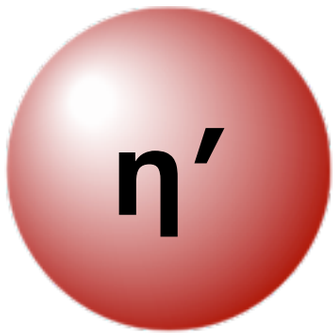
Experimental spectroscopy of pionic atoms and eta'-mesic nuclei

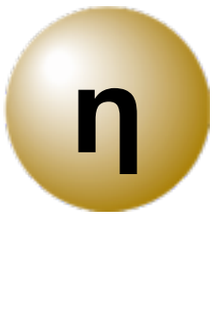
Kenta Itahashi

RIKEN NiSHiNA CENTER

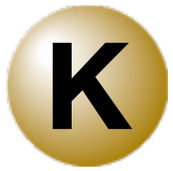
Mass of PS mesons



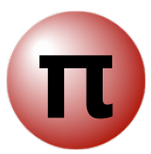
M=958 MeV/c^2



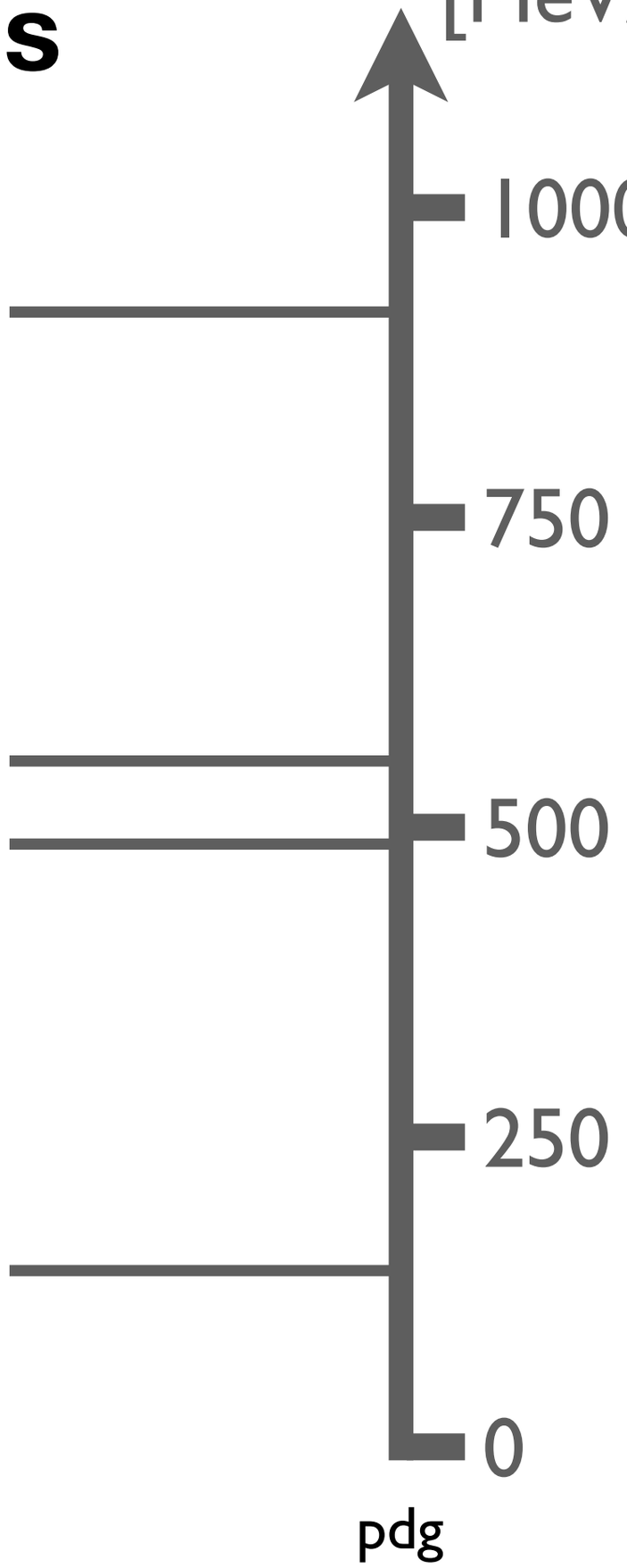
M=548 MeV/c^2



M=498 MeV/c^2



M=140 MeV/c^2



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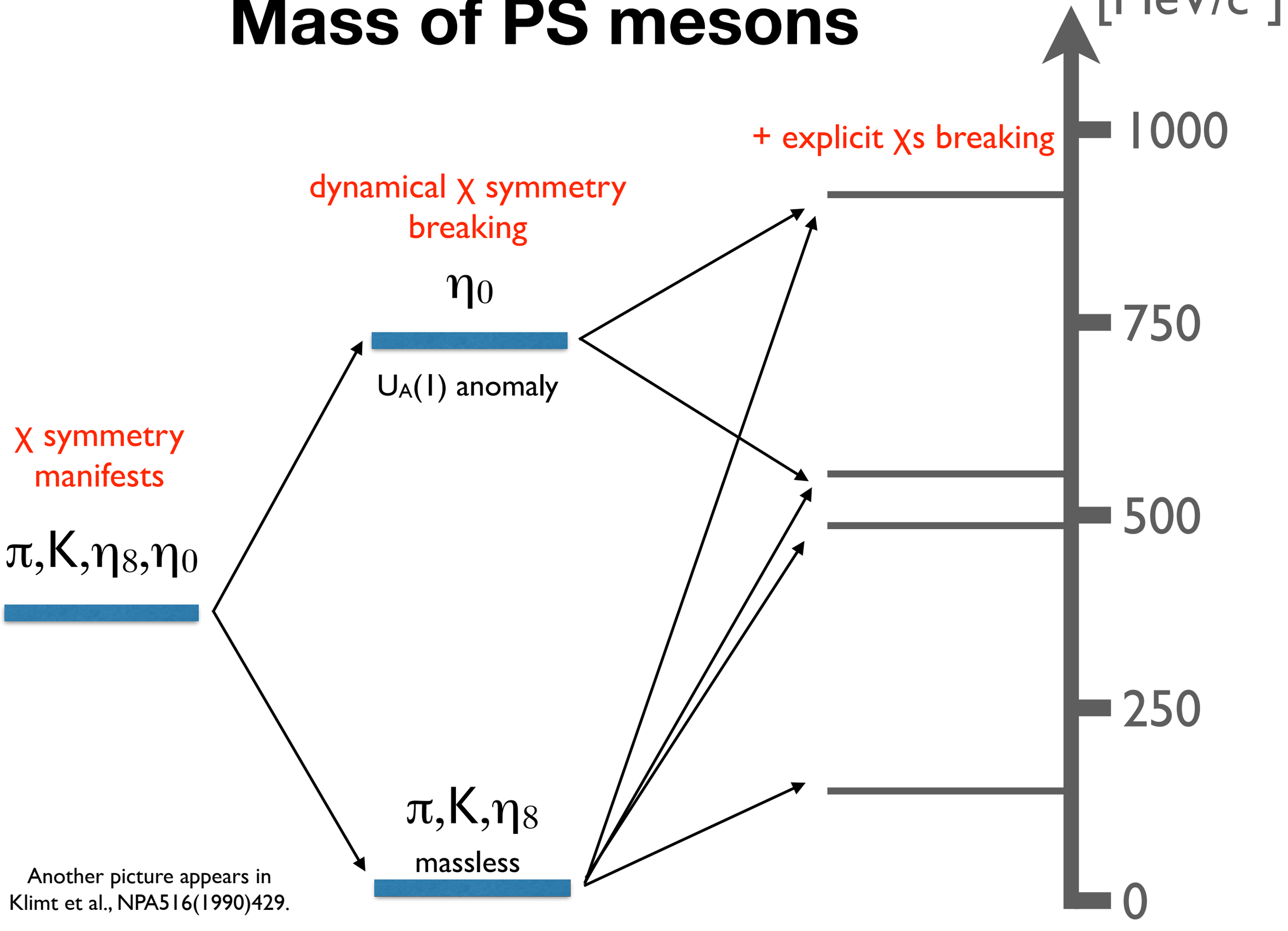
Mass of PS mesons



Another picture appears in Klimt et al., NPA516(1990)429.

Nagahiro et al., PRC 87 (2013) 045201
Jido et al., NPA 914 (2013) 354

Contents

- **piAF project (RIBF-54) at RIBF**

  Physics

  Pilot run 2010 and achievements

  Main run 2014

  Challenges for piA with unstable nuclei

- **EtaPrime (GSI-S437) at GSI/FAIR**

  Physics and strategy → Detail in next talk

  Pilot run 2014

  Future perspectives

Precision measurement of deeply bound pionic Sn atoms in RIBF

Kenta Itahashi

Advanced Meson Science Laboratory, RIKEN
for piAF collaboration

DeukSoon Ahn, Georg P. A. Berg, Masanori Dozono, Hiroyuki Fujioka, Naoki Fukuda, Nobuhisa Fukunishi, Hans Geissel, Emma Haettner, Ryugo S. Hayano, Satoru Hirenzaki, Hiroshi Horii, Natsumi Ikeno, Naoto Inabe, Kenta Itahashi*, Masahiko Iwasaki, Daisuke Kameda, Nobuyuki Kobayashi, Toshiyuki Kubo, Hiroaki Matsubara, Shin'ichiro Michimasa, Kenjiro Miki, Go Mishima, Daichi Murai, Hiroyuki Miya, Hideko Nagahiro, Megumi Niikura, Takahiro Nishi**, Shumpei Noji, Shinsuke Ota, Haruhiko Outa, Naruhiko Sakamoto, Hiroshi Suzuki, Ken Suzuki, Motonobu Takaki, Hiroyuki Takeda, Yoshiki K. Tanaka, Tomohiro Uesaka, Yuni N. Watanabe, Helmut Weick, Hiroki Yamakami, Koichi Yoshida.

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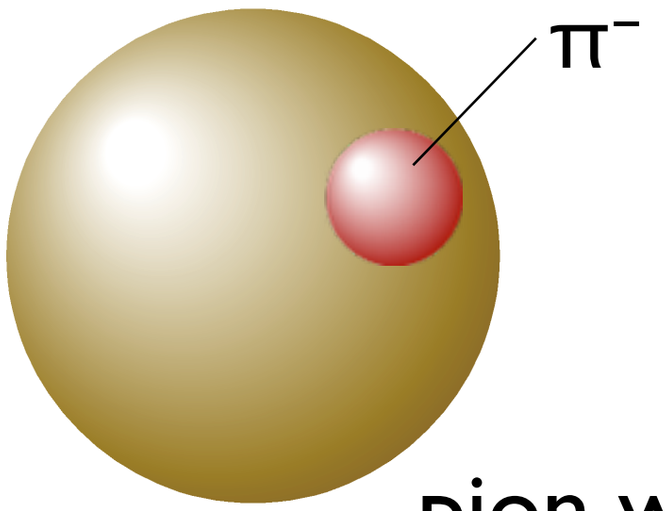
Department of Physics, The University of Tokyo
Department of Physics, Nara Women's University
National Institute of Radiological Sciences
Center of Nuclear Study, The University of Tokyo
Research Center for Nuclear Physics, Osaka University
National Superconducting Cyclotron Laboratory, Michigan State University
Stefan-Meyer-Institut für subatomare Physik, Österreichische Akademie der Wissenschaften

Pionic Atoms and piA interaction

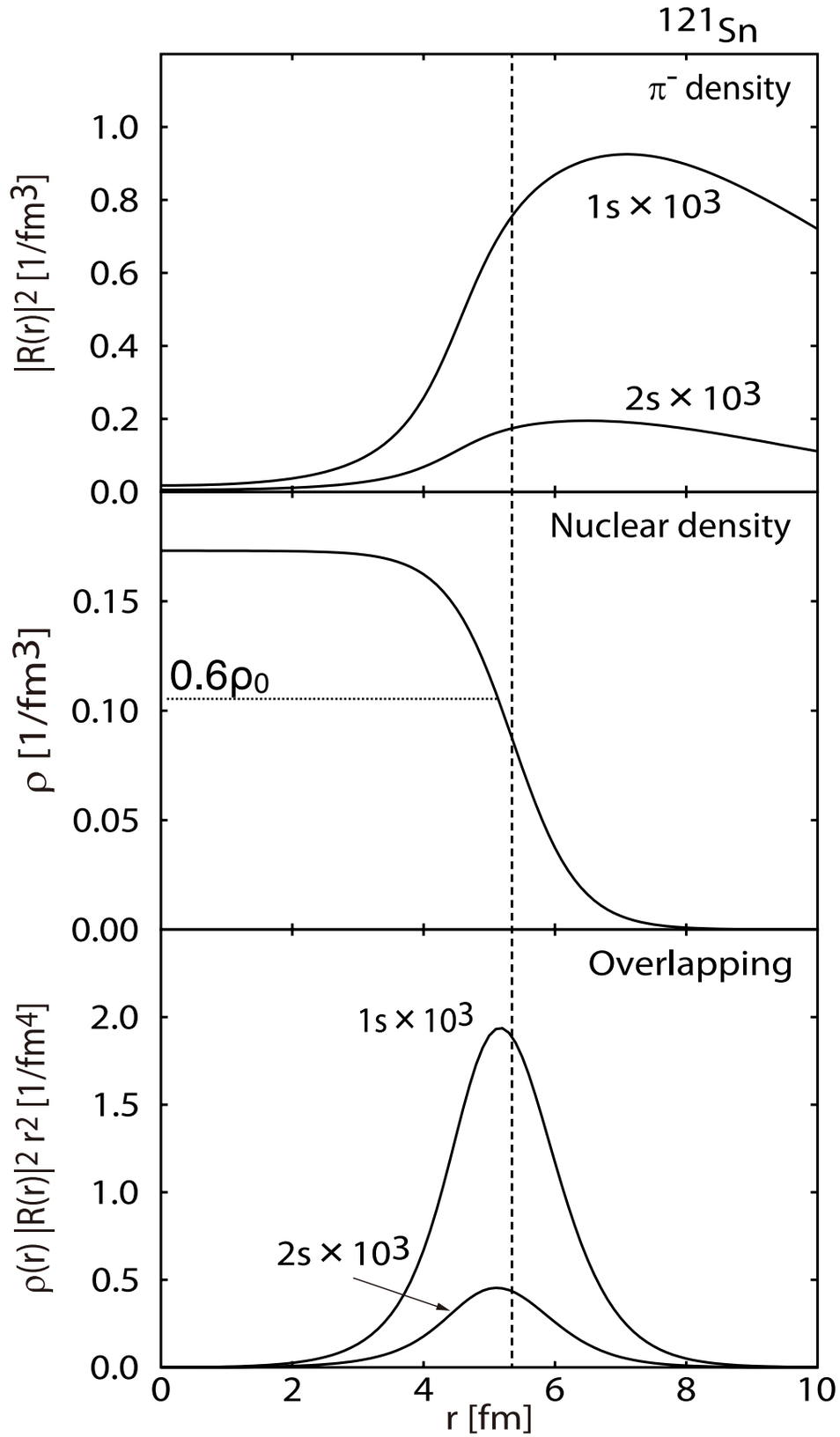


pion wave function locates at vicinity of nucleus

sensitivity to
π-nucleus *s*-wave potential

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

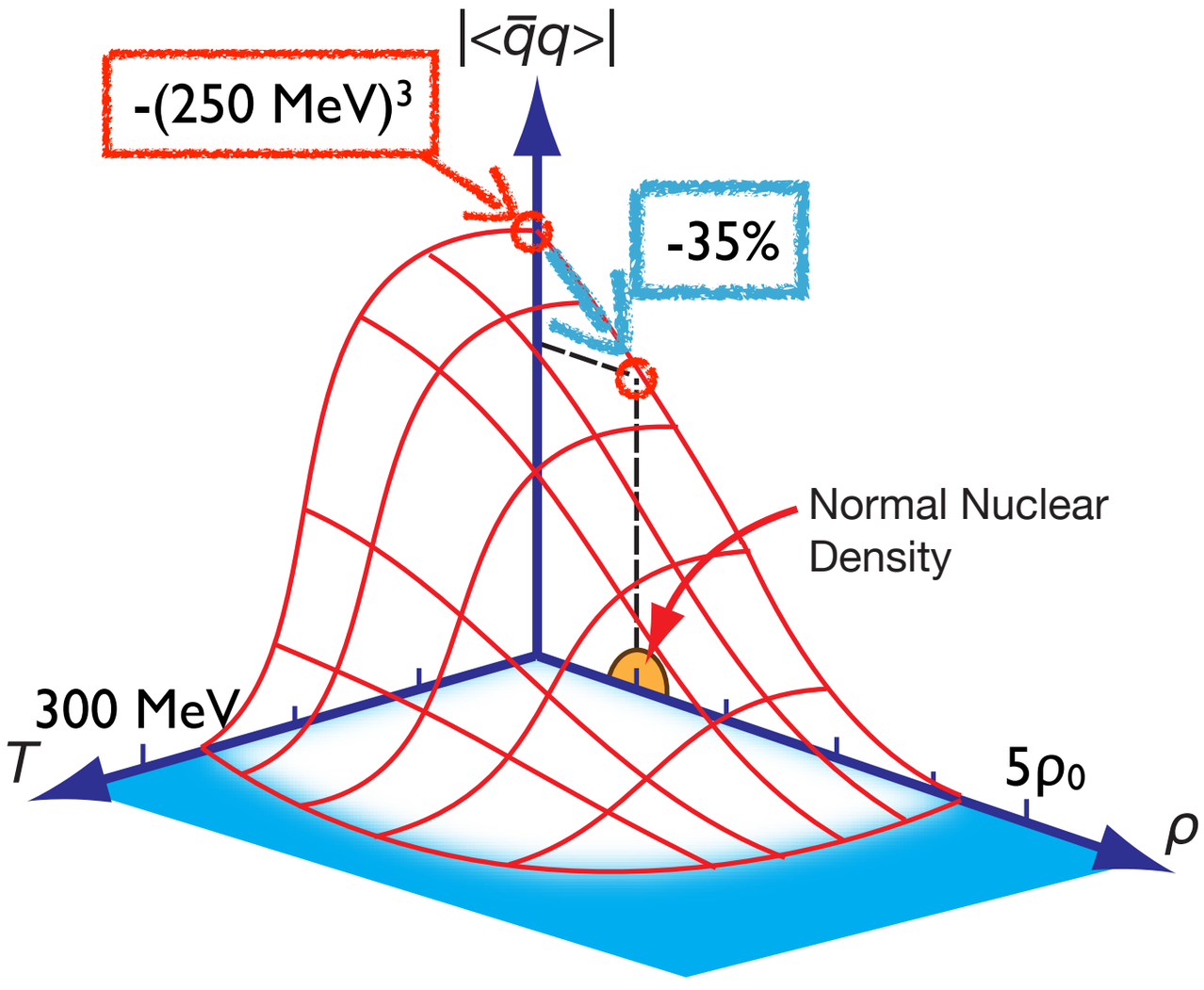
for $\rho_e = 0.6\,\rho_0$



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

Chiral symmetry at finite density

Jido, Hatsuda, Kunihiro, Phys.Lett.B670:109-113,2008.
Kolomeitsev, Kaiser, Weise, Phys. Rev. Lett. 90(2003)092501



M. Gell-Mann *et al.*, PR175(1968)2195.

Gell-Mann-Oakes-Renner relation

$$f_\pi^2 m_\pi^2 = -2m_q \langle \bar{q}q \rangle$$

f_π : pion decay constant

Y. Tomozawa, NuovoCimA46(1966)707.
S. Weinberg, PRL17(1966)616.

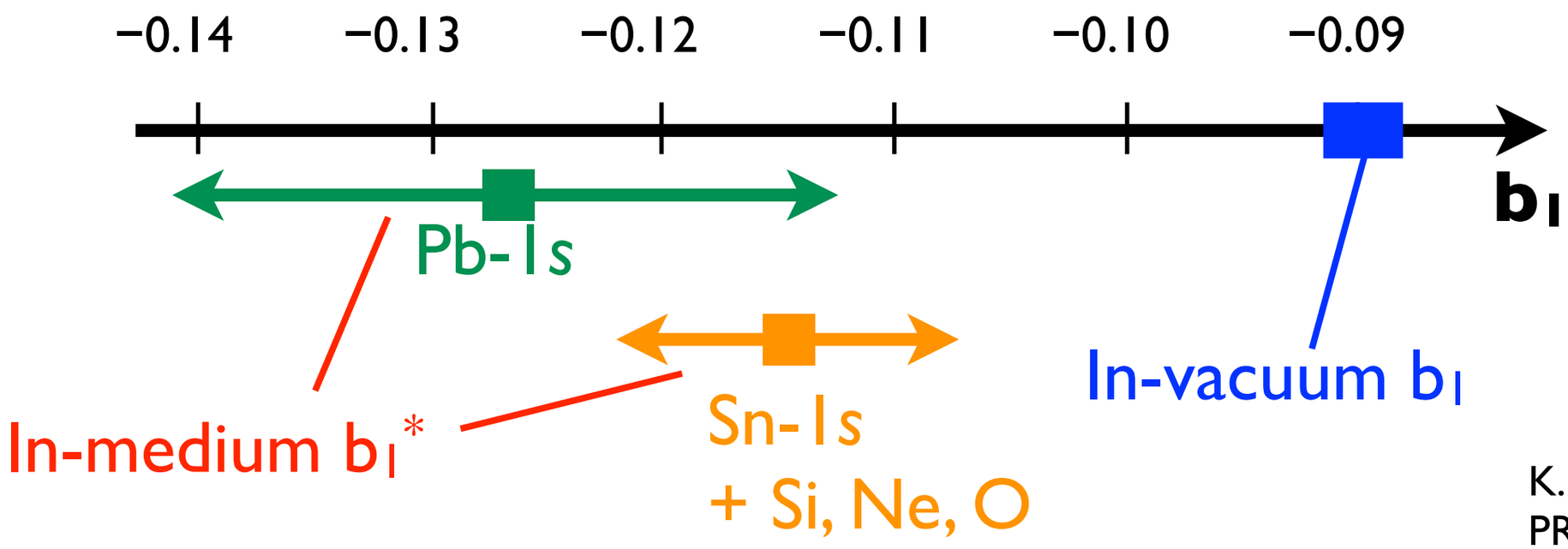
Tomozawa-Weinberg relation

$$b_1 = -\frac{m_\pi}{8\pi f_\pi^2}$$

b_1: isovector πN scattering length

$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} \approx \frac{b_1^{\mathrm{free}}}{b_1(\rho)}$$

Present b_1 precision



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

b_1^* still has a large error

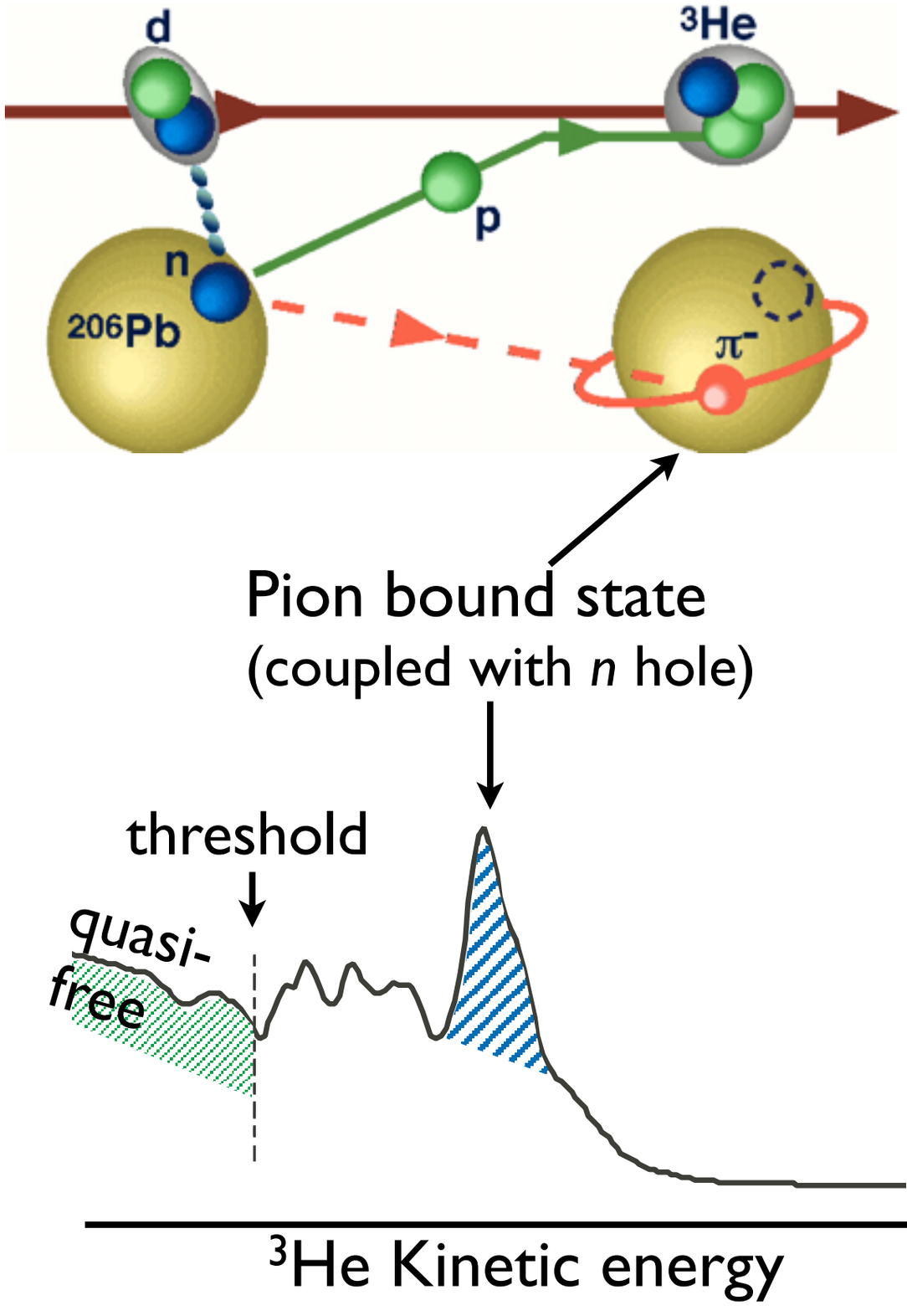
$$V_{s\text{-wave}} = b_0\,\rho + b_1\,(\rho_n - \rho_p) + B_0\,\rho^2$$

← spectroscopy of pionic atoms

In-medium b_1 is calculated based on deeply bound pionic states data combined with light spherical pionic atom data.

Spectroscopy of pionic atoms

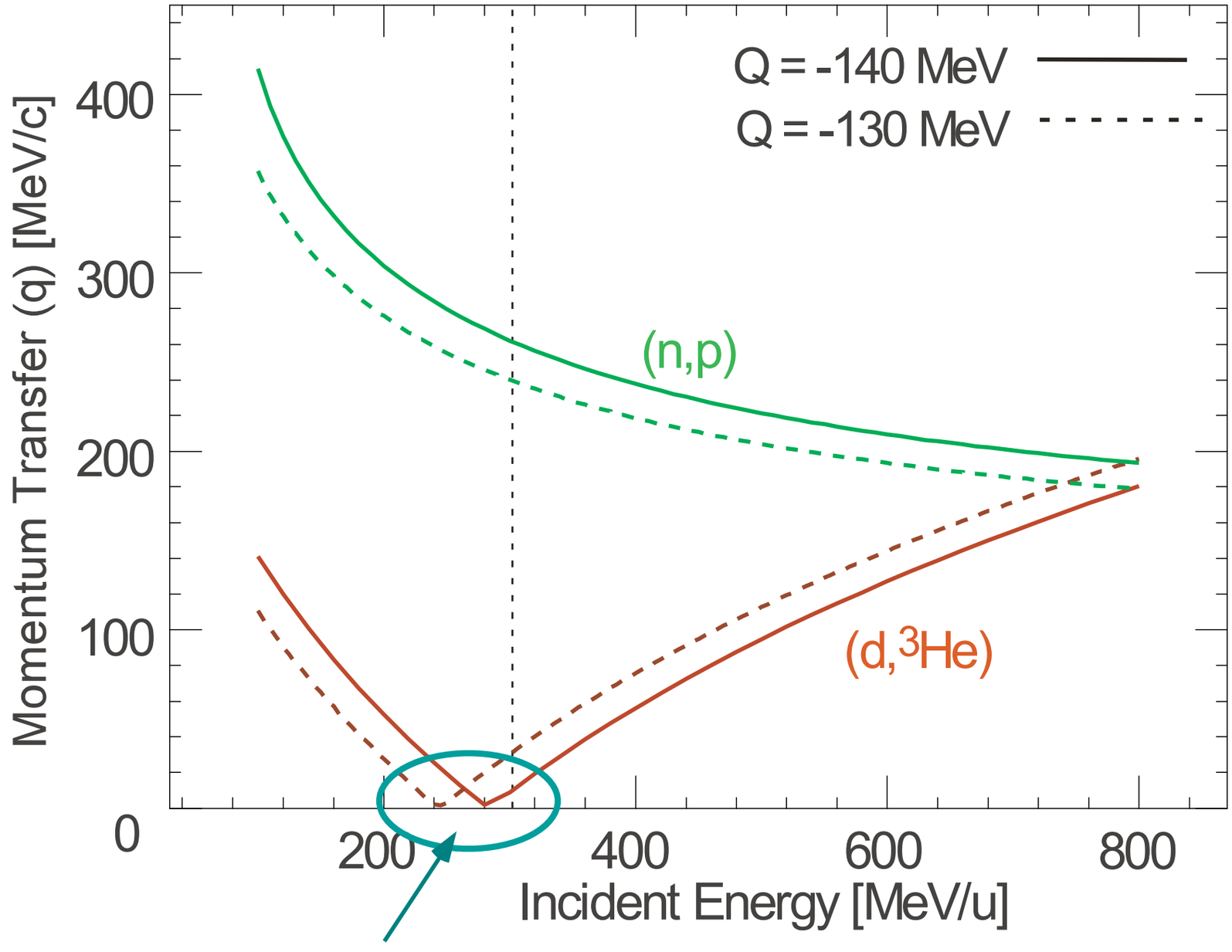
(d,^{3}He) nuclear reaction
to directly produce deeply bound pionic atom i.e. hidden states in X-ray spectroscopy



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

We are aiming at
300 keV (FWHM) resolution.
(prev. 400 keV)

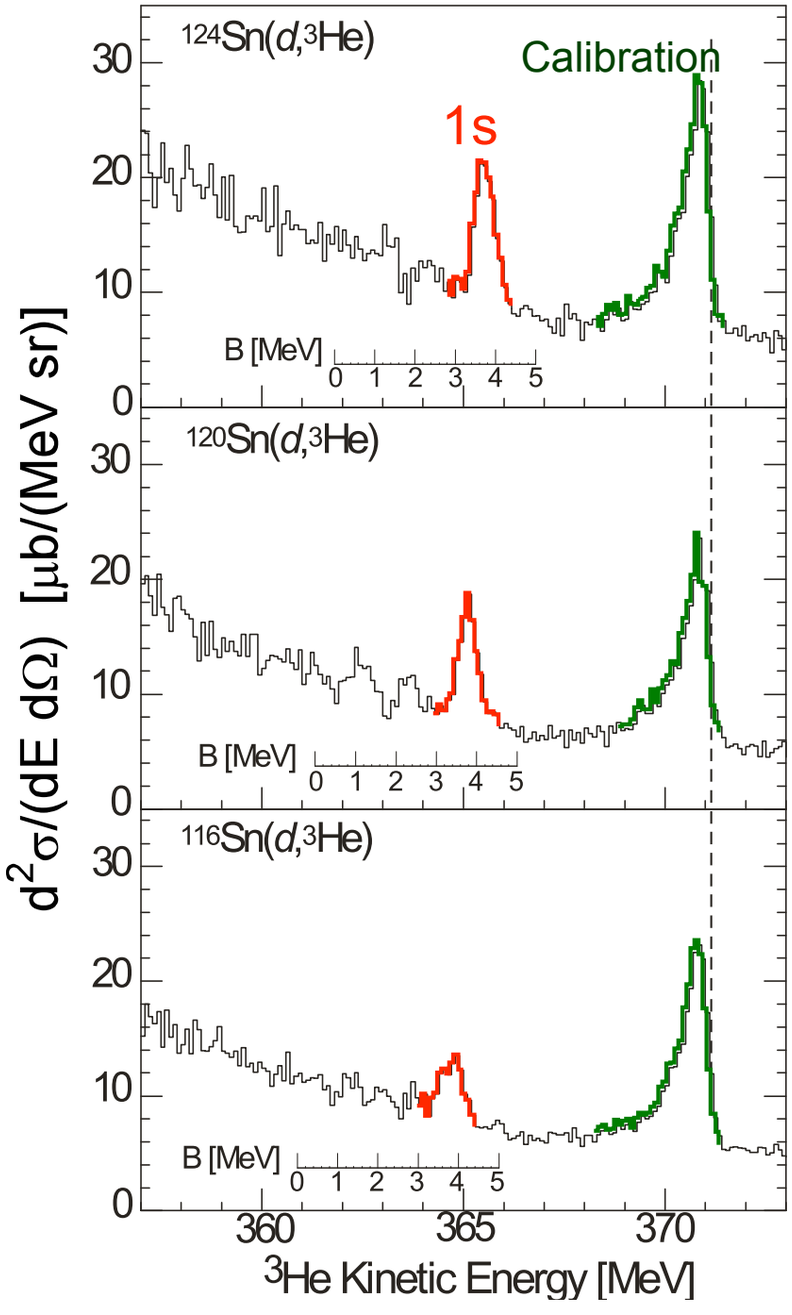
Momentum Transfer



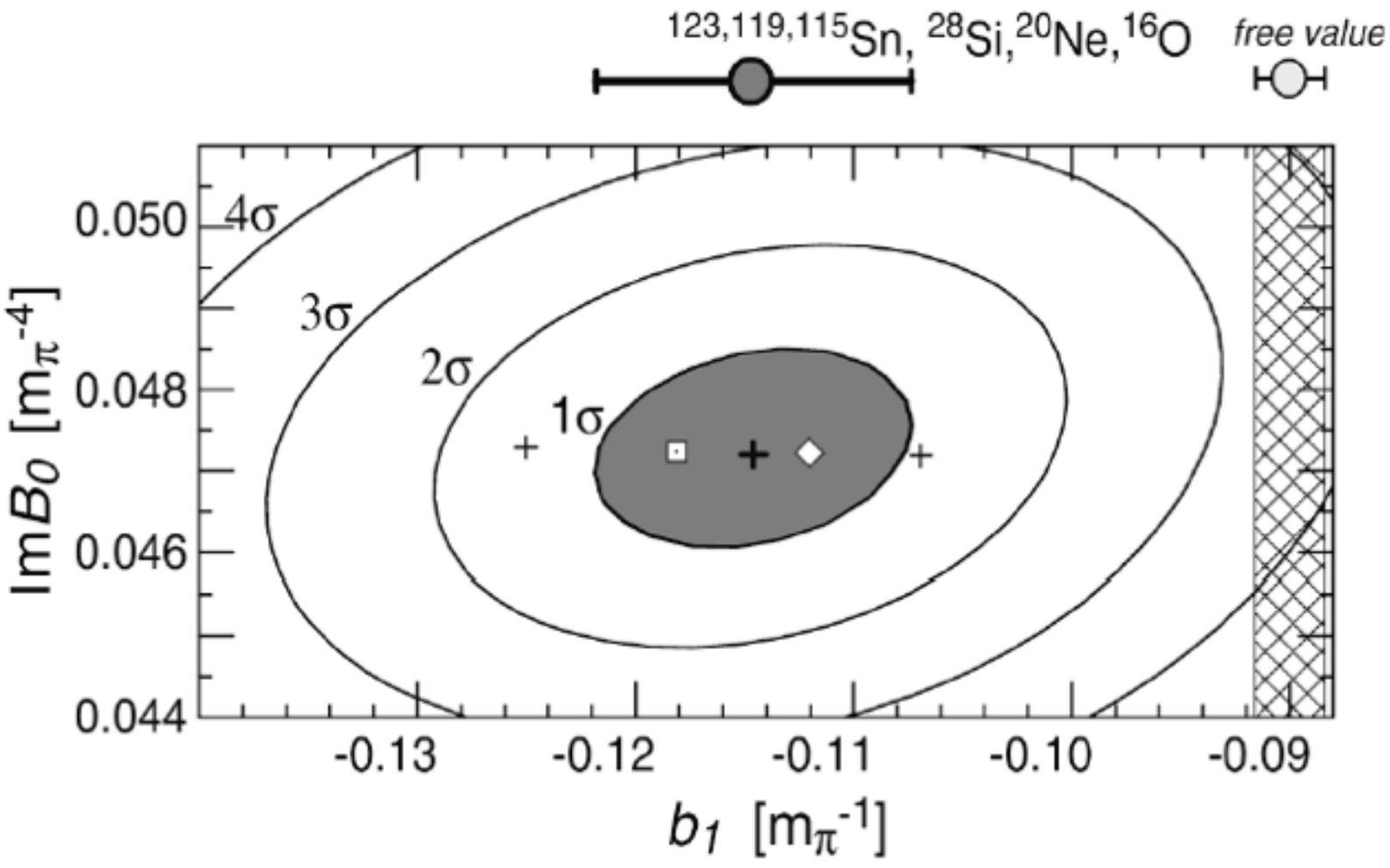
Quasi-substitutional (Δ~0) reaction
Small momentum transfer(q)

(d,^{3}He) reaction

Present b_1 precision



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



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

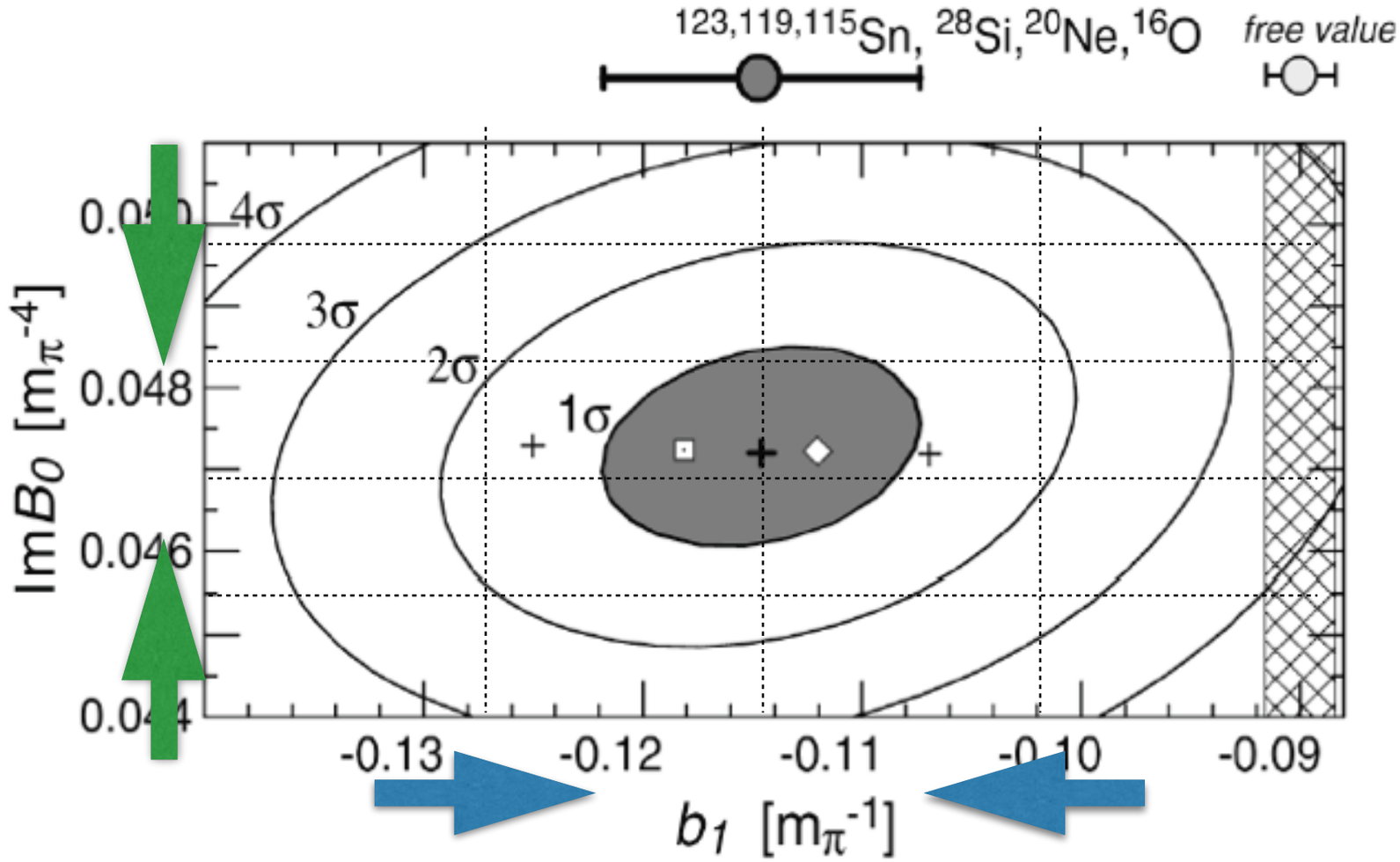
$$\rho_e = 0.6\,\rho_0$$

In-medium b_1 is calculated based on deeply bound pionic states data combined with light spherical pionic atom data.

Present b_1 precision

Γ_{1s}
^{115}Sn 0.441 ± 0.087
^{119}Sn 0.326 ± 0.080
^{123}Sn 0.341 ± 0.072

B_{1s}
^{115}Sn 3.906 ± 0.024
^{119}Sn 3.820 ± 0.018
^{123}Sn 3.744 ± 0.018



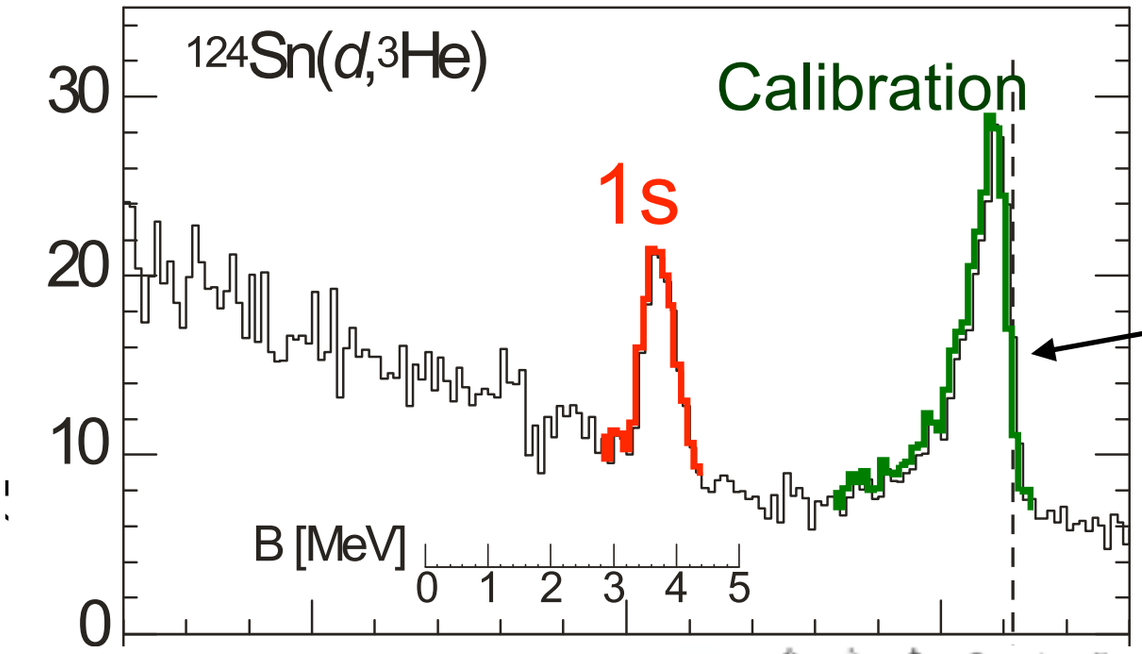
$$V_{s\text{-wave}} = b_0\,\rho + b_1\,(\rho_n - \rho_p) + B_0\,\rho^2$$

$$\rho_e = 0.6\,\rho_0$$

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

In-medium b_1 is calculated based on deeply bound pionic states data combined with light spherical pionic atom data.

Experimental resolution / systematic errors



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

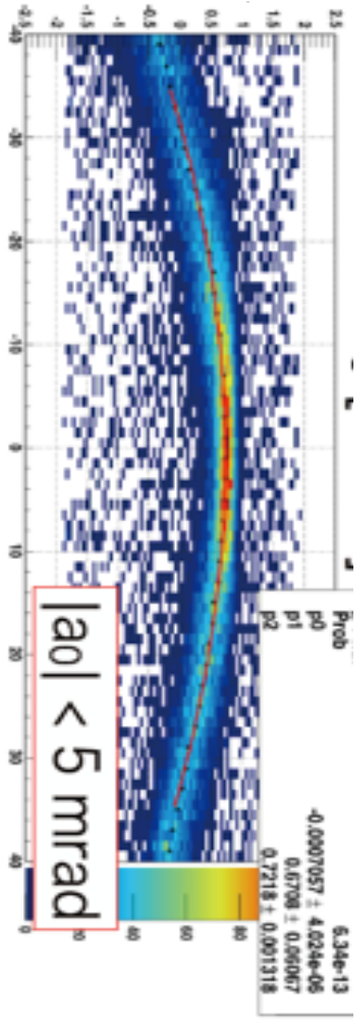


Figure based on
data taken at RIBF

in-situ Calibration
$p(d,^3\mathrm{He})\pi^0$

using CH2 pasted Sn target

Resolution ~ 400 keV
(beam p spread, target thickness)

Systematic errors
in absolute energy scale
(calibration, incident energy, dx/dp…)

We want to improve precision.

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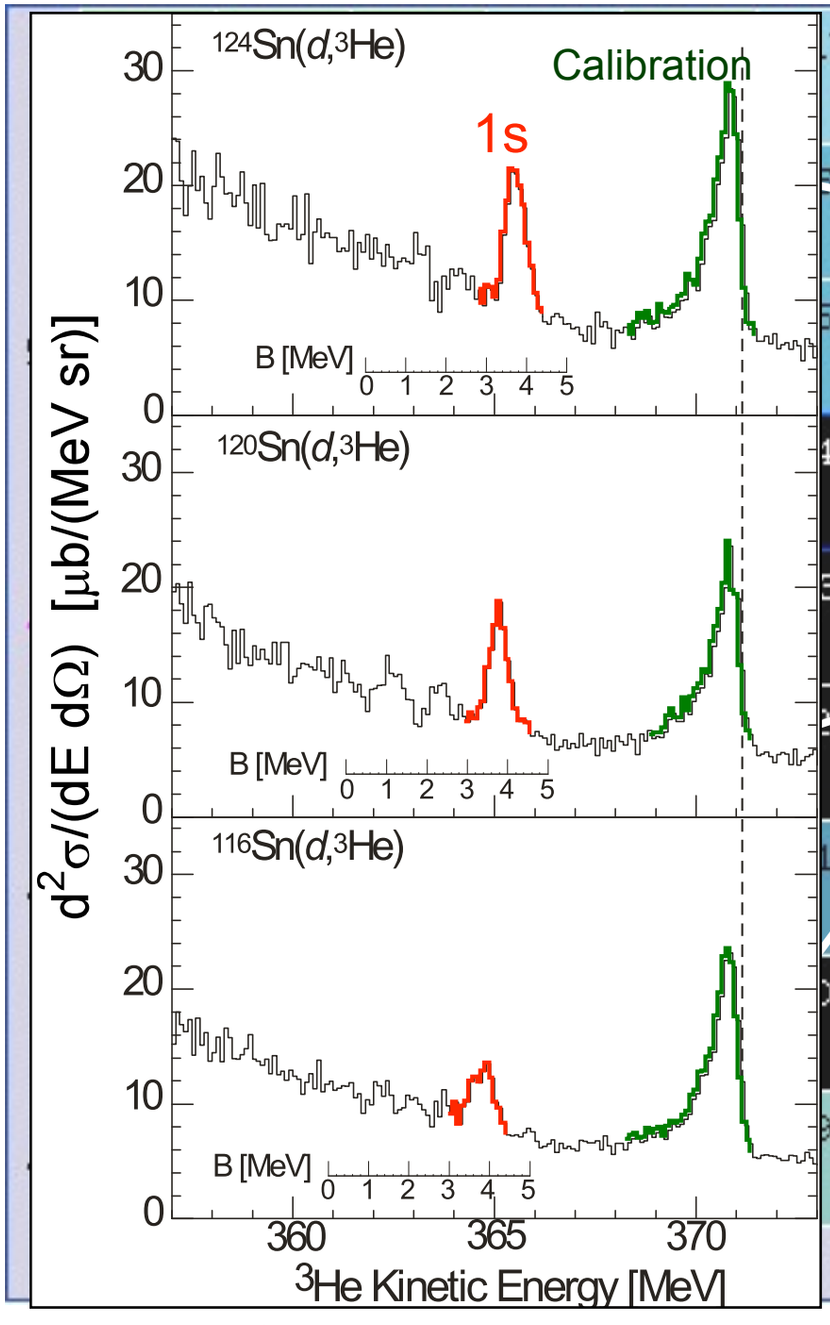
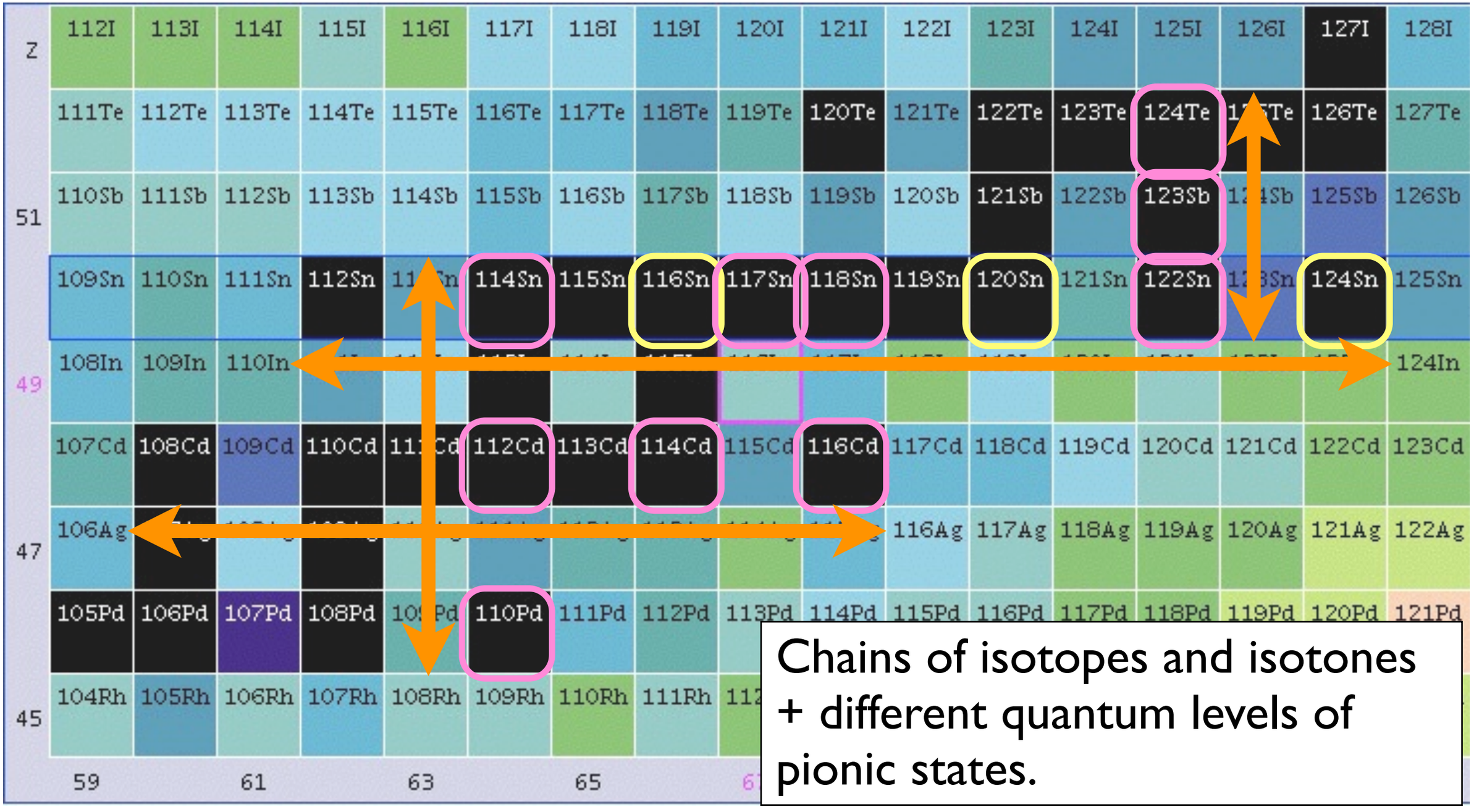
Pionic Atom Factory Project in RIBF



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

NNDC,BNL

Pionic Atom Factory Project in RIBF

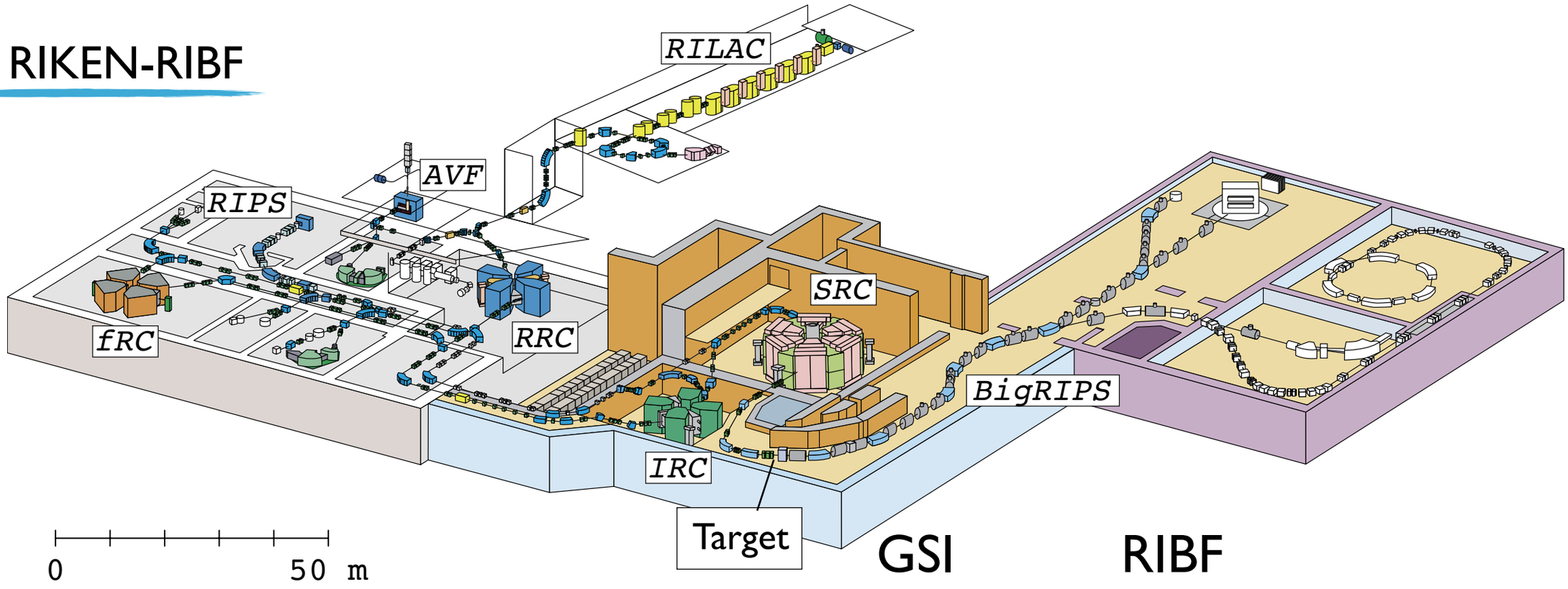


Chains of isotopes and isotones
+ different quantum levels of pionic states.

NNDC,BNL

Precision Spectroscopy at RI Beam Factory

RIKEN-RIBF



	GSI	RIBF
d beam Intensity	10	>10
Target	20 mg/cm	10 mg/cm
Δ	0.03%	0.1%
Resolution (FWHM)	400 keV	1000 keV
Acceptance (mrad)	15H, 10V	40H, 60V

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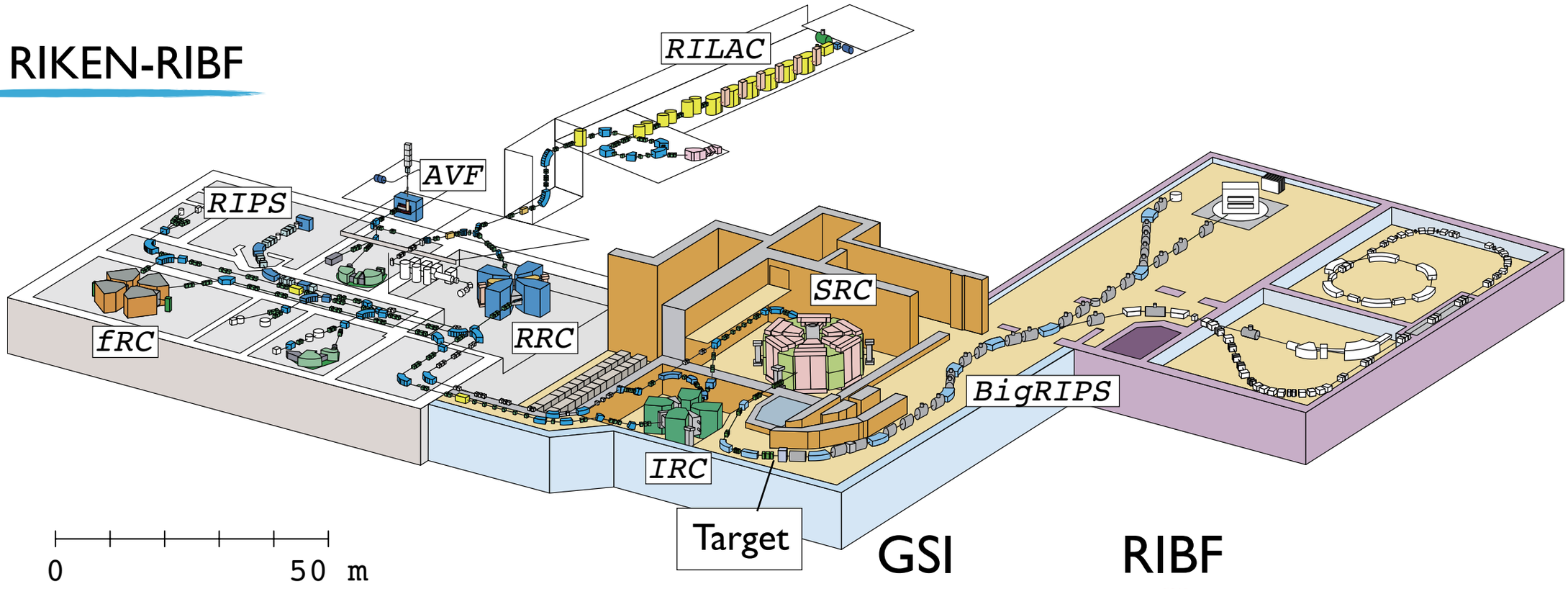
Precision Spectroscopy at RI Beam Factory

RIKEN-RIBF



	GSI	RIBF
d beam Intensity	10	>10
Target	20 mg/cm	10 mg/cm
Δ	0.03%	0.1%
Resolution (FWHM)	400 keV	1000 keV ▲
Acceptance (mrad)	15H, 10V	40H, 60V

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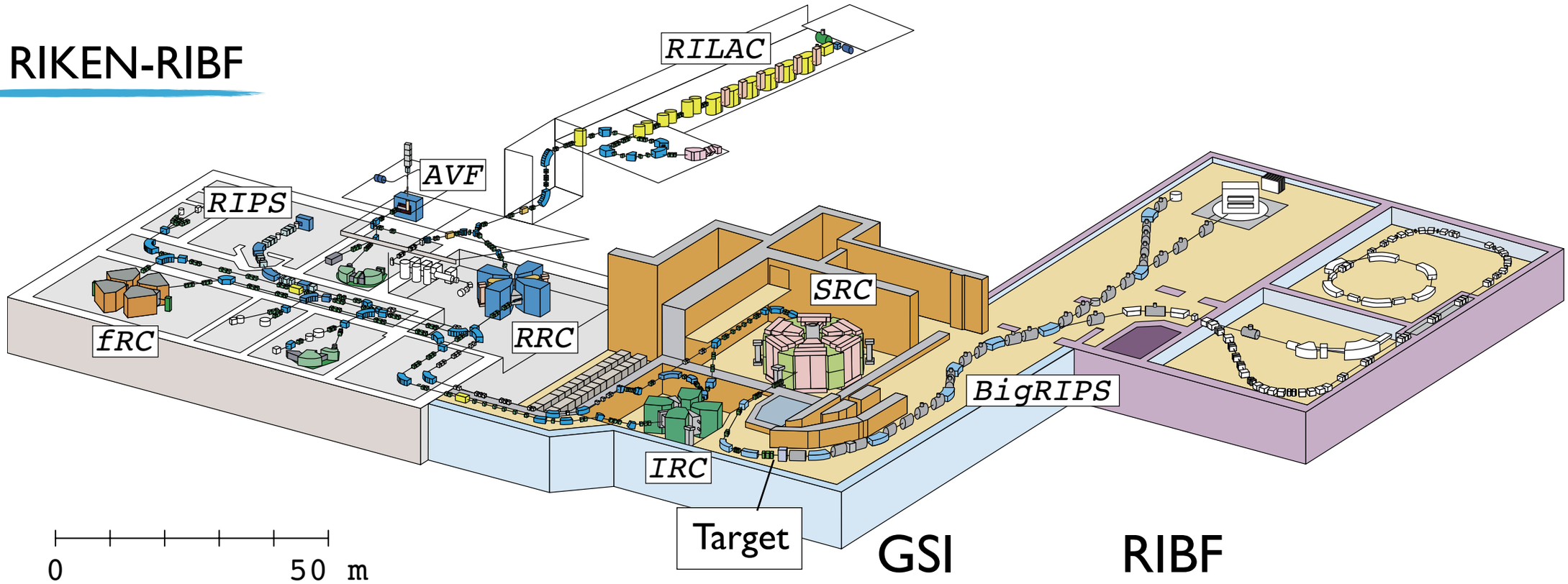
Precision Spectroscopy at RI Beam Factory

RIKEN-RIBF



	GSI	RIBF
d beam Intensity	10	>10
Target	20 mg/cm	10 mg/cm
Δ	0.03%	0.06%
Resolution (FWHM)	400 keV	>500 keV
Acceptance (mrad)	15H, 10V	40H, 60V

Slit optimization

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Dispersion matching

$$\begin{pmatrix} x \\ a \\ \delta \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{16} \\ s_{21} & s_{22} & s_{26} \\ 0 & 0 & 1 \end{pmatrix} T \begin{pmatrix} b_{11} & b_{12} & b_{16} \\ b_{21} & b_{22} & b_{26} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ a_0 \\ \delta_0 \end{pmatrix}$$

Spectrometer

Beam line to Target

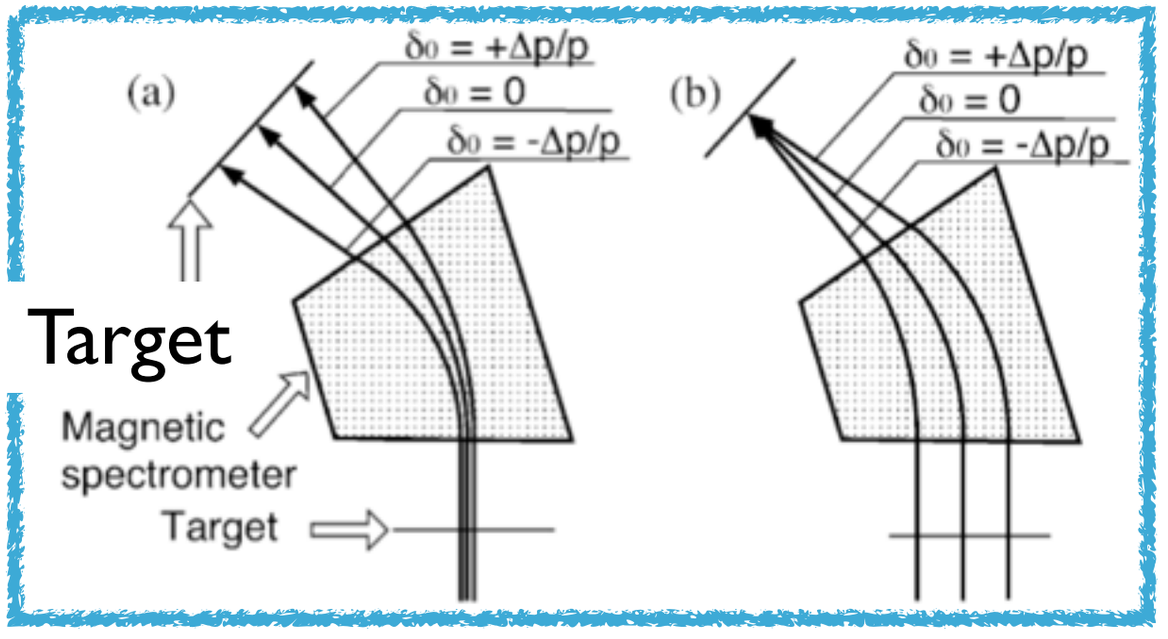
$\delta = C\delta_0$
$C = 1.31$

(*d*,^{3}He)

Beam position at focal plane

$$x = (s_{11}b_{11} + s_{12}b_{21})x_0 + (s_{11}b_{12} + s_{12}b_{22})a_0 + (s_{11}b_{16} + s_{12}b_{26} + s_{16}C)\delta_0$$

H. Fujita *et al.*, NIMA484(2002)17



Dispersion matching condition

$$s_{11}b_{16} + s_{12}b_{26} + s_{16}C = 0$$

$$b_{16} = -\frac{s_{16}C}{s_{11}} = 44.6 \text{ mm/\%}$$

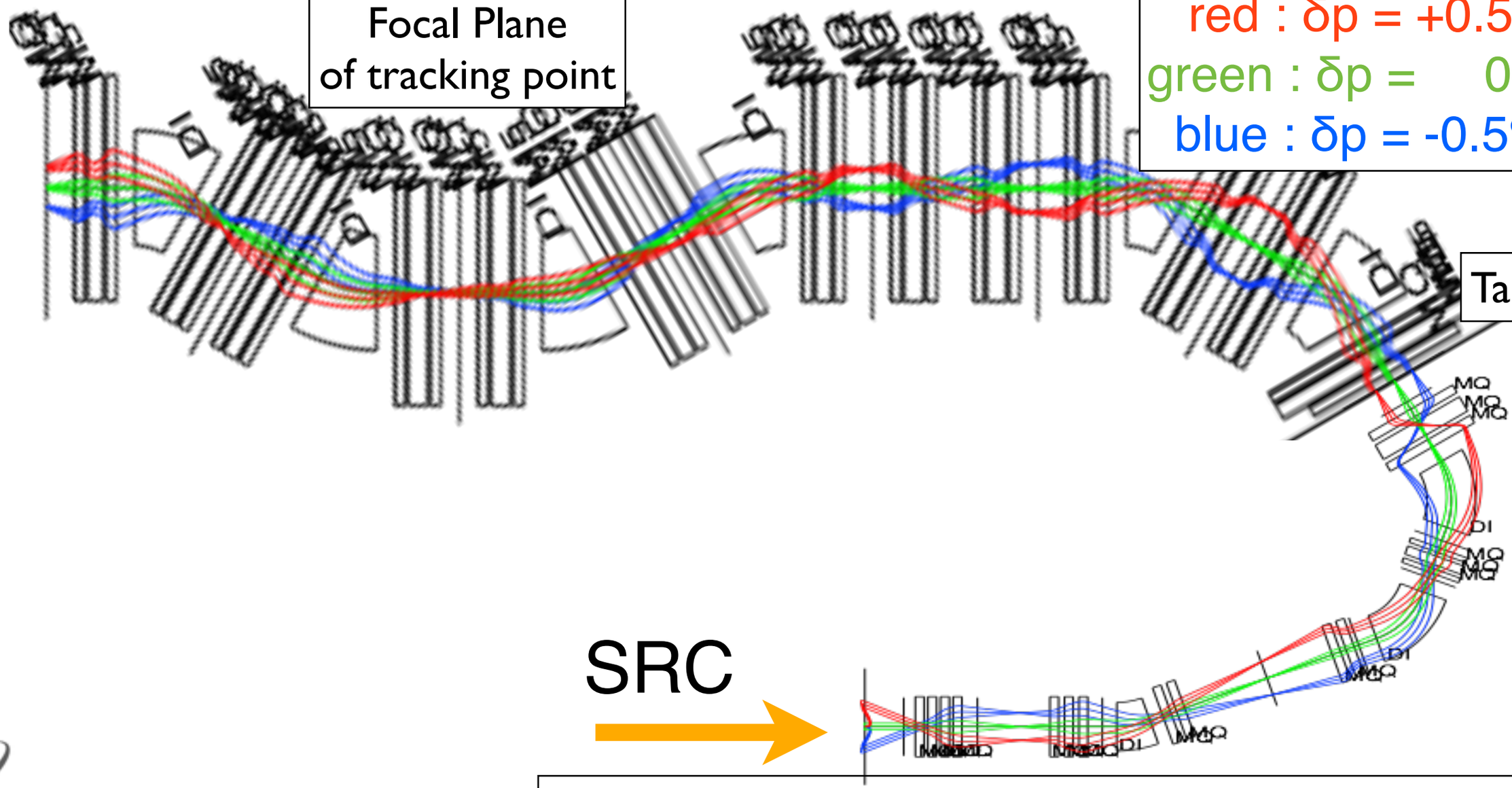
Ion Optics

T.Nishi

BigRIPS = Spectrometer

Focal Plane
of tracking point

red : δp = +0.5%
green : δp = 0%
blue : δp = -0.5%

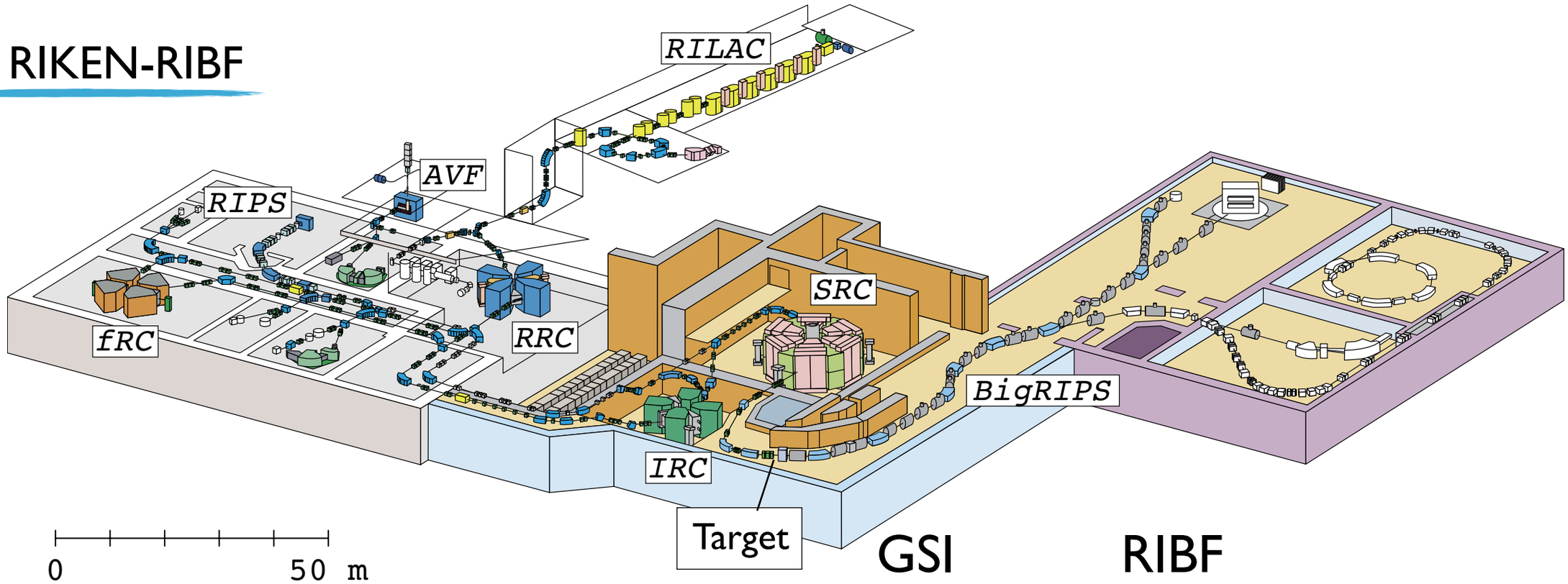


SRC

Beam Transfer line = Analyzer

Precision spectroscopy at RI Beam Factory

RIKEN-RIBF



	GSI	RIBF
d beam Intensity	10	10
Target	20 mg/cm	10 mg/cm
Δ	0.03%	0.06%
Resolution (FWHM)	400 keV	< 300 keV
Acceptance (mrad)	15H, 10V	40H, 60V

Resol. Matching

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RIBF-54 Objectives

- 2010 Pilot run (~3 days)

  Establish experimental methods

  (calibration, optics, detectors etc.)

  Take a short production run w. Sn target for overall test

- 2014 Main run (~10 days)

  Achieve world highest resolution < 400 keV

  First observation of 1*s* + 2*s* pionic Sn states

  → better precision + better sys. error for B and Γ

  First data for pionic even *N* Sn atom

Pionic Atom Factory Project in RIBF

NNDC,BNL

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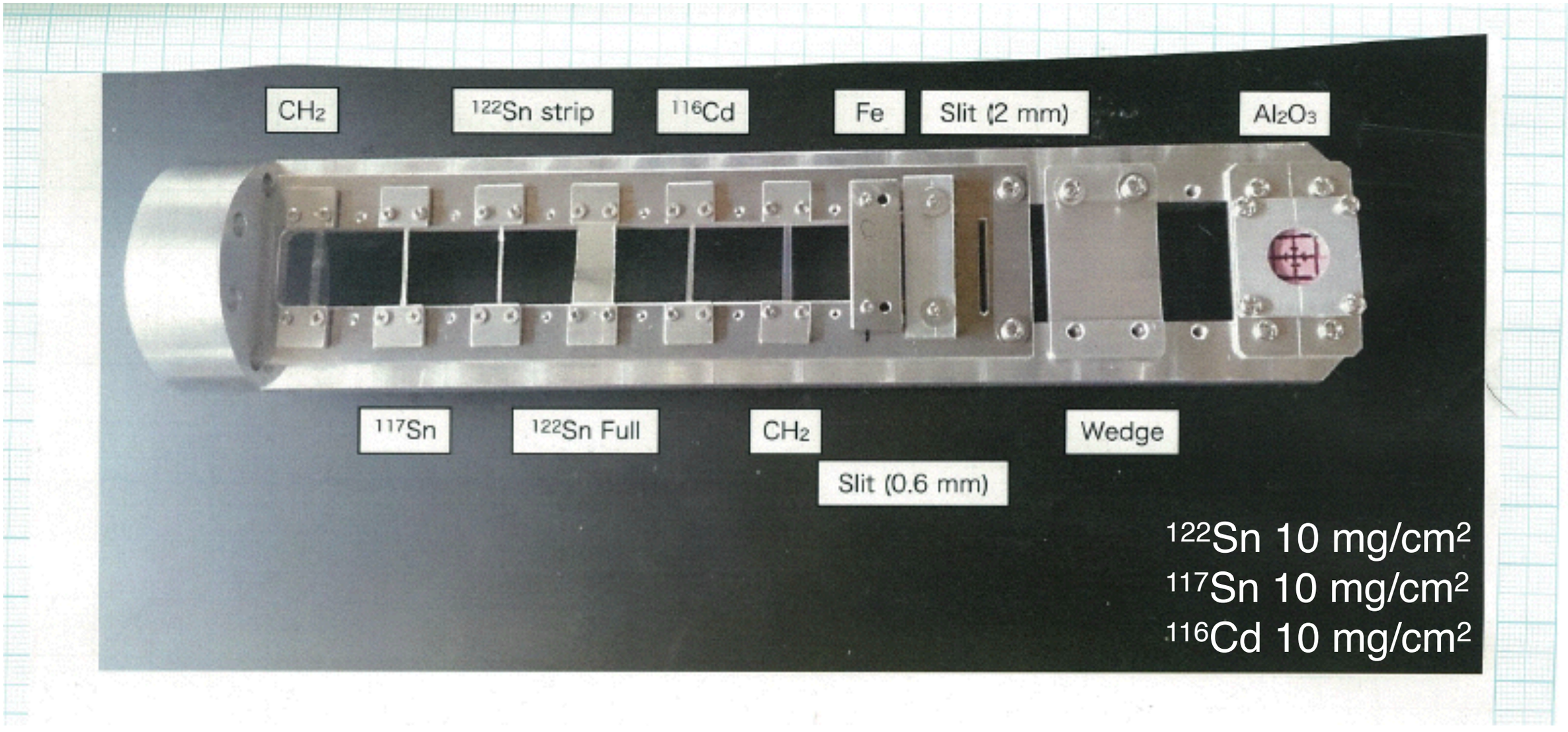
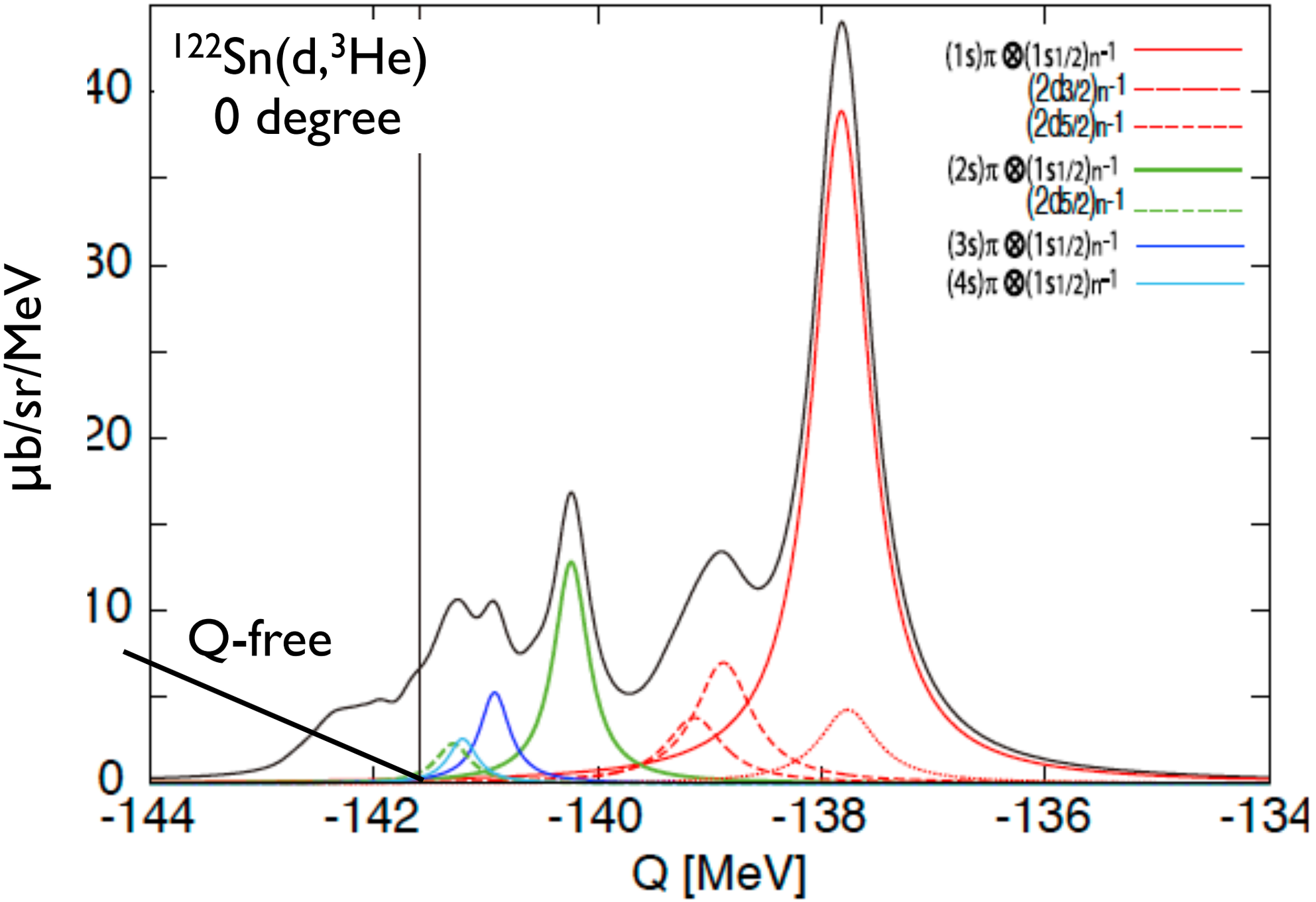
Prepared targets



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



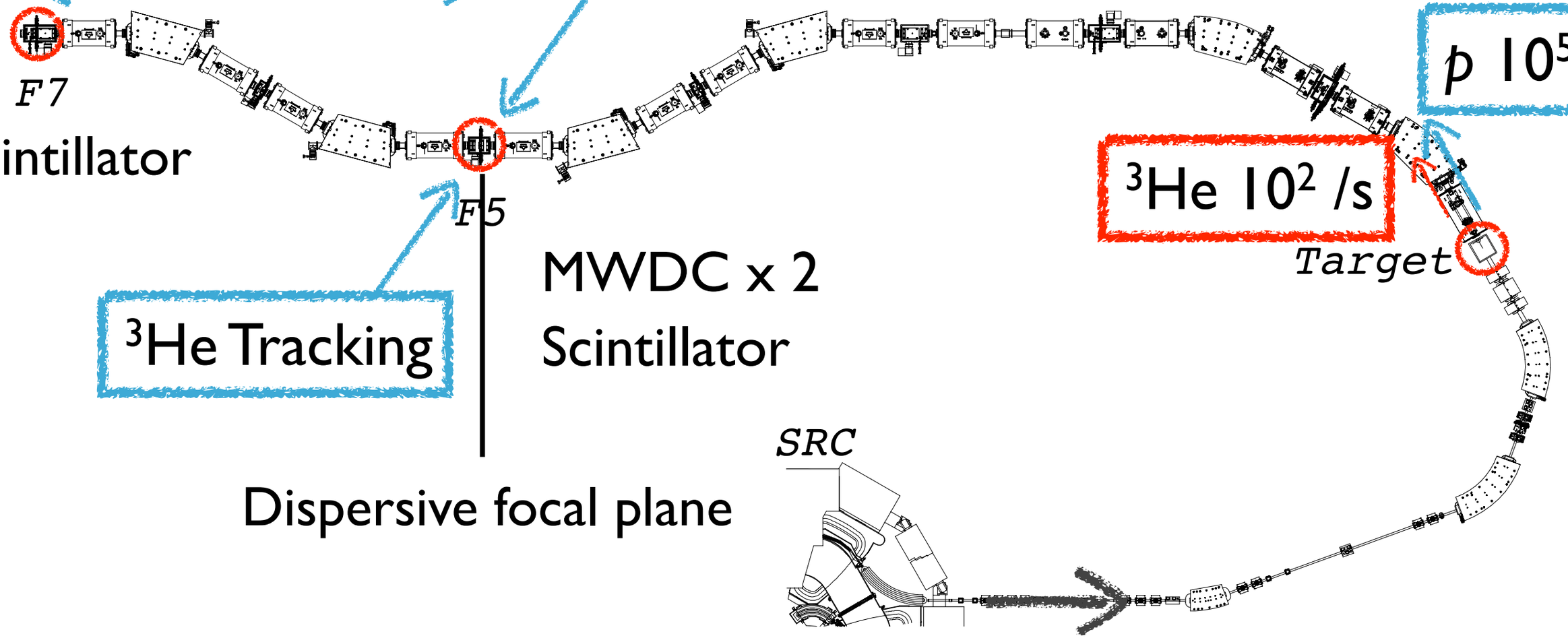
N. Ikeno, Eur.Phys.J. A47 (2011) 161

Experimental setup

BigRIPS

TOF measurement

ΔE measurement



Scintillator

p 10^5 /s

^{3}He 10^2 /s

^{3}He Tracking

MWDC x 2

Scintillator

Dispersive focal plane

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

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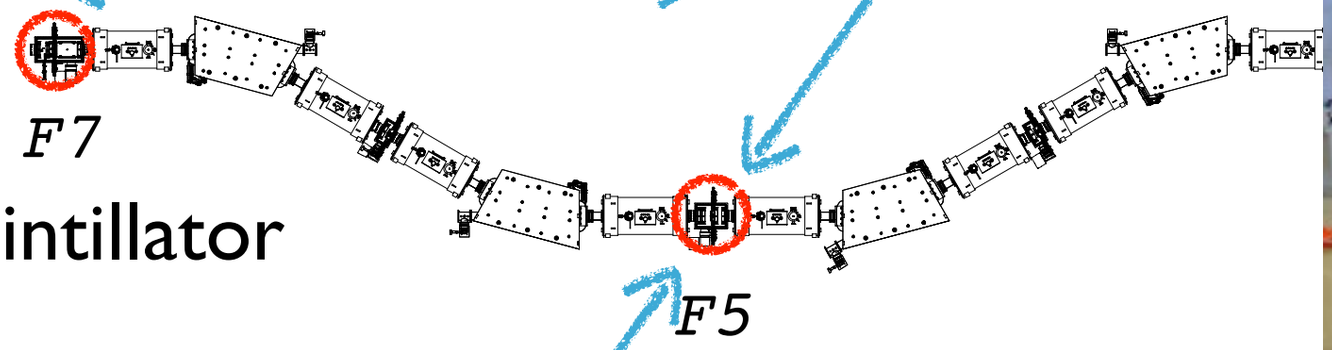
Experimental setup

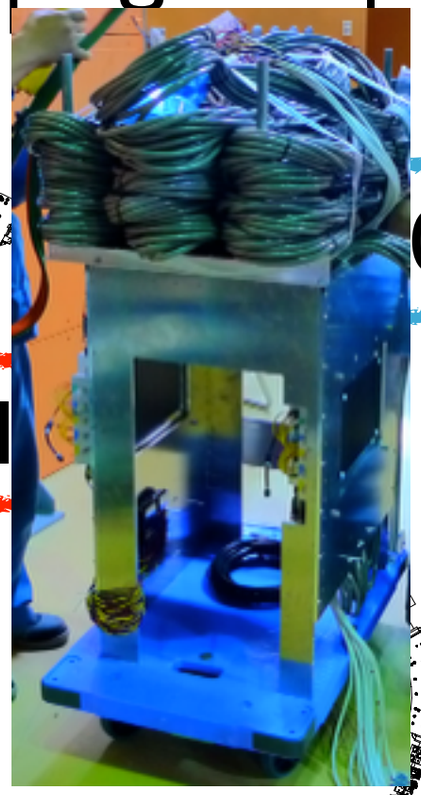
TOF measurement

ΔE measureme

BigRIPS



Scintillator

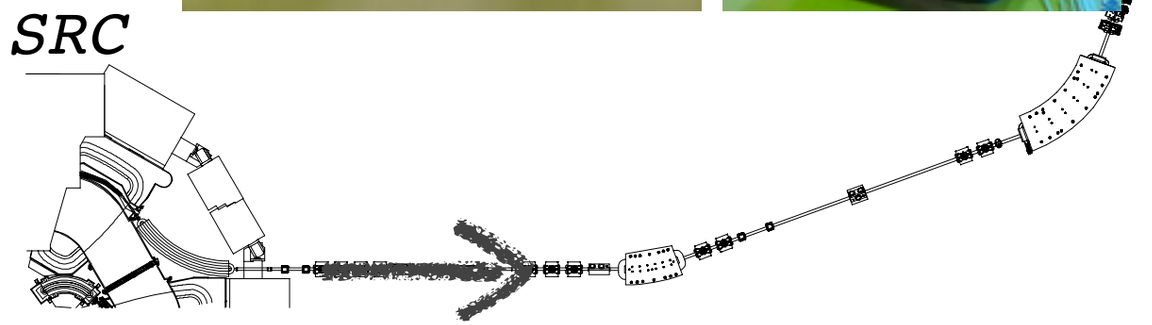


0^5 /s

^{3}He Tracking

MWDC x 2

Scintillator



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

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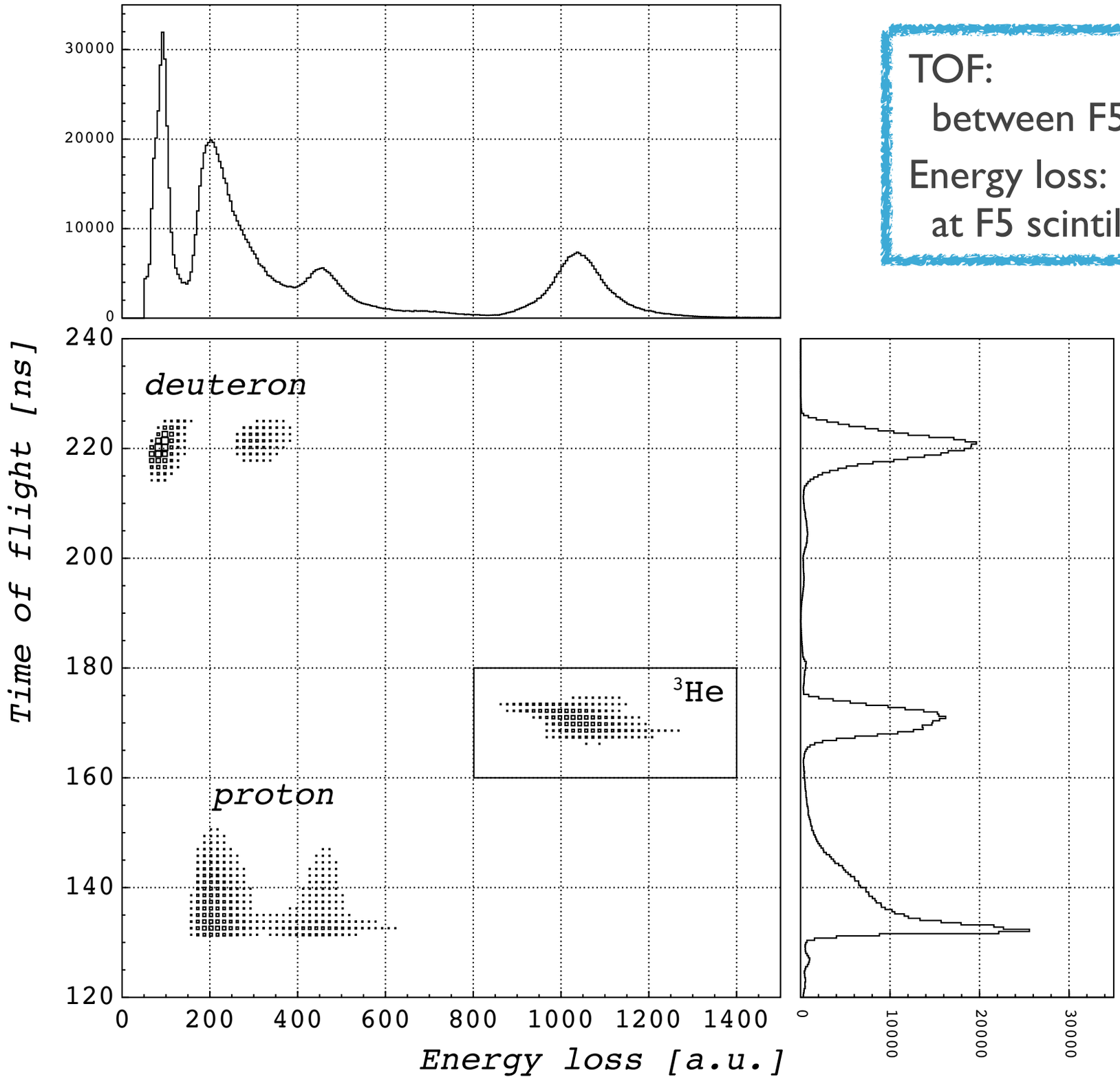
Particle identification



TOF:
between F5 and F7

Energy loss:
at F5 scintillators

RIBF-54

Focal Plane ^{3}He Spectrum in 2010

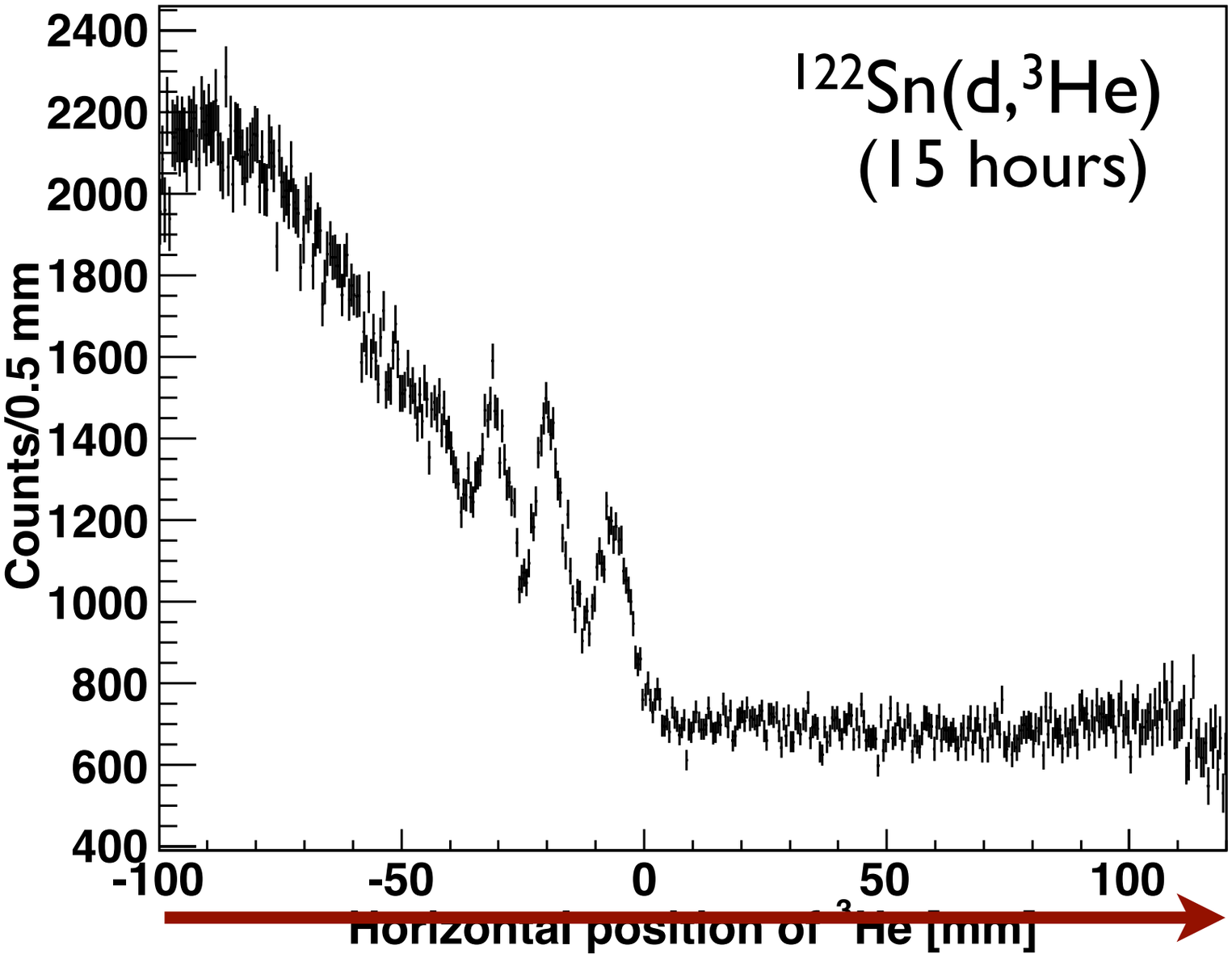
(acceptance roughly corrected)

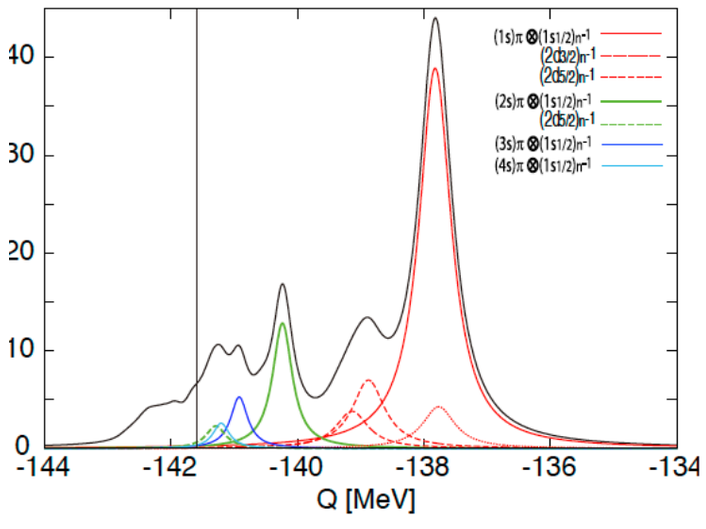
15 hours

data accumulatio

with 10^{12}/s beam

for pilot exp.





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

RIBF-54

Focal Plane ^{3}He Spectrum in 2010

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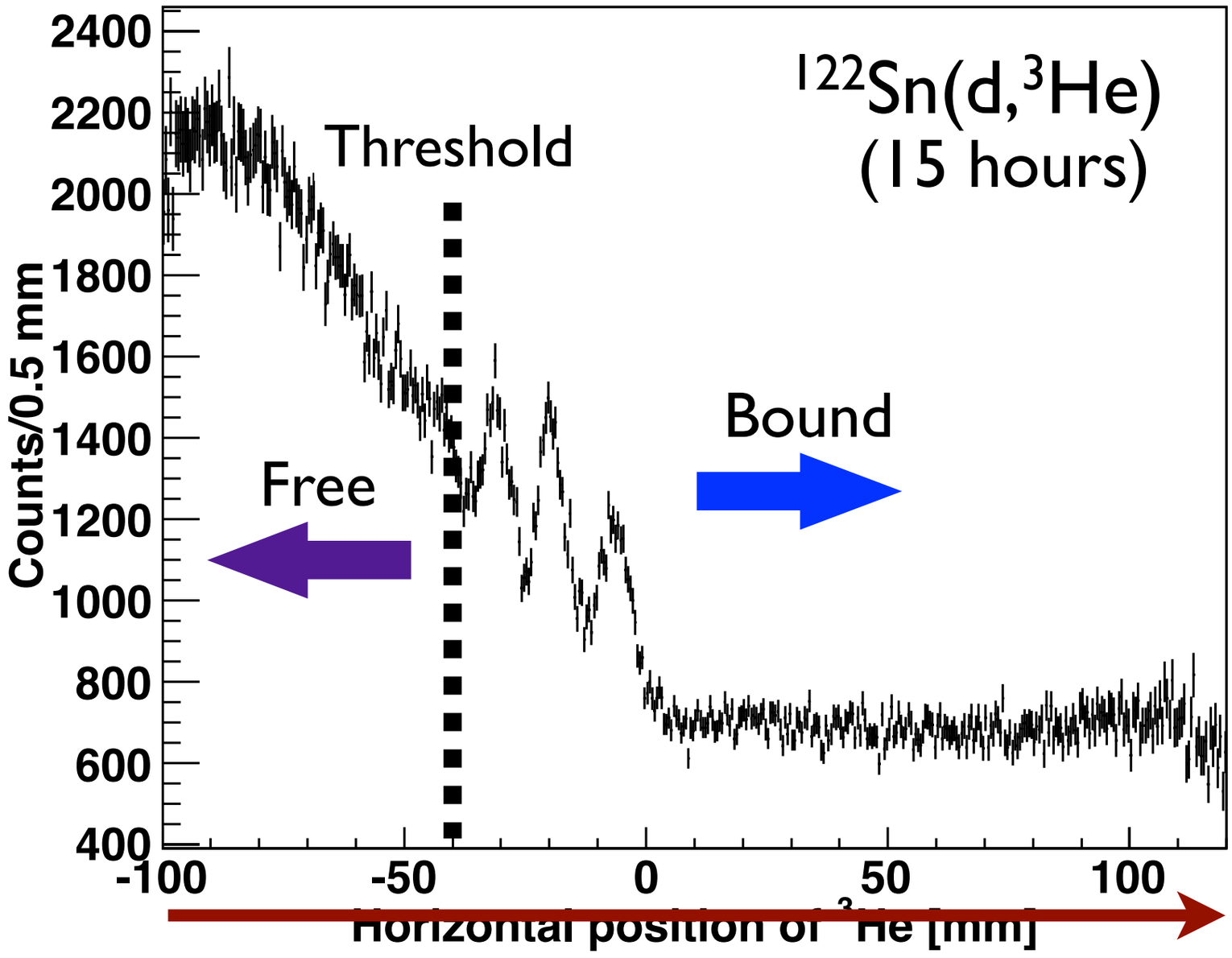

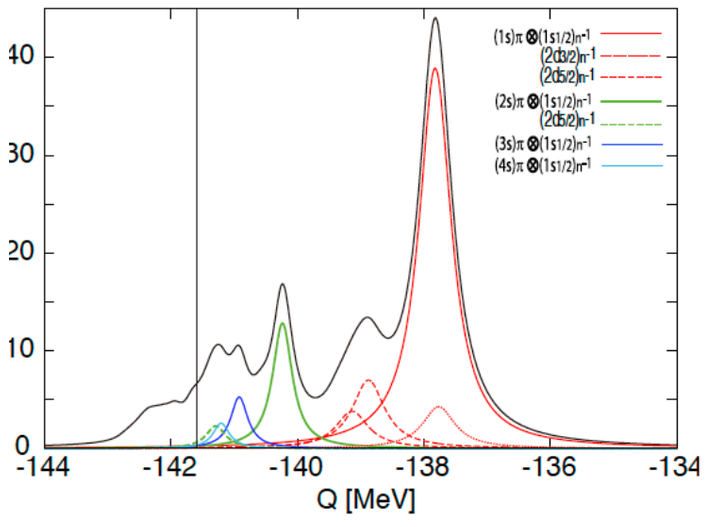

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RIBF-54

Focal Plane ^{3}He Spectrum in 2010

(acceptance roughly corrected)

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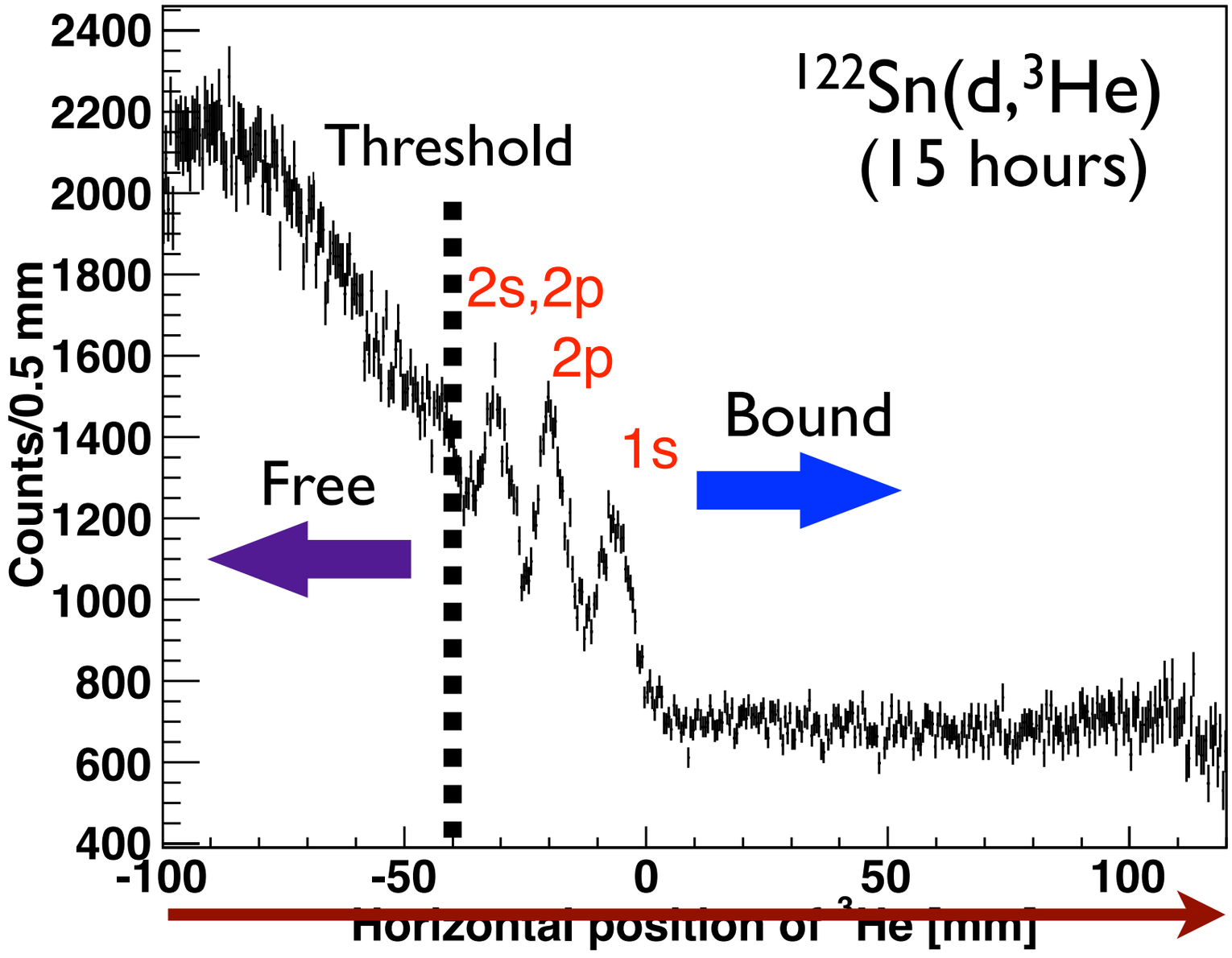
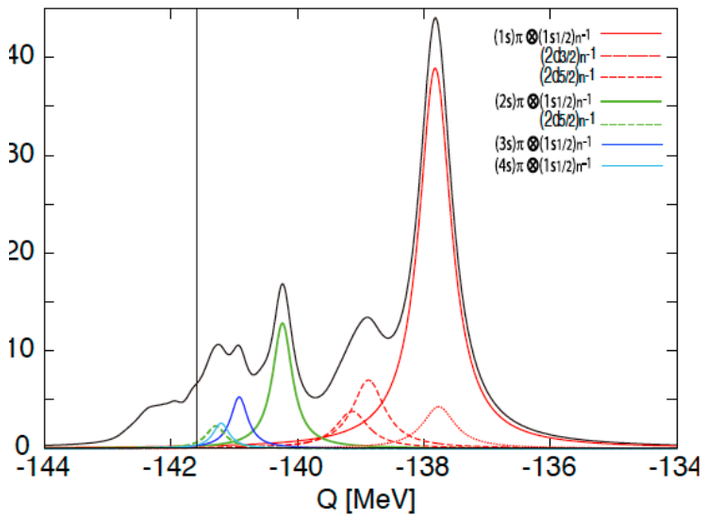
data accumulatio

with 10^{12}/s beam

for pilot exp.





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

RIBF-54

Achievements in pilot run 2010 and goals for main run 2014

Achievements in 2010

All system works & surprisingly good statistics in a short time

First observation of pionic ^{121}Sn

First observation of angular dependence of piA formation

(however w. insufficient calibration/correction data…)

Goals for 2014

Achieve better resolution

Take calibration / acceptance / aberration correction data

Attempt to systematic study

Improvements in 2014

incident beam (dp/p, I_d), beam optics, detectors, DAQ,/online…

Online spectrum from 2014

2014

^{122}Sn(d,^{3}He)

Acceptance not corrected
Higher order aberration roughly corrected

^{3}He energy Smaller

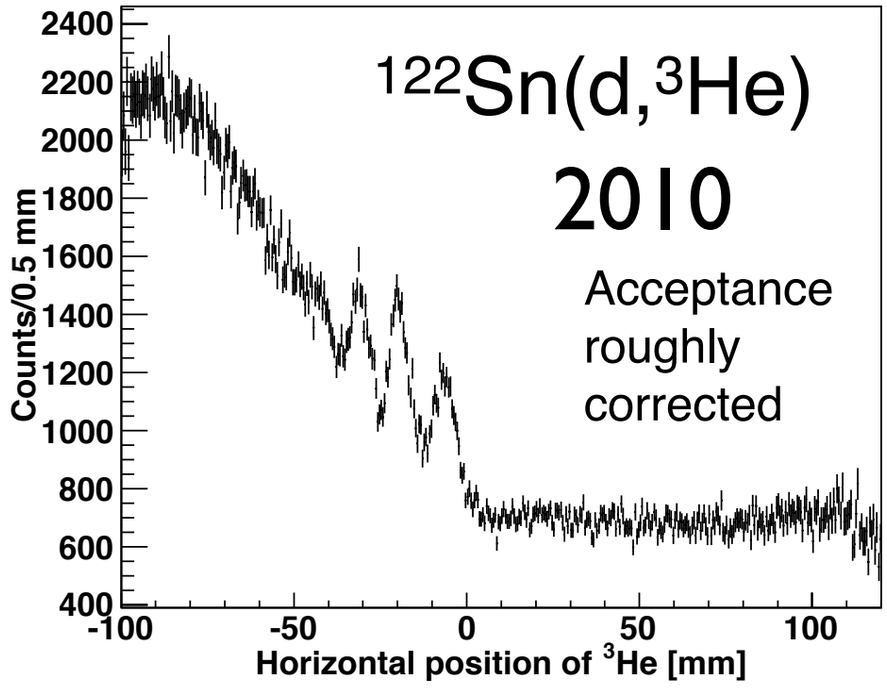
Focal Plane Position [mm]

^{3}He energy Larger

RIBF-54

Online spectrum from 2014

2014



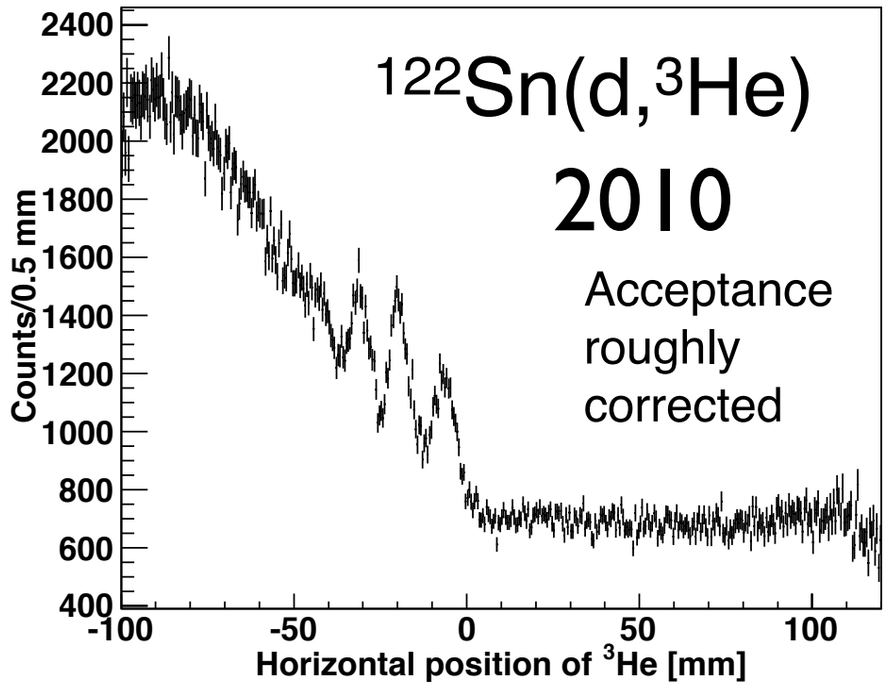
Acceptance not corrected
Higher order aberration roughly corrected

^{3}He energy Smaller — Focal Plane Position [mm] — ^{3}He energy Larger

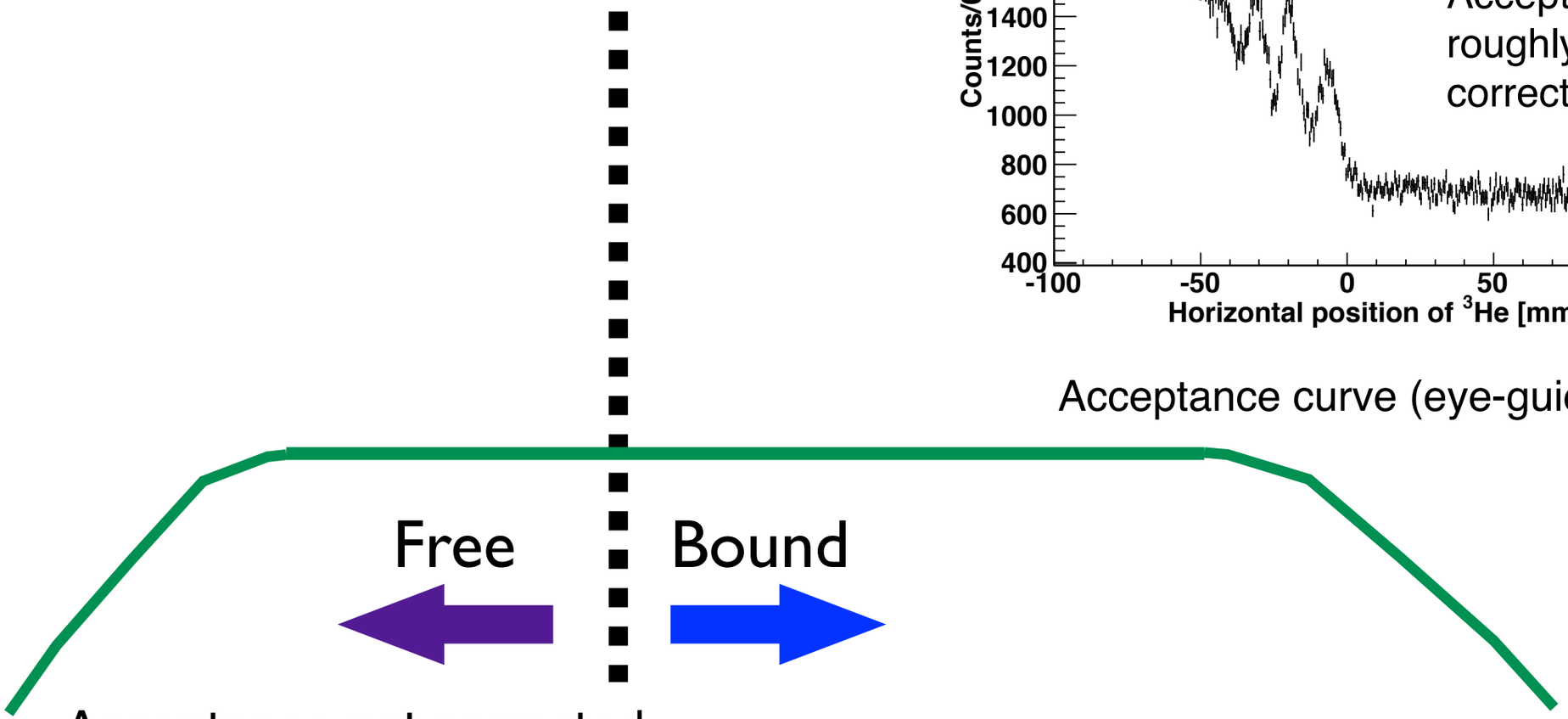
RIBF-54

Kenta Itahashi, RIKEN

Online spectrum from 2014



Acceptance curve (eye-guide)

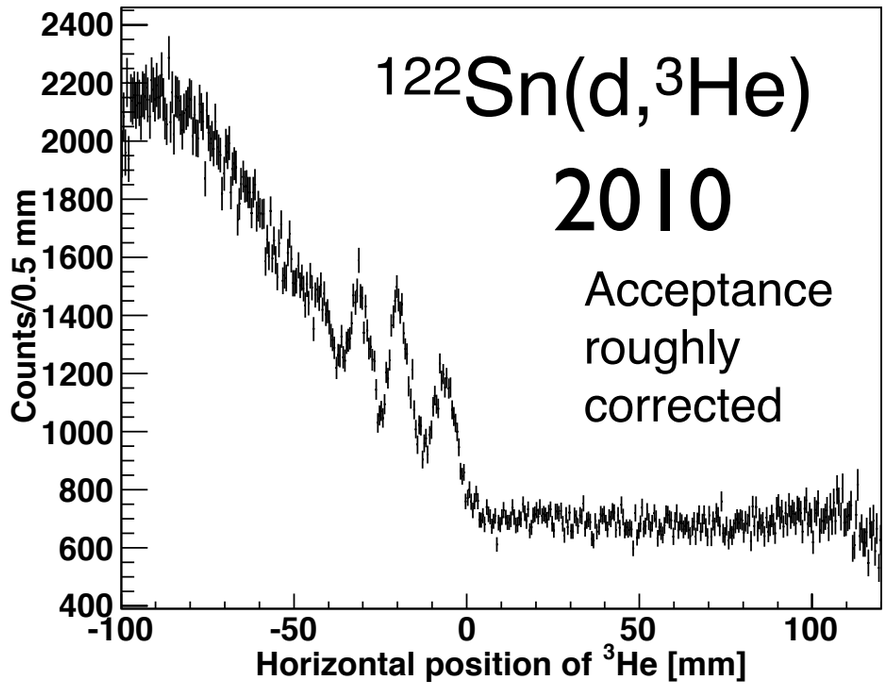


Acceptance not corrected
Higher order aberration roughly corrected

RIBF-54

Kenta Itahashi, RIKEN

Online spectrum from 2014



RIBF-54

Measured focal spectrum with angles

^{122}Sn(d,^{3}He) 2s,2p… 2p 1s

Angle [mrad]

^{3}He energy Smaller → ^{3}He energy Larger

Focal Position [mm]

RIBF-54

Measured focal spectrum with angles

^{122}Sn(d,^{3}He)

2s,2p… 2p 1s

Angle [mrad]

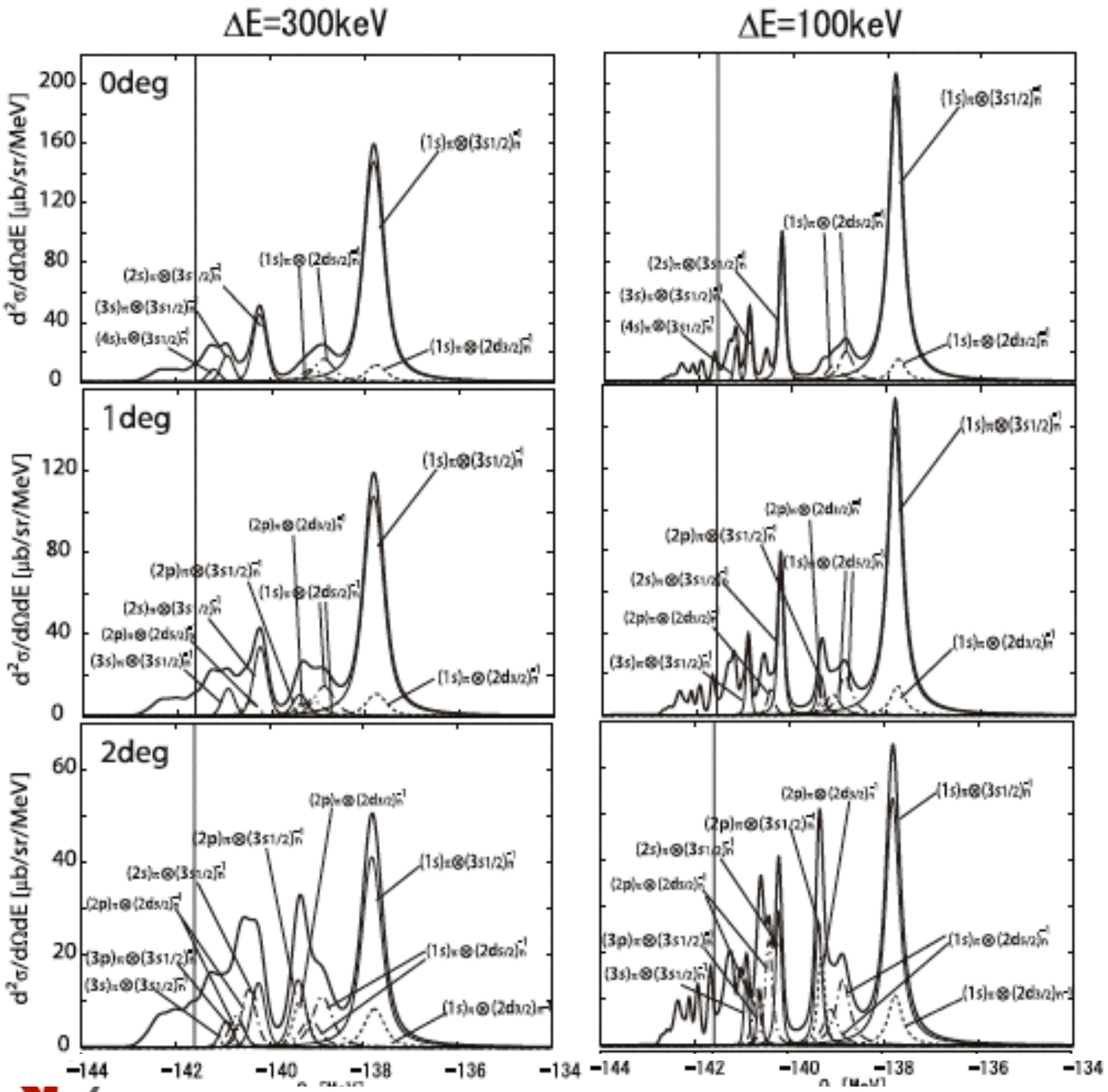
We clearly observe the angular dependence (= momentum transfer dependence) of pionic atom production cross section in (d,^{3}He) reaction

^{3}He energy Smaller

^{3}He energy Larger

Focal Position [mm]

^{122}Sn(d,^{3}He) Theory vs Experiment (2014)



0 deg

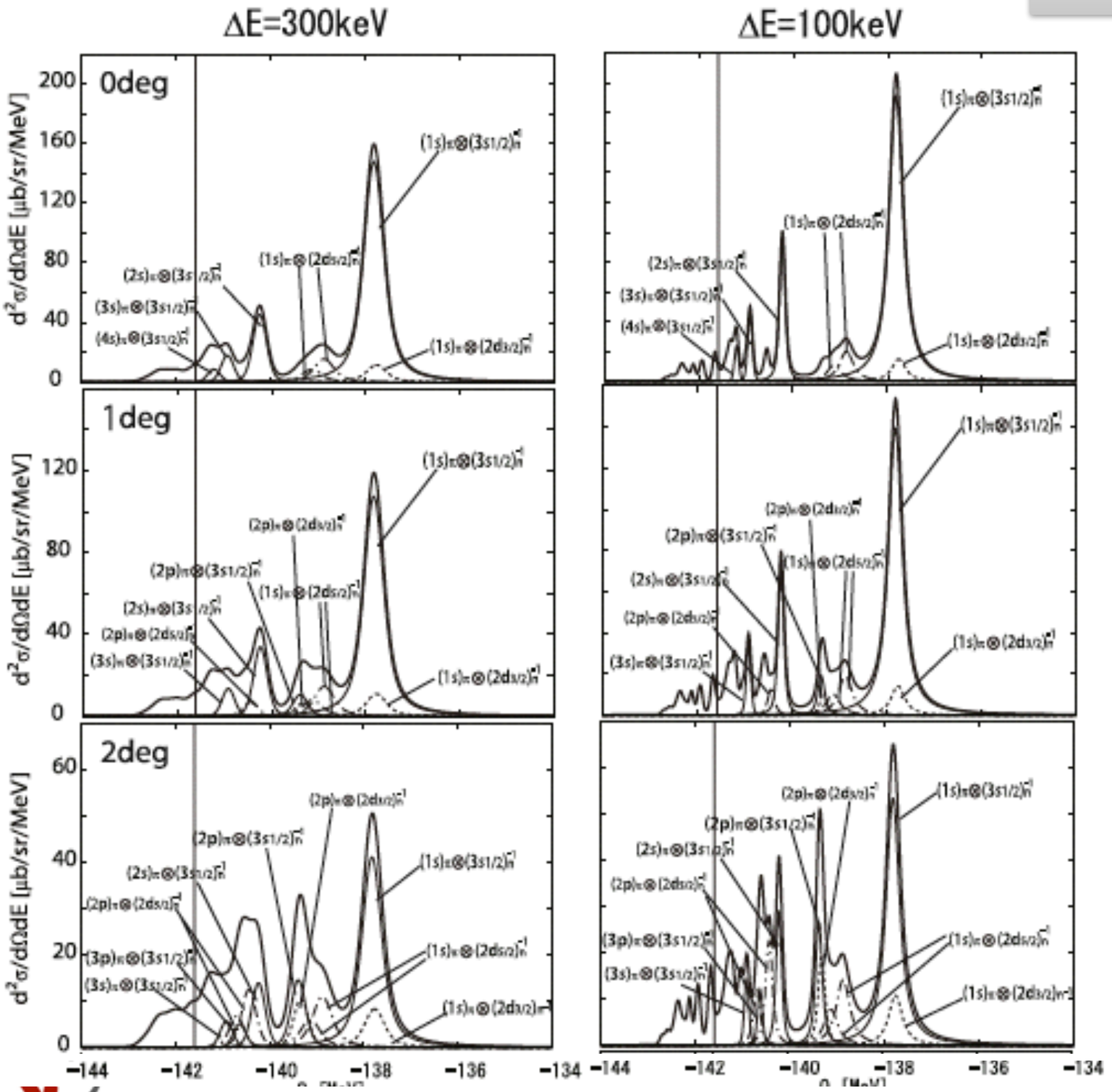
0.5 deg

1 deg

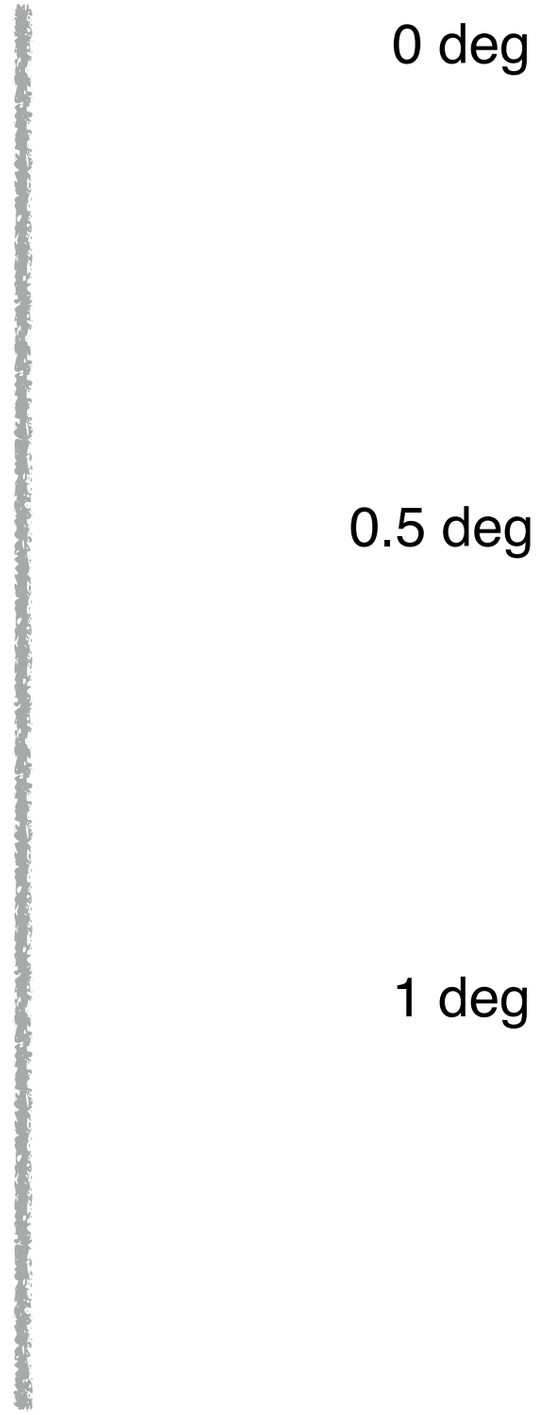
*N. Ikeno et al., Eur. Phys. J. A 47, 161 (2011)

^{122}Sn(d,^{3}He) Theory vs Experiment (2014)

Theory and exp. basically agree.
Very good resolution at 0 degree.
The analysis still take time.



*N. Ikeno et al., Eur. Phys. J. A 47, 161 (2011)



RIBF-54

First observation with an even neutron number nucleus

Online spectrum from 2014

^{117}Sn(d,^{3}He)

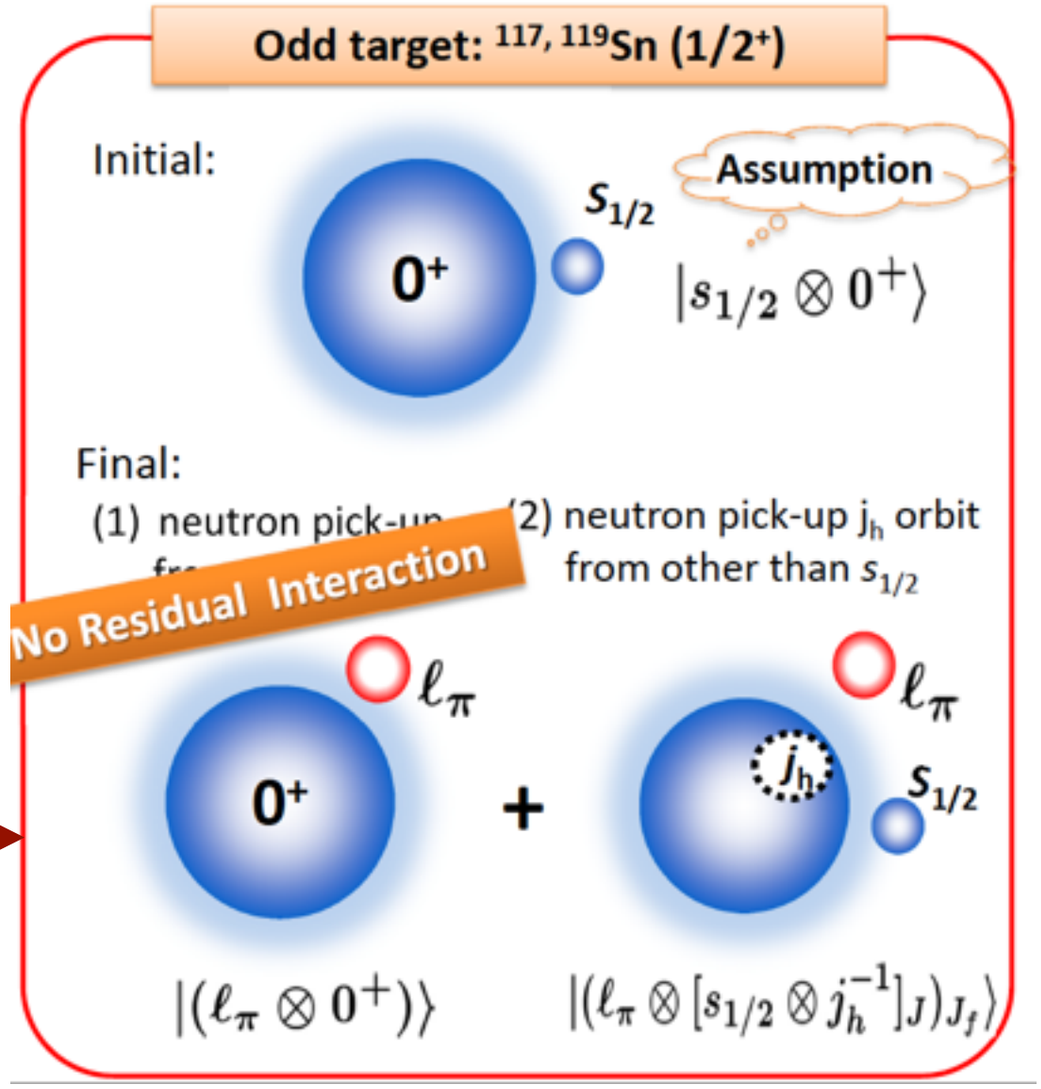
θ < 10 mrad
no acc. correction

1s

^{3}He energy smaller ← Focal Position [mm] → ^{3}He energy higher

First observation of pionic atom with even N
→ better separation in the neutron hole configurations.

Ikeno et al., Prog. Theor. Exp. Phys. 2013 , 063D01



N. Ikeno (Hadron 2013)

Summary for piAF

- World highest resolution
- Extremely good statistics for ^{121}Sn-pi
- First data for pionic even *N* atom
- Analysis is ongoing now (by T. Nishi)
- Publish 2010 results in short

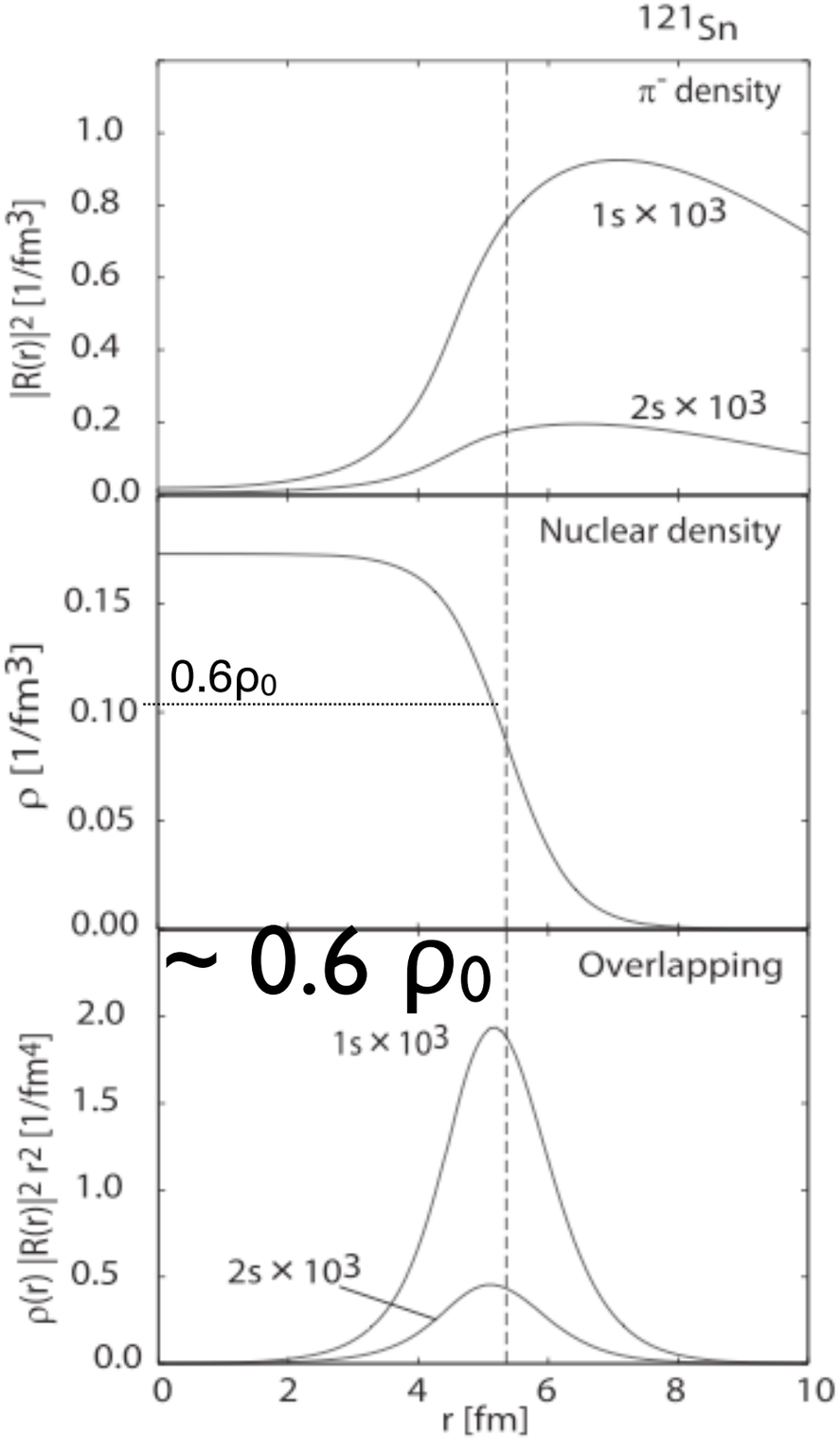
Feasibility study has started for

Deeply-Bound Pionic Atoms with Unstable Nuclei

Y.N. Watanabe

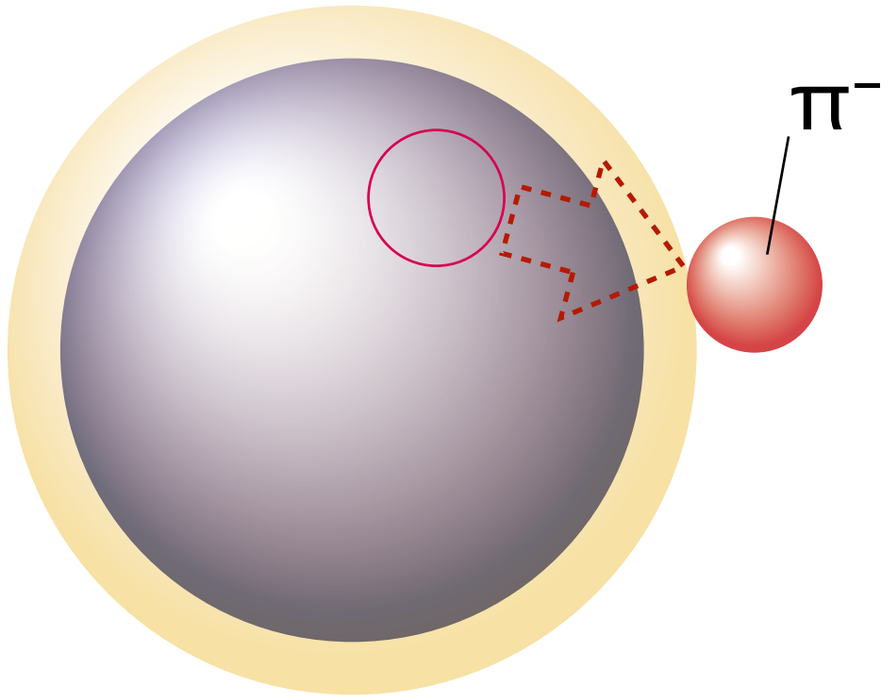
Kenta Itahashi, RIKEN

Deeply-Bound Pionic Atoms with Unstable Nuclei



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

neutron rich nucleus



neutron skin

Pion bound at $\rho < 0.6\ \rho_0$

ρ_0 : normal nuclear density

Density dependence of $\langle\bar{q}q\rangle$

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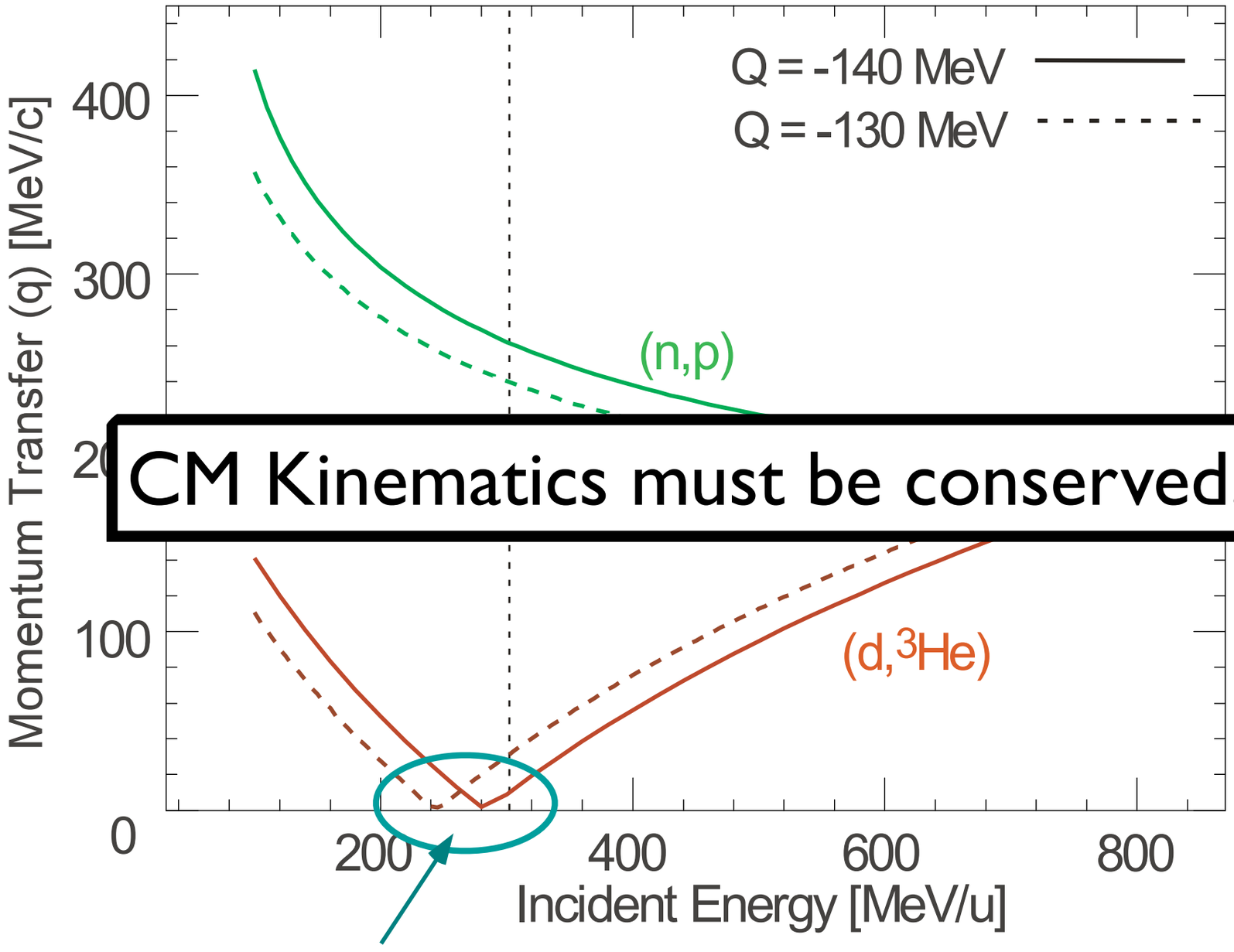
Momentum Transfer



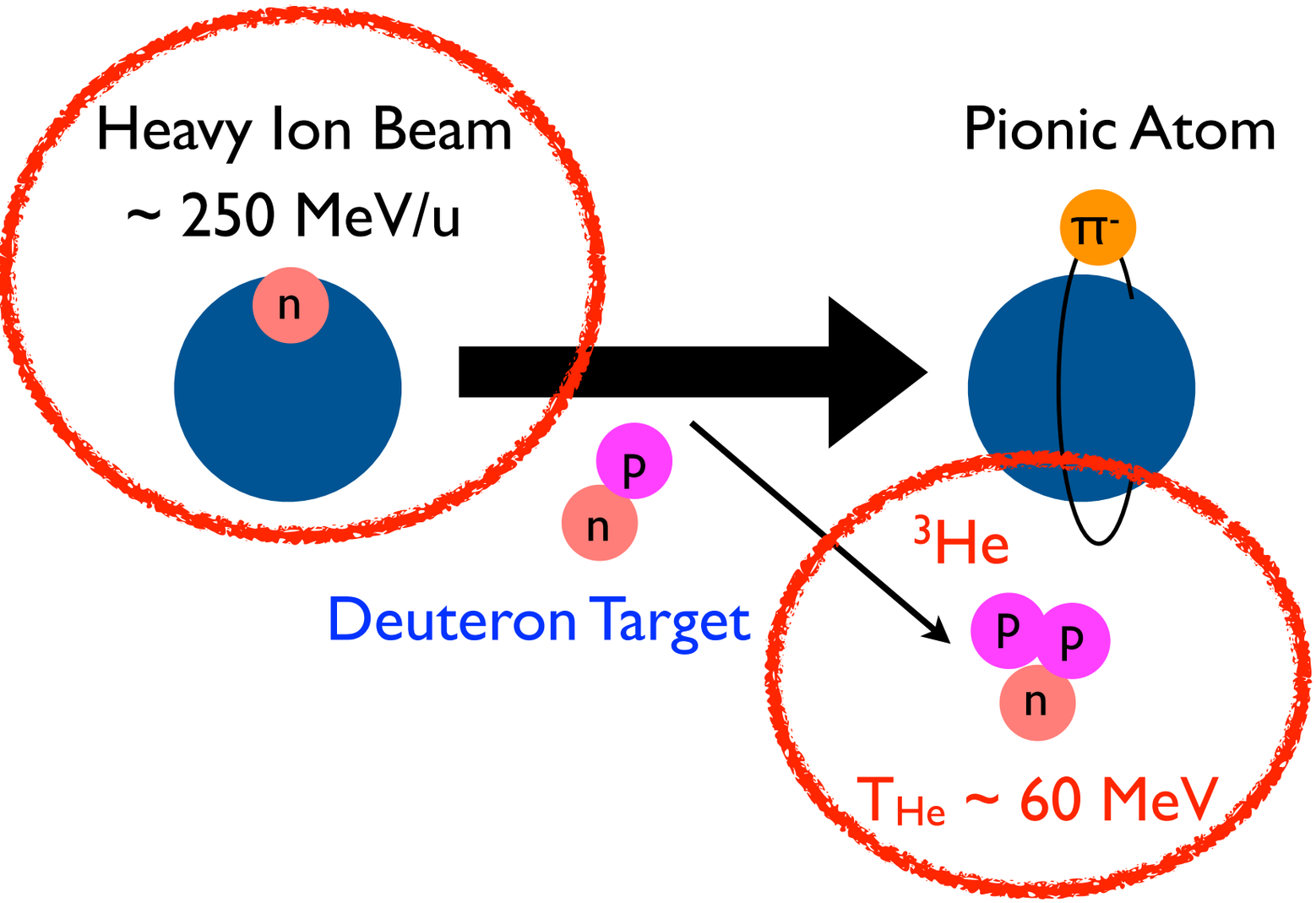
CM Kinematics must be conserved.

Quasi-substitutional (ΔL~0) reaction
Small momentum transfer(q)

(d,^{3}He) reaction

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

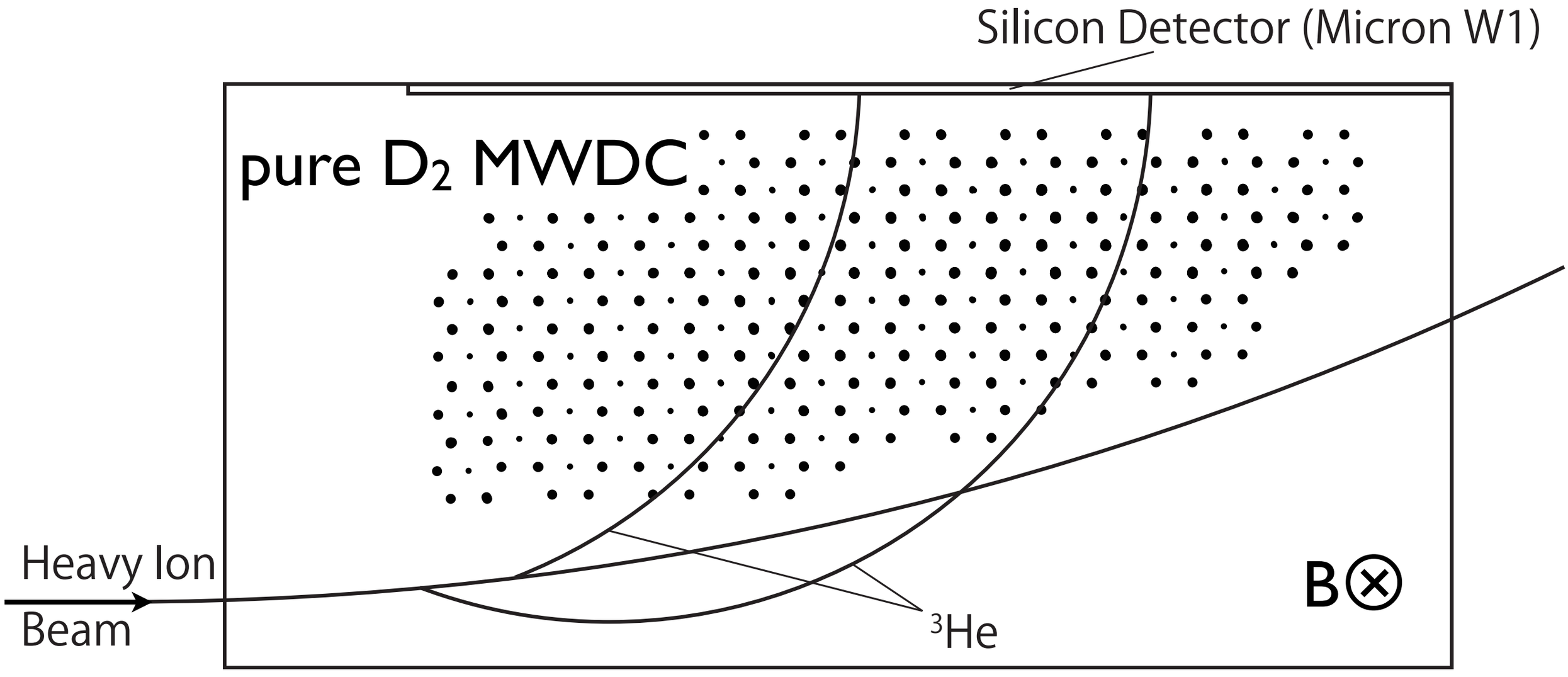
Q value

60 MeV ^{3}He range is 1.8 mm in Silicon

Conceptual design at RIBF as a first step

Kenta Itahashi, RIKEN

Experimental Setup



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

ΔE, Full Energy by Si +
Trajectory by MWDC
Incident beam < 10^6/s

Q Value Resolution

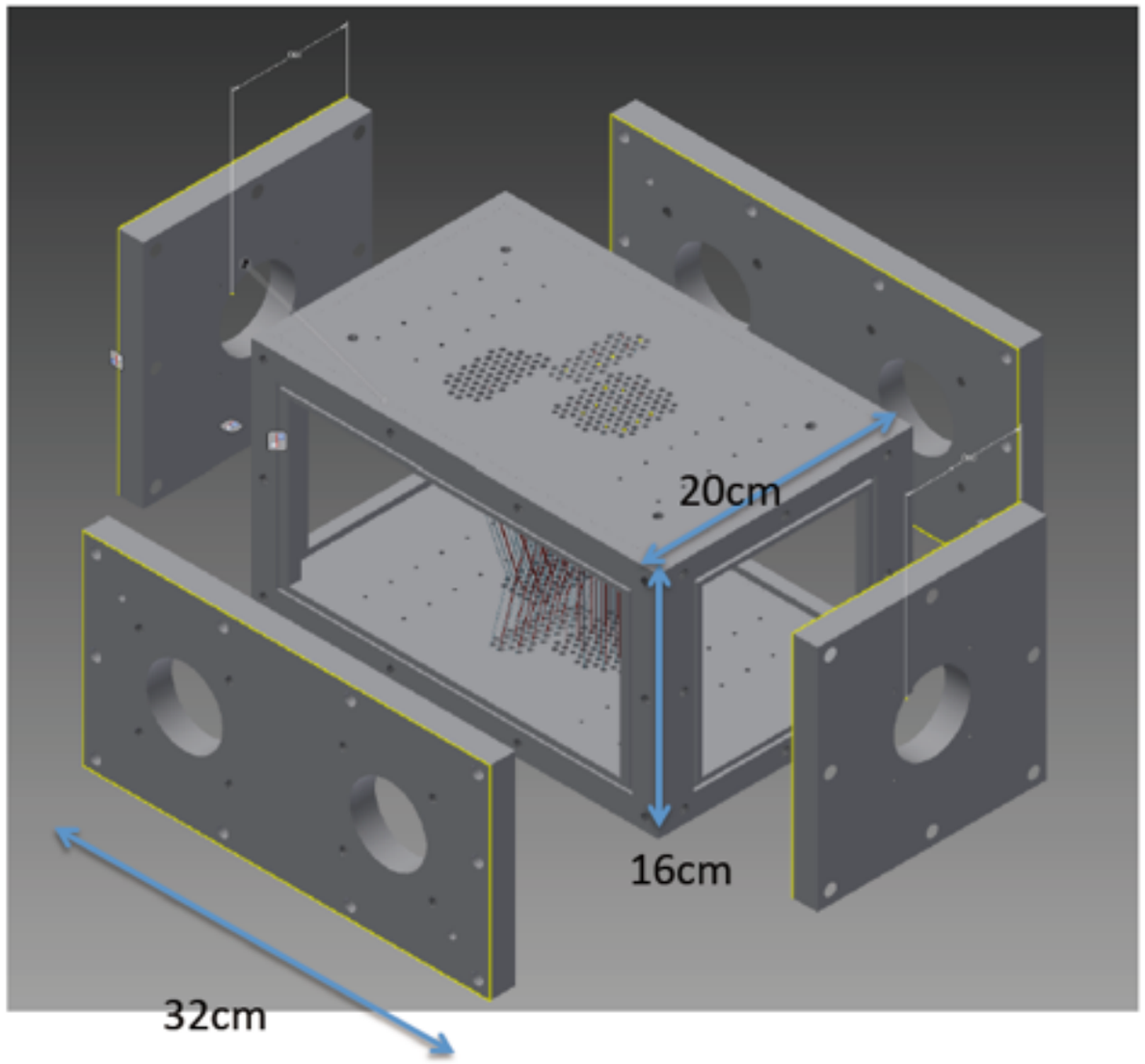
Cause	ΔQ (FWHM) [keV]
Energy Resolution of Si at T_{He} ~ 60 MeV σ_{Si} = 0.1 %	~ 350
Energy Straggling of ^{3}He in TPC	~ 350
Vertex Reconstruction With Incident Beam σ_{TPC} = 500 μm	~ 130
Total	**~ 500**

cf. 400 keV for normal kinematics

Detector Development

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

prototype MWDC in construction



First test run with
stable nuclei in HIMAC

Y.N. Watanabe and S. Ogawa

Kenta Itahashi, RIKEN

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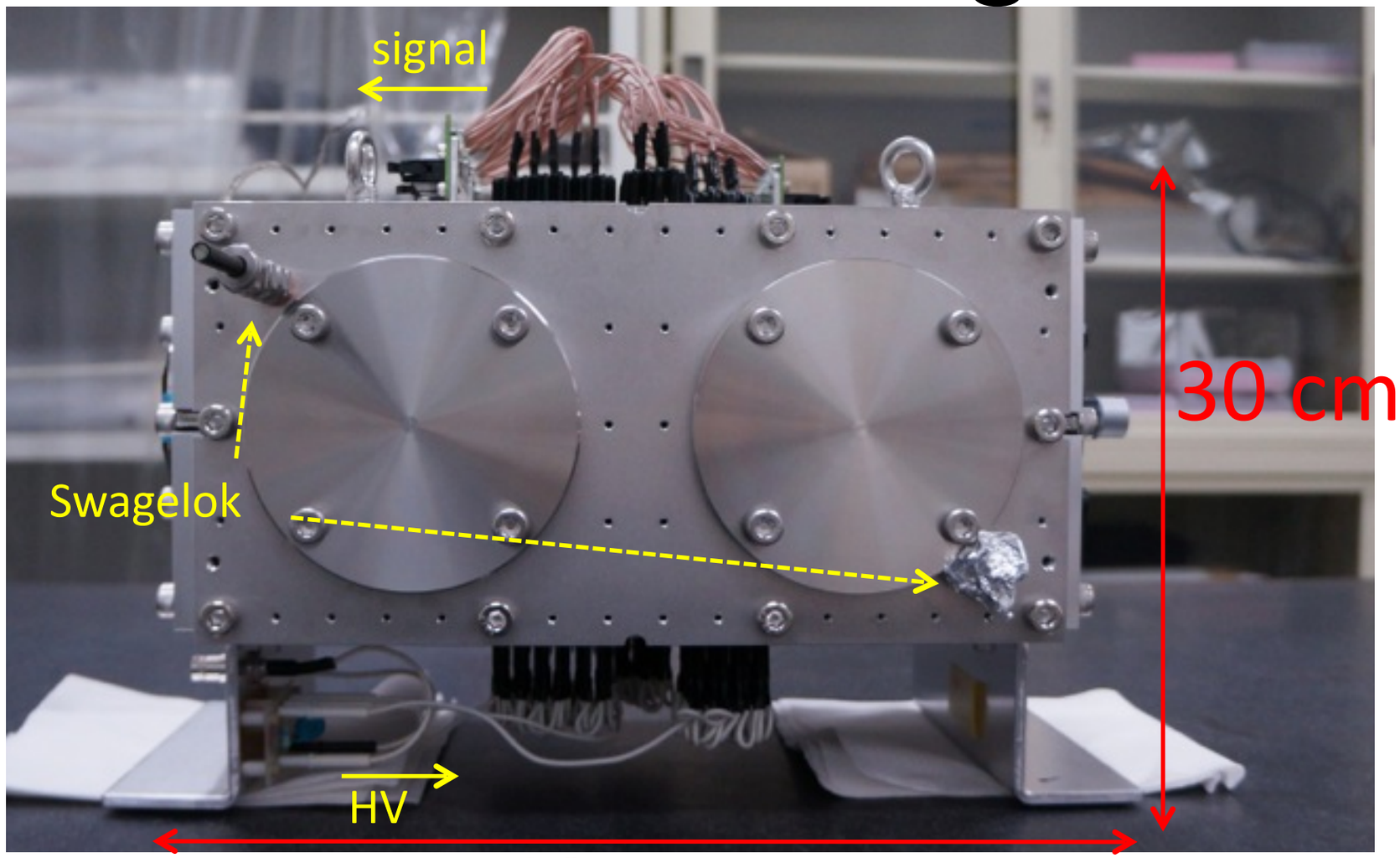
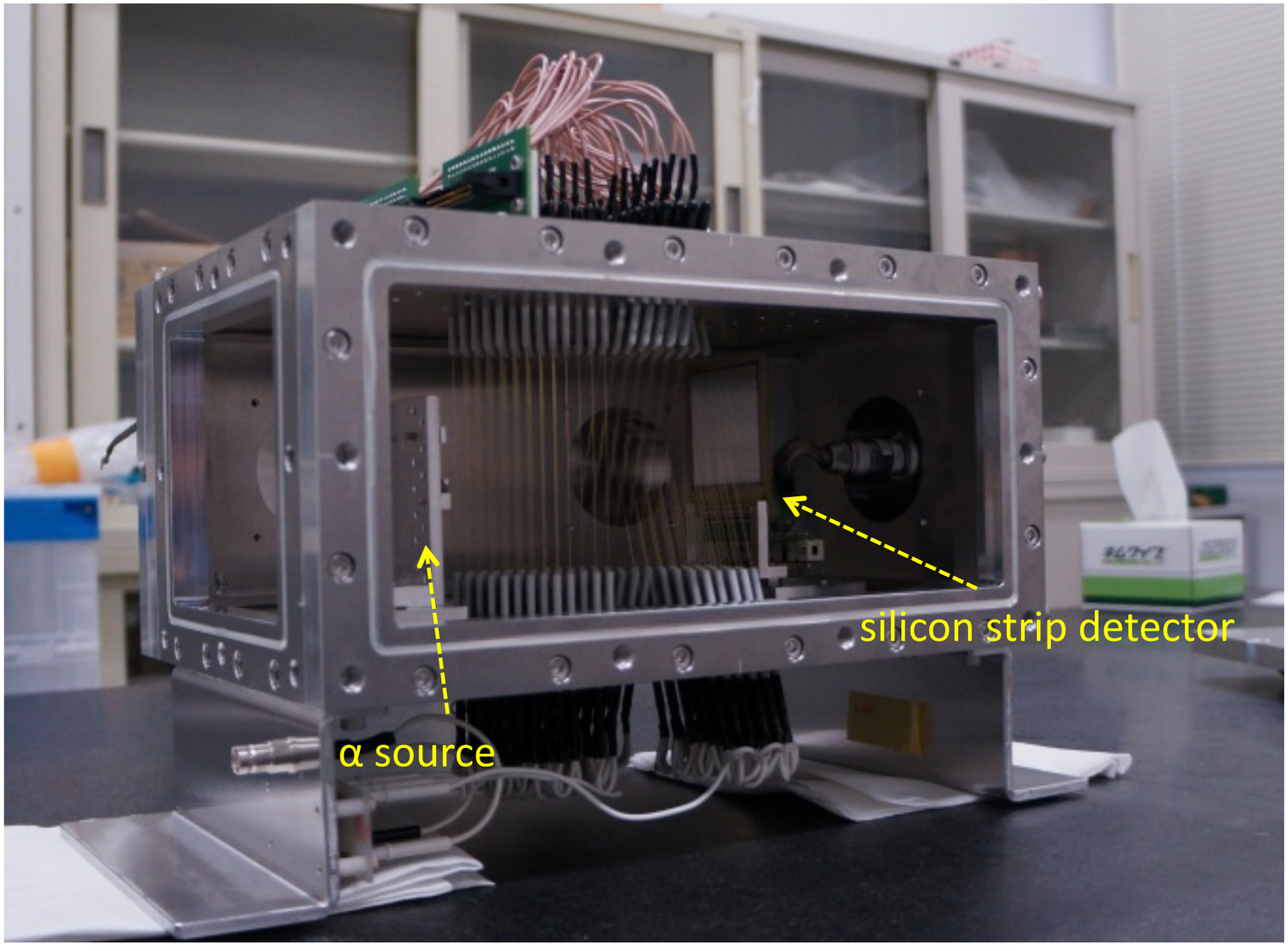
Detector Design



- Wire feedthrough, hexagonal wire geometry
- Raw material is Al
- Side walls are flange

Detector Design



- Inside the drift chamber, SSD and α source were installed

Summary for pionic unstable atoms

- Started feasibility study for pionic atoms with unstable nuclei
- Chance to approach chiral condensate at different density
- Testing with pure hydrogen active target MWDC now
- Possible alternative setups are also in consideration

Spectroscopy of η′ mesic nuclei

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. R. 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

PRiME

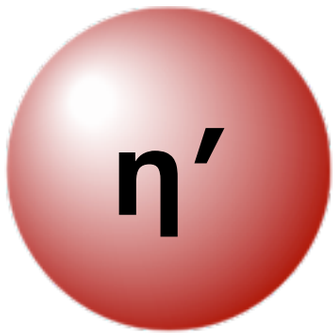
for Super-FRS collaboration

*spokesperson, ** co-spokesperson

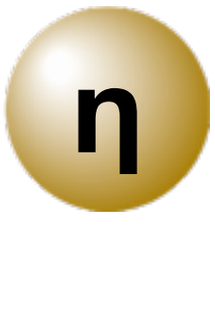
Osaka University, Universidade de Santiago de Compostela, Universitaet Giessen, Kyoto University, GSI, University of Groningen, Beihang University, The University of Tokyo, Nara Women's University, KEK, RIKEN, Tokyo Metropolitan University, Saint Mary's University, Technische Universitaet Darmstadt,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

Nagahiro, Jido, Fujioka, KI, Hirenzaki, PRC87(13)045201.
KI, Fujioka et al., PTP 128 (12) 601.

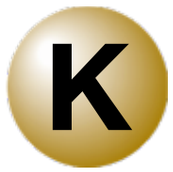
Mass of PS mesons



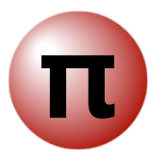
M=958 MeV/c^2



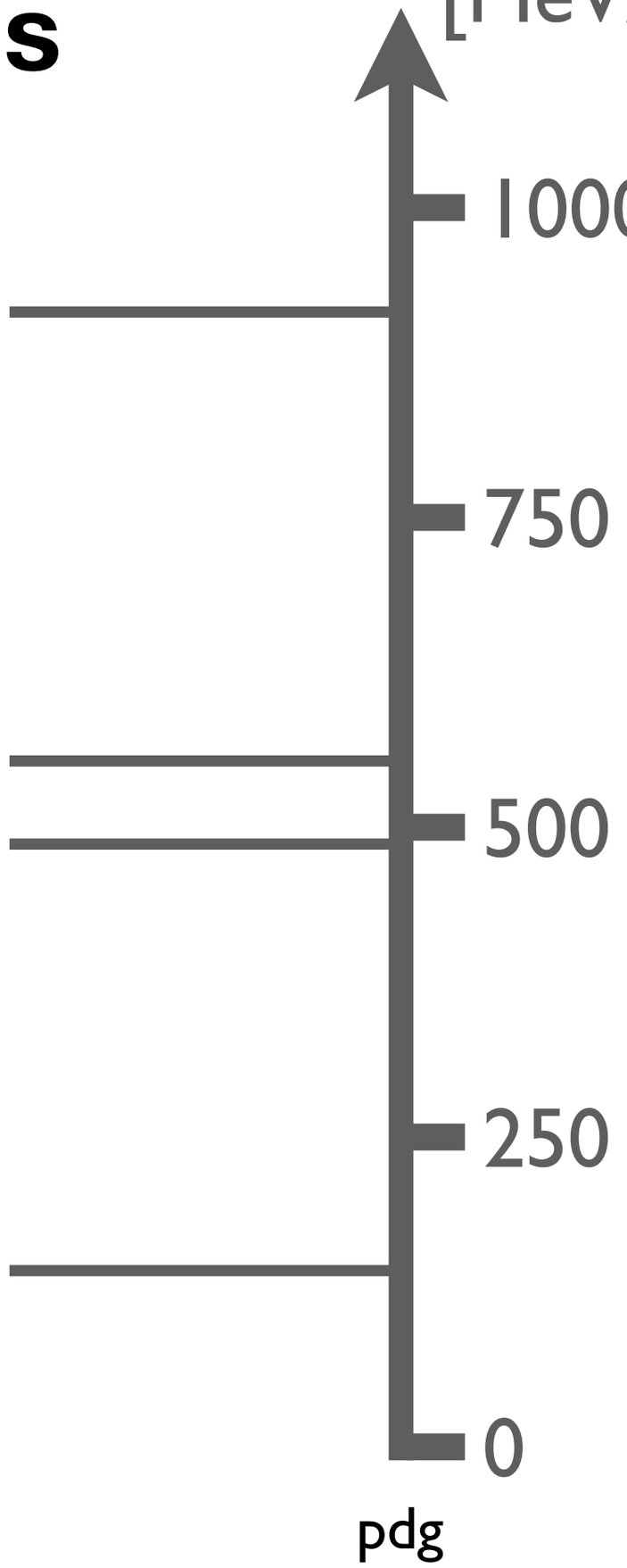
M=548 MeV/c^2



M=498 MeV/c^2



M=140 MeV/c^2



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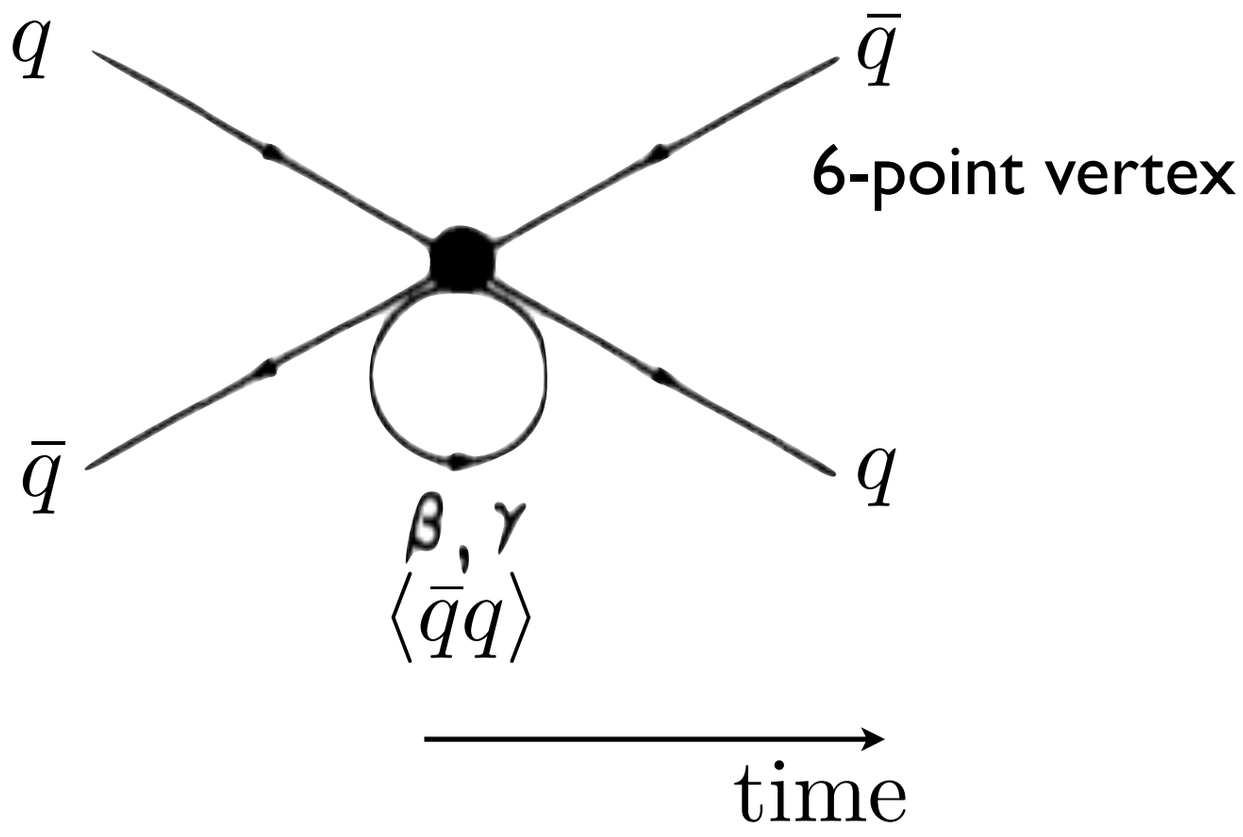
Large η′ mass can be explained

$U_A(1)$ symmetry breaking term of
effective Lagrangian



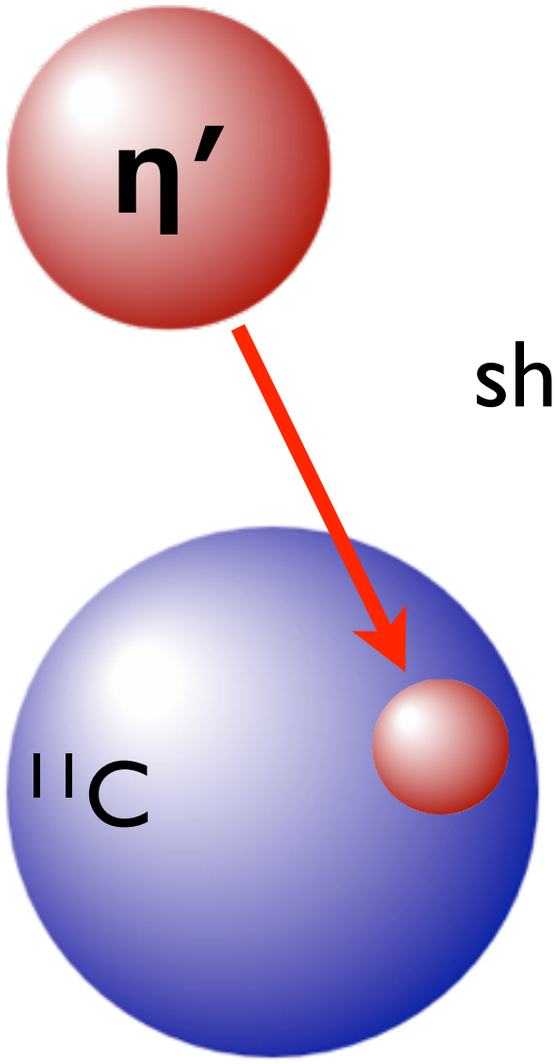
Kobayashi-Maskawa-'t Hooft-type interaction

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

Jido, Nagahiro, Hirenzaki,
PRC85(2012)032201(R)

Jido *et al.*, NPA 914 (2013) 354

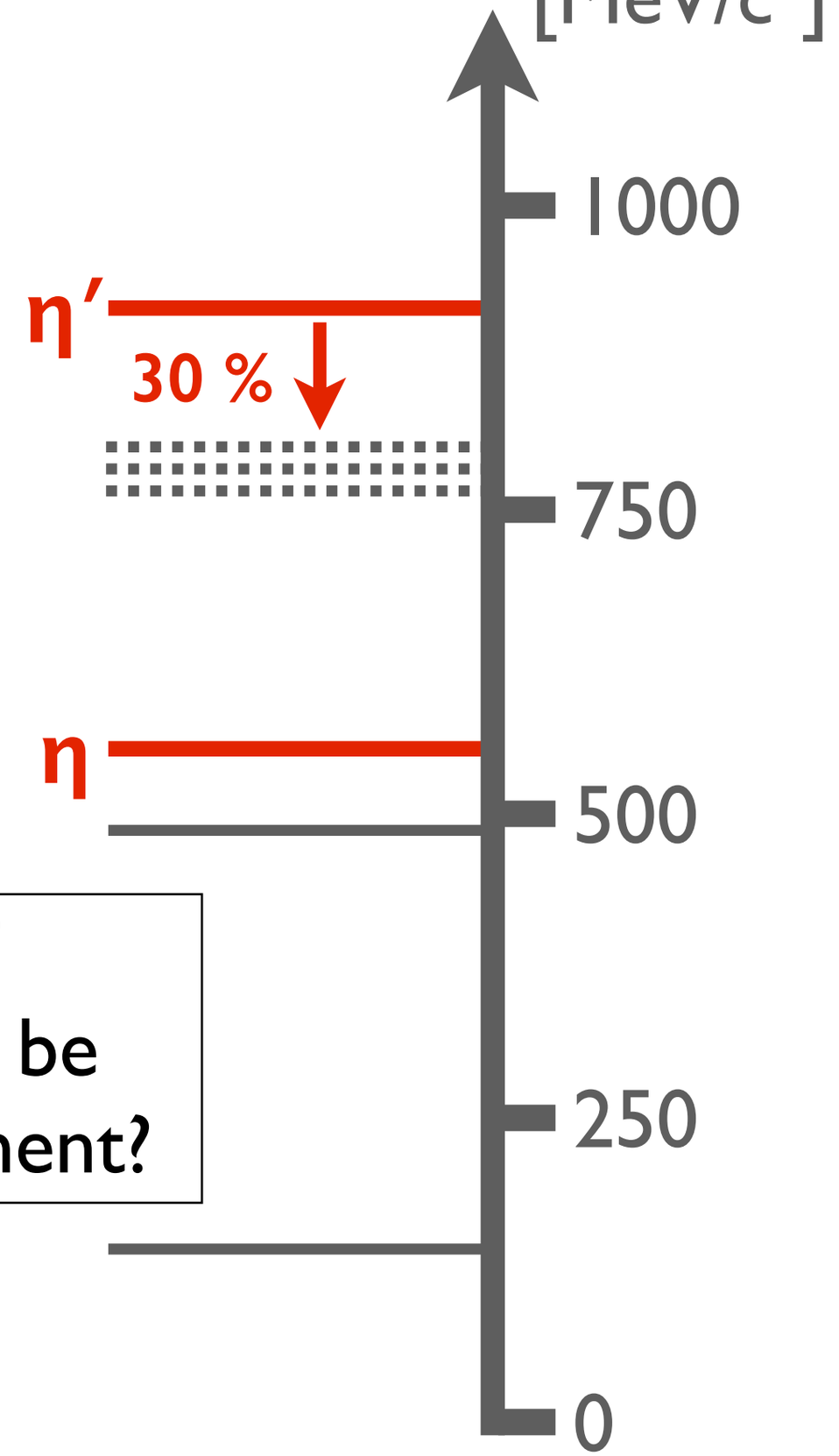
η′ mesic nuclei search



Jido, Nagahiro, Hirenzaki,
PRC85(2012)032201(R)

Naive estimation
shows 30% reduction
of $|m_{\eta'} - m_{\eta}|$

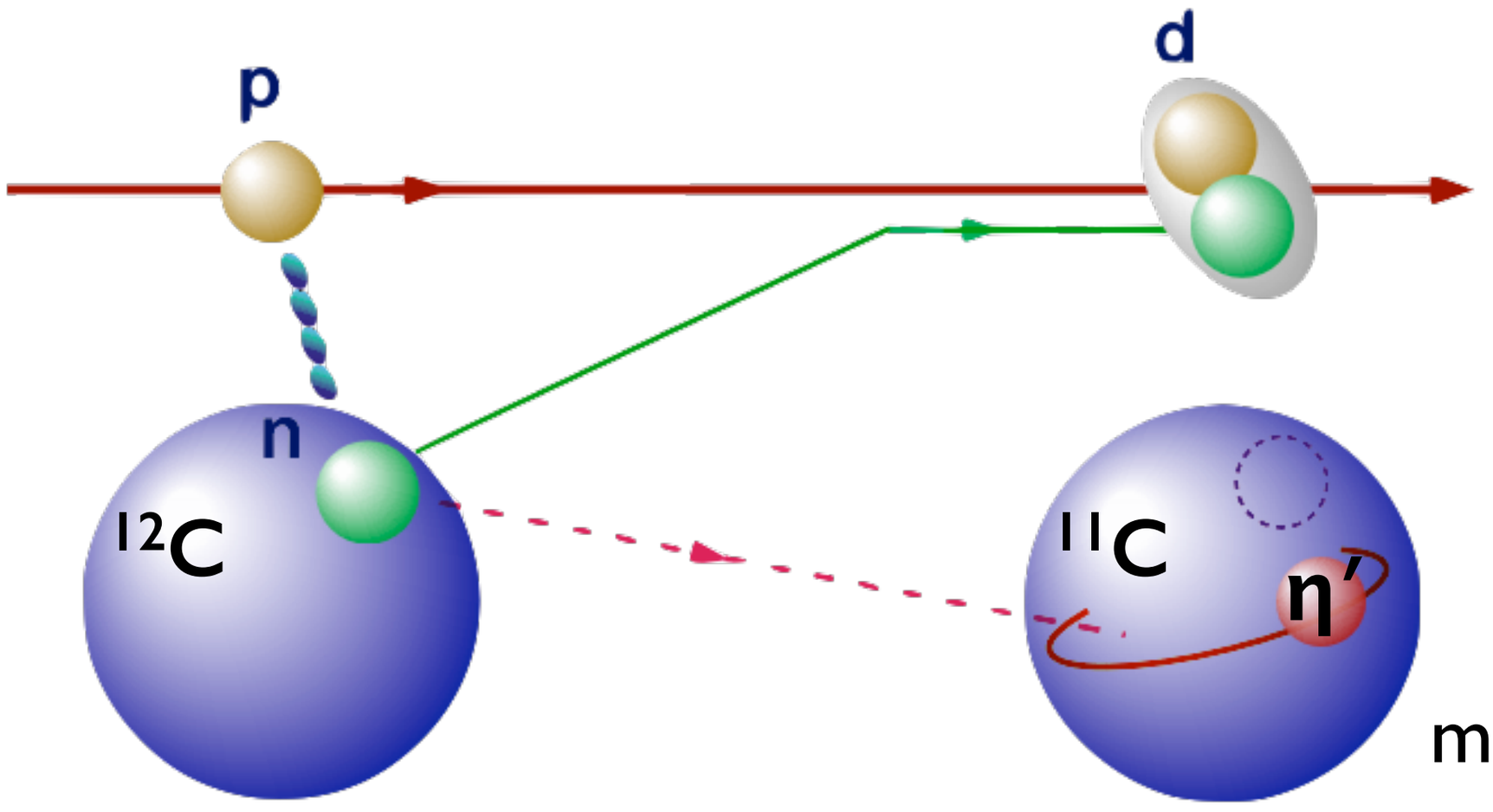
Q. Mass shift of
~ 150 MeV/c^2 can be
observed in experiment?



η′ Mesic Nuclei in (*p*,*d*) Reaction

next talk

η′ transfer reaction + Missing mass measurement



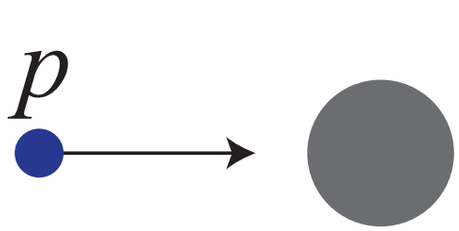
η′ × ^{11}C
mesic nuclei

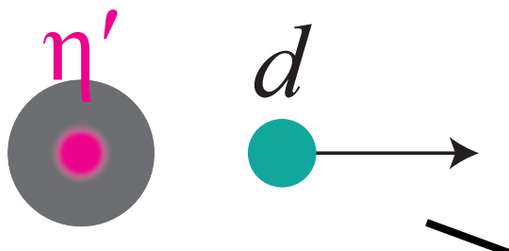
T_p = 2.50 GeV → q ~ 400 MeV/c

KI, Fujioka et al., PTP 128 (12) 601.

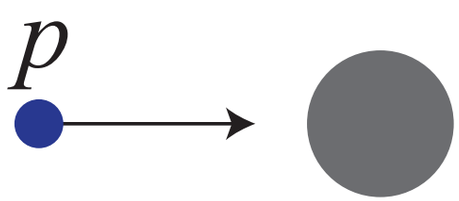
Spectrum in Inclusive Measurement at GSI

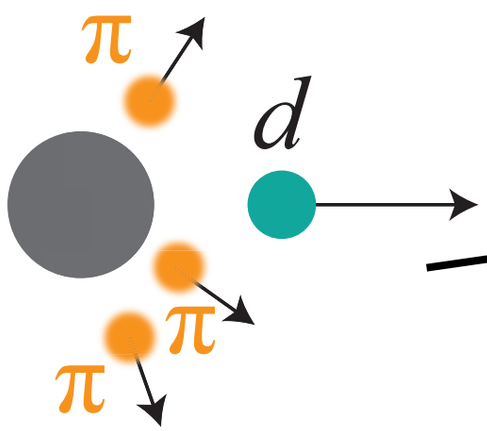
Signal



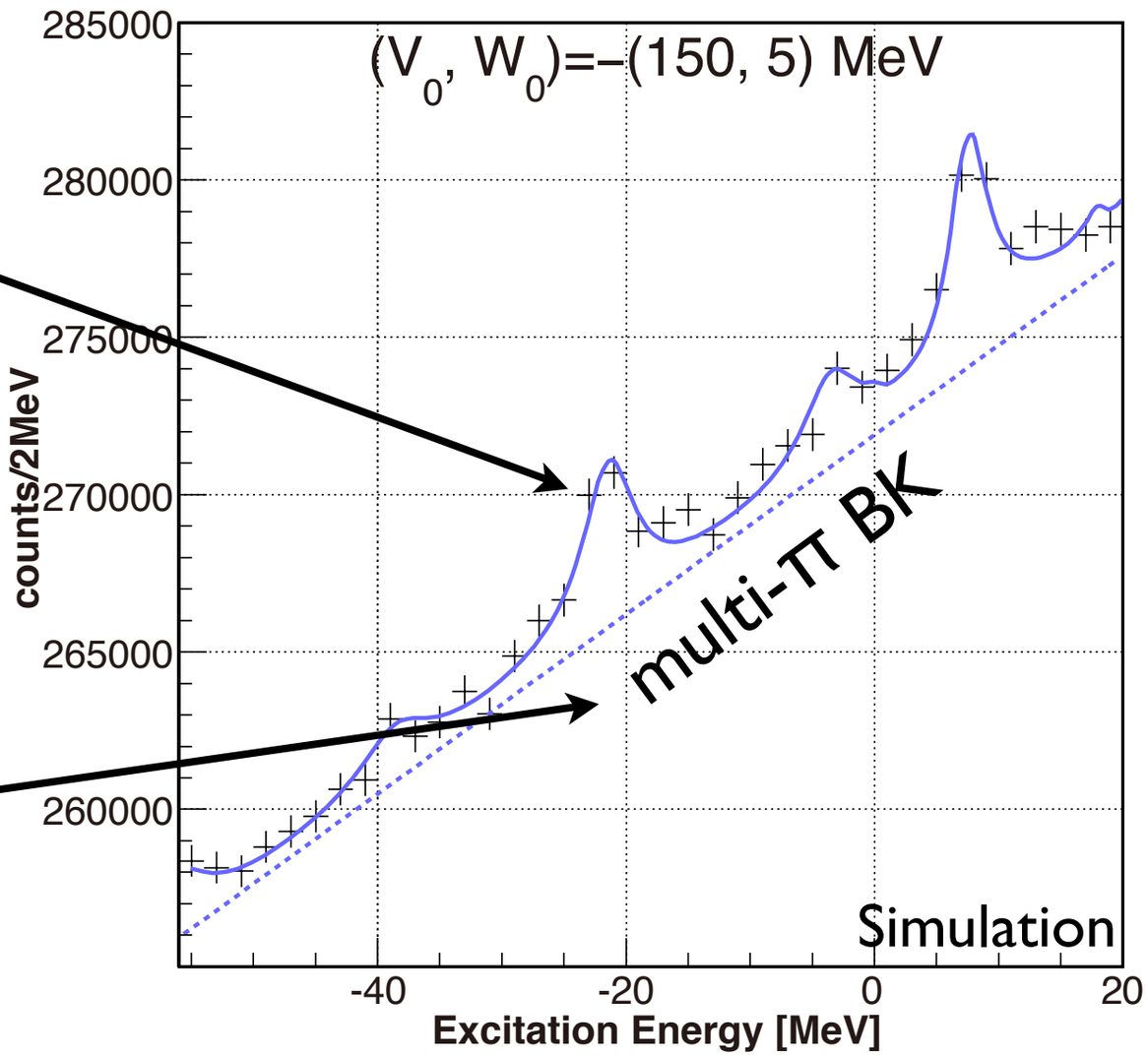


Background



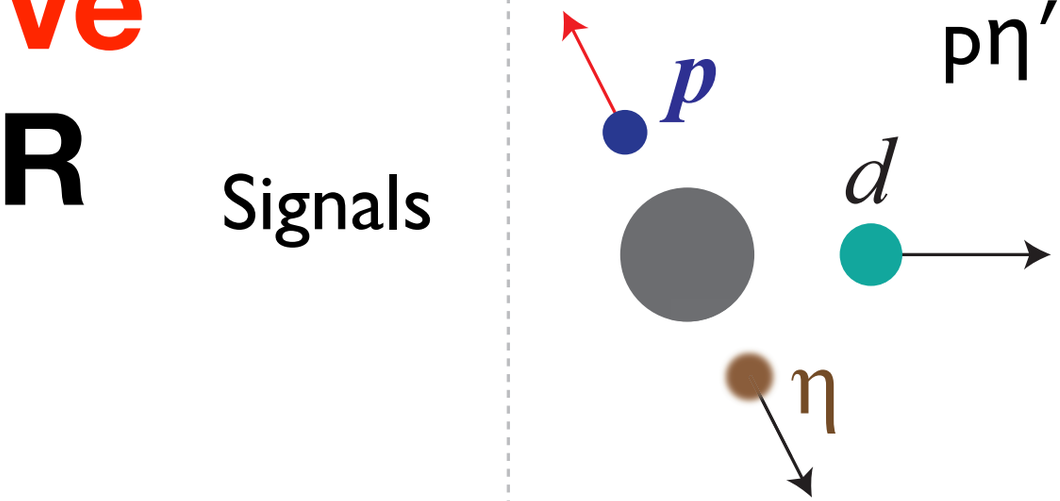


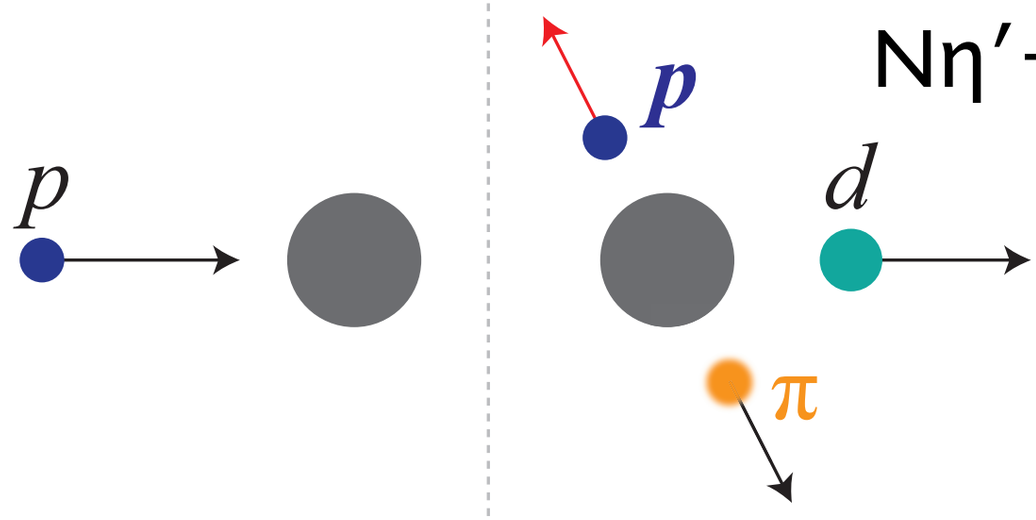
$^{12}C(p,d)^{11}C \otimes \eta'$



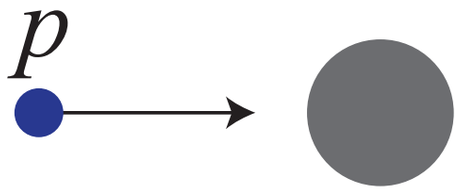
Principles of Exclusive Measurement at FAIR

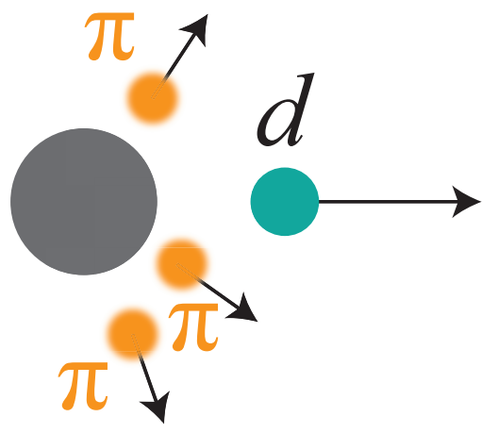
Signals

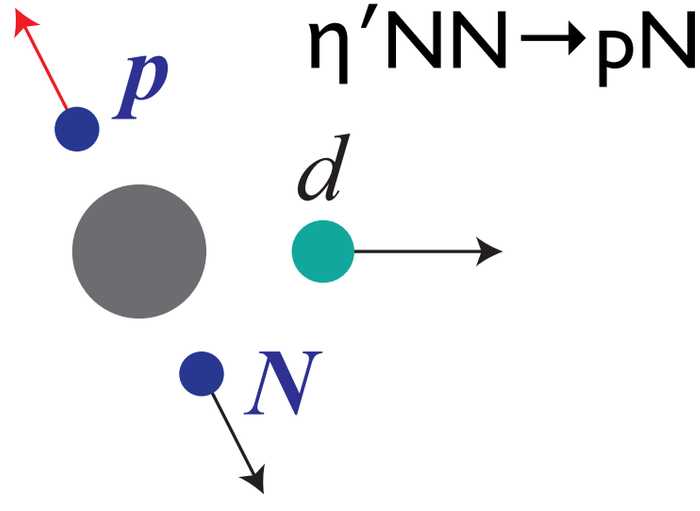




Background



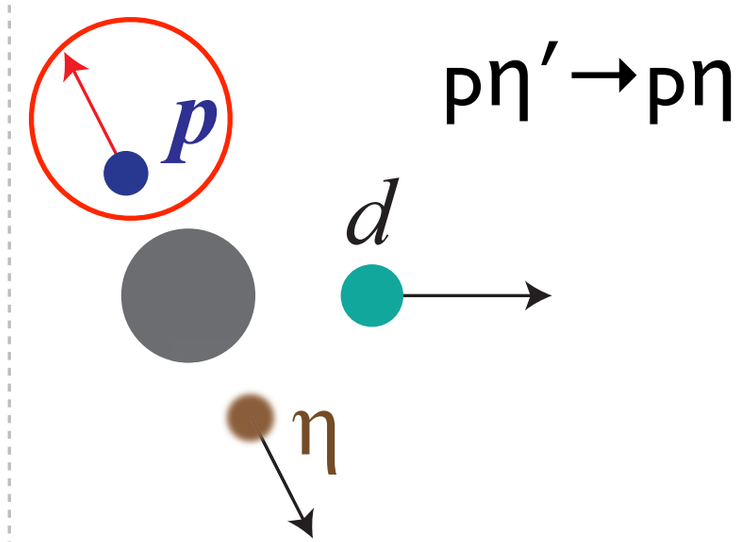


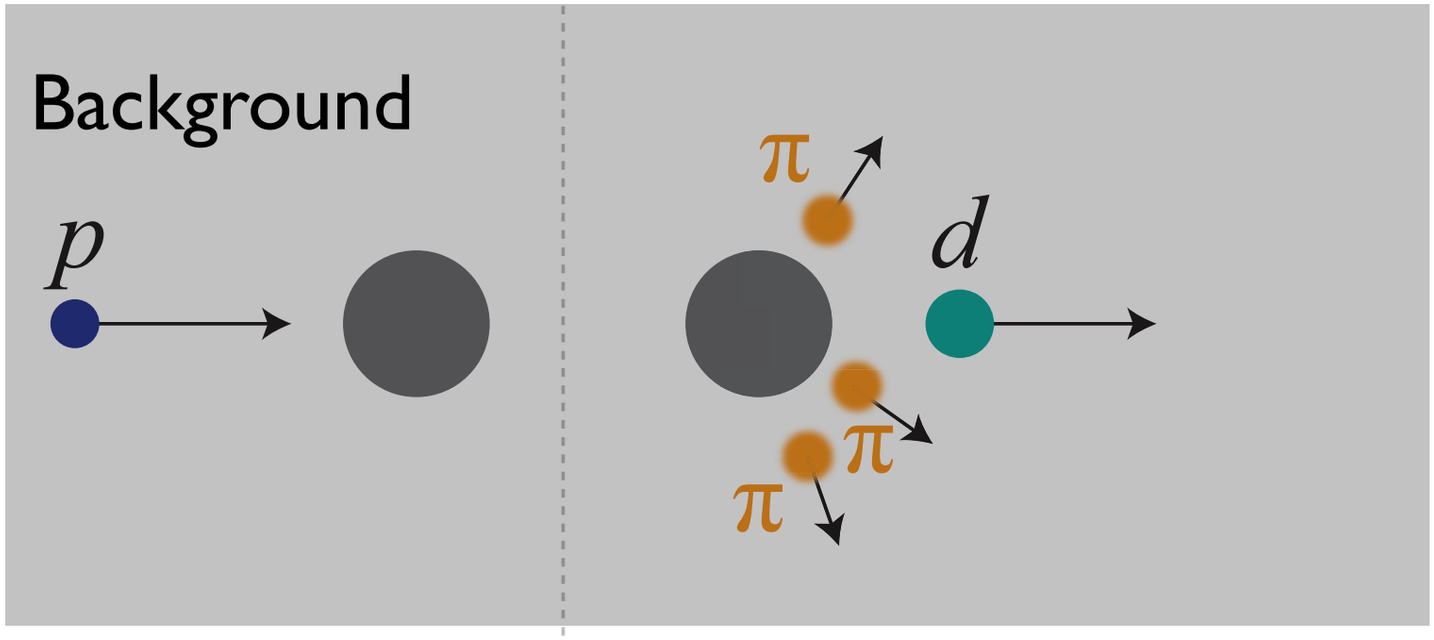


Principles of Exclusive Measurement at FAIR

Signals

tagging high-momentum protons
(300-600 MeV)



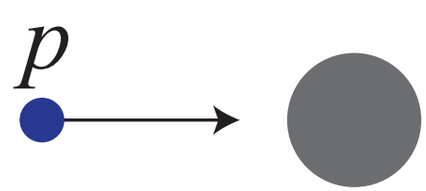


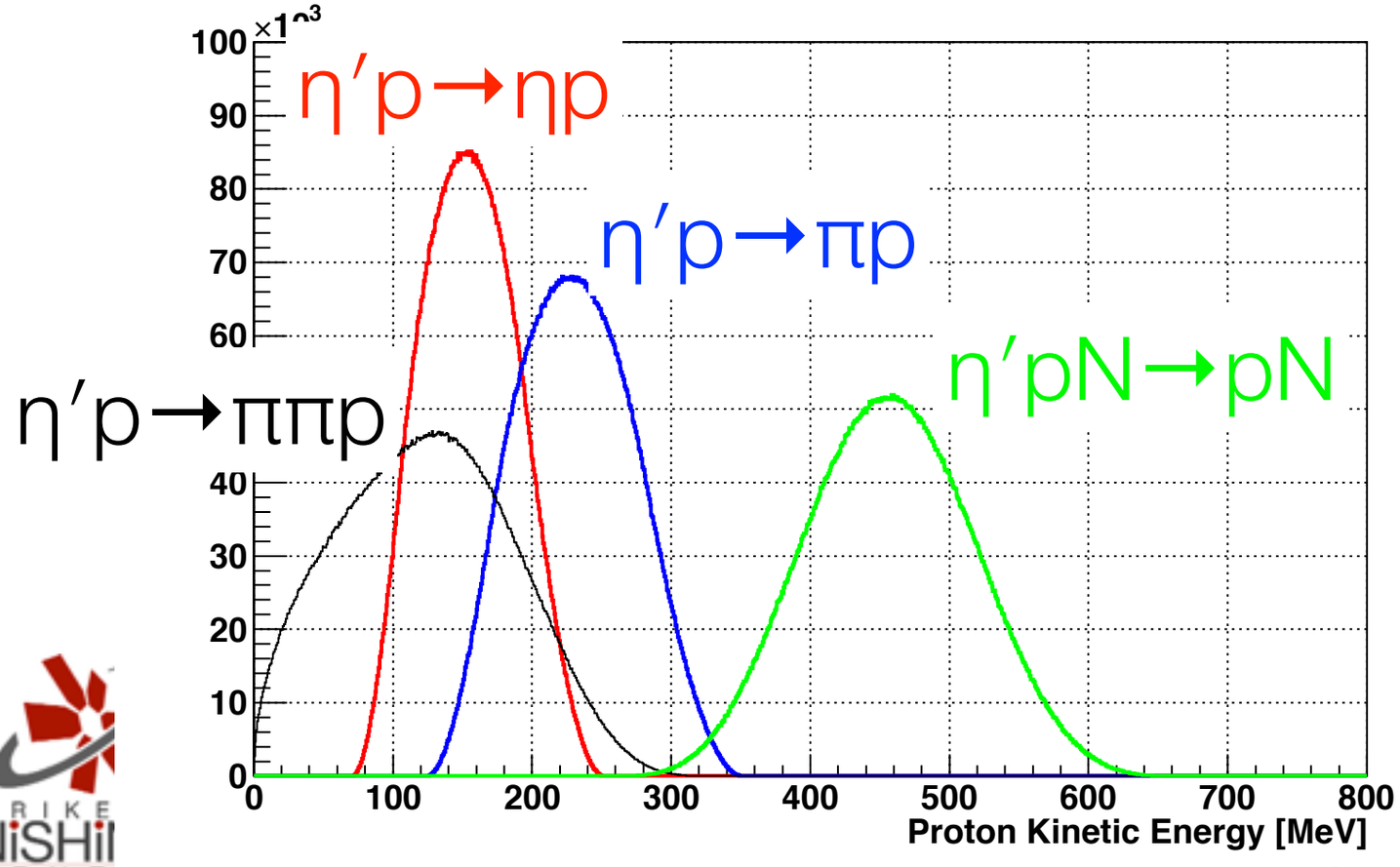
Principles of Exclusive Measurement at FAIR

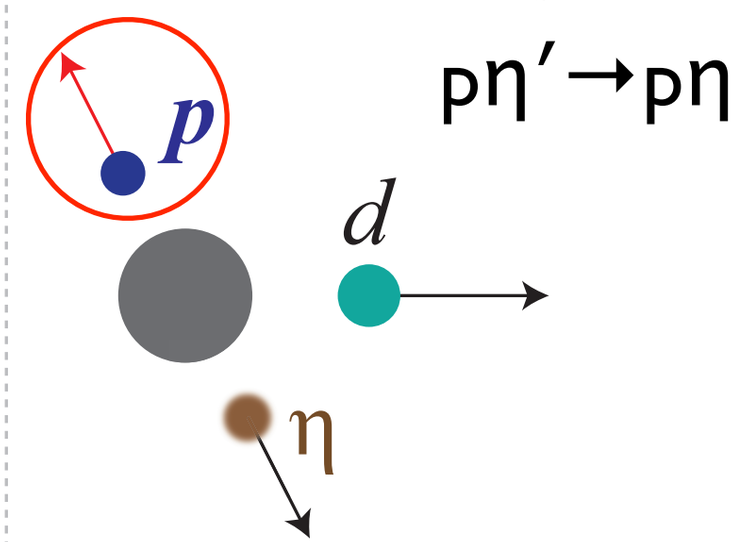
Signals

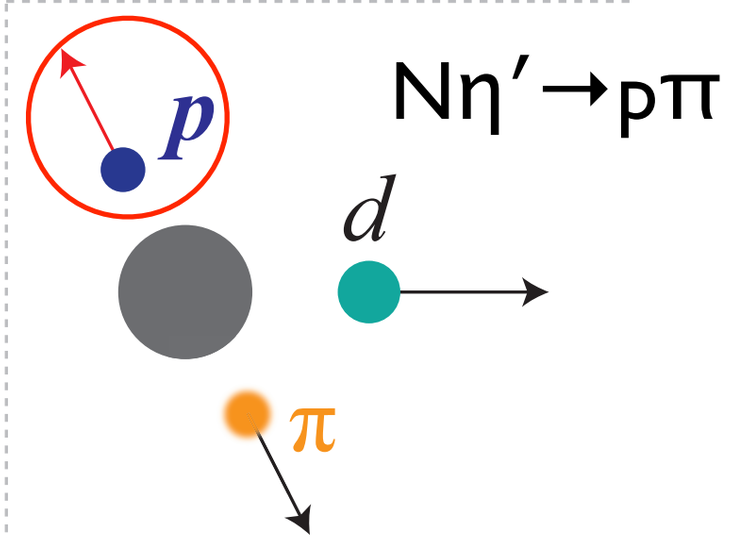
tagging high-momentum protons
(300-600 MeV)

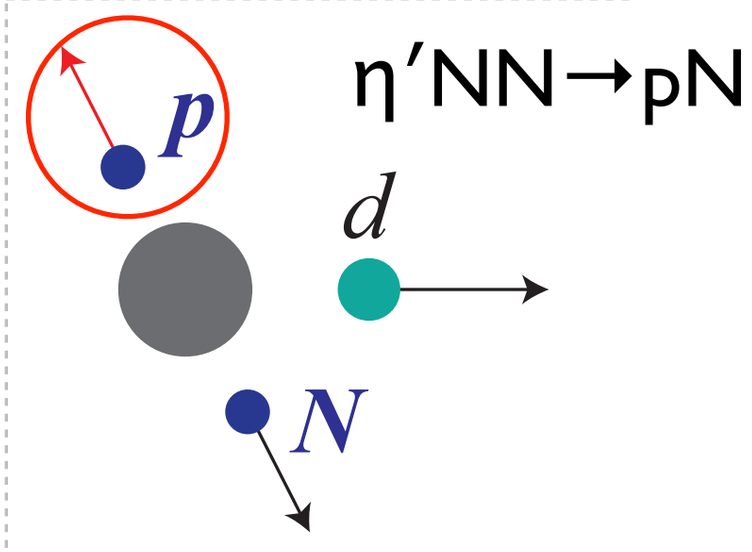
Y.K. Tanaka











EN

Summary

- Spectroscopy of meson bound states for pi and η′ in missing mass spectroscopy
- piAF is in a harvest season after long straggling and will soon start a precision systematic measurement
- Spectroscopy of piA in unstable nuclei is in progress
- η′ is interesting in relation to $U_A(1)$ anomaly
- Just finished first physics run for inclusive (*p*,*d*)
- Preparation for exclusive measurement is in progress