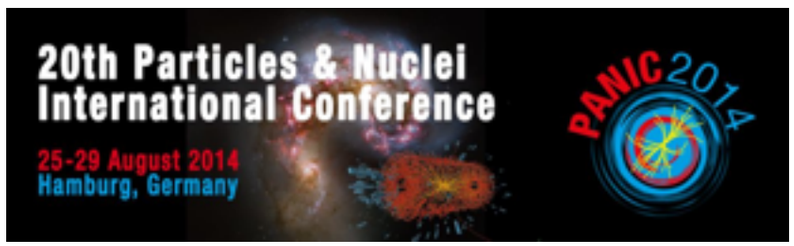
η′ Mesic Nucleus Spectroscopy with (*p*,*d*) Reaction at GSI

Yoshiki K. Tanaka (Univ. of Tokyo)

for the η-PRiME collaboration



東京大学 THE UNIVERSITY OF TOKYO

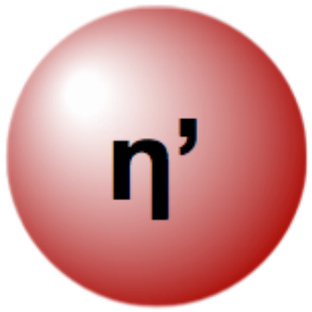
η′ PRiME

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, P. Reiter, J. L. R. Sanchez, C. Scheidenberger, H. Simon, B. Sita, 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

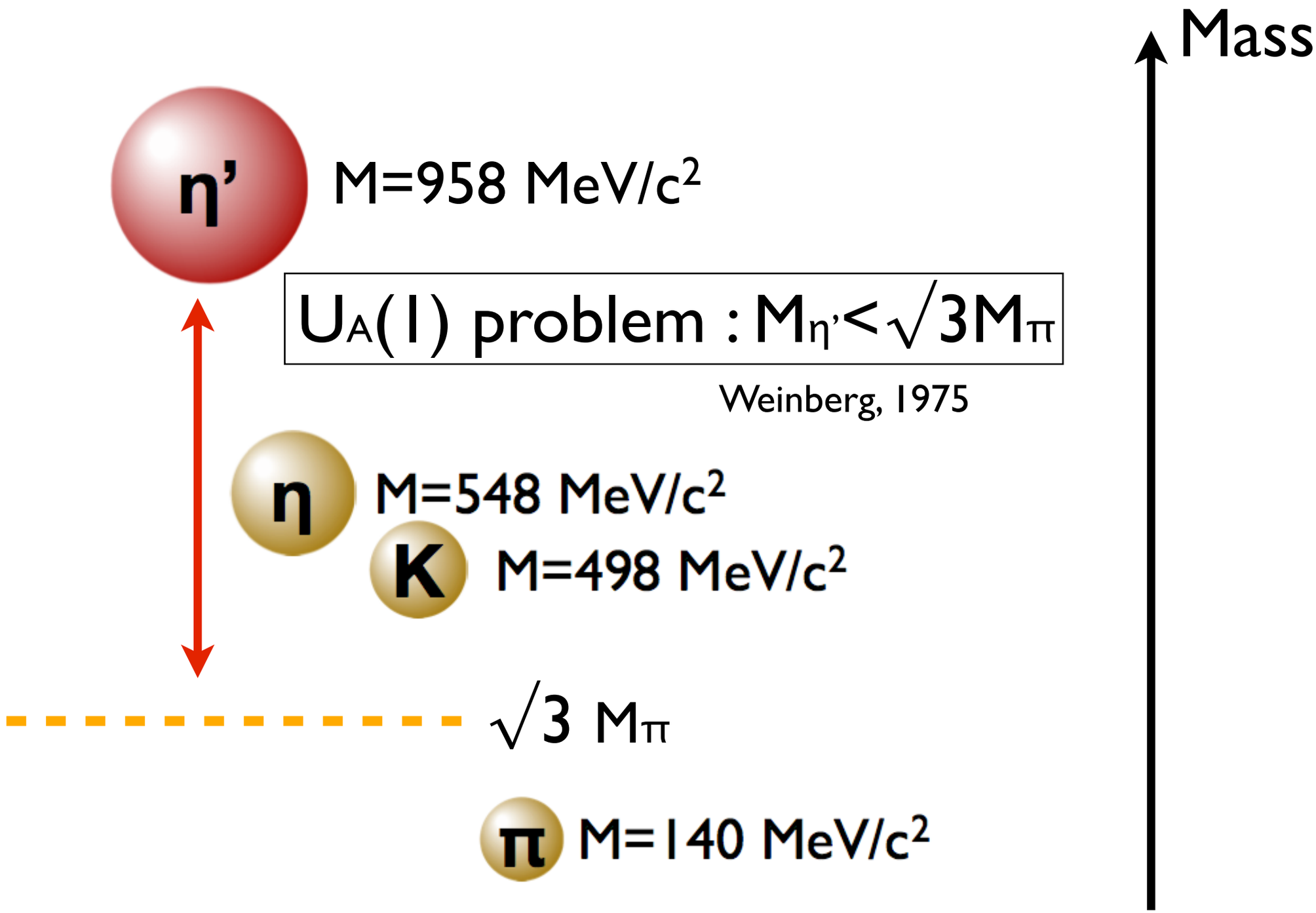
η′ meson



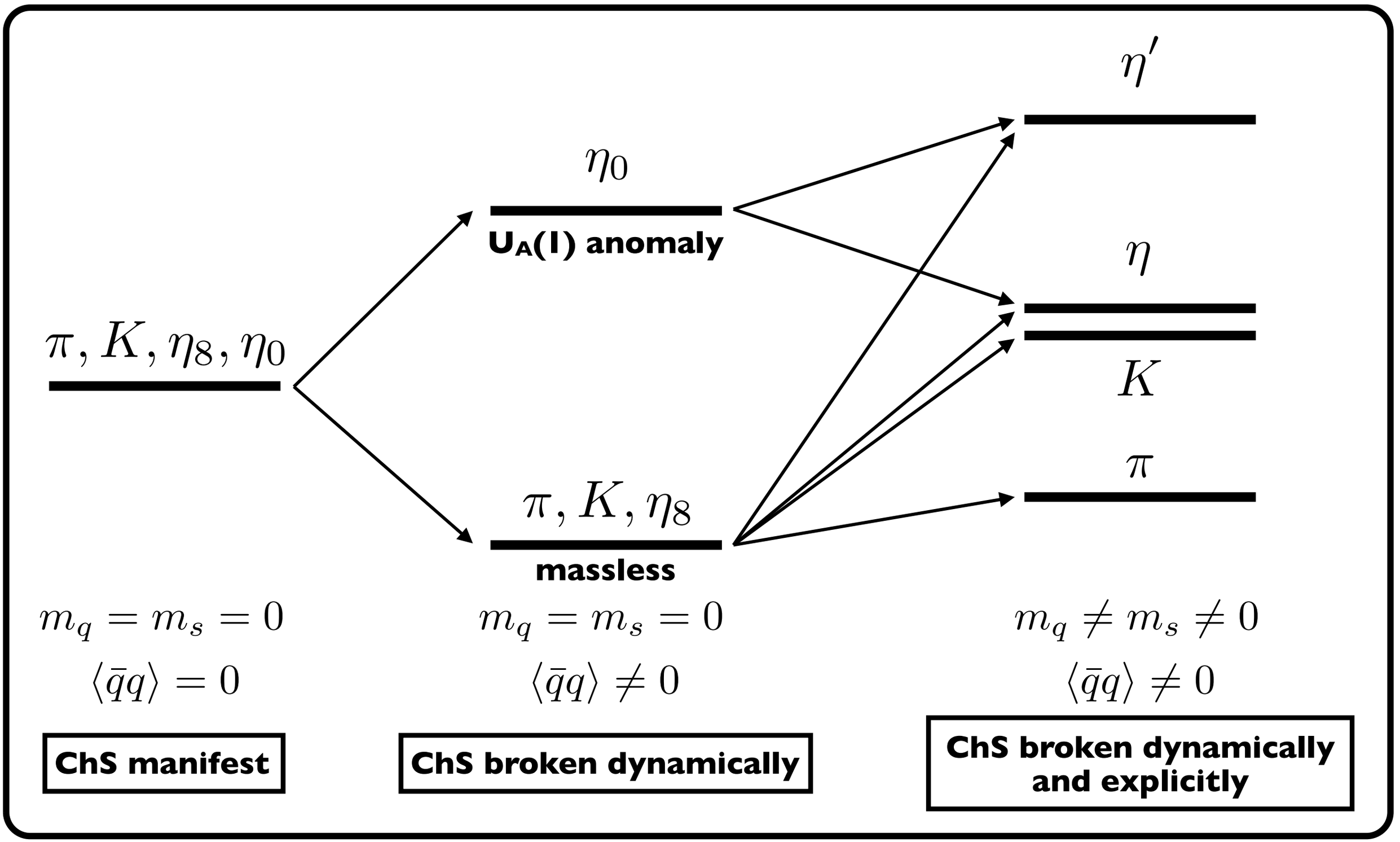
M=958 MeV/c^2
Γ=0.199 MeV
Pseudoscalar meson ($J^{\pi}=0^{-}$)

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

η′ meson


Mass
η'
M=958 MeV/c²
UA(1) problem : Mη'<√3Mπ
Weinberg, 1975
η
M=548 MeV/c²
K
M=498 MeV/c²
√3 Mπ
π
M=140 MeV/c²

η′ meson

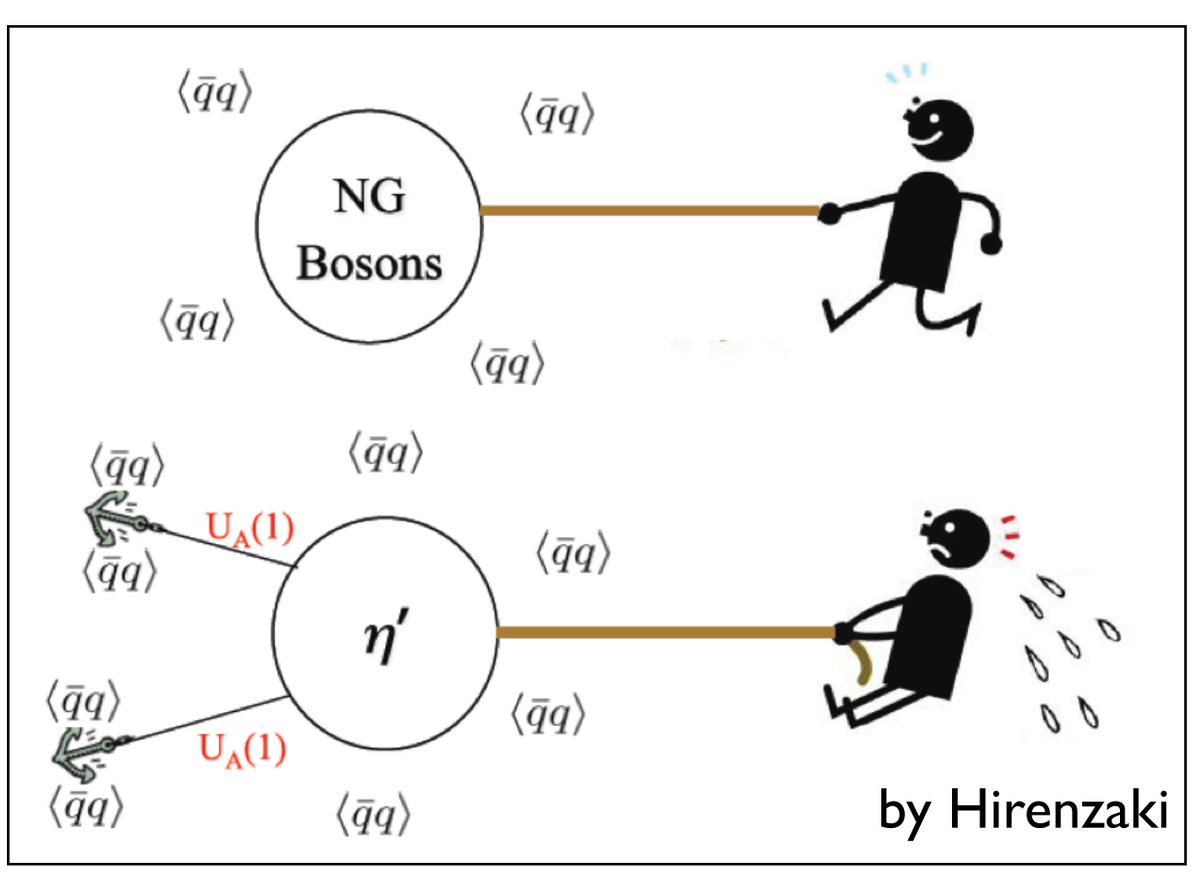


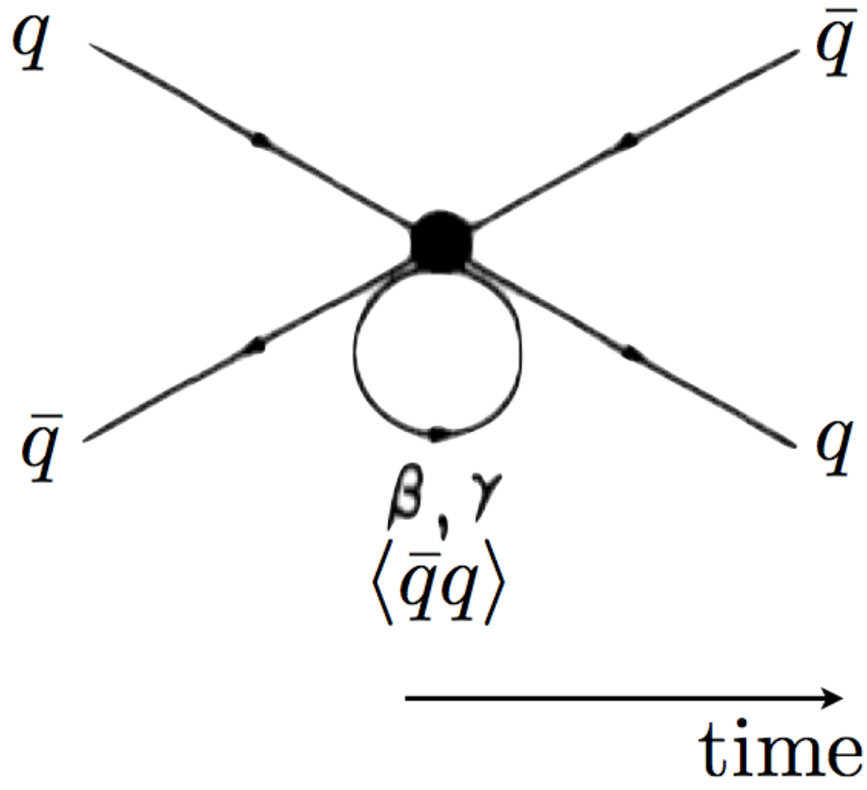
H.Nagahiro et al.,PRC 87 (2013) 045201.

η′ meson

$U_A(1)$ anomaly effect on η' mass

- KMT interaction in NJL model
- related to the strength of chiral condensate $<\bar{q}q>$





Kobayashi-Maskawa-'t Hooft 6-point vertex

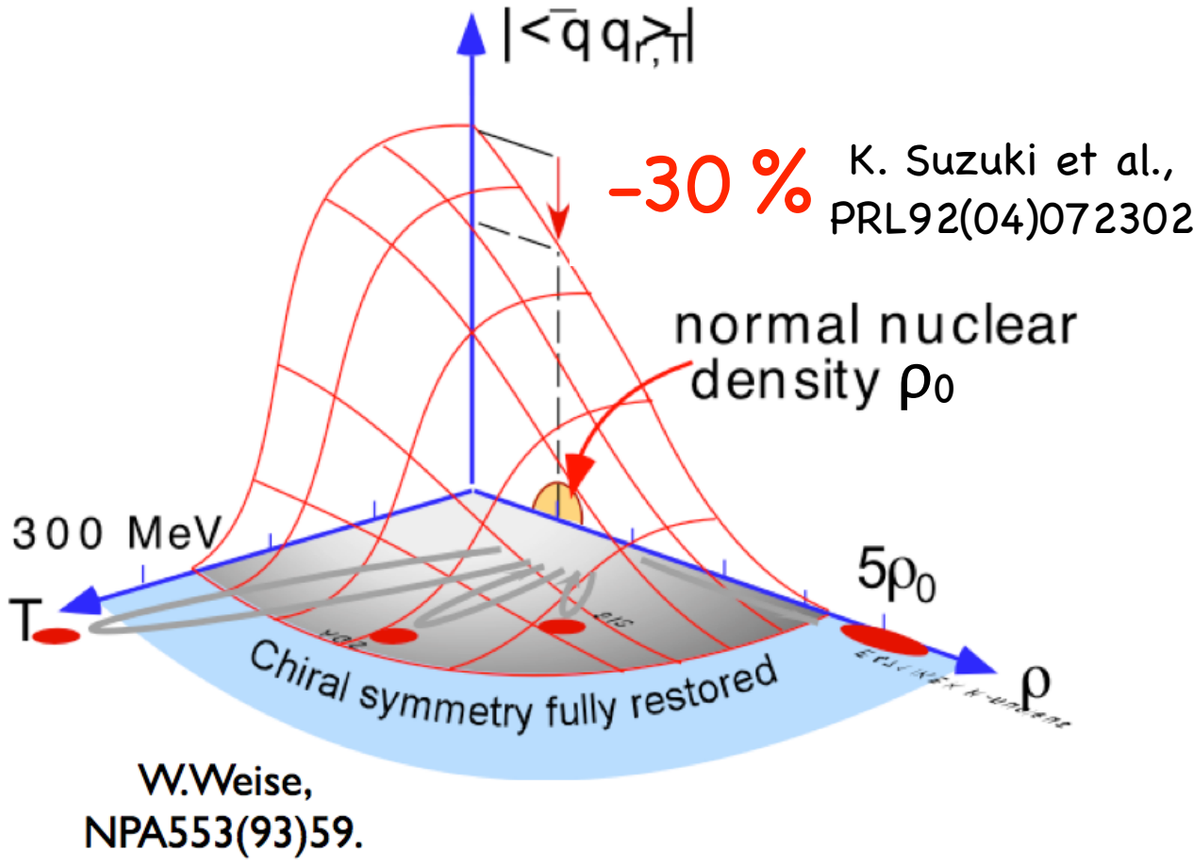
Kobayashi, Maskawa, PTP44(70)1422
't Hooft, PRD14(76)3432.
T. Kunihiro, Phys. Lett. B219(89)363.
Klimt, Lutz, Vogl, Weise, NPA516(90)429.

η′ meson in medium

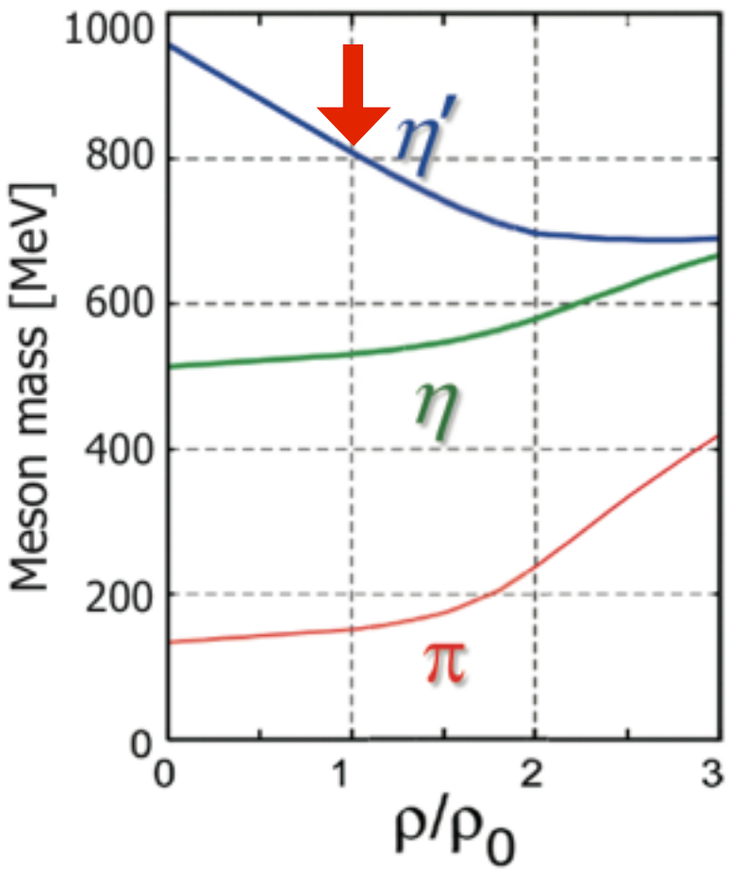
- Chiral condensate $\langle\bar{q}q\rangle$ decreases by ~30% at ρ_0.

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

partial restoration of chiral symmetry



W.Weise,
NPA553(93)59.



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

in-medium mass and width

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

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

- NJL model prediction

$V_0 \sim$ -150 MeV → **strong attraction ?**

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- CBELSA/TAPS

  $V_0 = -37 \pm 10(\text{stat}) \pm 10(\text{syst})$ MeV

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

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

- relatively small scattering length of the s-wave η'-proton interaction

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

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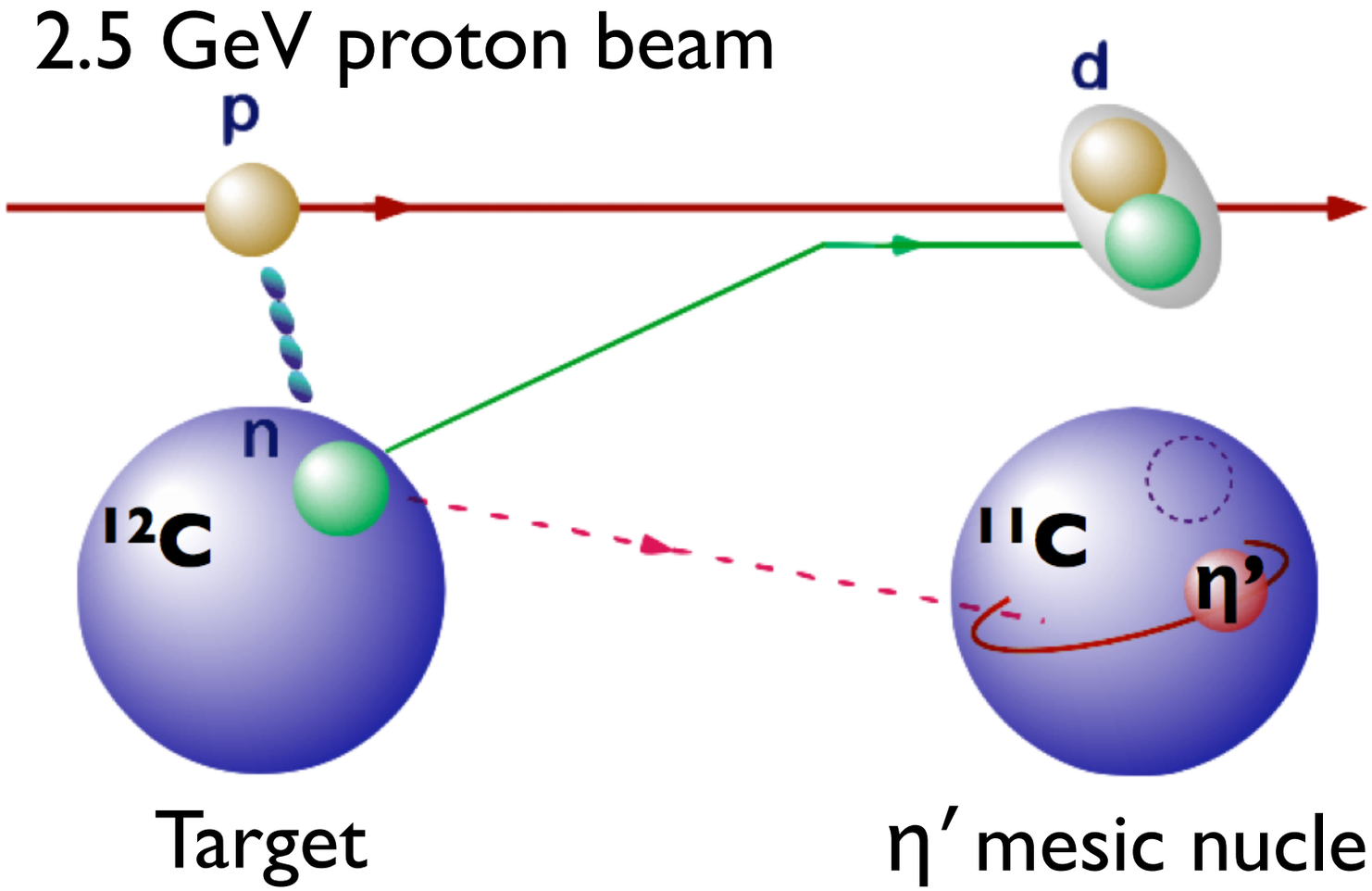
→ $|W_0|$ smaller than possible mass reduction $|V_0|$

→ possibility to observe η' meson-nucleus bound state (η' mesic nuclei)

Experiment at FRS-GSI

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



momentum measurement
by Fragment Separator

⬇

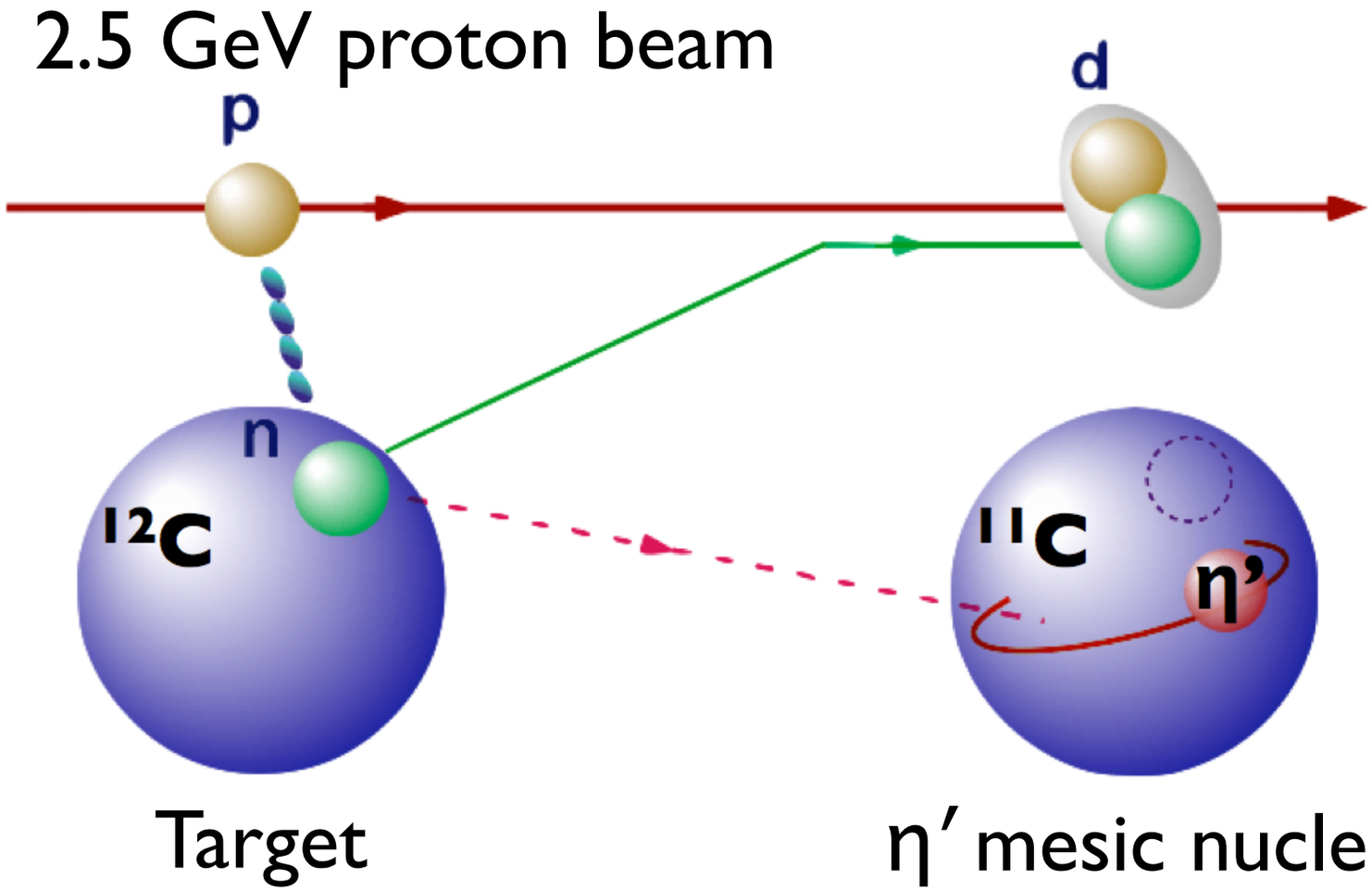
missing-mass spectrum

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

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

- no assumption on decay process
- poor S/N ratio due to BG processes (e.g., multi-pion production)

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



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

- no 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

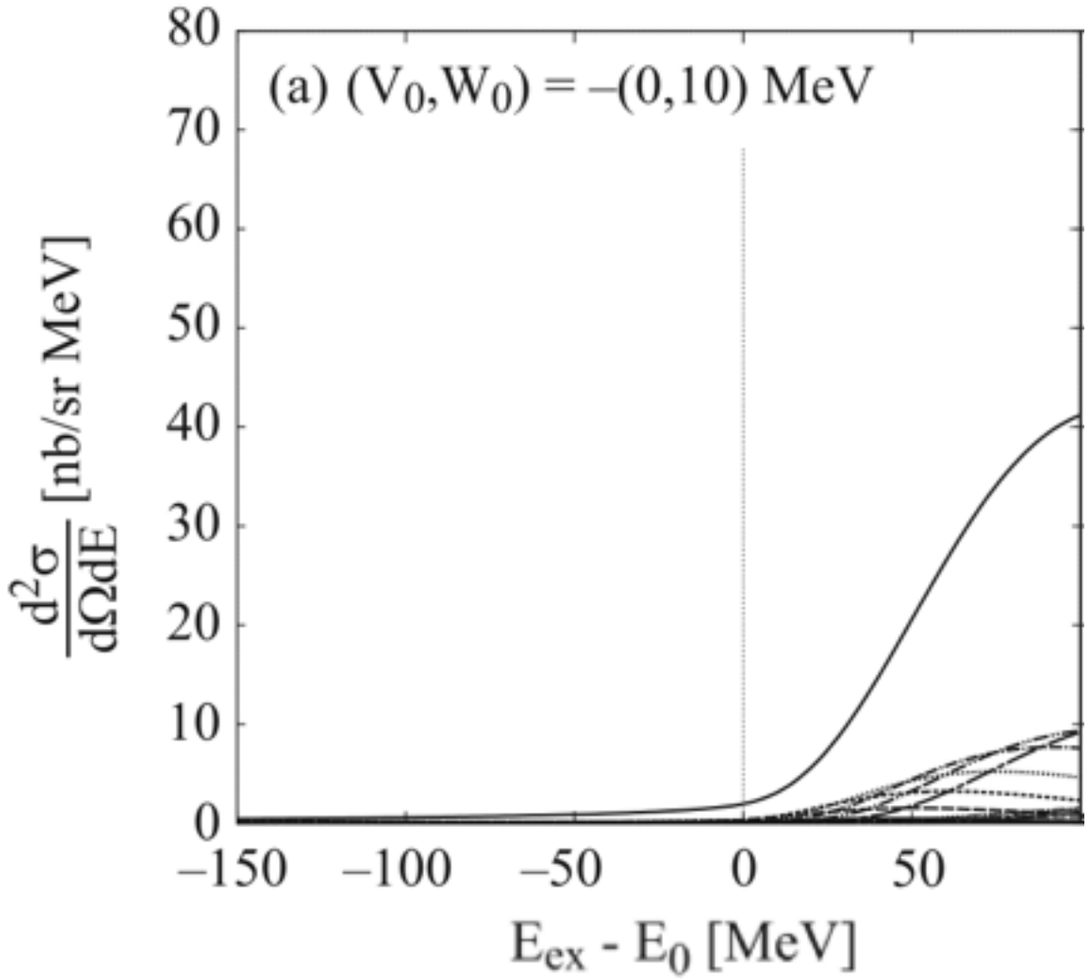
Theoretical spectra of $^{12}C(p,d)^{11}C\times\eta'$

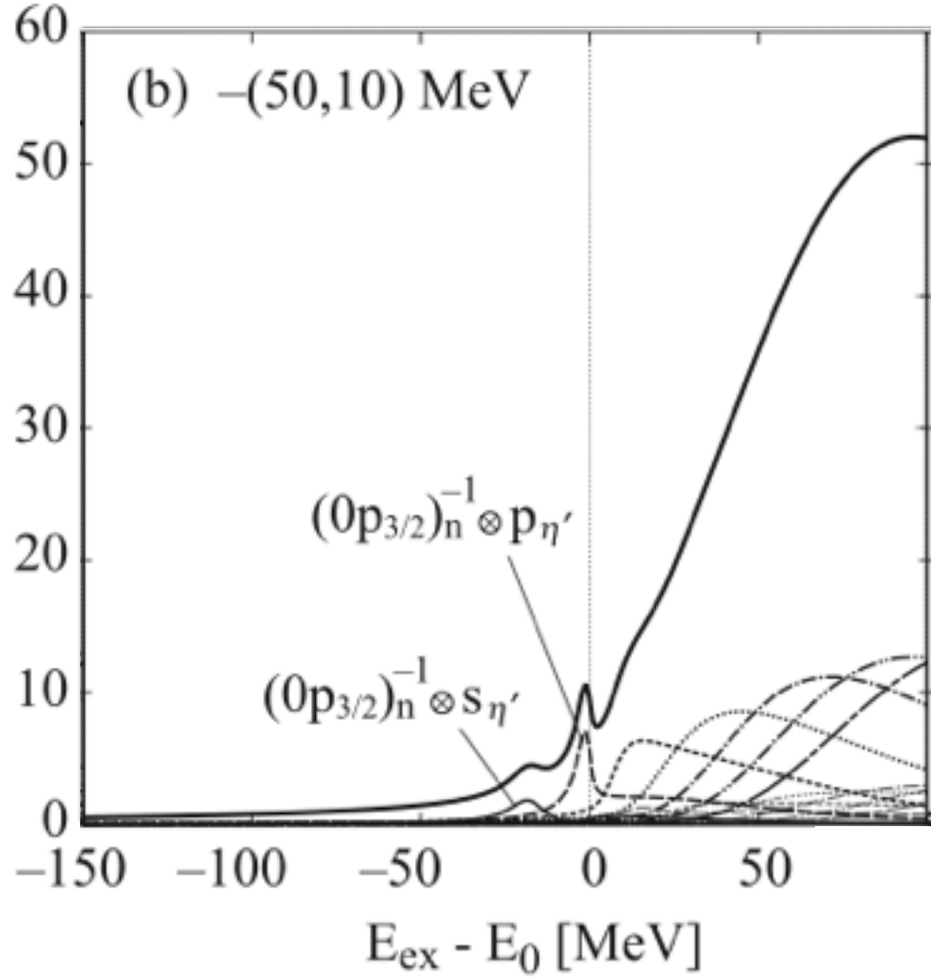
- Green's function method
- proton energy 2.5 GeV,
  mom. transfer ~ 400 MeV/c

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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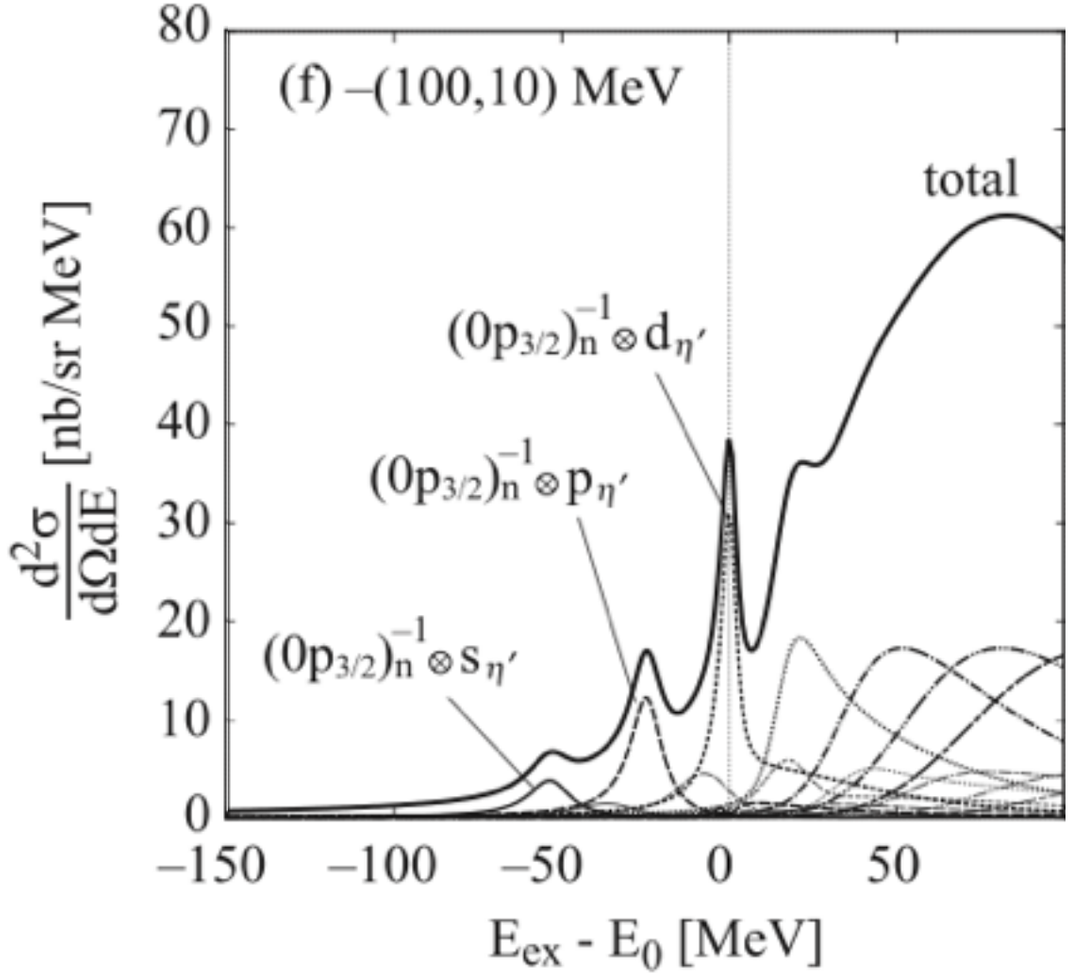
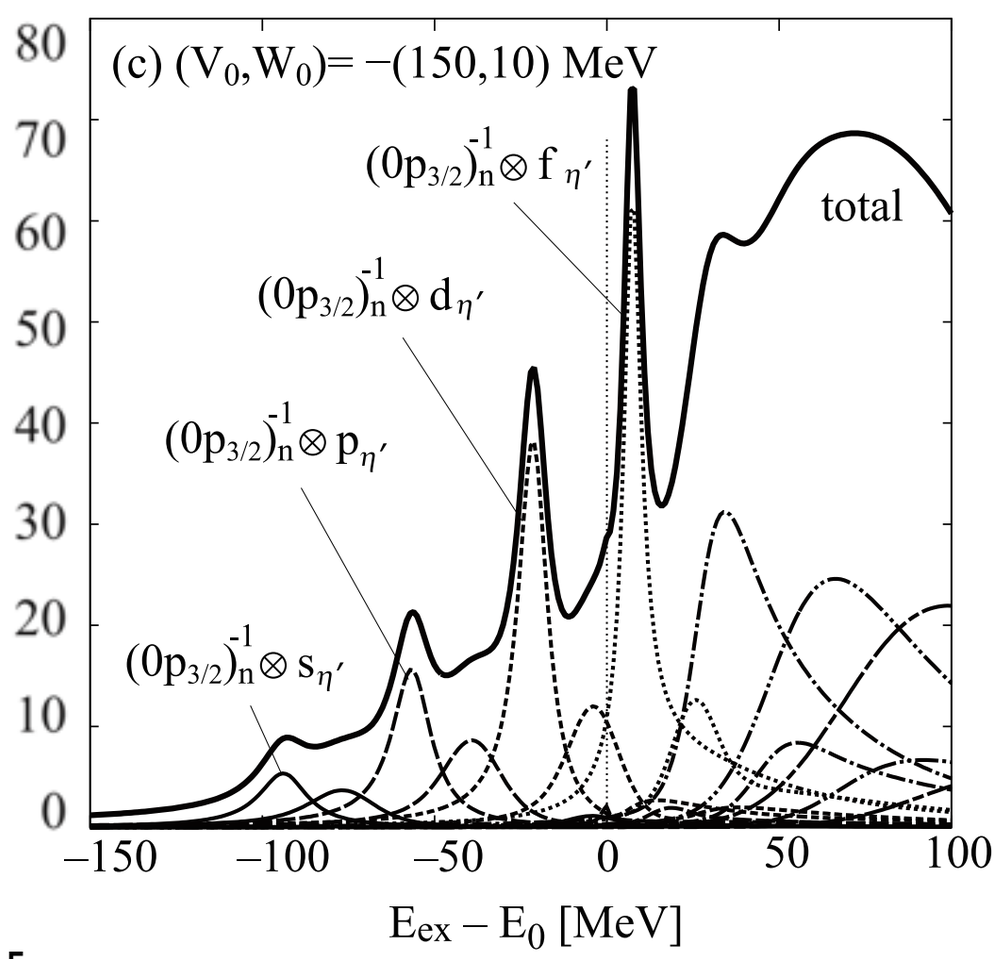




H.Nagahiro et al.,PRC 87 (2013) 045201.

Simulated spectrum in 4.5 days DAQ

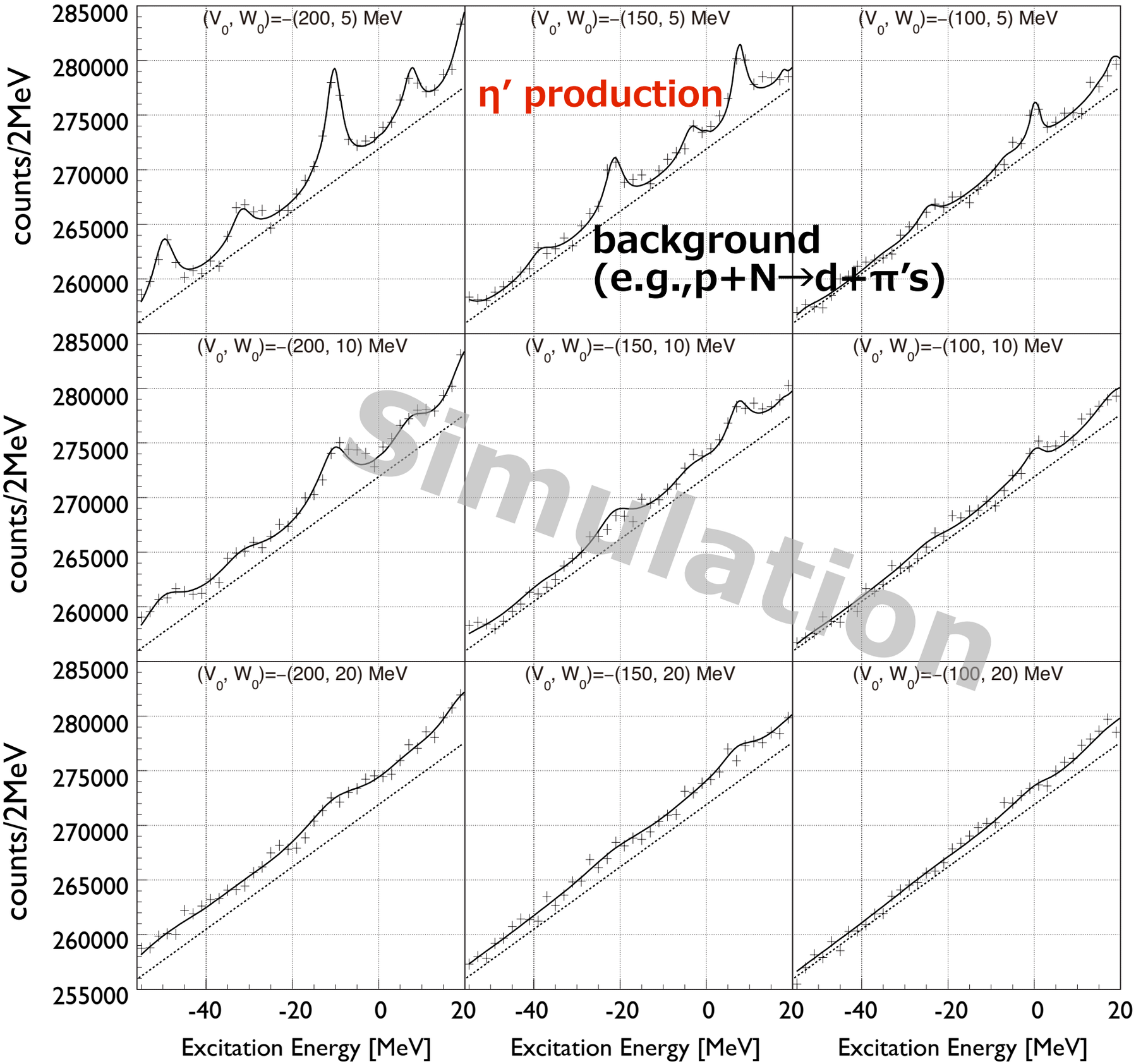
Inclusive spectrum
assuming 4.5 day DAQ

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

V_0, W_0 :
real, imaginary part
of optical potential

- background processes based on COSY-ANKE data/simulation [1]

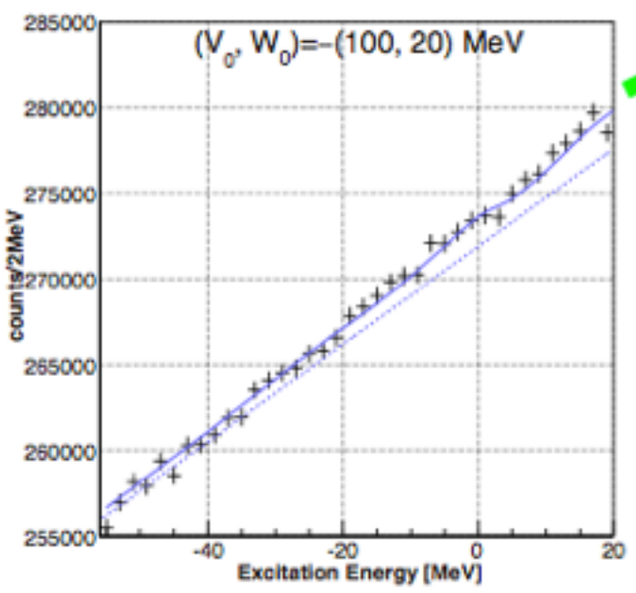
- S/N ratio
  ~ O(1/100) at most

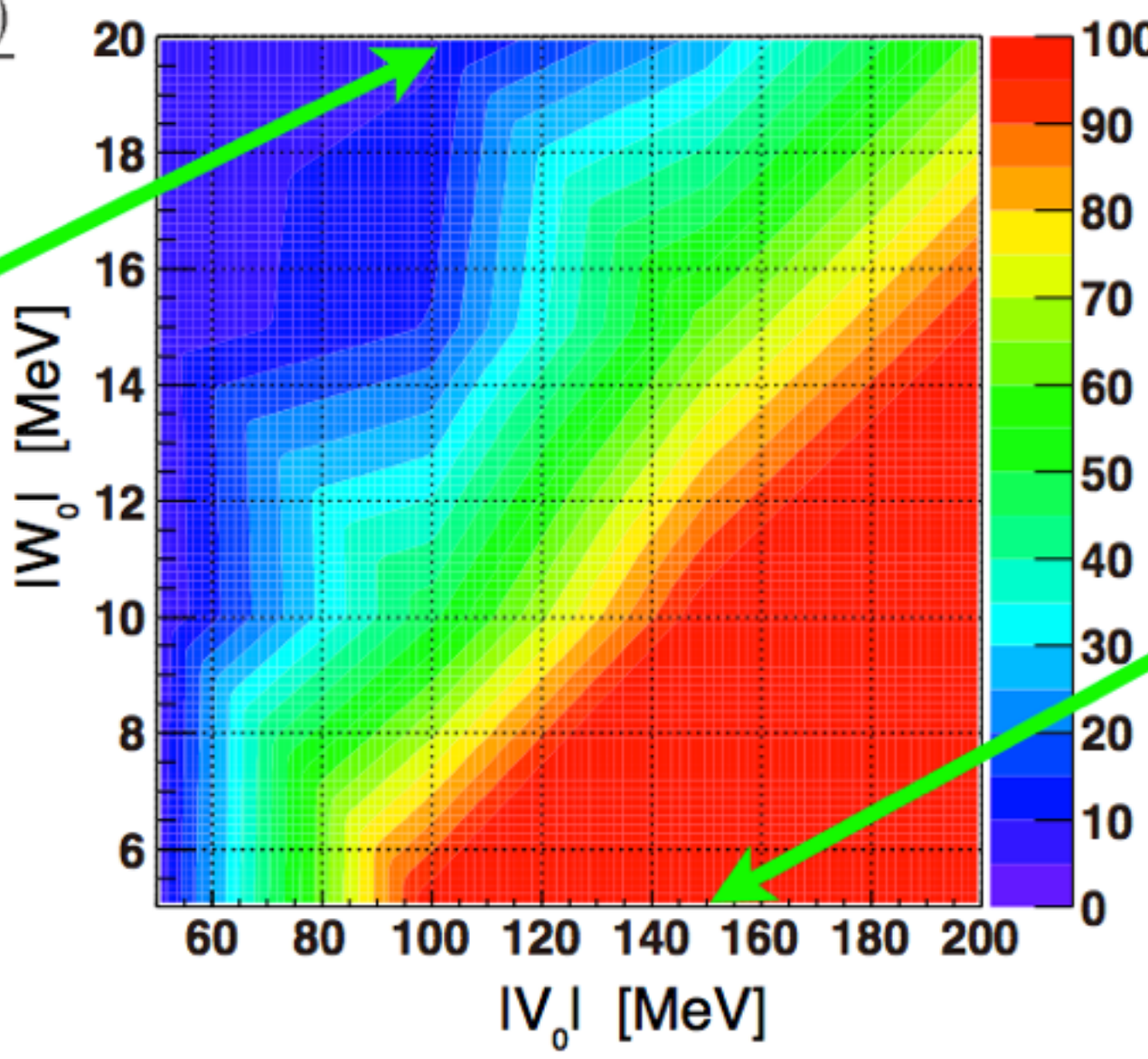


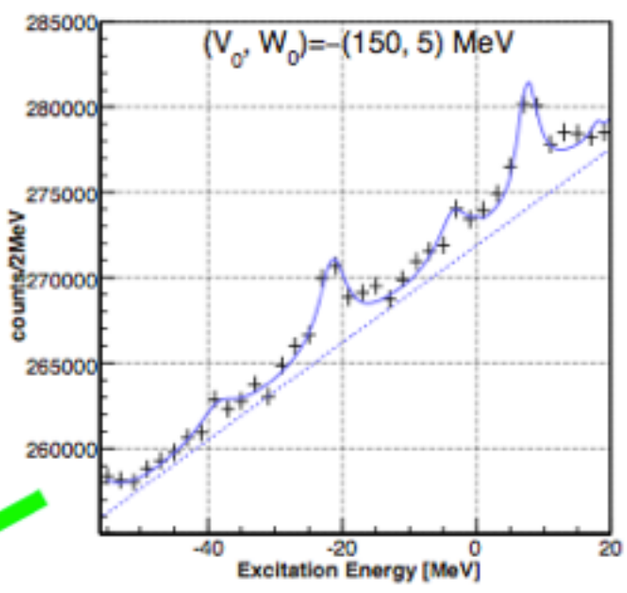
[1] S. Barsov et al., EPJ A21, 521 (2004);
I. Lehmann, Ph.D thesis (2003)

Structure-finding probability

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







in 4.5 days DAQ

for 95 % C.L.

Structure-finding probability

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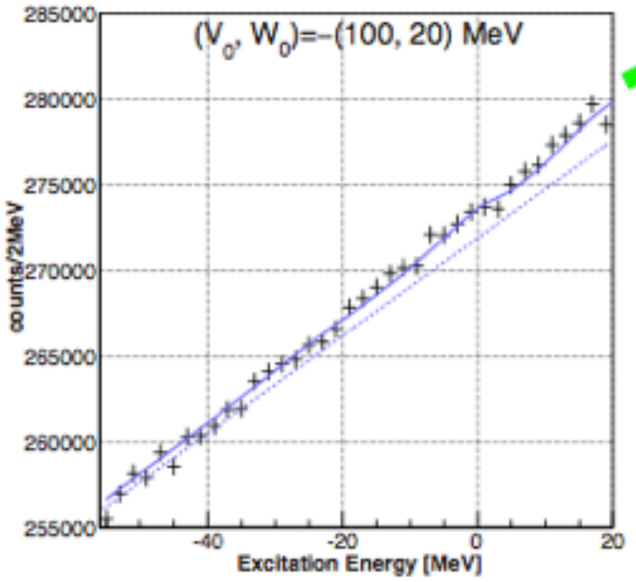
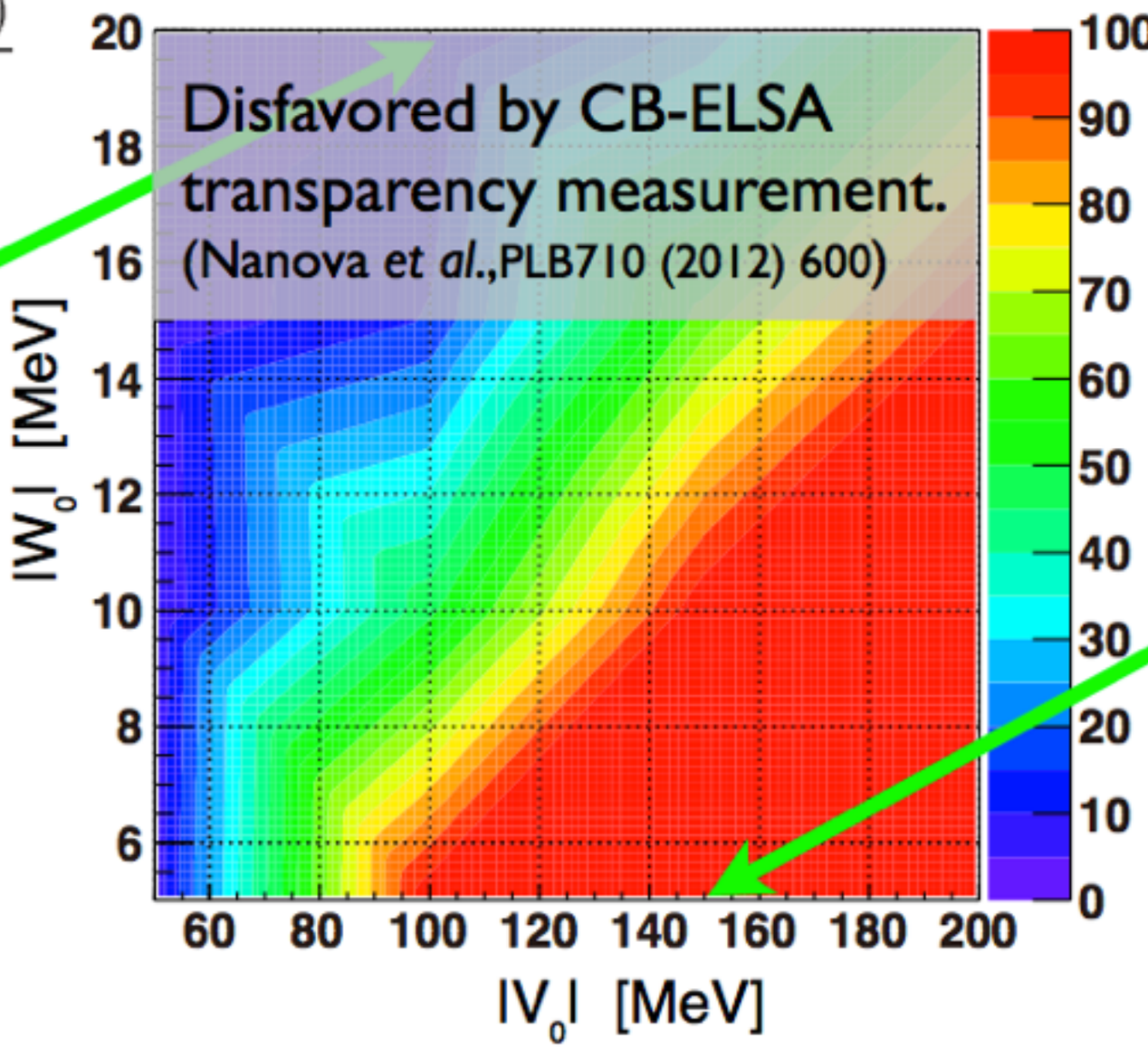
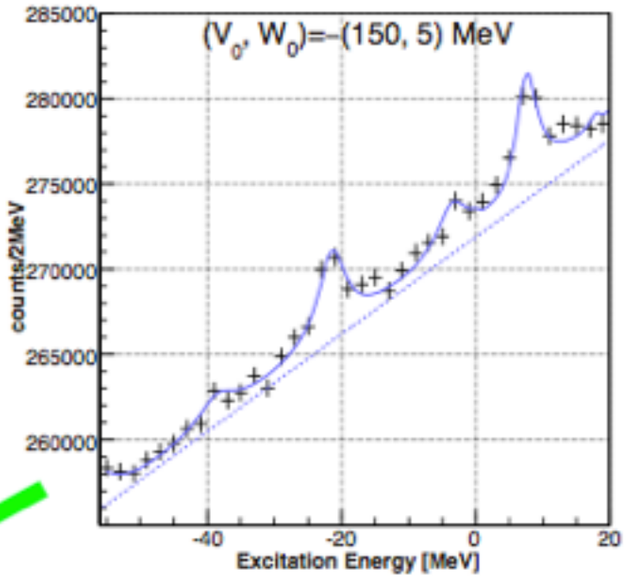


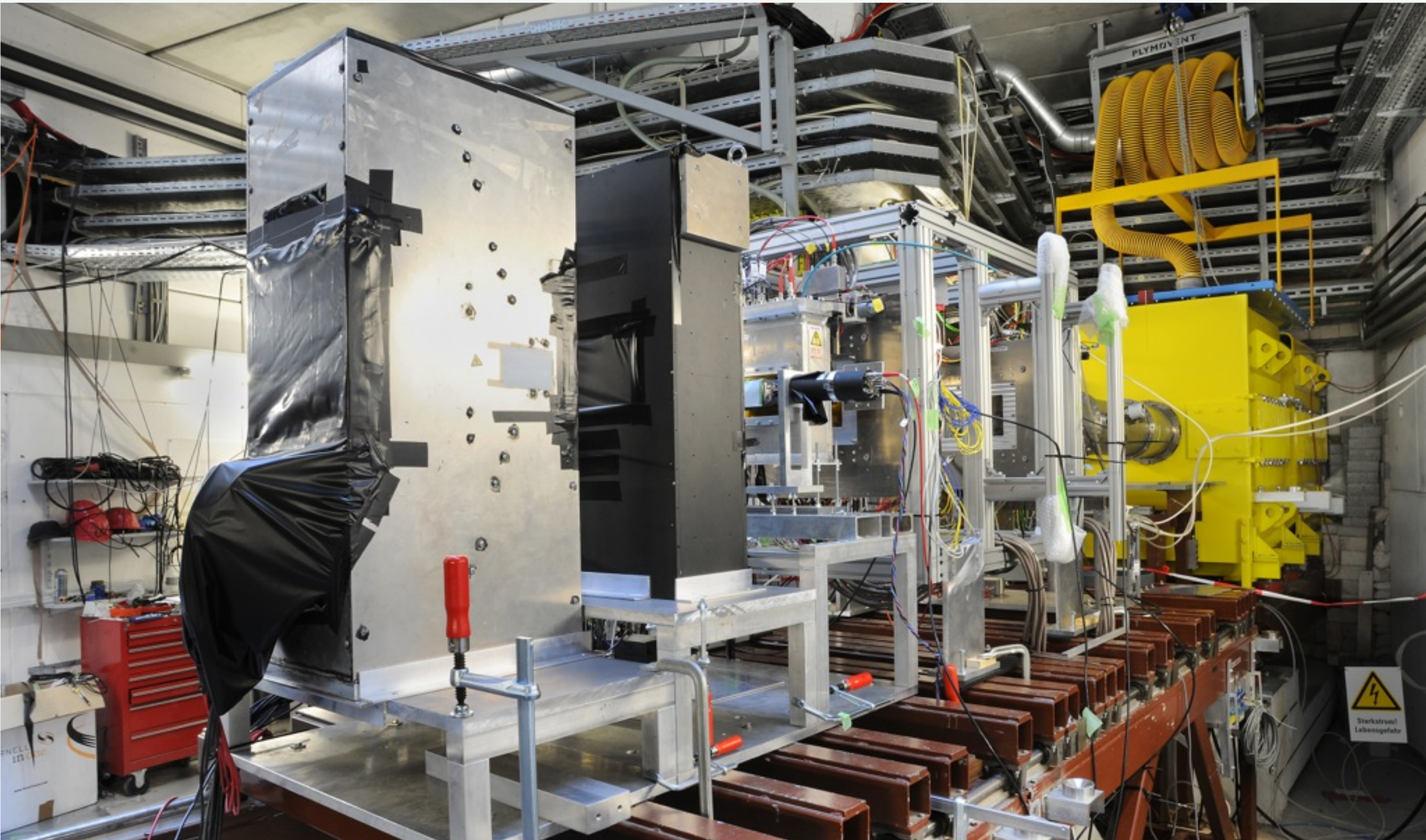




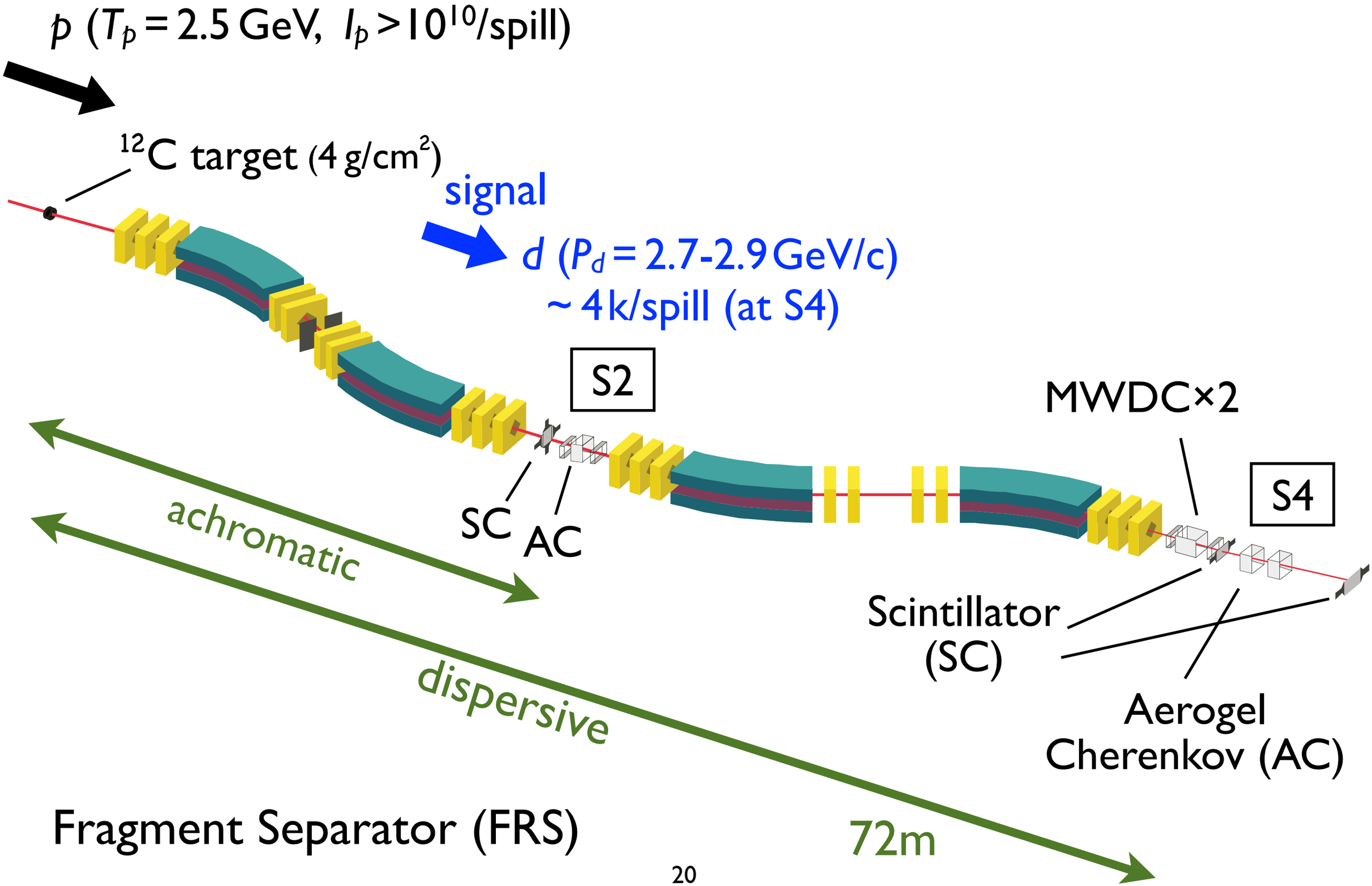
in 4.5 days DAQ

for 95 % C.L.

First Pilot Experiment at GSI
2014 Aug.1 - Aug.8



Experimental setup at FRS



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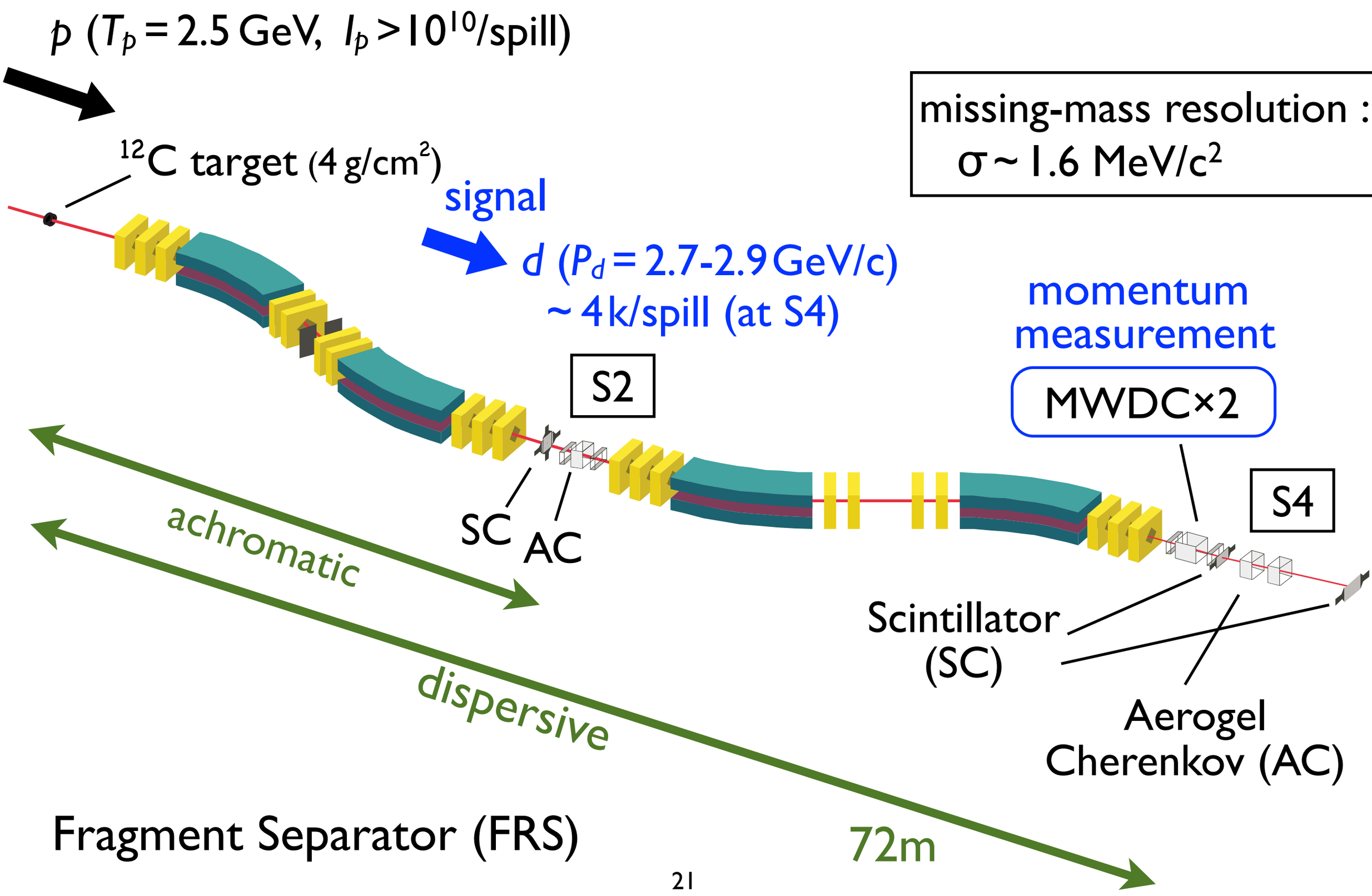


missing-mass resolution :
$\sigma \sim 1.6$ MeV/c^2

Experimental setup at FRS

p (T_p = 2.5 GeV, I_p > 10^{10}/spill)

background

p' ~ 800 k/spill

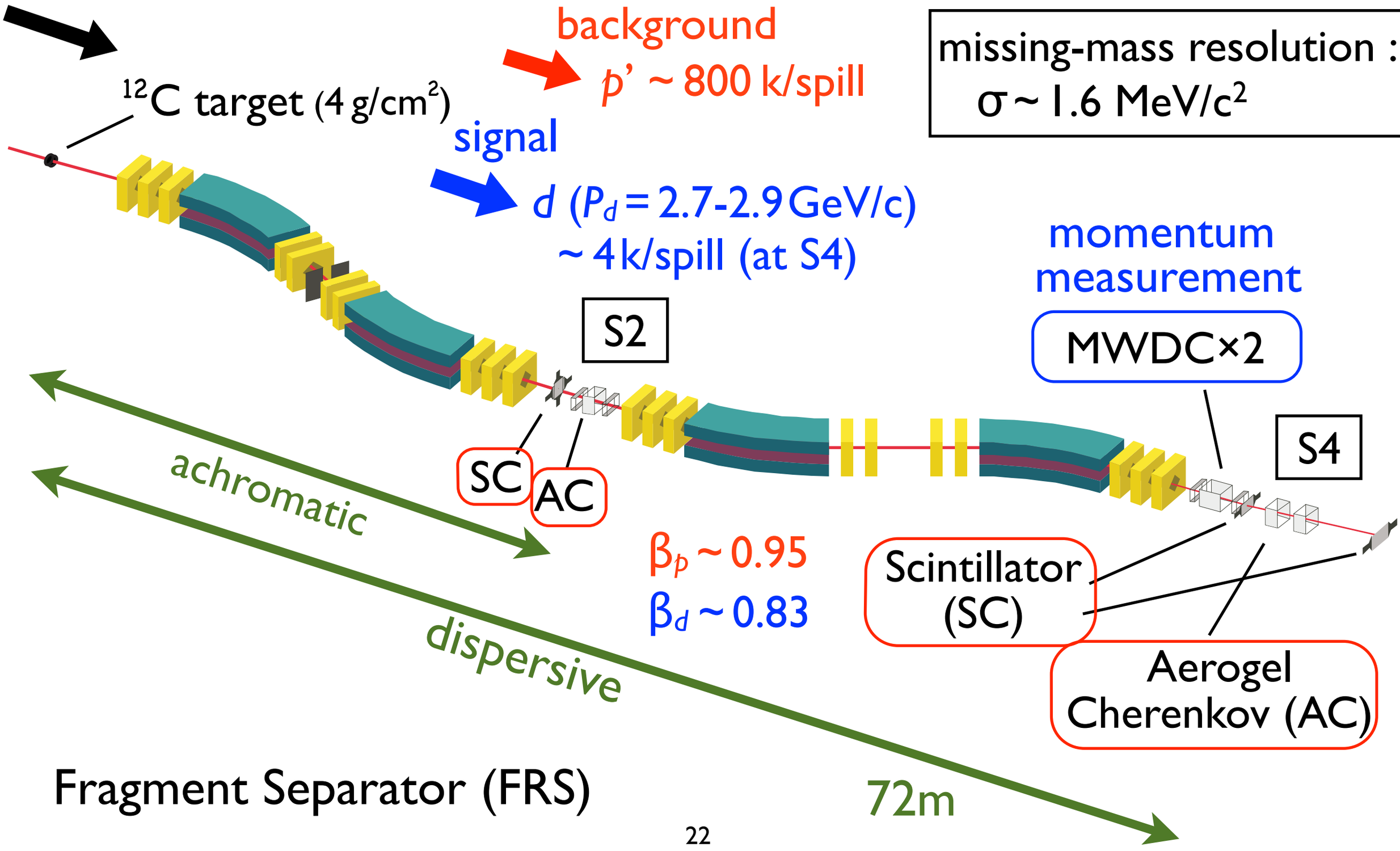
missing-mass resolution :
σ ~ 1.6 MeV/c^2

^{12}C target (4 g/cm^2)

signal

d (P_d = 2.7-2.9 GeV/c)
~ 4 k/spill (at S4)

momentum measurement



Particle Identification

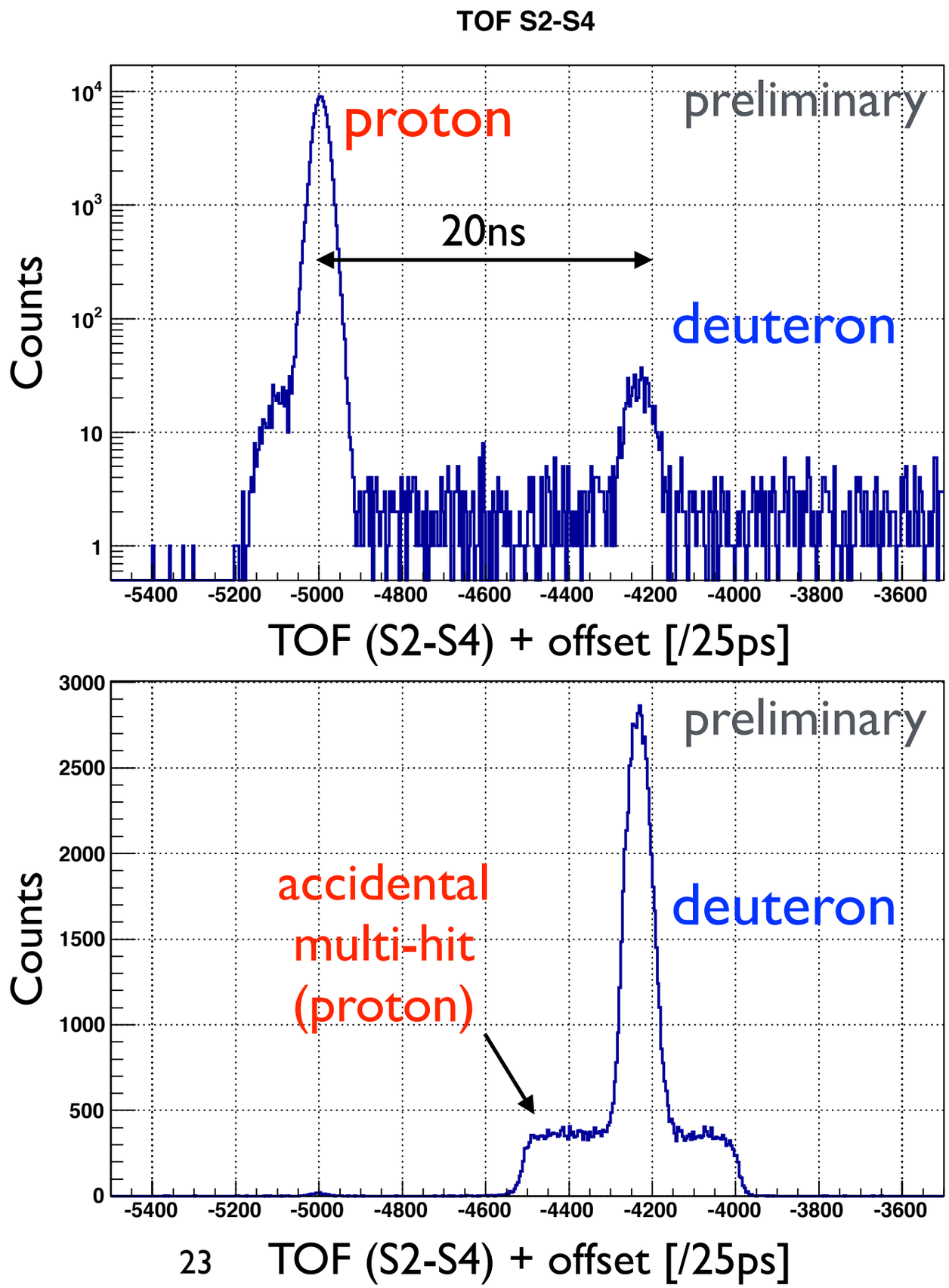
S2-S4 TOF (unbiased)

p/*d* ratio ~ 200 / 1

S2-S4 TOF with
hardware TOF trigger

p/*d* ratio ~ 1 / 1

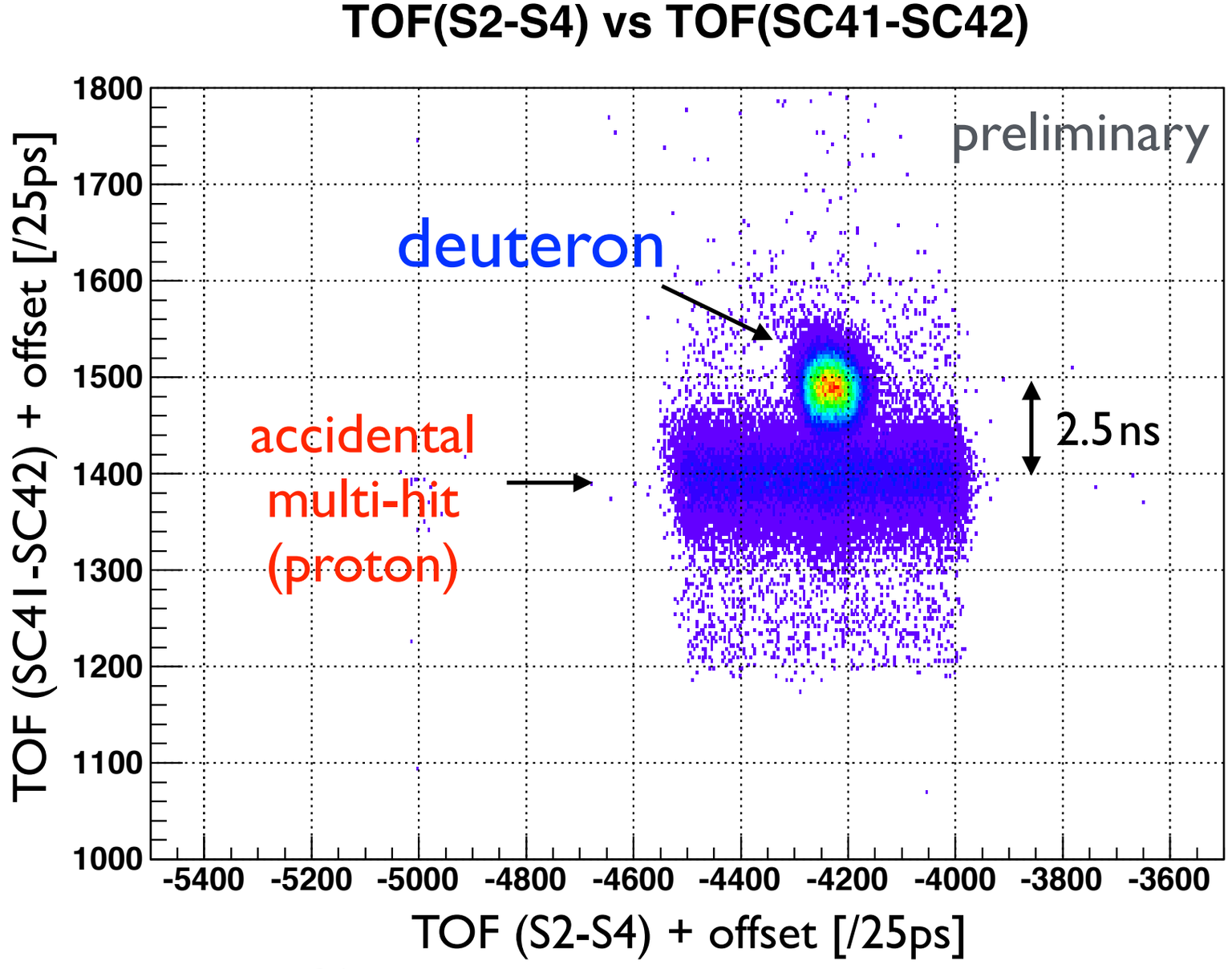
99.5 % of BG protons were rejected by TOF trigger without using Aerogel Cherenkov detector



Particle Identification

Further rejection of the accidental multi-proton in analysis :

- TOF in the last focal plane (SC41-SC42)
- Waveform analysis
- Aerogel Cherenkov detectors



Calibration Reaction

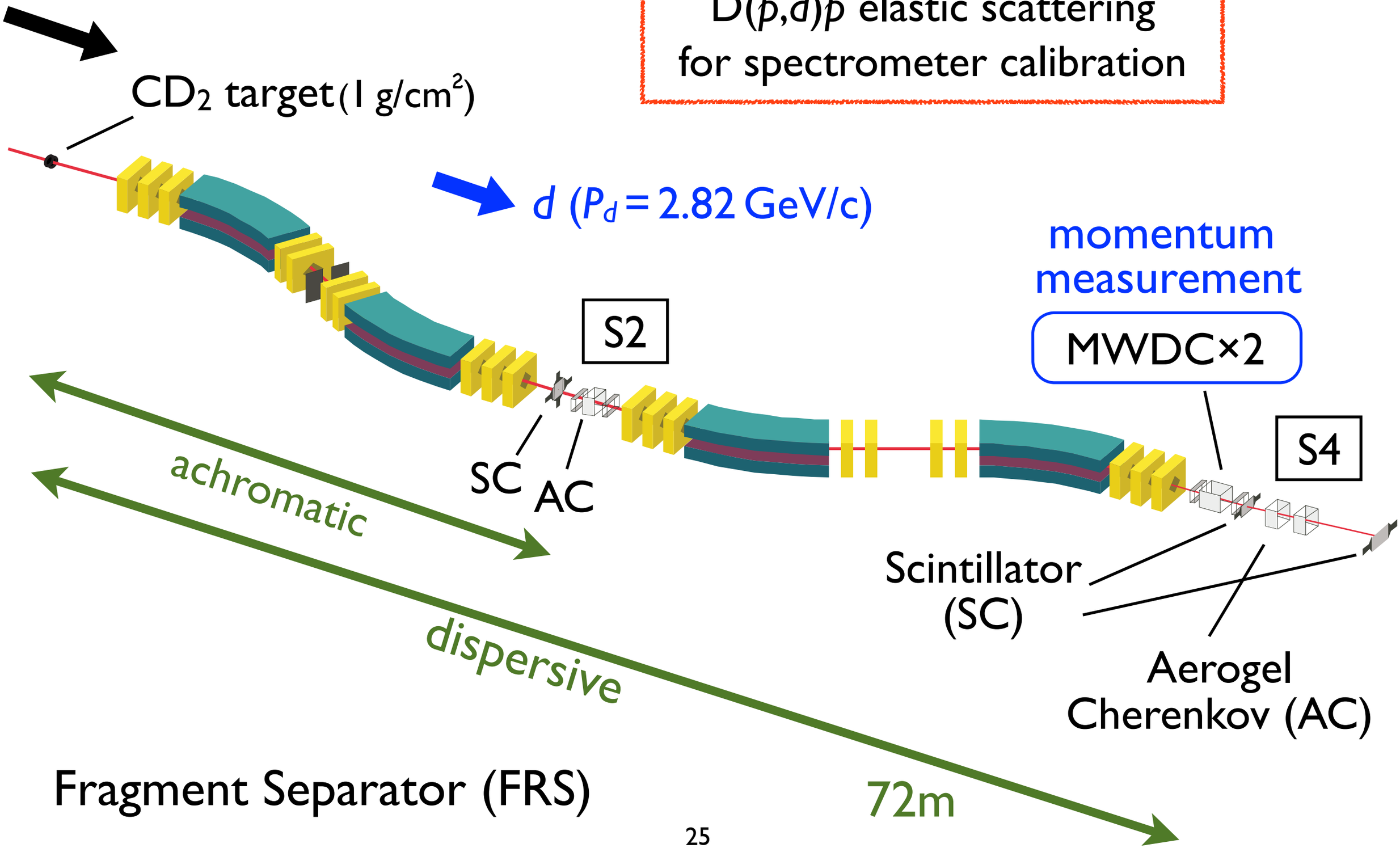
p (T_p = 1.6 GeV)

D(p,d)p elastic scattering
for spectrometer calibration

CD_2 target ($1\ g/cm^2$)

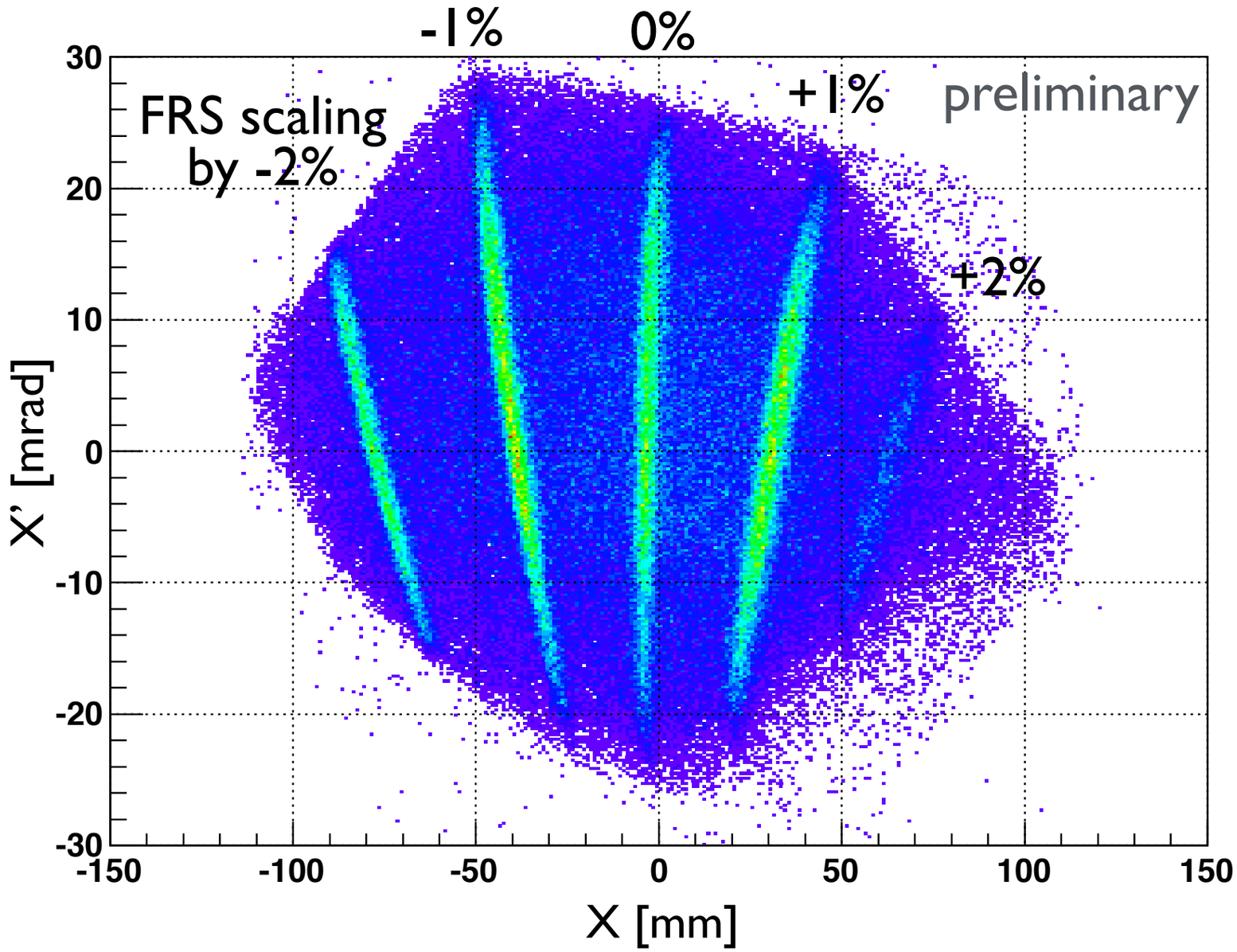
d (P_d = 2.82 GeV/c)

momentum measurement



Calibration Reaction

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



- Confirmation of the whole system
- Ion-optical information (focus, dispersion, higher-order aberration)
- Stability check

Run Summary

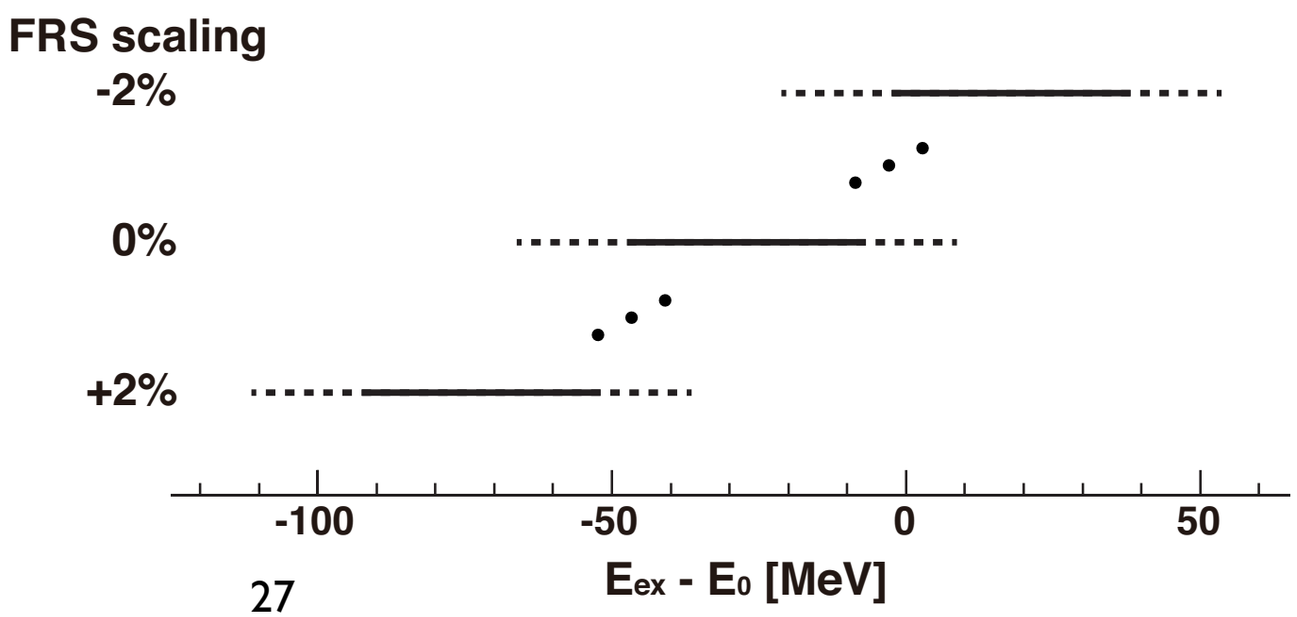
Production run (~ 5 days)

- C(*p*,*d*) reaction at T_p=2.5 GeV
  using $10^{10\text{-}11}$/spill proton beam and 4 g/cm^2 C target
- scaling of FRS Bρ from -2% to 2%
- for each setting, 5−10×10^6 deuterons were accumulated.
- calibration run 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 of FRS Bρ from -2% to 2%

Region in excitation energy

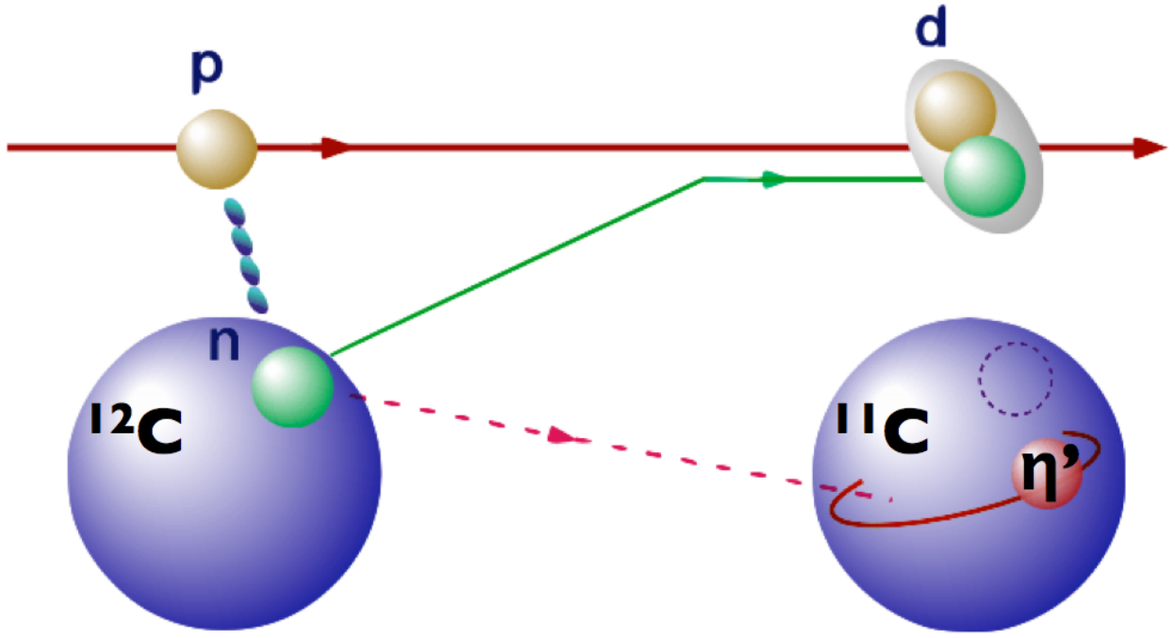


Future Plan at FAIR

Future plan at FAIR

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

2nd Step : 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

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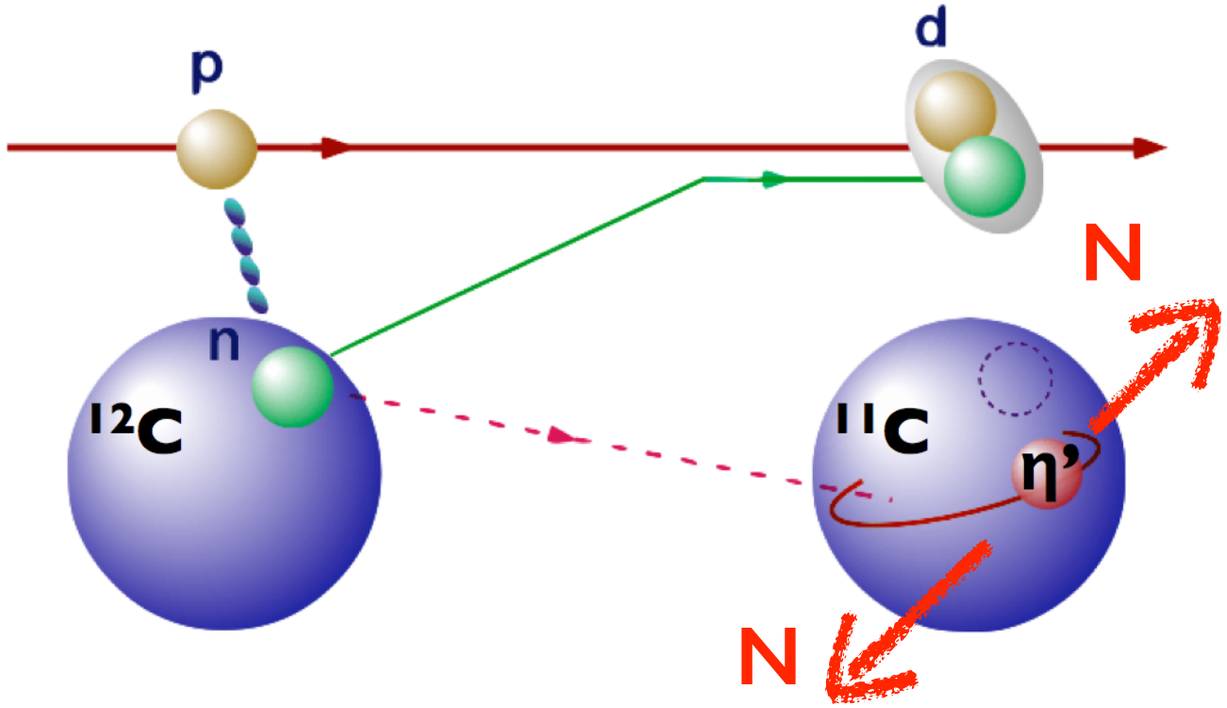
2nd Step : Semi-exclusive measurement of (*p*,*dp*) with Super-FRS at FAIR



Target

η′ mesic nuclei

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**

Summary

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

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

- The first inclusive measurement using FRS at GSI has been performed in this August. Analysis of spectra is currently underway.

- At FAIR, we plan a semi-exclusive measurement of (*p*,*dp*) reaction with decay proton counter and Super-FRS. Tagging decay protons could improve S/N ratio. R&D is presently on-going.