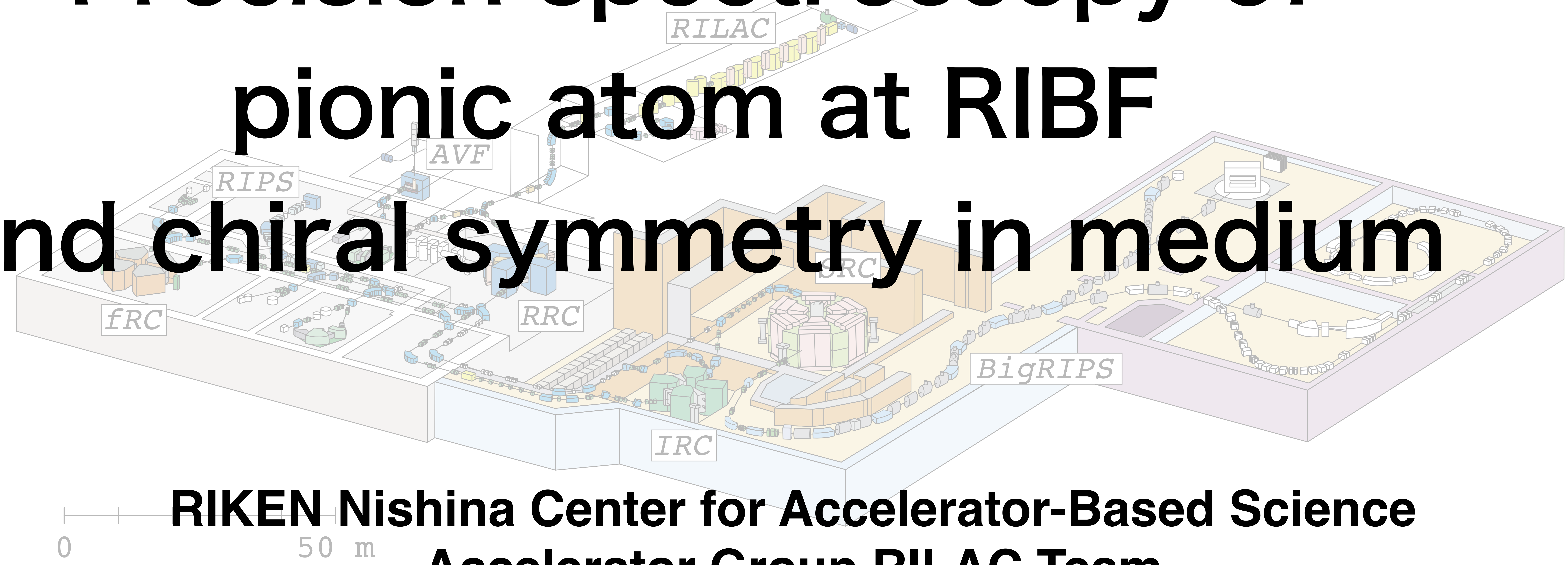
Precision spectroscopy of pionic atom at RIBF and chiral symmetry in medium



RIKEN Nishina Center for Accelerator-Based Science

Accelerator Group RILAC Team

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研修生 (2009~) SPDR(2015~) part timer (2016) @ Iwasaki lab.

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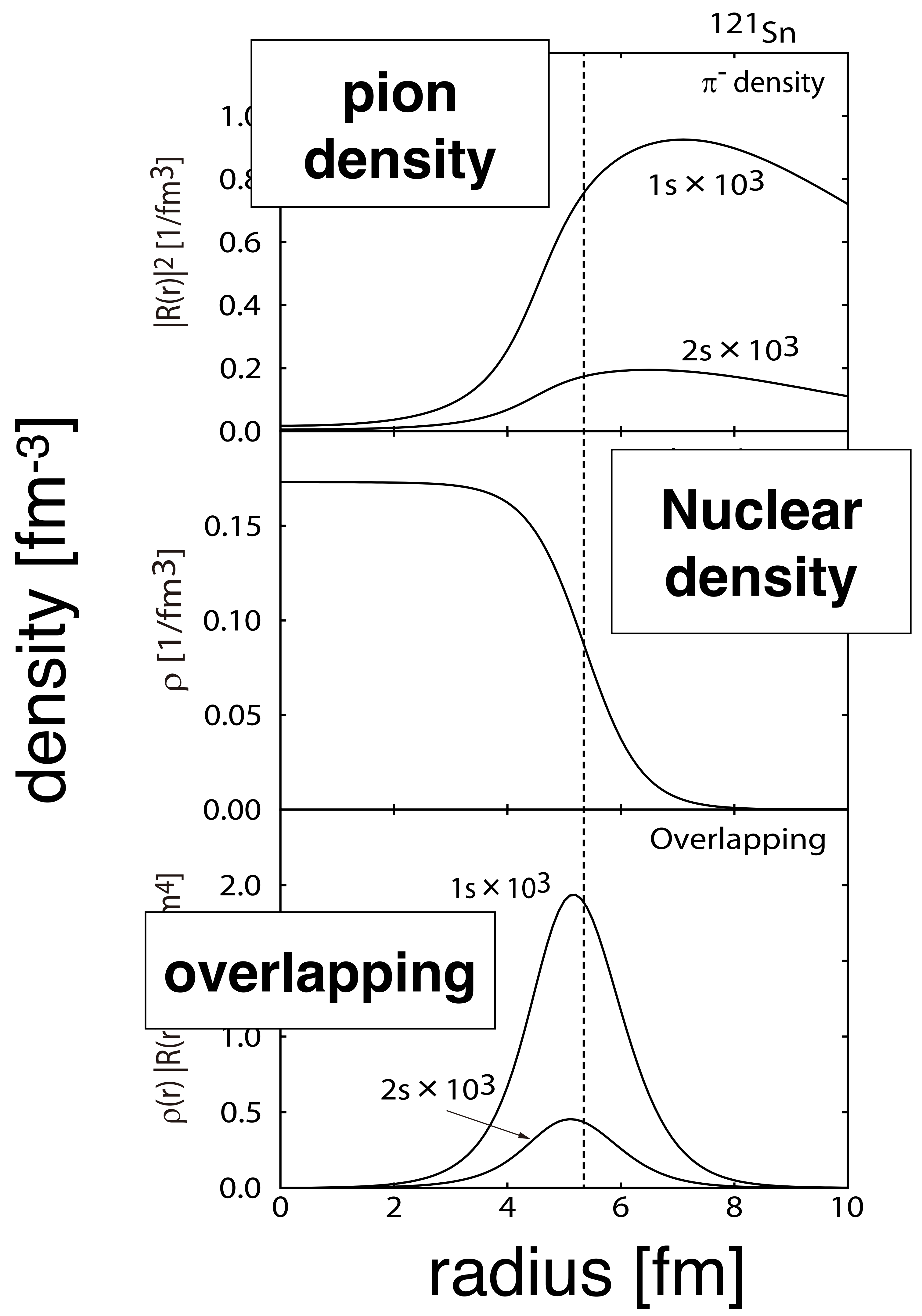
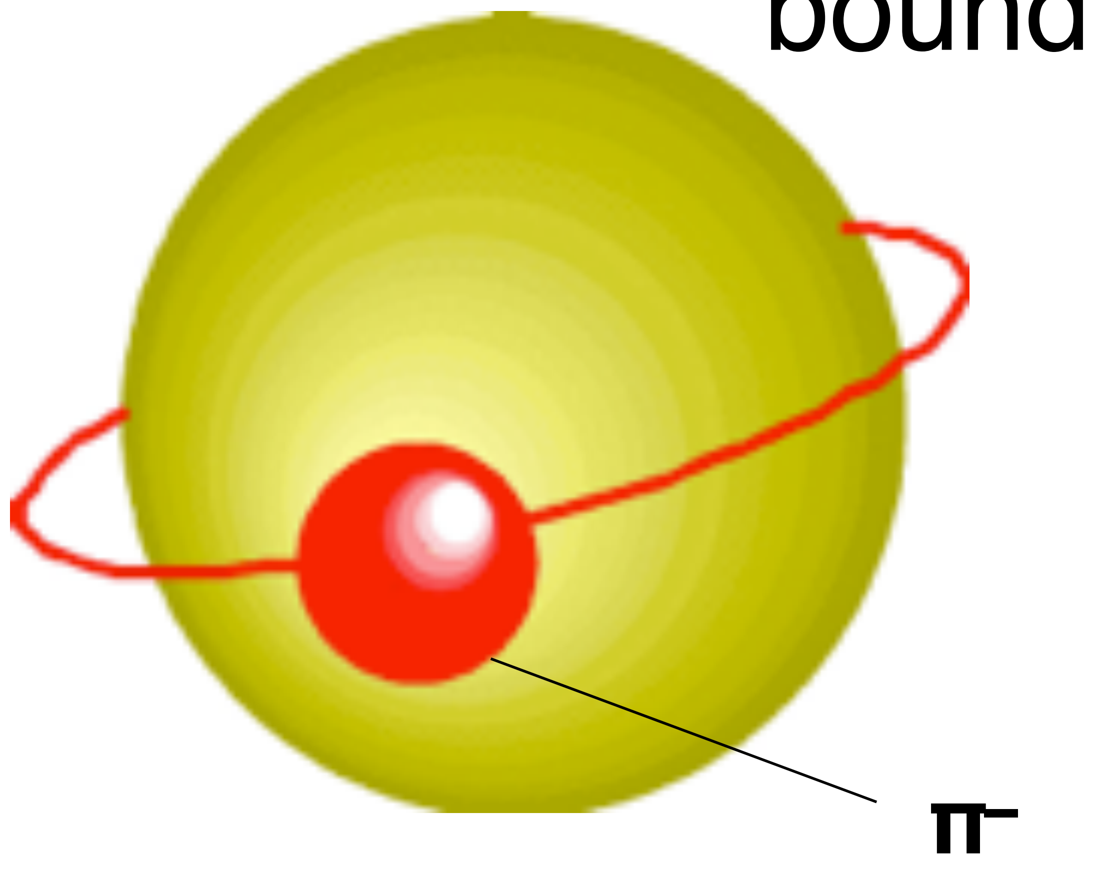
56 collaborators

Deeply bound pionic atoms



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

bound system of π⁻ & nucleus



very unique objects in terms of

1) Bound system of meson-nucleus
One of the two "meson in nucleus" system established so far

2) Quasi-stable state
Quantitative evaluation of strong interaction in medium

B_{1s}^{π} / Γ_{1s}^{π} and chiral symmetry in medium

BE, Γ of 1*s* pionic state
⇔ strong interaction effect

π-A s-wave optical potential (s-wave)

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

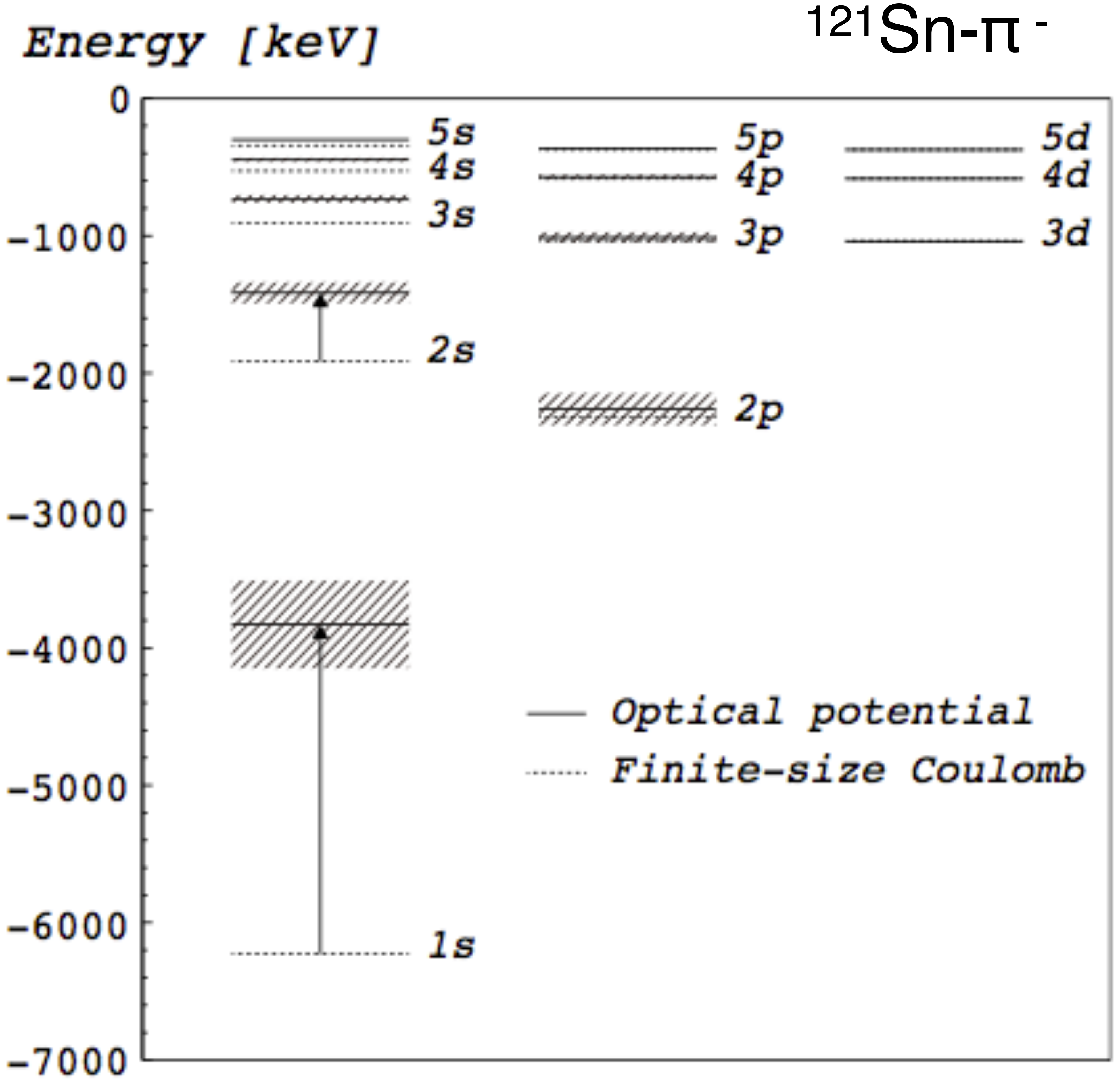
$$\frac{\langle q\bar{q}\rangle_{\rho=\rho}}{\langle q\bar{q}\rangle_{\rho=0}} = \left(\frac{b_1(0)}{b_1(\rho)}\right)^{1/2}\left(1 - \gamma\frac{\rho}{\rho_0}\right)$$

※ γ = 0.184 ± 0.003

D. Jido T. Hatsuda, T. Kunihiro, PLB 670, 109(2008).

$\langle q\bar{q}\rangle$ ⇔ Chiral symmetry in medium
is probed by pionic atom!

^{121}Sn-π $^{-}$



N. Ikeno et al., Prog. Theor. Phys. 126 (2011) 483.
S. Itoh, Doctoral Dissertation, Univ. of Tokyo (2011)

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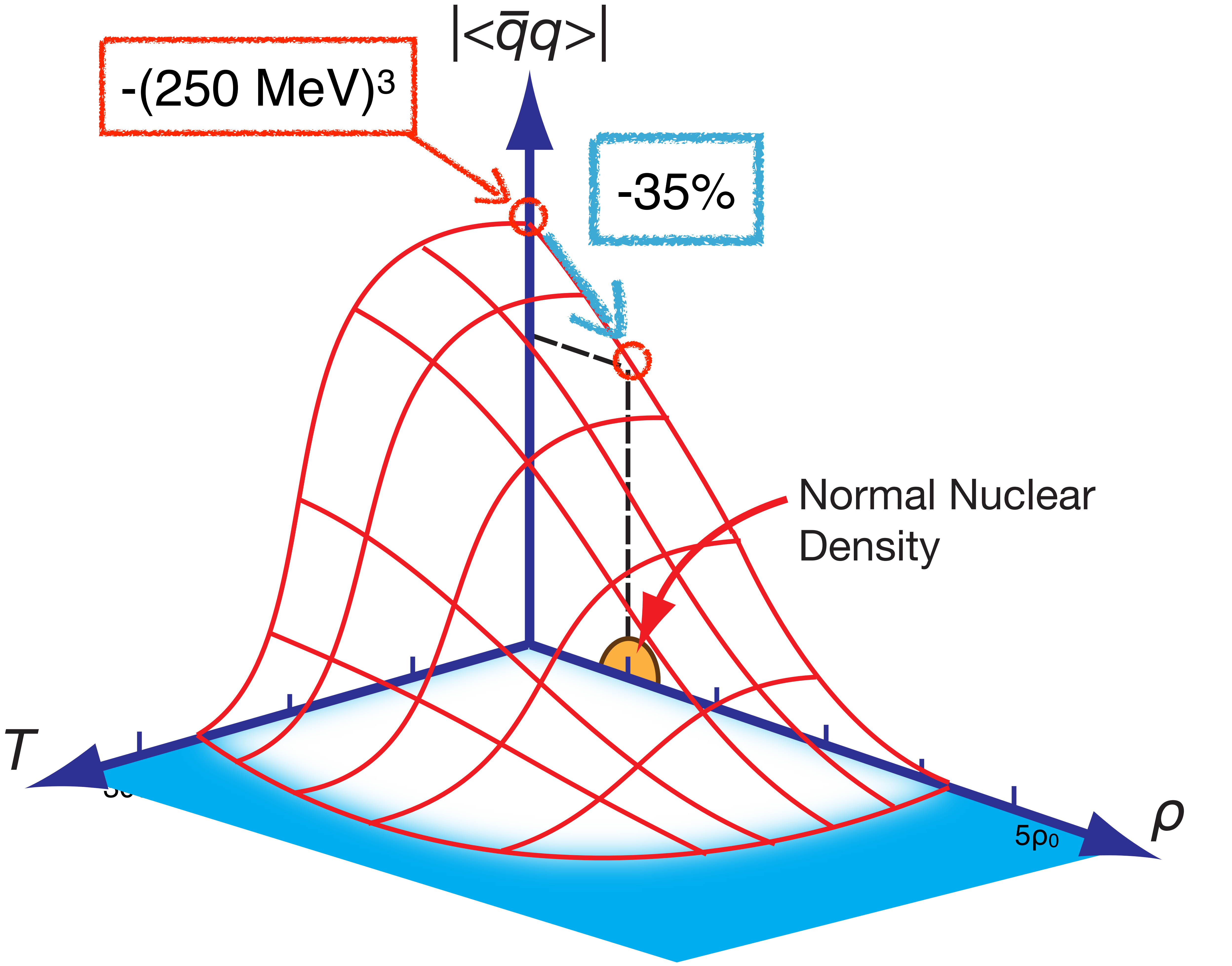
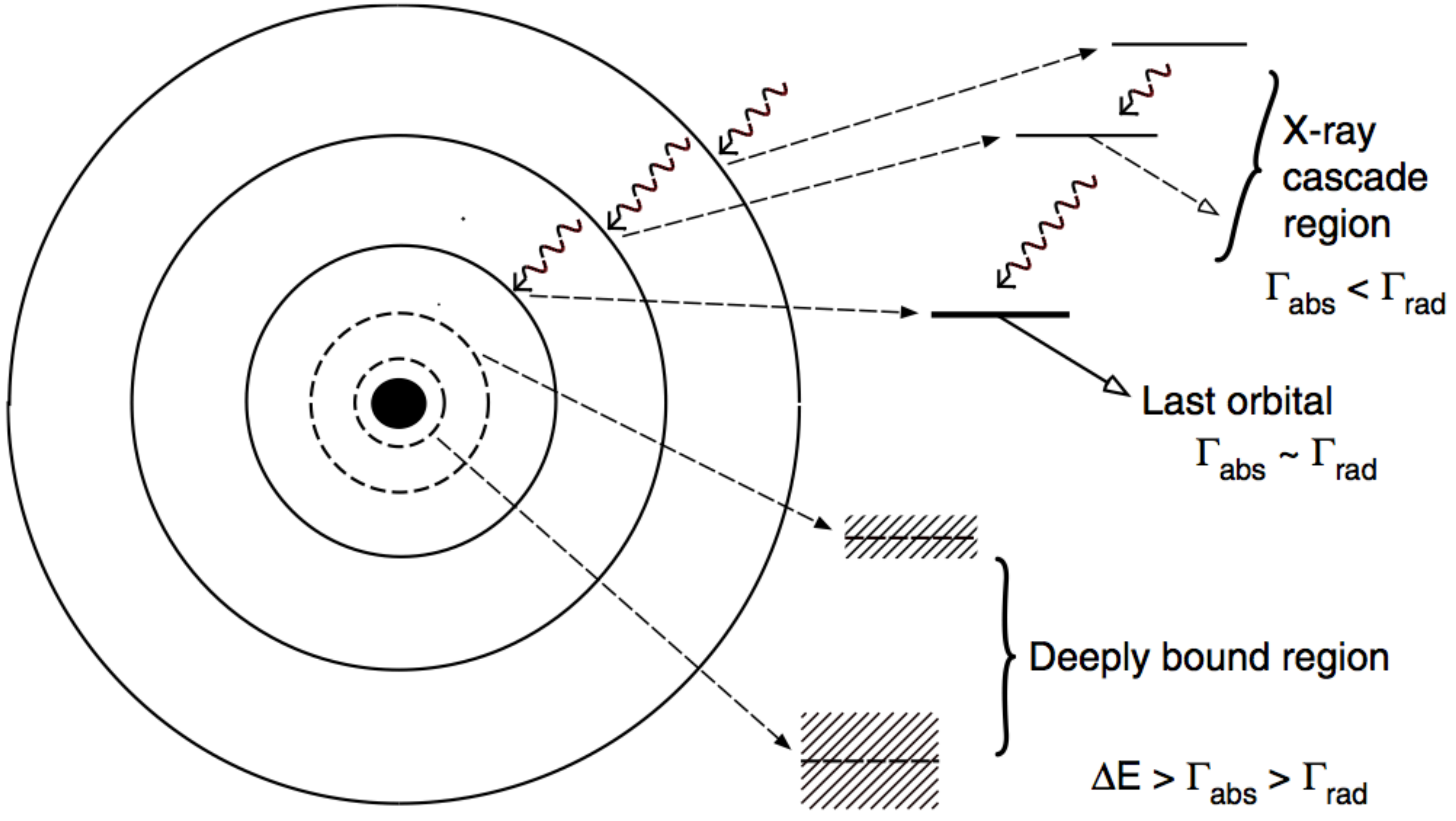


W. Weise, Nucl. Phys. A, vol. 553, pp. 59–72, Mar. 1993.

Conventional production; π⁻ beam



Yamazaki *et al,* Phys. Rep. 514, 1(2012)

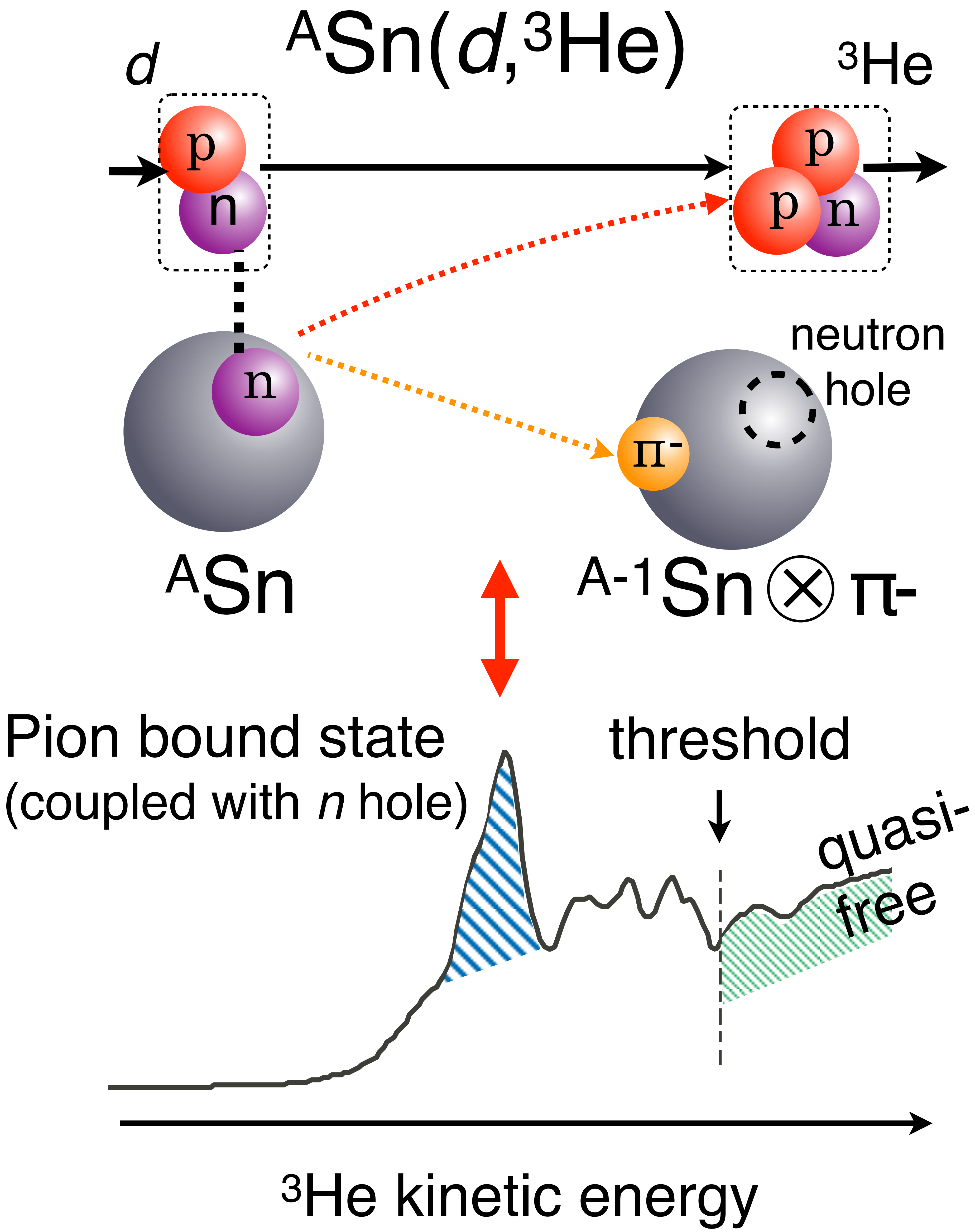
x rays during atomic cascade
→ higher orbits / light nuclei
(~ ^{24}Mg for 1s)

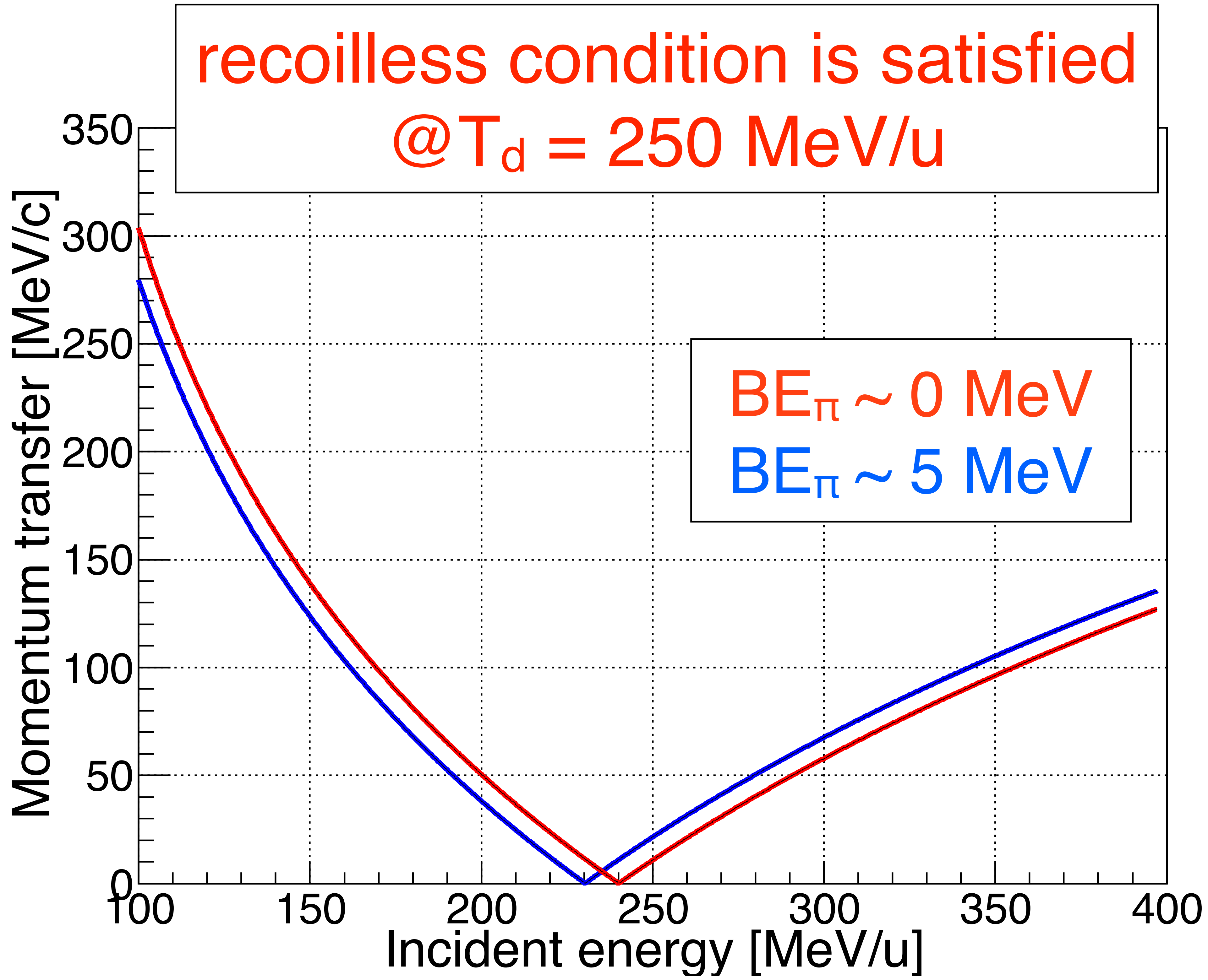
pionic 1s state in H
→ b_1 in vacuum
H. Schröder *et al.*, Eur. Phys. J. C 21, 473 (2001).

$\Gamma_{abs} > \Gamma_{rad}$
for deep orbit in heavy nuclei
absorption is faster

This method can NOT produce “deeply-bound” pionic atom…

Direct production: (d,^{3}He) reaction



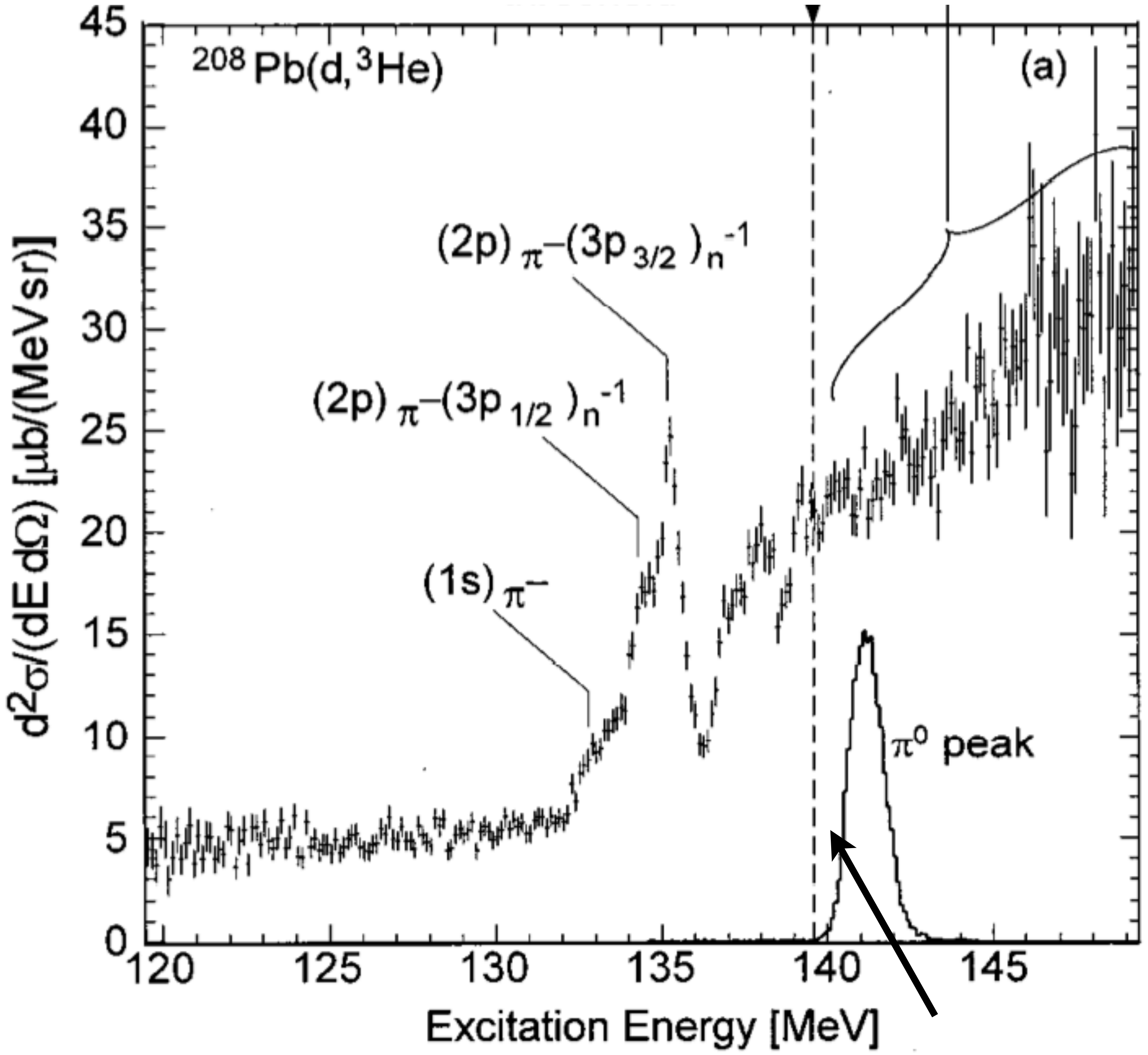


Recoilless → angular momentum transfer = 0

$(1s)_\pi \otimes (3s_{1/2})_n^{-1}$ etc··· are relatively enhanced!

Prior research: Experiment at GSI

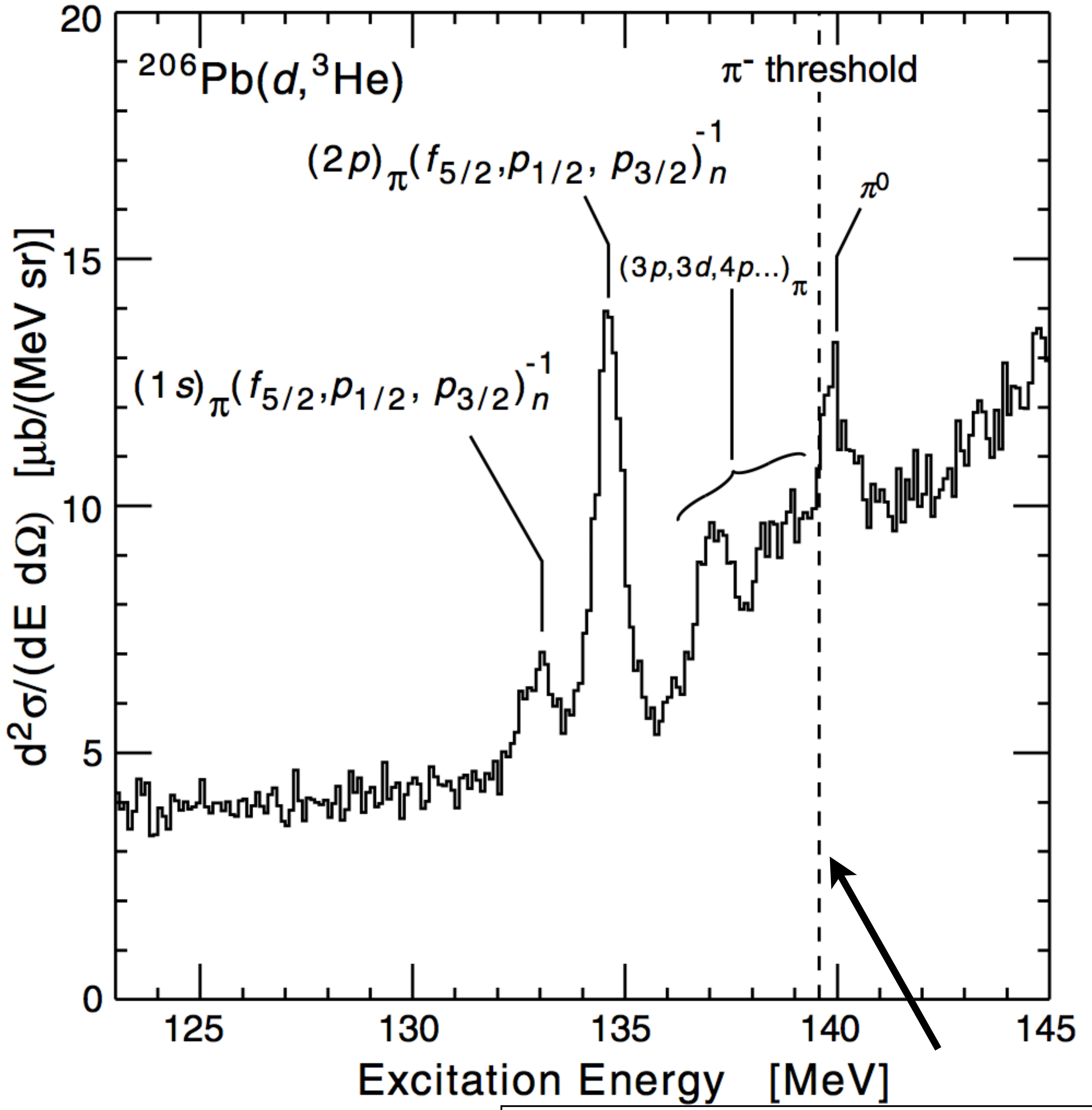
experimental spectrum for pionic ^{207}Pb@GSI



pion production threshold

K. Itahashi, et al.,
Phys. Rev. C62 (2000) 025202

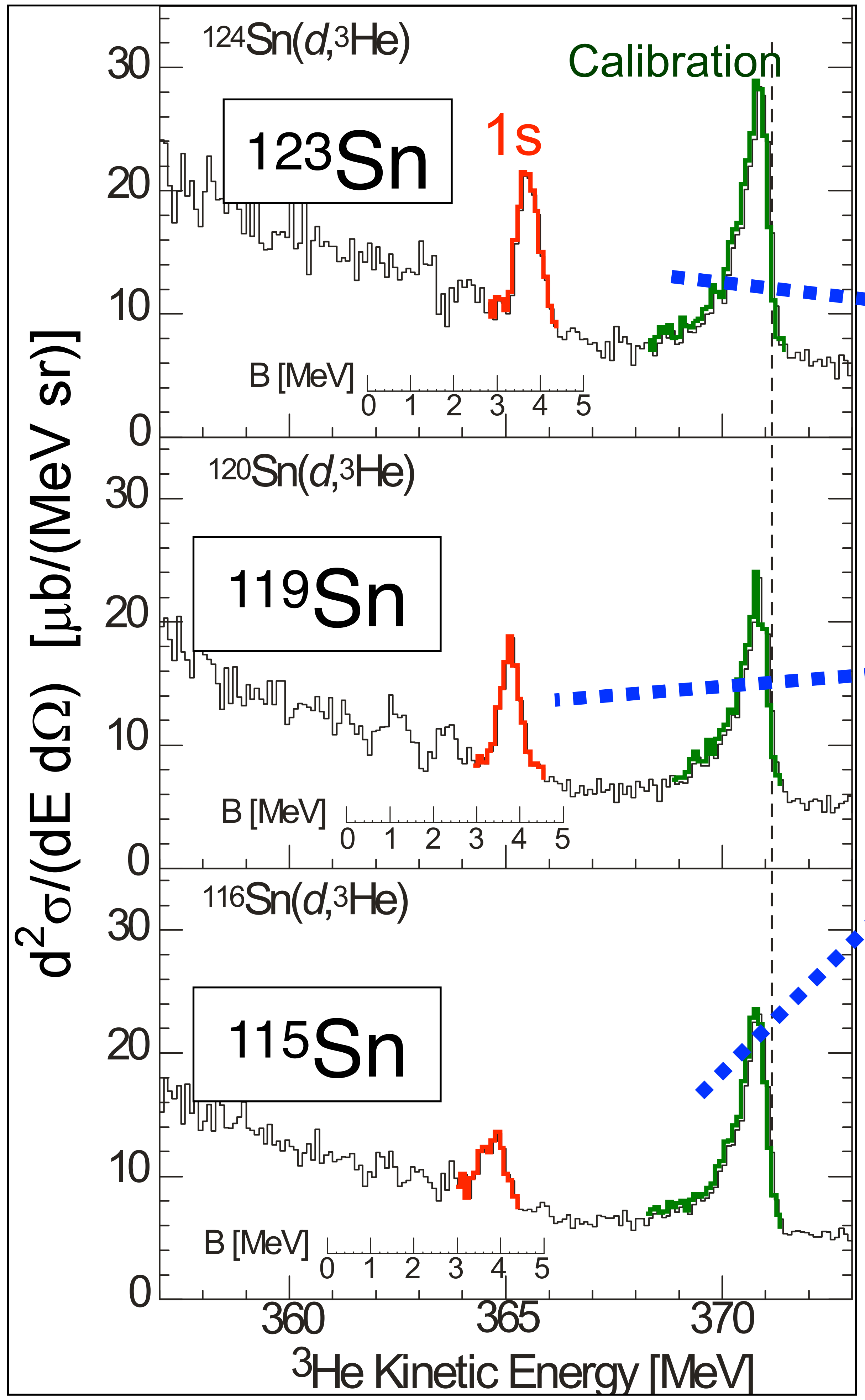
experimental spectrum for pionic ^{205}Pb@GSI

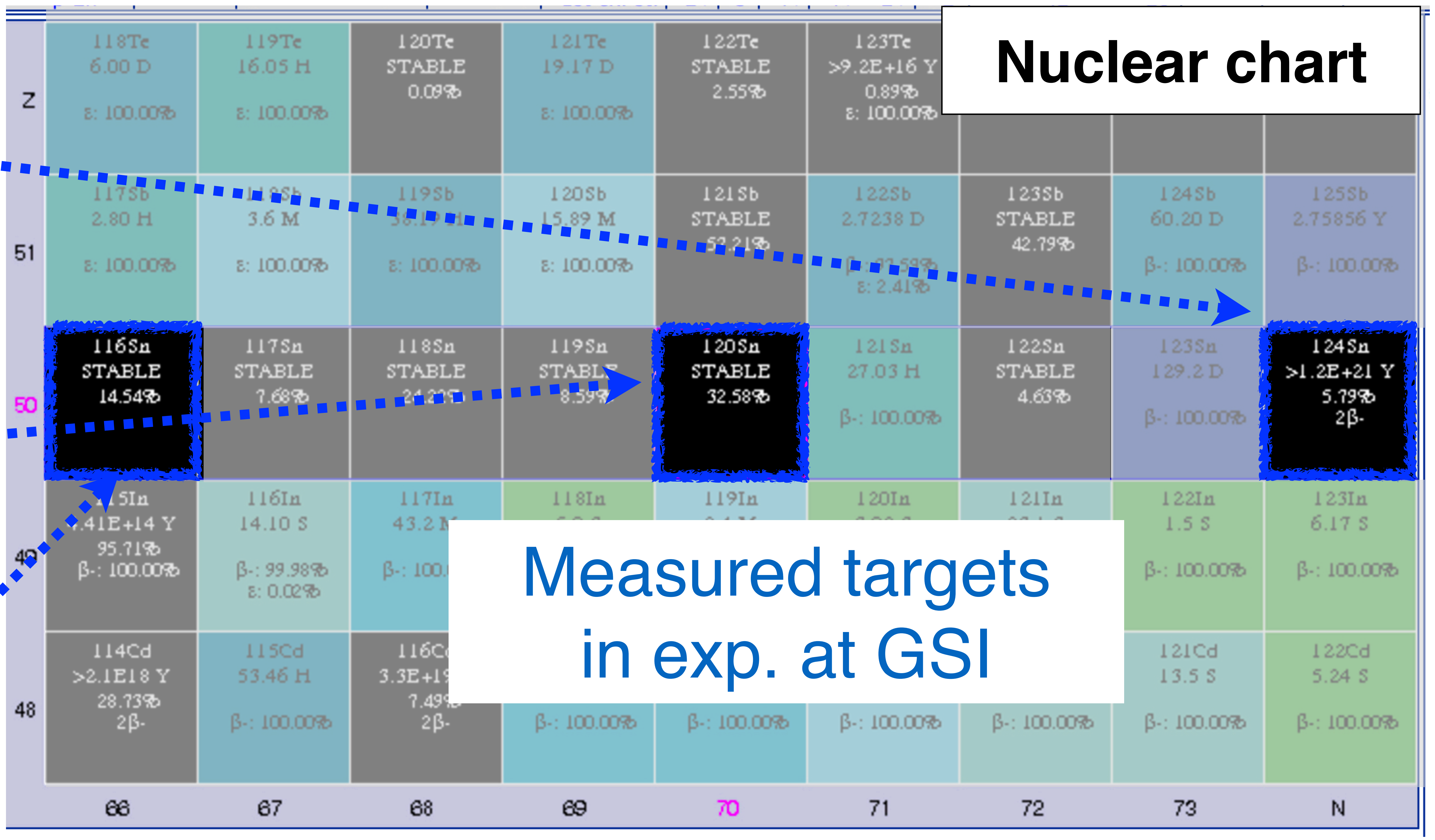


pion production threshold

H. Geissel, et al.,
Phys. Rev. Lett. 88 122301 (2002)

Prior research: Experiment at GSI





NuDat2 (https://www.nndc.bnl.gov/nudat2/)

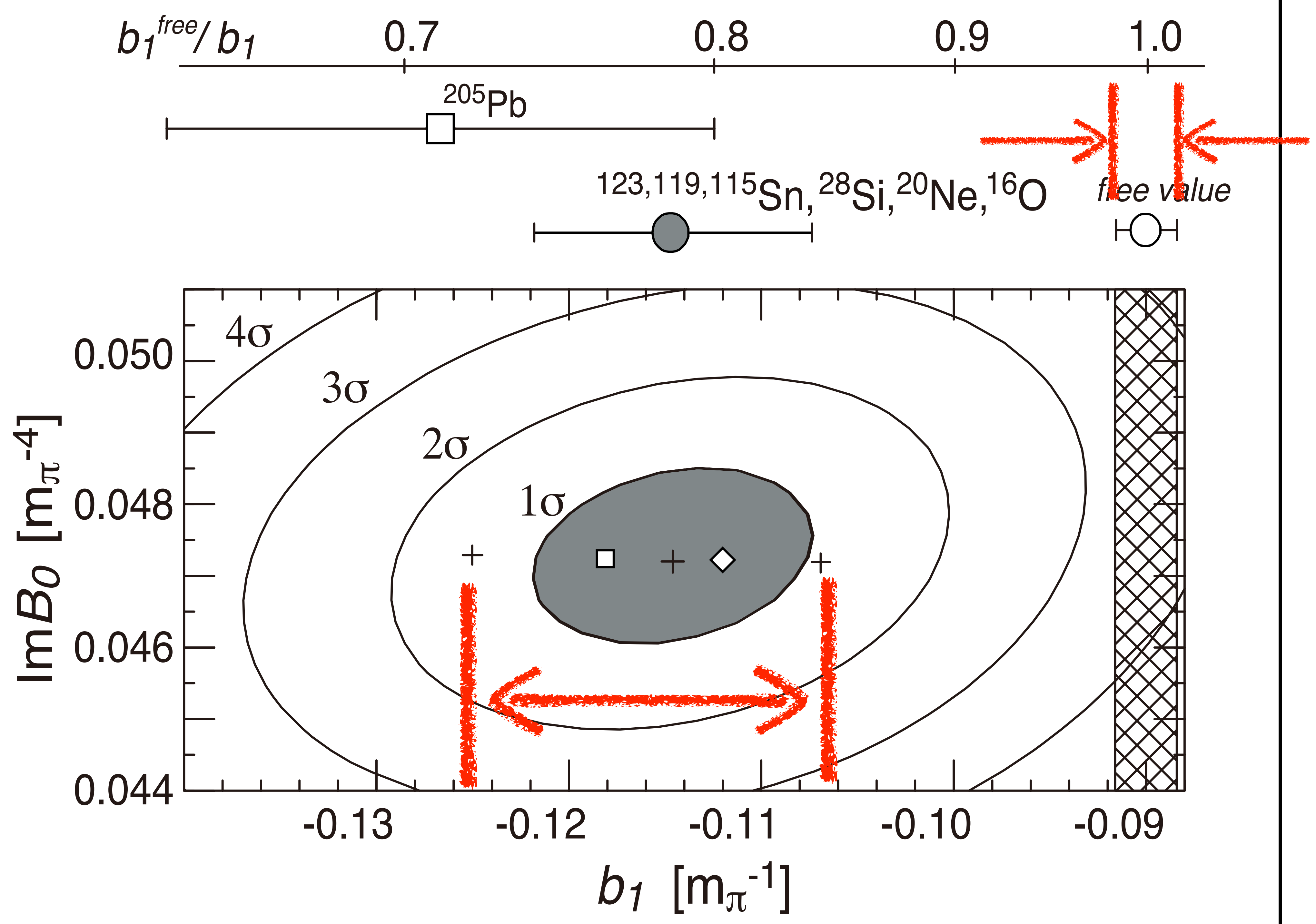
K. Suzuki et al., PRL92 072302 (2004)

Systematic study of pionic Sn isotopes

~ **2 month** measurement for 3 isotopes (w/ detector tuning etc…)

Extract b_1 from exp. data at GSI

Contour plot of χ^2



$$\frac{b_1^{\text{free}}}{b_1} = 0.78 \pm 0.05$$

$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle} \approx 0.66 \pm 0.06$$

cf. theoretical prediction ~ 0.65

π-A s-wave optical potential

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

error of b_1 in medium is still large compared with that in vacuum!!
two main sources are

- **experimental error**
- **neutron distribution ambiguities**

To extract b_1 with higher precision

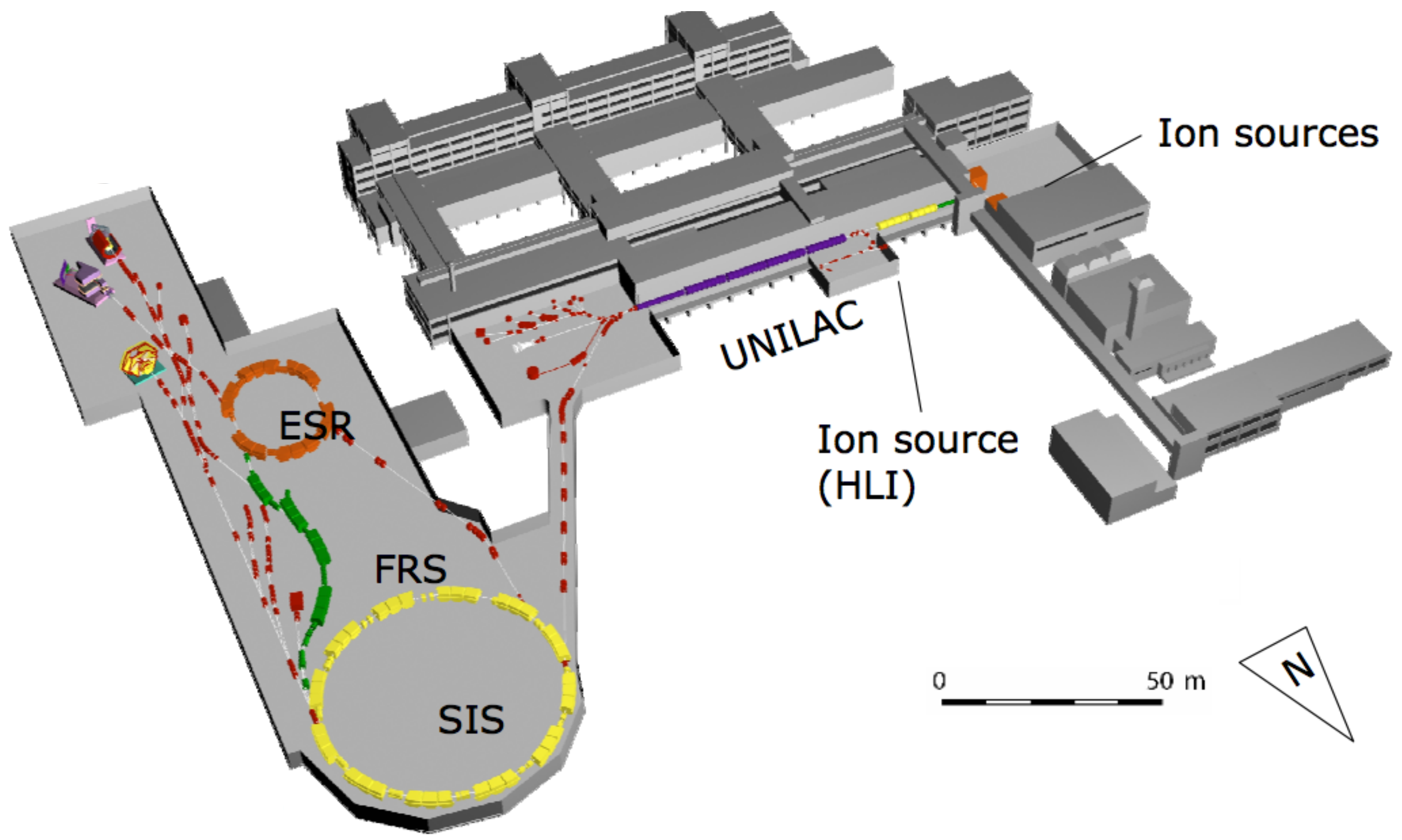
improve resolution / calibration

systematic study by Isotope shift

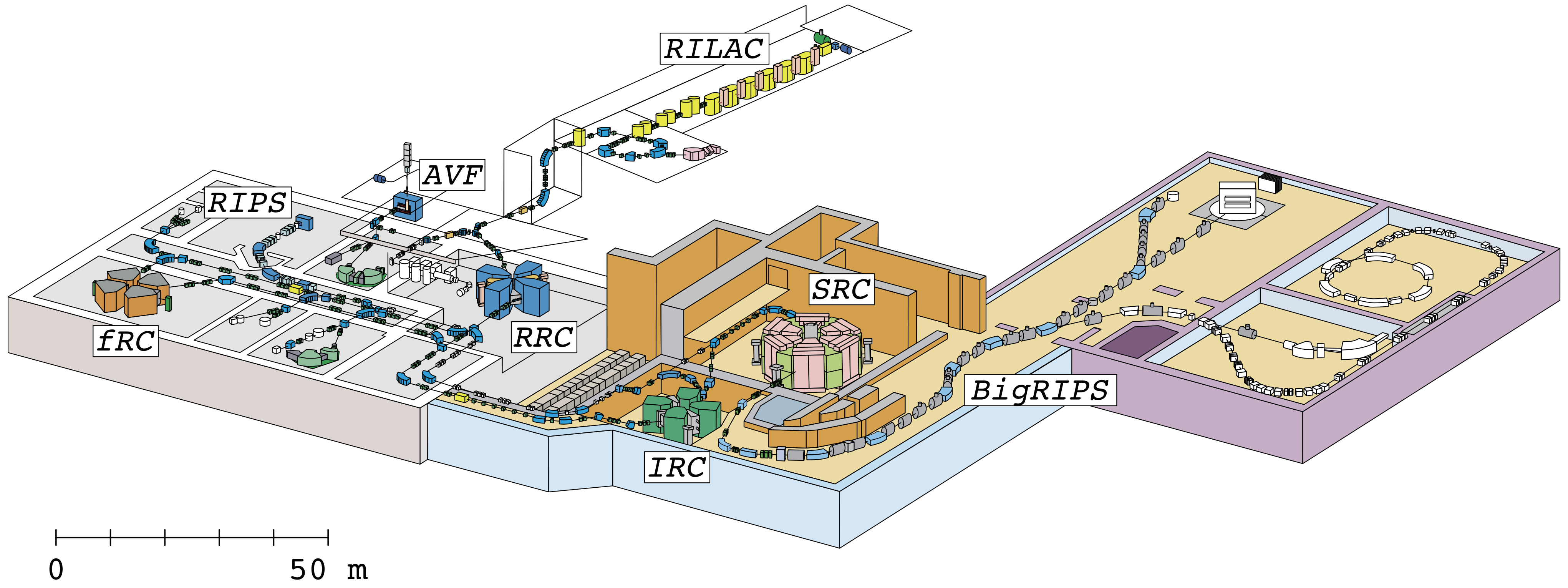
※ b_0 , ReB_0 are deduced from data of light / symmetric pionic atoms

Comparison between RIBF and GSI

GSI facilities



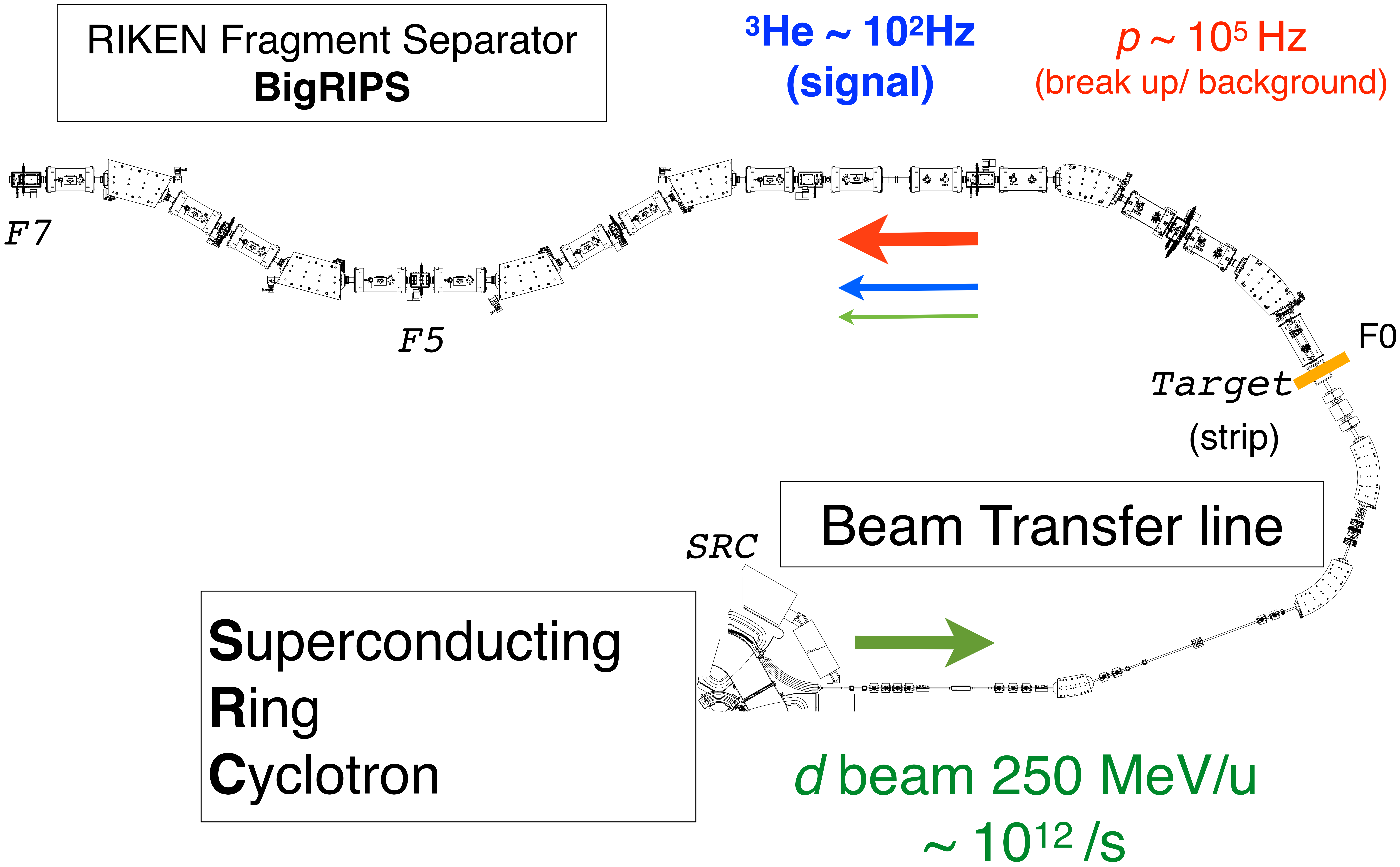
RIKEN RIBF facilities



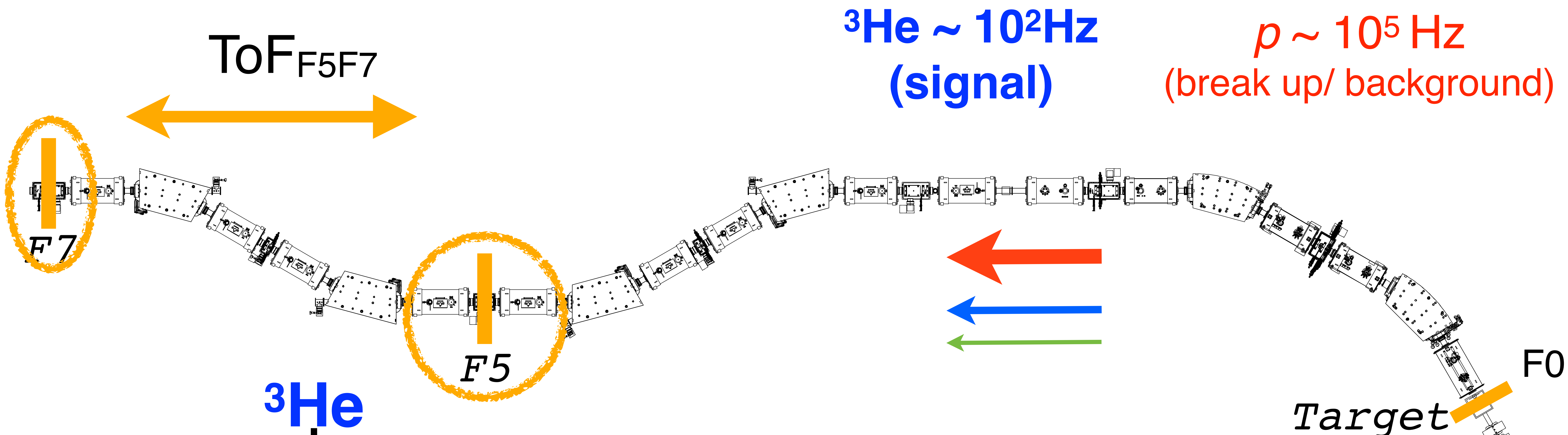
	GSI (FRS)	RIBF (BigRIPS)	Improvement
intensity	~ 10^{11}/ 6 s (1 spill)	~ 10^{12}/ s	**× 60**
angular acceptance (H / V)	15 / 10 mrad	40 / 60 mrad	×16
resolution (FWHM)	400 keV	**200 ~ 300 keV**	improve

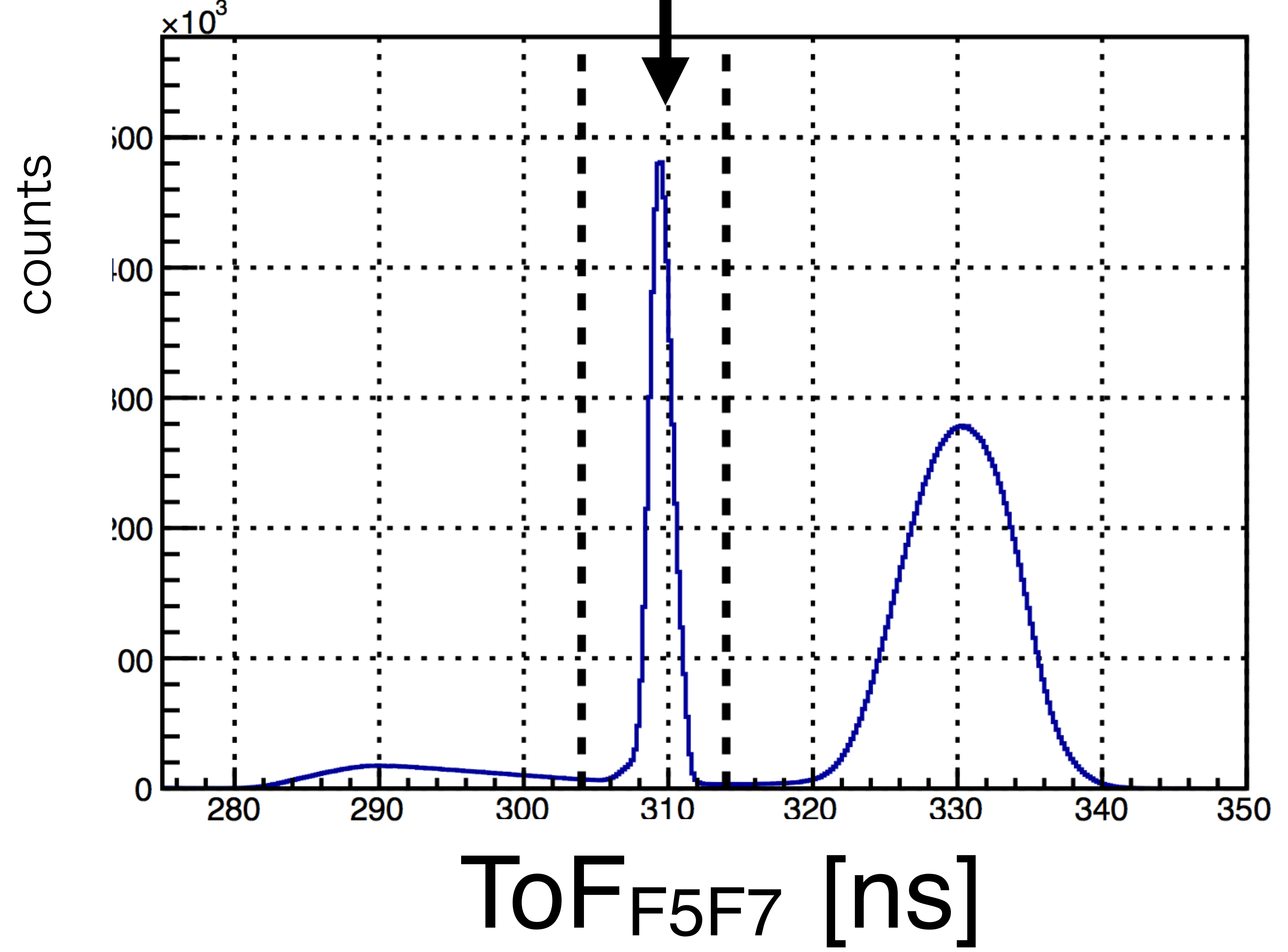
by dispersion matching optics   cf. $\Gamma_{1s} \sim$ 300 keV

Experimental setup at RIBF



Experimental setup at RIBF : pID





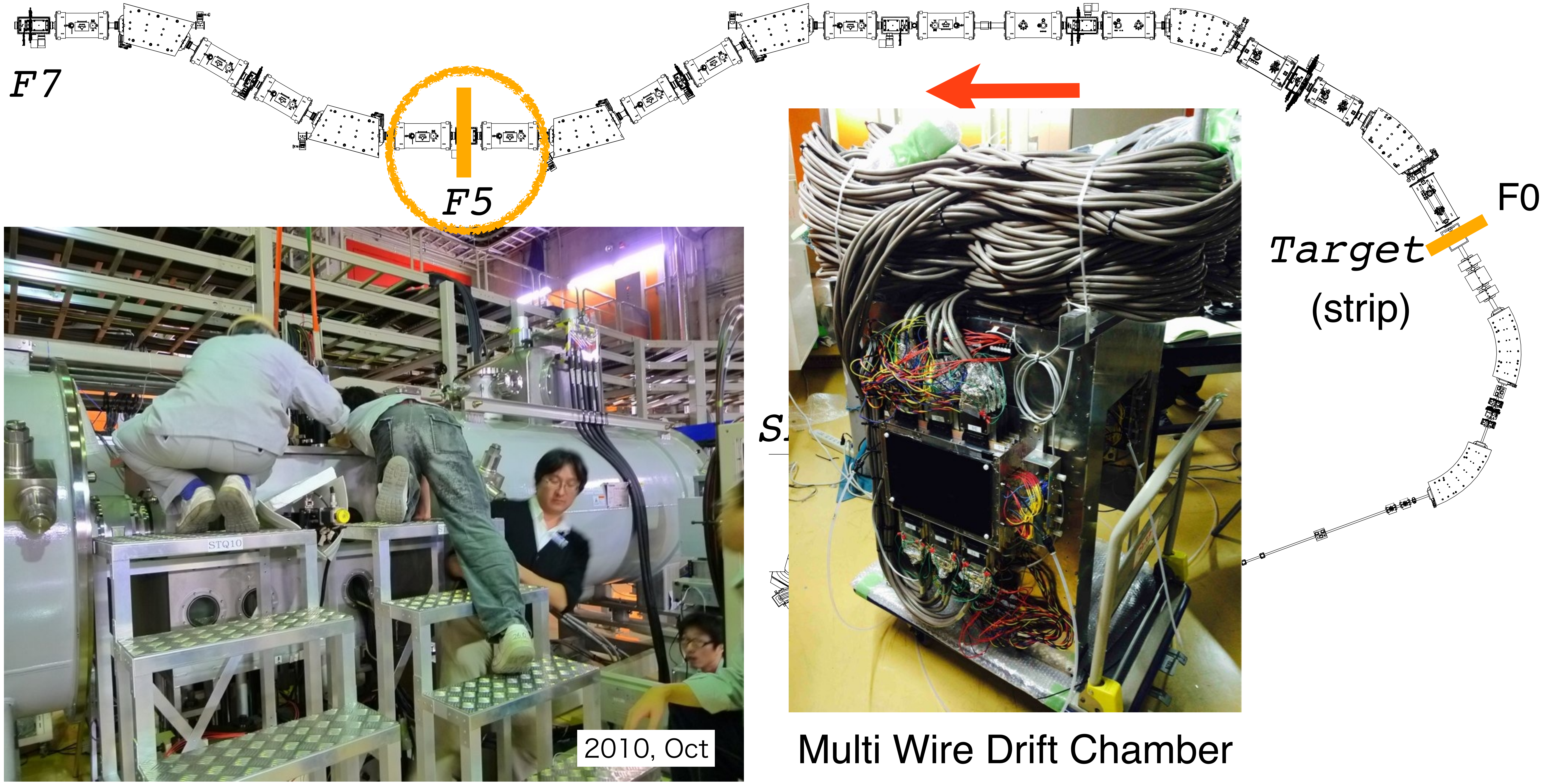
pID
efficiency : ≧ 98 %
purity : ≧ 99.5 %

Experimental setup at RIBF : tracking

RIKEN Fragment Separator
BigRIPS

^{3}He ~ 10^{2}Hz
(signal)

p ~ 10^{5} Hz
(break up/ background)



Multi Wire Drift Chamber

Experimental setup at RIBF : optics tuning

Dispersion matching:
Eliminate contribution of beam momentum spread
※ w/ usual primary beam settings, the contribution become ~ 800 keV (FWHM)

Spectrometer (BigRIPS) | reaction | Analyzer (Beam Transfer Line)

$$\begin{pmatrix} x_{fp} \\ \theta_{fp} \\ \delta p_{fp} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{16} \\ S_{21} & S_{22} & s_{26} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & C \end{pmatrix} \begin{pmatrix} A_{11} & A_{12} & A_{16} \\ A_{21} & A_{22} & A_{26} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_0 \\ \delta p_0 \end{pmatrix}$$

F5

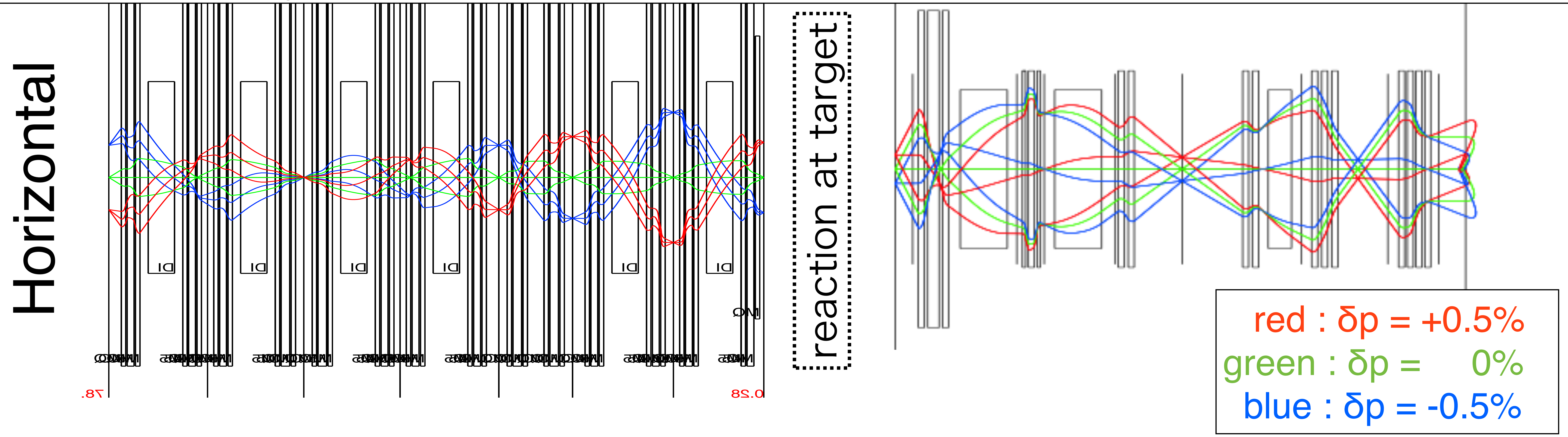
*C: kinematical factor = 1.31

inside SRC

$$x_{fp} = \cdots + (S_{11}A_{16} + CS_{16})\delta p_0$$

Experimental setup at RIBF : optics tuning

Dispersion matching:
Eliminate contribution of beam momentum spread
※ w/ usual primary beam settings, the contribution become ~ 800 keV (FWHM)



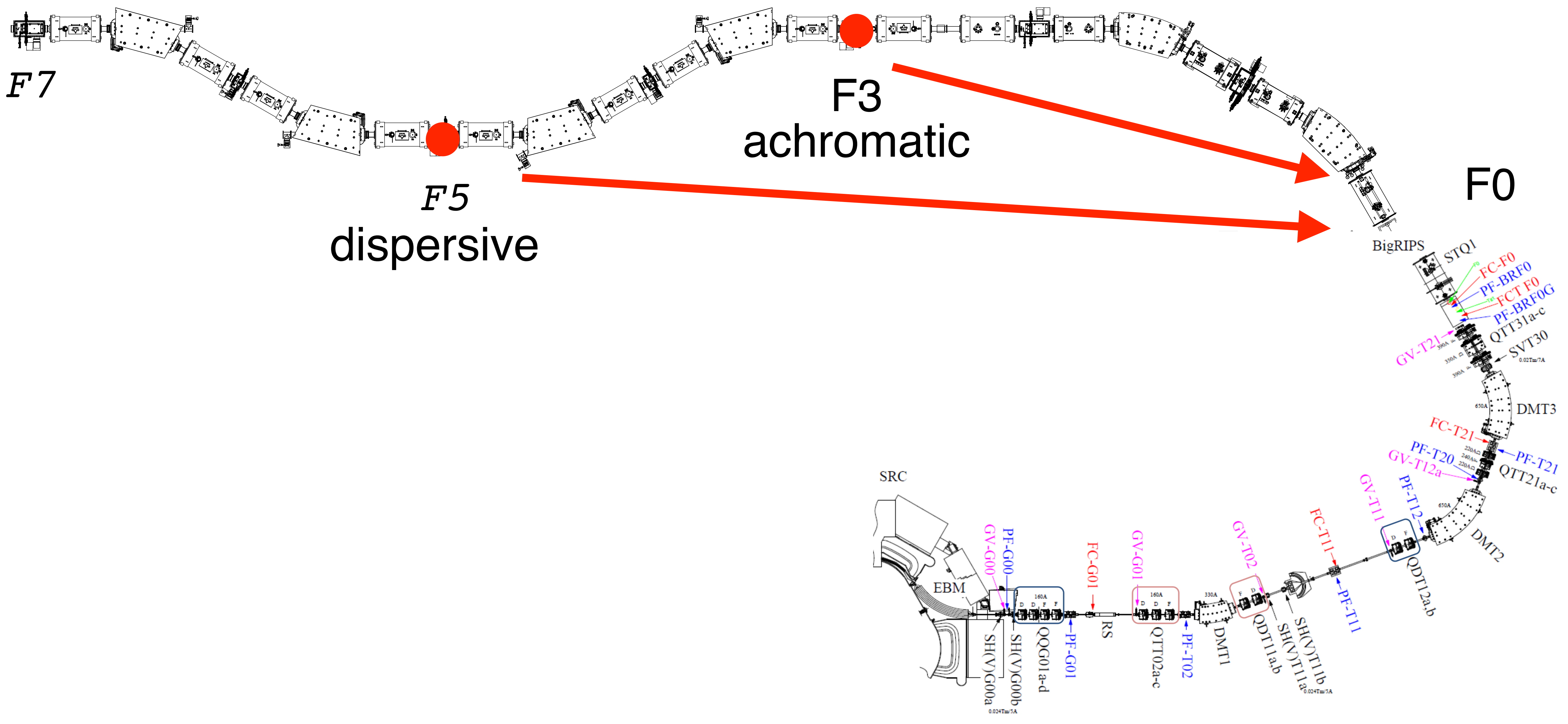
$$x_{fp} = \cdots + (S_{11}A_{16} + CS_{16})\delta p_0$$

Cancel out

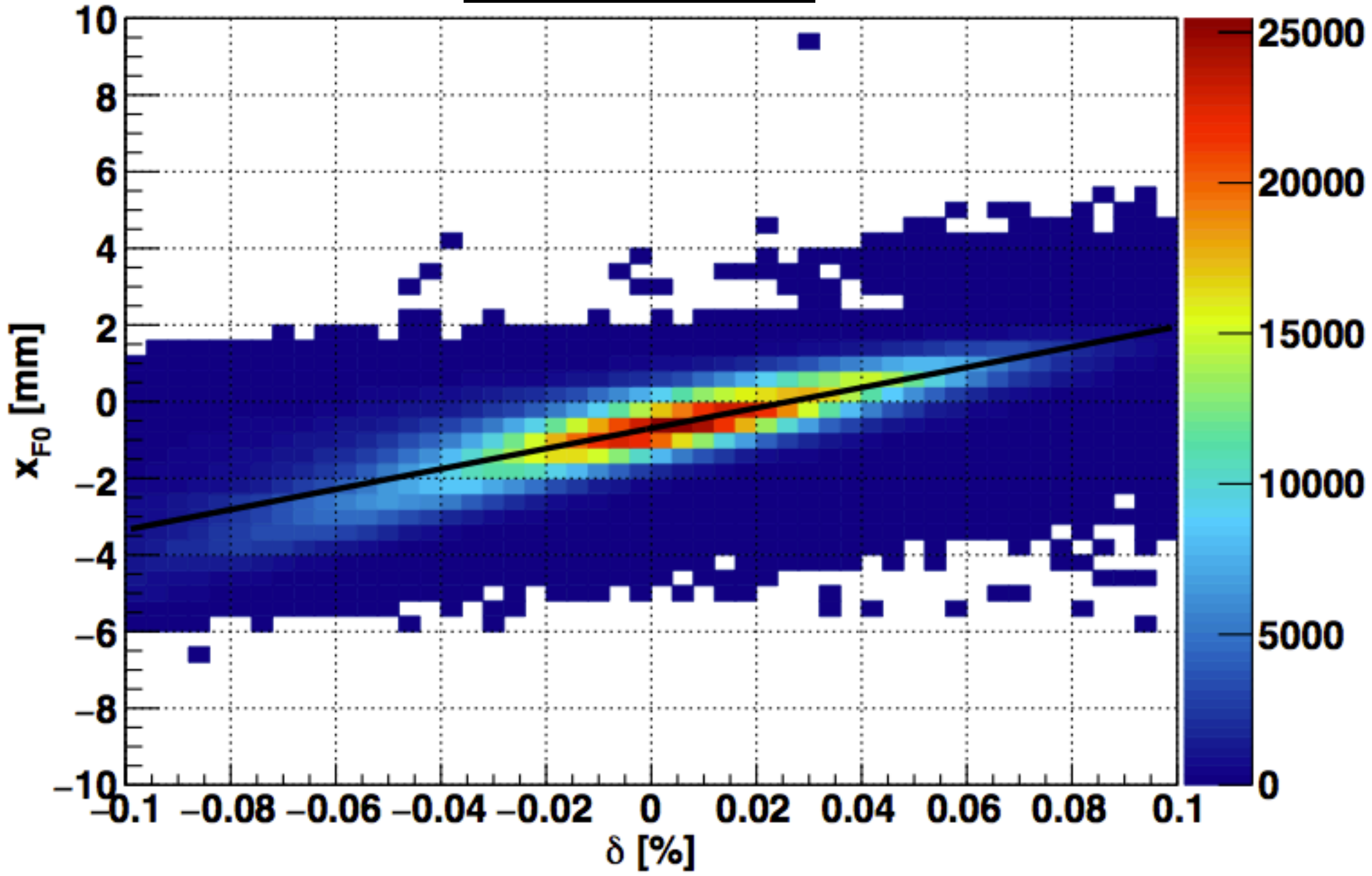
design values: $S_{11} = -1.8$ **A_{16} = 44.6 mm/% (dispersion in transport line)**
$C = 1.31$ $S_{16} = 62$ mm/%

Experimental setup at RIBF : optics tuning

Use BigRIPS as a diagnostics of BT line
- measure the position / angle at F3 and F5 focal plane
- trace back to F0



x_{F0} vs δ



measured dispersion in BT line
→ 24 mm/% !!!

(cf. designed value: 44.6 mm/%)

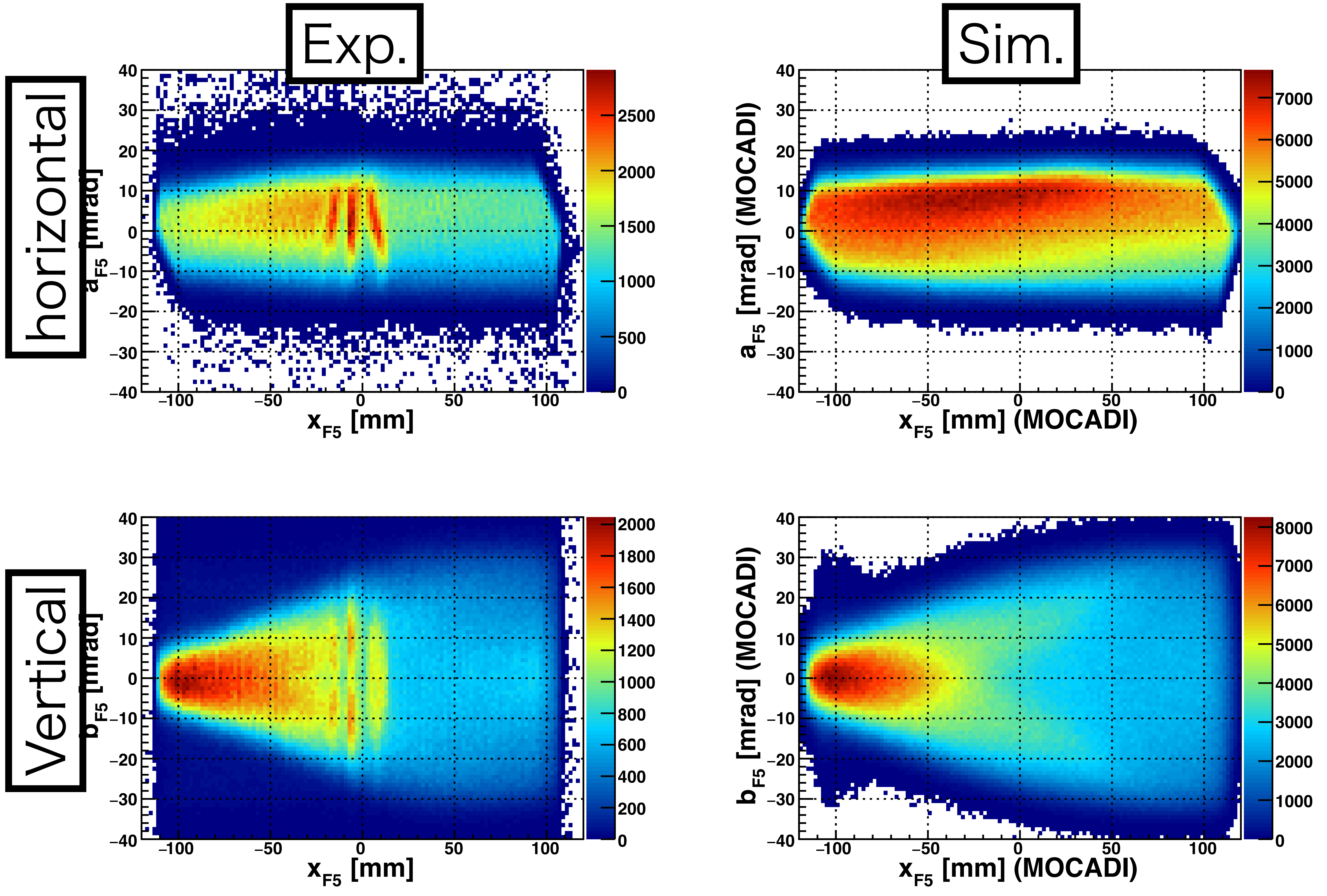
The difference may be caused by the optics inside SRC

After phenomenological tuning, dispersion is improved to be **28 mm/%**
⇔ reduce the contribution of δp by ~ 40%

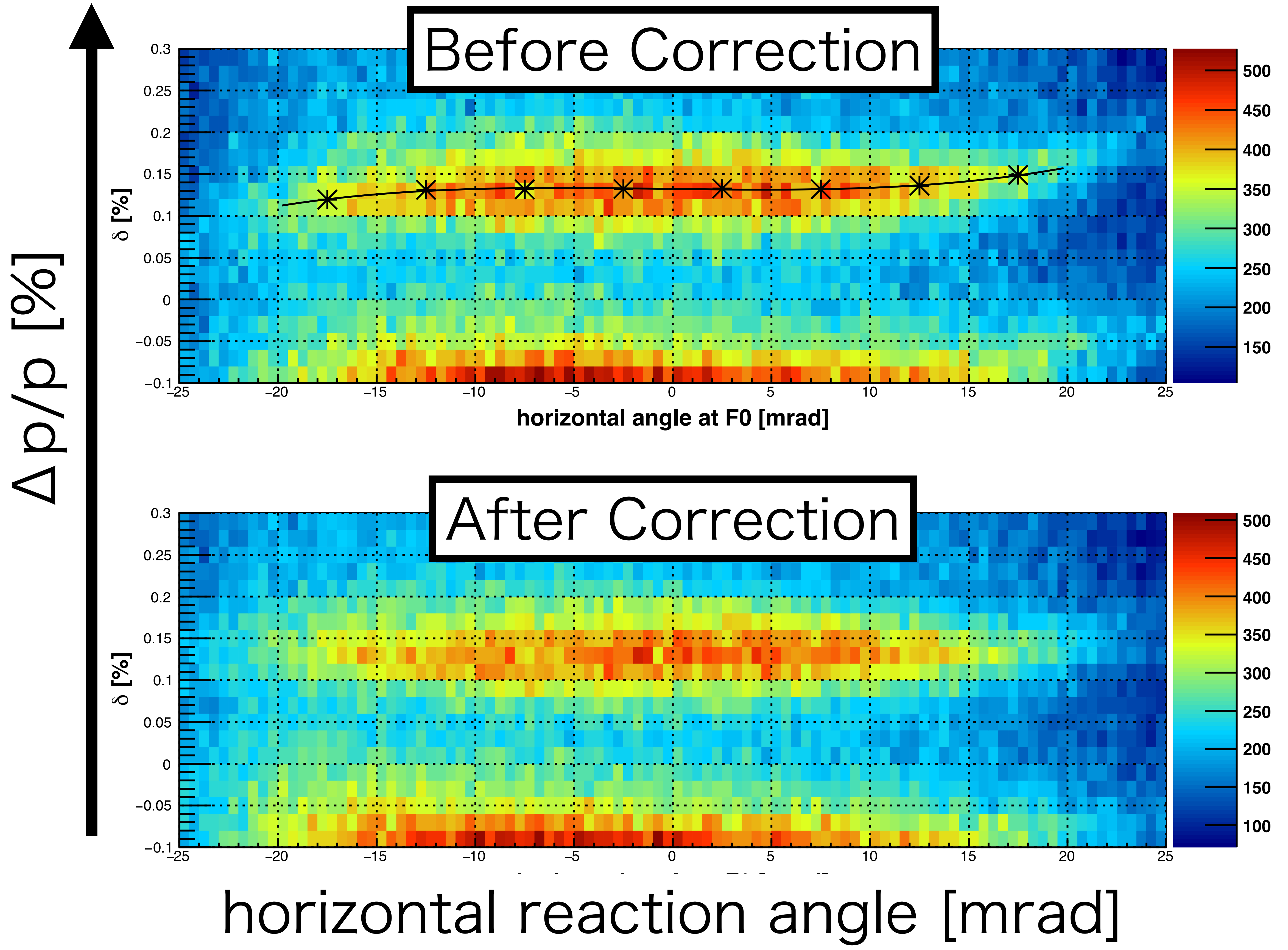
After optimization of primary beam emittance → contribution ~ 220 keV

Experimental setup at RIBF : optical correction

Acceptance correction
reproduced by MC simulation (MOCADI)

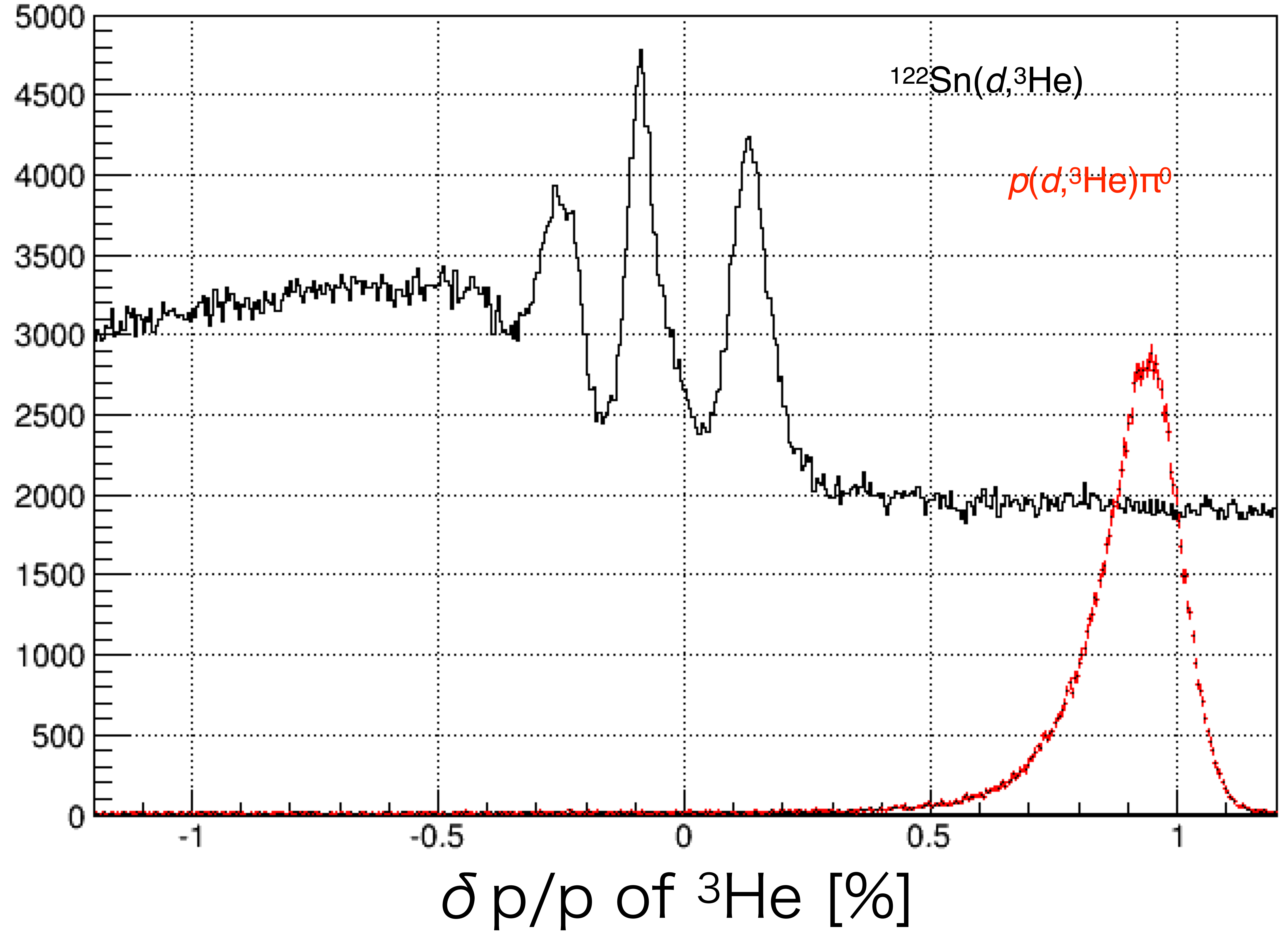


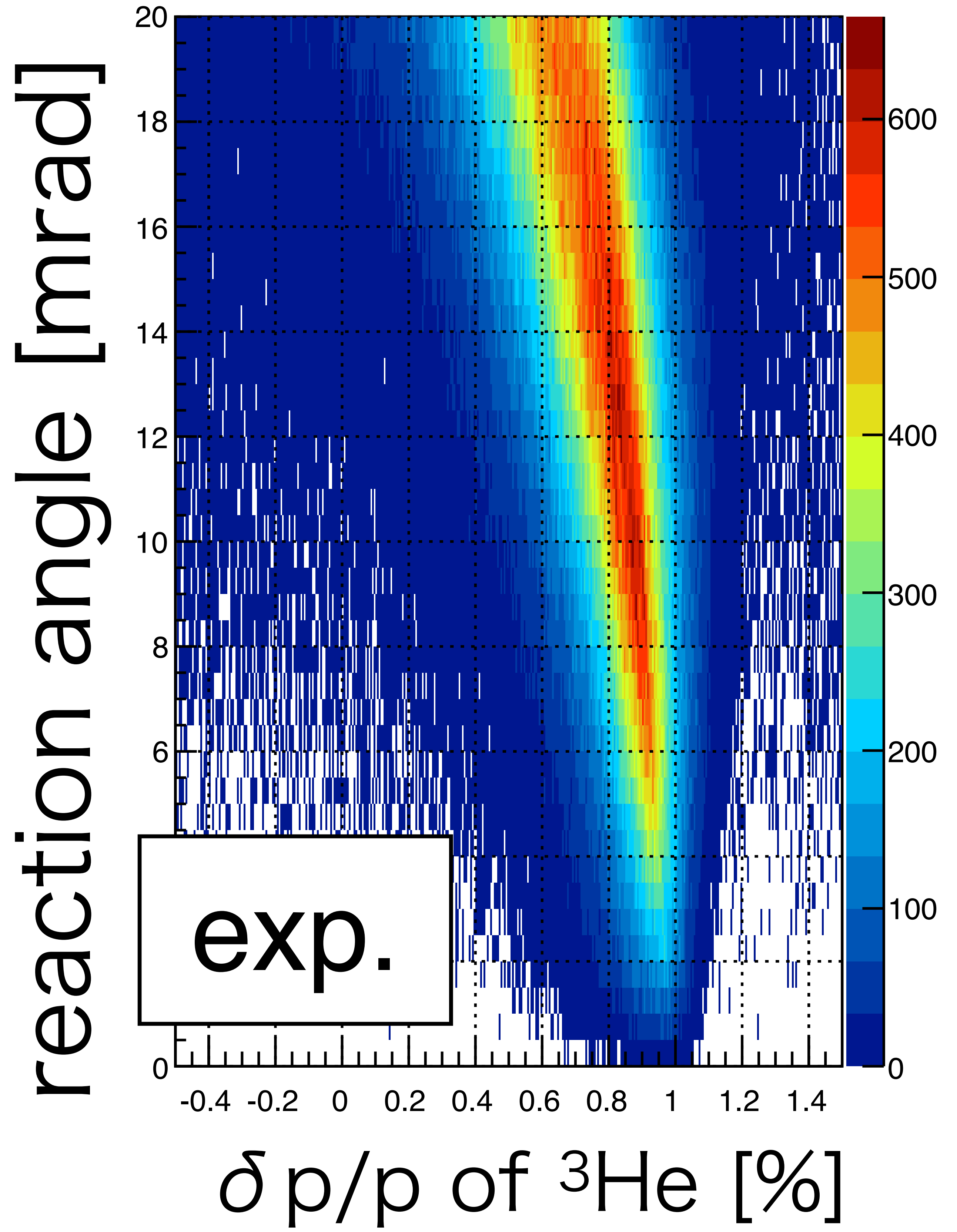
Optical correction
by 3rd-order matrix element

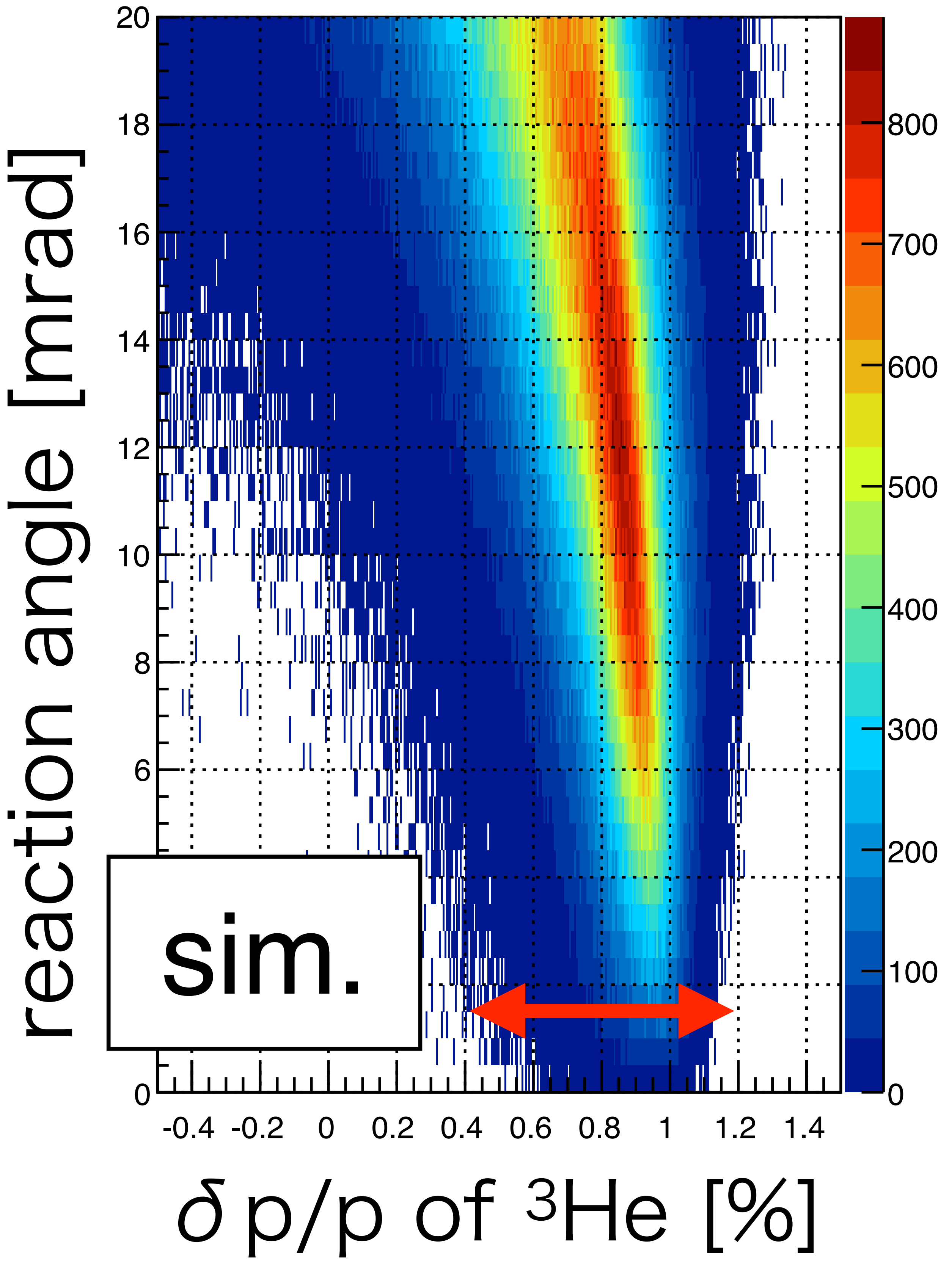


Experimental setup at RIBF : calibration

Calibration of E_{3He} : $p(d,^3He)\pi^0$ reaction
(CH_2 target / 2-body kinematics)







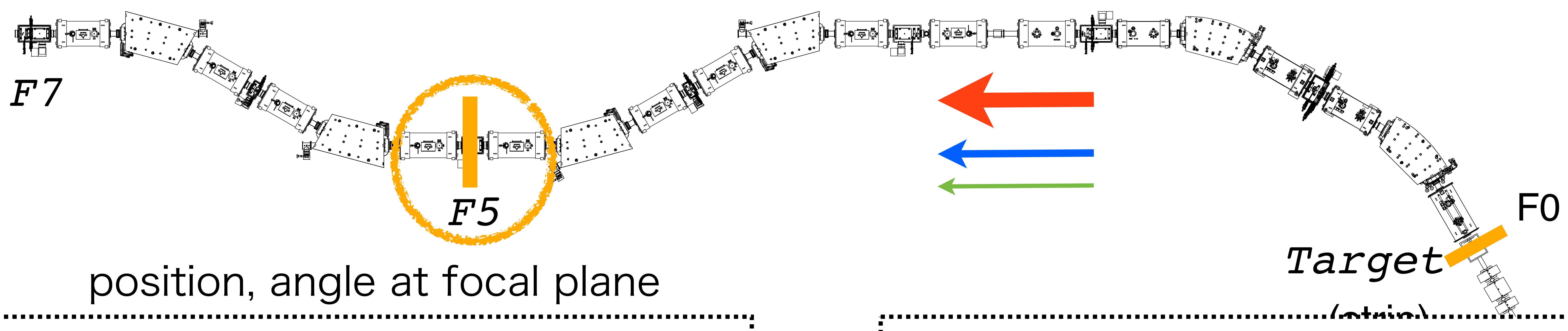
E_{3He} at center of focal plane = 362.458 ± 0.003 (stat.) ± 0.005 (sys.) [MeV]
(Ambiguity of the primary beam energy is not included)

Experimental setup at RIBF : tracking

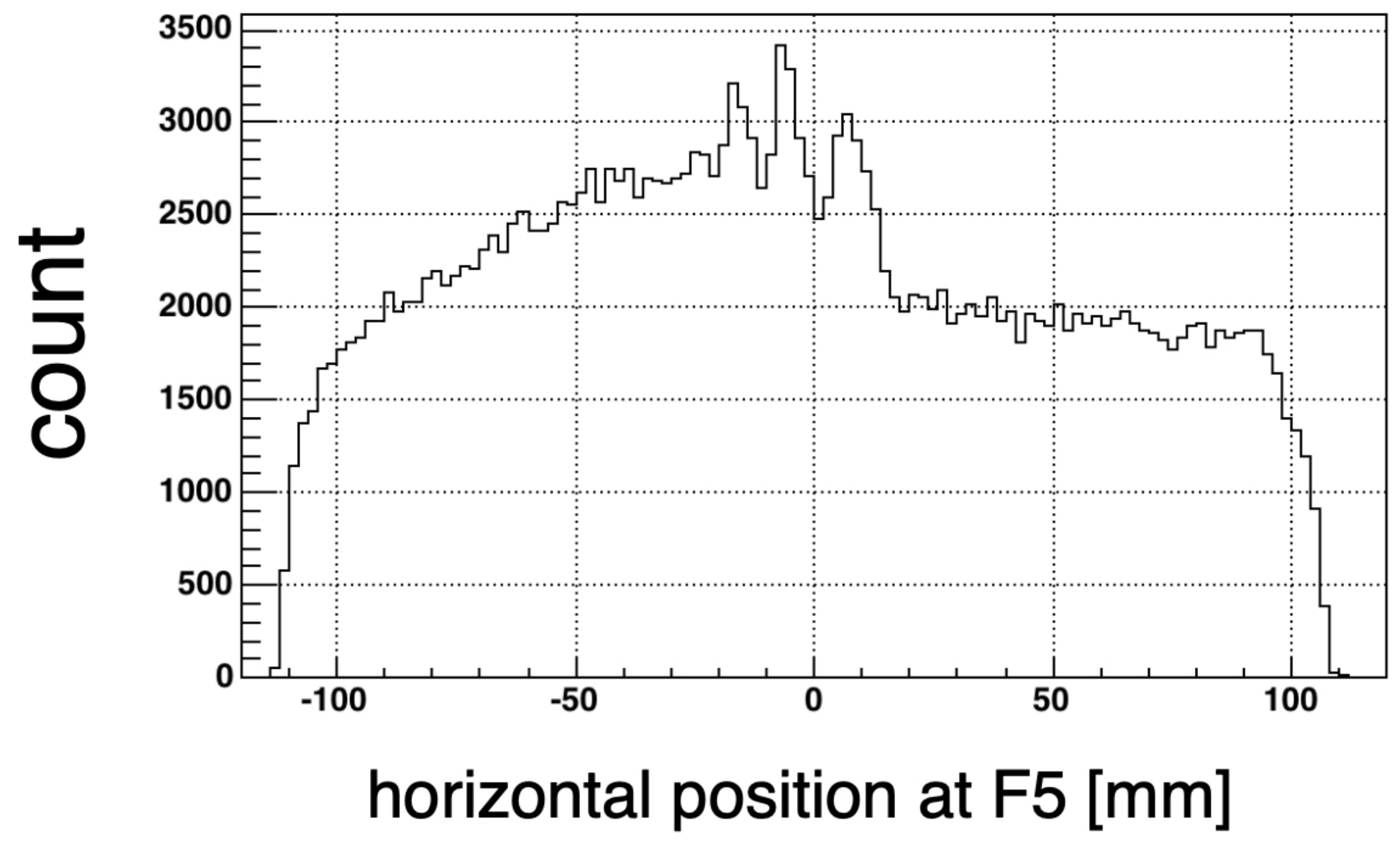
RIKEN Fragment Separator
BigRIPS

^{3}He ~ 10^2Hz
(signal)

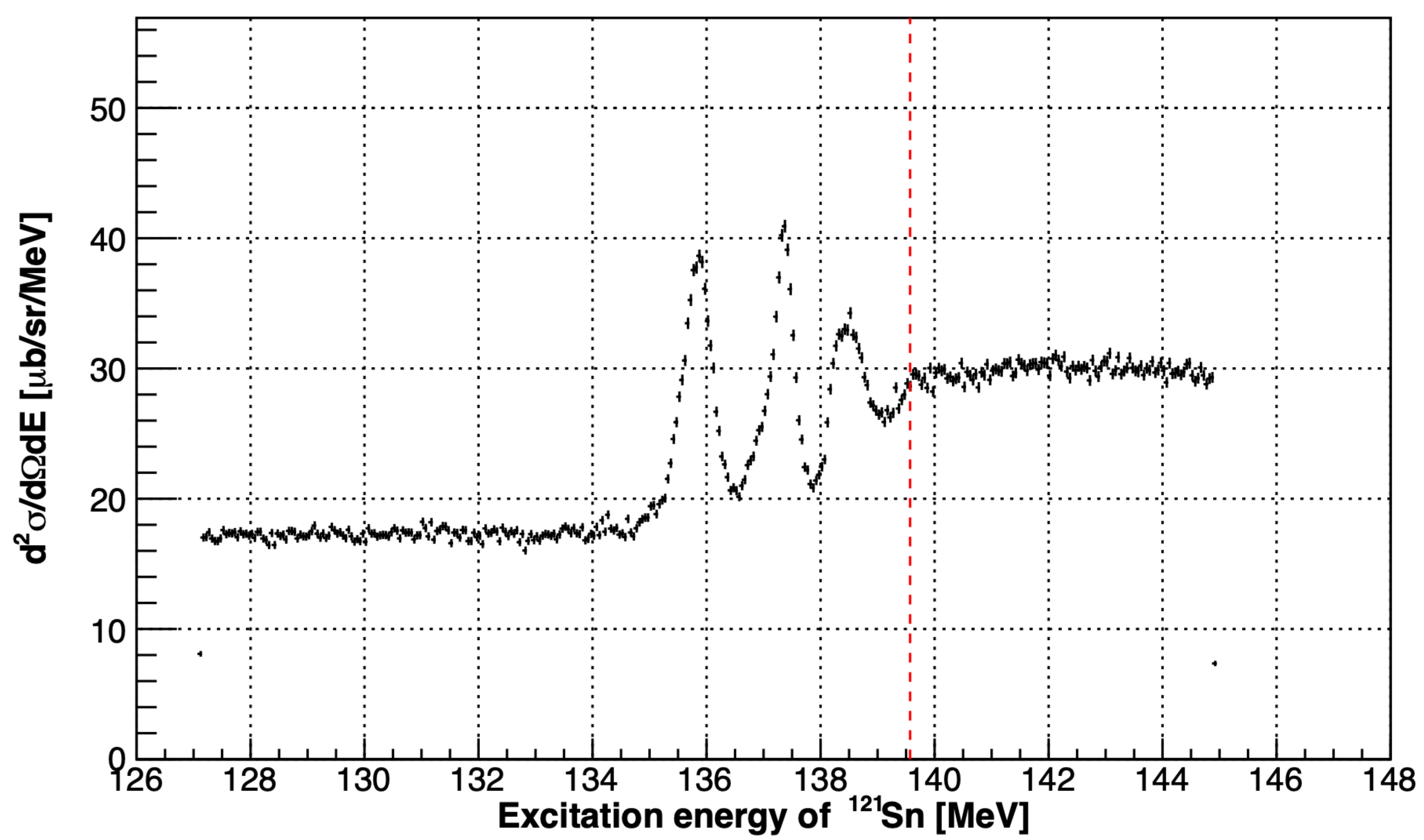
p ~ 10^5 Hz
(break up/ background)



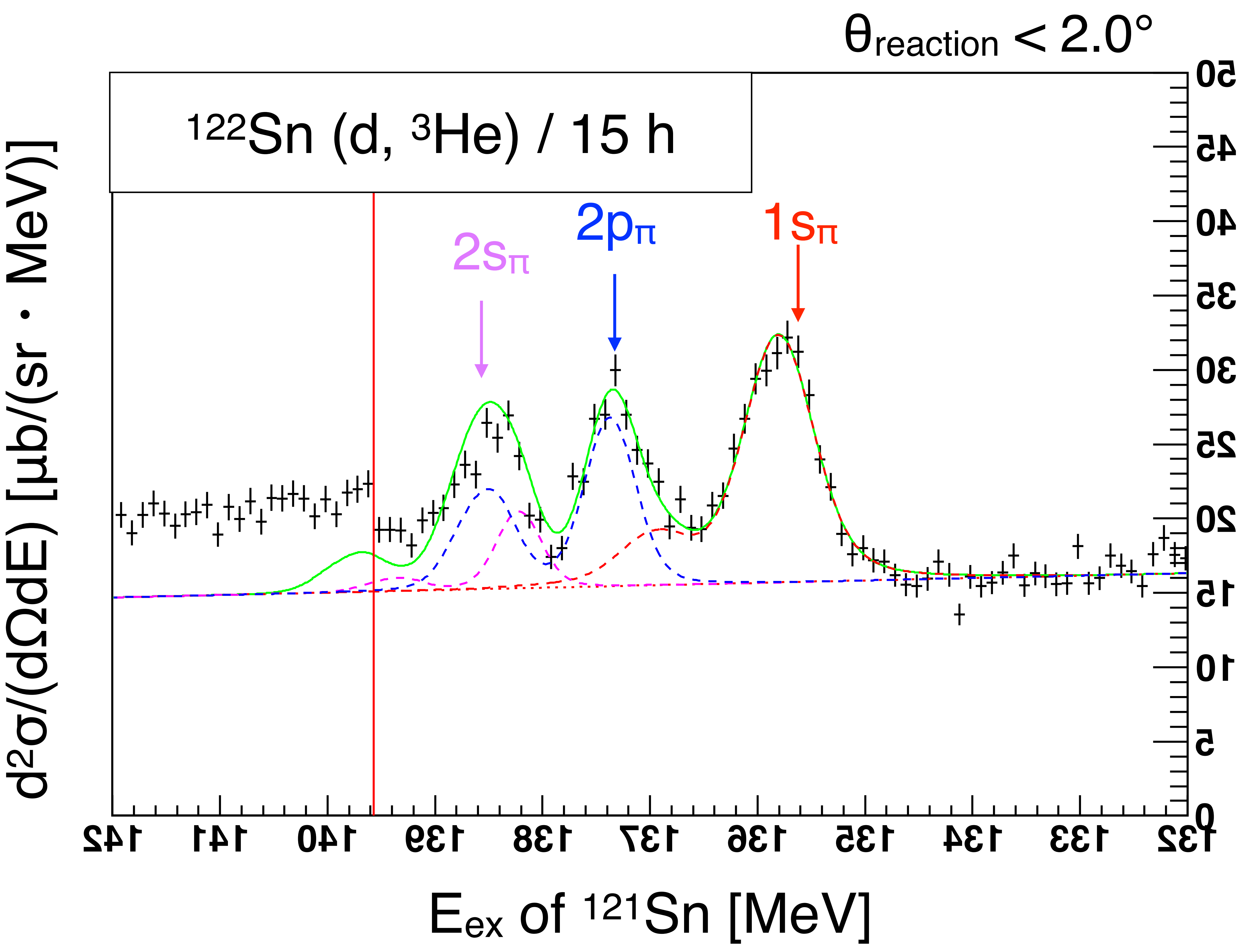
position, angle at focal plane

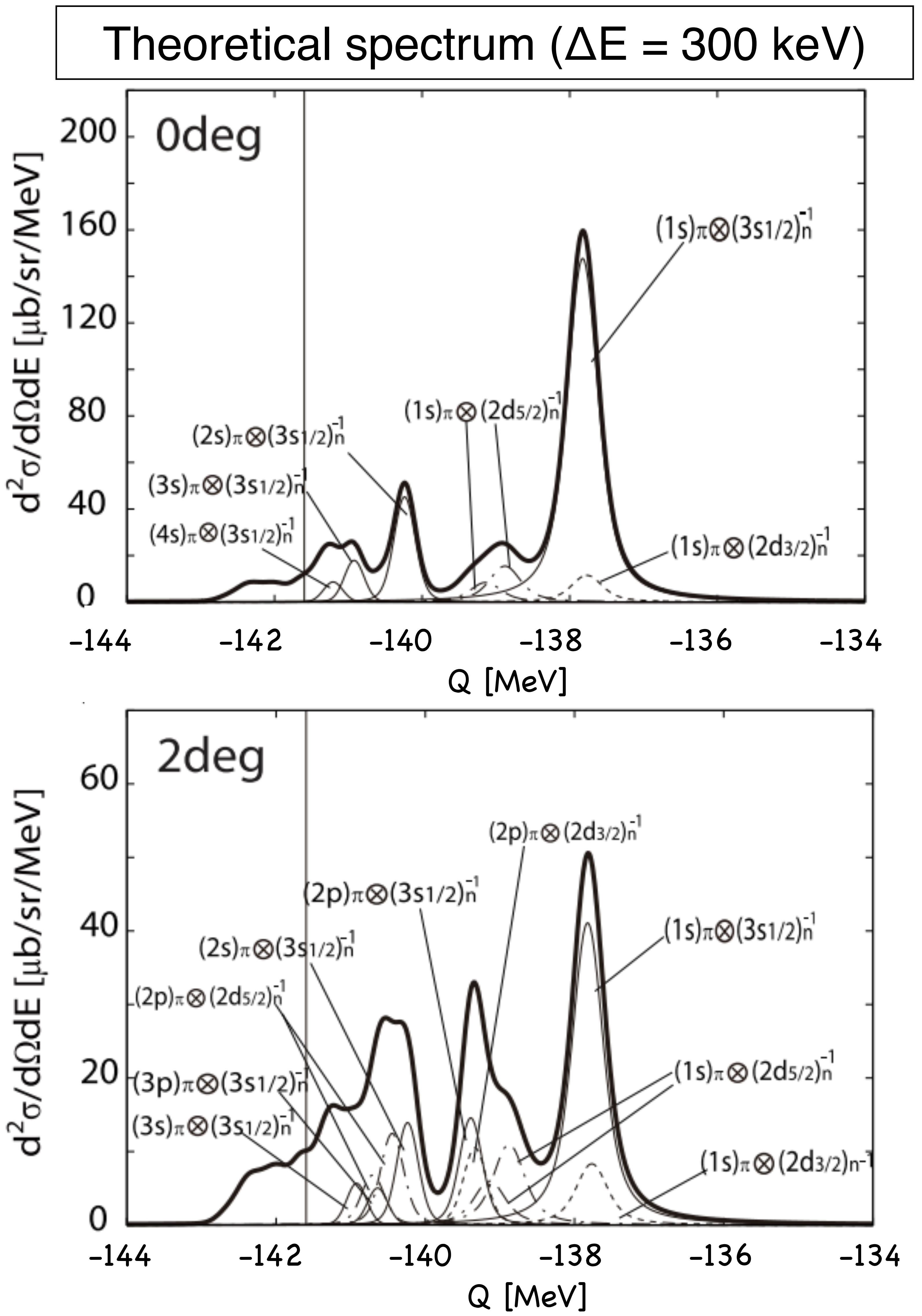


SRC



Polot experiment @ RIKEN in 2010





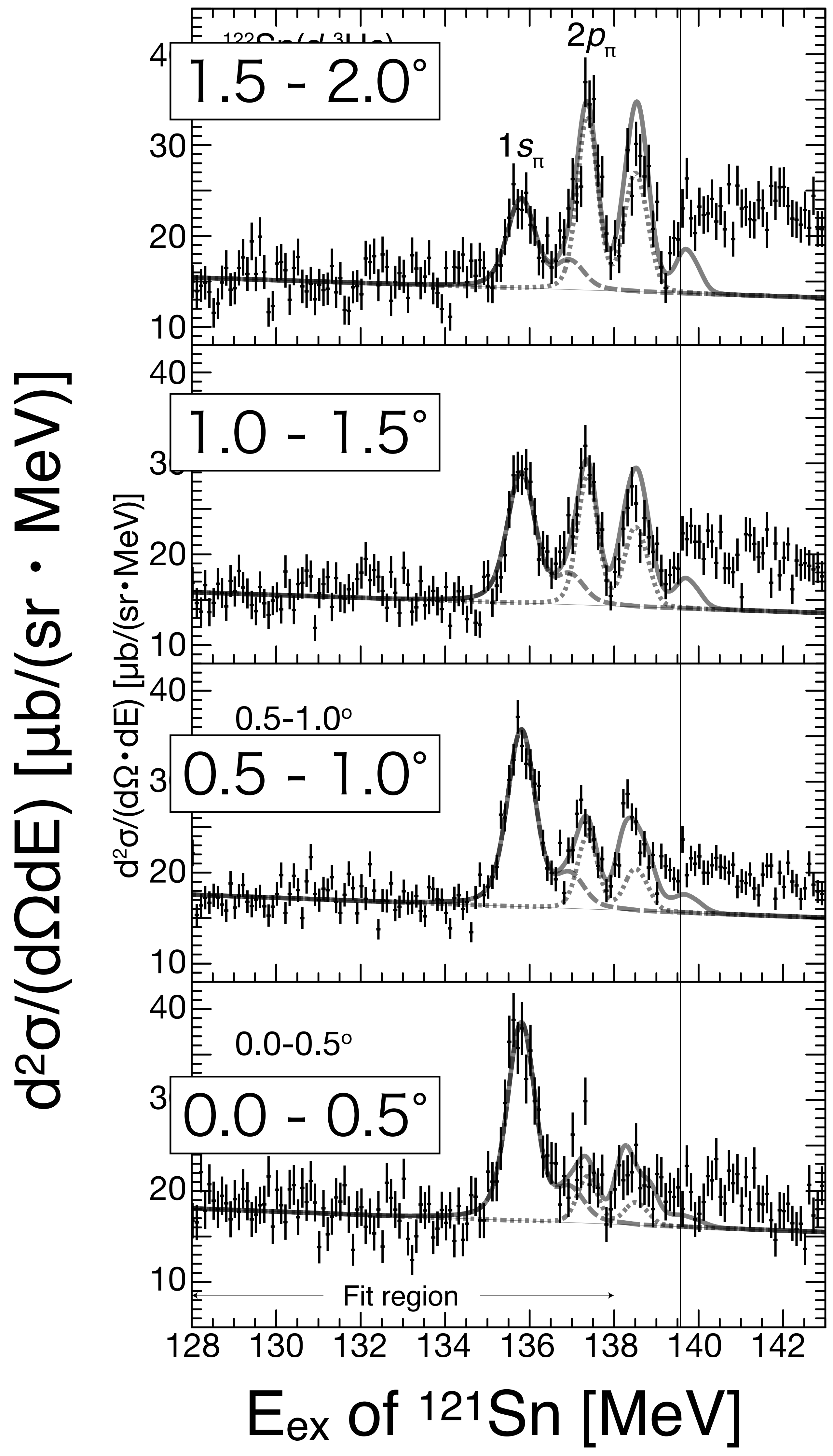
・Clear peaks are observed in 15-h measurement

・Center peak corresponds to the $(2p)_\pi \otimes (3s_{1/2})_n^{-1}, (2d_{5/2})_n^{-1} \cdots$

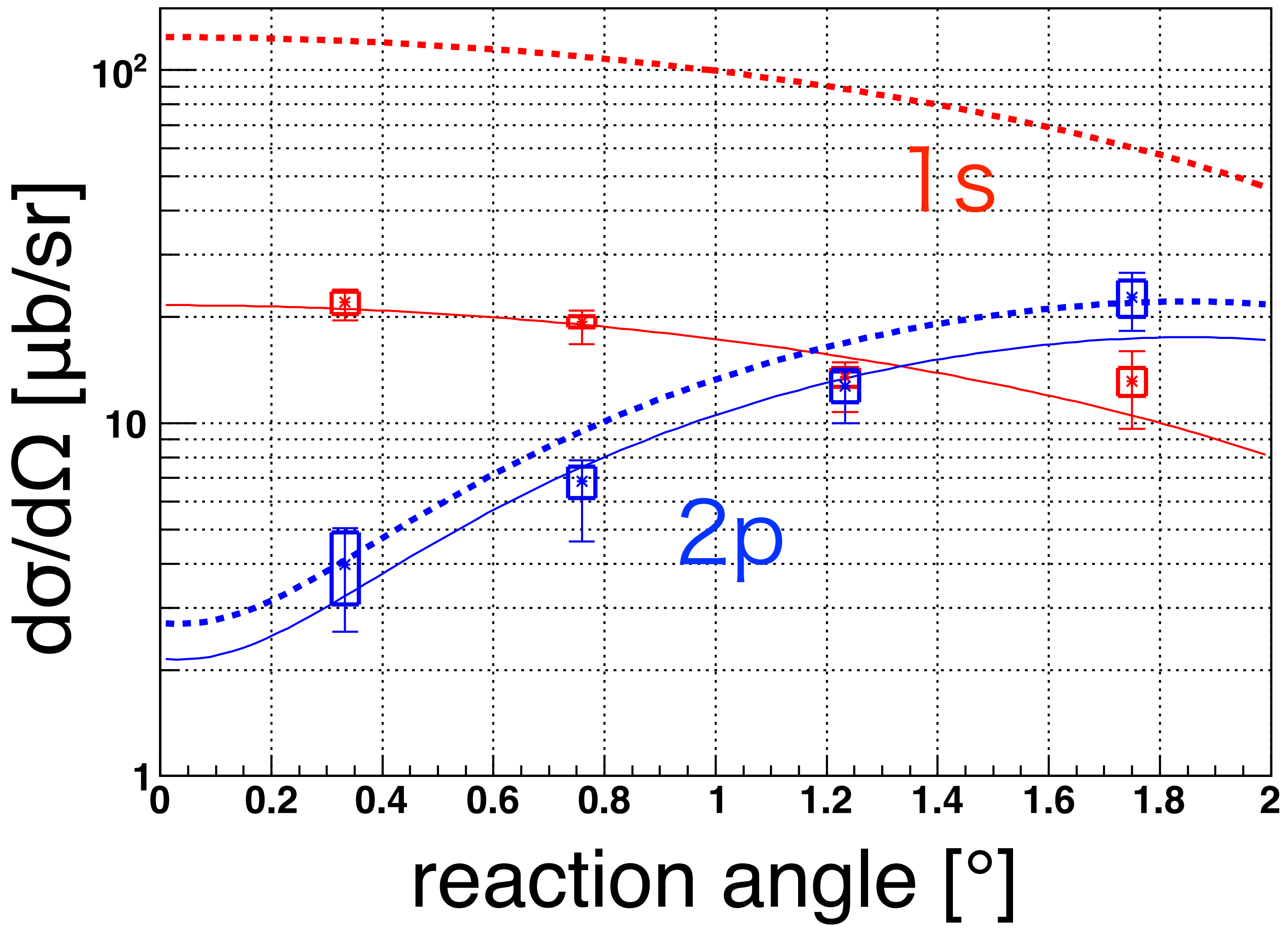
(grow up with finite reaction angle)

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

Polot experiment @ RIKEN in 2010



T. Nishi et al, PRL.120.152505 (2018)



dot line : theoretical calc. (Neff. approach)
solid line: scaled theoretical calc.

- $\theta_{reaction}$ dependence
  → well reproduced by theoretical calculation
- absolute value of the reaction cross section
  → $S_{1s}^{exp} \fallingdotseq S_{1s}^{theory} \times$ **0.17**
  $S_{2p}^{exp} \fallingdotseq S_{2p}^{theory} \times$ **0.8**

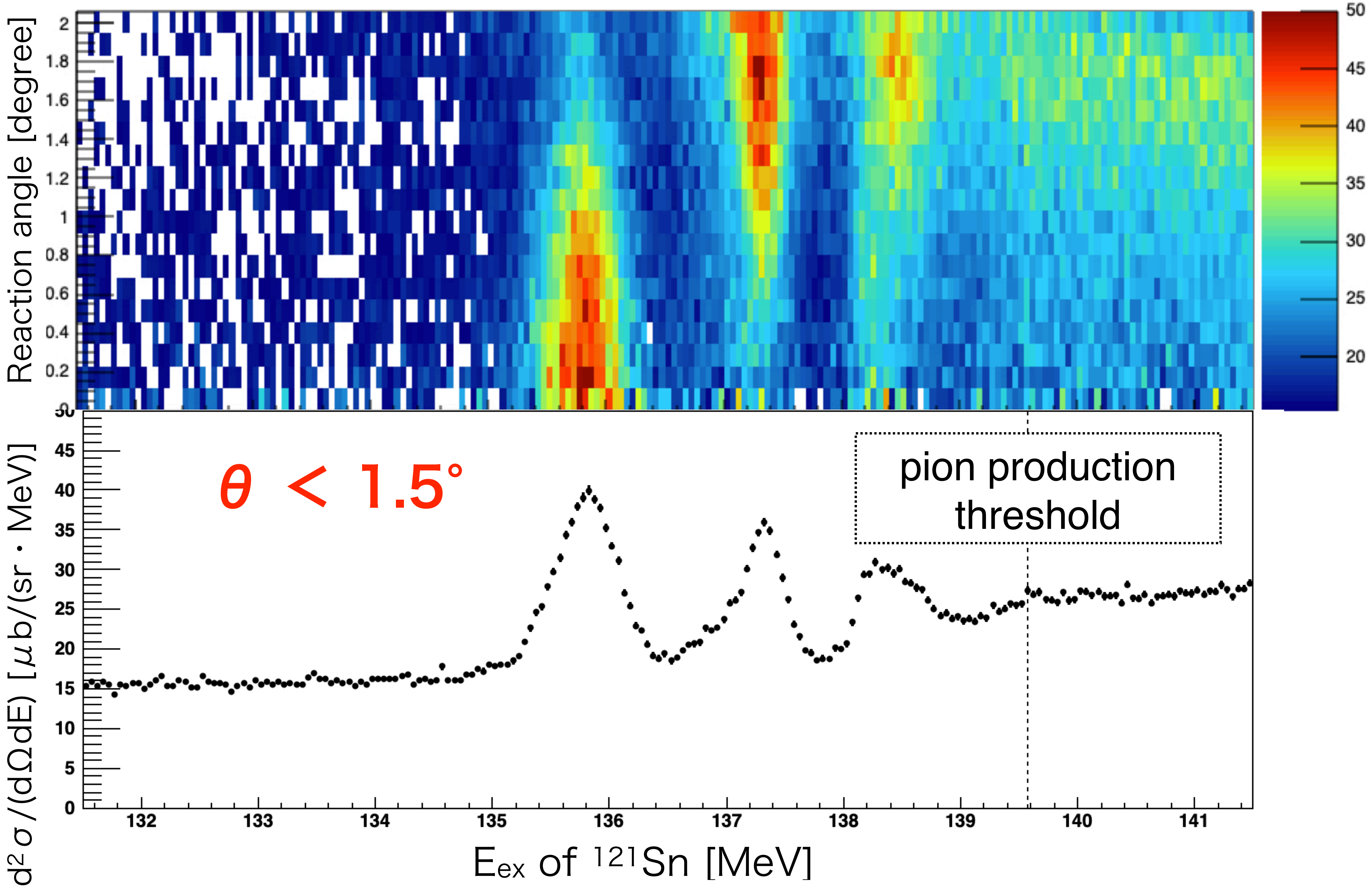
Angular configuration is well understood.
Angular dependences are almost reproduced quite well except S_{1s}/S_{2p} ratio.
Missing factor for reaction dynamics ??

Precision measurement @ RIKEN in 2014: $^{117,121}Sn$

◉ Presicion measurement (~11 days)
target: ^{122}Sn, ^{117}Sn
goal : precision measurement of pionic states in ^{121}Sn
first measurement of pionic states in odd nuclei

- **improve optics → improve resolution**
- **simultaneous measurement of *1s*, *2p* → reduce systematic error**

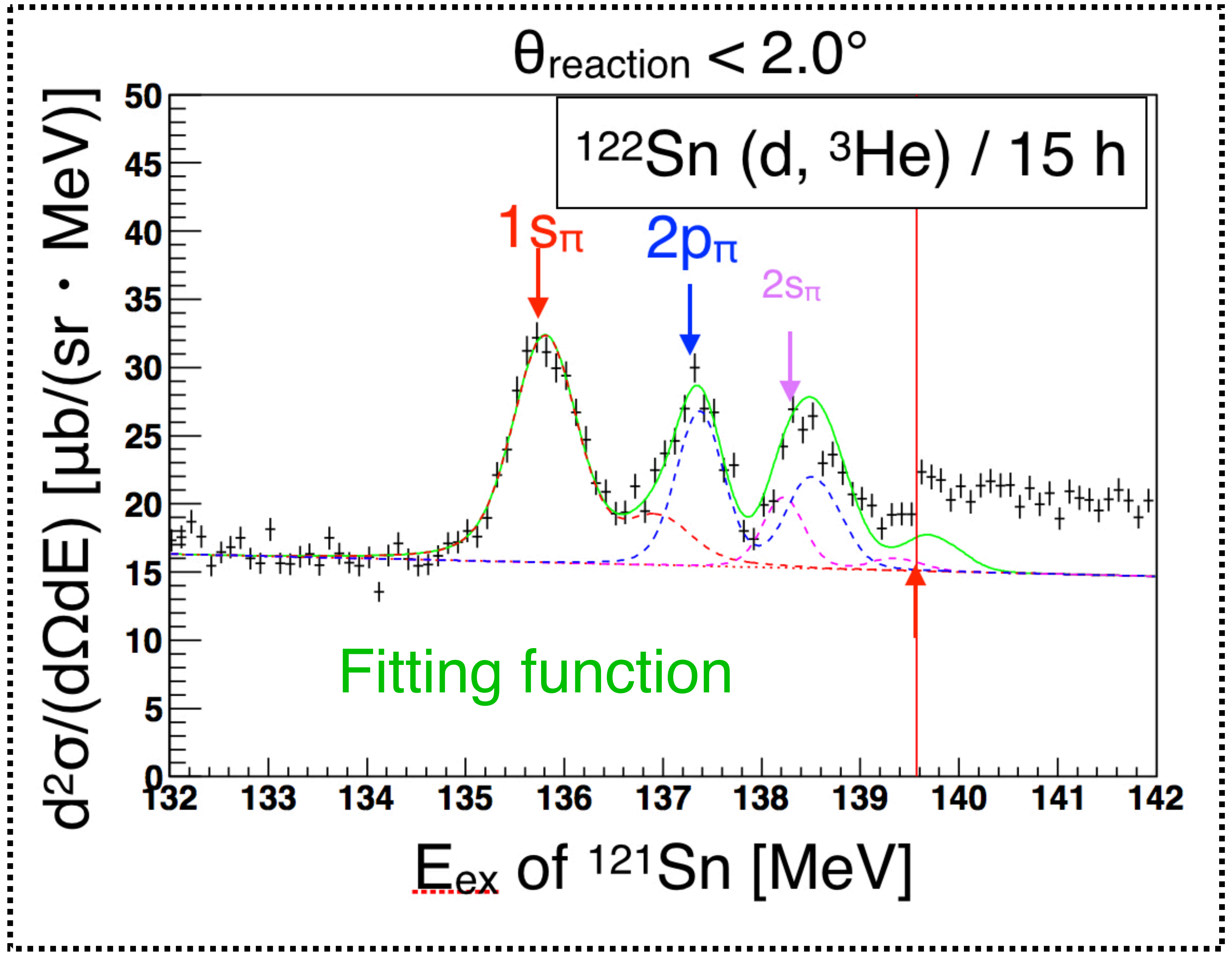
Precision measurement @ RIKEN in 2014: ^{121}Sn



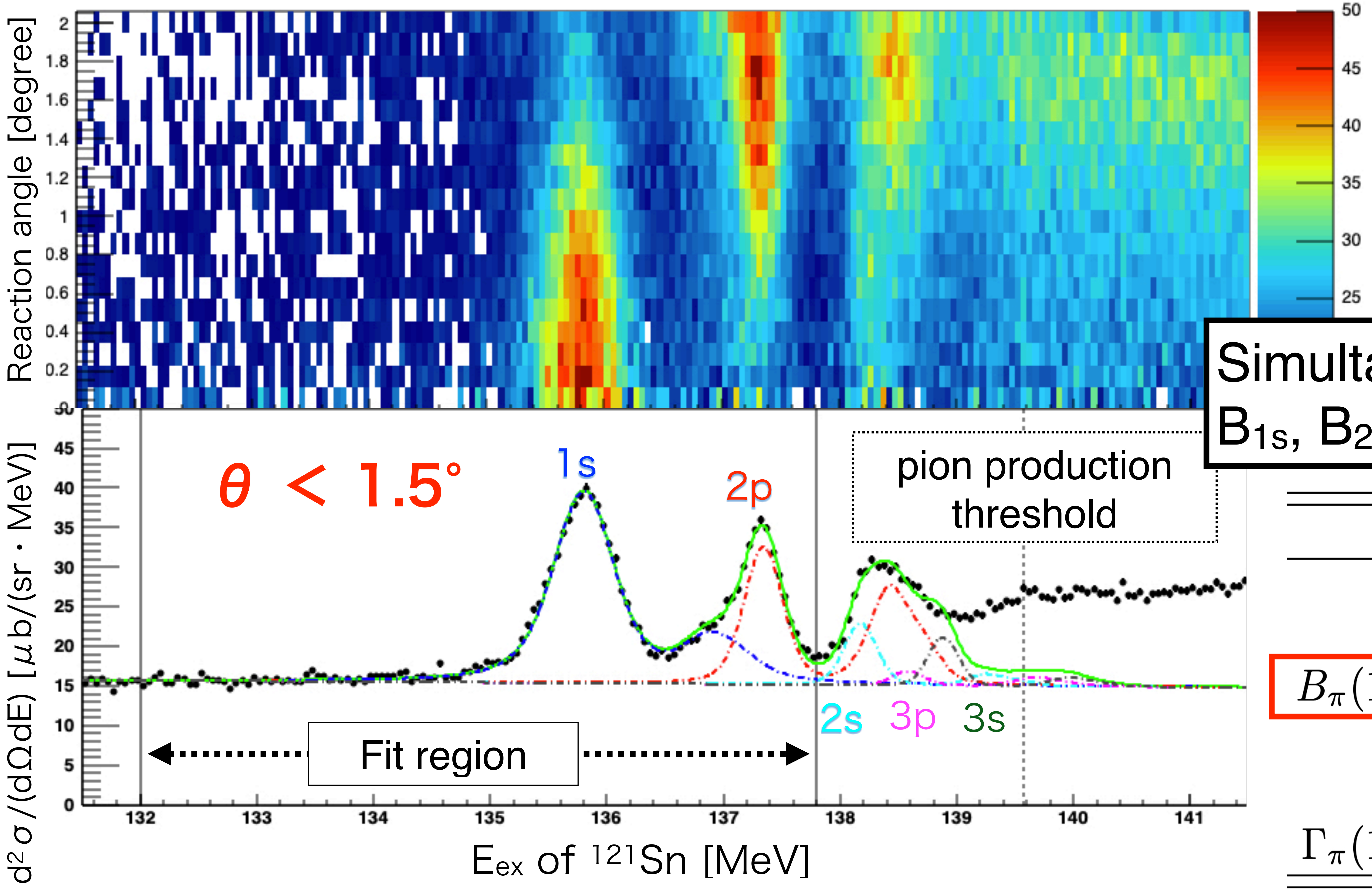
Improve

- resolution (400 → **250 keV**)
- accumulated events number (~ × 10 from pilot exp.)

c.f. Result of pilot exp.



Precision measurement @ RIKEN in 2014: ^{121}Sn



Improve

- resolution (400 → **250 keV**)
- accumulated events number (~ × 10 from pilot exp.)

Simultaneous & precise measurement of B_{1s}, B_{2p}, Γ_{1s}, Γ_{2p}, and **B_{1s} - B_{2p}**

	[keV]	Statistical	Systematic
$B_\pi(1s)$	3830	± 3	$+78-76$
$B_\pi(2p)$	2265	± 3	$+84-83$
$B_\pi(1s)-B_\pi(2p)$	1565	± 4	± 11
$\Gamma_\pi(1s)$	314	± 12	$+43-40$
$\Gamma_\pi(2p)$	120	± 17	$+49-28$
$\Gamma_\pi(1s)-\Gamma_\pi(2p)$	194	± 20	$+31-42$

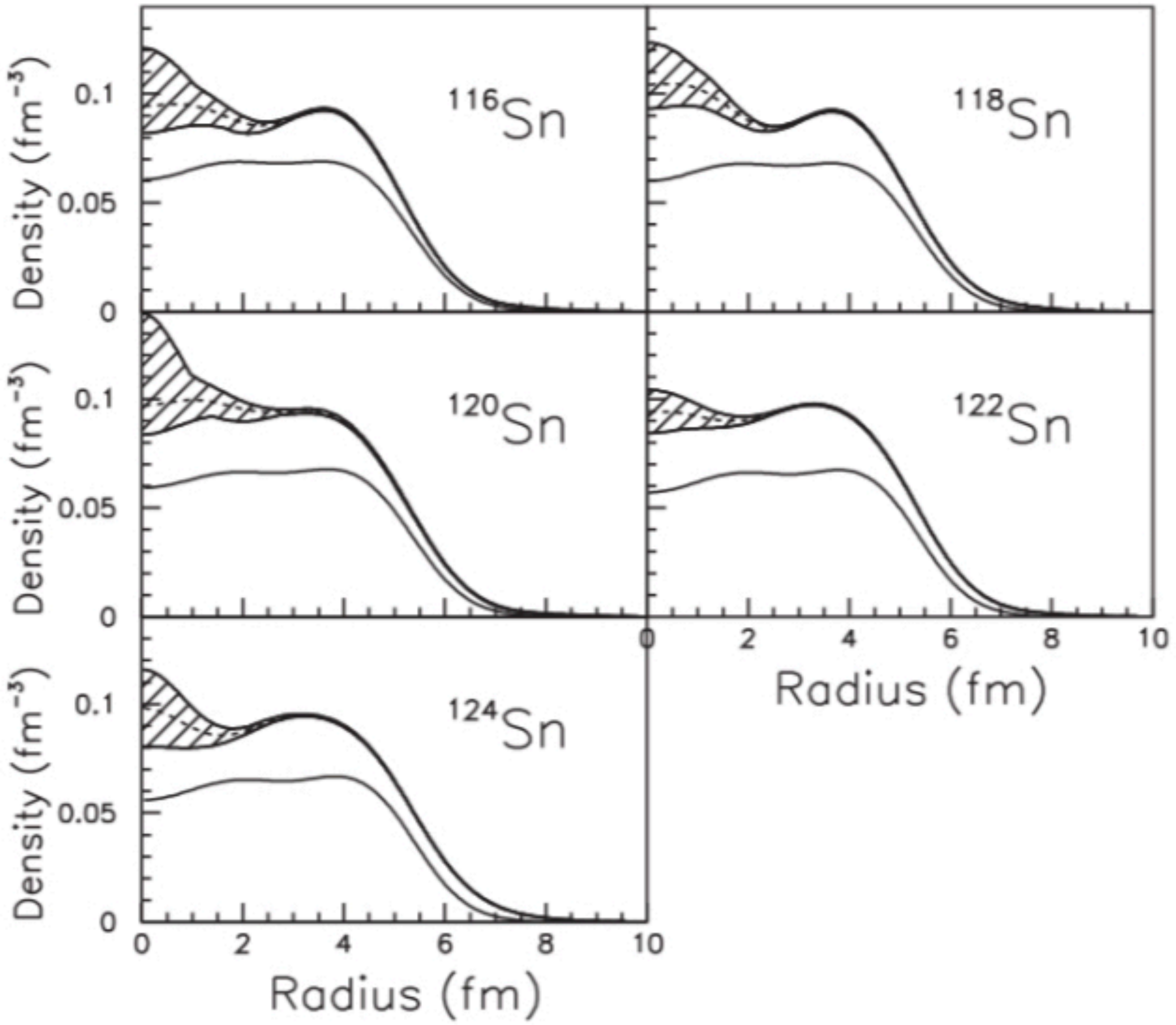
Deduce b1 parameter from B^{π}, Γ^{π}

b_1, ImB_0:
Solve Klein-Gordon equation and search best parameter to reproduce experimental results.

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

・ b_0, ReB_0 :
  simultaneous fit with symmetric light nuclei (^{16}O, ^{20}Ne, ^{28}Si)
・ p-wave parameters (c_0, c_1, ReC_0, ImC_0):
  fixed to global fit results
  ※ E. Friedman and A. Gal, Nucl. Phys. A 724 (2003)

S. Terashima et al., Phys. Rev. C 77, 024317 (2008).



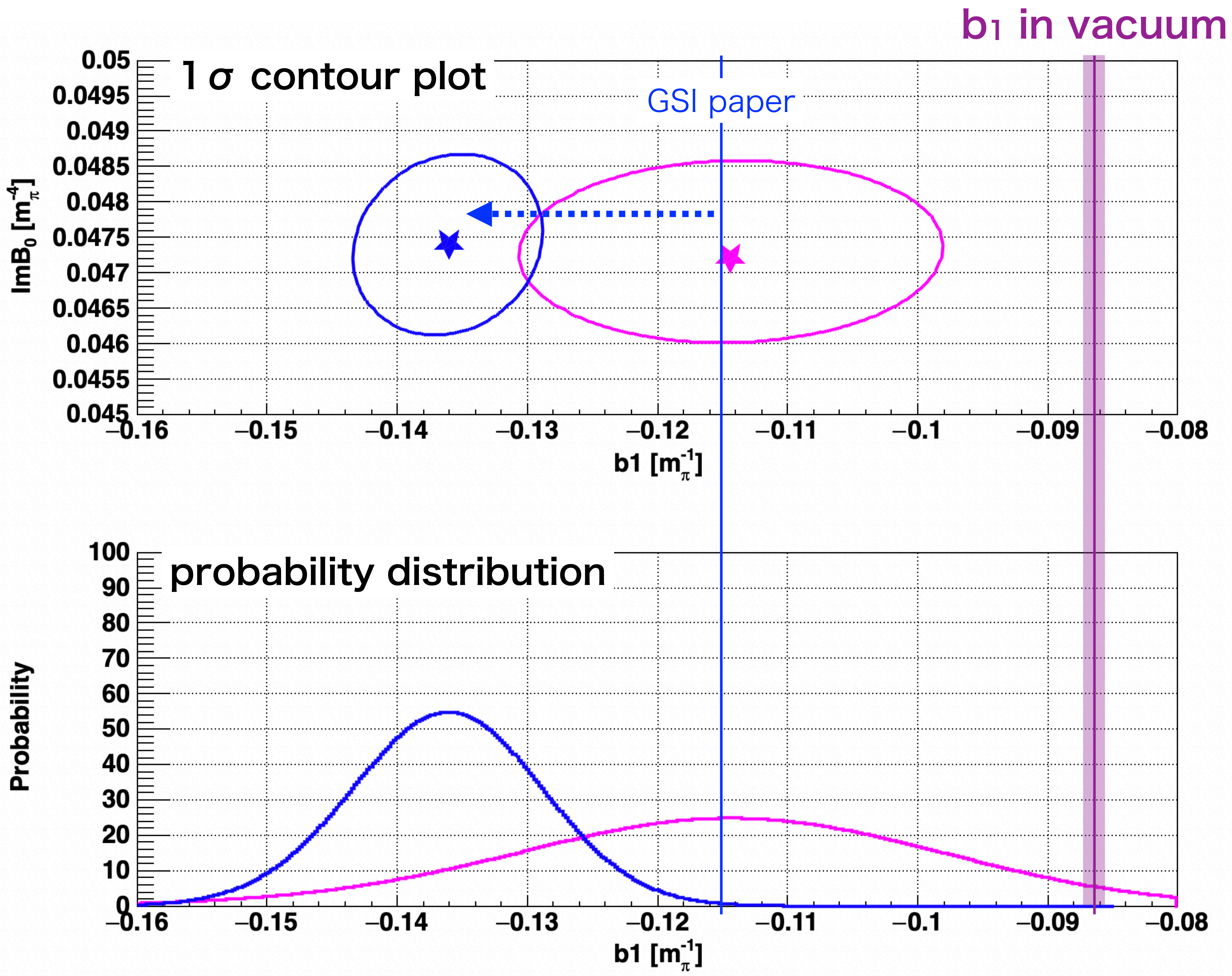
Improved points for the analysis

- **neutron distribution (p-elastic exp. @RCNP)**
- Effective number approach ⇔ Green function method※
- Residual interaction between pion and neutron hole※※
- modification of absorption term ($\rho_p^2 + 2\rho_n\rho_p +$ ~~ρ_n^2~~)
- new spectroscopic factor data. Szwec et al., Phys. Rev. C **104**, 054308 (2021).

※ N. Ikeno et al., Prog. Theor. Exp. Phys. 2015, 033D01 (2015).
※※ N. Nose-Togawa et al., Phys. Rev. C 71, 061601 (2005).

Deduce b1 parameter from B^{π}, Γ^{π}

b_1, $\mathrm{Im}B_0$:
Solve Klein-Gordon equation and search best parameter to reproduce experimental results.



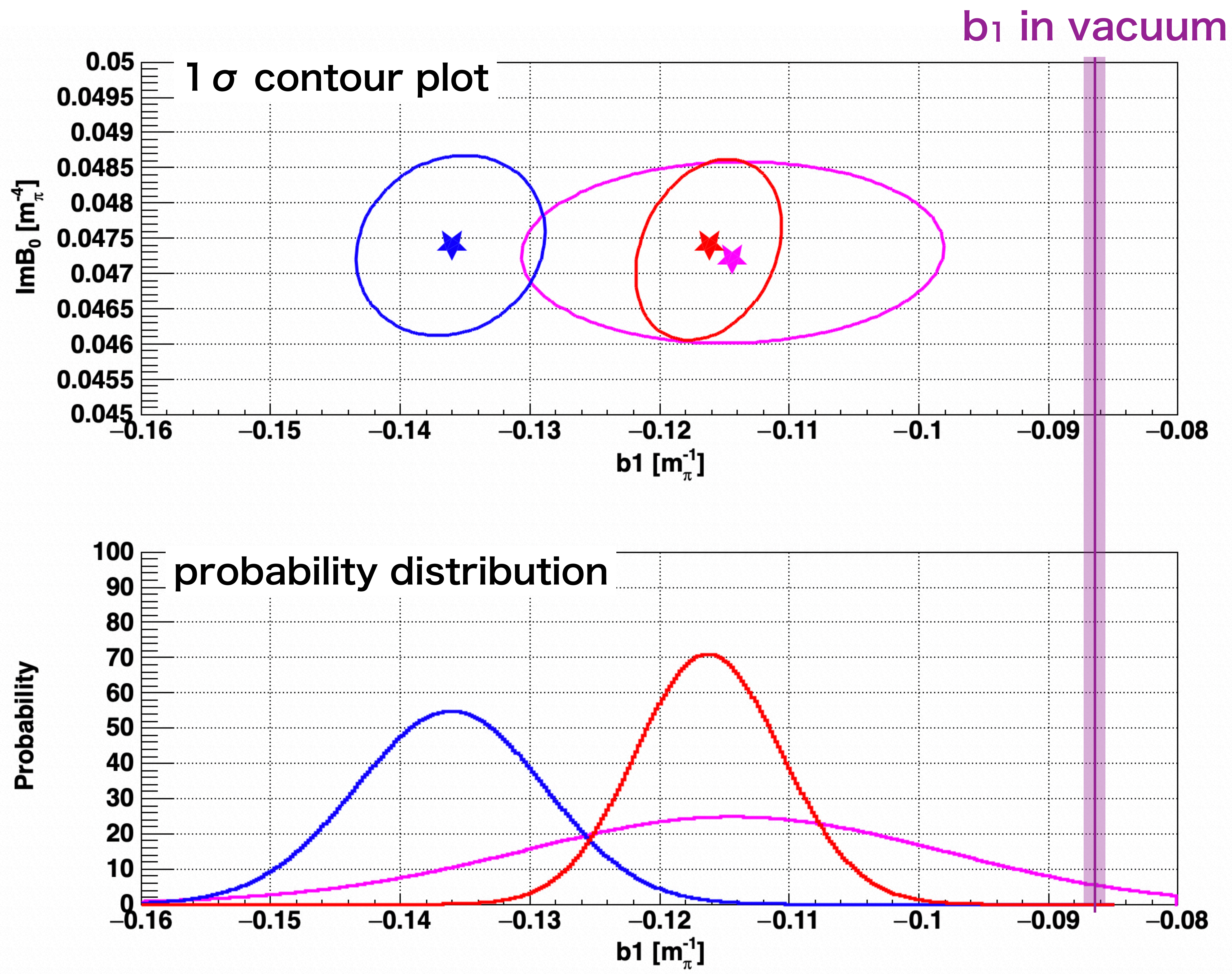
B_{1s} / Γ_{1s} in ^{115,119,123}Sn @ GSI (re-analyzed)

B_{1s} / Γ_{1s} in ^{121}Sn @ RIKEN RIBF

- Analysis method improvement
  → $\Delta b_1 \sim 0.02$
- 1s state info. alone does not determine b1 precisely at RIKEN exp.

Deduce b1 parameter from B_π, Γ_π

b_1, ImB_0:
Solve Klein-Gordon equation and search best parameter
to reproduce experimental results.



B_{1s} / Γ_{1s} in [115, 119, 123] Sn @ GSI (re-analyzed)

B_{1s} / Γ_{1s} in [121] Sn @ RIKEN RIBF

B_{1s}, B_{2p} / Γ_{1s}, Γ_{2p} in [121] Sn @ RIKEN RIBF

- Analysis method improvement
  → $\Delta b_1 \sim 0.02$
- 1s state info. alone does not determine b1 precisely at RIKEN exp.
- b1 is determined most precisely so far from 1s and 2p info.

$$b_1 = (-0.1163 \pm 0.0056) m_\pi^{-1}$$

Chiral symmetry in medium

b₁ in medium ⇔ chiral symmetry in medium

$$\frac{\langle q\bar{q}\rangle_{\rho=\rho}}{\langle q\bar{q}\rangle_{\rho=0}} = \left(\frac{b_1(0)}{b_1(\rho)}\right)^{1/2}\left(1-\gamma\frac{\rho}{\rho_0}\right)$$

※ γ = 0.184 ± 0.003

D. Jido T. Hatsuda, T. Kunihiro, PLB 670, 109(2008).

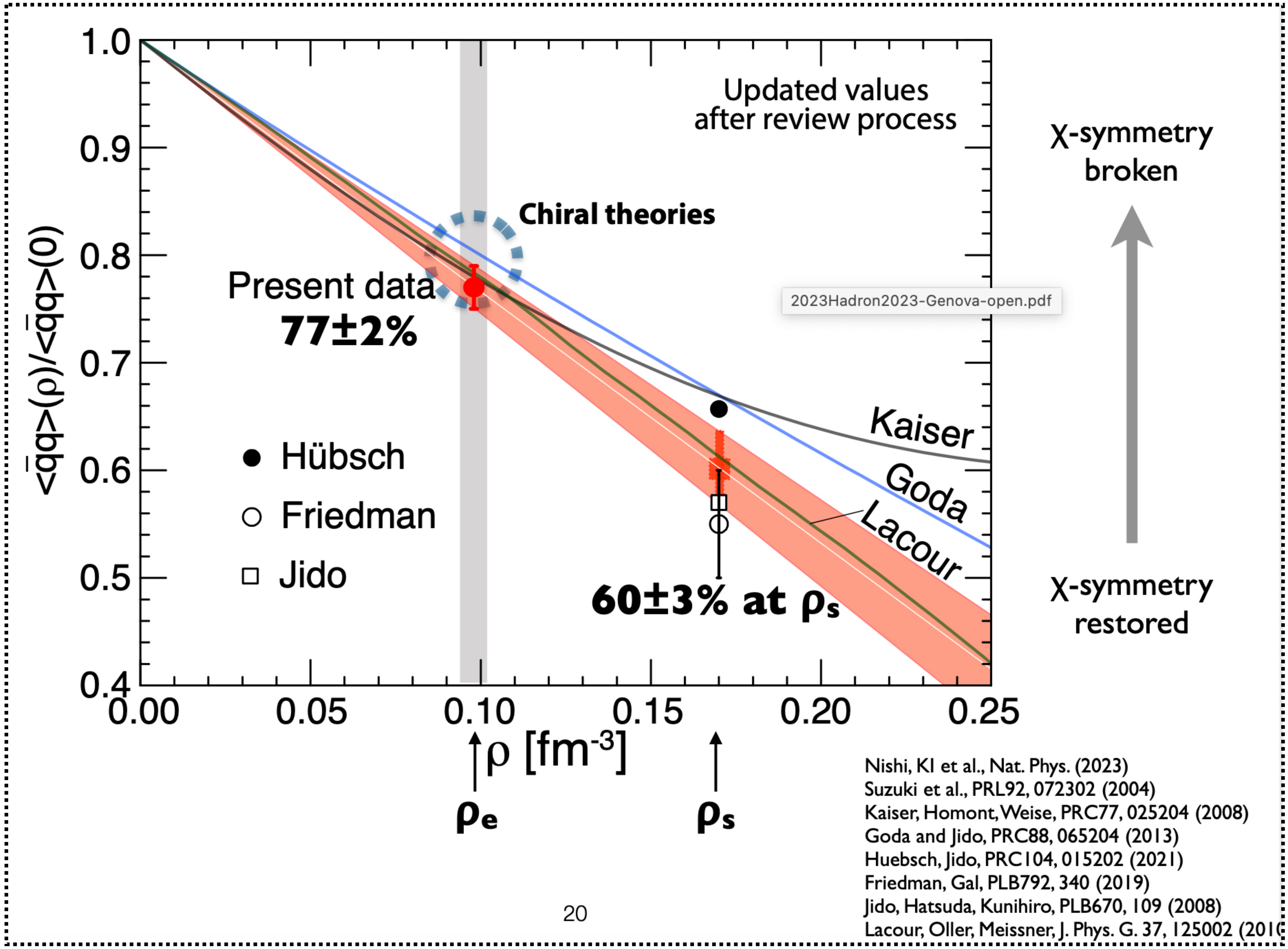
$b_1 = (-0.1163 \pm 0.0056)\ m_\pi^{-1}$

⇔ $\langle q\bar{q}\rangle_{\rho=\rho}/\langle q\bar{q}\rangle_{\rho=0}$ = **77 ± 2** [%] @ $\rho_{eff.}$

⇔ $\langle q\bar{q}\rangle_{\rho=\rho}/\langle q\bar{q}\rangle_{\rho=0}$ = 60 ± 3 [%] @ ρ_s

T. Nishi *et al.*, *Nat. Phys.*, vol. 19, no. 6, pp. 788–793, 2023.

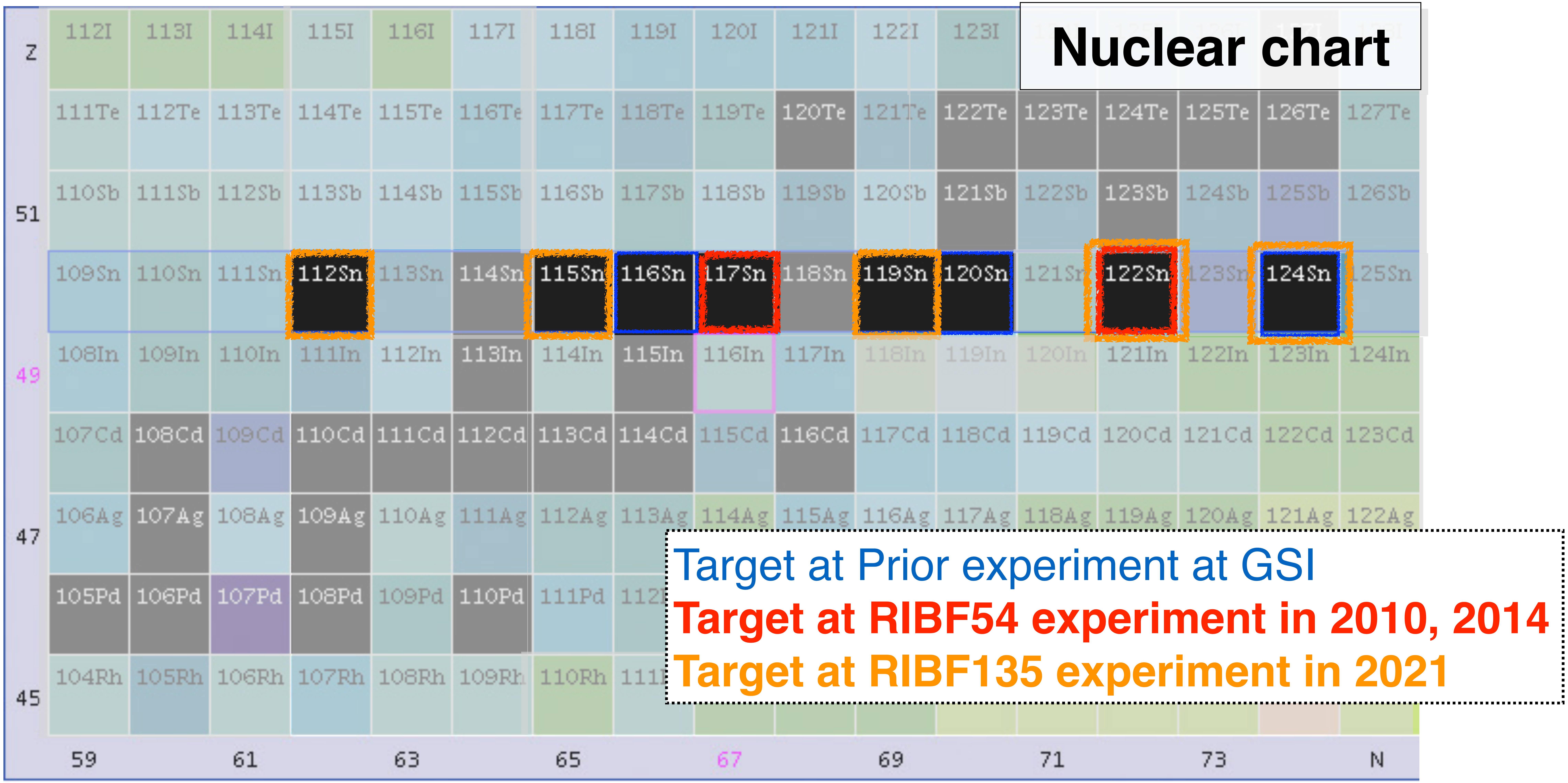
from K. Itahashi *et al.*, Hadron 2023



Summary

- Deeply bound pionic atom is a unique "meson in nucleus" system, and is a good probe for the QCD in finite density.
- So far, we performed the precision measurement of the deeply bound pionic atom at RIKEN RIBF to evaluate the chiral symmetry in medium.
- In the pilot experiment in 2010, we measure the E_{ex} of ^{121}Sn, and succeeded in
  - establishment of the experimental method for pionic atom spectroscopy,
  - observation of the angular dependence of (*d*, 3He) reaction cross section
  - discovery of the discrepancy S_{1s}/S_{2p} in measurement and theoretical prediction.
- In the precision experiment in 2014, we improved experimental/analytical methods and succeeded in
  - Simultaneous and precision measurement of $(1s)_\pi$, $(2p)_\pi$ state
  - determination of b_1 with unprecedented precision, which indicate the $\langle q\bar{q}\rangle(\rho_{eff})$ is reduced by **77 ± 2 %**, corresponding to the 68 ± 3 % reduction of $\langle q\bar{q}\rangle(\rho_0)$ with linear extrapolation.

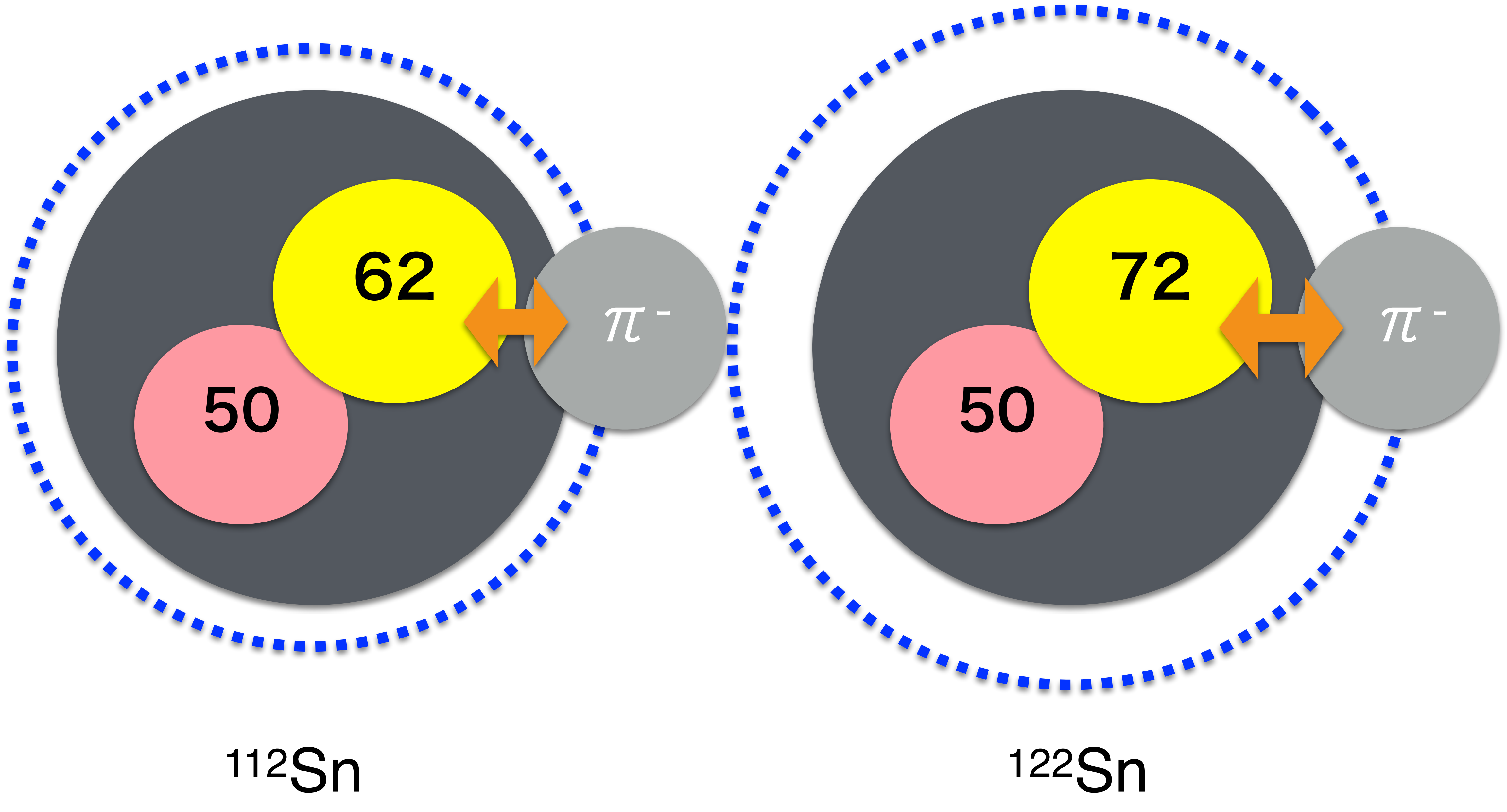
Targets in the experiment at RIKEN

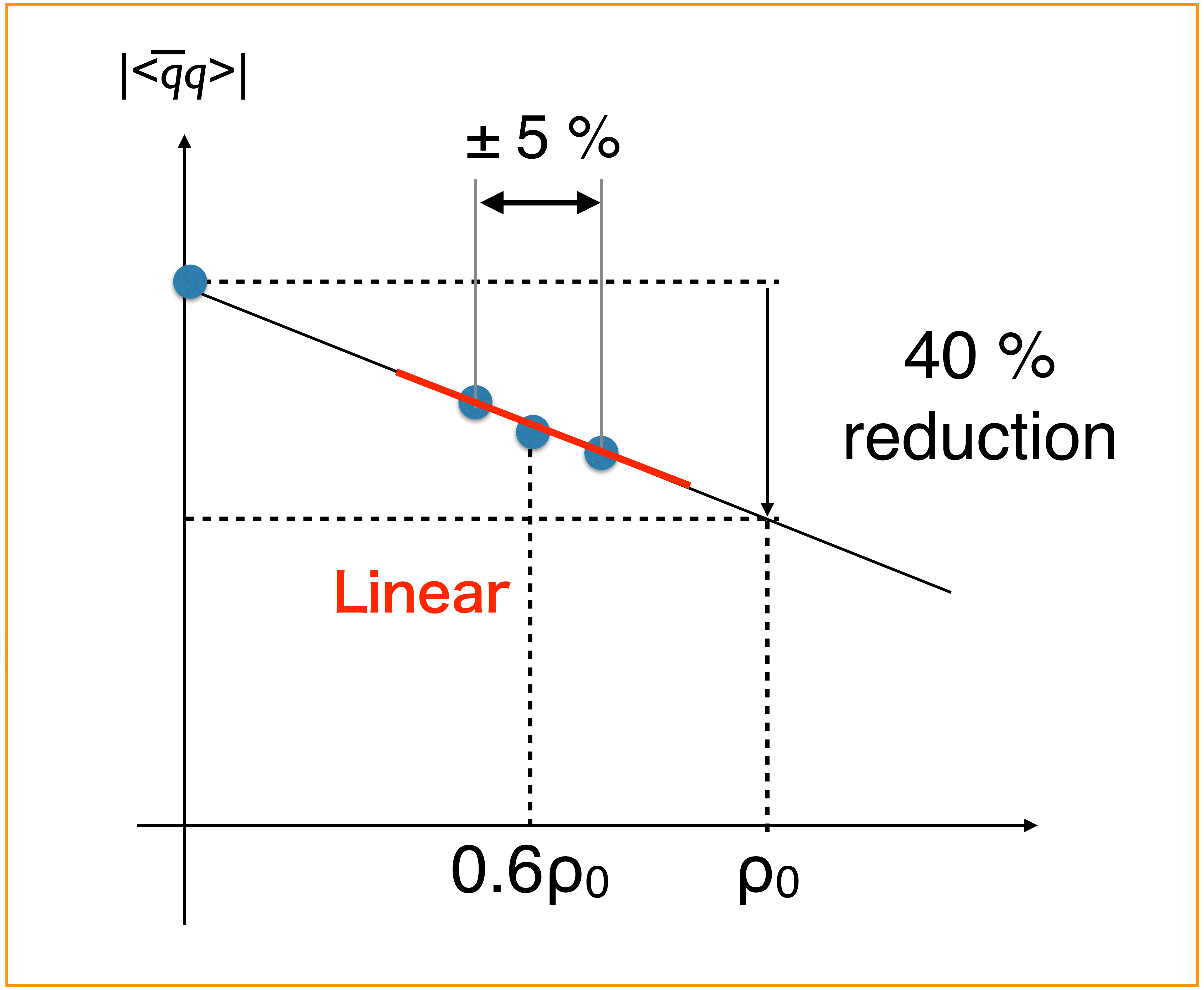


NuDat2 (https://www.nndc.bnl.gov/nudat2/)

Purpose of the next exp. :
Study of **density dependence of potential parameters**

Densities that can be probed by pionic atoms depend on mass number A





Pionic atoms are known to probe ~$0.6\rho_0$

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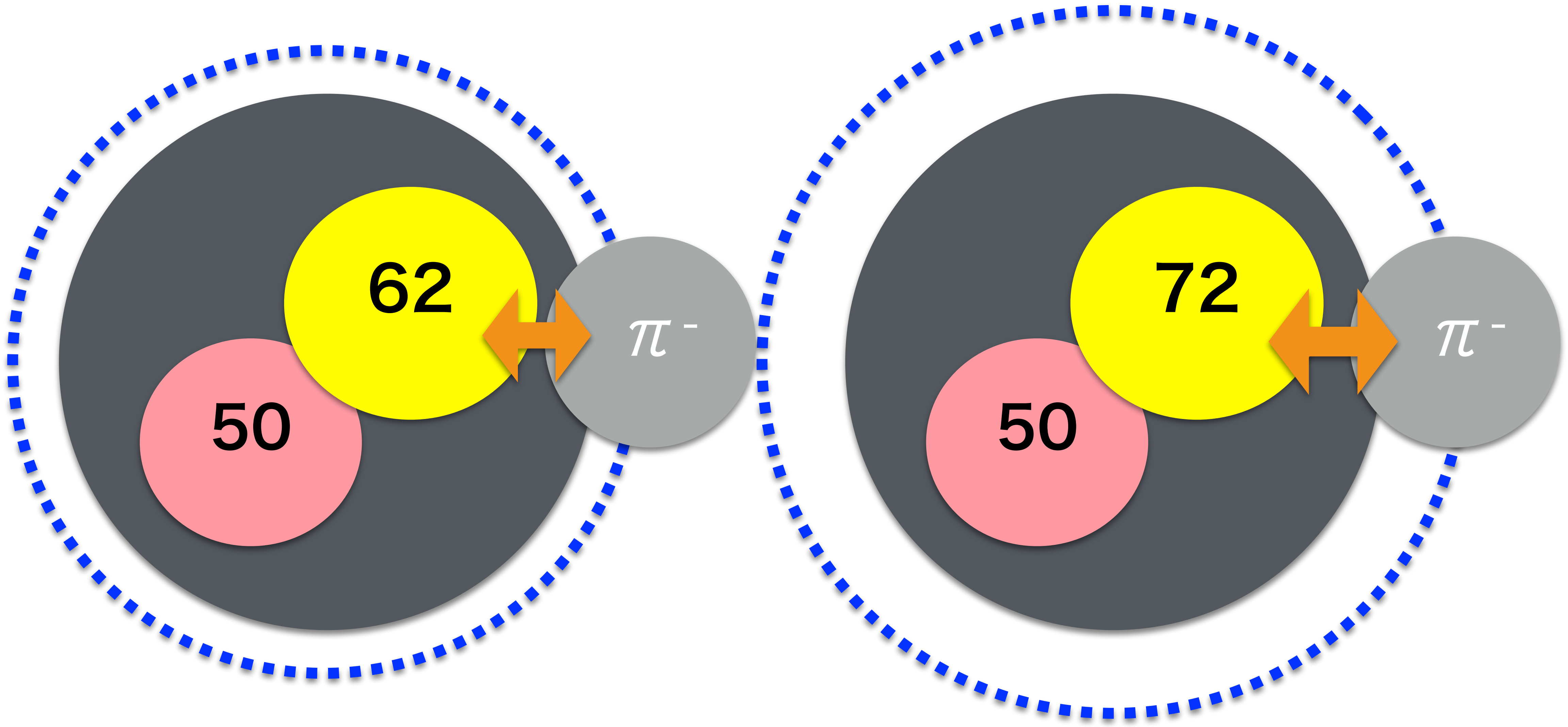
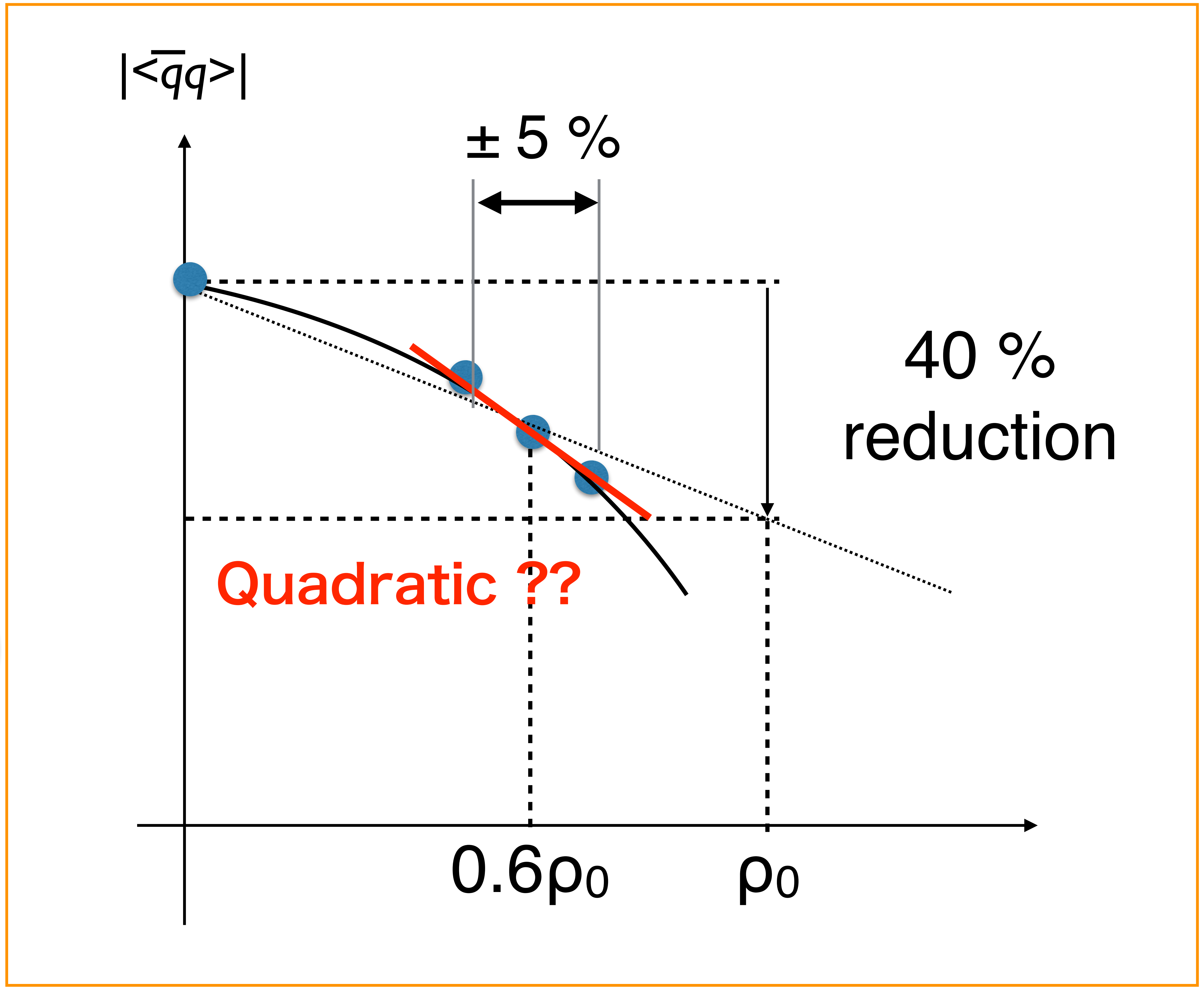


^{112}Sn ^{122}Sn



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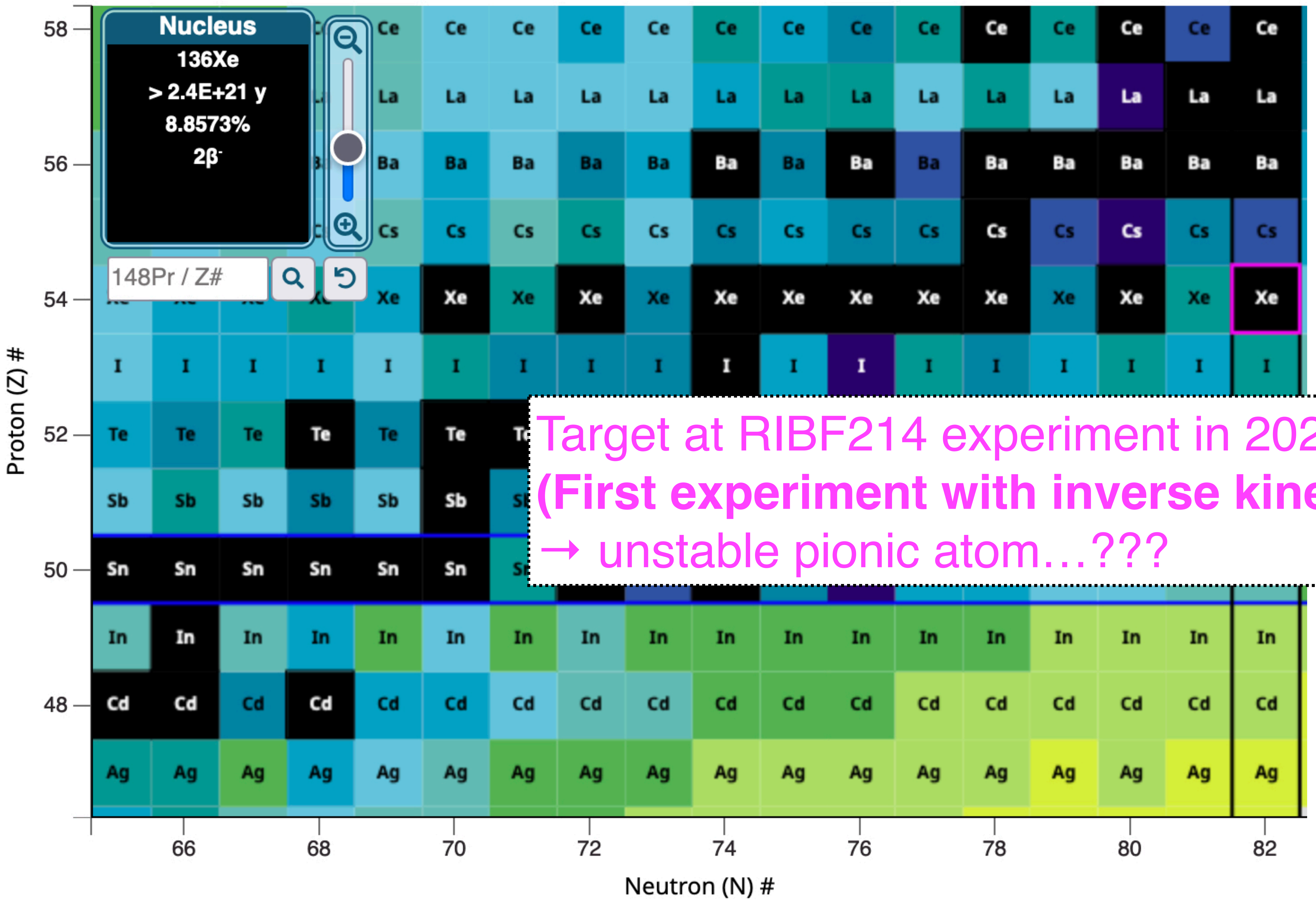
Targets in the experiment at RIKEN



Target at RIBF214 experiment in 202X
(First experiment with inverse kinematics!!)
→ unstable pionic atom…???

Current works: beam dynamics × machine learning

not deep learning

Beam dynamics × Machine learning

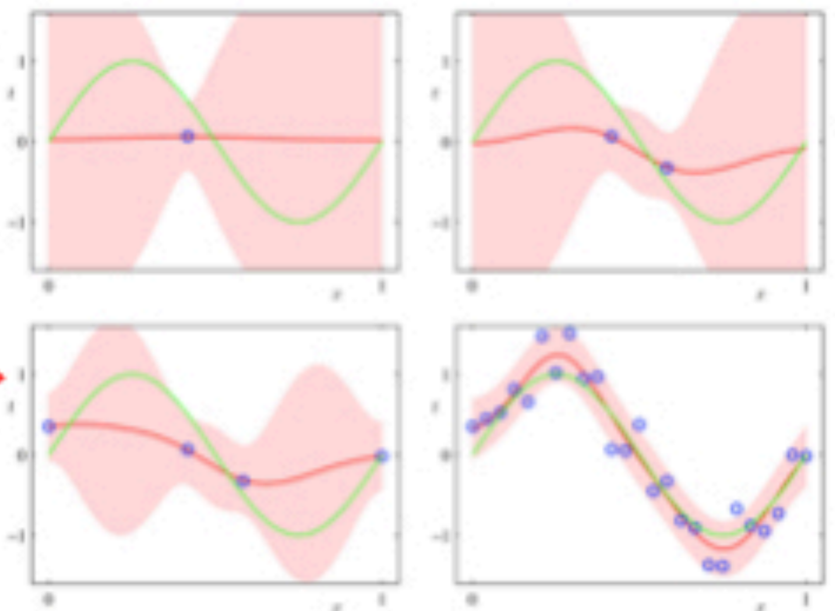
Optics tuning at RIBF:
many operation parameters (≧ 600) under environmental changes

Beam tuning with Humans

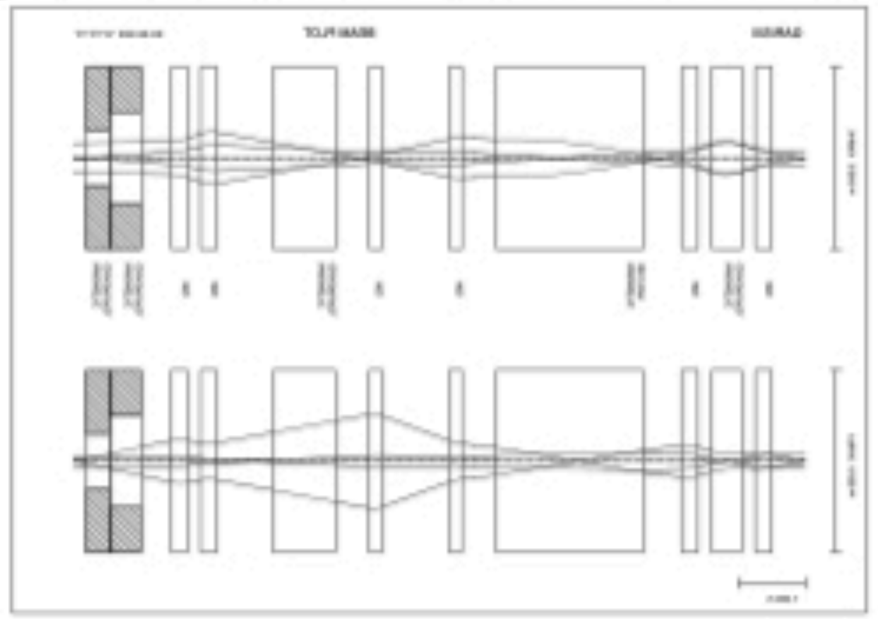
Beam dynamics calculation

Manual tuning based on
15 years of experience

Beam tuning with Beam dynamics × Machine learning



C. M. Bishop, Pattern Recognition and Machine Learning, Springer (2006)



Beam dynamics calculation

feedback

Optimize beyond human ← Machine learning
Continuous adjustment ← Beam dynamics × BPM※

※ Beam Position Monitor

Welcome for the various difficult requirements to the primary beam !
(not just beam intensity…)

Thank you for all your support over the past 15 years at the Iwasaki Lab.!