BigRIPS as a high resolution spectrometer for pionic atoms

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for Pionic Atom Factory Project

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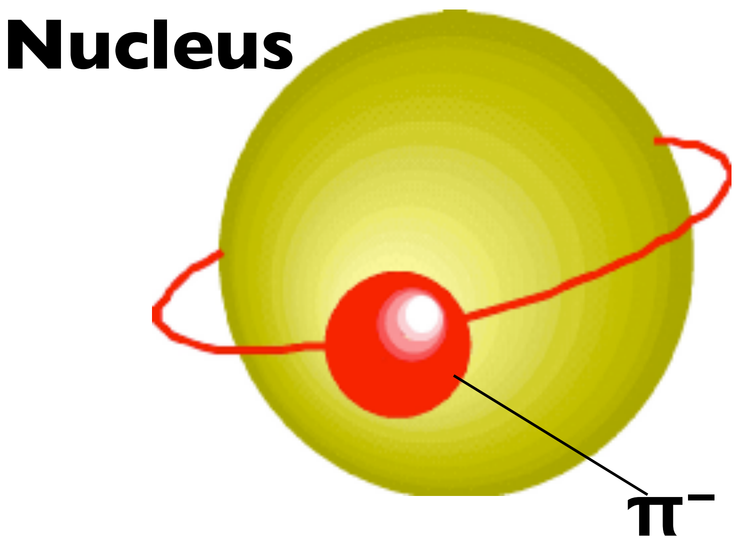
Univ. of Tokyo, Univ. of Notre Dame[A], RIKEN[B], Kyoto Univ.[C], GSI[D],Osaka Univ.[E], Michigan State Univ.[F] , SMI[G], Tohoku Univ. [H]

deeply-bound Pionic Atom



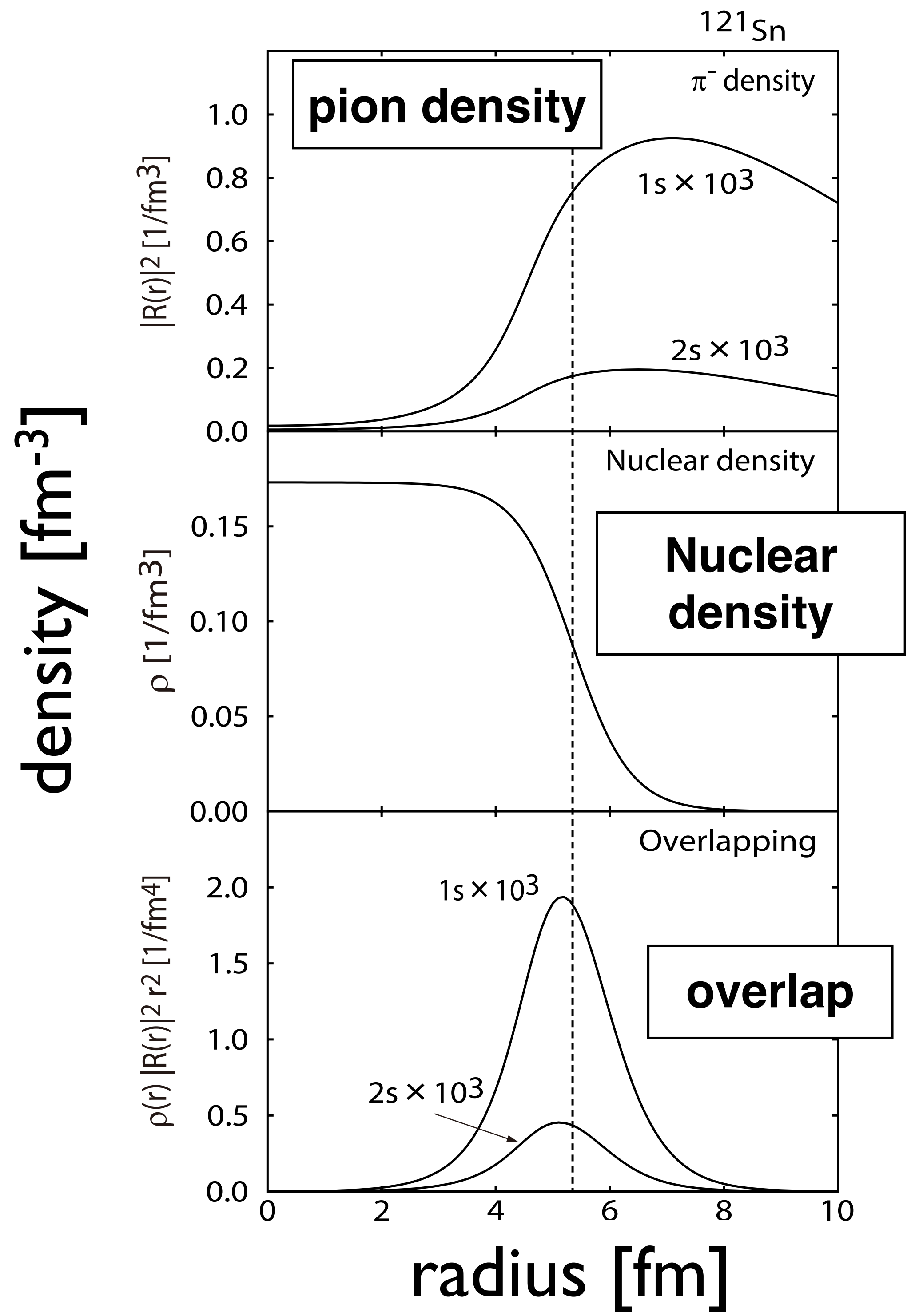
Coulomb

\+

Strong

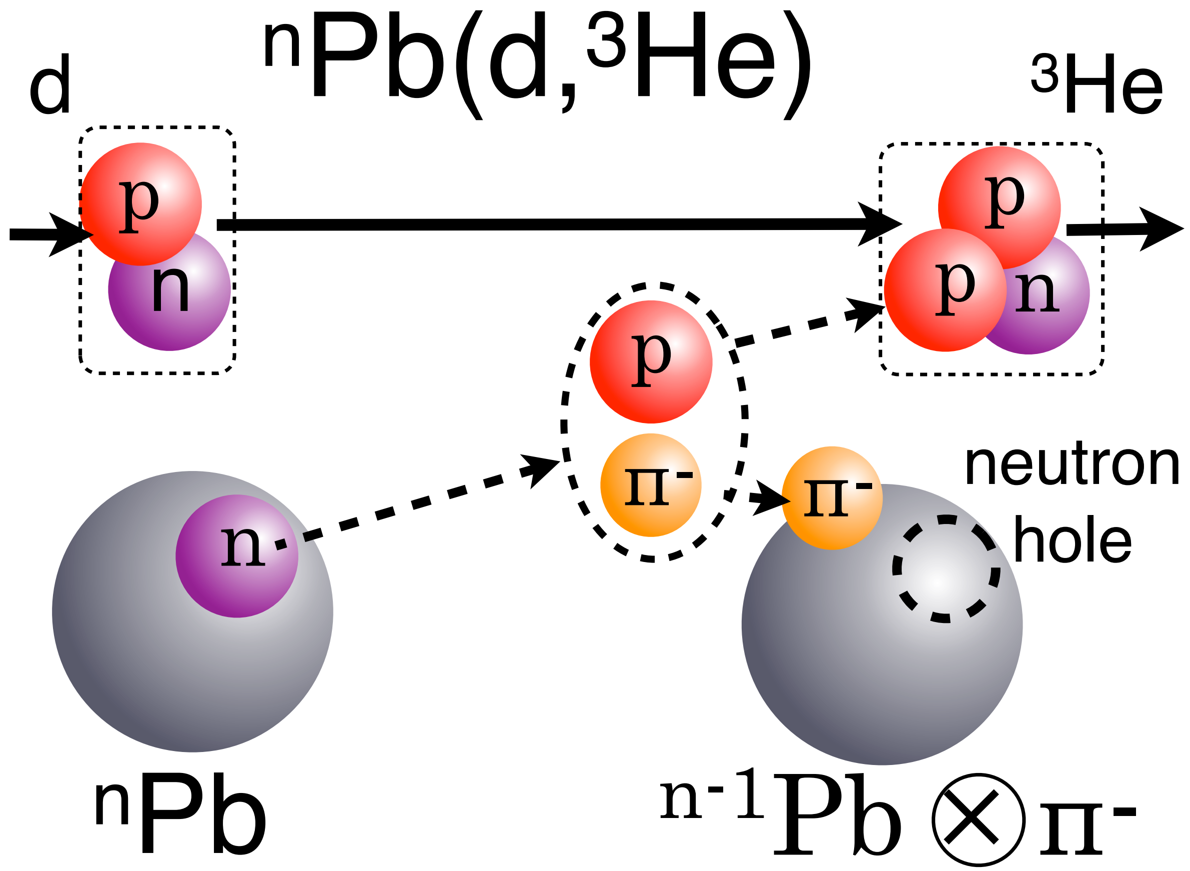
Large overlap between pion and nucleus

→ probe for QCD in finite density



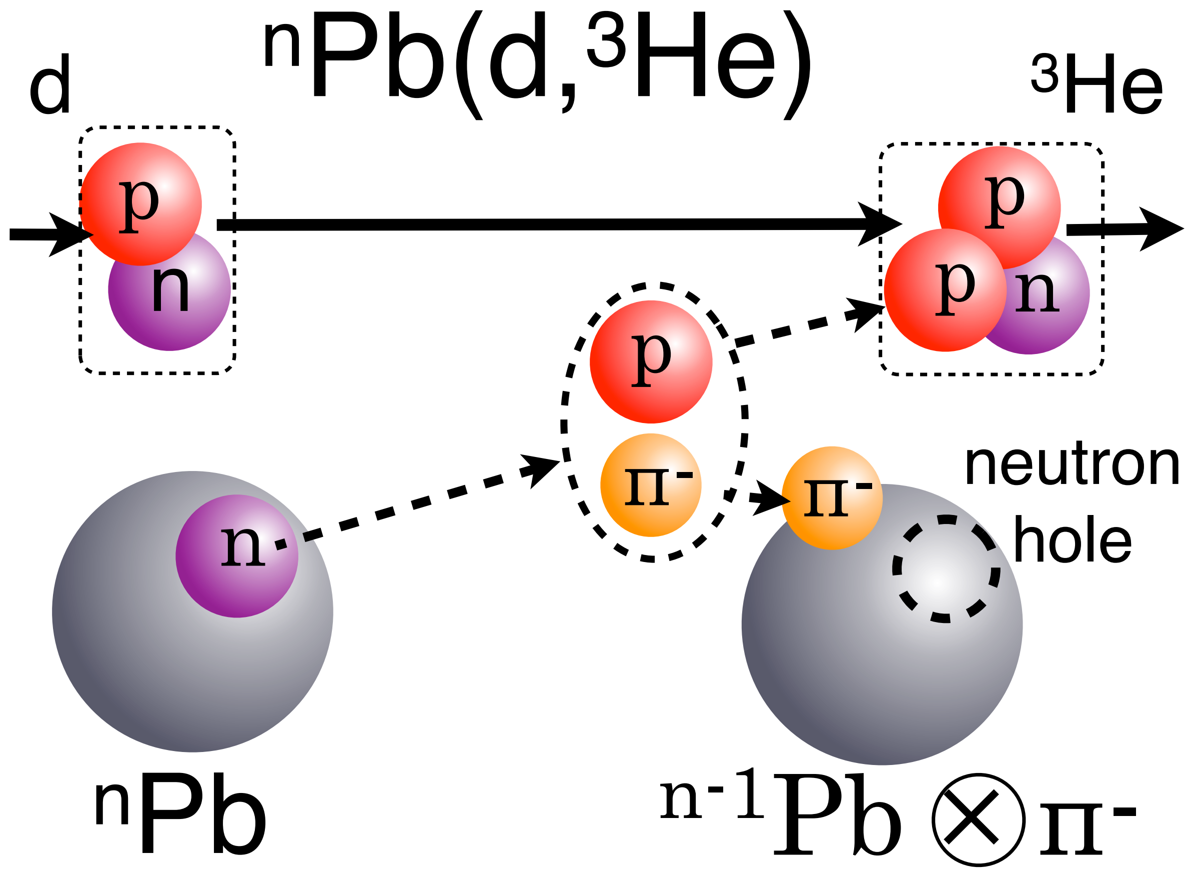
N. Ikeno *et al.*, PTP126(2011)483.

(d,³He) reaction



Missing mass spectroscopy

(d,^{3}He) reaction

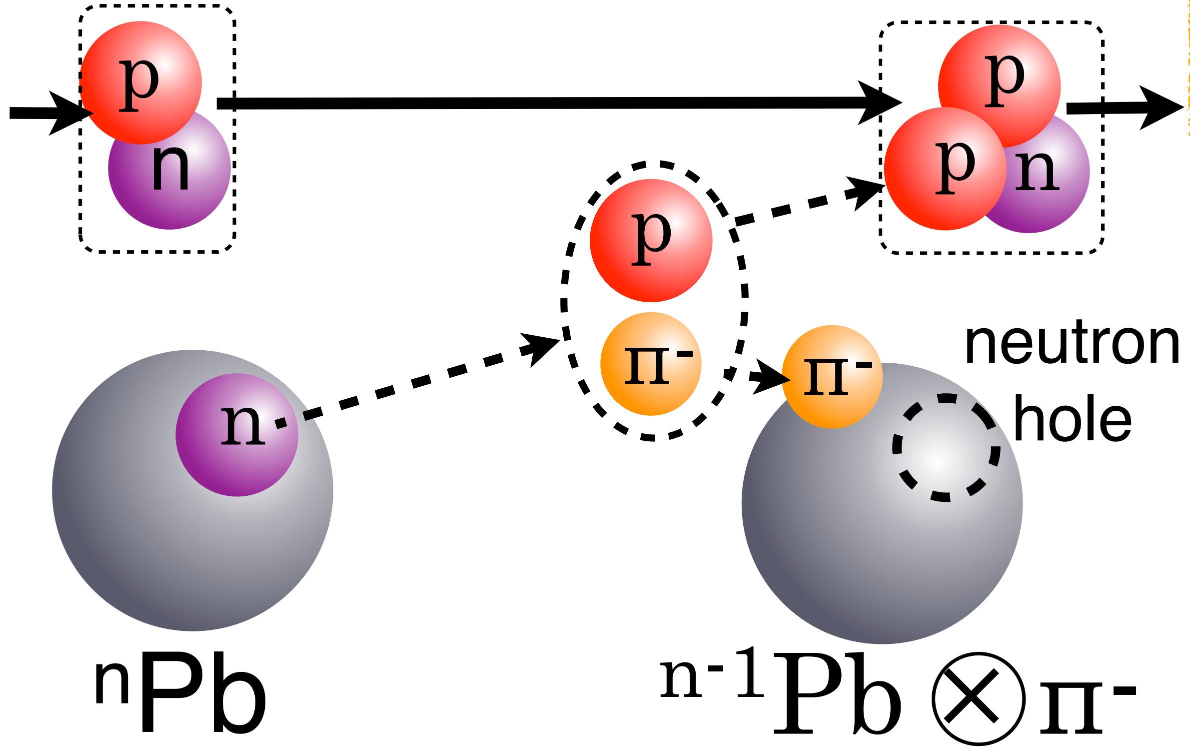


2 body kinematics
→mass of the pionic atom
can be calculated from Q-value

Calculated from E_d, E_{3He}

Missing mass spectroscopy

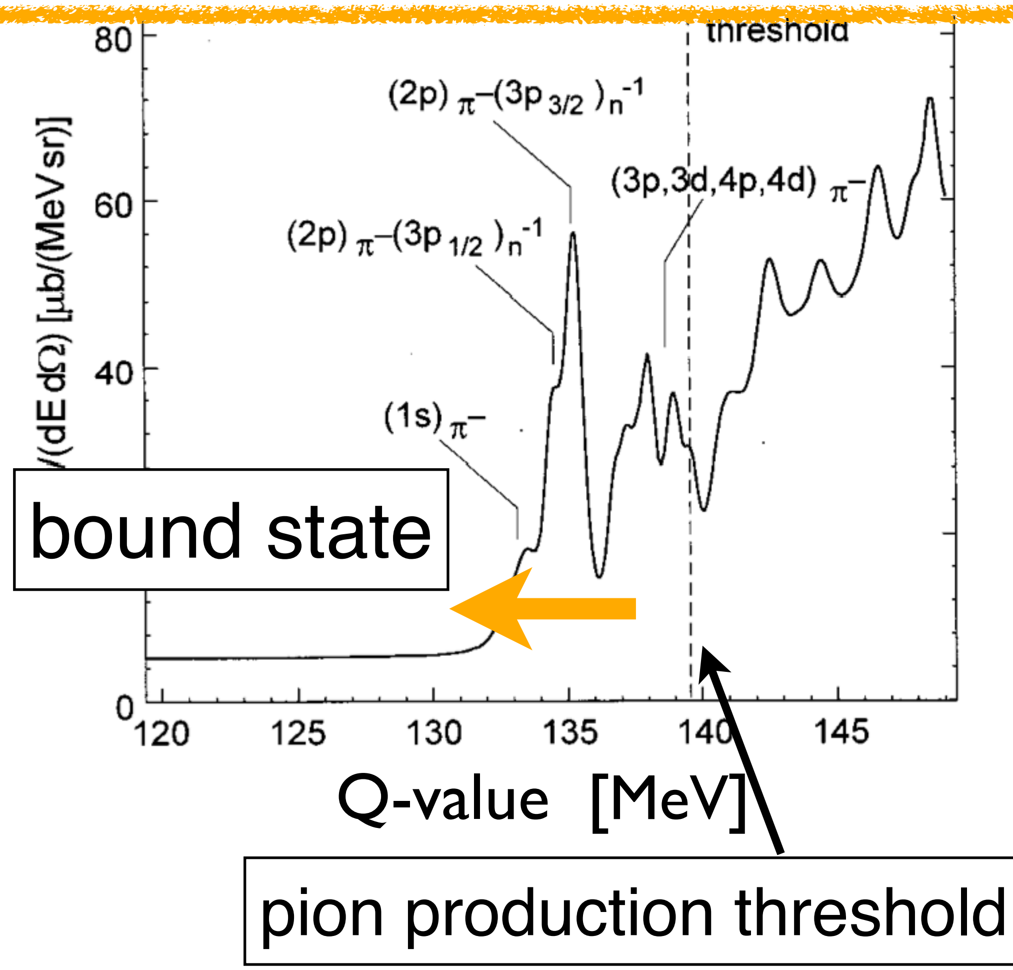
(d,³He) reaction



Missing mass spectroscopy

Theoretical spectrum pionic Pb[207]

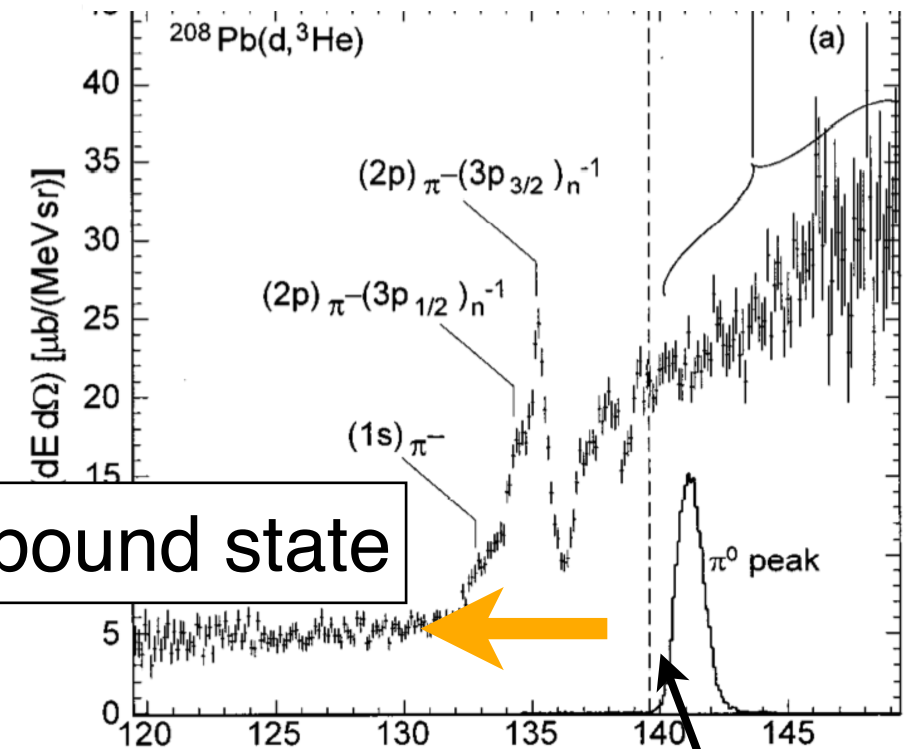
couple of pion and neutron hole state



S. Hirenzaki, H. Toki, T. Yamazaki, Phys. Rev. C44 (1991) 2472

(d,³He) reaction

experimental spectrum
for pionic Pb^{207}@GSI



bound state

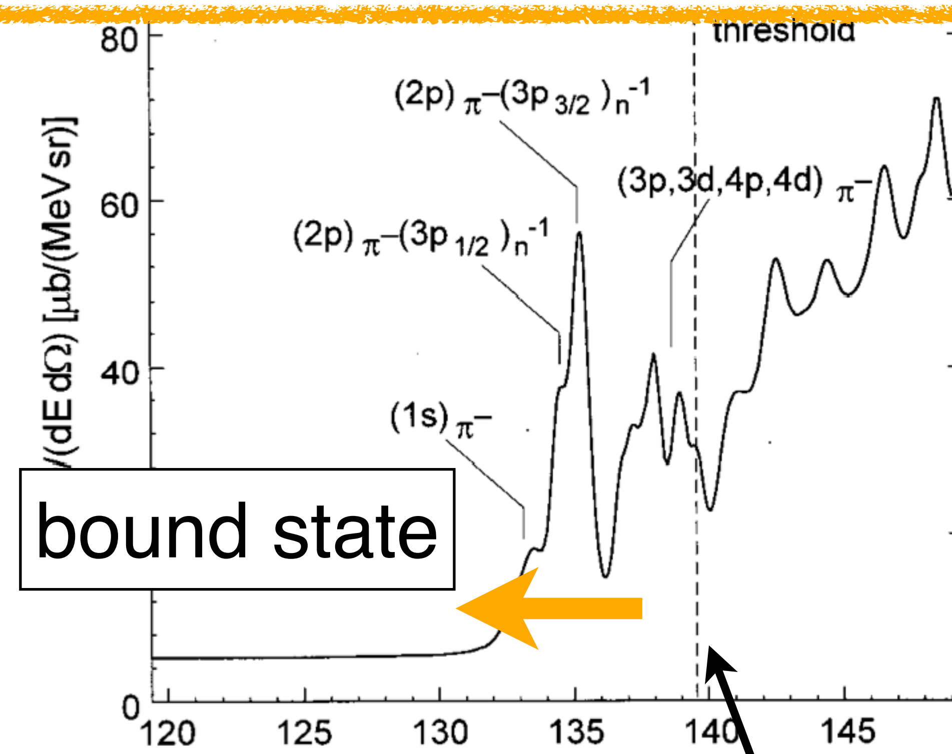
Q-value [MeV]

pion production threshold

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

Theoretical spectrum pionic Pb^{207}

couple of pion and neutron hole state



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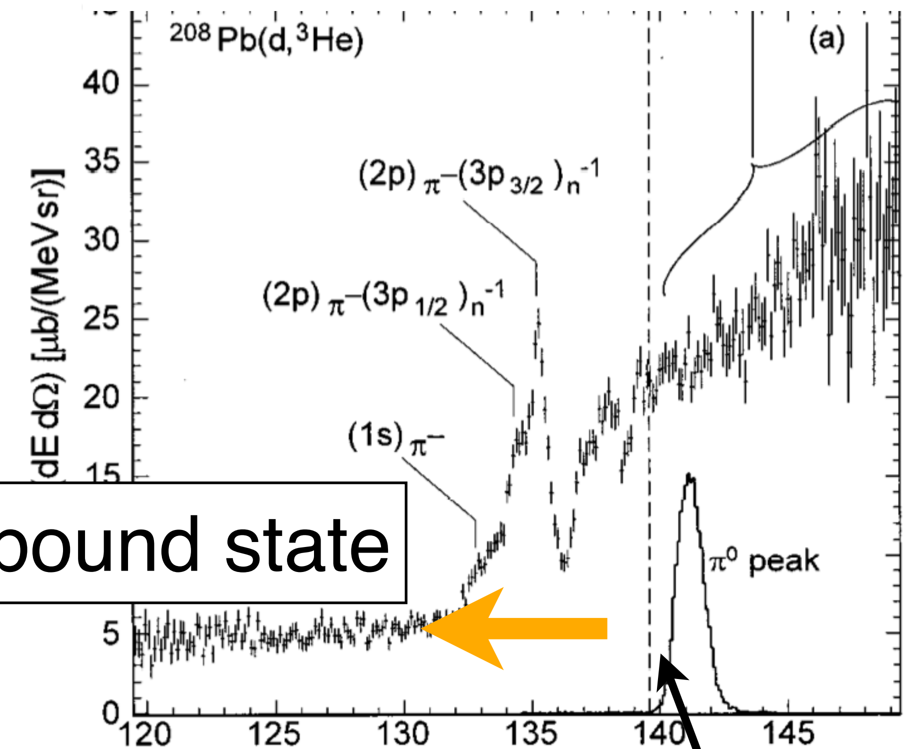


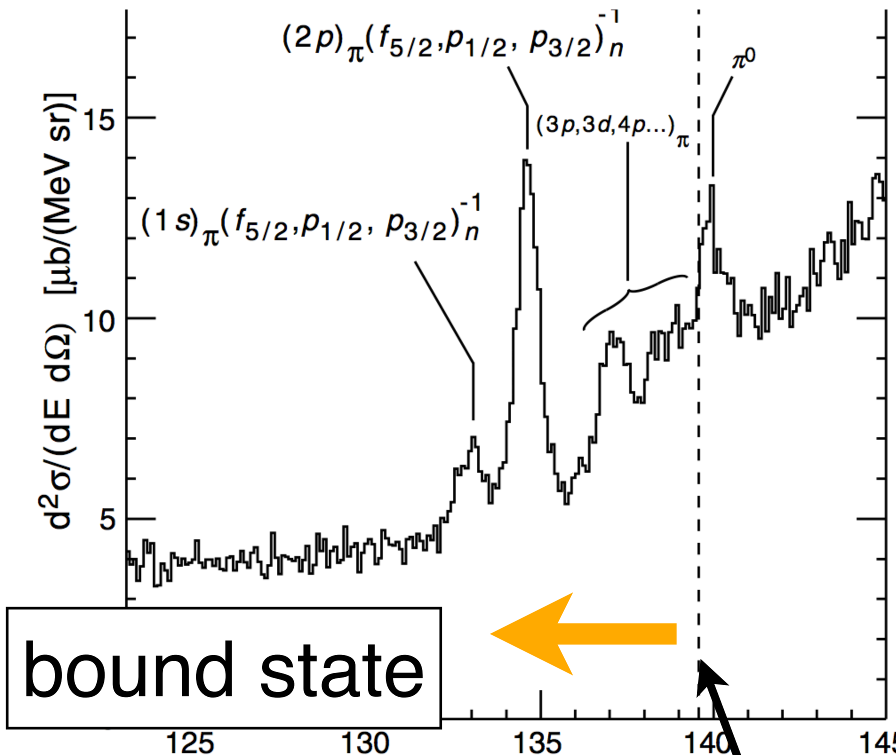
bound state

Q-value [MeV]

pion production threshold

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

experimental spectrum
for pionic Pb205@GSI



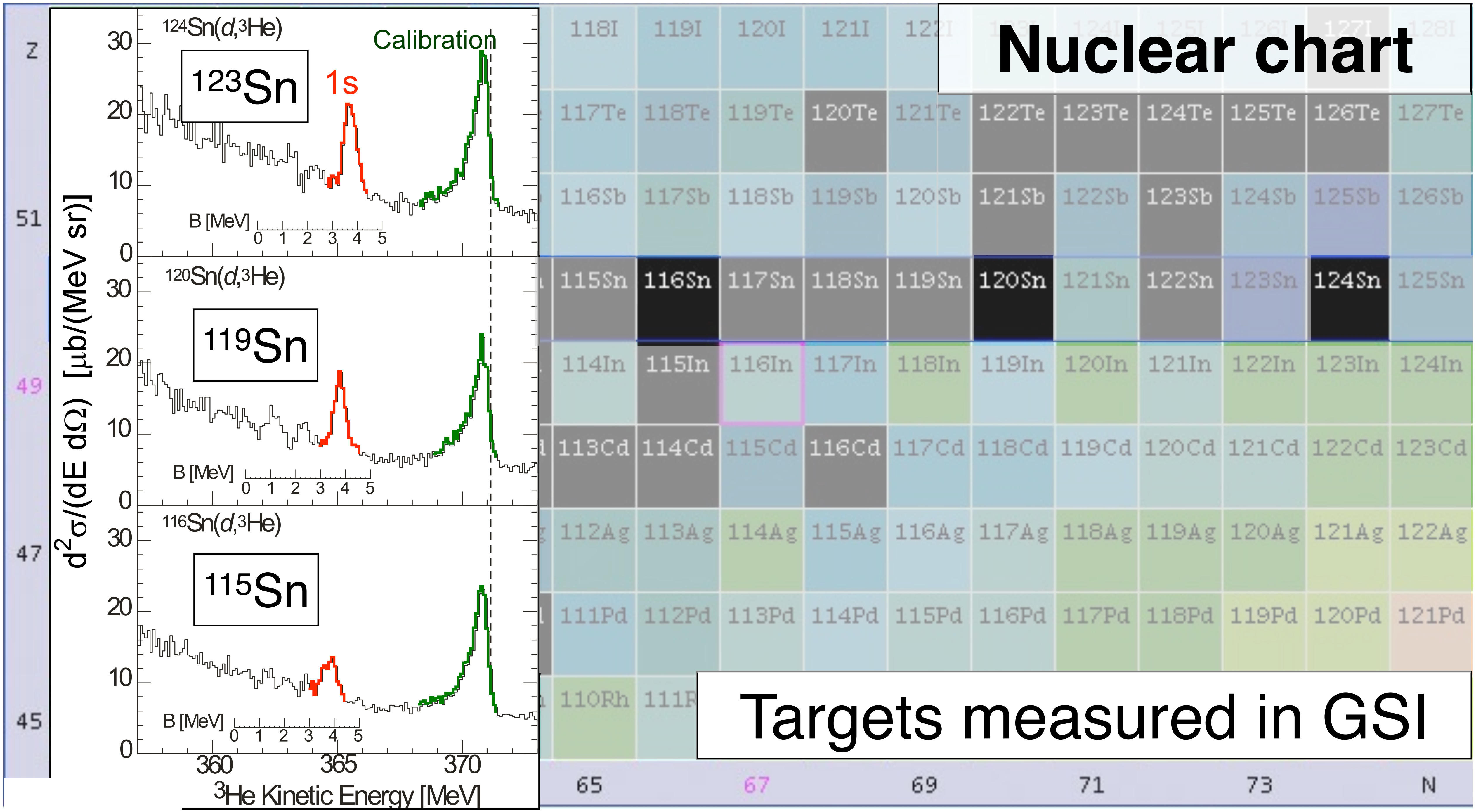
bound state

Q-value [MeV]

pion production threshold

S. Hirenzaki, H. Toki, T. Yamazaki,
Phys. Rev. C44 (1991) 2472

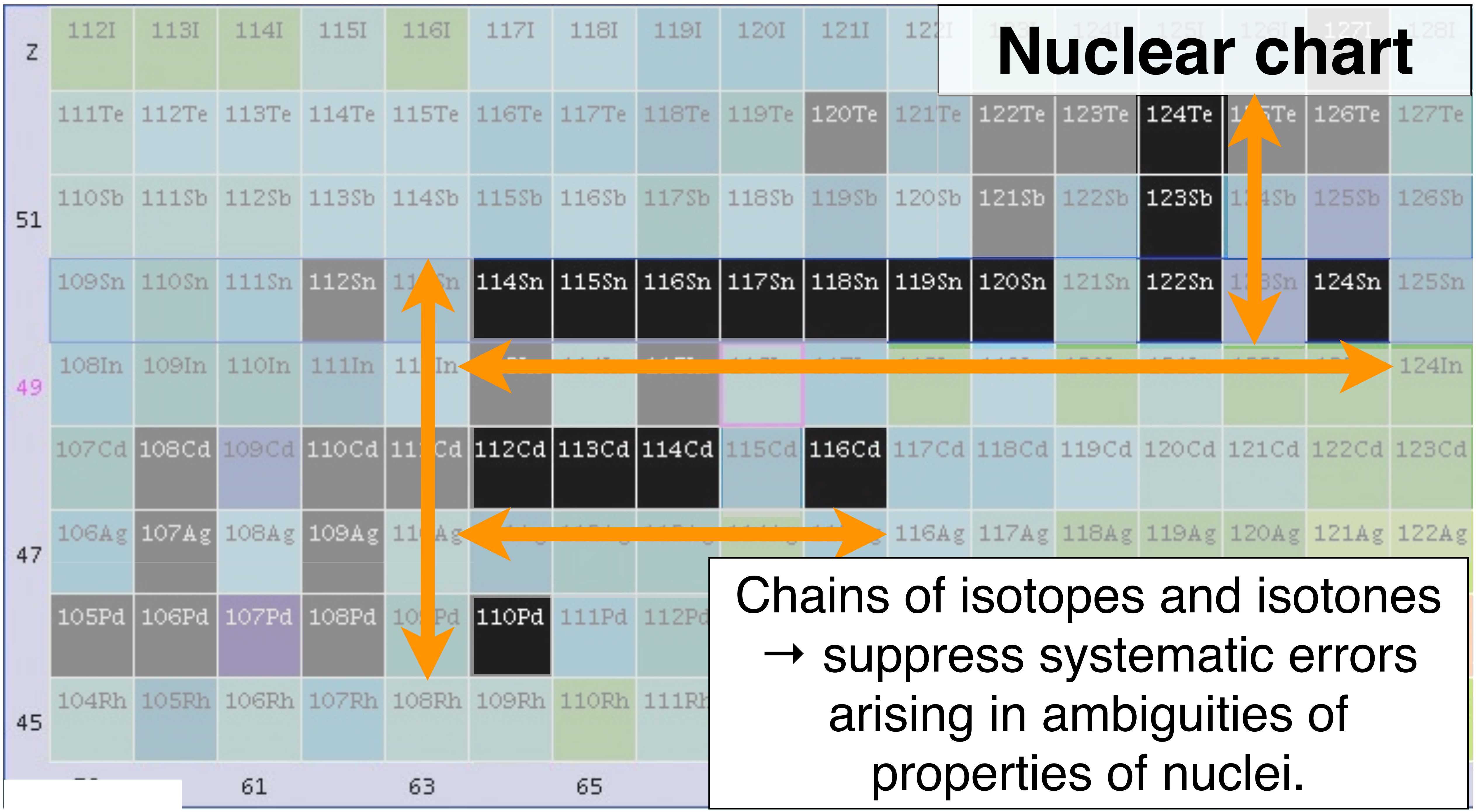
The experiment at GSI



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

NNDC,BNL

Spectroscopy of Pionic Atom at RIBF



NNDC,BNL

Comparison with GSI

	GSI	RIBF	
intensity	~10^{11}/spill	~10^{12}/s	×50
Target	20 mg/cm^2	10 mg/cm^2	×0.5
angular acceptance	~10 mrad	40 / 60 mrad	×20
Δp_d / p_d (FWHM)	0.03%	0.1%	×3
resolution (FWHM)	400 keV	~ 850 keV	

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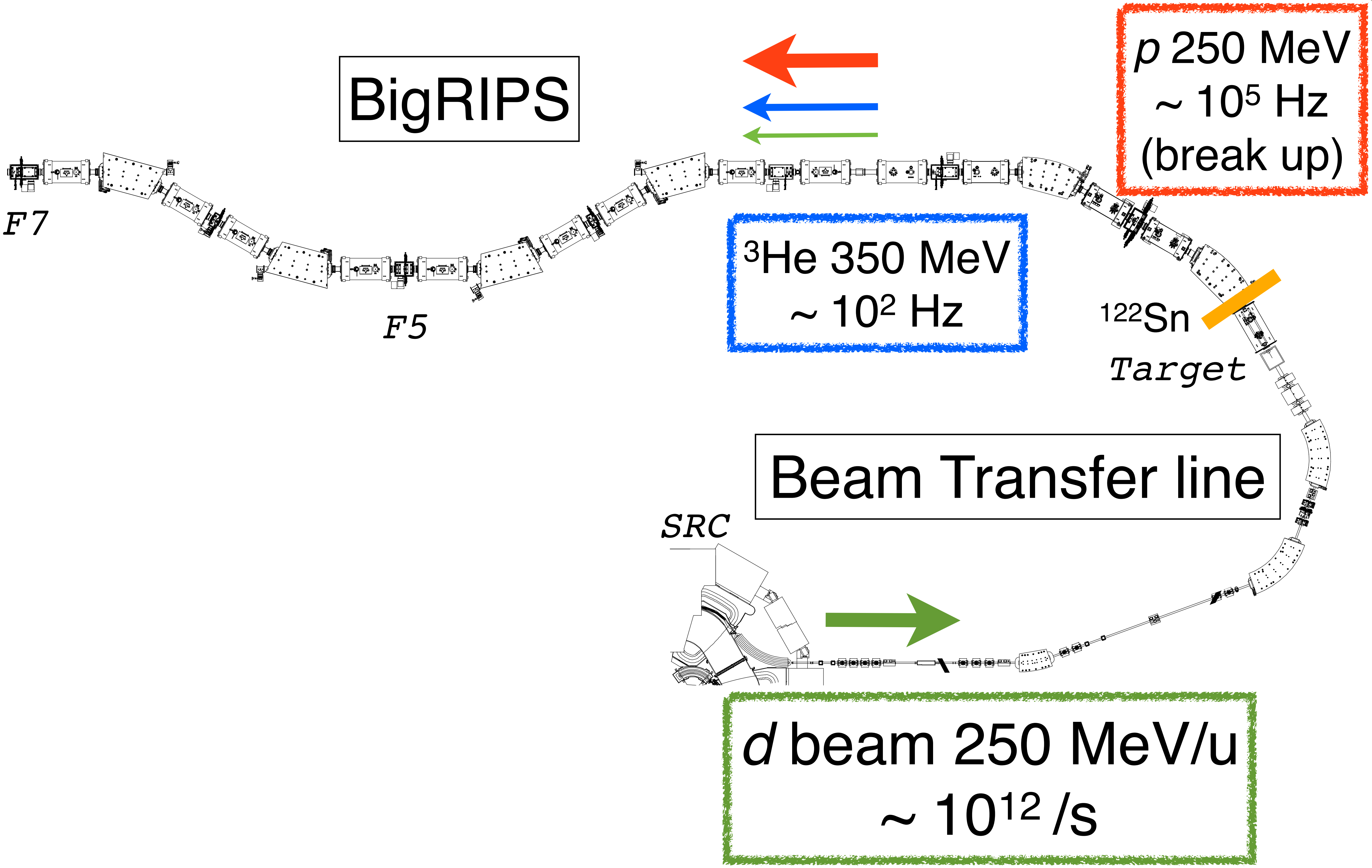
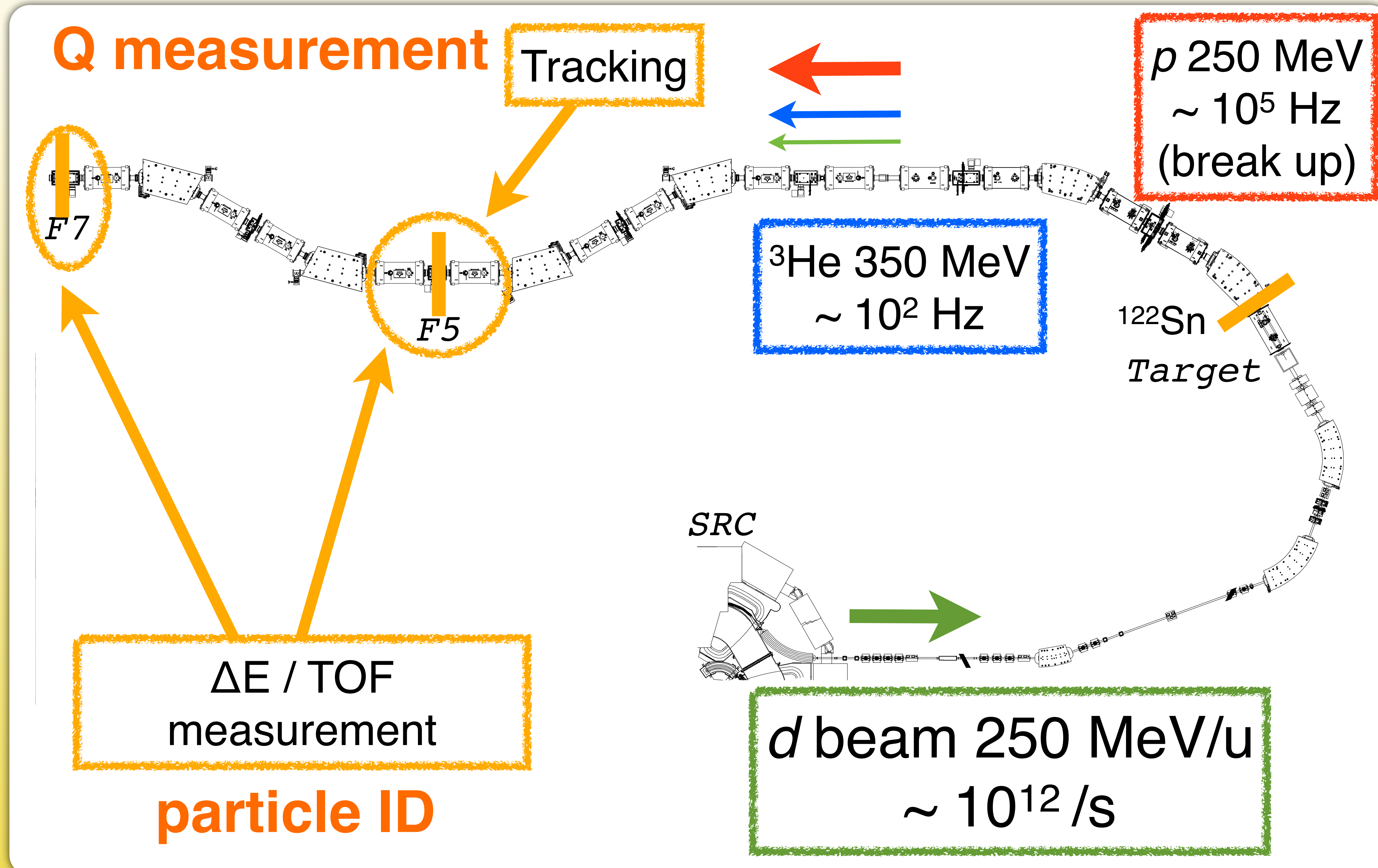
Δp_d / p_d (FWHM)	0.03%	0.1%	**×3**
resolution (FWHM)	400 keV	**200~300 keV**	factor 1.3 ~ 2

eliminate the effect of Δp_d / p_d
using dispersion matching

Experimental Setup



Experimental Setup



Dispersion Matching

Eliminate contribution of beam momentum spread to the resolution

Spectrometer (BigRIPS)	reaction	Analyzer (Beam Transfer Line)

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

*C: kinematical factor = 1.31

$$\begin{aligned} x_{fp} = & (S_{11}A_{11} + S_{12}A_{21})x_0 \\ & + (S_{11}A_{12} + S_{12}A_{22})\theta_0 \\ & + (S_{11}A_{16} + S_{12}A_{26} + CS_{16})\delta p_0 \end{aligned}$$

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→0 by focusing

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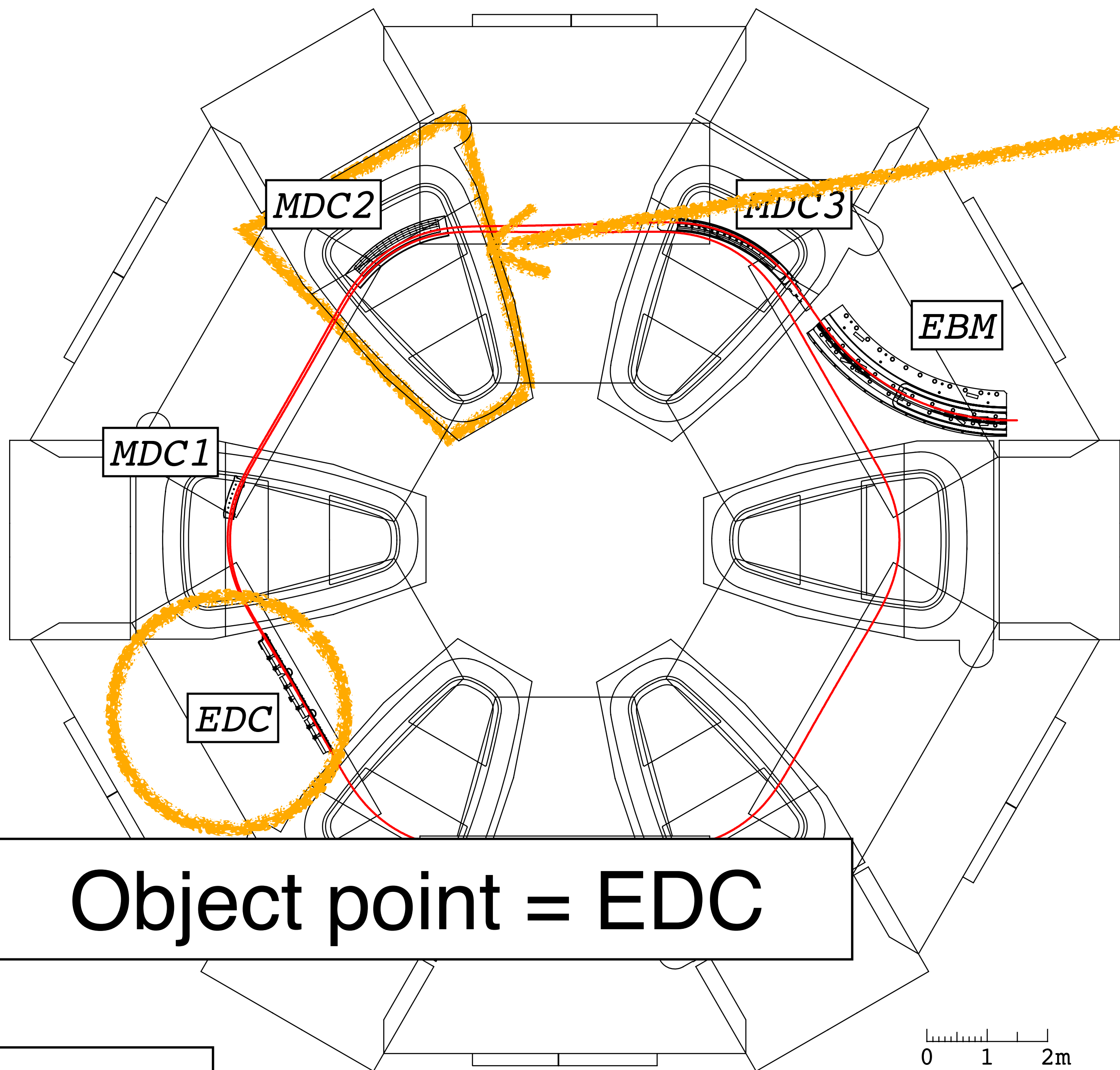
→0 by focusing

$$A_{16} = -CS_{16}/S_{11}$$

matching condition realized by adjusting A_{16} = dispersion of Analyzer

Ion Optics

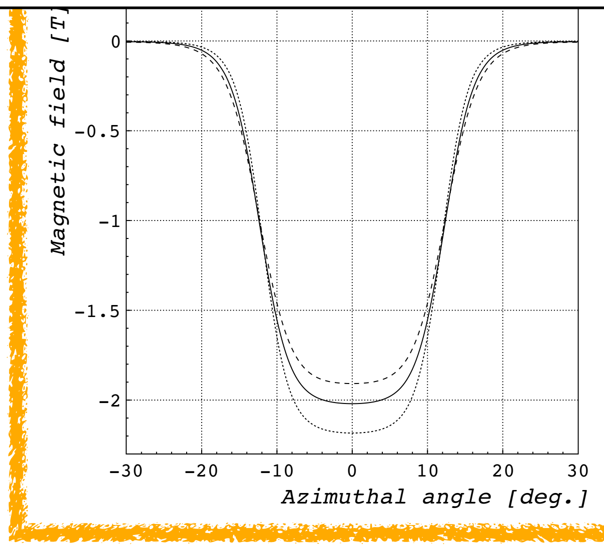
Dispersion matching using primary beam



Object point = EDC

SRC

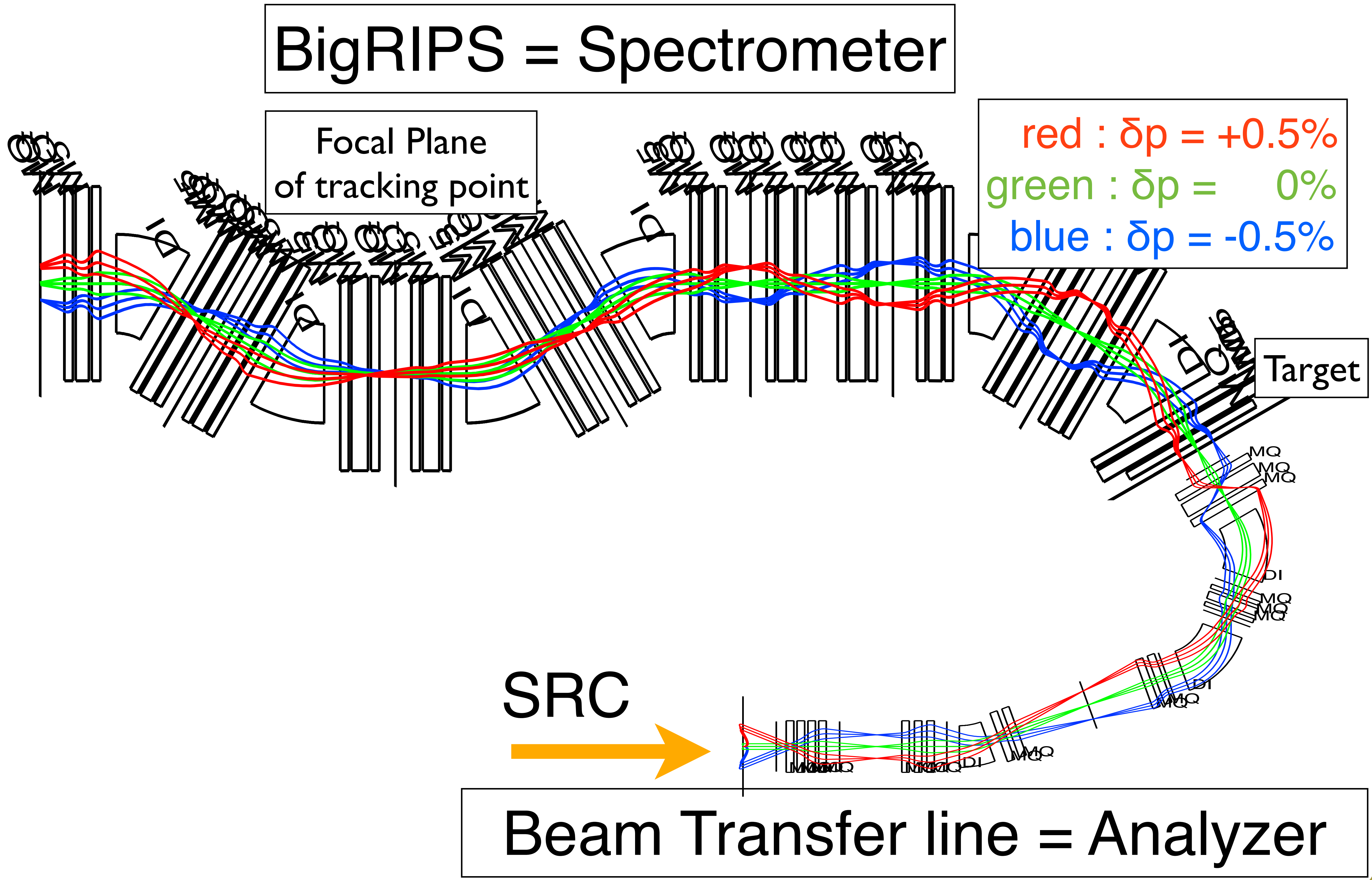
magnetic field in the magnet



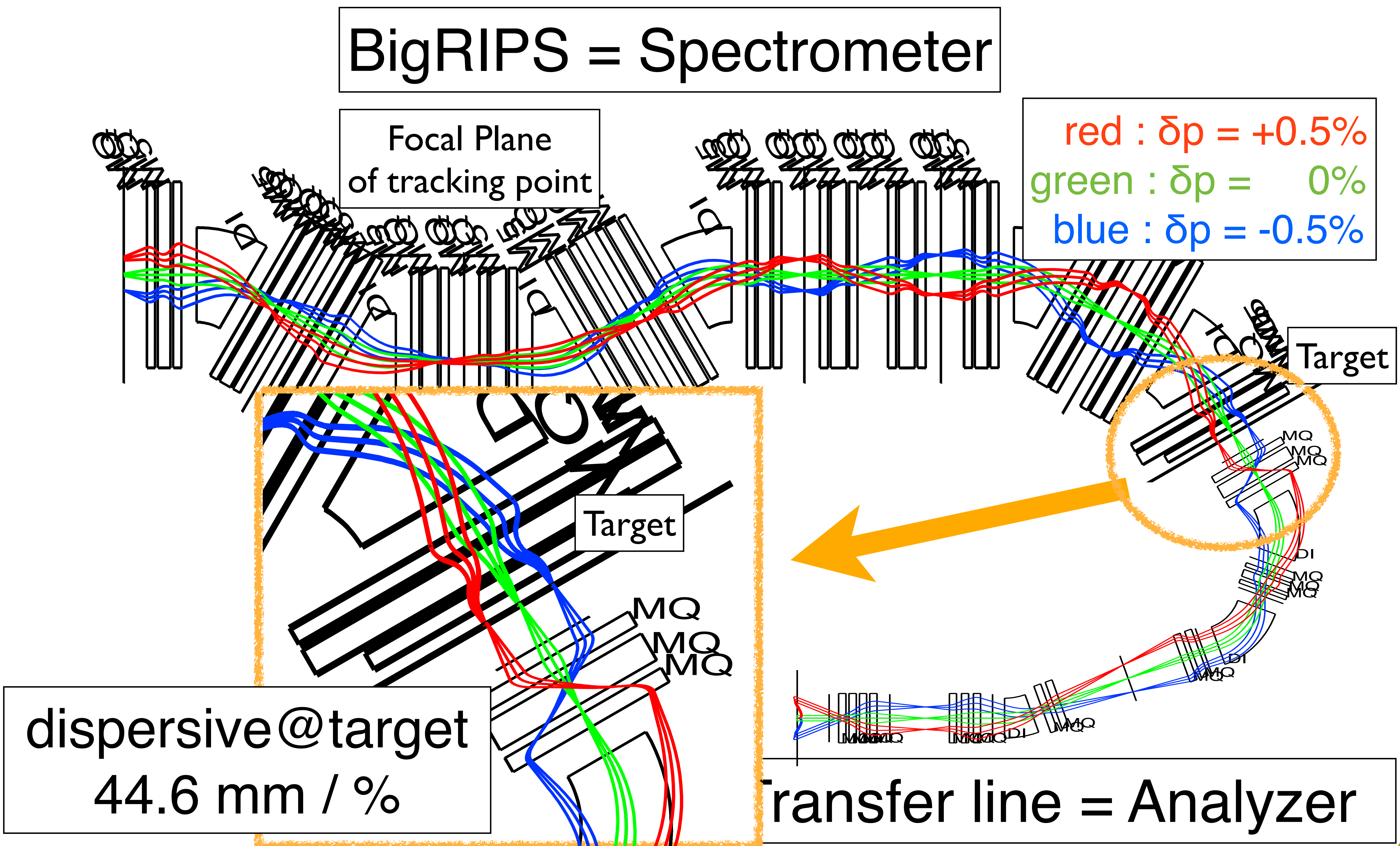
calculate the transfer matrix using Runge-Kutta method

$$\begin{pmatrix} (x|x) & (x|a) & (x|y) & (x|b) & (x|\delta) \\ (a|x) & (a|a) & (a|y) & (a|b) & (a|\delta) \\ (y|x) & (y|a) & (y|y) & (y|b) & (y|\delta) \\ (b|x) & (b|a) & (b|y) & (b|b) & (b|\delta) \end{pmatrix}_{\mathrm{EDC}\to\mathrm{EBM}} = \begin{pmatrix} -1.00 & -3.35 & 0.0 & 0.0 & 76.9 \\ 0.30 & -0.01 & 0.0 & 0.0 & -25.4 \\ 0.0 & 0.0 & -1.03 & -1.75 & 0.0 \\ 0.0 & 0.0 & -0.09 & -1.12 & 0.0 \end{pmatrix}$$

Ion Optics

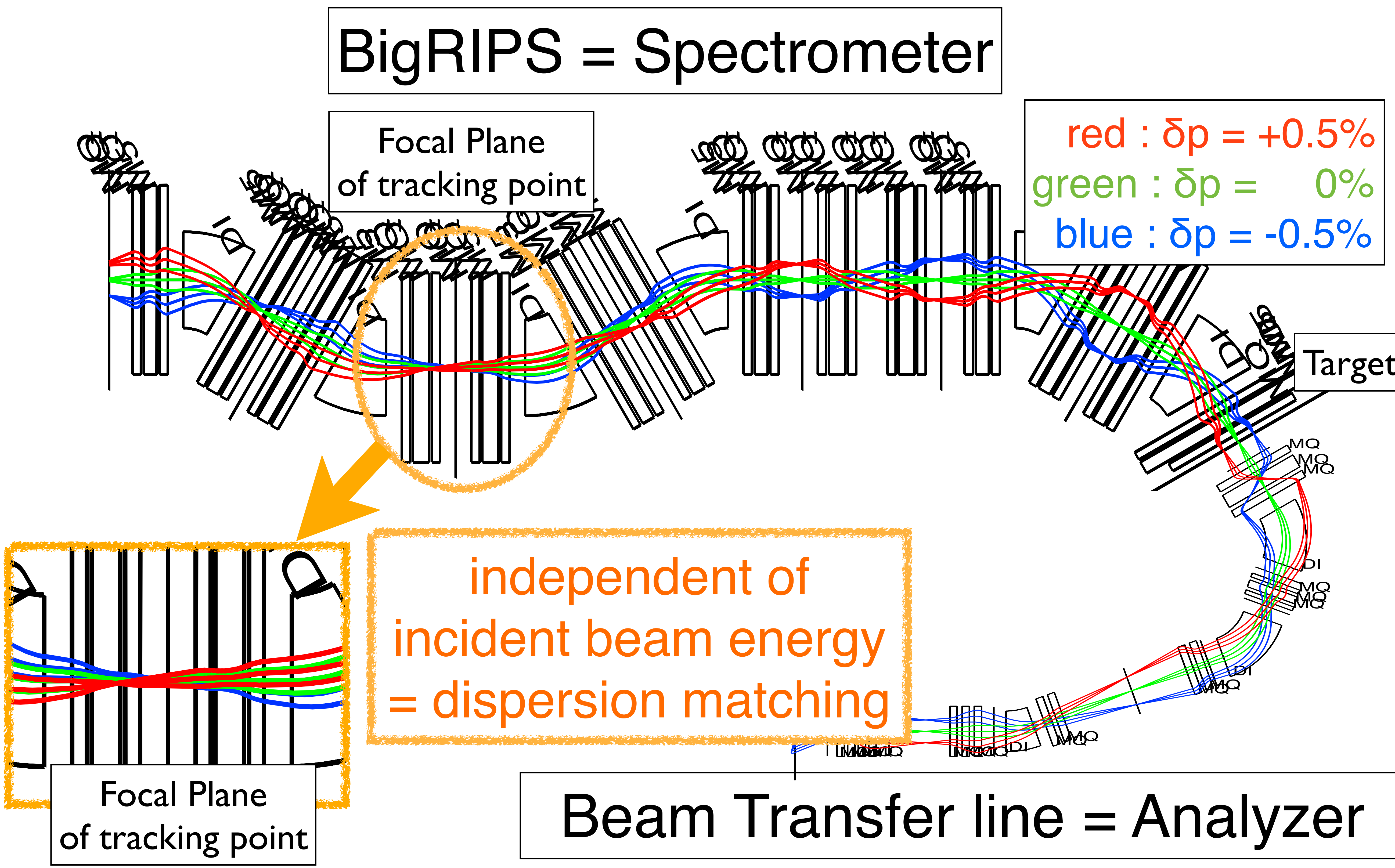

BigRIPS = Spectrometer
Focal Plane
of tracking point
red : δp = +0.5%
green : δp = 0%
blue : δp = -0.5%
Target
SRC
Beam Transfer line = Analyzer

Ion Optics



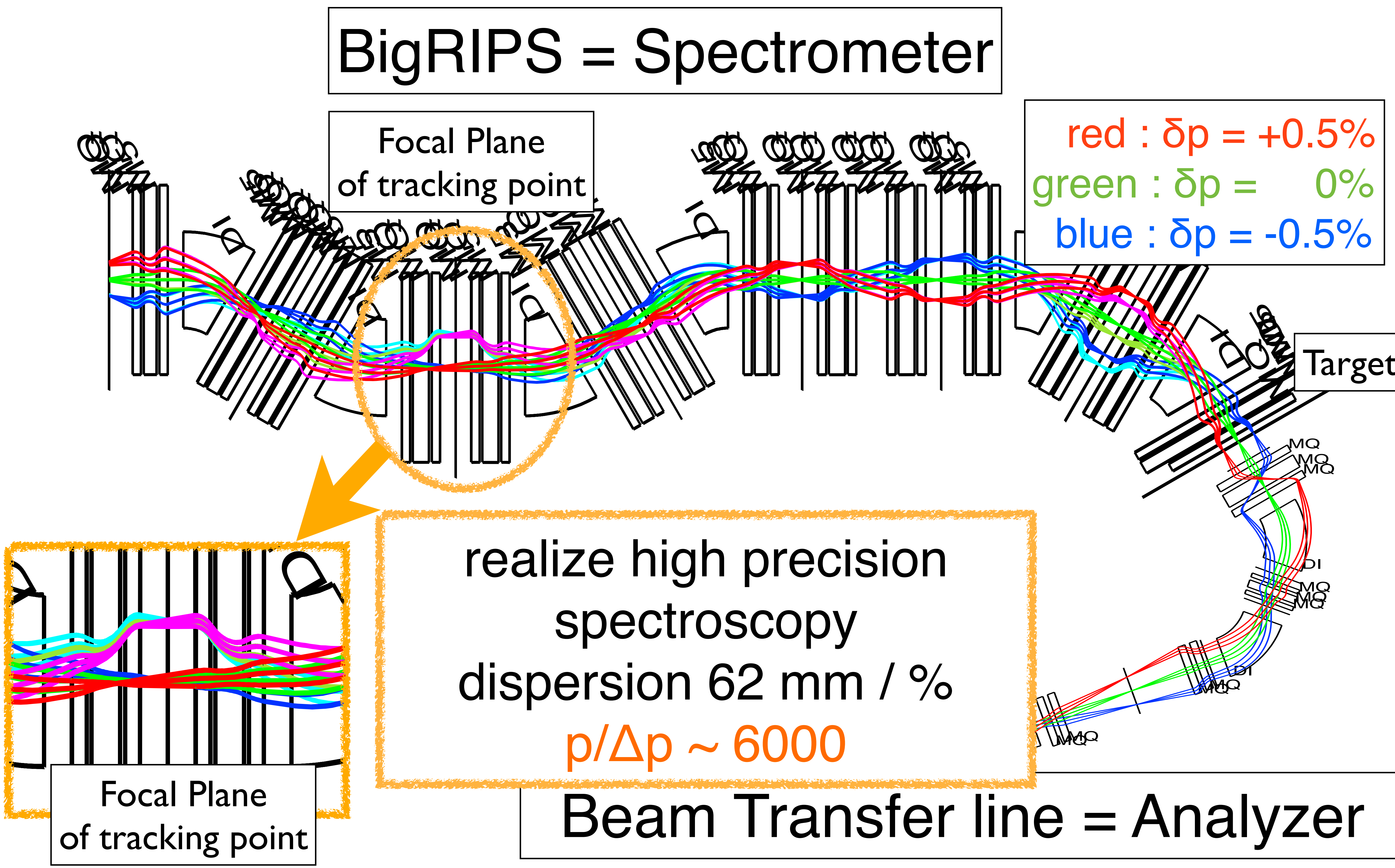
BigRIPS = Spectrometer
Focal Plane
of tracking point
red : δp = +0.5%
green : δp = 0%
blue : δp = -0.5%
Target
Target
MQ
MQ
MQ
dispersive@target
44.6 mm / %
Transfer line = Analyzer

Ion Optics

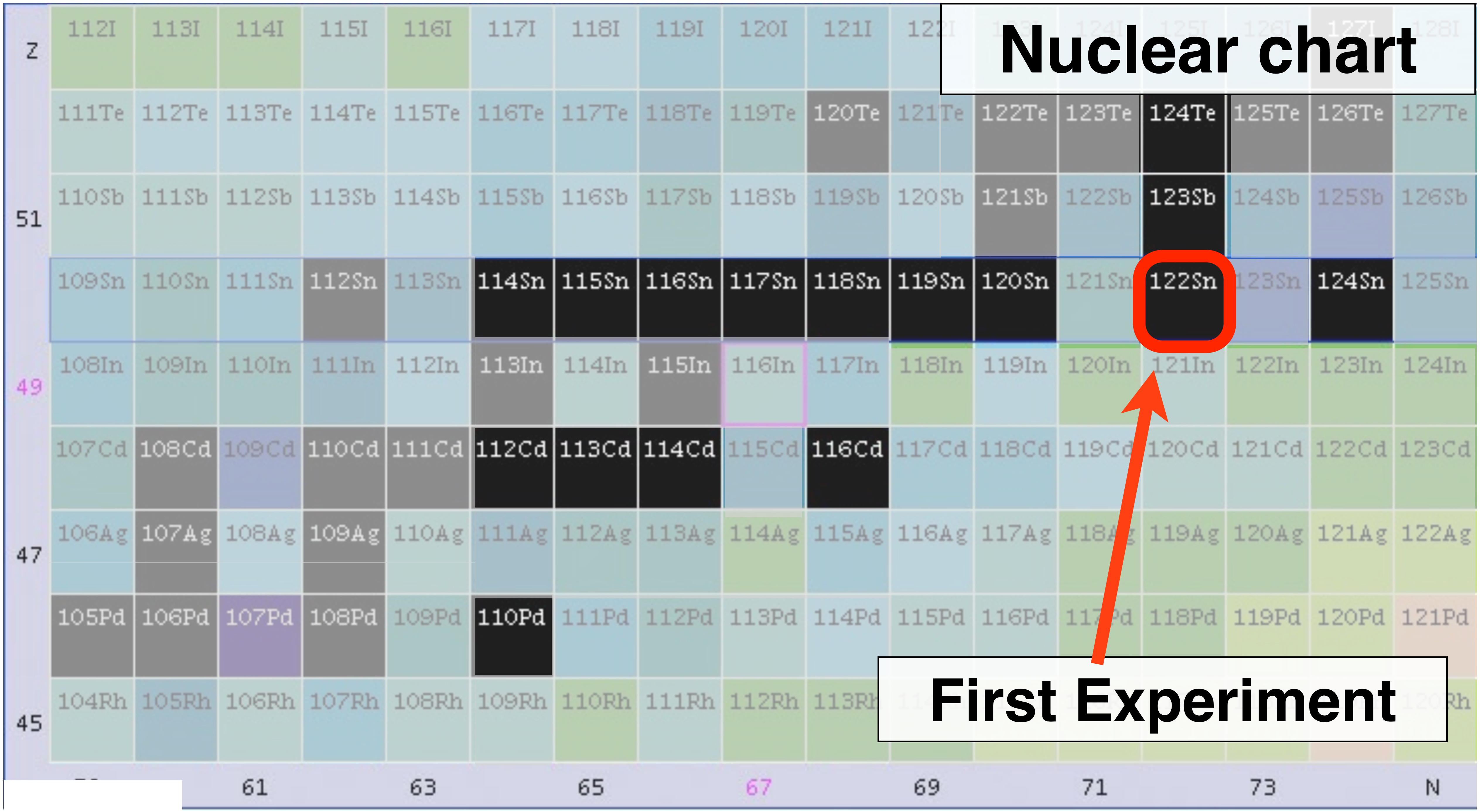


BigRIPS = Spectrometer
Focal Plane
of tracking point
red : δp = +0.5%
green : δp = 0%
blue : δp = -0.5%
Target
MQ
MQ
MQ
DI
independent of
incident beam energy
= dispersion matching
Focal Plane
of tracking point
Beam Transfer line = Analyzer

Ion Optics

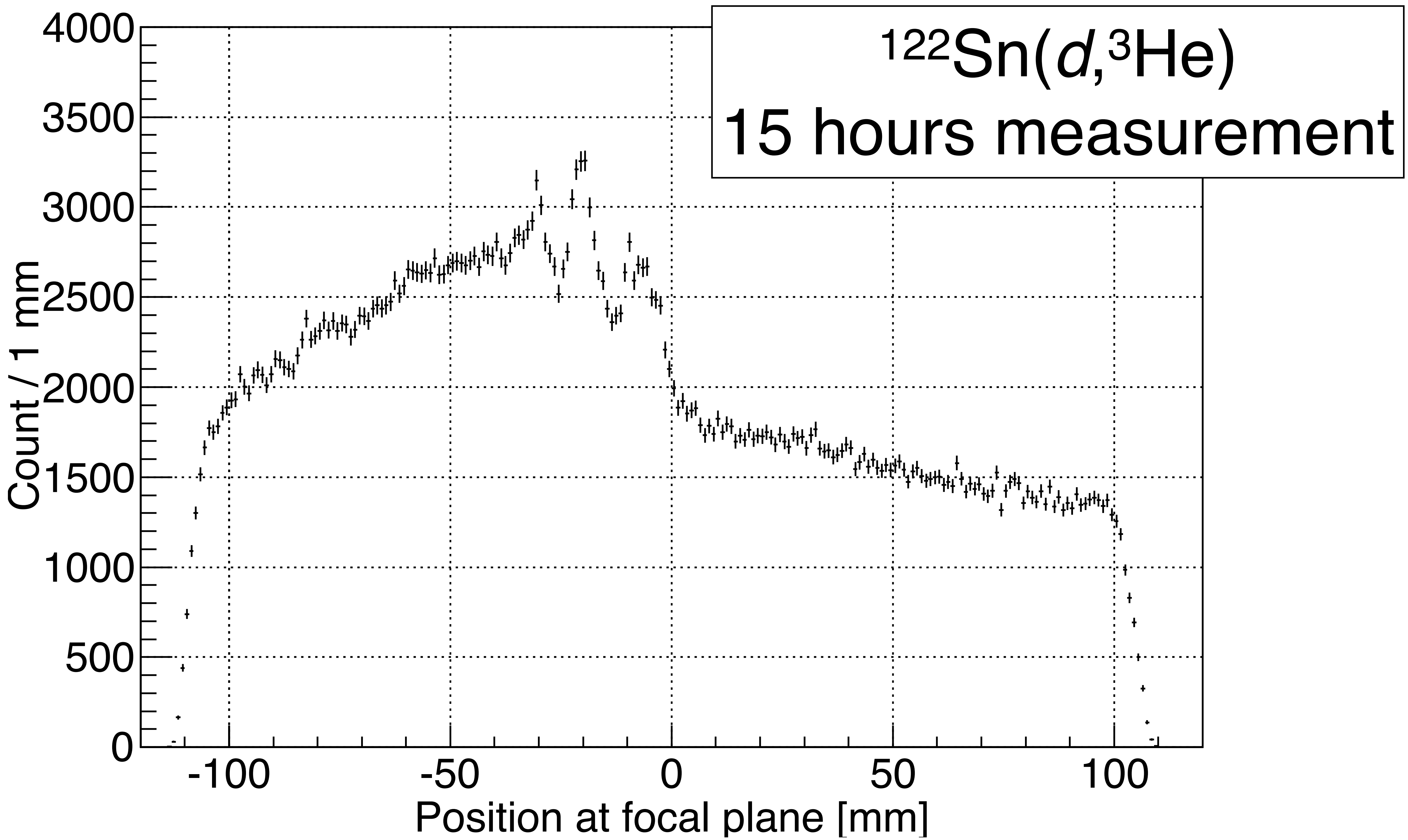

BigRIPS = Spectrometer
Focal Plane
of tracking point
red : δp = +0.5%
green : δp = 0%
blue : δp = -0.5%
Target
MQ
DI
realize high precision
spectroscopy
dispersion 62 mm / %
p/Δp ~ 6000
Focal Plane
of tracking point
Beam Transfer line = Analyzer

The pilot experiment



NNDC,BNL

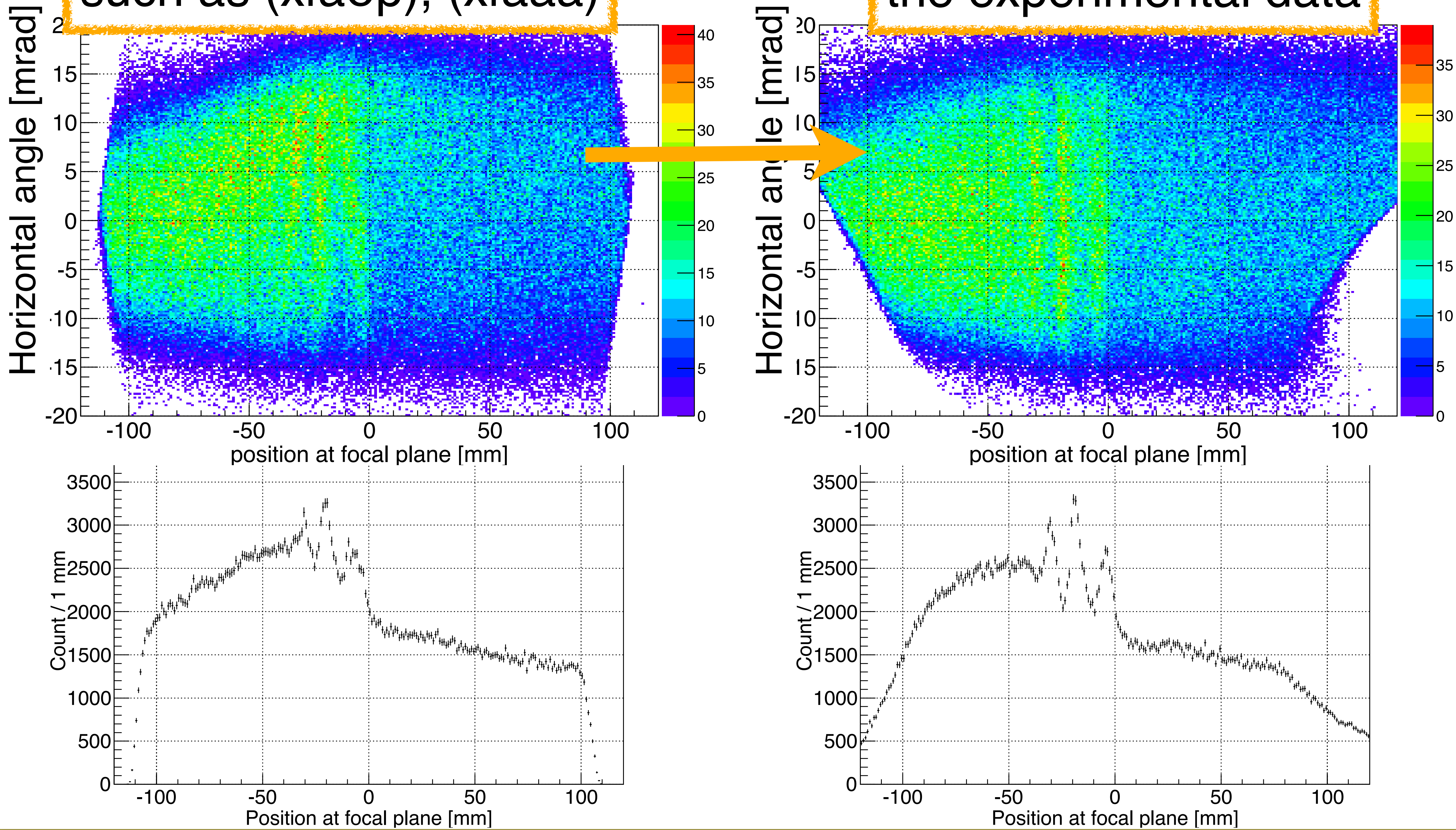
The result of pilot experiment



The result of pilot experiment

higher order aberration
such as (xlaδp), (xlaaa)

corrected by
the experimental data



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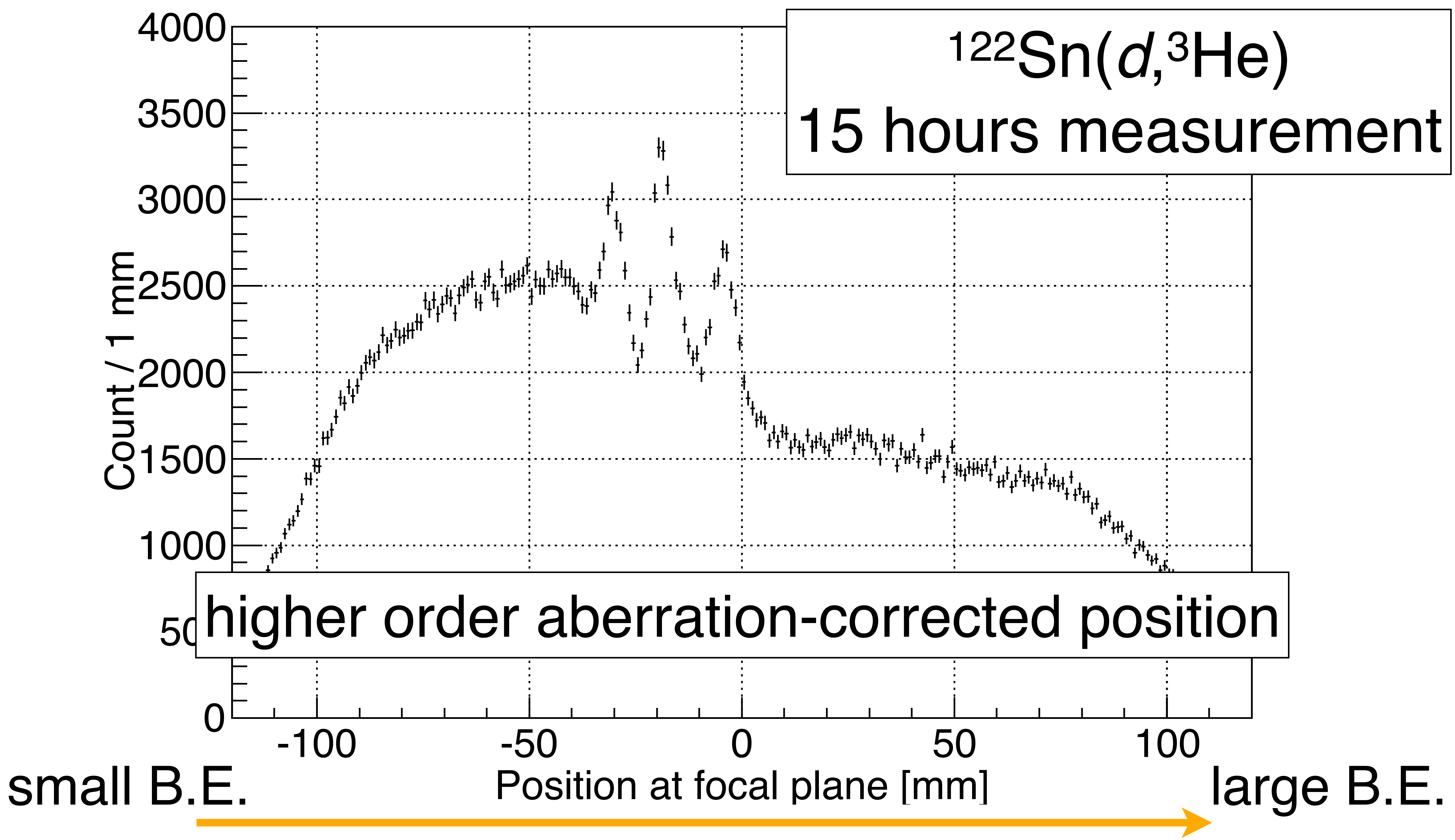
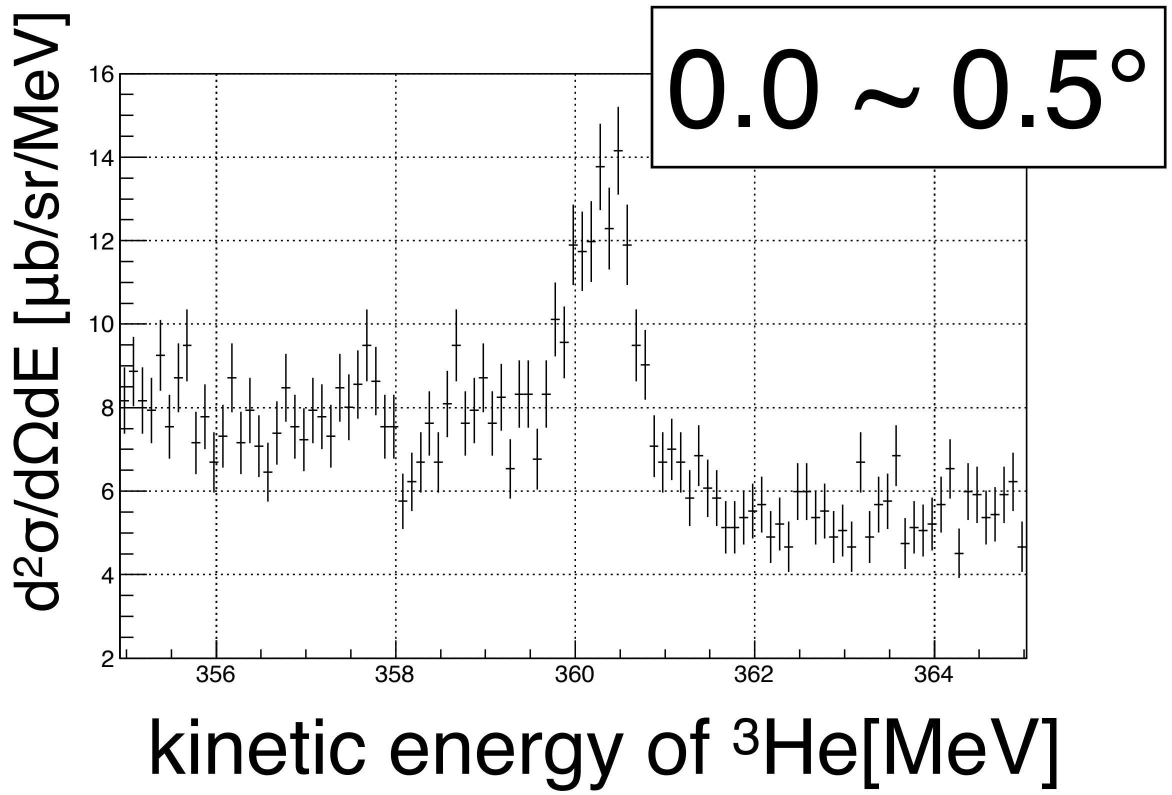
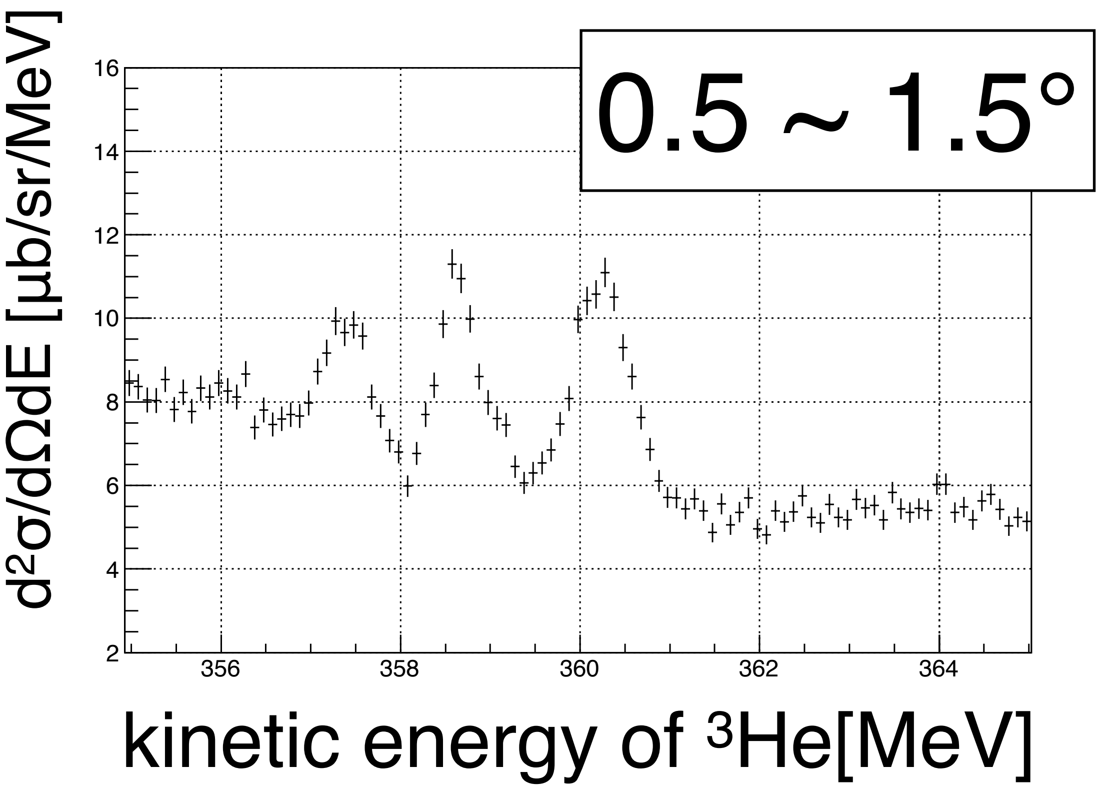
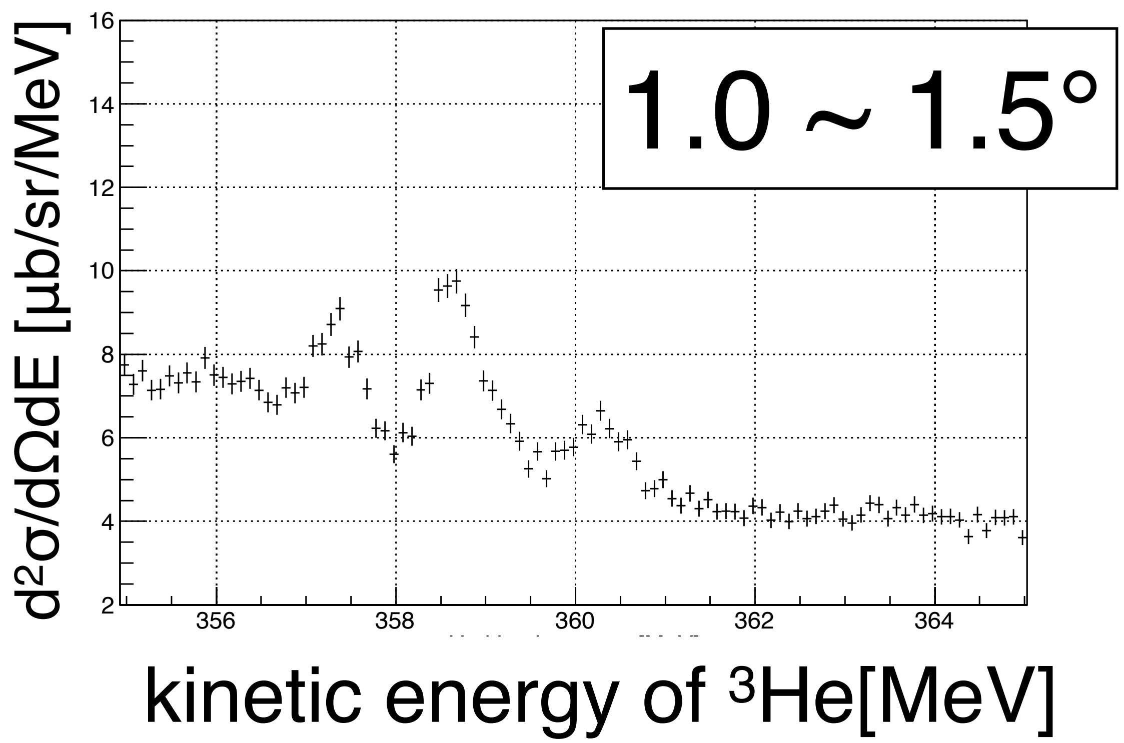
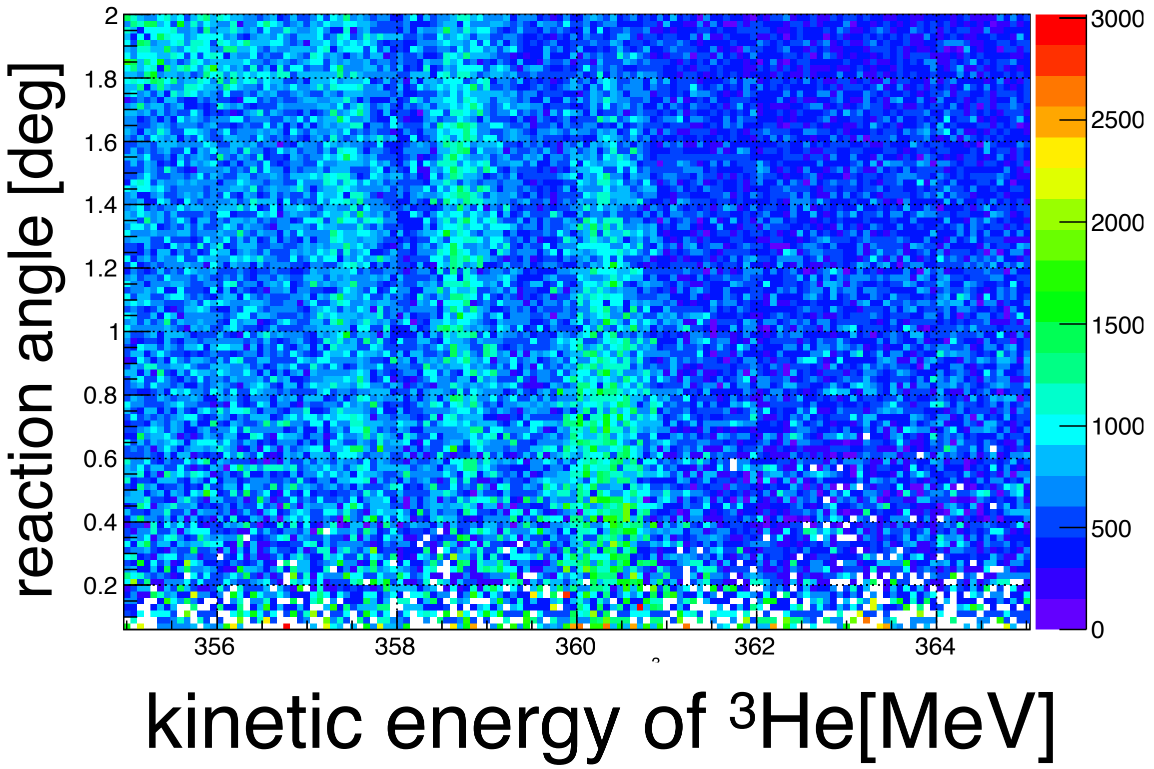


$d^2\sigma/d\Omega dE$ vs T_{He} Spectra

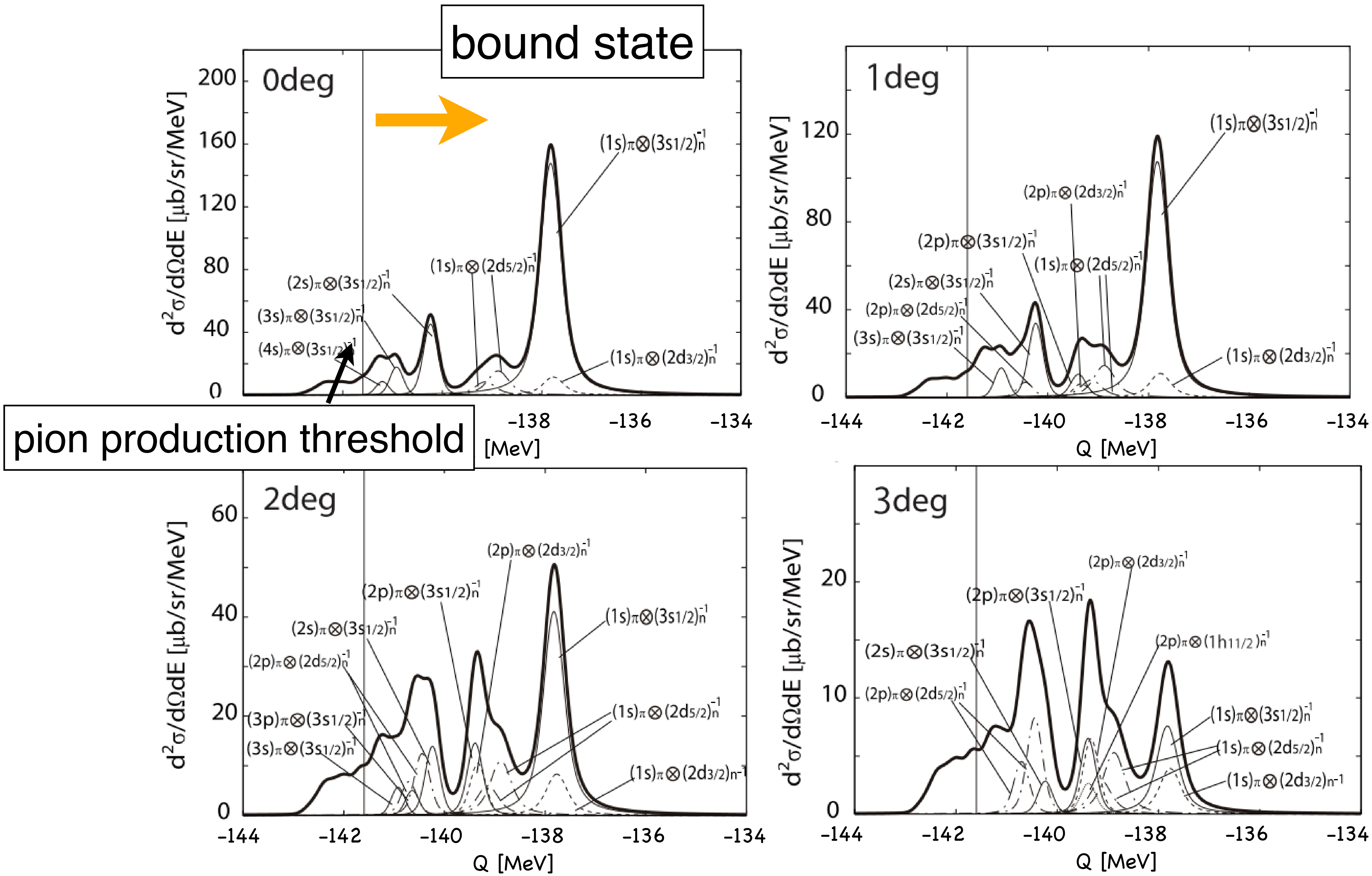








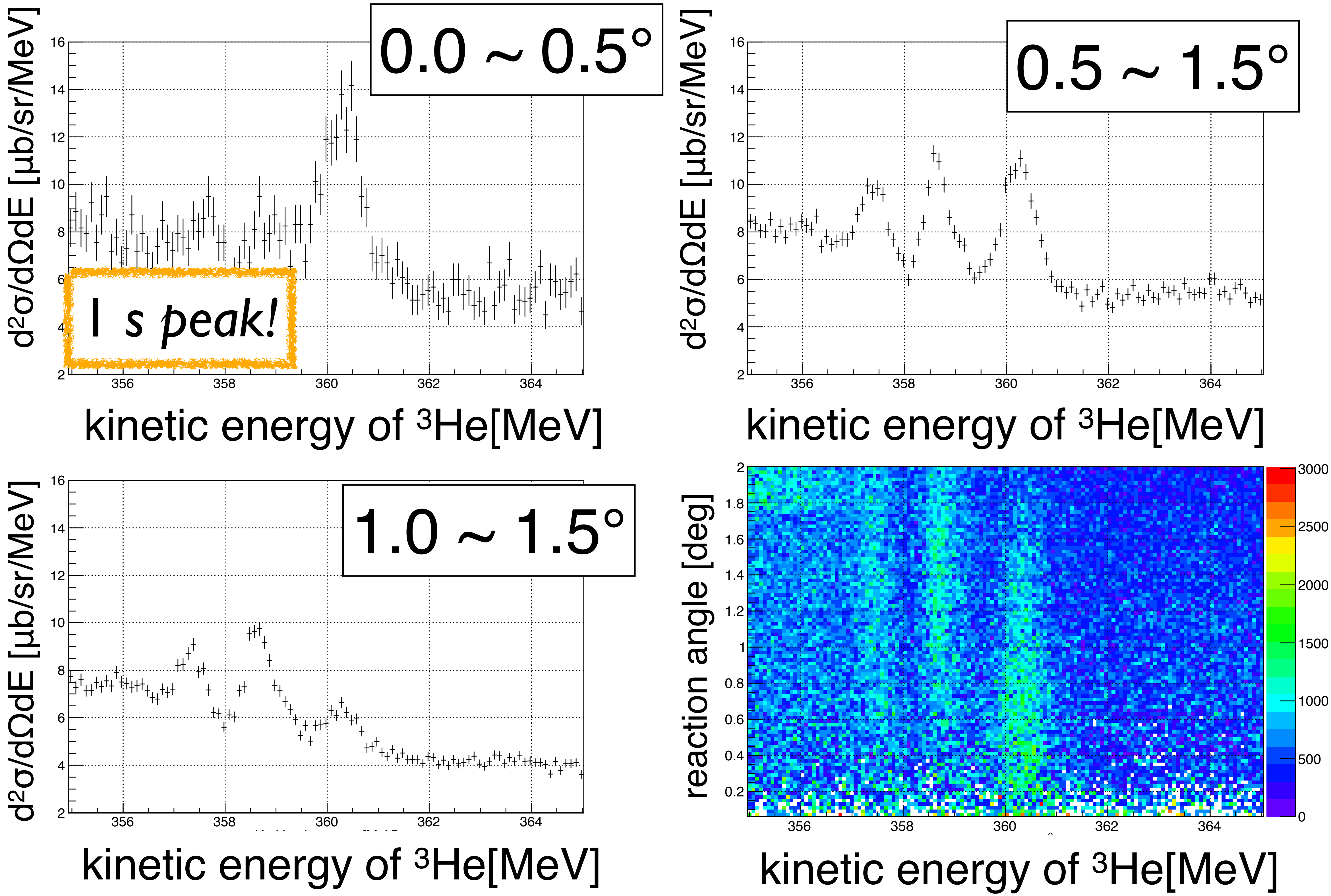
Theoretical calculated spectrum



resolution ~ 300 keV

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

$d^2\sigma/d\Omega dE$ vs T_{He} Spectra



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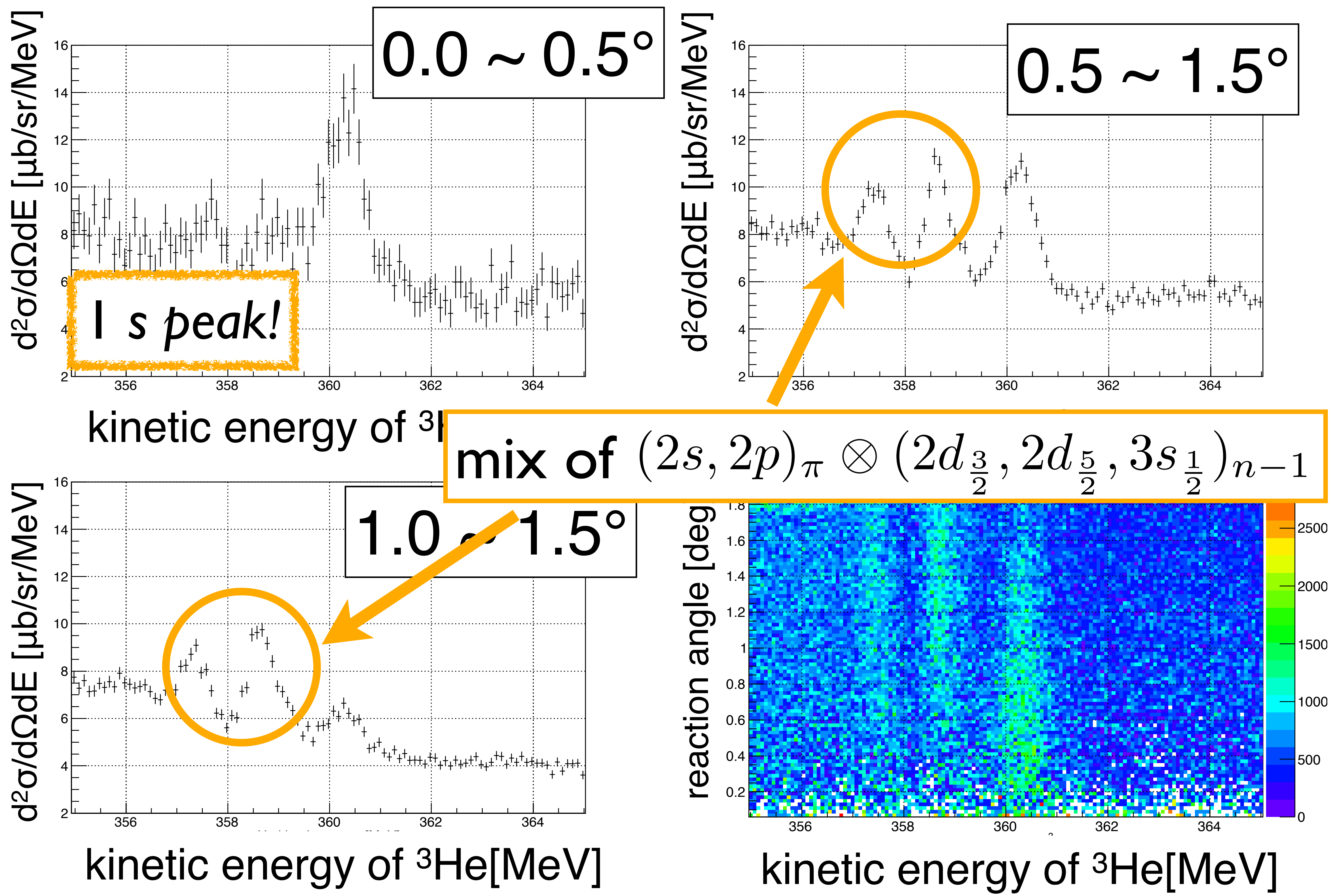
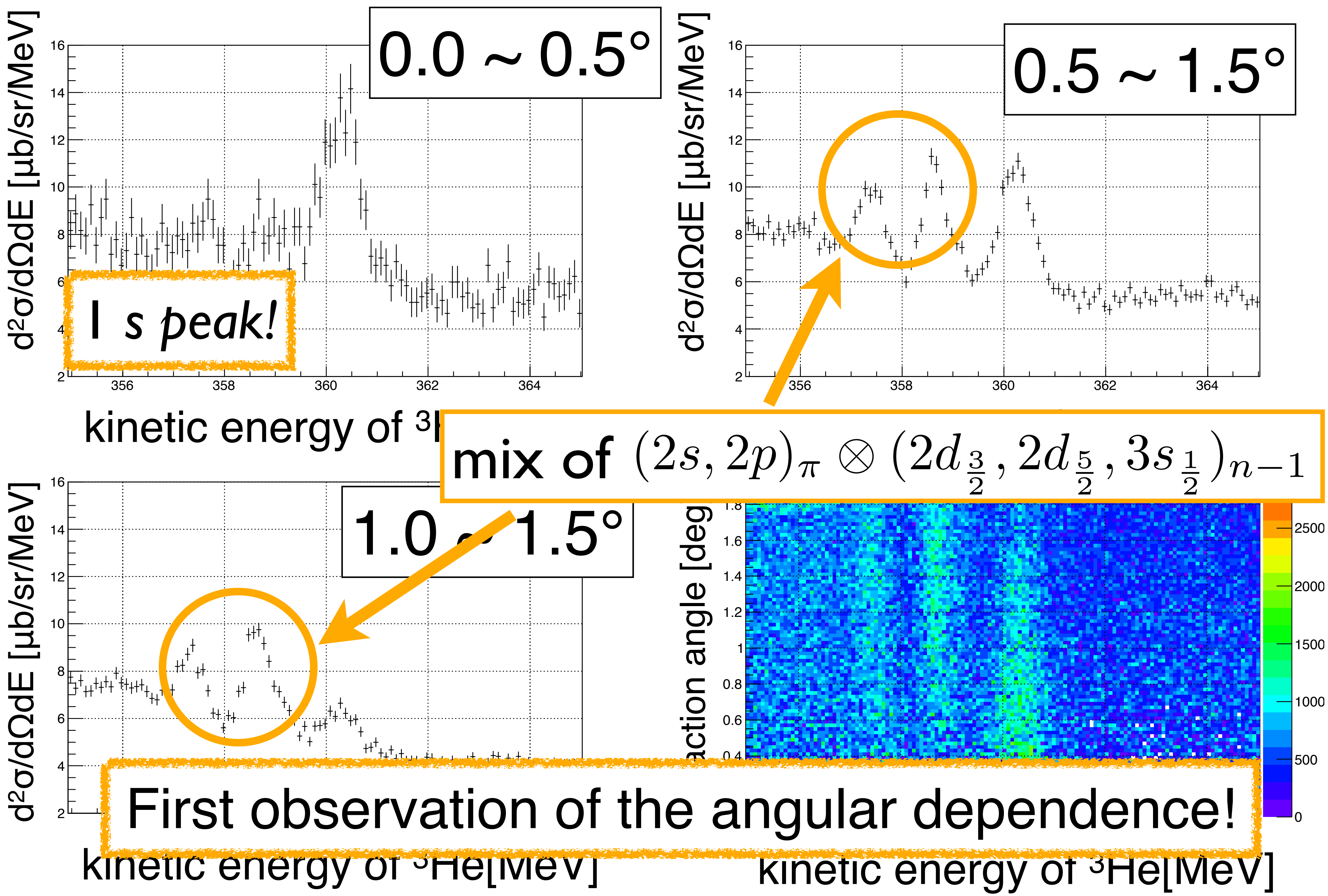


$d^2\sigma/d\Omega dE$ vs T_{He} Spectra



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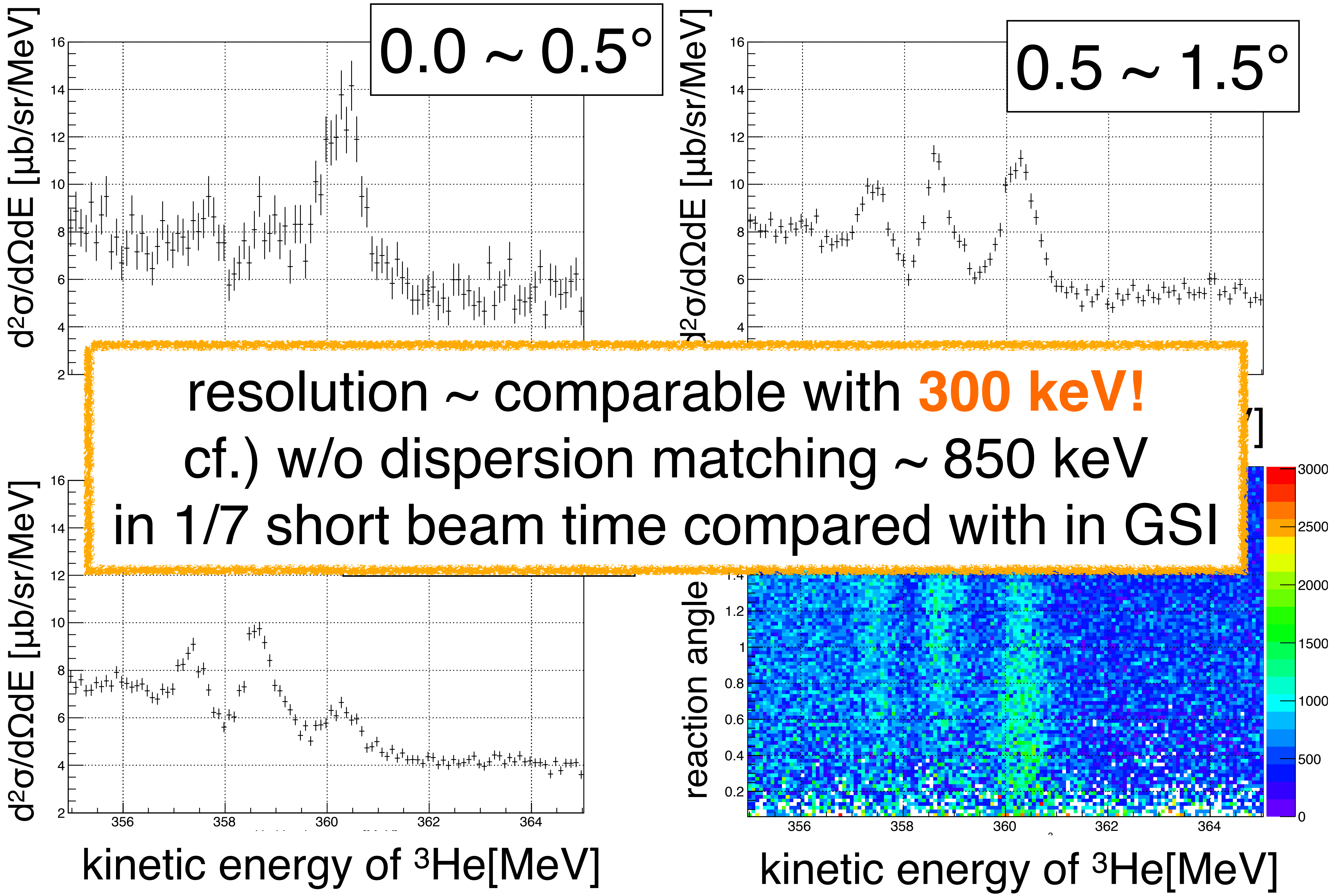

resolution ~ comparable with **300 keV!**
cf.) w/o dispersion matching ~ 850 keV
in 1/7 short beam time compared with in GSI

Summary and future works

- We constructed new optics using dispersion matching with primary beam at RIBF, RIKEN for deeply-bound pionic atom experiment.
- We performed the pilot experiment with the target of ^{122}Sn.
- The deeply bound pionic states in ^{121}Sn was observed successfully.
- Thanks for large angular acceptance of BigRIPS, angular dependence of the (*d*, ^{3}He) reaction cross section was also observed.
- Now we are finalizing the result of the pilot experiment to extract binding energy and width of deeply bound pionic states.
- In the main experiment, we will optimize the dispersion matching condition and improve the resolution.

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the first observation in the world

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- In the main experiment, we will optimize the dispersion matching condition and improve the resolution.

Ongoing other projects in our group

Feasibility study of inverse kinematics
for pionic atom → pionic unstable nuclei

η’ mesic nuclei by using C(p,*d*) reaction
@GSI

(2.5 GeV proton / high resolution spectrometer)