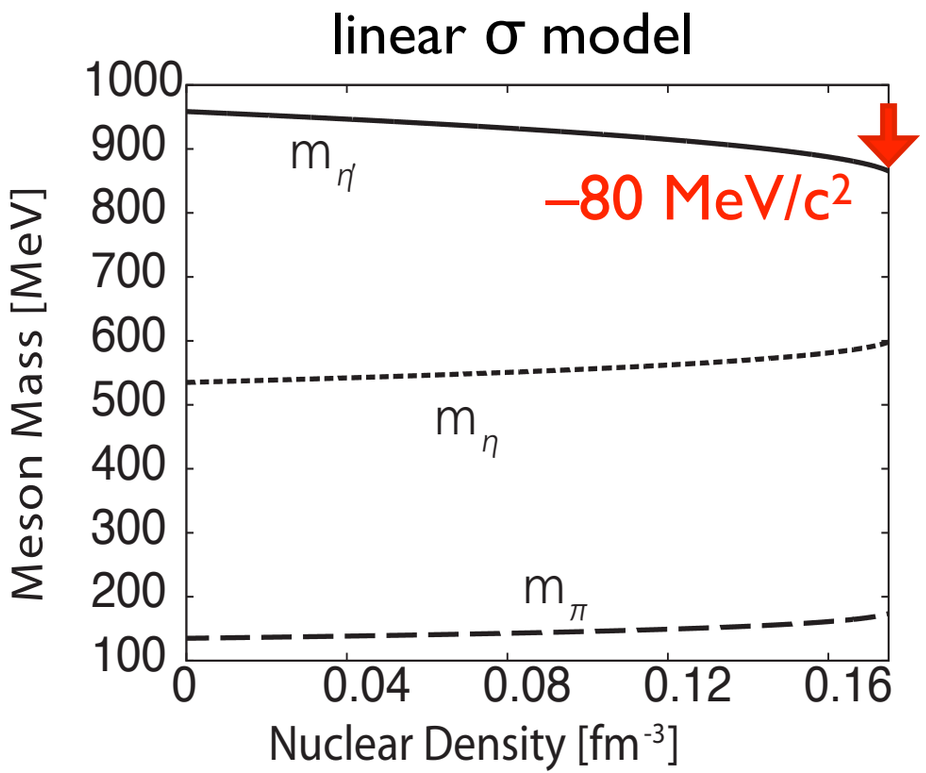


η′ meson at nuclear density

- Partial restoration of chiral symmetry ($\langle \bar{q}q \rangle$ reduced ~ 30%)
- Mass reduction is expected

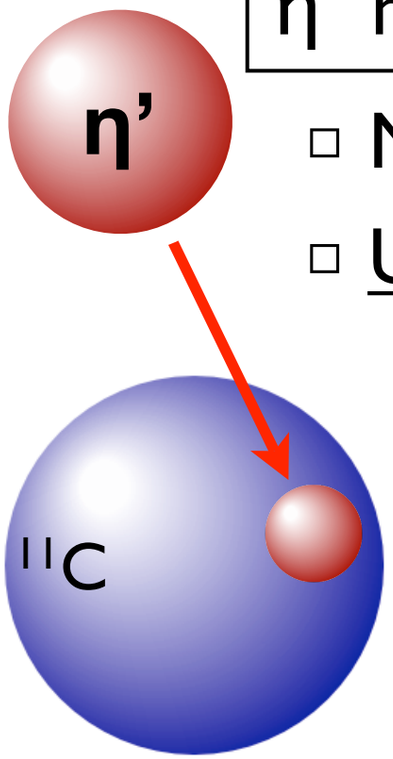




QMC model :
$\Delta m \sim -37$ MeV/c^2
(for $\theta_{\eta\eta'} = -20°$)

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

η' meson



η′ meson in vacuum

- Mass = 958 MeV/c^2 (especially large), Width : 0.2 MeV, $J^P = 0^-$
- $U_A(1)$ anomaly and spontaneous breaking of chiral symmetry

η′ meson at nuclear density

- Partial restoration of chiral symmetry ($\langle \bar{q}q \rangle$ reduced ~ 30%)
- Mass reduction is expected

↓

Attractive potential

↓

Bound states (mesic-nuclei)

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

direct probe for studying meson properties in medium

η′-nucleus potential

η′-nucleus optical potential : $V_{\eta'} = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$

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

Theoretical predictions

$\Delta m(\rho_0) \sim -150$ MeV/c^2 (NJL), -80 MeV/c^2 (linear σ), -37 MeV/c^2 (QMC)

H. Nagahiro *et al.*, PRC 74, 045203(2006).
S. Sakai, D. Jido, PRC 88, 064906 (2013).
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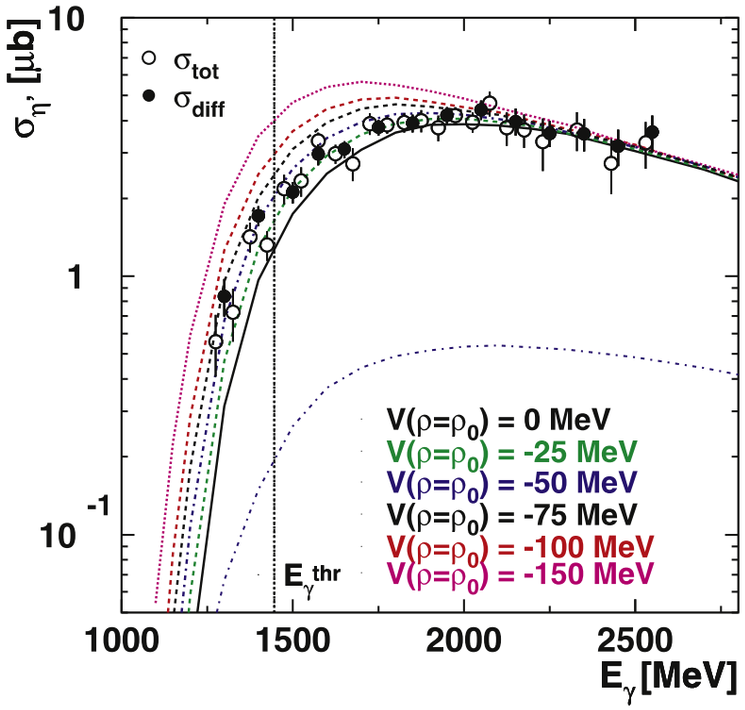
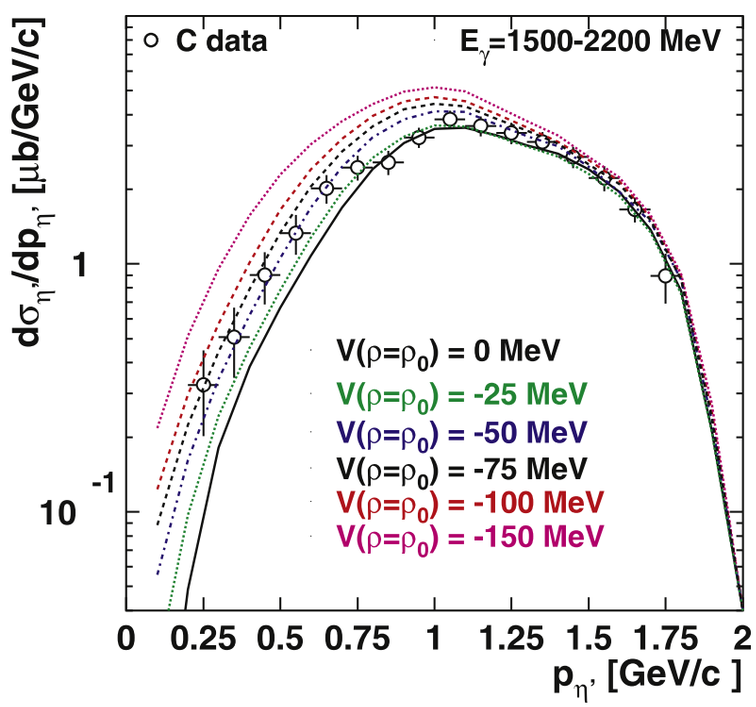
Experimental indications (CBELSA/TAPS)

- $V_0 \sim -40$ MeV (excitation function, mom. distribution)





M. Nanova *et al.*, PRC 94 025205 (2016).
M. Nanova *et al.*, PLB 727, 417 (2013).

η′ photo-production off C target

η′-nucleus potential

η′-nucleus optical potential : $V_{\eta'} = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$

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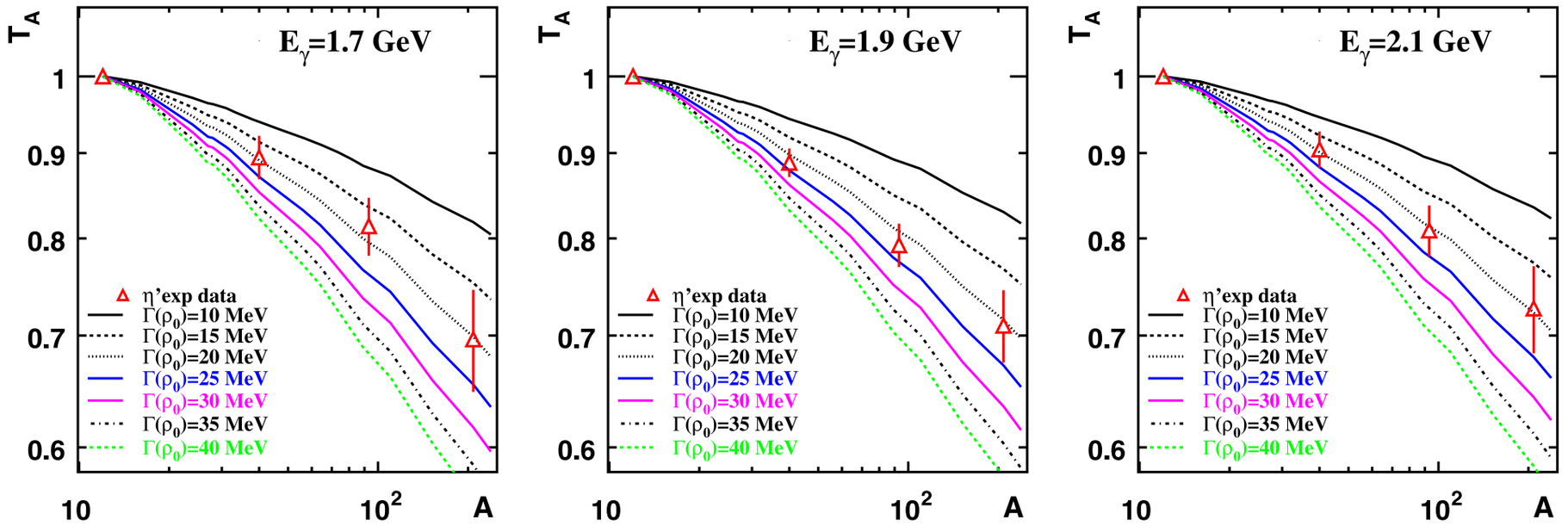
Experimental indications (CBELSA/TAPS)

- $V_0 \sim -40$ MeV (excitation function, mom. distribution)
- $W_0 = -13 \pm 3(\text{stat}) \pm 3(\text{syst})$ MeV (transparency ratio)



M. Nanova *et al.*, PLB 710, 600 (2012).

S. Friedrich *et al.*, EPJA 52, 297 (2016).

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η′-*p* scattering length by COSY-11 E. Czerwiński et al., PRL 113, 062004 (2014)

- $\mathrm{Re}(a_{\eta' p}) = 0 \pm 0.43$ fm, $\mathrm{Im}(a_{\eta' p}) = 0.37^{+0.40}_{-0.16}$ fm

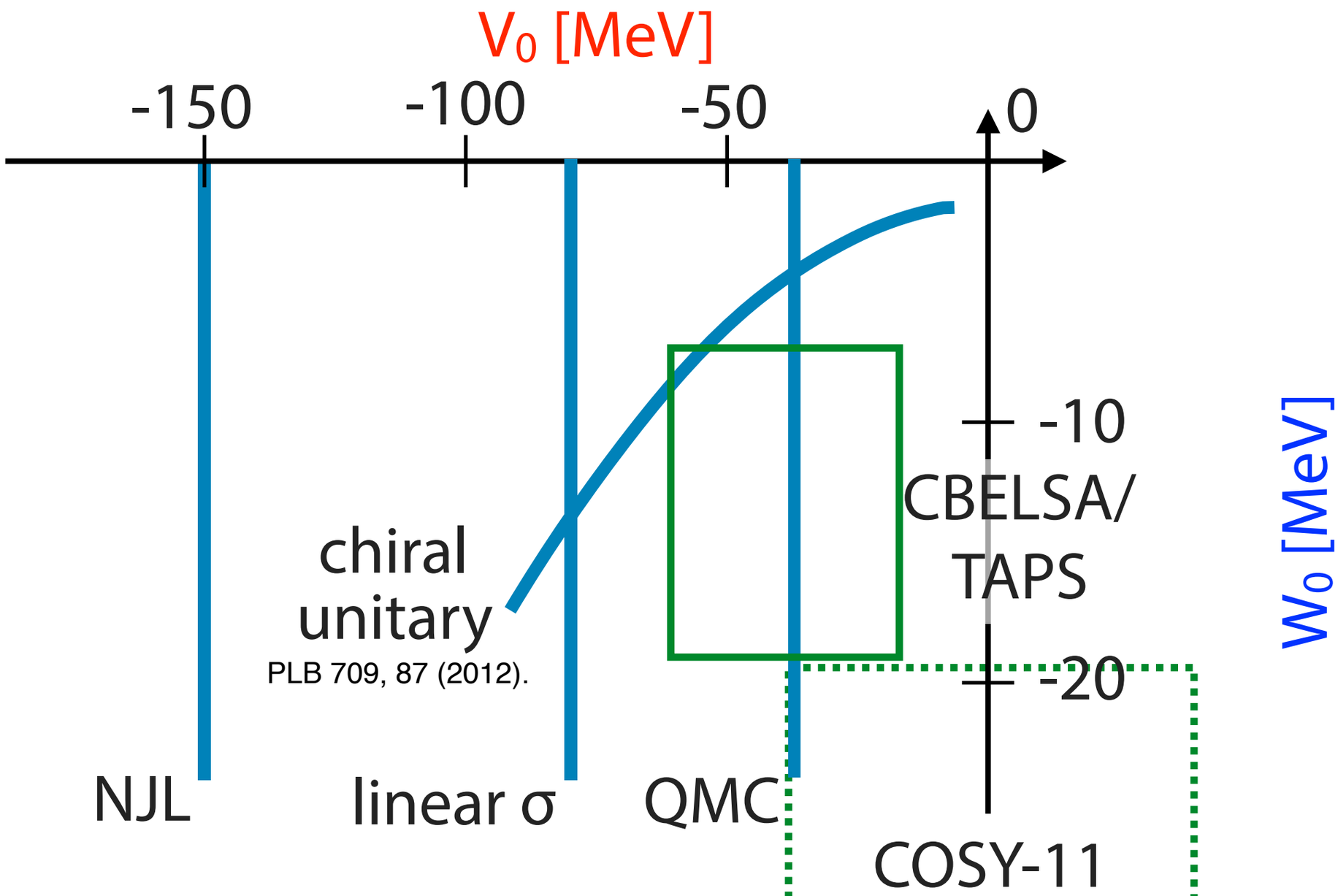
  → $|V_0| < 38$ MeV, $W_0 = -(33^{+40}_{-14})$ MeV (low density approx.)

η′-nucleus potential

η′-nucleus optical potential :

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

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



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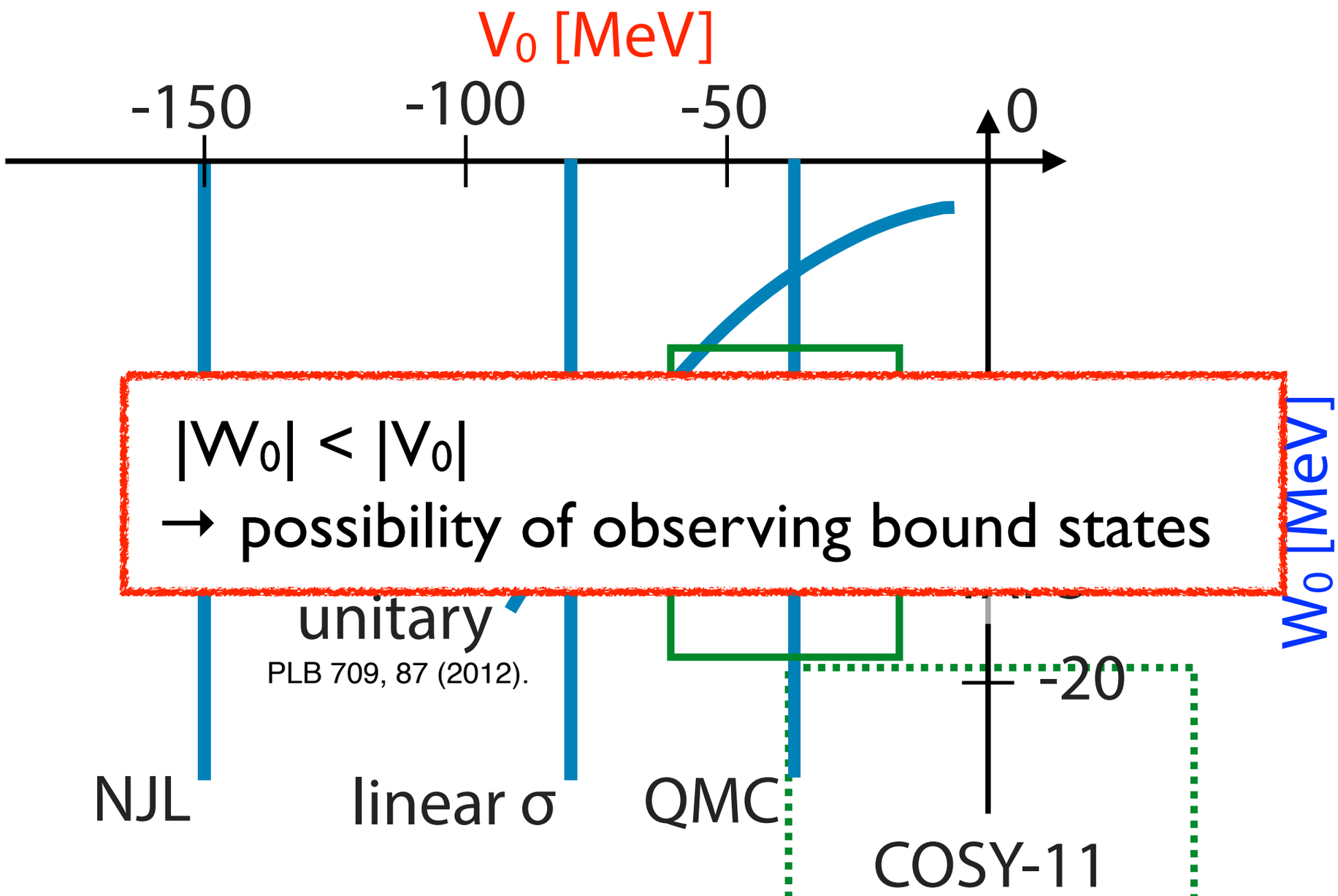
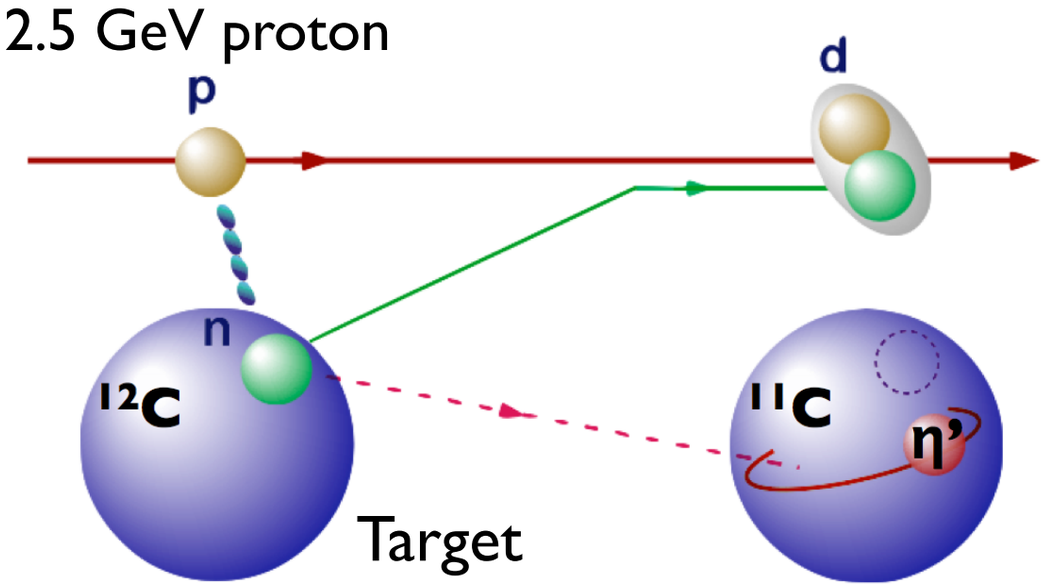


η'-mesic nuclei spectroscopy (1st experiment, 2014)

Missing-mass spectroscopy of $^{12}C(p,d)$ reaction



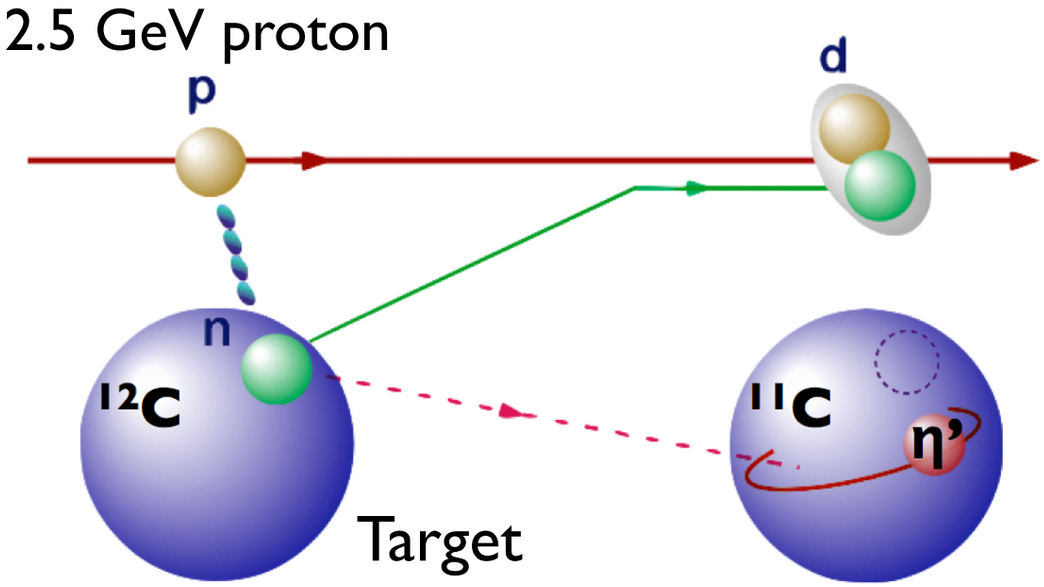
Momentum measurement (FRS)

⬇

Excitation energy

η'-mesic nuclei spectroscopy (1st experiment, 2014)

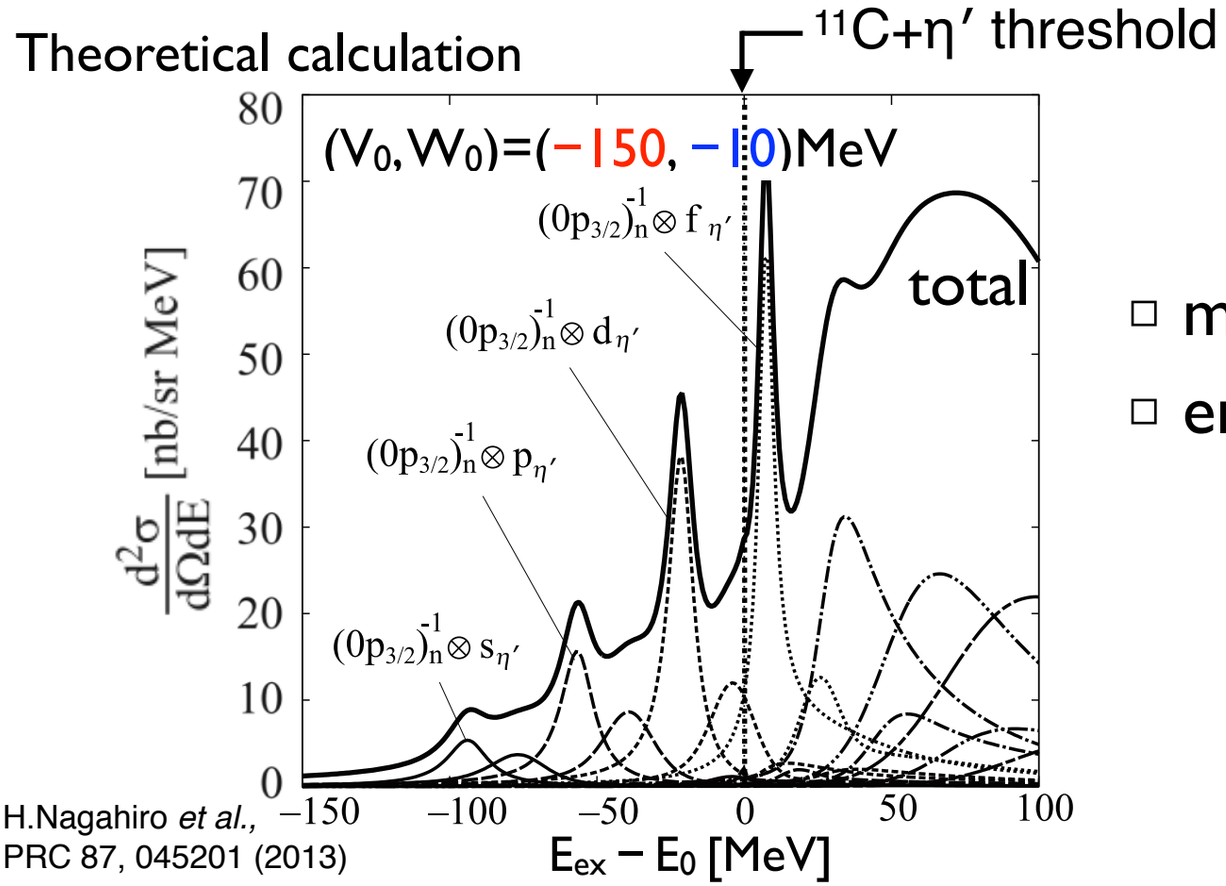
Missing-mass spectroscopy of $^{12}C(p,d)$ reaction



Momentum measurement (FRS)

⬇

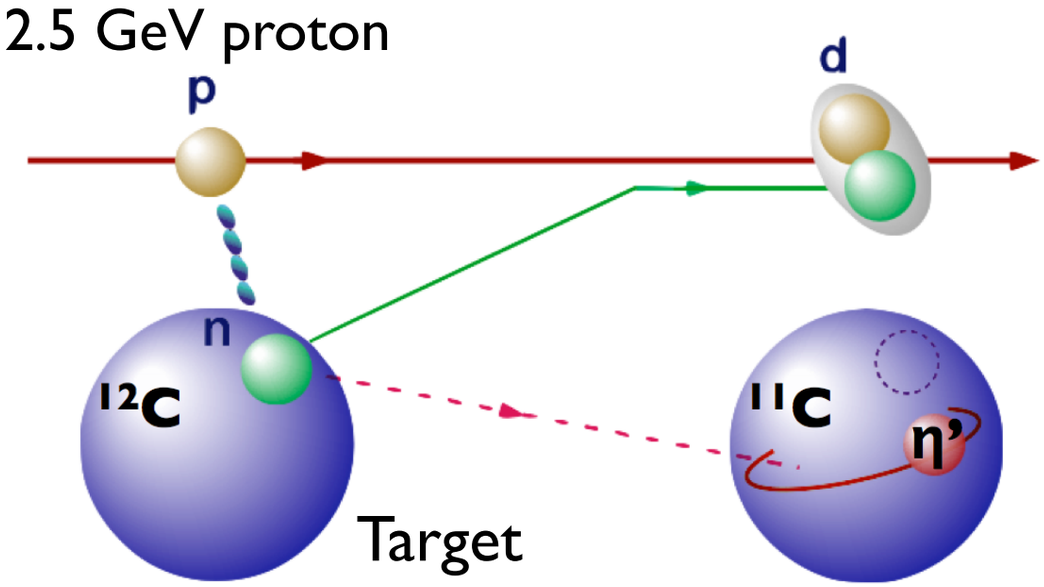
Excitation energy



- momentum transfer ~ 400 MeV/c
- enhanced excited states near threshold

η'-mesic nuclei spectroscopy (1st experiment, 2014)

Missing-mass spectroscopy of $^{12}C(p,d)$ reaction

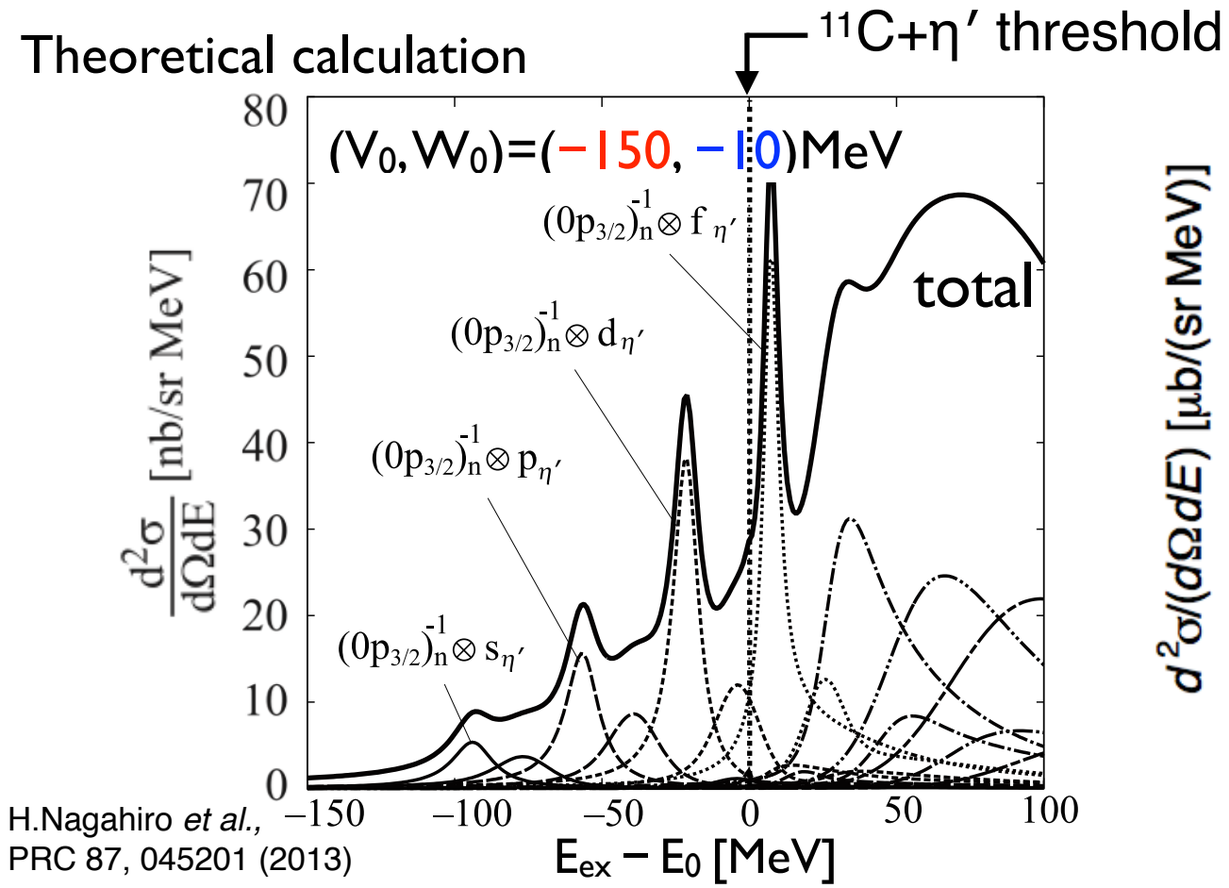


Momentum measurement (FRS)

⬇

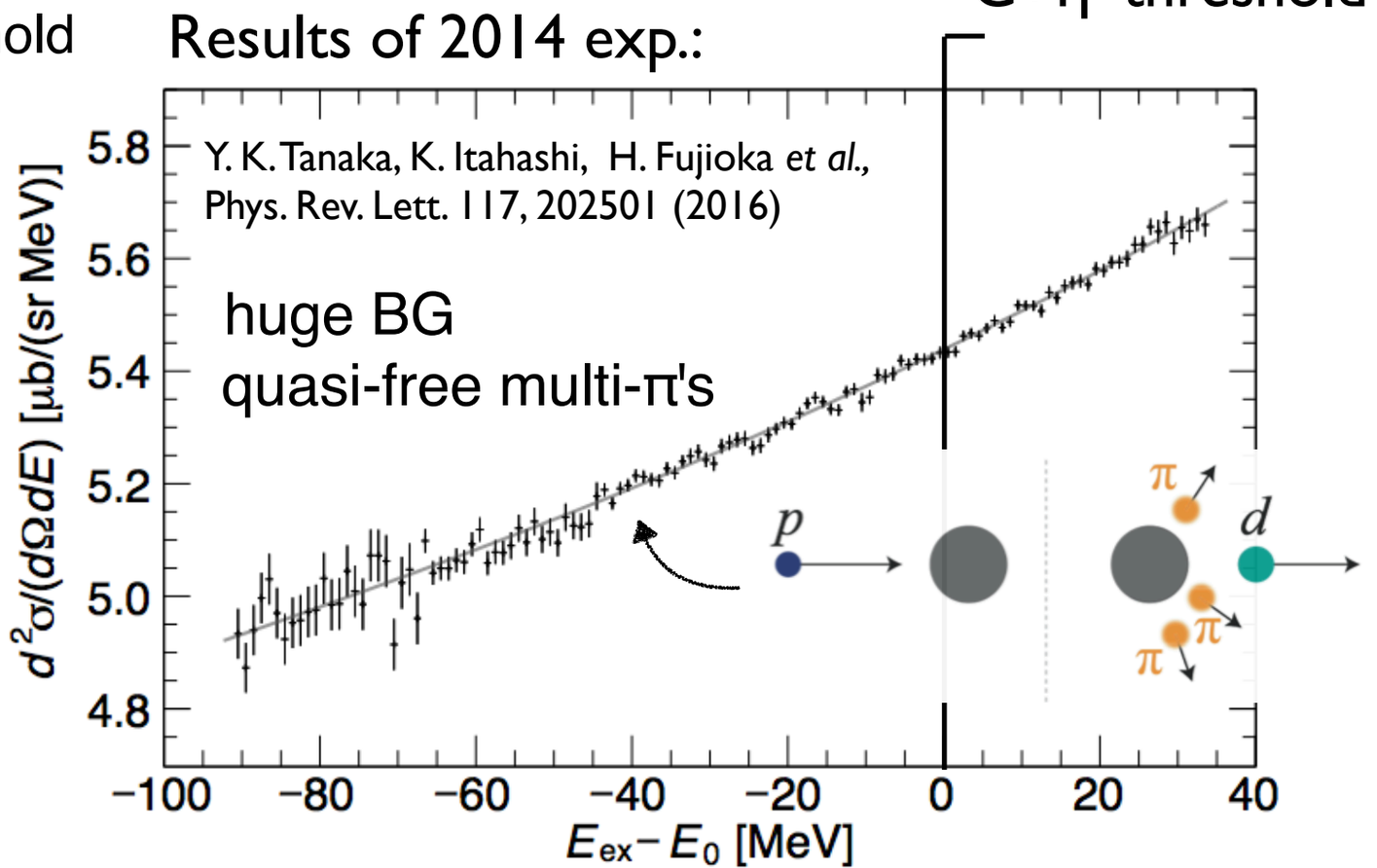
Excitation energy

Theoretical calculation



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

Results of 2014 exp.:



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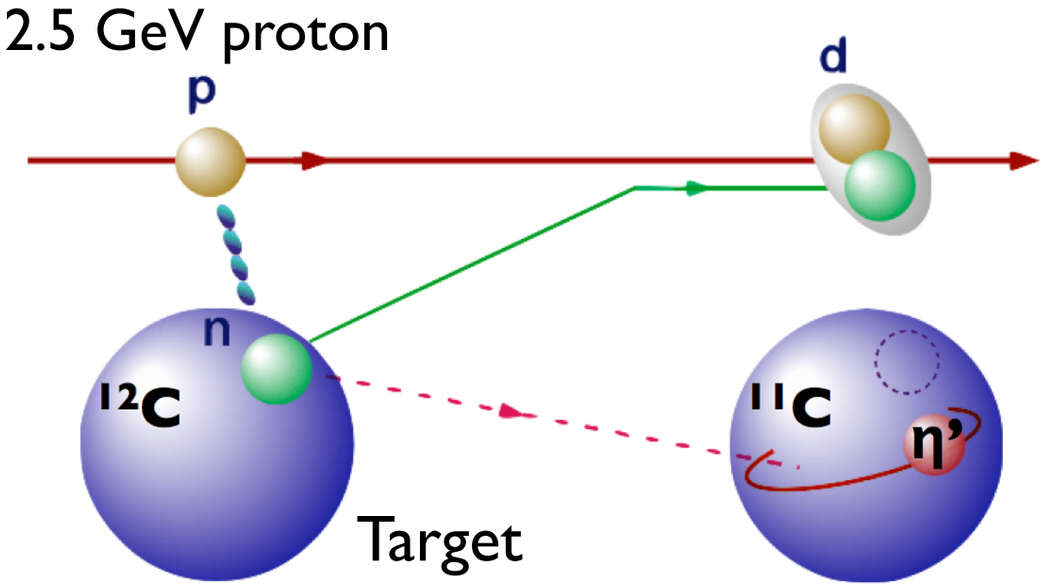
Missing-mass spectroscopy of $^{12}C(p,d)$ reaction

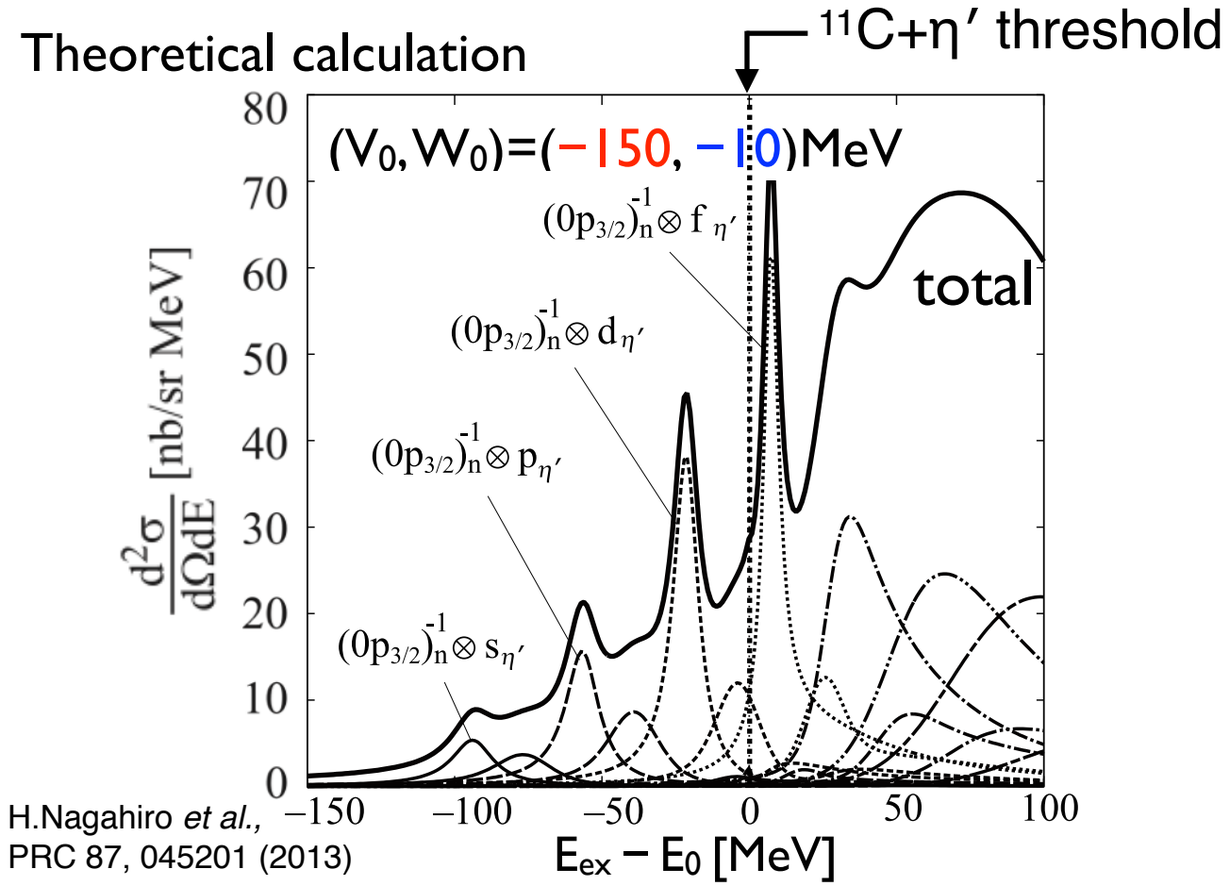


Momentum measurement (FRS)

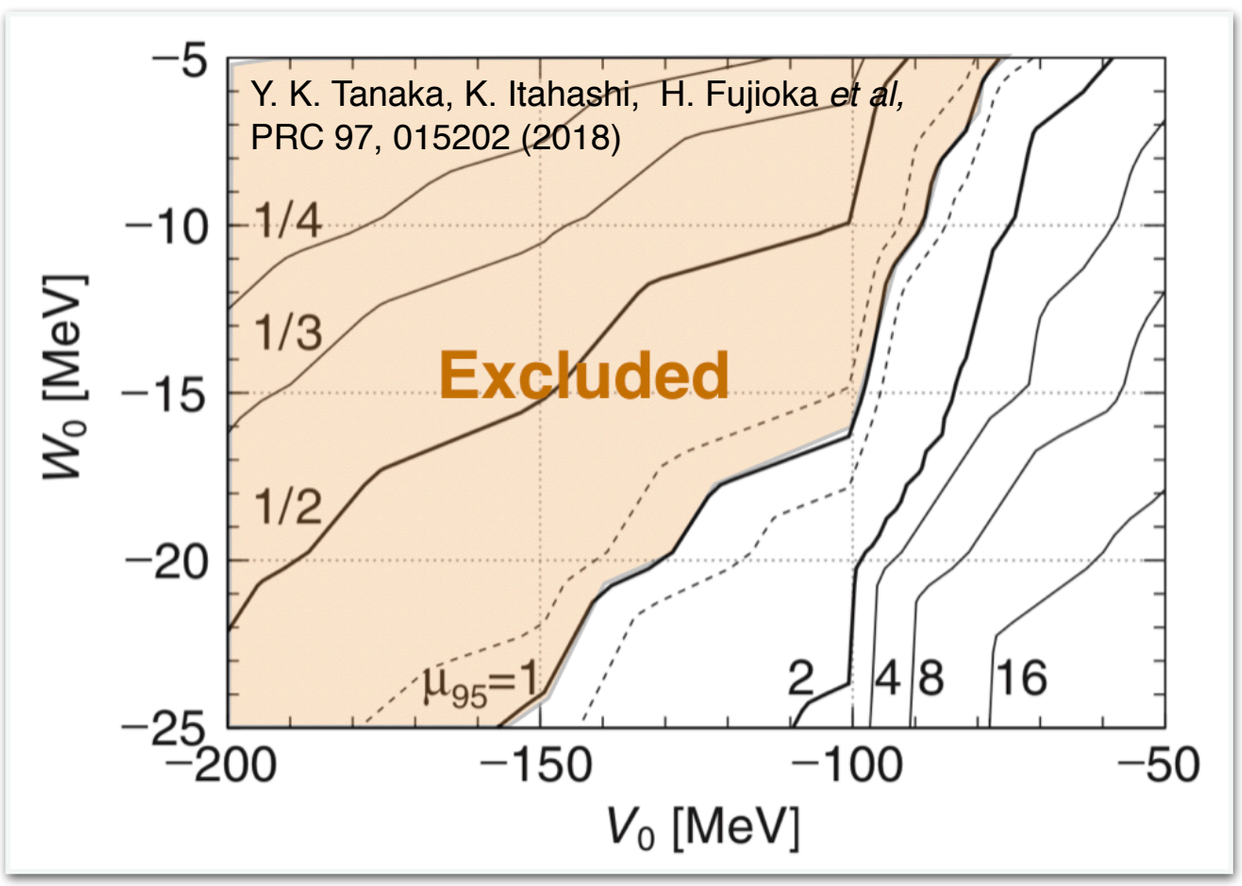
⬇

Excitation energy

Theoretical calculation



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



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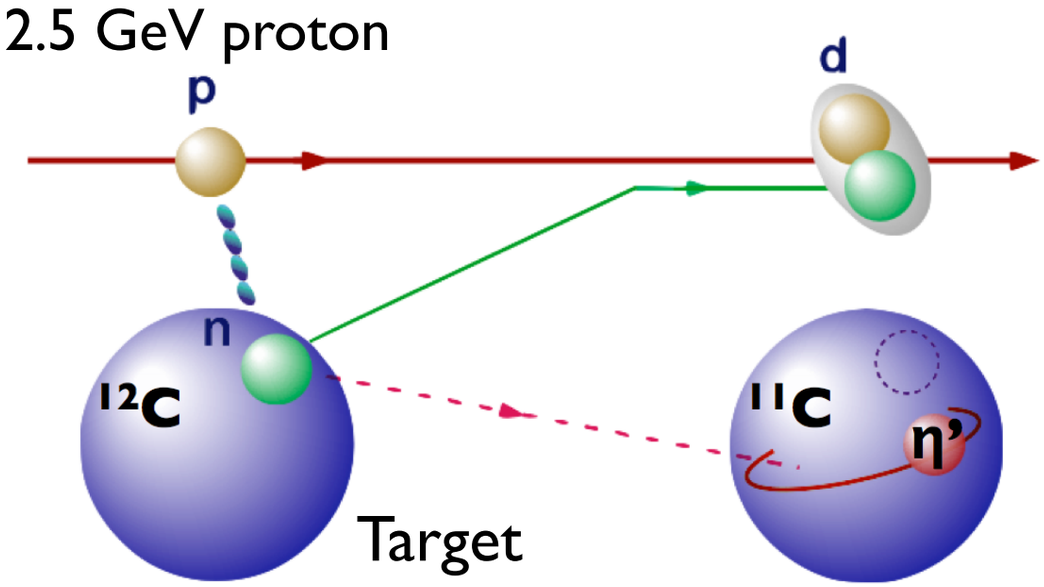

Momentum measurement (FRS)

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Excitation energy

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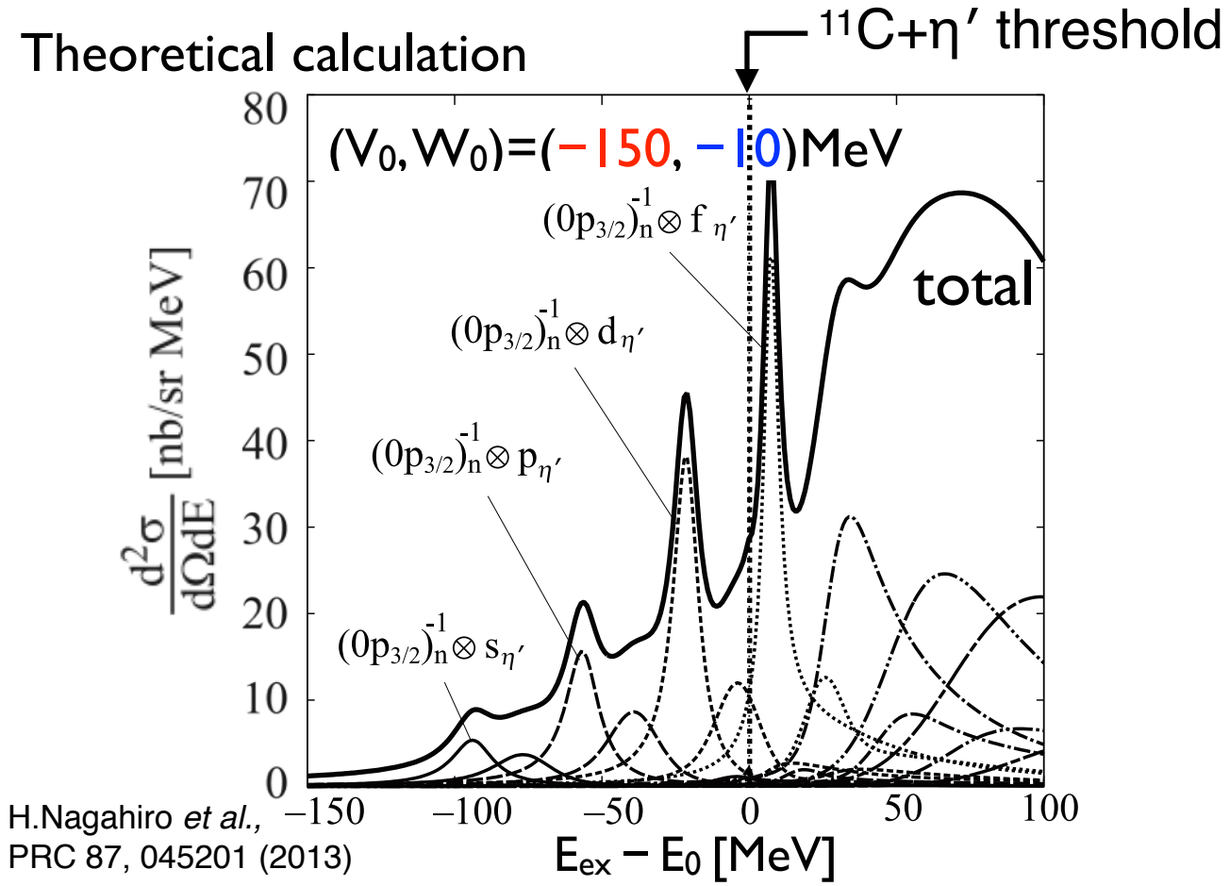
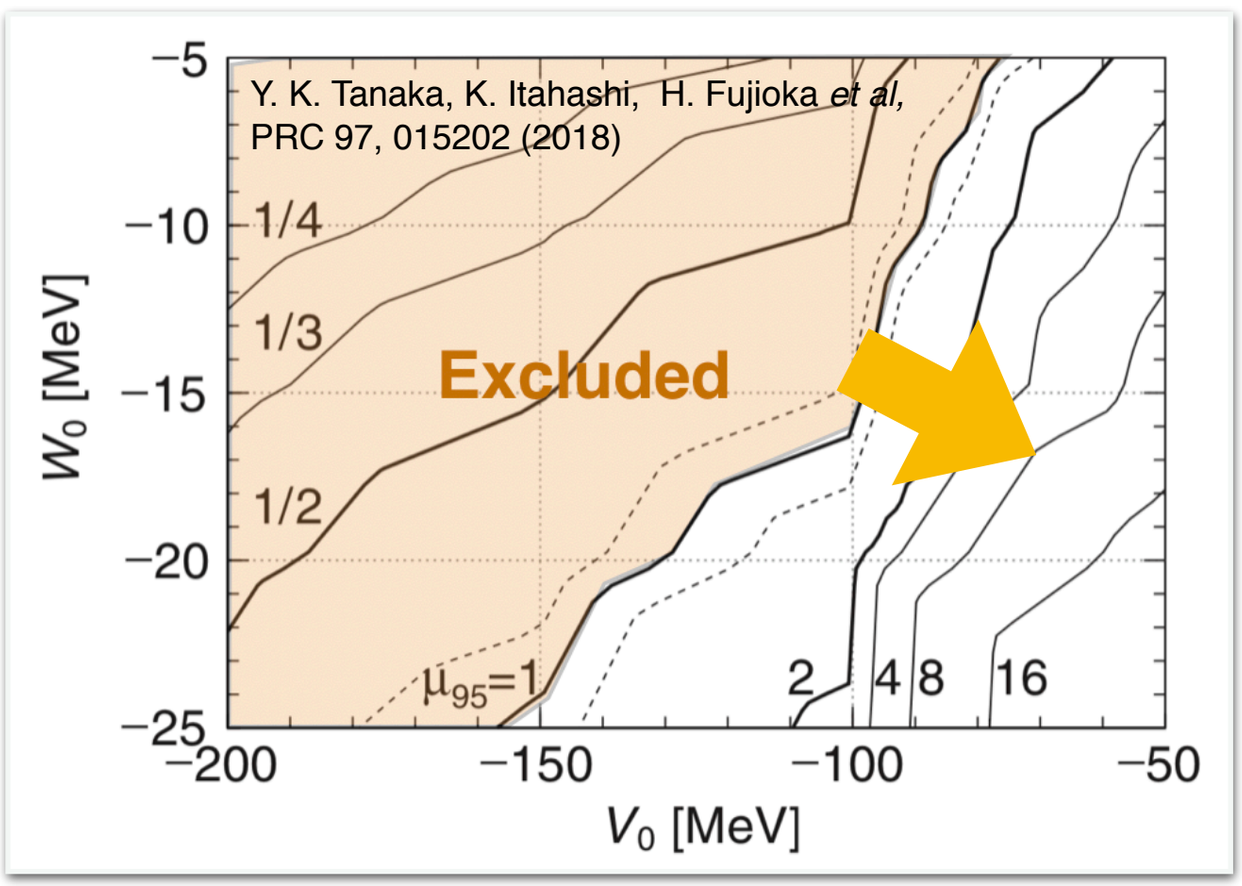


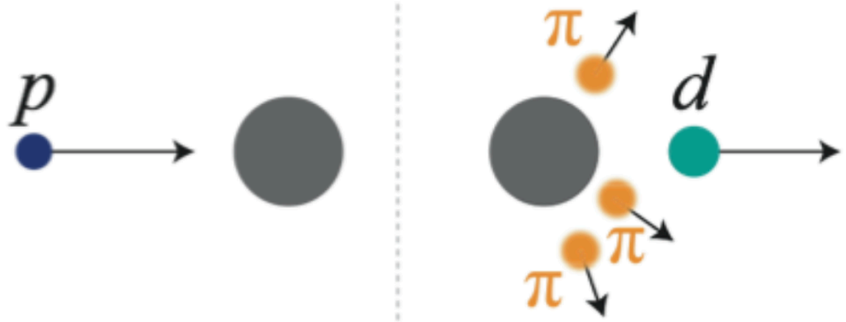
H.Nagahiro *et al.*, PRC 87, 045201 (2013)

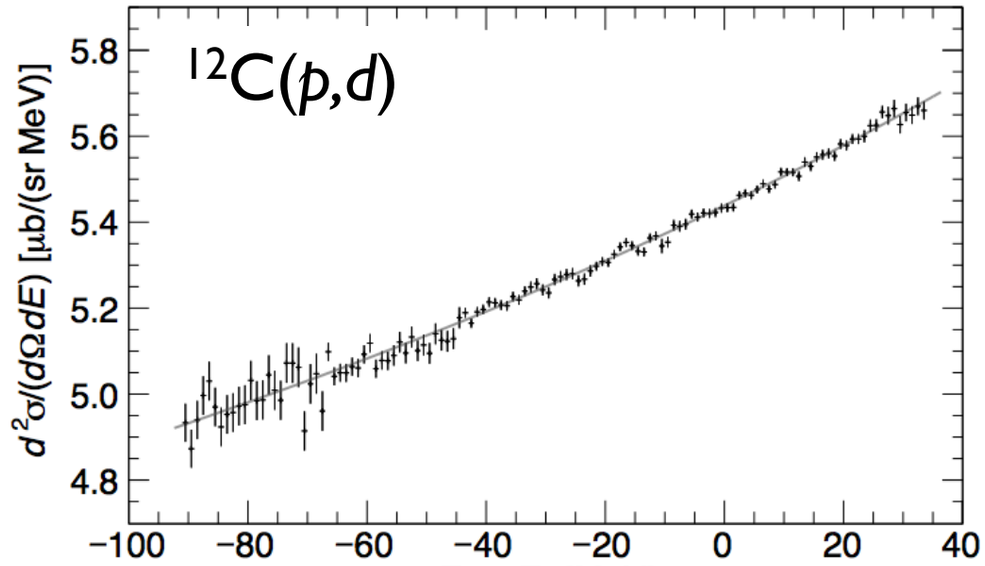


Semi-exclusive measurement with decay tagging

Background

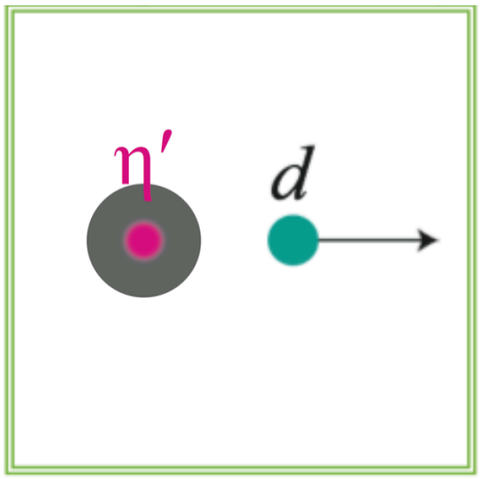
multi-π production





Signal

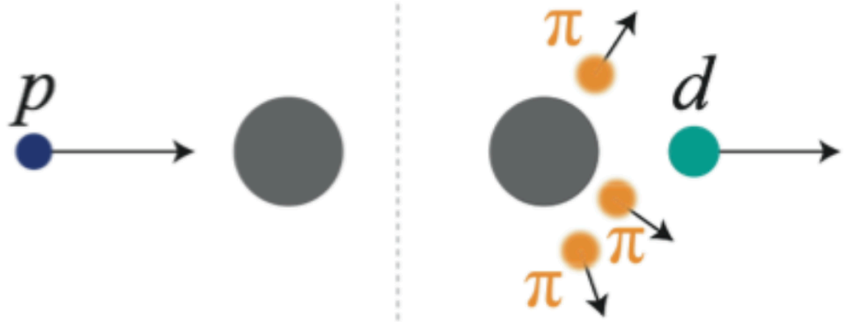
η′-mesic nuclei formation

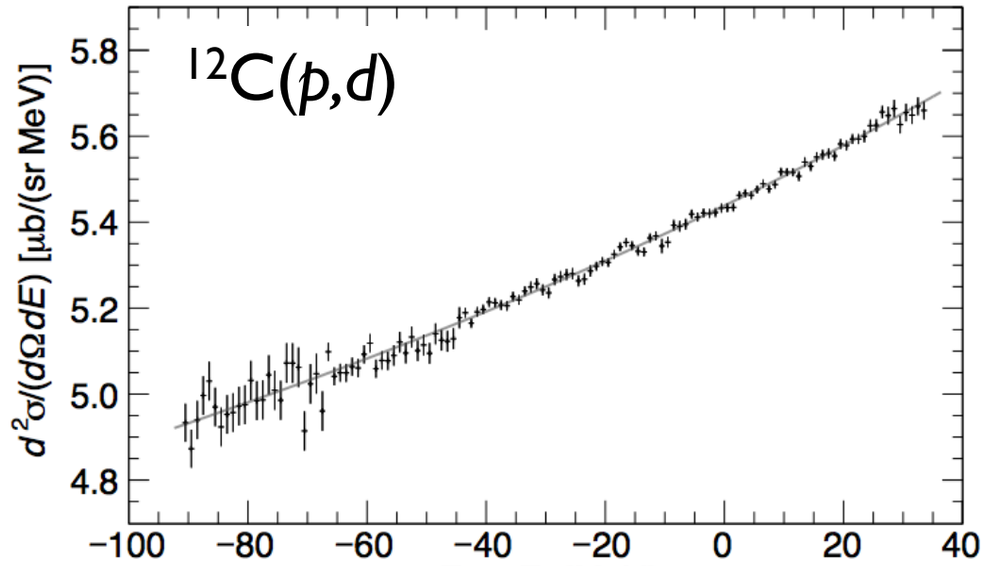


Semi-exclusive measurement with decay tagging

Background

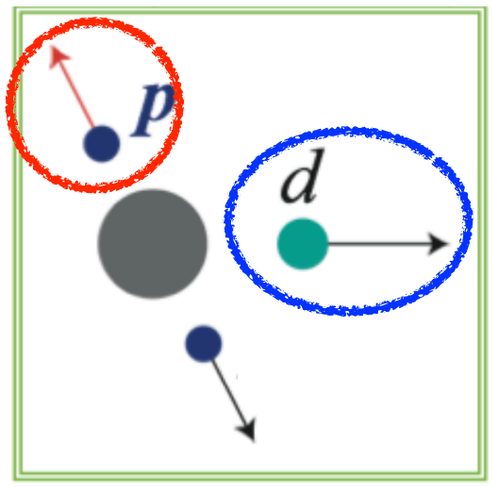
multi-π production





Signal

η′-mesic nuclei formation



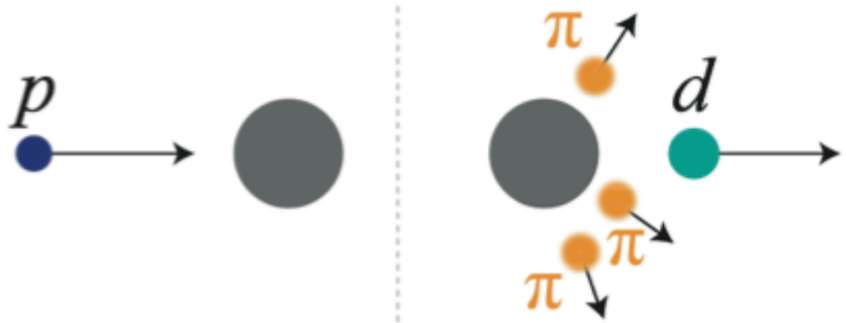
η'NN→ NN,
η'N→ ηN, πN

FRS : missing-mass spectroscopy (*d*)
WASA : tagging decay particles (*p*)

Semi-exclusive measurement with decay tagging

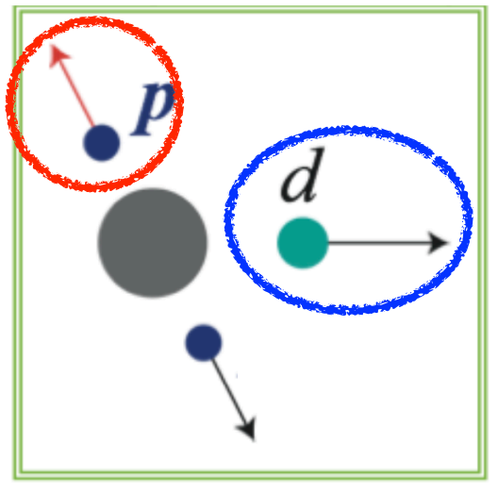
Background

multi-π production



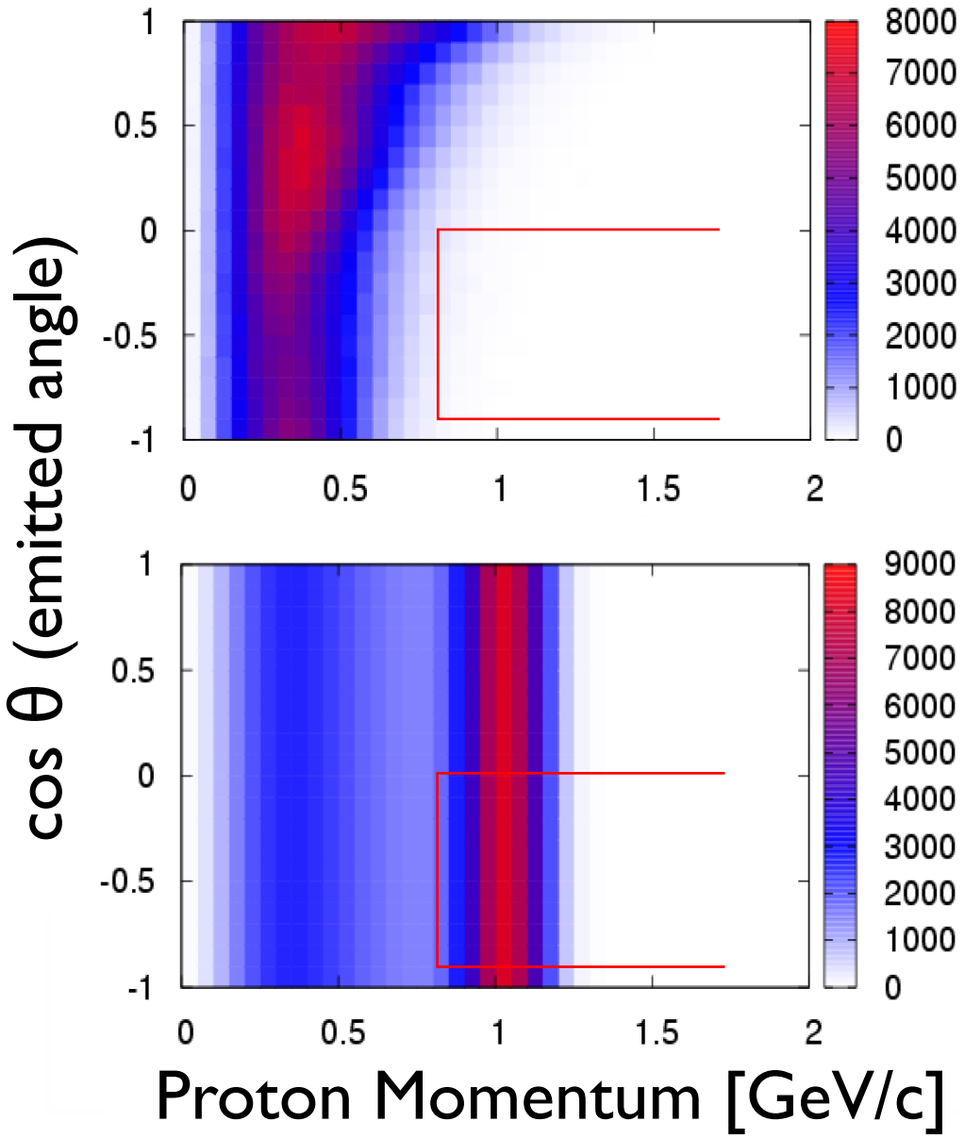
Signal

η′-mesic nuclei formation



η'NN→ NN,
η'N→ ηN, πN

Calculation by microscopic transport model (JAM)



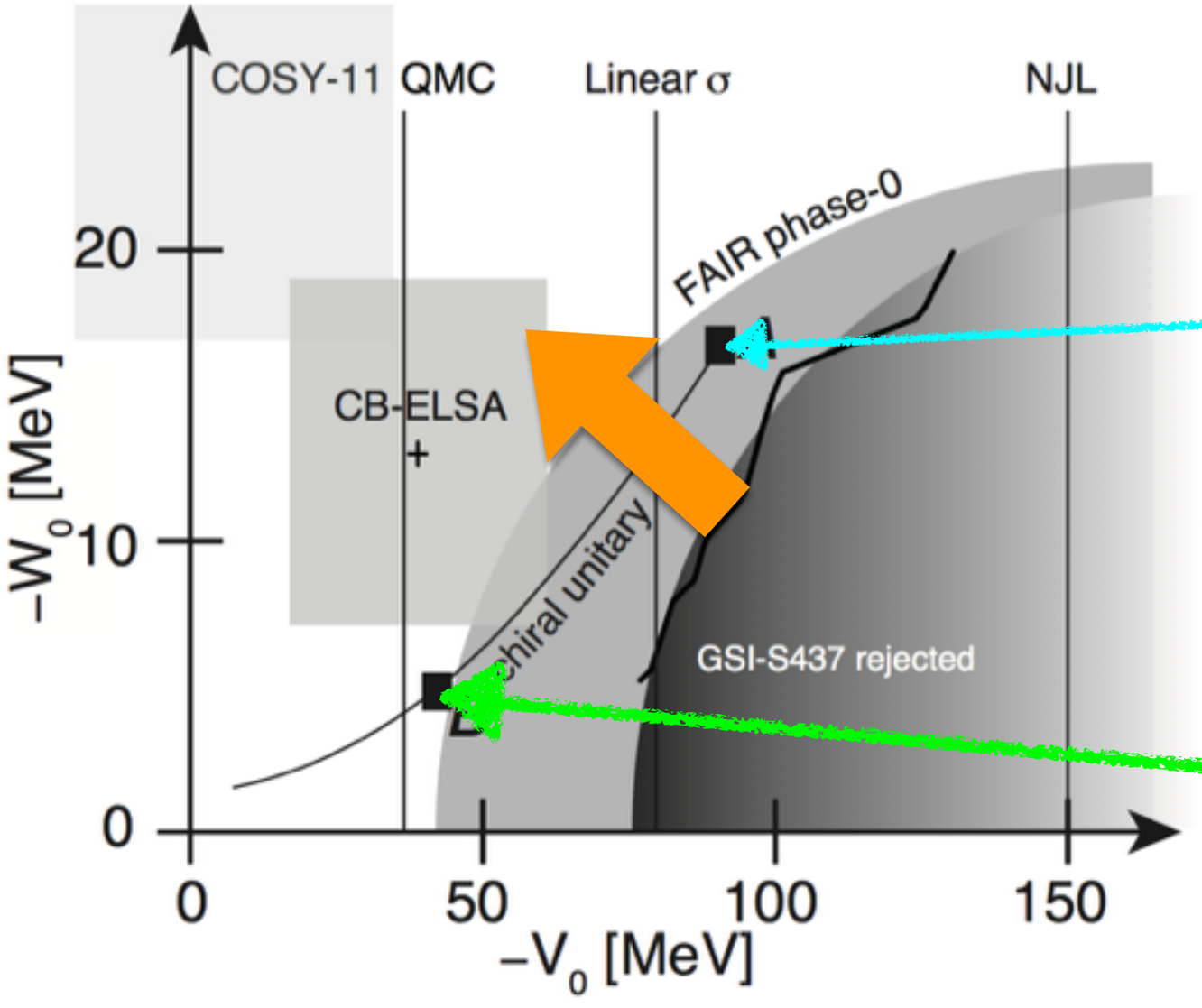
Y. Higashi

FRS : missing-mass spectroscopy (*d*)
WASA : tagging decay particles (*p*)

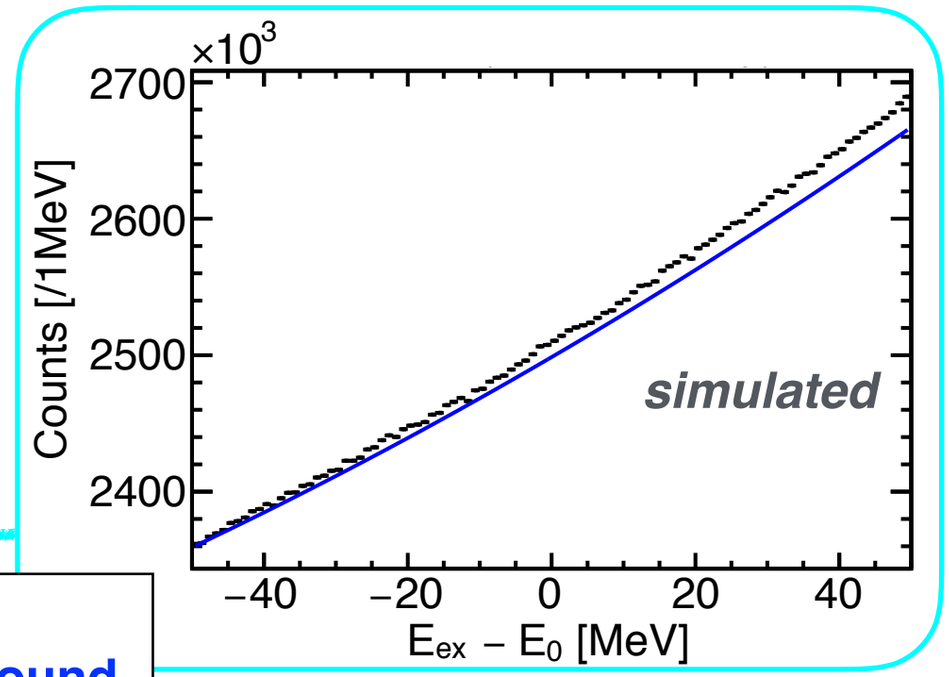
→ factor ~100 improvement in Signal / BG ratio

Simulation of semi-exclusive measurements

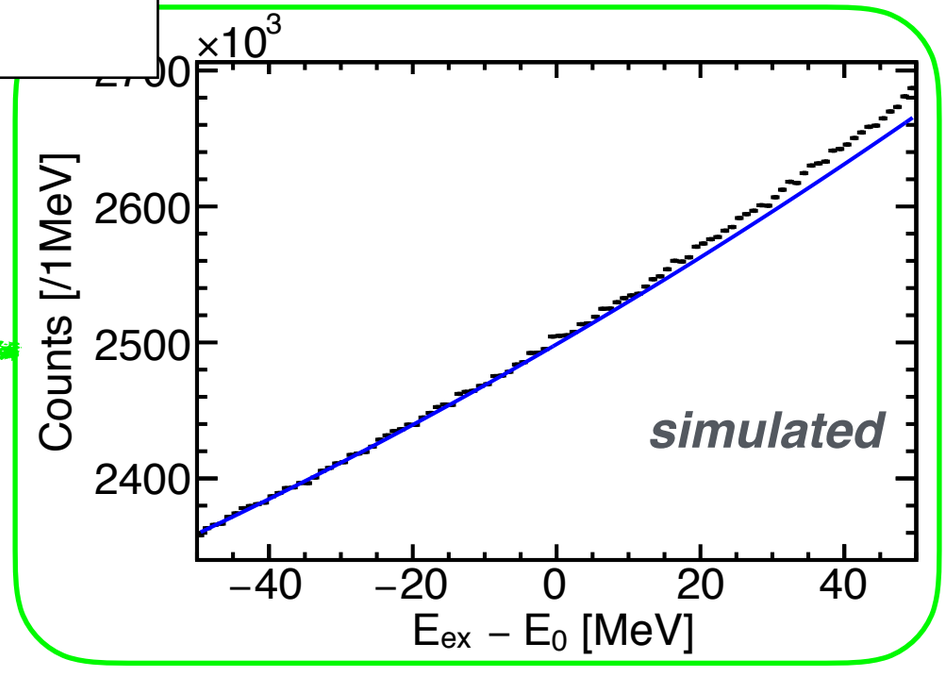
η′-nucleus potential depth ($V_0 + iW_0$)



Inclusive (without proton tagging)



Total
Background
Signal

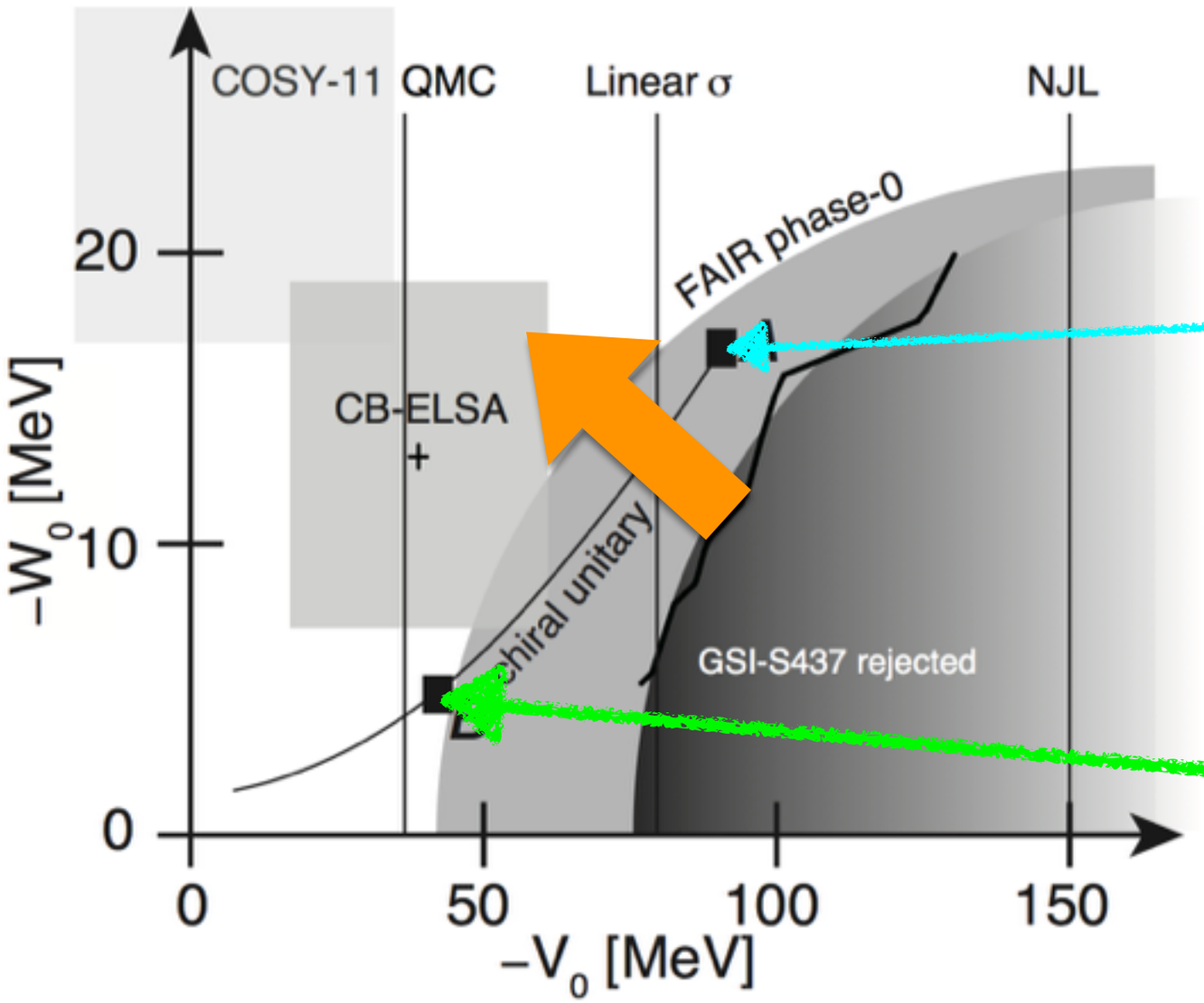


◇ Assumed branching ratio (to η′*NN*→*NN*) ~ 50%

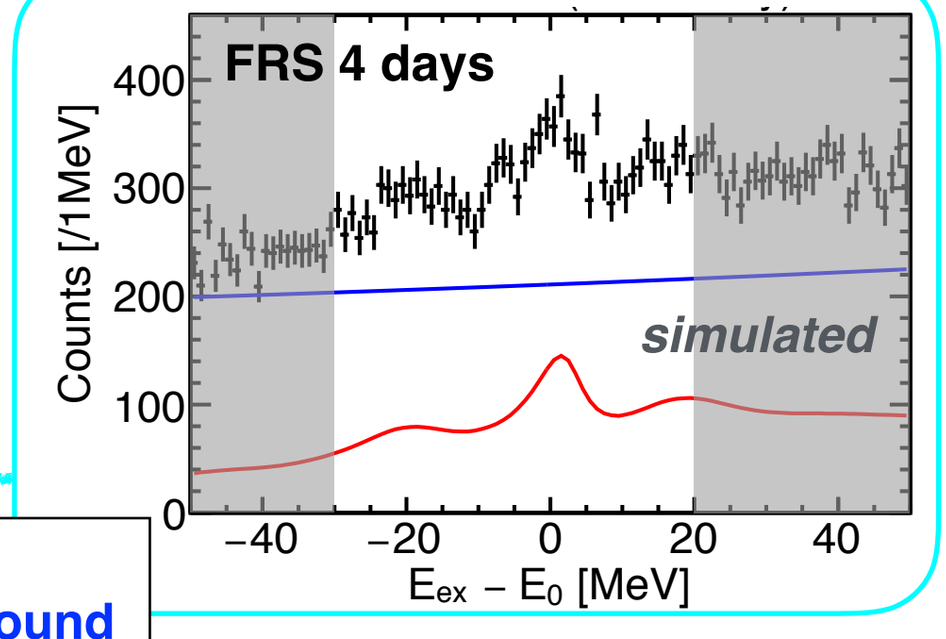
H.Nagahiro *et al.,* PRC 87, 045201 (2013), Phys. Lett. B 709, 87 (2012).

Simulation of semi-exclusive measurements

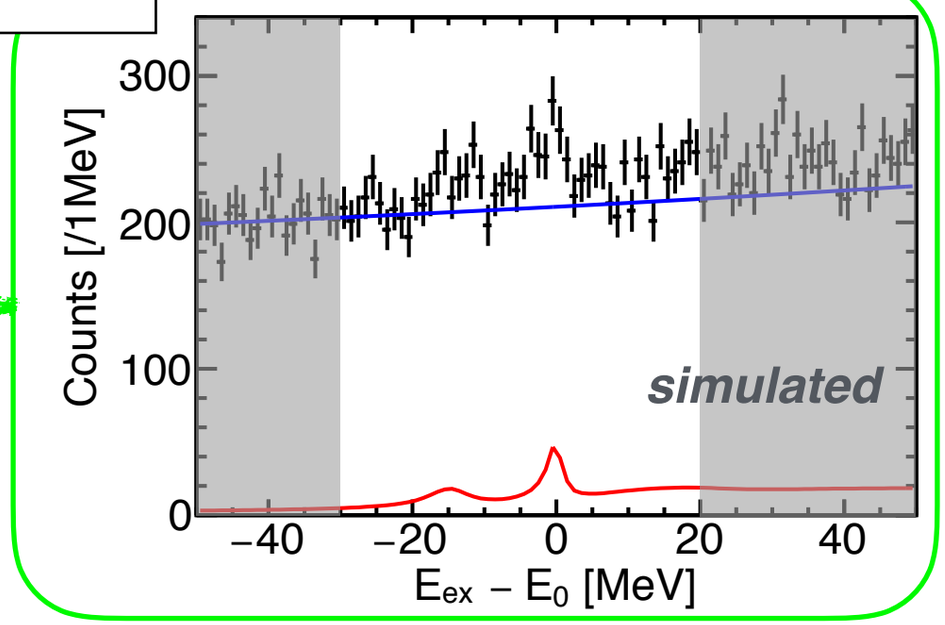
η′-nucleus potential depth ($V_0 + iW_0$)



Semi-exclusive (proton tagging)



Total
Background
Signal



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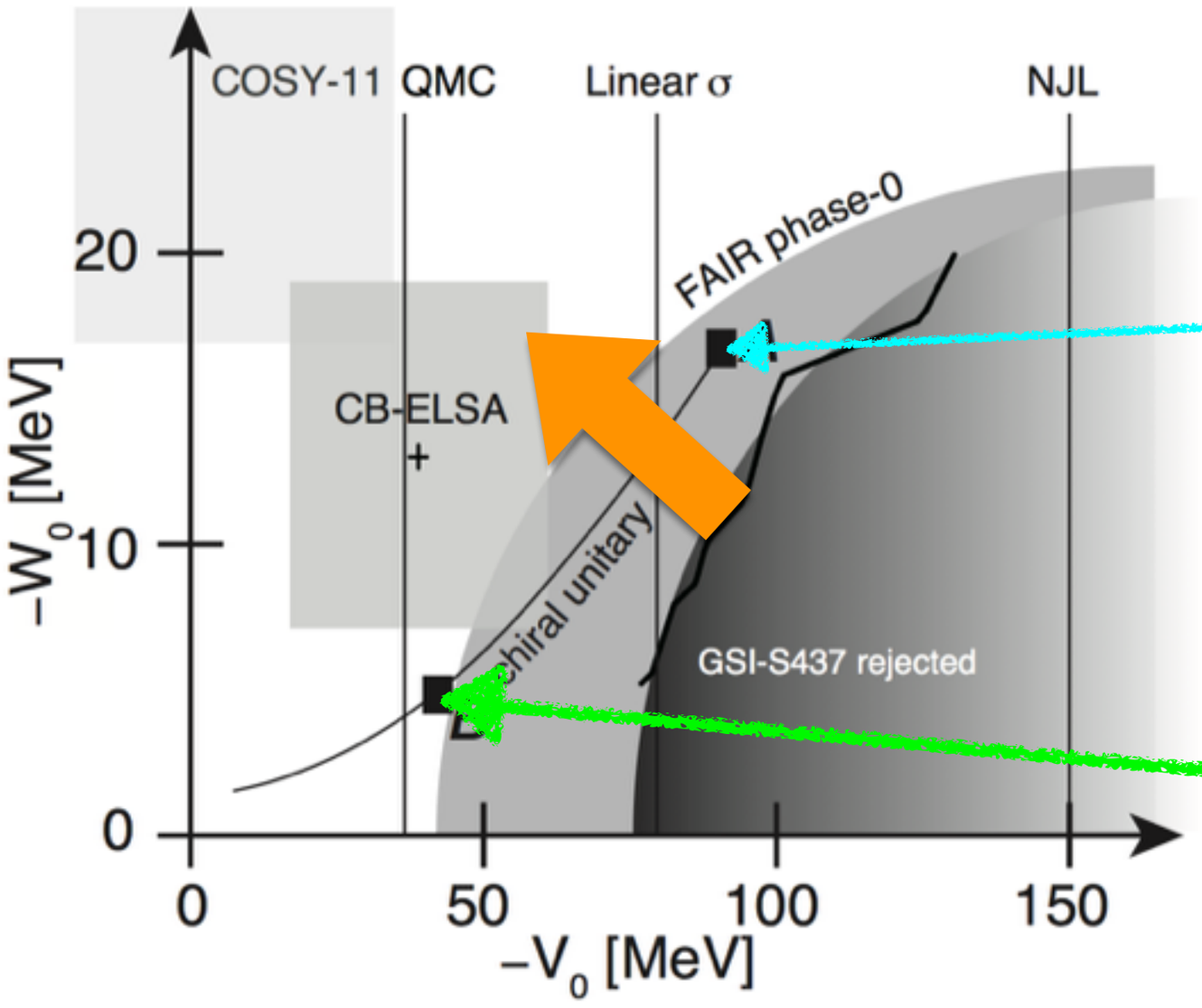

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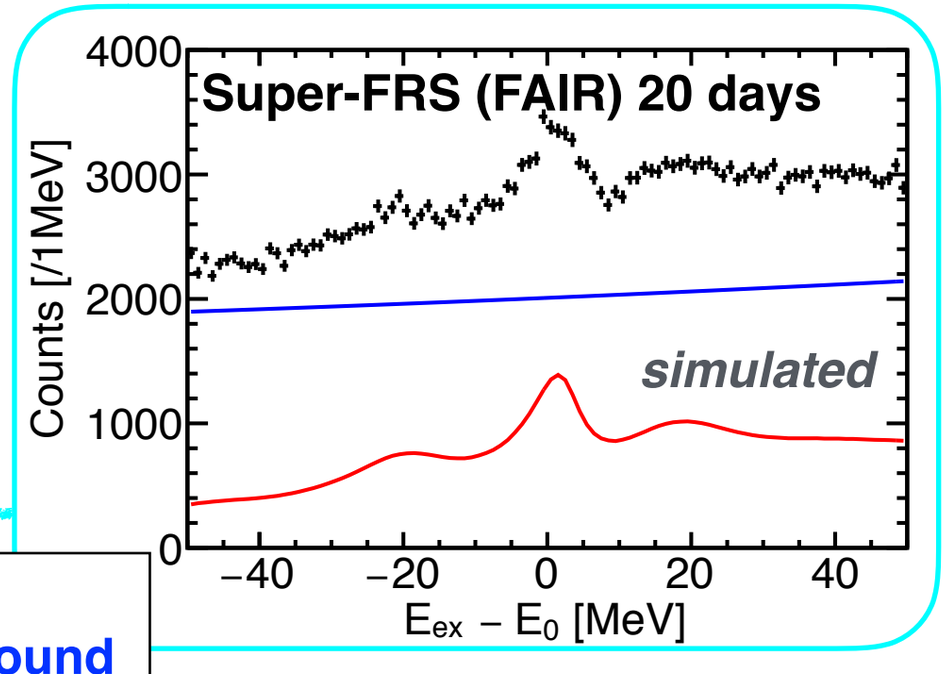
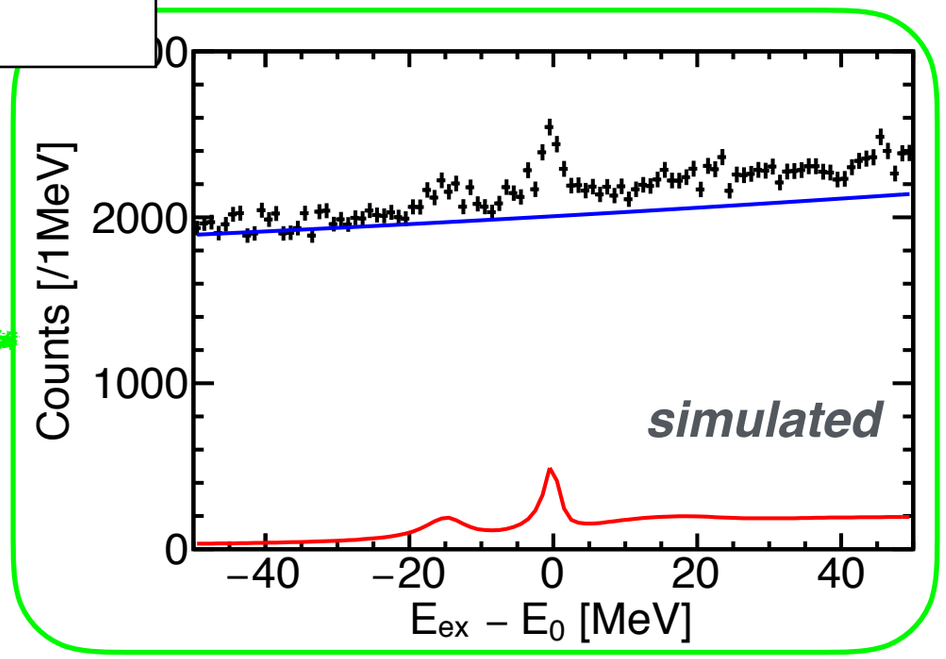


Total
Background
Signal



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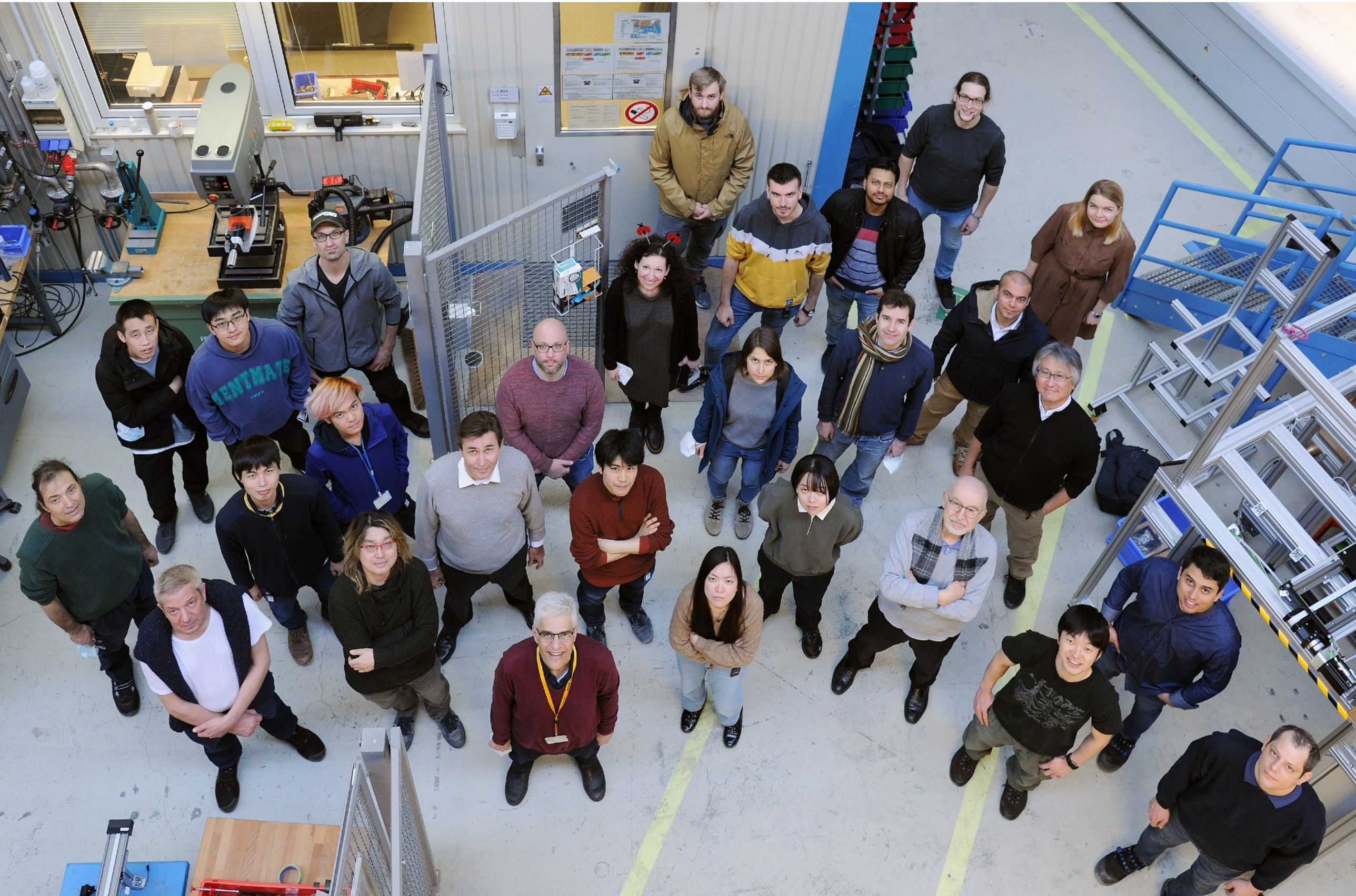
H.Nagahiro *et al.,* PRC 87, 045201 (2013), Phys. Lett. B 709, 87 (2012).

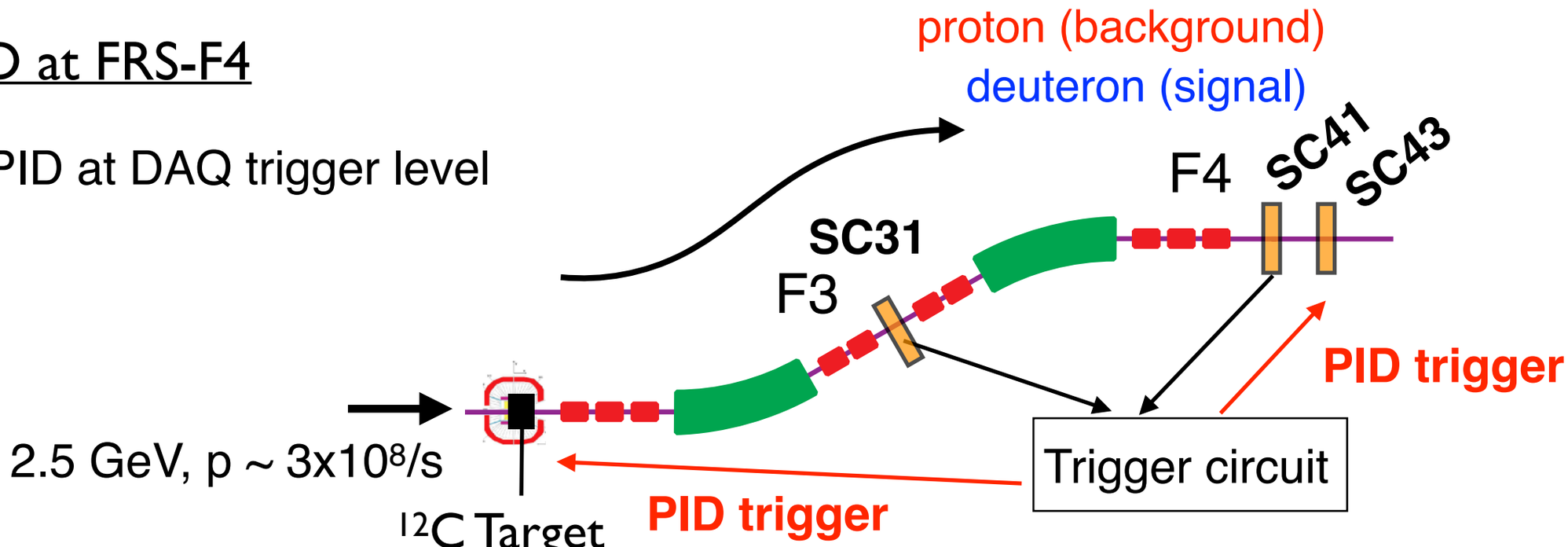
Beam Time in February 2022

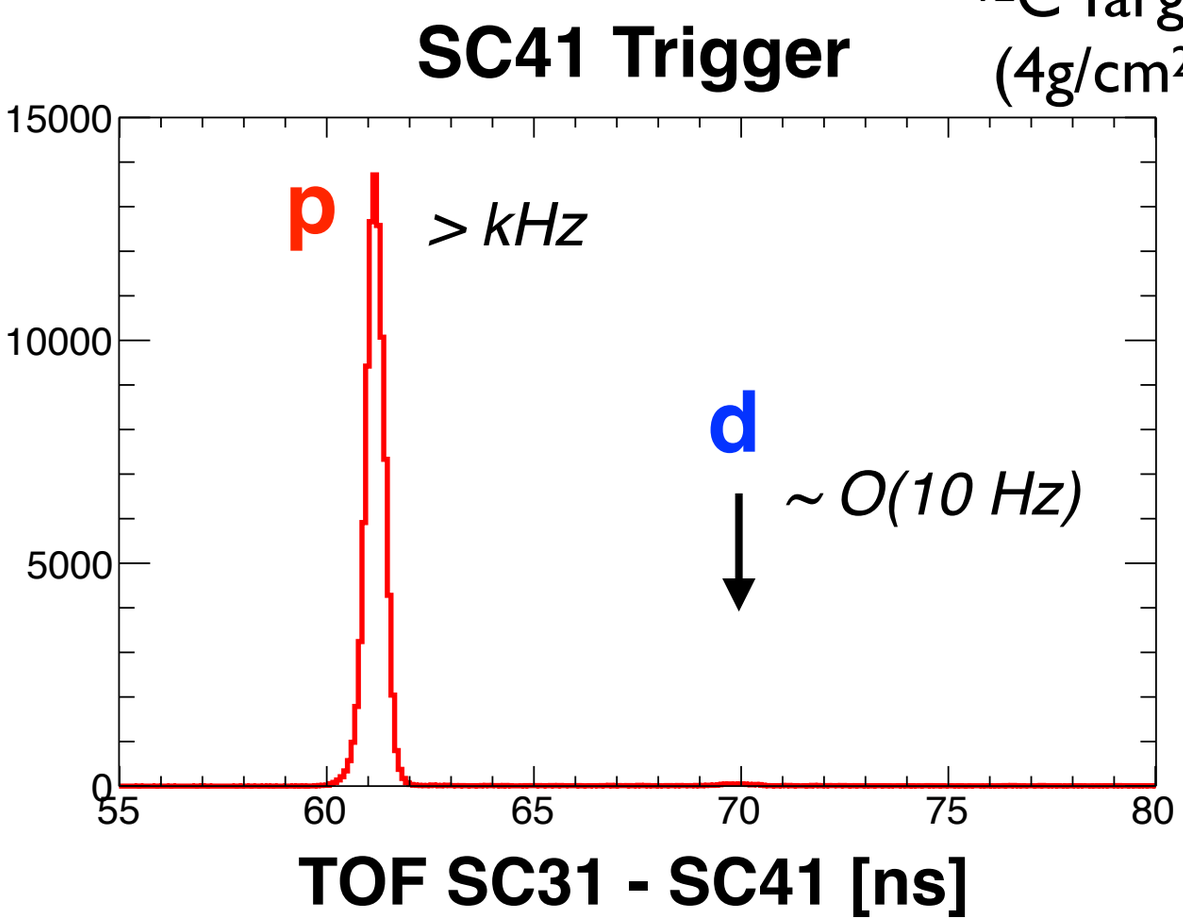


η'-mesic nuclei spectroscopy (S490)

Deuteron PID at FRS-F4

◇ Very clean PID at DAQ trigger level





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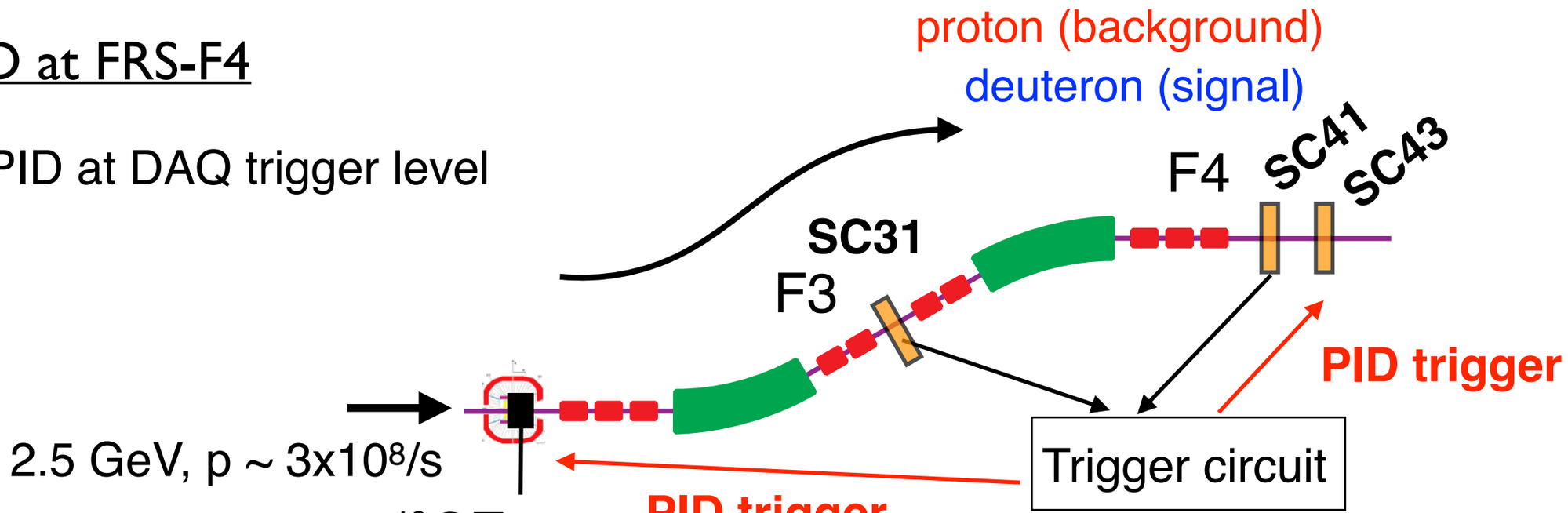
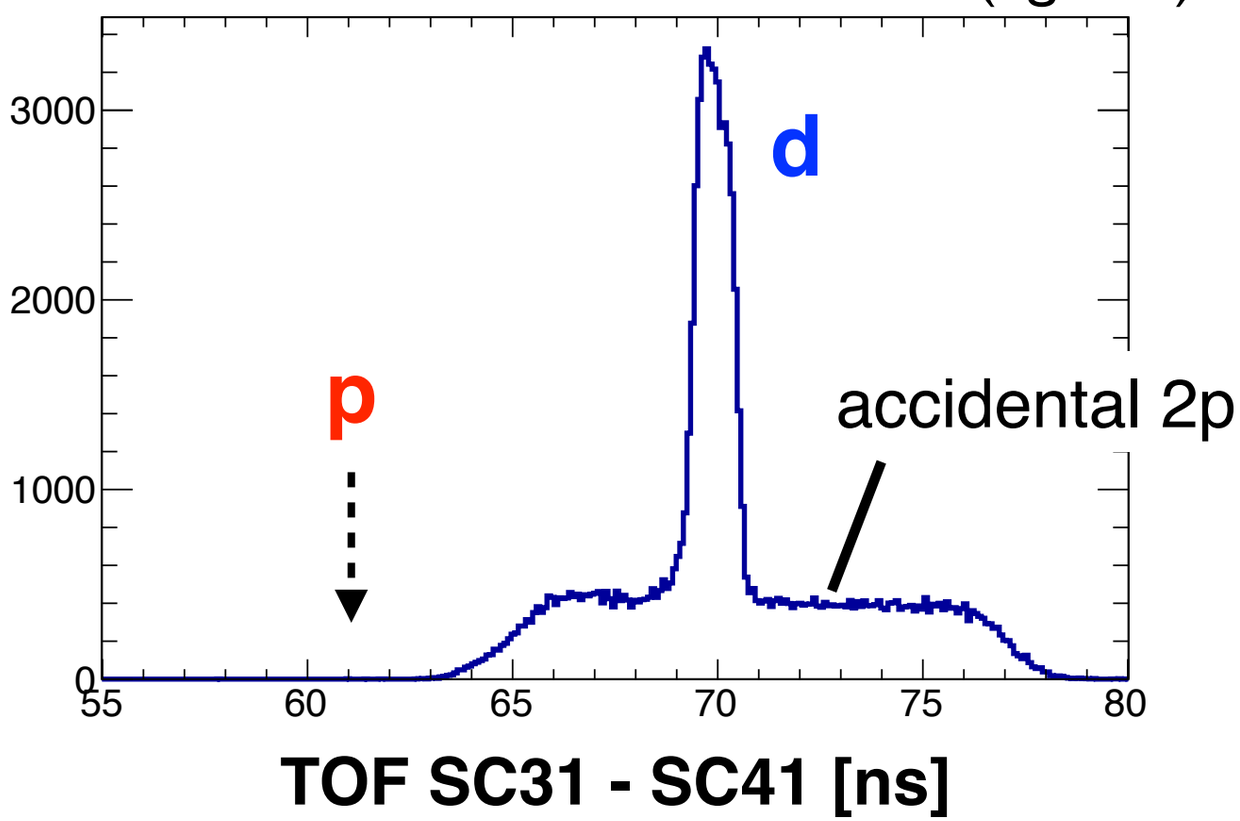
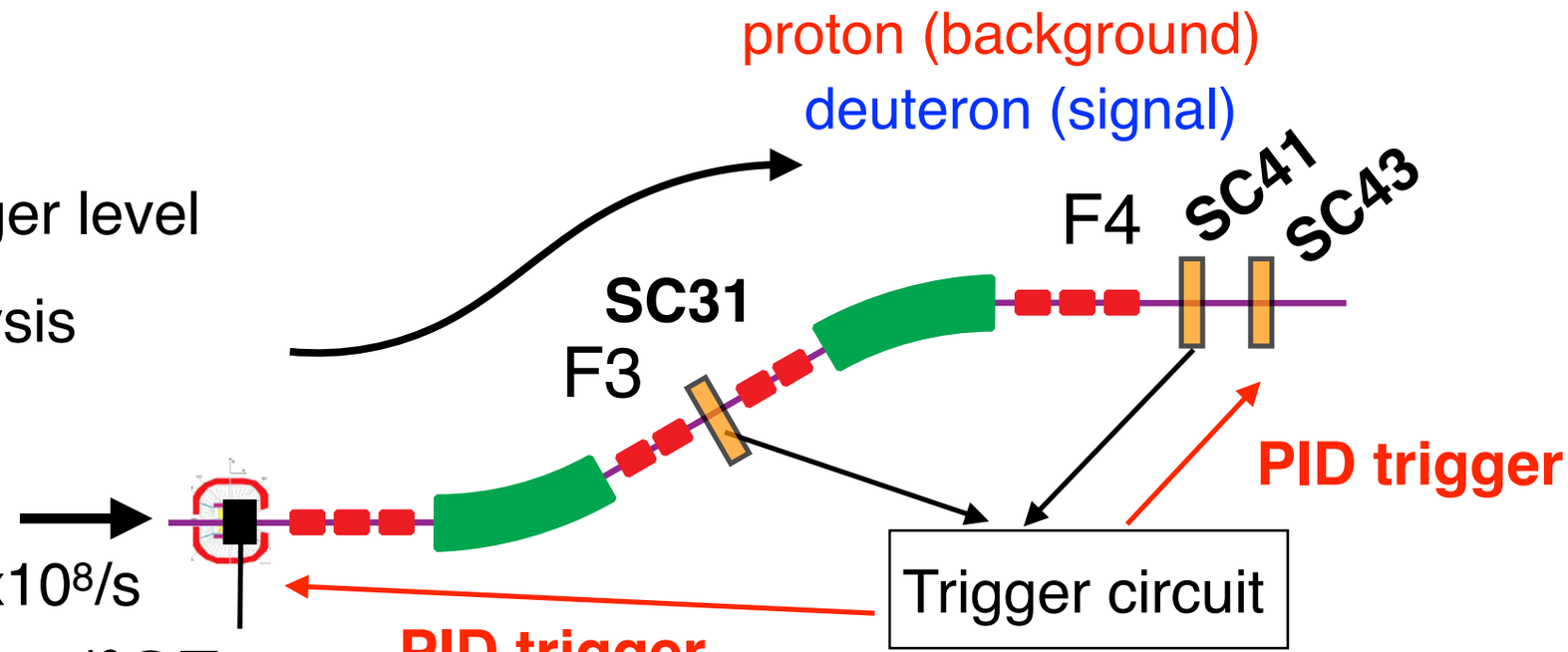


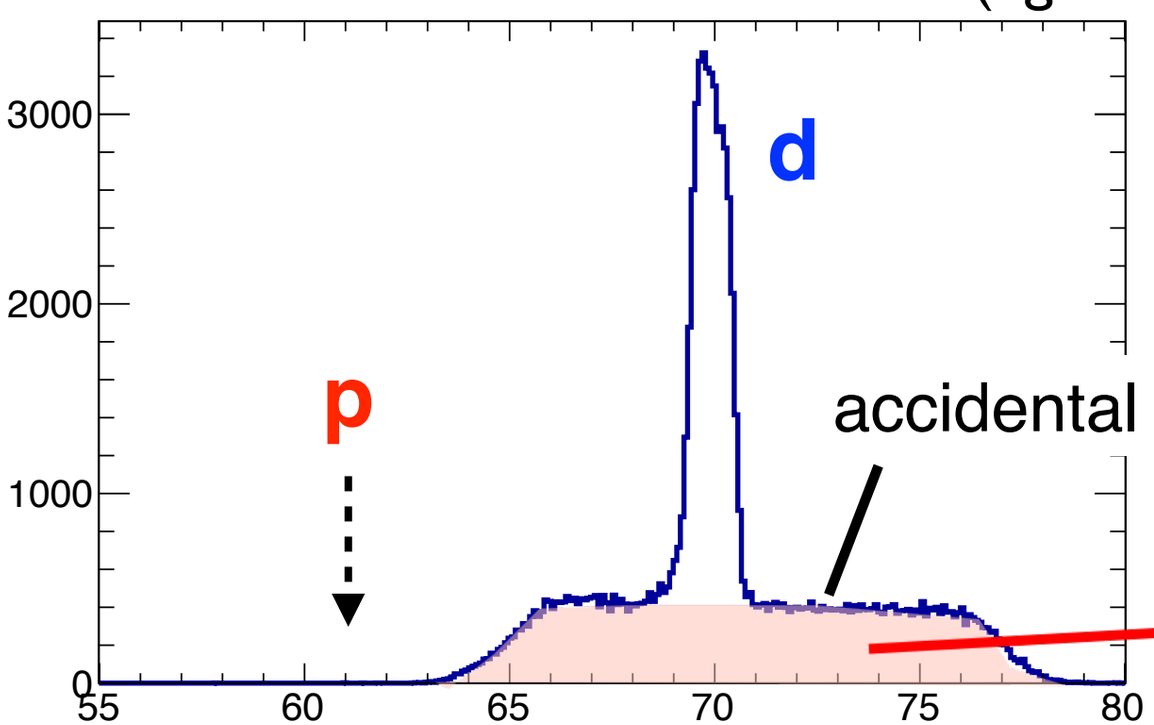


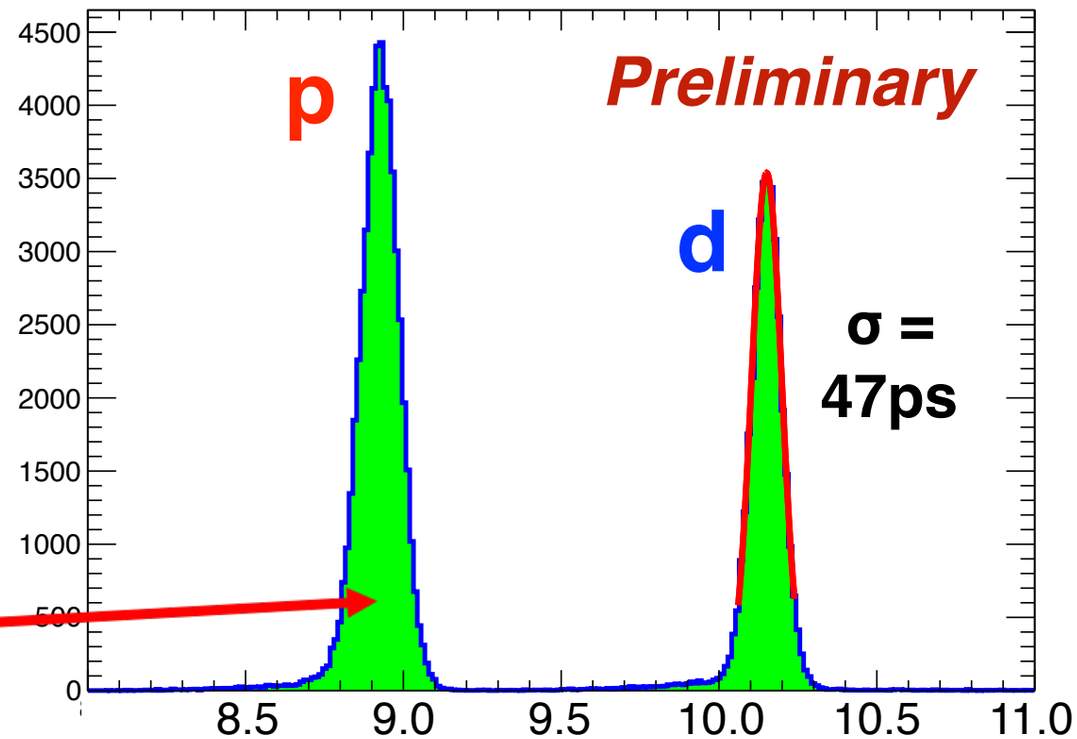
η'-mesic nuclei spectroscopy (S490)

Deuteron PID at FRS-F4

- ◇ Very clean PID at DAQ trigger level
- ◇ TOF(SC41-43) in final analysis to remove accidental 2p's







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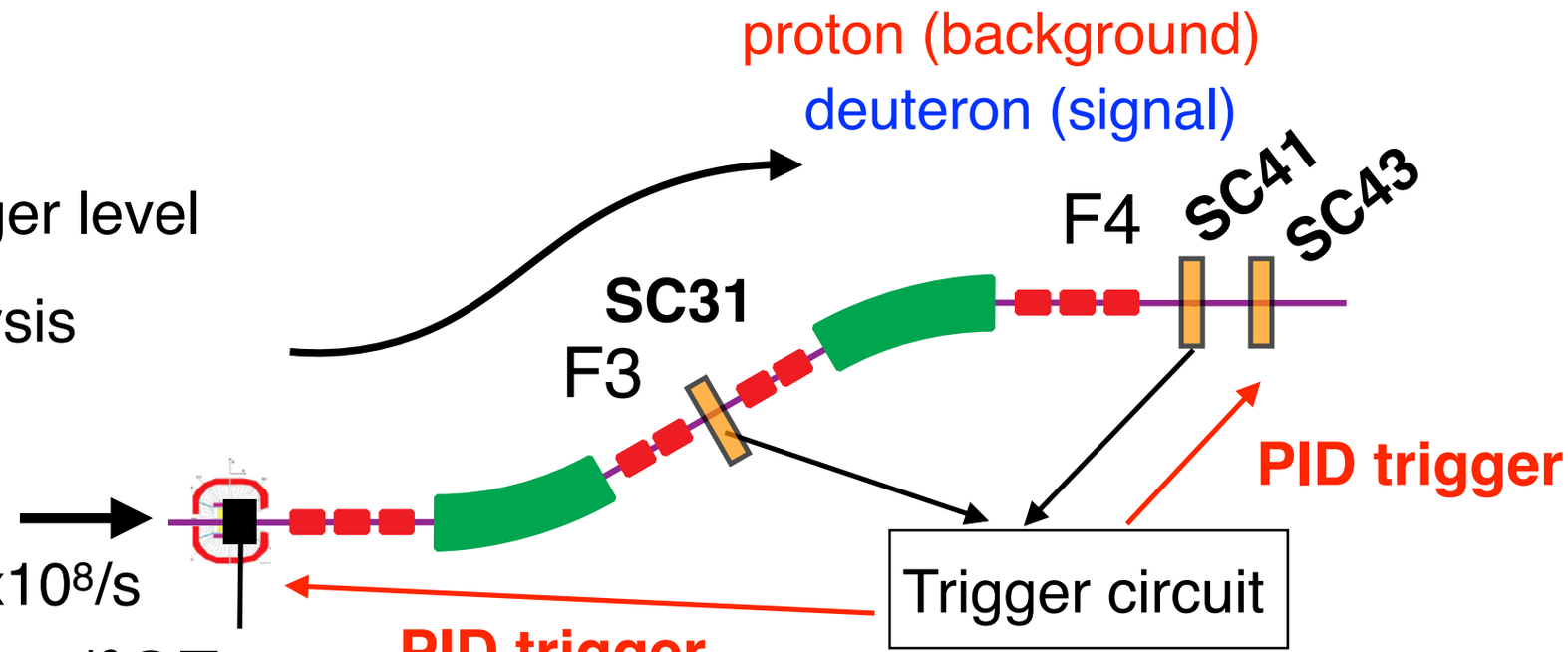
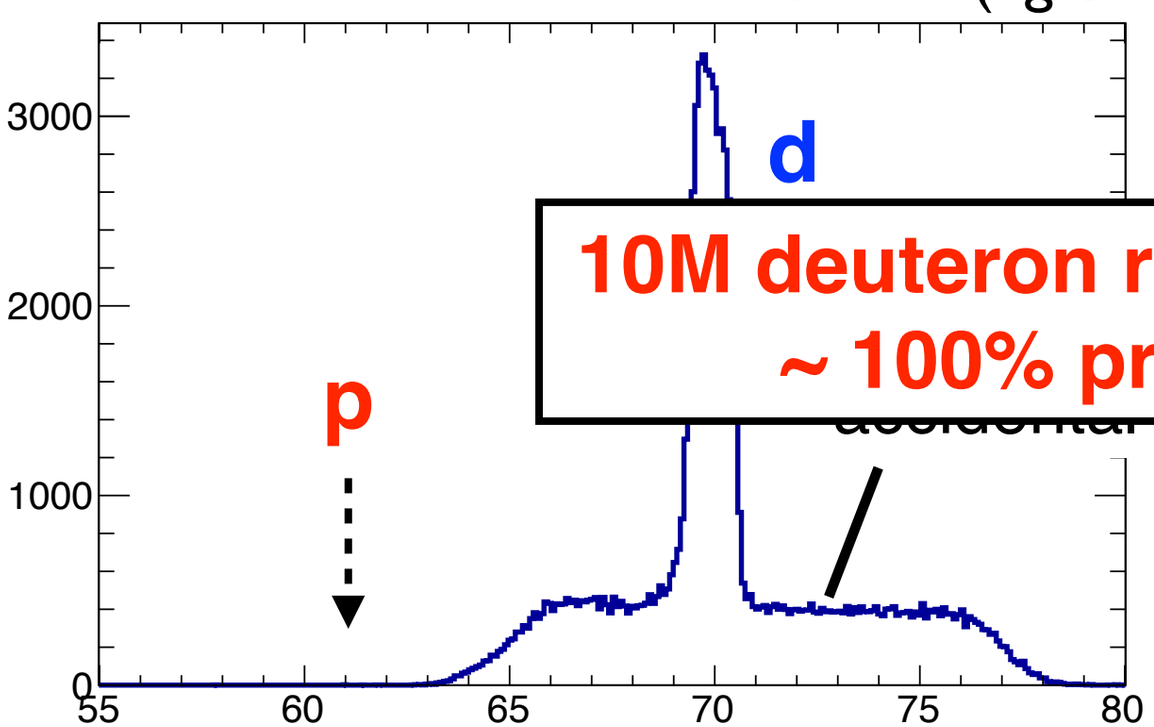
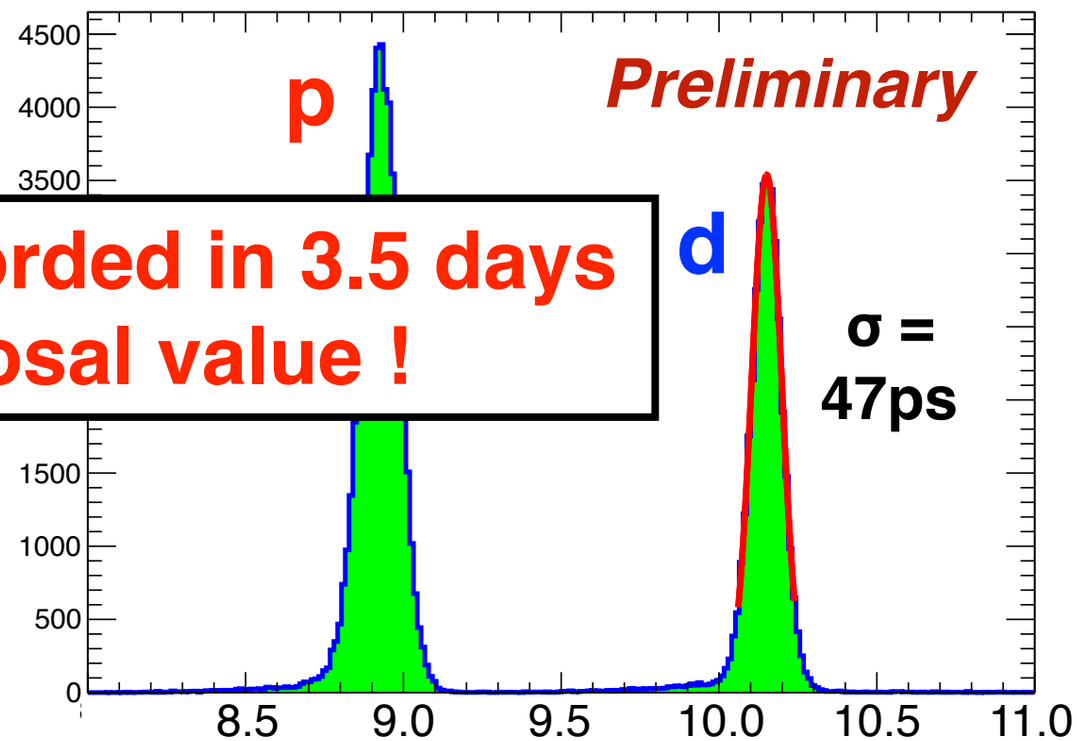




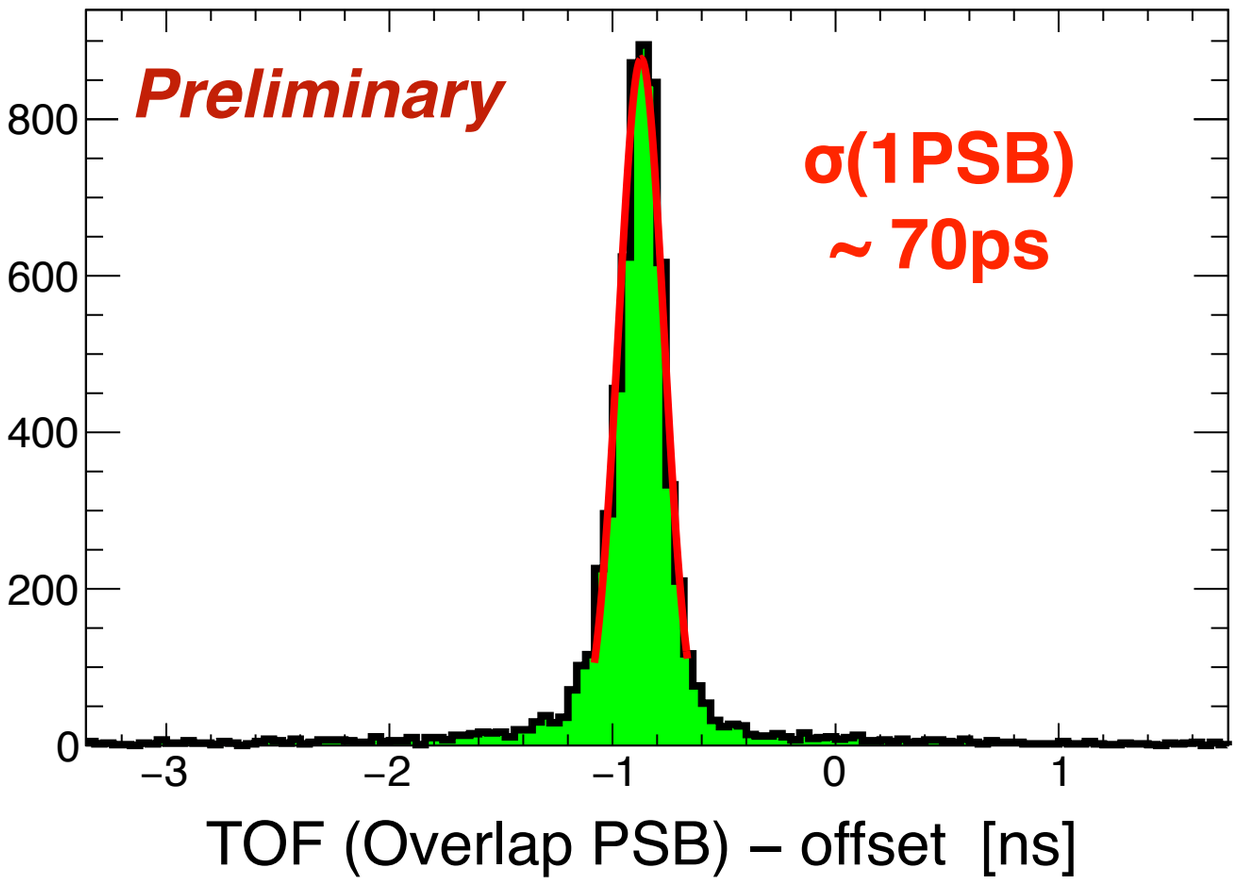
10M deuteron recorded in 3.5 days
~ 100% proposal value !



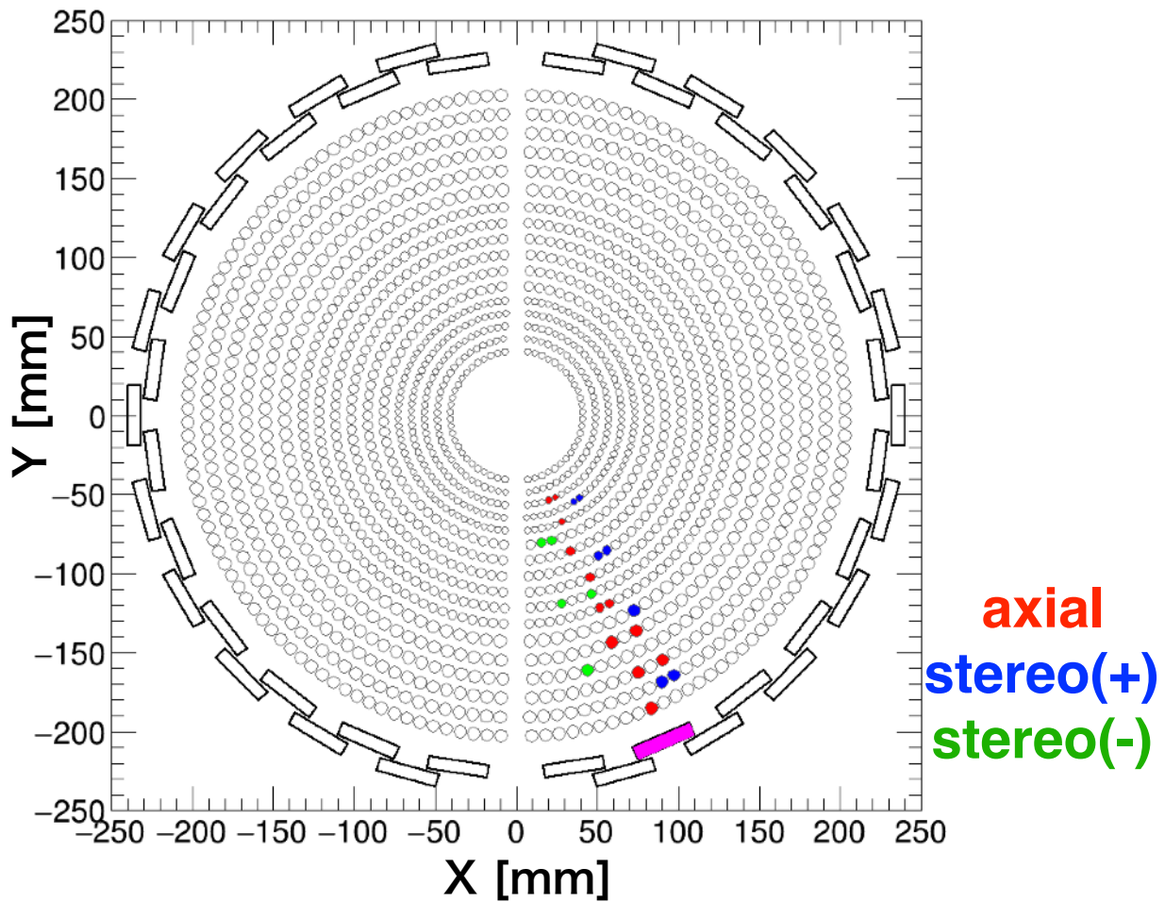
η'-mesic nuclei spectroscopy (S490)

Performance of WASA-PSB and MDC

Stable performance of PSB



Example of MDC/PSB hit pattern with deuteron at FRS-F4

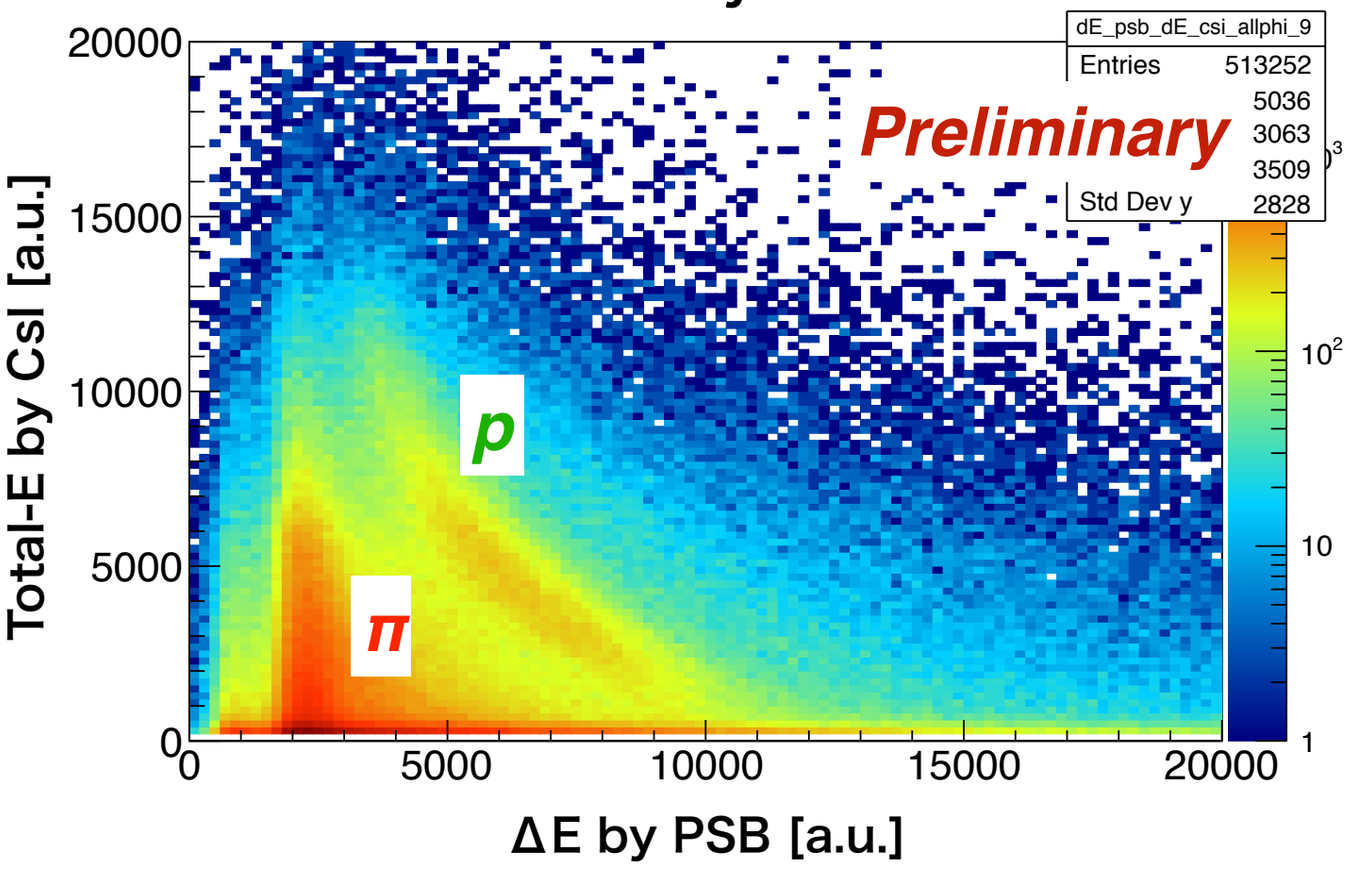


Track and momentum reconstruction analysis in progress

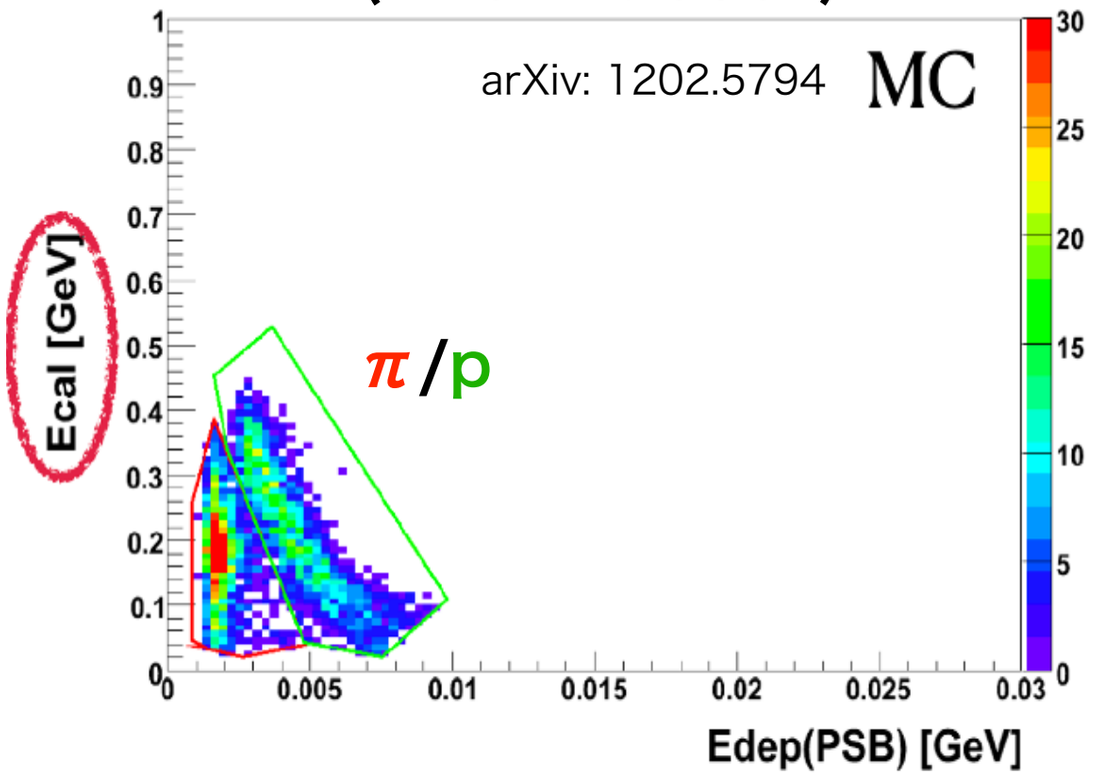
η'-mesic nuclei spectroscopy (S490)

Performance of WASA-CsI

Particle ID by PSB-CsI



Reference Simulation (WASA-at-COSY)



Refinement of analysis, Reconstruction of γ (π^0, η, η' decay) are in progress

Summary + Outlook

◇ We have developed a new experimental setup combining WASA+FRS

- high resolution forward (0°) spectroscopy with FRS
- decay particle measurement in large solid angle by WASA

◇ 2 first experiments have been successfully performed in 2022

*** η'-mesic nuclei spectroscopy (S490) with ^{12}C(*p,dp*) reaction with decay particle tagging**

□ a probe to study in-medium η' meson properties

□ with extended sensitivity to shallow potential case

□ aimed statistics of the 1st semi-exclusive measurement was achieved.

*** Hypernuclei spectroscopy (S447): Talk by T. Saito afternoon**

◇ We are going to expand these and also new experiments further with WASA + FRS at GSI and with (Super-)WASA + Super-FRS at FAIR

WASA-FRS collaborators from Beamtime 2022 (not yet complete list)

- **High Energy Nuclear Physics Laboratory, RIKEN, Japan:**
  H. Ekawa, Y. Gao, Y. He, A. Kasagi, E. Liu, A. Muneem, M. Nakagawa, T.R. Saito, Y. Tanaka,
- **HRS-HYS group, GSI, Germany**
  H. Alibrahim Alfaki, V. Drozd, T.R. Saito, T. Weber
- **FRS/SFRS Research Group, GSI, Germany:**
  K.-H. Behr, B. v. Chamier Gliszezynski, T. Dickel, S. Dubey, J. Eusemann, D. Kostyleva, B. Franczak, H. Geissel, E. Haettner, C. Hornung, P. Roy, C. Scheidenberger, P. Schwarz, B. Szczepanczyk, M. Will, J. Zhao
- **Meson Science Laboratory, RIKEN, Japan:**
  K. Itahashi, R. Sekiya
- **Instituto de Estructura de la Materia – CSIC, Spain:**
  S. Escrig, C. Rappold
- **Cryogenic Department, GSI, Germany:**
  A. Beusch, H. Kollmus, C. Schroeder, B. Streicher
- **Experiment Electronics Department, GSI, Germany:**
  H. Heggen, N. Kurz, S. Minami
- **Detector Laboratory, GSI, Germany:**
  C. Nociforo, E. Rocco
- **Nuclear Spectroscopy Group, GSI, Germany:**
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- **Super-FRS Project, GSI, Germany:**
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- **Target Laboratory, GSI, Germany:**
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- **Institut für Kernphysik, Technische Universität Darmstadt, Germany:**
  G. Schaumann
- **University of Applied Sciences, Giessen, Germany:**
  S. Kraft
- **Department of Engineering, Gifu University, Japan:**
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- **Energy and Sustainability Research Institute Groningen, University Groningen, The Netherlands:**
  V. Drozd, M. Harakeh, N. Kalantar-Nayestanaki, M. Kavatsyuk
- **Institute of Modern Physics, China:**
  L. Duan, Y. Gao, E. Liu, J. Ong, X. Tang
- **Institute of Physics, Jagiellonian University, Poland:**
  A. Khreptak, M. Skurzok
- **Department of Low and Medium Energy Physics, Jožef Stefan Insti**
  Slovenia:
  Z. Brencic
- **Department of Physics, Kyoto University, Japan:**
  R. Sekiya
- **School of Nuclear Science and Technology, Lanzhou University, Ch**
  Y. He, J. Ong, T.R. Saito, X. Tang
- **Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, Ge**
  P. Achenbach, J. Pochdzalla
- **Michigan State University, USA:**
  D. Morrissey
- **Universidad de Santiago de Compostela, Spain:**
  J. Benlliure, M. Fontan, A. Gonzalez, G. Jimenez, J. Rodríguez-Sánchez