Meson bound states spectroscopy in nuclei

Pionic atoms at RIBF and Eta-prime mesic nuclei at GSI/FAIR

Kenta Itahashi

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- General introduction
- Precision spectroscopy of pionic atoms
- Pionic atoms with unstable nuclei
- Spectroscopy of eta-prime mesic nuclei

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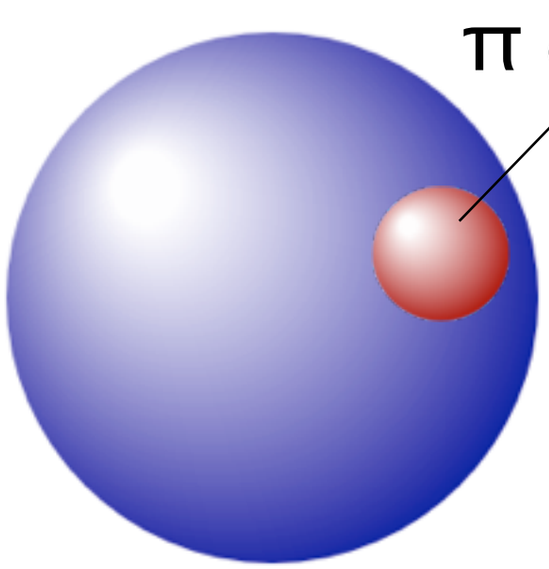
Motivations



High precision bound meson spectroscopy to determine (B,Γ)

Understanding low energy region of QCD

1. Chiral symmetry
   ← Isovector scattering length between π and nuclei

2. Origin of η' mass
   ← $U_A(1)$ anomaly + <qbar q>

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Two experiments: π^- atoms & η' mesic nuclei

	π^-	η'
Bound by	EM	Strong
~B,Γ [MeV]	4, 0.4	80-150, <13-20
Reaction	(d,^{3}He) at q~0	(p,d) at q≠0
Facility	(GSI→)RIBF	GSI→FAIR
Research Stage	Precision systematic → more exotic	Discovery

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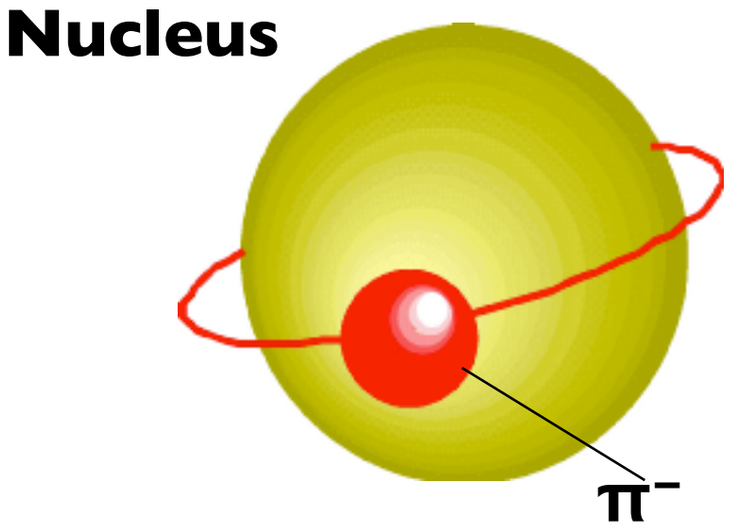
Precision Spectroscopy of Pionic Atoms

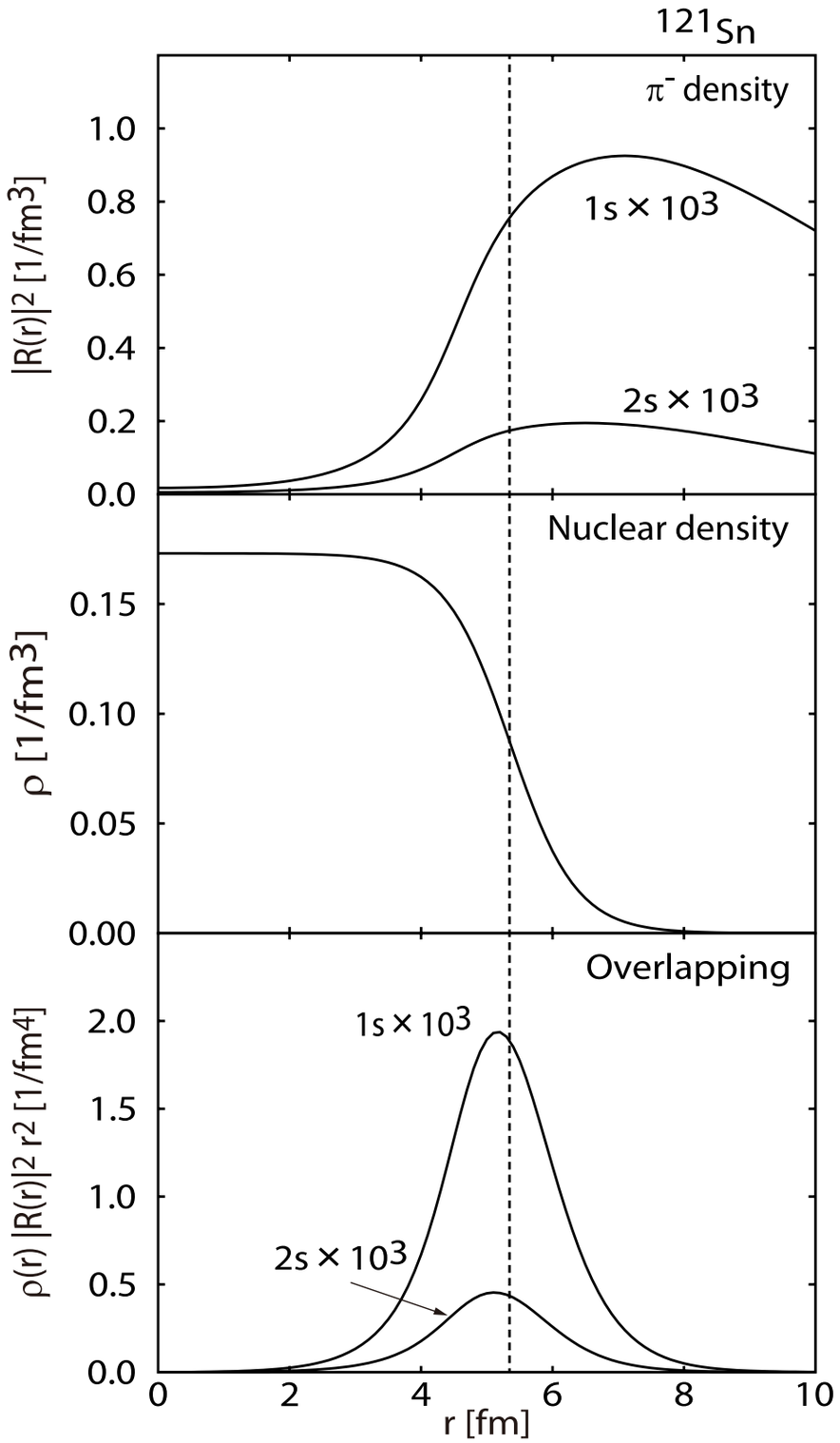
G.P.A. Berg, M. Dozono, H. Fujioka, N. Fukuda, T. Furuno, H. Geissel, R.S. Hayano, N. Inabe, K. Itahashi, S. Itoh, D. Kameda, T. Kubo, H. Matsubara, S. Michimasa, K. Miki, G. Mishima, H. Miya, Y. Murakami, M. Nakamura, N. Nakatsuka, M. Niikura, T. Nishi, S. Noji, S. Ogawa, K. Okochi, S. Ota, H. Suzuki, K. Suzuki, M. Takagi, H. Takeda, Y. K. Tanaka, K. Todoroki, K. Tsukada, T. Uesaka, Y.N. Watanabe, H. Weick, H. Yamada, H. Yamakami and K. Yoshida

JINA and Department of Physics, University of Notre Dame
RIKEN Nishina Center, RIKEN
Department of Physics, Kyoto University
Department of Physics, The University of Tokyo
GSI Helmholtzzentrum für Schwerionenforschung GmbH
Department of Physics, Osaka University
Department of Physics, Michigan State University
Stefan Meyer Institut für subatomare Physik
Department of Physics, Tohoku University

Strong Interaction between pi and A



Large overlap between pion and nucleus



N. Ikeno *et al.*, PTP126(2011)483.

sensitivity to
π-nucleus strong interaction potential

$$V_{s\text{-wave}} = b_0\,\rho + \mathbf{b_1}\,(\rho_n - \rho_p) + B_0\,\rho^2$$

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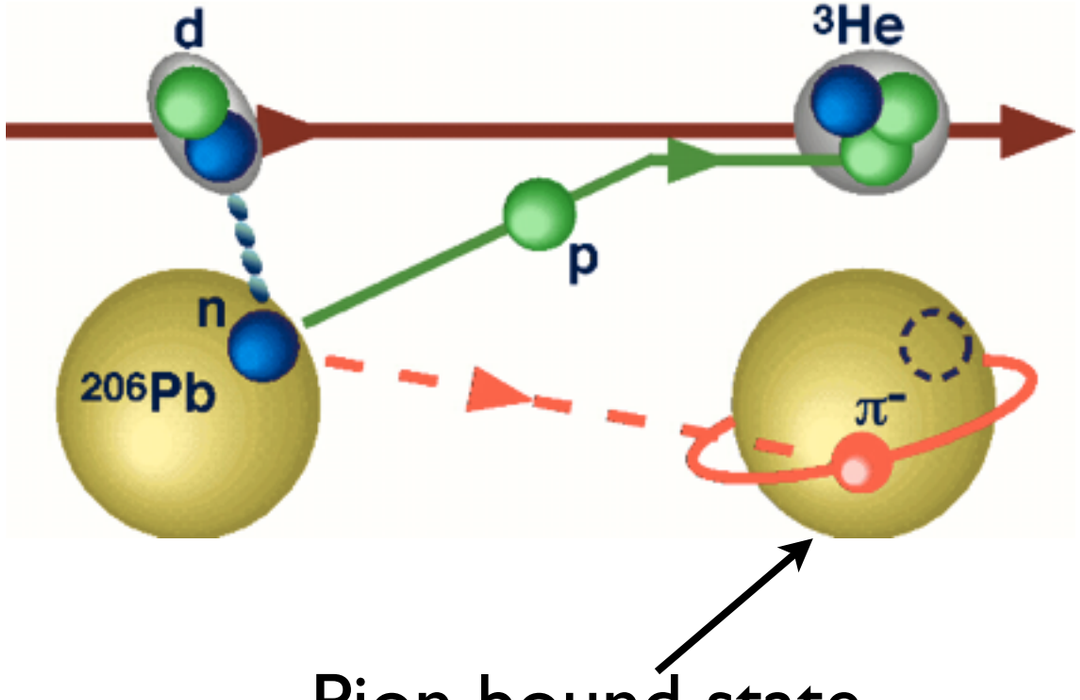
Experimental Method

(d,^{3}He) nuclear reaction
to directly produce pionic atom

Missing mass spectroscopy
to measure excitation spectrum
by Q-value measurement

We are aiming at
< 400 keV (FWHM) resolution
at ~140 MeV excitation energy.



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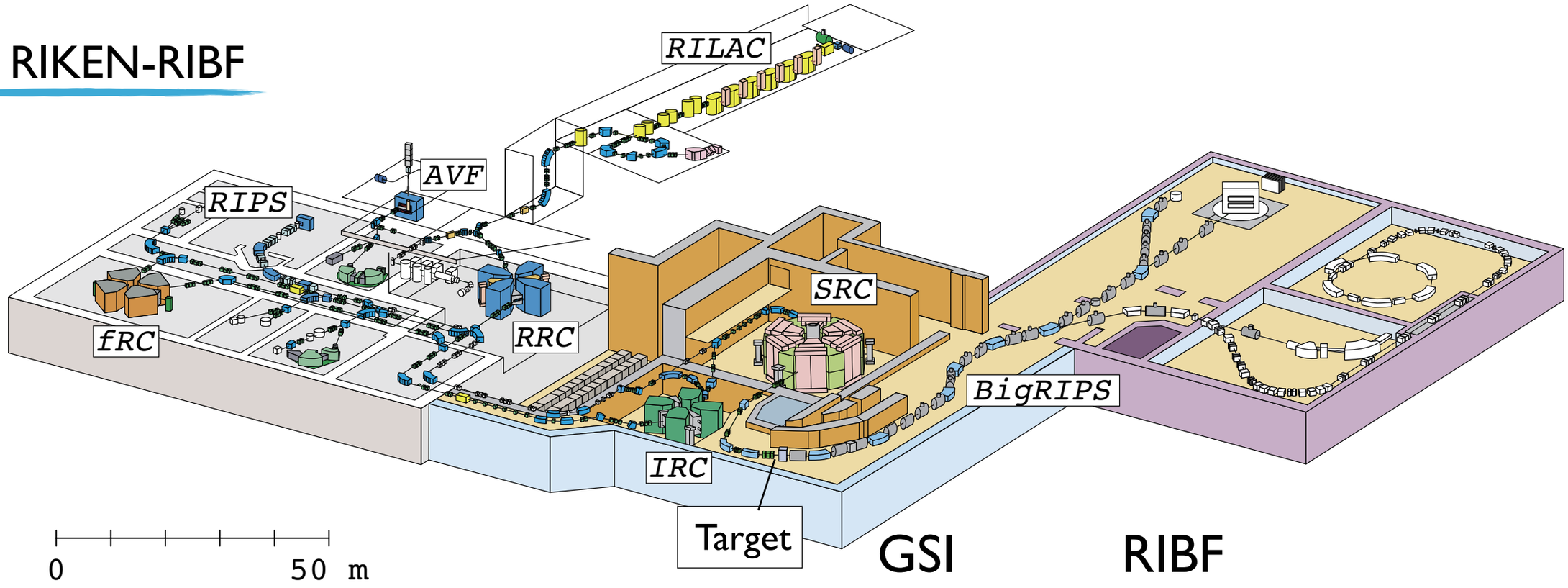
Precision spectroscopy at RI Beam Factory

RIKEN-RIBF



	GSI	RIBF
d beam Intensity	10^{11}/spill	10^{12}/s
Target	20 mg/cm^2	10 mg/cm^2
$\Delta p_d/p_d$ (FWHM)	0.03%	0.1%
Resolution (FWHM)	400 keV	< 400 keV

by using the dispersion matching

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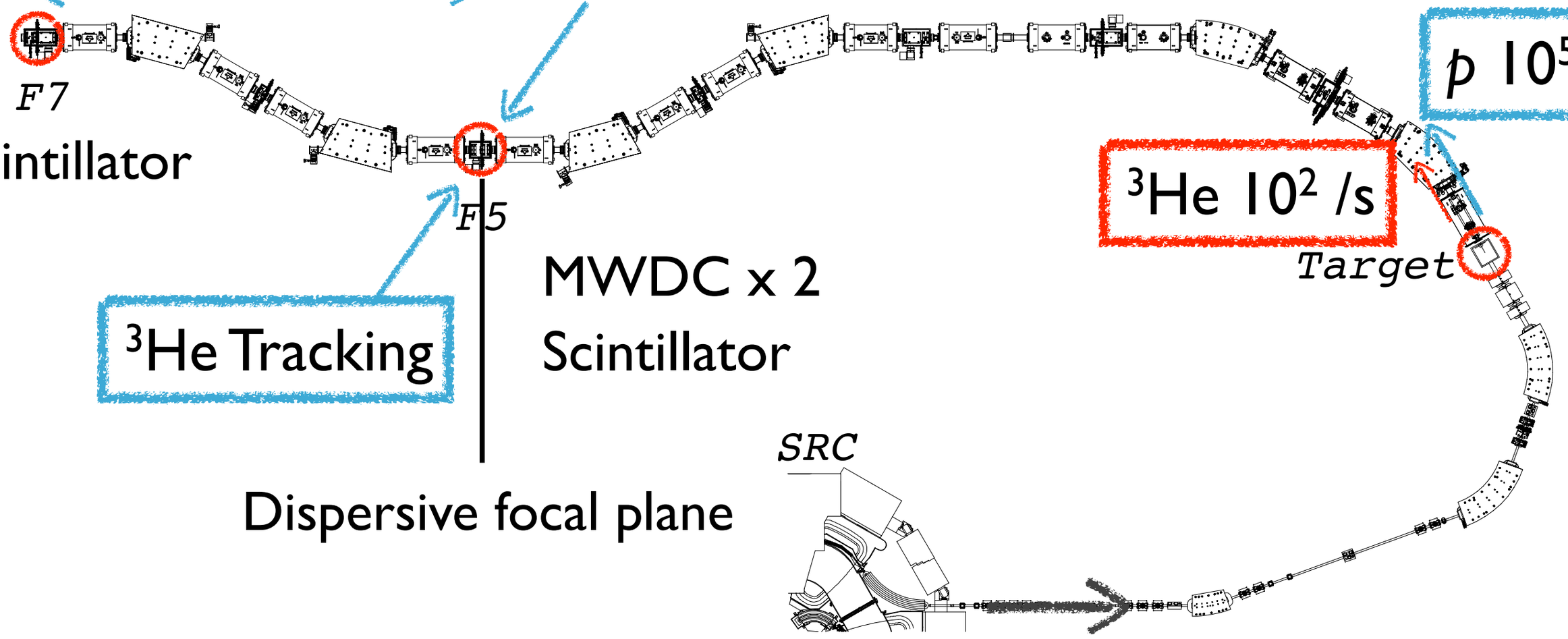
Experimental setup

BigRIPS

TOF measurement

ΔE measurement



p 10^5 /s

^{3}He 10^2 /s

^{3}He Tracking

Dispersive focal plane

d beam 10^{12} /s, 250 MeV/u

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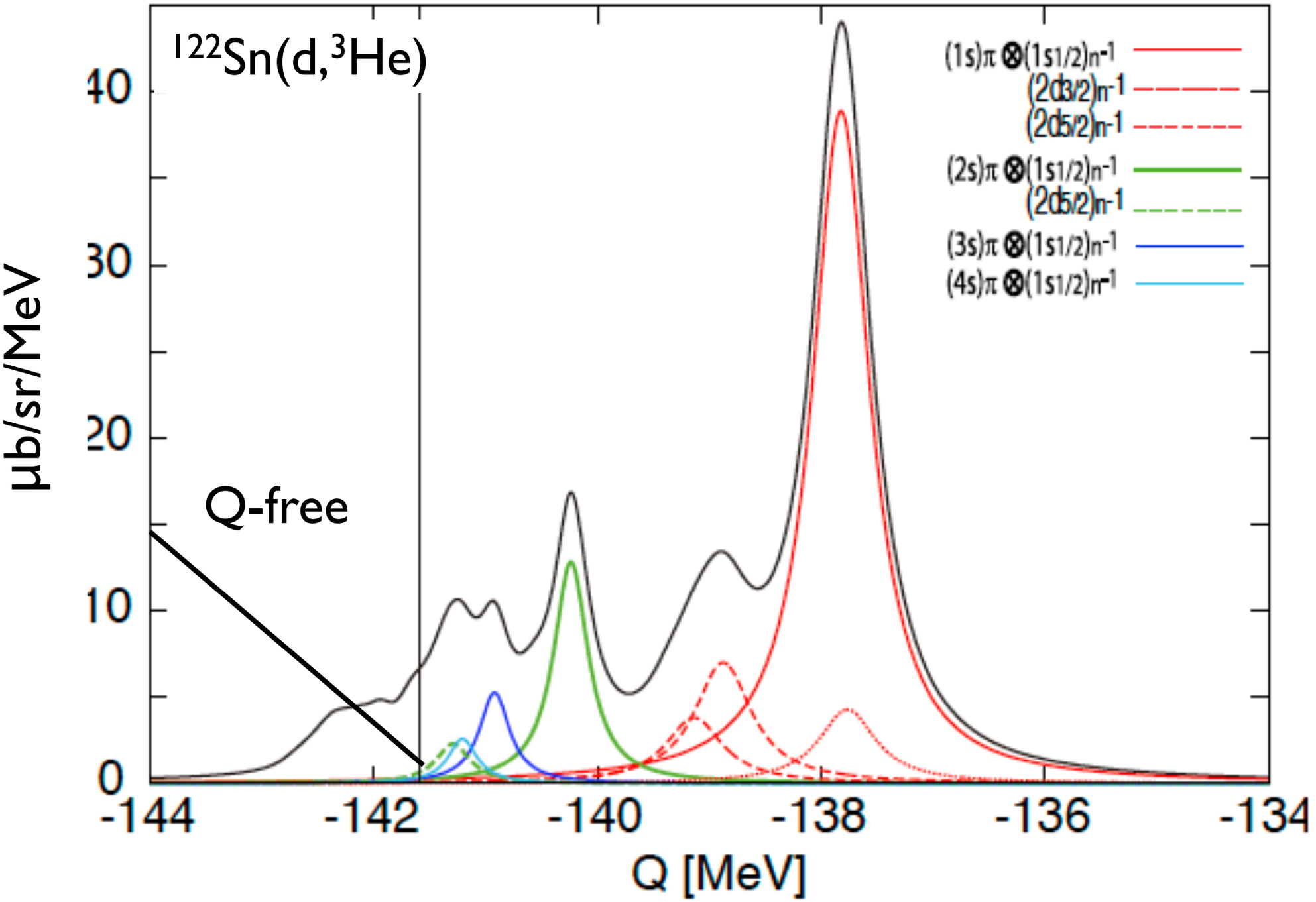
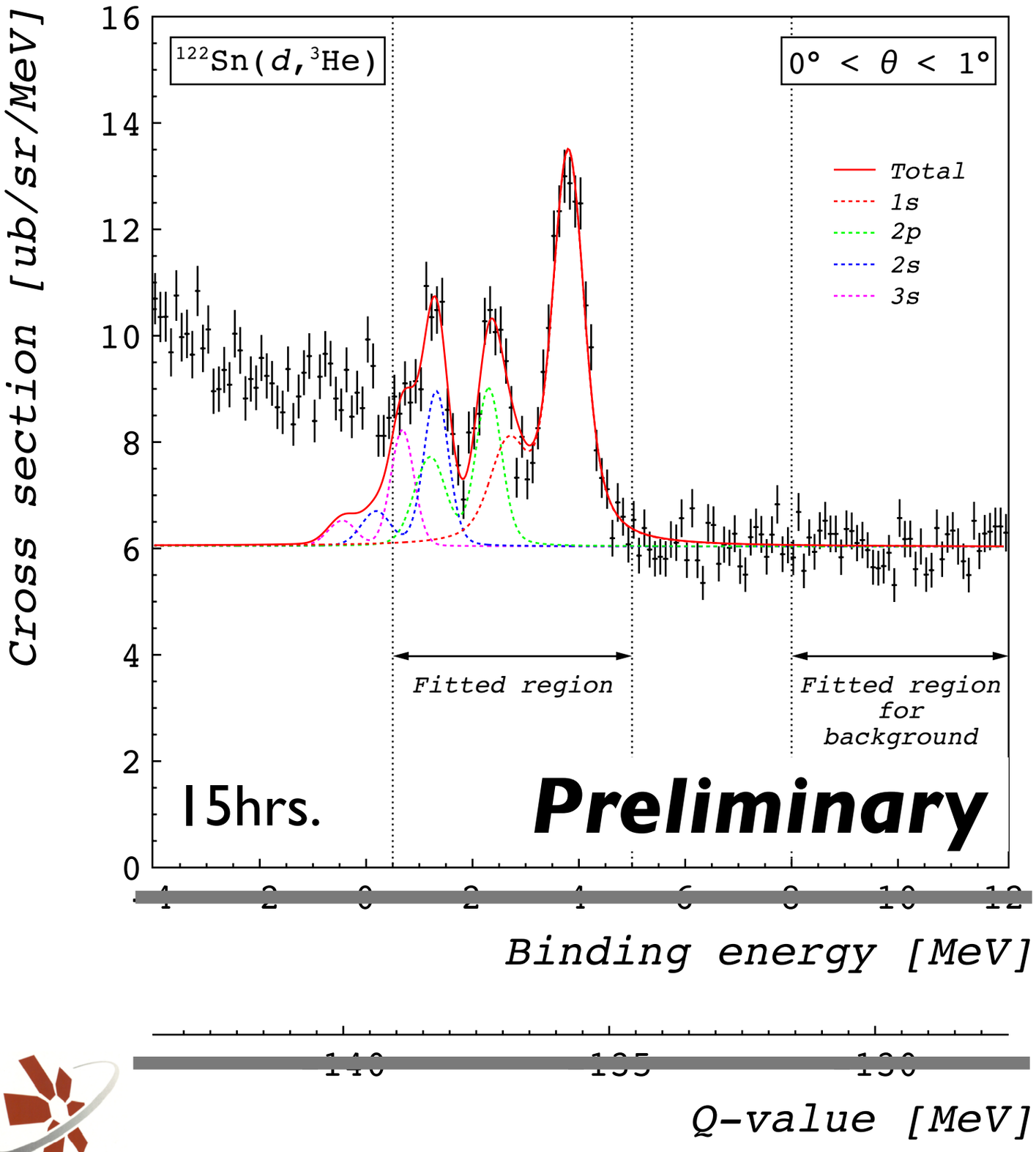
Theoretical Spectrum for ^{122}Sn(d,^{3}He)



N. Ikeno, Eur.Phys.J.A47 (2011) 161

K. Itahashi, Advanced Meson Science Laboratory, RIKEN Nishina Center

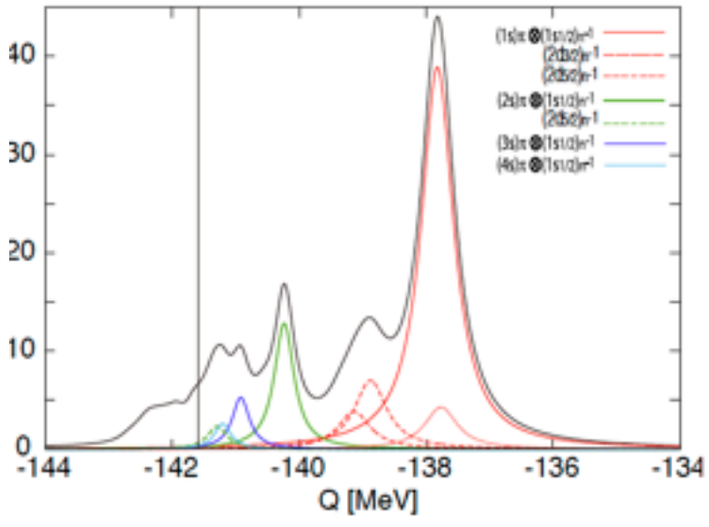
Spectrum decomposition



Fit parameters

	No.	Name	Description	State
Background	1	c_0	constant	free
	2	c_1	slope	free
$1s$	3	S_{1s}	scaling factor	free
	4	B_{1s}	binding energy	free
	5	Γ_{1s}	width	free
$2p$	6	S_{2p}	scaling factor	free
	7	B_{2p}	binding energy	free
	8	Γ_{2p}	width	fixed
$2s$	9	S_{2s}	scaling factor	free
	10	B_{2s}	binding energy	free
	11	Γ_{2s}	width	fixed
$3s$	12	S_{3s}	scaling factor	free
	13	B_{3s}	binding energy	fixed
	14	Γ_{3s}	width	fixed

Theoretical Spectrum for ^{122}Sn(d,^{3}He)



N. Ikeno, Eur.Phys.J.A47 (2011) 161

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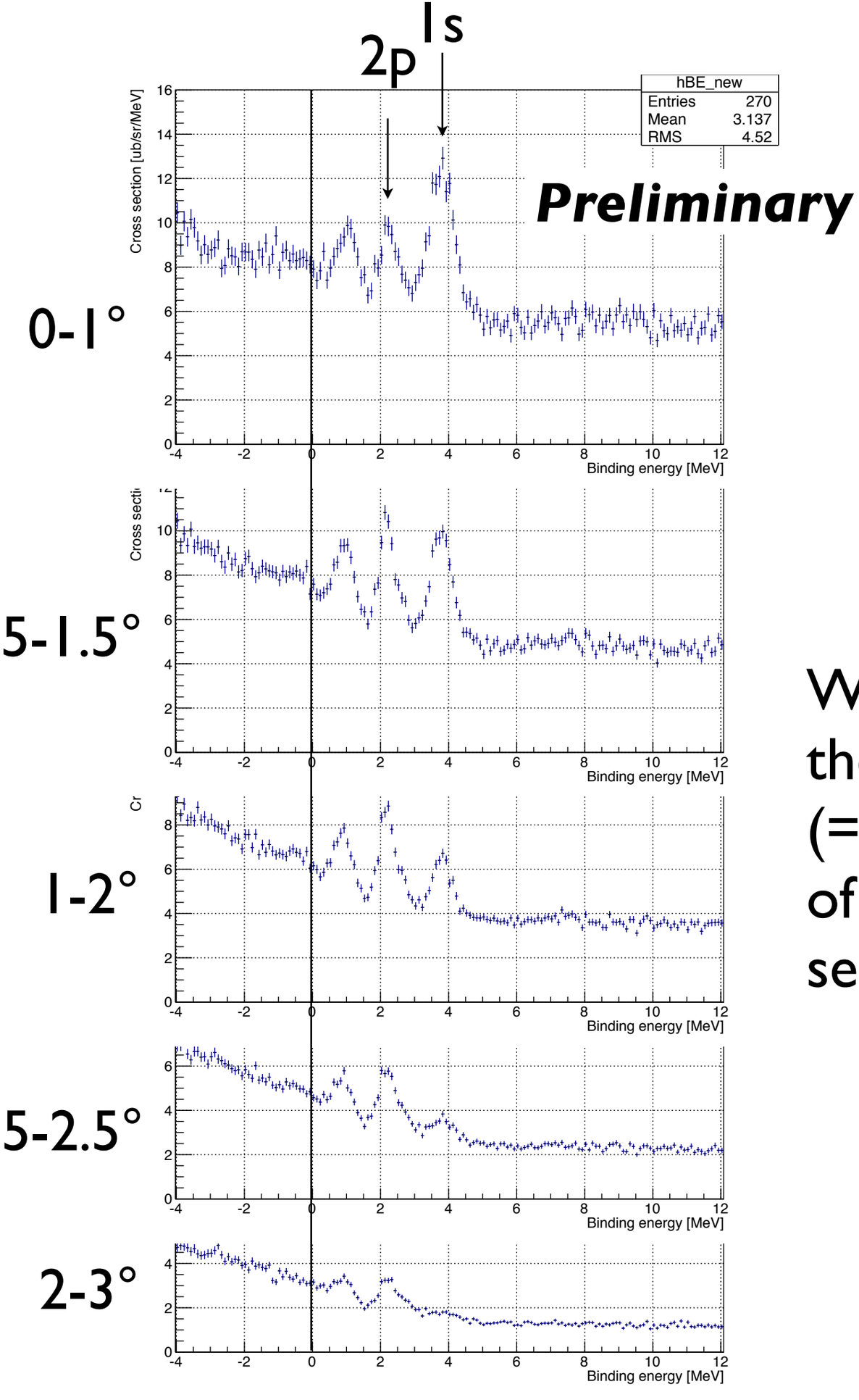
Measured Spectra for different angles

^{122}Sn(d,^{3}He) at T_d=250 MeV/u



We are observing for the first time the angular dependence (= momentum transfer dependence) of pionic atom production cross section in (d,^{3}He) reaction

before going to “ongoing project”...

Summary for piAF

Achievements

✓ We have successfully measured ^{121}Sn x pi for the first time with surprisingly rapid accumulation of statistics.

✓ Angular dependence of the production cross section is measured for the first time.

Perspectives

- We’re analyzing energy spectra to extract binding energies and widths by finalizing acceptance and aberration correction.
- We’re trying for further resolution improvements.
- We are waiting for allocation of our main experiment leading to systematic precision spectroscopy.

K. Itahashi, Advanced Meson Science Laboratory, RIKEN Nishina Center

An ongoing project

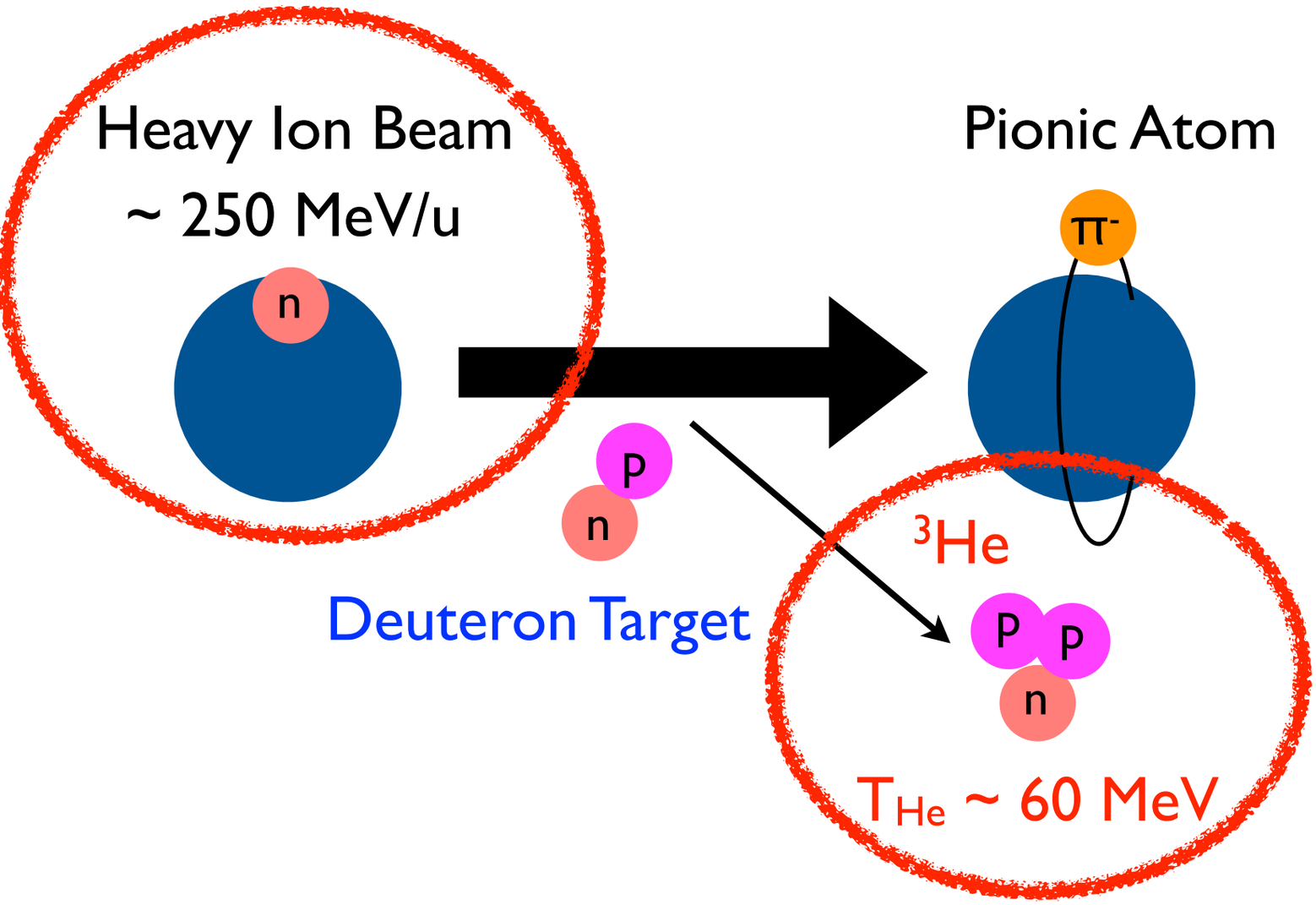
Deeply-Bound Pionic Atom with Unstable Nuclei

K. Okochi & Y.N. Watanabe

K. Itahashi, Advanced Meson Science Laboratory, RIKEN Nishina Center

Missing mass spectroscopy in d(HI, ^{3}He) reaction

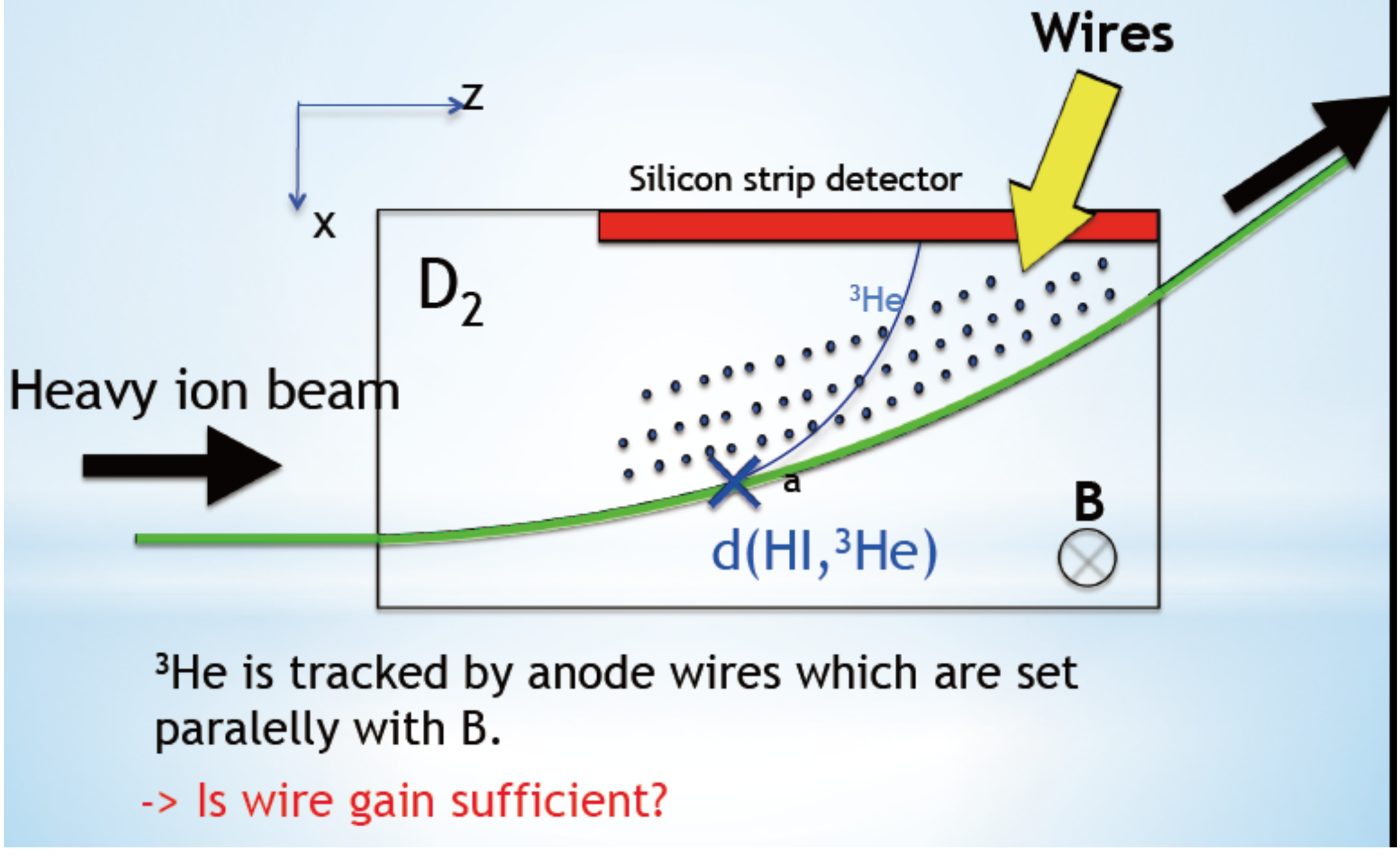
Keeping the same kinematical condition as normal kinematics !!



- ^{3}He recoil angle
- ^{3}He kinetic energy

Q value

Inverse kinematics with simple setup



^{3}He is tracked by anode wires which are set paralelly with B.

-> Is wire gain sufficient?

by courtesy of Y.N. Watanabe

Yield Estimation

Target	D_2 gas (1 atm, 293.15 K) 100 cm
Beam Intensity [/s]	1×10^{6}
Cross Section [μb]	2.54×10^{-1}
Is Yield [/day]	**1.1×10^{2}**

Sufficient.

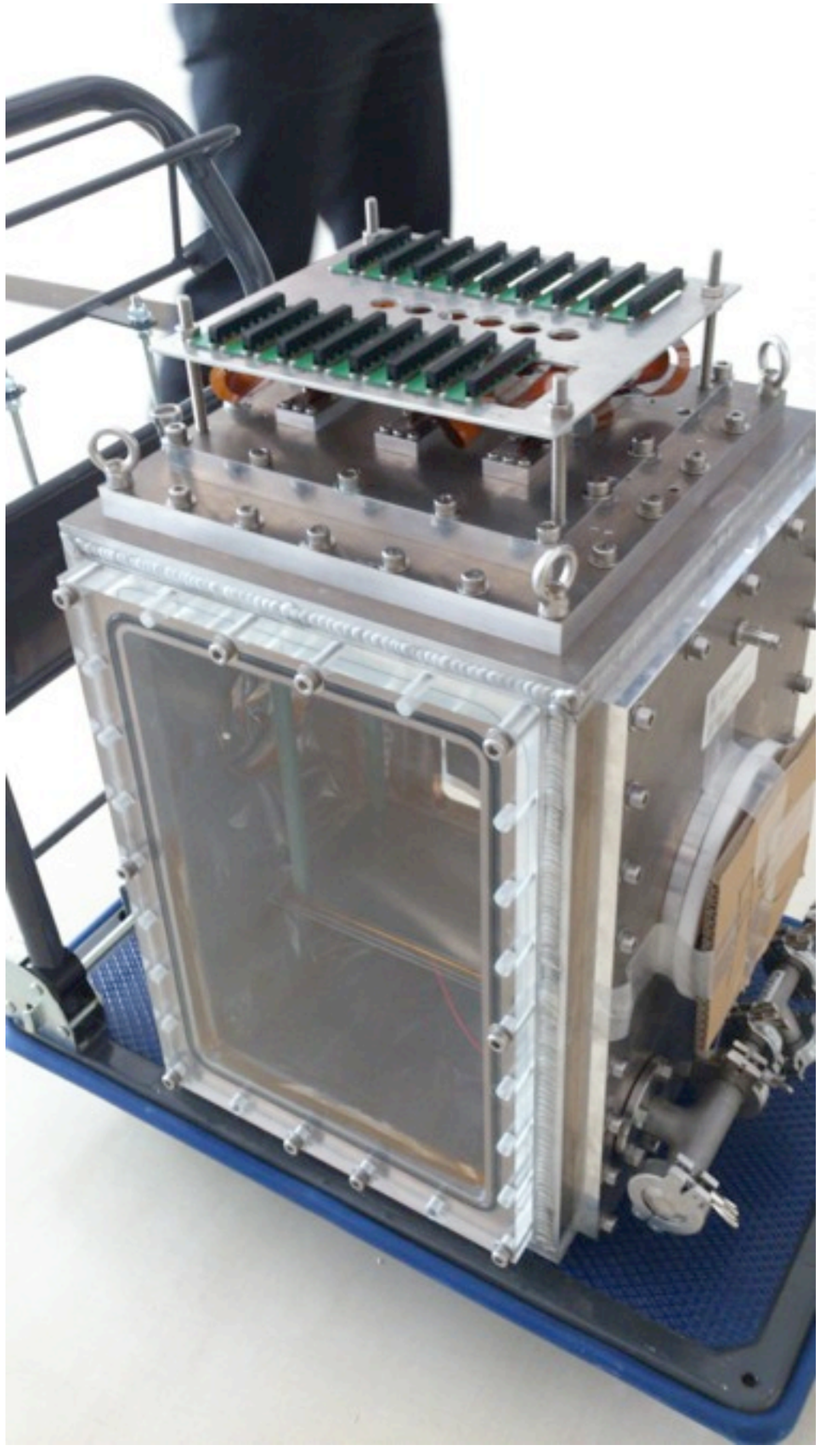
2×10^{3} for normal kinematics

Q Value Resolution

Cause	ΔQ (FWHM) [keV]
Energy Resolution of Si at T_{He} ~ 60 MeV σ_{Si} = 0.1 %	~ 350
Energy Straggling of ^{3}He in TPC	~ 350
Vertex Reconstruction With Incident Beam σ_{TPC} = 500 μm	~ 130
Total	**~ 500**

cf. 400 keV for normal kinematics

Silicon in deuterium test
+ pure deuterium GEM-TPC
(w. CNS) development.



Y.N. Watanabe and S. Ogawa

Inverse Kinematics Summary

- Spectroscopy of pionic atoms with unstable nuclei will open a possibility to approach density dependence of the chiral condensate.
- Simulation with realistic experimental setup shows reasonable yield + resolution.
- We are presently working on development of fundamental detector technologies.

Search for η′ Bound States

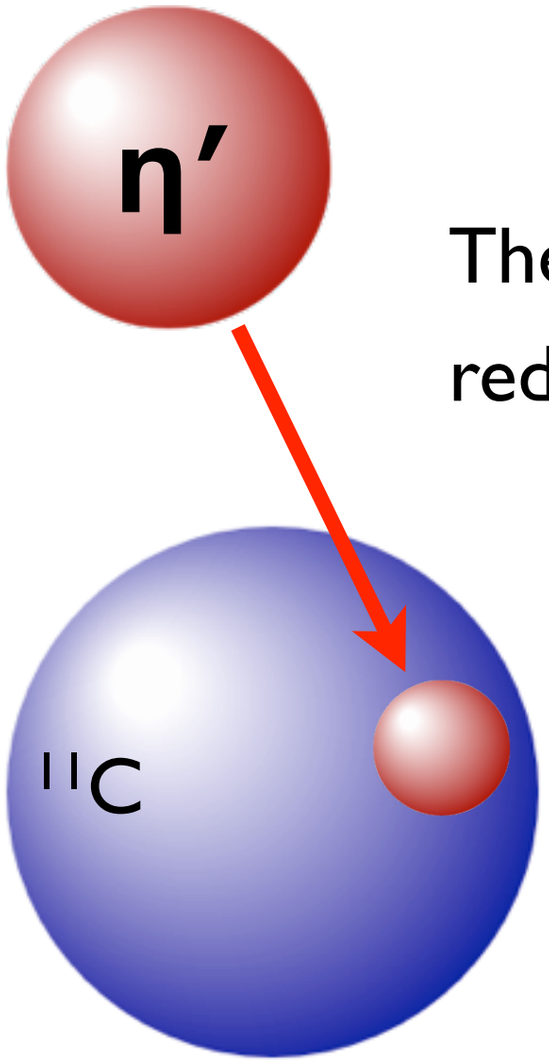
K. Brinkmann, S. Friedrich, H. Fujioka, H. Geissel, R.S. Hayano,
Y. Higashi, S. Hirenzaki, K. Itahashi, S. Itoh, M. Iwasaki, D. Jido,
V. Metag, T. Nagae, H. Nagahiro, M. Nanova, T. Nishi, K. Okochi,
H. Outa, K. Suzuki, T. Suzuki, Y.K. Tanaka, Y.N. Watanabe, H. Weick,
E. Widmann, and H. Yamakami

II. Physikalisches Institut, Universiät Gießen
Department of Physics, Kyoto University
GSI Helmholtzzentrum für Schwerionenforschung GmbH
Department of Physics, The University of Tokyo
Department of Physics, Nara Women's University
RIKEN Nishina Center, RIKEN
Department of Physics, Tokyo Metropolitan University
Stefan Meyer Institut für subatomare Physik

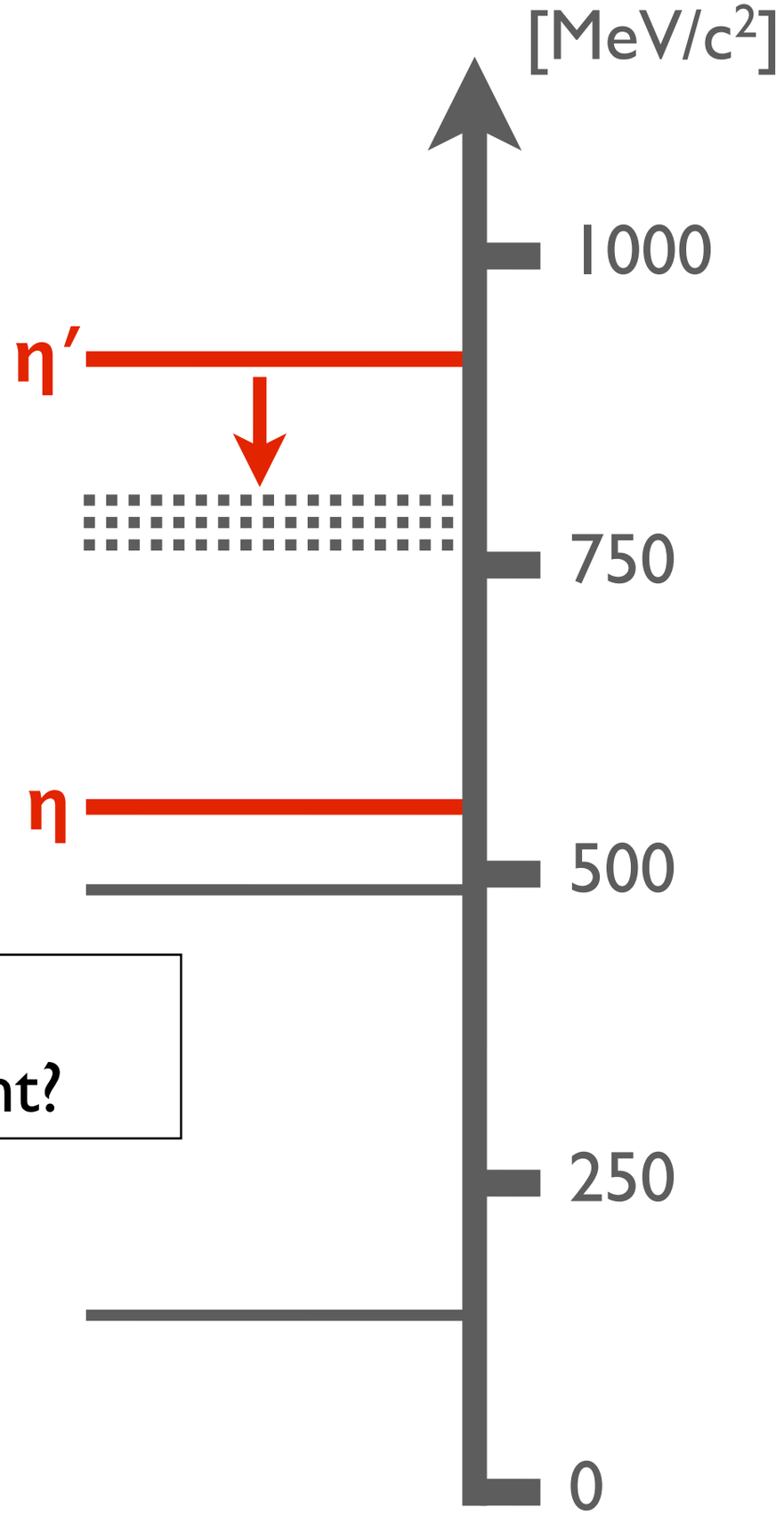
KI, Fujioka *et al.*, PTP 128 (2012) 601

Nagahiro *et al.*, PRC87(2013)045201

η′ in-medium



Theories show
reduction of $|m_{\eta'} - m_{\eta}|$

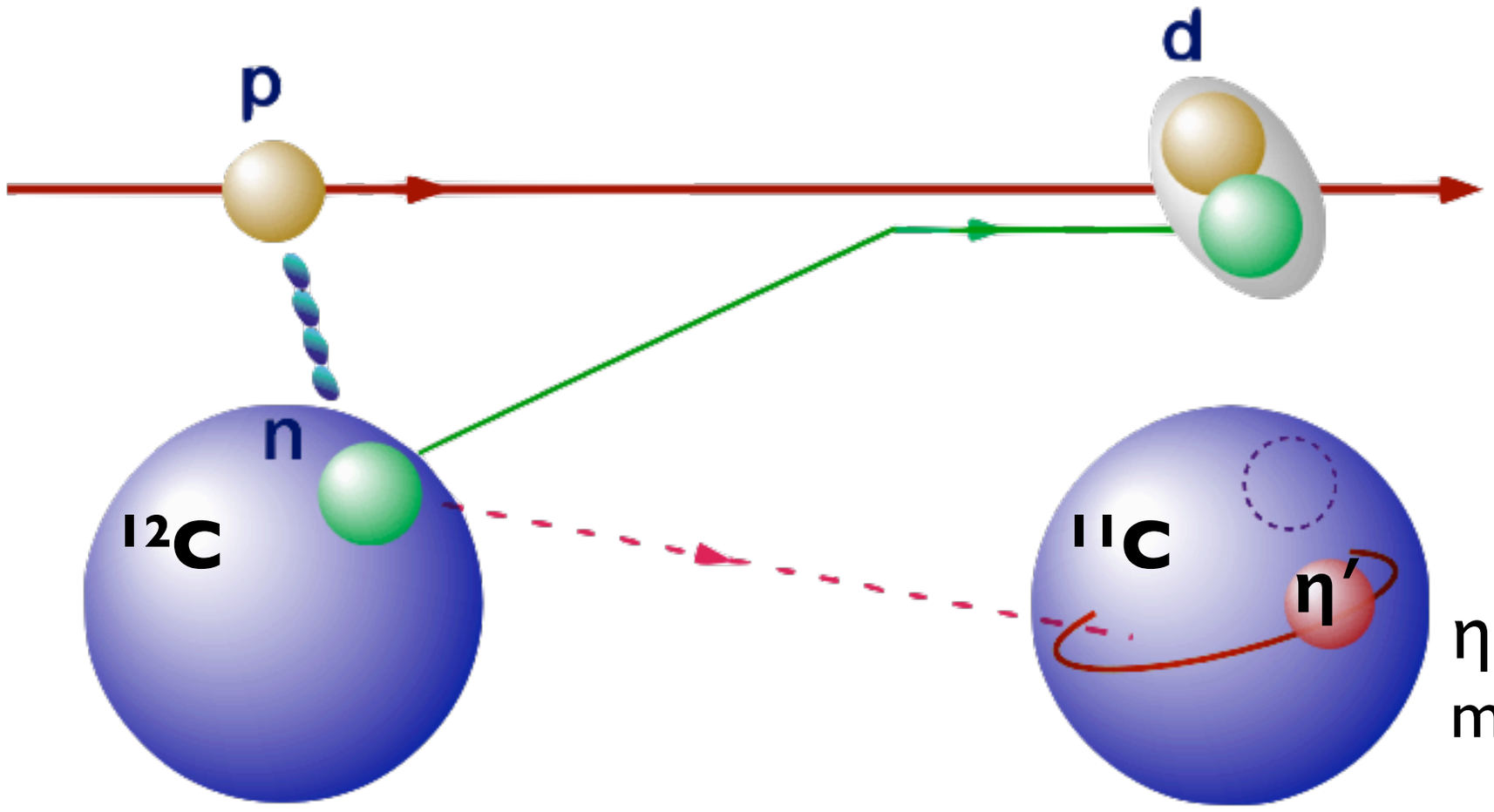


Q. Mass shift can be
observed in experiment?

for example
Jido et al., Phys.Rev. C85 (2012) 032201

η′ Mesic Nuclei in (*p*,*d*) Reaction

η′ transfer reaction + Missing mass measurement



η′ × ^{11}C
mesic nuclei

q ~ 300-400 MeV/c

cf. (γ,p)
by BGO-OD at Bonn or
by LEPS2 at SPring-8

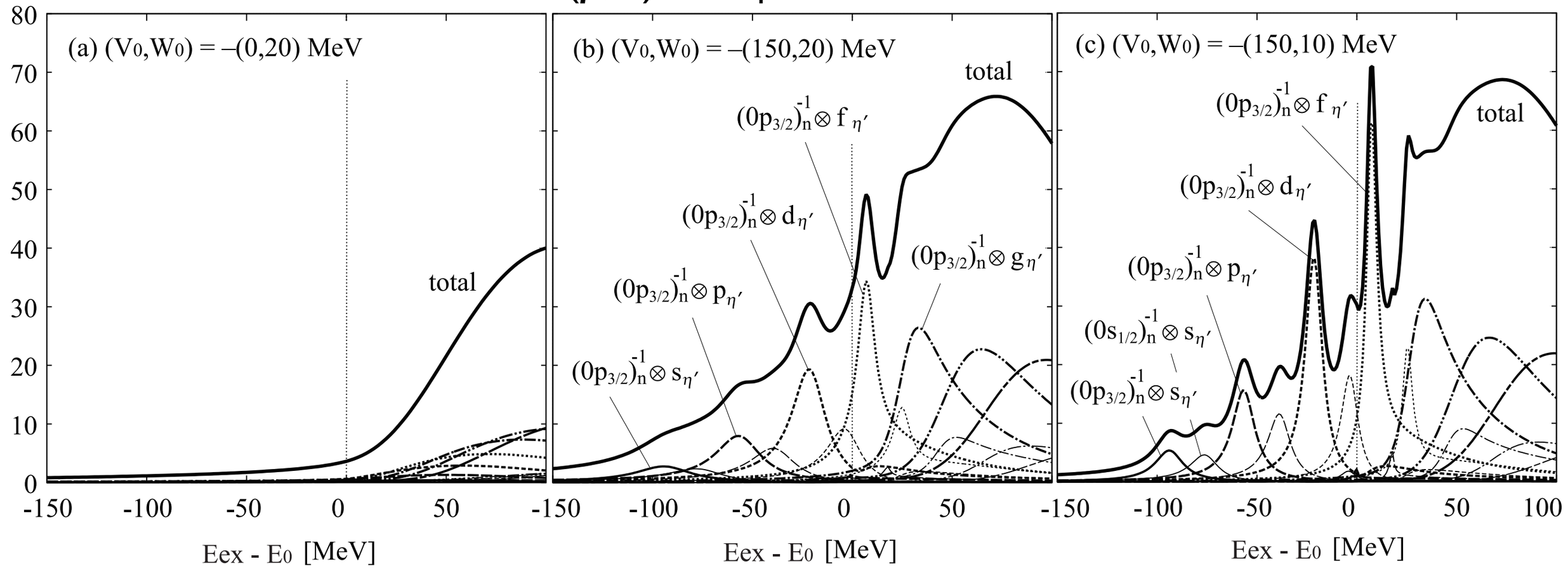
Theoretical Prediction

η′-nucleus potential:

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

ρ: nucleon density
V_0: Real potential depth
W_0: Imaginary potential depth

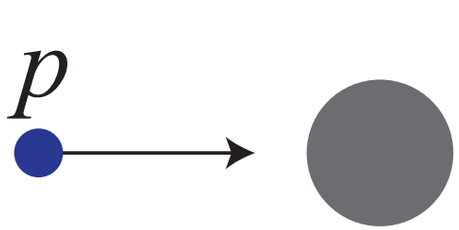
^{12}C(*p*,*d*) at T_p = 2.50 GeV

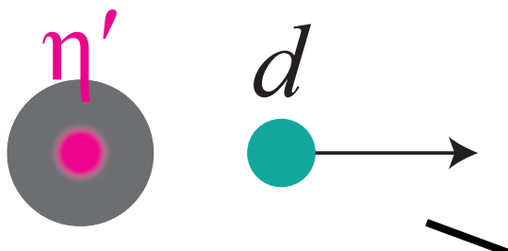


Nagahiro *et al.*,
PRC87(13)045201.

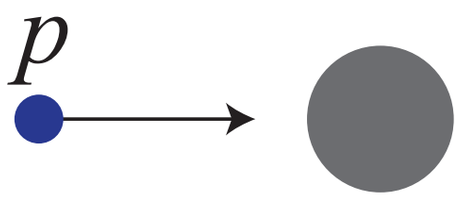
Background in Inclusive Measurement at GSI

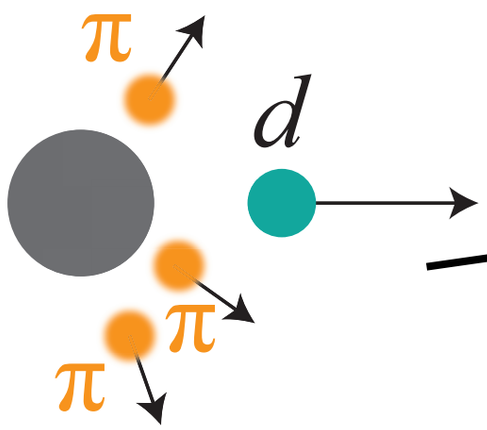
Signal

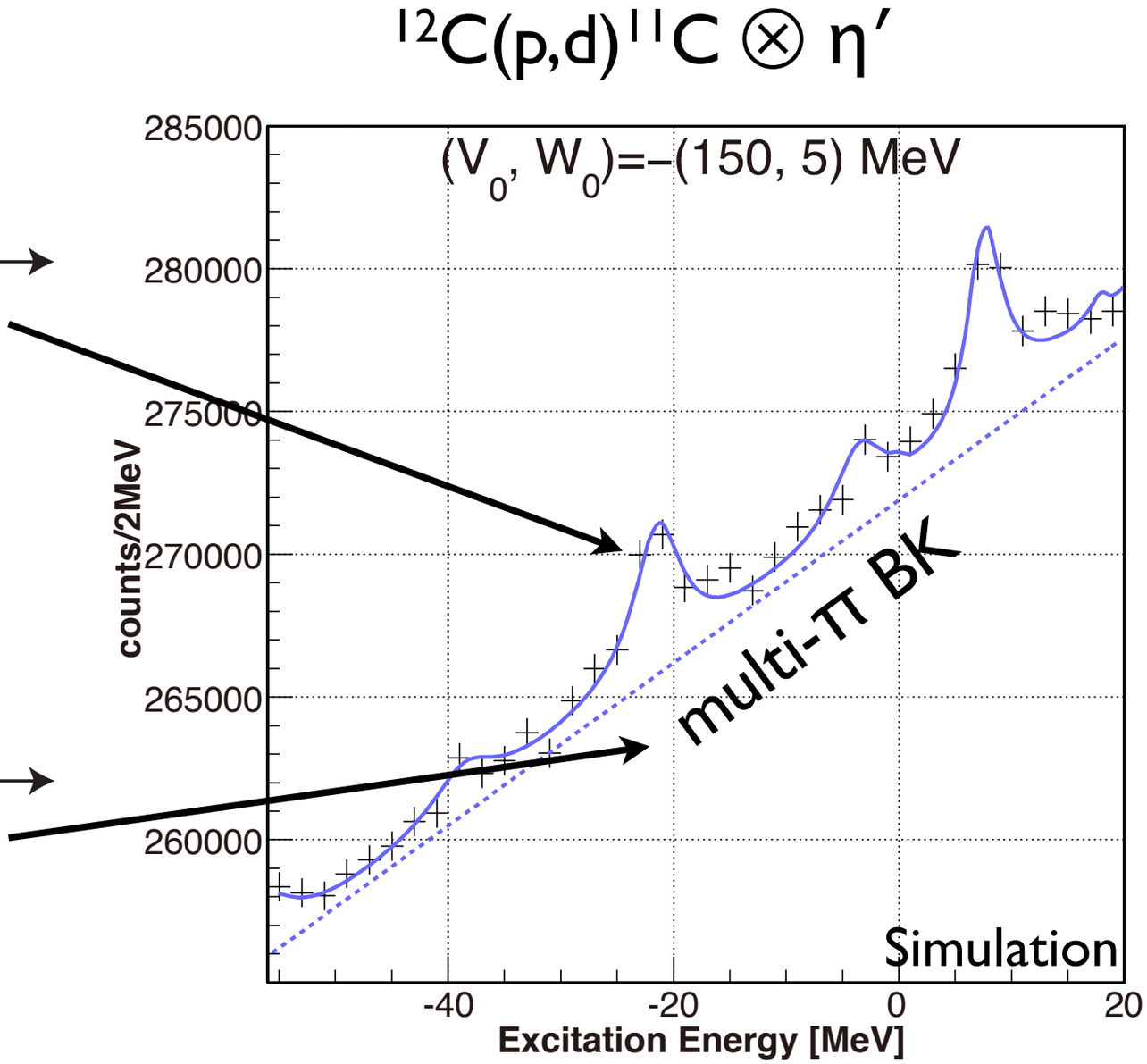




Background



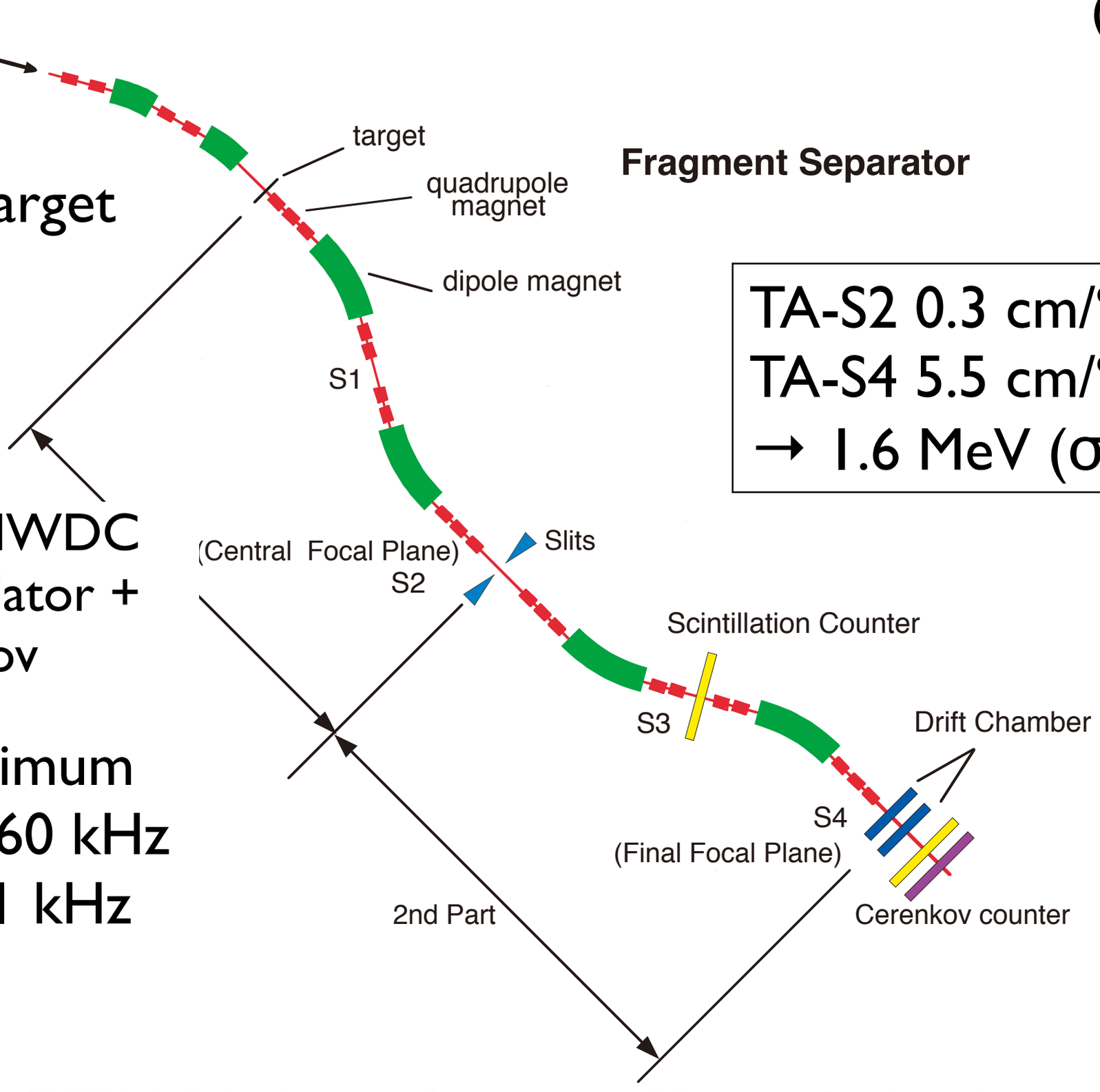




Inclusive Measurement at GSI

(First Stage)

$I_p = 10^{10}$/spill
4 g/cm^2 ^{12}C target



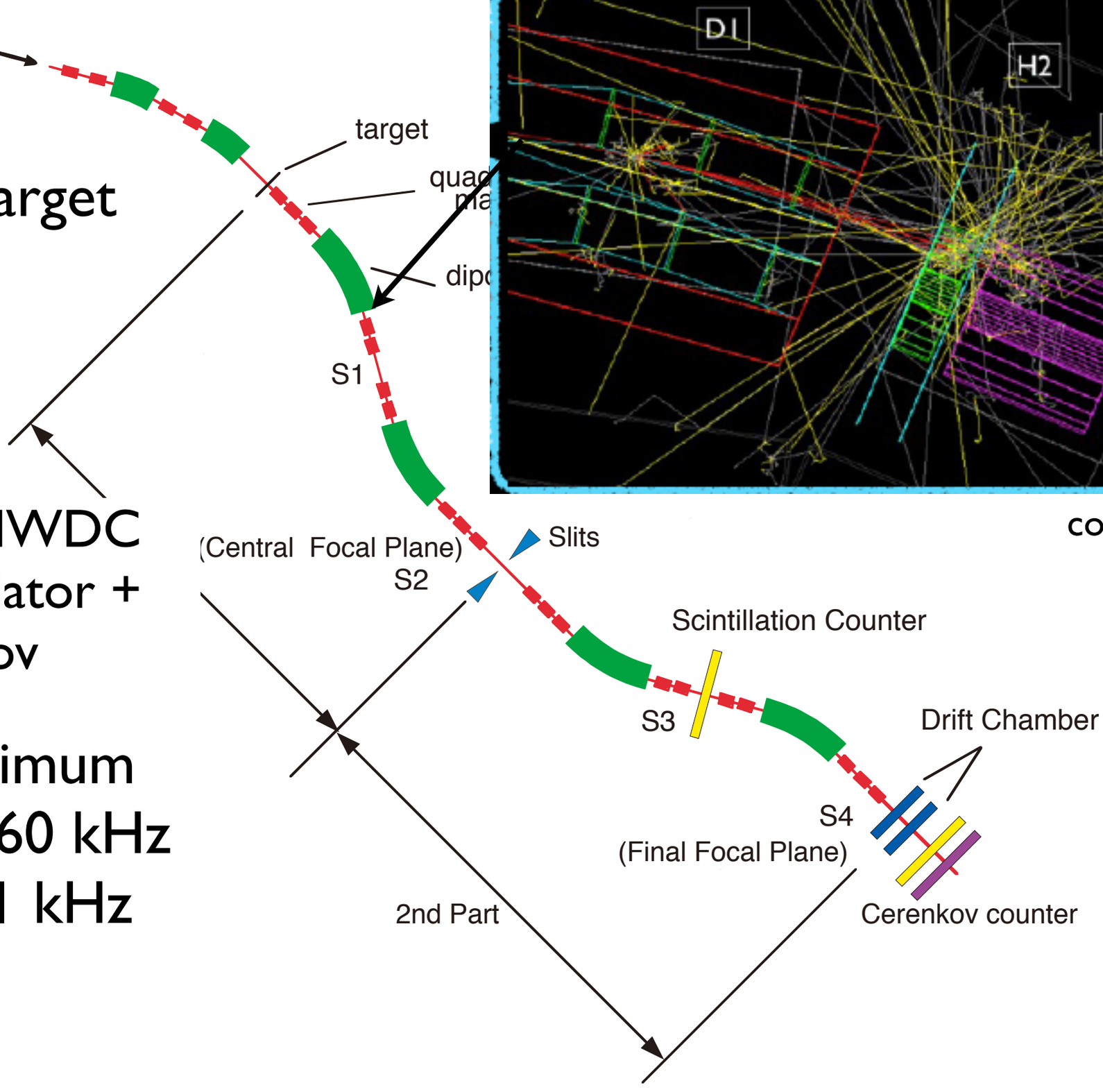
TA-S2 0.3 cm/%
TA-S4 5.5 cm/%
→ 1.6 MeV (σ)

Tracking = 2 x MWDC
PiD = 2 x Scintillator +
Aerogel Cerenkov

Estimated maximum
proton rate ~ 60 kHz
trigger rate = 1 kHz

Inclusive Measurement at GSI

$I_p = 10^{10}$/spill
4 g/cm^2 ^{12}C target



courtesy of Tanaka

Tracking = 2 x MWDC
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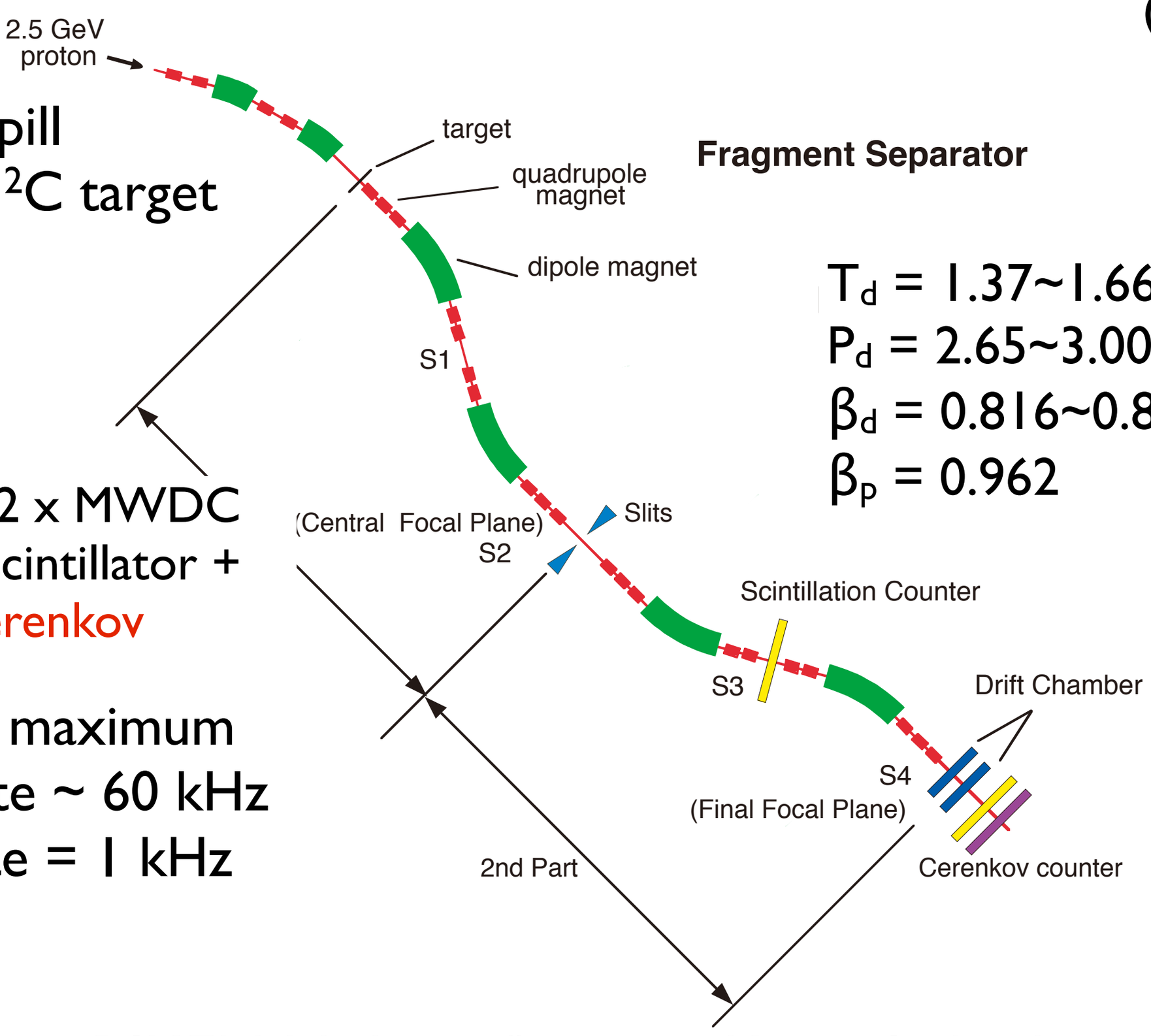


Fragment Separator

T_d = 1.37~1.66 GeV

P_d = 2.65~3.00 GeV/c

β_d = 0.816~0.848

β_p = 0.962

Tracking = 2 x MWDC

PiD = 2 x Scintillator +

Aerogel Cerenkov

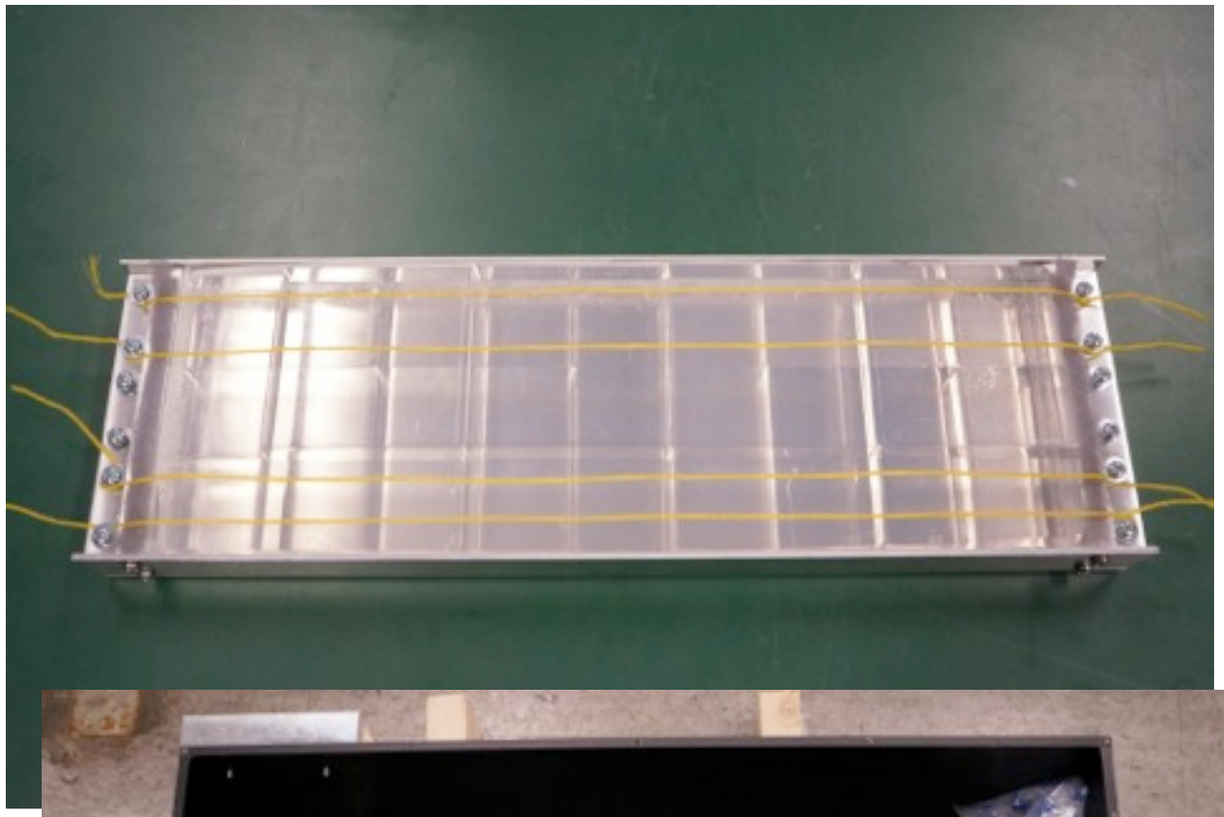
Estimated maximum

proton rate ~ 60 kHz

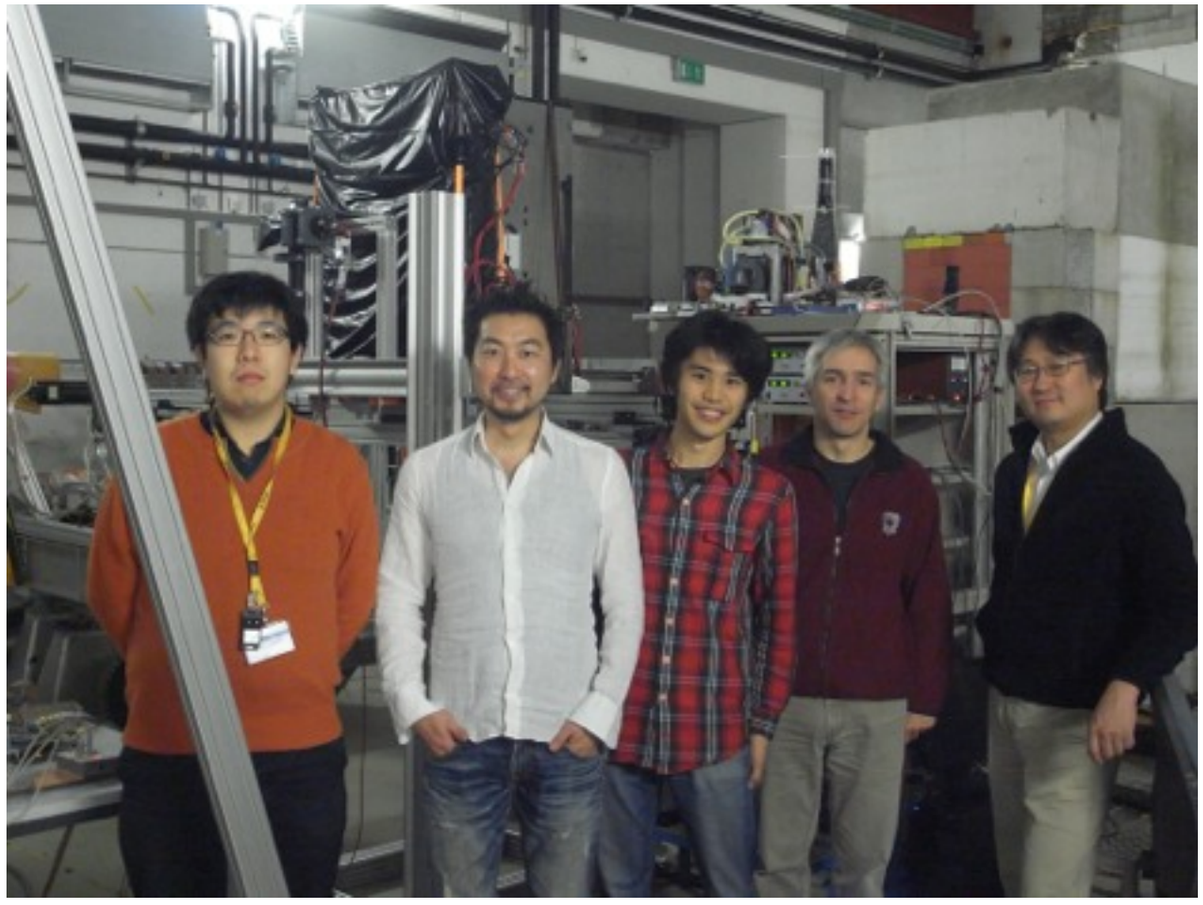
trigger rate = 1 kHz

Test of High Ref. Index Cerenkov Counter

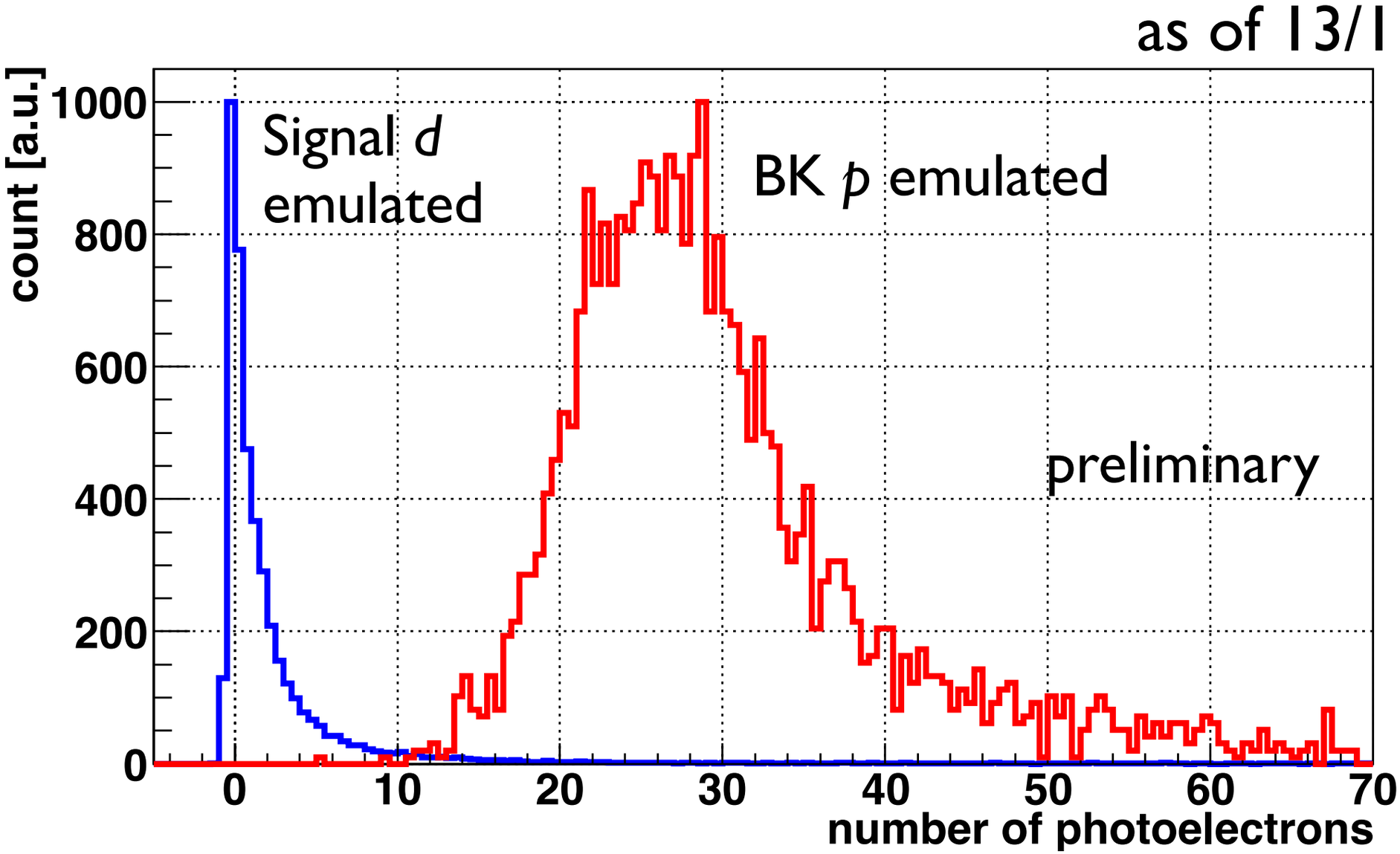
Aerogel (n=1.2) first time!



Monday 12/Nov/2012, CAVE-B



Test Result of Cerenkov Counter

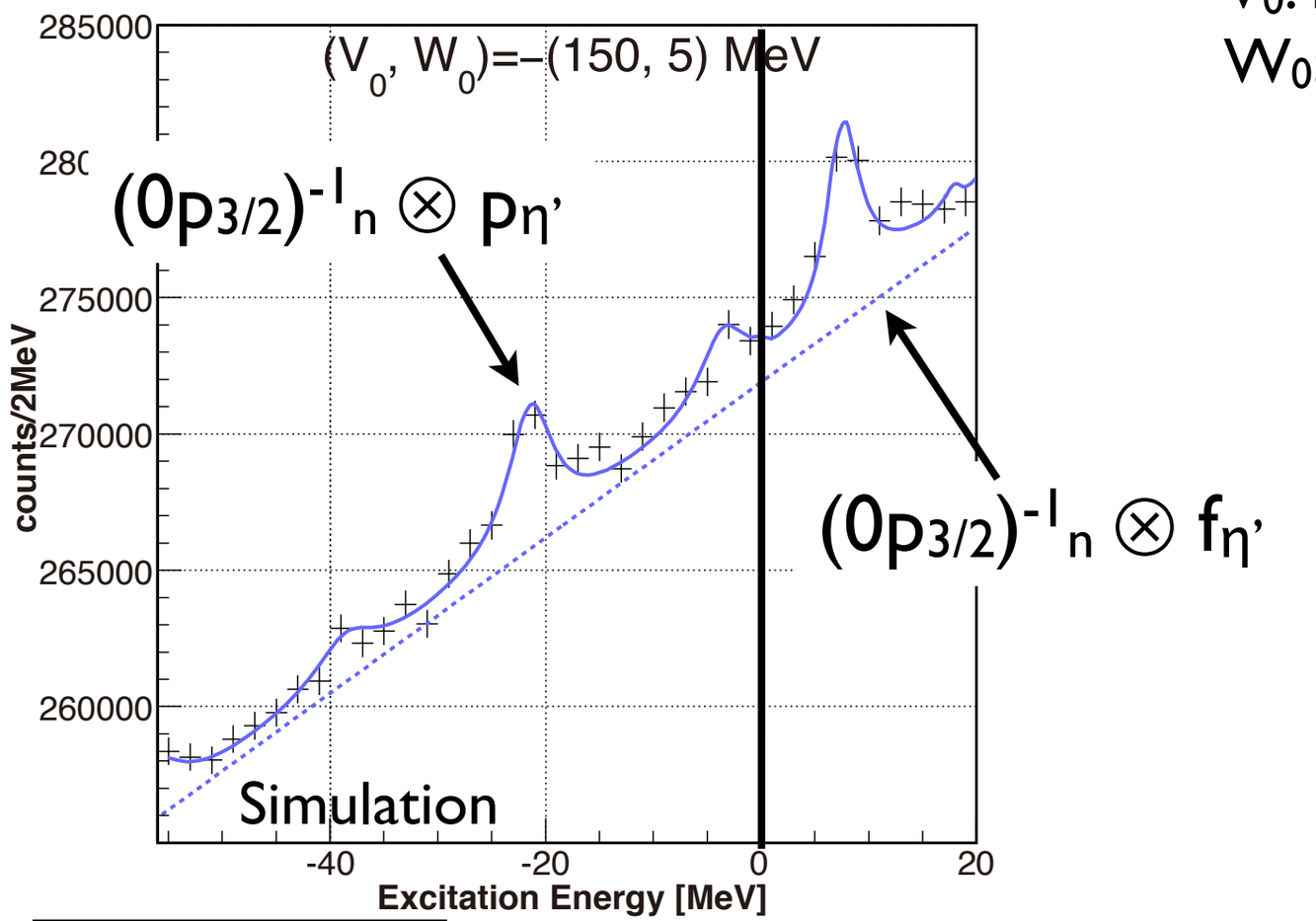


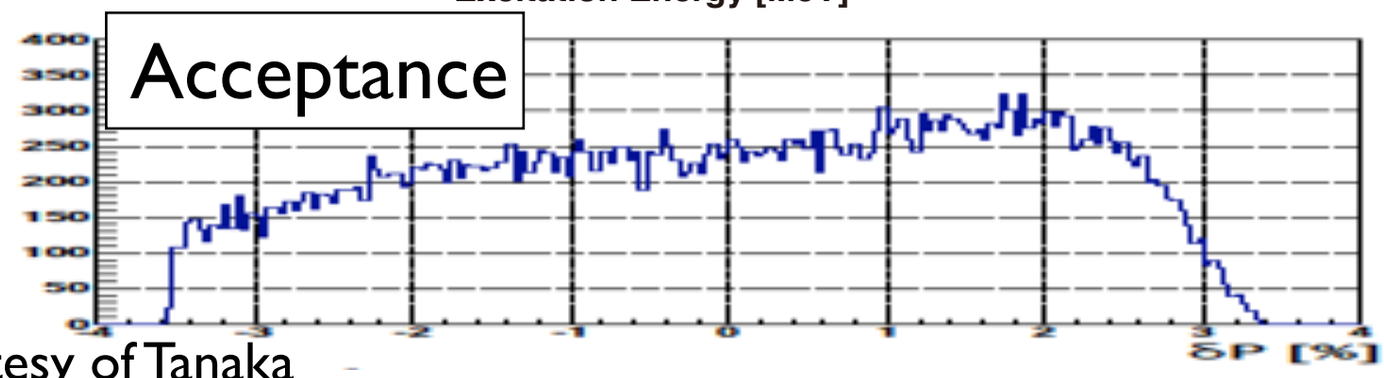
We can achieve > 99 % rejection
with a few % overkill at online level.

Expected Spectra at First Step (GSI)

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

ρ: nucleon density
V_0: Real potential depth
W_0: Imaginary potential depth

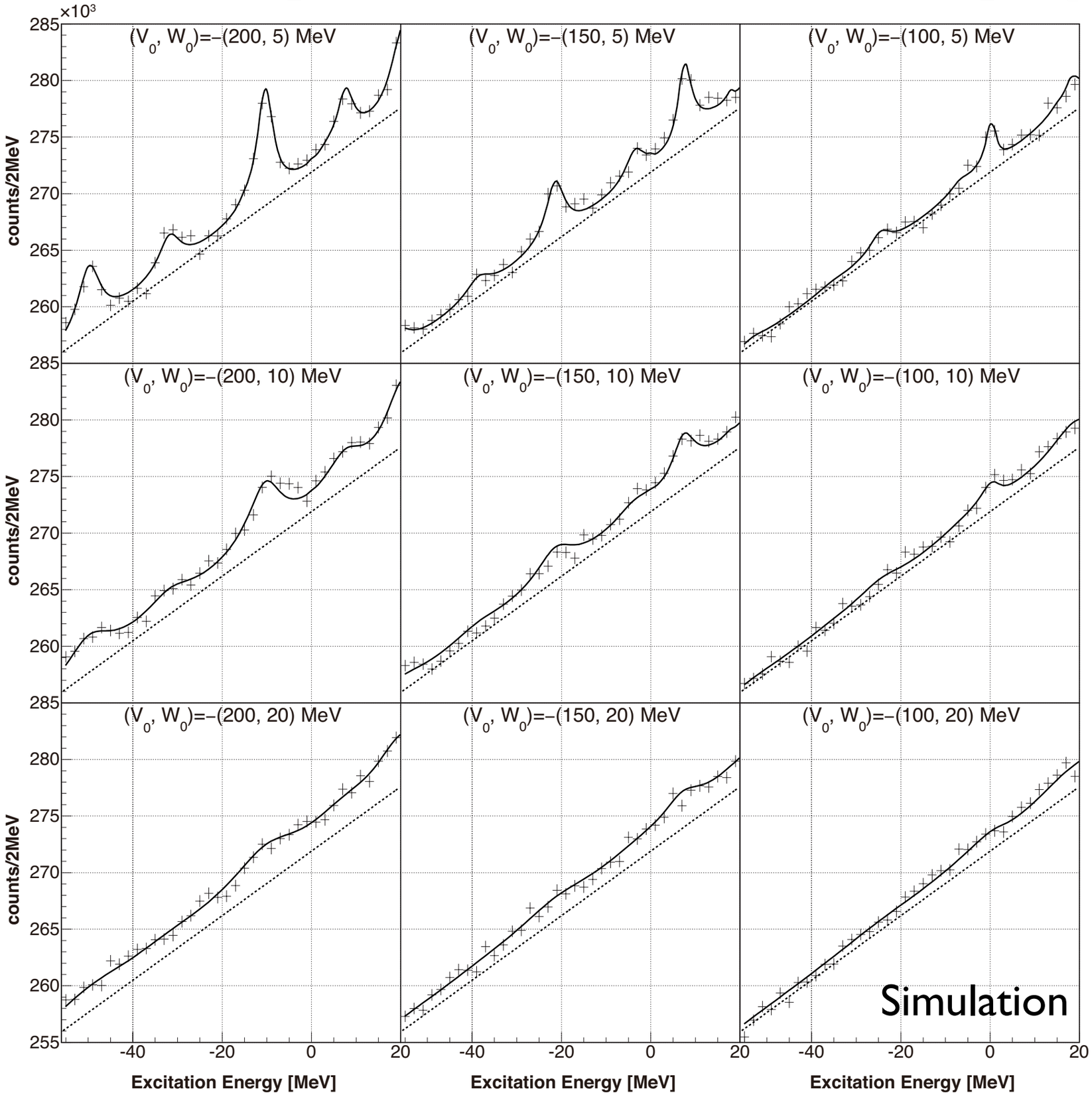




courtesy of Tanaka

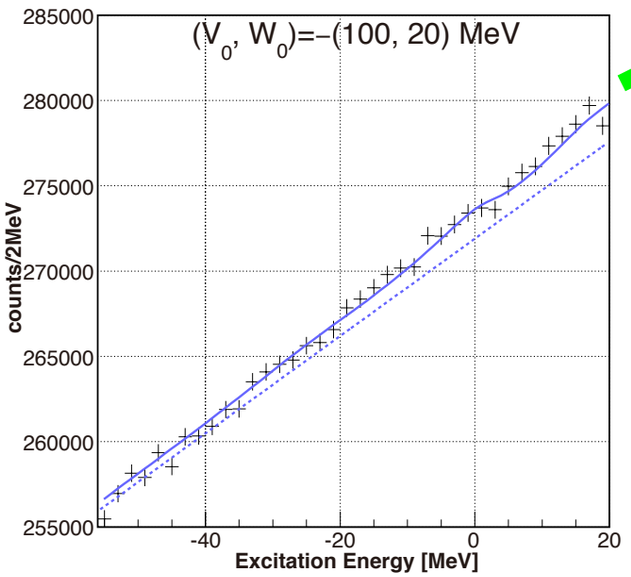
in 4.5 days DAQ

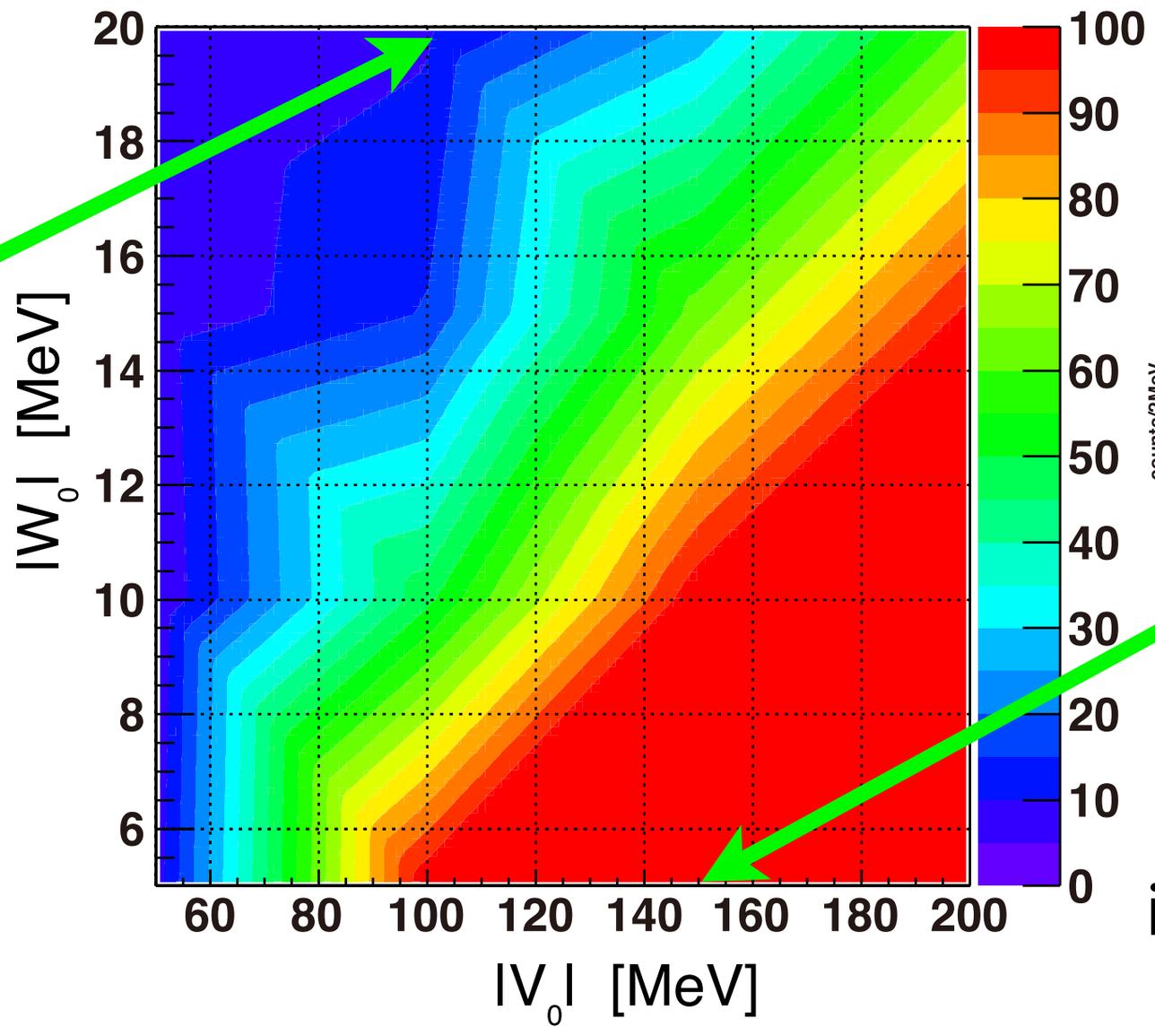
Expected Spectra at First Step (GSI)

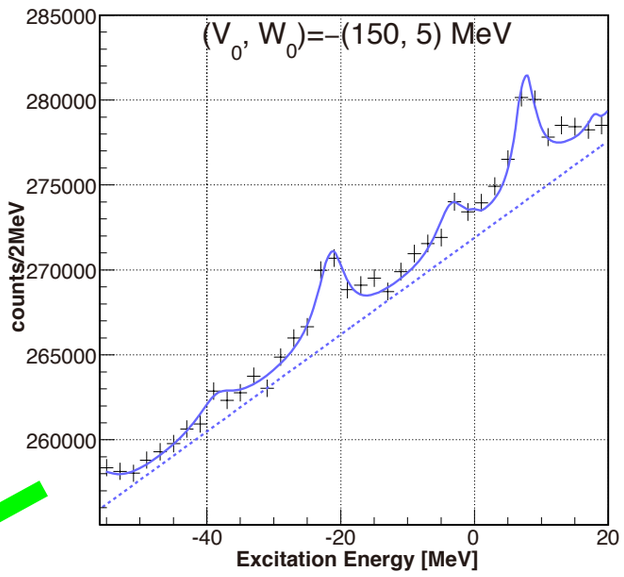


Structure-finding Probability for First Step (GSI)

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





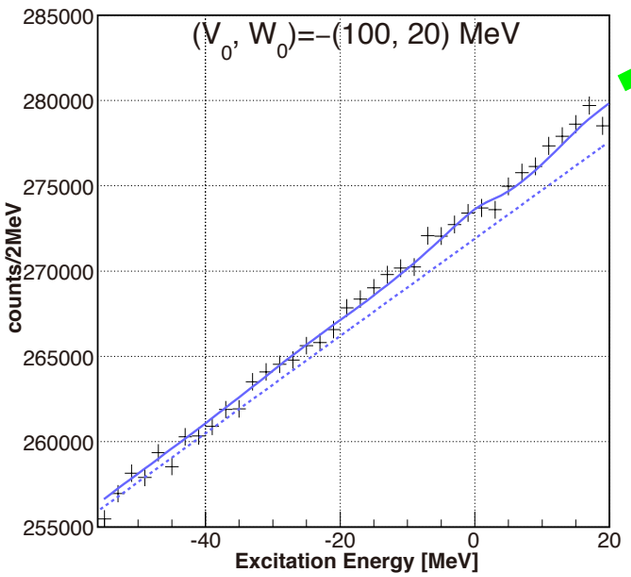


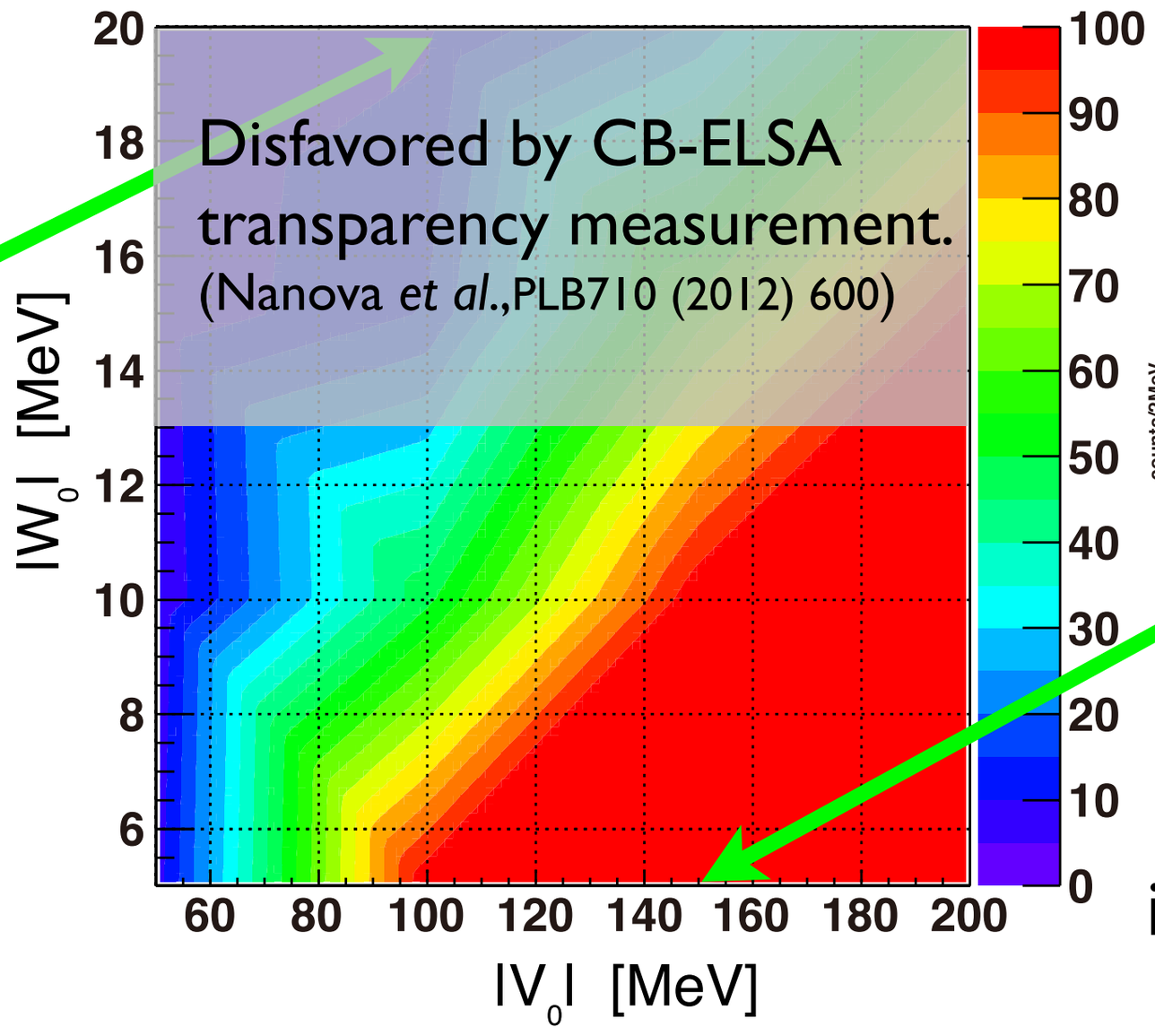
in 4.5 days DAQ

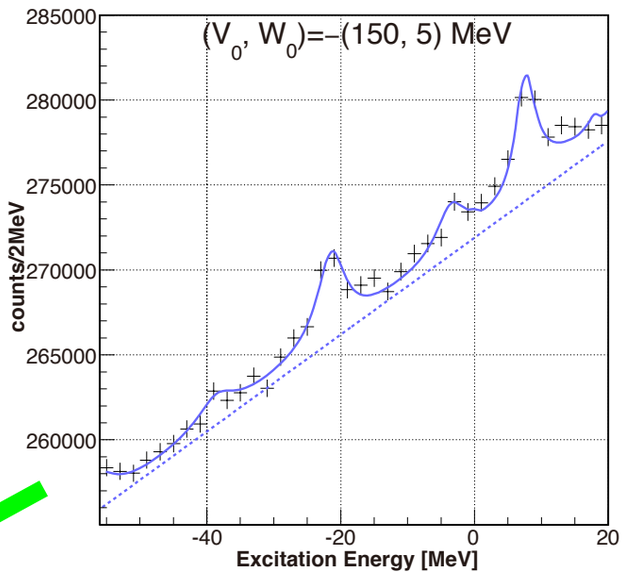
for 95 % C.L.

Structure-finding Probability for First Step (GSI)

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







in 4.5 days DAQ

for 95 % C.L.

Step by Step from GSI to FAIR

	reaction	objectives	S/N
GSI	(*p*,*d*) inclusive	overall structure + BK study	poor
FAIR	(*p*,*dp*) exclusive*	extended sensitivity → excited + ground states	good

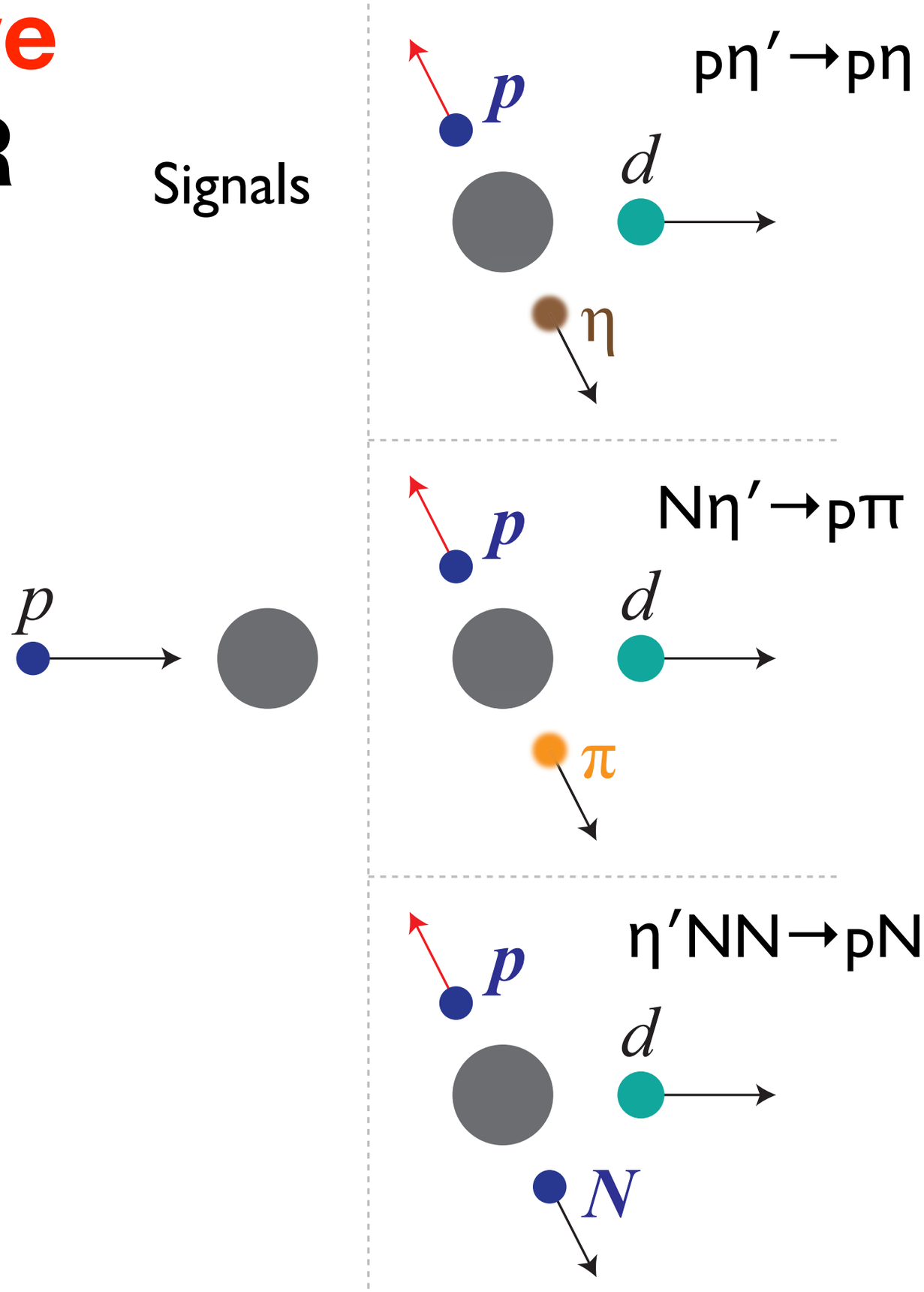
Feed Back

*) decay protons from η′ mesic nuclei in coincidence.

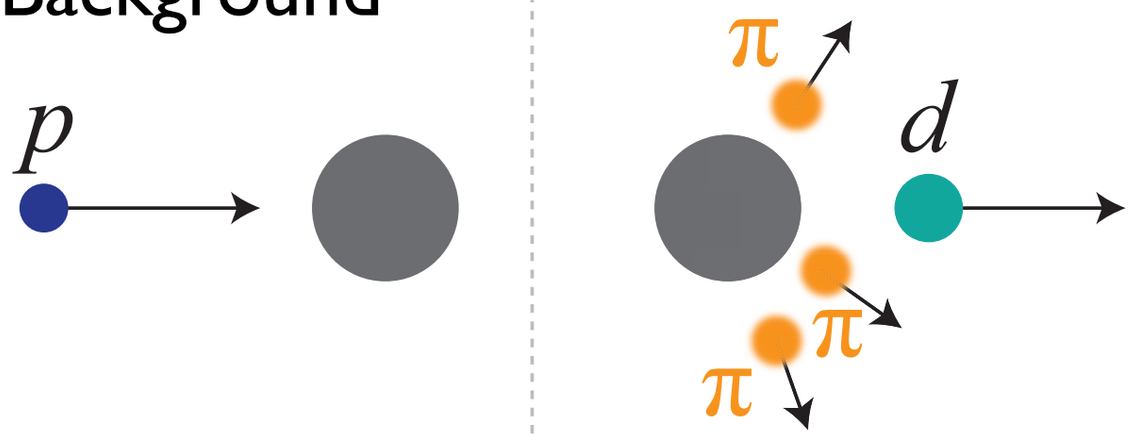
For decay branching ratio:
both inclusive and exclusive measurements are necessary

Principles of Exclusive Measurement at FAIR

Signals

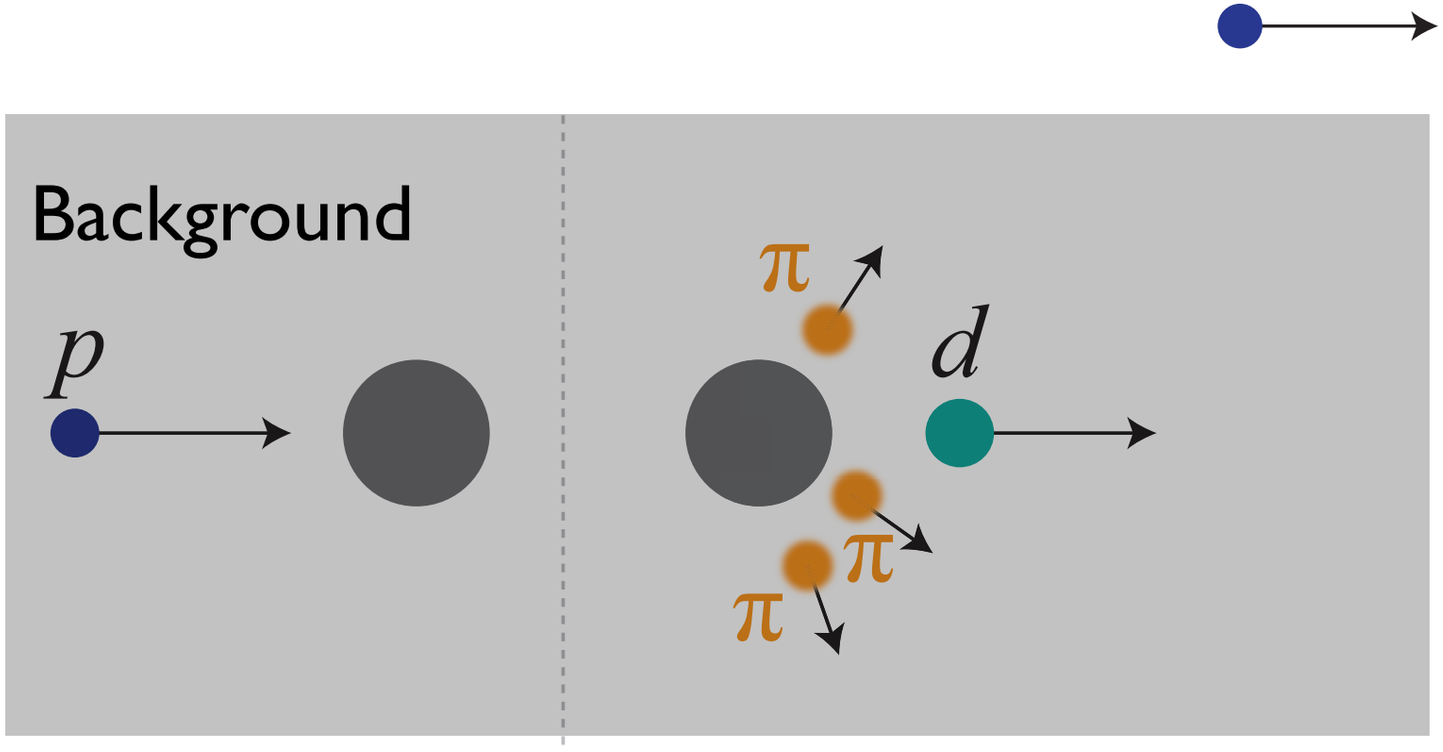


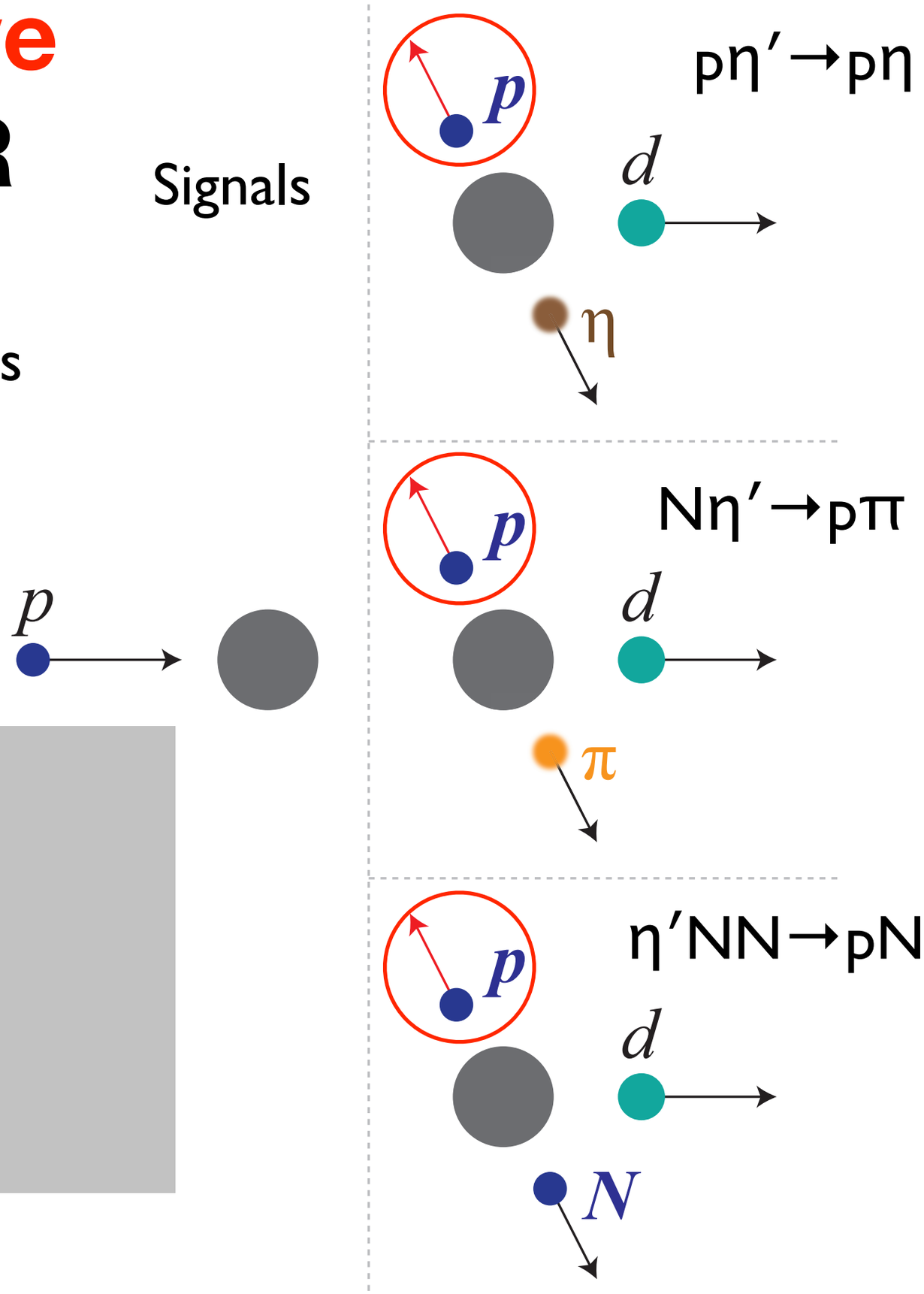
Background



Principles of Exclusive Measurement at FAIR

tagging high-momentum protons
(300-600 MeV)





Principles of Exclusive Measurement at FAIR

tagging high-momentum protons
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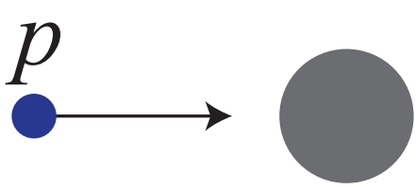
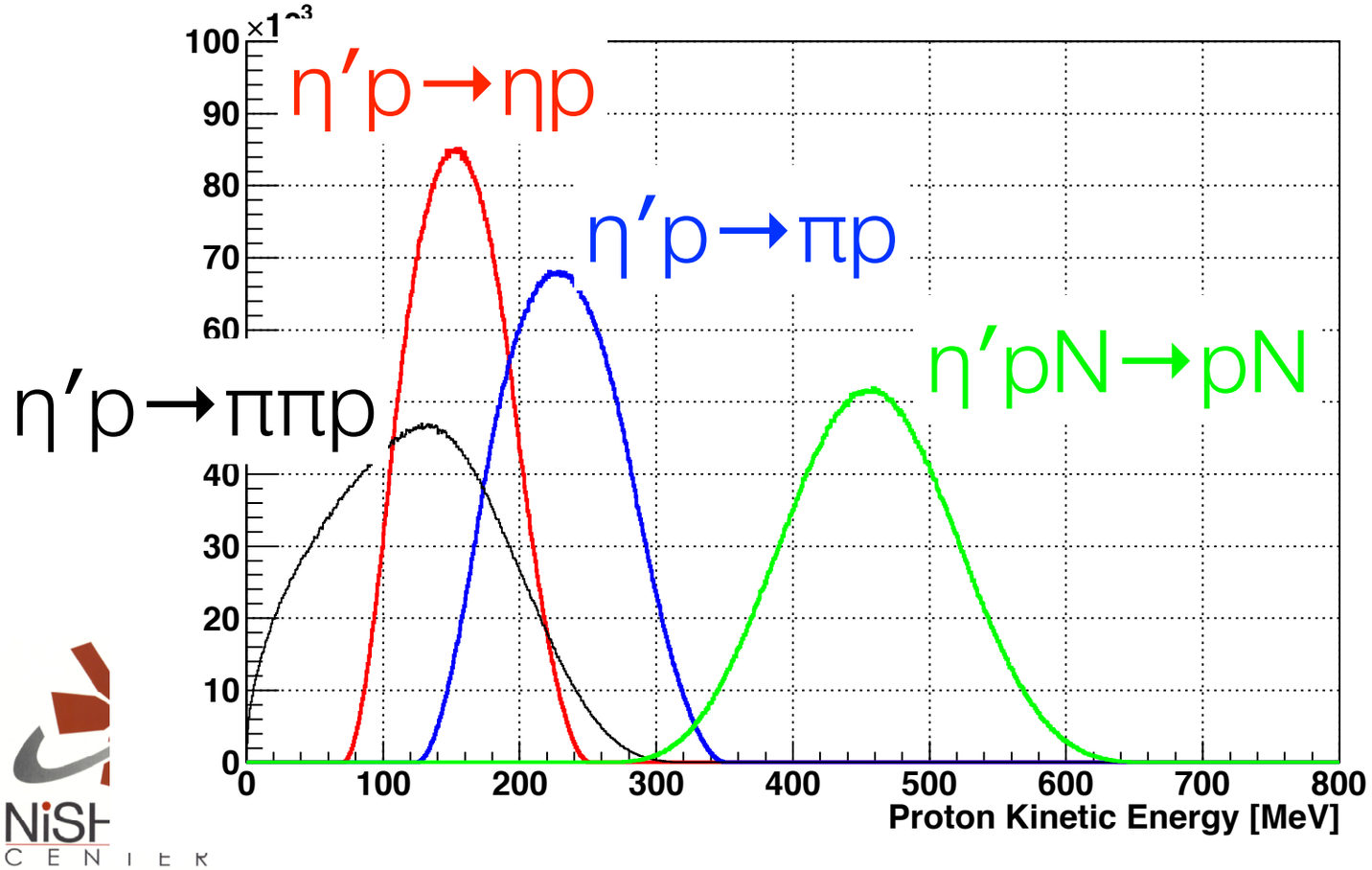
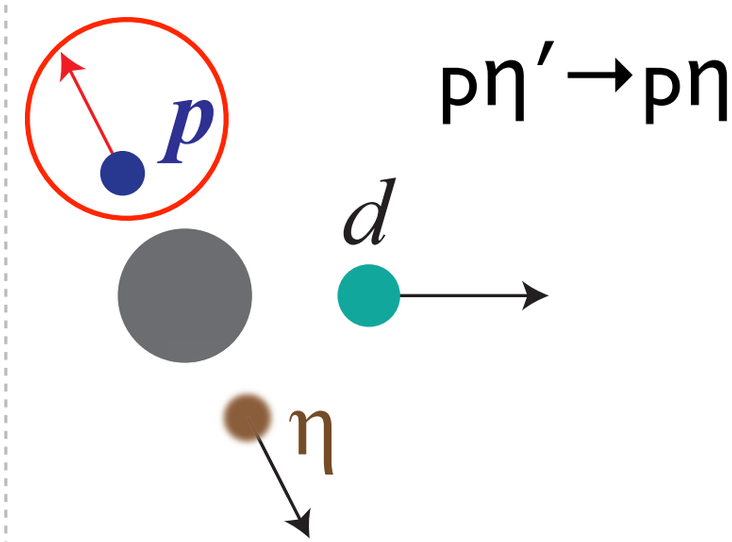
Y.K. Tanaka





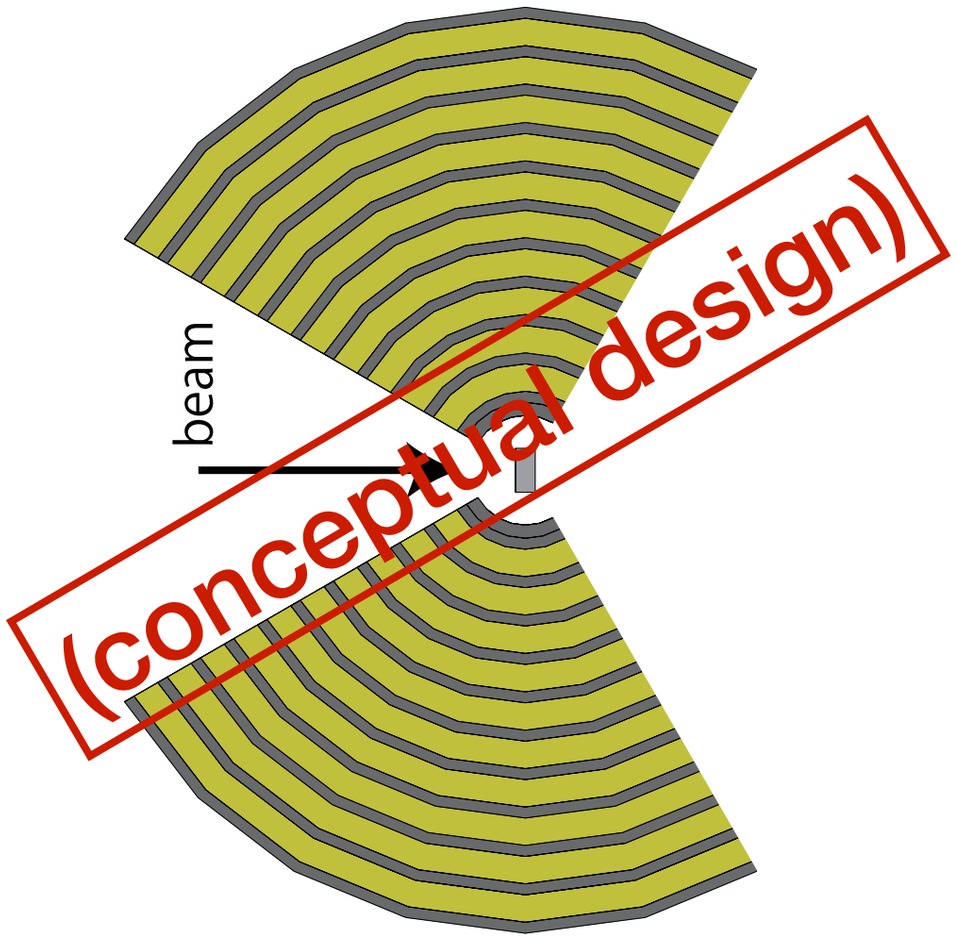
Signals

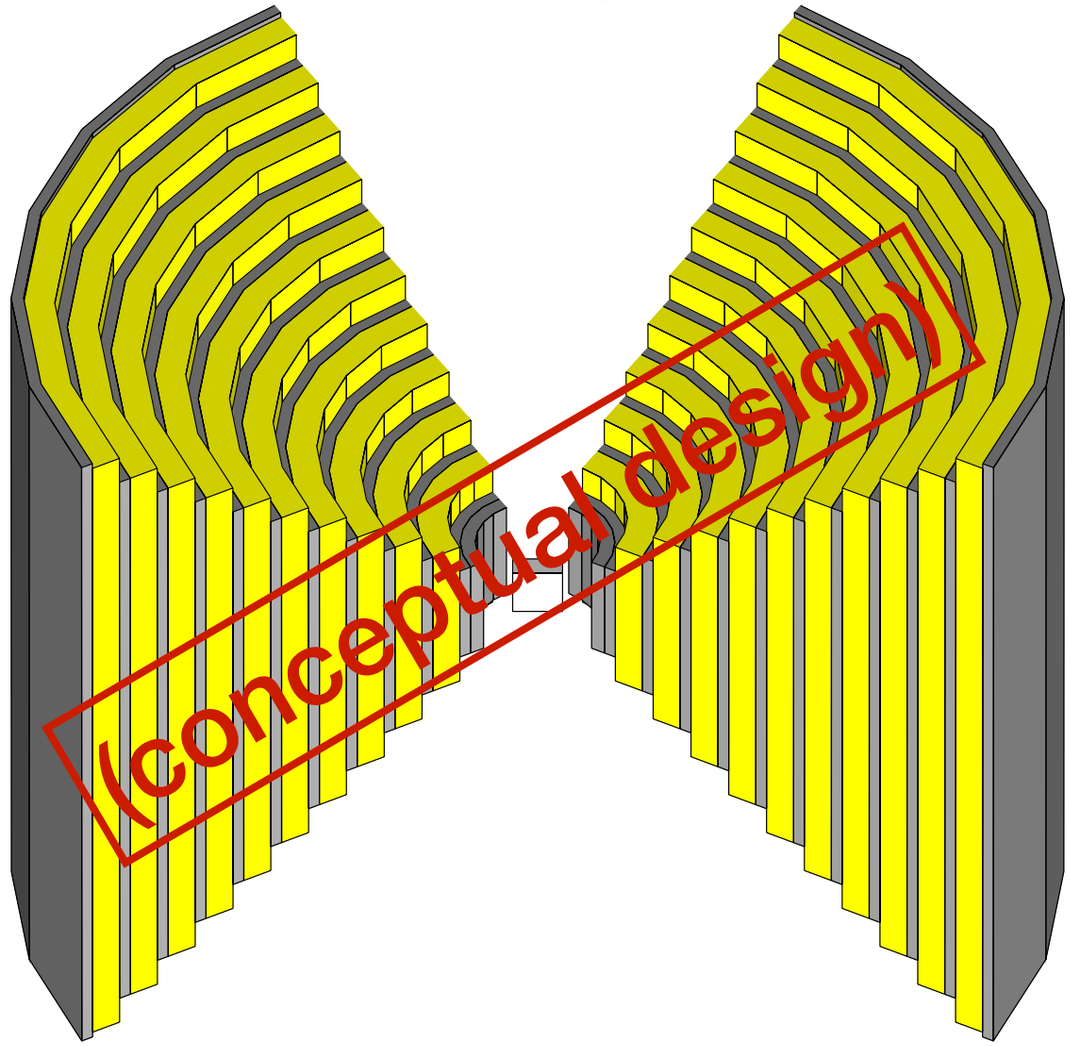


enta Itahashi

Conceptual design of decay proton counter

10 layers of Sci/Brass sampling calorimeter for p/pi separation





design in progress

RIKEN Nishina Center, Kenta Itahashi

Summary

- We are working for two projects: piAF, η' mesic nuclei spectroscopy.
- piAF is waiting for main experiment after successful pilot experiment.
- Pionic atom spectroscopy with unstable nuclei is also in progress.
- η′ mesic nuclei spectroscopy is in preparation at GSI/FAIR.
- Detector integrity test in Jan/2014 at COSY.
- Detector design for FAIR combined with nuclear cascade code is in progress to optimize BG suppression in semi-exclusive measurement.

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