First Precision Spectroscopy of Pionic Atoms at RI Beam Factory

Kenta Itahashi

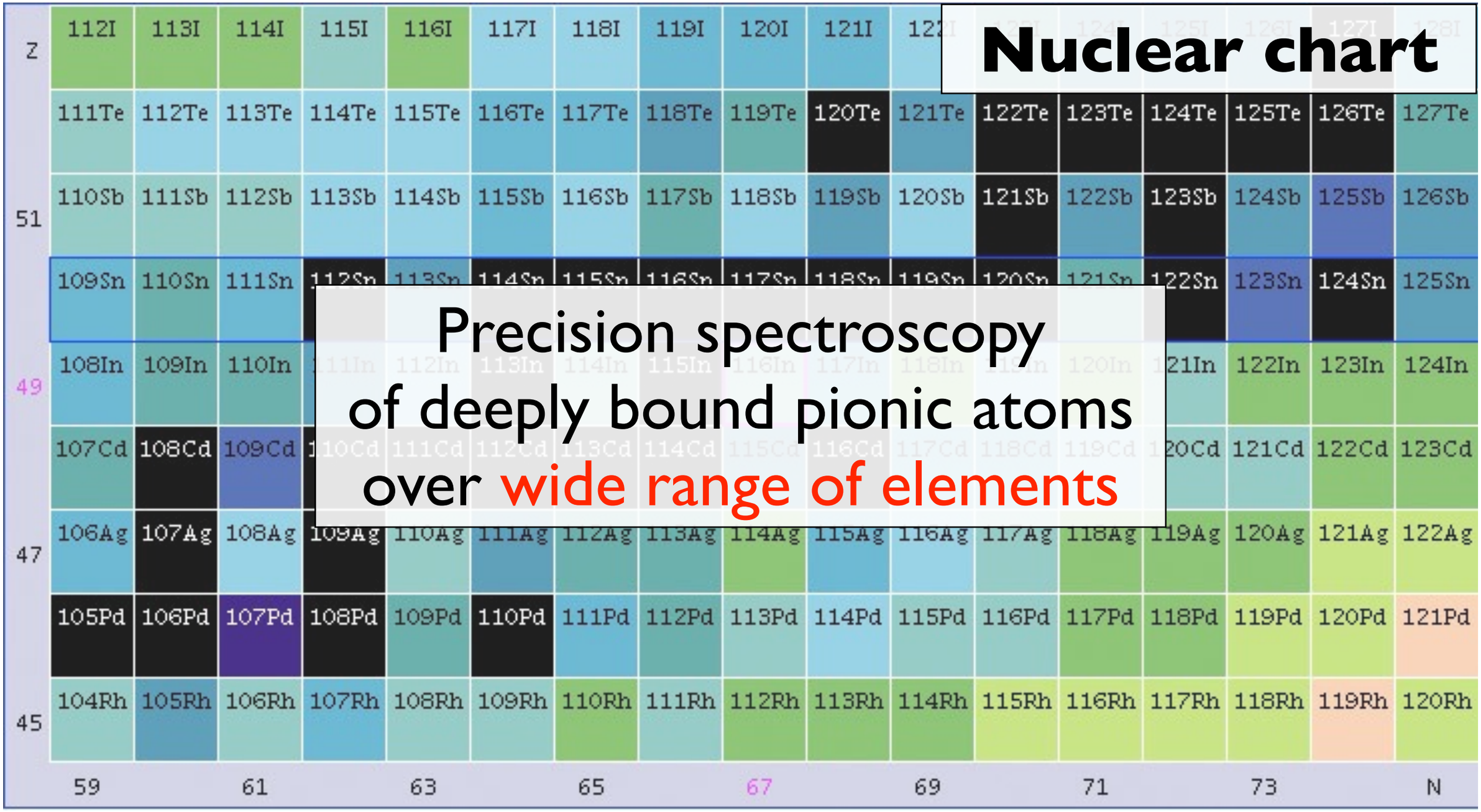
Advanced Meson Science Laboratory, RIKEN

for Pionic Atom Factory Project

RIKEN
INABE Naohito, ITAHASHI Kenta, KAMEDA Daisuke, KUBO Toshiyuki, NAKAMURA Masaki, TAKEDA Hiroyuki, UESAKA Tomohiro, YOSHIDA Koichi
GSI
GEISSEL Hans, WEICK Helmut
The University of Tokyo
HAYANO Ryugo S., ITOH Satoshi, KAWASE Shoichiro, MATSUBARA Hiroaki, MICHIMASA Shin'ichiro, MIKI Kenjiro, MIYA Hiroyuki, NISHI Takahiro, NOJI Shumpei, OTA Shinsuke, TODOROKI Koichi
University of Notre Dame
BERG Georg P.A.
SMI
SUZUKI Ken
Tohoku University
TSUKADA Kyo
Nara Women's University
HIRENZAKI Satoru, IKENO Natsumi, YAMAGATA-SEKIHARA Junko
Kyoto University
FUJIOKA Hiroyuki

For detailed theoretical discussion, see **N. Ikeno**'s poster #22.

Pionic Atom Factory Project in RIBF



Nuclear chart

Precision spectroscopy
of deeply bound pionic atoms
over wide range of elements

NNDC,BNL

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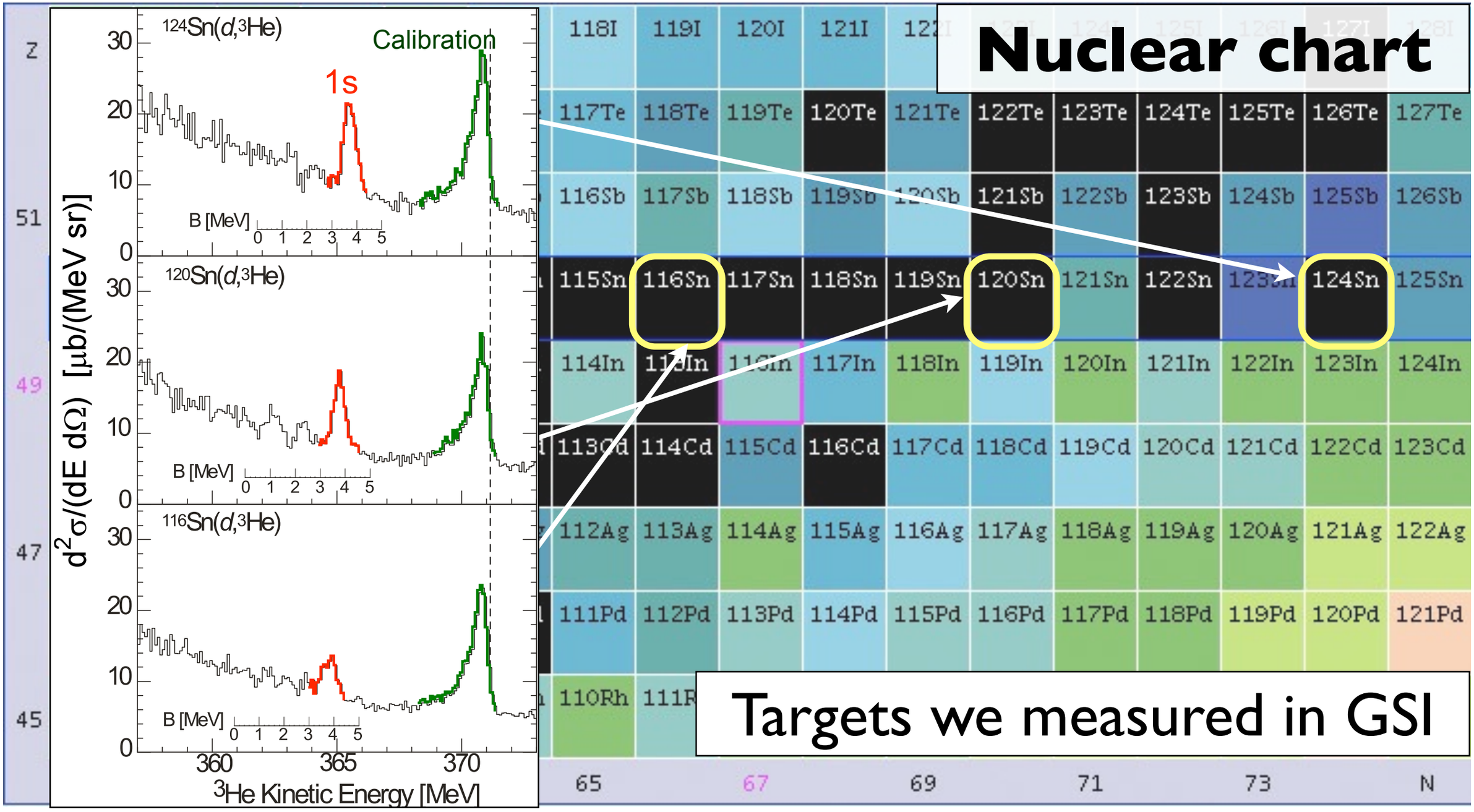
Pionic Atom Factory Project in RIBF



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

NNDC,BNL

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Pionic Atom Factory Project in RIBF

Z																	
	112I	113I	114I	115I	116I	117I	118I	119I	120I	121I	122I	123I	124I	125I	126I	127I	128I
	111Te	112Te	113Te	114Te	115Te	116Te	117Te	118Te	119Te	120Te	121Te	122Te	123Te	124Te	125Te	126Te	127Te
51	110Sb	111Sb	112Sb	113Sb	114Sb	115Sb	116Sb	117Sb	118Sb	119Sb	120Sb	121Sb	122Sb	123Sb	124Sb	125Sb	126Sb
	109Sn	110Sn	111Sn	112Sn	113Sn	114Sn	115Sn	116Sn	117Sn	118Sn	119Sn	120Sn	121Sn	122Sn	123Sn	124Sn	125Sn
49	108In	109In	110In	111In	112In	113In	114In	115In	116In	117In	118In	119In	120In	121In	122In	123In	124In
	107Cd	108Cd	109Cd	110Cd	111Cd	112Cd	113Cd	114Cd	115Cd	116Cd	117Cd	118Cd	119Cd	120Cd	121Cd	122Cd	123Cd
47	106Ag	107Ag	108Ag	109Ag	110Ag	111Ag	112Ag	113Ag	114Ag	115Ag	116Ag	117Ag	118Ag	119Ag	120Ag	121Ag	122Ag
	105Pd	106Pd	107Pd	108Pd	109Pd	110Pd	111Pd	112Pd	113Pd	114Pd	115Pd	116Pd	117Pd	118Pd	119Pd	120Pd	121Pd
45	104Rh	105Rh	106Rh	107Rh	108Rh	109Rh	110Rh	111Rh	112Rh	113Rh	114Rh	115Rh	116Rh	117Rh	118Rh	119Rh	120Rh
	59		61		63		65		67		69		71		73		N

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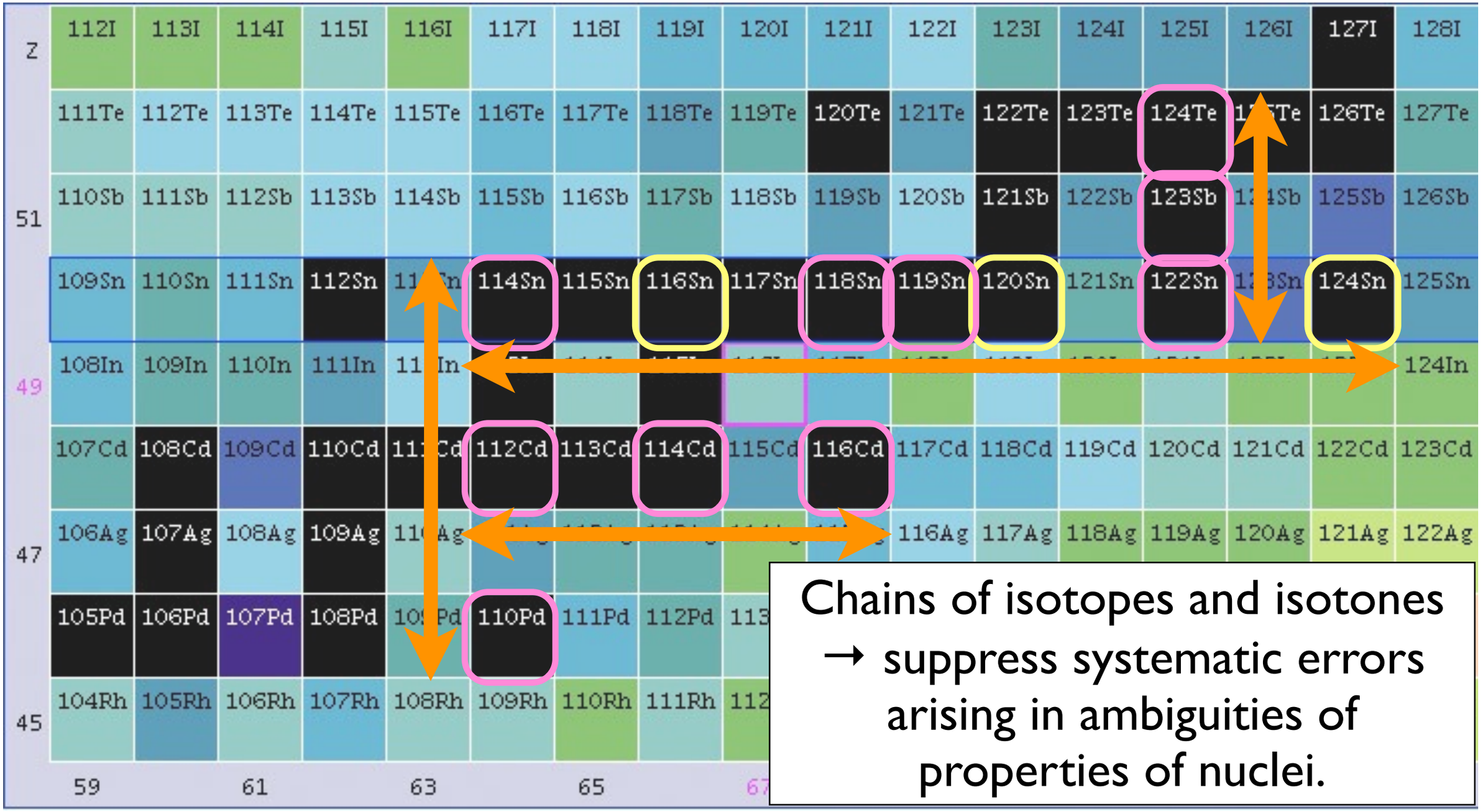
Pionic Atom Factory Project in RIBF



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

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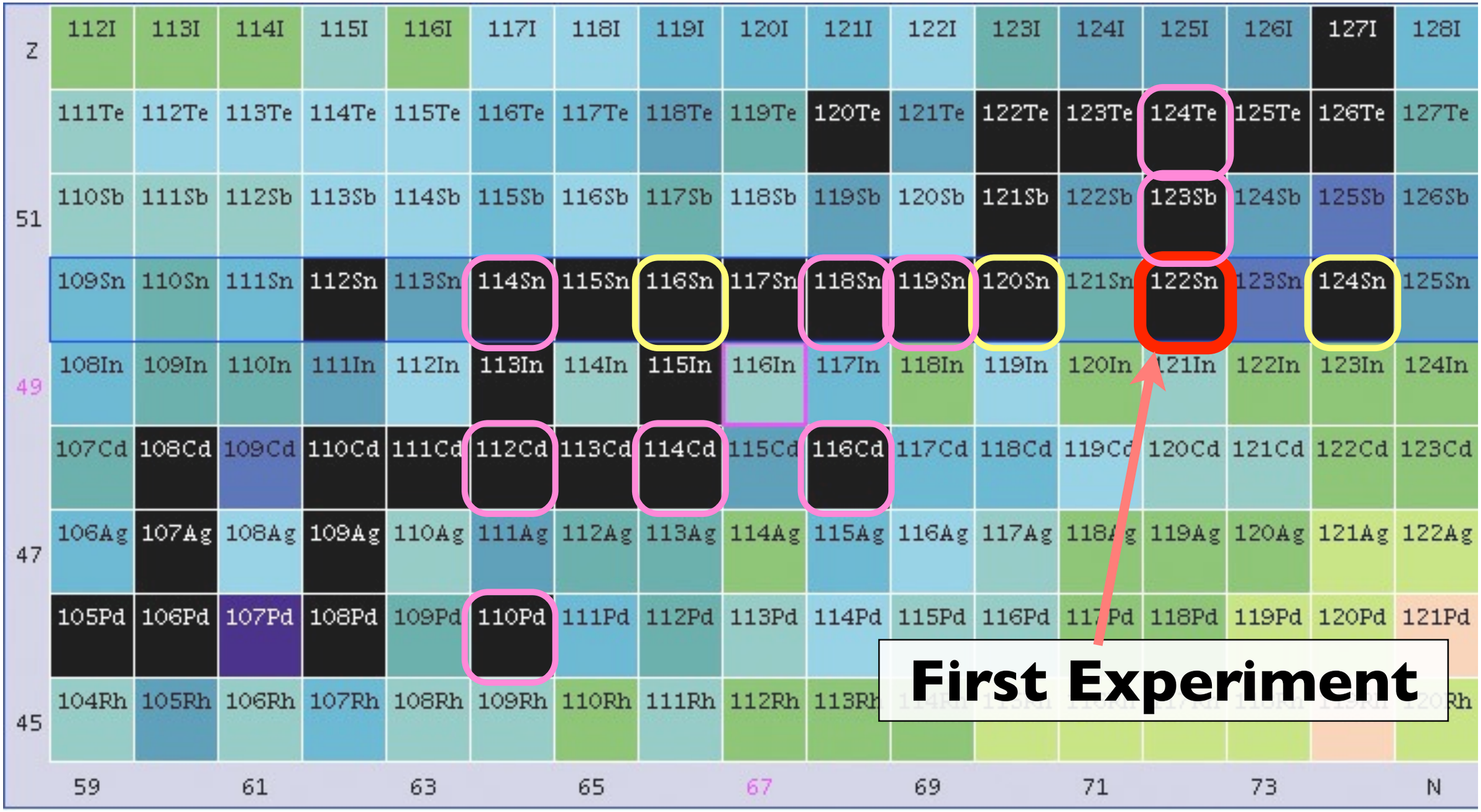
Pionic Atom Factory Project in RIBF



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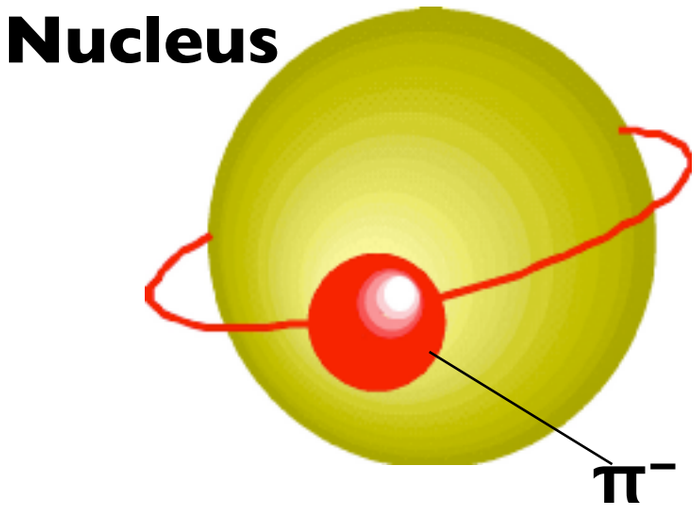
Motivation

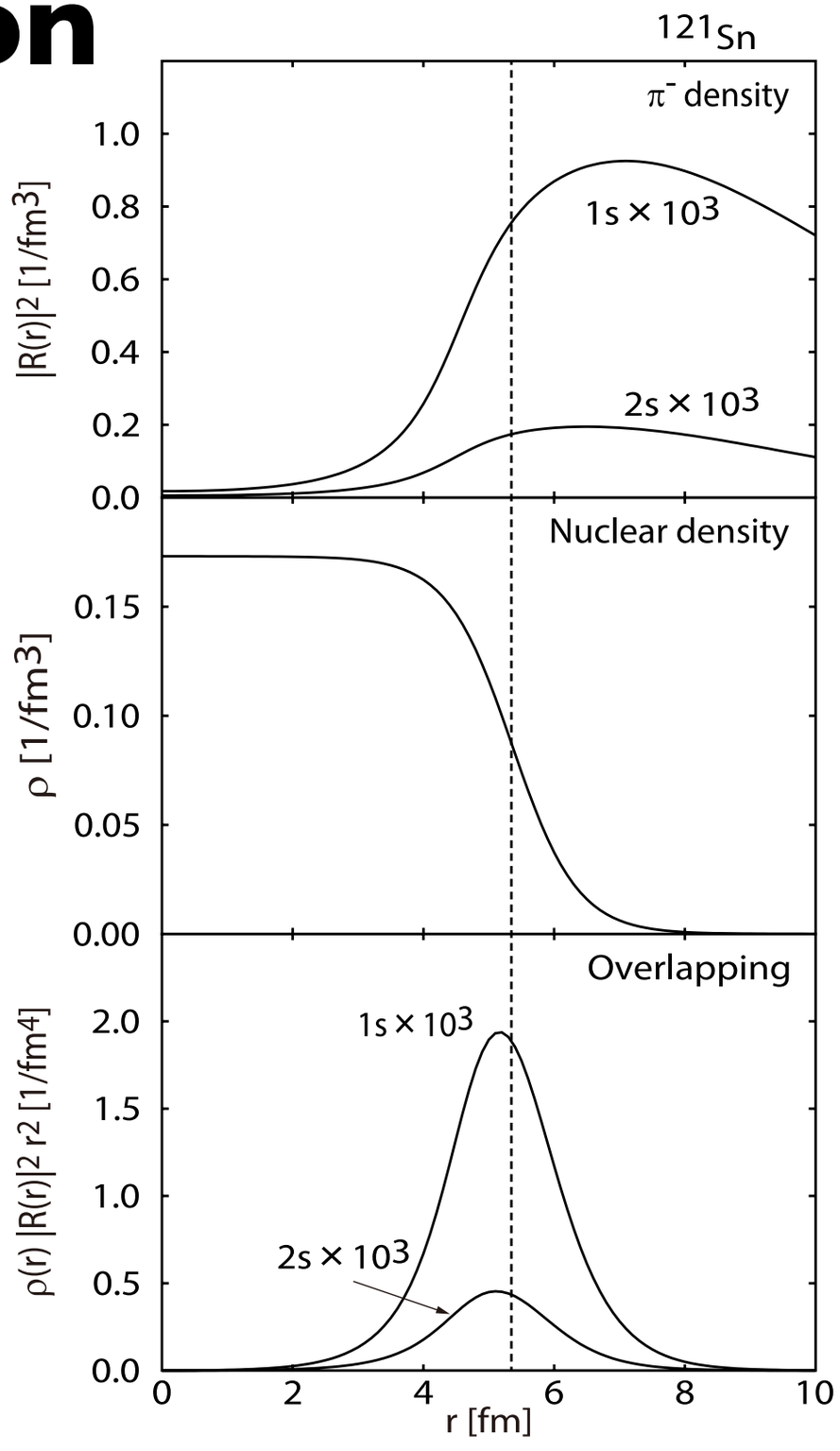


Large overlap between pion and nucleus

sensitivity to

π-nucleus strong interaction potential

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



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

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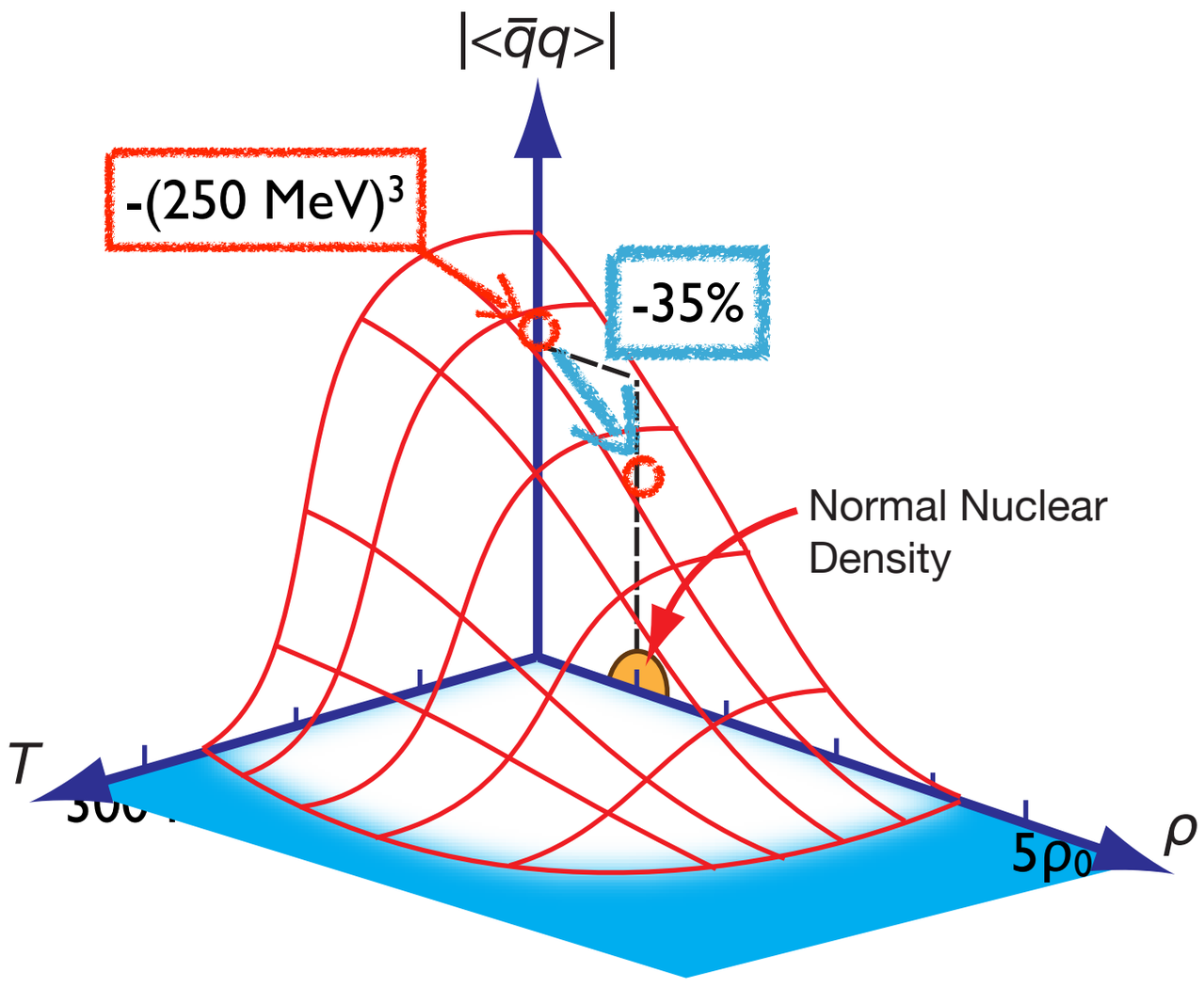
Chiral symmetry at finite density

Daisuke Jido, Tetsuo Hatsuda, Teiji Kunihro, 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

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

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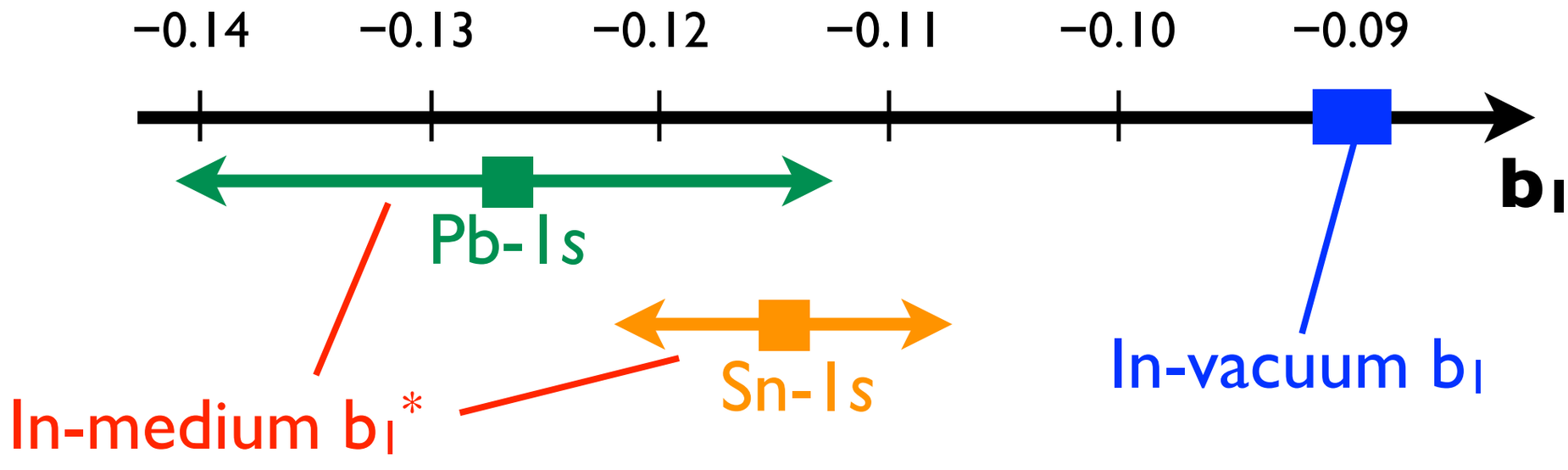
Present b_1 precision



b1 still has a large error
← exp. error in
pionic atom spectroscopy

In-medium b1 is calculated based on deeply bound pionic states data combined with light spherical pionic atom data.

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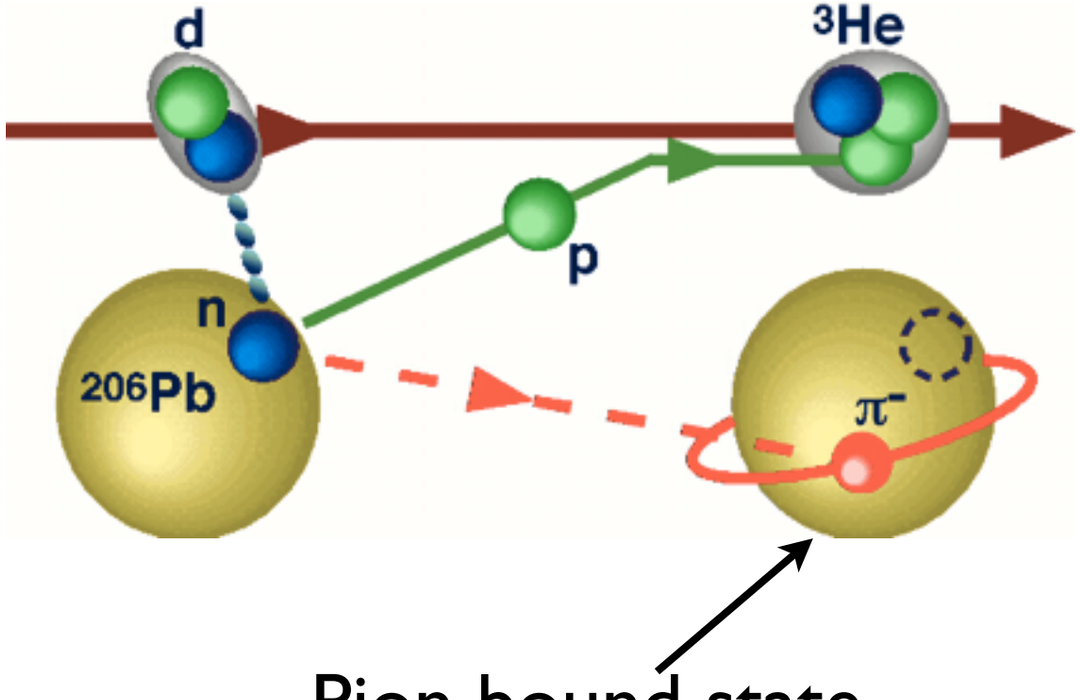
Experimental Method

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

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

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



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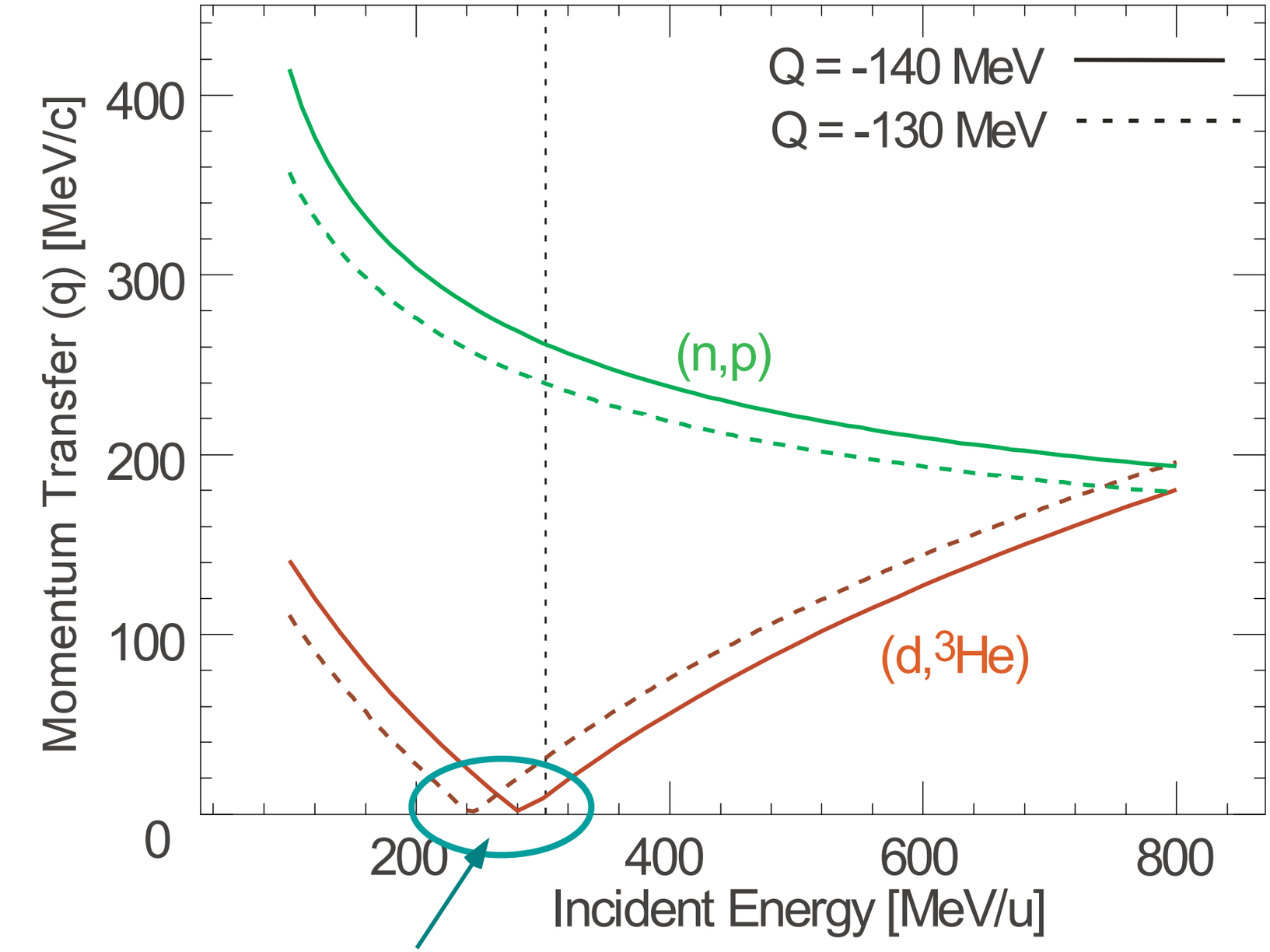
Momentum Transfer



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

(d,^{3}He) reaction

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Precision spectroscopy at RI Beam Factory

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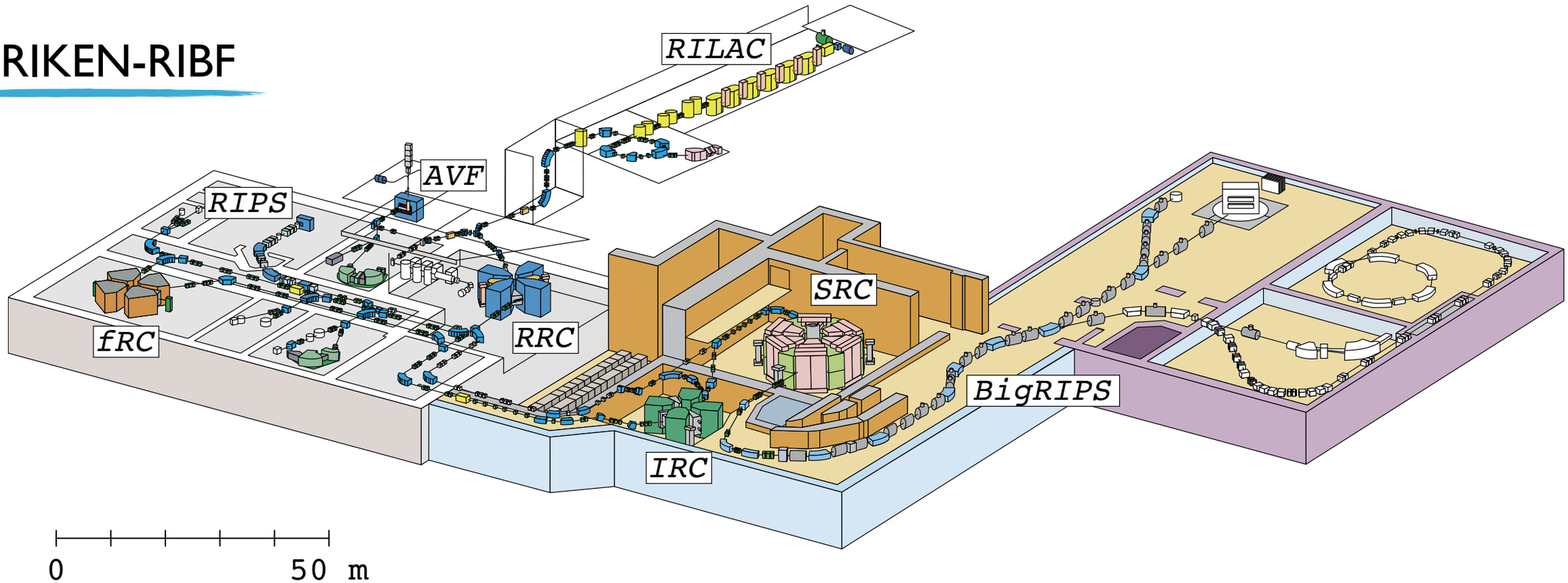

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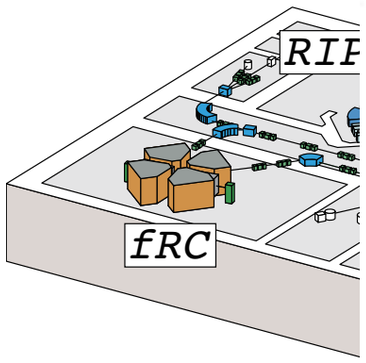
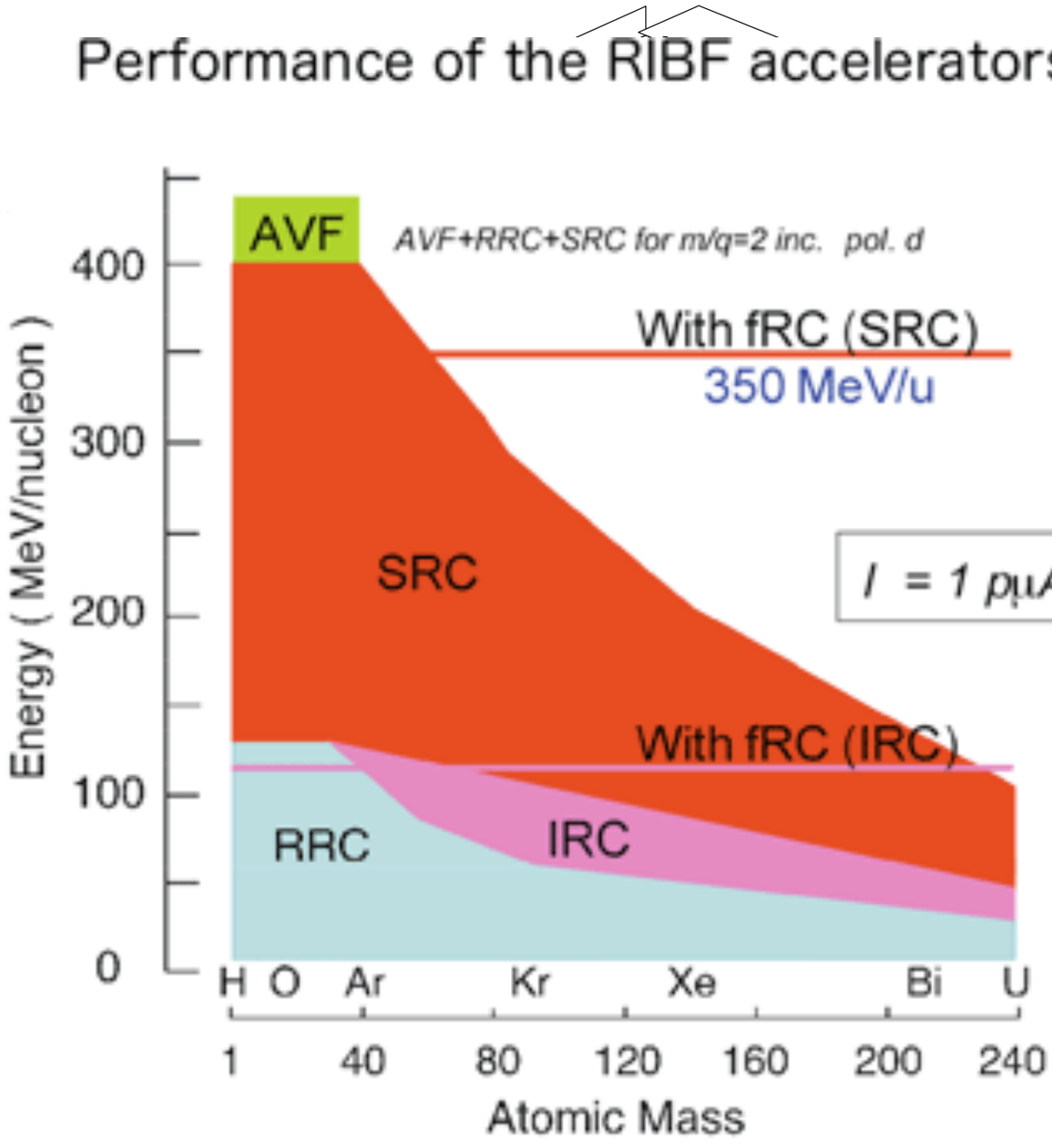
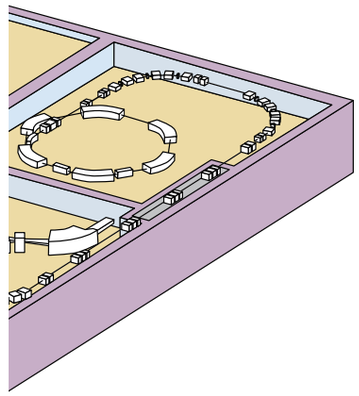
Precision spectroscopy at RI Beam Factory

RIKEN-RIBF







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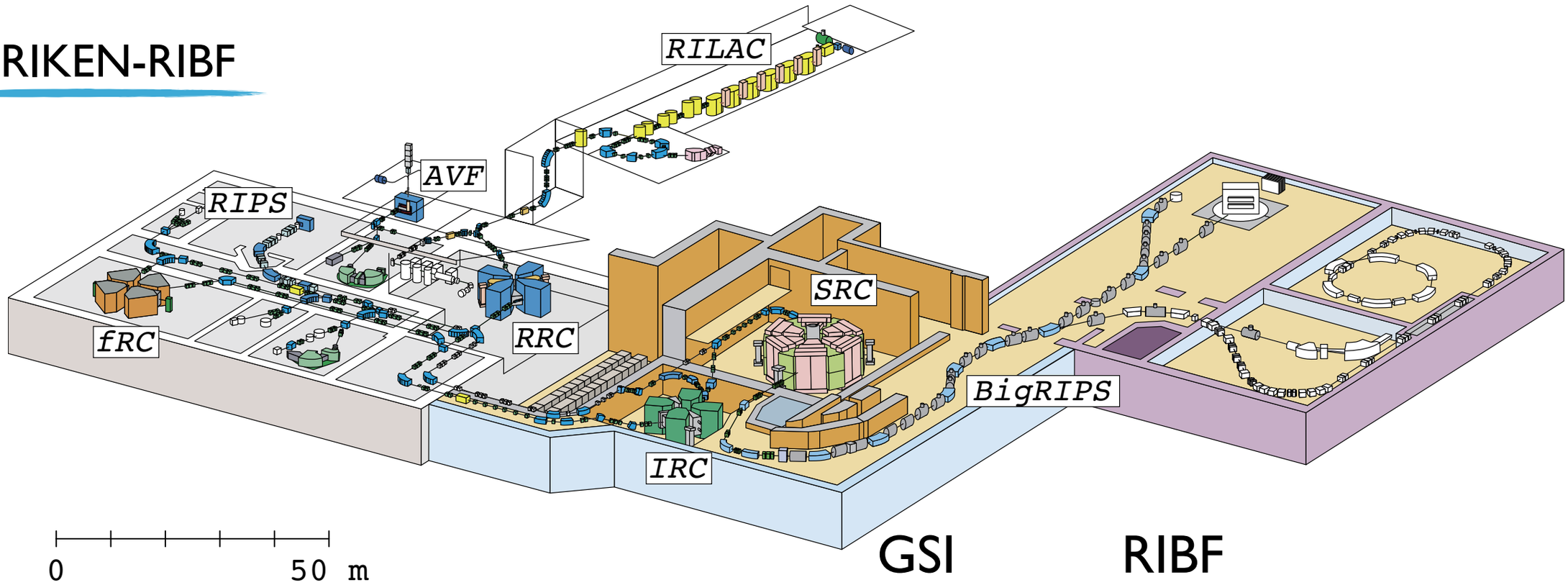
Precision spectroscopy at RI Beam Factory

RIKEN-RIBF



	GSI	RIBF
d beam Intensity	10^{11}/s	10^{12}/s
Target	20 mg/cm^2	10 mg/cm^2
$\Delta p_d/p_d$ (FWHM)	0.03%	0.1%
Resolution (FWHM)	400 keV	1000 keV

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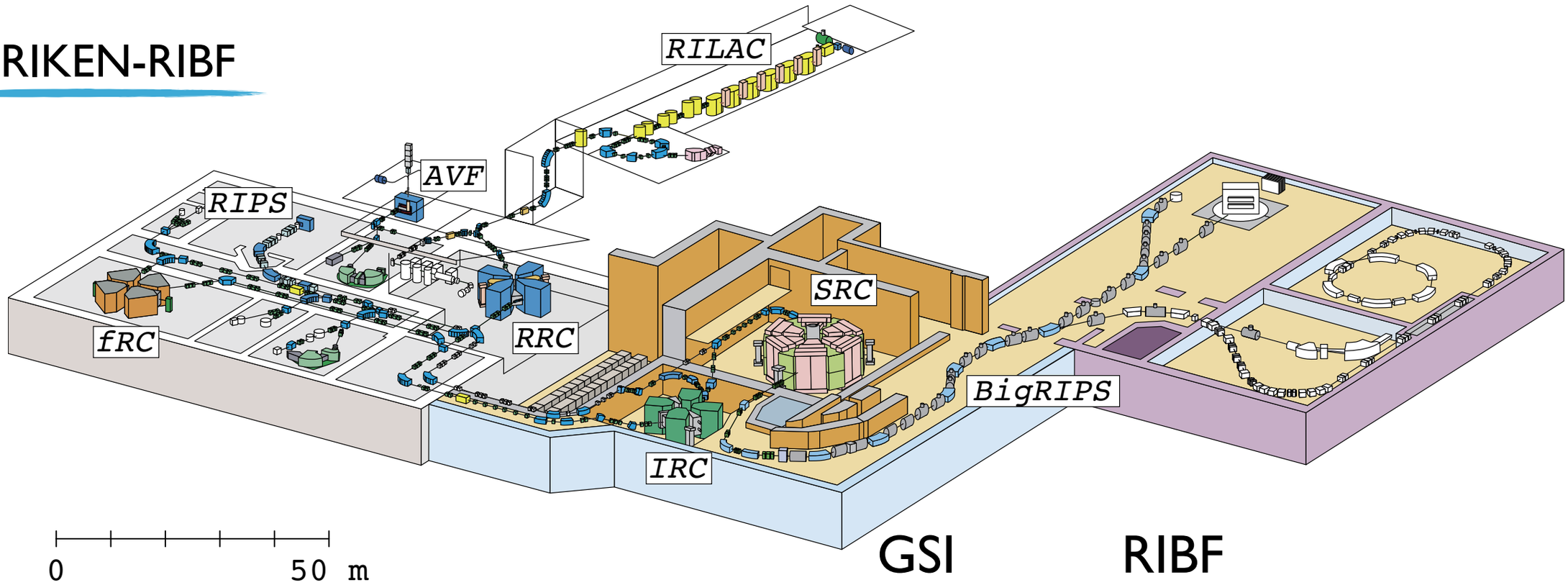
Precision spectroscopy at RI Beam Factory

RIKEN-RIBF



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Target	20 mg/cm^2	10 mg/cm^2
$\Delta p_d/p_d$ (FWHM)	0.03%	0.1%
Resolution (FWHM)	400 keV	200 keV

by using the dispersion matching

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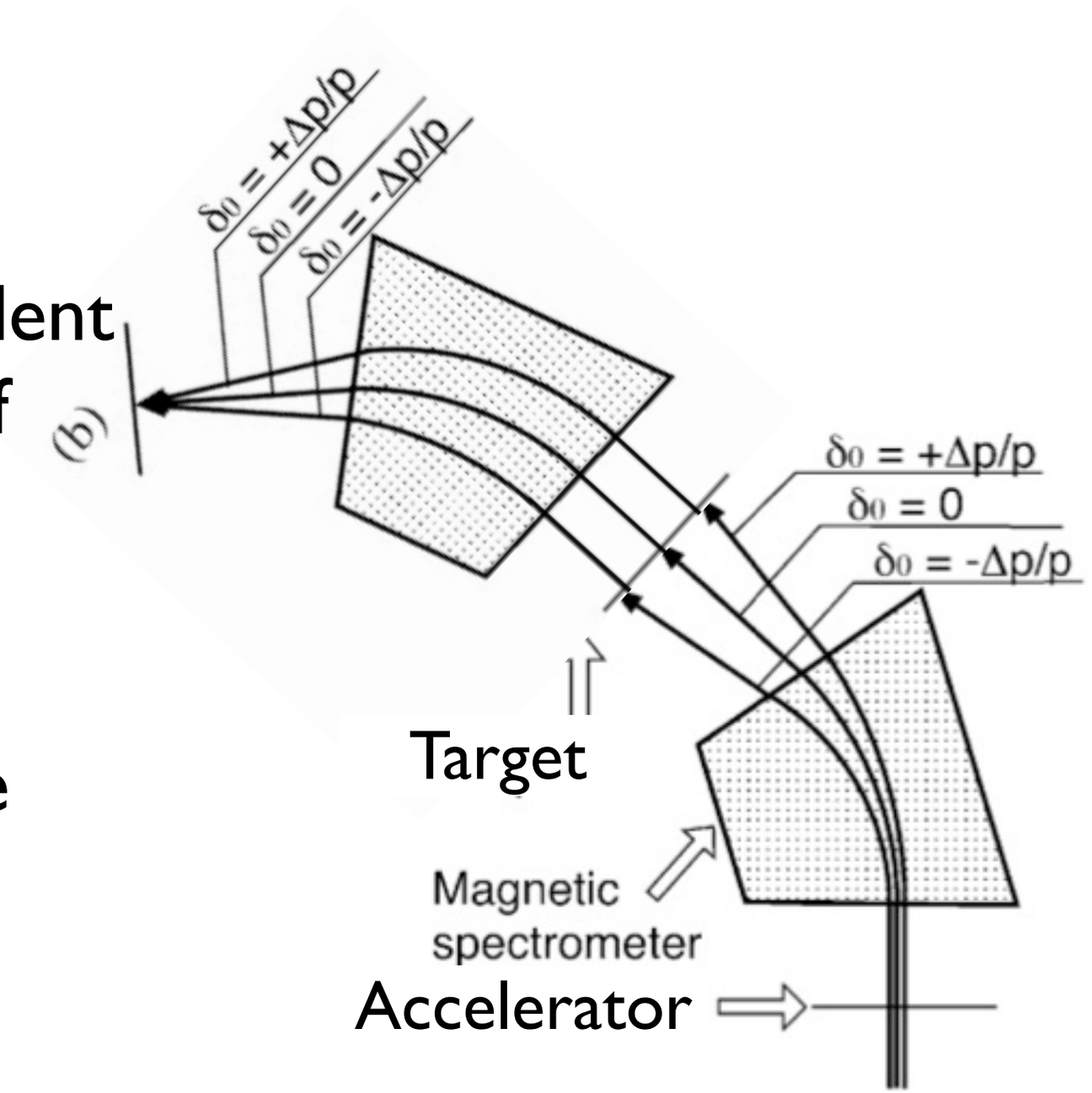
Dispersion matching

DM: resolving power of incident beam momentum = r.p of emitted particles

→contribution of beam momentum spread to the resolution is eliminated.



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

Precision spectroscopy at RI Beam Factory

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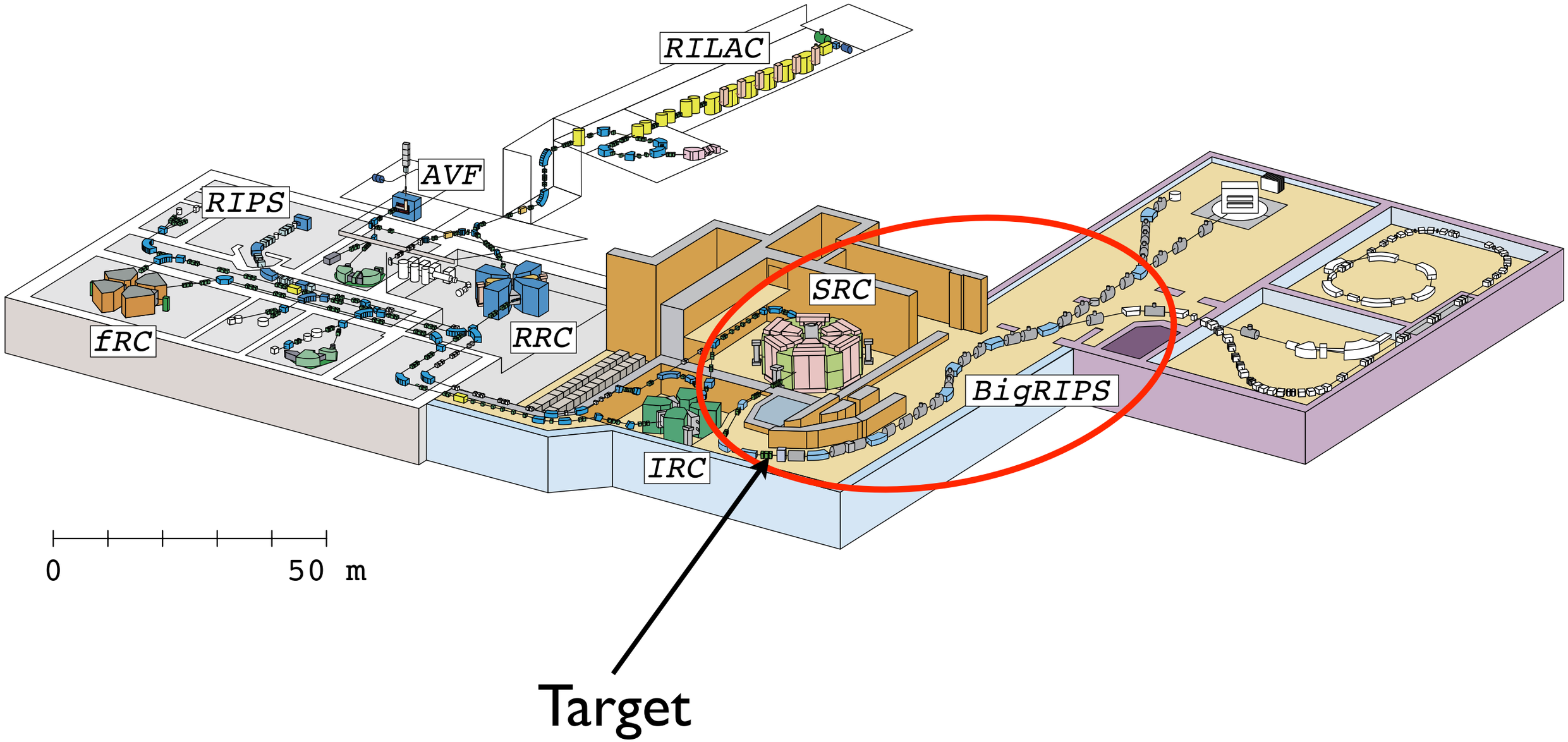

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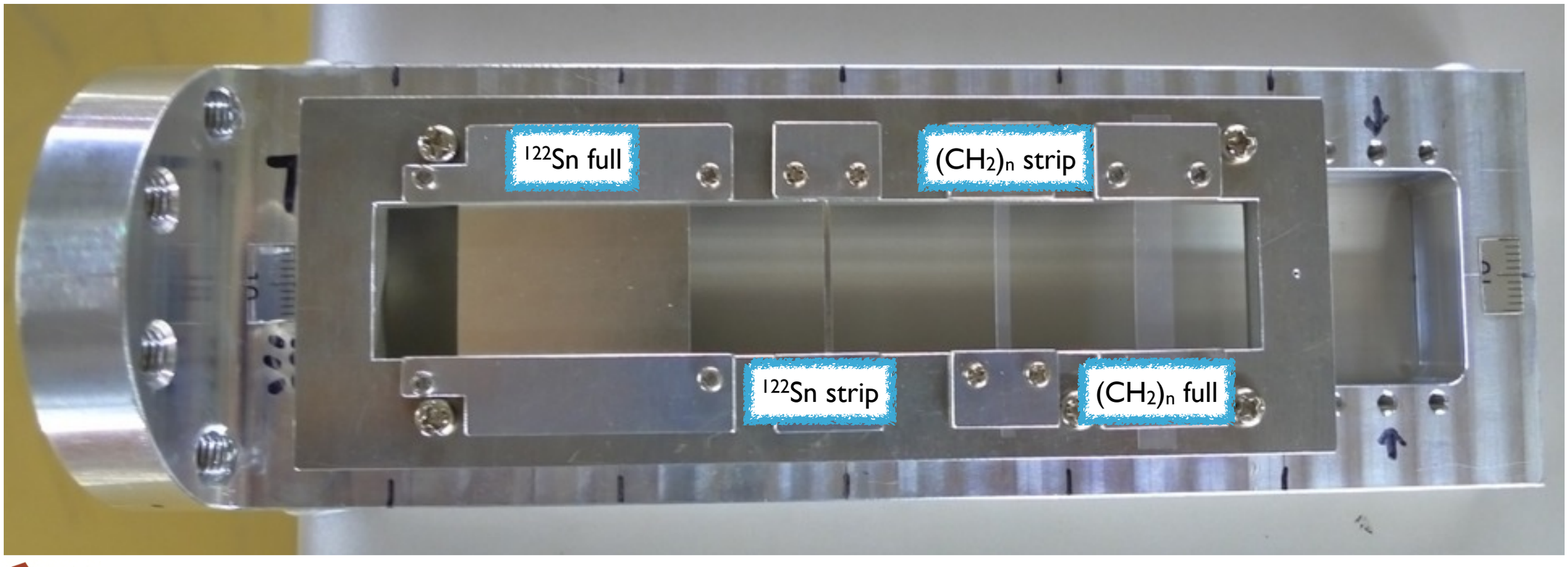
Target

Material	Thickness	Width	Purpose
^{122}Sn	10 mg/cm^2	1.0 mm	Production
^{122}Sn	10 mg/cm^2	full	Production
$(CH_2)_n$	100 μm	2.0 mm	Calibration
$(CH_2)_n$	100 μm	full	Calibration

Target	Run	Duration	^{3}He entry
^{122}Sn strip	12	926 min.	565626
^{122}Sn full	3	169 min.	213084
$(CH_2)_n$ strip	3	51 min.	244216
$(CH_2)_n$ full	1	17 min.	122535

$p(d,^3He)\pi^0$



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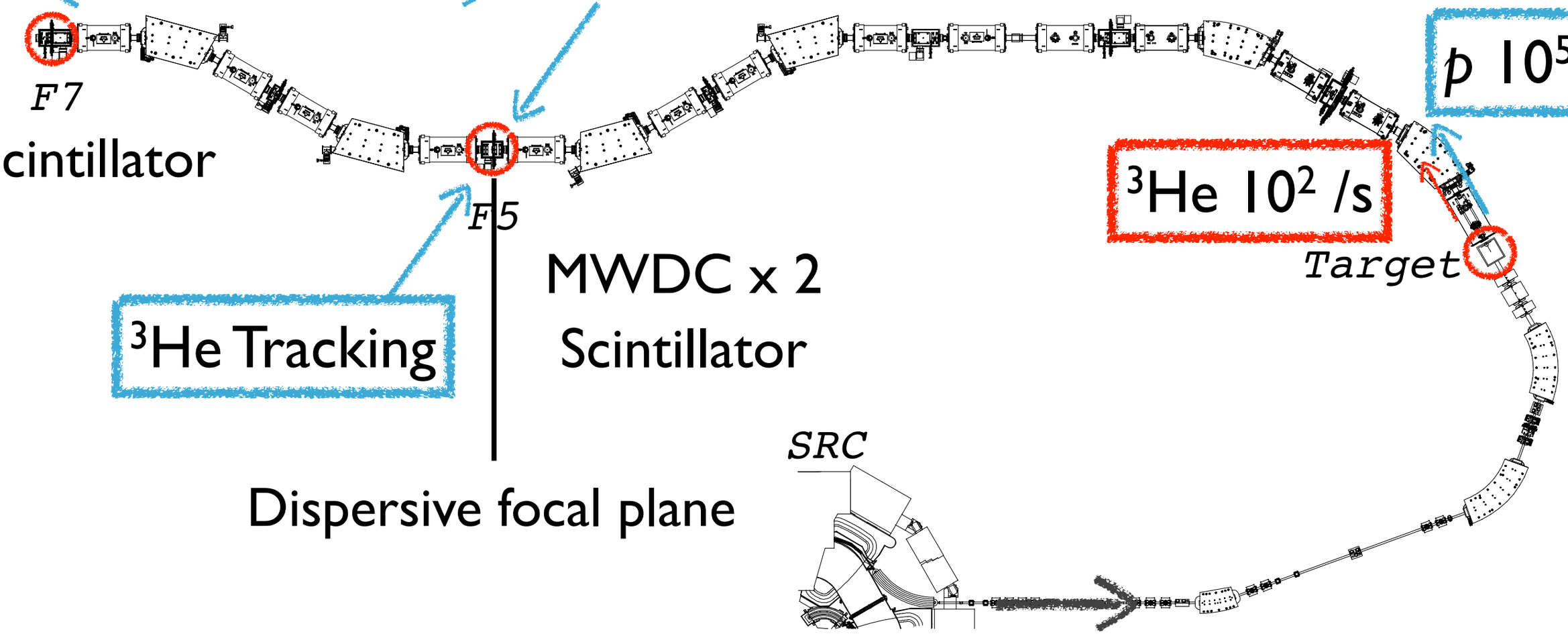
Experimental setup

BigRIPS

TOF measurement

ΔE measurement



p 10^5 /s

^{3}He 10^2 /s

^{3}He Tracking

Dispersive focal plane

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

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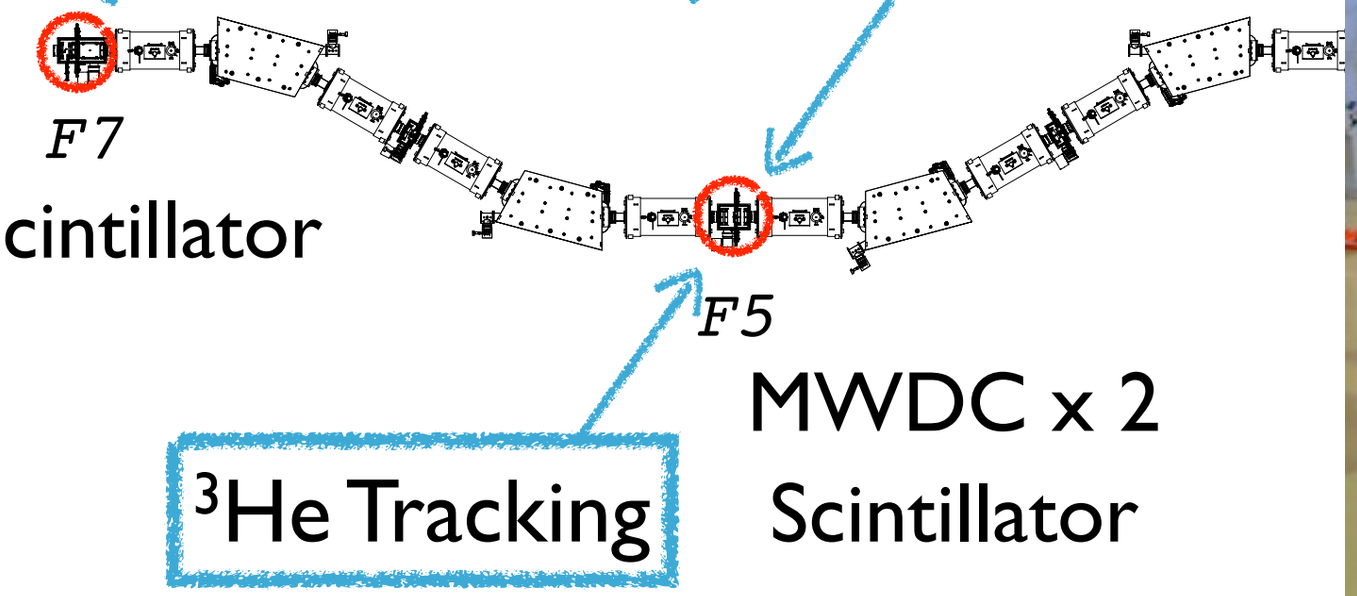
Experimental setup

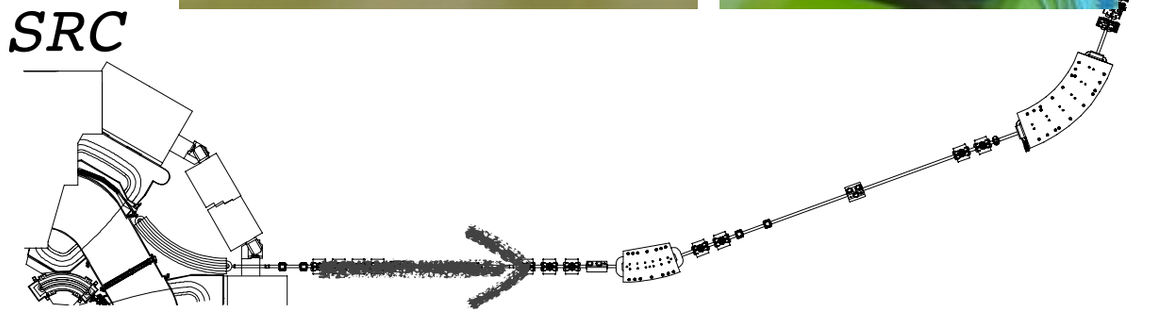
TOF measurement

ΔE measuremen

BigRIPS



10^5 /s



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

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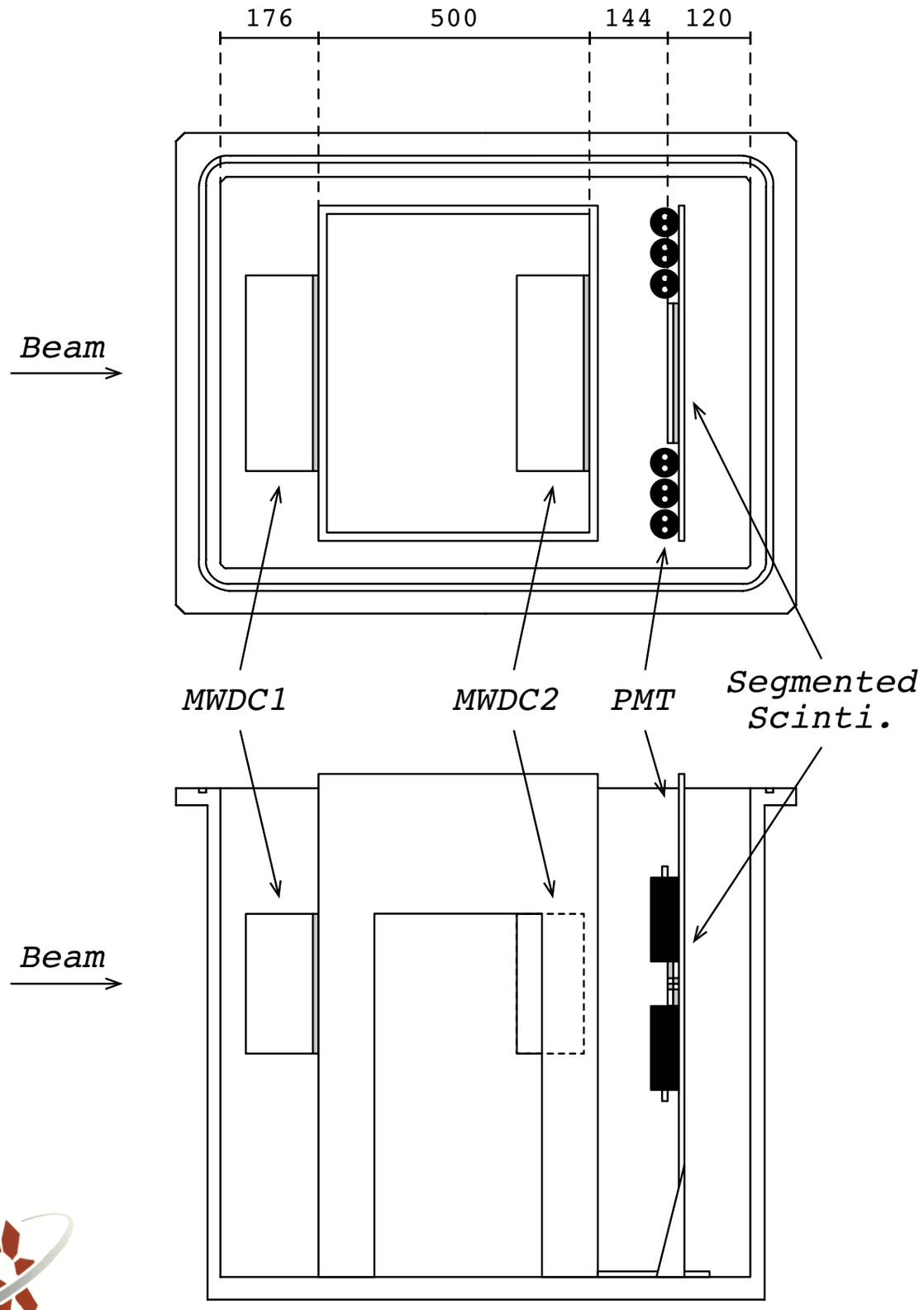
Focal plane detectors

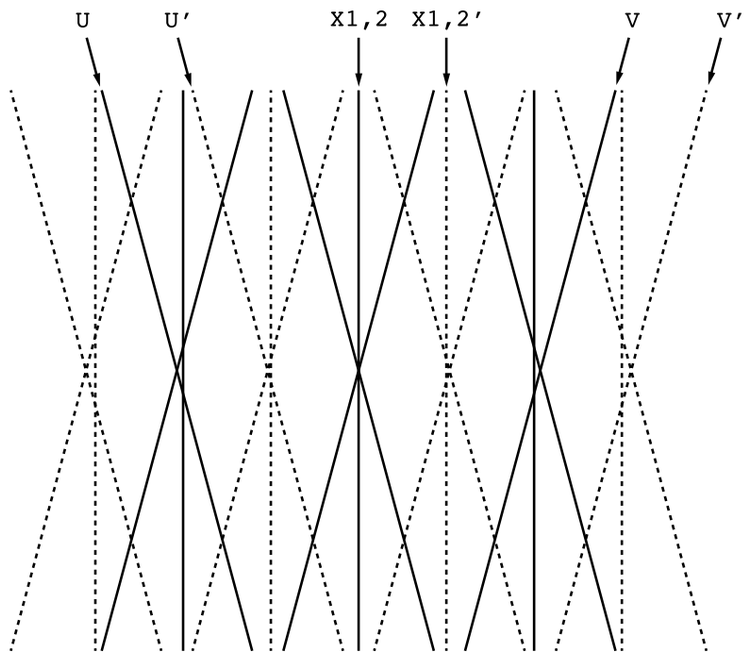


MWDC

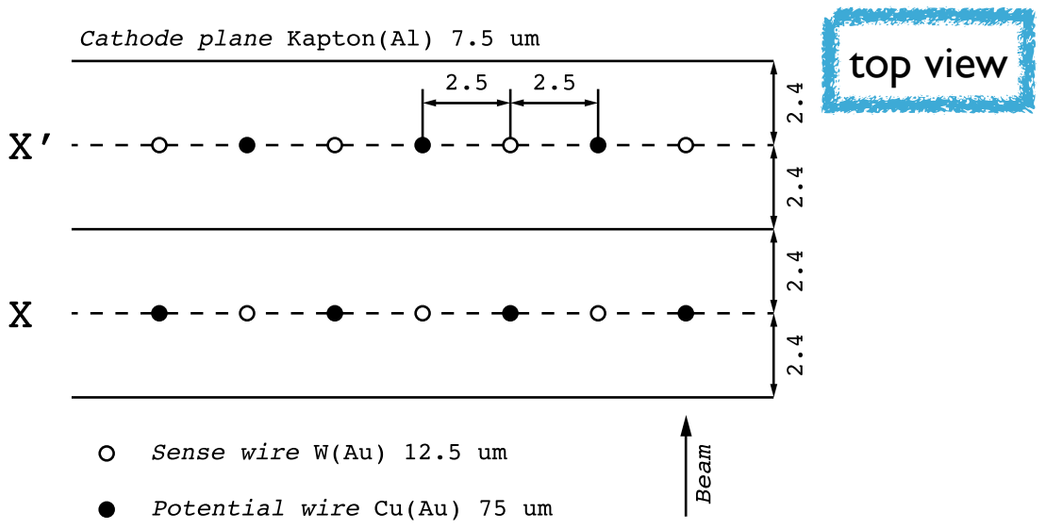
Plane: X1, X1', X2, X2', U, U', V, and V'

Position resolution: 0.3 mm (FWHM)

Efficiency: more than 99% (each plane)



front view



top view

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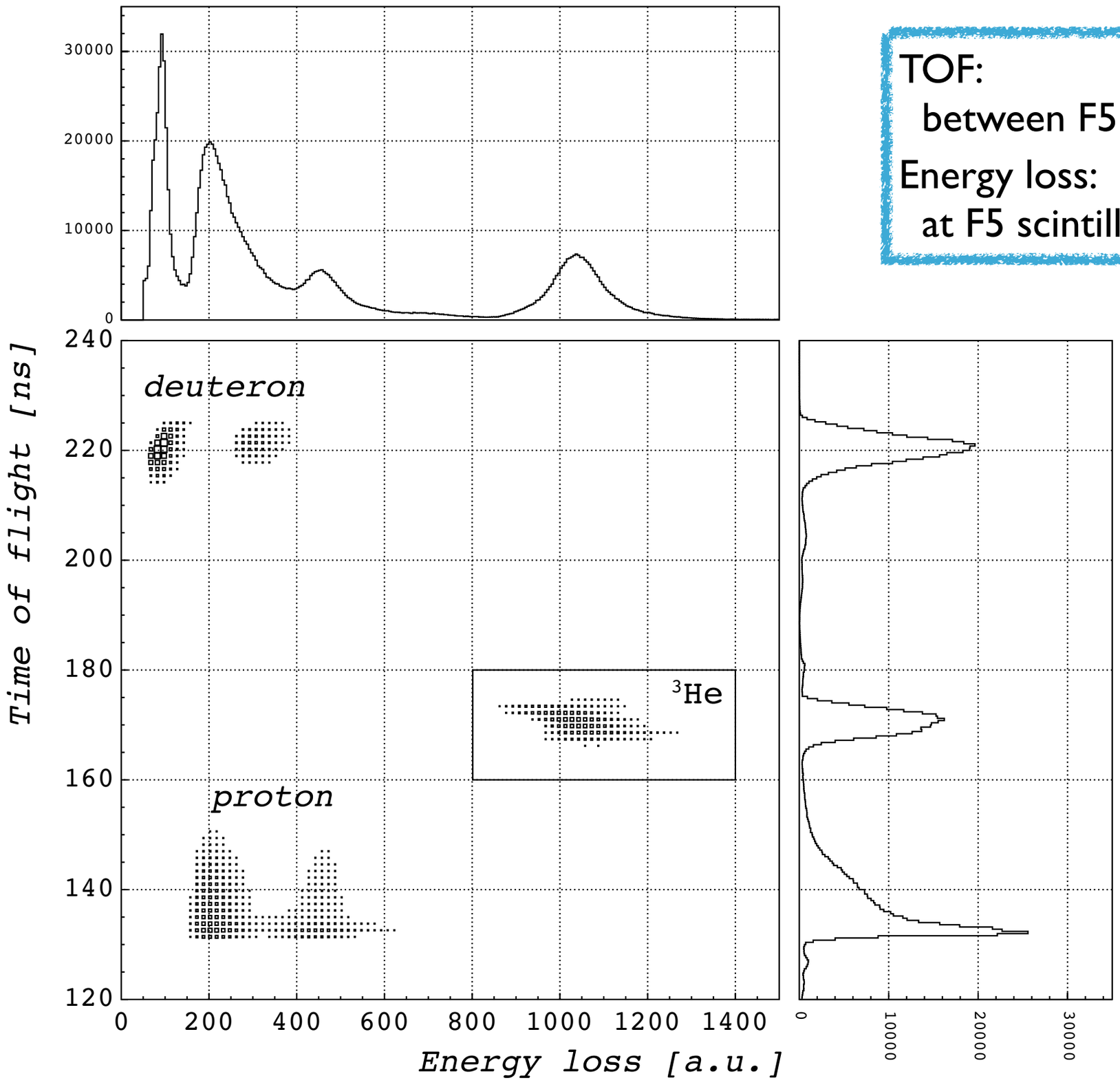
Particle identification



TOF:
between F5 and F7

Energy loss:
at F5 scintillators

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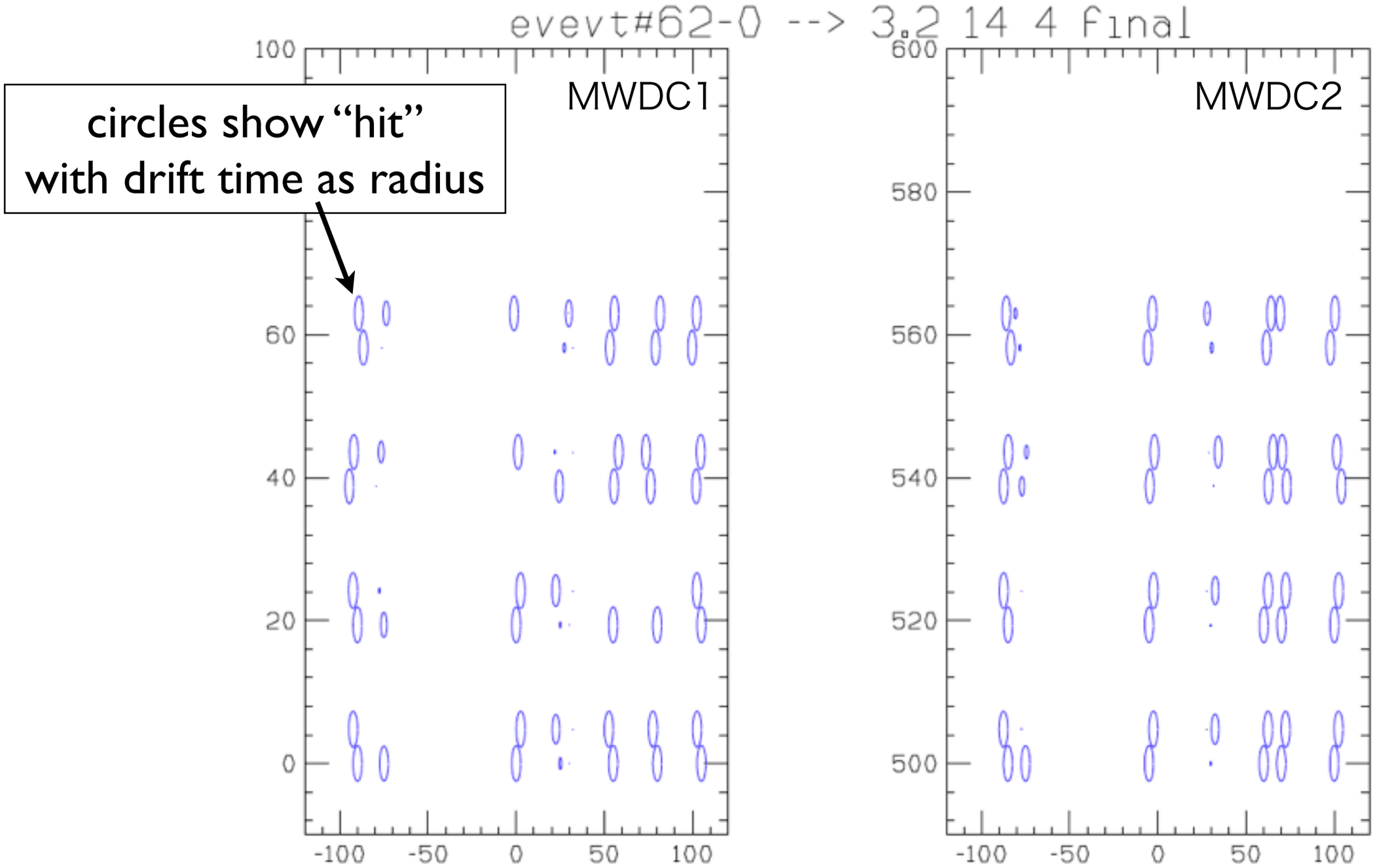
Typical Event in MWDC



7 tracks in 200 ns = 35 MHz

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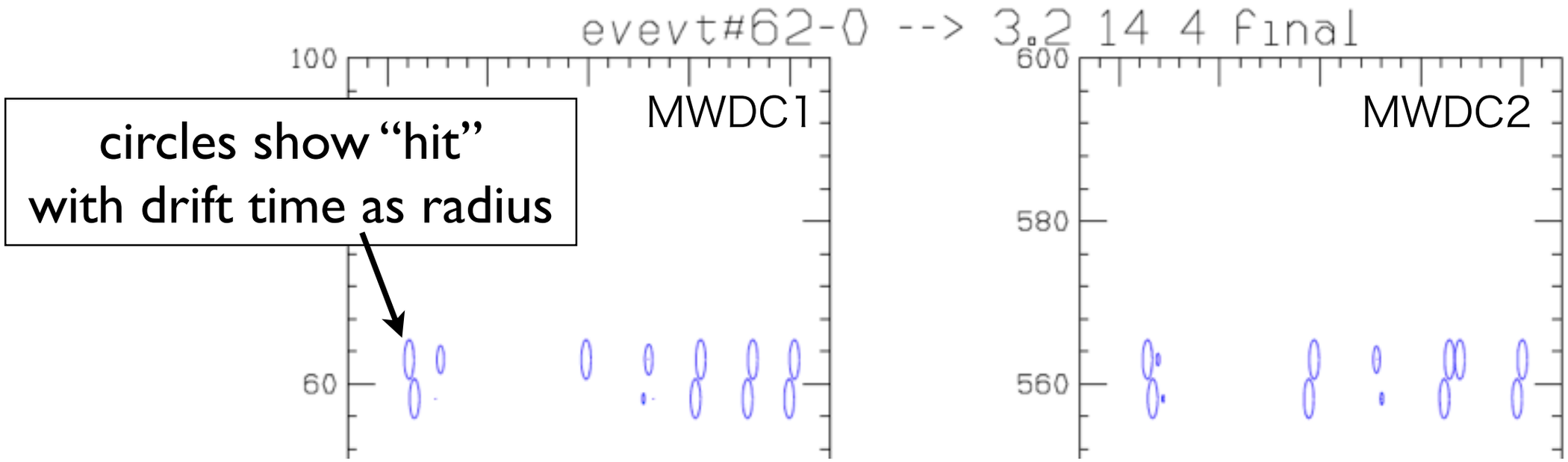
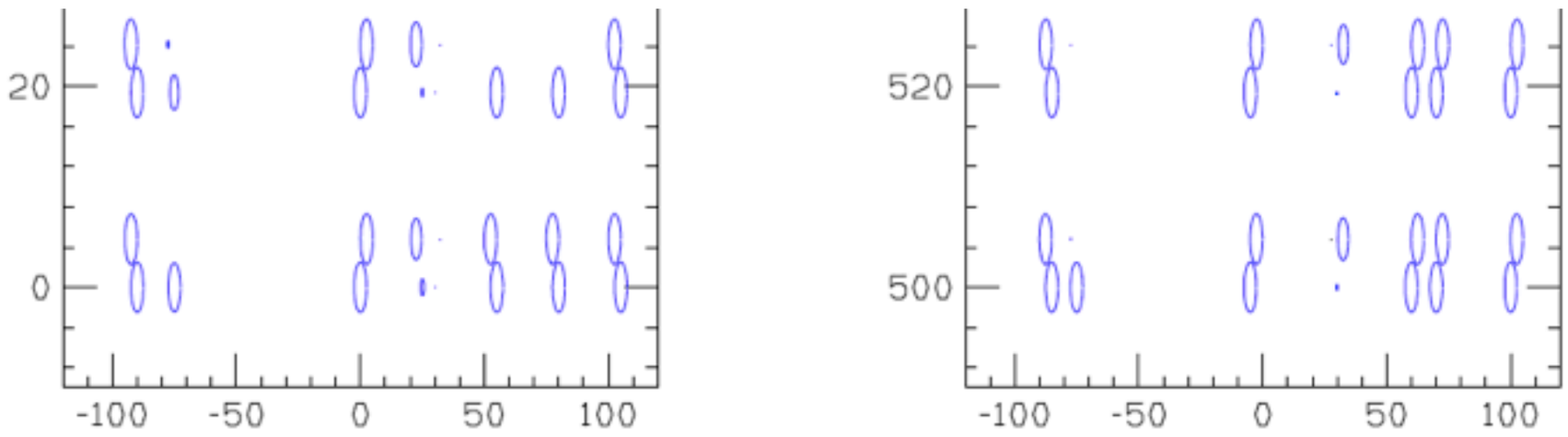
Typical Event in MWDC



6 tracks are "protons" and only one 3He track exists.

So which?



7 tracks in 200 ns = 35 MHz

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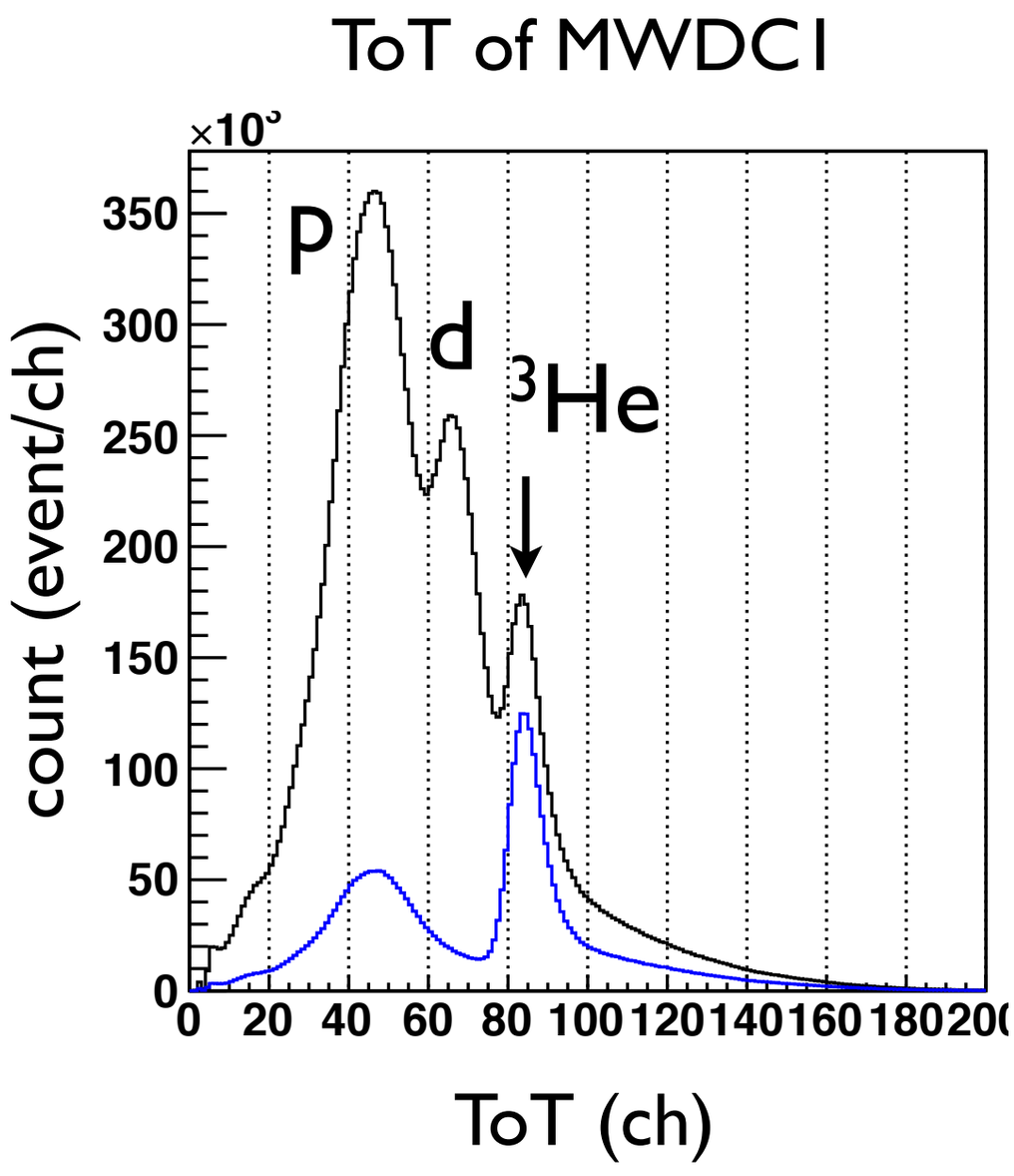
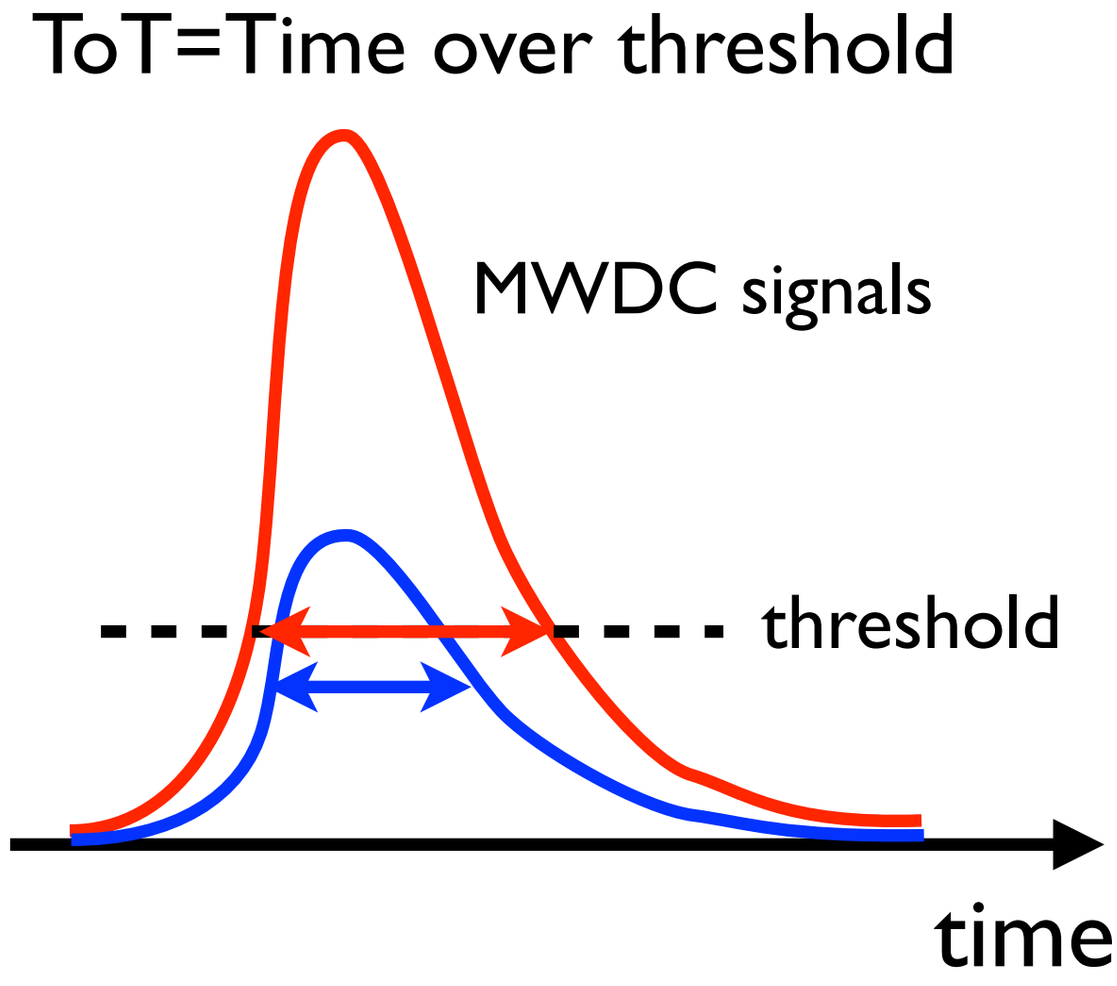
Particle ID by MWDC itself





After combination with scintillator information →

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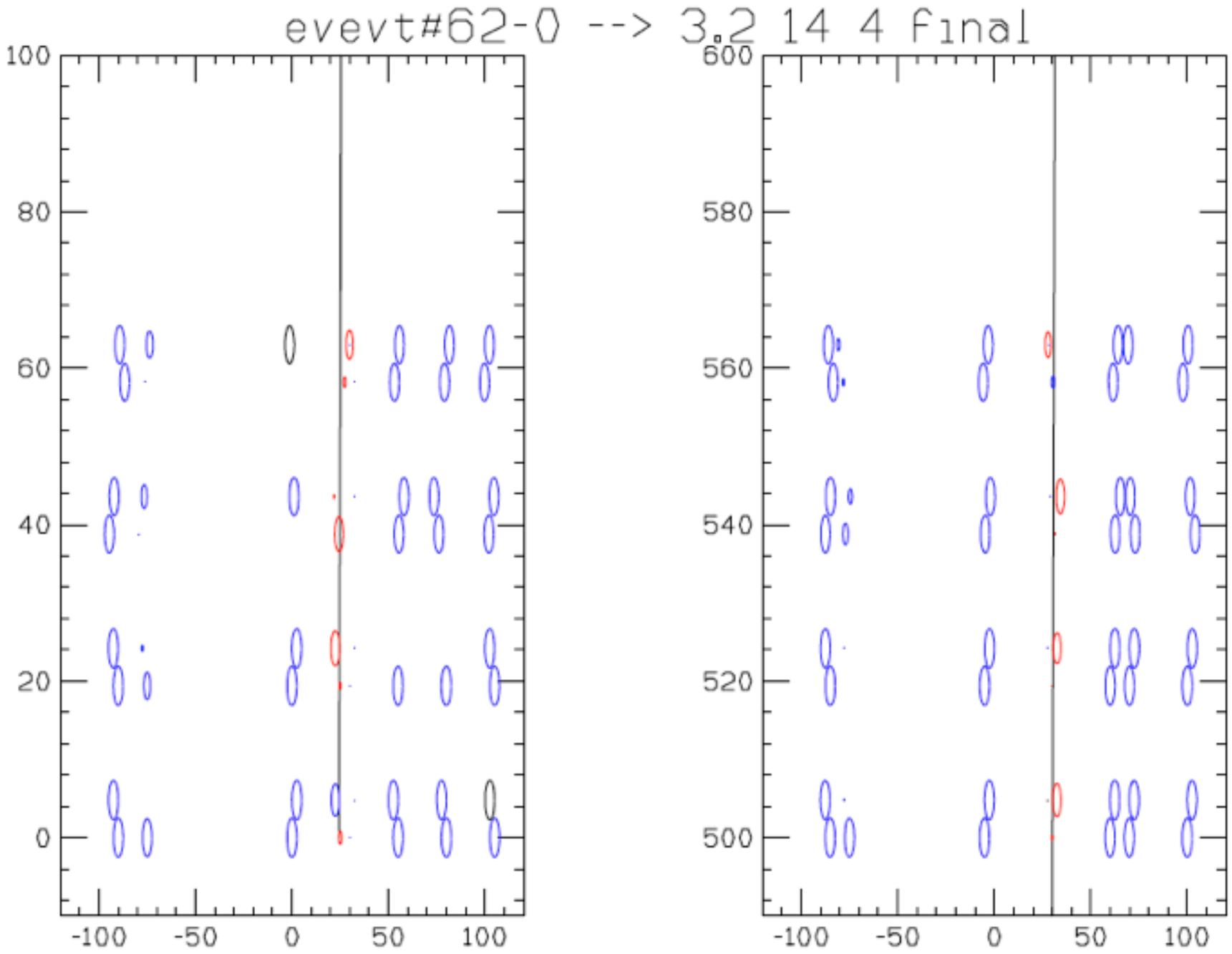
^{3}He Track is reconstructed



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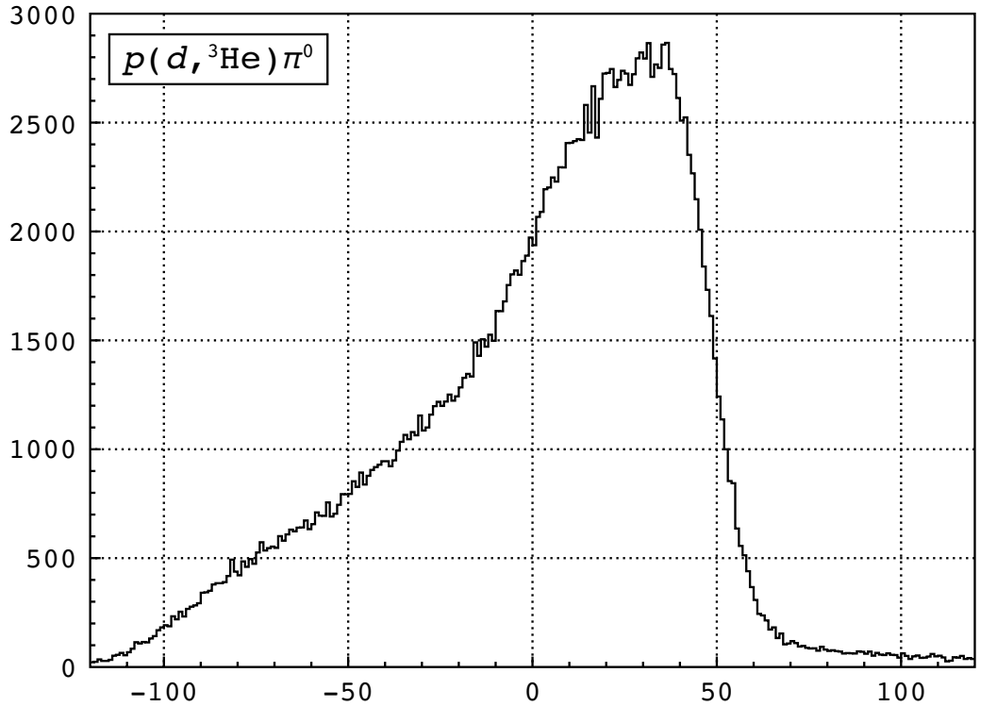
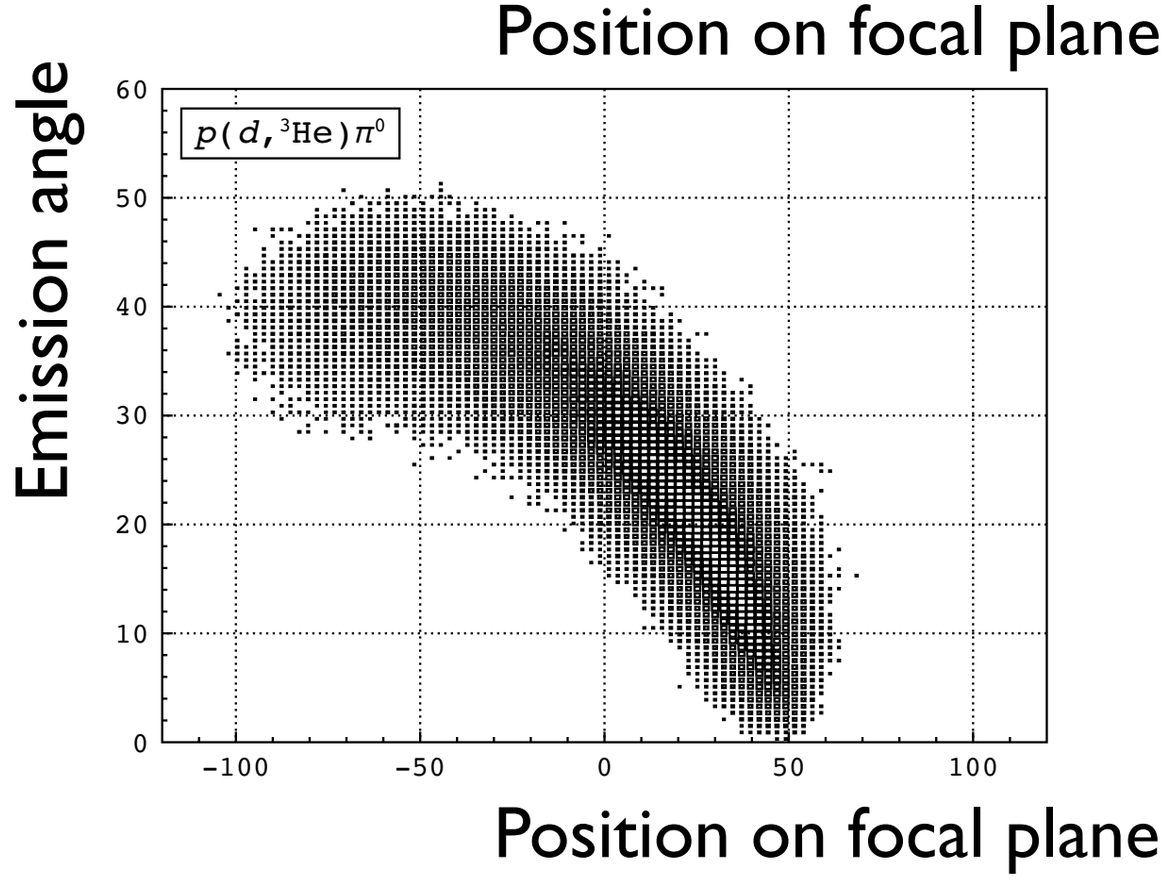
Energy calibration

Position → Energy conversion



Kinematics:
two body reaction
$p(d,{}^3He)\pi^0$
Quadratic correlation between angle and momentum



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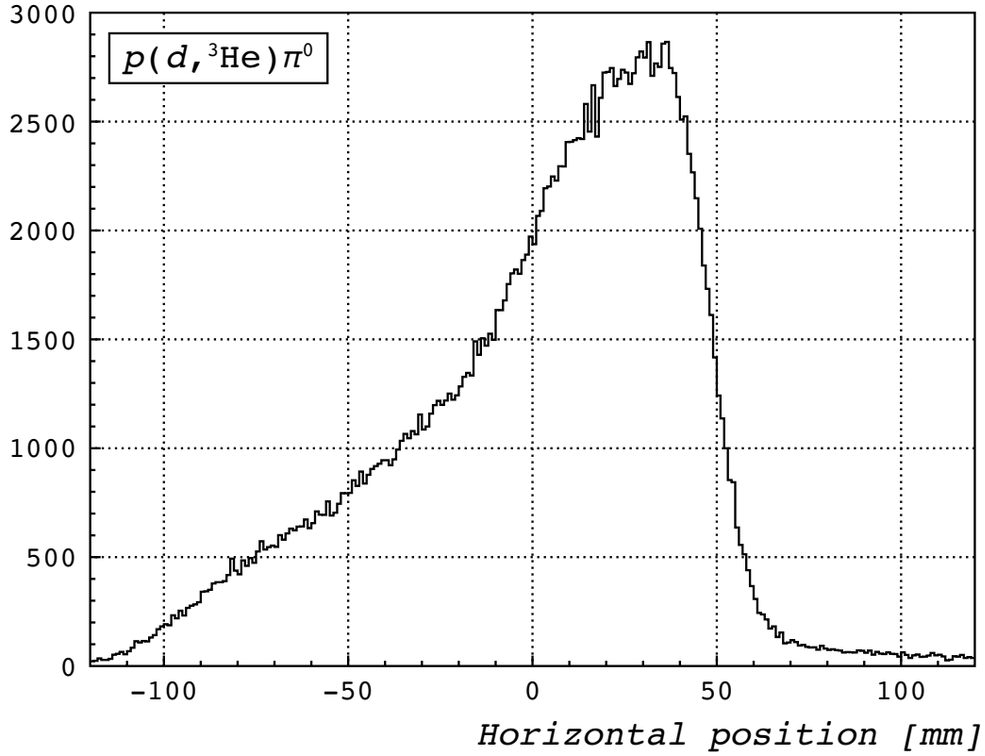
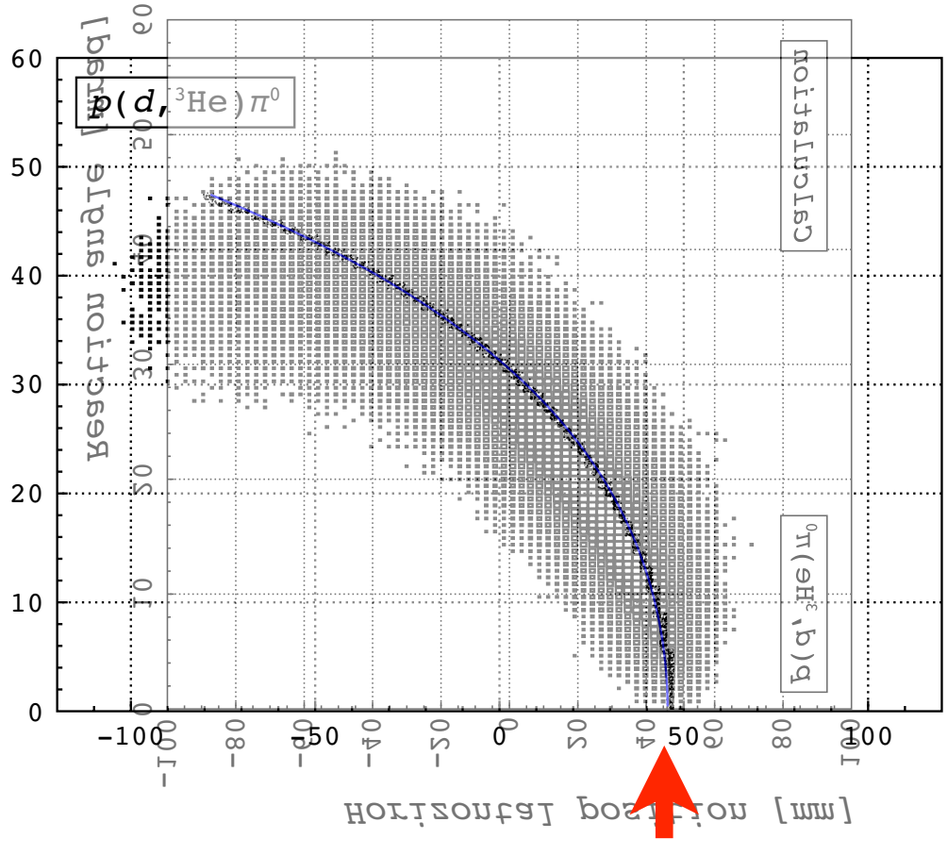
Energy calibration



Kinematically determined calibration of ^{3}He Energy



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Pionic Atom Spectra in (d,^{3}He) reactions

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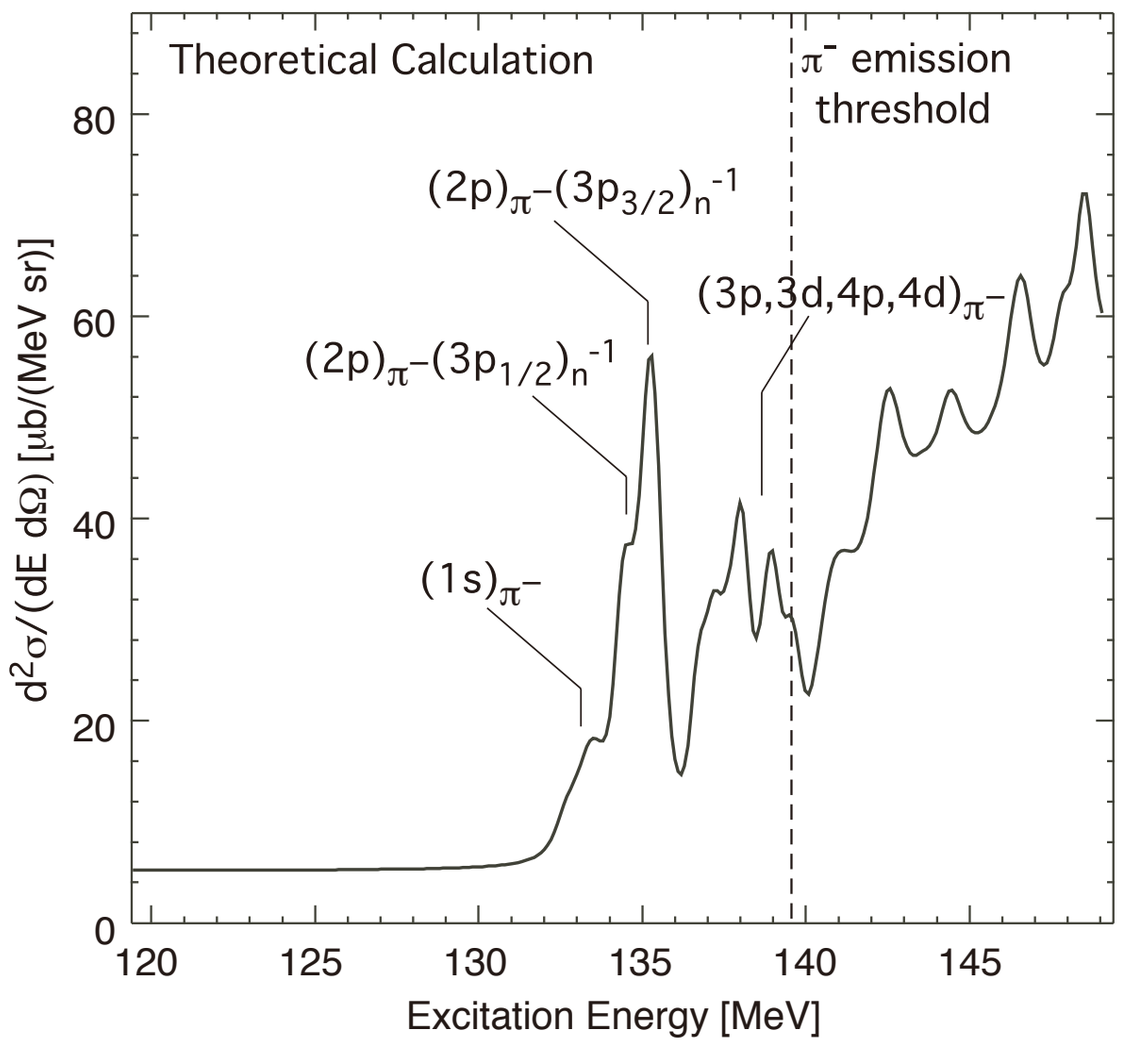
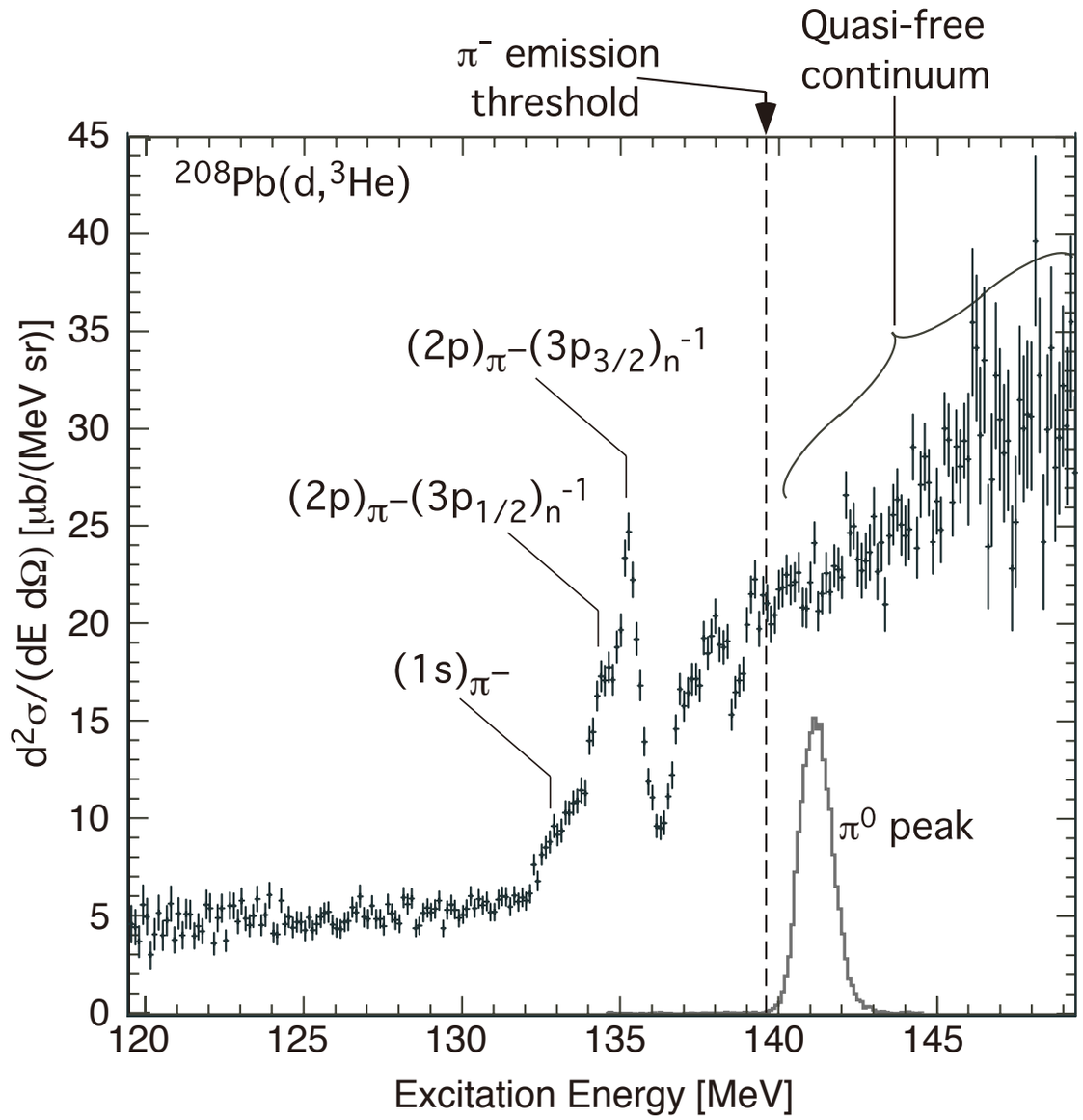
Theory and Experiment

Preceding exp. at GSI for pionic lead atoms in **^{208}Pb(d,^{3}He)** reaction





Strinkingly good agreement between theory and exp.

K.I et al., PRC62,025202

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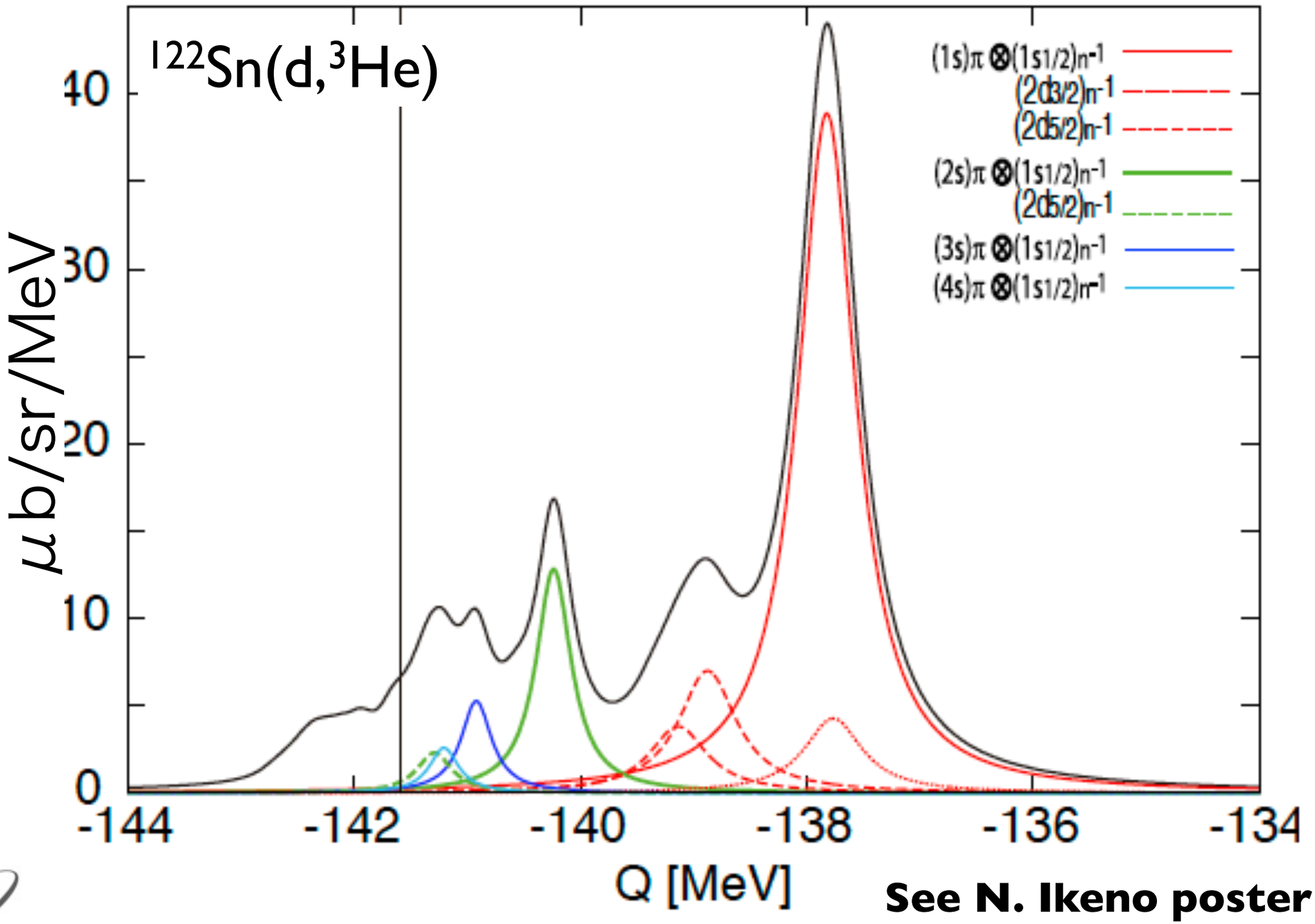
Theoretical Spectrum for ^{122}Sn(d,^{3}He)



See N. Ikeno poster #22

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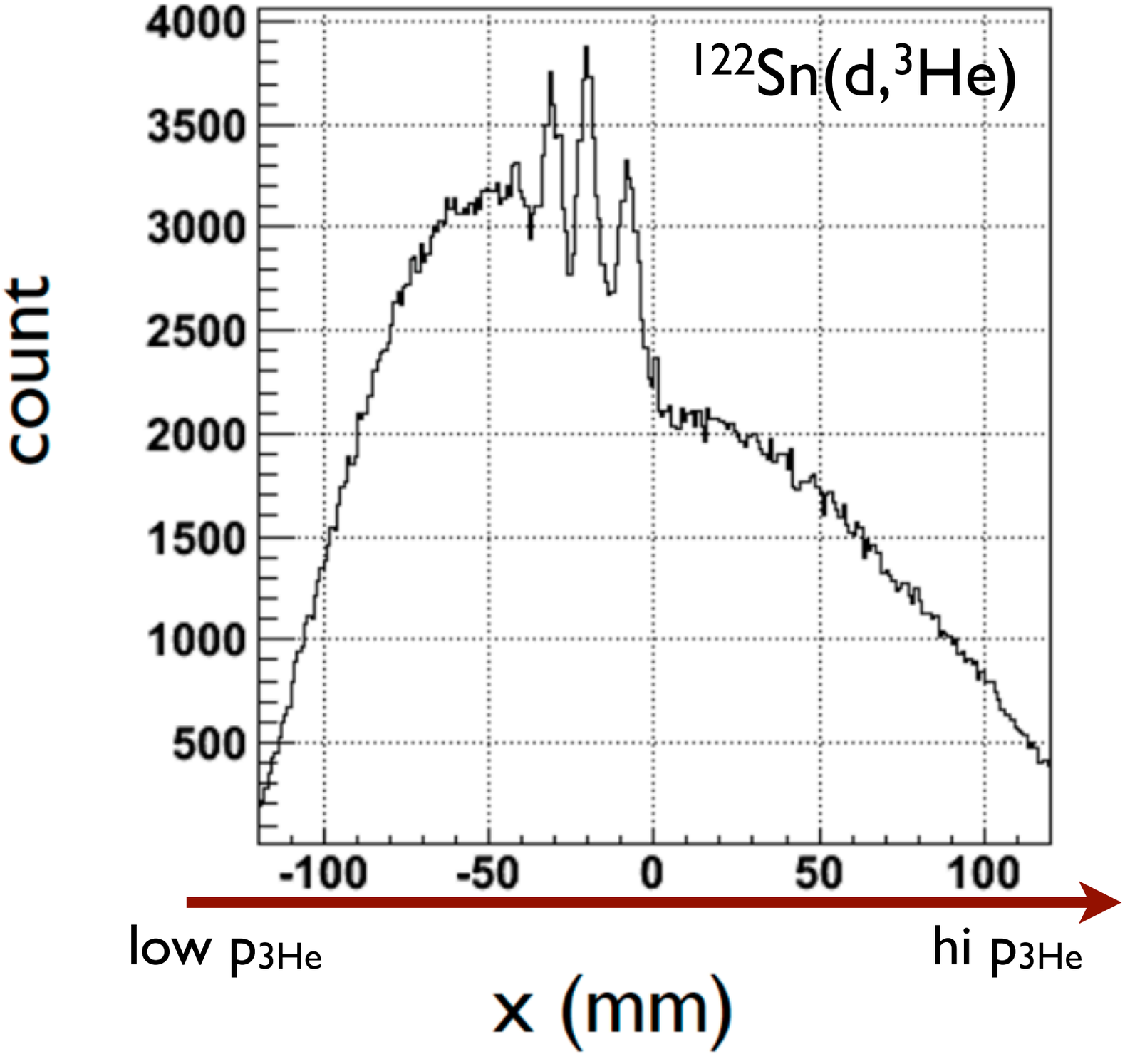
Focal Plane ^{3}He Spectrum

(acceptance uncorrected)

15 hours

data accumulation
with 10^{12}/s beam



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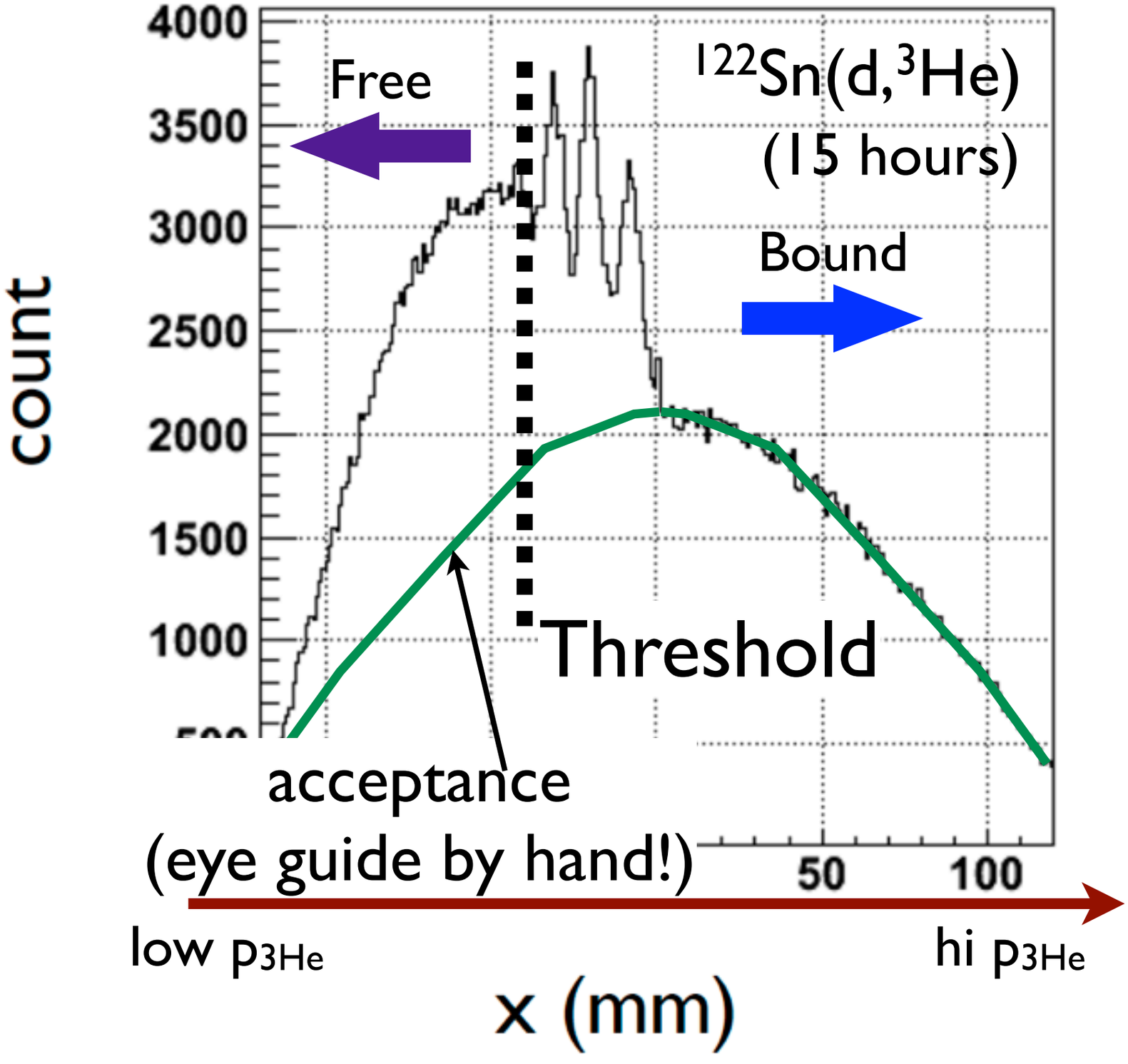
Focal Plane ^{3}He Spectrum

(acceptance uncorrected)

15 hours

data accumulation

with 10^{12}/s beam



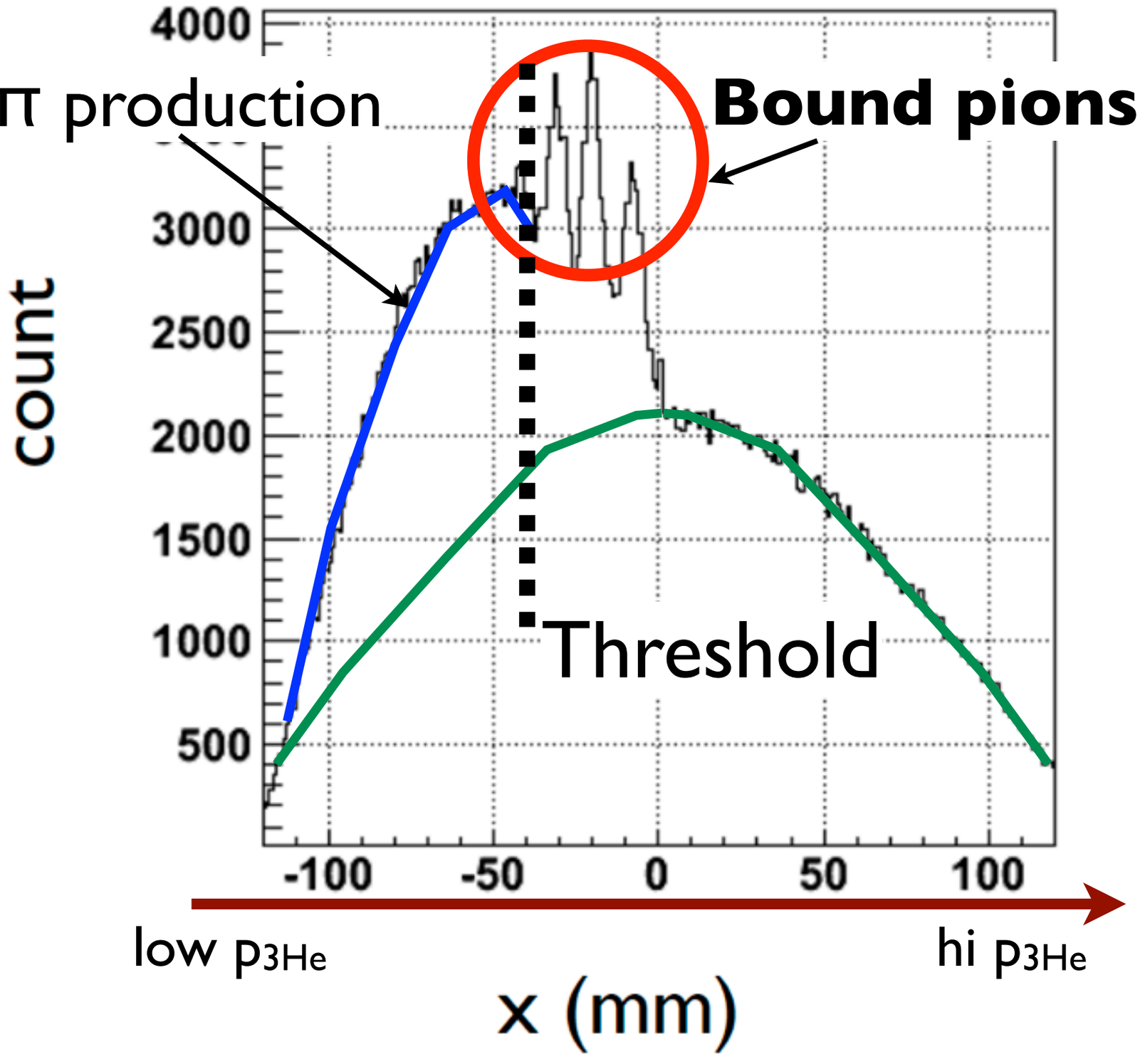
Focal Plane ^{3}He Spectrum

(acceptance uncorrected)

15 hours

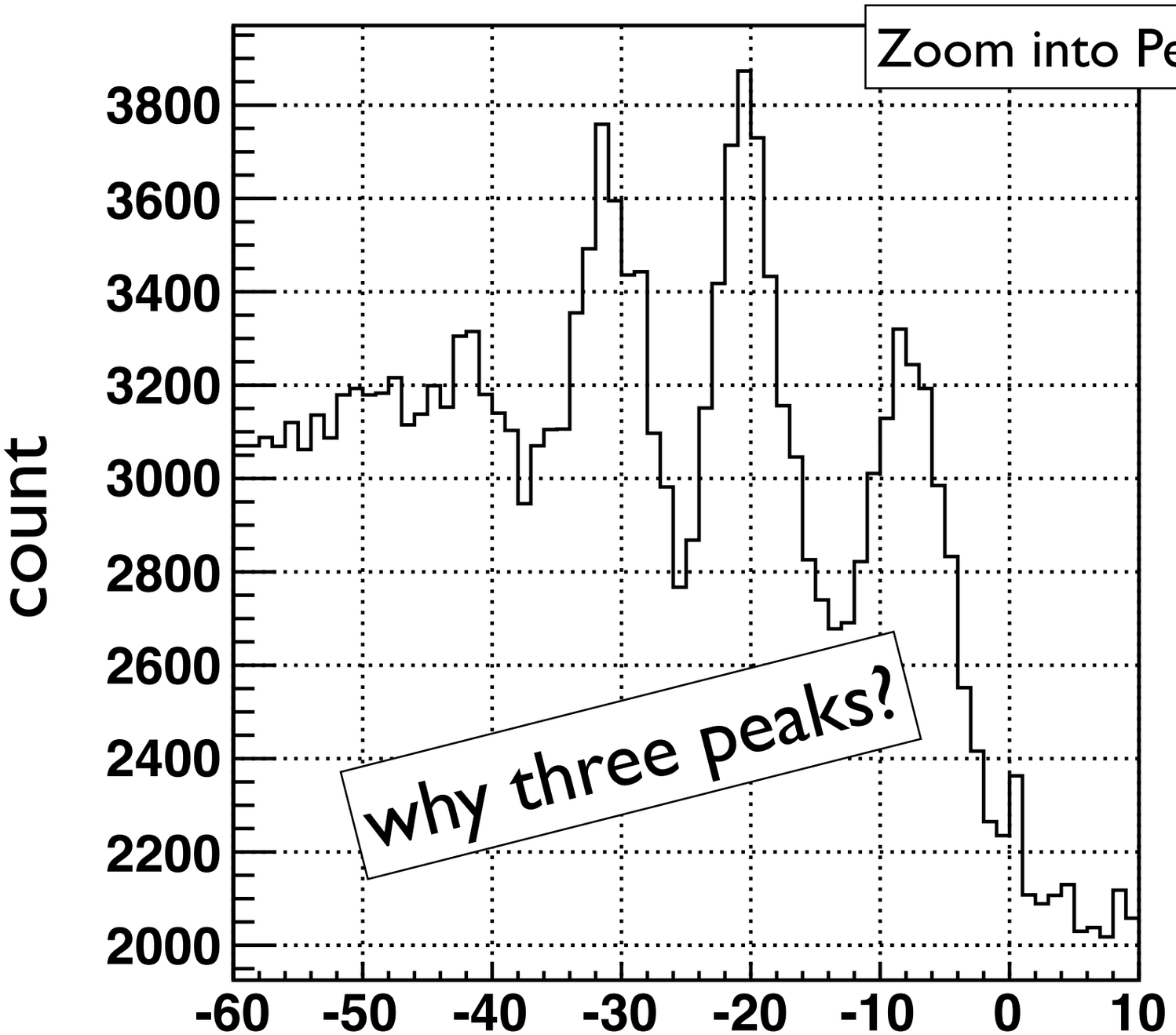
data accumulation
with 10^{12}/s beam

We observed 3 peaks...
while we expected
1s and 2s peaks...

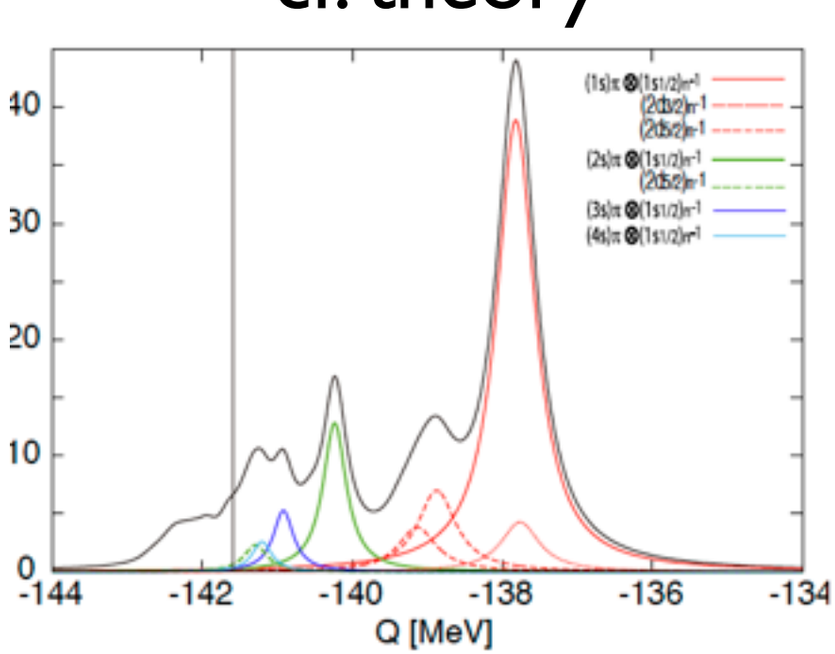


Focal Plane ^{3}He Spectrum

(acceptance uncorrected)

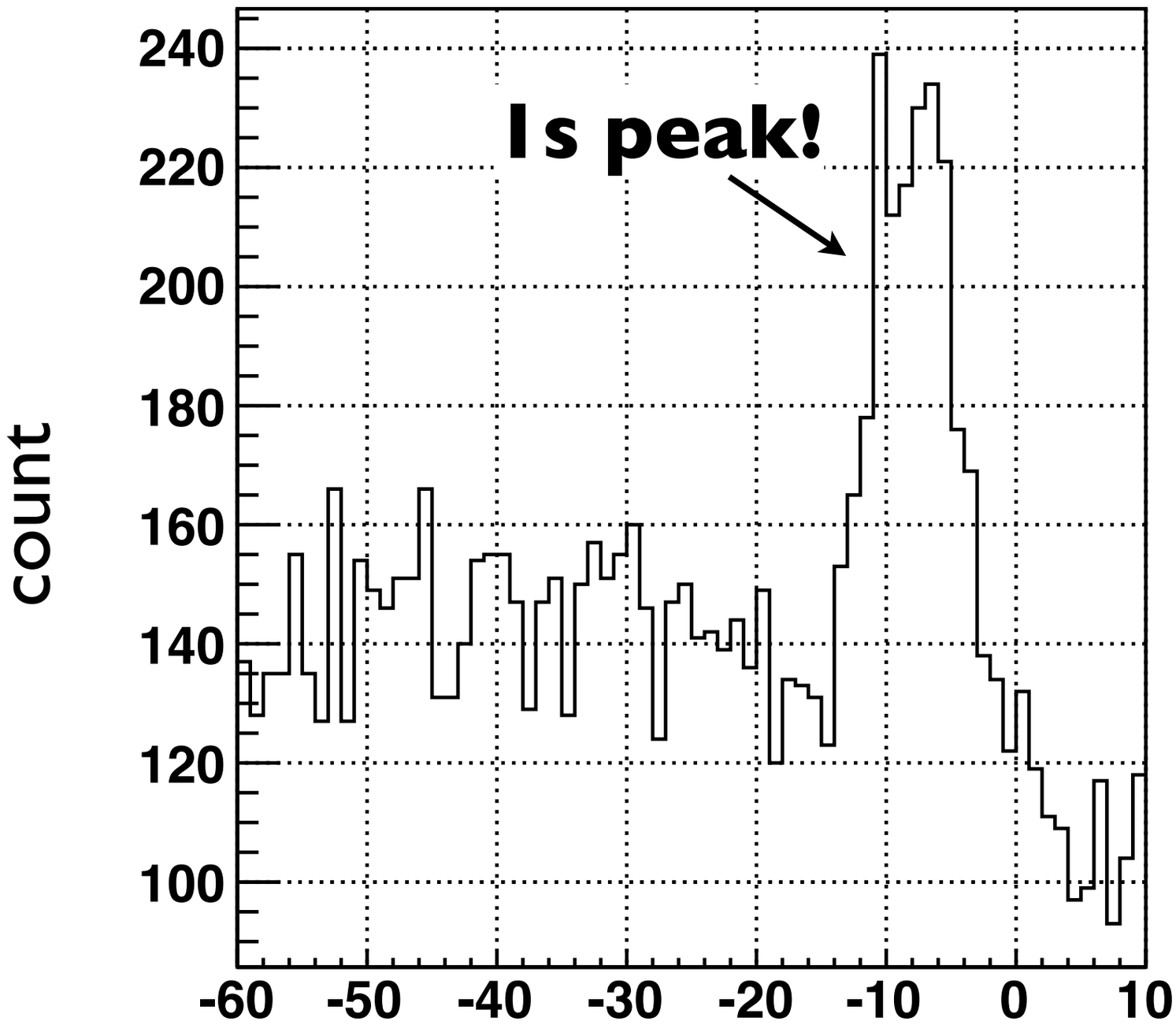


cf. theory

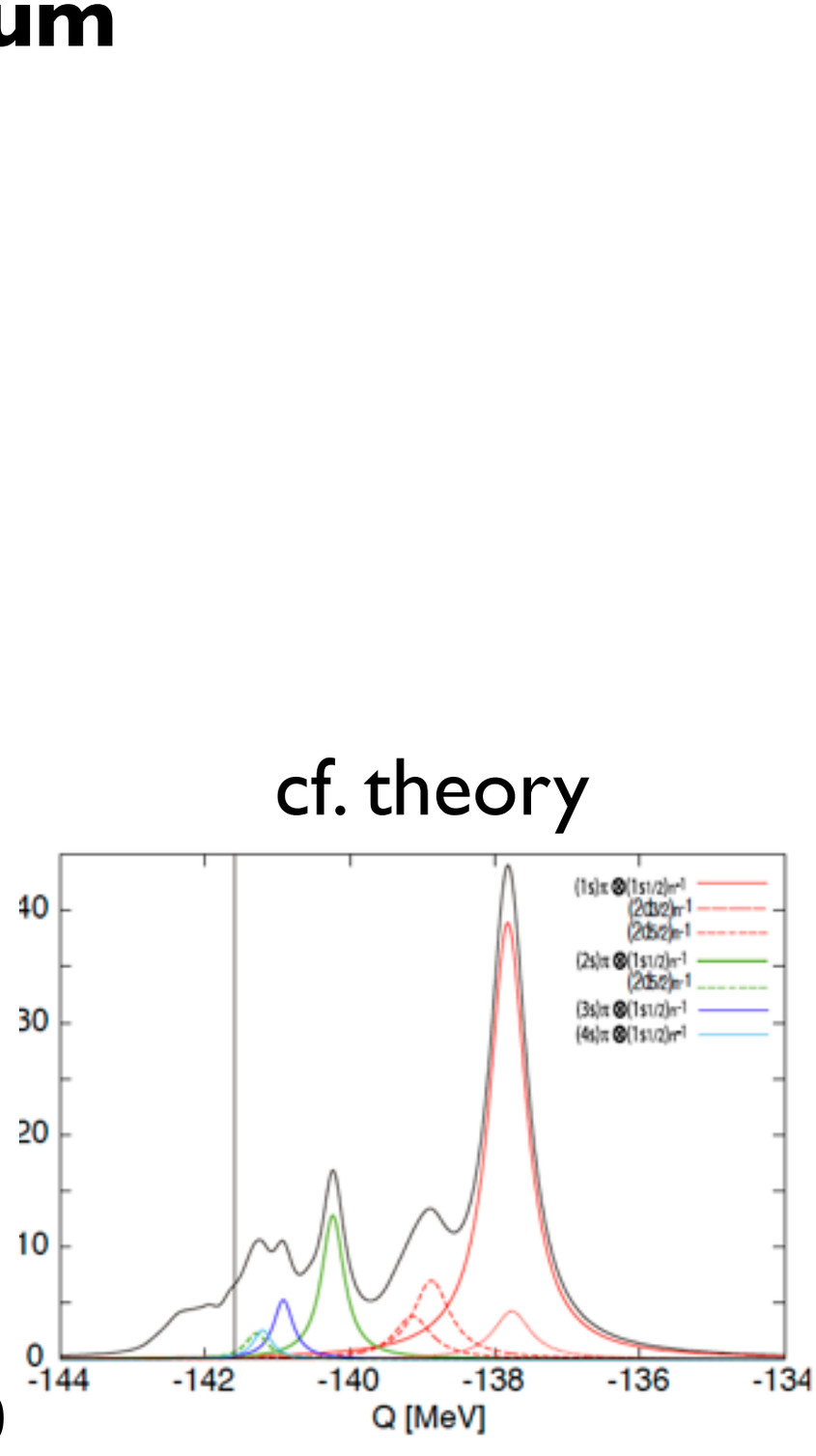


Focal Plane ^{3}He Spectrum

(acceptance uncorrected)



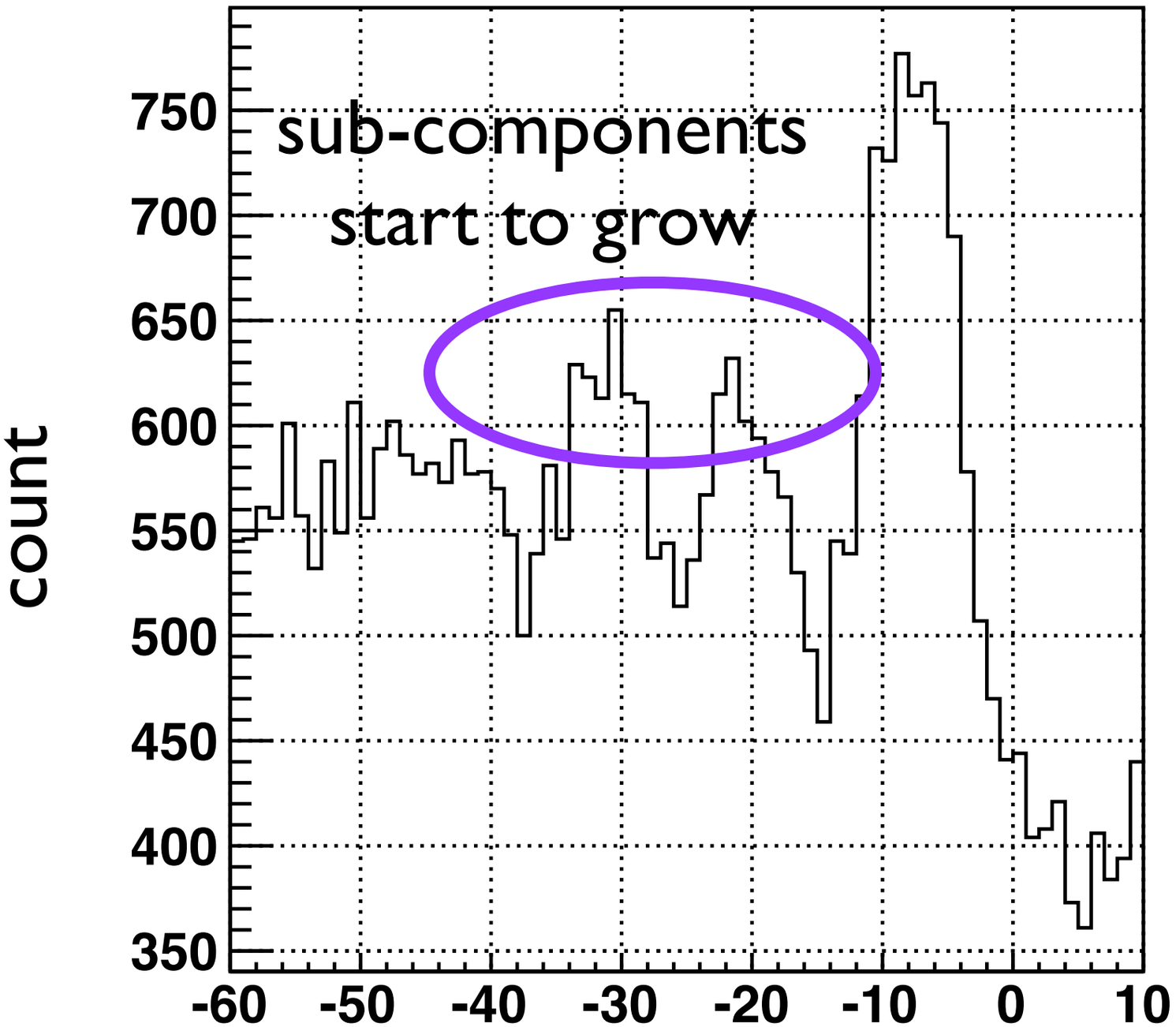
cf. theory



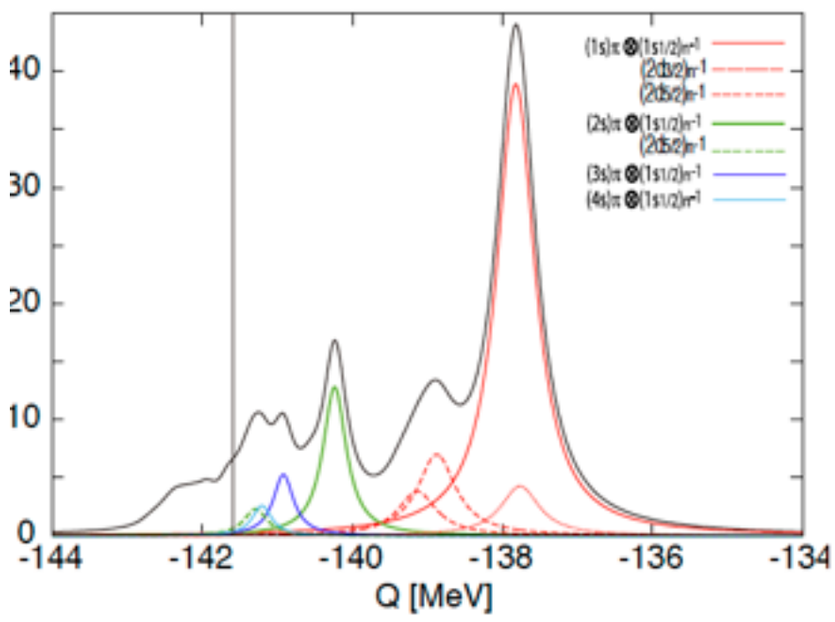
$\theta_{reaction}$<5 mrad

Focal Plane ^{3}He Spectrum

(acceptance uncorrected)



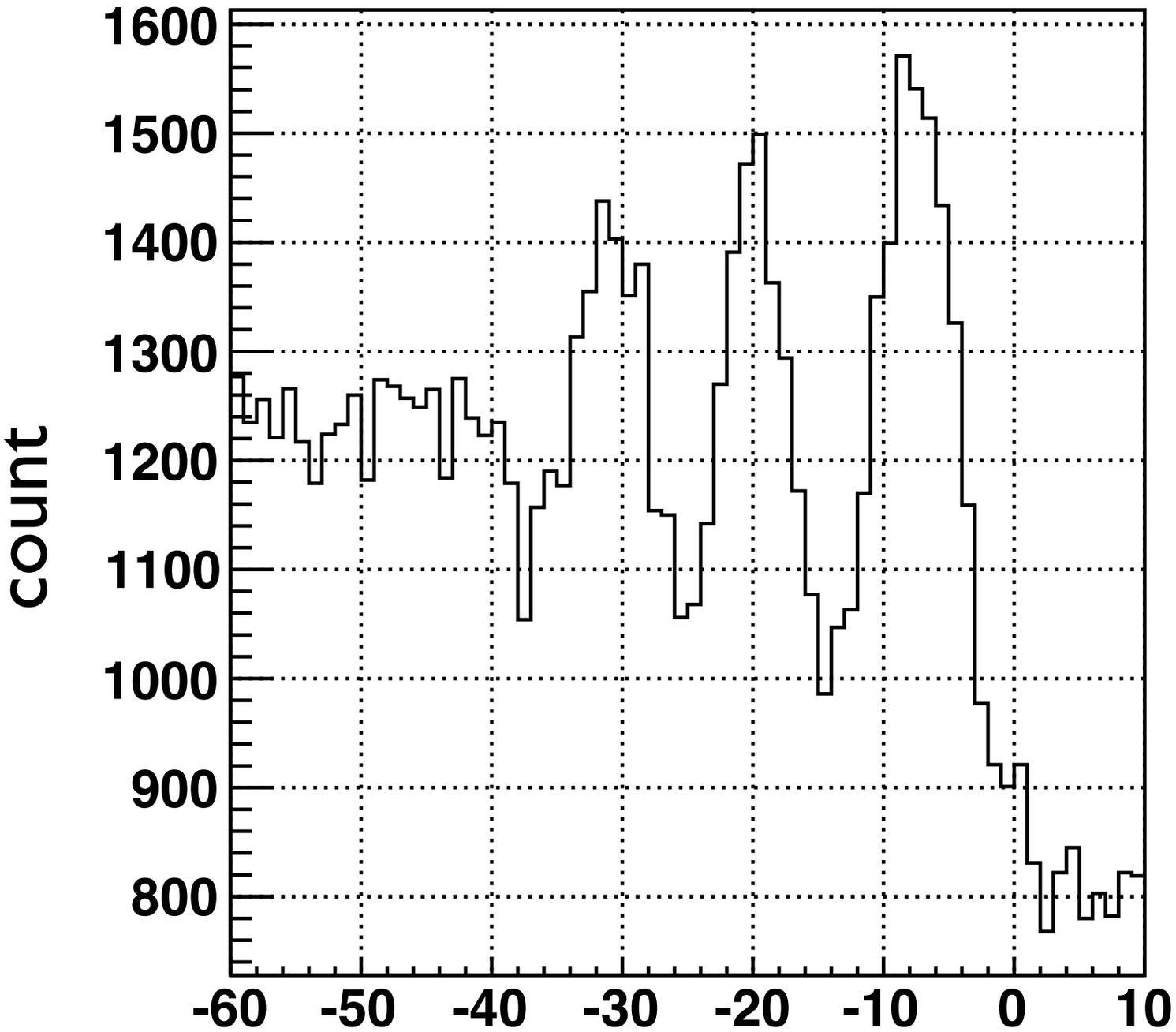
cf. theory



$\theta_{reaction}$<10 mrad

Focal Plane ^{3}He Spectrum

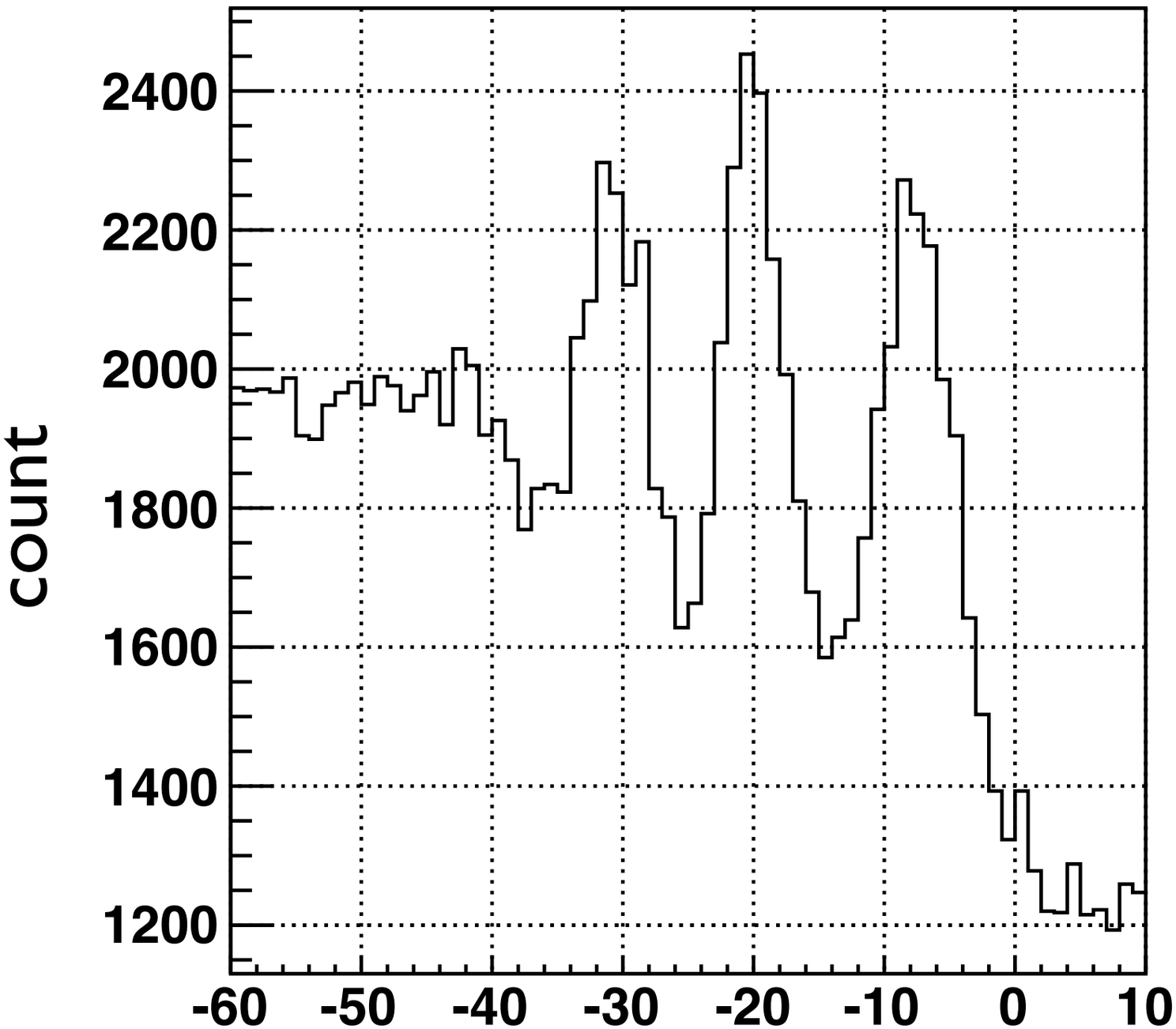
(acceptance uncorrected)



$\theta_{reaction}$<15 mrad

Focal Plane ^{3}He Spectrum

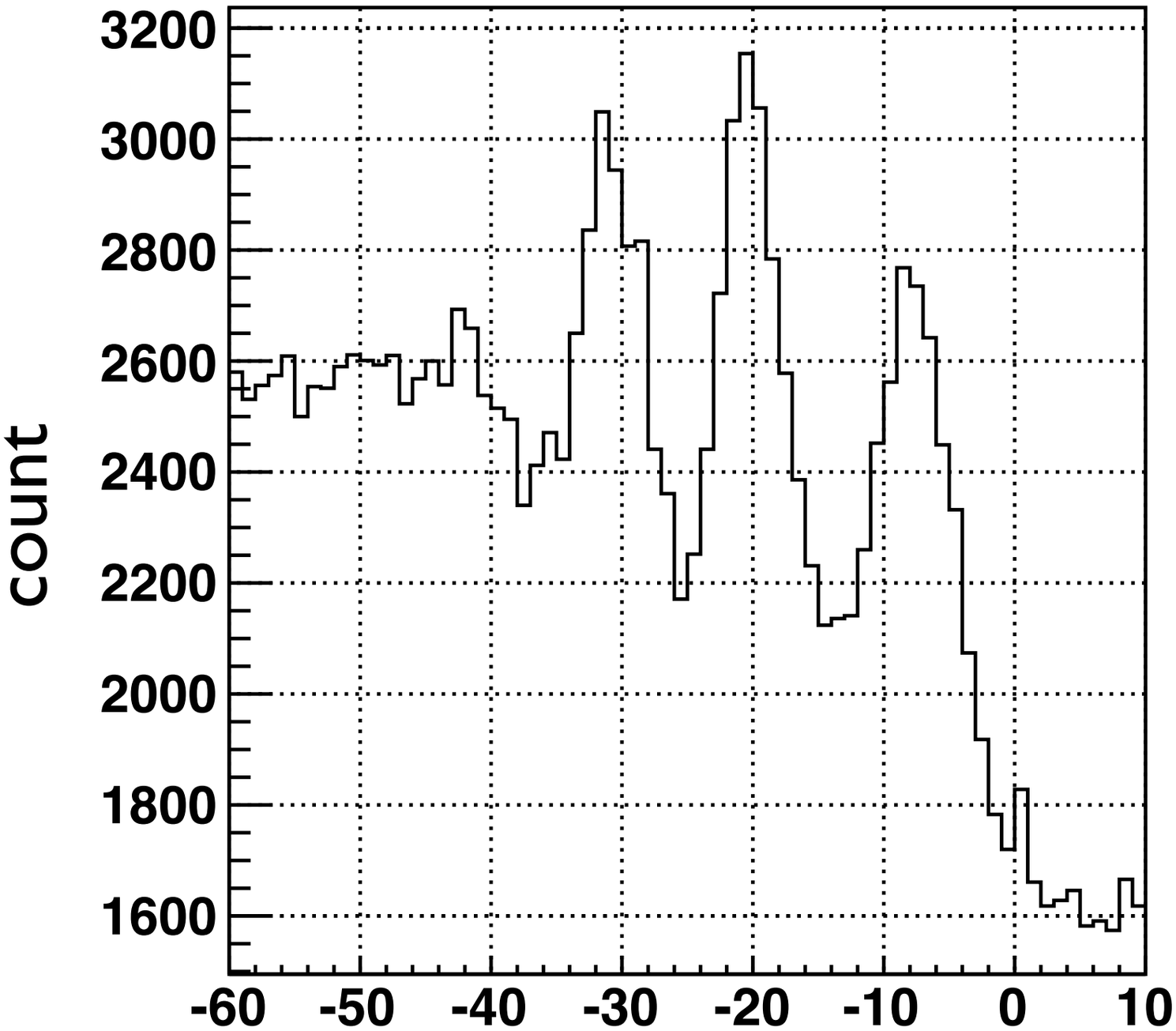
(acceptance uncorrected)



$\theta_{reaction}$<20 mrad

Focal Plane ^{3}He Spectrum

(acceptance uncorrected)



sub-components have almost same strengths as 1s

$\theta_{reaction}$<25 mrad

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

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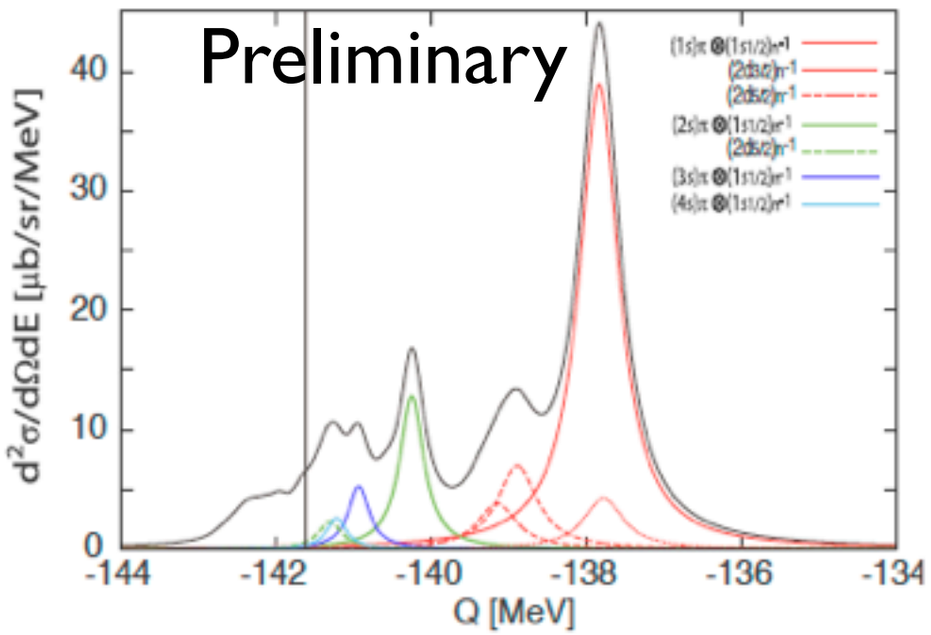
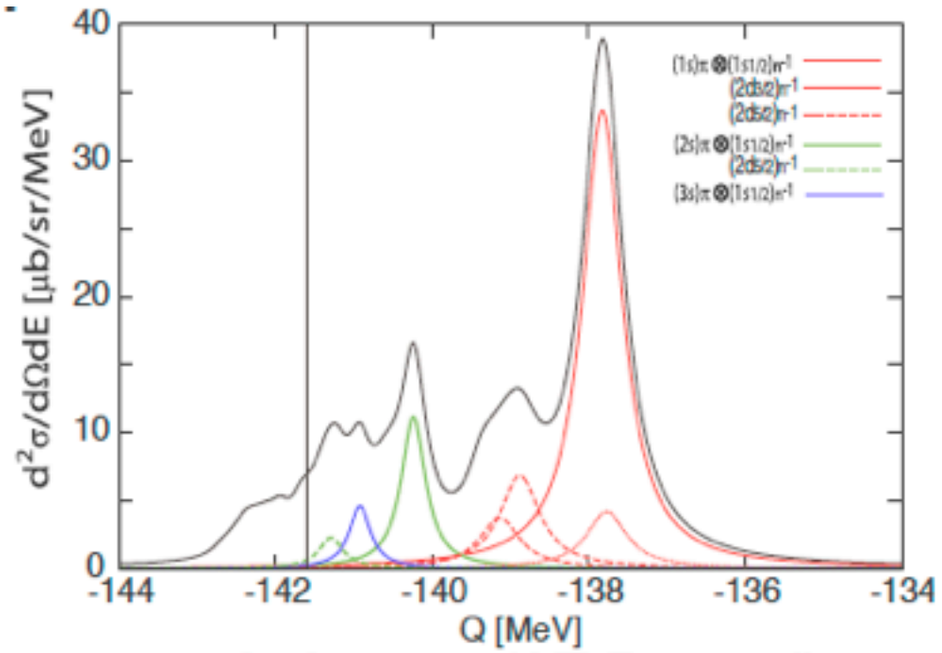
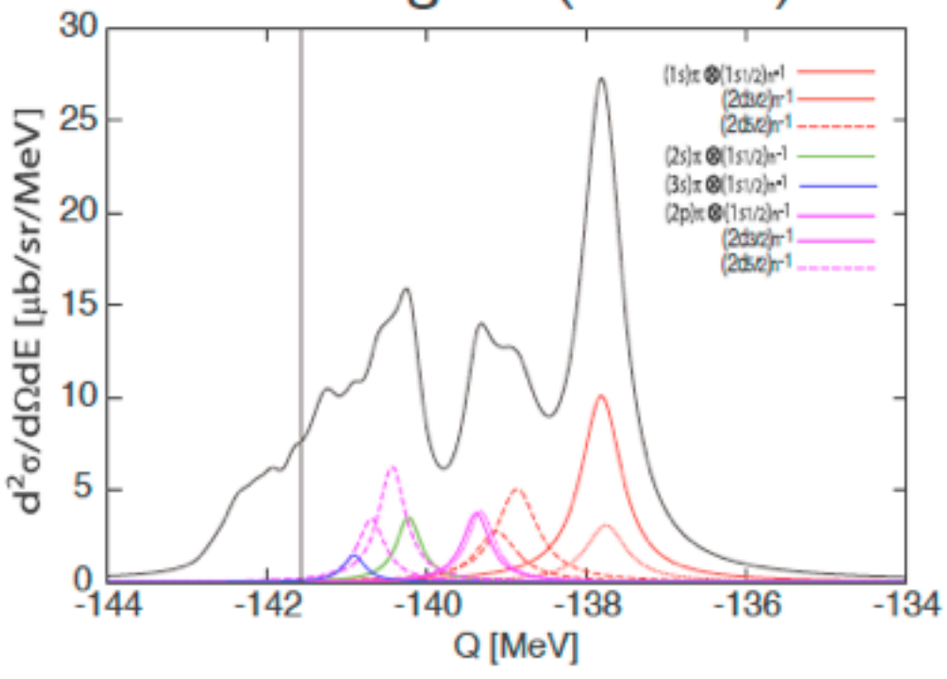
Theoretical Calculation at Finite Angles

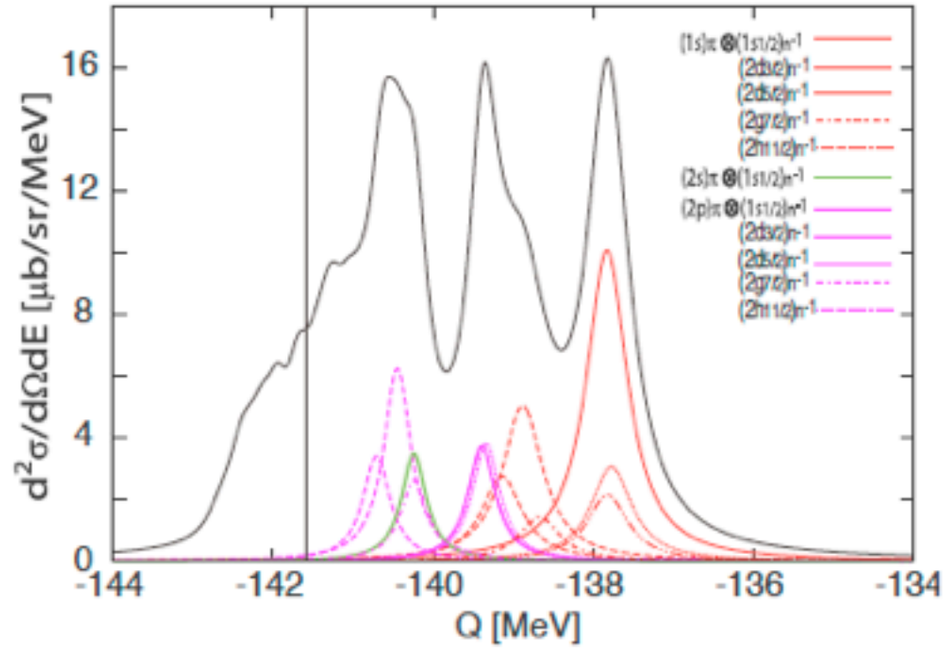




0 degree (0 mrad)



1 degree (17.5 mrad)



2 degree (34.9 mrad)

3 degree (52.4 mrad)

See N. Ikeno's poster #22

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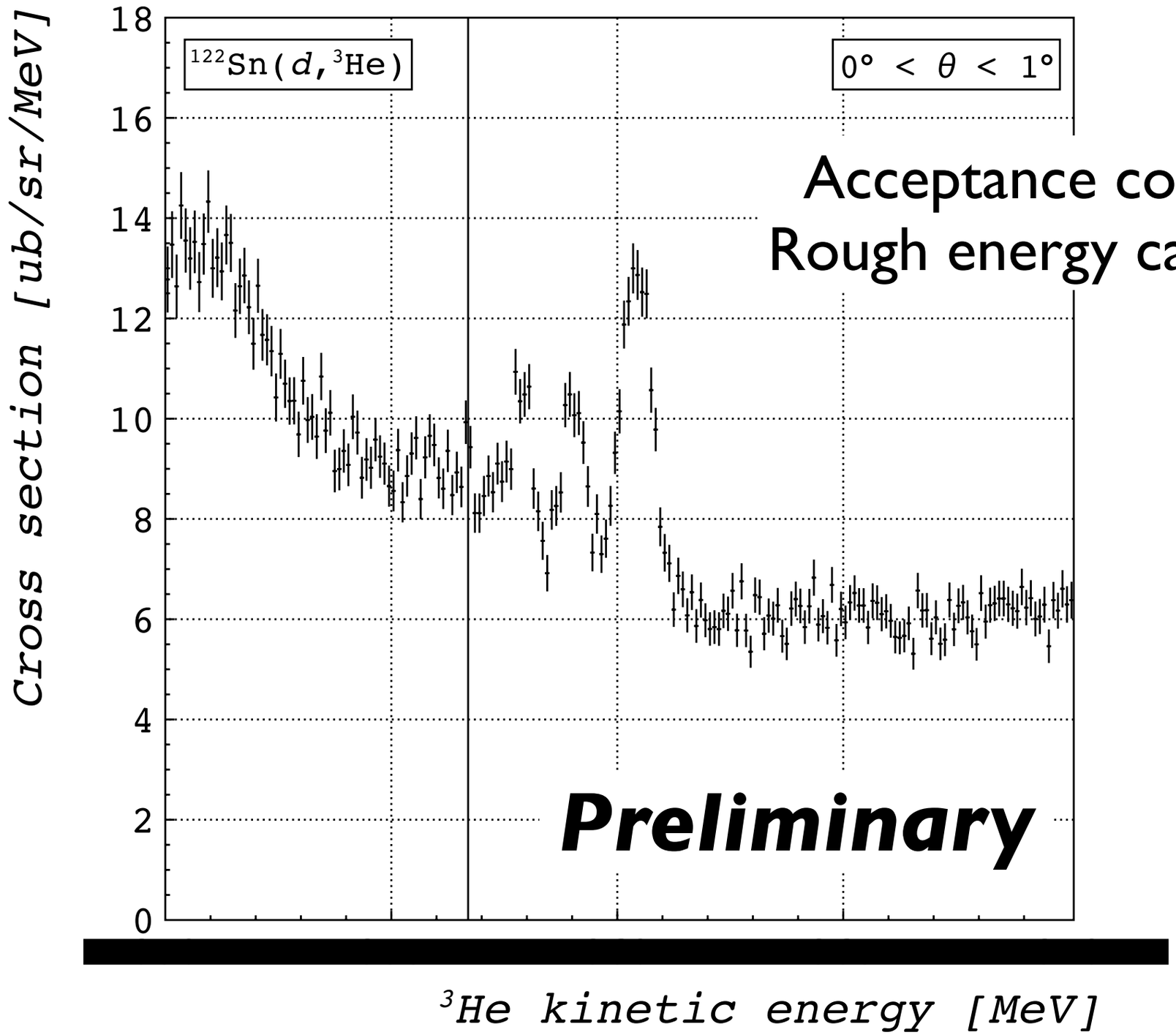
Energy spectrum



Acceptance corrected.
Rough energy calibration.

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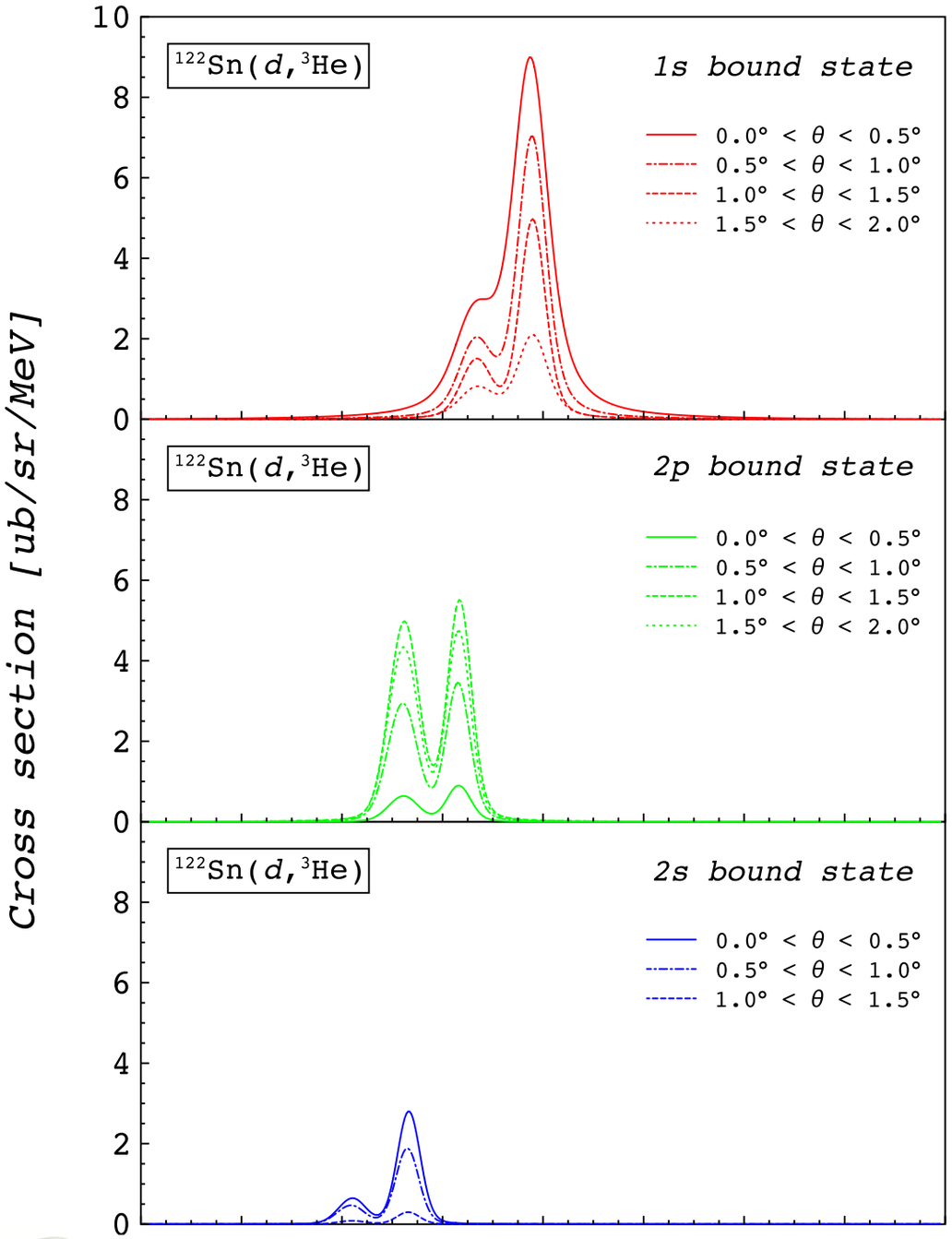
Decomposition Procedure



Components:
π x n^{-1} combinations

Fitting parameters:
Binding energies,
Widths,
Strengths.

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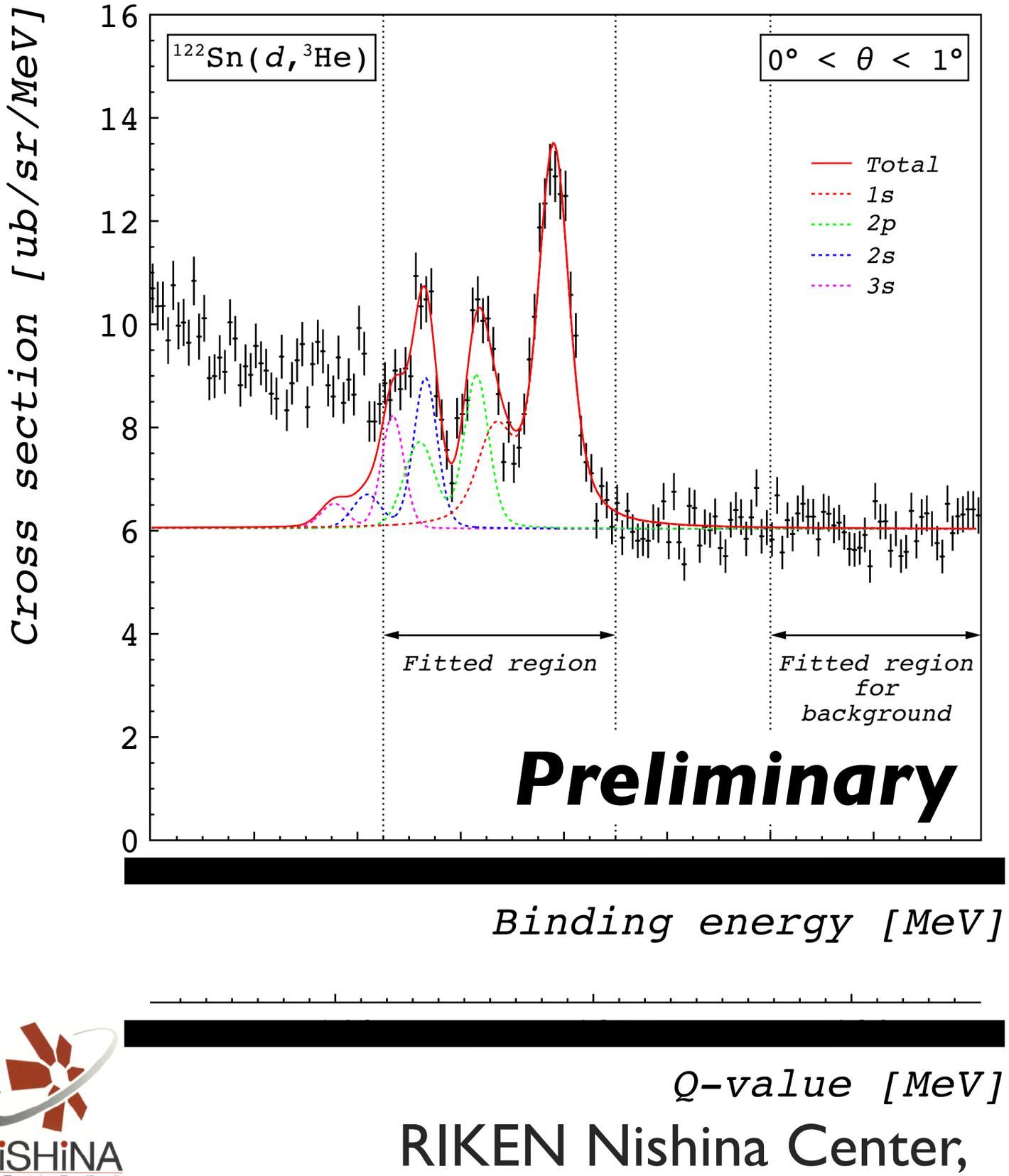
Spectrum decomposition



Fit parameters

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

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Summary

Achievements

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

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

✓We are close to start systematic study.

Perspectives

- We're analyzing energy spectra to extract binding energies and widths.
- We still have room for resolution improvements.
- Main experiment will come soon (Jan/2013?).
- Feasibility study is ongoing for "inverse kinematics".