Systematic study of deeply-bound pionic atom and future perspectives

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3)Future perspectives ~ pionic unstable nuclei ~

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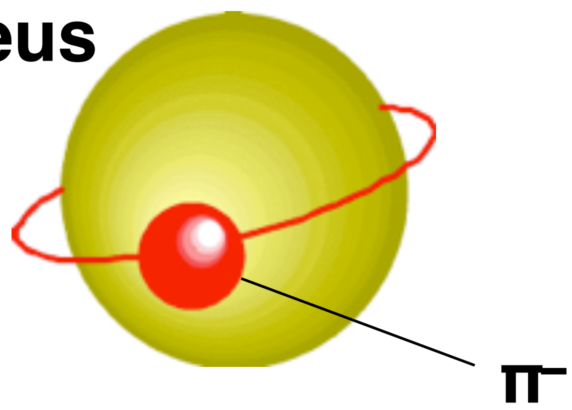
1. Spectroscopy of deeply-bound pionic atom

Deeply-bound pionic atom



Coulomb

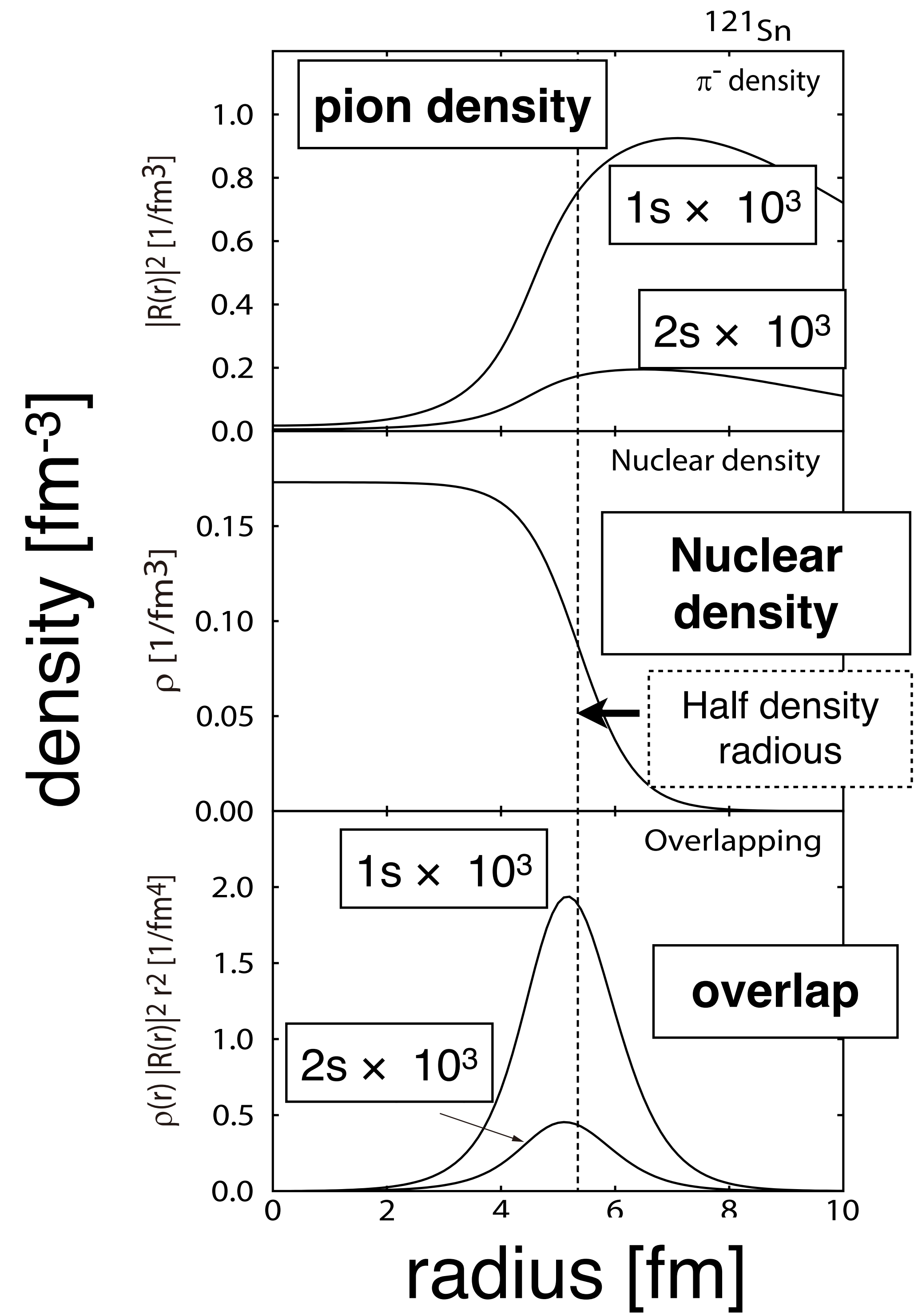
\+

Strong

deep orbit in Heavy atom

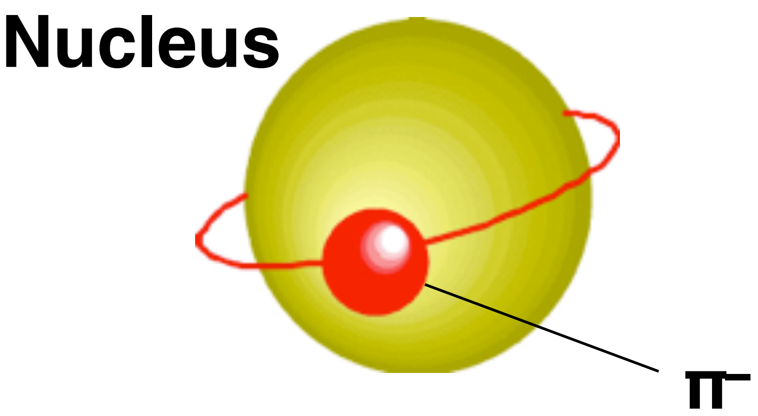
= Large overlap between pion and nucleus

→ probe for QCD in finite ρ



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

Deeply-bound pionic atom



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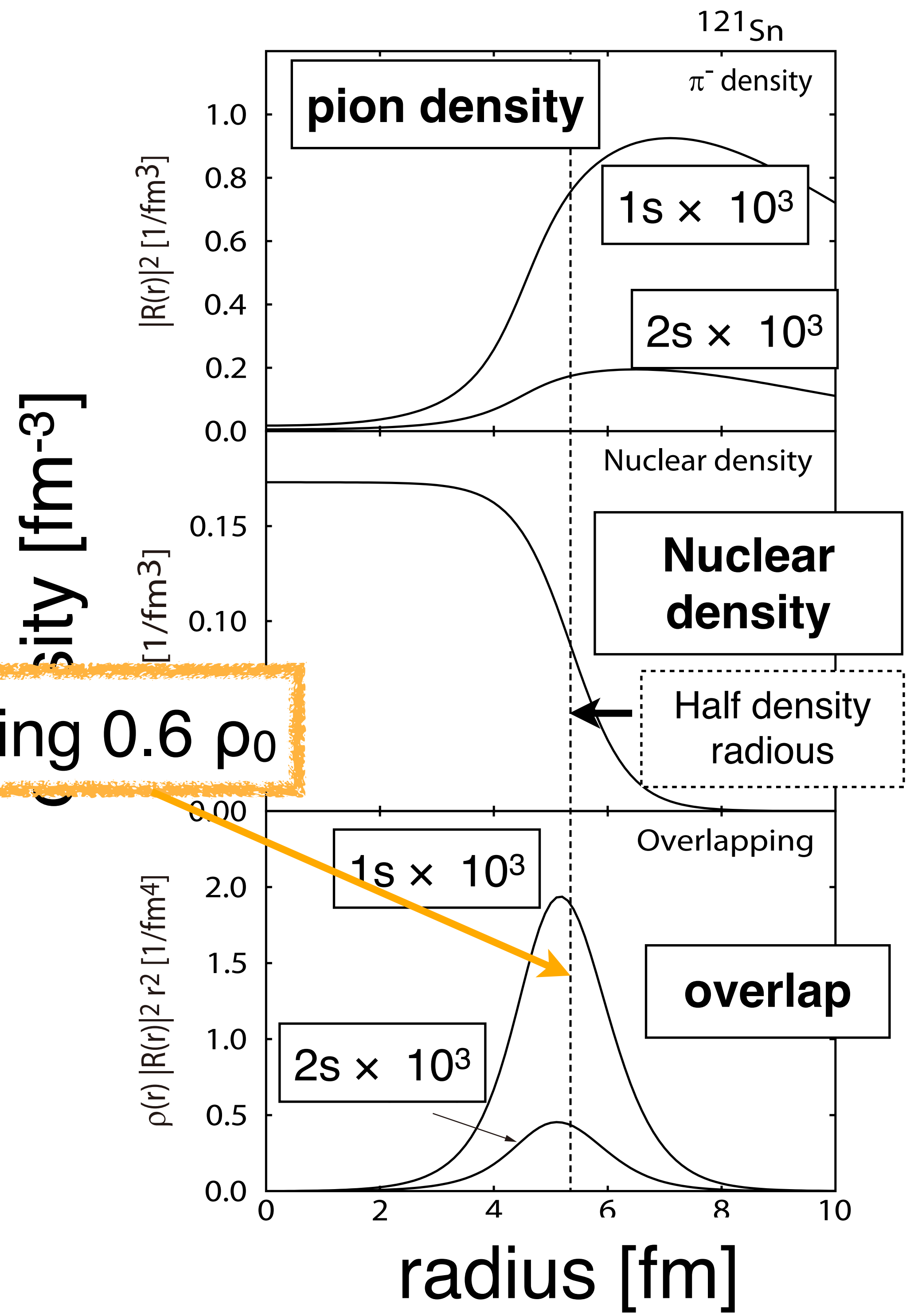
~ probing 0.6 ρ_0



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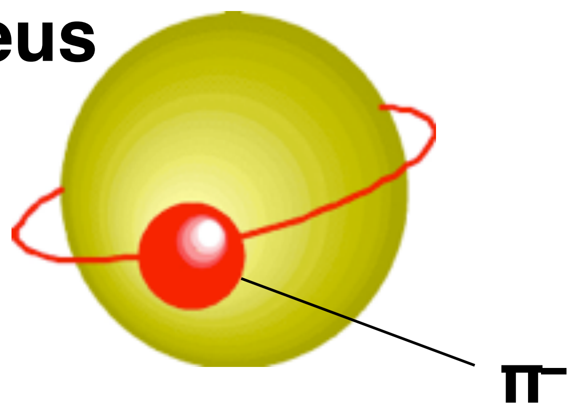

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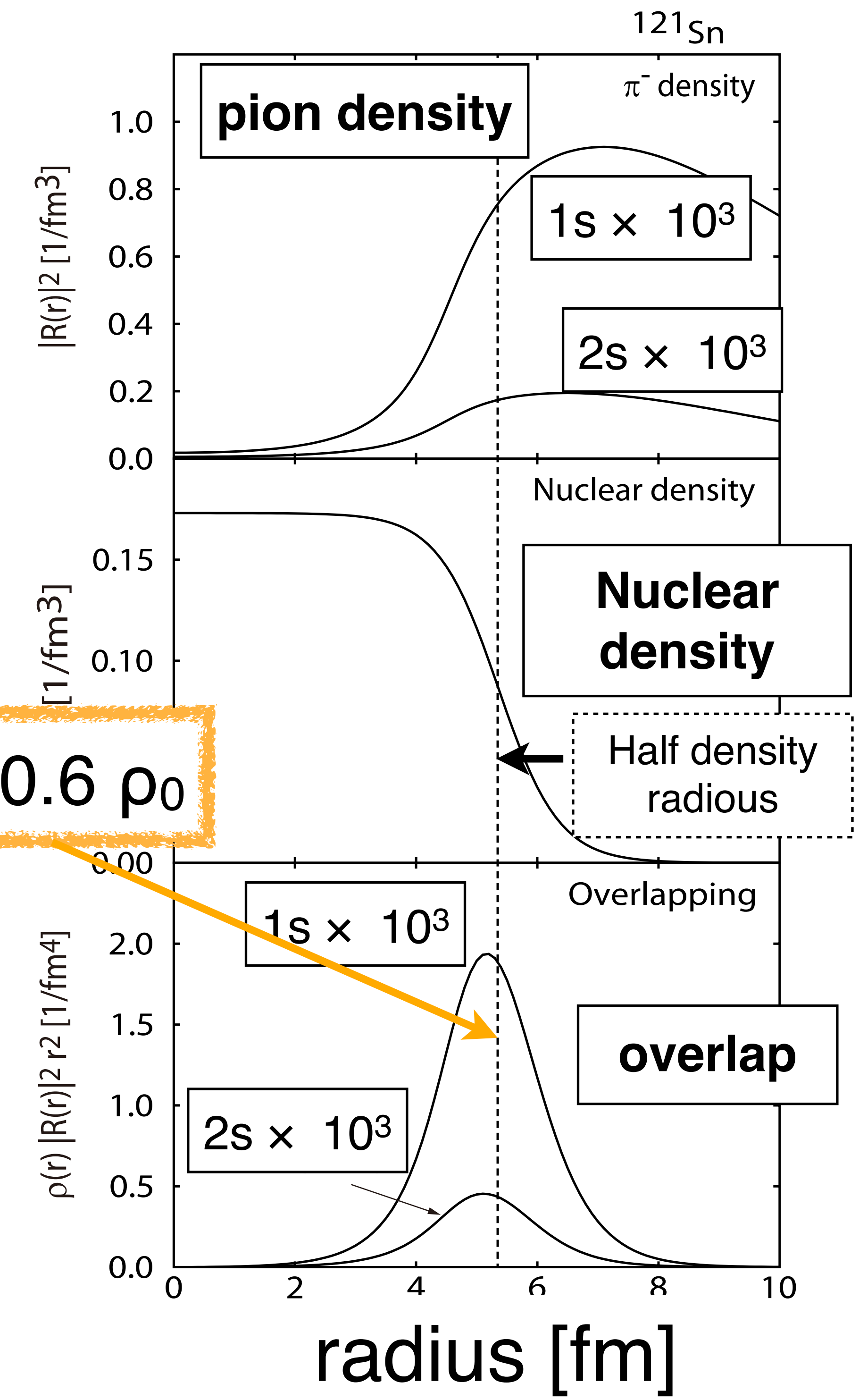
<u>E / Γ of pionic deep (1s, 2s, …) states</u>

π-A s-wave optical potential

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



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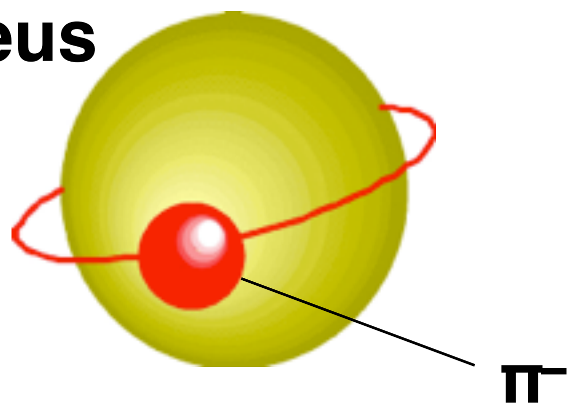
Deeply-bound pionic atom

Nucleus



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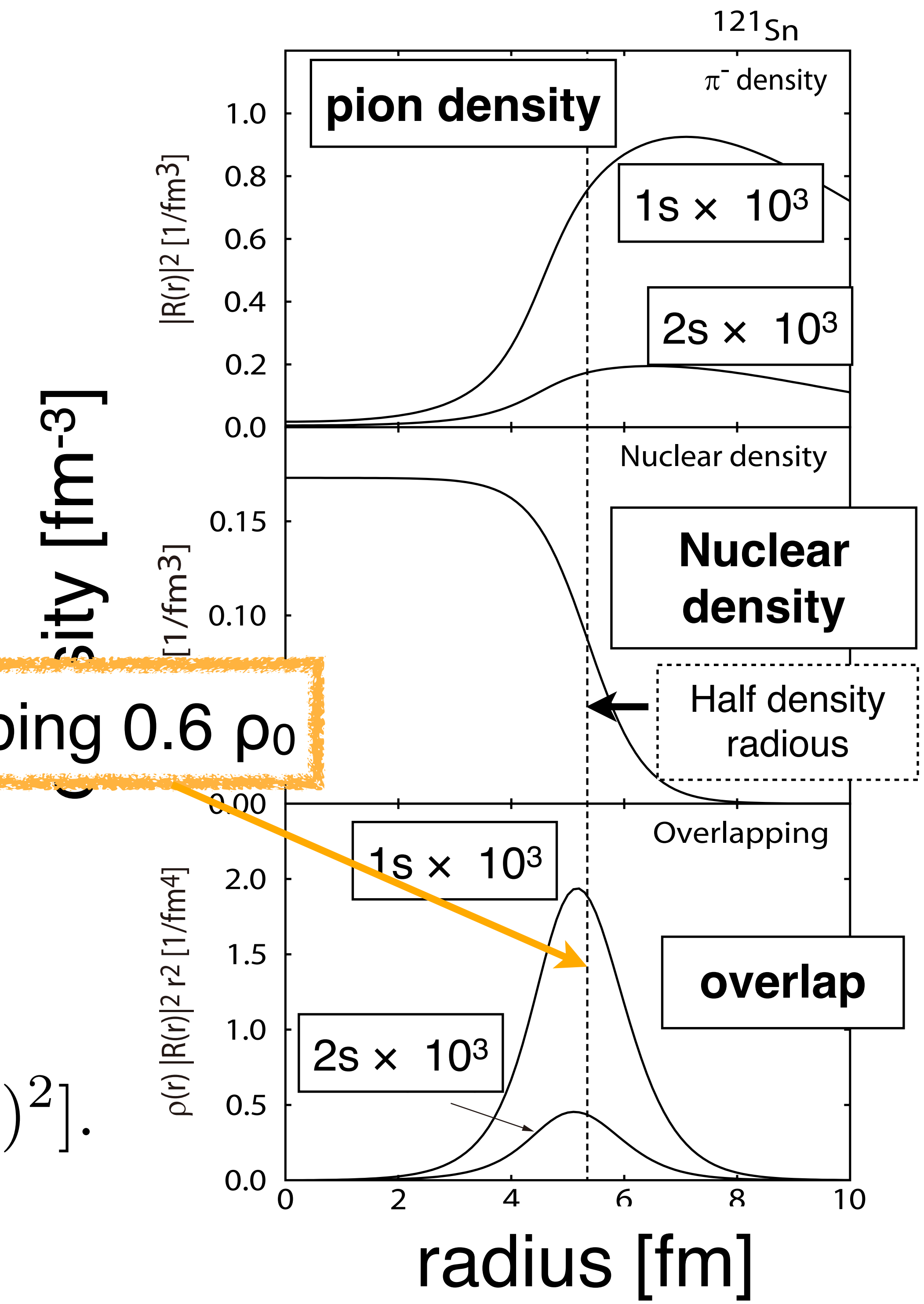

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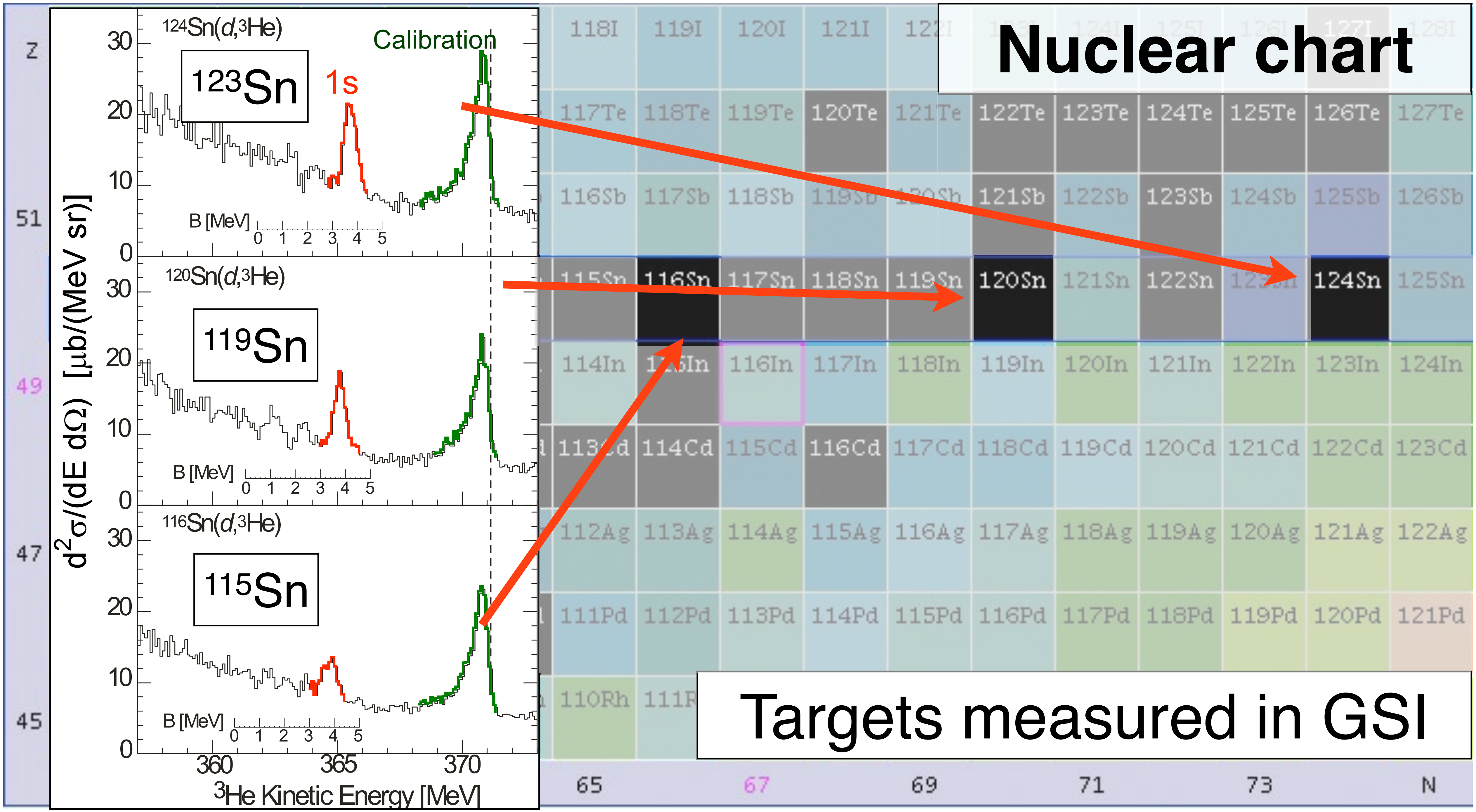
<u>E / Γ of pionic deep (1s, 2s, ...) states</u>

π-A s-wave optical potential

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

isovector scattering length

Experiment at GSI



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

NNDC,BNL

Deduction of b_1 from experimental data

TABLE I. Observed binding energies (B_{1s}) and widths (Γ_{1s}) of the 1s π^- states in ^{115,119,123}Sn isotopes.

Isotope	B_{1s} (MeV)	ΔB_{1s} (MeV) Stat.	Syst.	Total	Γ_{1s} (MeV)	$\Delta\Gamma_{1s}$ (MeV) Stat.	Syst.	Total
^{115}Sn	3.906	±0.021	±0.012	±0.024	0.441	±0.068	±0.054	±0.087
^{119}Sn	3.820	±0.013	±0.012	±0.018	0.326	±0.047	±0.065	±0.080
^{123}Sn	3.744	±0.013	±0.012	±0.018	0.341	±0.036	±0.063	±0.072

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

π-A s-wave optical potential

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

4 parameters (b_0, b_1, ReB_0, ImB_0) in equation
⇔ 2 parameters from each atom BE_{1s}, Γ_{1s}

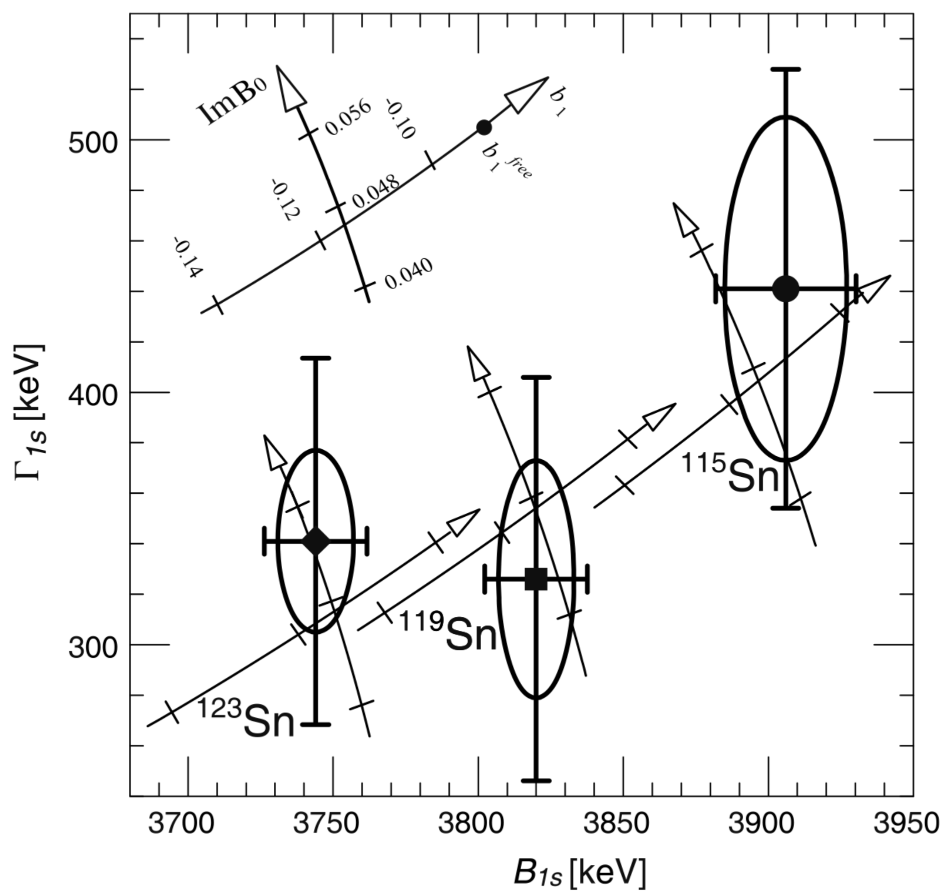
(i) Seki-Masutani relation (b_0 and ReB_0 has strong correlation)

(ii) pionic atom of light / symmetric nuclei (^{16}O, ^{20}Ne, ^{28}Si)

$$b_0^* = b_0 + 0.025ReB_0 = -0.0274 \pm 0.0002$$

Deduction of b_1 from experimental data

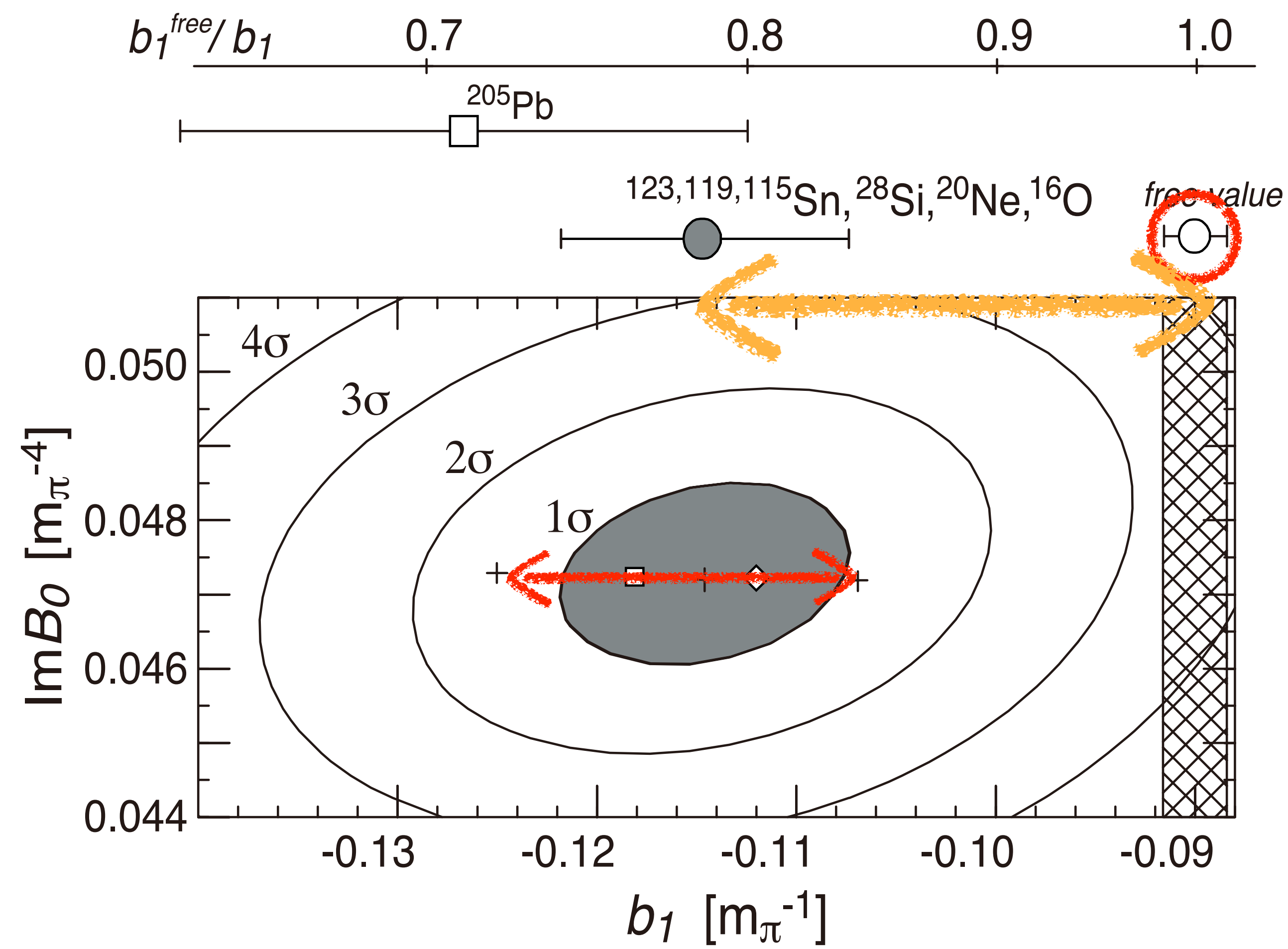
BE_{1s} vs Γ_{1s}



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

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

Contour plot of χ^2



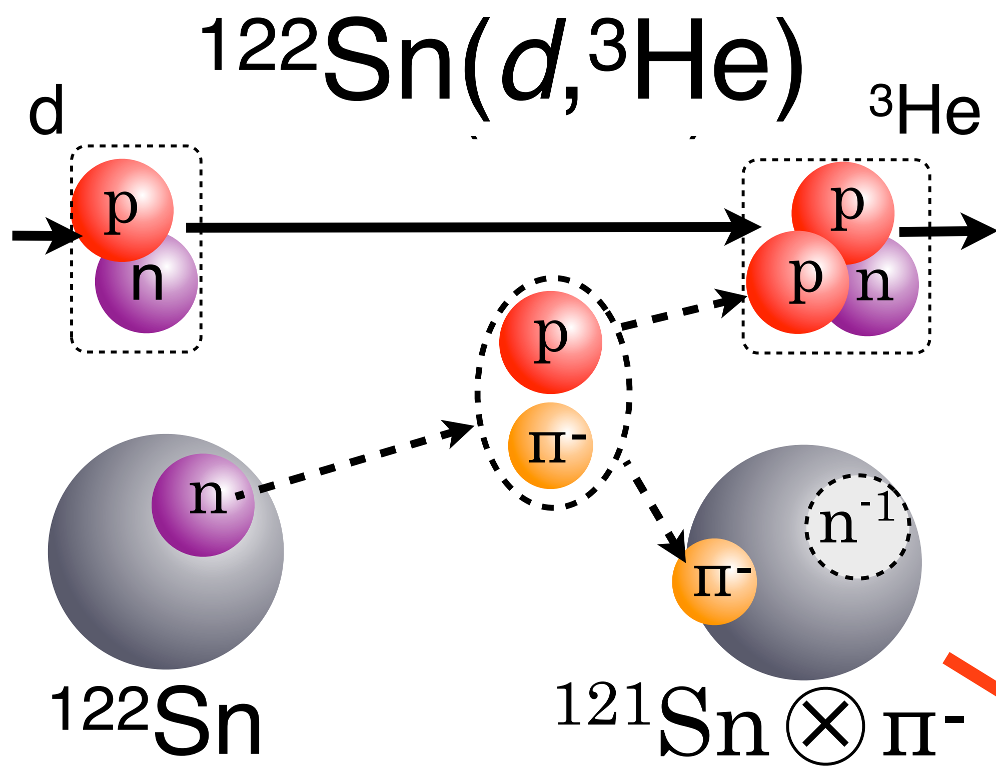
$$\frac{b_1^{\mathrm{free}}}{b_1} = 0.78 \pm 0.05 \quad \rightarrow \quad \frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle} \approx 0.66 \pm 0.06$$

cf. theoretical prediction ~ 0.65

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

2. Precise / systematic experiment at RIBF, RIKEN

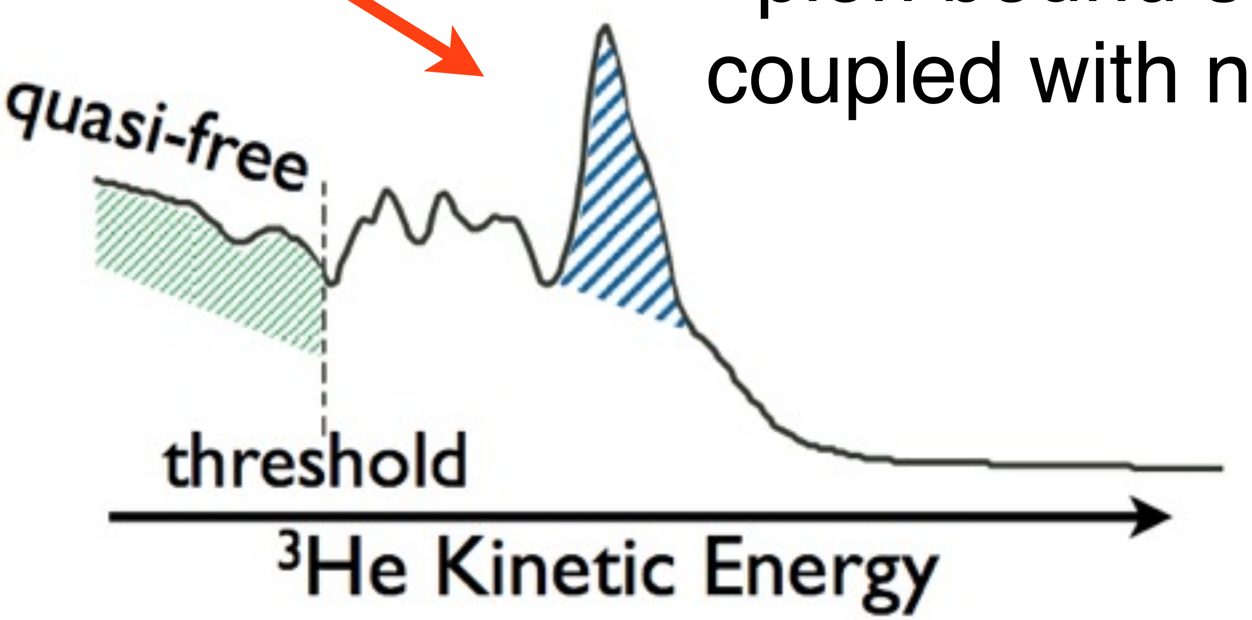
Production method; (d,³He) reaction



Missing mass spectroscopy

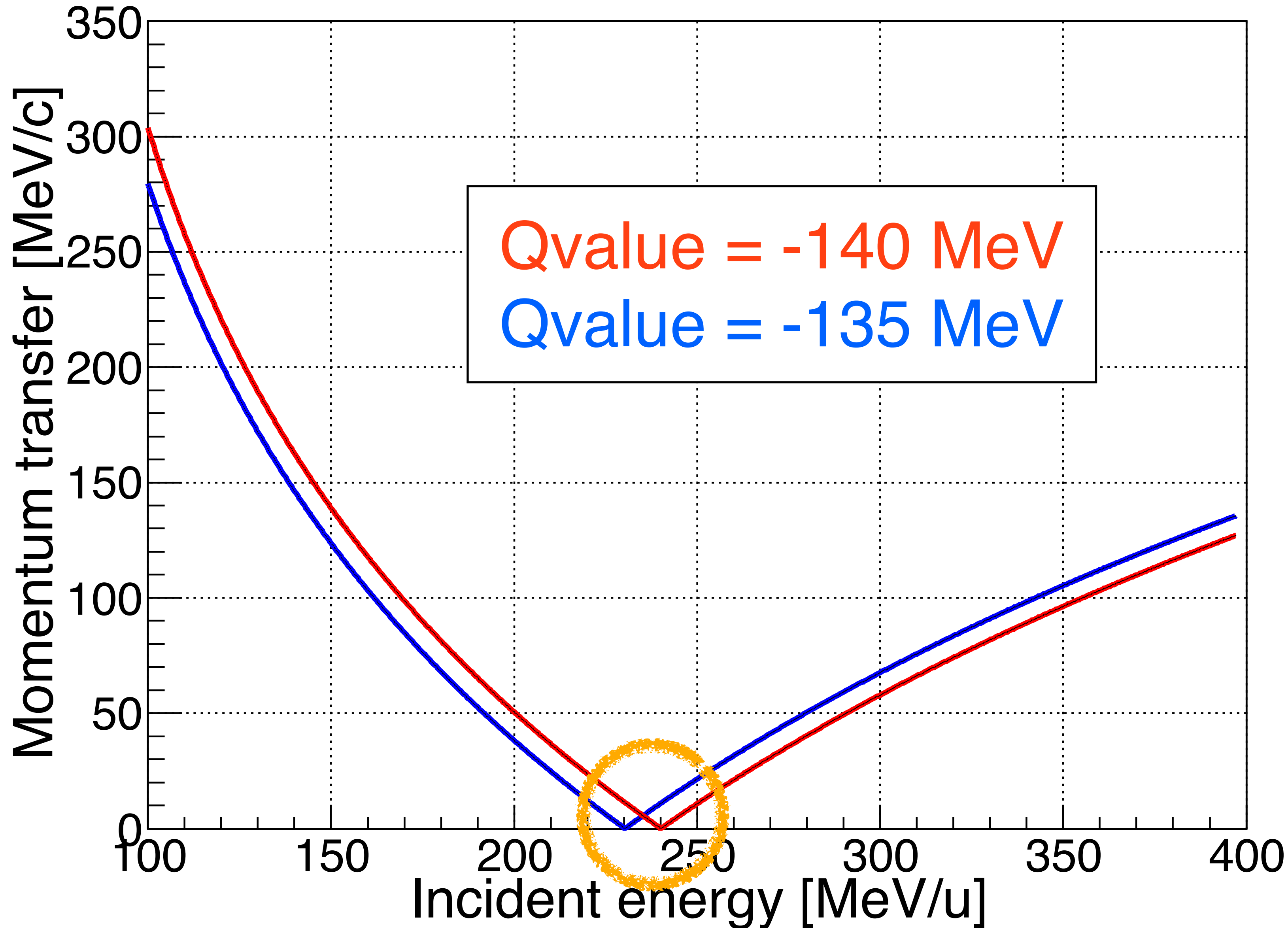
2 body kinematics
→mass of the pionic atom
can be calculated from Q-value

Calculated from E_d , E_{3He}



Production method; (d,^{3}He) reaction

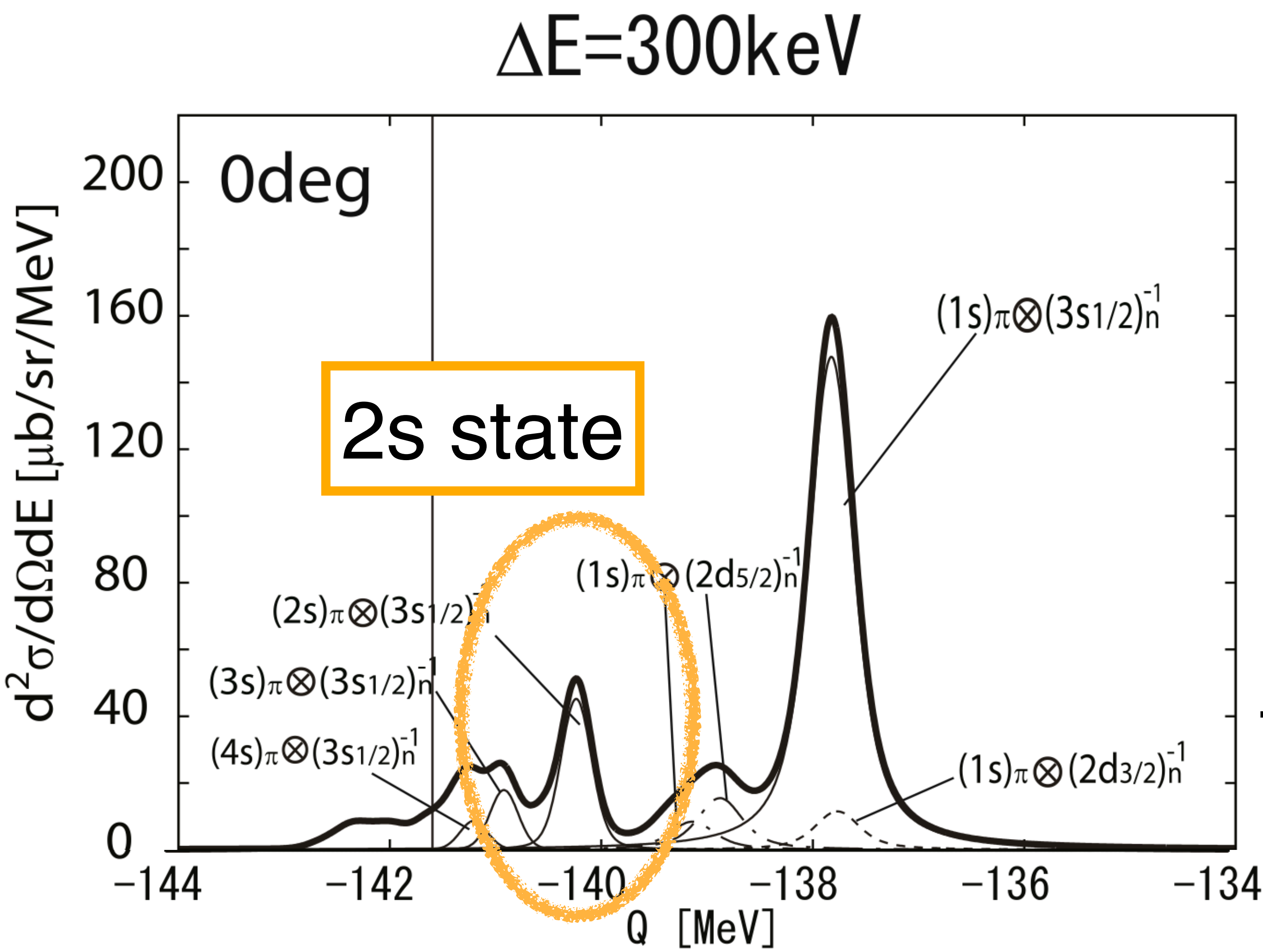
recoilless condition at $T_d \fallingdotseq 250$ MeV/u



- large cross section
- Enhance $(1s)_{\pi^-}$ $(3s)_{n}^{-1}$ configuration

Experiment for precise / systematic study

Theoretical calculated Spectrum



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

More statistics / resolution enable us to observe 2s state.

↓

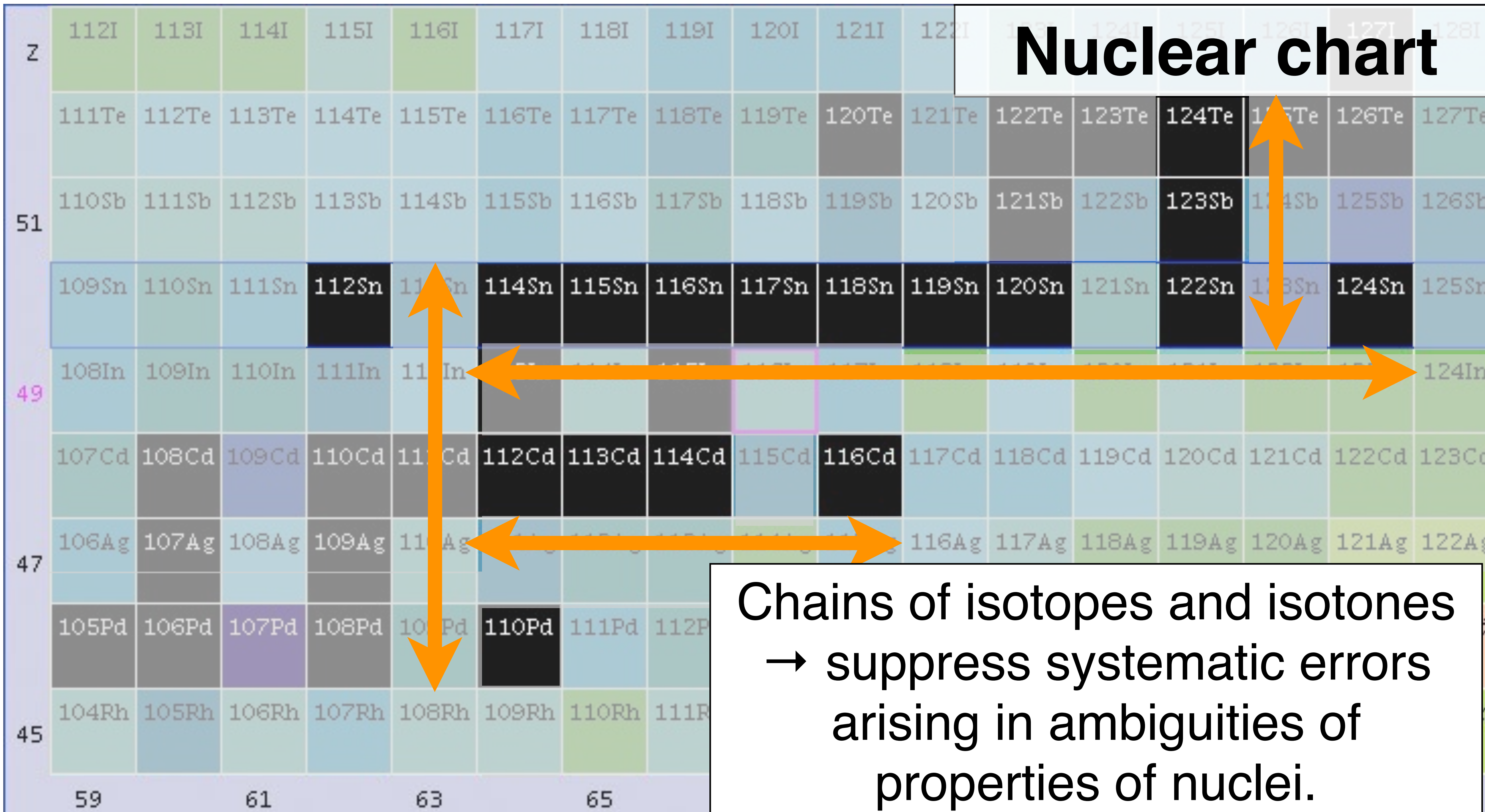
BE_{1s} - BE_{2s} / Γ_{1s} - Γ_{2s}

These value are less affected from the systematic errors.

cf. ΔE ~ 400 keV in GSI experiment

Experiment for precise / systematic study

systematic study of pionic nuclei in isotope / isotone chain

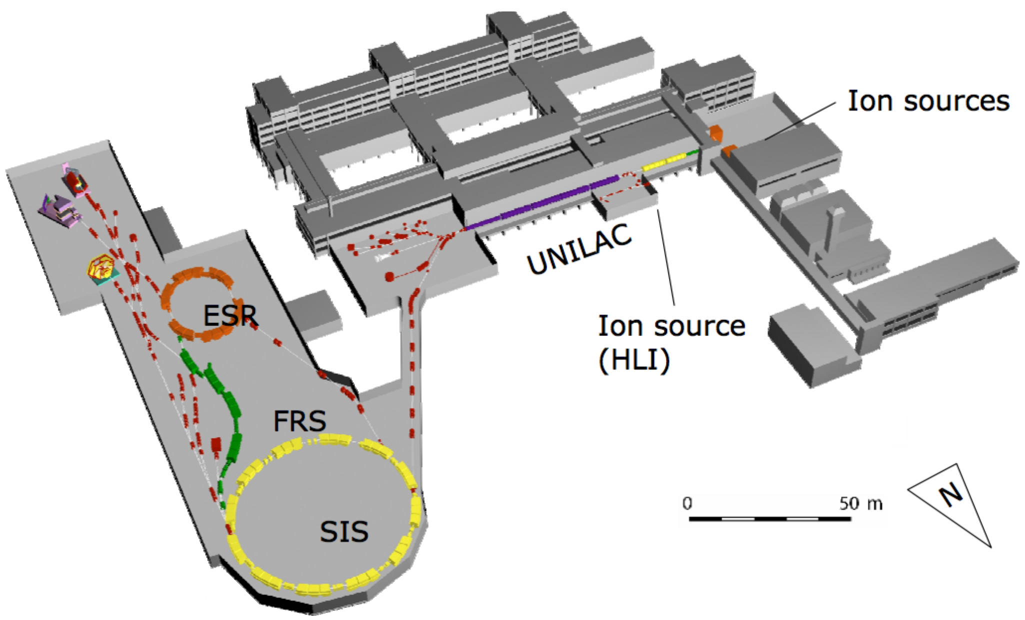


Chains of isotopes and isotones
→ suppress systematic errors
arising in ambiguities of
properties of nuclei.

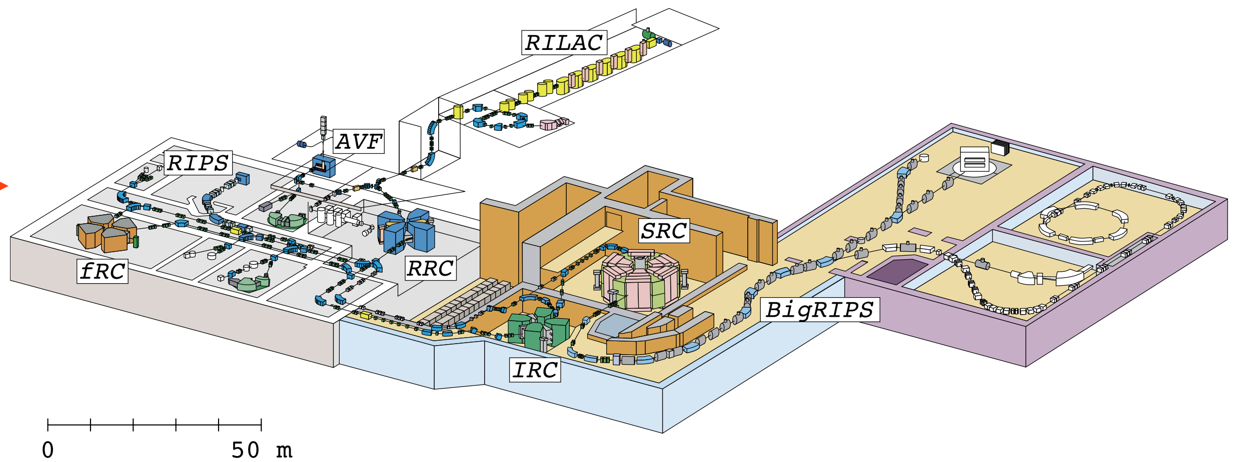
NNDC,BNL

Experiment at RIKEN

GSI facilities

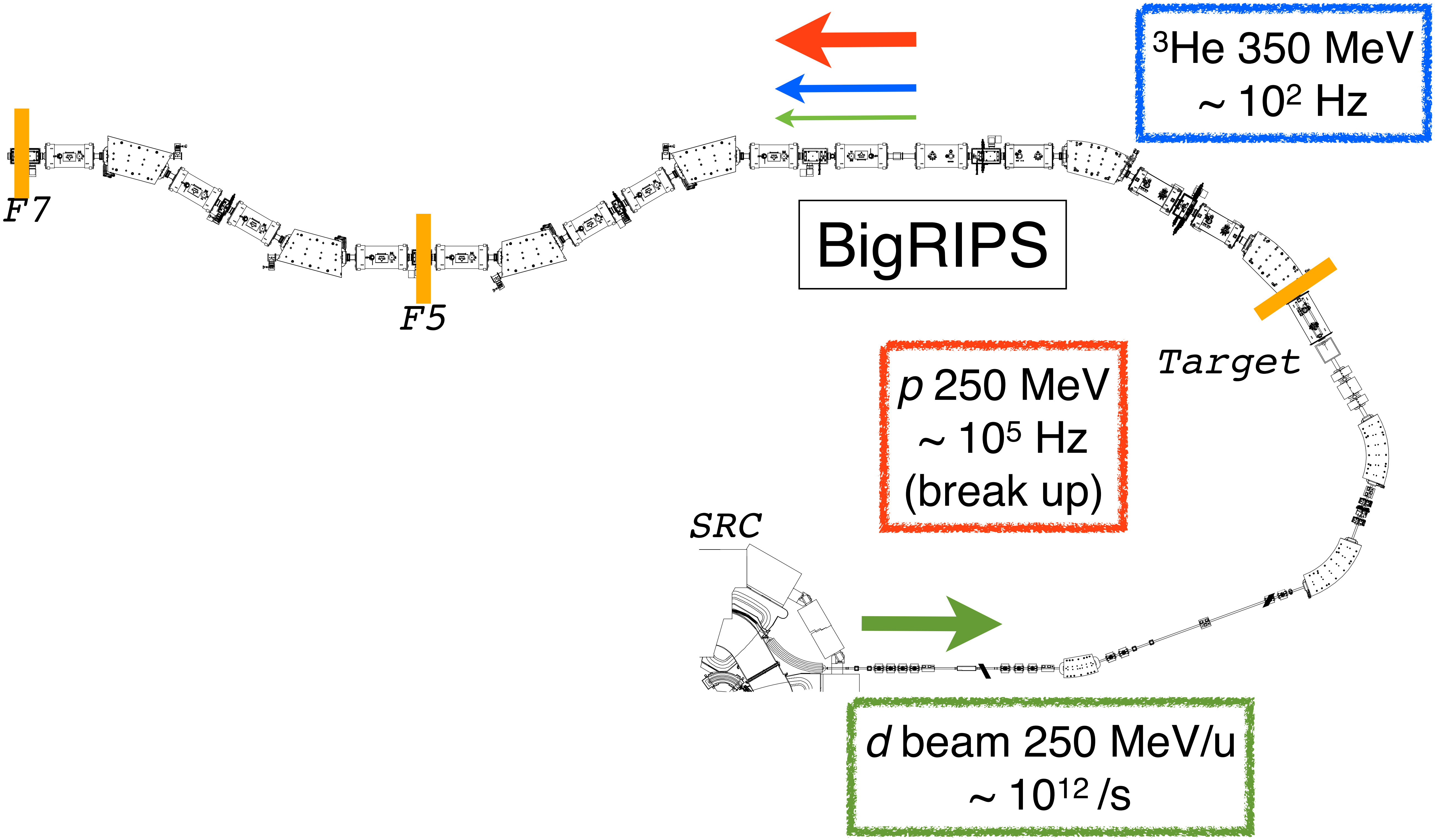


RIKEN facilities

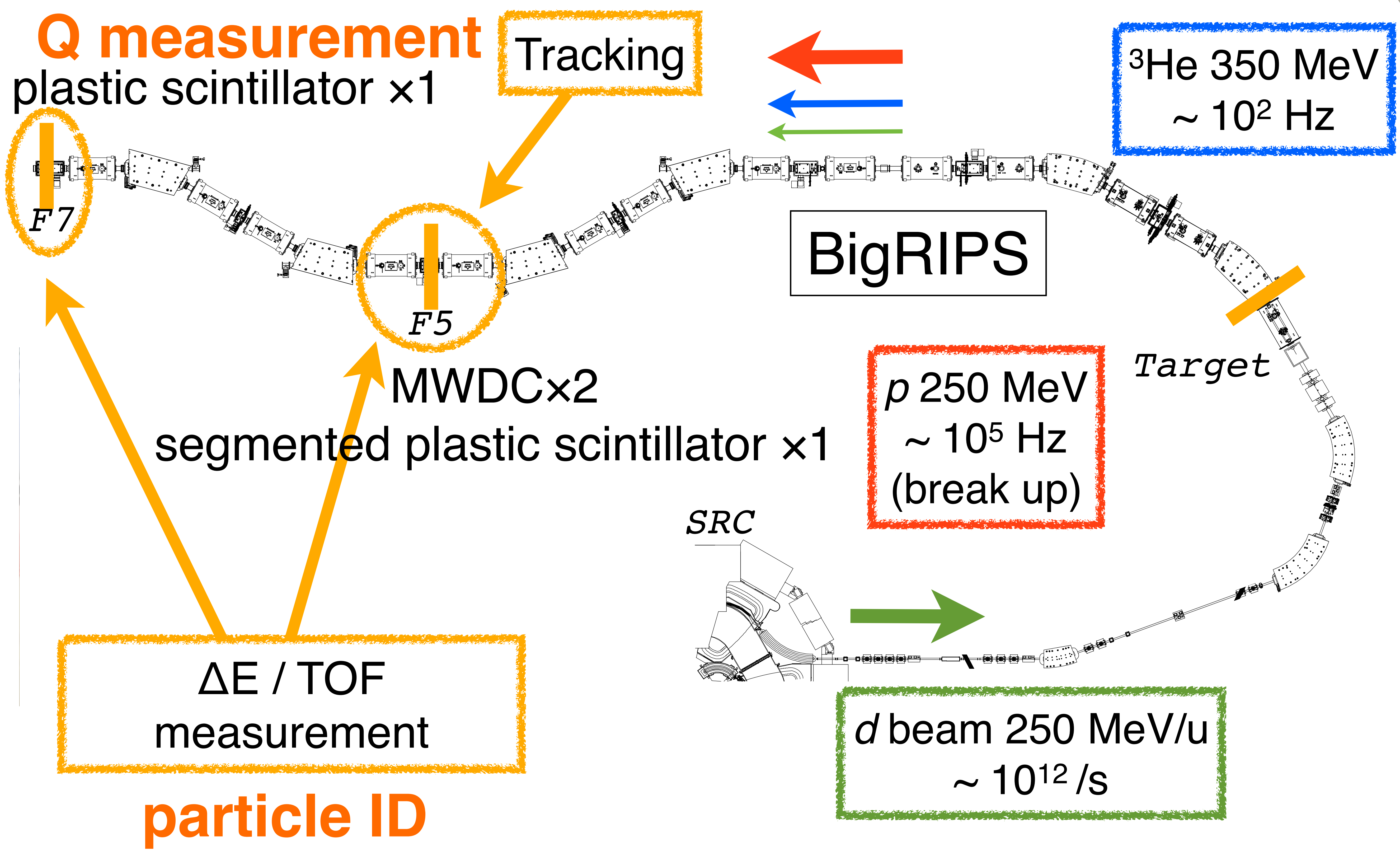


	GSI	RIBF	
intensity	~10^{11}/spill	~10^{12}/s	**×50**
angular acceptance	~10 mrad	40 / 60 mrad	**×20**

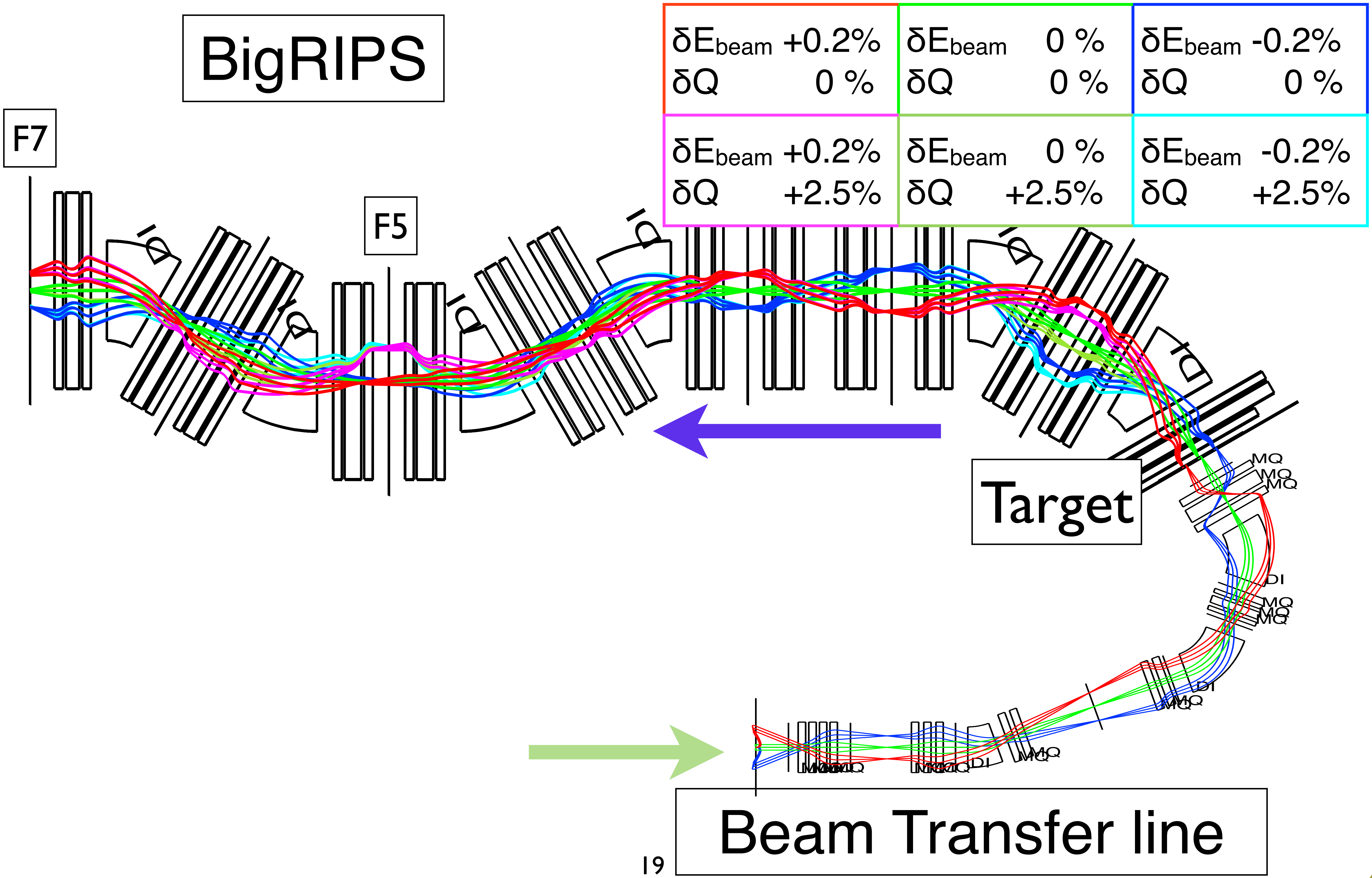
Experimental setup



Experimental setup



Ion optics (dispersion matching)



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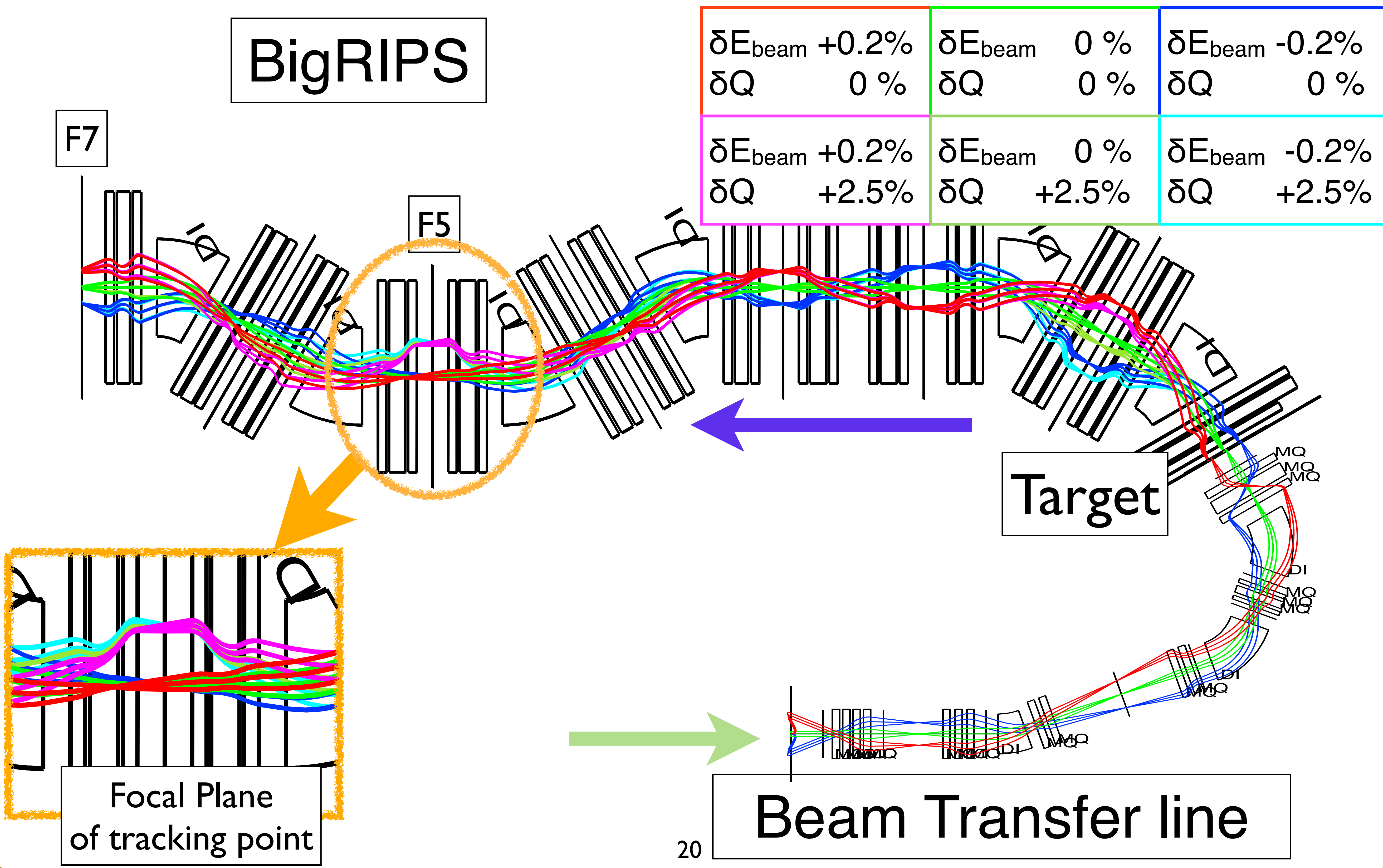
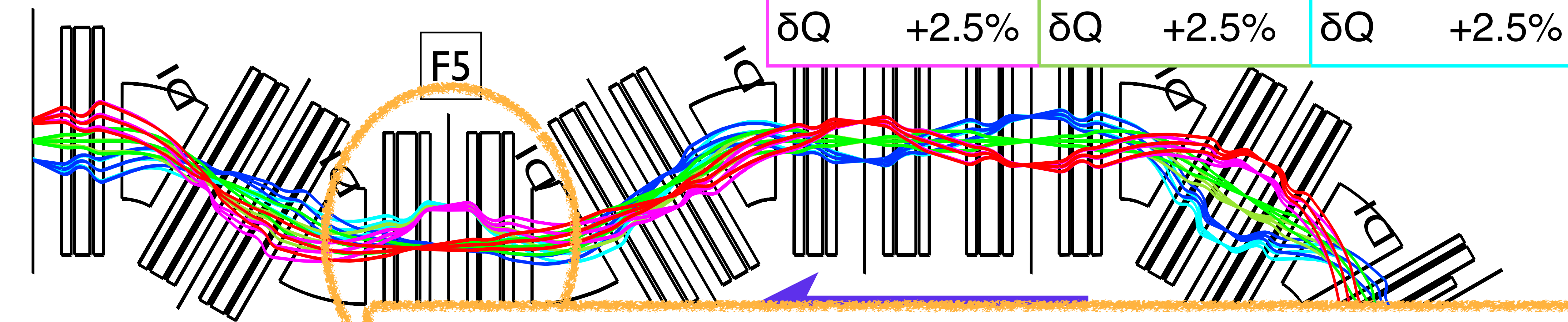


Ion optics (dispersion matching)

BigRIPS



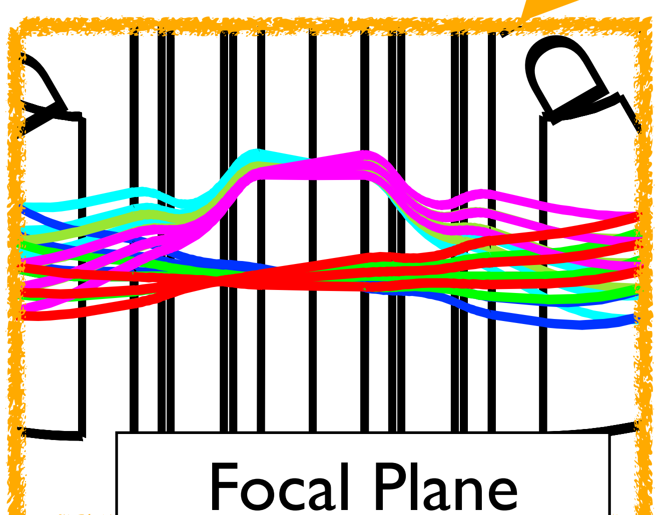
δE_{beam} +0.2% δQ 0 %	δE_{beam} 0 % δQ 0 %	δE_{beam} -0.2% δQ 0 %
δE_{beam} +0.2% δQ +2.5%	δE_{beam} 0 % δQ +2.5%	δE_{beam} -0.2% δQ +2.5%

realize high precision spectroscopy

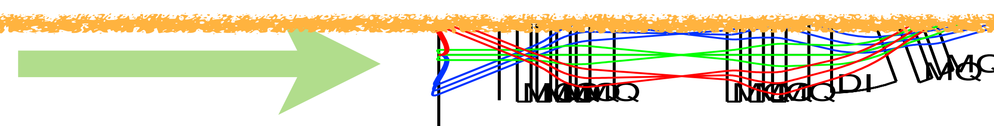
- independent on beam Energy spread

  → *dispersion matching*

- depend on Q value ($\delta p/p$ = 1% ⇄ 62 mm)



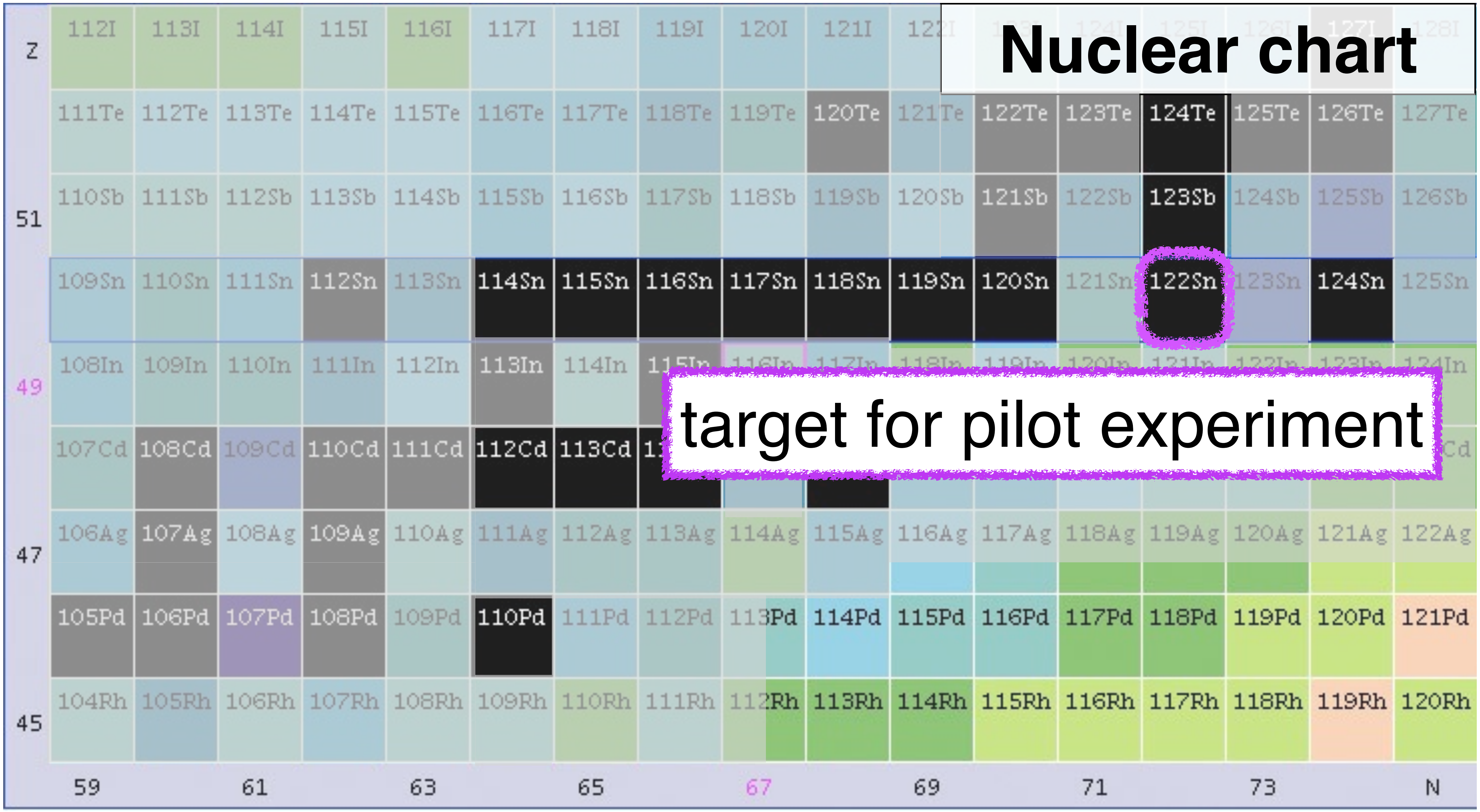
Focal Plane of tracking point



Beam Transfer line

Pilot experiment

pilot experiment; performed in 2010



NNDC,BNL

Pilot experiment

pilot experiment; performed in 2010

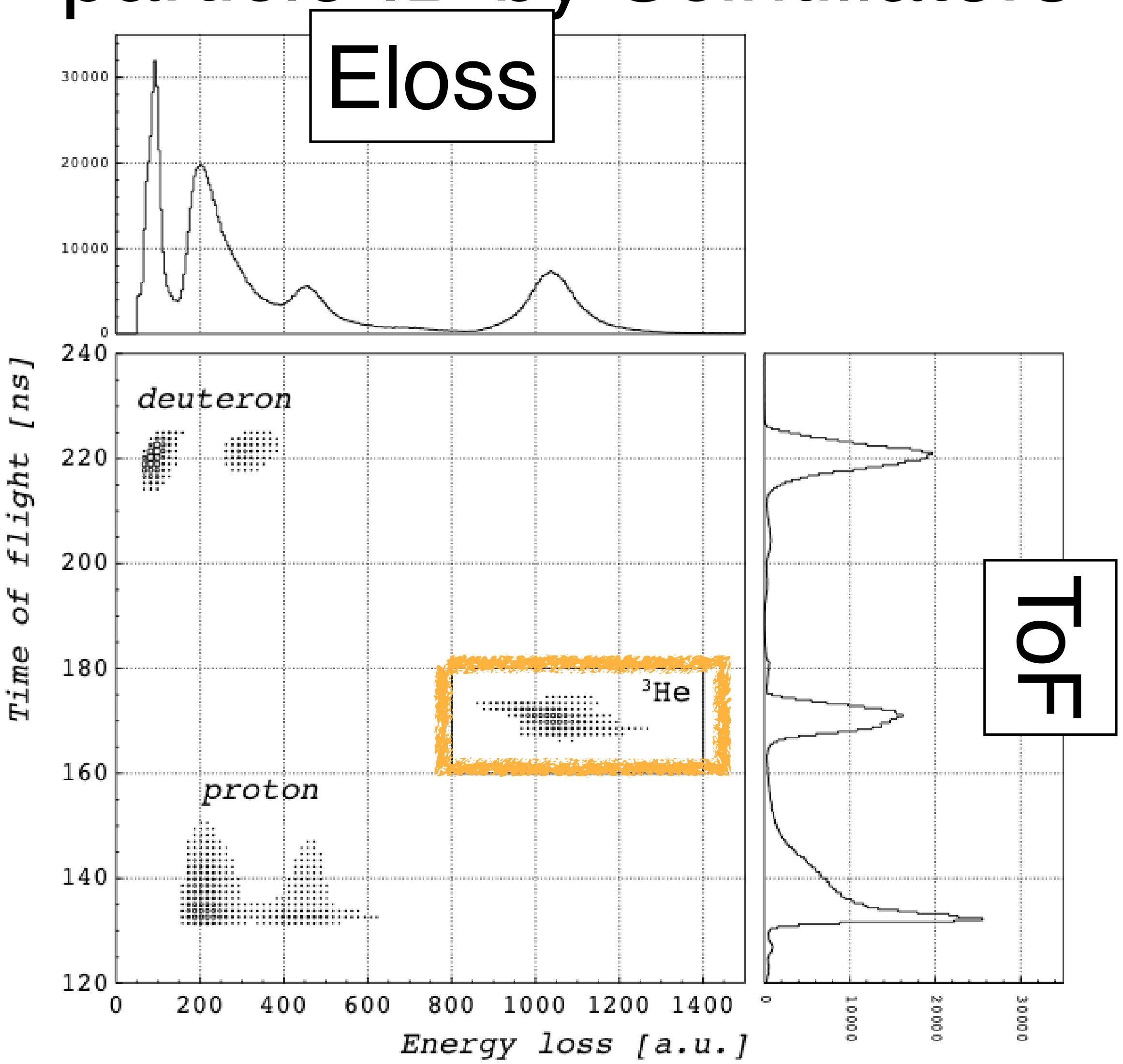
Target ; ^{122}Sn
Purpose ; test for

- **all detector system**
- **ion optics**

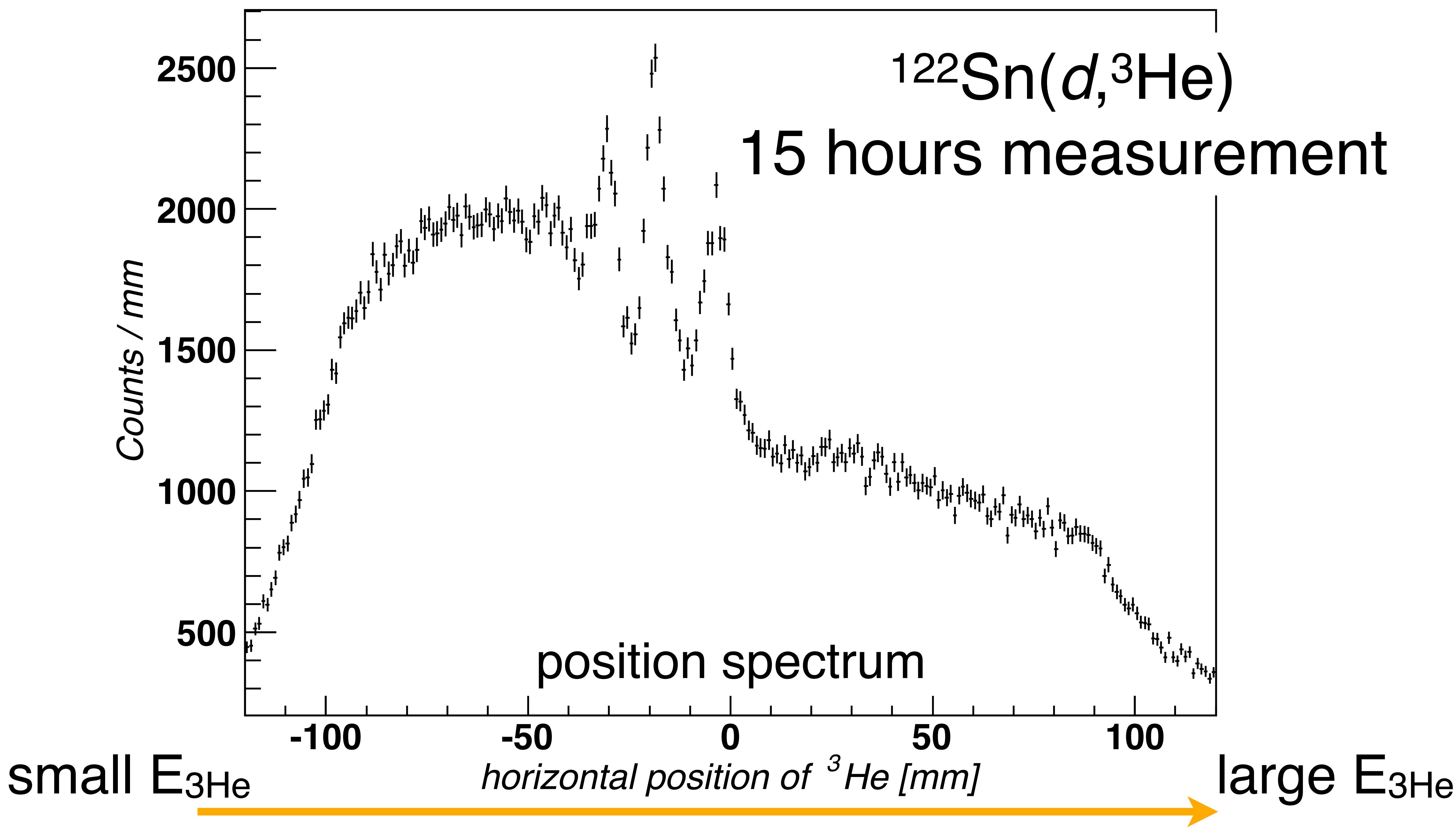
Pilot experiment

pilot experiment; performed in 2010

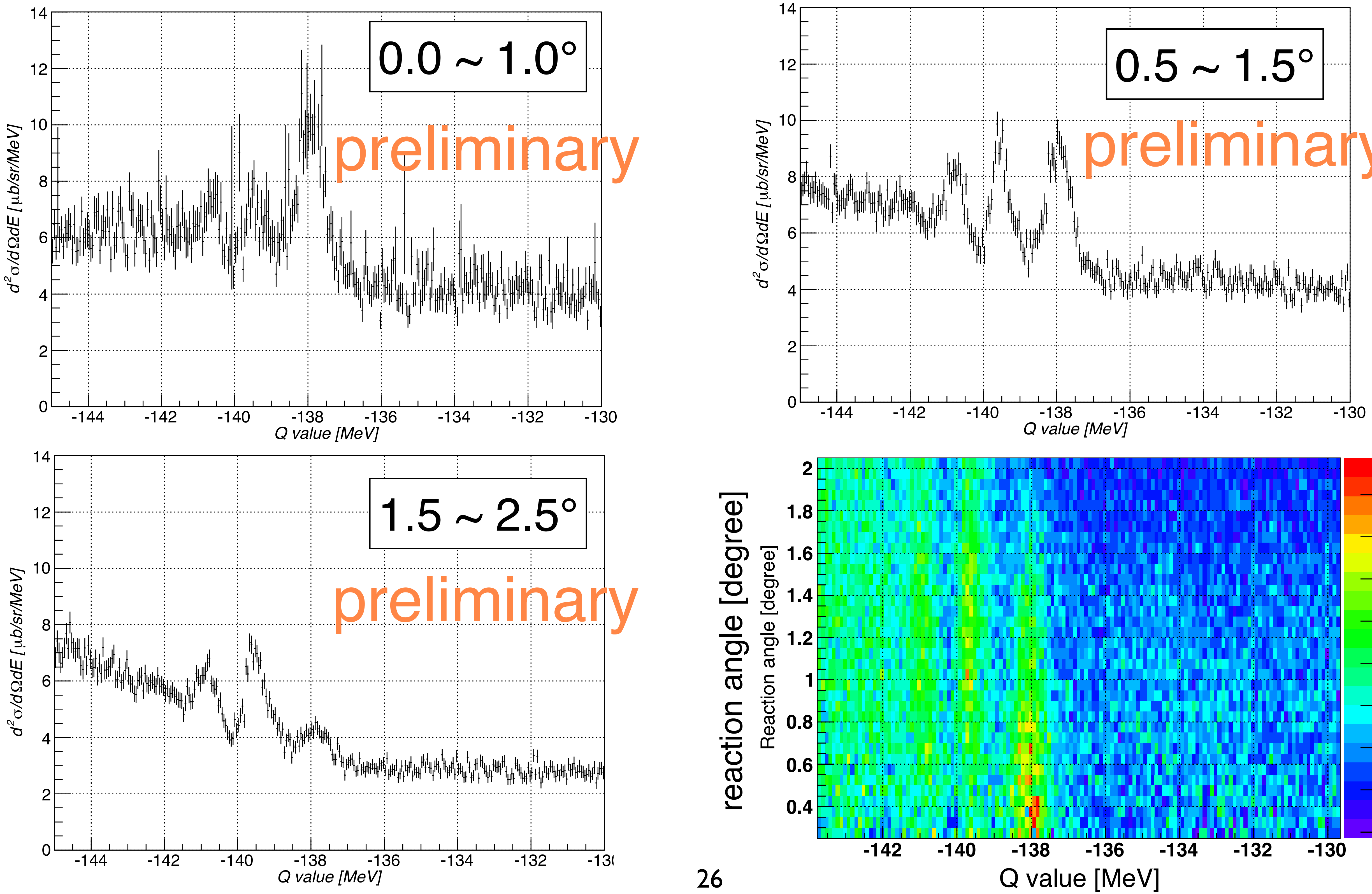
particle ID by Scintillators



Pilot experiment



Experimental Q-value spectra



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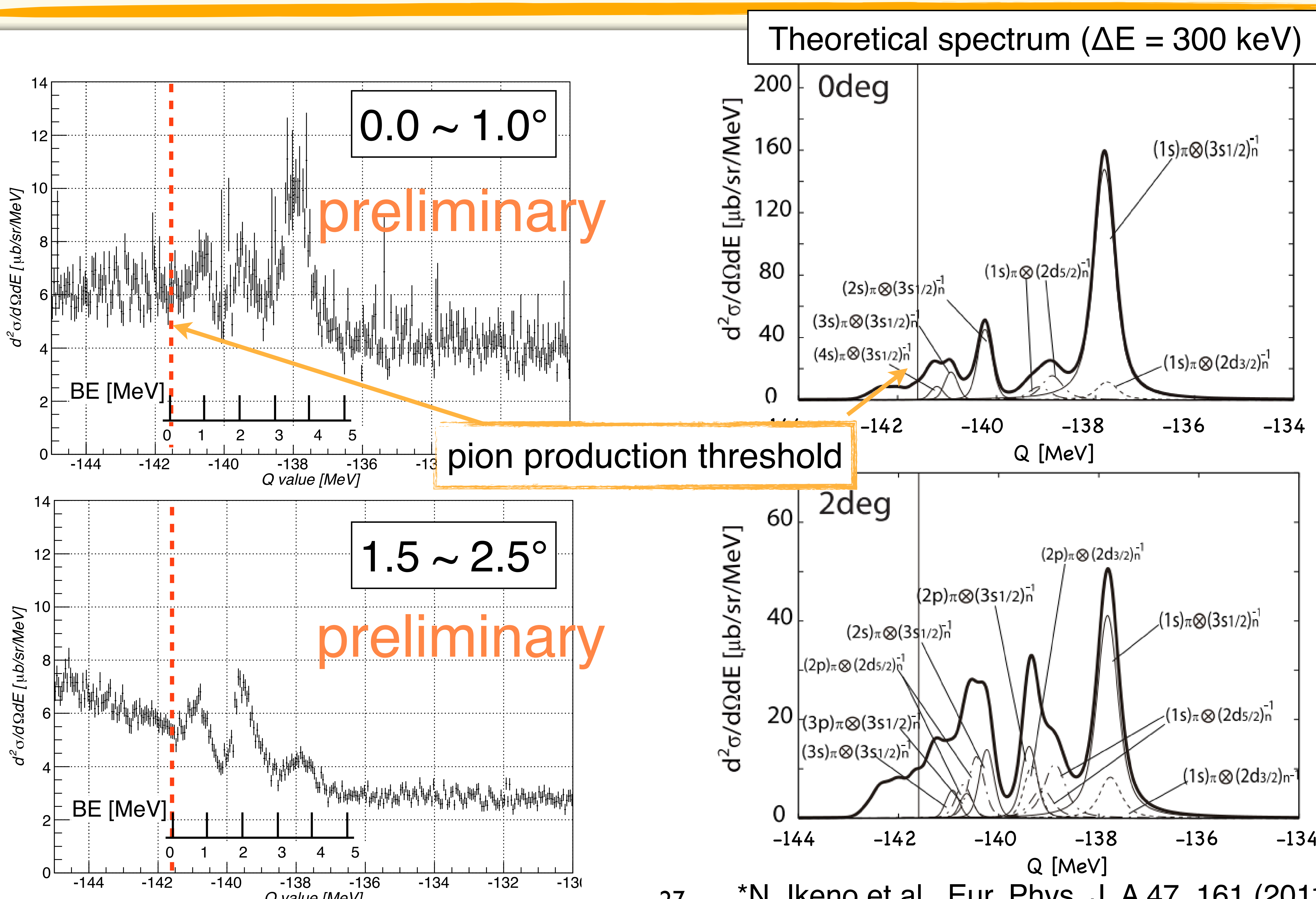

*N. Ikeno et al., Eur. Phys. J. A 47, 161 (2011)

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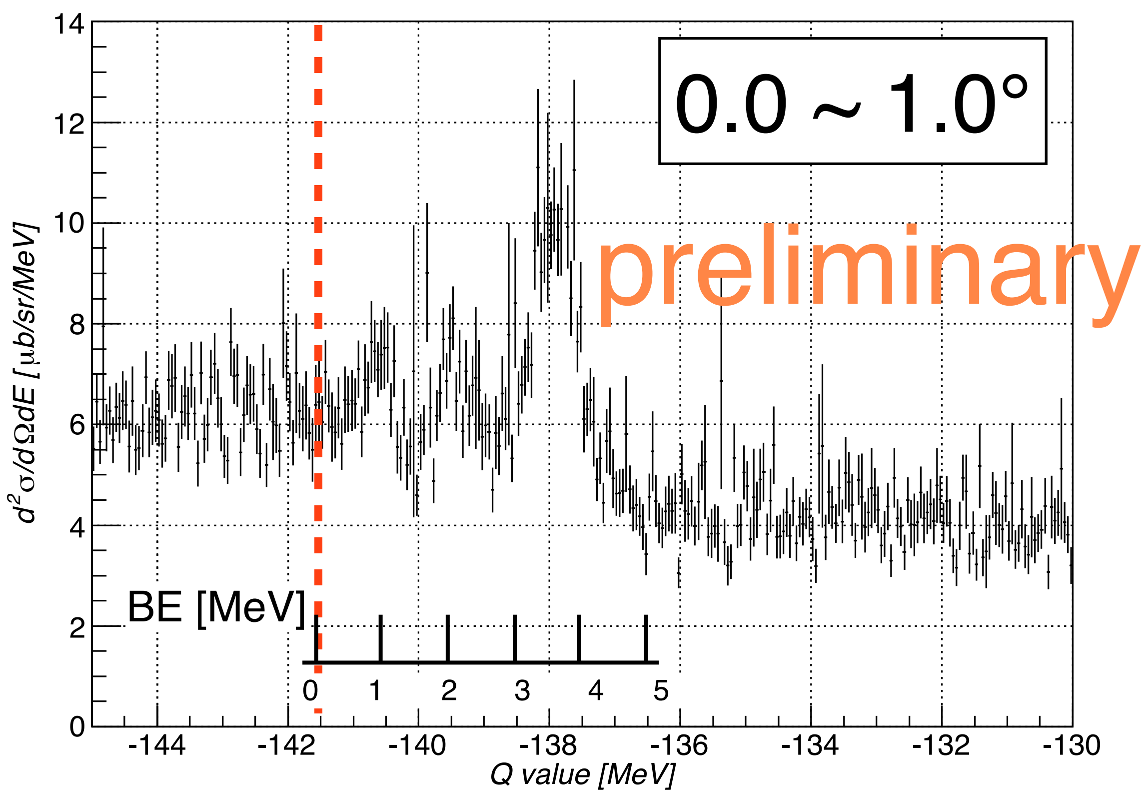
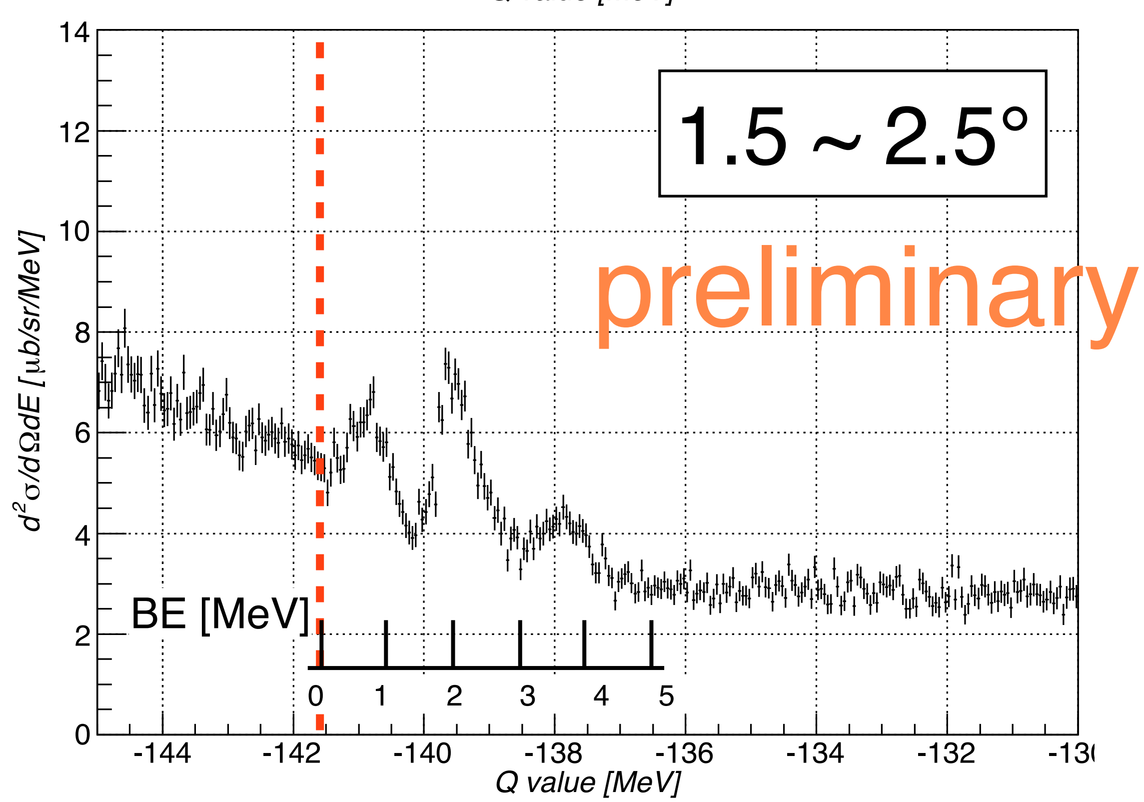
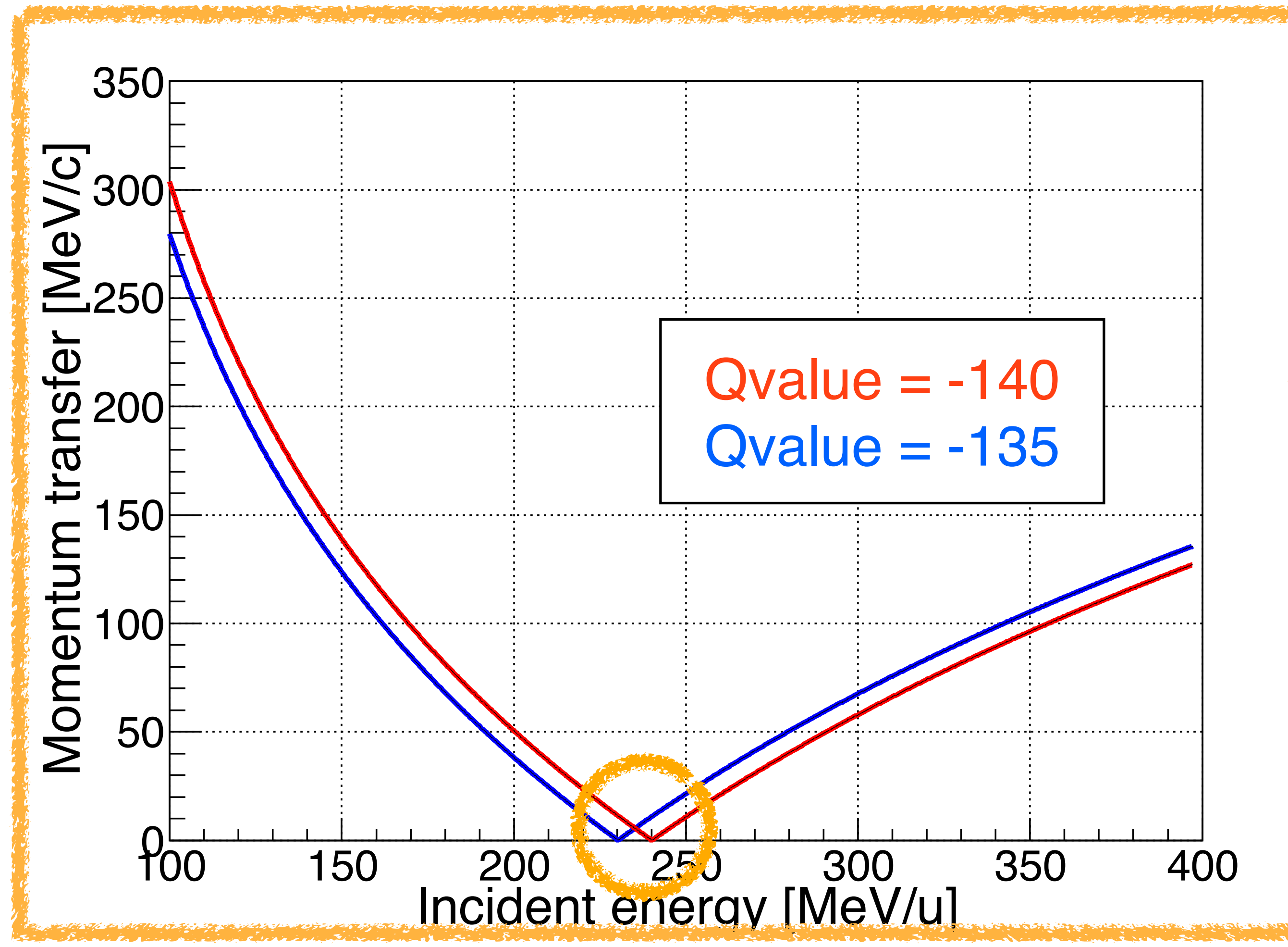




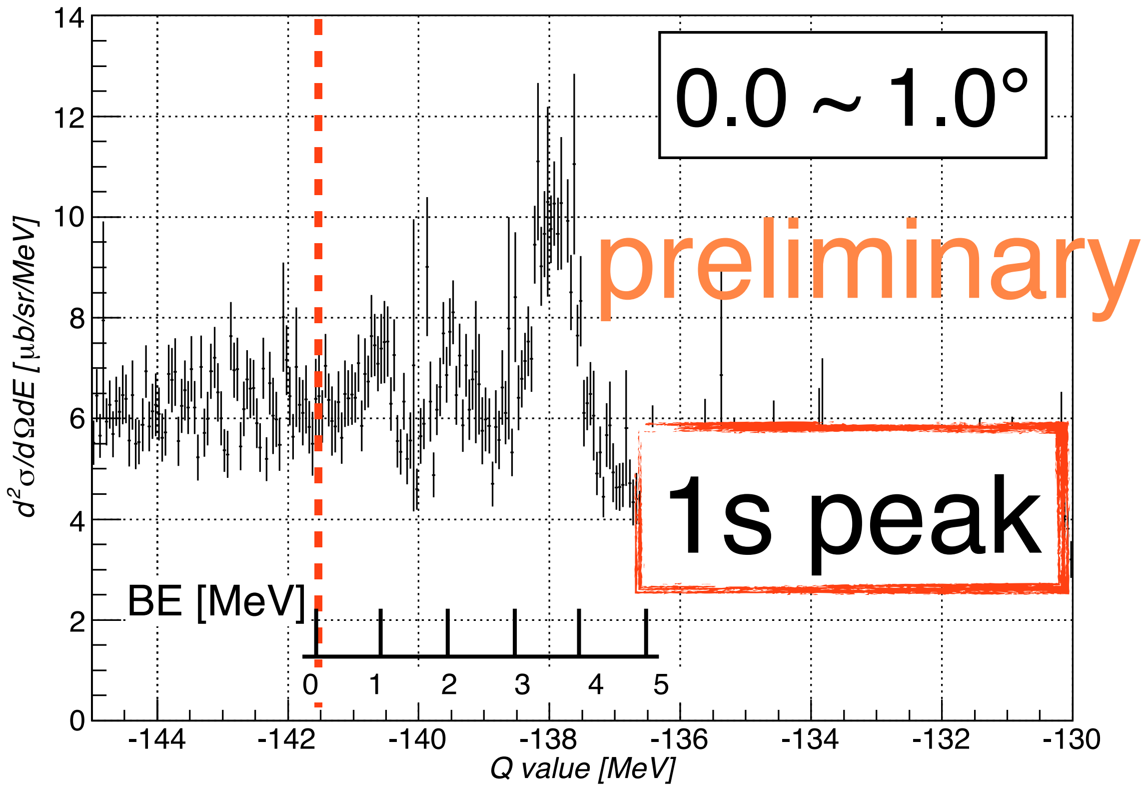


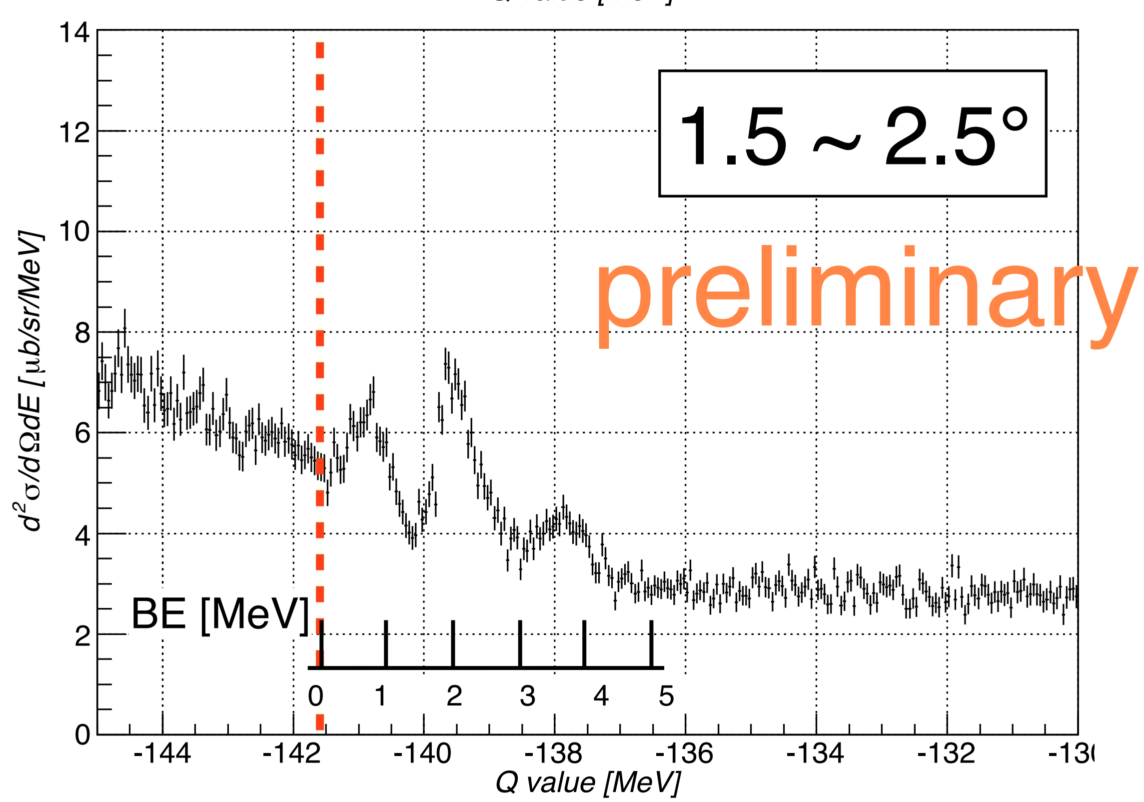
finite angle

→ recoilless condition is broken

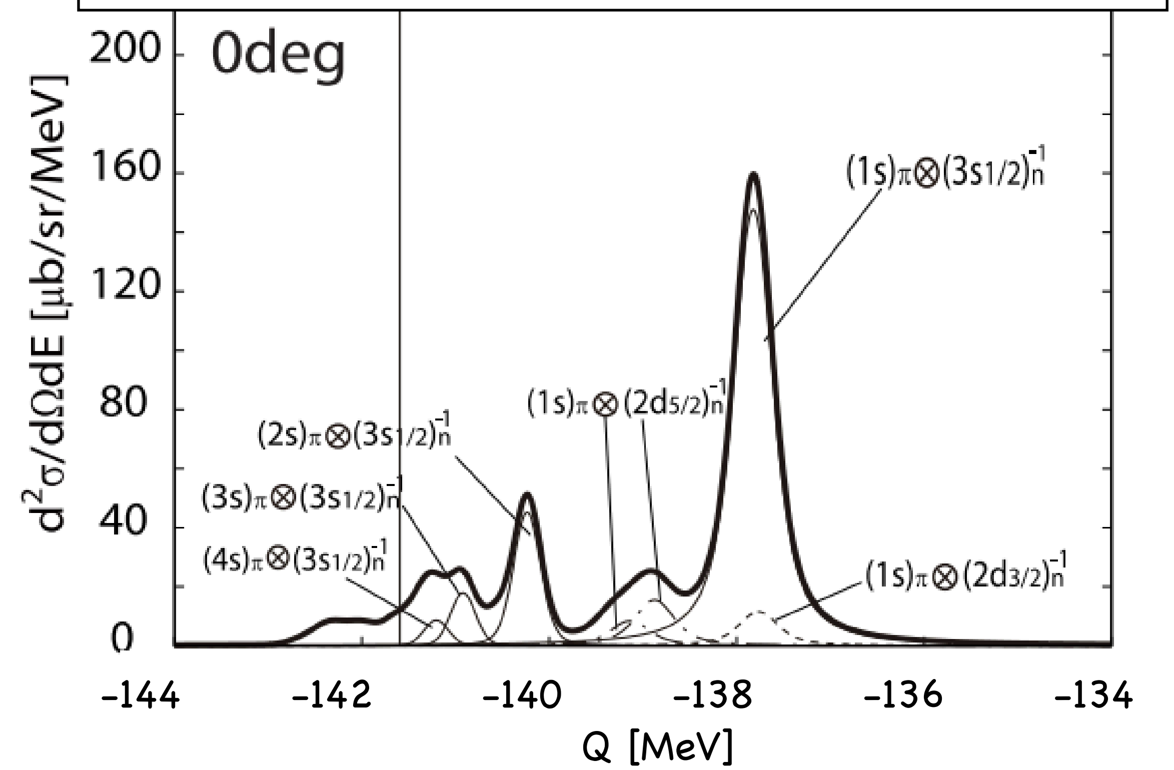
→ configuration with finite Δl grow up

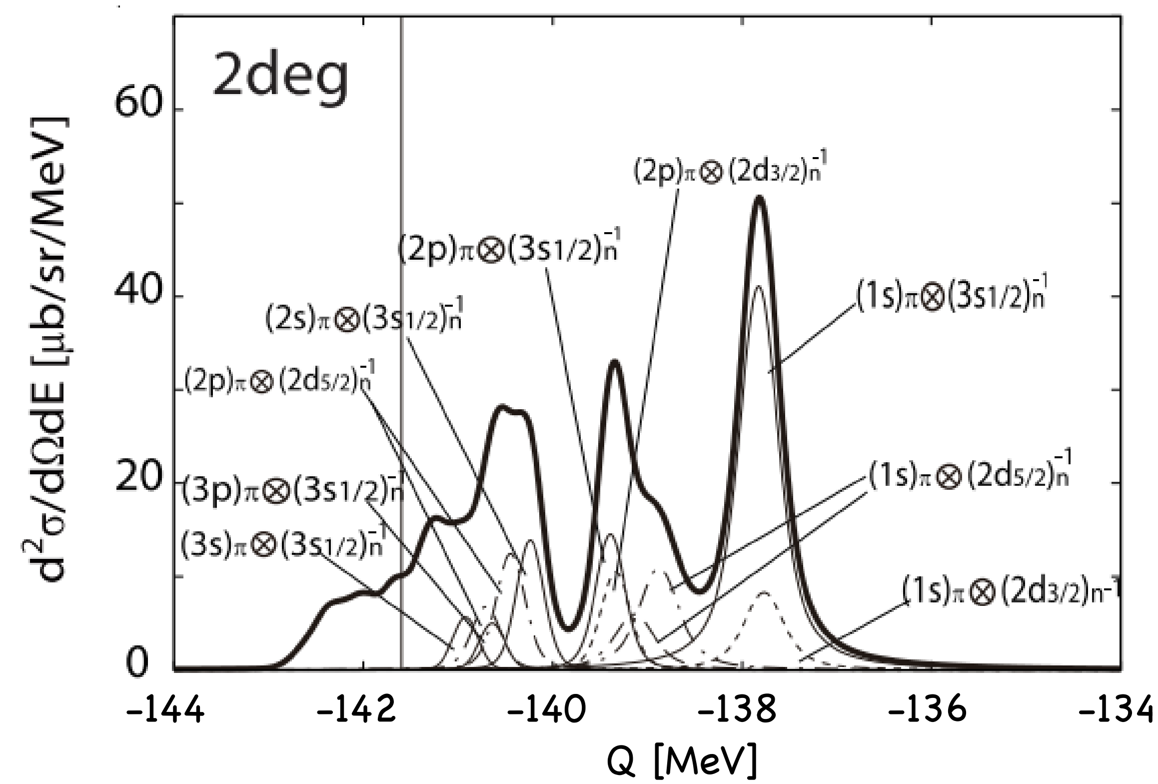
Experimental Q-value spectra





Theoretical spectrum (ΔE = 300 keV)





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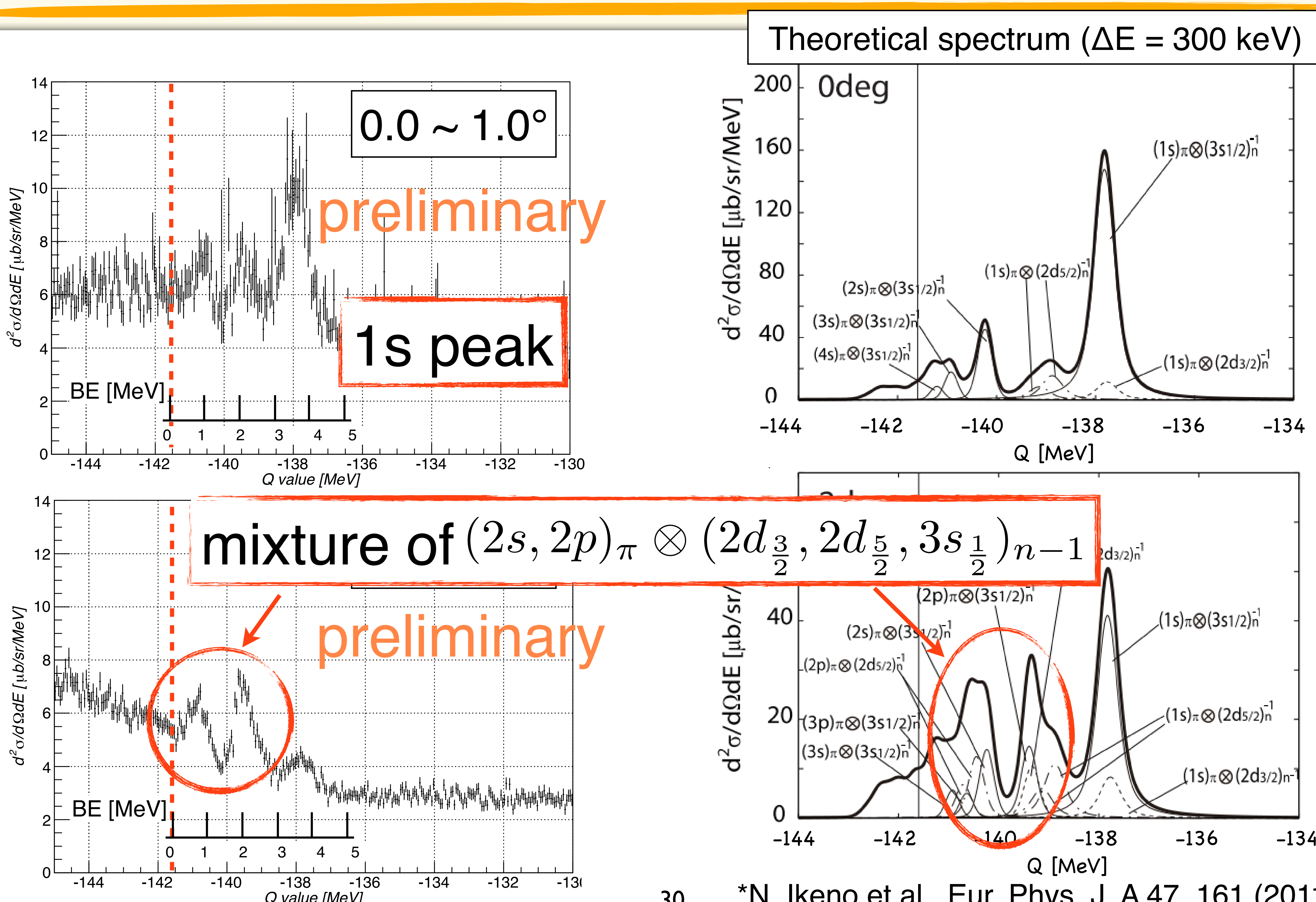
Experimental Q-value spectra



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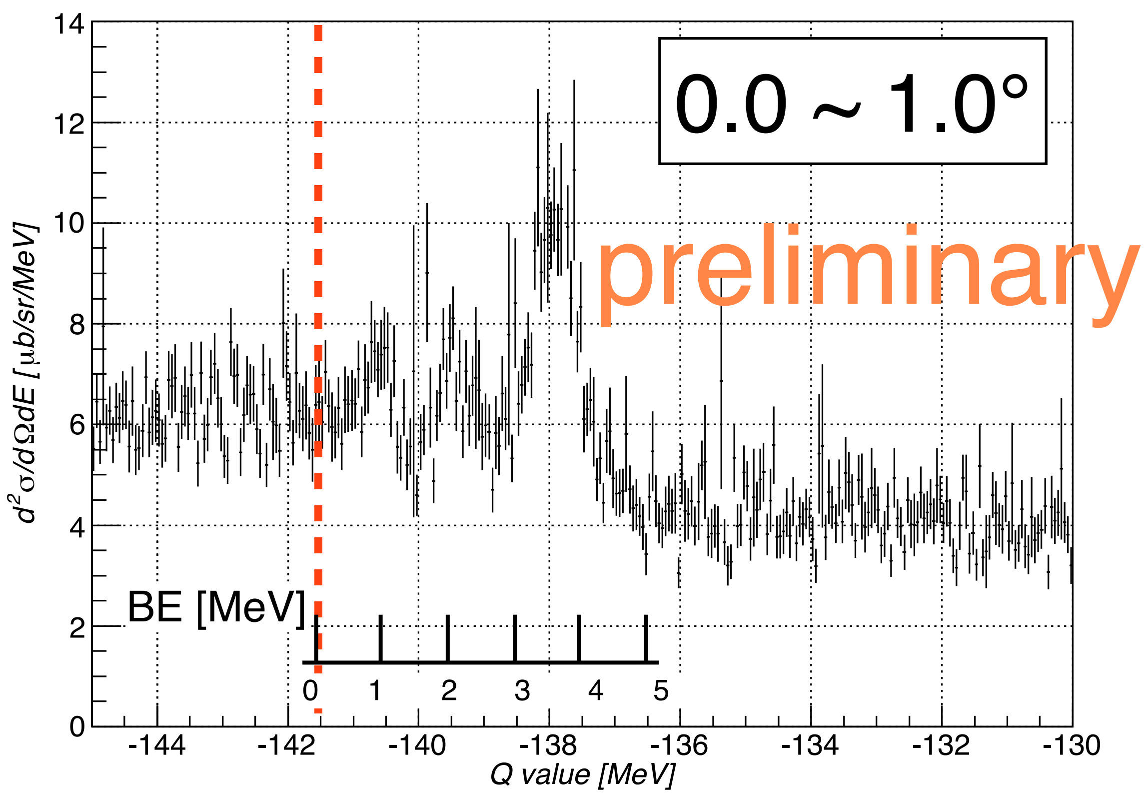
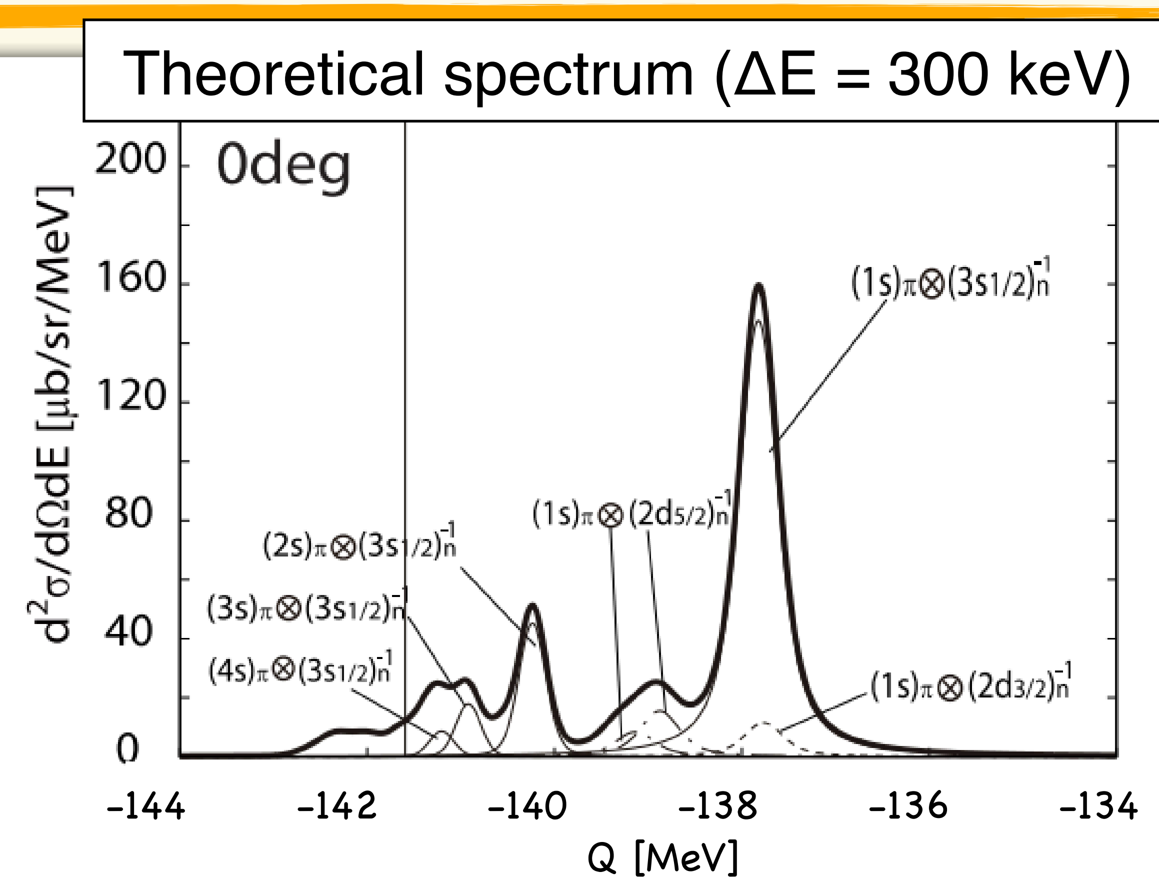
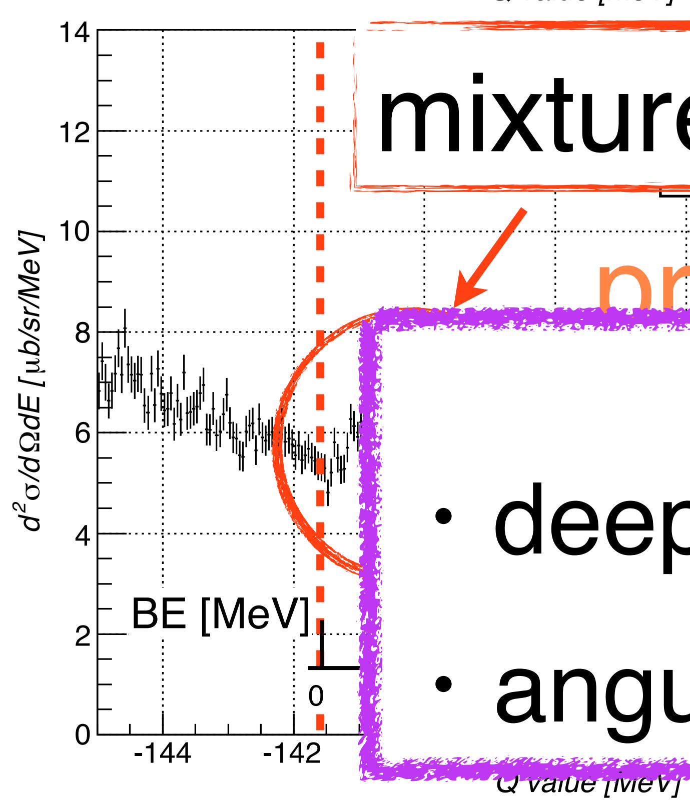
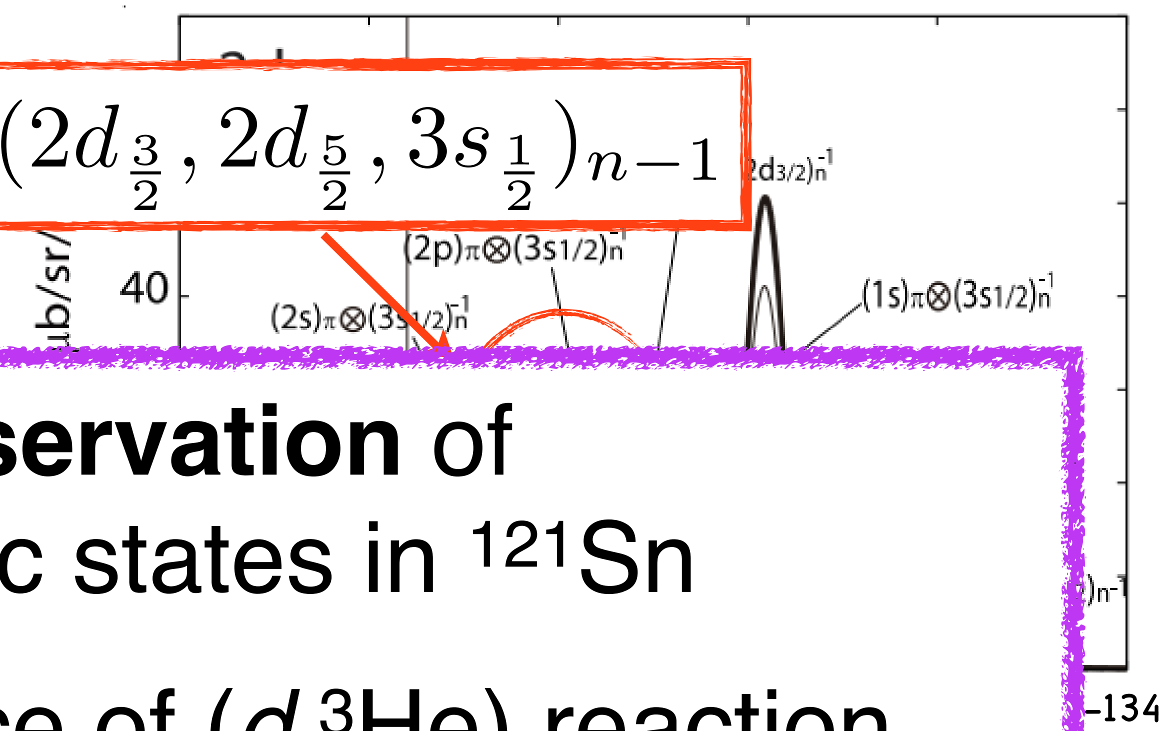








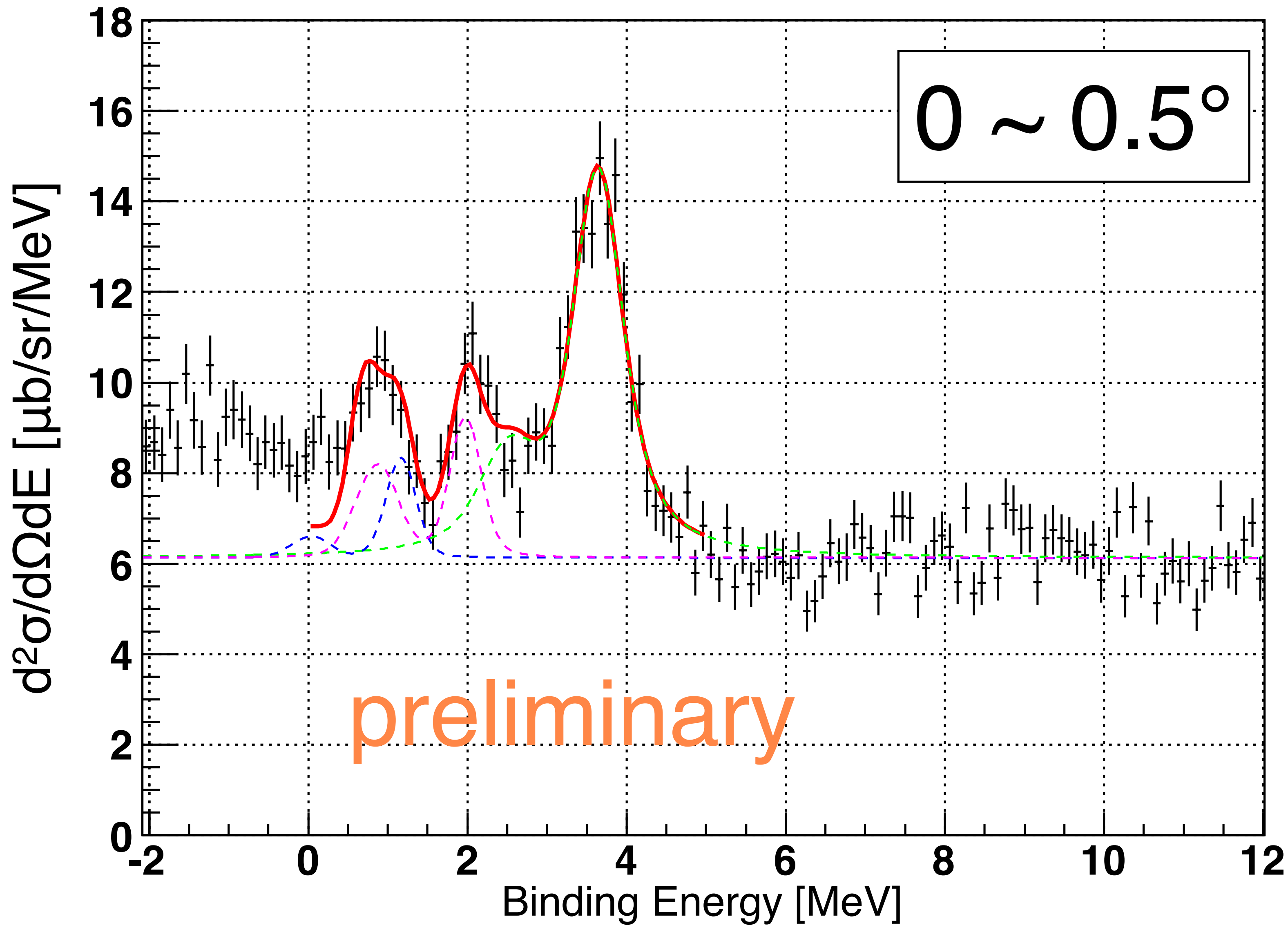
mixture of $(2s, 2p)_\pi \otimes (2d_{\frac{3}{2}}, 2d_{\frac{5}{2}}, 3s_{\frac{1}{2}})_{n-1}$

First observation of

- deeply bound pionic states in ^{121}Sn
- angular dependence of (d,^{3}He) reaction

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

Decomposition of Spectra



fit function; $F(E) = F_{bg} + \Sigma_{nl} F_{nl}$

free parameter

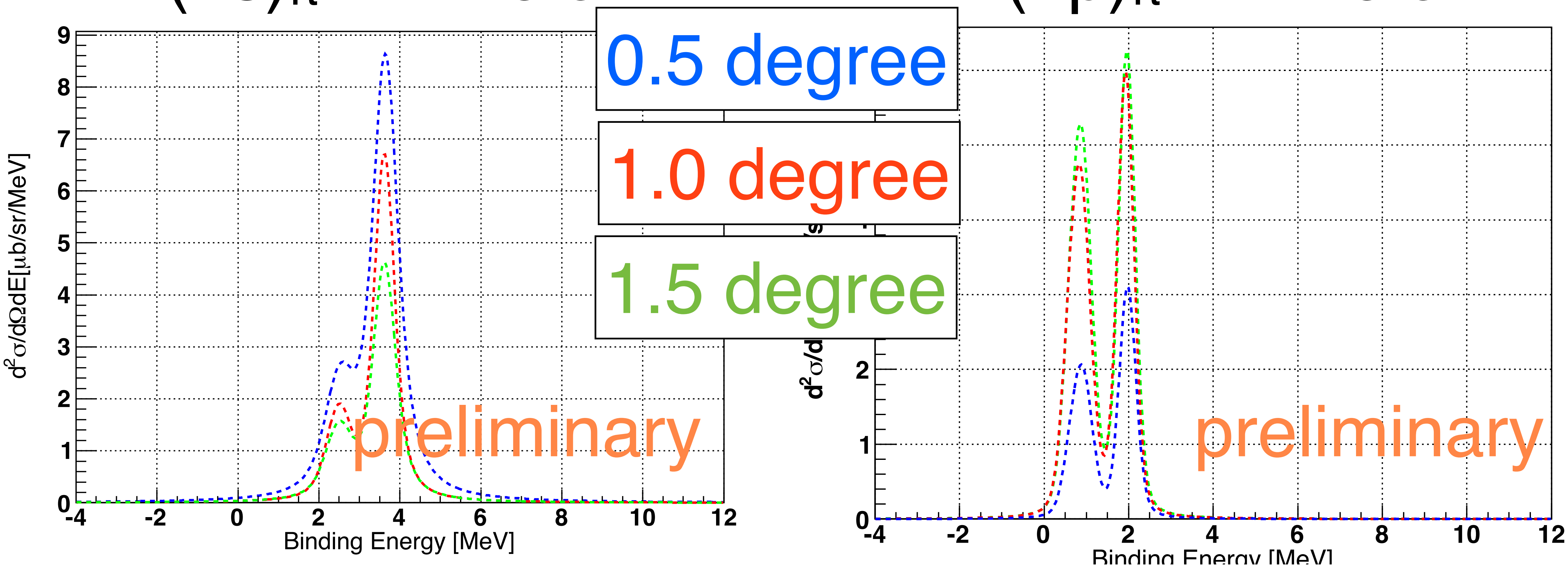
$$F_{nl}(E) = S_{nl} \Sigma_{j_m} N_{eff}^{nl,j_m} \text{Voigt}(E - B.E._{\pi^-}^{nl} + E_{hole}^{j_m}, \Gamma_{\pi^-}^{nl}, \sigma_{exp})$$

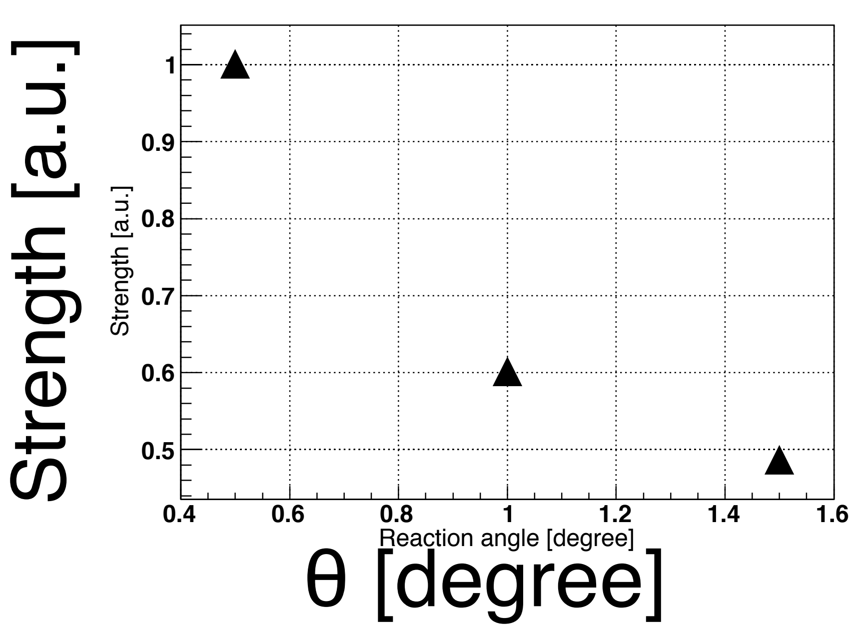
nl ; index for pionic states / j_m ; index for neutron hole states

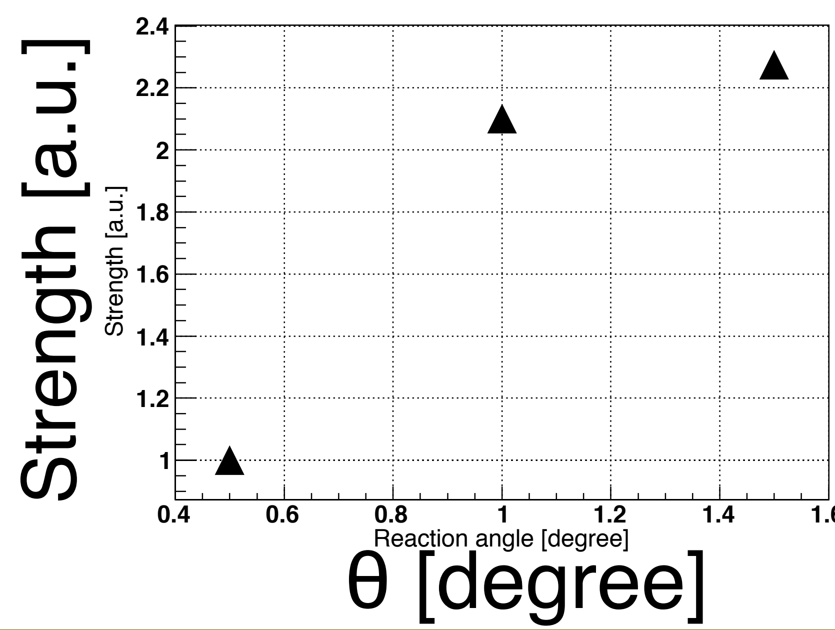
Decomposition of Spectra

$(1s)_{\pi^-} \times$ n hole

$(2p)_{\pi^-} \times$ n hole







Current status

Finalizing

- optical aberration
- acceptance including angular dependence
- energy calibration by $p(d,{}^3\mathrm{He})\pi^0$ reaction

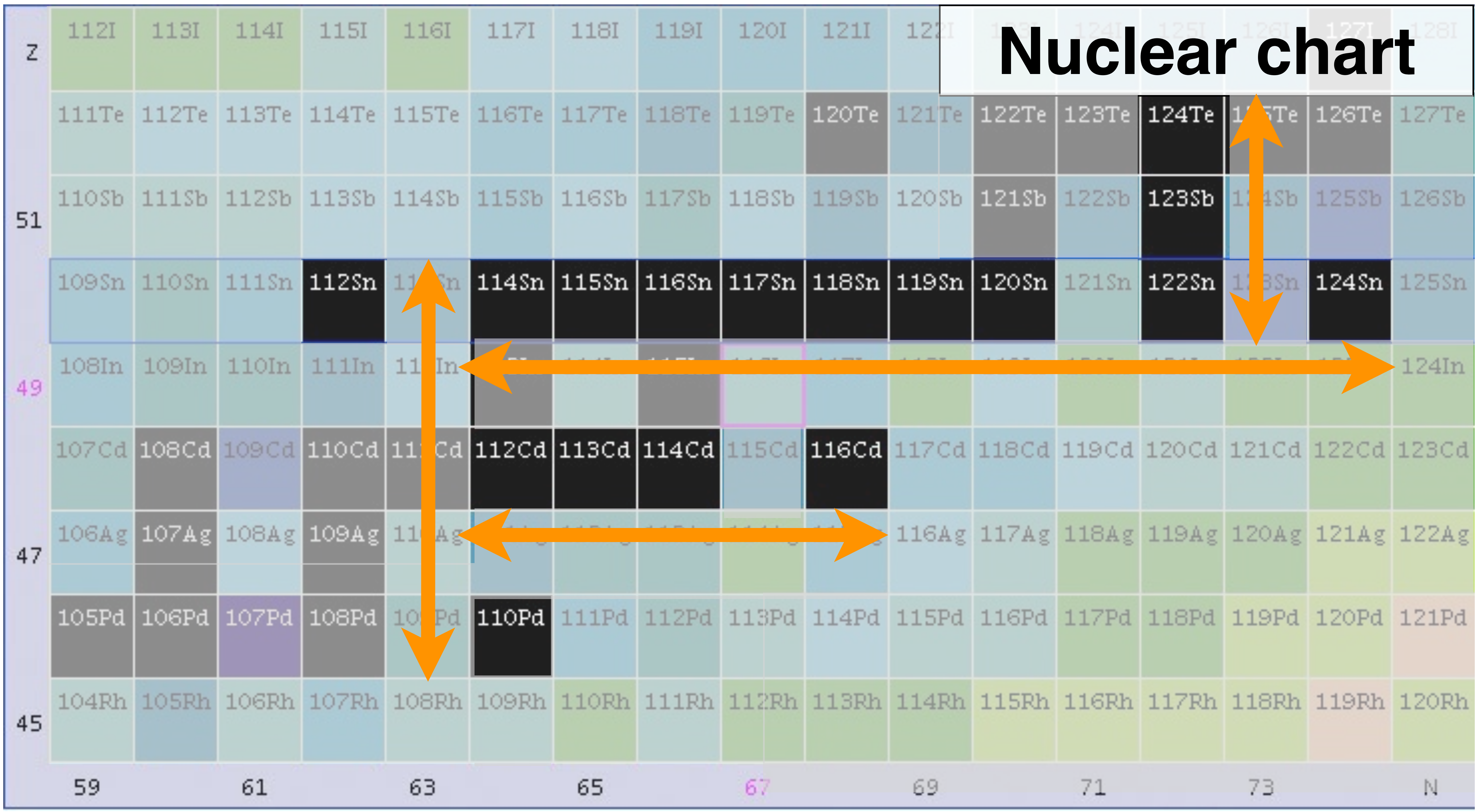
main experiment

- some improvements are suggested
- preparing for the main experiment

3. Future perspectives
~ pionic unstable nuclei ~

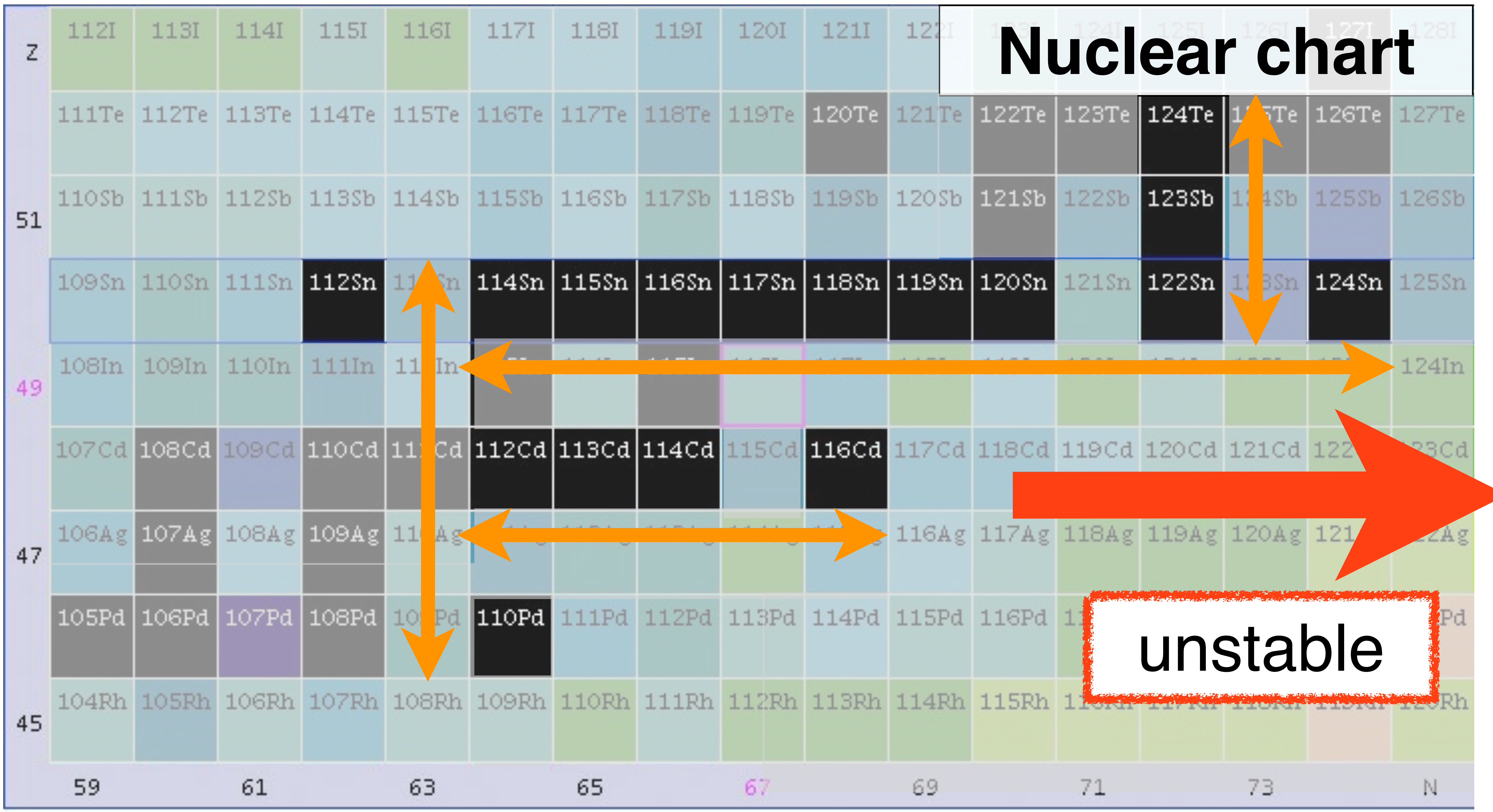
Pionic atom of unstable nuclei

systematic study of stable nuclei



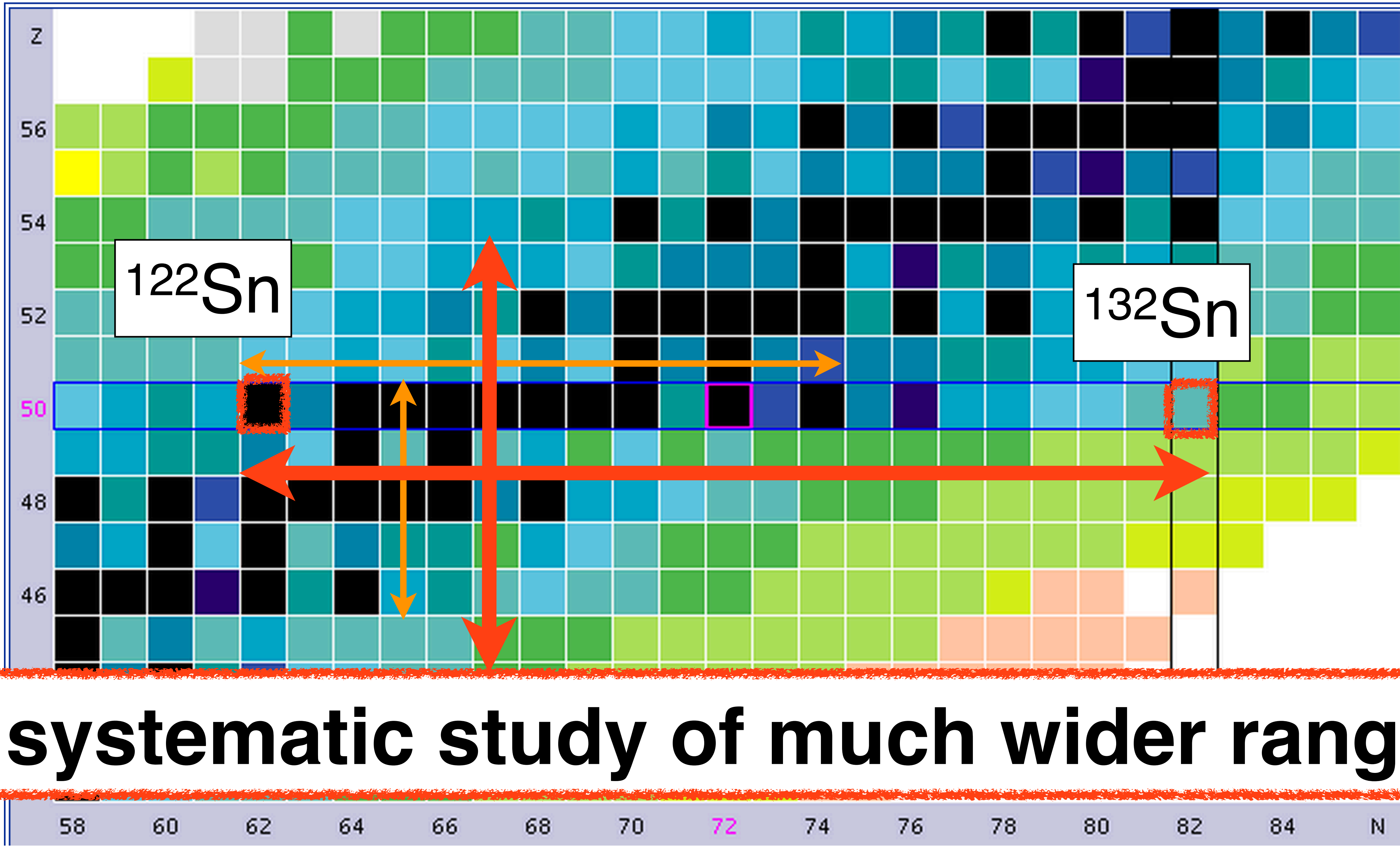
Pionic atom of unstable nuclei

systematic study of stable nuclei



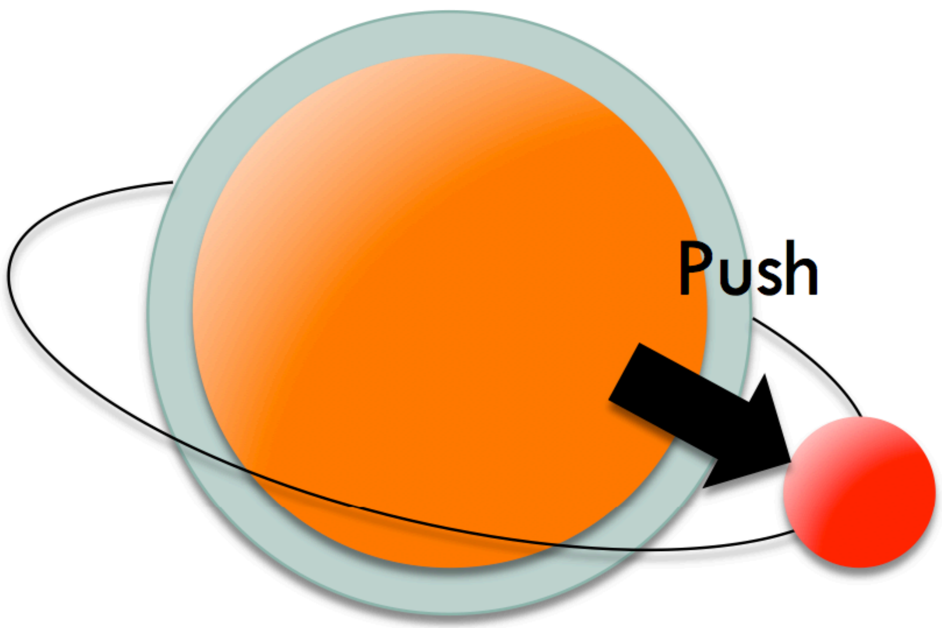
Pionic atom of unstable nuclei

systematic study of unstable nuclei



systematic study of much wider range

Pionic atom of neutron rich nuclei



Pion-Neucleus Interaction

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

Neutron-Pion: Repulsive!

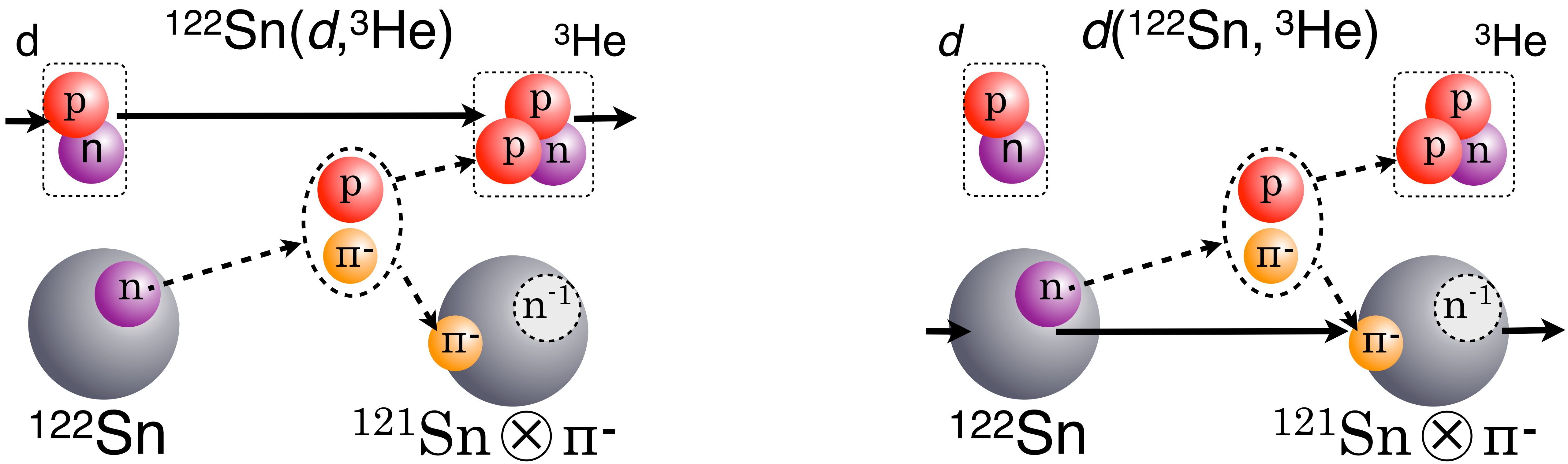
Pion is pushed outward

Different density lower than 0.6 ρ_0 is probed

⬇

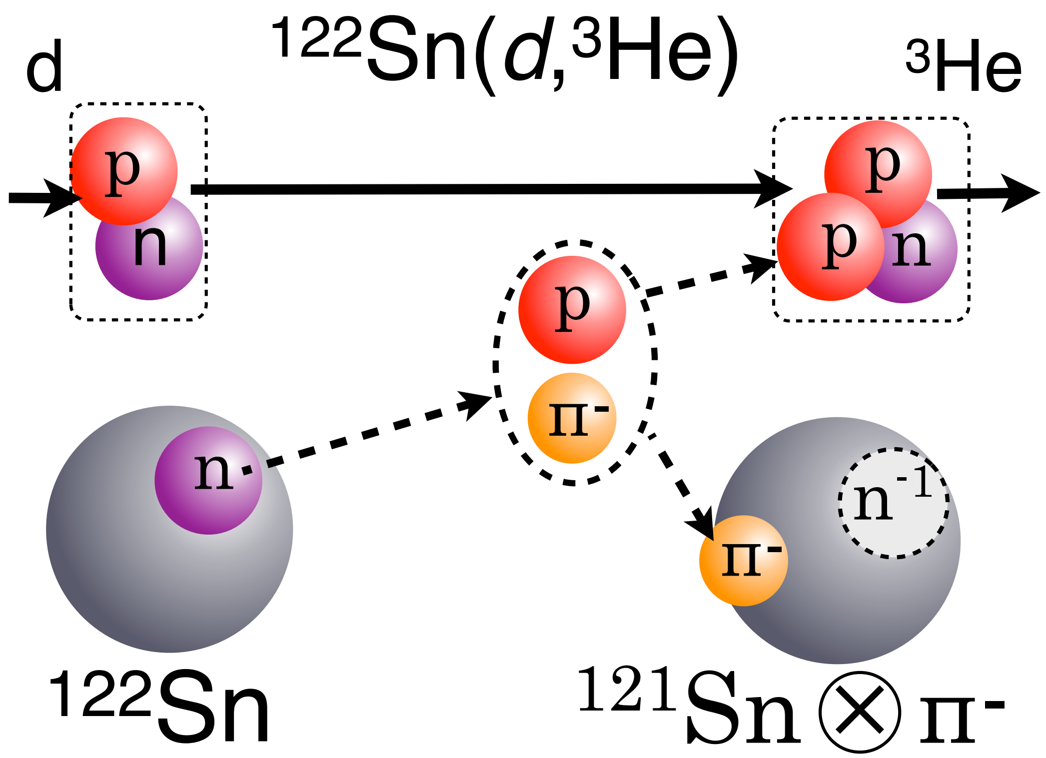
Density dependence of $|\langle\bar{q}q\rangle|$ will be deduced

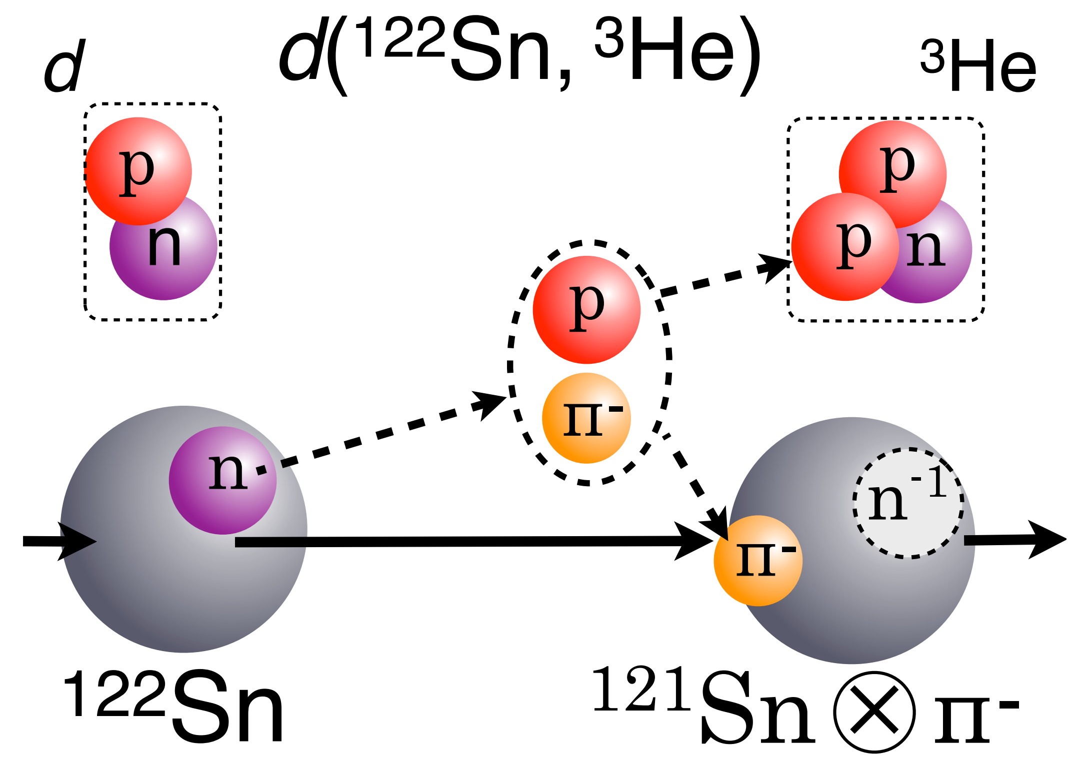
Inverse kinematics of (d,³He) reaction



	normal	inverse
Beam	deuteron	(unstable) nuclei
target	stable nuclei	deuteron
Beam energy	250 MeV/u	250 MeV/u
Detecting particle	^{3}He	^{3}He

Inverse kinematics of (d,^{3}He) reaction





	normal	inverse
Beam	deuteron	(unstable)
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Beam energy	250 MeV/u	250 MeV/u
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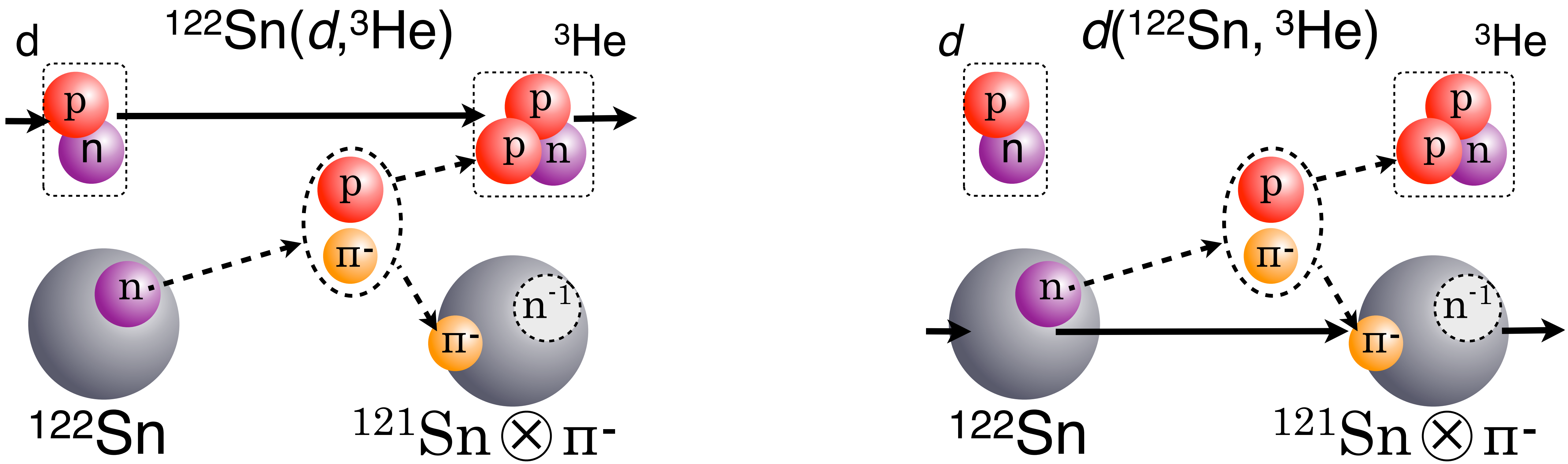
D_2 gas

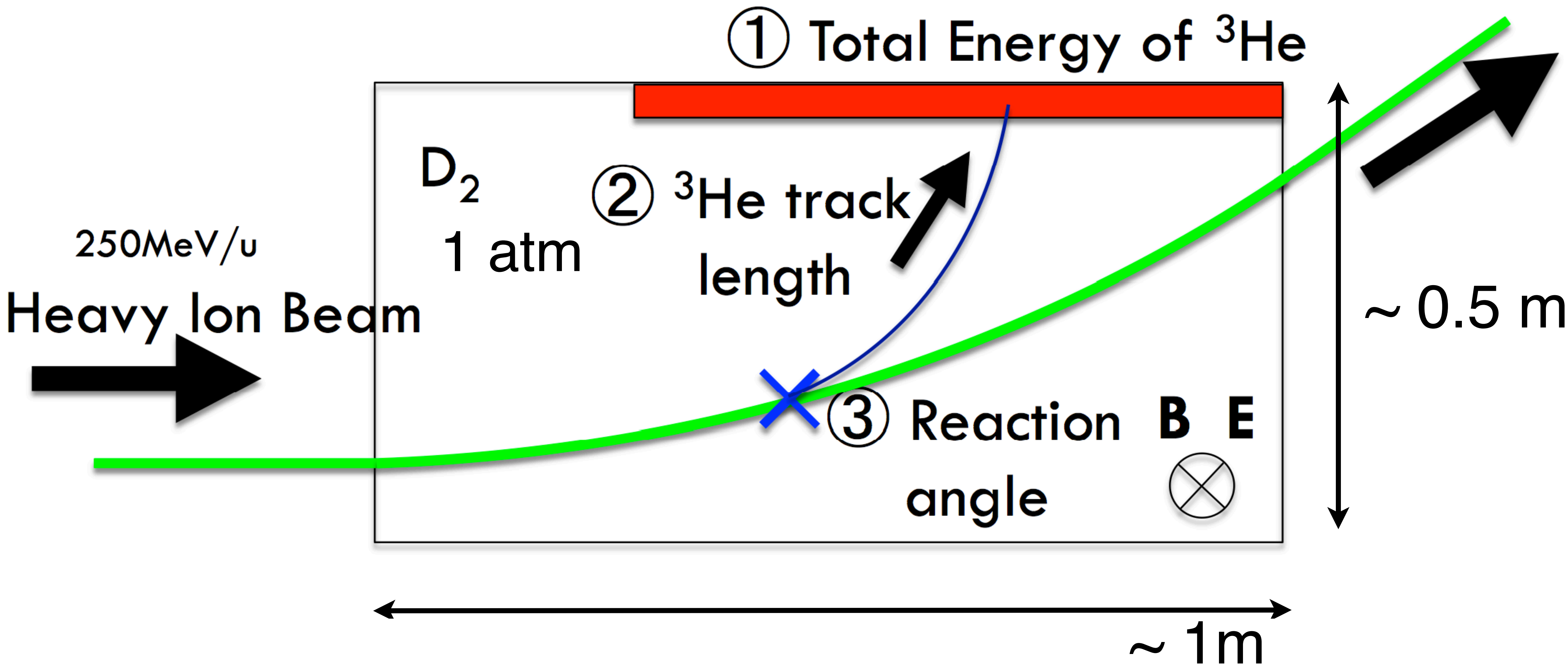
Inverse kinematics of (d,³He) reaction



	normal	inverse
Beam	deuteron	(unstable) D_2 gas
target	stable nuclei	deuteron
Beam energy	~ 365 MeV MeV/u	250 M ~ 60 MeV
Detecting particle	^{3}He	^{3}He

Experimental design for inverse kinematics

Detectors ; Active target TPC & Si detector



① ³He energy is measured at Si
② ΔE deduced from track length
③ θ deduced from track

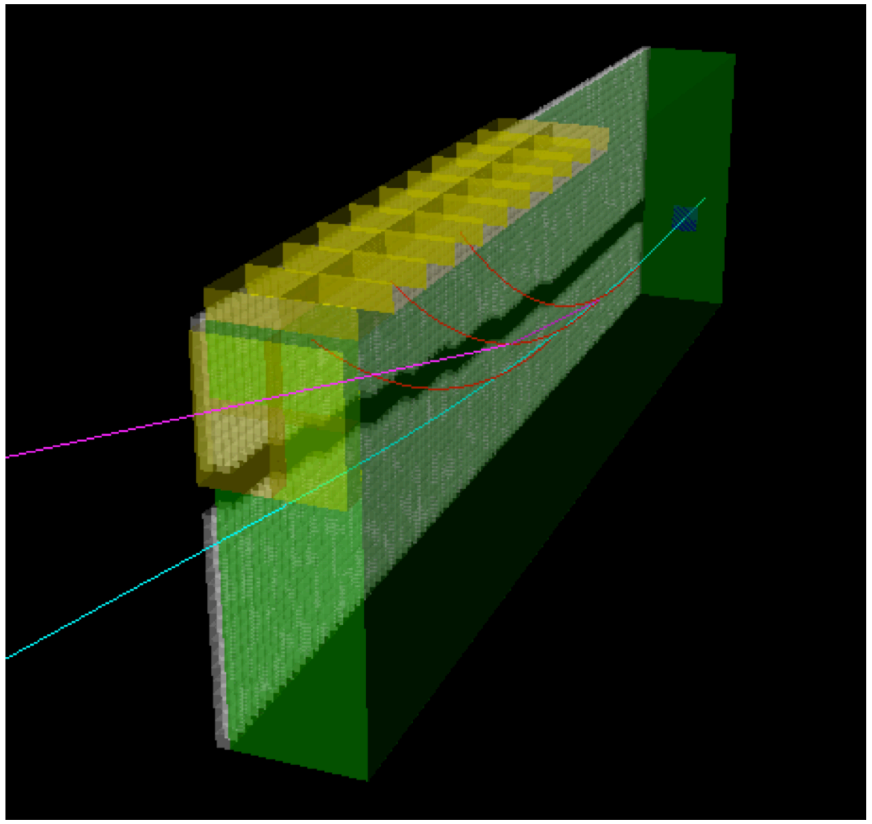
→ p_{3He} at reaction point

Yield and resolution estimation (simulation)

	requirement
yield	10^2 / day (for 1s state)
resolution	ΔQ < 1 MeV (FWHM)

input parameter

intensity	~ 10^6/s (^{124}Sn)
TPC resolution	~ 500 μm
Si resolution	0.1%@60MeV



GEANT4 simulation

Yield and resolution estimation (simulation)

yield

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

Yield and resolution estimation (simulation)

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**

Yield and resolution estimation (simulation)

requirement

yield	10^2 / day (for 1s state)
resolution	$\Delta Q < 1$ MeV (FWHM)

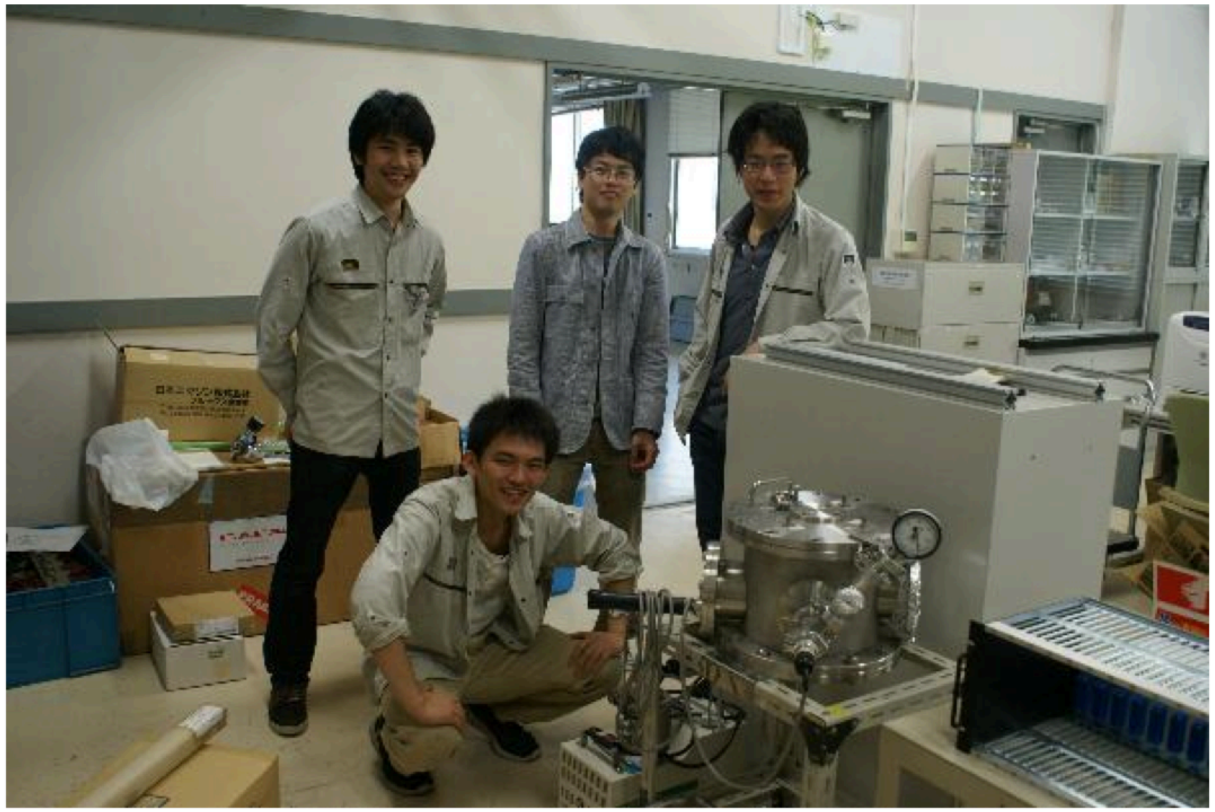
simulation result

yield	1.1×10^2 / day (for 1s state)
resolution	$\Delta Q \sim 500$ keV (FWHM)

This design satisfy the requirement of the experiment

Current status

We are evaluating the resolution of Si detector with α source.



Summary

- Deeply-bound pionic atom is good probe for quark condensate in finite density.
- We are planning the precise / systematic measurement of deeply-bound pionic atom and performed a pilot experiment.
- We succeed to observe the deeply bound pionic states in ^{121}Sn and angler dependence of the (*d*, ^{3}He) reaction cross section for the first time with in 15-hour measurement.
- Now we are finalizing the result of the pilot experiment to extract binding energy and width of deeply bound pionic states.
- We are also preparing for main experiment with ^{122}Sn target.
- Experiment with inverse kinematics enable us to produce unstable pionic atom and to approach the density dependence of quark condensate.
- The feasibility was confirmed by GEANT4 simulation and we are starting the study of detectors.

Deduction of b_1 from experimental data

TABLE I. Observed binding energies (B_{1s}) and widths (Γ_{1s}) of the 1s π^- states in ^{115,119,123}Sn isotopes.

Isotope	B_{1s} (MeV)	ΔB_{1s} (MeV) Stat.	ΔB_{1s} (MeV) Syst.	ΔB_{1s} (MeV) Total	Γ_{1s} (MeV)	$\Delta\Gamma_{1s}$ (MeV) Stat.	$\Delta\Gamma_{1s}$ (MeV) Syst.	$\Delta\Gamma_{1s}$ (MeV) Total
^{115}Sn	3.906	±0.021	±0.012	±0.024	0.441	±0.068	±0.054	±0.087
^{119}Sn	3.820	±0.013	±0.012	±0.018	0.326	±0.047	±0.065	±0.080
^{123}Sn	3.744	±0.013	±0.012	±0.018	0.341	±0.036	±0.063	±0.072

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

π-A s-wave optical potential

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

4 parameters (b_0, b_1, ReB_0, ImB_0) in equation
⇔ 2 parameters from experiment BE_{1s}, Γ_{1s}

Physics motivation; quark condensate

Measurement of quark condensate in finite density

Gell-Mann-Oakes-Renner relation

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

$$f_\pi^2 m_{\pi^\pm}^2 = -m_q \langle \bar{q}q \rangle + O(m_q^2)$$

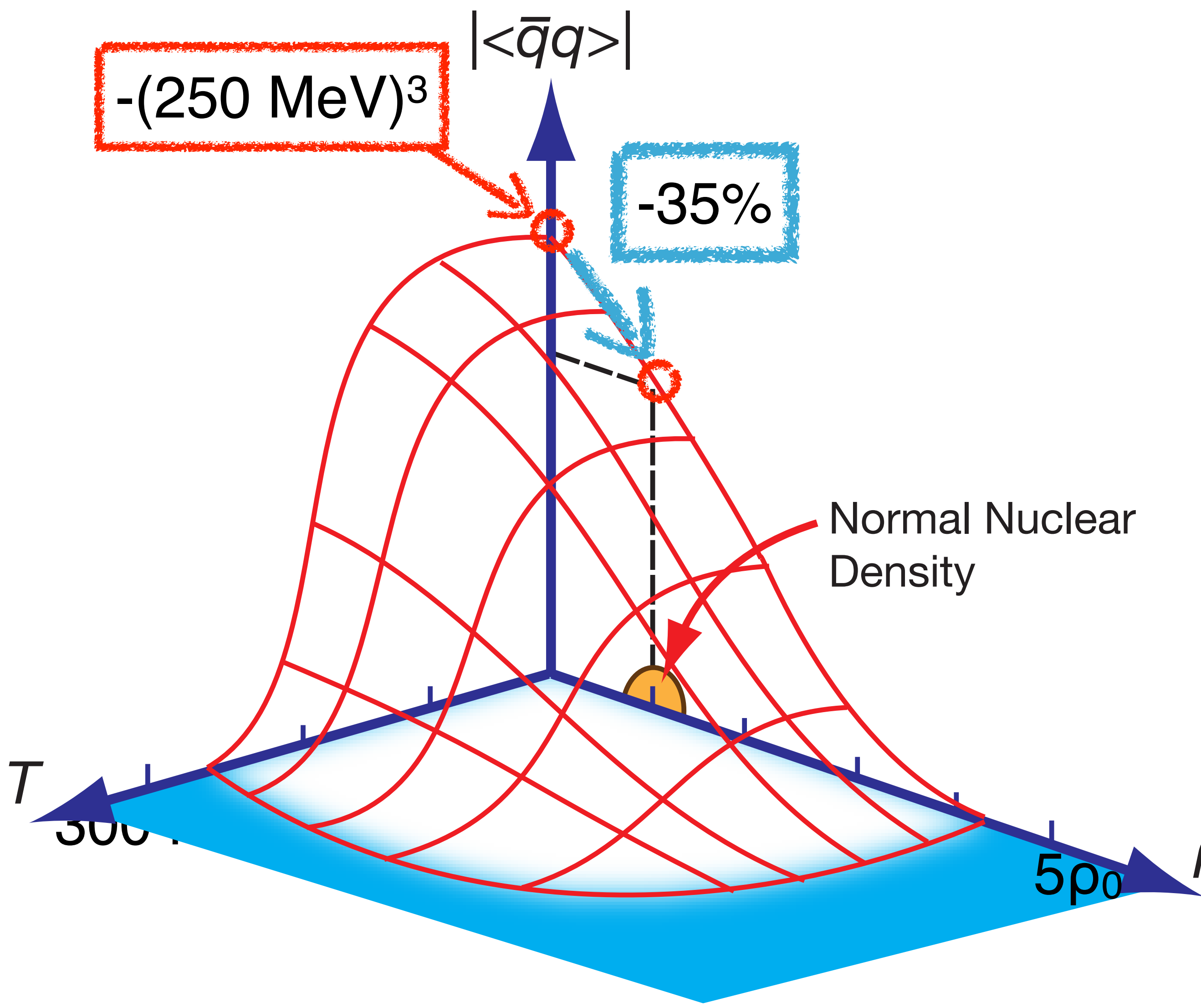
f_π: pion decay constant

Tomozawa-Weinberg relation

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

$$b_1 \simeq \frac{1}{4(1 + m_\pi / M_{Nucleon})} \frac{m_\pi}{2\pi f_\pi^2}$$

b_1: isovector scattering length



W. Weise, NPA553(93)59.

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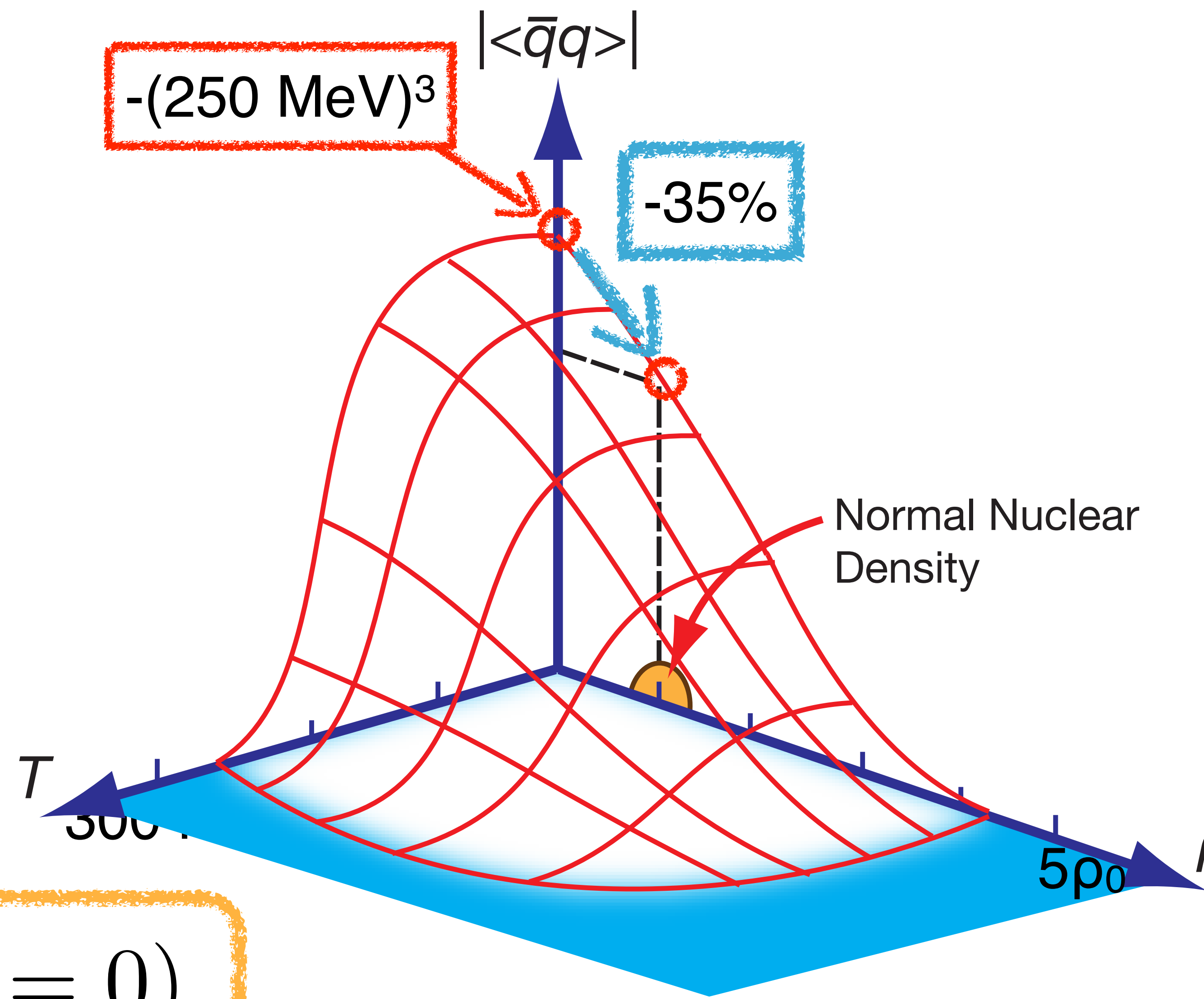
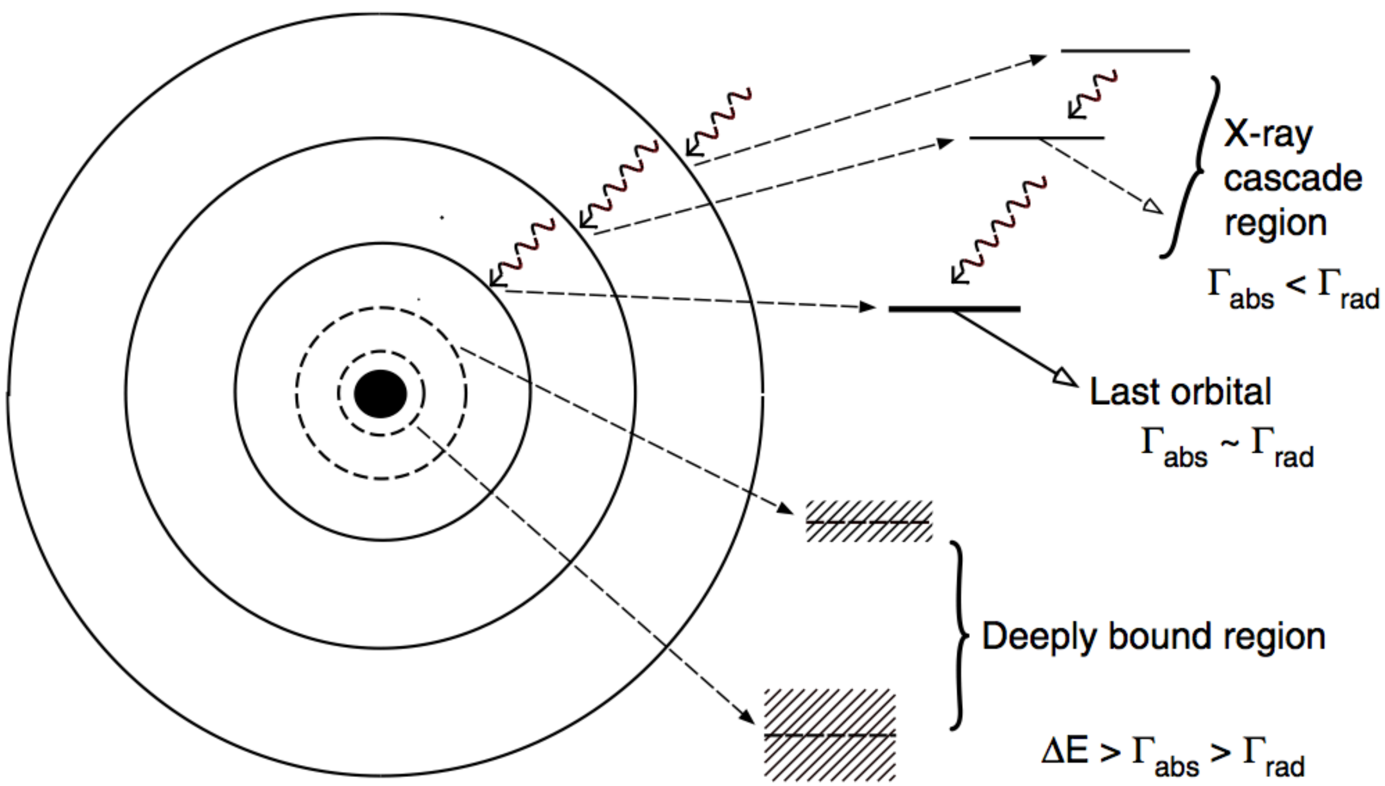


W. Weise, NPA553(93)59.

$$\frac{\langle \bar{q}q \rangle_{\rho=\rho_0}}{\langle \bar{q}q \rangle_{\rho=0}} \simeq \left(\frac{m_\pi^*}{m_\pi}\right)^2 \frac{\mathrm{b}_1(\rho=0)}{\mathrm{b}_1(\rho=\rho_0)}$$

Conventional method; use π^- beam

slow pion beam is captured in target nuclei and cascade emitting X-ray



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

pionic 1s state in H
→ b_1 in vacuum

This method is applied only for
- higher orbits
- light nuclei (~ ^{24}Mg for 1s)

This method cannot produce "deeply-bound" pionic atom…