HHIQCD Workshop 2015 at YITP

Search for η' mesic nuclei with (*p,d*) reaction at GSI

Yoshiki K. Tanaka (Univ. of Tokyo)
for the η-PRiME collaboration

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. Knoebel, 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. Winfield, X. Xu, H. Yamakami, J. Zhao

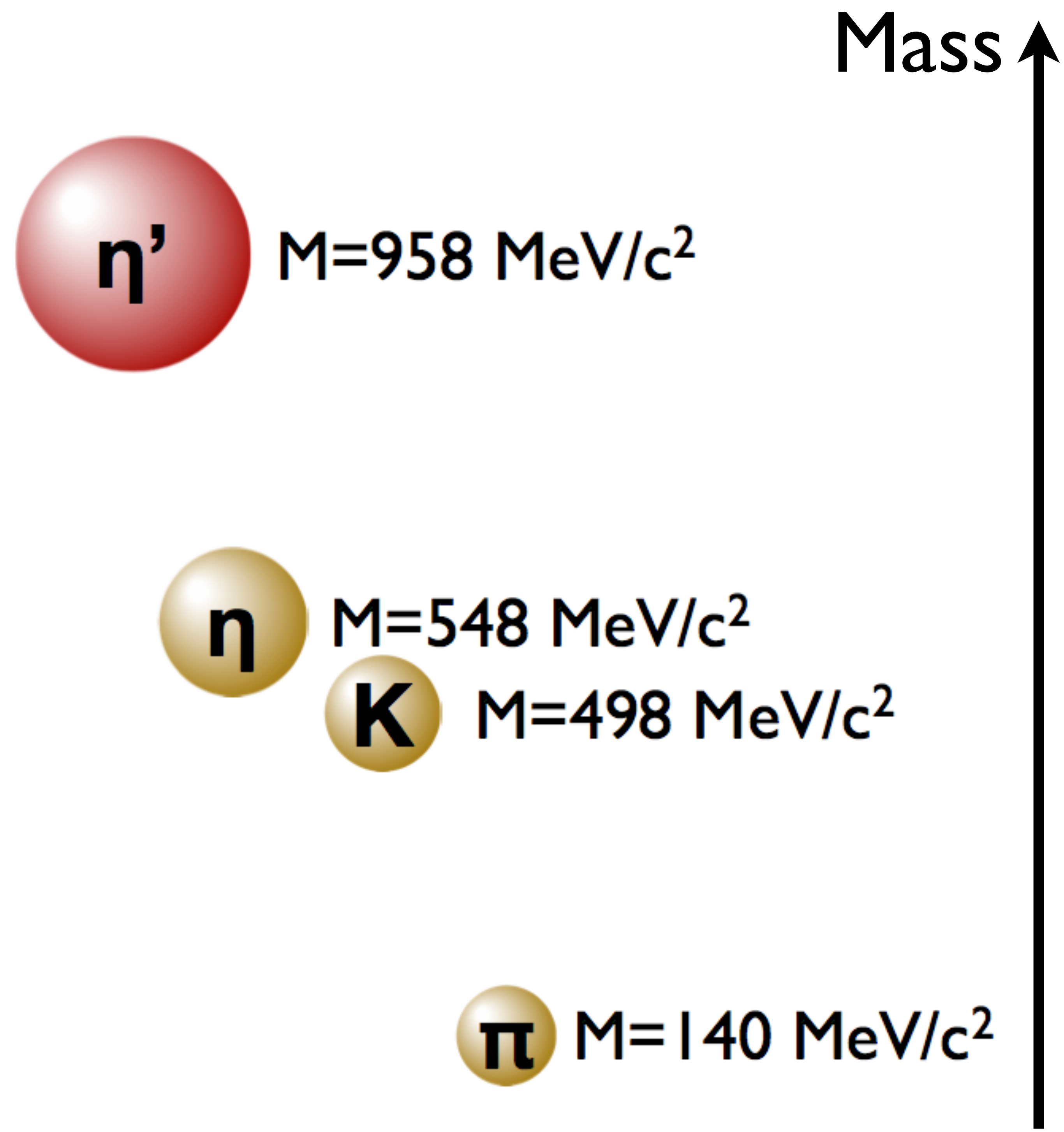
Osaka University, Universidade de Santiago de Compostela, Universitaet Giessen, Kyoto University, GSI, University of Groningen, Beihang University, The University of Tokyo, Nara Women's University, KEK, RIKEN, Tokyo Metropolitan University, Saint Mary’s University, Technische Universitaet Darmstadt, Comenius University Bratislava, Stefan Meyer Institut, Niigata University

η' meson

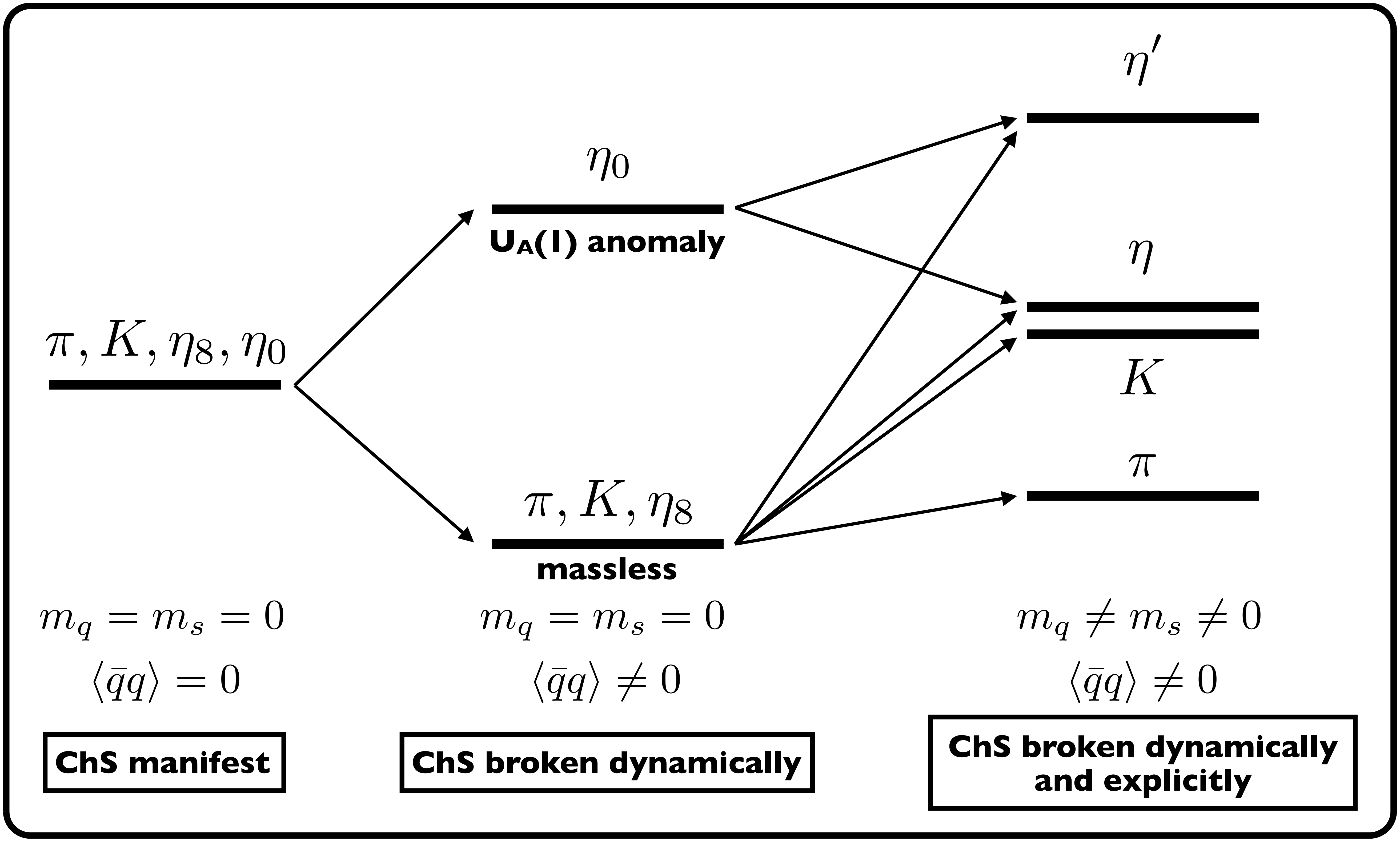
η′ meson

M=958 MeV/c^2
Γ=0.198 MeV
Pseudoscalar meson ($J^{\pi}=0^{-}$)

Decay mode
- $\pi^{+}\pi^{-}\eta$(43%),
- $\rho^{0}\gamma$(29%),
- $\pi^{0}\pi^{0}\eta$(22%)



η′ meson

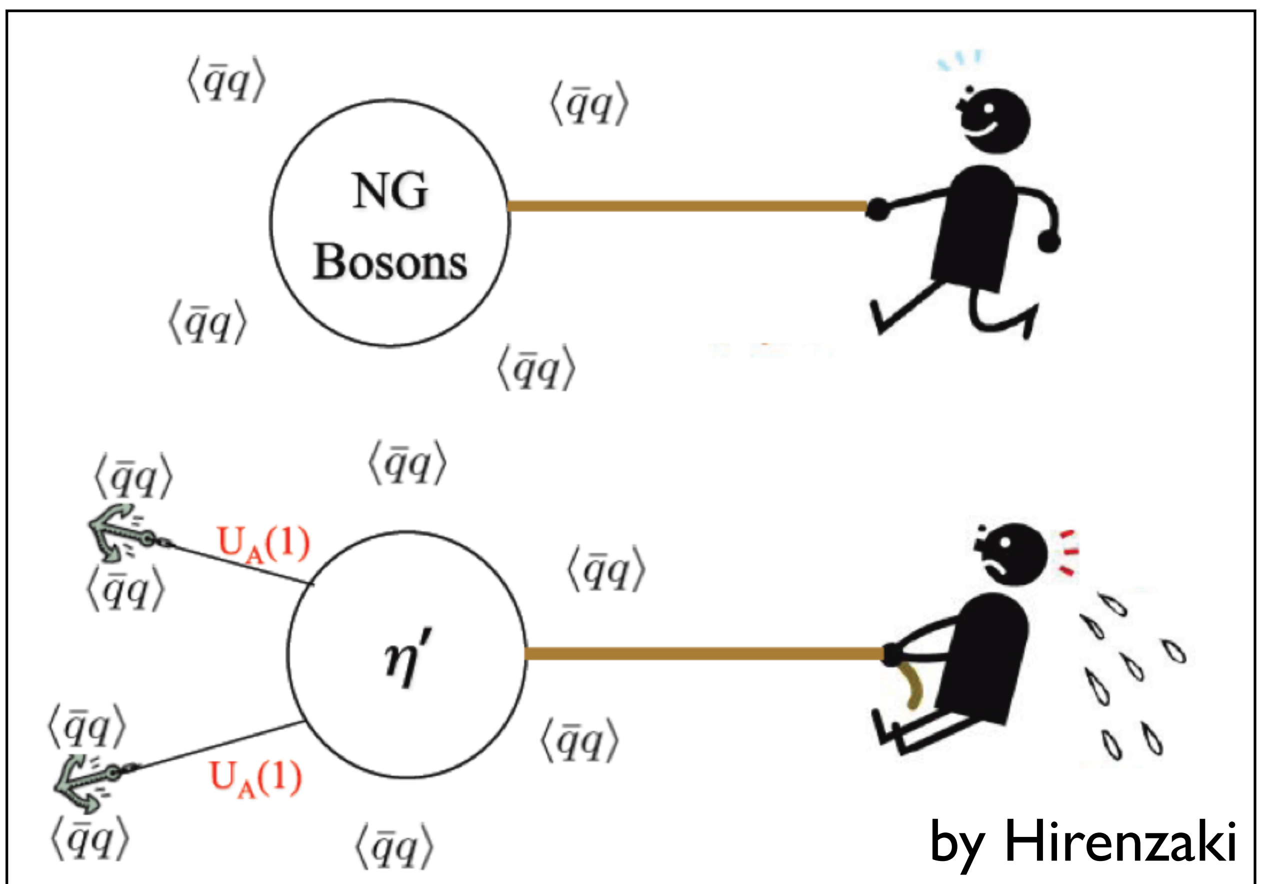


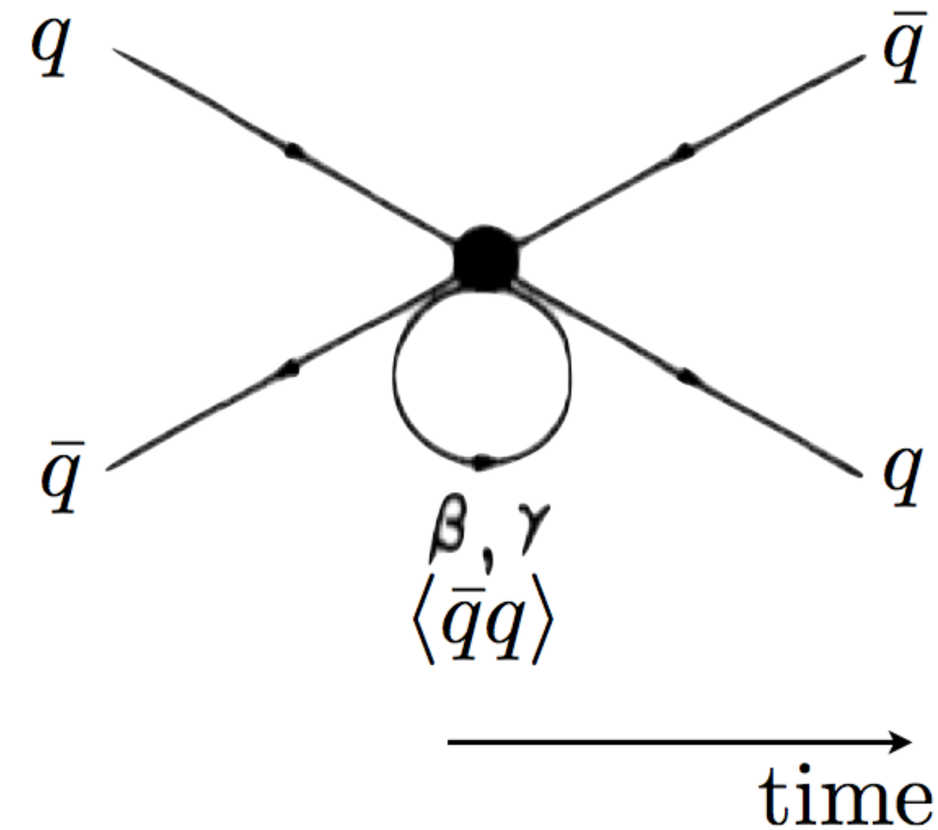
H.Nagahiro et al.,PRC 87 (2013) 045201.

η′ meson

$U_A(1)$ anomaly effect on η′ mass

- KMT interaction in NJL model
- related to the strength of chiral condensate <q̄q>





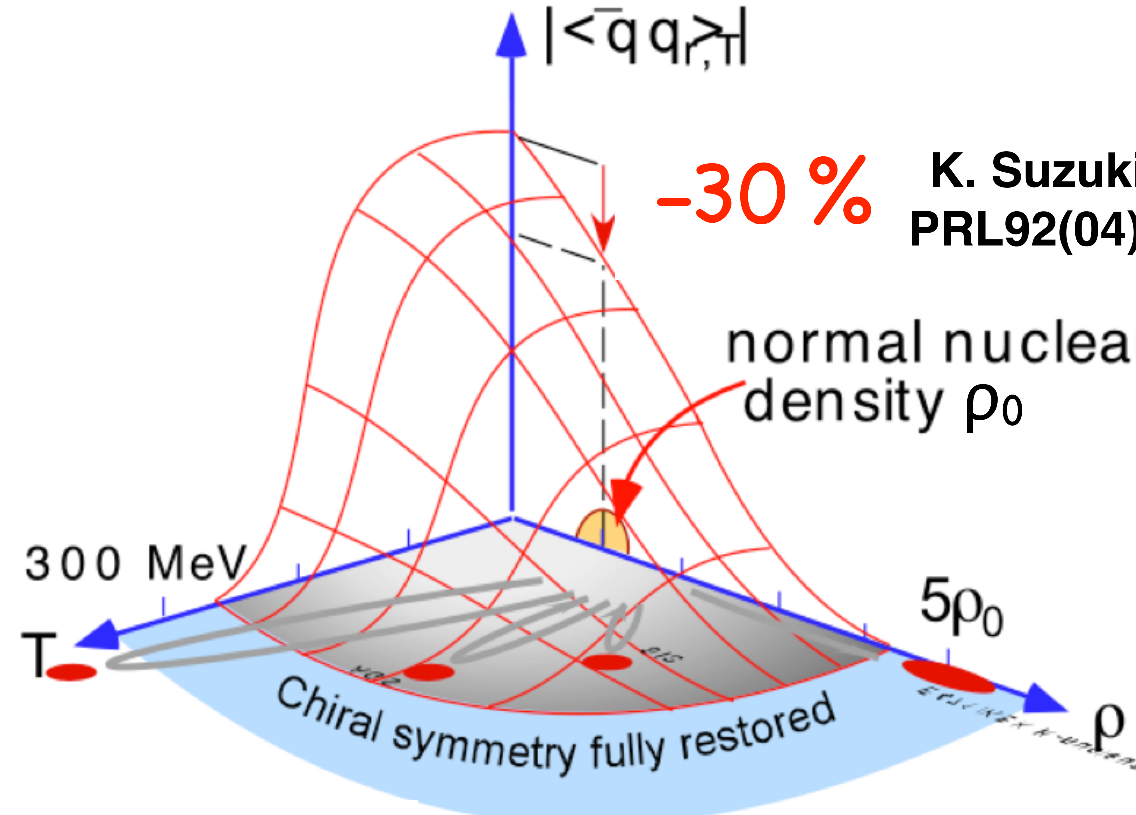
Kobayashi-Maskawa-'t Hooft
6-point vertex

Kobayashi, Maskawa, PTP44(70)1422
't Hooft, PRD14(76)3432.
T. Kunihiro, Phys. Lett. B219(89)363.
Klimt, Lutz, Vogl, Weise, NPA516(90)429.

η′ meson in medium

- Chiral condensate $|\langle\bar{q}q\rangle|$ reduced by ~30% at ρ_0.

partial restoration of chiral symmetry



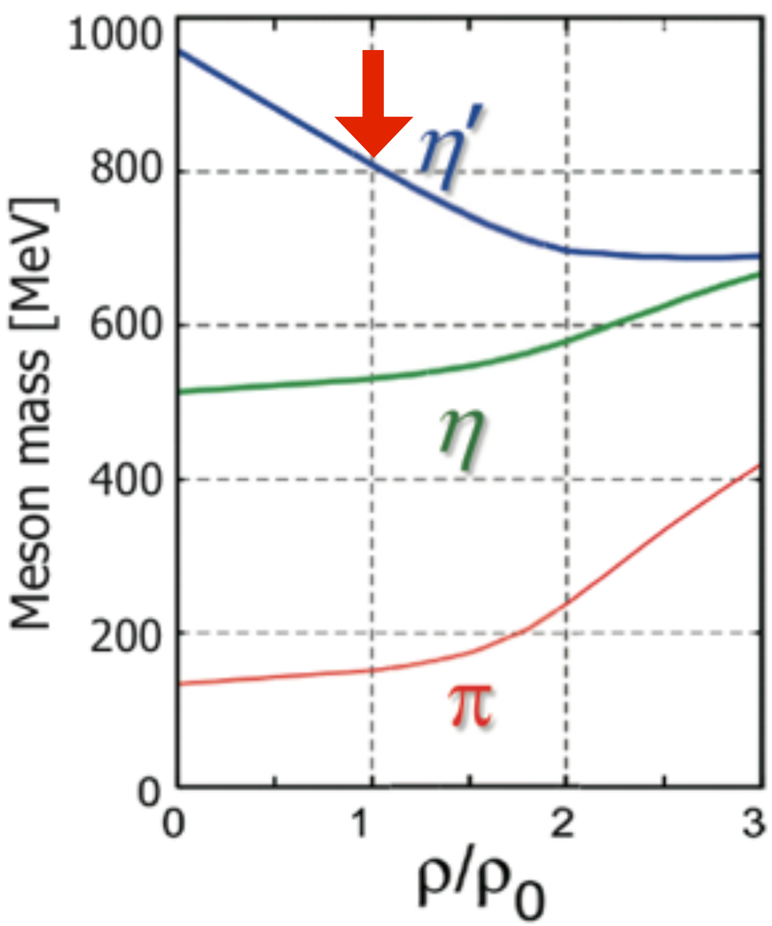
K. Suzuki et al., PRL92(04)072302

W. Weise, NPA553(93)59.

η′ meson in medium

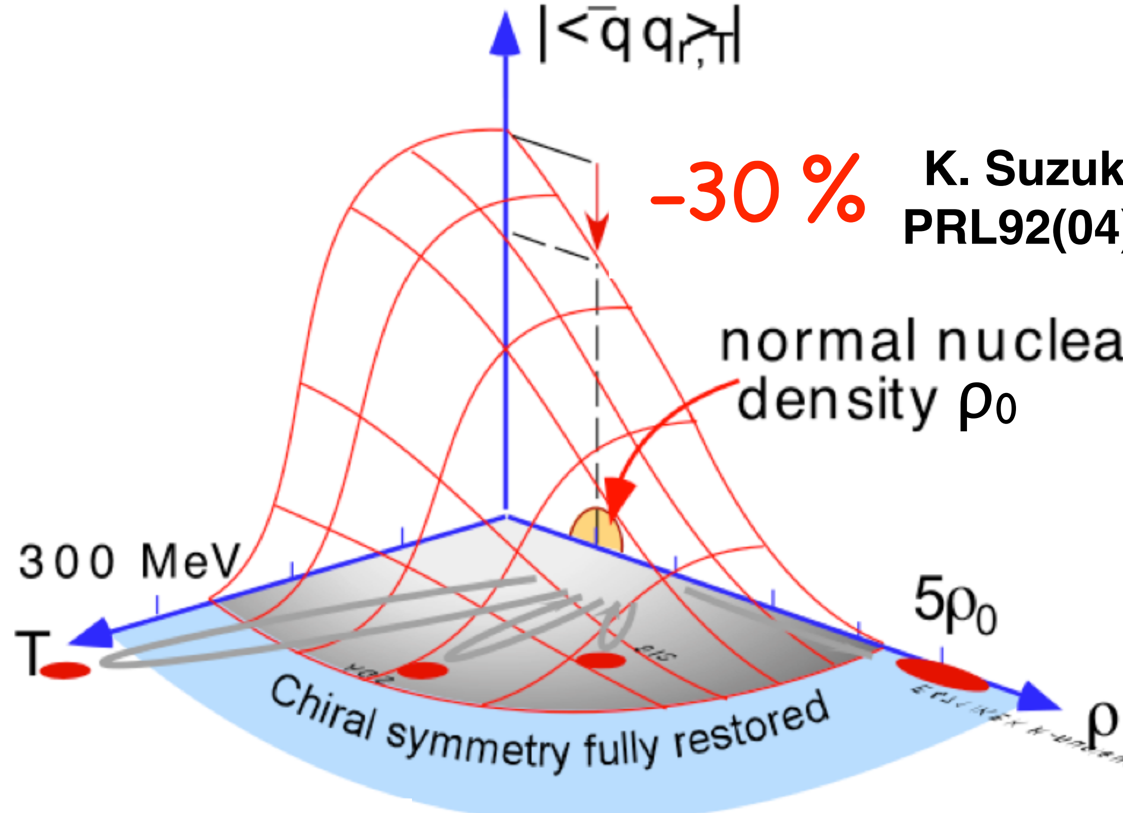
- Chiral condensate |<q̄q>| reduced by ~30% at ρ_0.

- Mass reduction expected e.g., NJL model calculation → 150 MeV/c^2 mass reduction



P.Costa et al.,PLB560, (2003) 171.
H.Nagahiro et al.,PRC 74, (2006) 045203.

partial restoration of chiral symmetry



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

W. Weise, NPA553(93)59.

in-medium mass and width

η′ nucleus optical potential :

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

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

- model predictions

  $\Delta m(\rho_0)$ ~ -150 MeV (NJL model) → **strong attraction ?**

  ~ - 80 MeV (linear σ model) S. Sakai, D. Jido, PRC 88, 064906 (2013)

  ~ - 37 MeV (QMC model) for $\theta_{\eta\eta'}$=-20°

  S.D. Bass, A.W. Thomas, PLB 634, 368 (2006)

- CBELSA/TAPS

  V_0 = -37 ±10(stat) ±10(syst) MeV

  M. Nanova et al., Phys. Lett. B 727 (2013) 417
  M. Nanova et al., PLB710, 600(2012)

  $\Gamma(\rho_0)$ = 15 - 25 MeV, for $P_{\eta',\,\mathrm{average}}$ =1.05GeV/c

- relatively small η′-proton scattering length

  $\mathrm{Re}\{a_{\eta' p}\}$= 0 ± 0.43 fm E. Czerwiński et al., PRL 113, 062004 (2014)

in-medium mass and width

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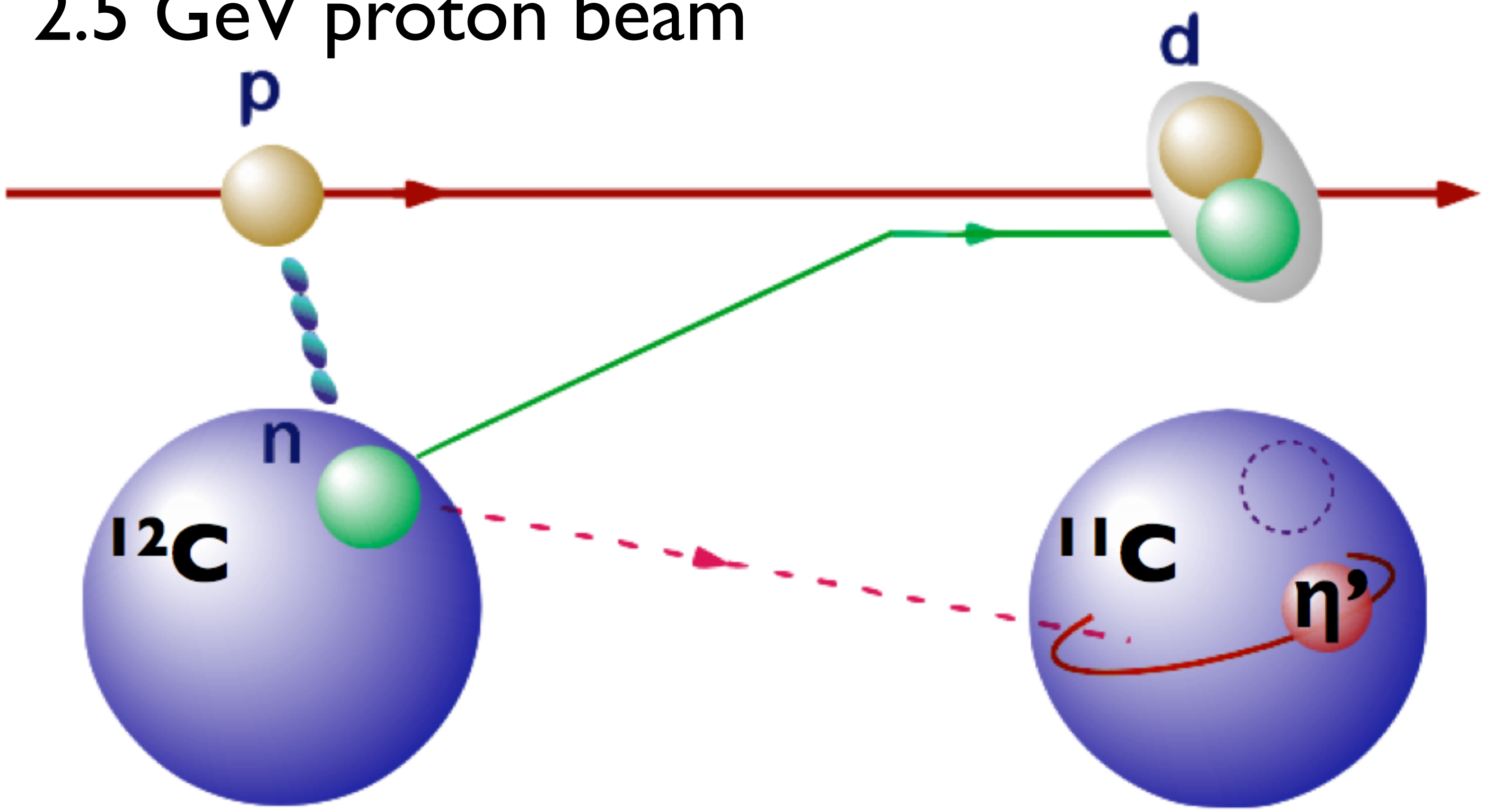
  $\text{Re}\{a_{\eta' p}\} = 0 \pm 0.43$ fm E. Czerwiński et al., PRL 113, 062004 (2014)

$|W_0|$ < possible potential depth $|V_0|$

→ possibility for observing η' meson-nucleus bound states (η'mesic nuclei) experimentally

Missing mass spectroscopy of (*p*,*d*) reaction

2.5 GeV proton beam



Target

η′ mesic nuclei

momentum measurement by Fragment Separator

⬇

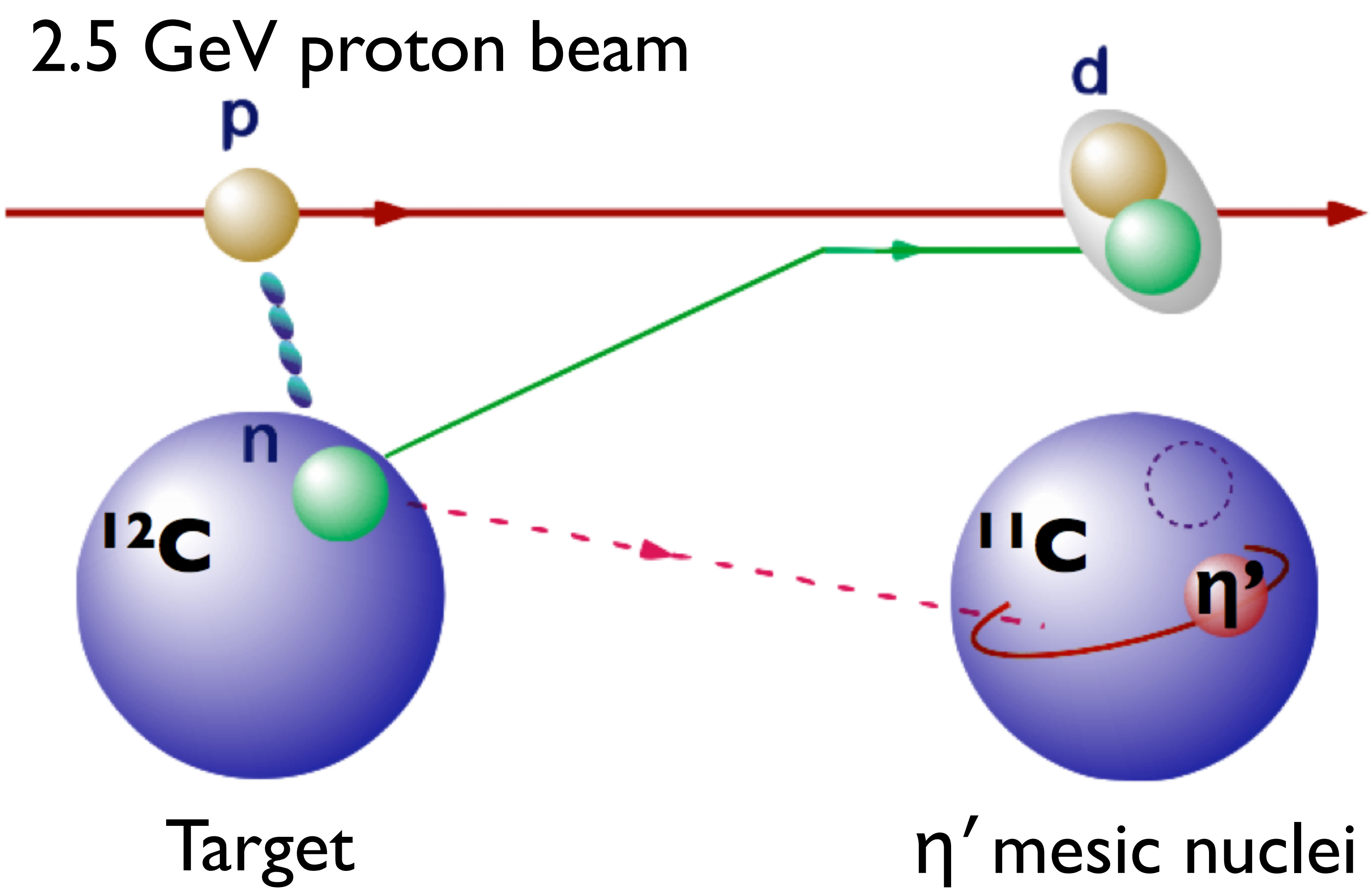
missing-mass spectrum

K. Itahashi et al.,
PTP 128,601(2012)

1st Step : <u>Inclusive measurement</u> of (*p*,*d*) reaction at GSI

- unbiased analysis without assumption on decay process
- poor S/N ratio due to BG processes (e.g., multi-pion production)

Missing mass spectroscopy of (*p*,*d*) reaction



momentum measurement by Fragment Separator

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1st Step : <u>Inclusive measurement</u> of (*p*,*d*) reaction at GSI

- unbiased analysis without assumption on decay process
- poor S/N ratio due to BG processes (e.g., multi-pion production)

High-statistics measurement is essential
using high-intensity beam + thick target

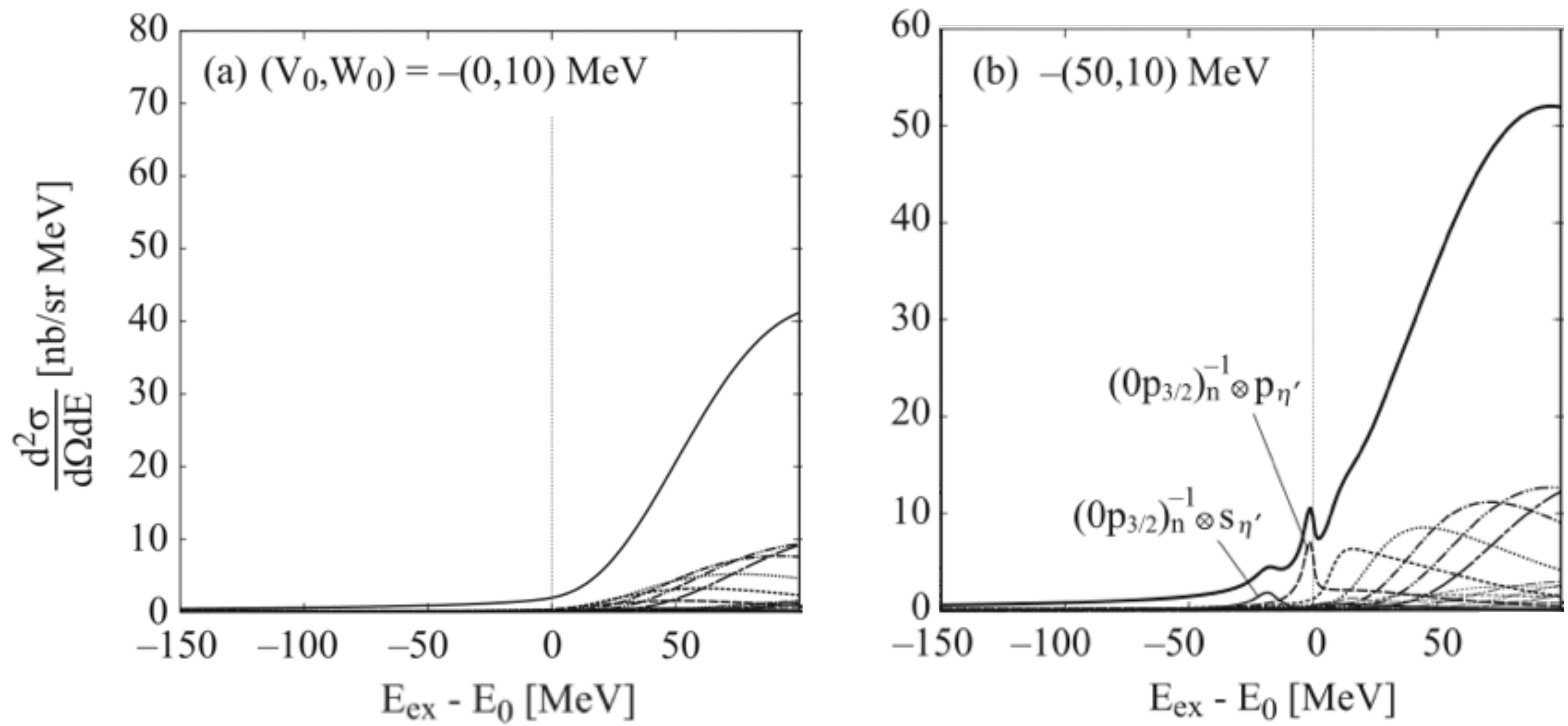
Theoretical cross section of $^{12}C(p,d)^{11}C\times\eta'$

- Green's function method
- proton energy 2.5 GeV, mom. transfer ~ 400 MeV/c

η' nucleus optical potential :

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

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



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

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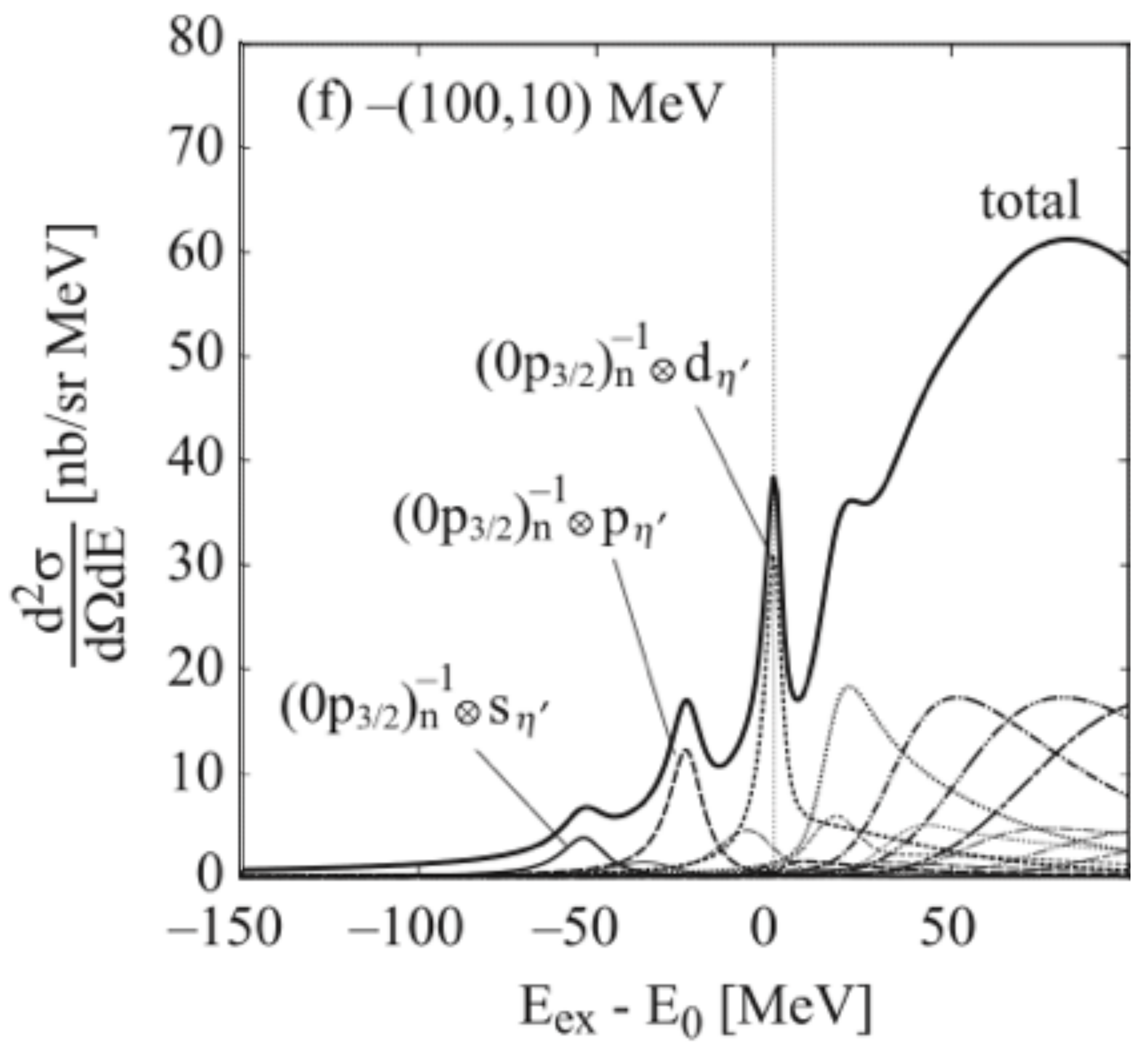
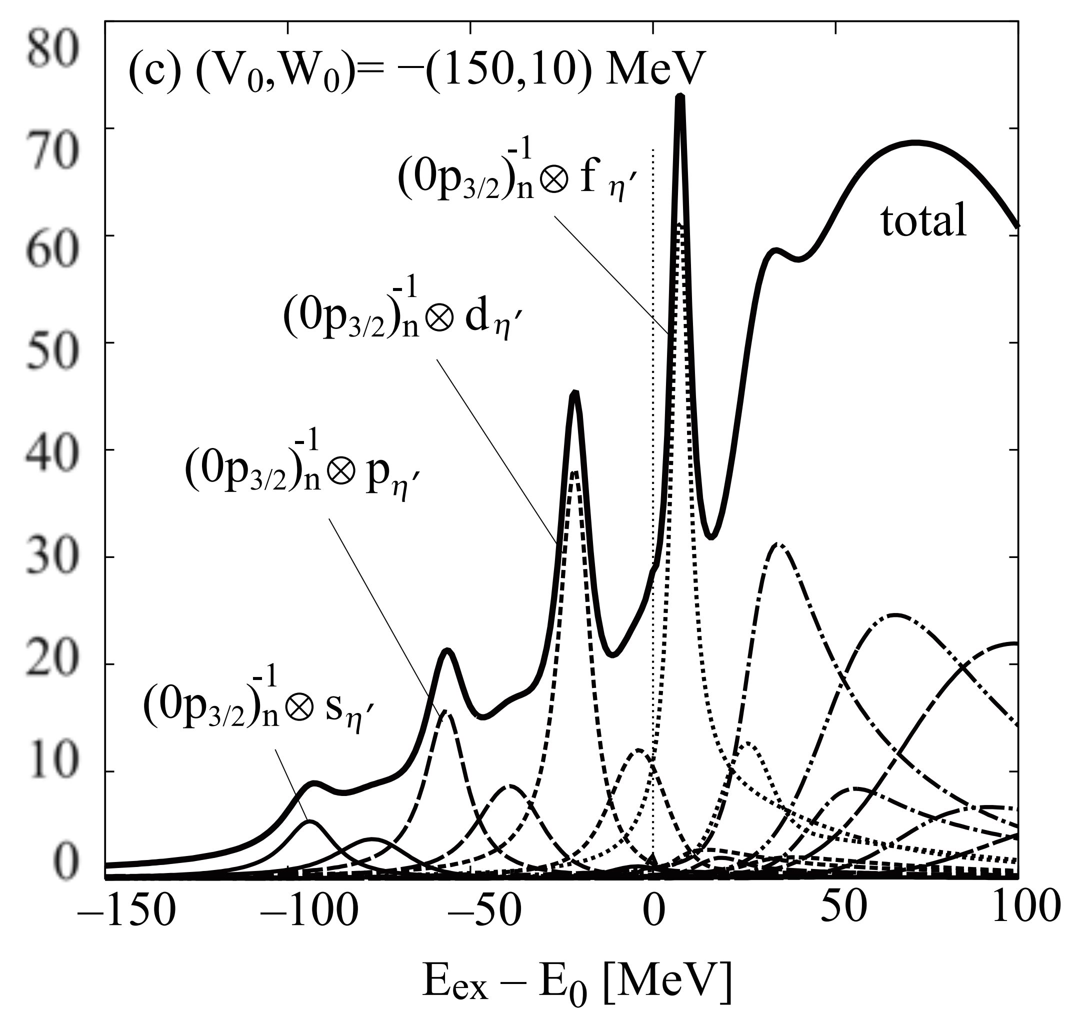




H.Nagahiro et al.,PRC 87 (2013) 045201.

Simulation of inclusive measurement

Simulated spectra of inclusive measurement assuming 4.5 day DAQ

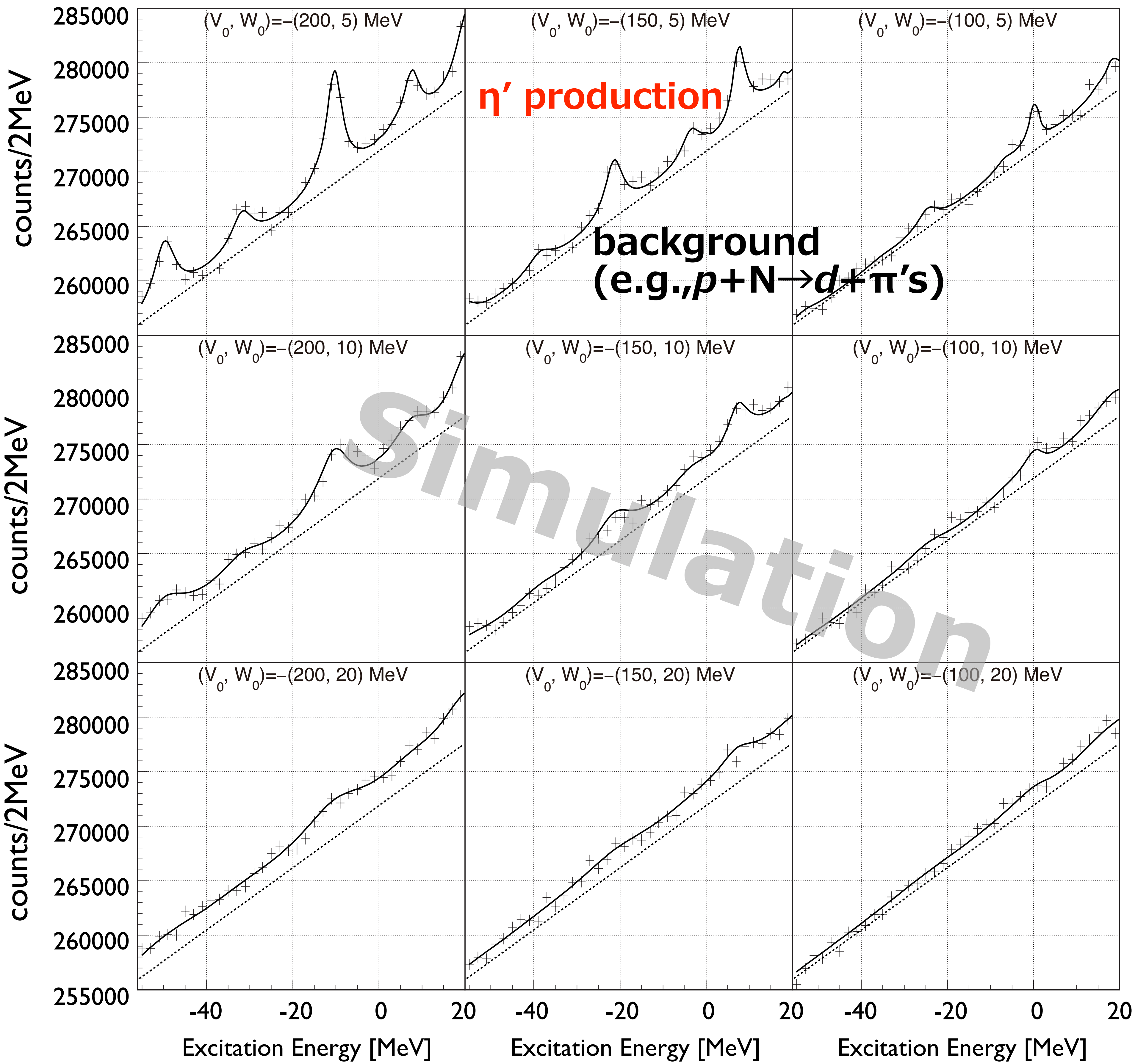
K. Itahashi et al., PTP 128,601(2012)

V_0, W_0 :
real, imaginary part of optical potential

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

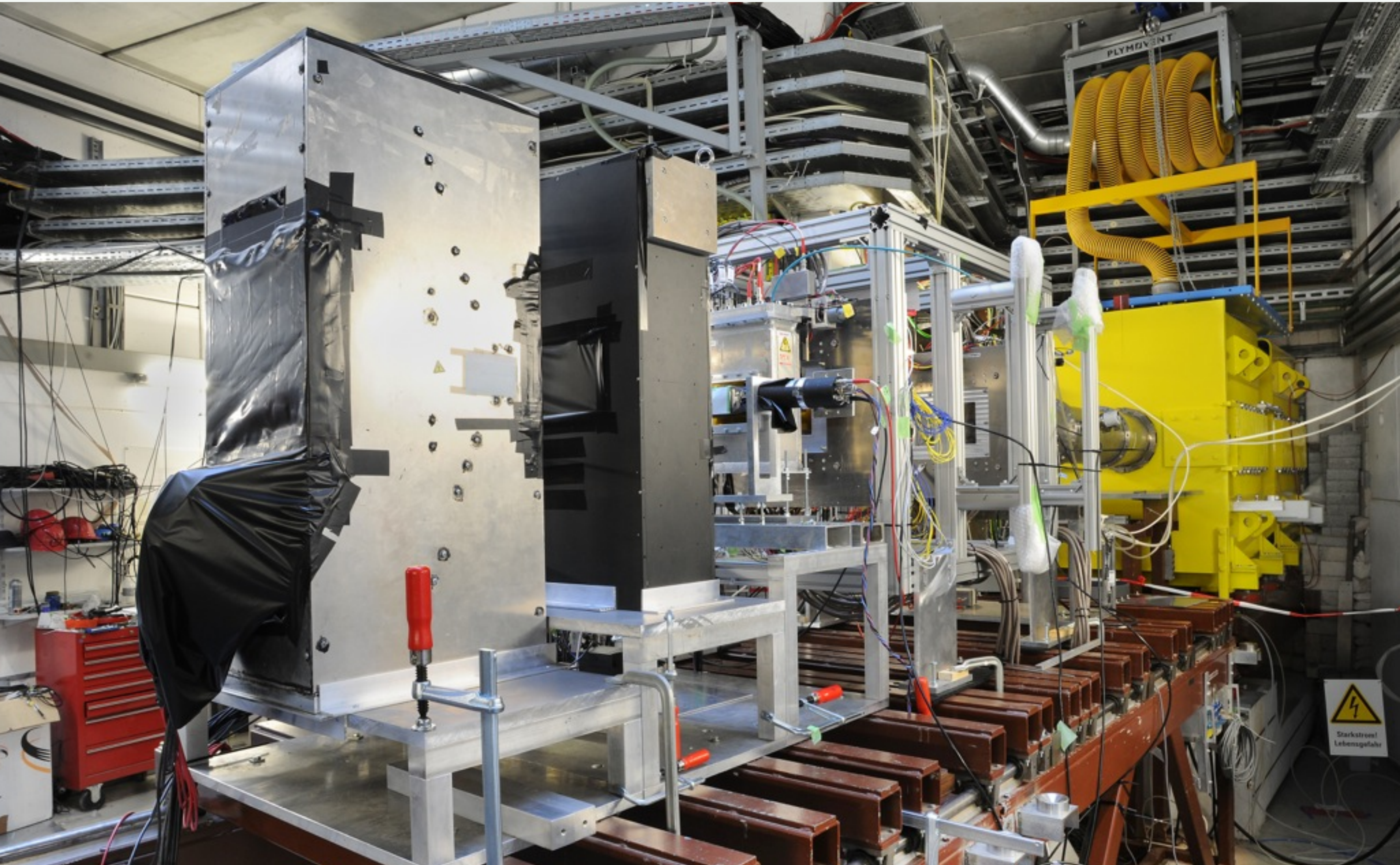
$(V_0 = \Delta m(\rho_0), W_0 = -\Gamma(\rho_0)/2)$

S/N ratio ~ O(1/100) at most

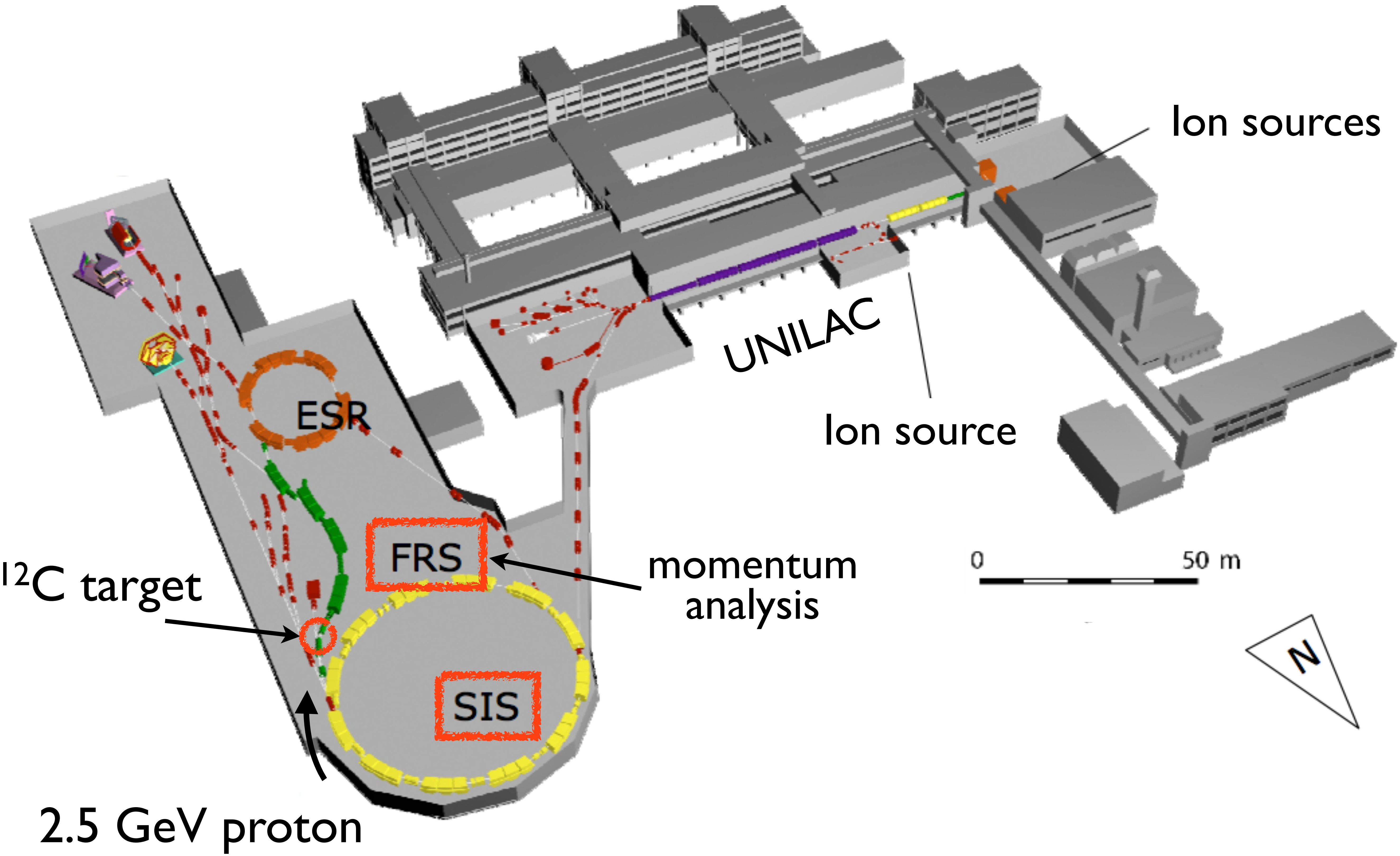


First experiment at GSI (2014 Aug.)

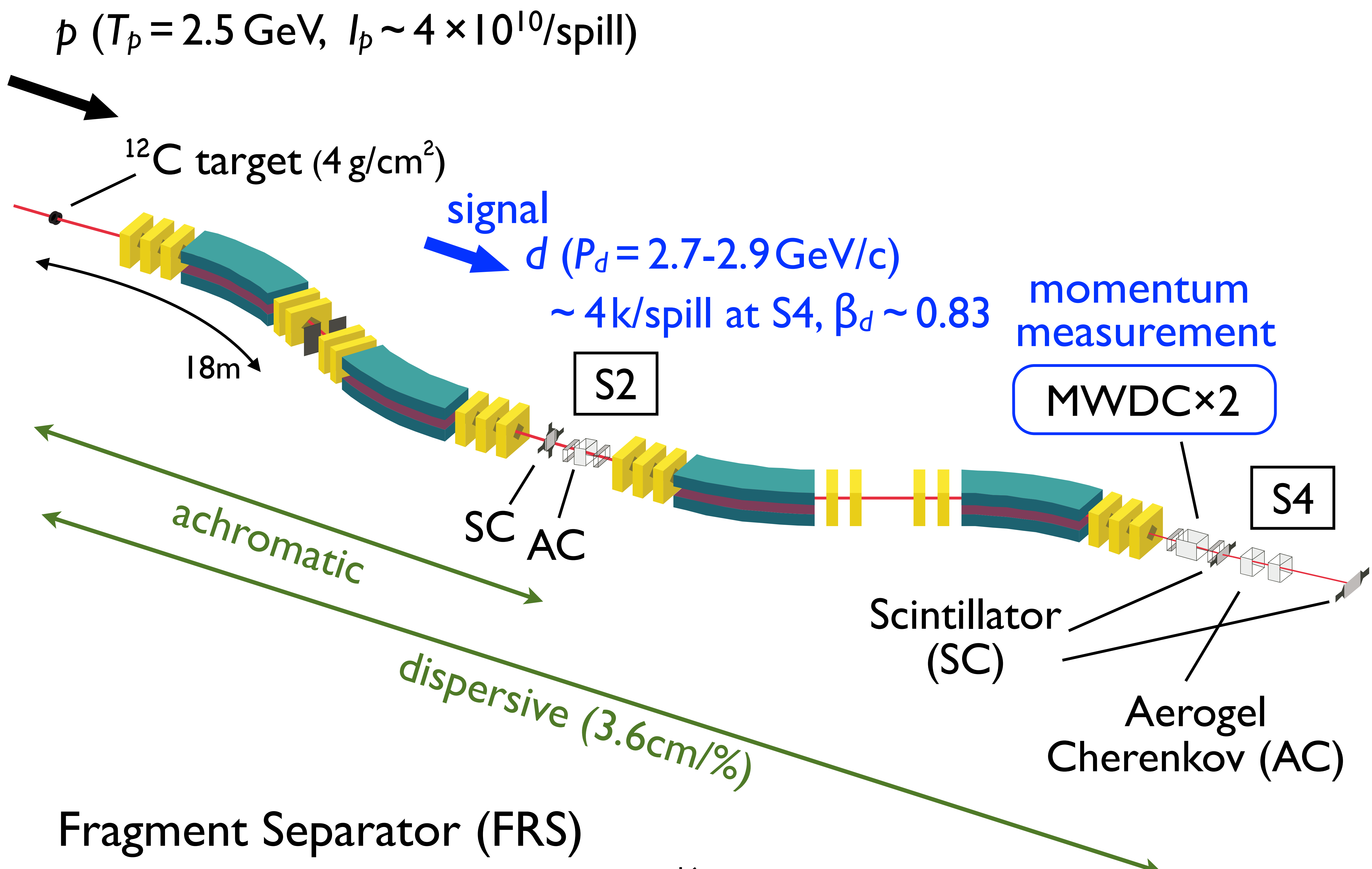
in a framework of the Super-FRS collaboration for FAIR



GSI facilities



Experimental setup at FRS



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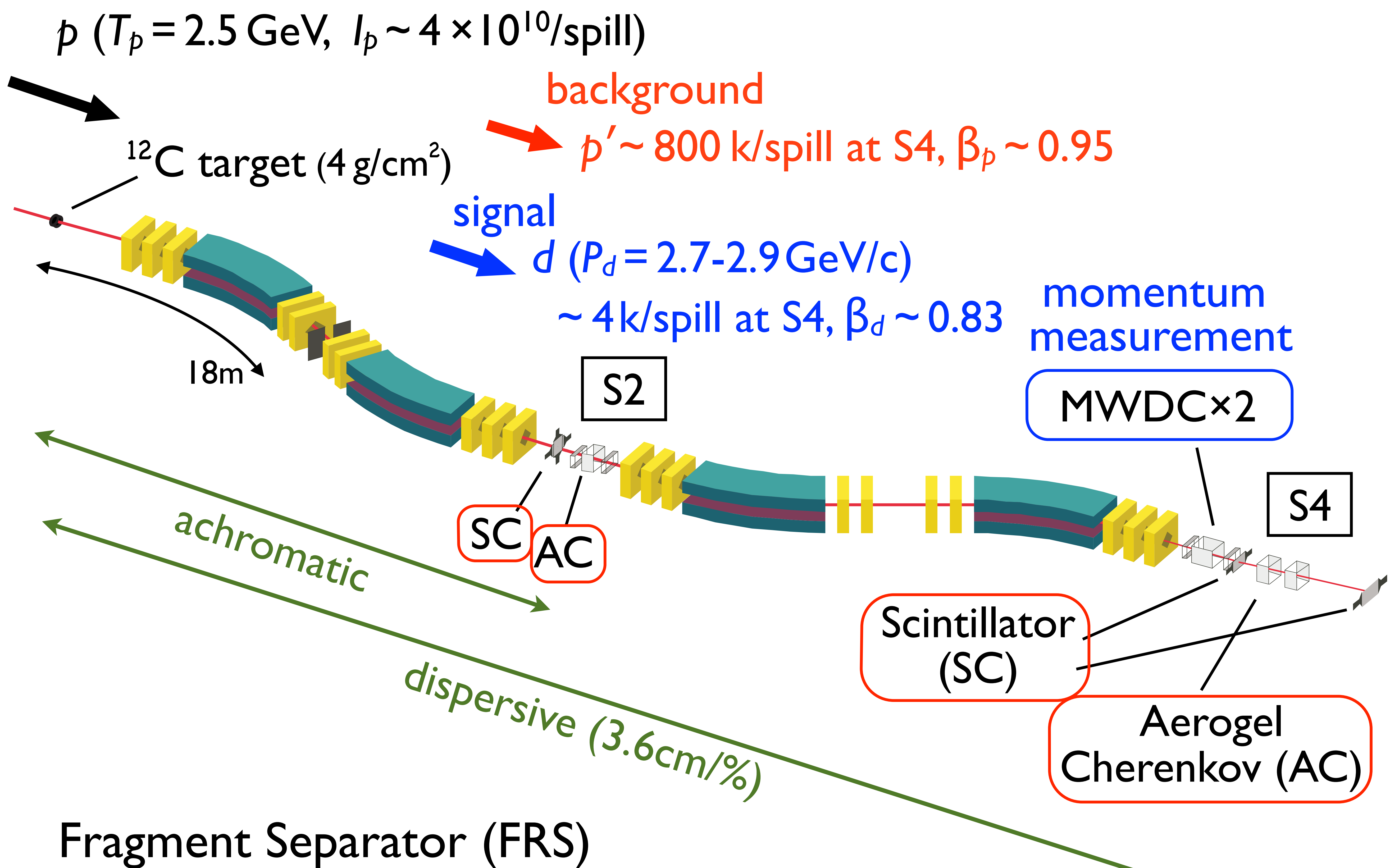
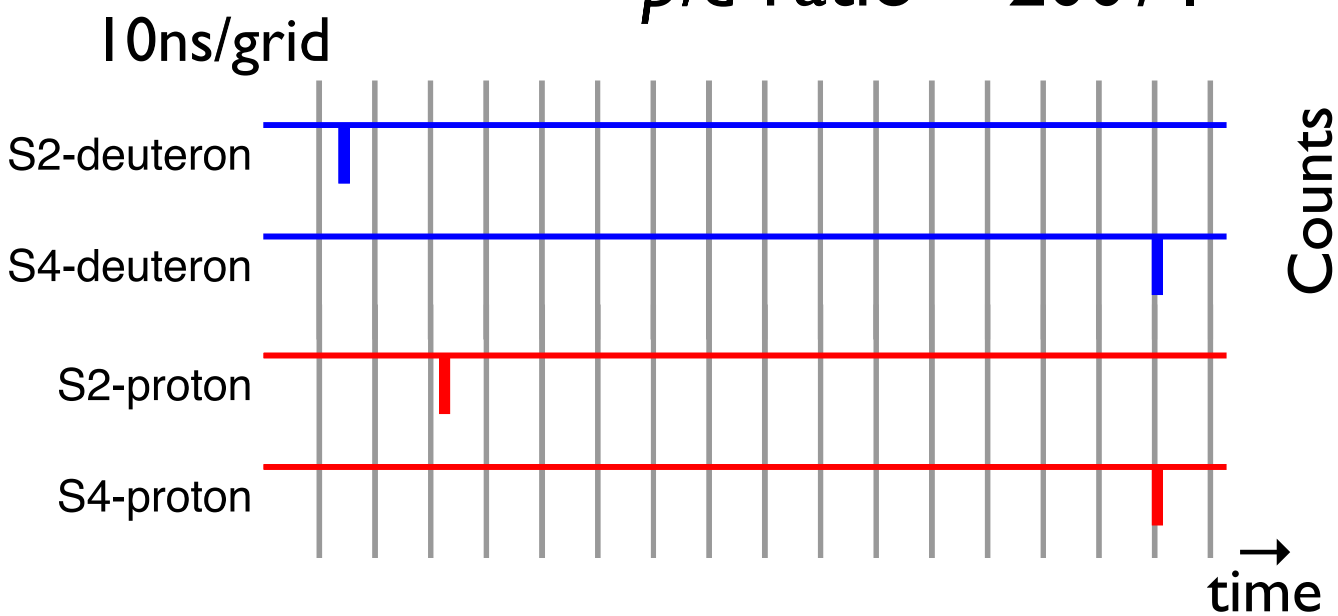
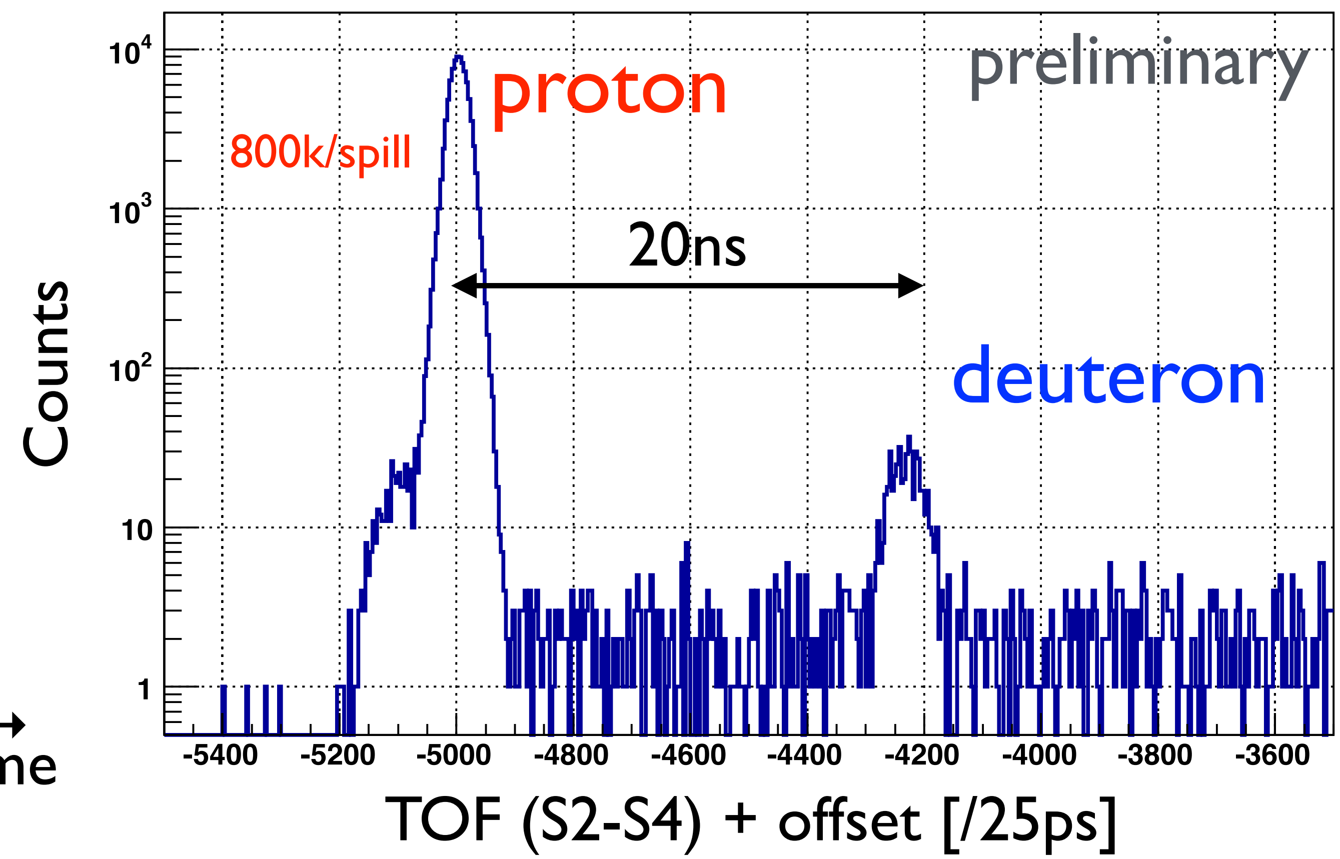


Particle Identification

S2-S4 TOF (unbiased)

p/*d* ratio ~ 200 / 1





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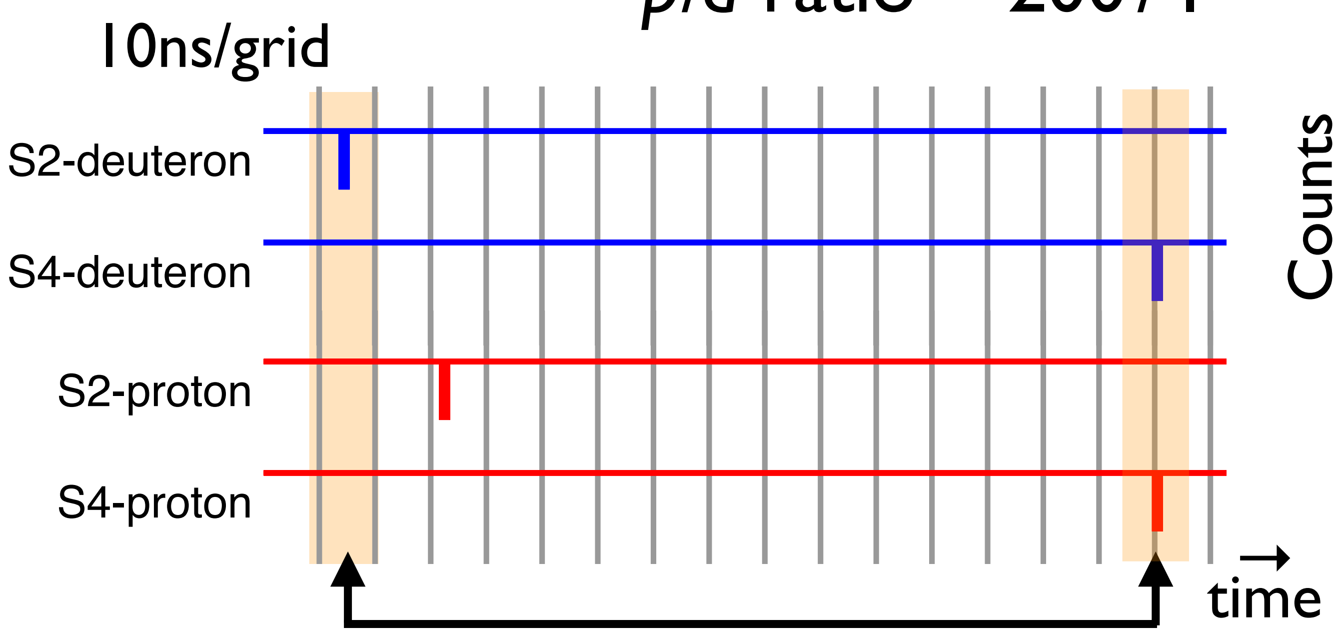
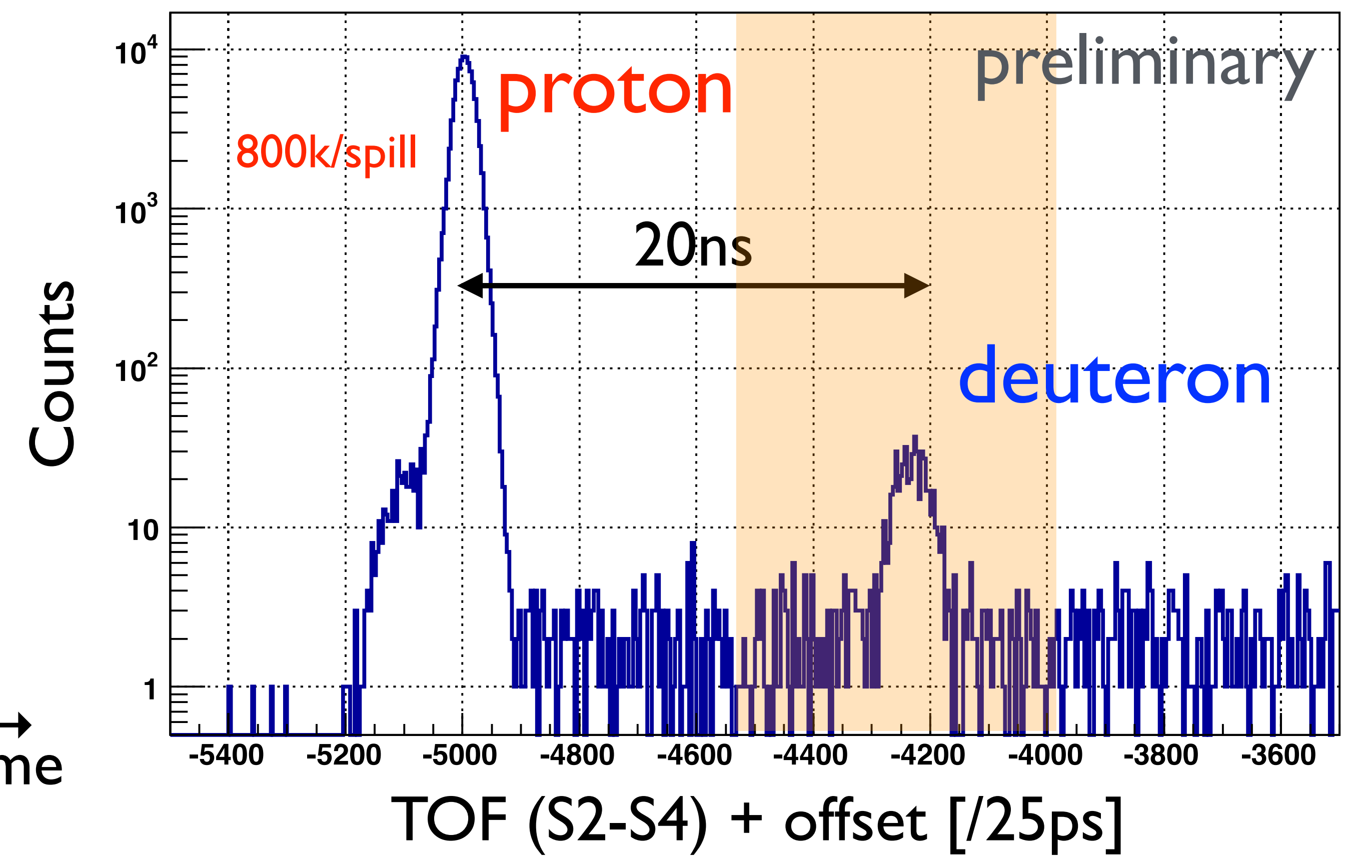
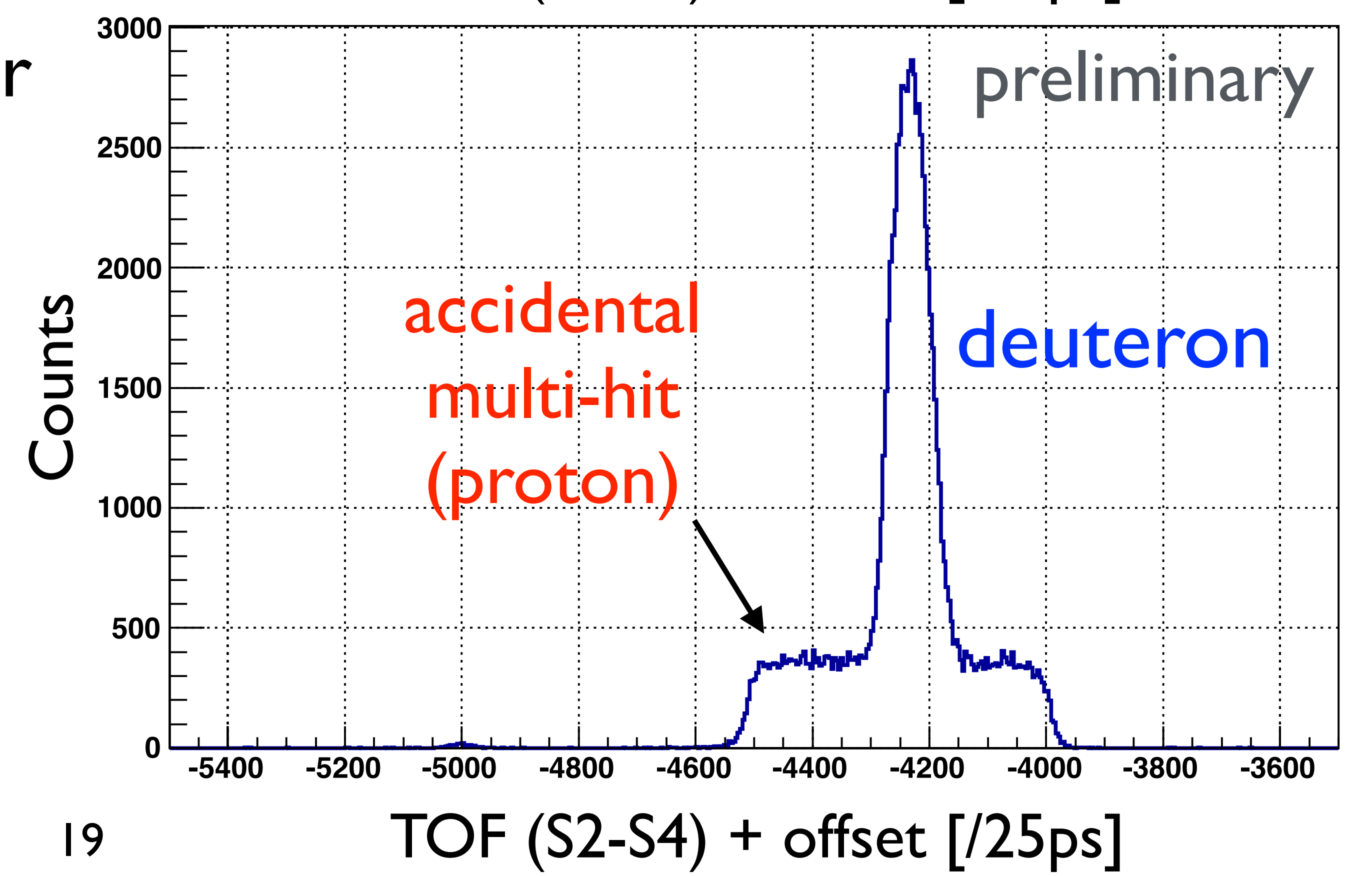




with hardware TOF trigger

p/*d* ratio ~ 1 / 1



Particle Identification

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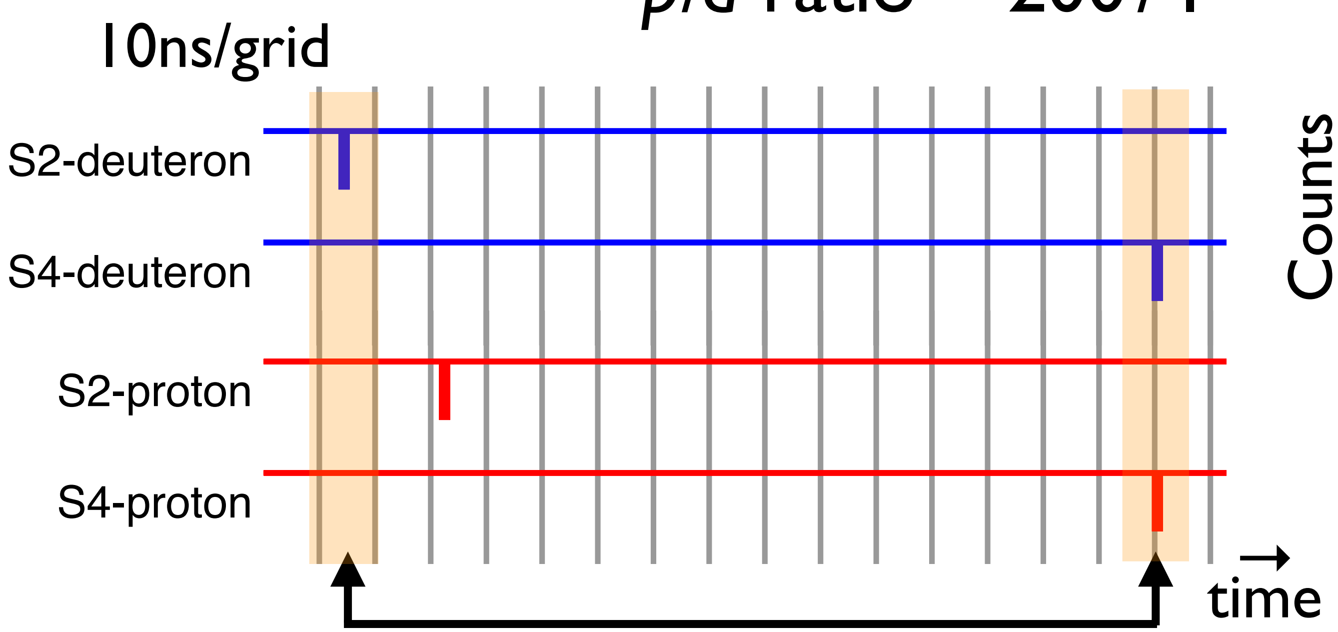
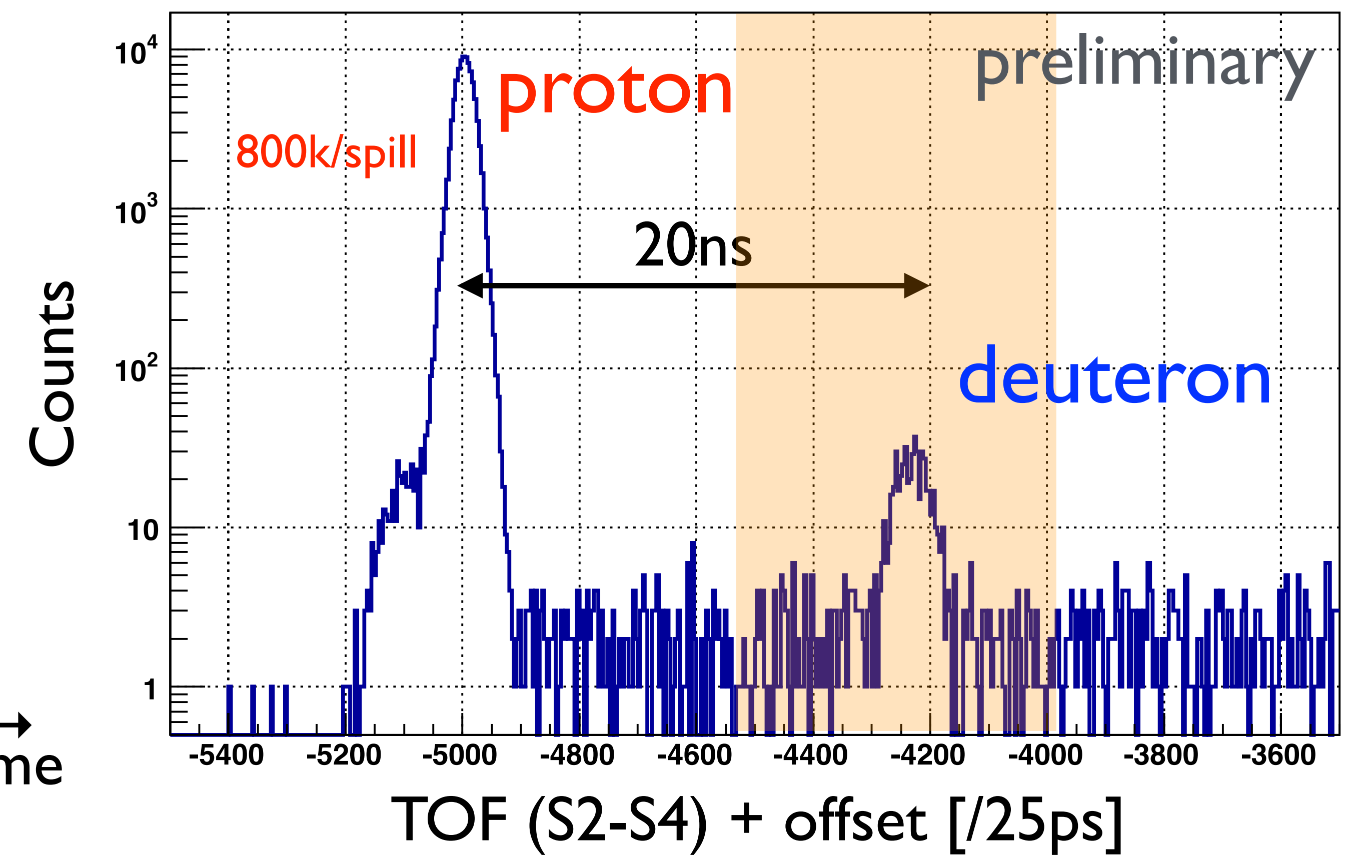
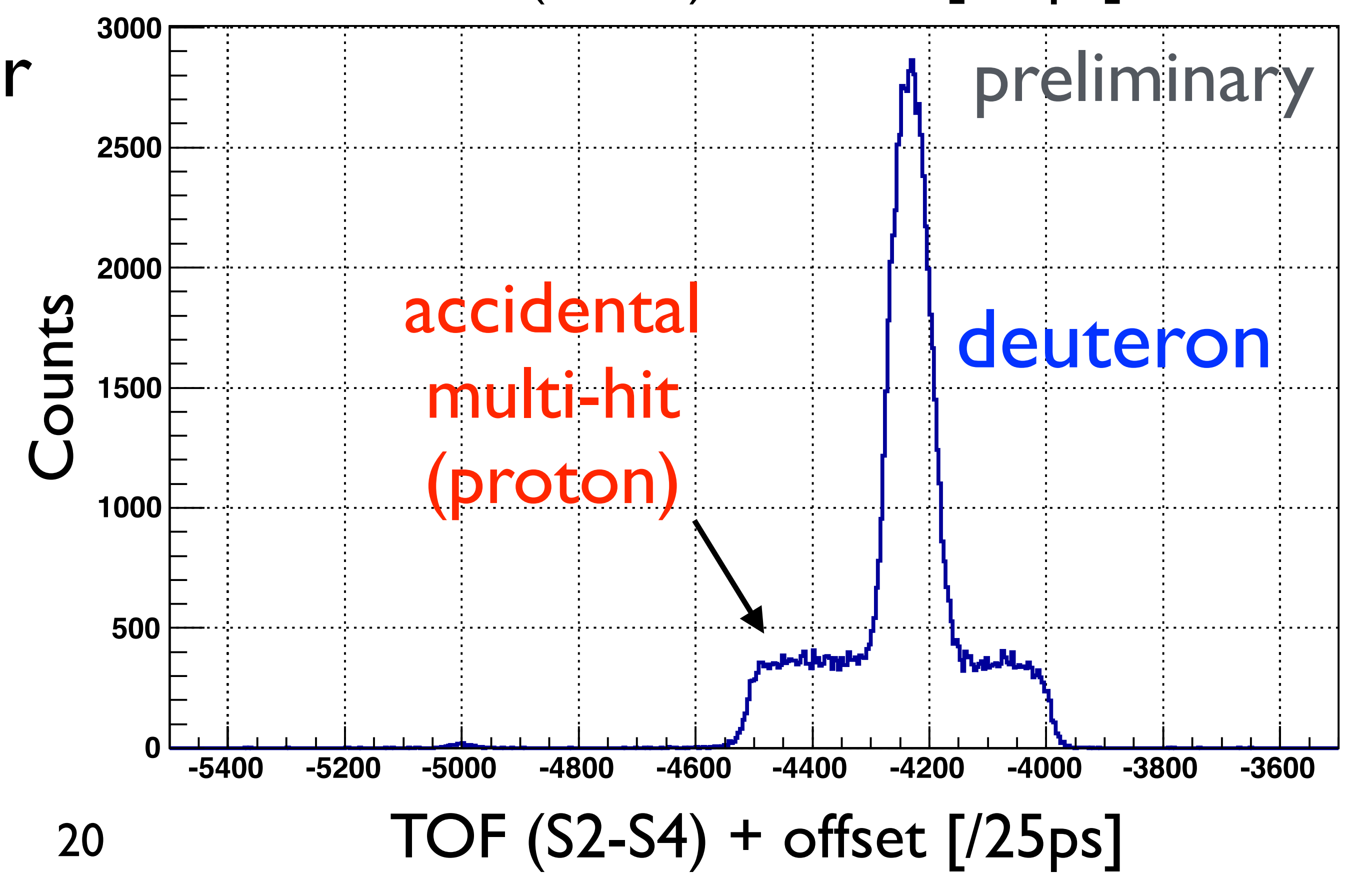




with hardware TOF trigger

p/*d* ratio ~ 1 / 1

99.5 % of BG protons were rejected by TOF trigger without using Aerogel Čerenkov detector



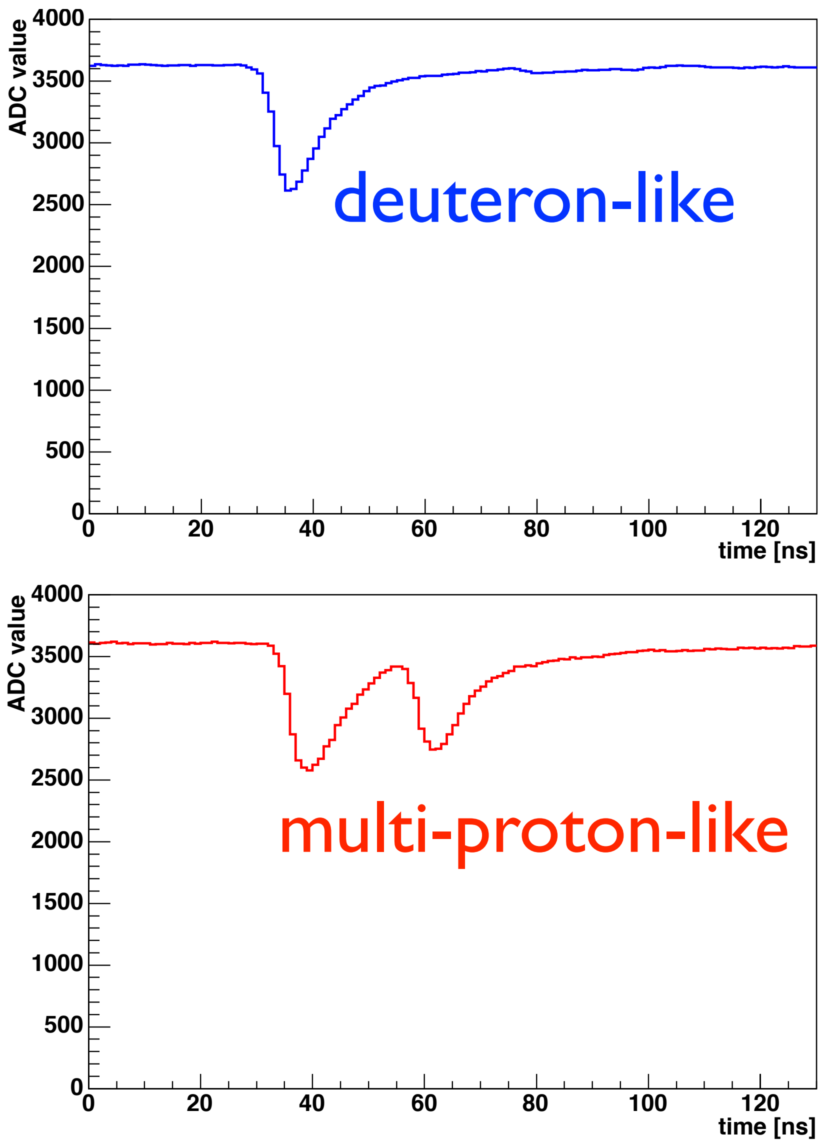
Particle Identification

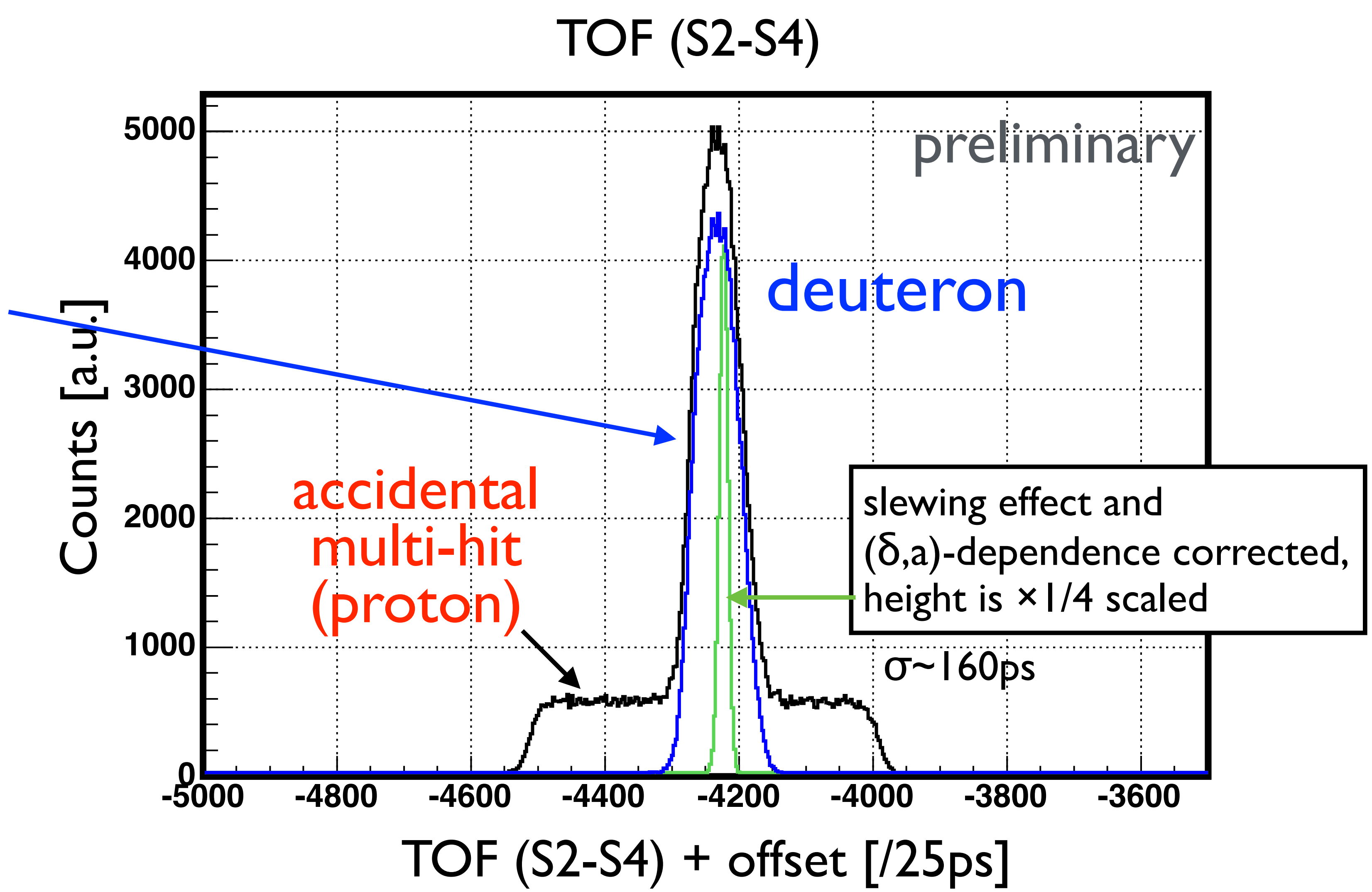
Further rejection of the accidental multi-proton in offline analysis

- Single pulse selection by waveform analysis
- Cut condition for corrected TOF (S2-S4)

→ proton contamination is sufficiently small

Examples of waveform of SC at S2

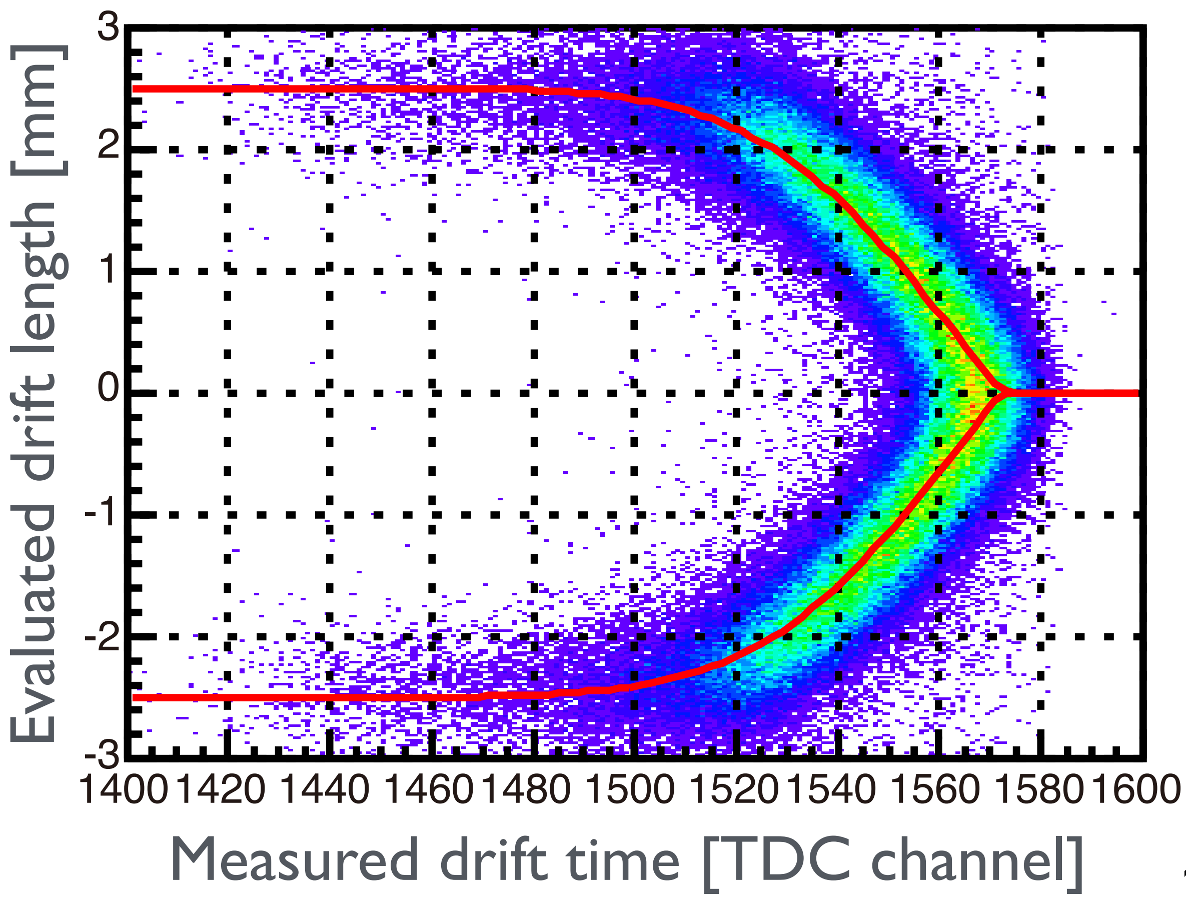




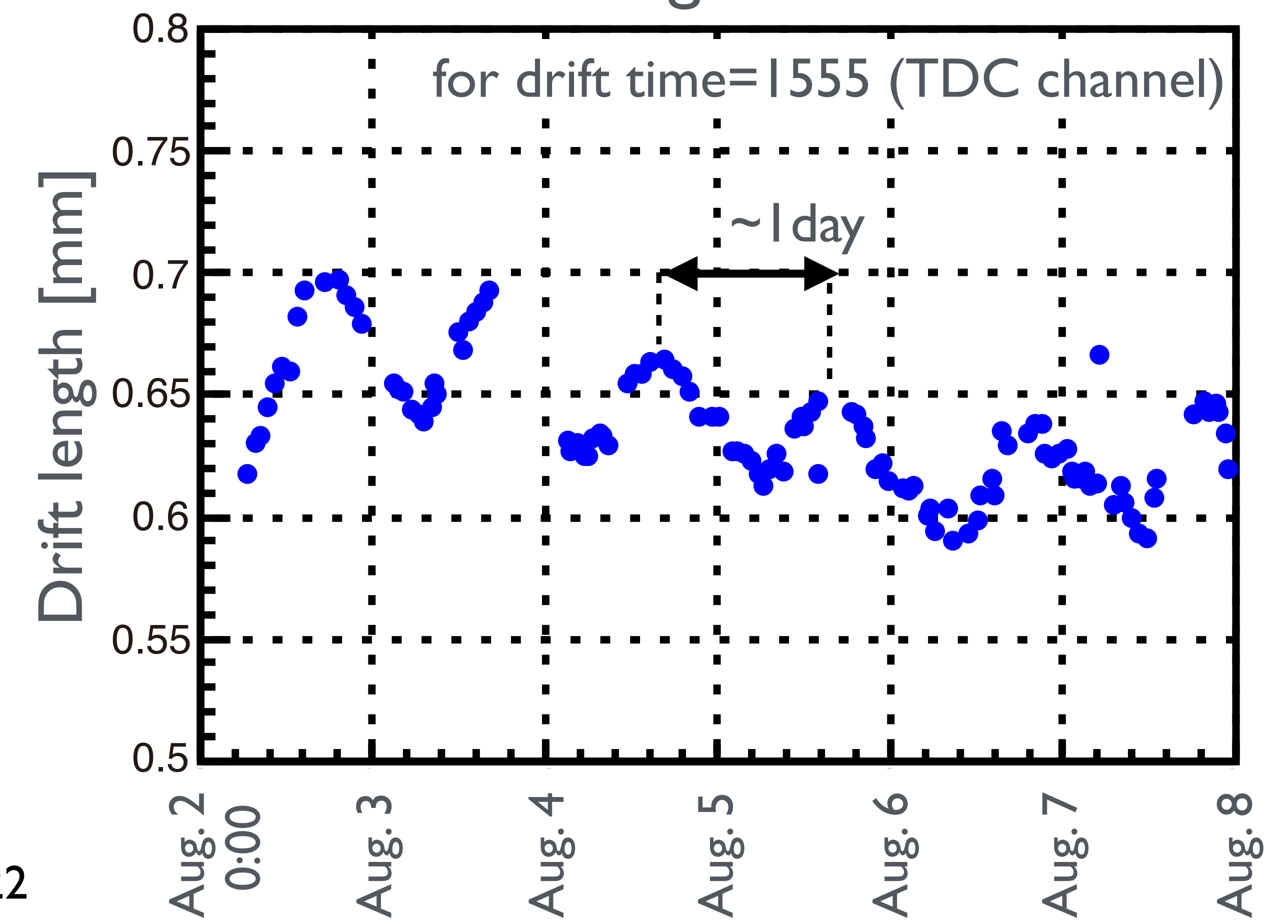
MWDC Analysis

- MWDC(XX'XX'UU'VV')×2 were used.
- Tracking :
  drift time (measured) → drift length → χ^2 fitting for 2 MWDCs
- Iterative analysis for calibration :
  temporary drift length → tracking → evaluate and update drift length
- Time dependence of relation between drift time and drift length

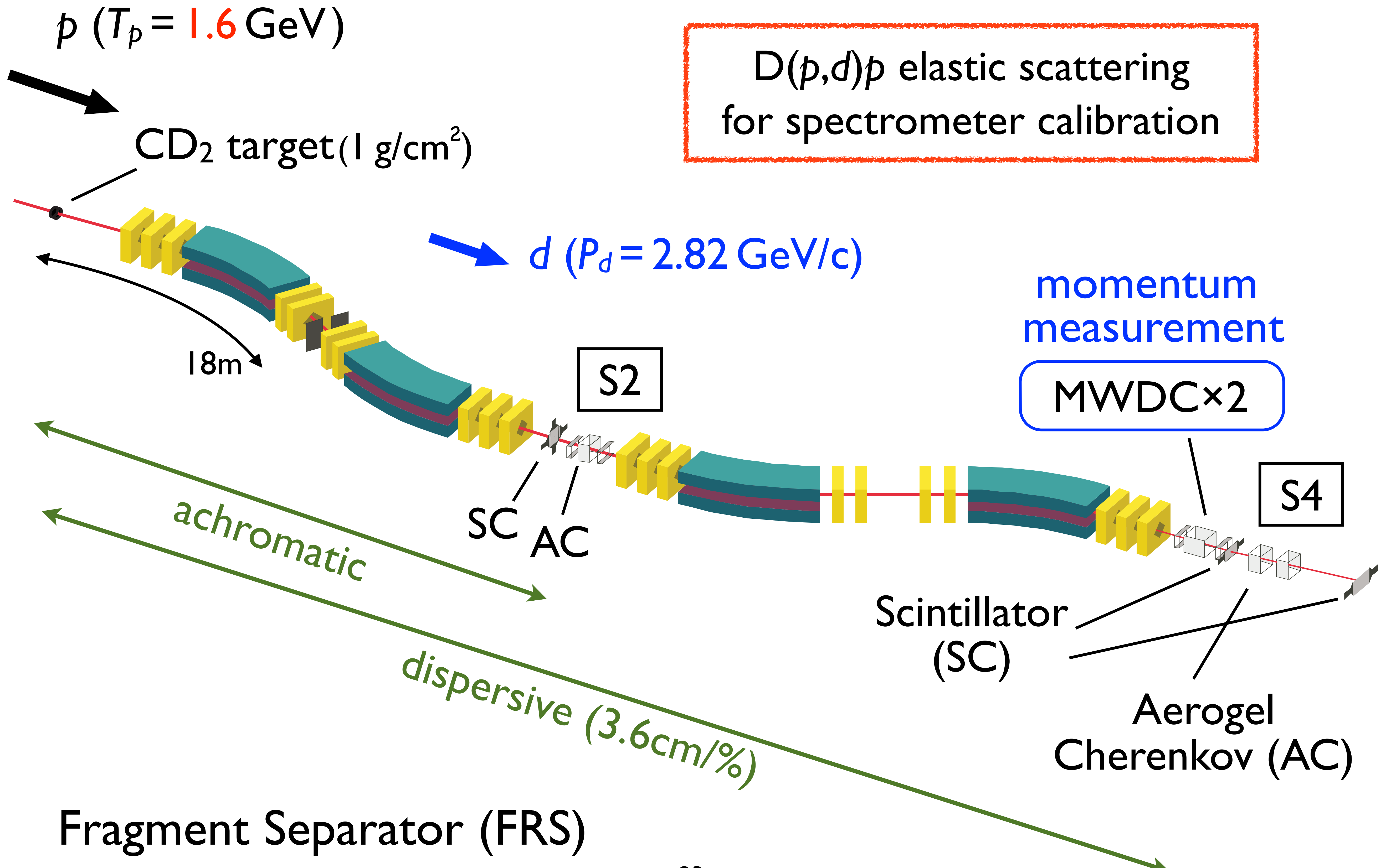
Drift length calibration



Time dependence of drift time to drift length relation

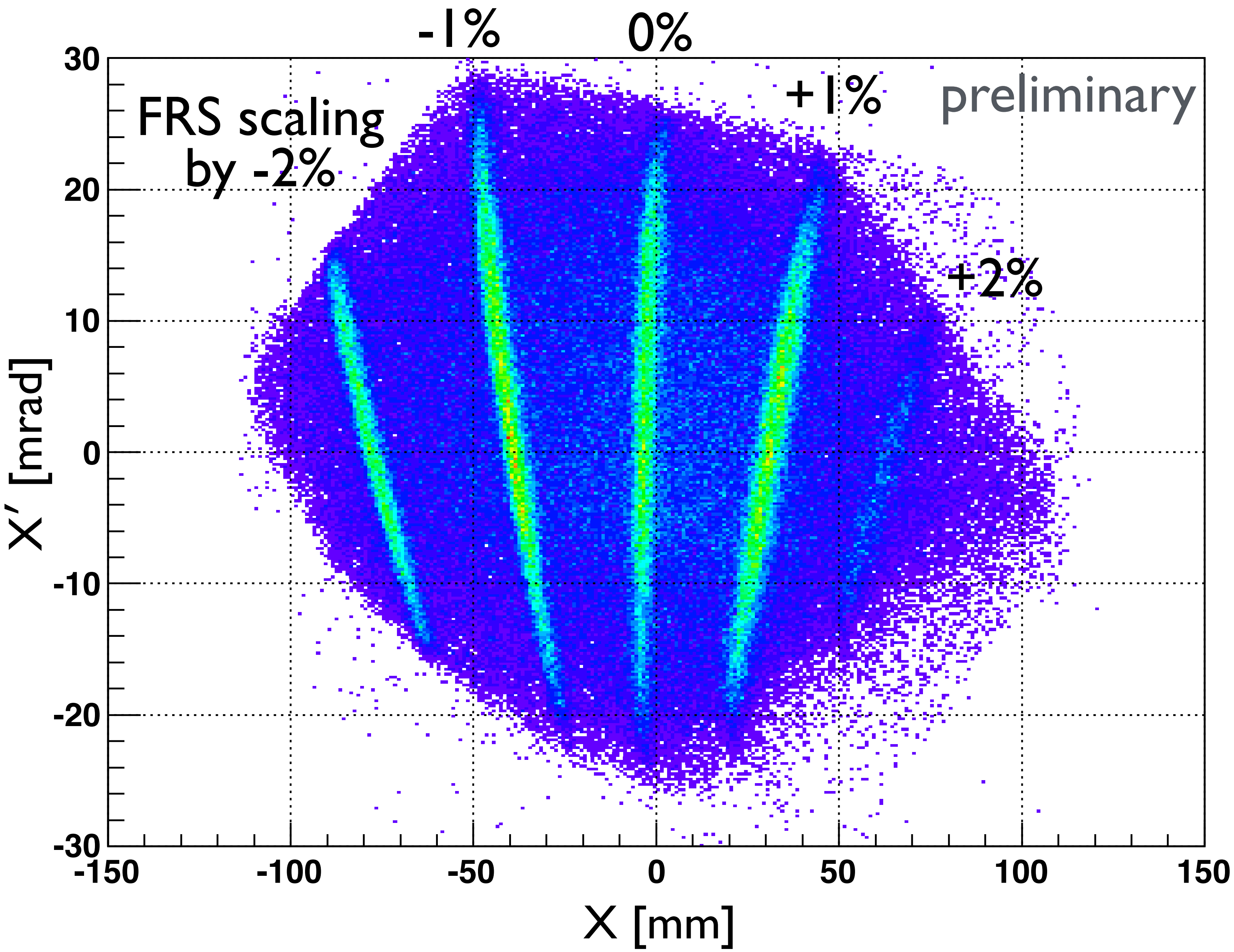


Spectrometer Calibration



Spectrometer Calibration

X (horizontal position) - X′(angle) by MWDC

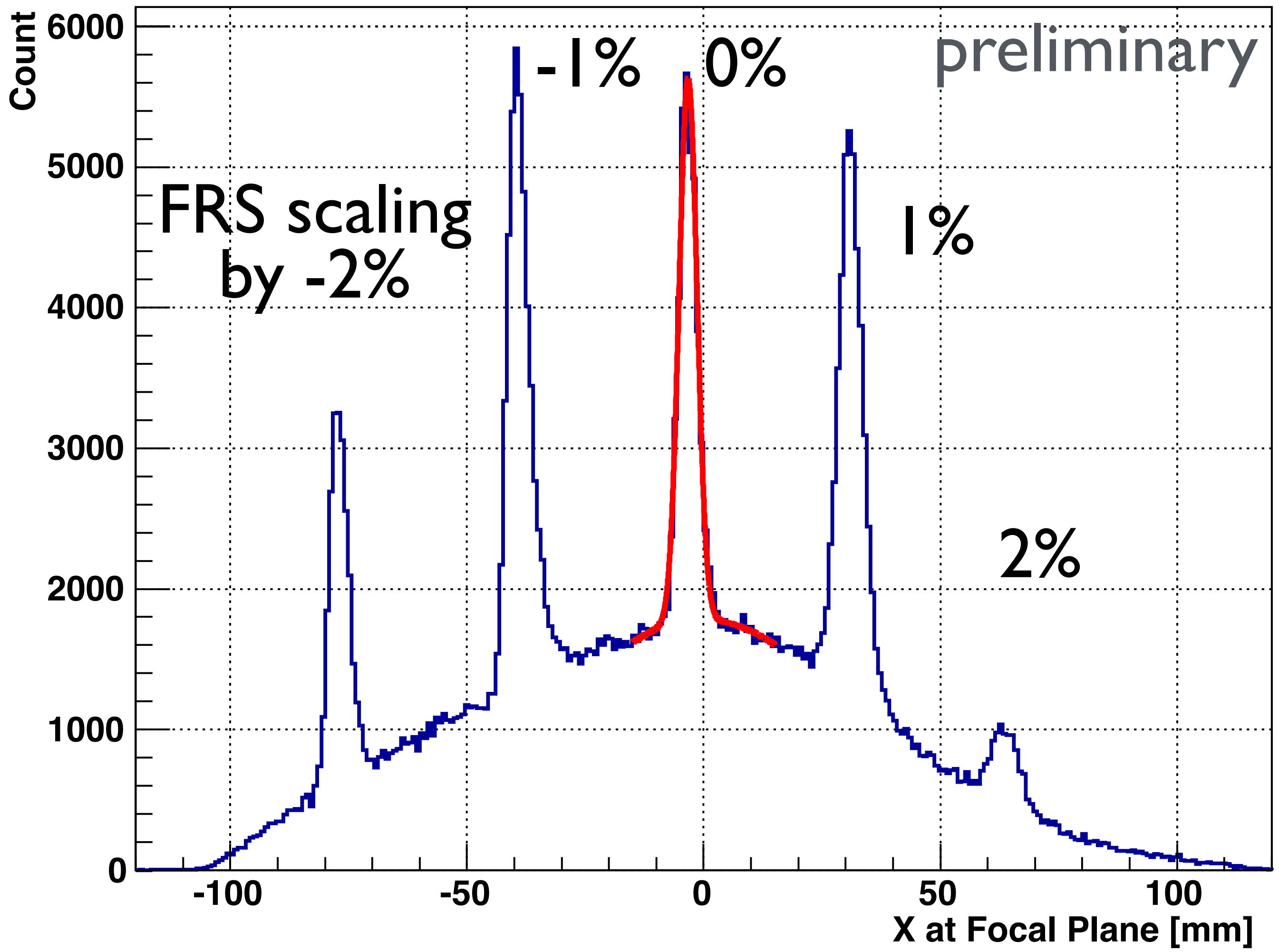


- the whole system is working well
- Ion-optical information (focus, dispersion, higher-order aberration)

→ (x|a), (x|δ), (x|aδ), (x|aa), ….

Spectrometer Calibration

Focal plane position (online, ion-optics roughly corrected)



σ_X = 2.7 mm (CD_2 calibration run)

- energy loss and straggling calculation
- spectrometer momentum resolution
- beam momentum spread

Expected resolution : $\sigma_{\text{missing mass}}$ ~ 2 MeV/c^2 (production run)

Run Summary

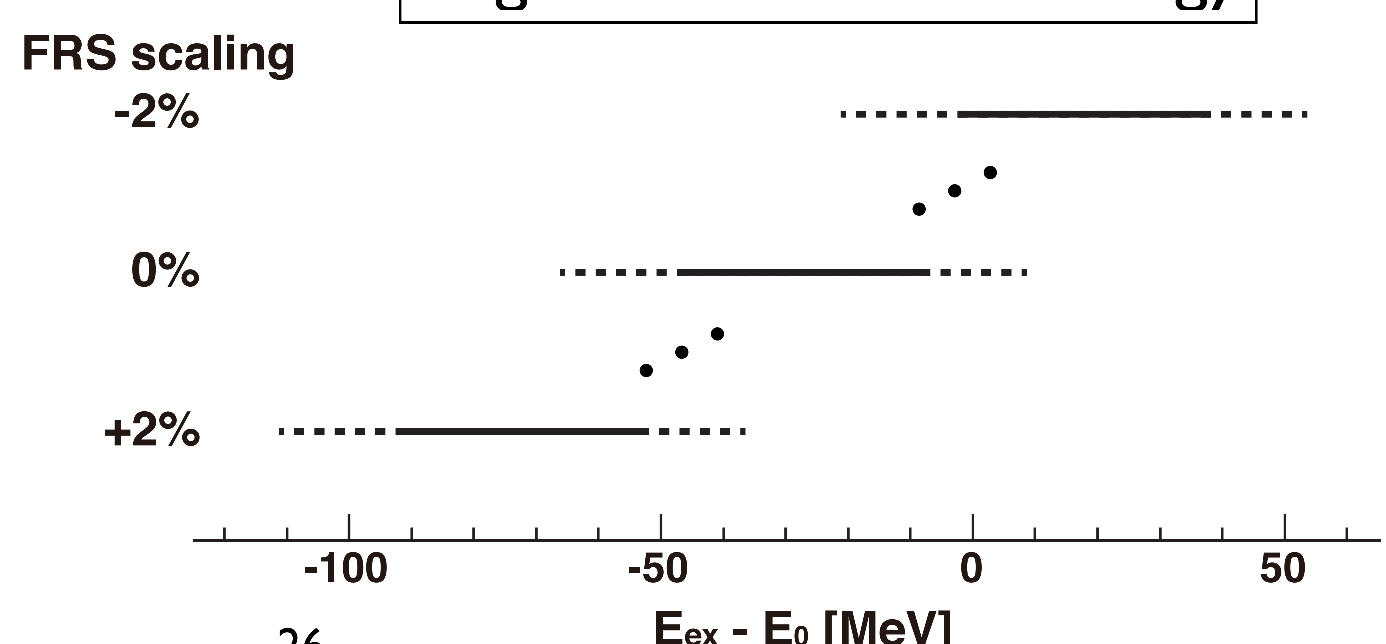
Production run (~ 5 days)

- C(*p*,*d*) reaction at T_p=2.5 GeV
  with ~ 4×10^{10}/spill proton beam and 4 g/cm^2 C target
- scaling FRS Bρ from -2% to 2% → -90 MeV < E_{ex}-E_0 < +40 MeV covered
- (5−10)×10^6 deuterons/setting were accumulated
- spectrometer calibration every 6 hours

Reference run (~ 0.5 day)

- production setting with CD_2 target, for D(*p*,*d*) spectrum
- for understanding background processes (e.g., *p*+N→*d*+π's)
- scaling FRS Bρ from -2% to 2%

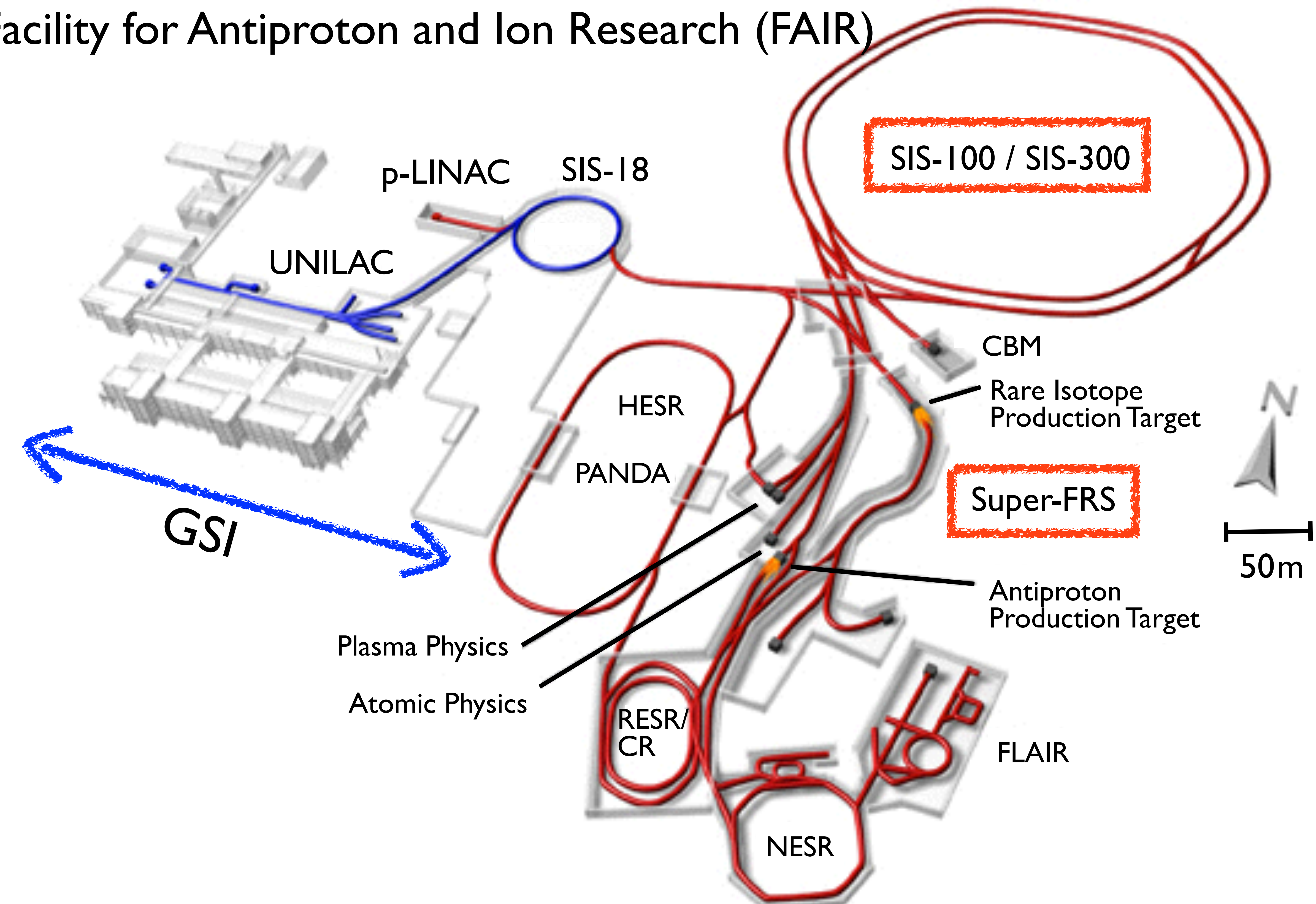
Region in excitation energy



Future plan at FAIR

FAIR facilities

Facility for Antiproton and Ion Research (FAIR)



Future plan at FAIR

1st Step : Inclusive measurement of (*p*,*d*) reaction with FRS at GSI

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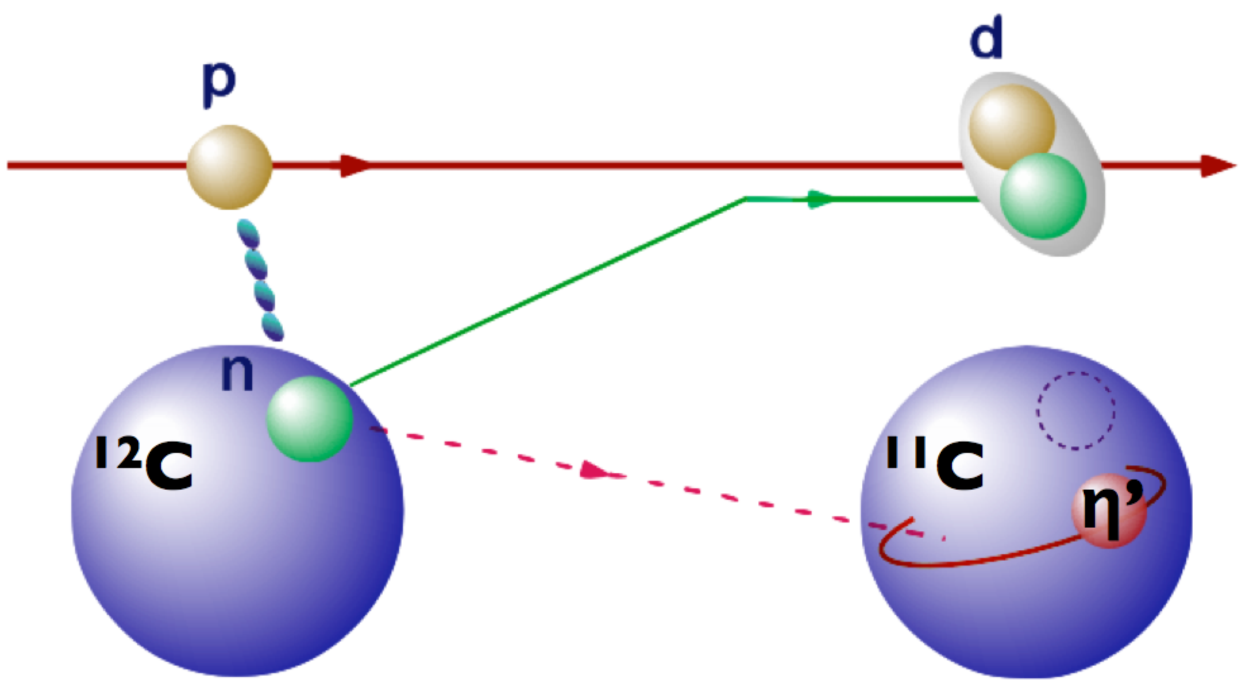
2nd Step : - Inclusive measurement with higher intensity beam at FAIR
- Semi-exclusive measurement of (*p*,*dp*) with Super-FRS at FAIR



missing-mass measurement w/ S-FRS

Target

η′ mesic nuclei

Future plan at FAIR

1st Step : Inclusive measurement of (*p*,*d*) reaction with FRS at GSI

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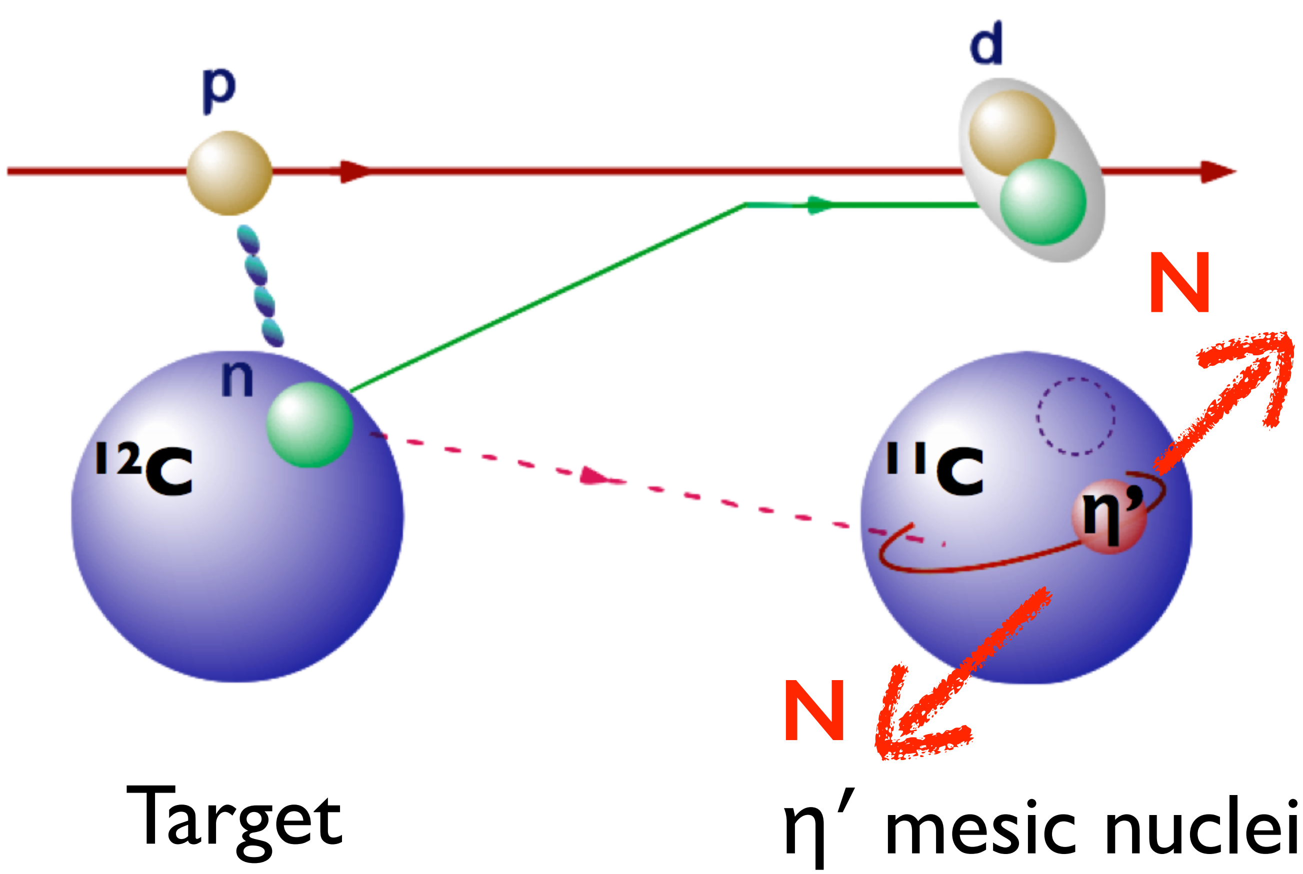


missing-mass measurement w/ S-FRS

decay of η' mesic nuclei :
- η′N → ηN or πN
- η′NN → NN

Tagging proton in coincidence with deuteron

→ S/N ratio can be improved

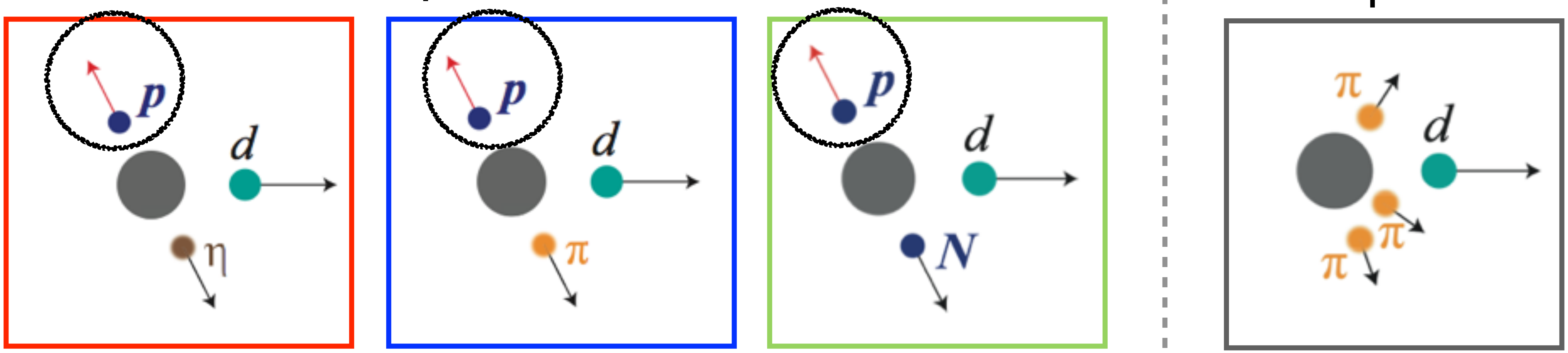
Tagging decay proton

signal

η′ mesic nuclei

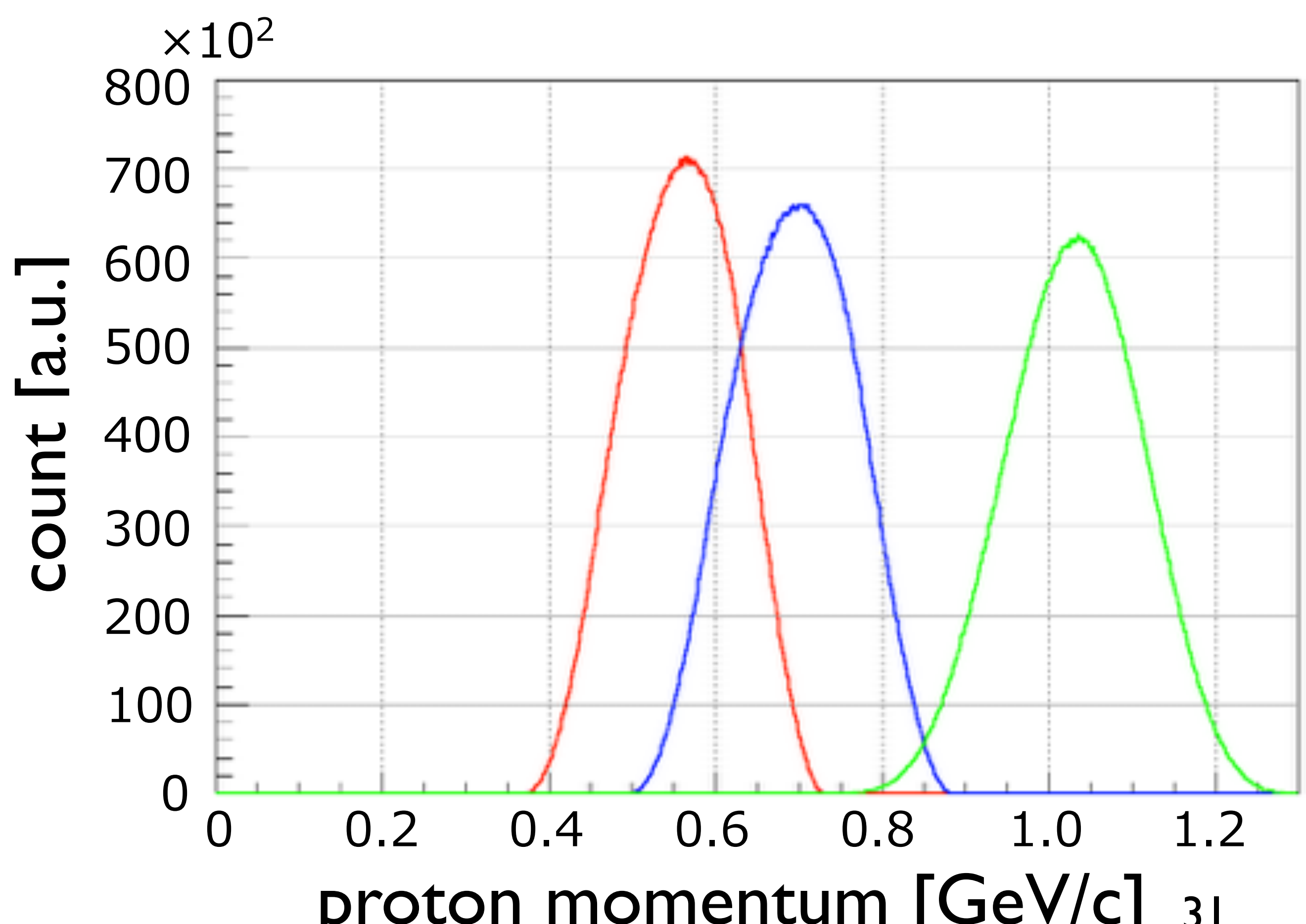
background

multi-π production

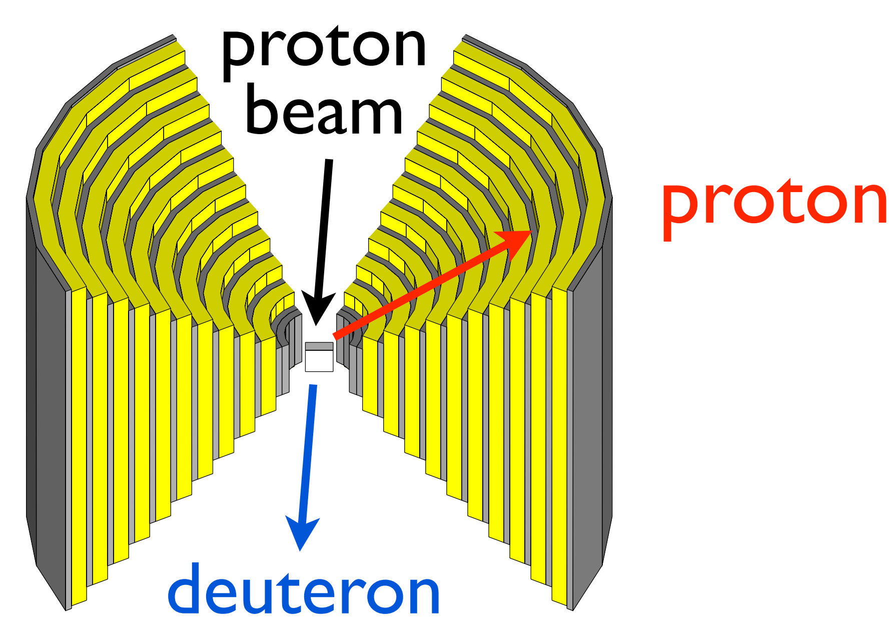


1 nucleon absorption

2 nucleon absorption



sampling calorimeter
(conceptual design)



Microscopic transport model calculation

An analysis of the 12C(p,d) reaction at eta'(958) meson production region by microscopic transport model (JAM)

Yuko Higashi, Natsumi Ikeno[A], Hideko Nagahiro, Satoru Hirenzaki, Hiroyuki Fujioka[B], Kenta Itahashi[C], Yoshiki Tanaka[D]

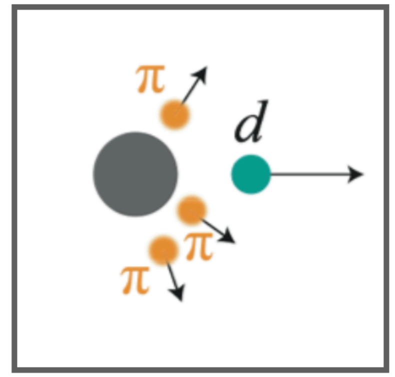
Nara Women's University,
Tohoku University[A], Kyoto University[B],
RIKEN Nishina Center[C], University of Tokyo[D]

1

JAM was developed by
Y. Nara, N. Otuka, A. Ohnishi, K. Niita,S. Chiba,
Phys. Rev. C61, 024901 (2000).

Y. Higashi (Nara WU)
Hadrons in Nuclear medium II
Workshop at J-PARC

Microscopic transport model calculation



multi-π production

JAM simulation

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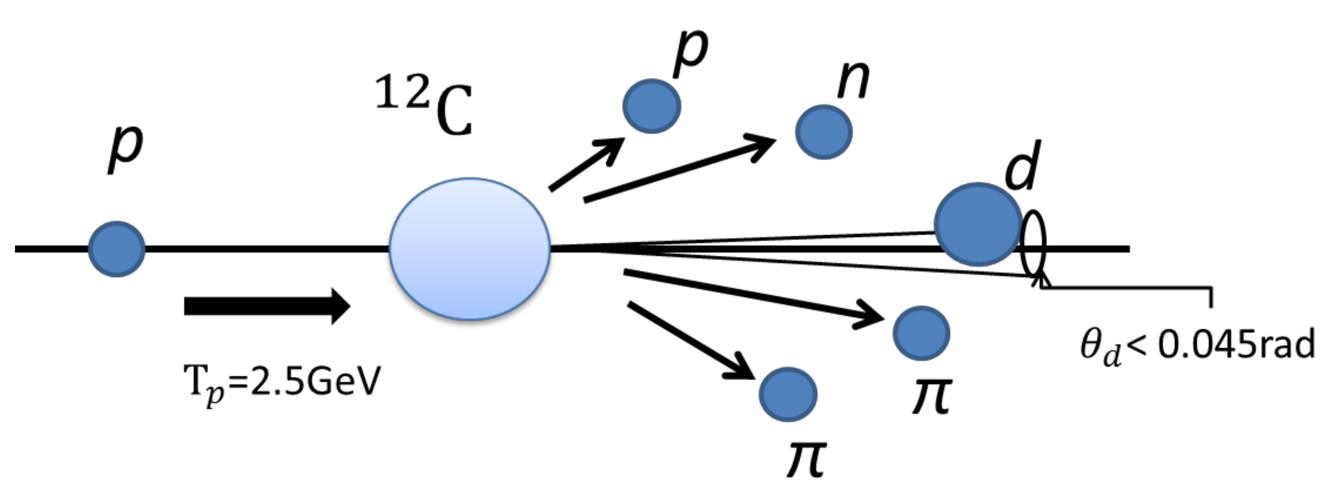
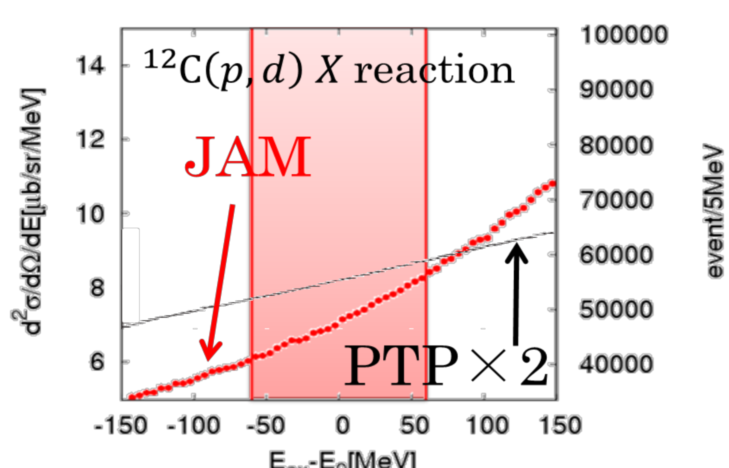
<u>Background events: </u>(mainly due to multi π production)



Considered range of the missing mass : η' threshold ±60MeV.

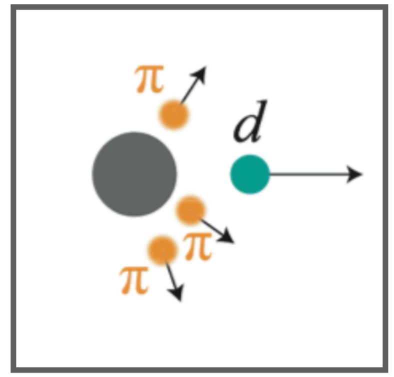


By JAM, the distributions of emitted particles from No-η'-Processes can be investigated.

⇒**<u>Background</u>**

4

Microscopic transport model calculation



multi-π production

JAM simulation

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Simulation results: Comparison of Signal with Background

- Signal ⟶ Emitted particles from η′ absorption.
- Background ⟶ Emitted particles from No-η′-processes.

To improve S/N ratio ⇒ **Focus on proton of $^{12}C(p,d)p\,X$**

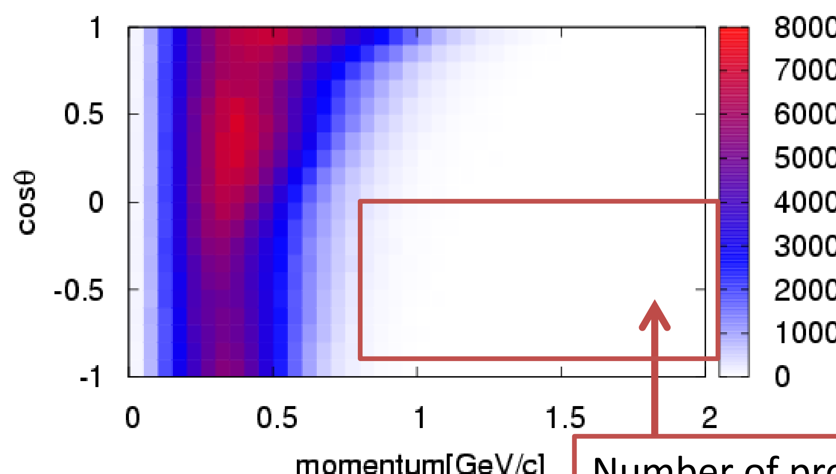
Background

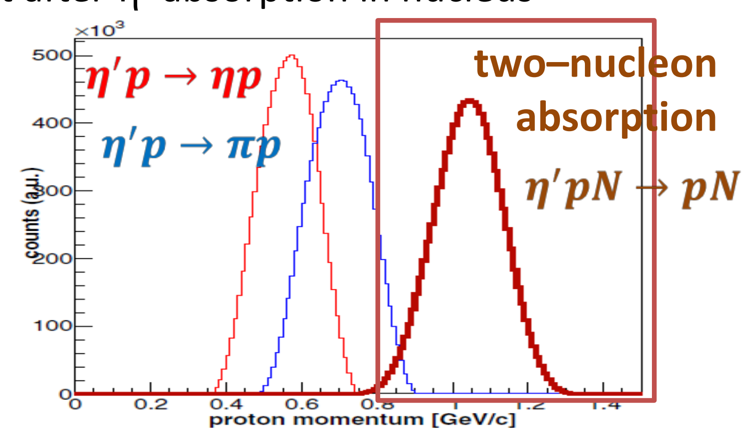
(calculation by JAM)

Signal

Expected momentum distribution of proton just after η′ absorption in nucleus

Proton momentum vs Angle (cosθ) ⟶





Number of protons with large momentum at backward directions : small!

high momentum proton at backward angle
→ clean region

The S/N ratio could be improved by using the protons from two-nucleon absorption of η′! (proton with large momentum at backward directions seems important.)

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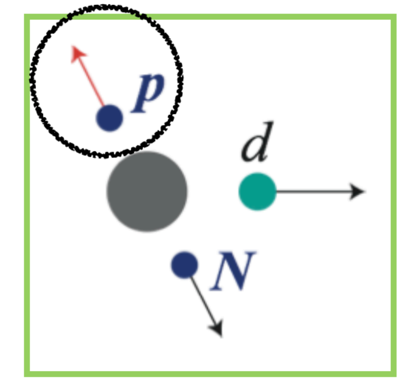
Microscopic transport model calculation

multi-π production



2 nucleon absorption

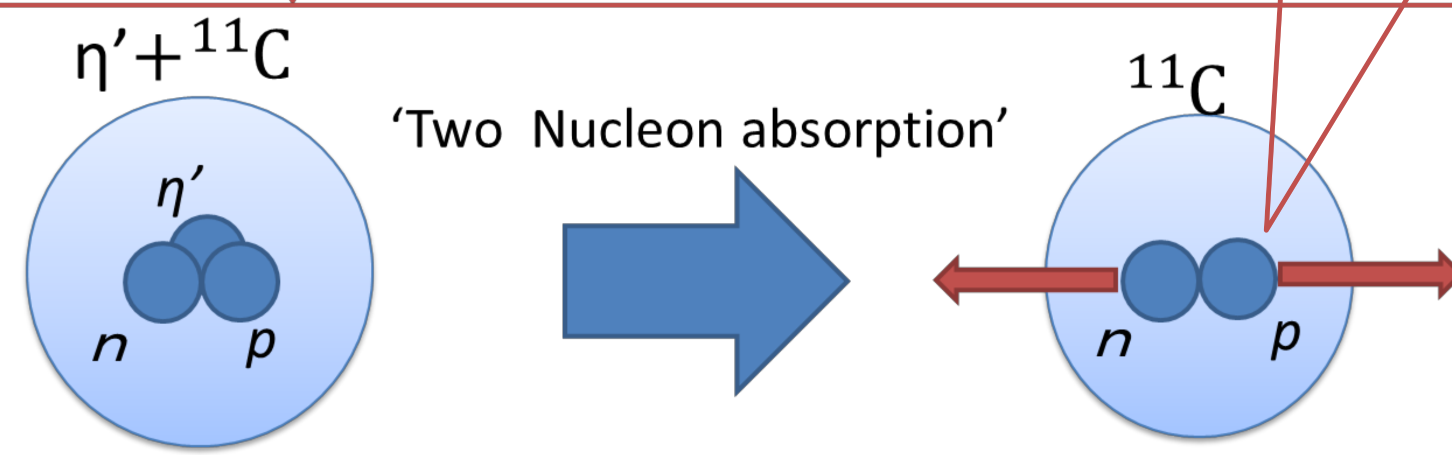
JAM simulation

Y. Higashi,
Hadrons in Nuclear medium II
Workshop at J-PARC

<u>**η' - Processes :**</u> Emitted particles from η' - Processes ⇒<u>**Signal**</u>
Here, we consider two-Nucleon absorption of η'

$$p + {}^{12}\mathrm{C} \rightarrow \mathrm{d} + (\eta' \;\; {}^{11}\mathrm{C})$$

Proton has
$T_p \sim \frac{m_{\eta'}}{2}$
$|\overrightarrow{P_p}| \sim 1\mathrm{GeV/c}$



Evolution of p is evaluated by JAM.

Simulation was started by putting 1.0×10^6 protons in nucleus.

Spatial distribution $\propto$ $\rho(\mathrm{r})^2$: 2 nucleon absorption

Momentum distribution $\propto$ $\exp\left[\frac{-(\vec{P}-\vec{P_0})^2}{2(\Delta\vec{P})^2}\right]$: Fermi Motion

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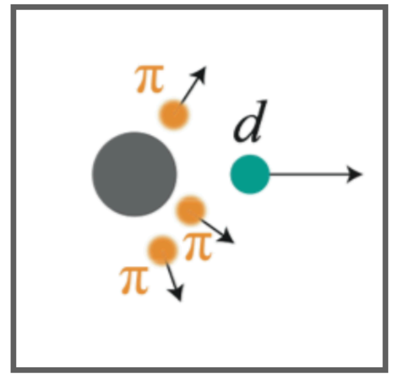
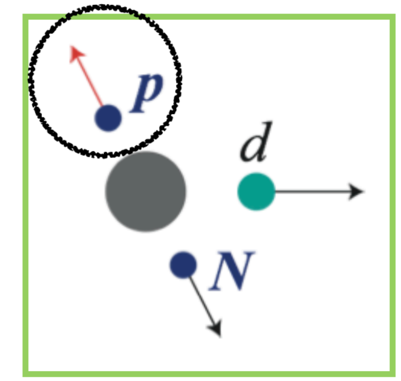
Microscopic transport model calculation



multi-π production



2 nucleon absorption

JAM simulation

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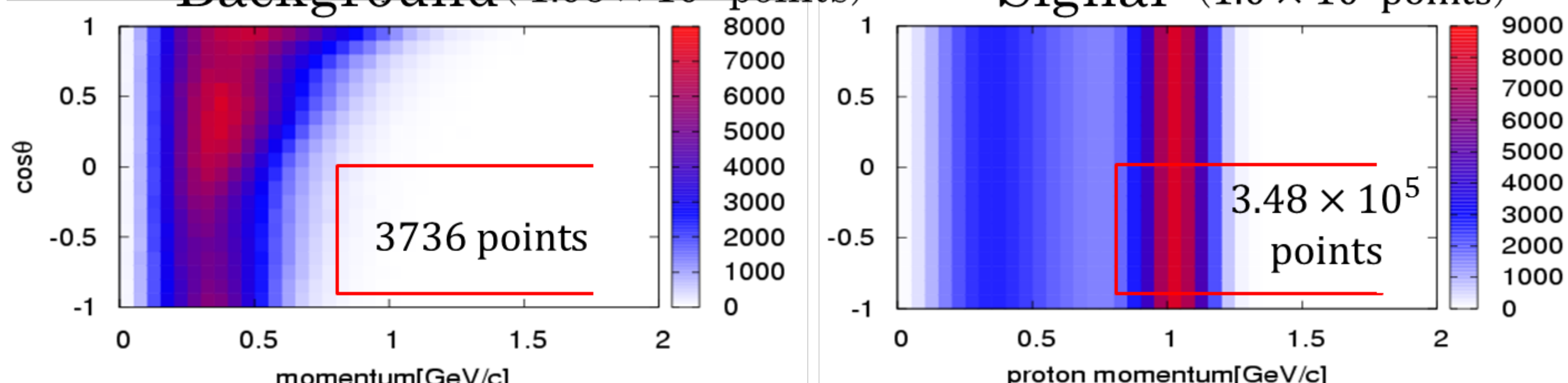
Proton momentum vs Angle (cosθ) →

S/N ratio can be improved by ~100

3.Discussion : Comparison of Signal with Background
(obtained by independent simulations)

Background (1.06×10^6 points) Signal (1.0×10^6 points)



	Inclusive(p,d) $\frac{d\sigma}{d\Omega_d}$ ※1	proton cut $\frac{d\sigma}{d\Omega_d}$ ※2
Background	760 [μb/sr] $\times \frac{3736}{1.06 \times 10^6}$ →	2.68 [μb/sr]
Signal	1.1 [μb/sr] $\times \frac{3.48 \times 10^5}{1.0 \times 10^6}$ →	0.38 [μb/sr]
S/N ratio	1.4×10^{-3} →	1.4×10^{-1}

The S/N ratio is improved by the factor of 100.

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Summary

- Missing-mass spectroscopy of η' mesic nuclei with (p,d) reaction is performed for studying in-medium properties of η' meson

- In case of large mass reduction (~100MeV) and narrow decay width (~20MeV), η' mesic nuclei may be observed in missing-mass spectrum.

- The first inclusive measurement using FRS at GSI has been performed. Data with good statistics and quality were obtained. Analysis of missing-mass spectra is currently underway.

- At FAIR, we plan semi-exclusive measurement of (p,dp) reaction as well as better-statistics inclusive measurement. Tagging decay protons can improve S/N ratio. R&D is presently on-going.