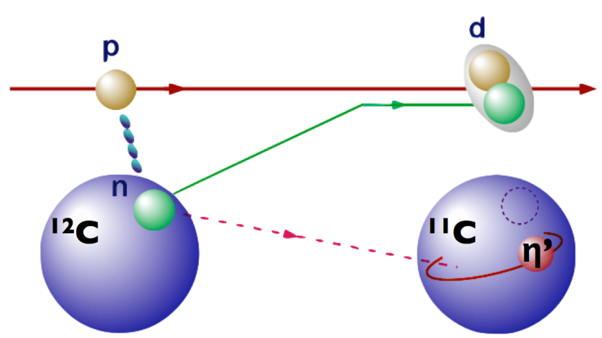
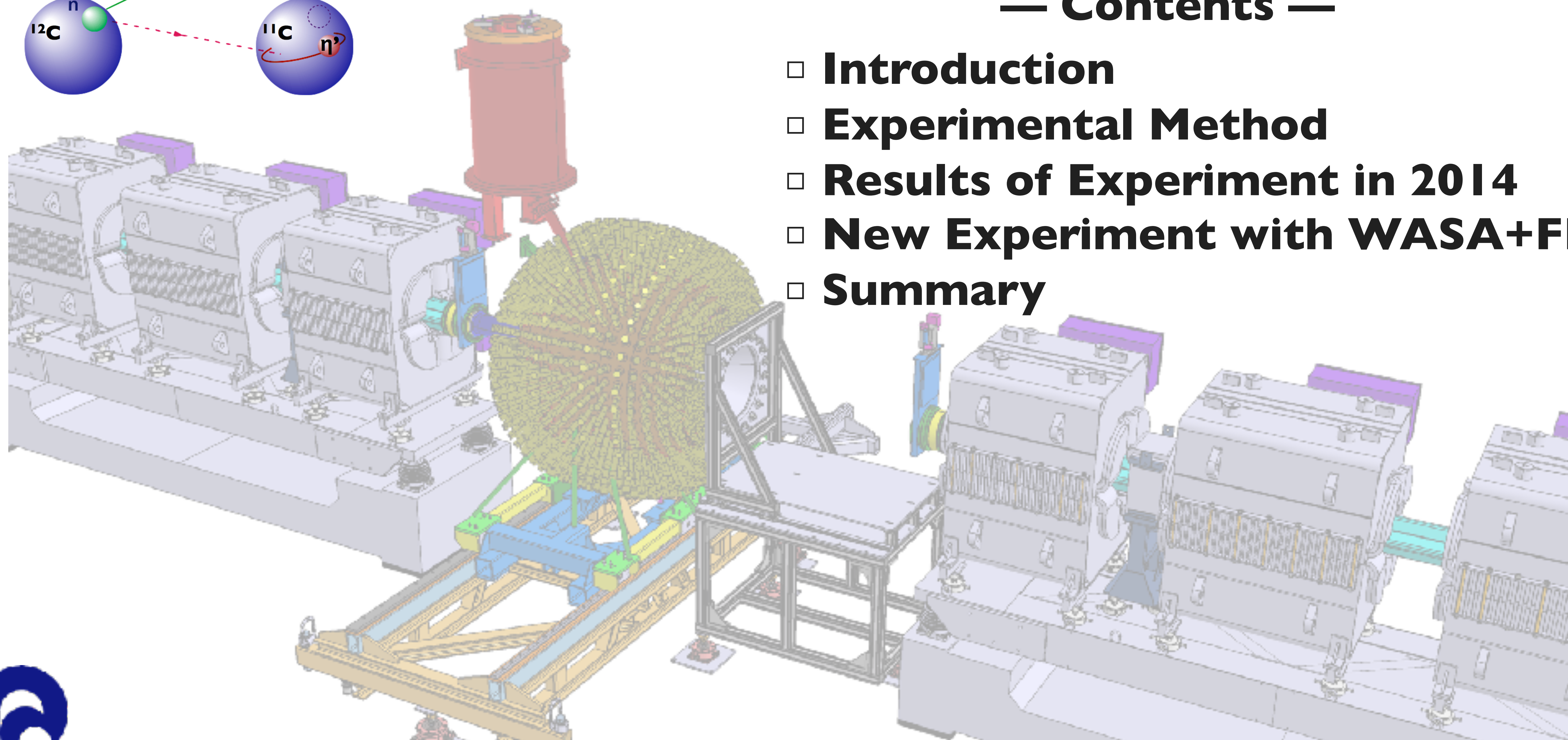
# Search for η′-meson nucleus bound states at GSI/FAIR

Yoshiki Tanaka (RIKEN)




— Contents —

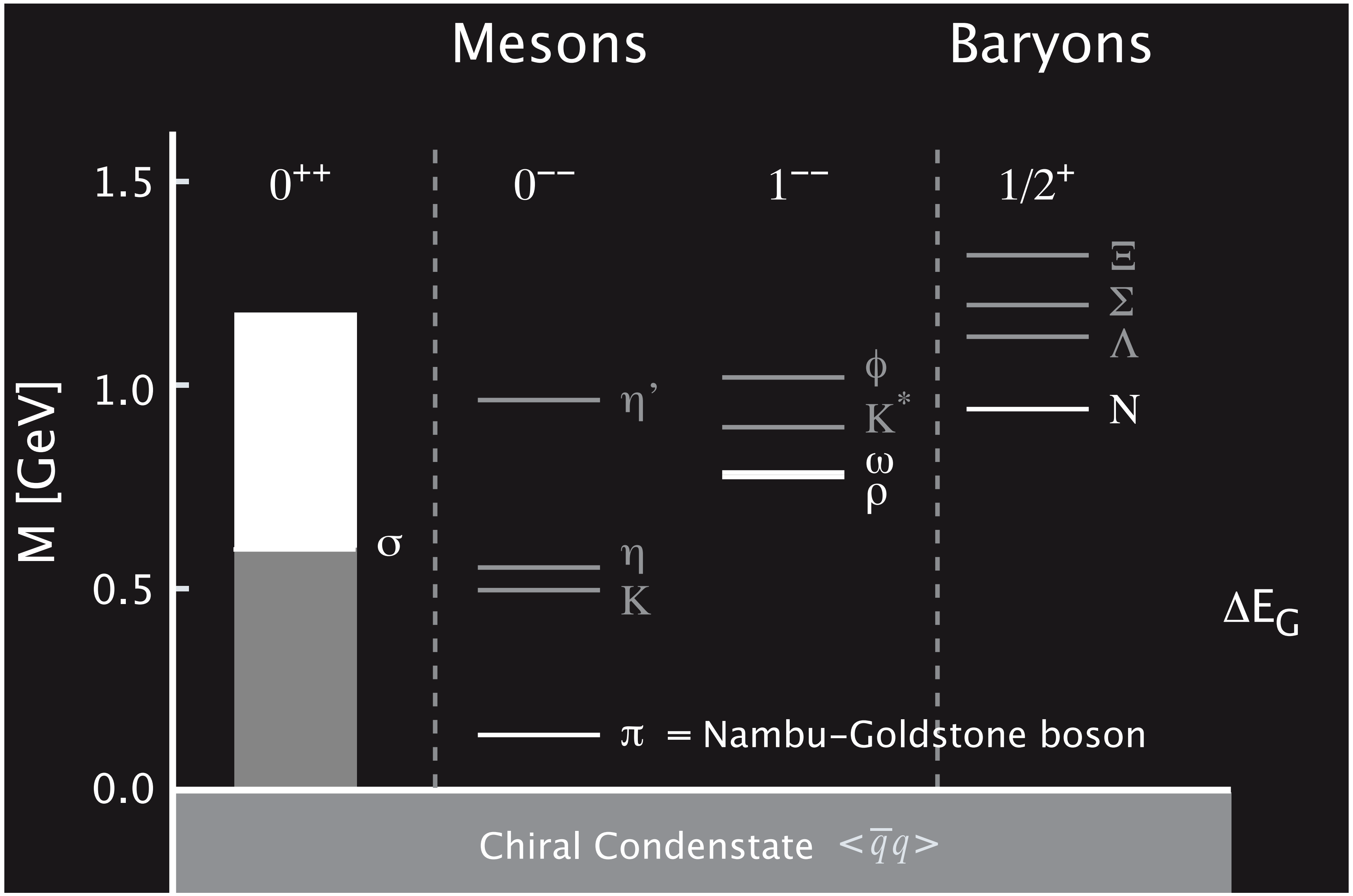
- Introduction
- Experimental Method
- Results of Experiment in 2014
- New Experiment with WASA+FRS
- Summary



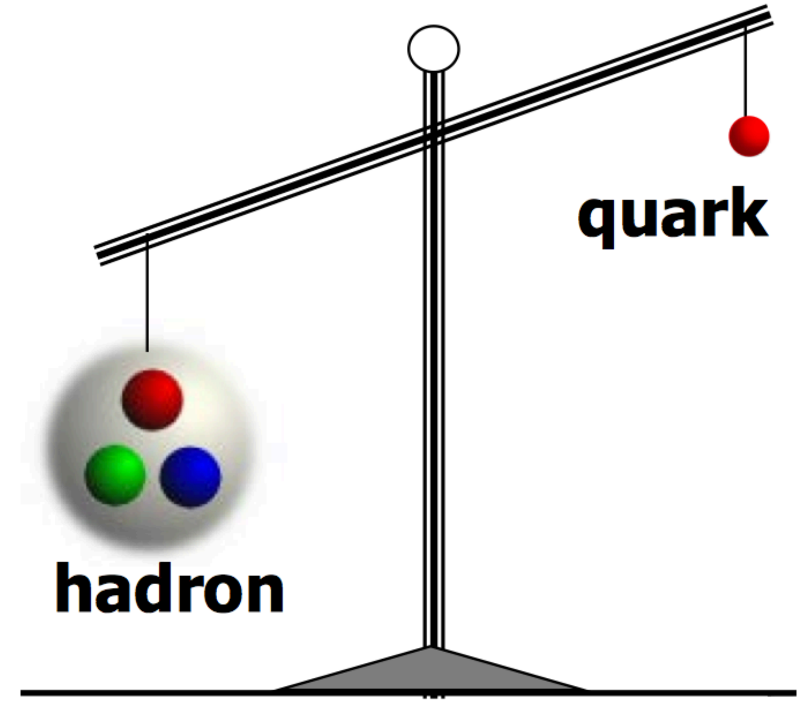
RIKEN GSI η′ PRiME

Jagiellonian University Seminar, 06. Dec. 2021

# Hadron mass




Hayano




$m_q \simeq 3$ MeV

$m_N \simeq 1000$ MeV

**"Chiral" condensate**

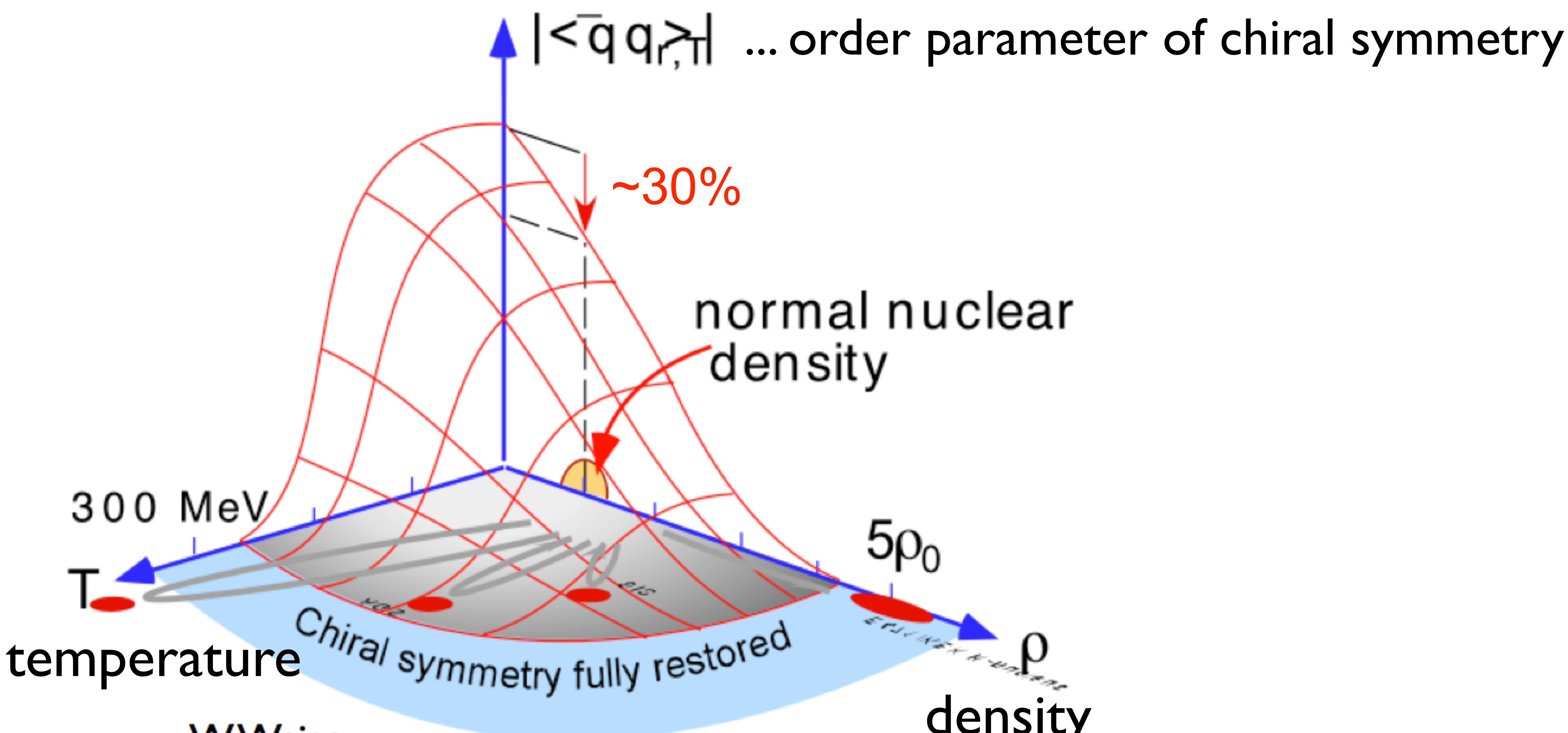
Nambu (1960) Hatsuda

QCD vacuum : spontaneous breaking of chiral symmetry

- Hadron masses are dynamically generated
- π, K, η ~ Nambu-Goldstone boson

# Restoration of chiral symmetry

- Chiral symmetry could be partially restored in finite T and/or ρ




W.Weise, NPA553(93)59.

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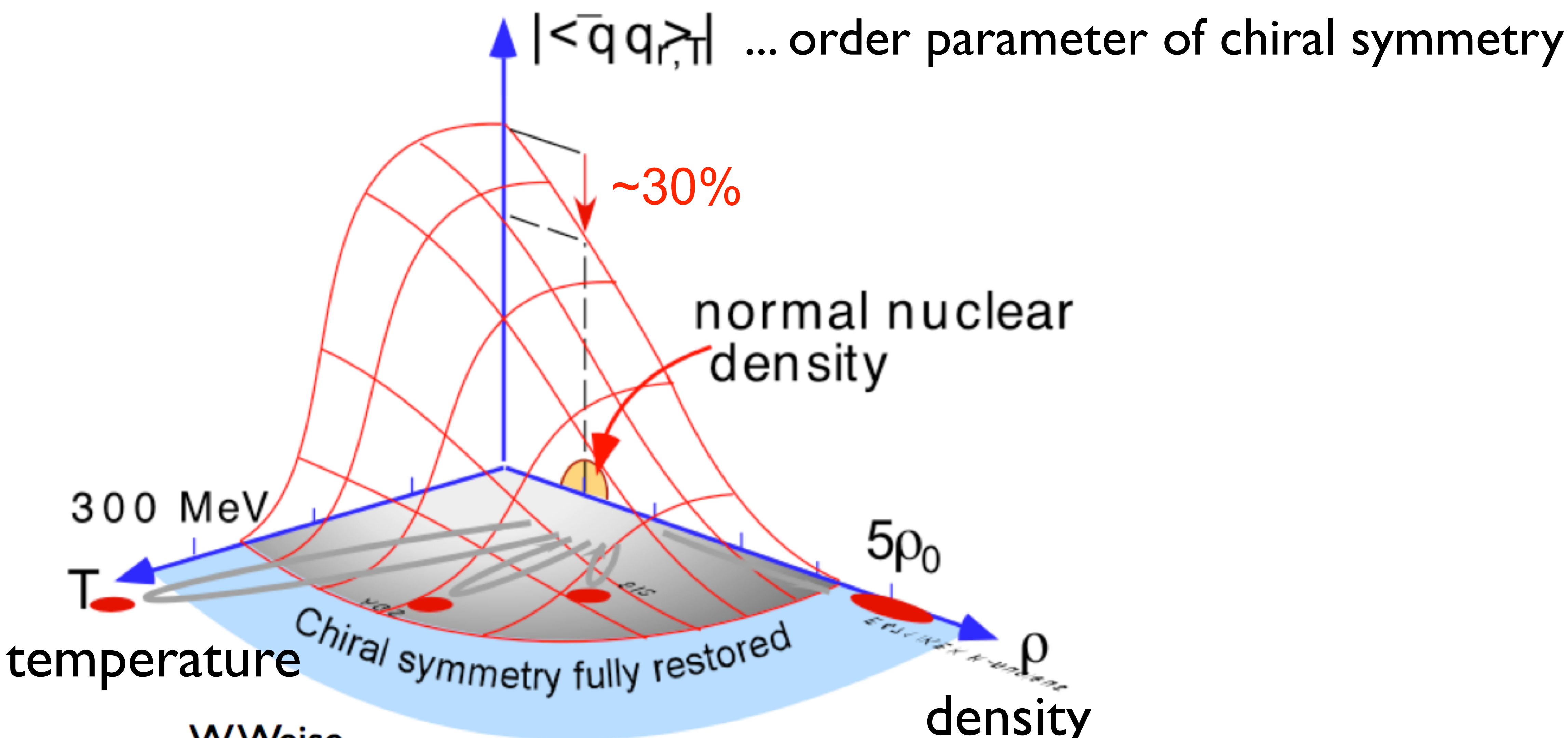
- Hadron properties (e.g., mass, width) under restoration of chiral symmetry

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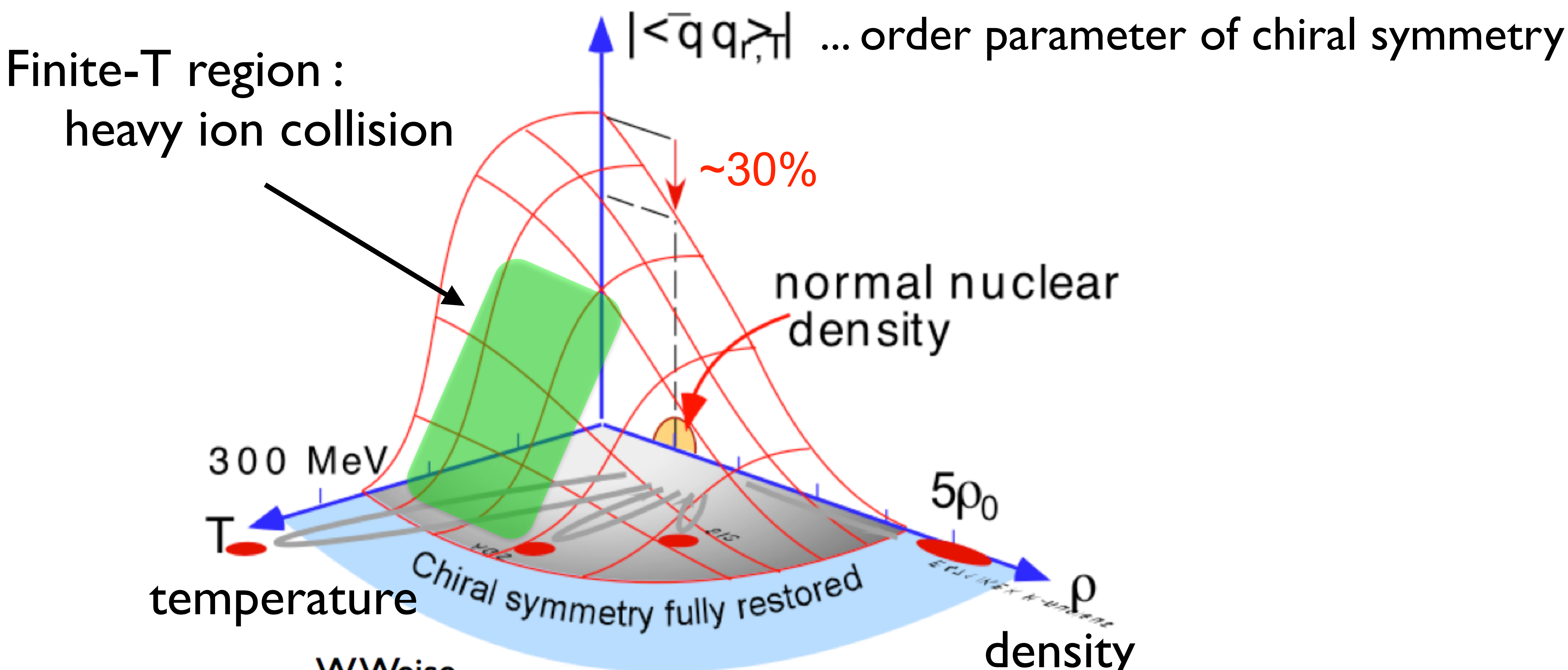


W.Weise, NPA553(93)59.

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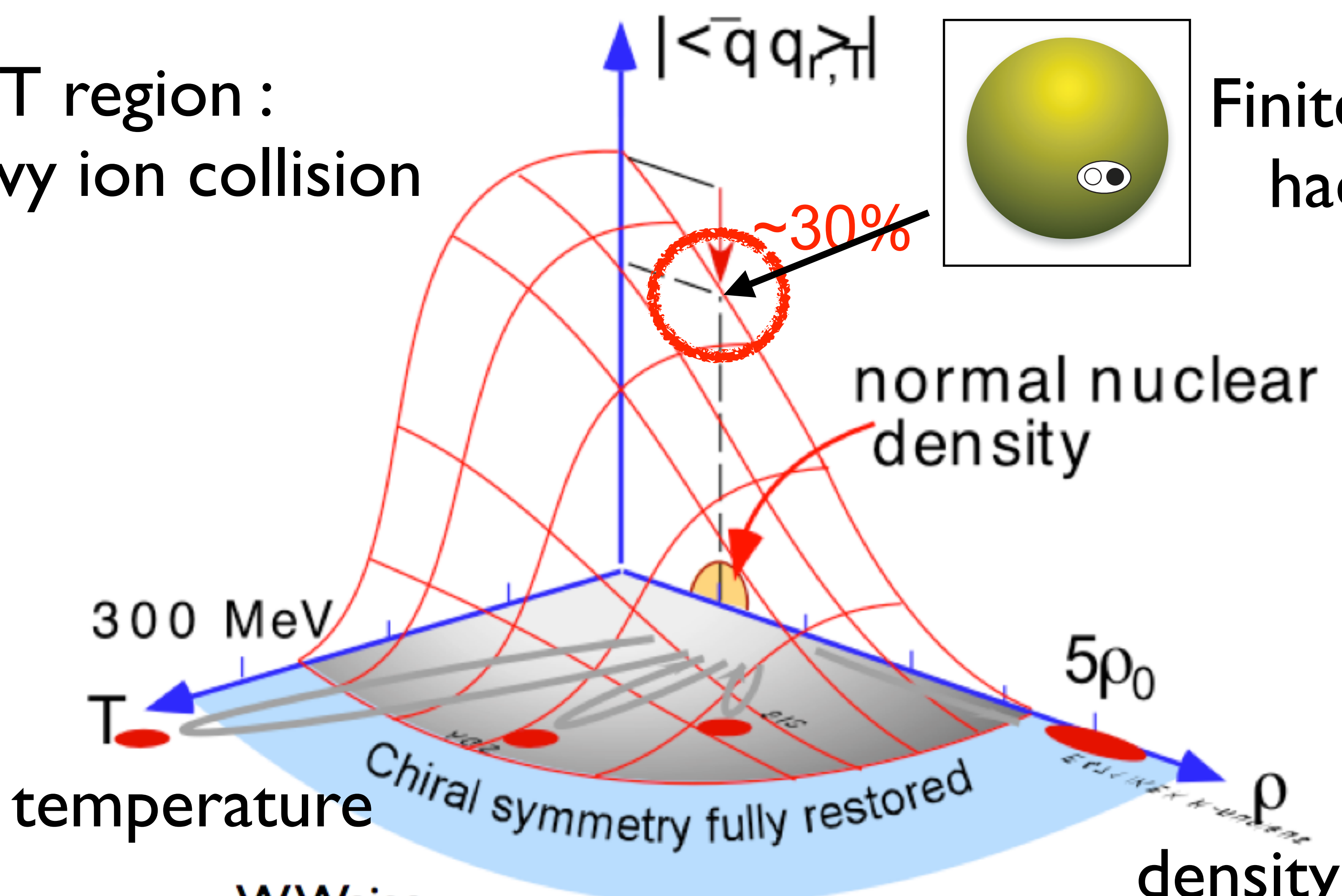
Finite-T region :
heavy ion collision

Finite-ρ, T=0 :
hadron in nuclear medium

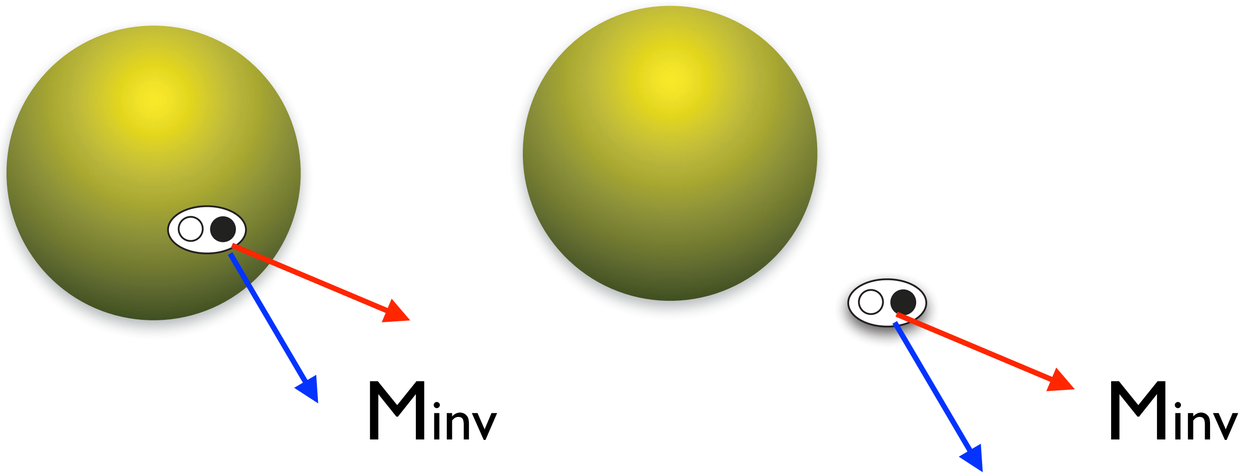



W.Weise, NPA553(93)59.

# Experimental approach

Invariant mass spectroscopy

- produce mesons in nucleus, some may decay in nucleus
- reconstruct invariant-mass from $e^+e^-$ decay etc.



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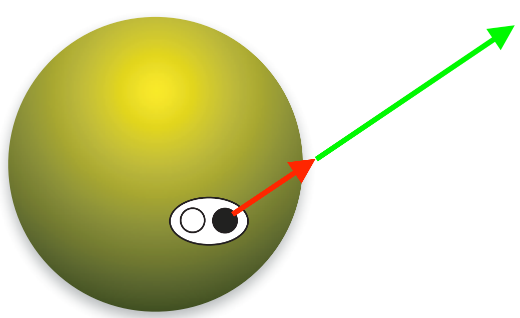
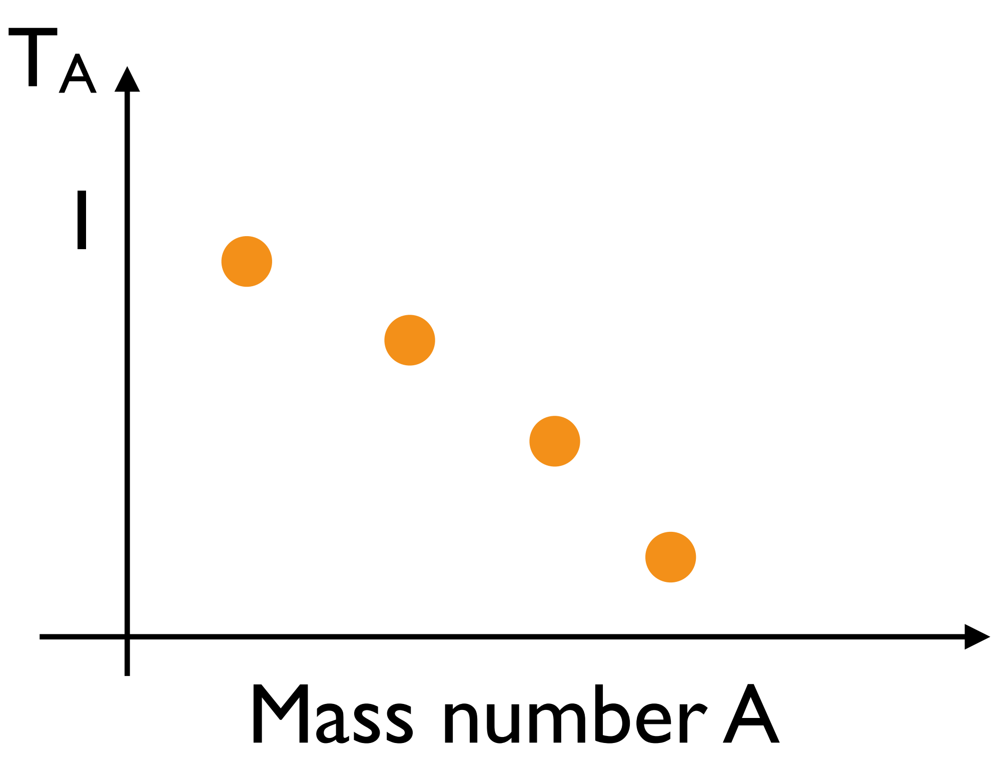
Transparency ratio

- $T_A = \sigma(\gamma A \rightarrow XA') \,/\, A \times \sigma(\gamma N \rightarrow XN)$
- information on in-medium width





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Excitation function, Momentum distribution

- enhancement in production cross section
- shift in momentum distribution of meson

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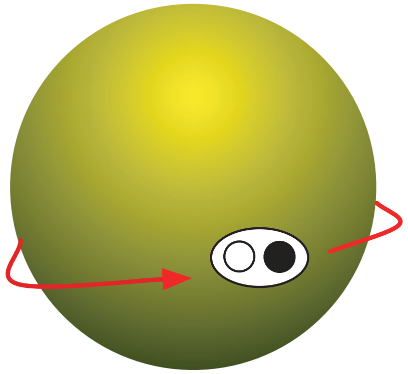
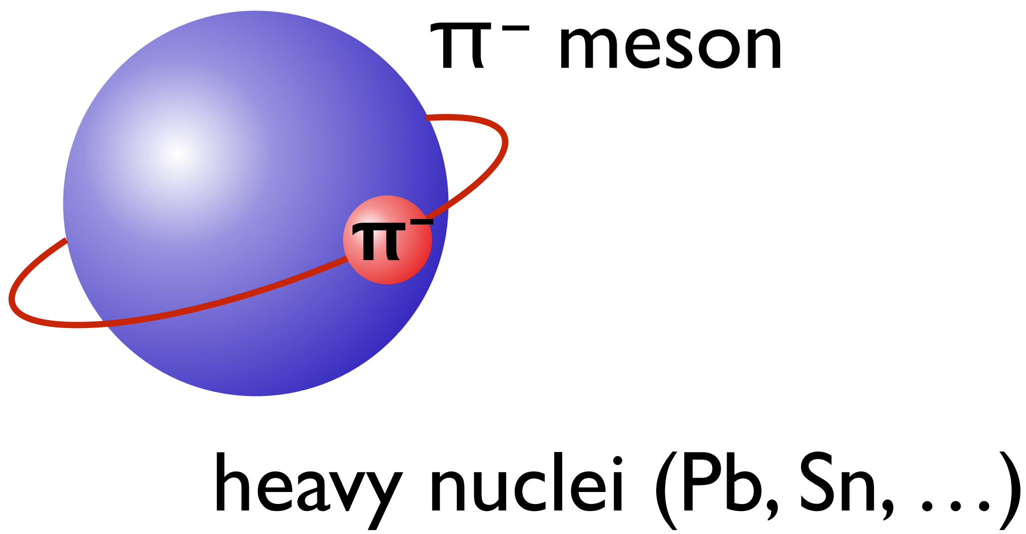
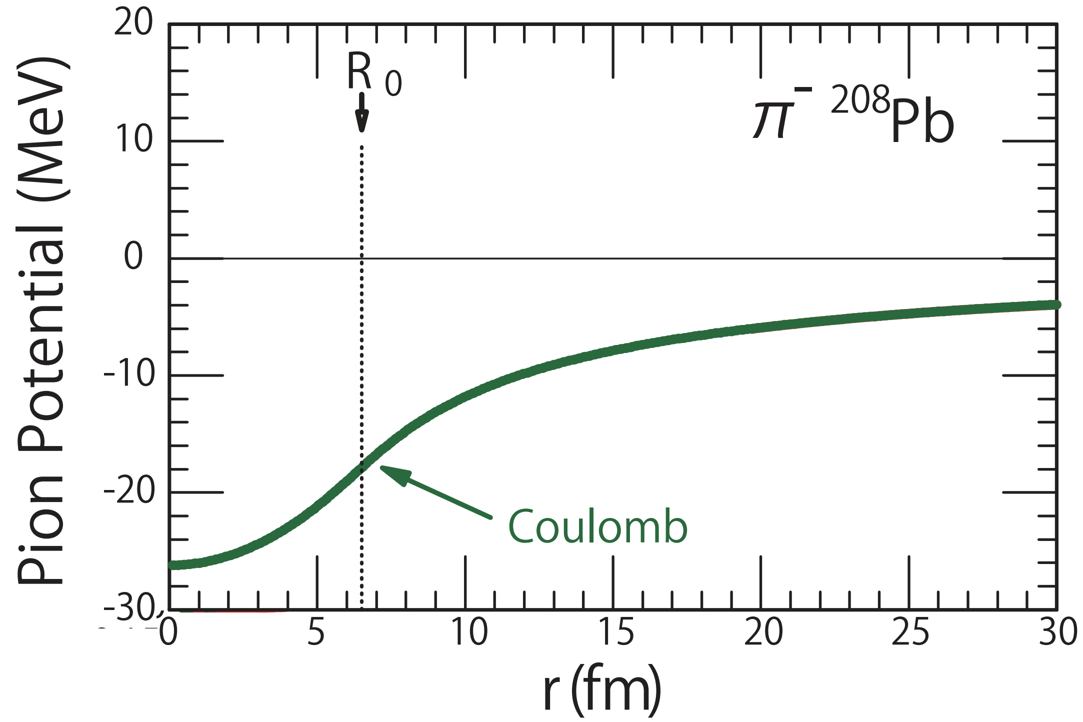
Spectroscopy of bound states in nuclei

- well defined quantum states (nucleus x meson)
- overlap with nucleus → probe for finite density



# Deeply bound π⁻ states in nuclei




- Coulomb + strong interaction

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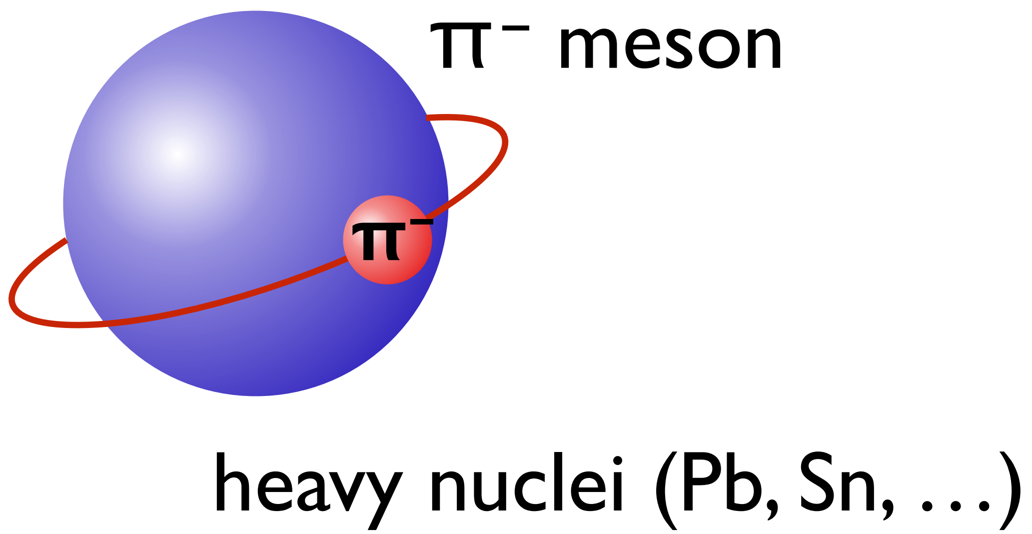


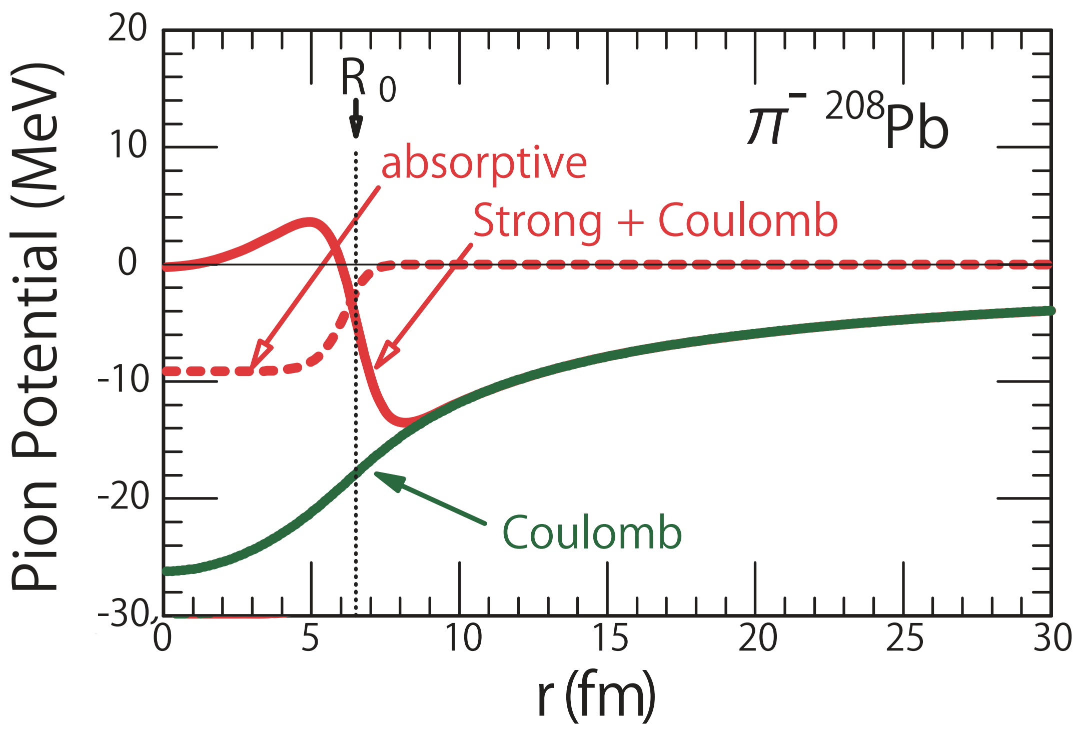


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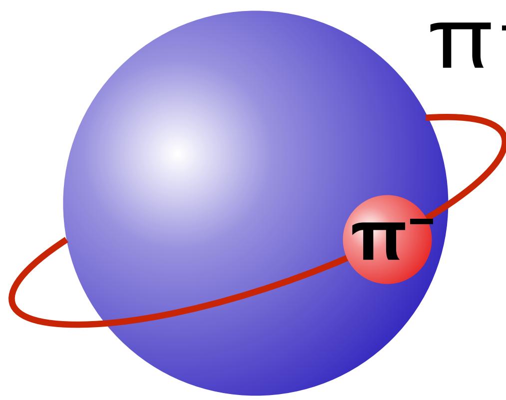
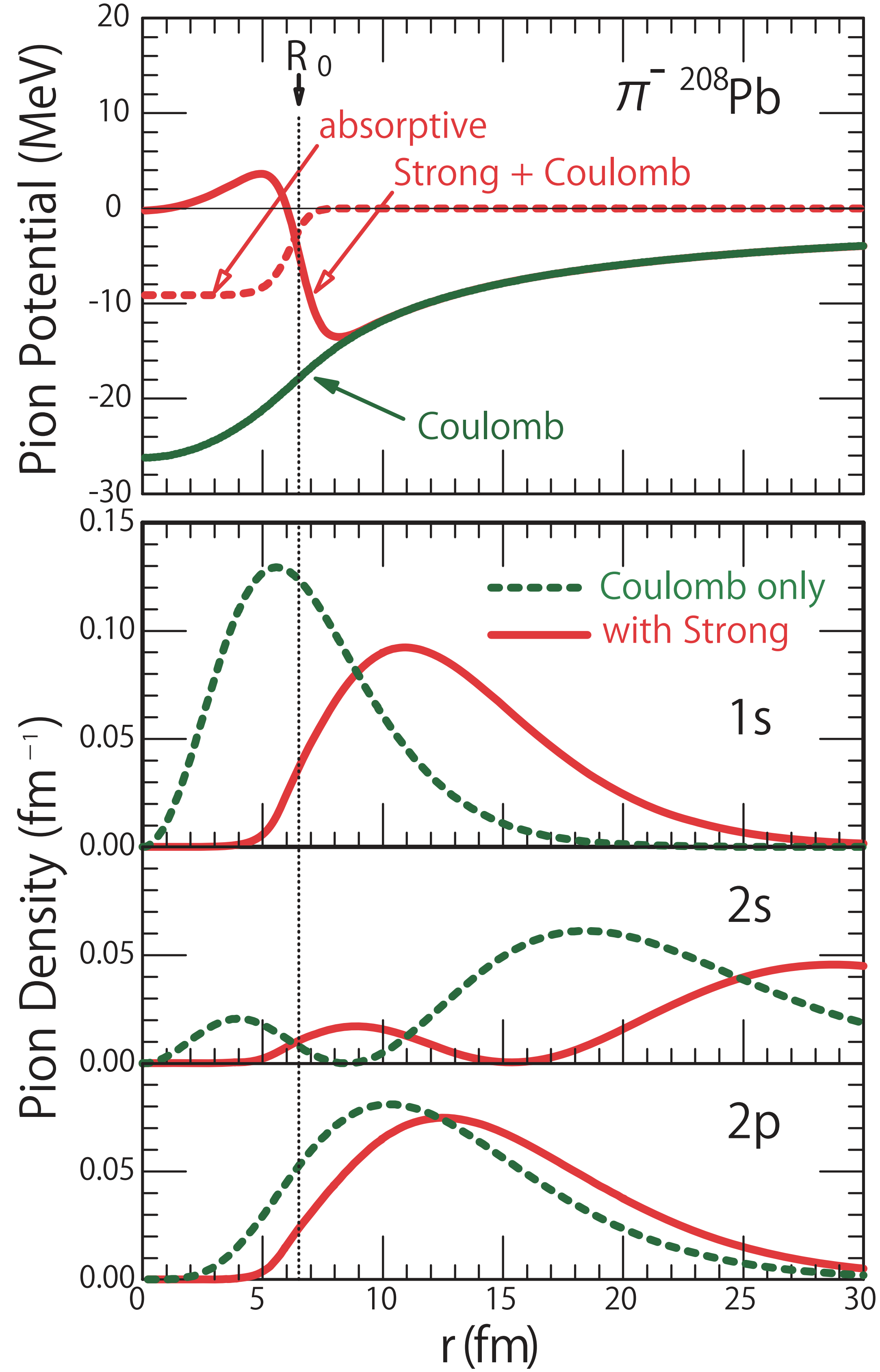



heavy nuclei (Pb, Sn, ...)

- Coulomb + strong interaction
- deeply bound states (1s, 2p, ...) near nuclear surface
  → probe for finite density




H. Toki, T. Yamazaki, Phys. Lett. B (1988).
E. Friedman, G. Soff, J. Phys. G11, L37 (1985).

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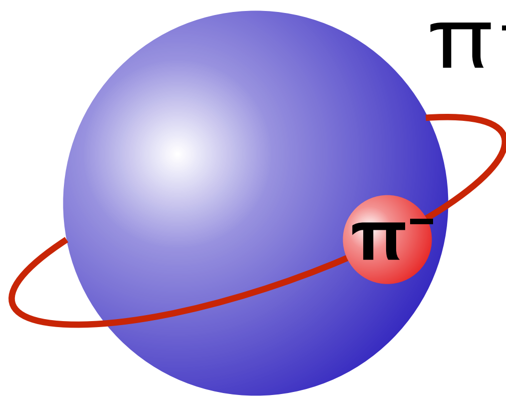


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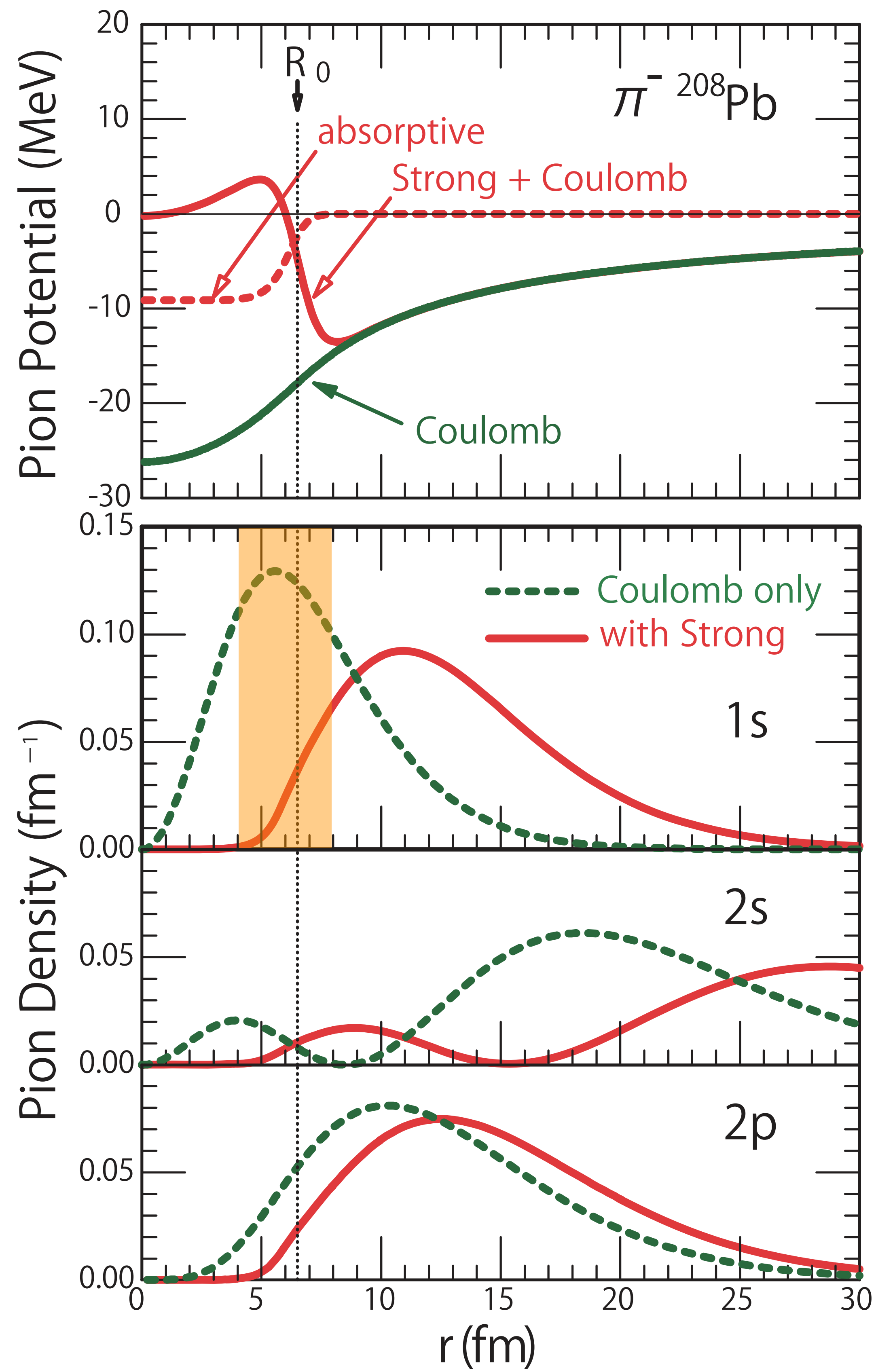
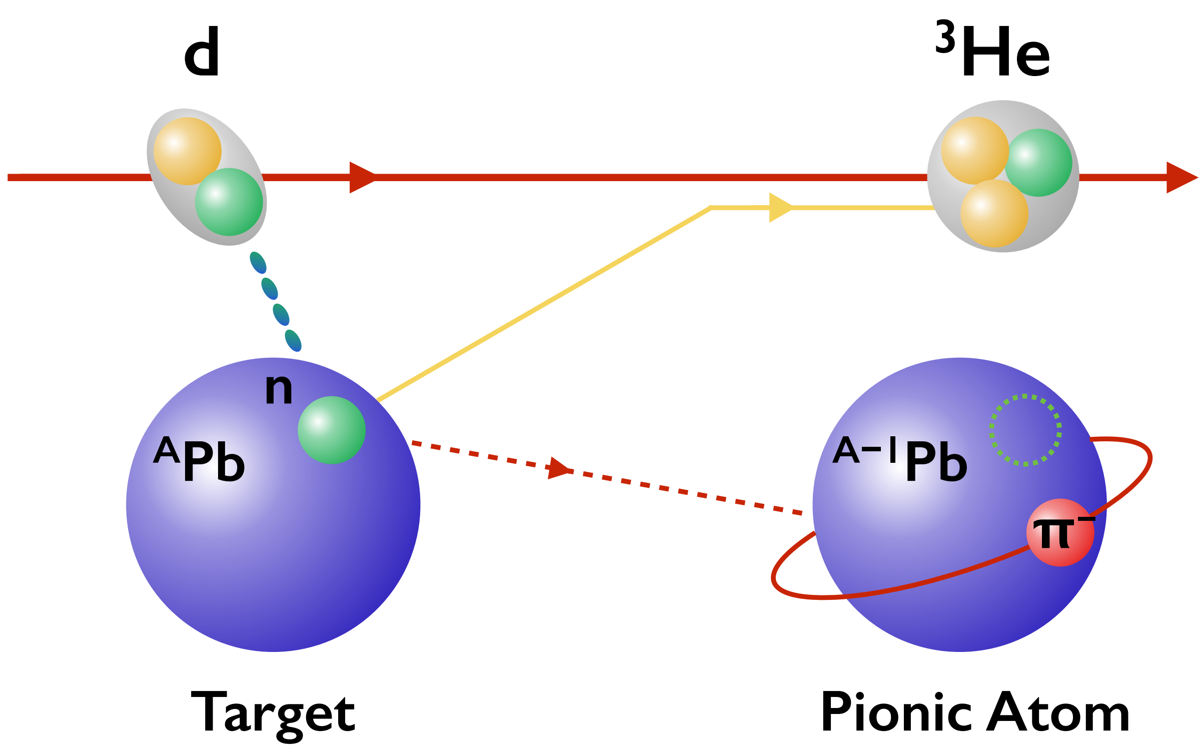



H. Toki, T. Yamazaki, Phys. Lett. B (1988).
E. Friedman, G. Soff, J. Phys. G11, L37 (1985).

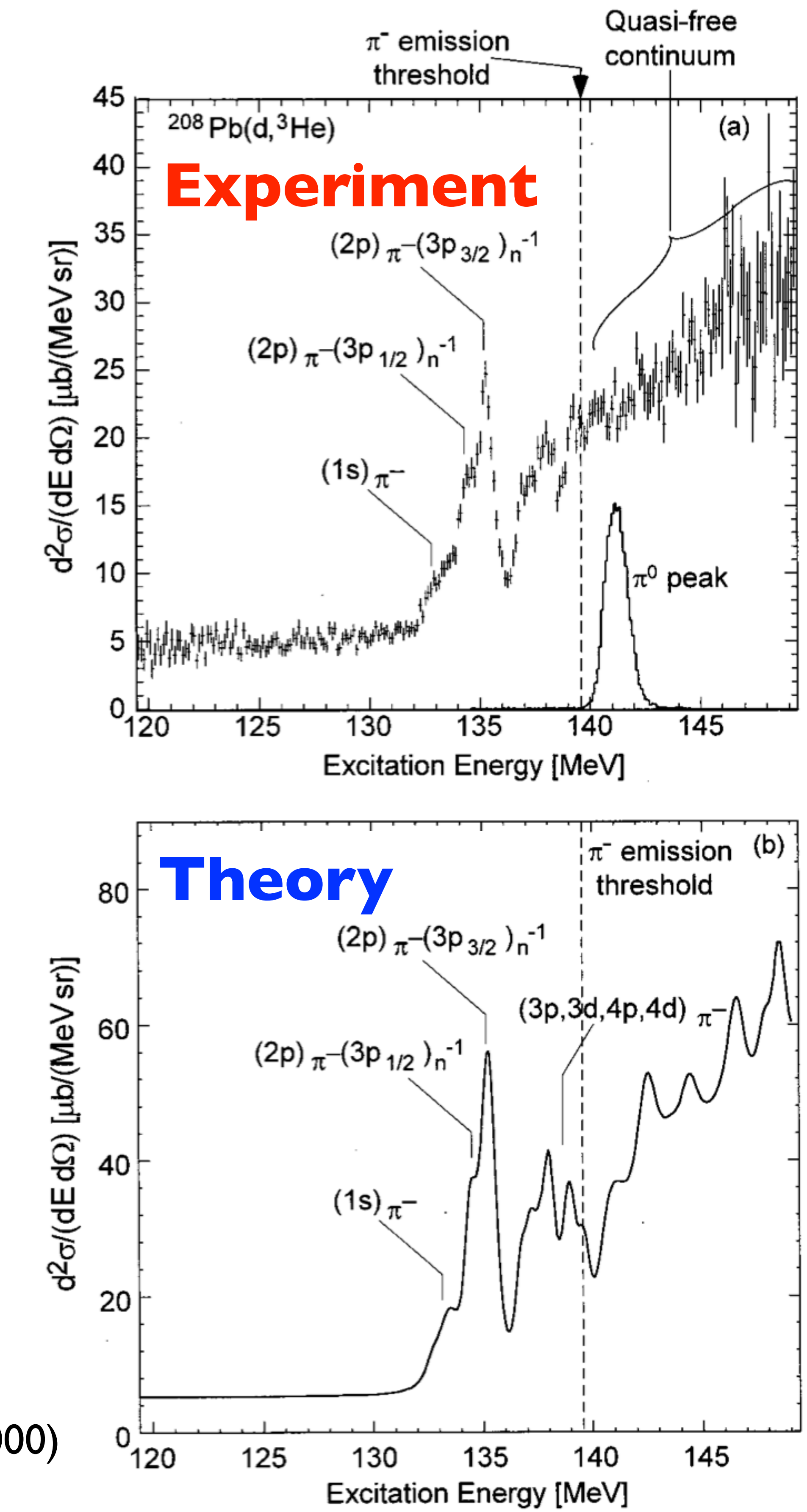
# Deeply bound π⁻ states in nuclei

Discovery at FRS, GSI (1996)

π-transfer ($d$, $^3$He) reaction




- recoil-free kinematics to directly populate deeply-bound states
- [π bound states] × [neutron hole states]




K. Itahashi *et al.*, PRC 62, 025202 (2000)

# Deeply bound $\pi^-$ states in nuclei

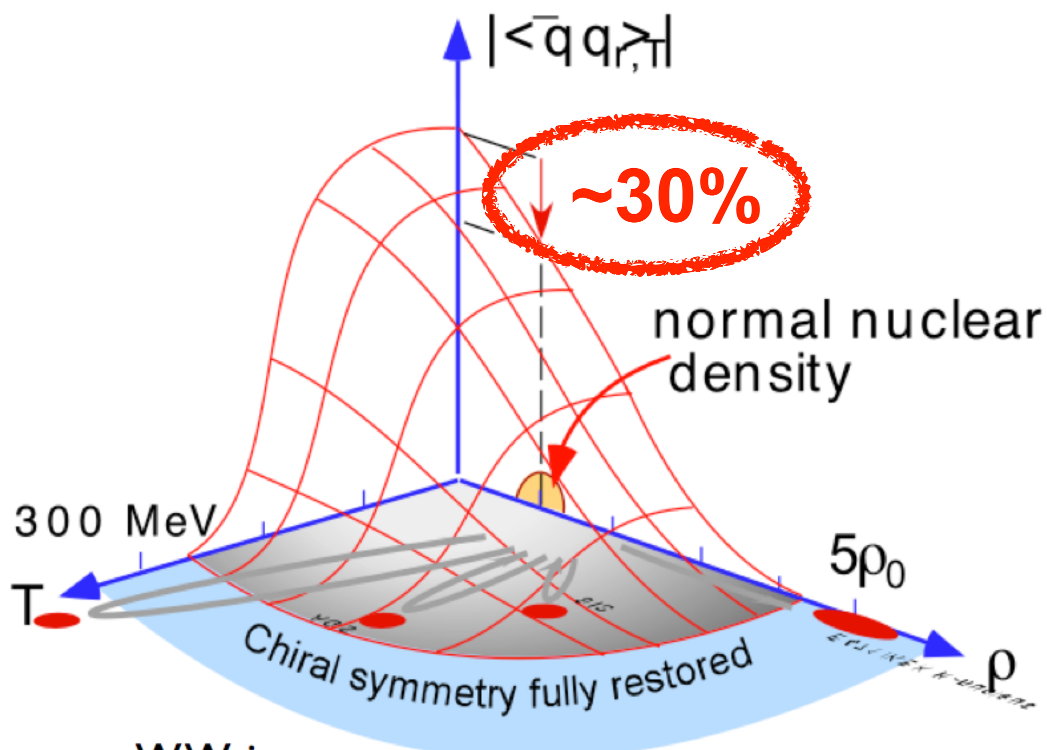
Pionic states in Sn isotopes

- 1s states in $^{115,119,123}$Sn observed
- in-medium s-wave isovector scattering amplitude

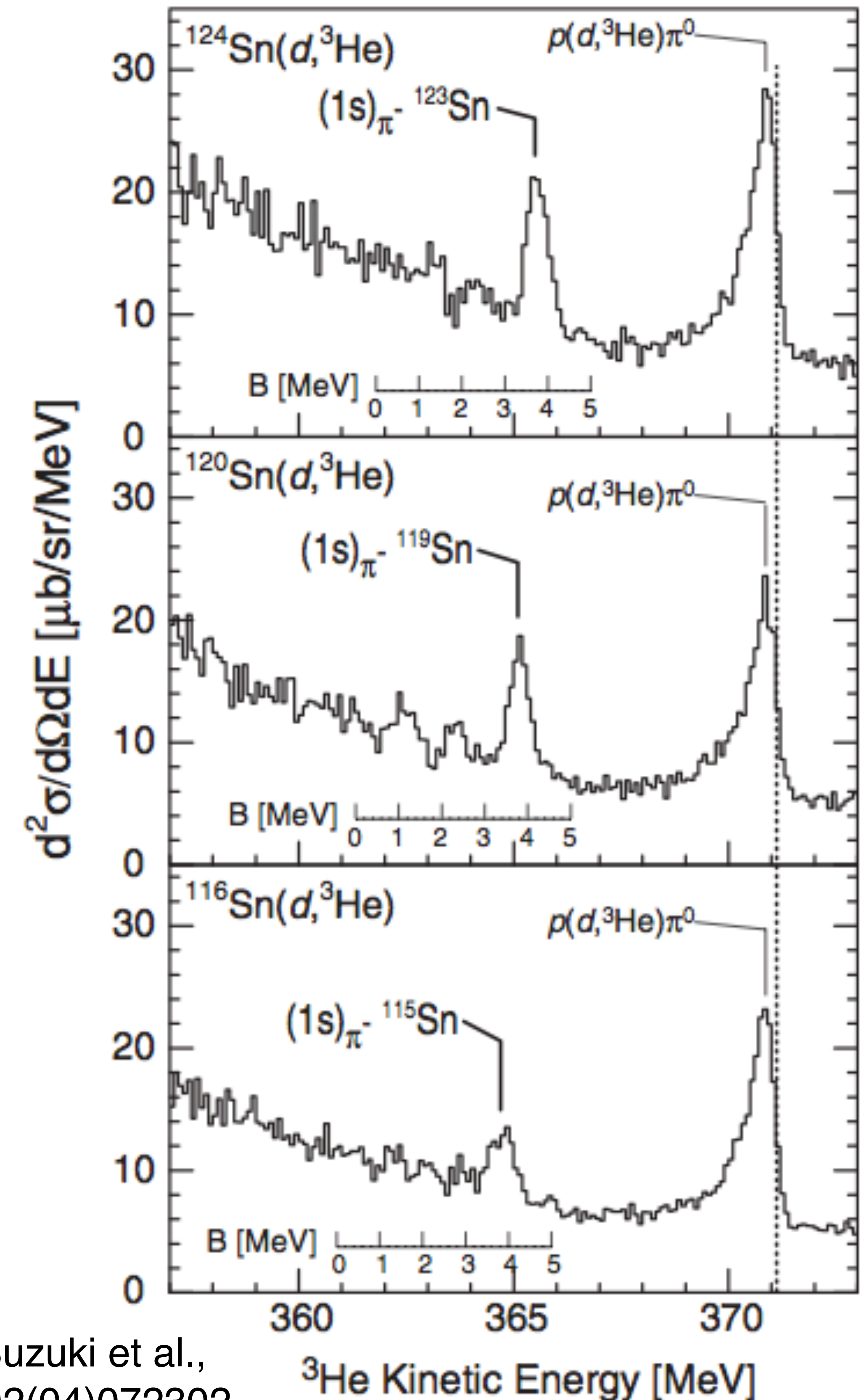
$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho(r) + b_1\delta\rho(r)\} + \epsilon_2 B_0 \rho(r)^2]$$

- comparison with free $b_1$

→ $\langle\bar{q}q\rangle_{\rho_0}/\langle\bar{q}q\rangle_0 \approx 0.67$




W.Weise, NPA553(93)59.



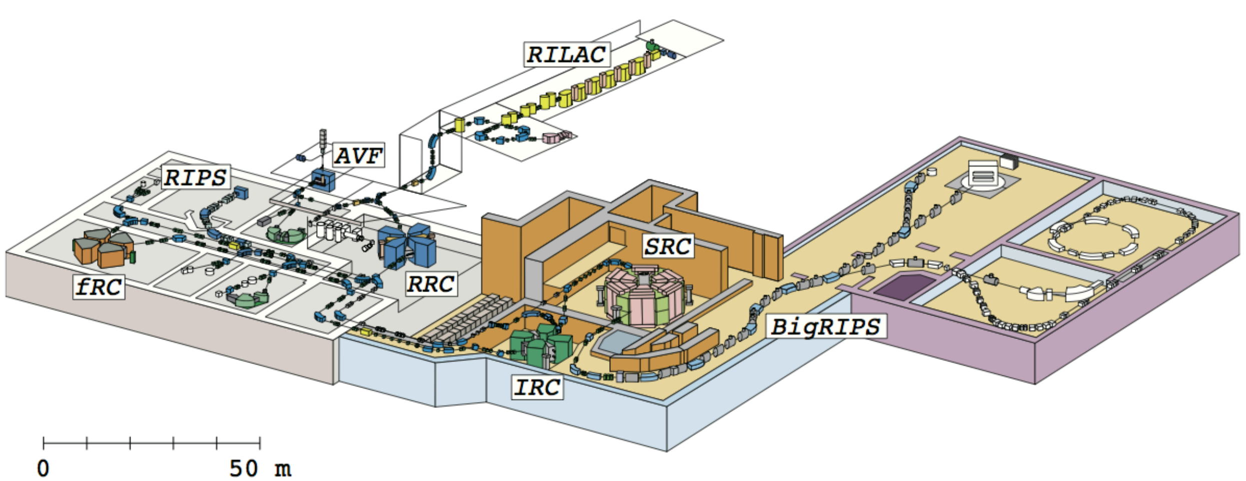

K. Suzuki et al., PRL92(04)072302

# Deeply bound $\pi^-$ states in nuclei

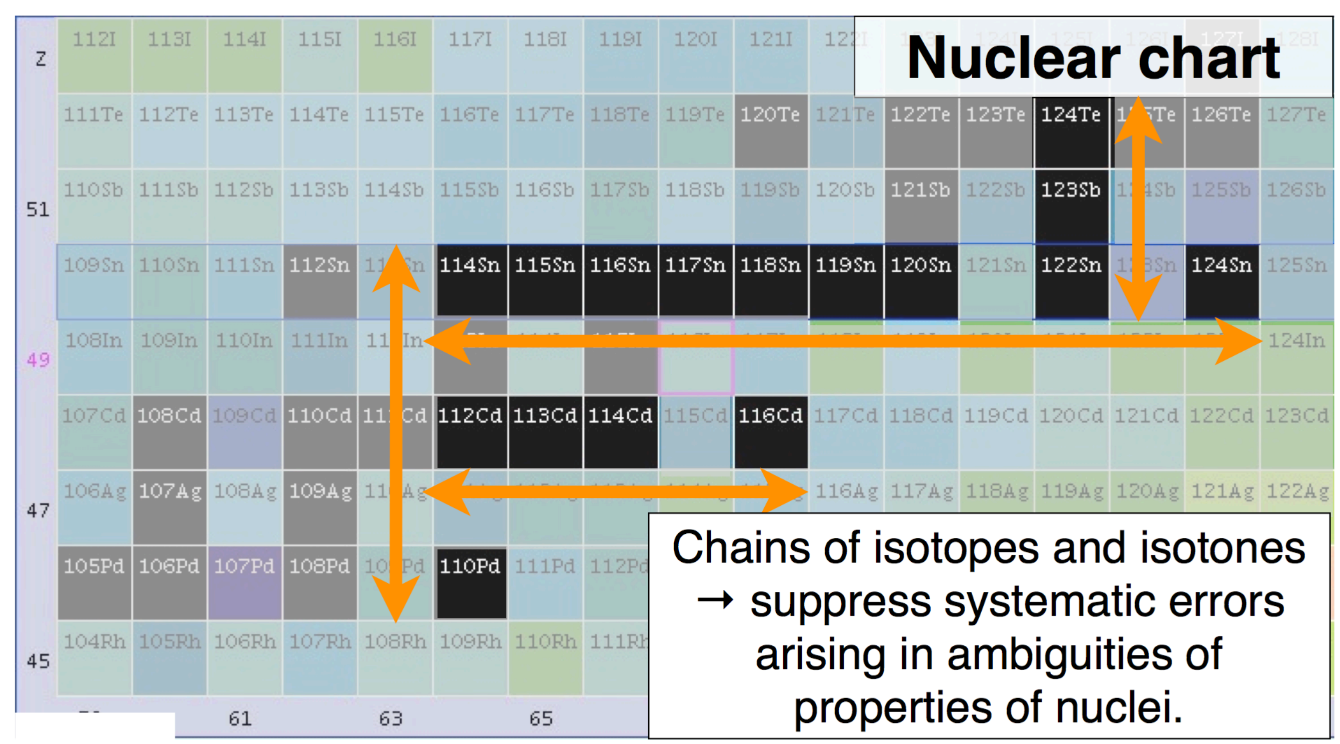
<u>Pionic-atom factory experiments at RIKEN (2010–)</u>

- intense *d* beam from SRC
  + large-acceptance BigRIPS spectrometer
- systematic study in a wide region along Sn isotopes

RIBF, RIKEN




T. Nishi




NNDC,BNL

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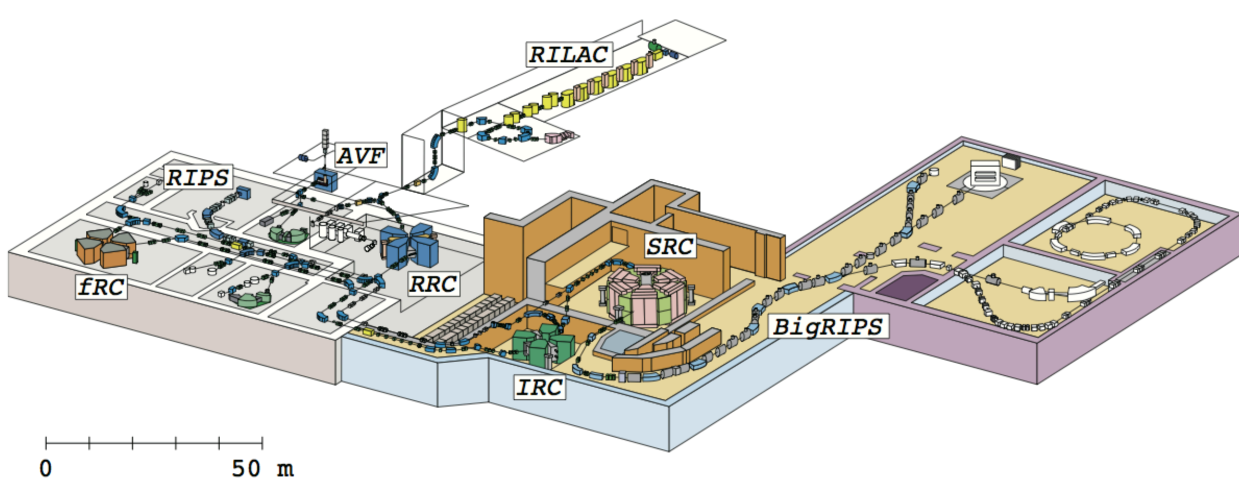
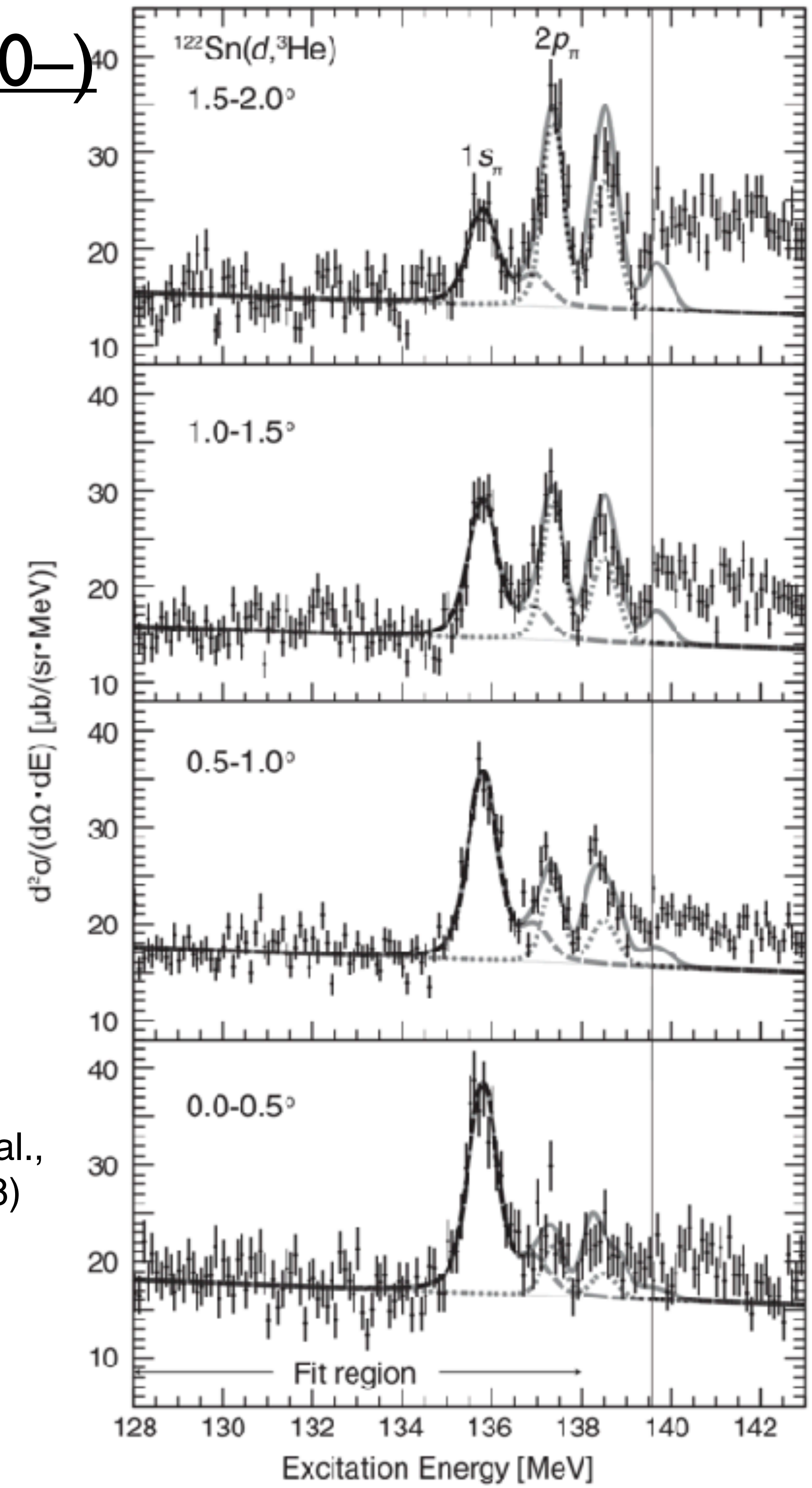



T. Nishi, K. Itahashi et al., PRL120, 152505 (2018)



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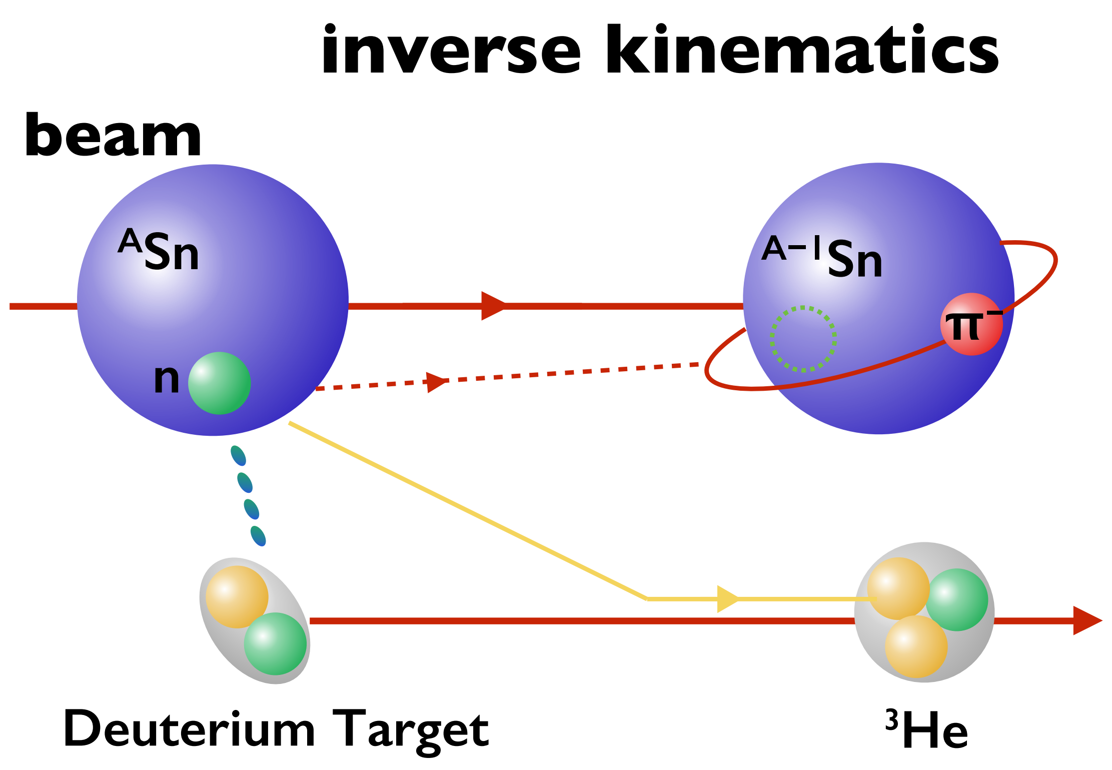
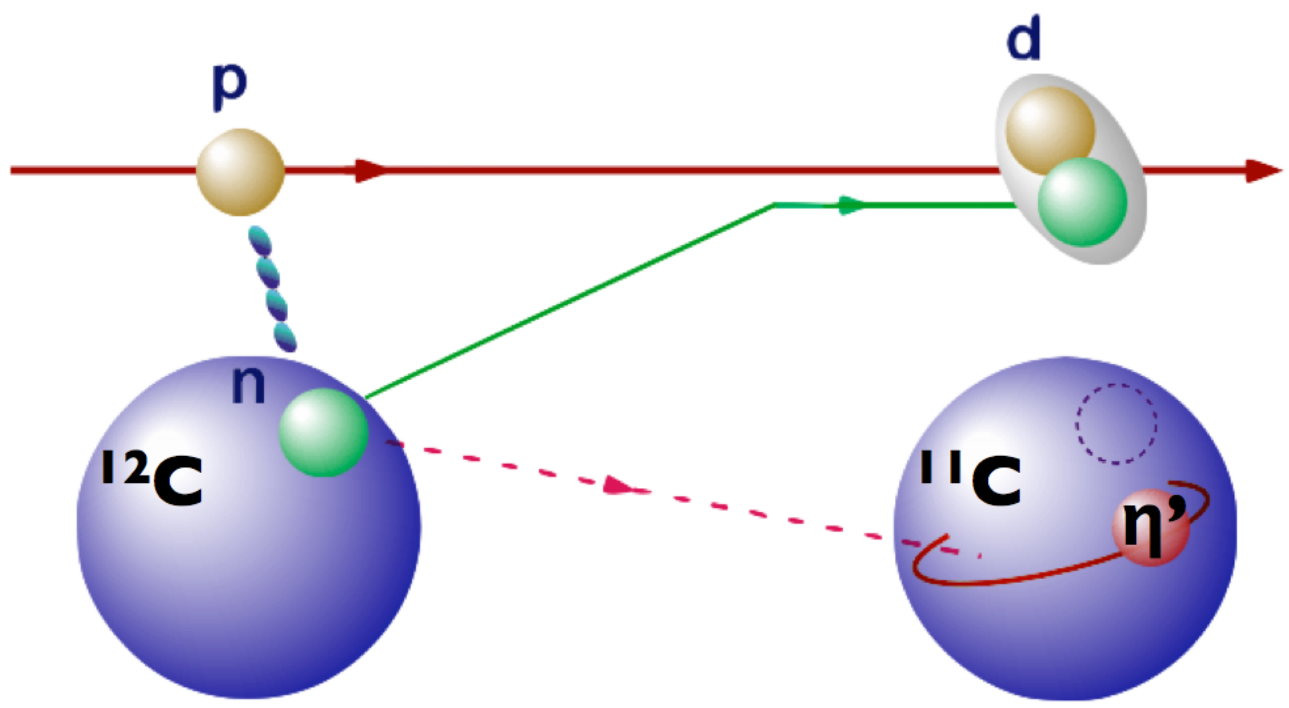
D(HI, $^{3}$He) reaction

- high resolution owing to its kinematics
- π atom is formed in projectile nucleus (Xe, U, or unstable nuclei?)
- ρ dependence of quark condensate



# Search for η′-nucleus bound states



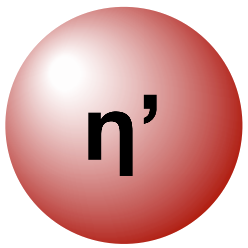
# η-PRiME/Super-FRS collaboration

## S437 experiment at GSI (2014)

Y. Ayyad, J. Benlliure, K.-T. Brinkmann, S. Friedrich, H. Fujioka, H. Geissel,
J. Gellanki, C. Guo, E. Gutz, E. Haettner, M. N. Harakeh, R. S. Hayano,
Y. Higashi, S. Hirenzaki, C. Hornung, Y. Igarashi, N. Ikeno, K. Itahashi,
M. Iwasaki, D. Jido, N. Kalantar-Nayestanaki, R. Kanungo, R. Knöbel,
N. Kurz, V. Metag, I. Mukha, T. Nagae, H. Nagahiro, M. Nanova, T. Nishi,
H. J. Ong, S. Pietri, A. Prochazka, C. Rappold, M. P. Reiter, J.L. Rodríguez-Sánchez
C. Scheidenberger, H. Simon, B. Sitar, P. Strmen, B. Sun, K. Suzuki,
I. Szarka, M. Takechi, Y. K. Tanaka, I. Tanihata, S. Terashima, Y. N. Watanabe,
H. Weick, E. Widmann, J. S. Winfield, X. Xu, H. Yamakami, J. Zhao

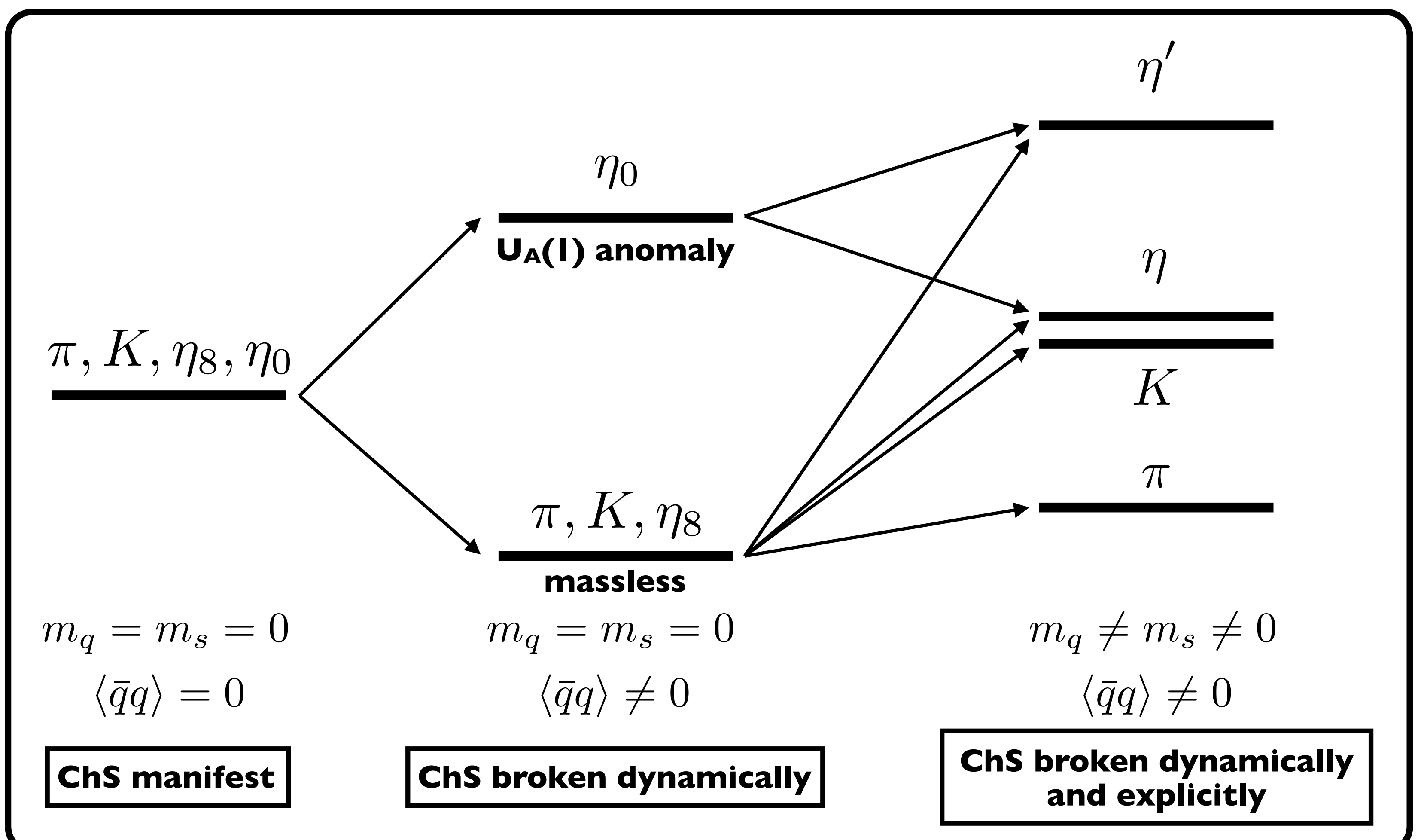
RCNP Osaka University, Universidade de Santiago de Compostela, Universität Giessen,
Kyoto University, GSI, KVI-CART University of Groningen, Beihang University,
The University of Tokyo, Nara Women's University, KEK, Tottori University,
RIKEN Nishina Center, Tokyo Metropolitan University, Saint Mary’s University,
Comenius University Bratislava, Stefan Meyer Institut, Niigata University

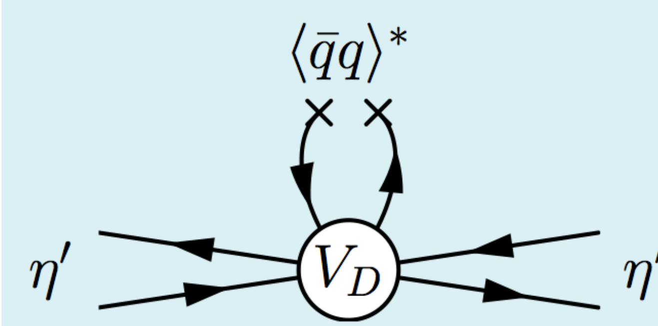
# η' meson




**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



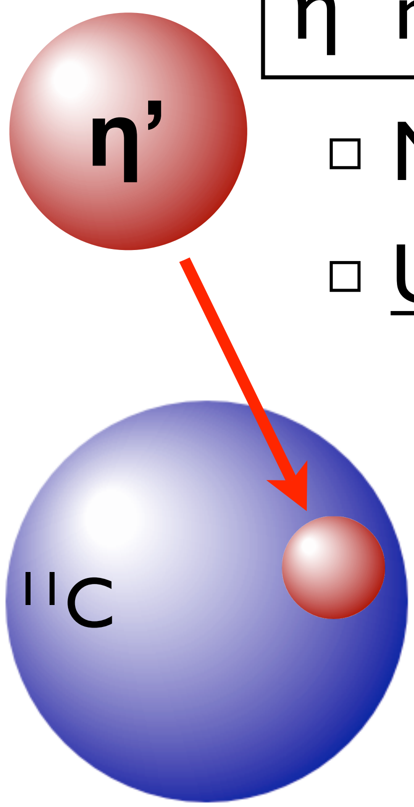




**$U_A$(1) anomaly contributes η’ mass through ChSB**

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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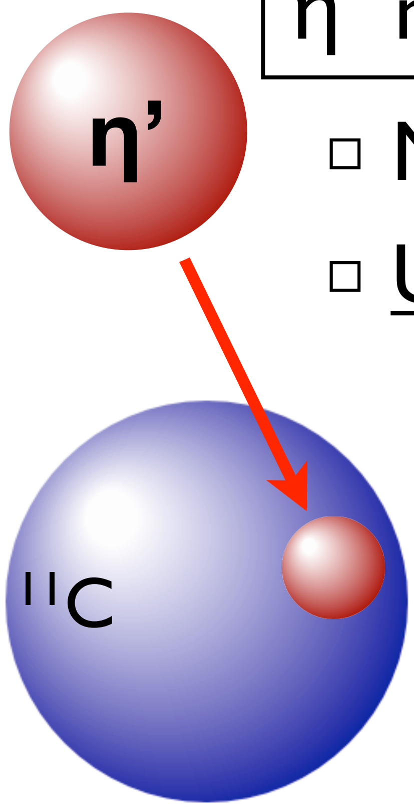
η′ meson at nuclear density

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

# η′ meson

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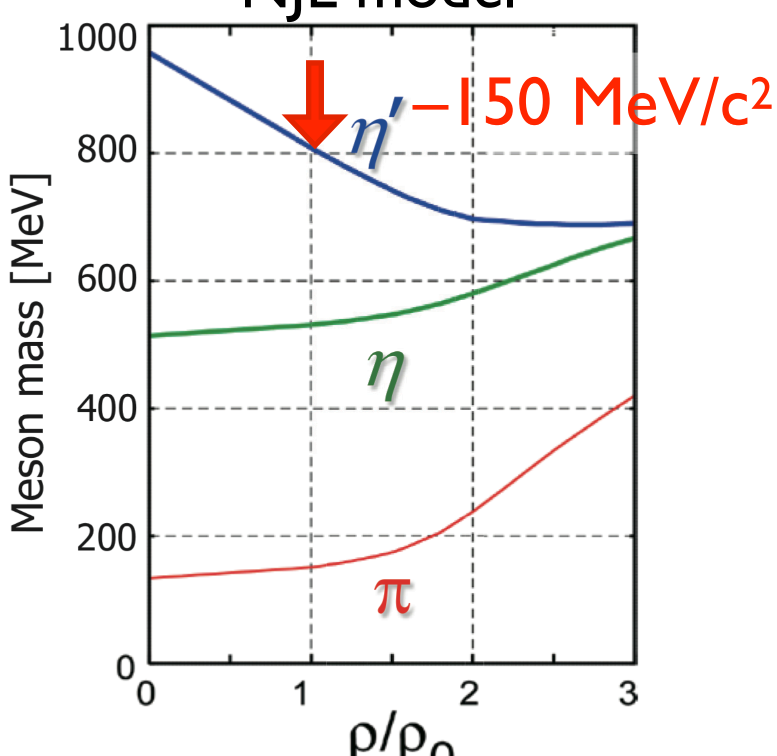
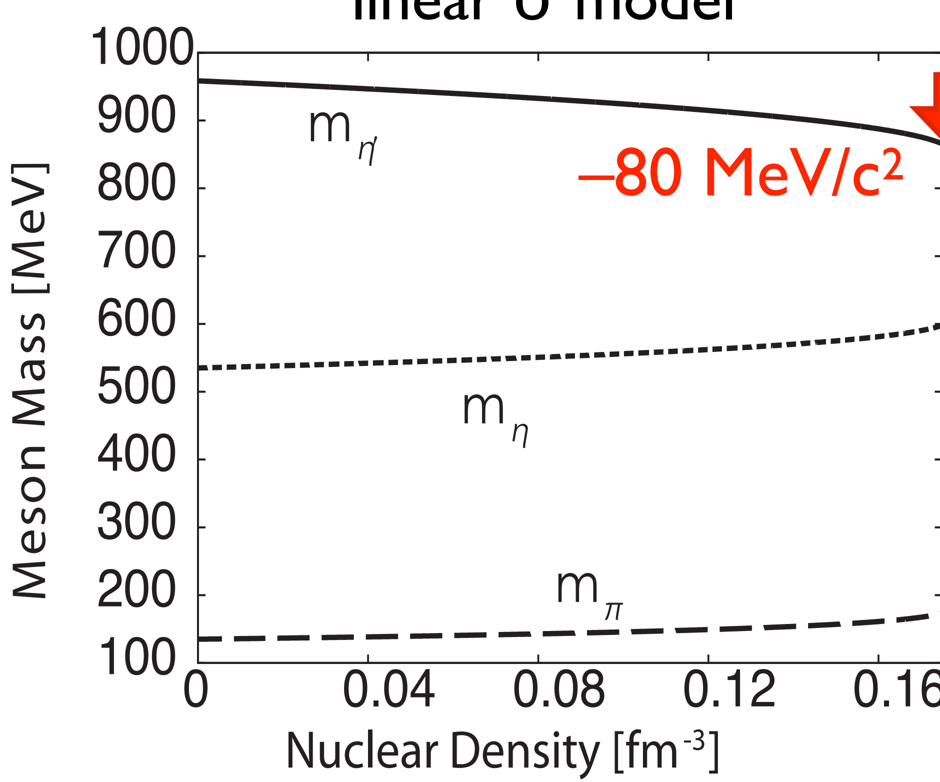
NJL model




linear σ model




QMC model :
Δm ~ −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′-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

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

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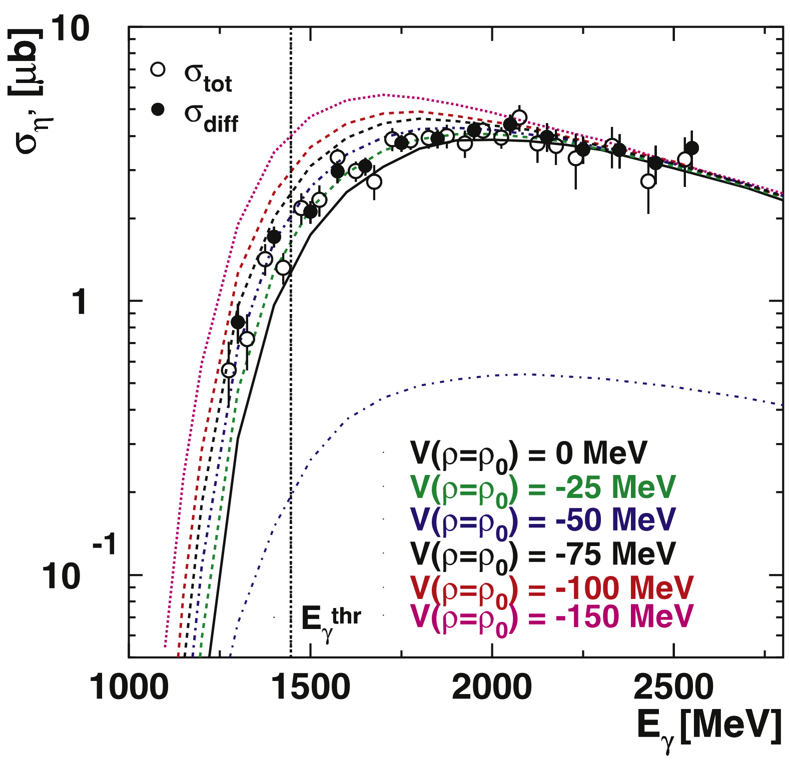
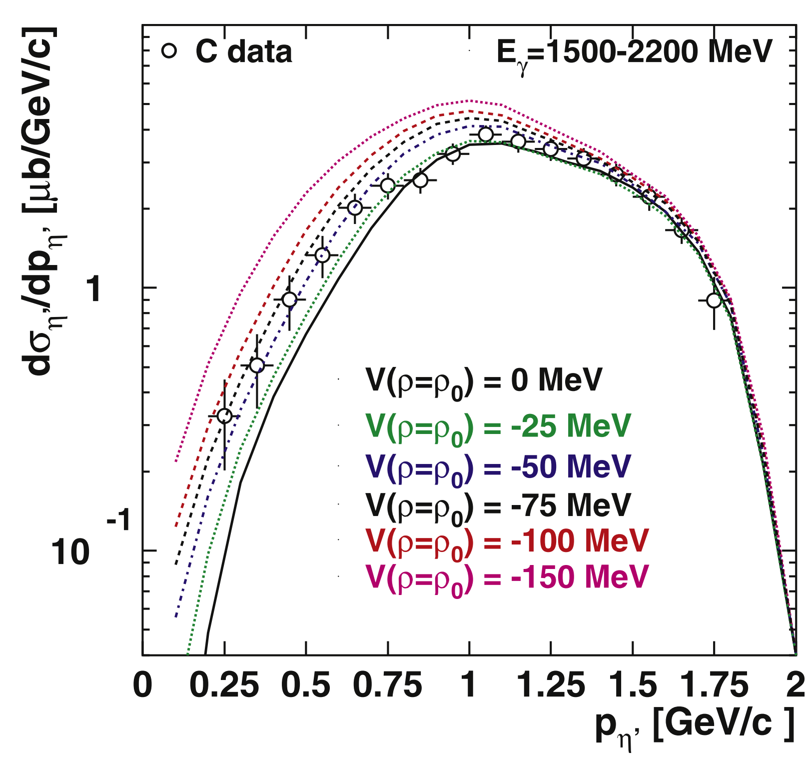
Experimental indications (CBELSA/TAPS)

- $V_0 \sim -40$ 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

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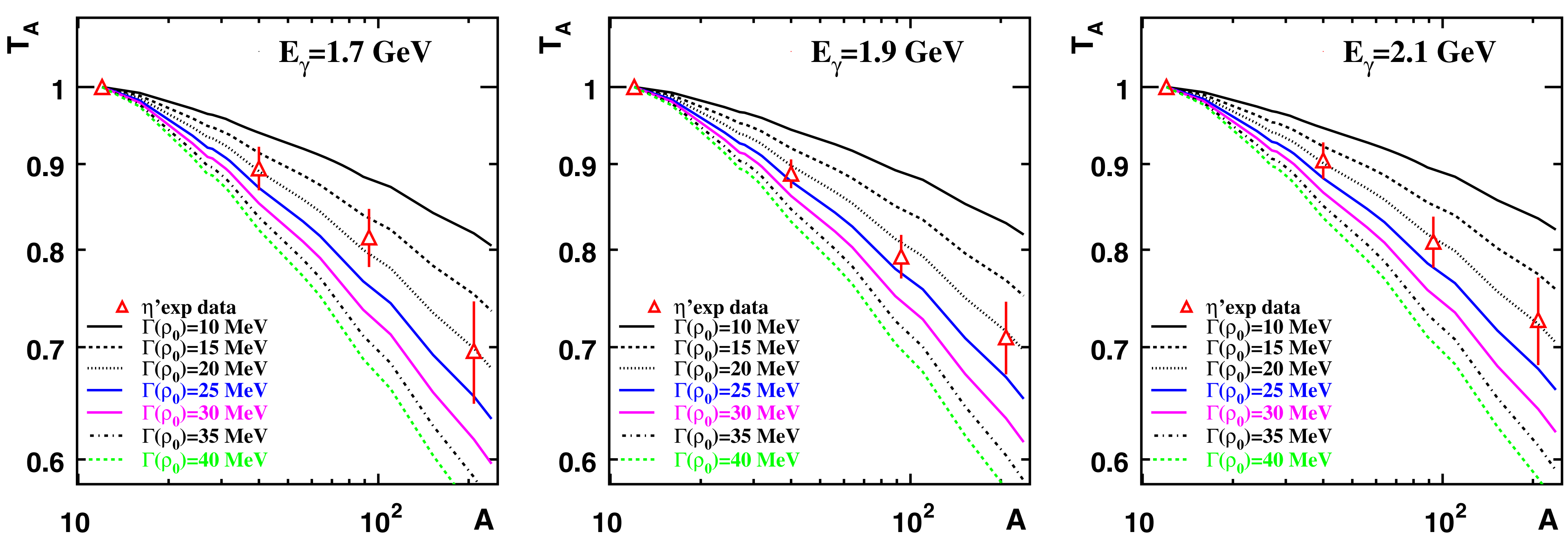
- $W_0 = -13 \pm 3\text{(stat)} \pm 3\text{(syst)}$ MeV (transparency ratio)




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.)

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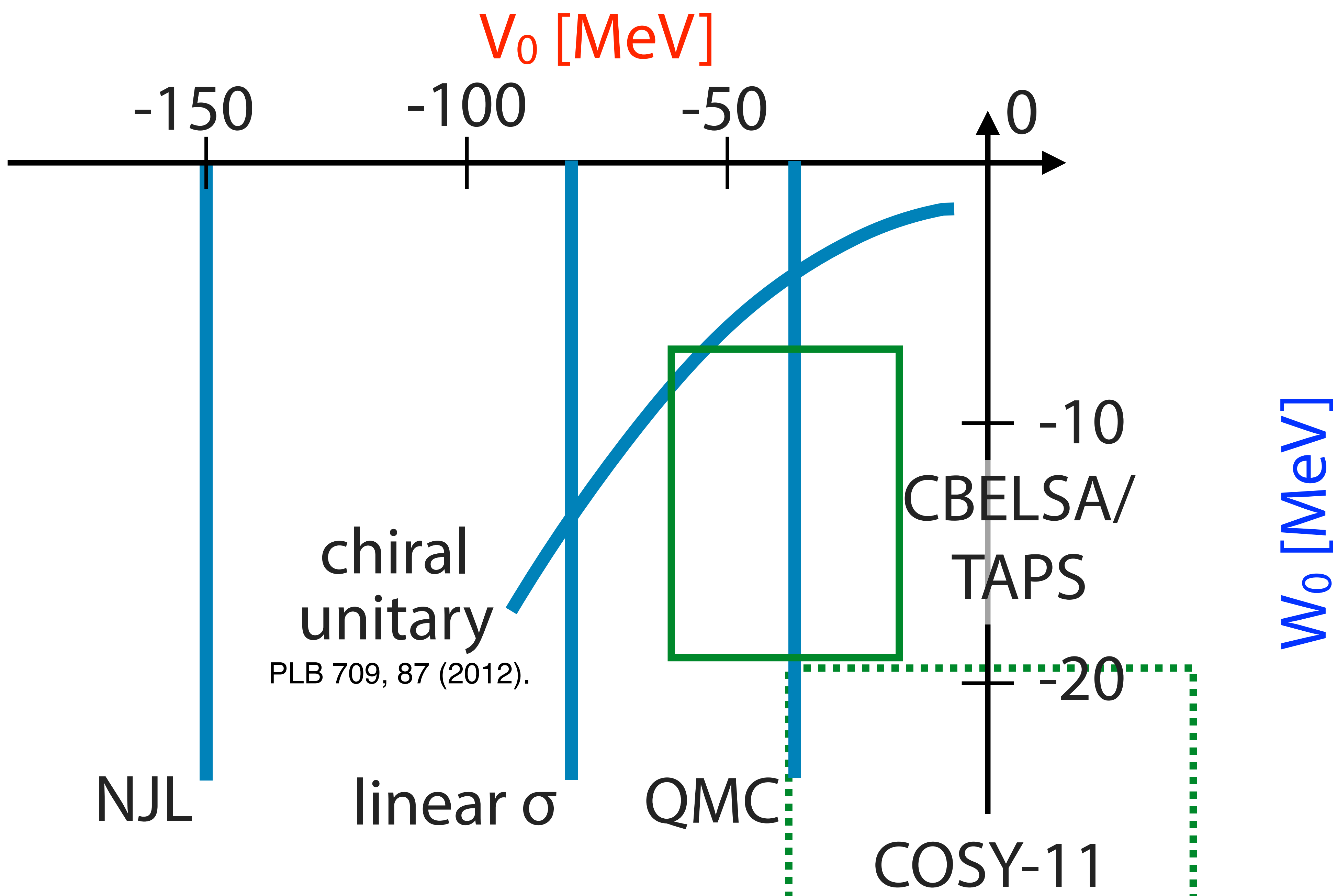

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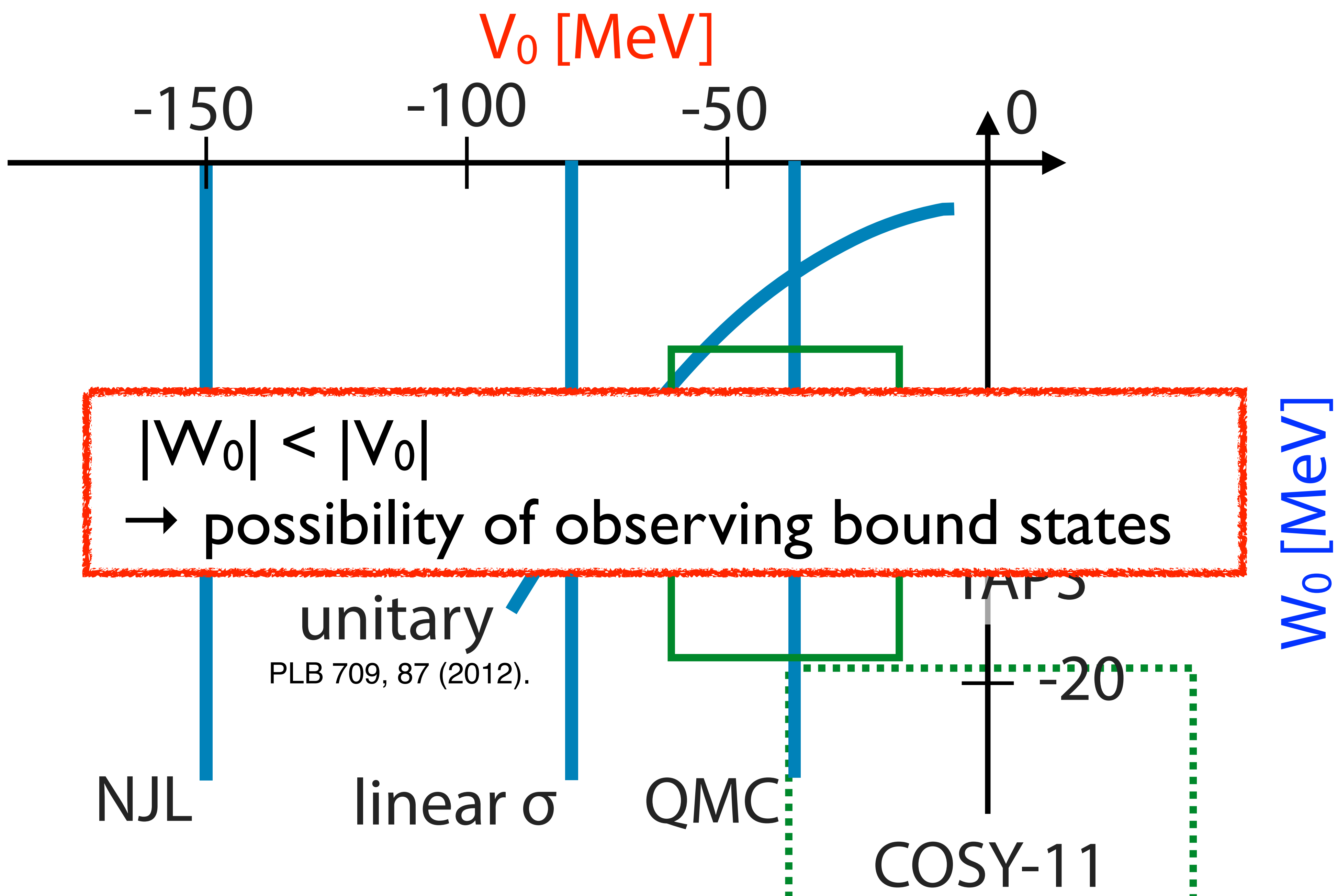
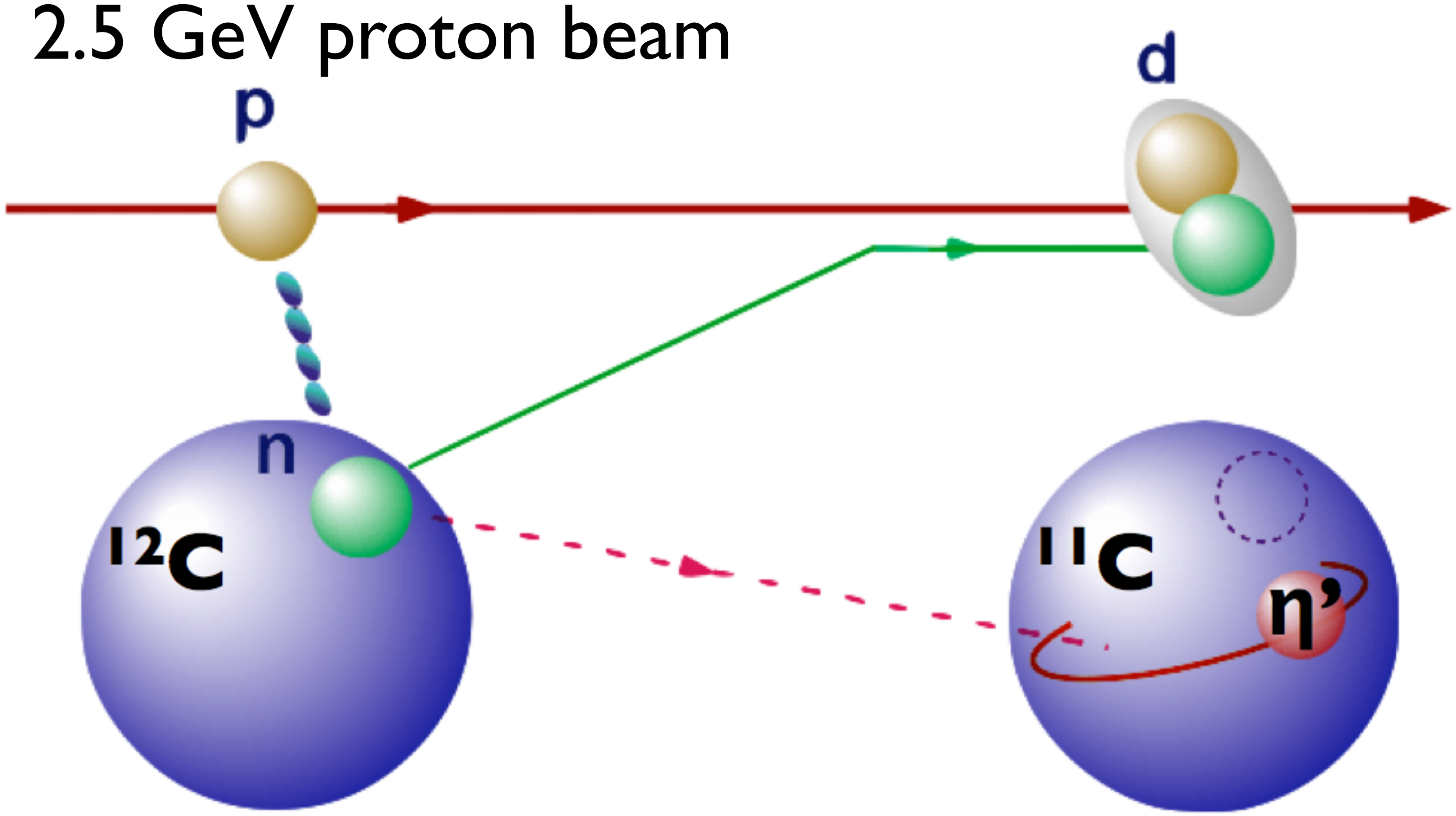



$|W_0| < |V_0|$

→ possibility of observing bound states

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

2.5 GeV proton beam




Momentum of deuteron

↓

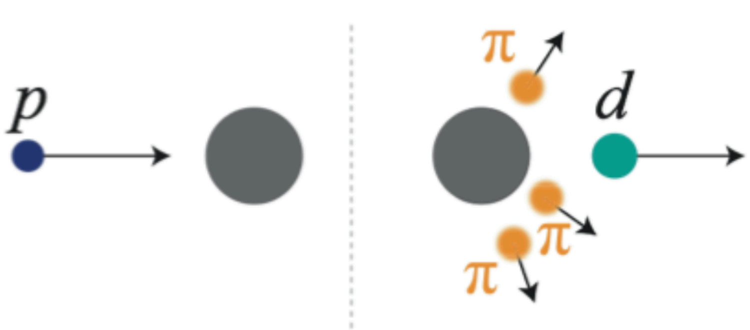
Missing mass

Target

η′ mesic nuclei

PTP 128, 601(2012)

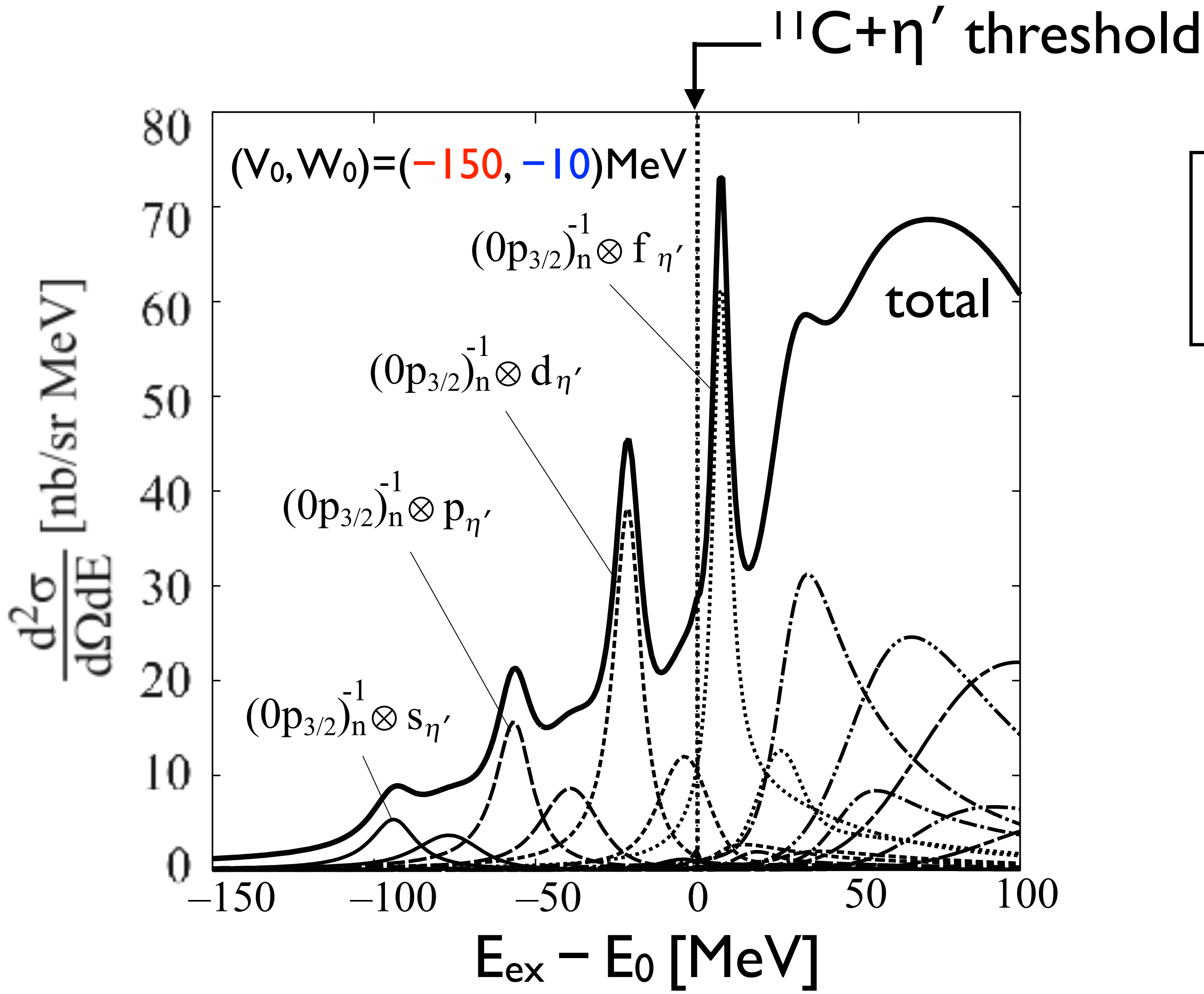
- overall structure w/o assuming decay process
- S/B ratio ≲ *O*(1/100) due to BG processes (e.g., *p*+*N*→*d*+π's)




**high statistical sensitivity is essential**

# Theoretically calculated formation spectra

## Calculated formation spectrum of $^{12}C(p,d)^{11}C \times \eta'$




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

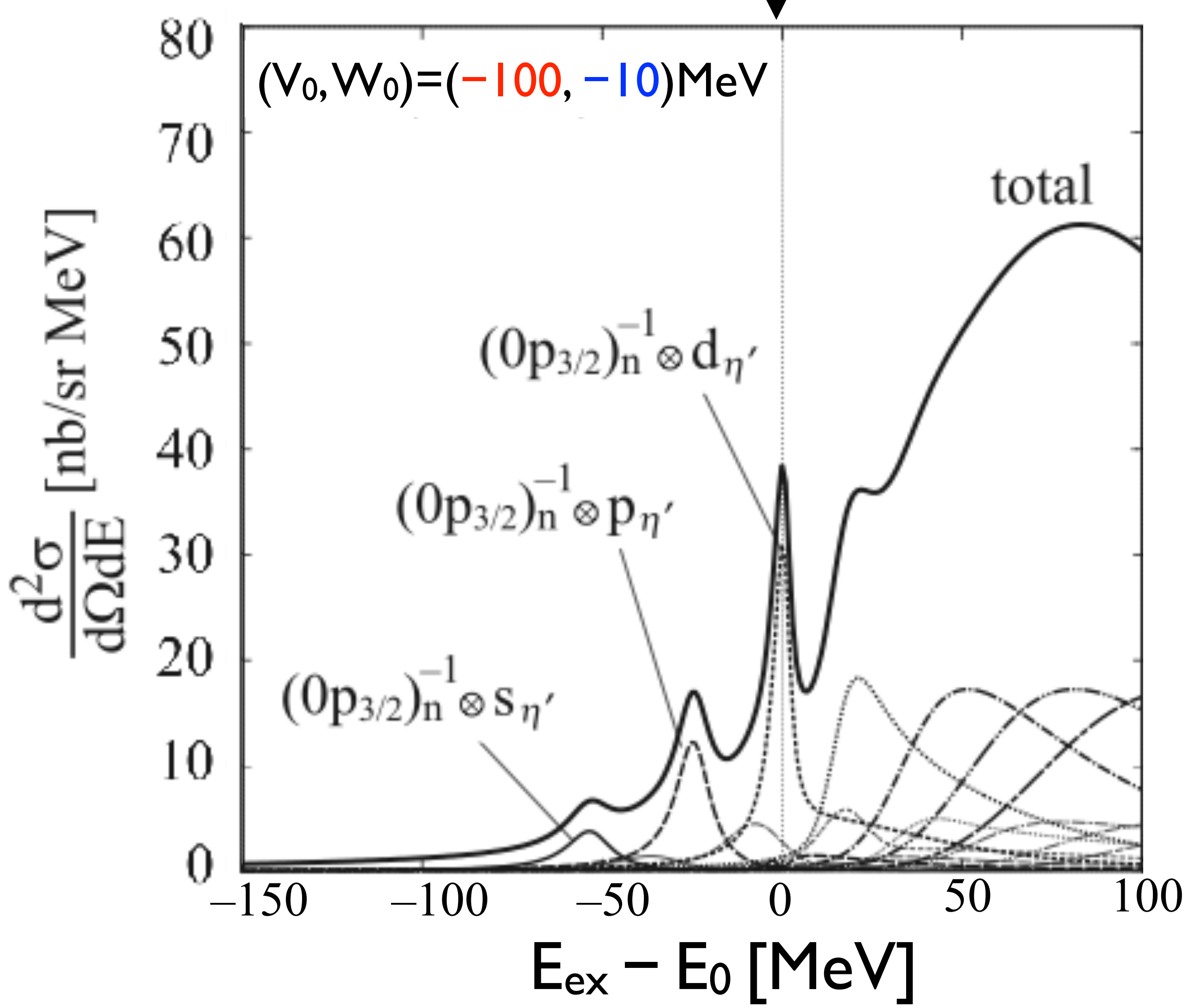
H.Nagahiro *et al.*,
PRC 87, 045201 (2013)

- momentum transfer ~400 MeV/c at $T_p$ = 2.5 GeV
- enhanced excited states near η′ emission threshold

# Theoretically calculated formation spectra

Calculated formation spectrum of $^{12}C(p,d)^{11}C\times\eta'$

$^{11}C+\eta'$ threshold

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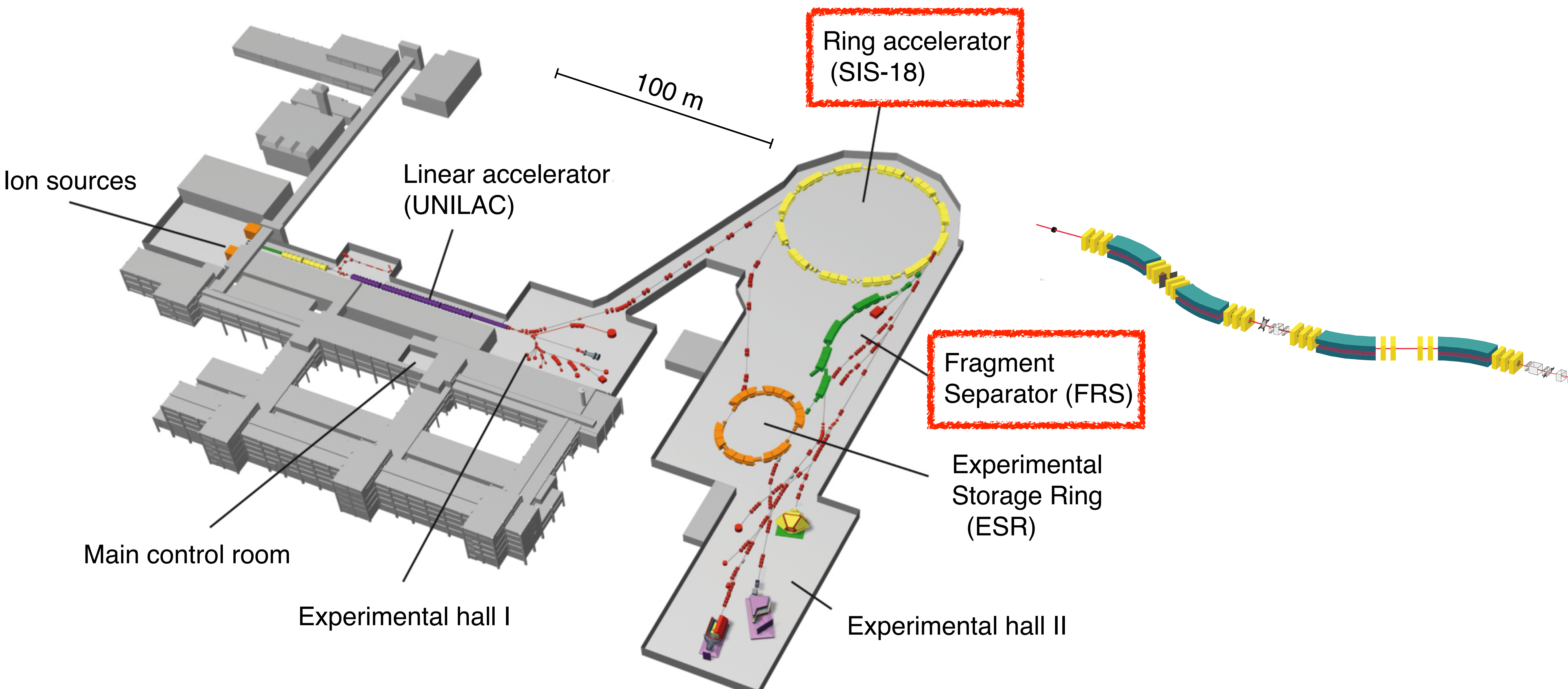
H.Nagahiro *et al.*,
PRC 87, 045201 (2013)

- momentum transfer ~400 MeV/c at $T_p = 2.5$ GeV
- enhanced excited states near η′ emission threshold

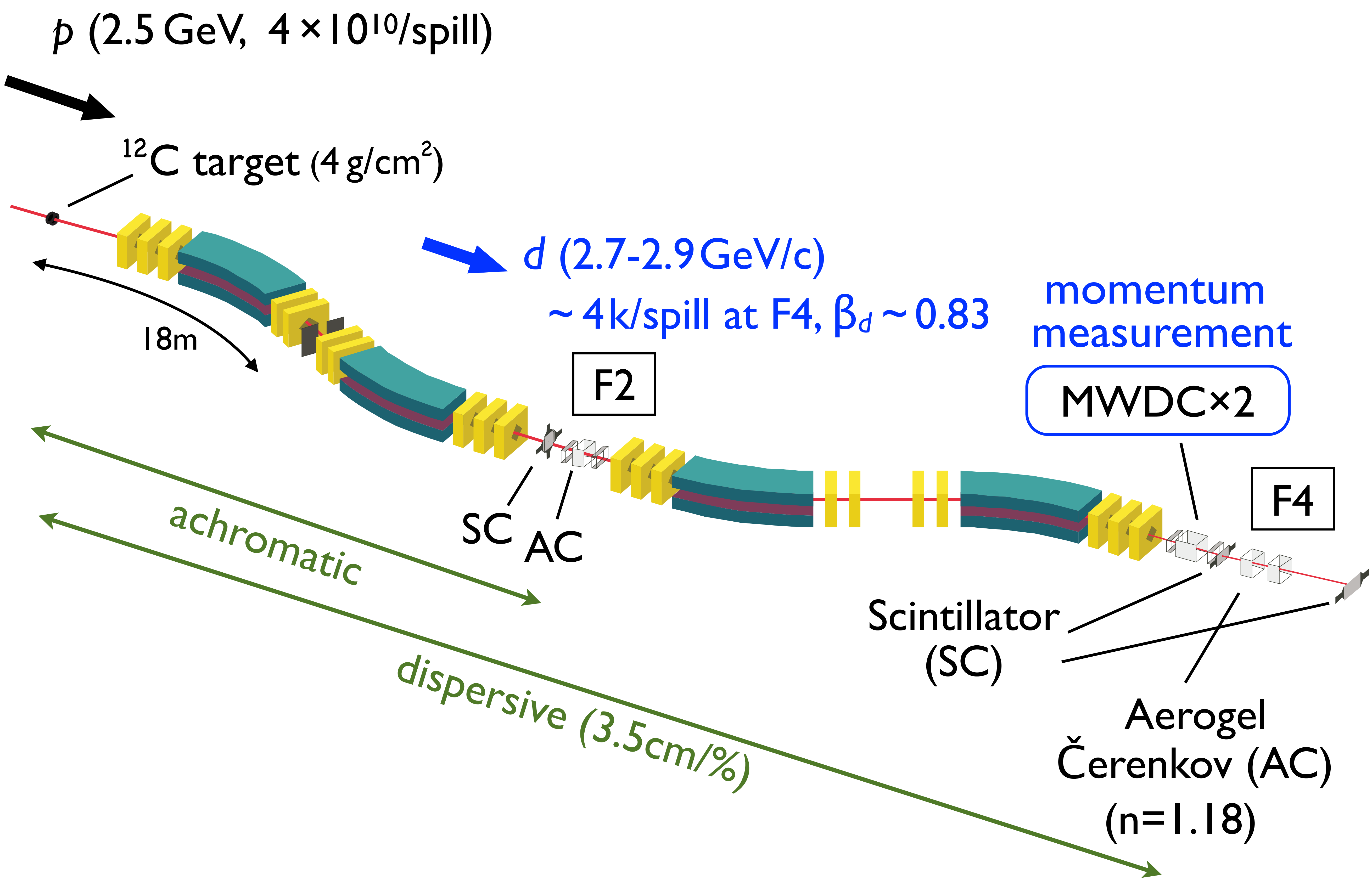
# GSI facilities

- SIS-18 : 2.5 GeV proton beam
- Fragment Separator (FRS) : high-resolution spectrometer
  + (instrumental) BG rejection

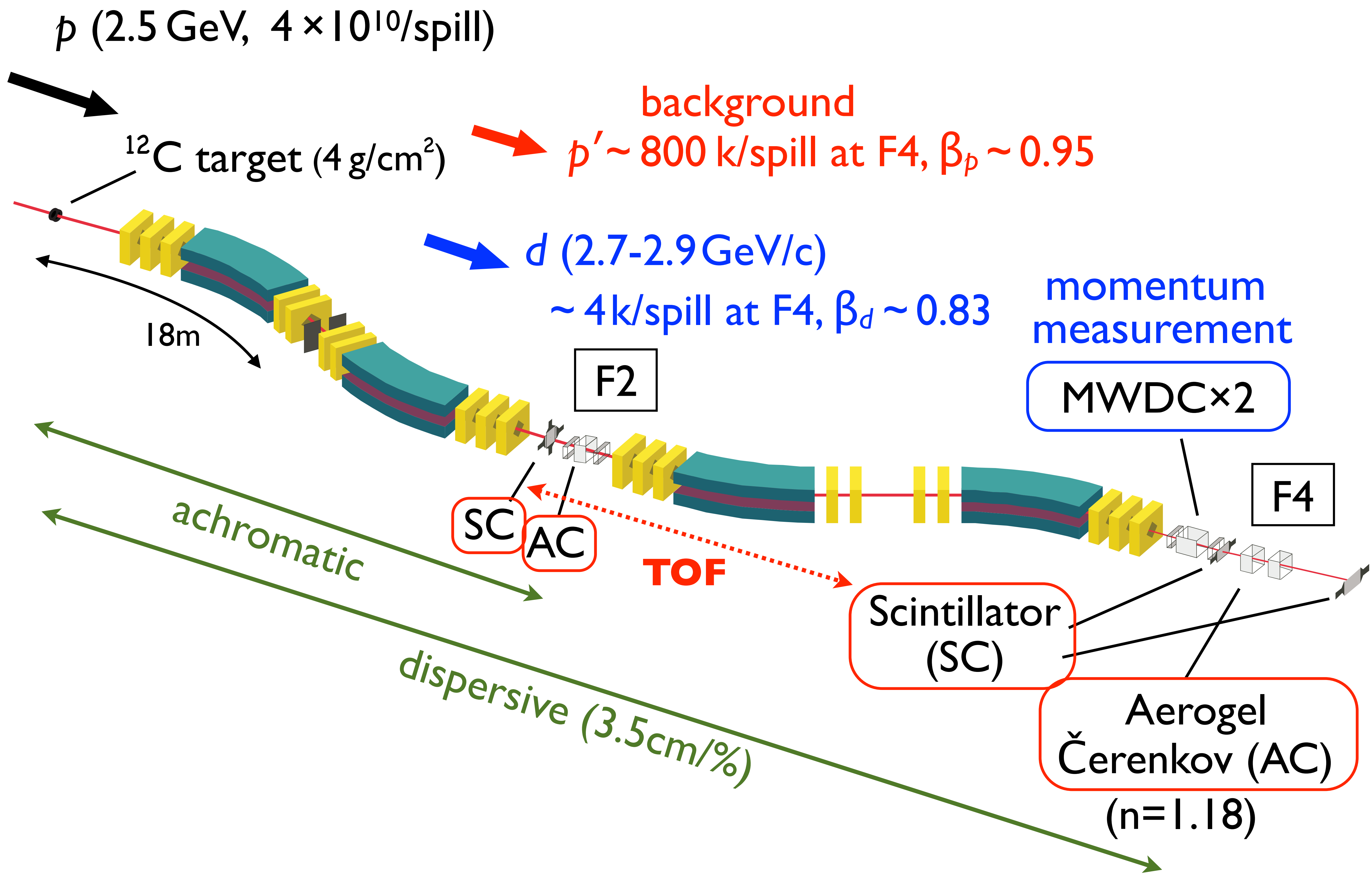



GSI webpage

# Experimental setup at FRS

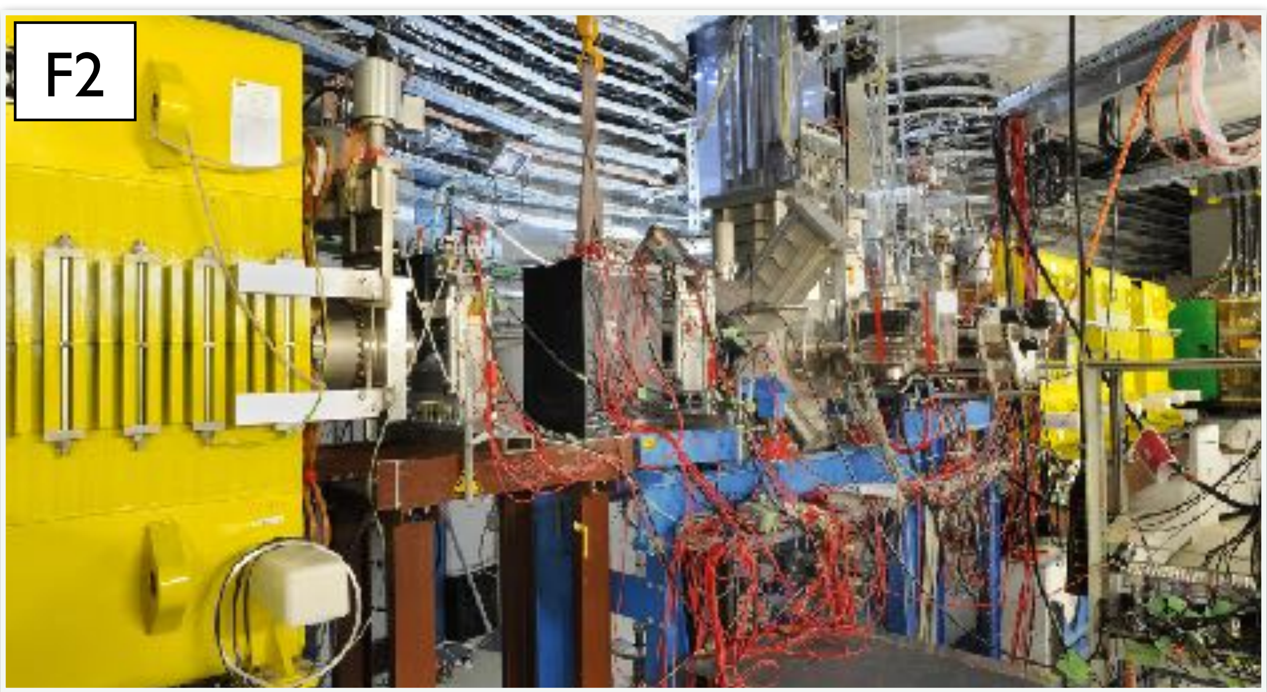


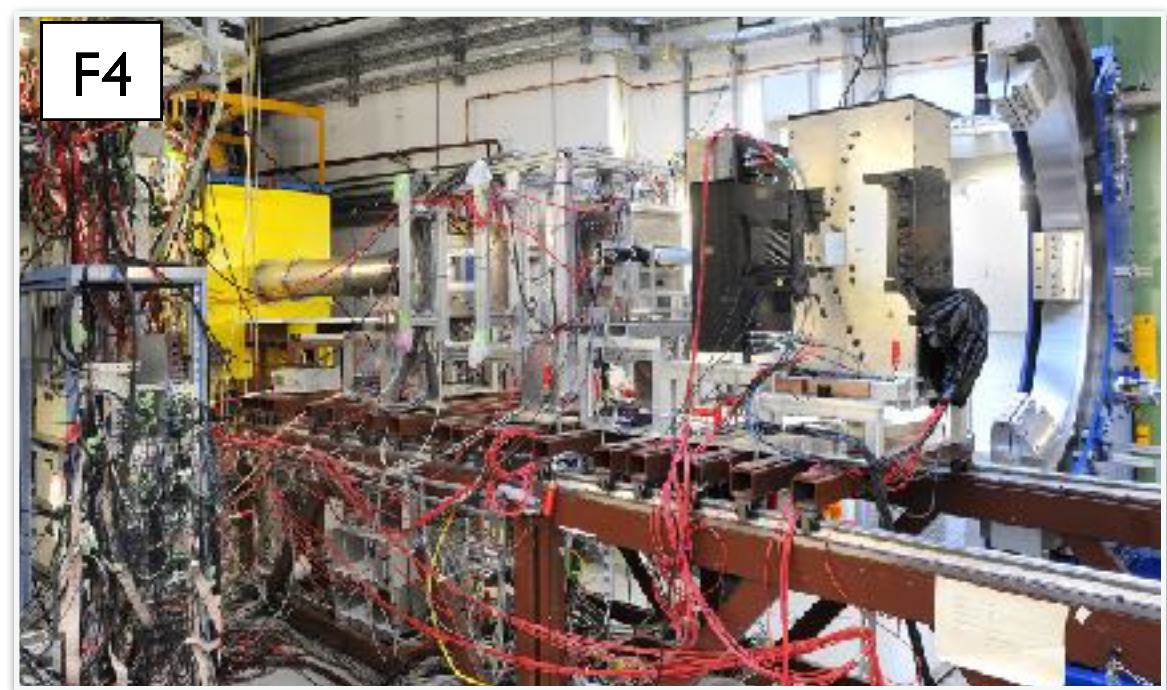
# Experimental setup at FRS



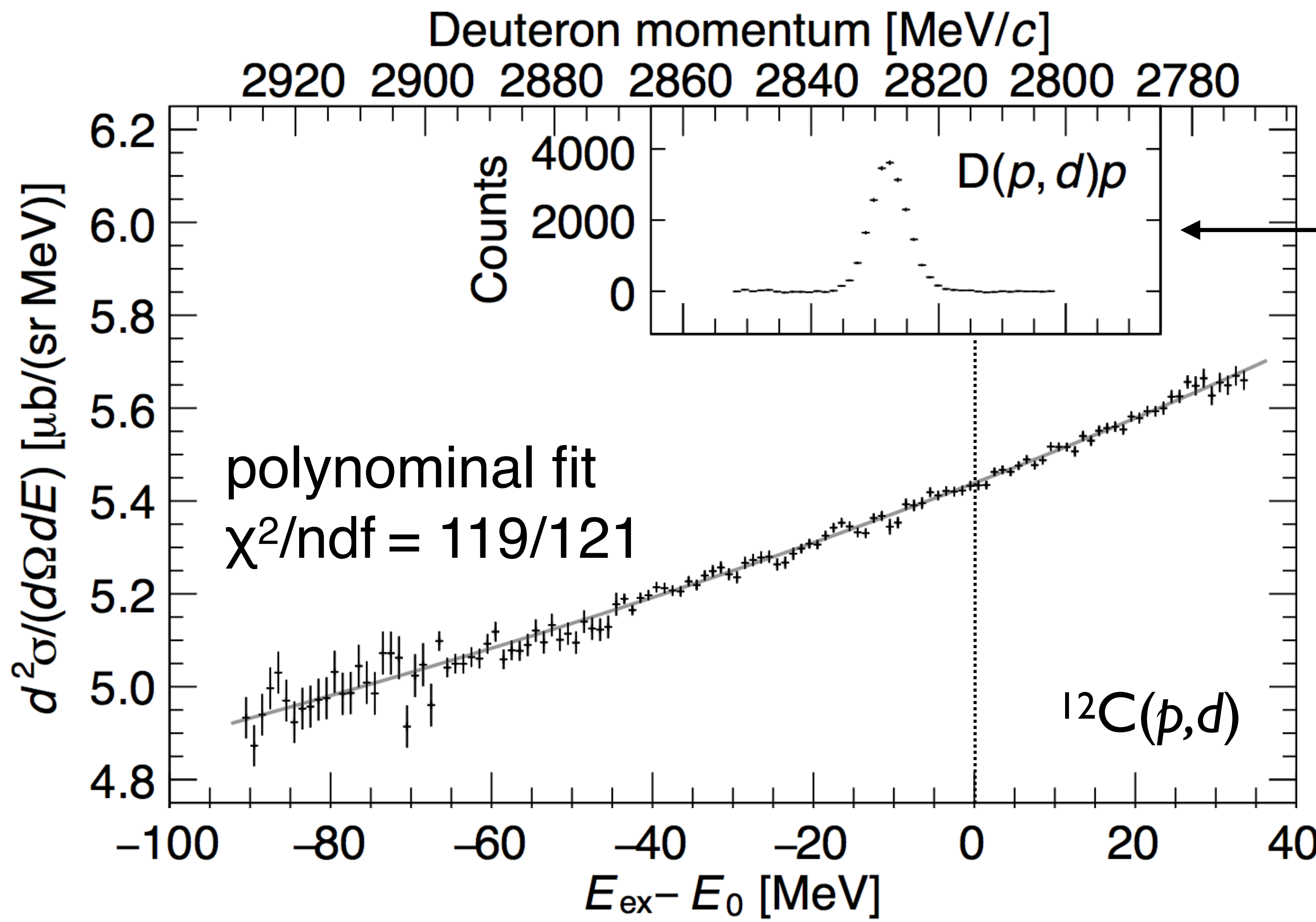
# First experiment in 2014

- production run of C($p$,$d$) reaction at $T_p$ = 2.5 GeV (~ 5 days)
- scaling momentum region of FRS
  → cover −90 to +40 MeV around η′ threshold
- good statistics : ~$O(10^7)$ deuteron events
- calibration with D($p$,$d$)$p$ elastic scattering at $T_p$ = 1.6 GeV



# Results — excitation spectrum —




calibration with D(*p*,*d*)*p* elastic scattering

Y. K. Tanaka, K. Itahashi, H. Fujioka *et al,* PRL 117, 202501 (2016)

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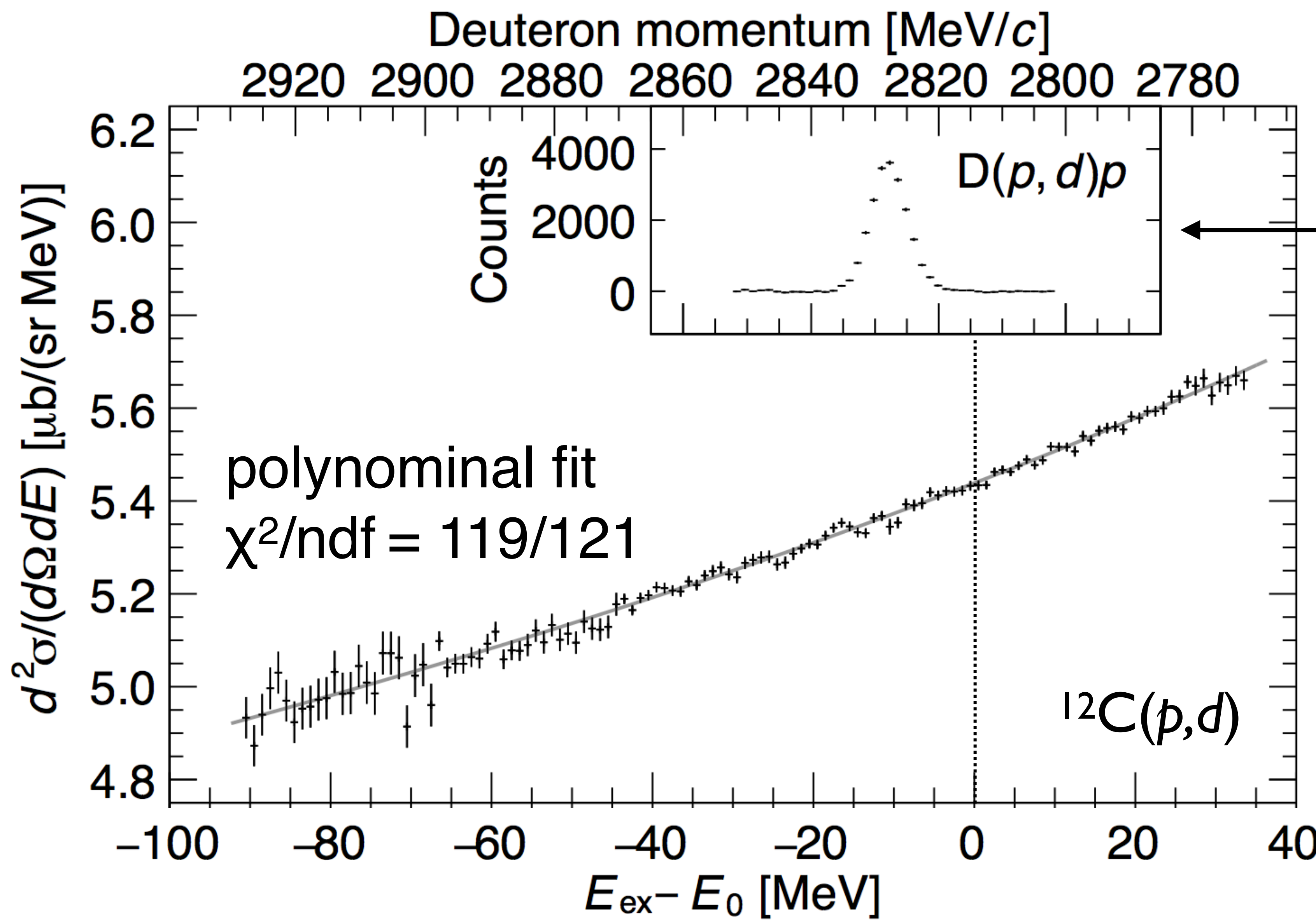



calibration with D($p$,$d$)$p$ elastic scattering

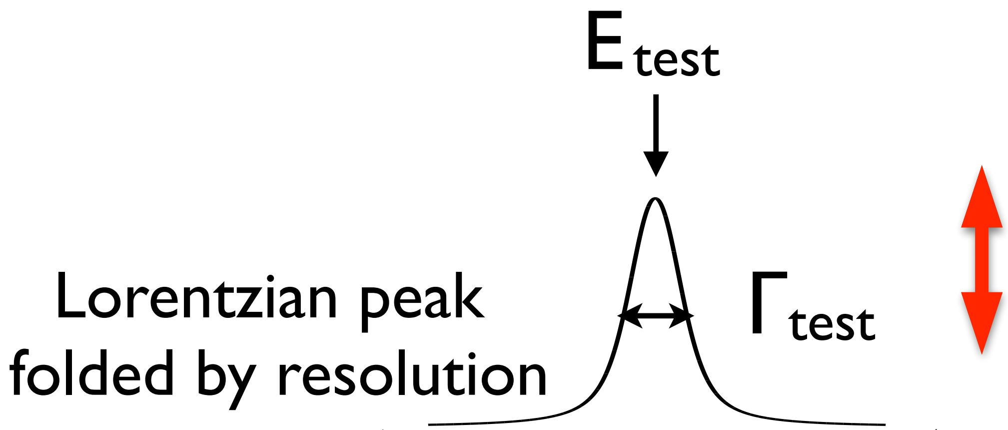
Y. K. Tanaka, K. Itahashi, H. Fujioka *et al*, PRL 117, 202501 (2016)

- □ good statistical sensitivity $\lesssim$ 1% is achieved
- □ overall ($p$,$d$) cross section consistent with quasi-free multi-π production
- □ sufficient resolution 2.5 MeV(σ) achieved
- □ no significant peak structure is observed
  - → upper limits for formation cross section of η′ mesic states

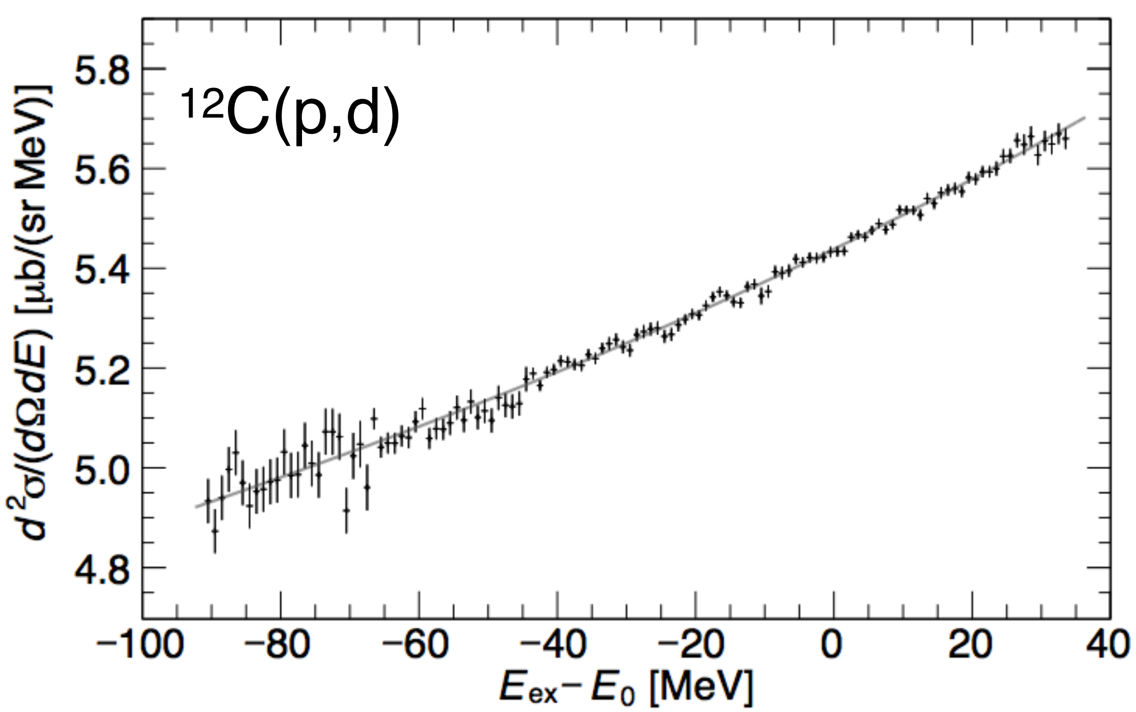
# Upper limit of formation cross section

Upper limit of Lorentzian-shaped formation cross section

- fit function: $A \times \mathrm{Voigt}(E; E_{test}, \Gamma_{test}, \sigma_{exp}) + \mathrm{Pol3}(E; p_0, p_1, p_2, p_3)$

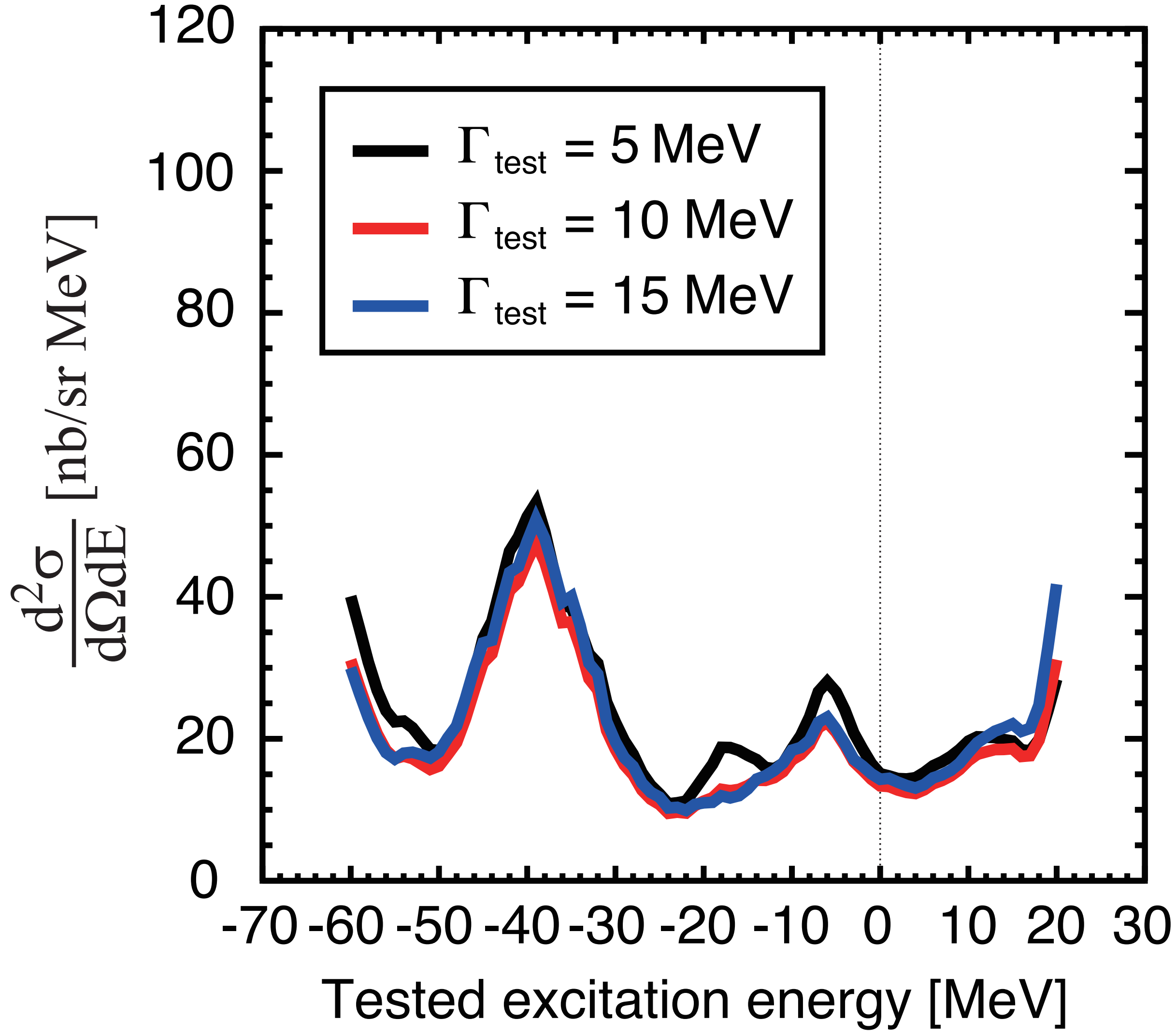



- evaluate upper limit of cross section for fixed ($E_{test}$, $\Gamma_{test}$)
- repeat analysis for other ($E_{test}$, $\Gamma_{test}$)



# Upper limit of formation cross section

Obtained 95% C.L. upper limits of Lorentzian peak height




- high statistical sensitivity better than 1% is achieved (as intended)

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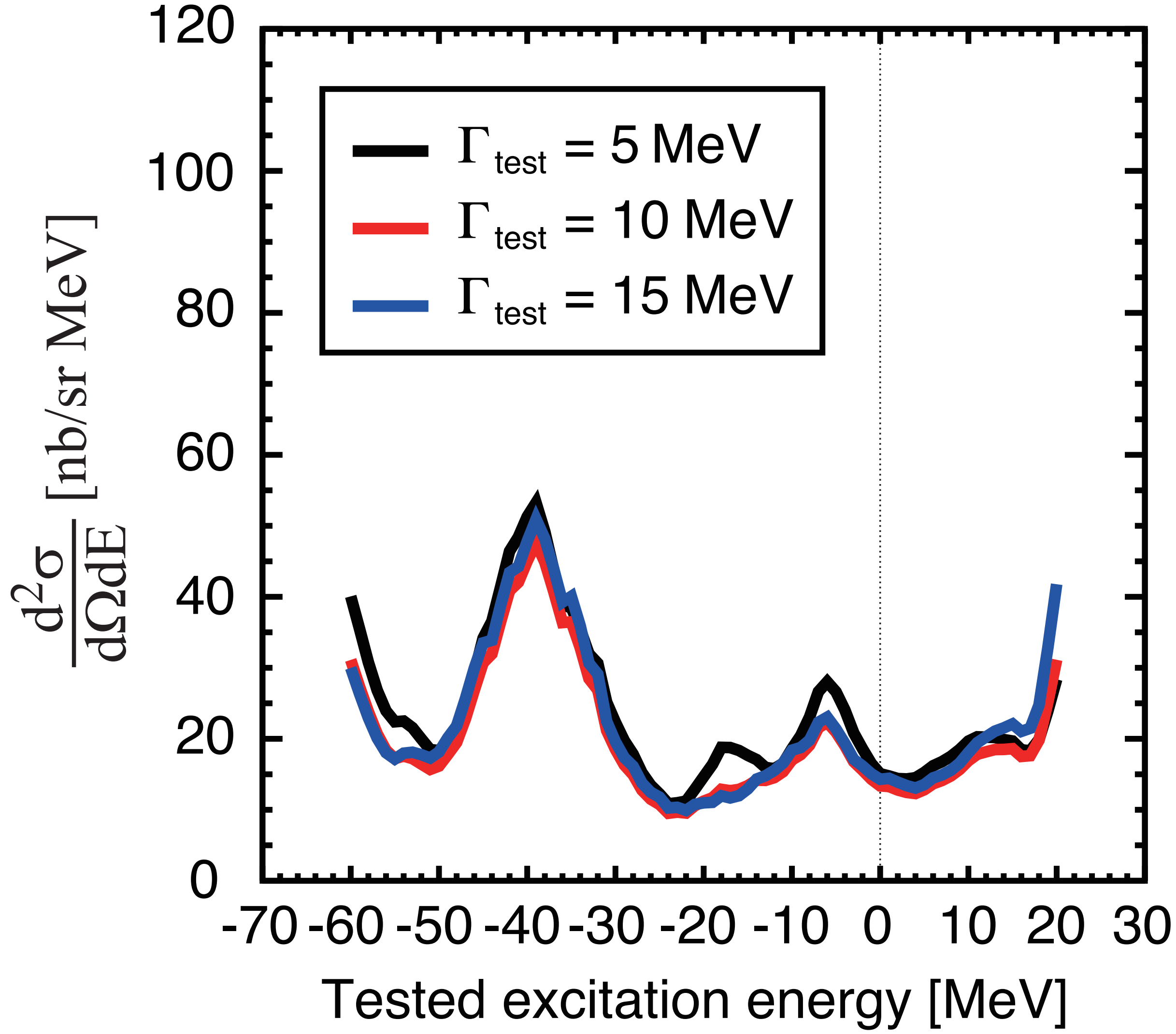
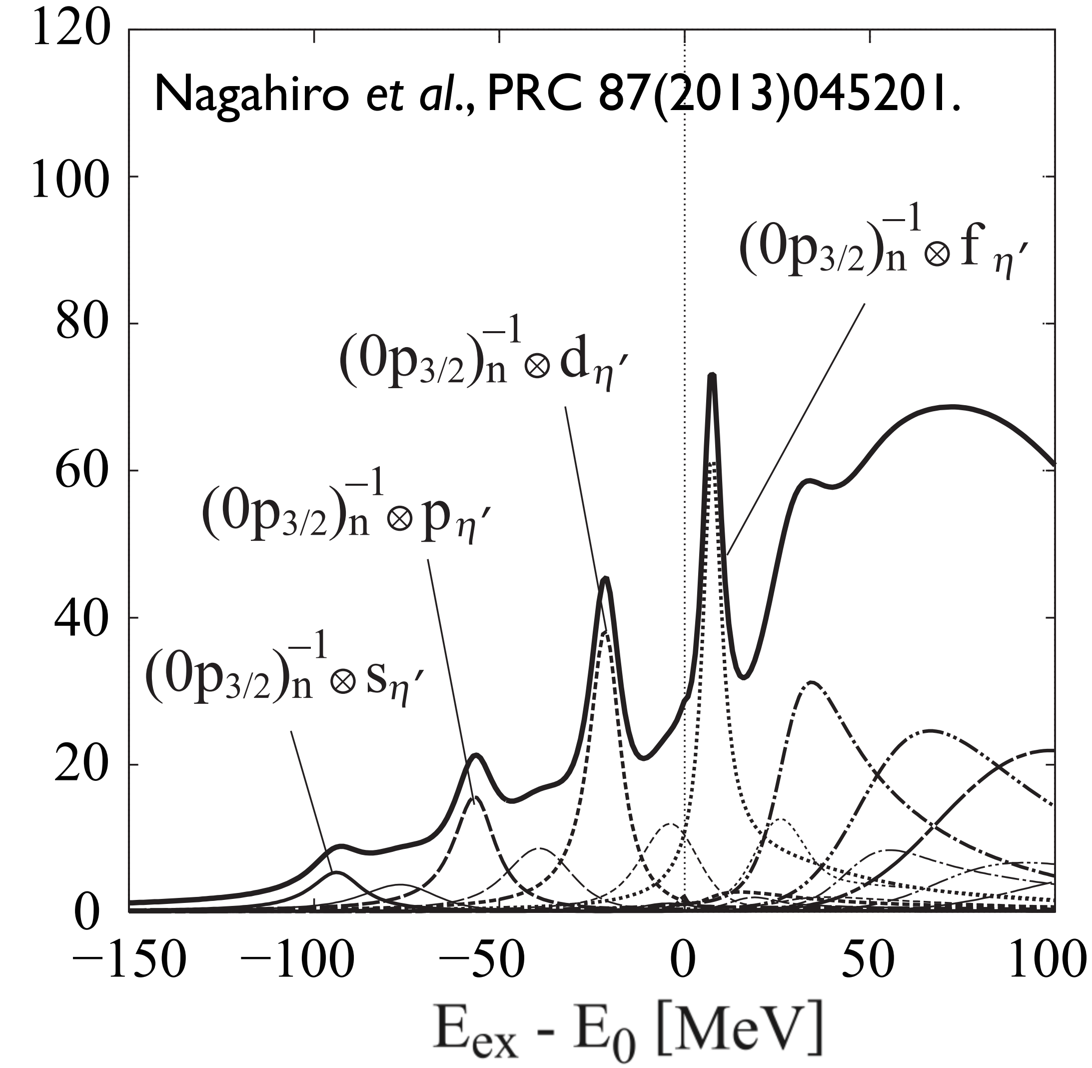


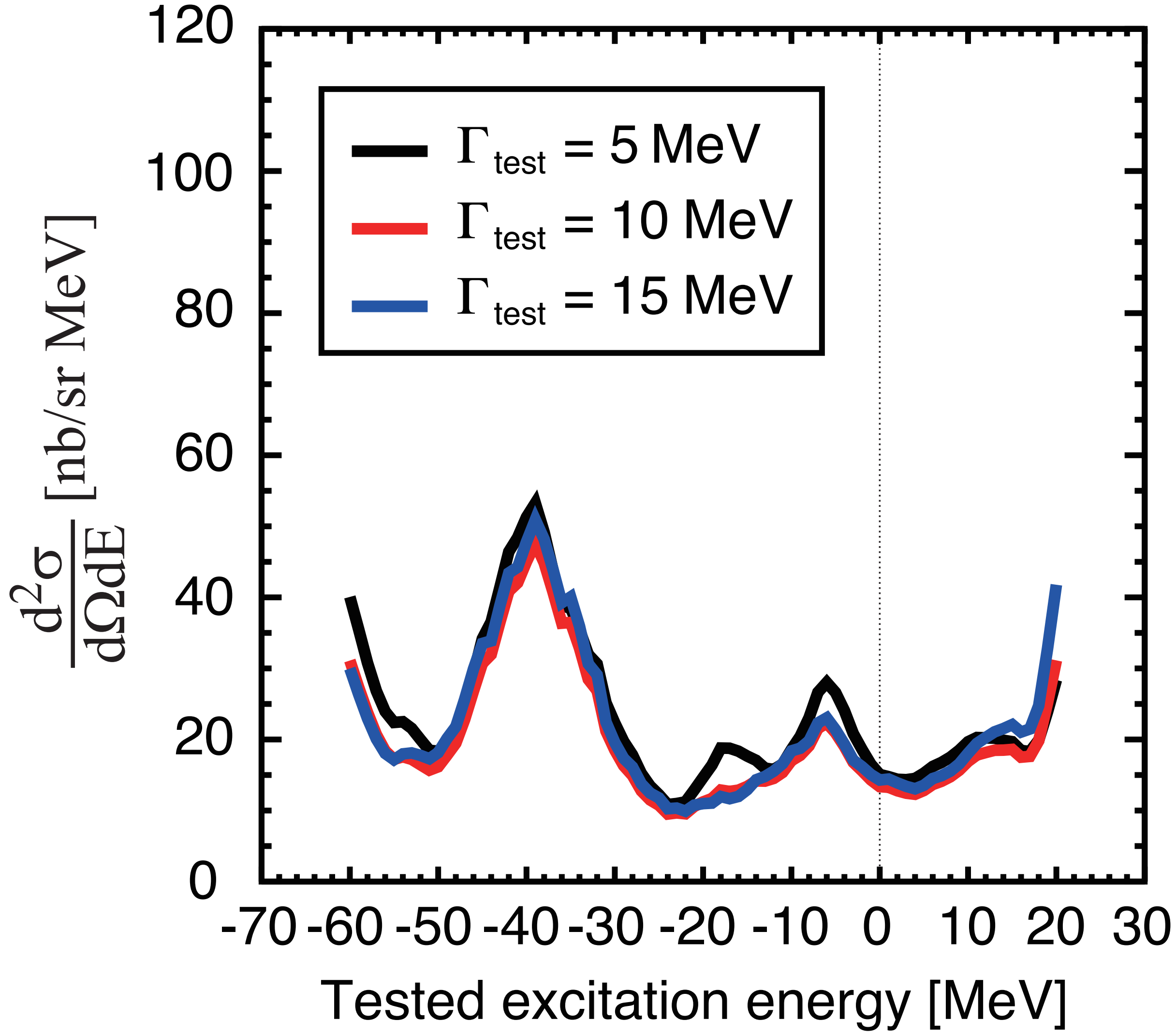

Theoretically expected spectrum for $(V_0, W_0) = (-150, -10)$ MeV



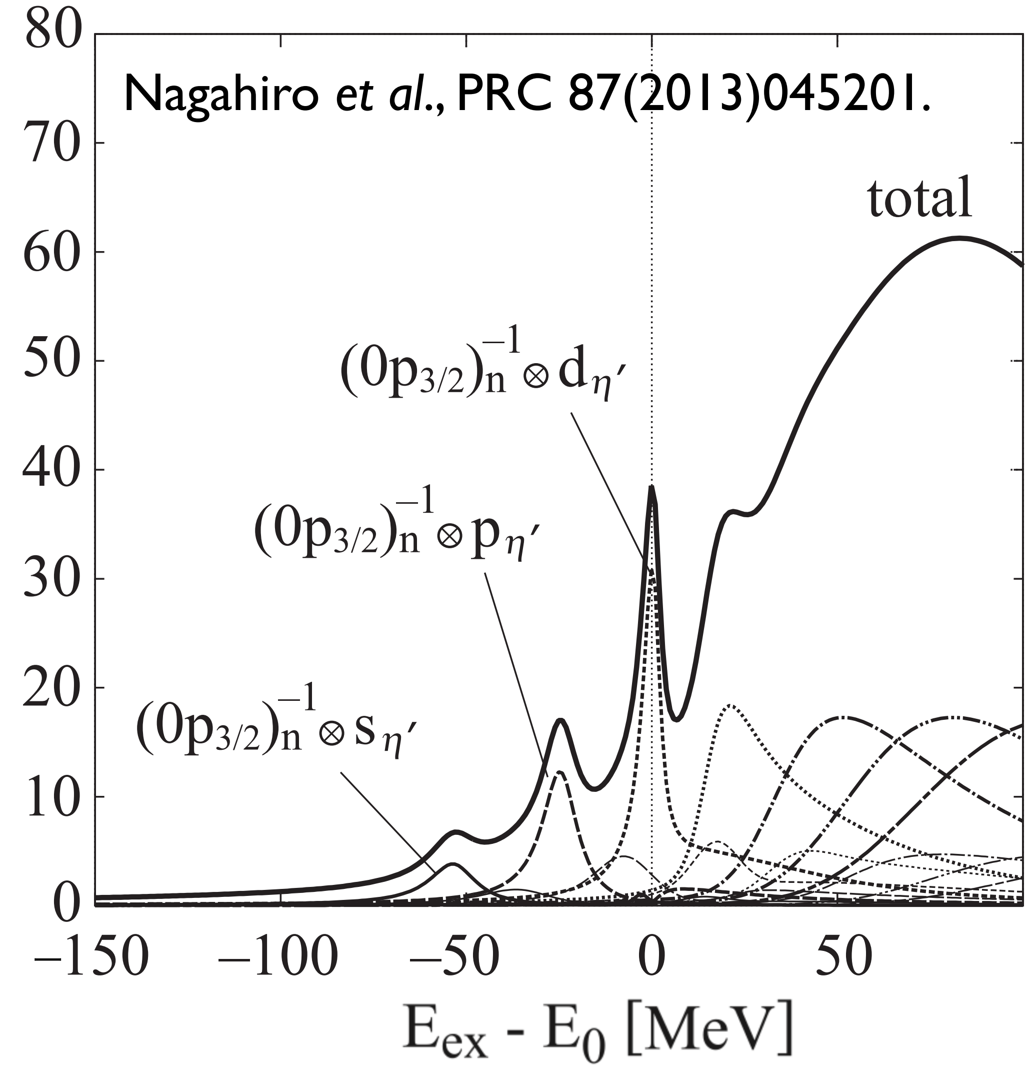

- high statistical sensitivity better than 1% is achieved (as intended)
- ~ 40 nb/(sr·MeV) peak expected for $(V_0, W_0) = (-150, -10)$ MeV is excluded at 95% C.L.

# Upper limit of formation cross section

Obtained 95% C.L. upper limits of Lorentzian peak height



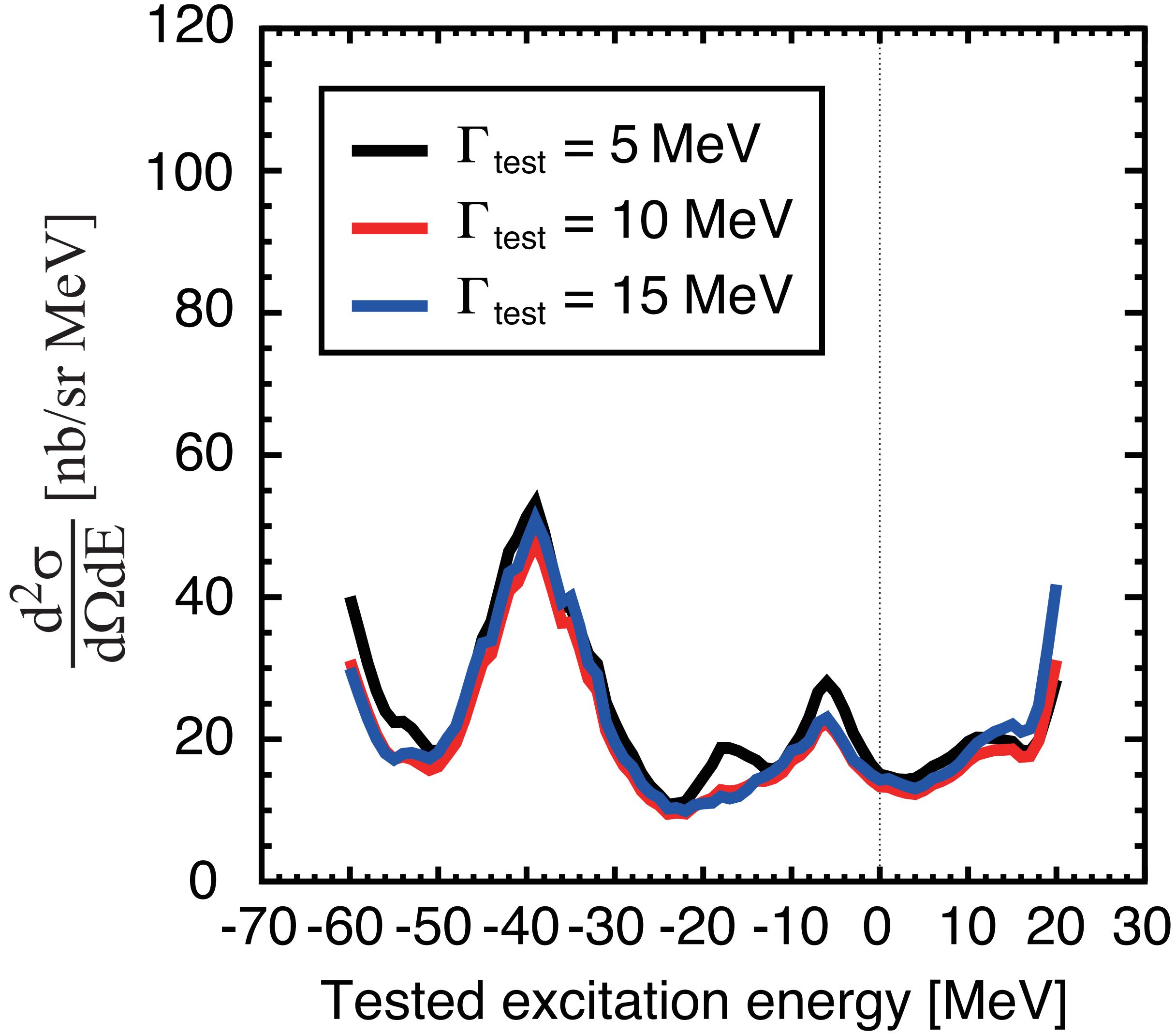

Theoretically expected spectrum for $(V_0, W_0) = (-100, -10)$ MeV



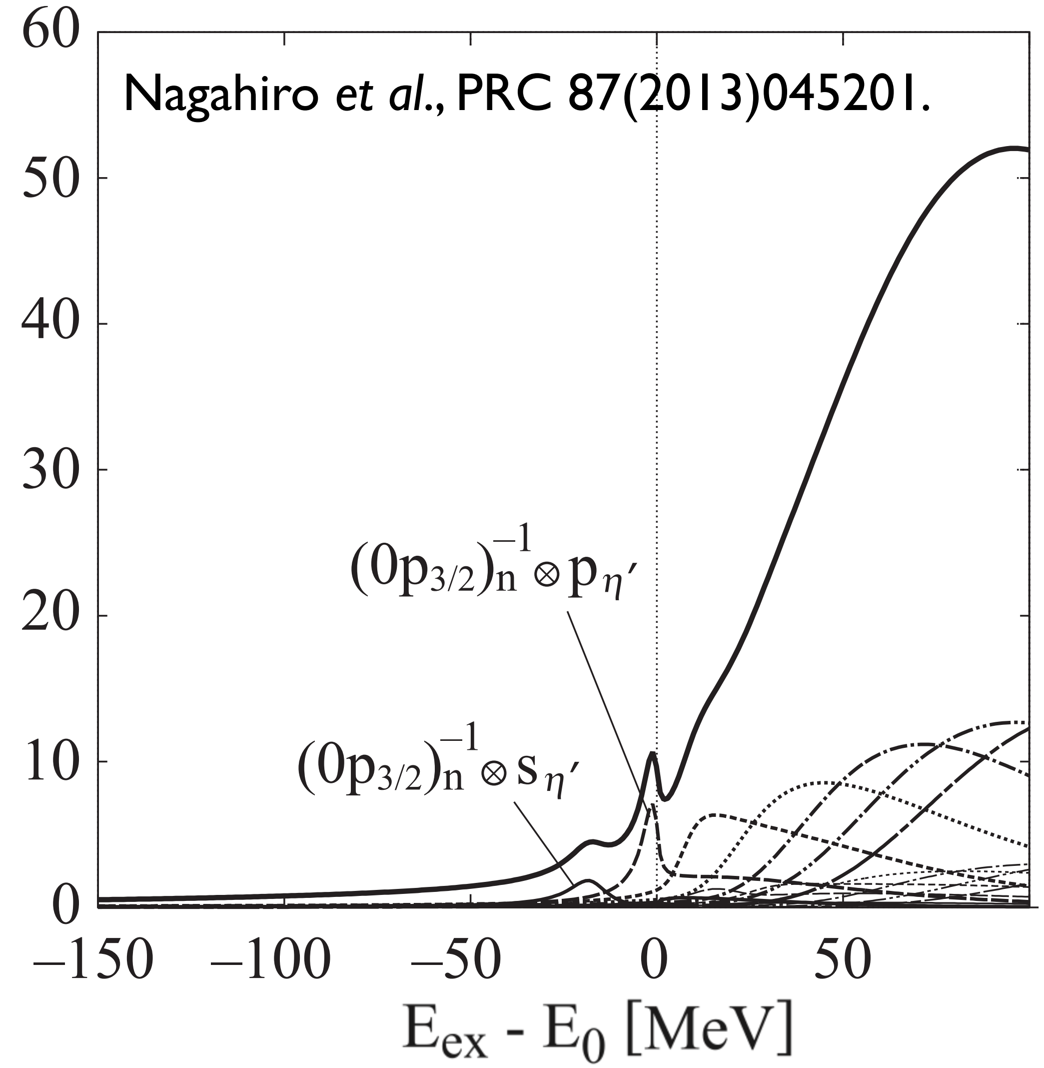

- high statistical sensitivity better than 1% is achieved (as intended)
- ~ 30 nb/(sr·MeV) peak expected for $(V_0, W_0) = (-100, -10)$ MeV is excluded at 95% C.L.

# Upper limit of formation cross section

Obtained 95% C.L. upper limits of Lorentzian peak height




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

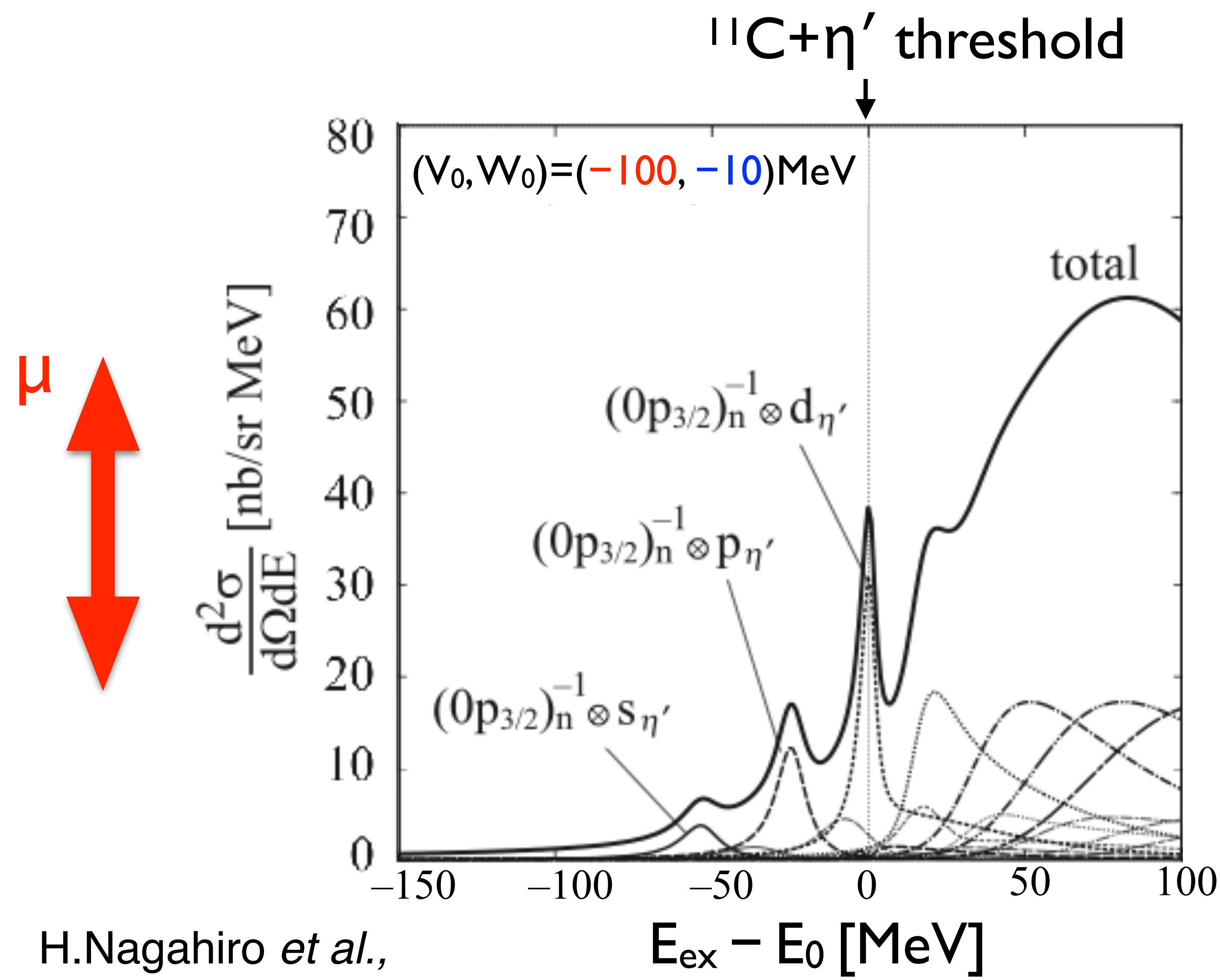



- high statistical sensitivity better than 1% is achieved (as intended)
- ~ 10nb/(sr·MeV) peak expected for $(V_0, W_0) = (-50, -10)$ MeV is not in conflict with present data

# Comparison with theoretical spectra

Analysis of possible scale μ for theoretically-calculated spectrum

- fit function: μ × $(d^2\sigma/d\Omega dE)^{theory \times resolution}$ + Pol3(E; $p_0, p_1, p_2, p_3$)
- upper limit of μ at 95% C.L.




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

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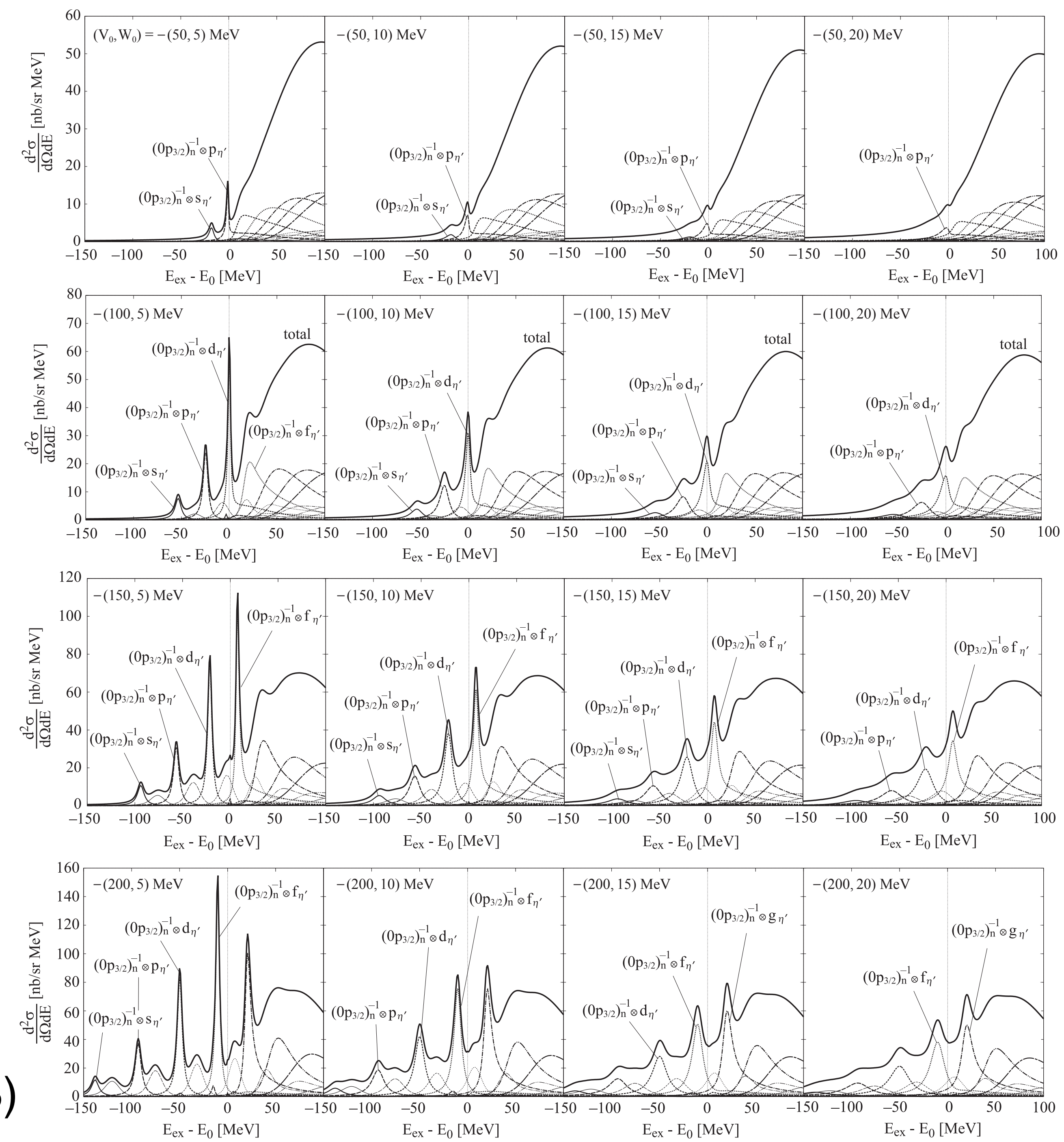
- upper limit of μ at 95% C.L.

for various sets of potential ($V_0$, $W_0$)

$-200$ MeV $\leq V_0 \leq -50$ MeV

$-25$ MeV $\leq W_0 \leq -5$ MeV

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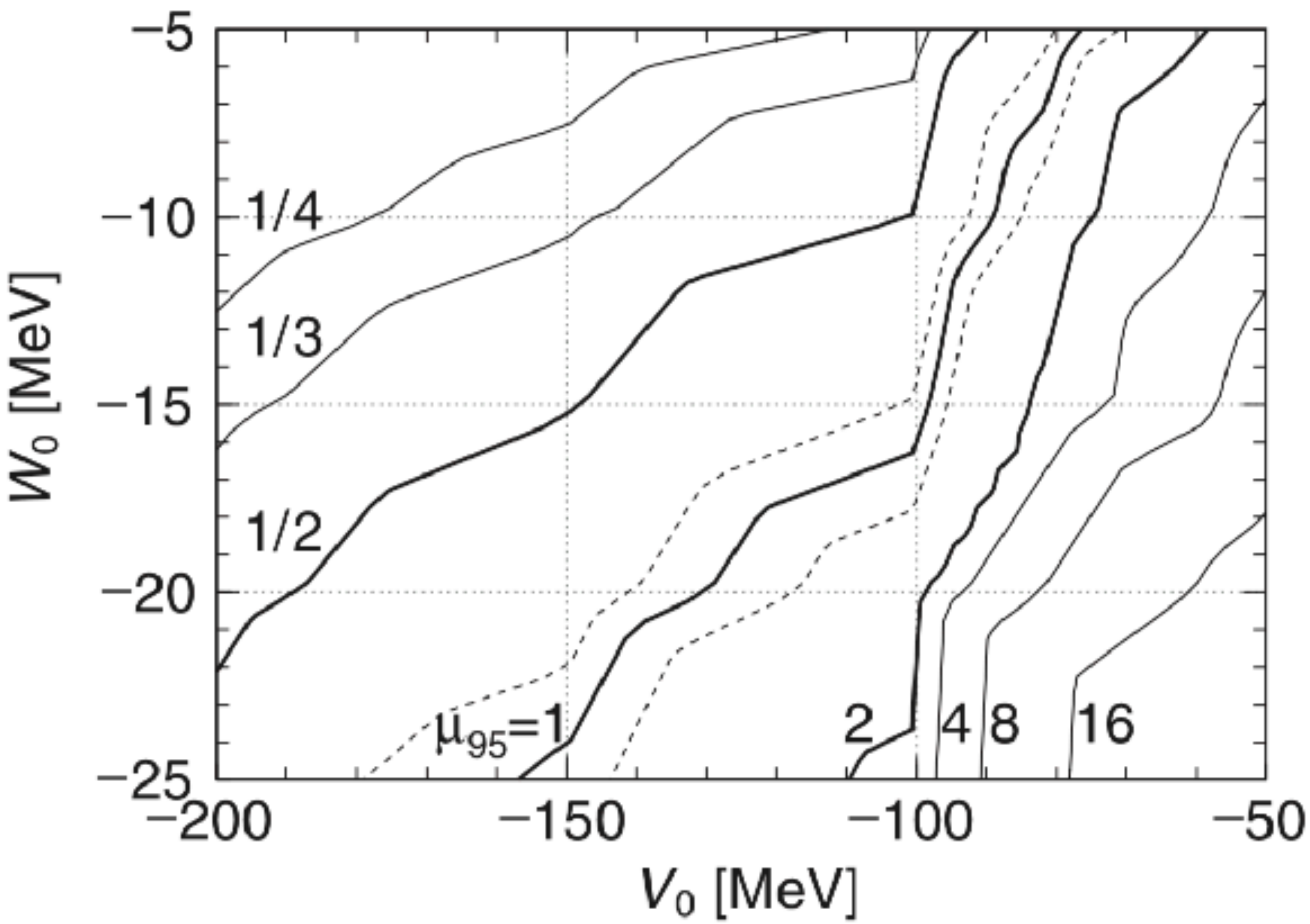
upper limit of μ (contour plot)




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

Y. K. Tanaka, K. Itahashi, H. Fujioka *et al*, PRC 97, 015202 (2018)

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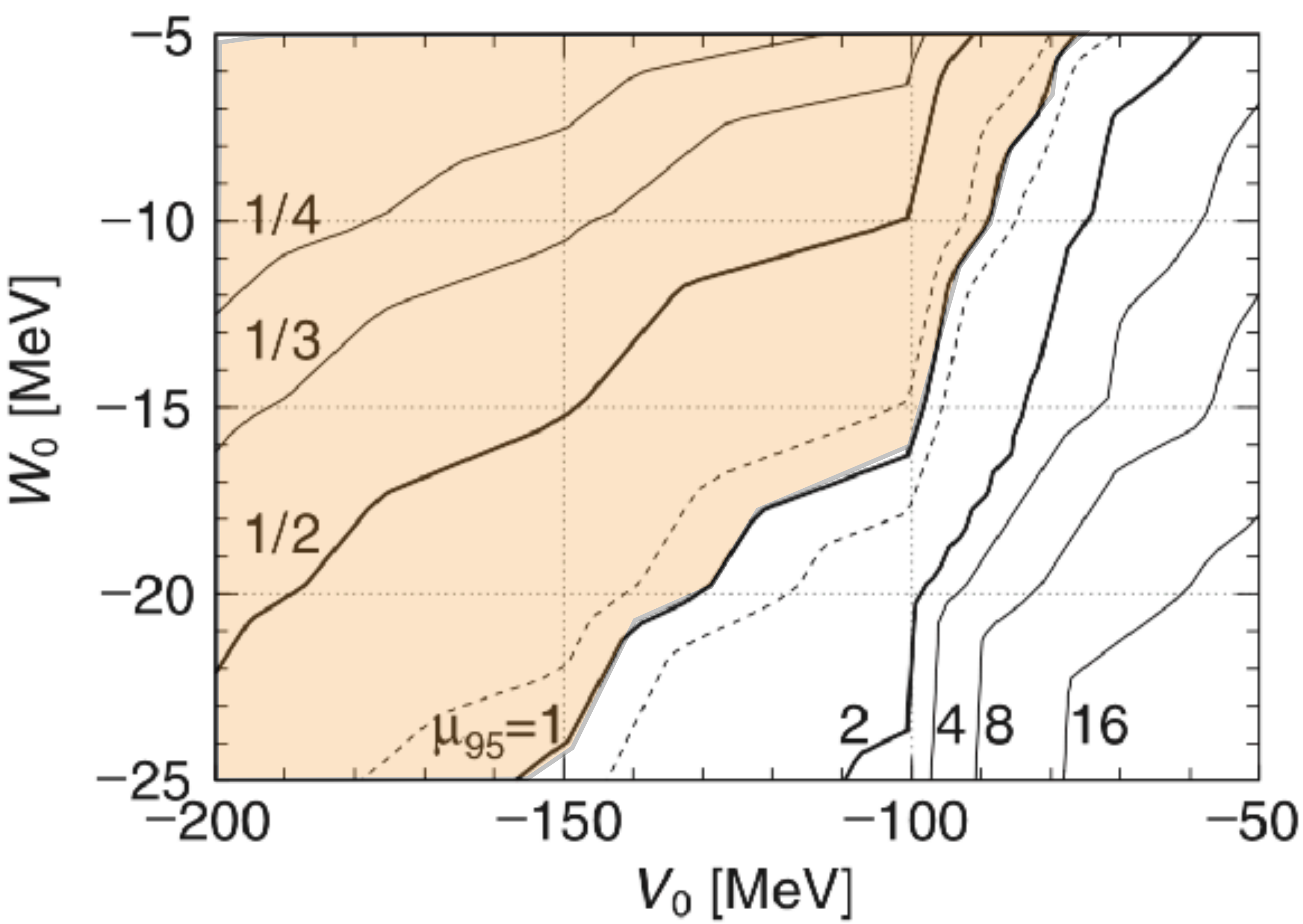


$$V_{\eta'} = (V_0 + iW_0) \frac{\rho(r)}{\rho_0}$$

($V_0$, $W_0$) with $\mu_{limit} < 1$ is excluded under this comparison

$|V_0| \sim 150$ MeV (NJL)
for $|W_0| \sim 10$ MeV

Y. K. Tanaka, K. Itahashi, H. Fujioka *et al*, PRC 97, 015202 (2018)

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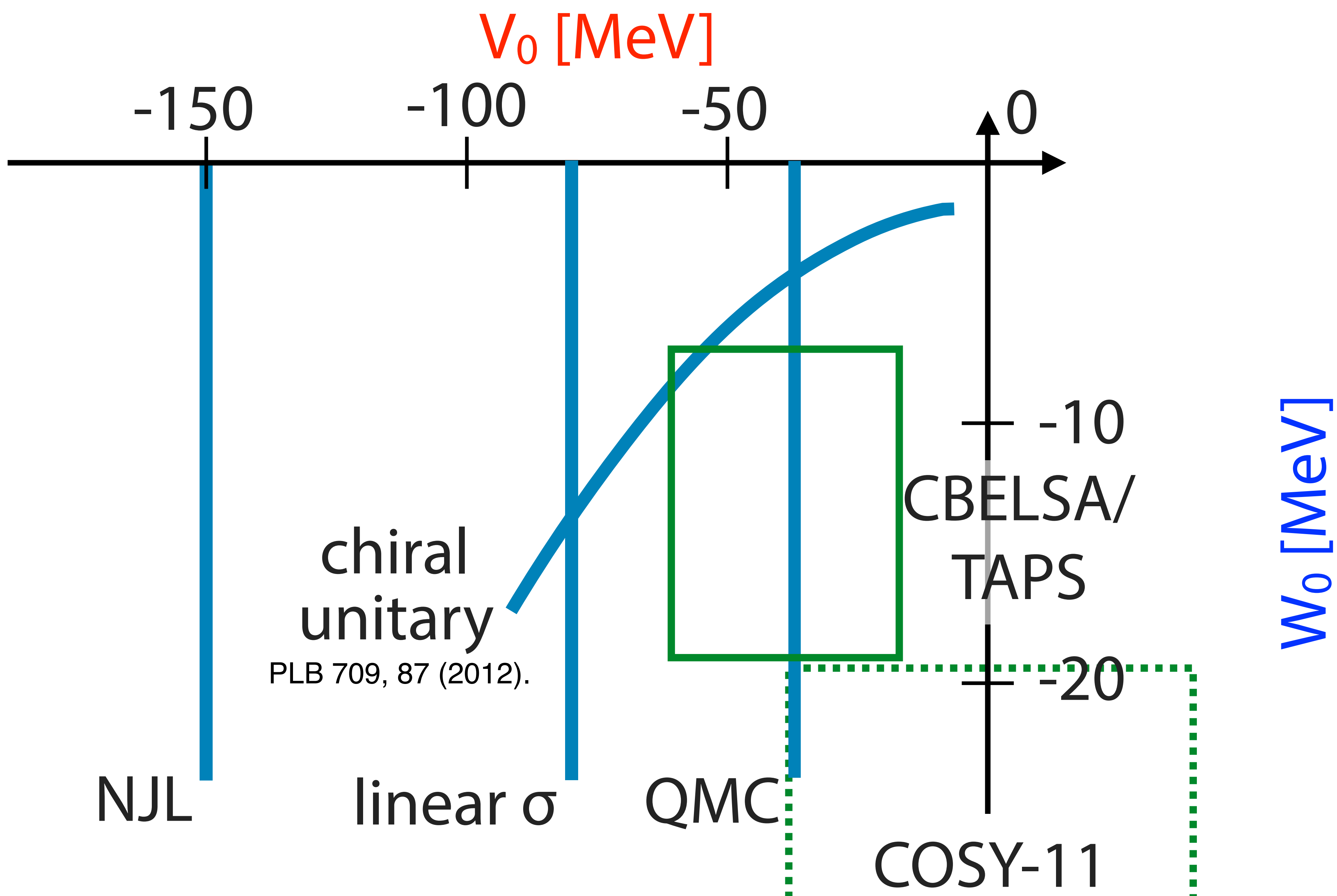

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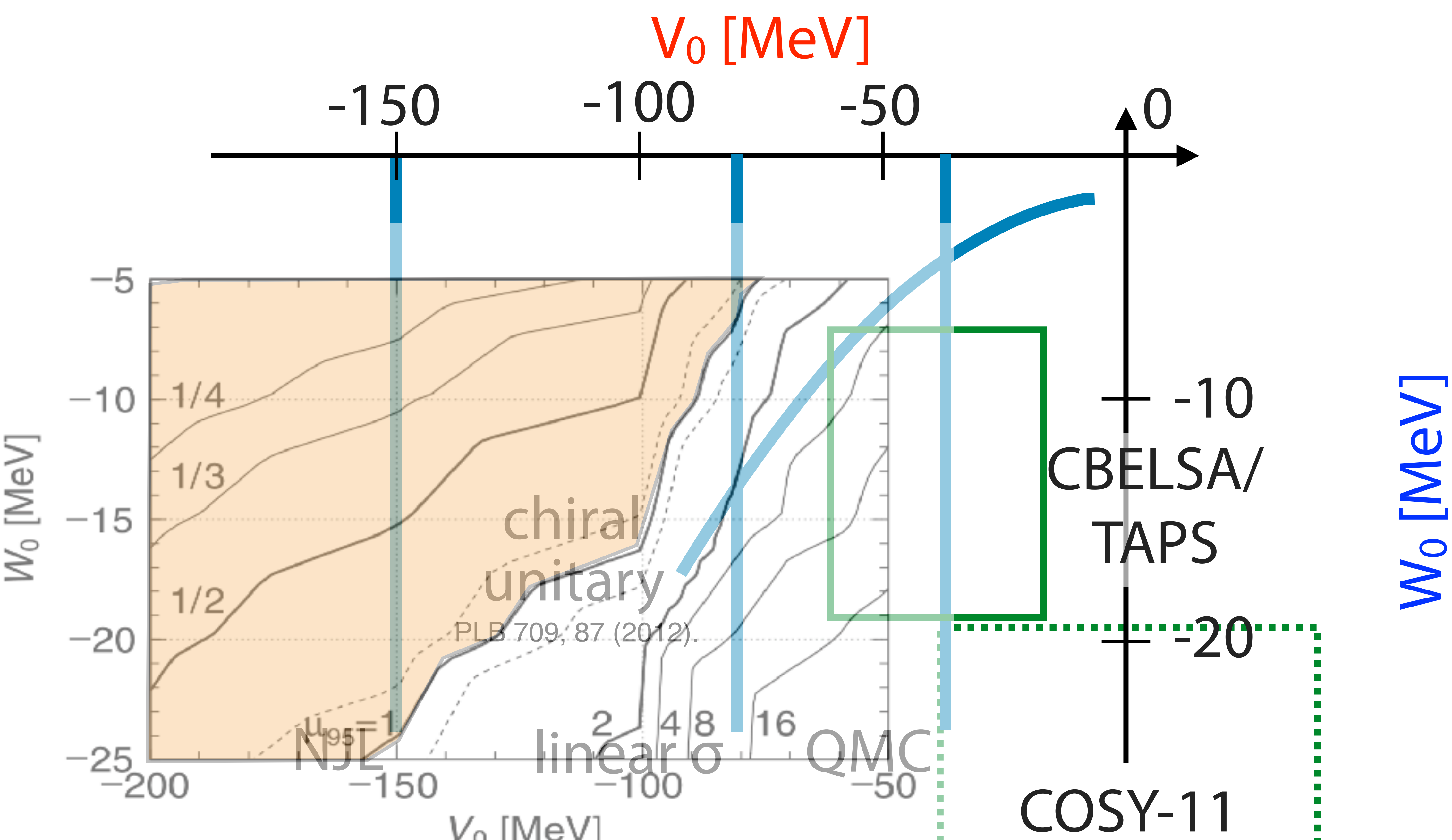

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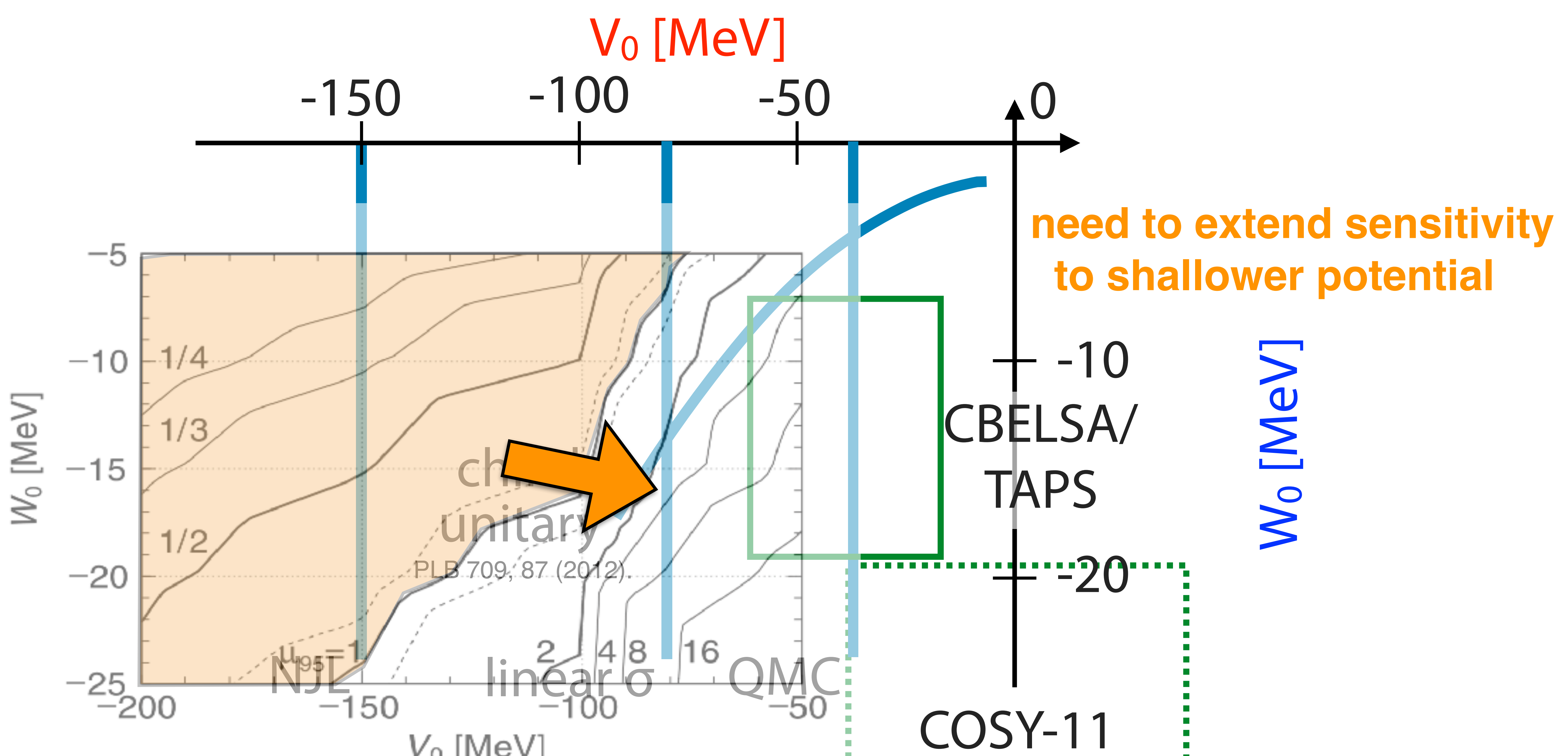
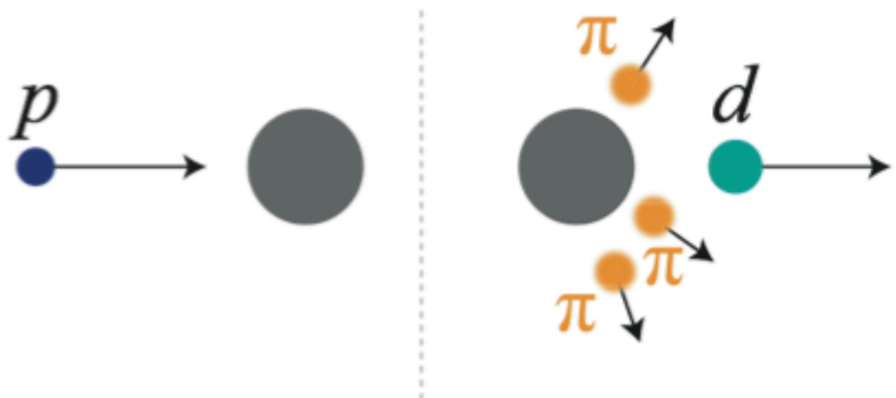
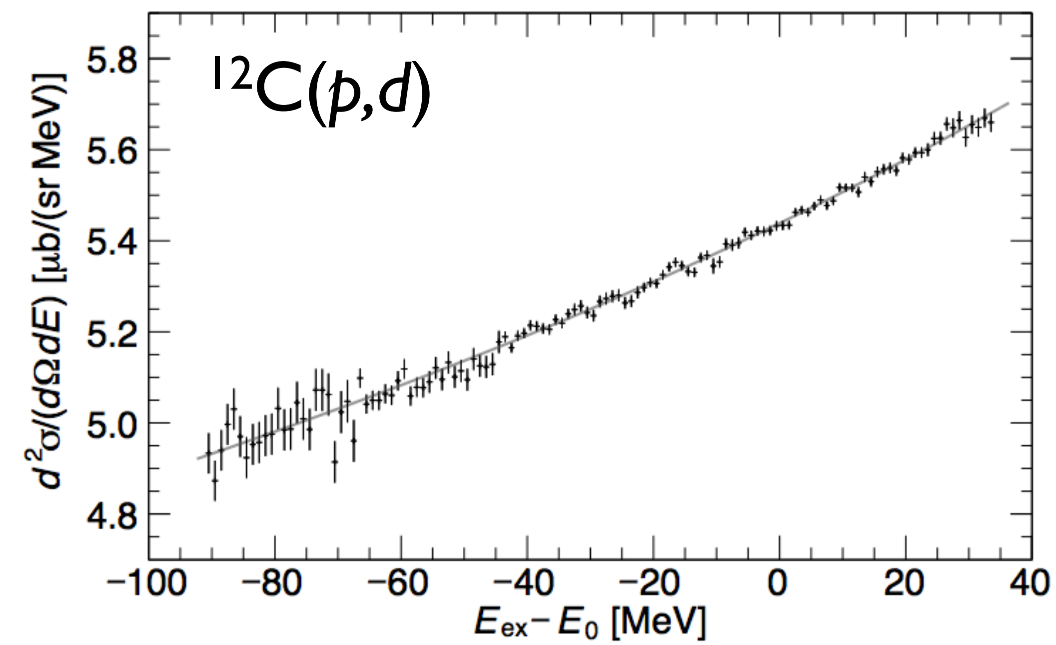


# Semi-exclusive measurement by tagging decay

**Background**

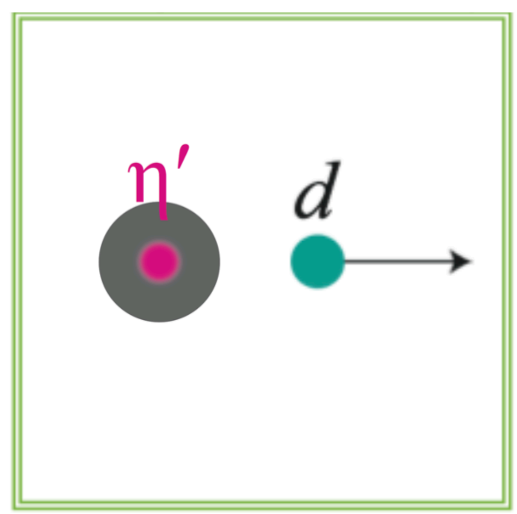
multi-π production




**Signal**

η′-mesic nuclei formation



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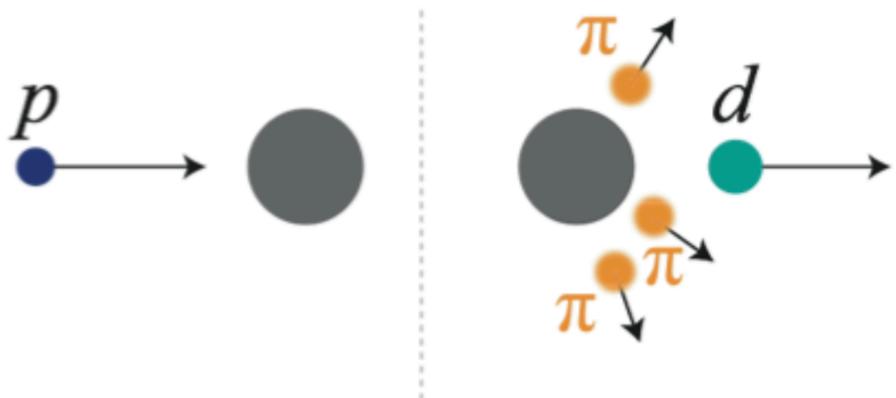


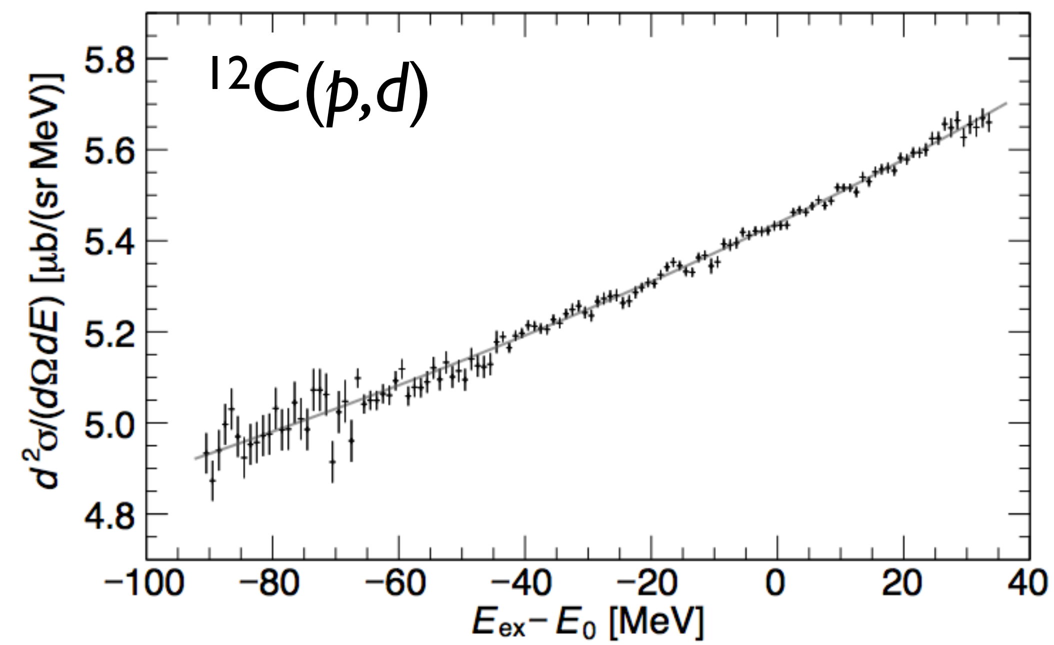


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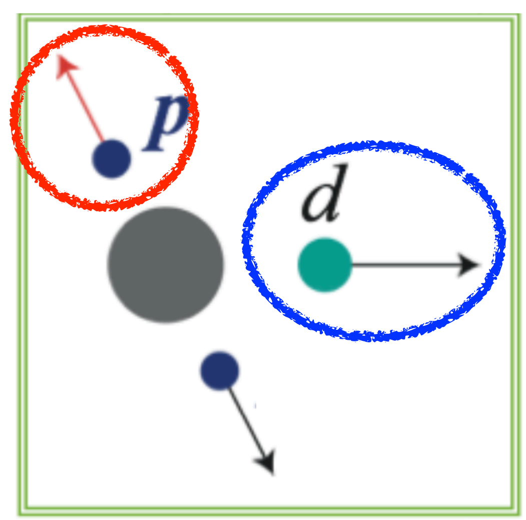
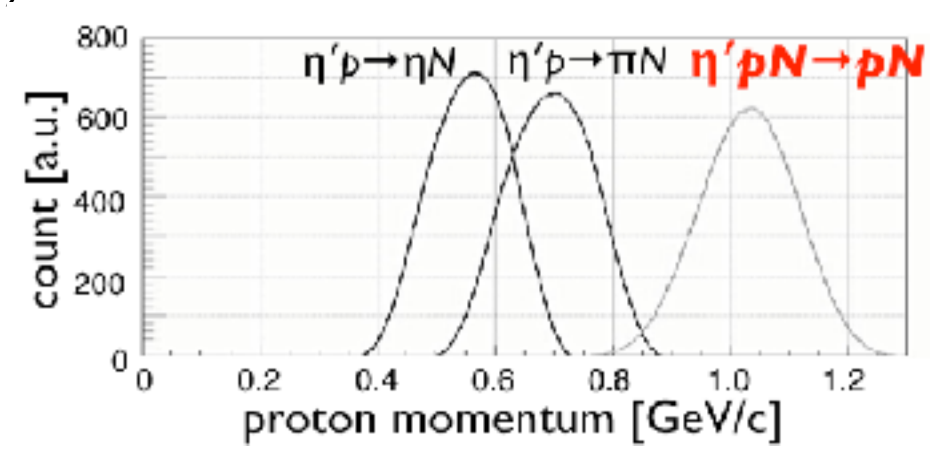



***η'NN→NN,*** *η'N→ηN, πN*

Coincidence measurement of decay proton and forward deuteron



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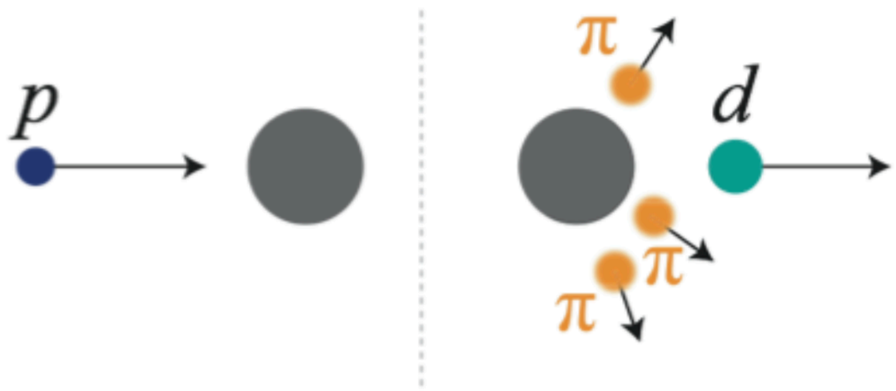


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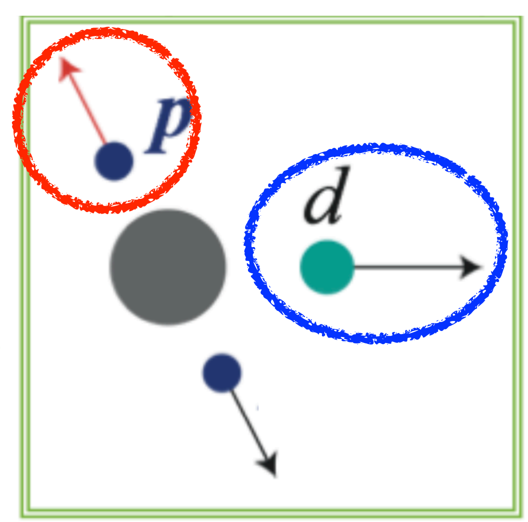
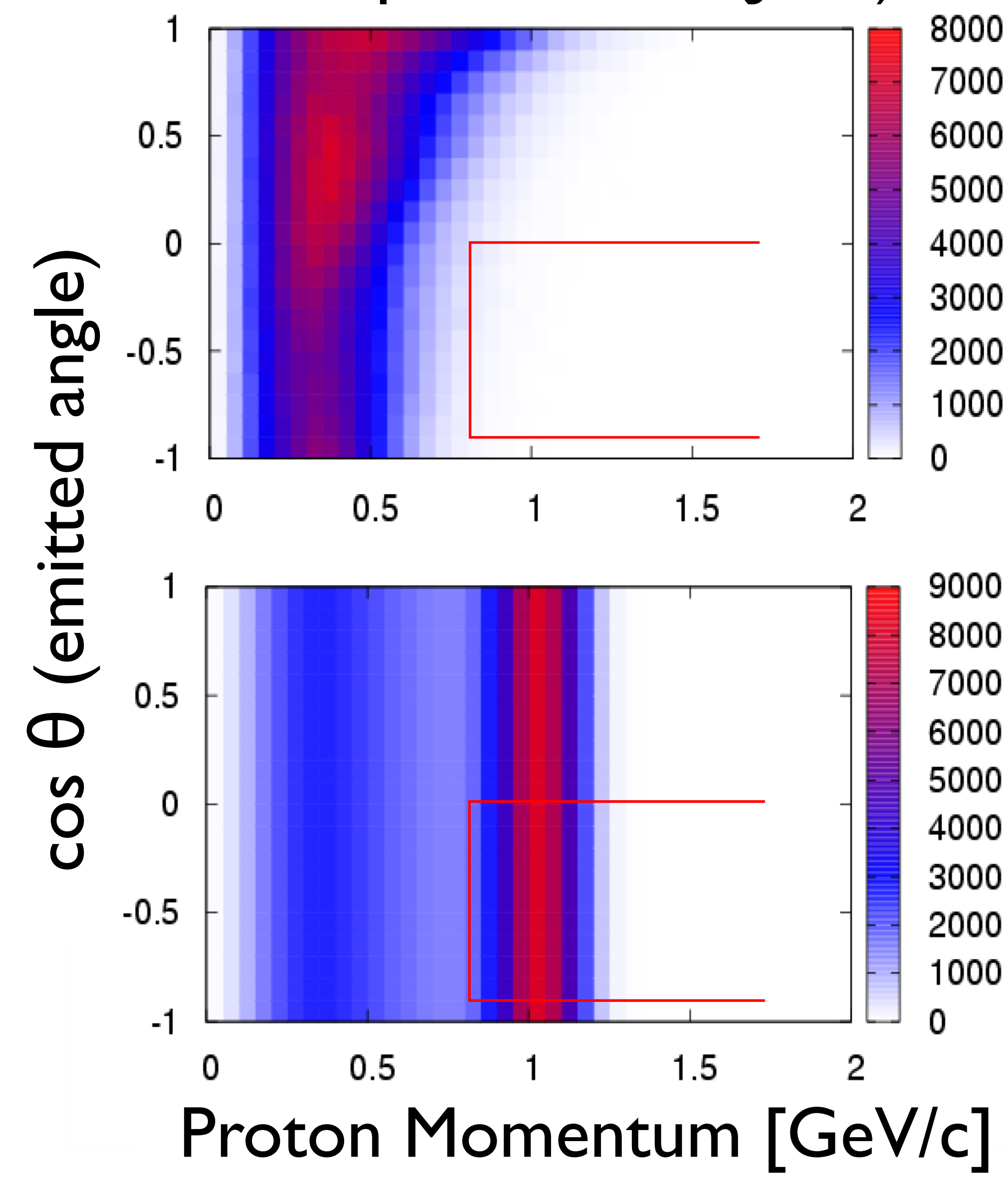
η′-mesic nuclei formation




***η'NN→NN***

Calculation by microscopic transport model (JAM)




Y. Higashi

Coincidence measurement of decay proton and forward deuteron

→ **factor ~100 improvement in Signal / BG ratio**

# Proposal of $^{12}$C($p$, $dp$) reaction measurement

## Search for $\eta'$-mesic nuclei in $^{12}$C$(p,dp)$ reaction

Spokesperson: K. Itahashi
Co-spokesperson: Y.K. Tanaka

$\eta$-PRiME Collaboration includes

K. Itahashi[1], Y. K. Tanaka[2], Y. Ayyad[3], S. Bagchi[2], J. Benlliure[4], T. Dickel[2], H. Fujioka[5], H. Geissel[2,6], F. Goldenbaum[7], C. Guo[8], E. Gutz[6], E. Haettner[2], M. N. Harakeh[9], R. S. Hayano[10], S. Hirenzaki[11], C. Hornung[6], Y. Igarashi[12], N. Ikeno[13], M. Iwasaki[1], D. Jido[14], N. Kalantar-Nayestanaki[9], R. Kanungo[15], B. Kindler[2], R. Knöbel[2,6], D. Kostyleva[2], N. Kurz[2], N. Kuzminchuk[2], B. Lommel[2], V. Metag[6], P. Moskal[16], I. Mukha[2], T. Nagae[5], H. Nagahiro[11], M. Nanova[6], T. Nishi[1], H. J. Ong[17], H. Outa[1], S. Pietri[2], W. Plass[2], A. Prochazka[2], S. Purushothaman[2], C. Rappold[2], M. P. Reiter[2], J. Ritman[7], J. L. Rodríguez-Sánchez[4], O. Rundel[16], T. Saito[2], C. Scheidenberger[2,6], H. Simon[2], B. Sitar[18], M. Skurzok[16], P. Strmen[18], B. Sun[8], K. Suzuki[19], I. Szarka[18], M. Takechi[20], I. Tanihata[8,17], S. Terashima[8], Y. N. Watanabe[10], H. Weick[2], E. Widmann[19], J. S. Winfield[2], X. Xu[8], and J. Zhao[8].

[1]RIKEN Nishina Center, [2]GSI Helmholtzzentrum für Schwerionenforschung, [3]LBNL, [4]Universidade de Santiago de Compostela, [5]Kyoto University, [6]Universität Giessen, [7]IKP, FZ Jülich, [8]Beihang University, [9]KVI-CART, University of Groningen, [10]The University of Tokyo, [11]Nara Women's University, [12]KEK, [13]Tottori University, [14]Tokyo Metropolitan University, [15]Saint Mary's University, [16]Jagiellonian University, [17]RCNP, Osaka University, [18]Comenius University Bratislava, [19]Stefan-Meyer-Institut für subatomare Physik, and [20]Niigata University.

### Abstract

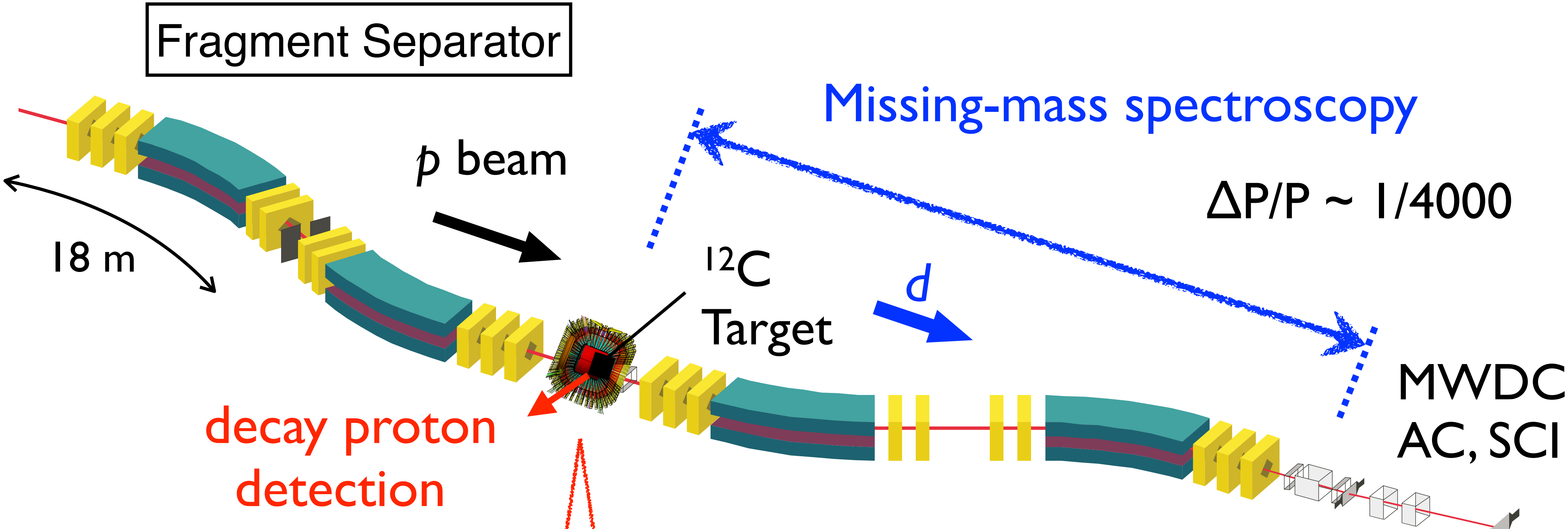
We propose to measure excitation spectrum of $^{11}$C near the $\eta'$-production threshold in order to search for narrow structures due to formation of $\eta'$-mesic nuclei, bound systems of an $\eta'$ meson and a nucleus. The expected spectra vary according to the assumed $\eta'$-nucleus interaction for which we have very limited knowledge. We have a concrete and strategic experimental

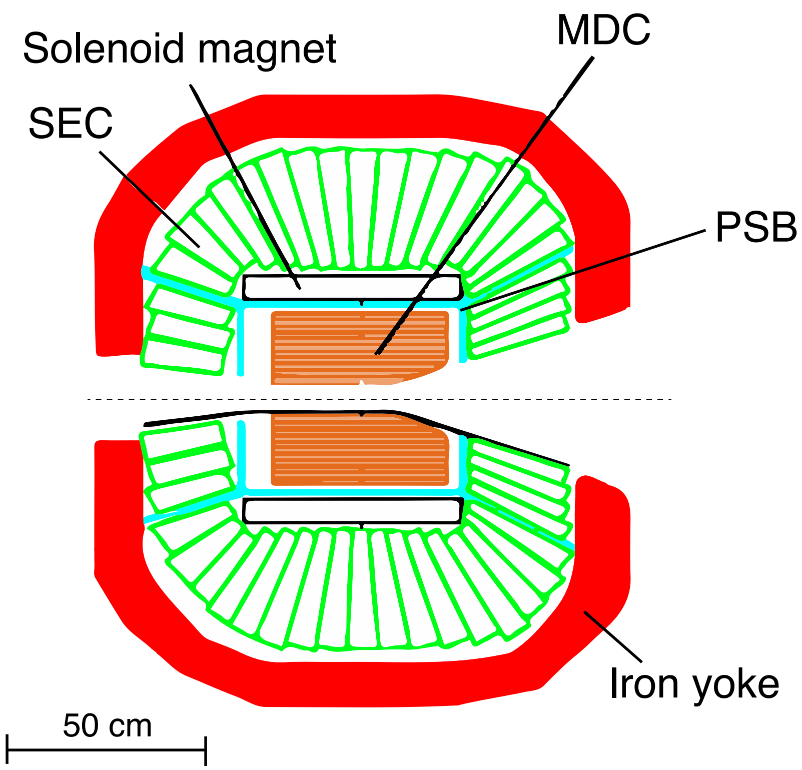
approved proposal in GPAC (2017)

**using WASA central detector at FRS-GSI**

**S490 experiment at GSI (scheduled in 2022 Feb.--Mar.)**

# Experimental setup with WASA at FRS




WASA Central Detector

operated @COSY (2006—2014)

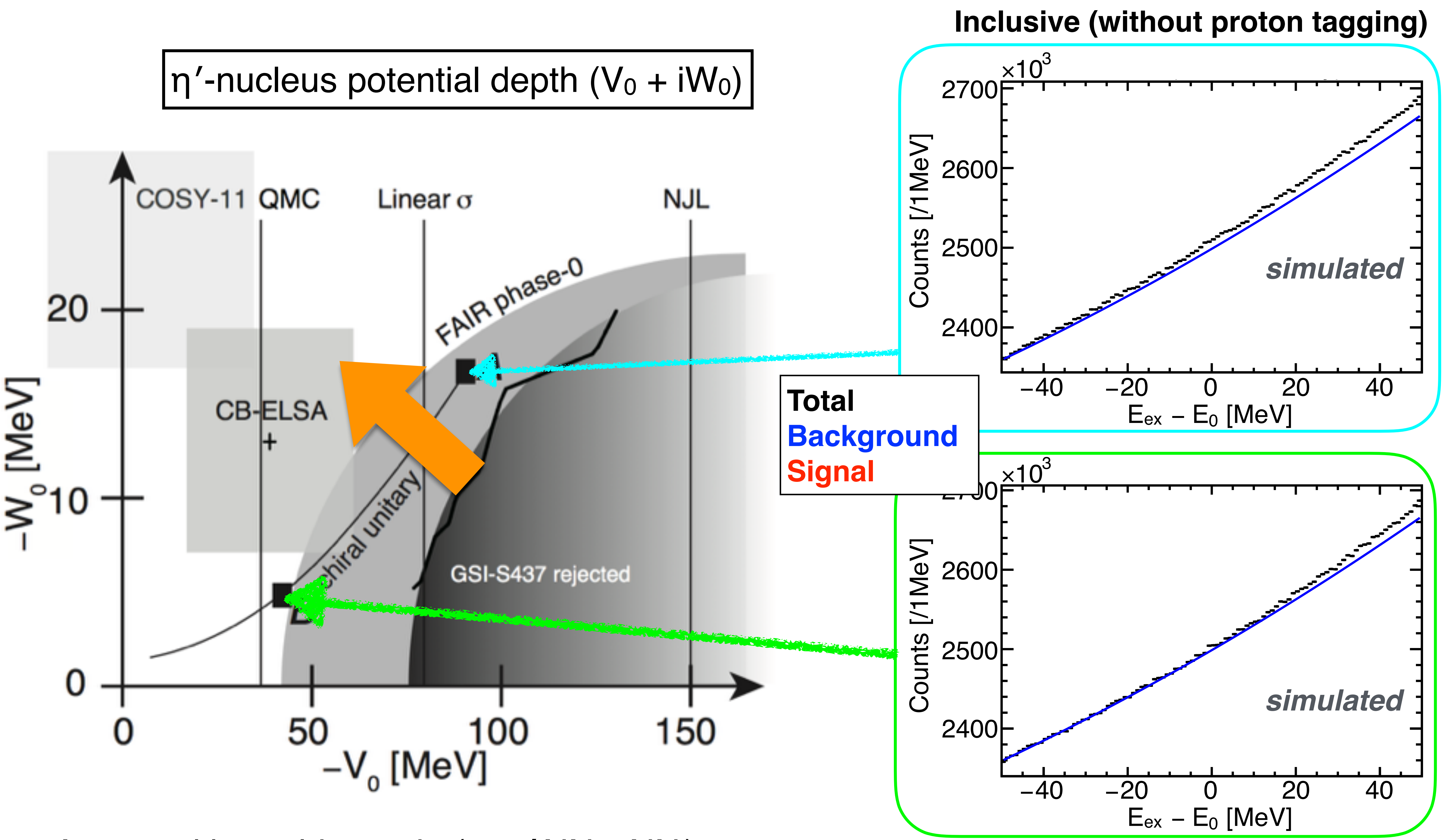
◇ Superconducting solenoid magnet (~1.3 T)

◇ Mini drift chamber (MDC) for tracking

◇ Plastic scintillator barrel (PSB) for ΔE,TOF

◇ CsI Electromagnetic calorimeter (SEC)

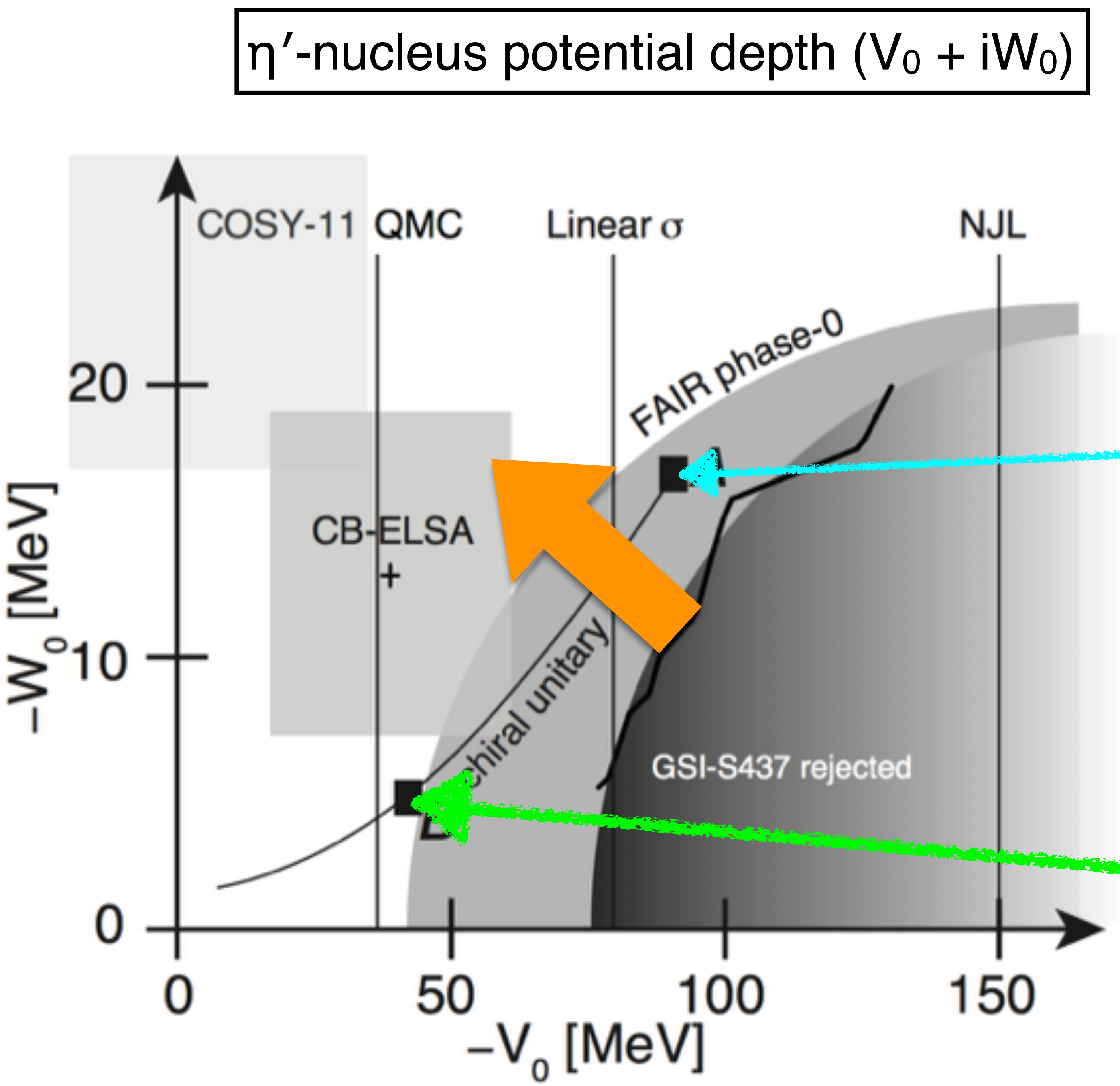
# Expected spectra in semi-exclusive measurement

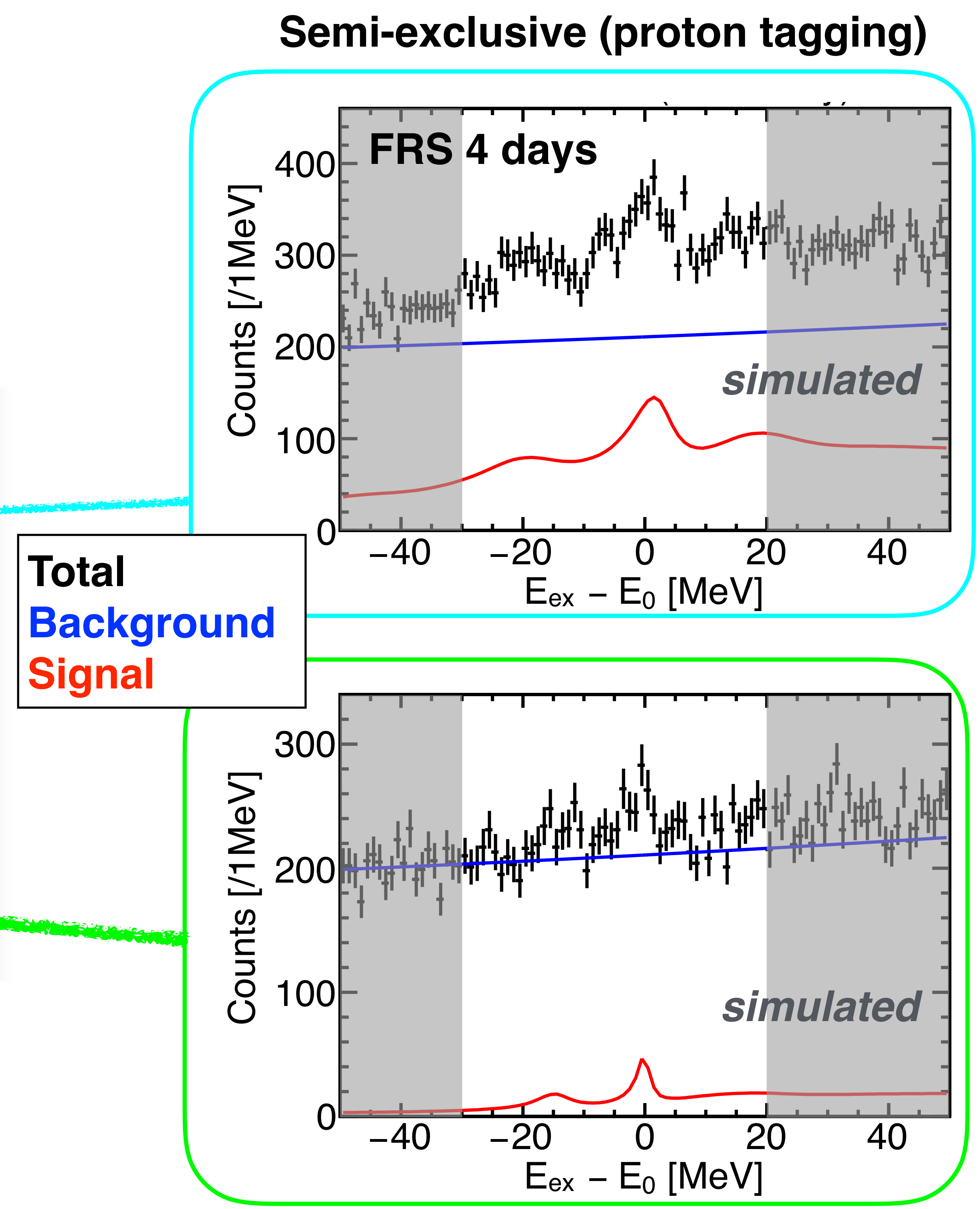



◇ Assumed branching ratio (to η′*NN*→*NN* ) ~ 50%

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

# Expected spectra in semi-exclusive measurement

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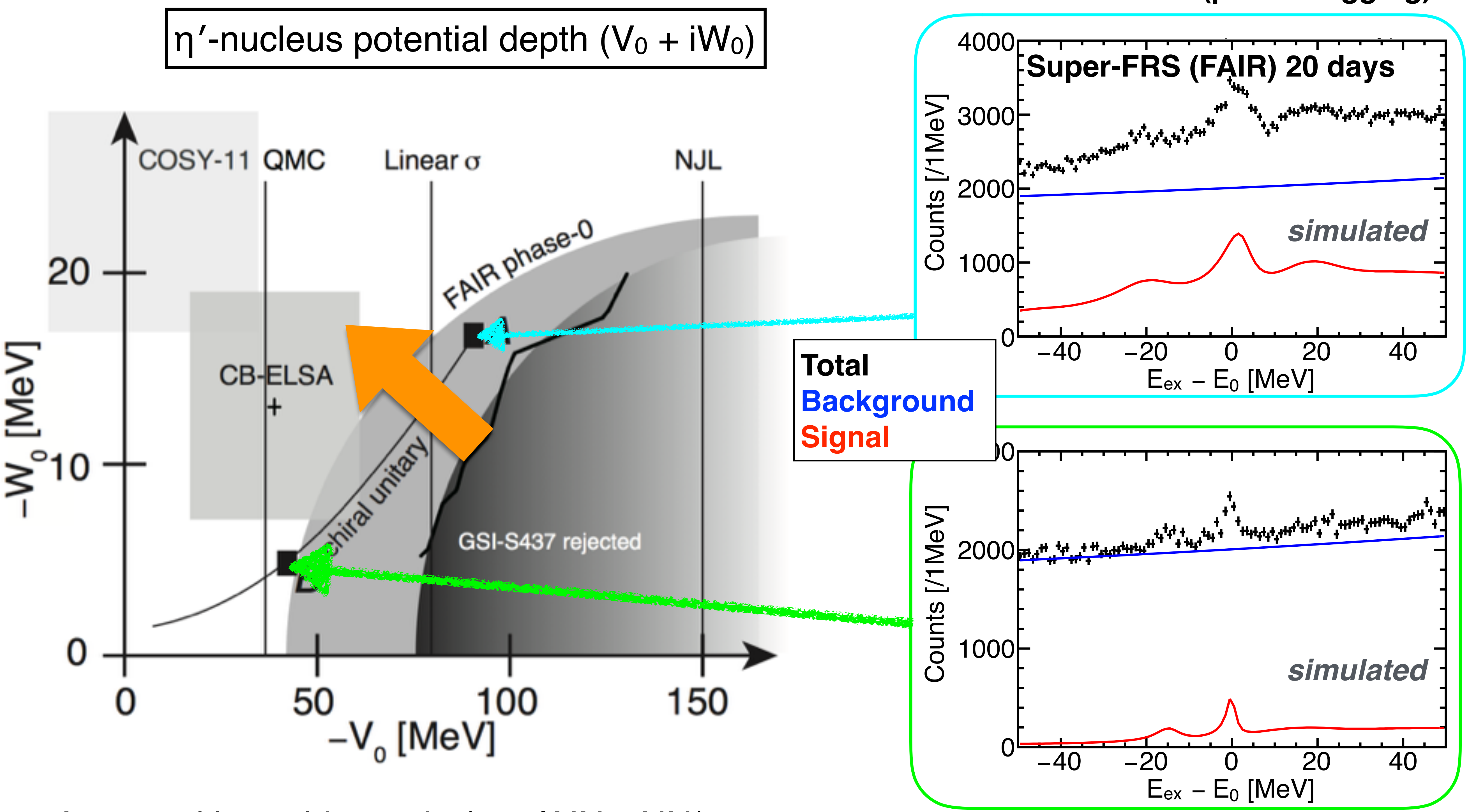
H.Nagahiro *et al.*, PRC 87, 045201 (2013), Phys. Lett. B 709, 87 (2012).

# Expected spectra in semi-exclusive measurement

**Semi-exclusive (proton tagging)**




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

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

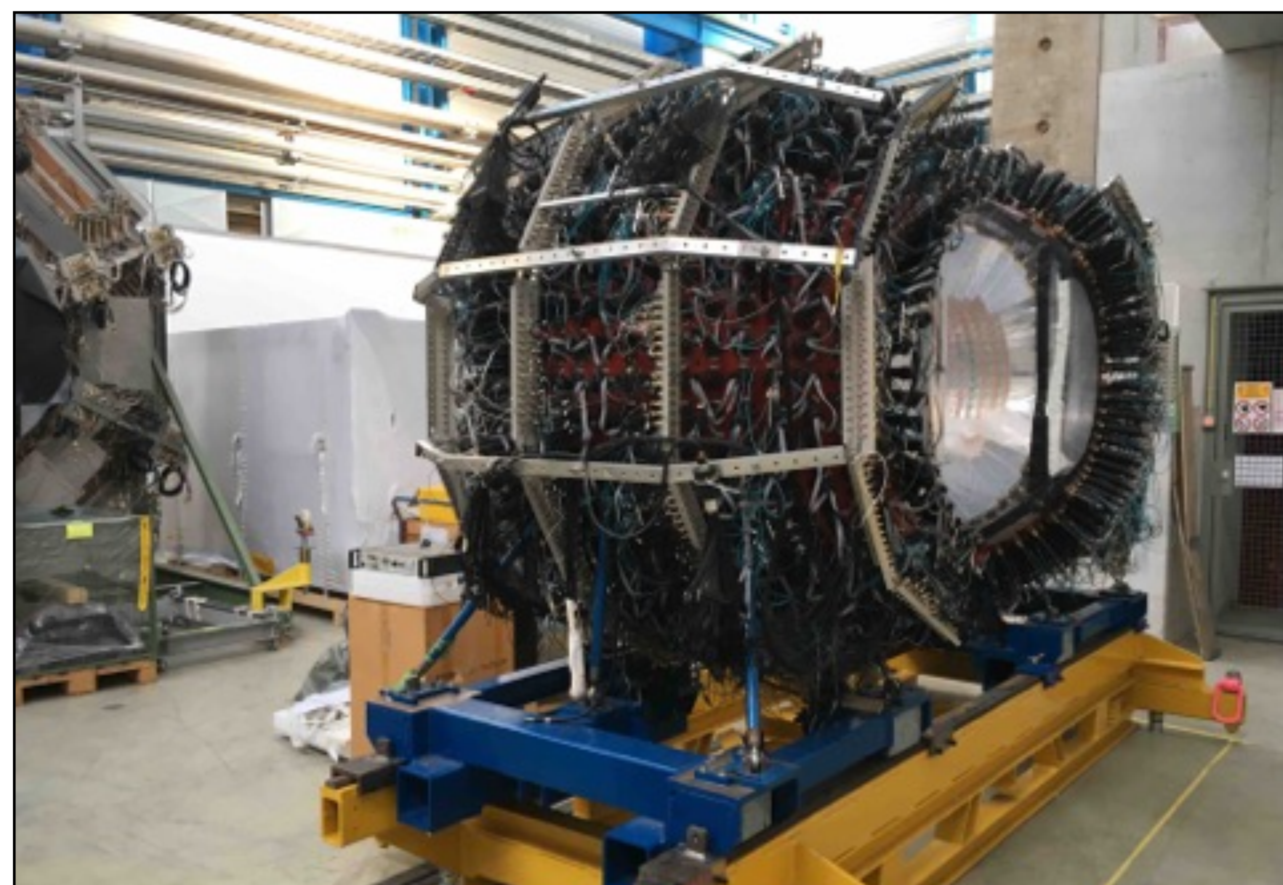
# Transportation of WASA from COSY to GSI

**Transportation of all items needed for FAIR phase-0**

**completed in 2019/March**

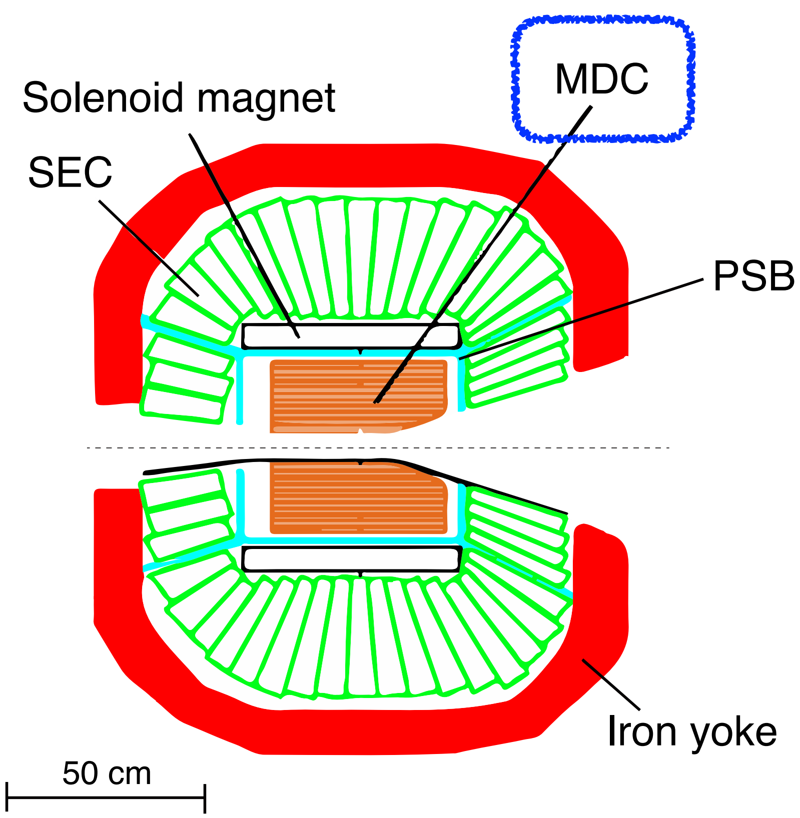
**@ COSY, FZ-Jülich**

**Testing area @ GSI**

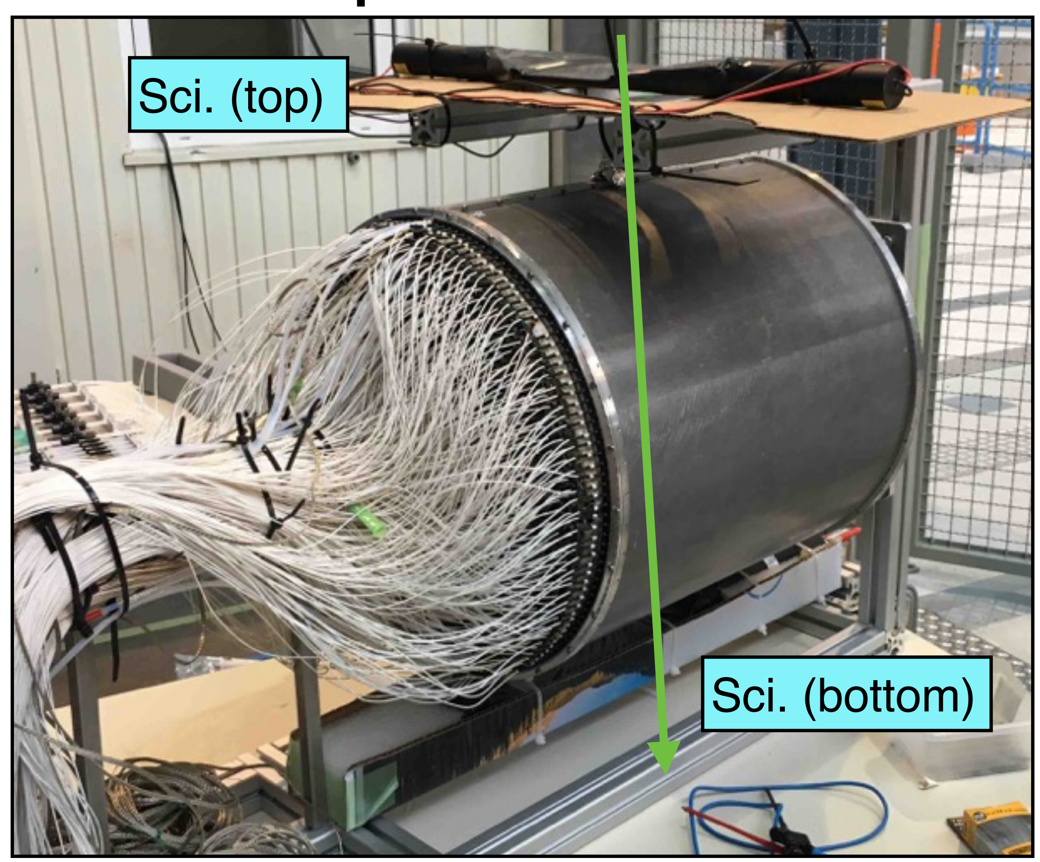


# Testing WASA-MDC at FRS/GSI

- ◇ Drift chambers base on straw tubes for charged particle tracking in the solenoid magnet
- ◇ 17 cylindrical layers (9 layers parallel to z axis, 8 layers “stereo”), in total 1738 channels
- ◇ Cosmic-ray test has been already performed in 2018-2019

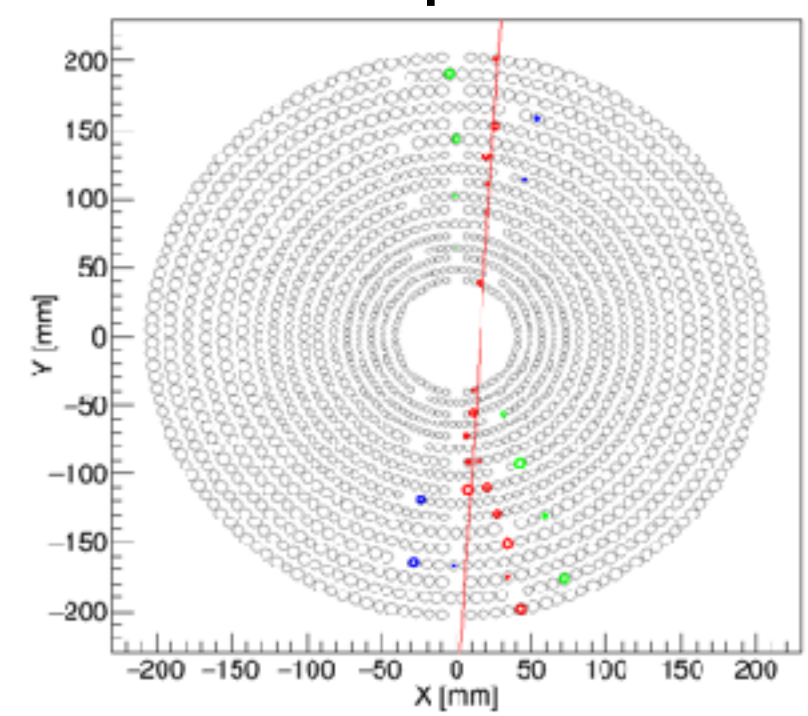



**test setup at WASA container**




Trigger = Scintillator (Top and Bottom) coincidence

**x-y projection of cosmic particles**




**axial / stereo(+) / stereo(−)**

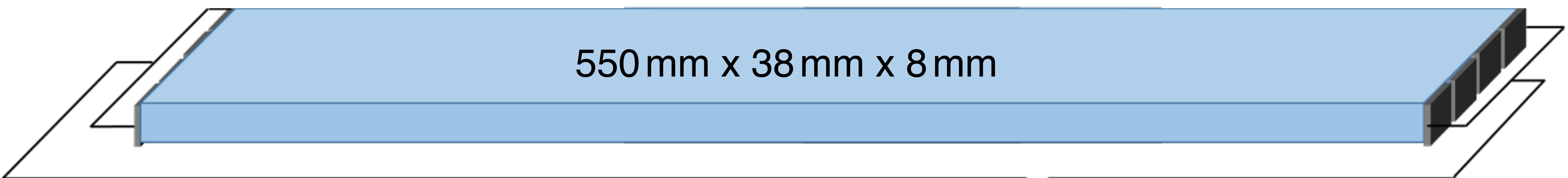
Y.K. Tanaka, V. Serdyuk, J.L.Rodiguez Sanchez, K. Itahashi, S.Y. Matsumoto, T. R. Saito with technical supports from FRS engineers

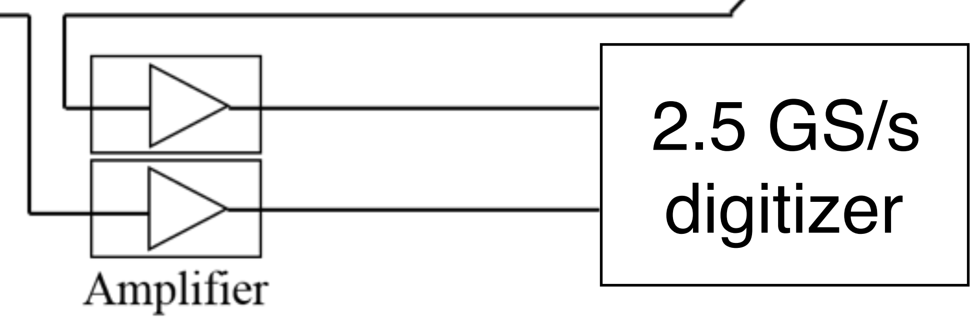
# Upgrading PSB (plastic scintillator barrel)

Prototype: MPPC readout at both sides to improve time resolution

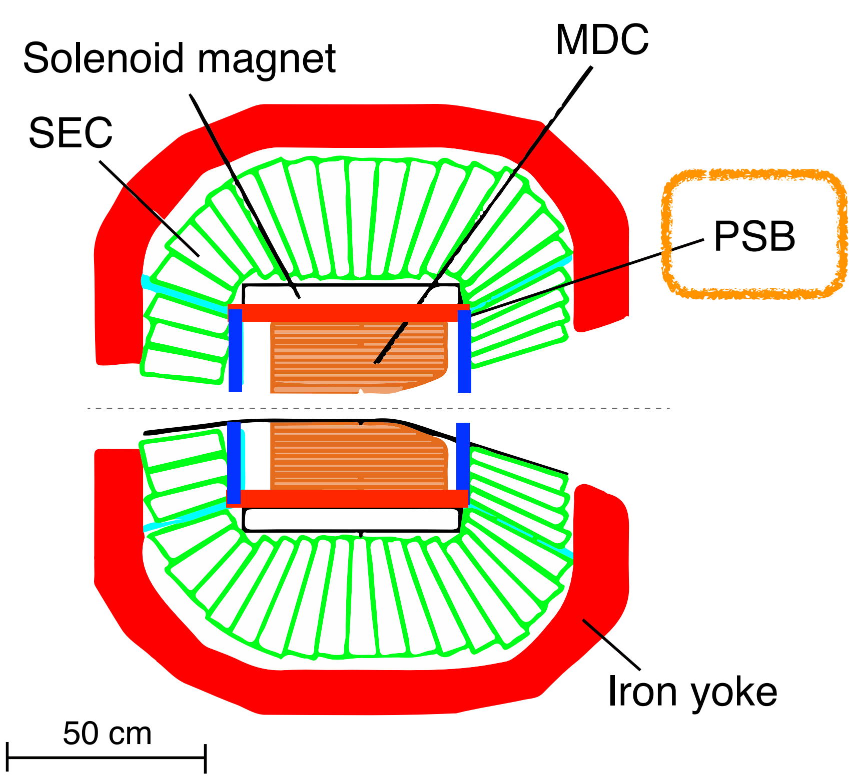
ELJEN-EJ230 plastic (attenuation L = 1.2 m)

MPPC (Hamamatsu S13360), 6 x 6 mm$^2$

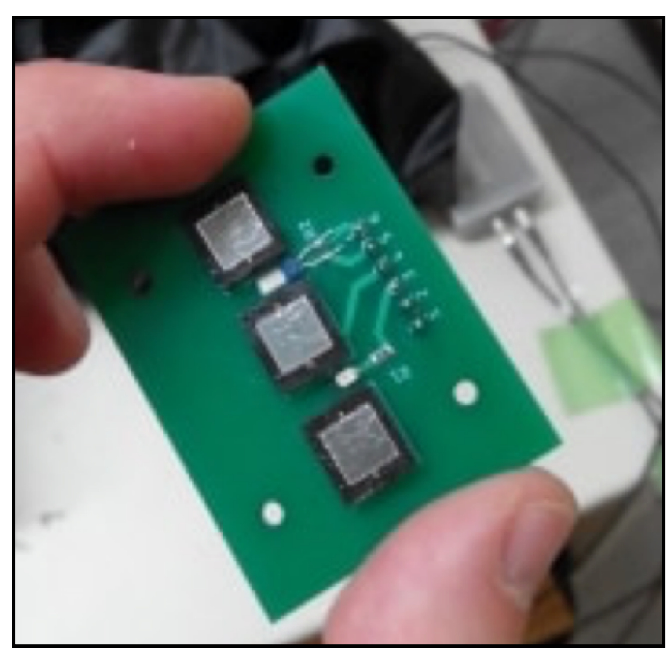


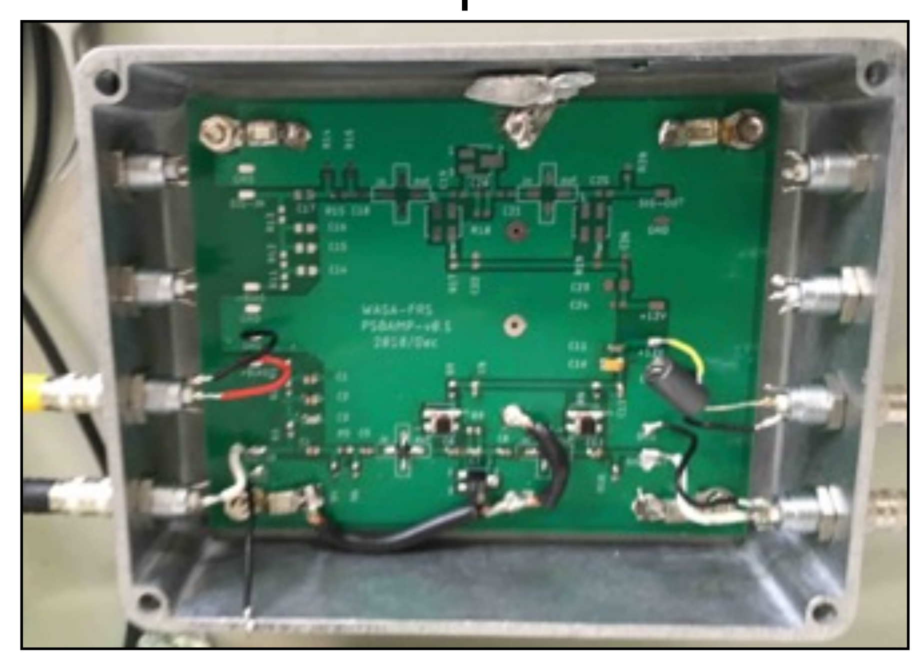

R. Sekiya, Y.K.Tanaka, K.Itahashi, V. Drozd,
H. Fujioka, S. Y. Matsumoto, T. R. Saito, K. Suzuki,




MPPC board

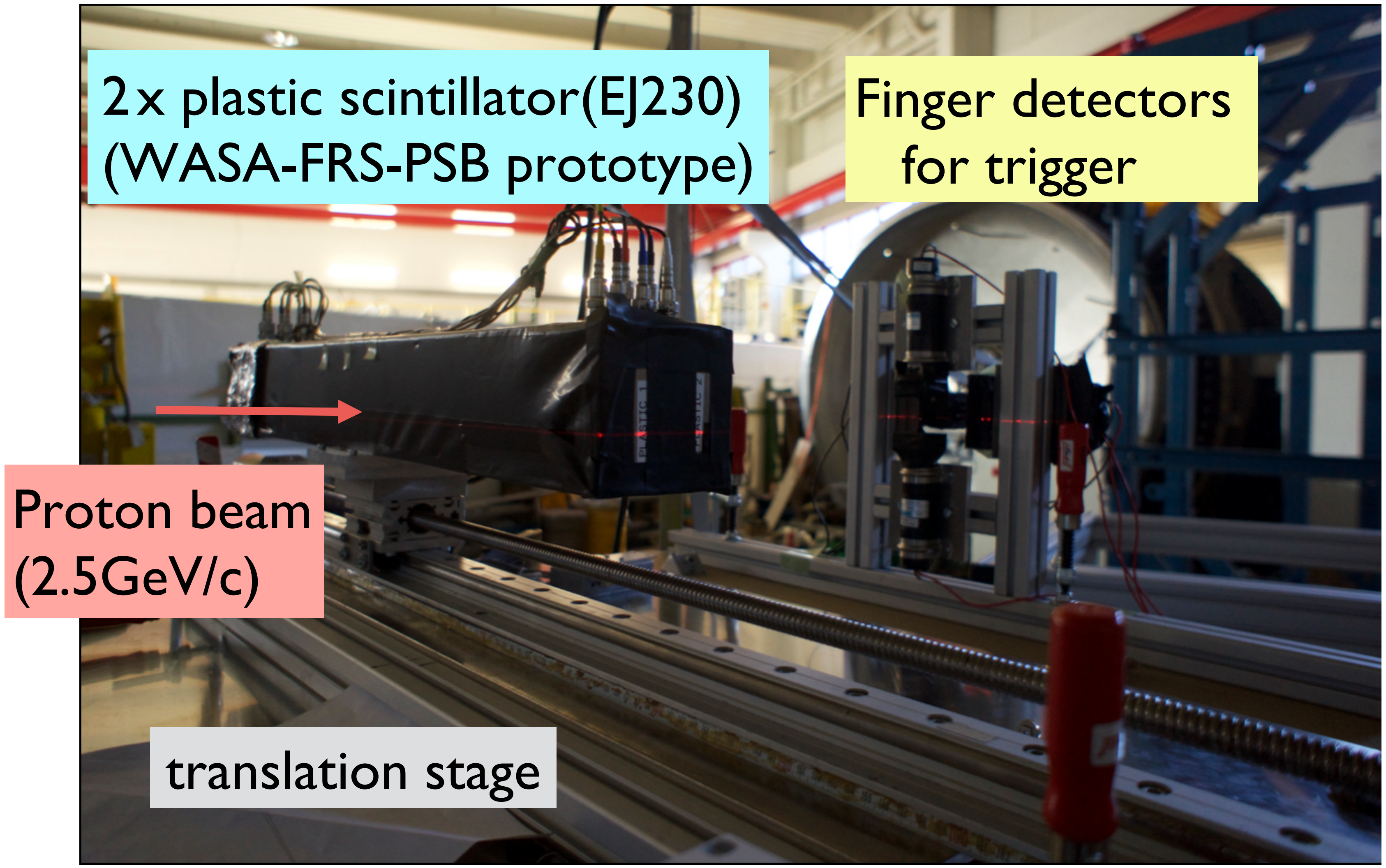


Amplifier



based on design given in IEEE Trans. Nucl. Sci. 61, 2657 (2014)

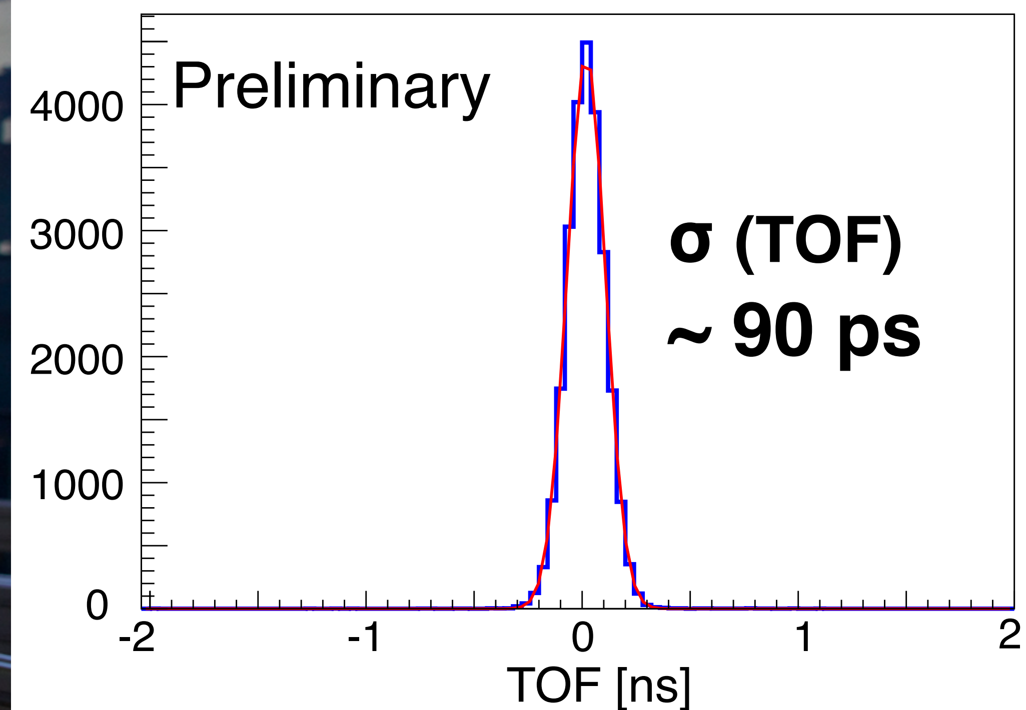
# Test of new PSB prototype using proton beam




2019 Feb., at COSY, Jülich

Example:

3MPPC in series, 0°, $V_{over}$ = 5V




→ $\sigma_{PSB}$ ~ 60 ps

for 2.5 GeV/c proton

We performed systematic studies of the time resolution by changing …

◇ Bias voltage ◇ Number of connected SiPMs

◇ Hit position ◇ Incident beam angles ◇ Readout electronics

R. Sekiya, V. Drozd, Y.K. Tanaka, K. Itahashi

Acknowledgment to PANDA-STT group and IKP, FZ-Jülich

# WASA Superconducting Solenoid Magnet

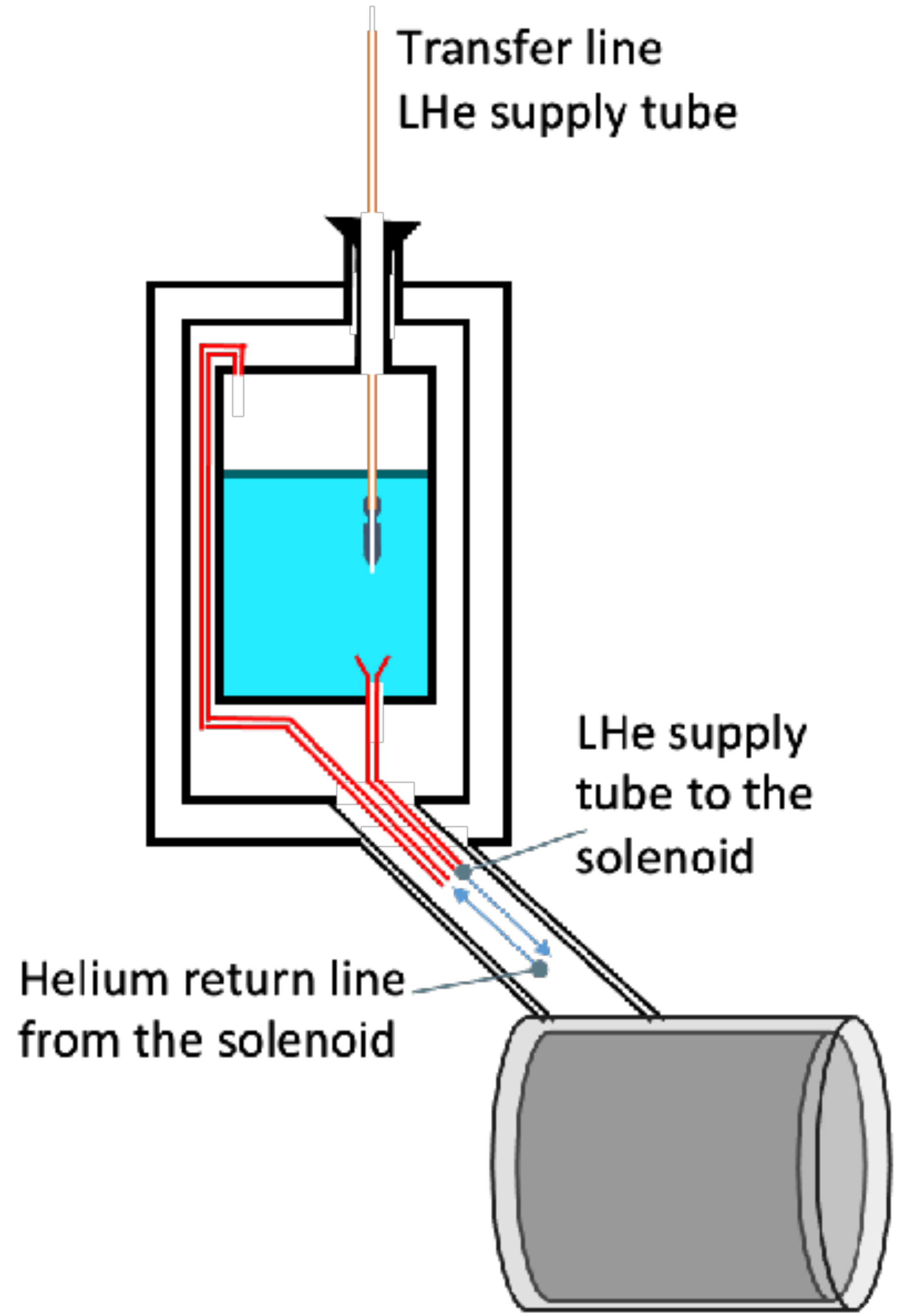
## WASA solenoid magnet

- superconducting magnet, $B_{max}$ ~ 1.3 T
- cooling with Liquid He, 4.5 K

| | |
|---|---|
| **Superconducting coil** | |
| Inner/outer radius [mm] | 267.8 / 288.8 |
| Superconductor (stabilizer) | NbTi/Cu (pure Al) |
| Total winding length | 465 mm |
| Maximum central magnetic flux density, $\mathbf{B}_c$ | 1.3 T |
| Field uniformity in the MDC | 1.22 T ±20% |
| Cooling | Liquid He, 4.5°K |
| **Cryostat** | |
| Material | Aluminium |
| Inner / outer radius [mm] | 245 / 325 |
| Overall length [mm] | 555 |
| **SCS wall thickness** (coil+cryostat) [radl] | **0.18** |

Table 5: Main parameters of the superconducting coil and its cryostat.

PhD Thesis , R.Ruber



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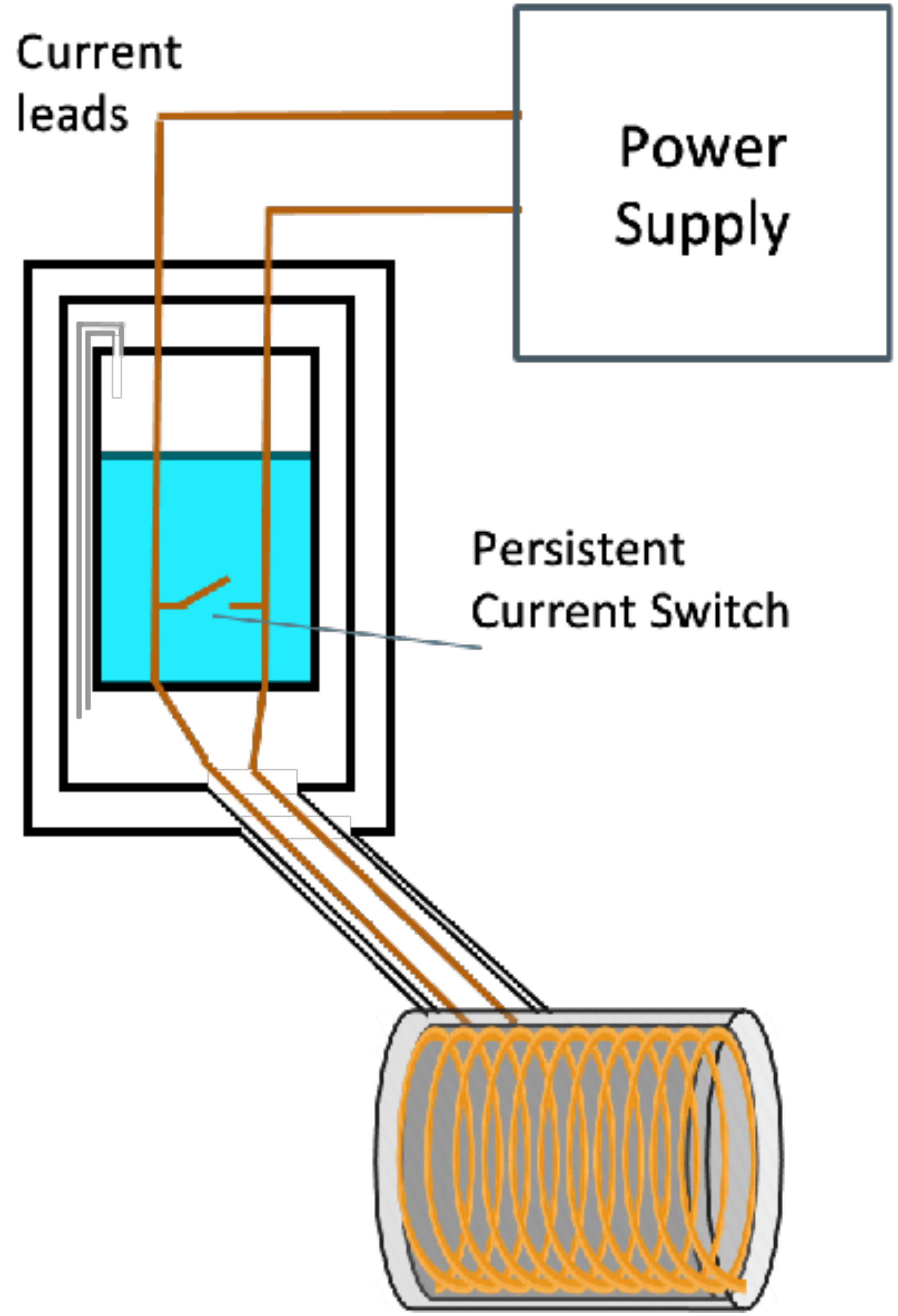
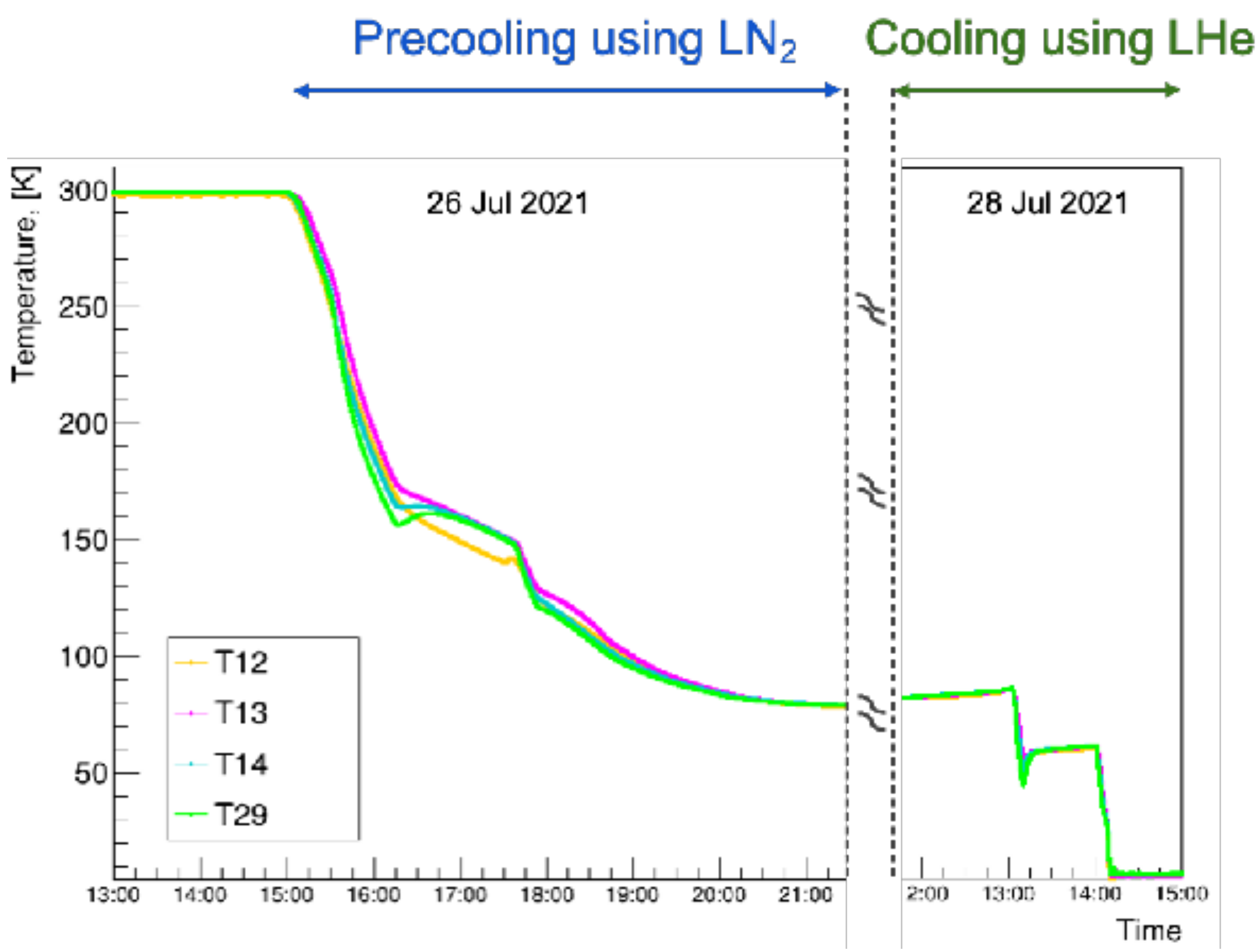


# Superconducting Solenoid Magnet

Test Phase at FOPI area (2019-2021)

- ✓ Cooling tests down to **4.5 K**
- ✓ Excitation tests
- ✓ Development of the control and monitoring system




**with support from GSI Cryogenic group**

V.Drozd, Y Tanaka, S. Purushothaman, B. Streicher, R. Ruber, A. Yamamoto

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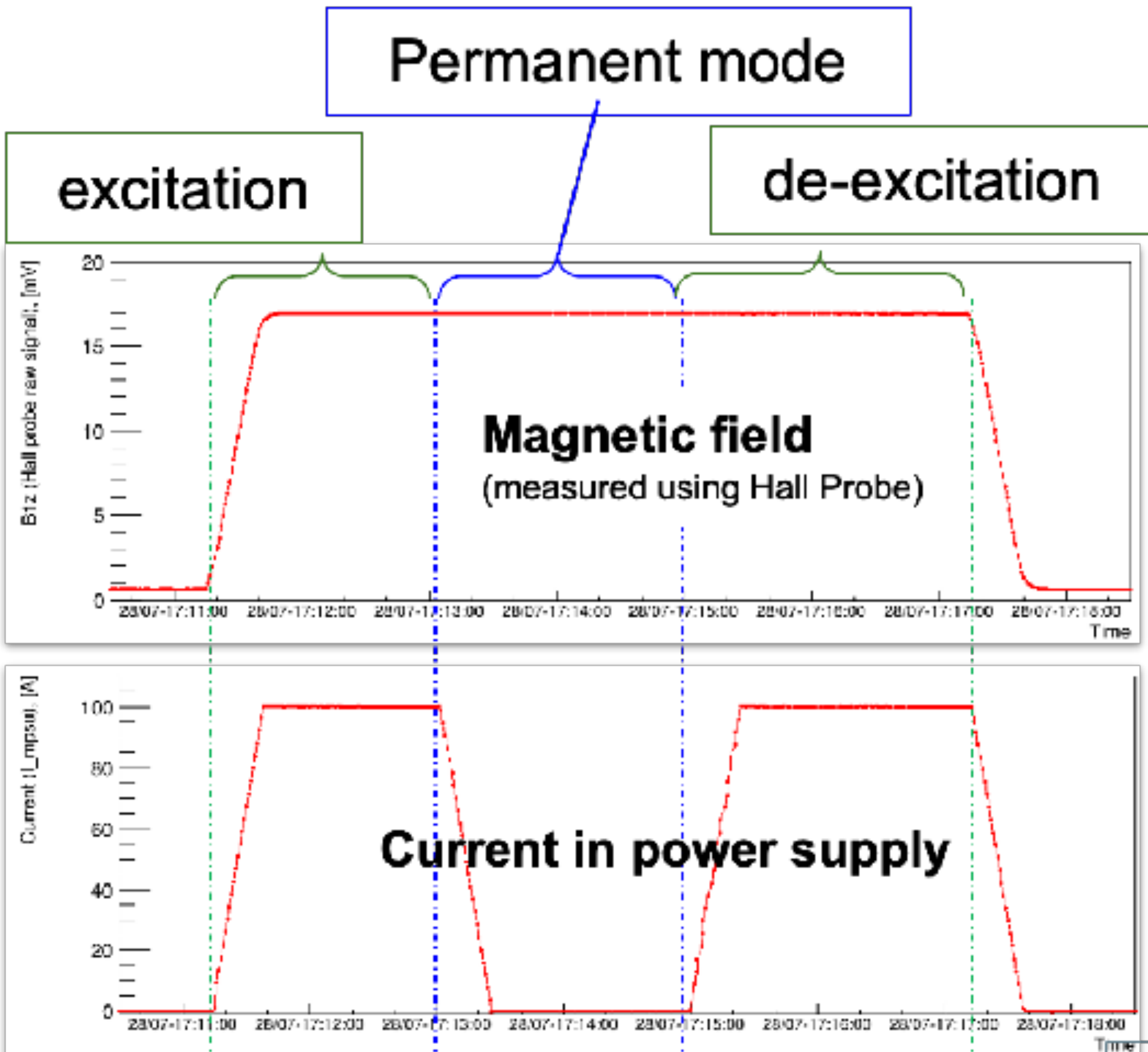


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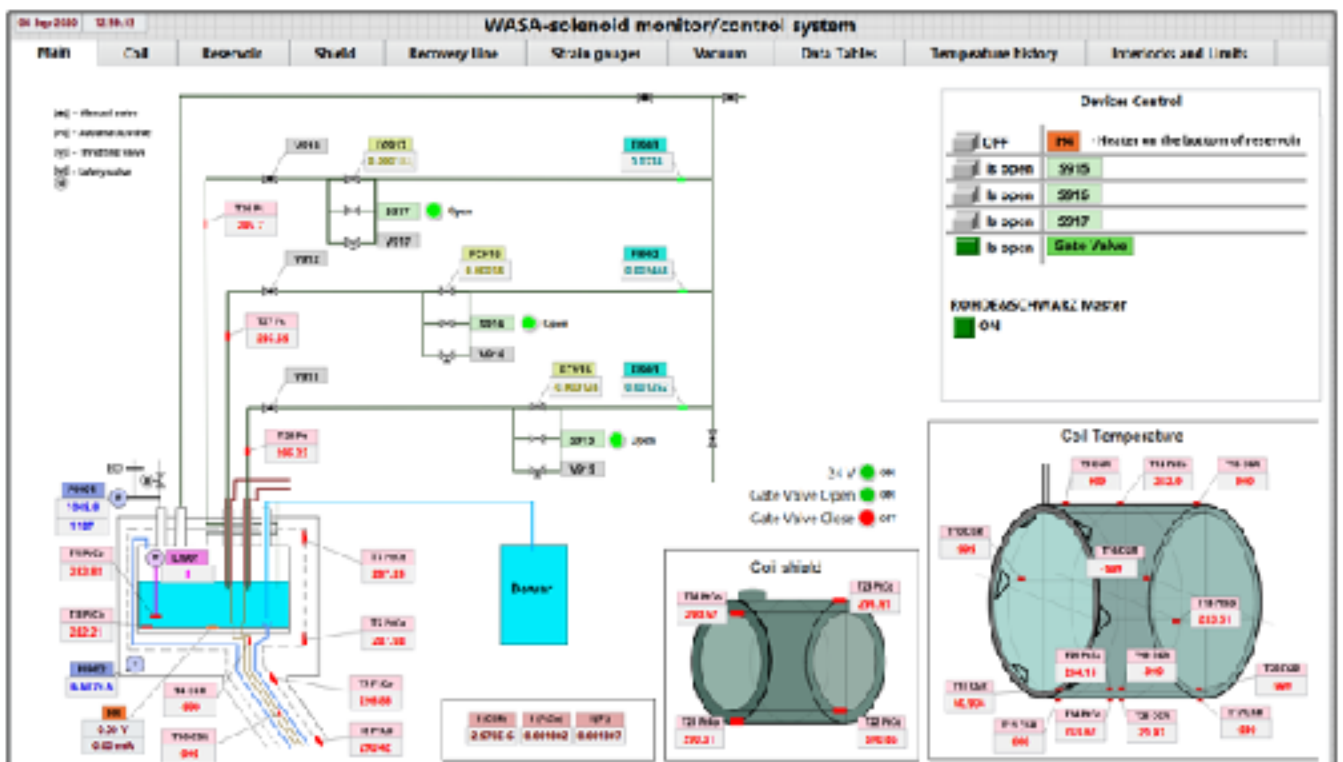
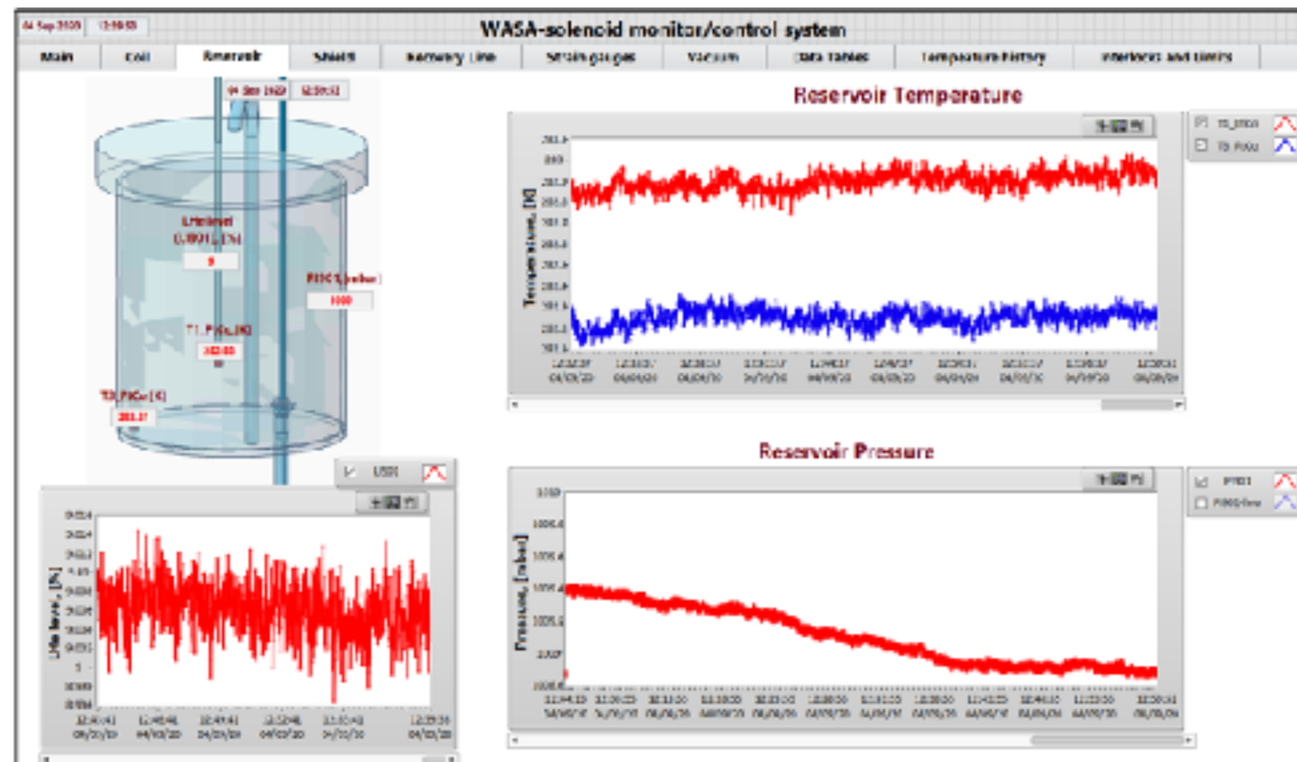
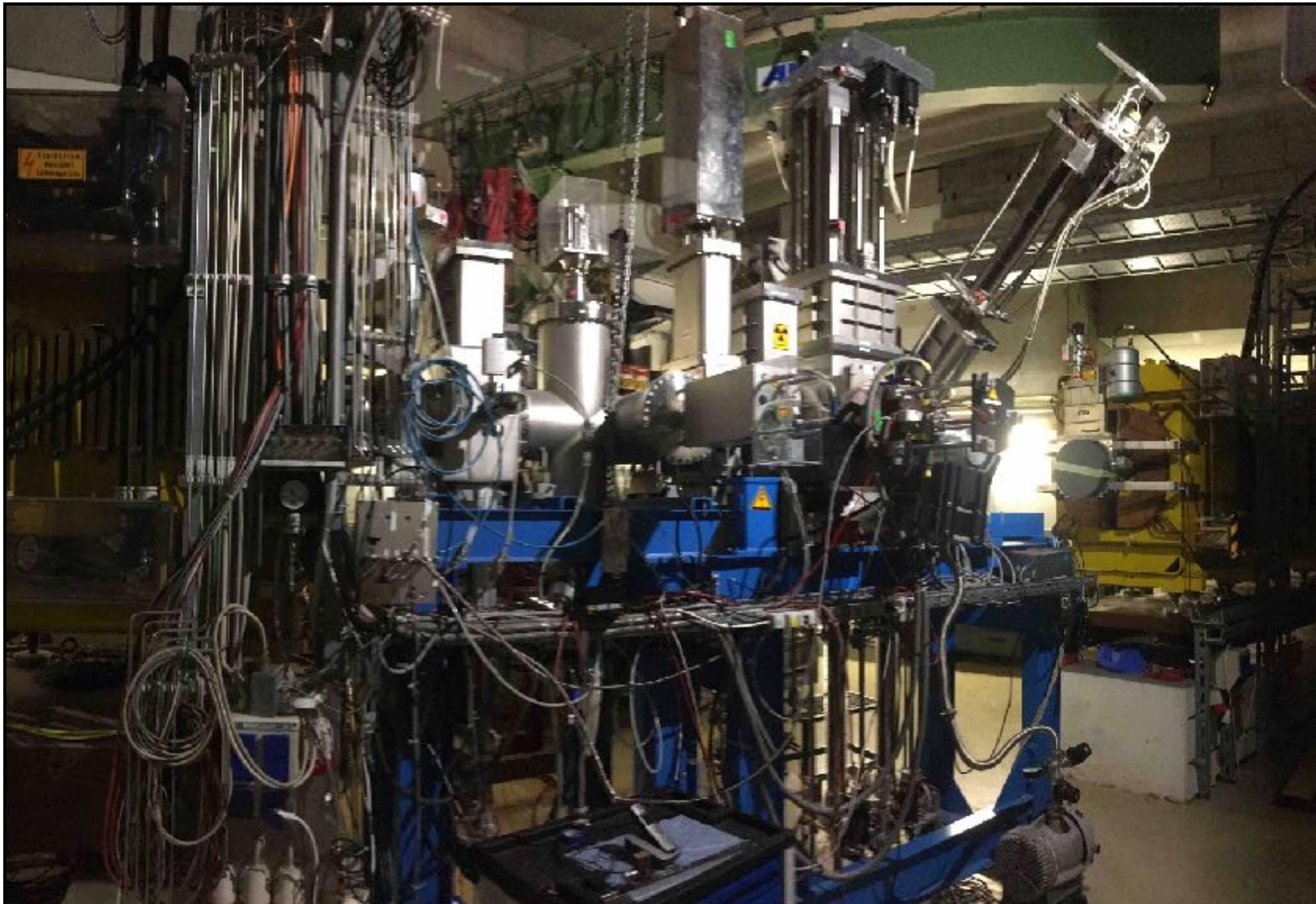



V. Drozd

# WASA Installation at GSI-FRS F2

2021 June    standard FRS-F2



essential devices for separation and identification of fragments for NUSTAR experiments

# WASA Installation at GSI-FRS F2

2021 July: Roof was opened; FRS standard chamber was removed

# WASA Installation at GSI-FRS F2

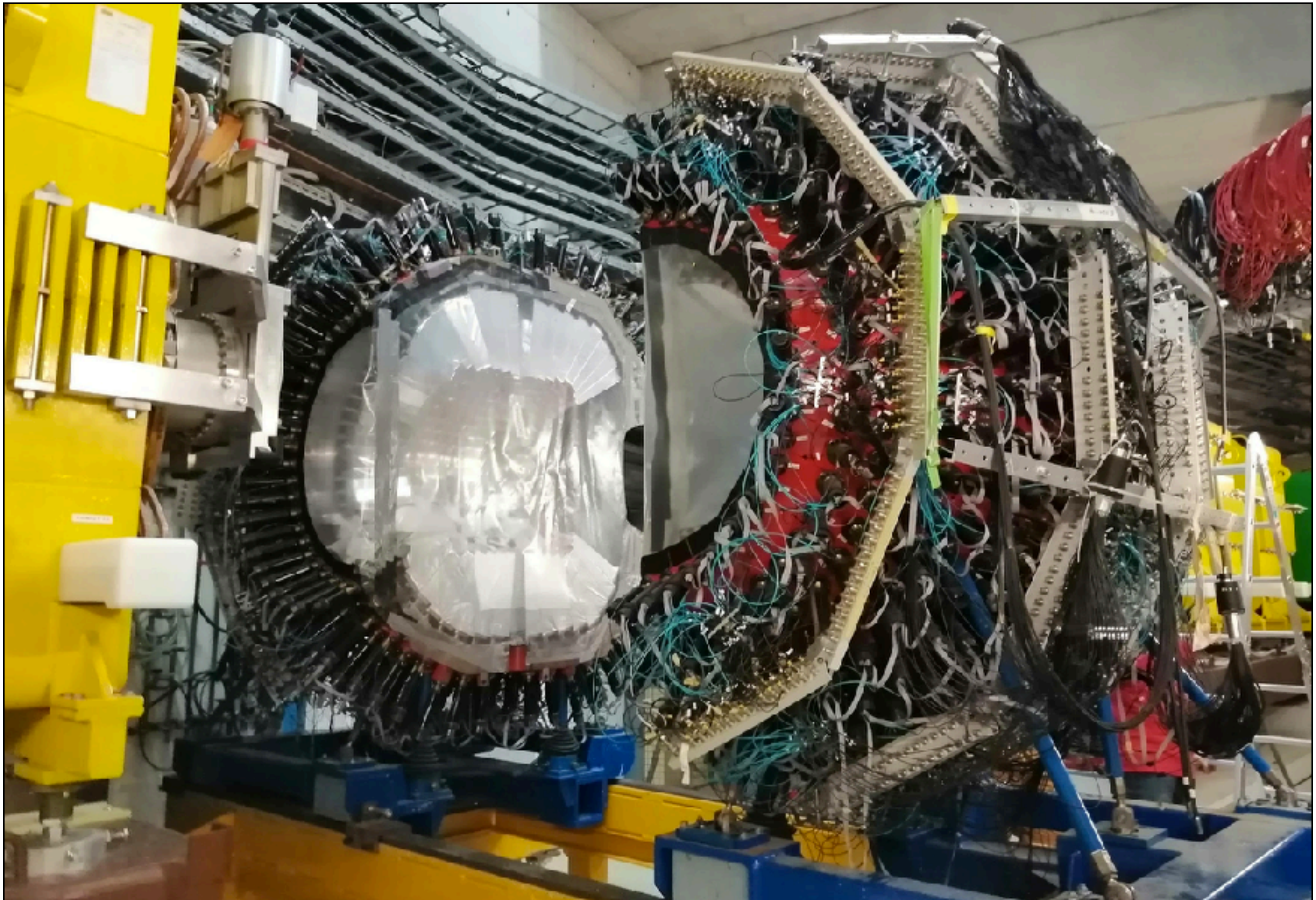
2021 August: Installation of CsI Rail structure

# WASA Installation at GSI-FRS F2

2021 August: Installation of CsI Rail structure

# WASA Installation at GSI-FRS F2

2021 August: Installation of CsI Rail structure

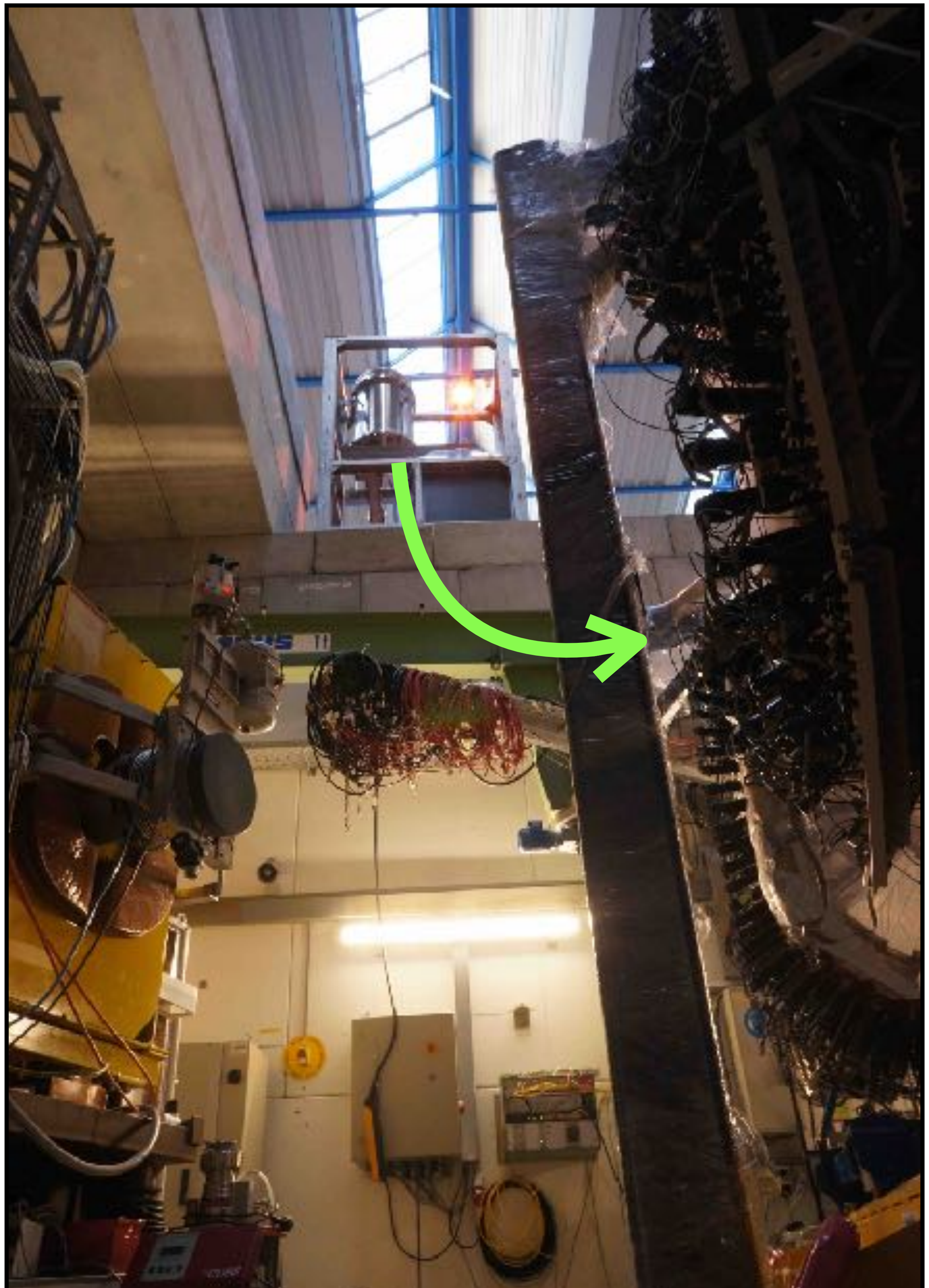


# WASA Installation at GSI-FRS F2

2021 September: Installation of Support frame for Magnet

# WASA Installation at GSI-FRS F2

October 5, 2021 Installation of Support frame for Magnet



# WASA Installation at GSI-FRS F2

October-November, 2021

Installation LHe transfer line from 3000L LHe storage dewar

# WASA Installation at GSI-FRS F2

November, 2021 Installation of inner detectors

MDC+PSB+miniFiber were integrated to the MDC structure and these were installed as one unit

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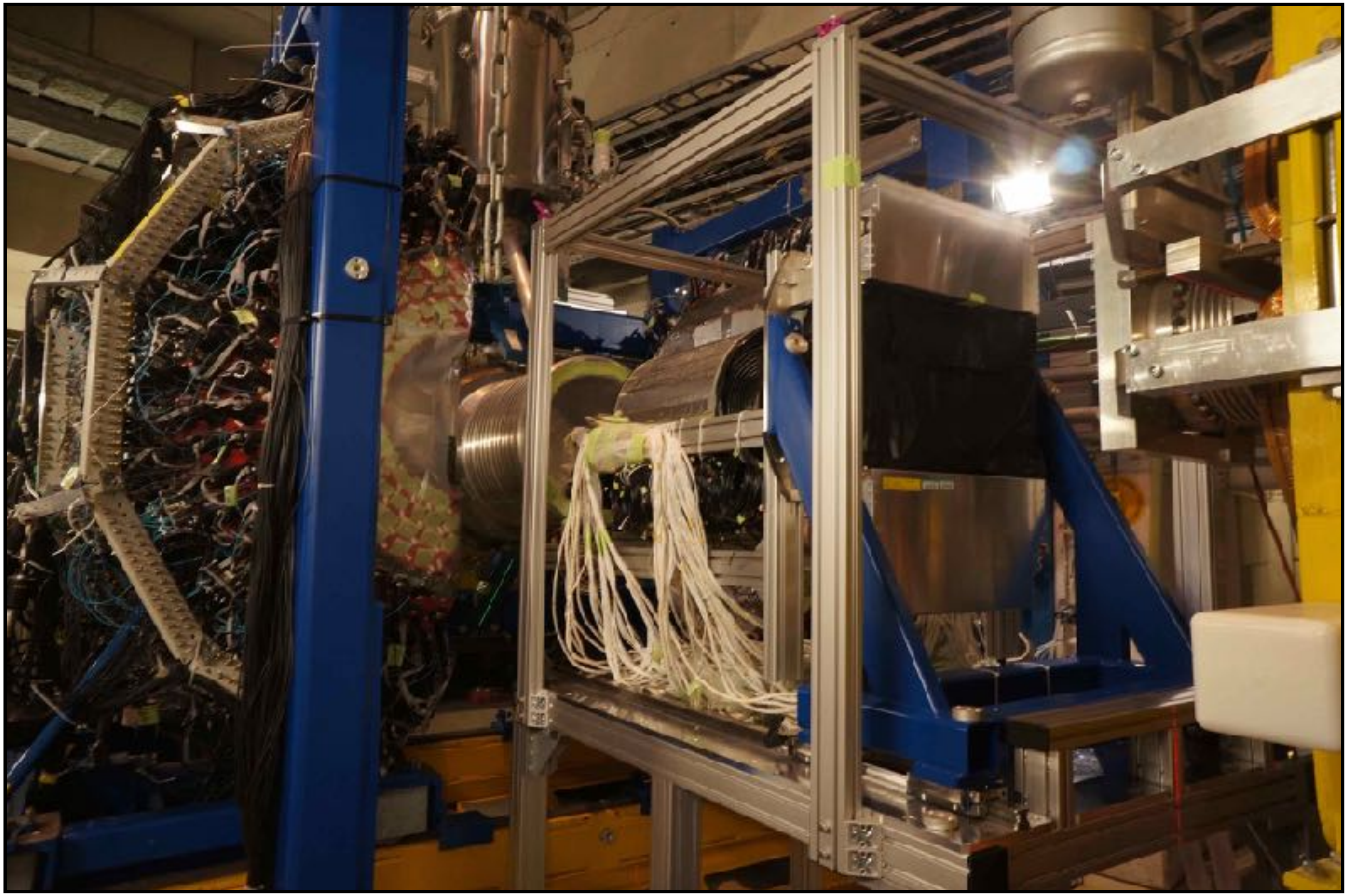

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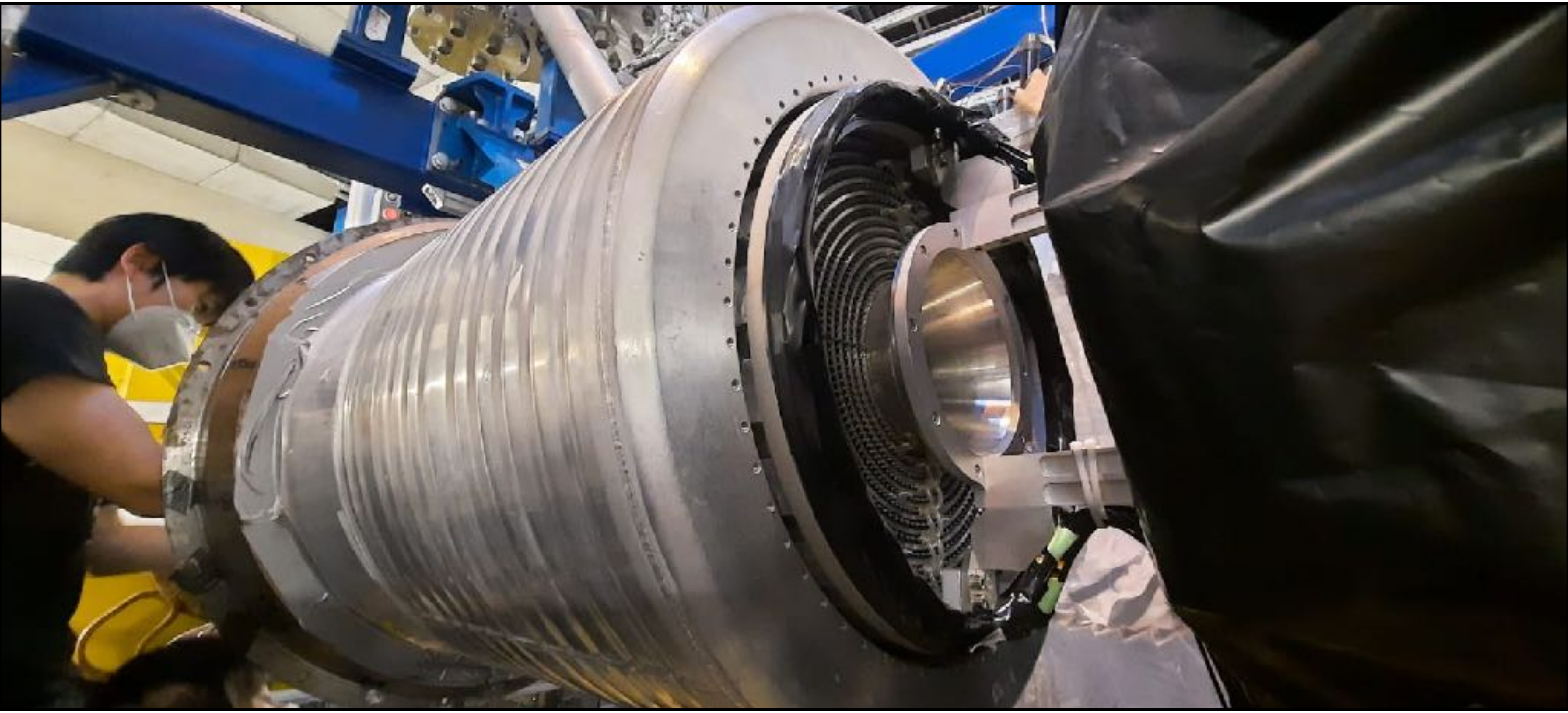

MDC+PSB+miniFiber were integrated to the MDC structure
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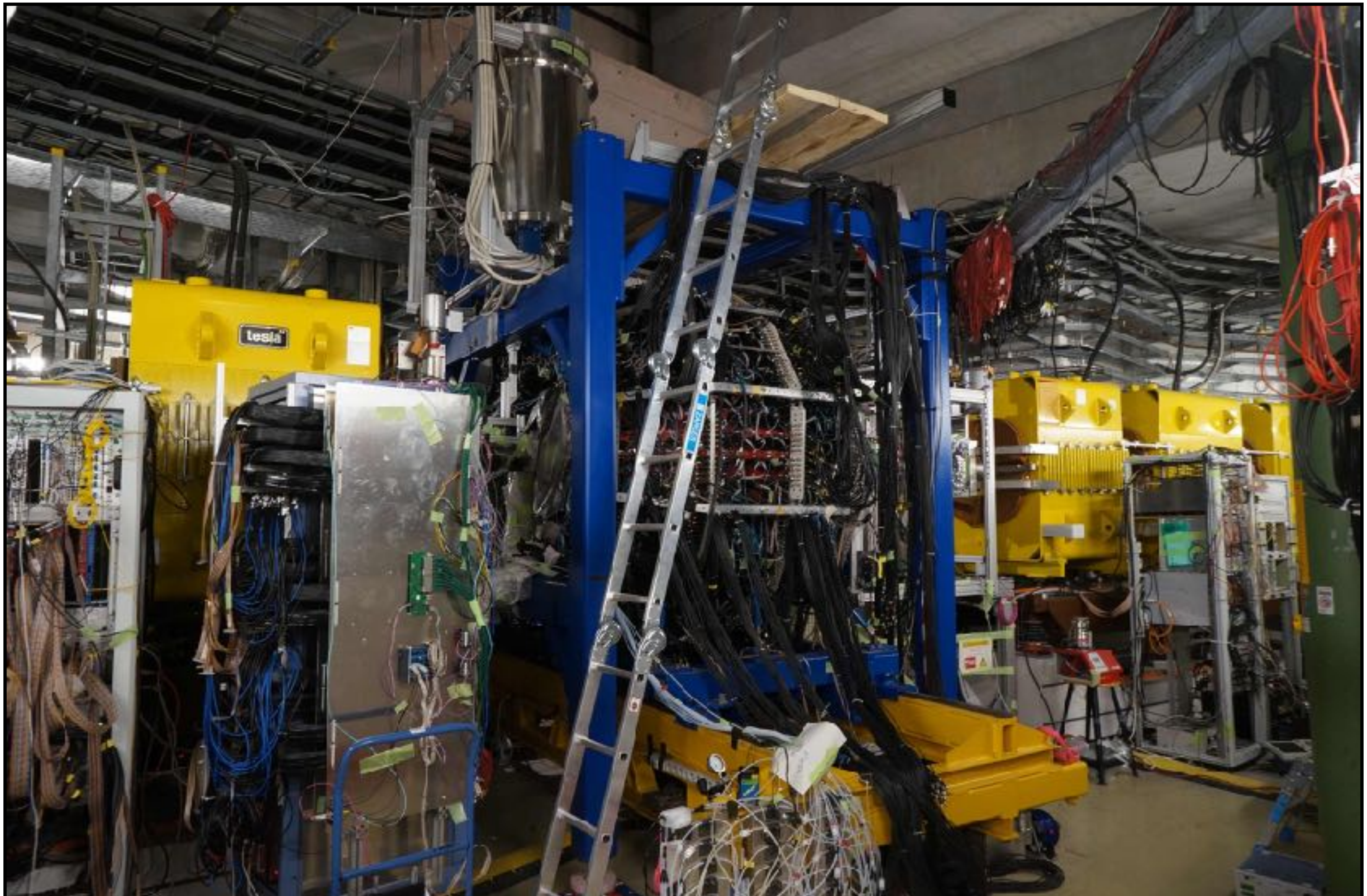
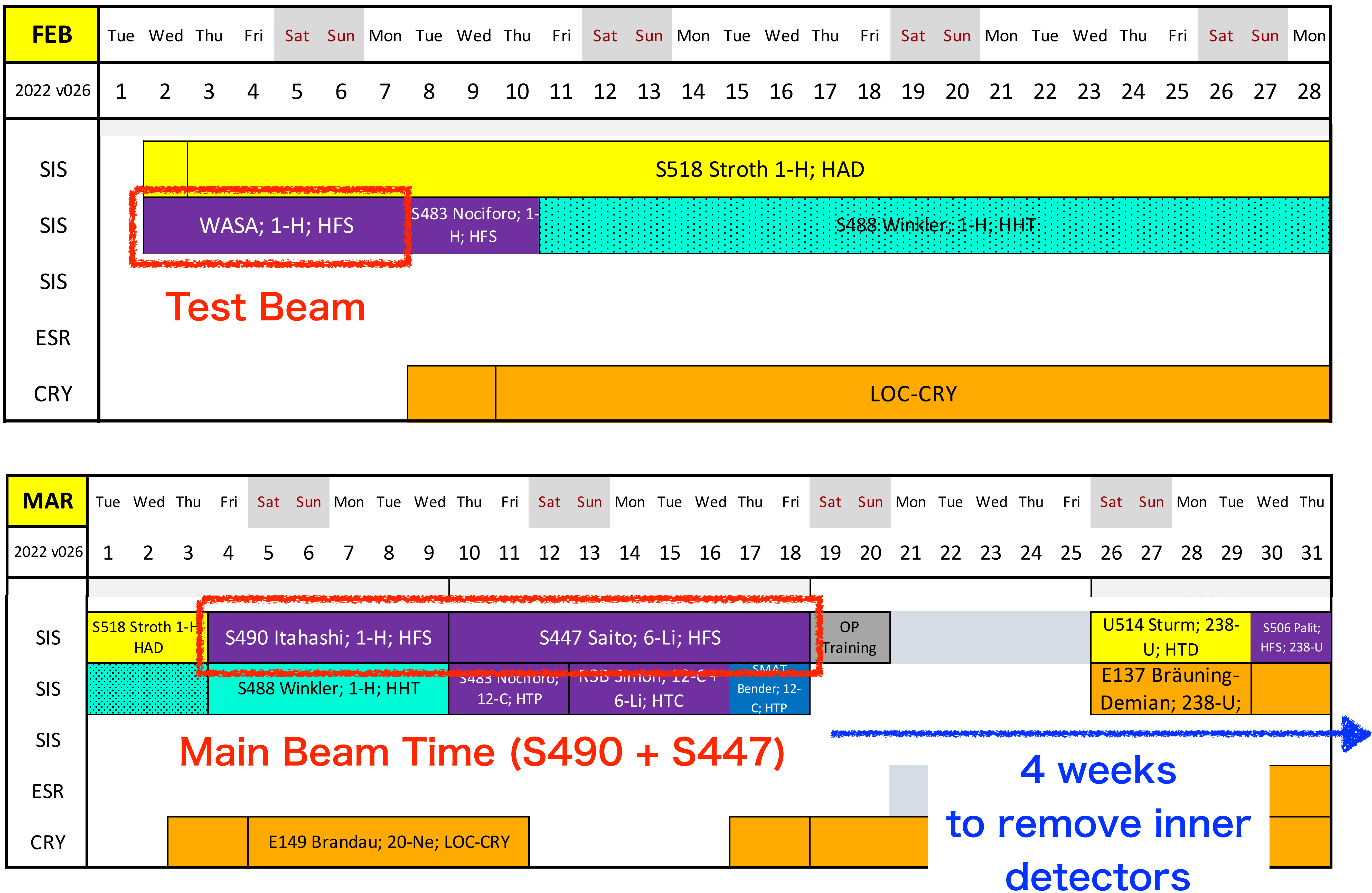
# WASA Installation at GSI-FRS F2

December, 2021 (last week)

WASA detector was closed for final tests



# Beam Time is scheduled in 2022



# Summary

- Spectroscopy of bound states in nucleus offers possibility to directly study in-medium properties of hadrons.

- We performed first experimental search for η′ mesic nuclei by missing-mass spectroscopy of the $^{12}C(p,d)$ reaction in 2014.
  - Excitation-energy spectrum of the $^{12}C(p,d)$ reaction has been obtained around the η′ emission threshold, with a high statistical sensitivity and sufficiently small resolution.
  - As no distinct peak structure is observed, upper limits of formation cross section have been determined.
  - From comparison with theoretically-calculated formation spectra, large potential depth $|V_0| \sim 150$ MeV is excluded around $|W_0| < 25$ MeV.

- We plan a new experiment to search for η′ mesic nuclei by combination of missing-mass spectroscopy and tagging decay particle.
  The experiment will be performed with WASA+FRS setup in 2022 soon !