Development and application of a dispersion-matched ion-optical mode of the SRC and BigRIPS system for high-resolution missing-mass spectroscopy experiments with primary beams

Yoshiki Tanaka (RIKEN)

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RIKEN 開拓研究所 Pioneering Research Institute

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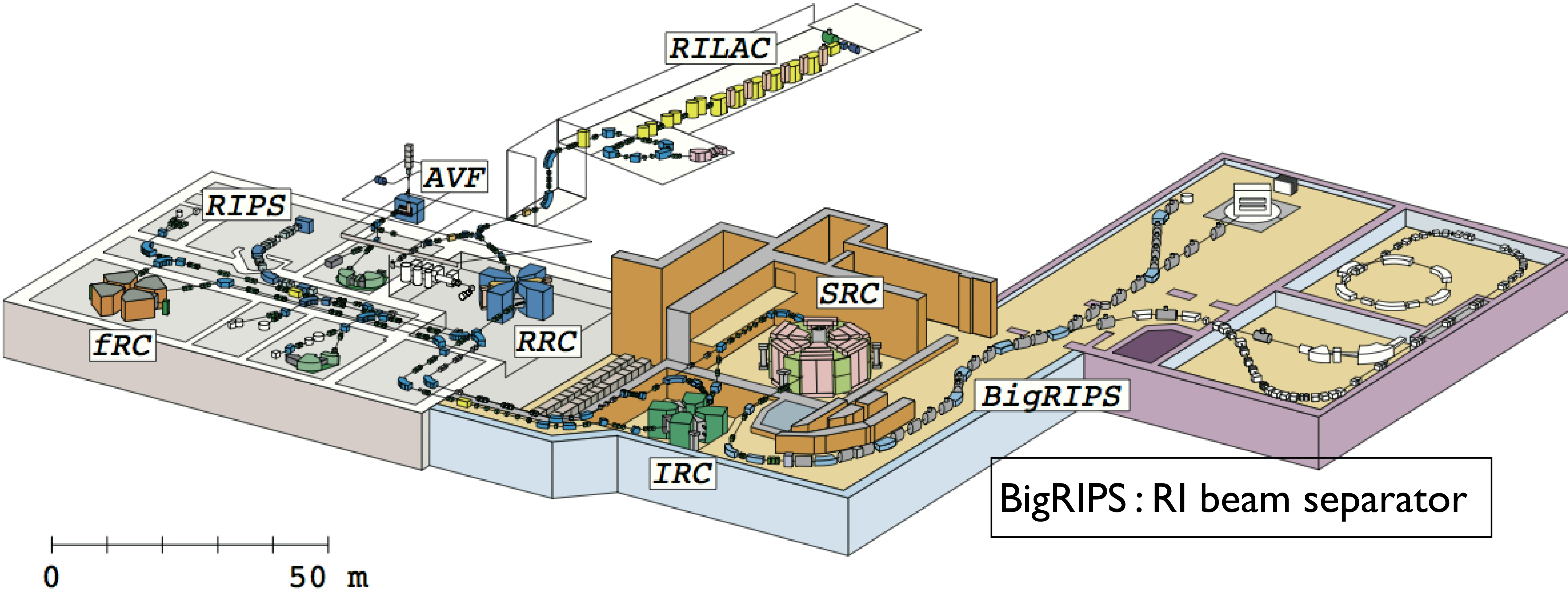
Spectroscopy with primary beams at RIBF

RI Beam Factory (RIBF), RIKEN, Japan



BigRIPS : RI beam separator

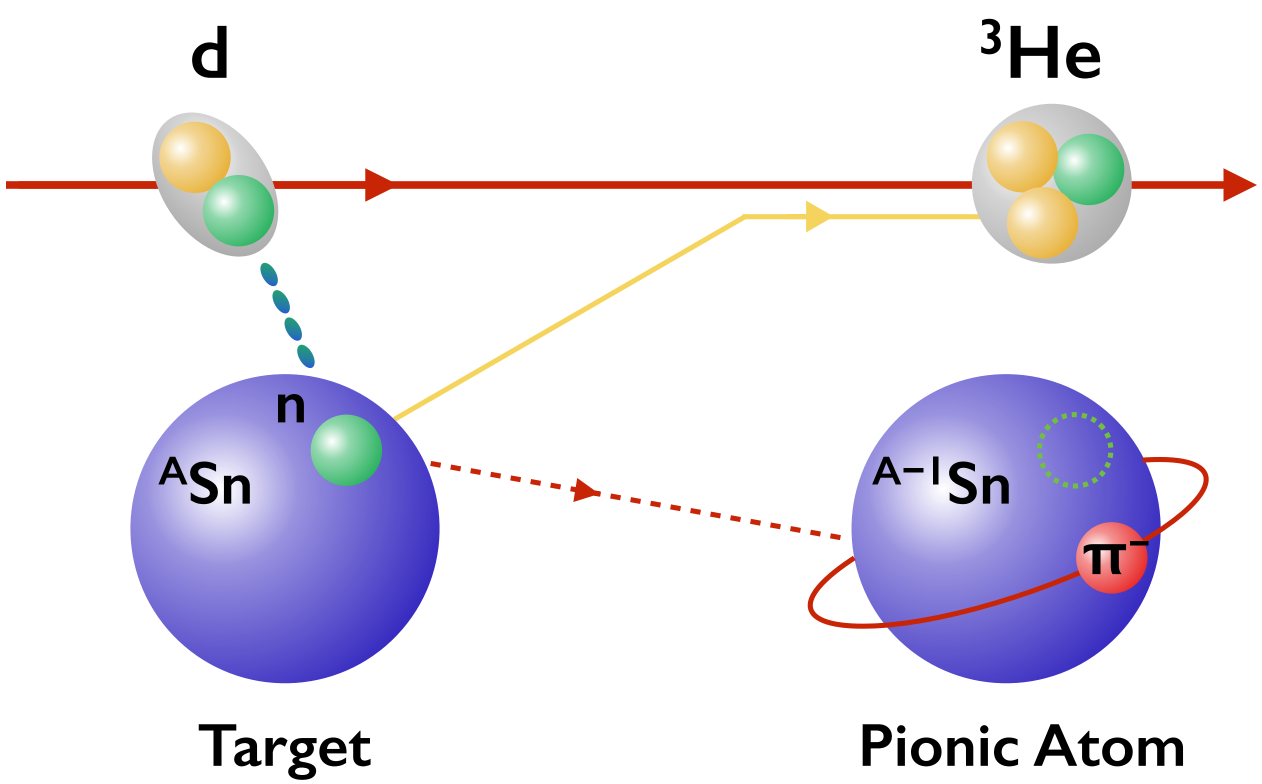
- ◇ High-intensity primary beam from SRC
- ◇ BigRIPS used as a high-resolution and large-acceptance spectrometer with powerful background suppression

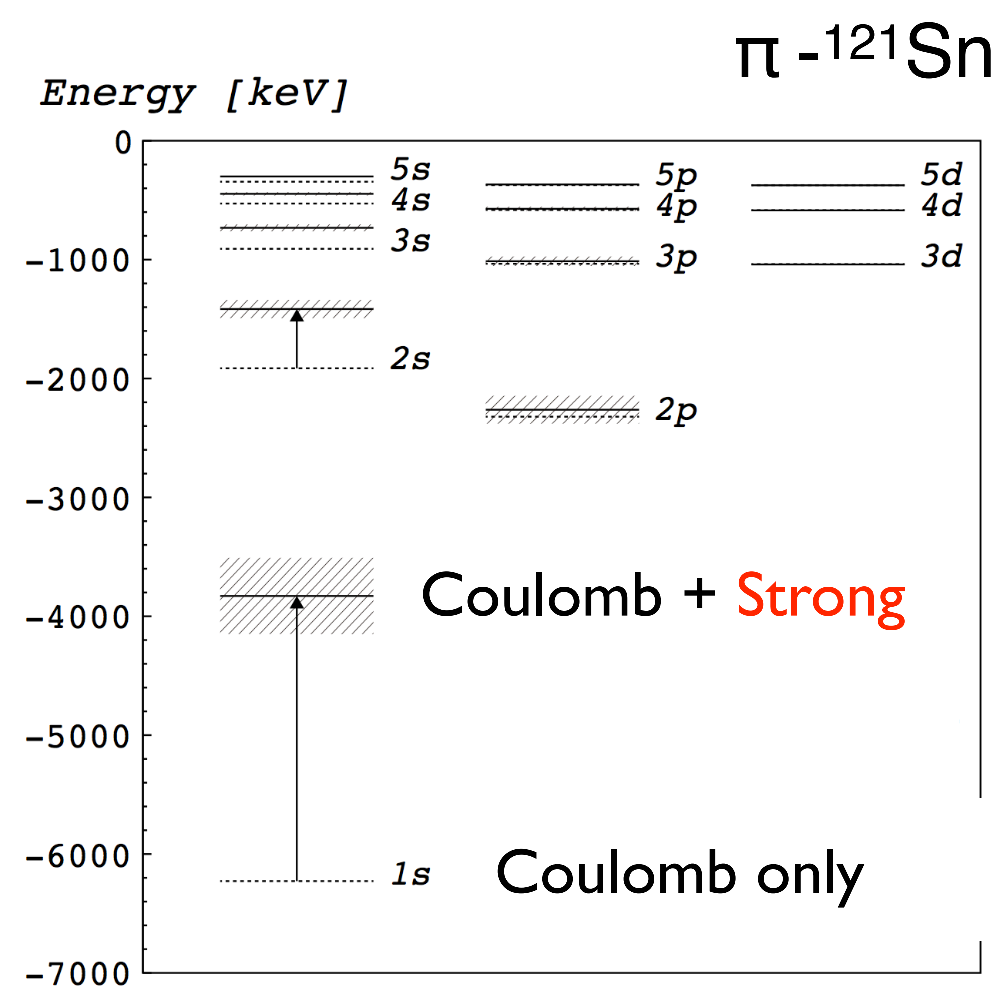
Opportunity for precision missing-mass spectroscopy with reactions using primary ion beams

Physics cases

Precision spectroscopy of deeply-bound π-atoms

- Missing mass spectroscopy of ^{A}Sn(d,^{3}He) reaction
- π-A strong interaction potential → Chiral symmetry restoration





N. Ikeno et al.,
PTP 126 (2011) 483.

Physics cases

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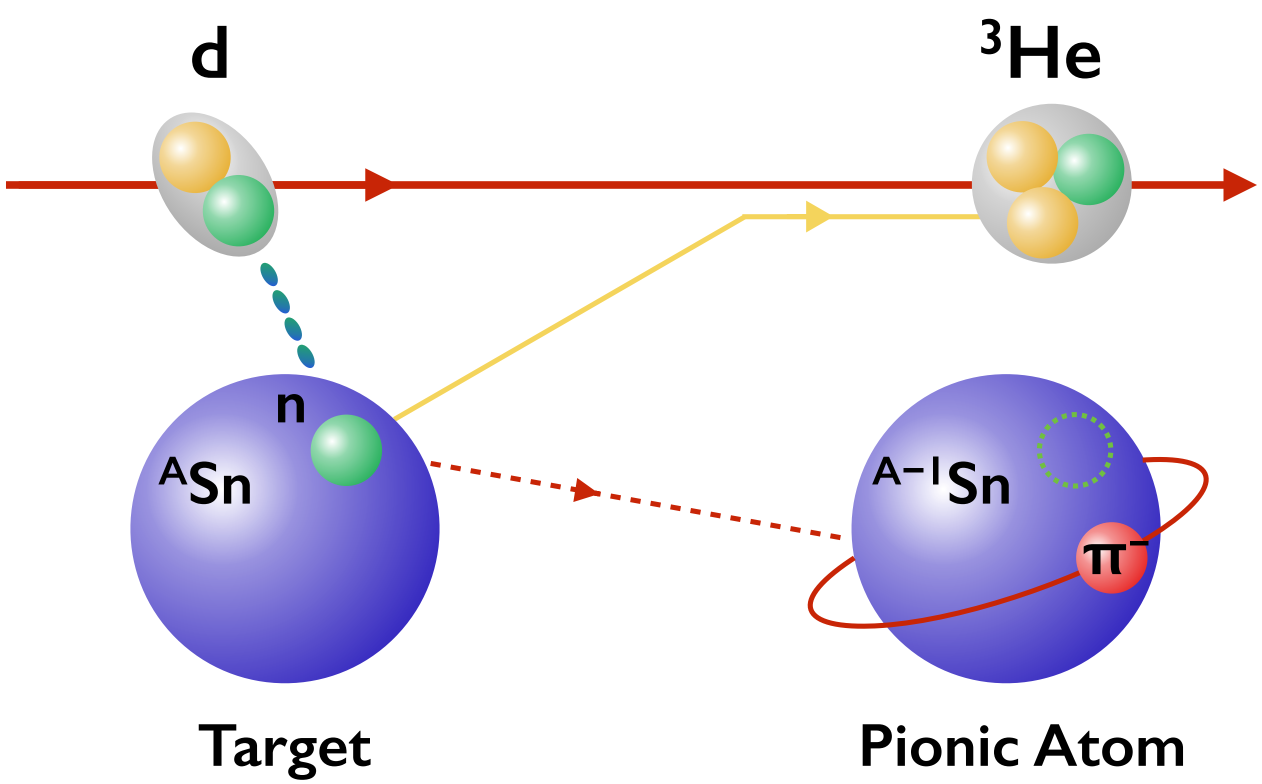

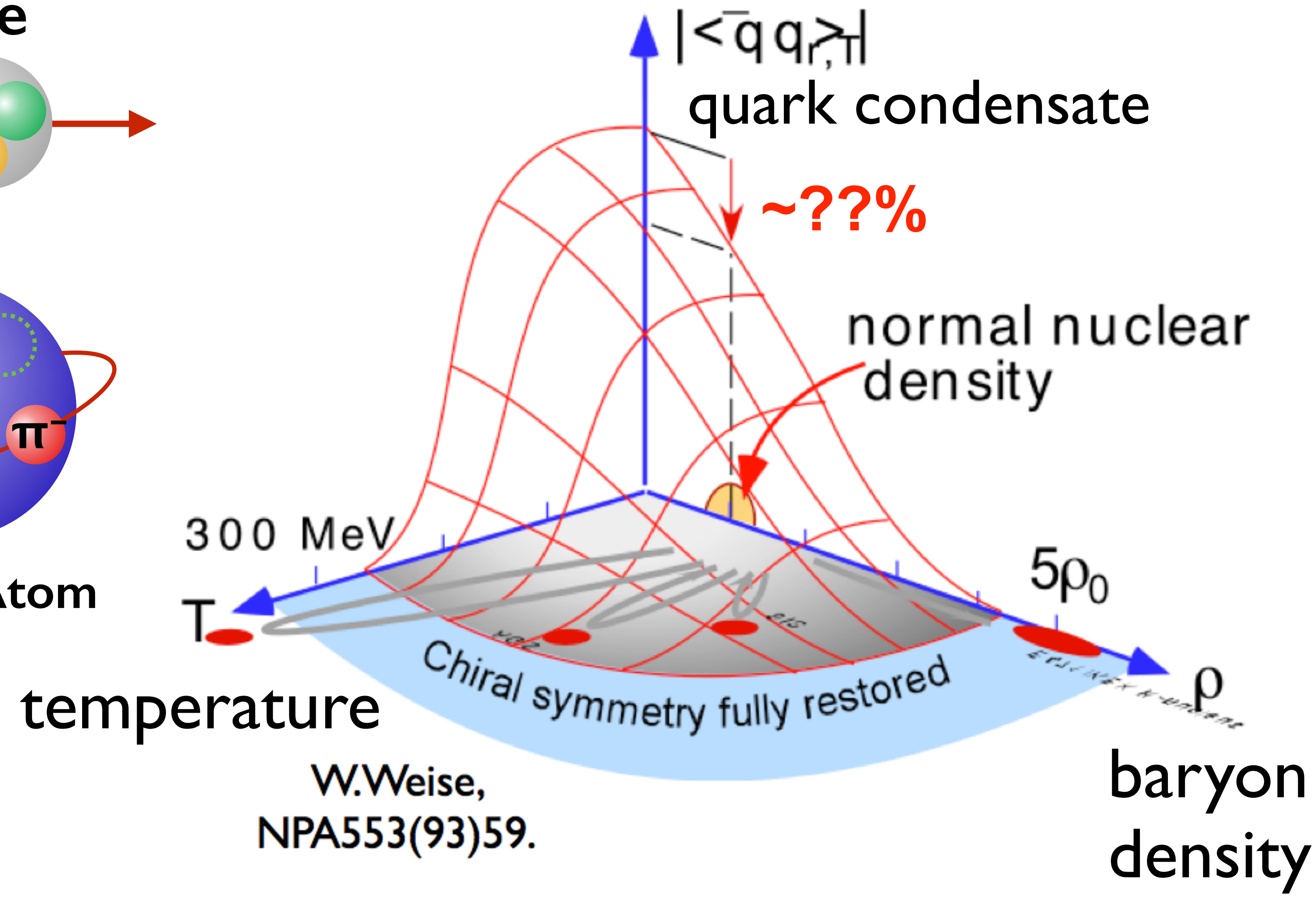

W.Weise, NPA553(93)59.

Physics cases

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- Missing mass spectroscopy of ^{A}Sn(d,^{3}He) reaction
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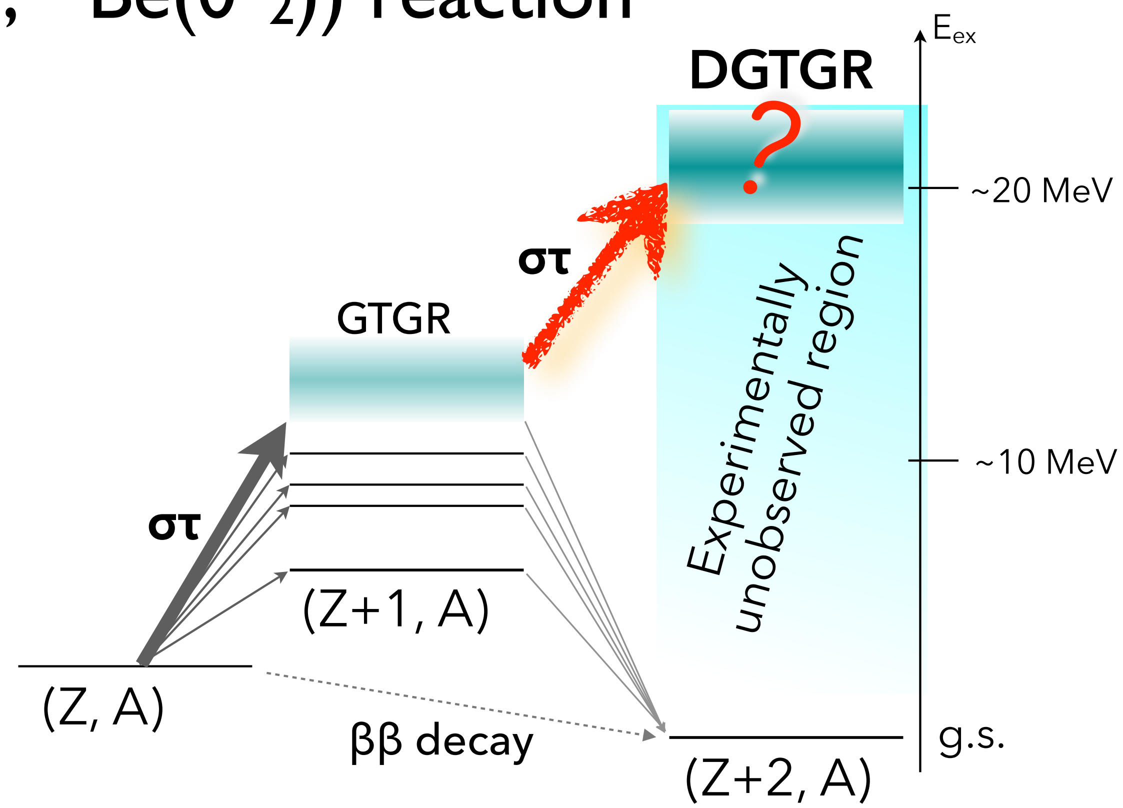
Search for Double Gamow–Teller Giant Resonance (DGTGR)

- Missing mass spectroscopy of ^{48}Ca(^{12}C, ^{12}Be(0^{+}_{2})) reaction
- yet to be established experimentally
- provide information on 0νββ NME



A. Sakaue et al.

Physics cases

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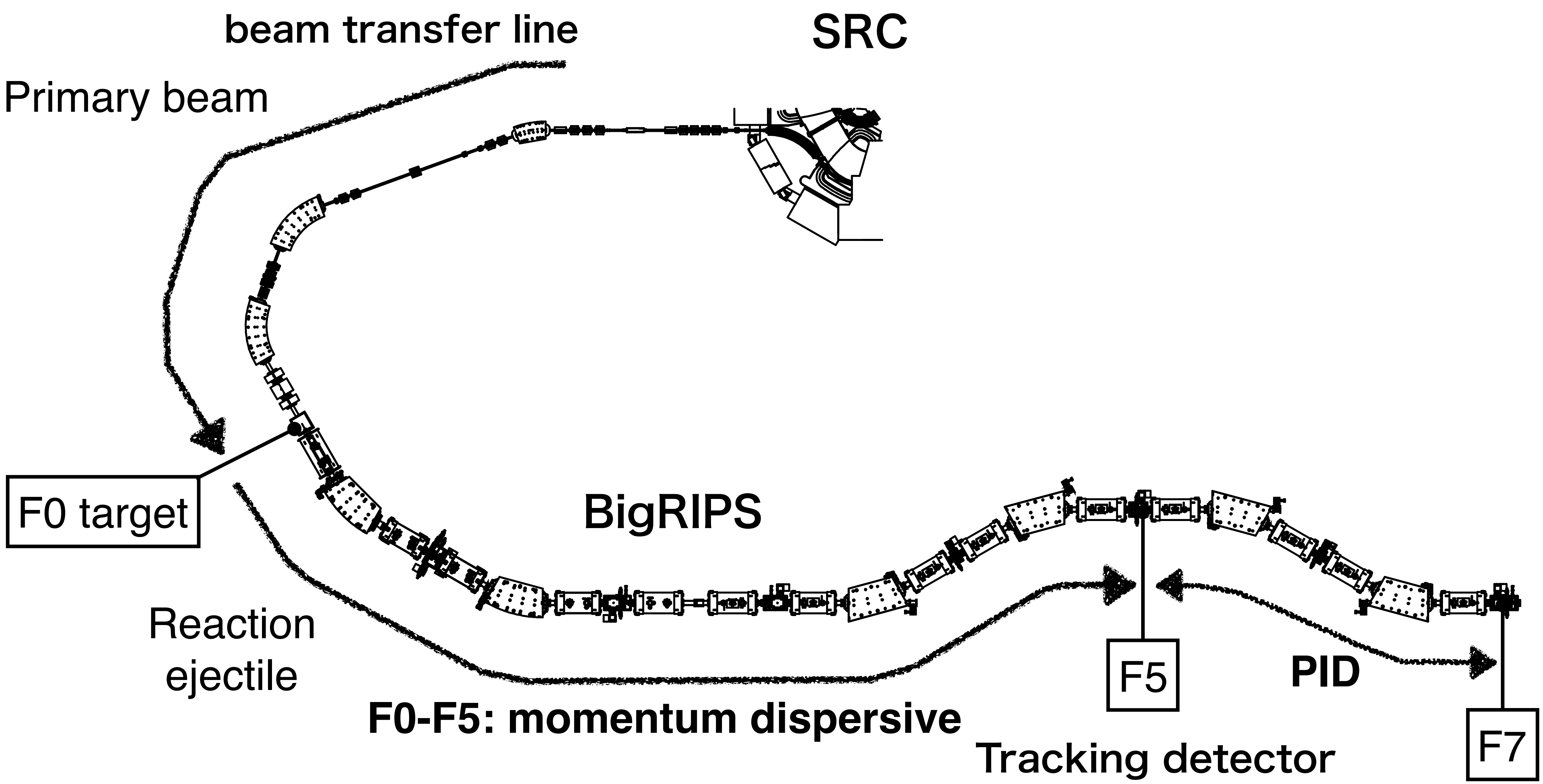
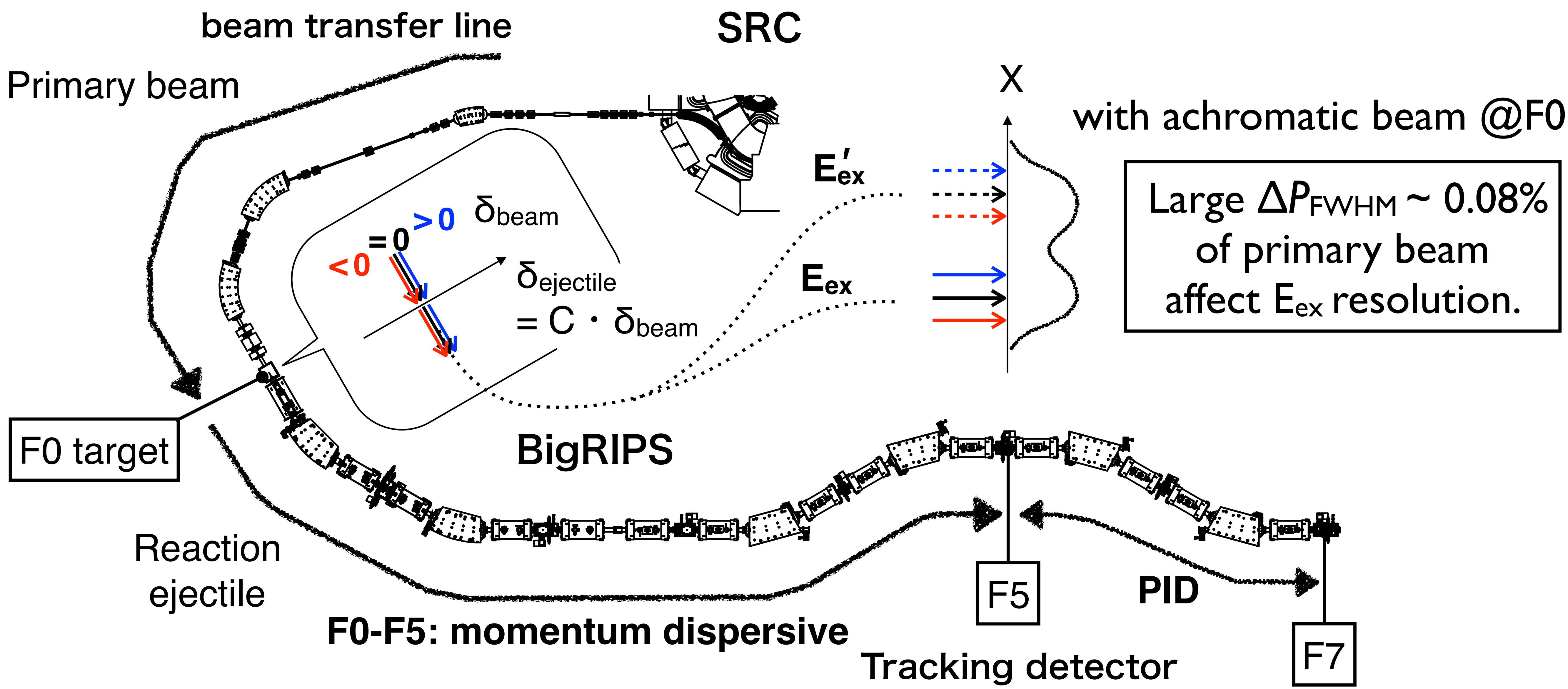
High-resolution is a key requirement
for both experiments

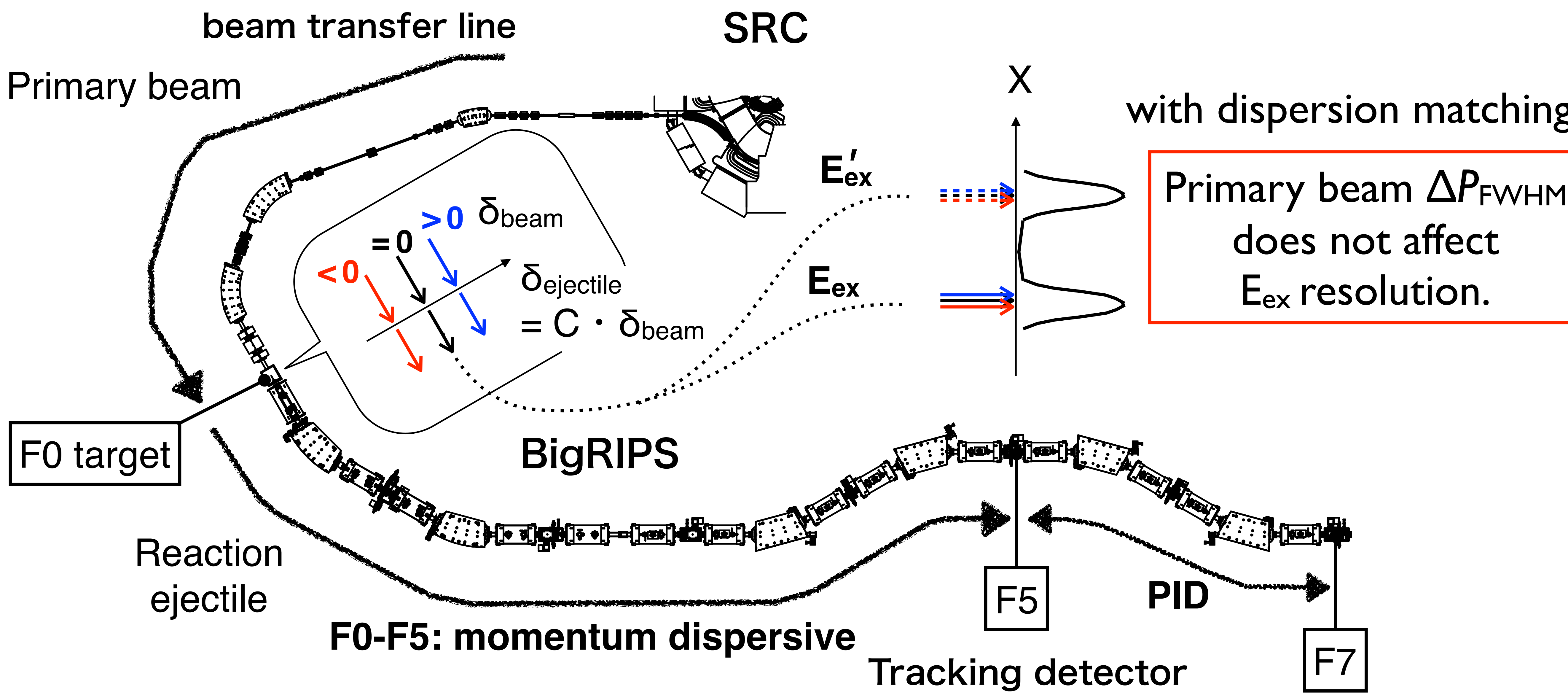
Dispersion-matched ion optics



Dispersion-matched ion optics

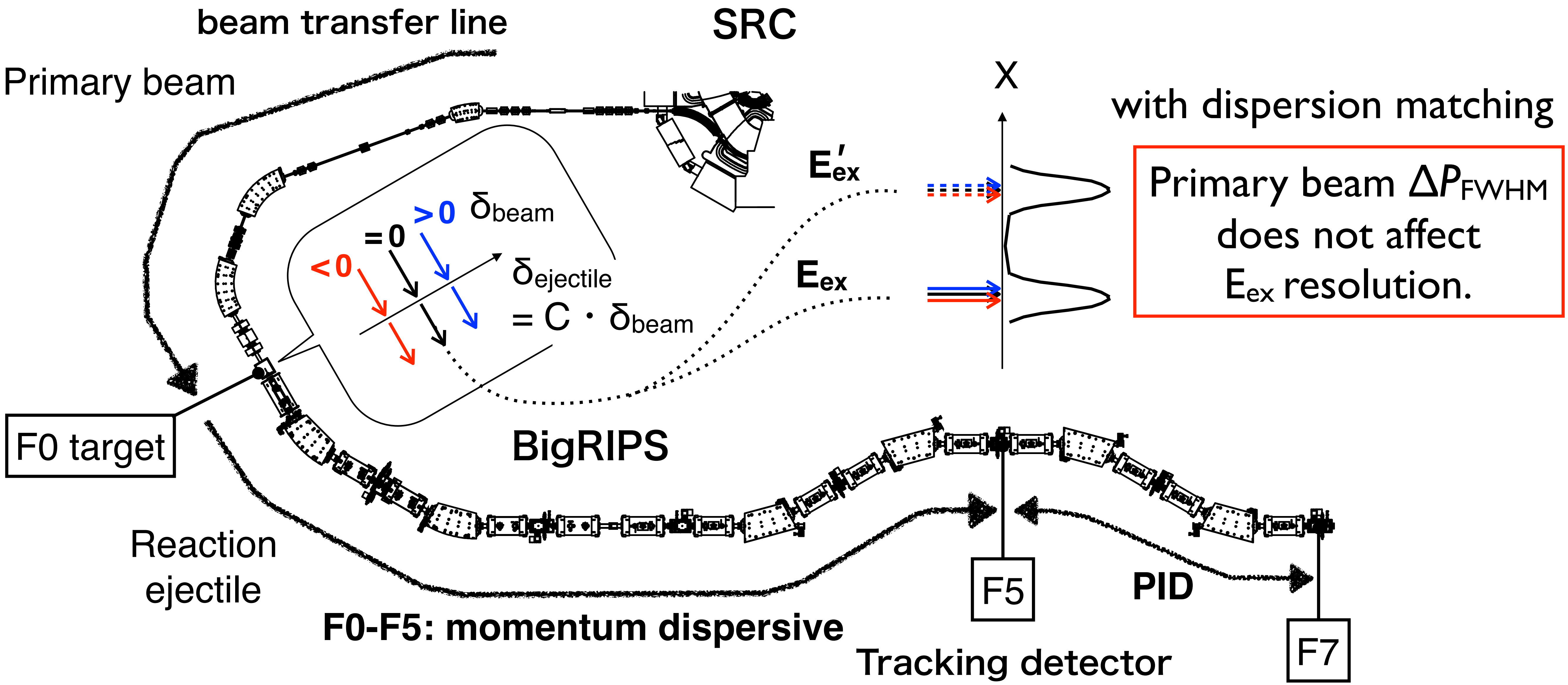


Dispersion-matched ion optics



Primary beam ΔP_{FWHM} does not affect E_{ex} resolution.

Dispersion-matched ion optics



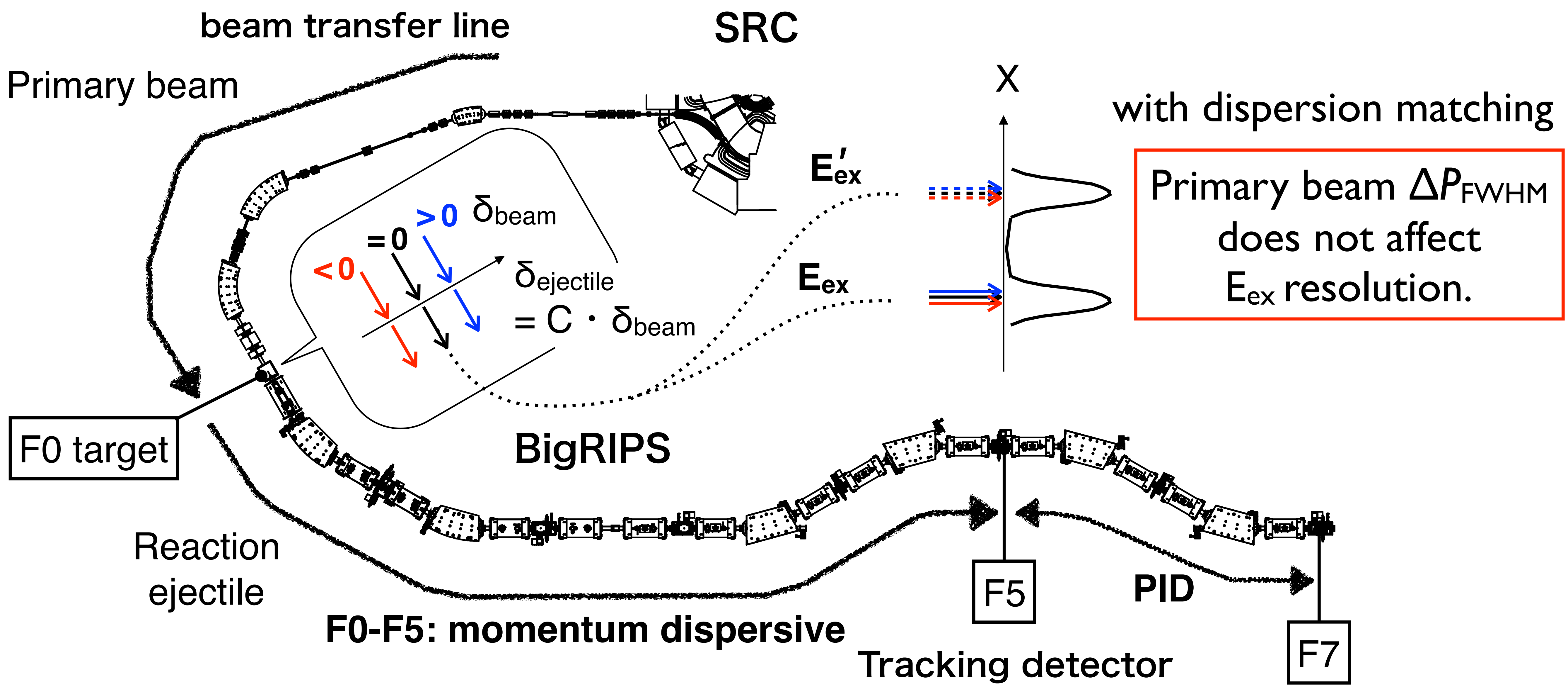
<u>Dispersion matching condition</u>

$$(X|\delta)_{SRC\text{-}F5} = 0 \longrightarrow \boxed{(X|\delta)_{SRC\text{-}F0}\,\overset{-1.82}{(X|X)_{F0\text{-}F5}} + C \cdot \overset{62\,mm/\%}{(X|\delta)_{F0\text{-}F5}} = 0}$$

π-atom : $C = 1.31$, $(X|\delta)_{SRC\text{-}F0} = 44.6$ mm/%

DGTGR : $C = 1.0$, $(X|\delta)_{SRC\text{-}F0} = 34.1$ mm/%

Dispersion-matched ion optics



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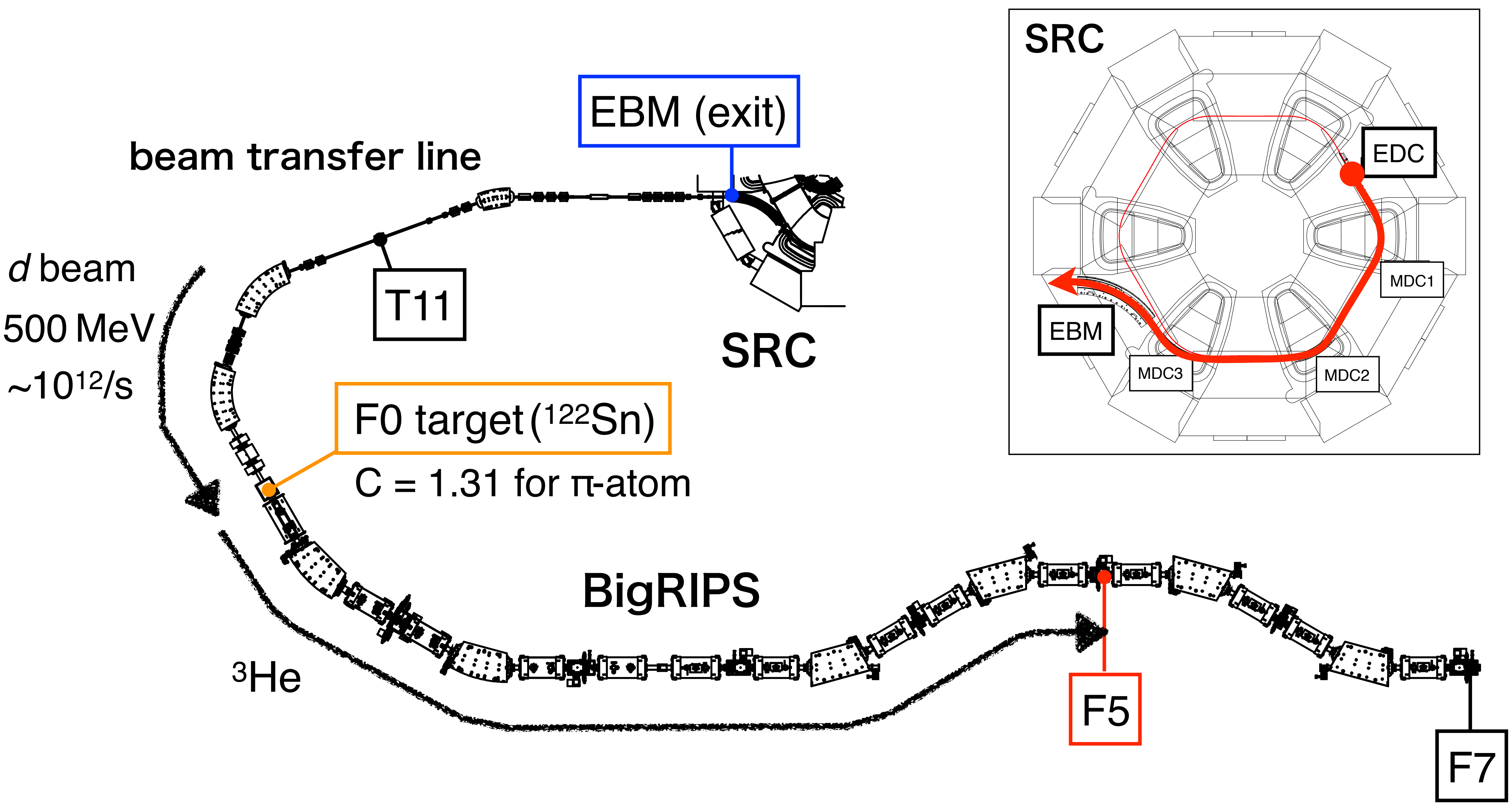
$$\text{Resolving power} = \left|\frac{(X|\delta)_{F0\text{-}F5}}{\Delta X_{F0} \cdot (X|X)_{F0\text{-}F5}}\right| = \left|\frac{(X|\delta)_{SRC\text{-}F0}}{C \cdot \Delta X_{F0}}\right|$$

First experiments of π-atom in 2010 and 2014

Simulation-based approach

1. Assume achromatic beam waist at EDC (electrostatic deflection channel)
2. EDC to EBM exit (extraction bending magnet) transport by Runge–Kutta calculation
3. Design EBM exit to Target (F0) to fulfill dispersion-matching condition



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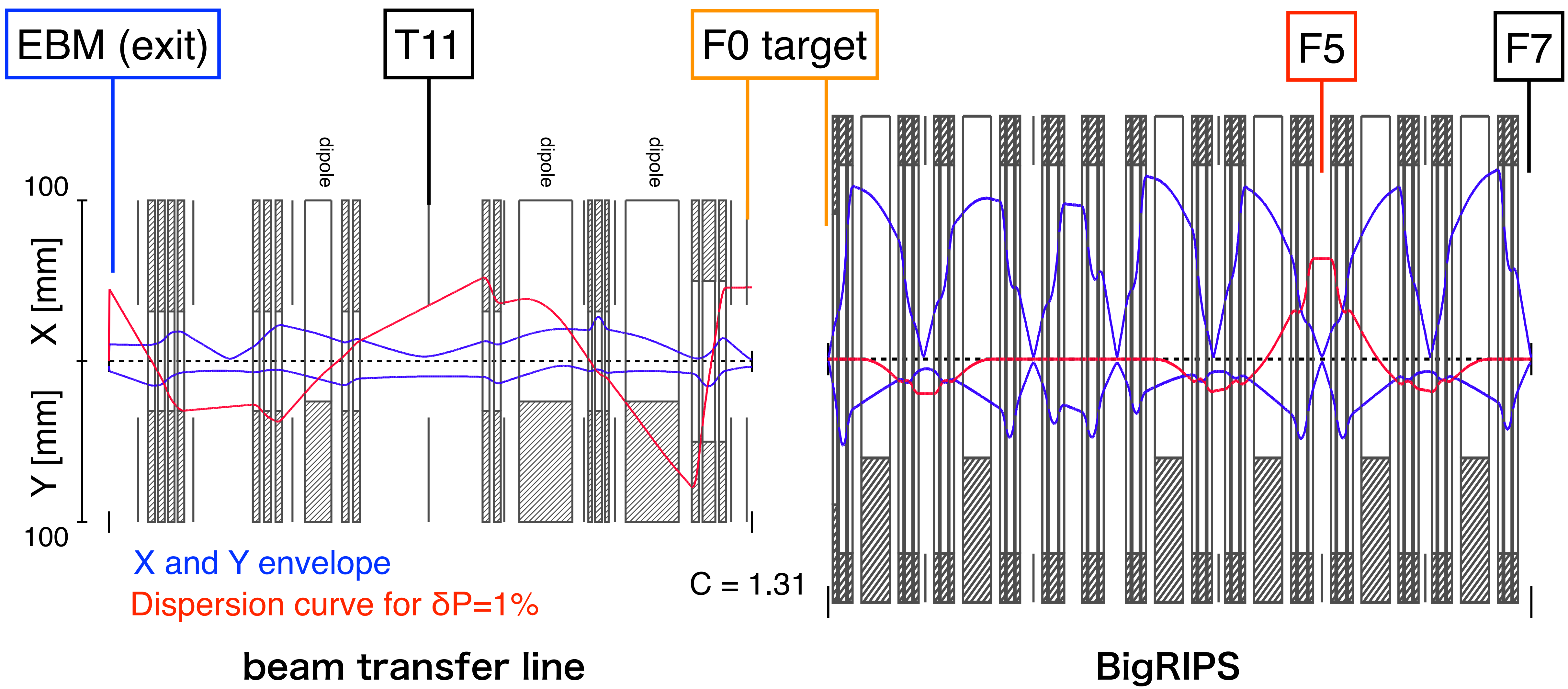

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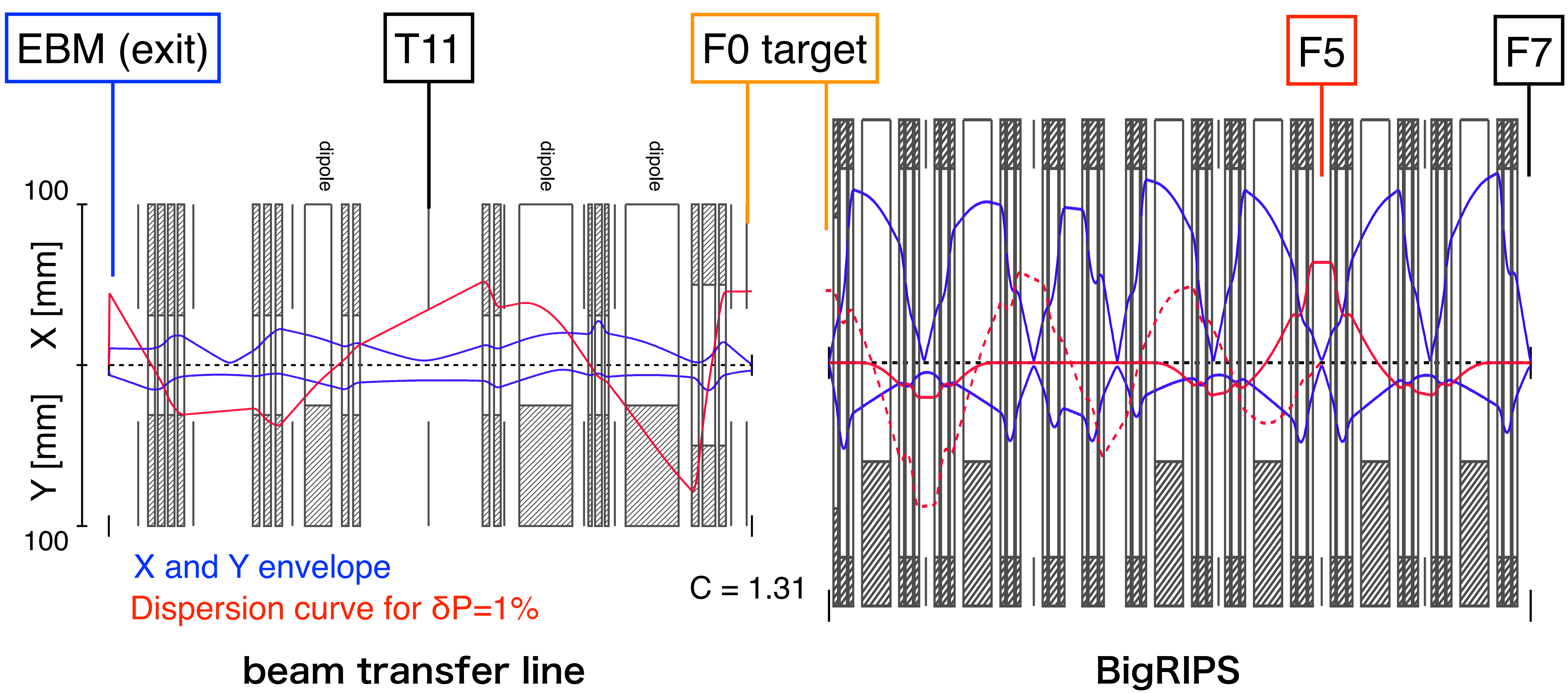
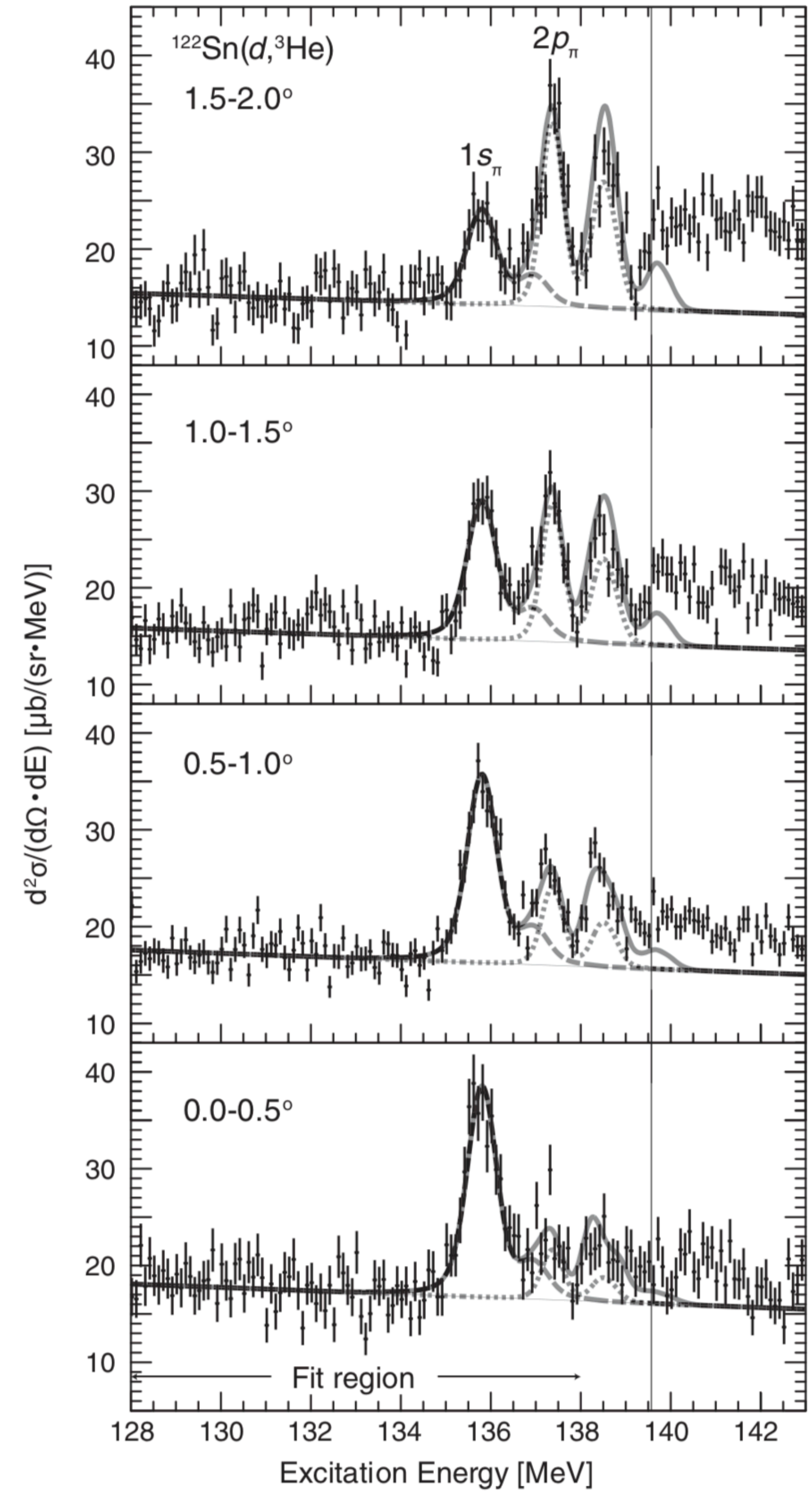


π-^{121}Sn excitation spectrum – pilot run in 2010 –

only 15 hours DAQ

First observation of angle-dependence of π-atom formation cross section

Takahiro Nishi, Kenta Itahashi, et al., Phys. Rev. Lett 120, 152505 (2018)



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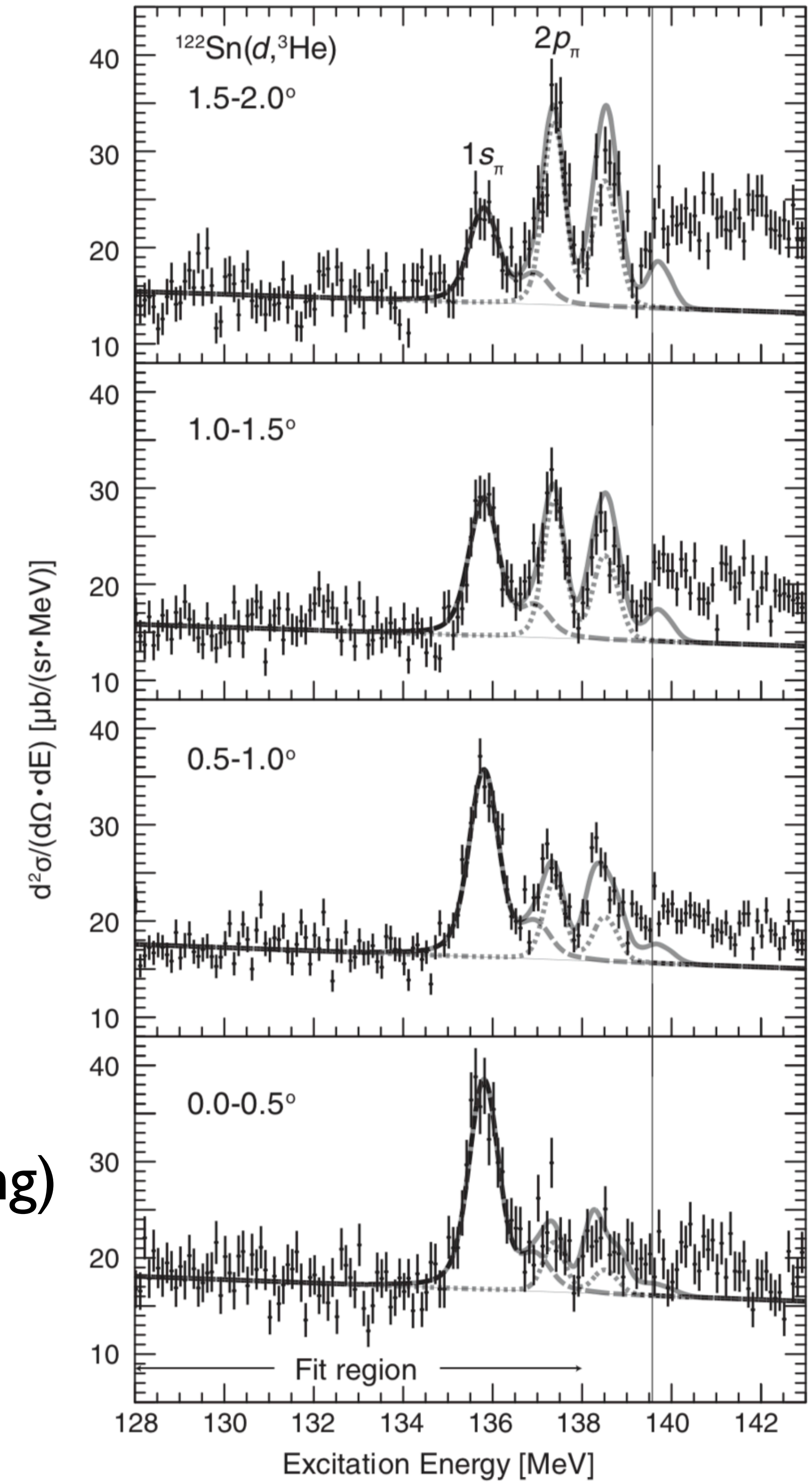


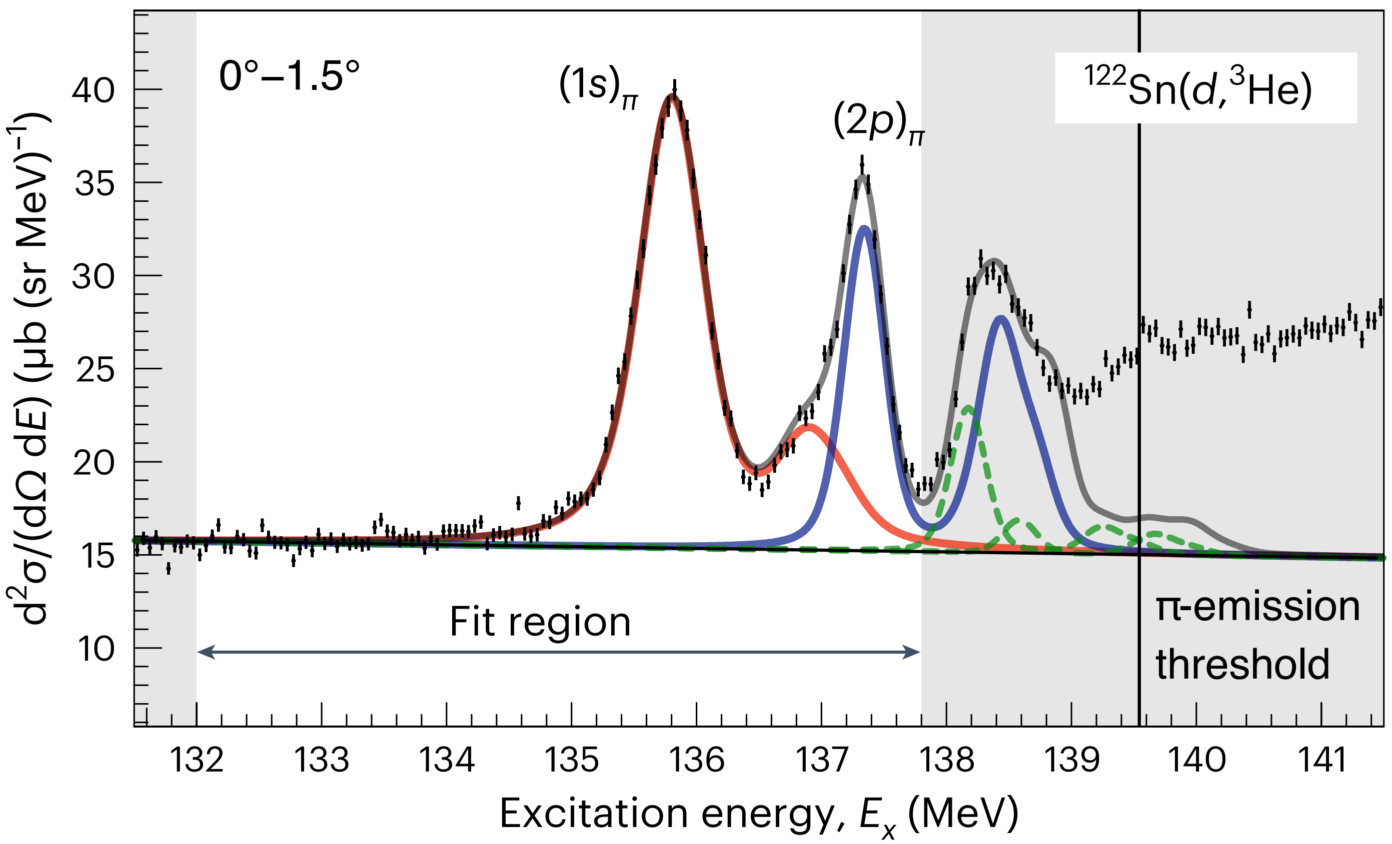
Achieved resolution :

Total (FWHM) : 420 keV
ΔP_{beam} contribution : 280 keV

Dispersion matching condition :

(X|δ) at F0 target ~ 24 mm/% (deduced)
44 mm/% (designed for matching)

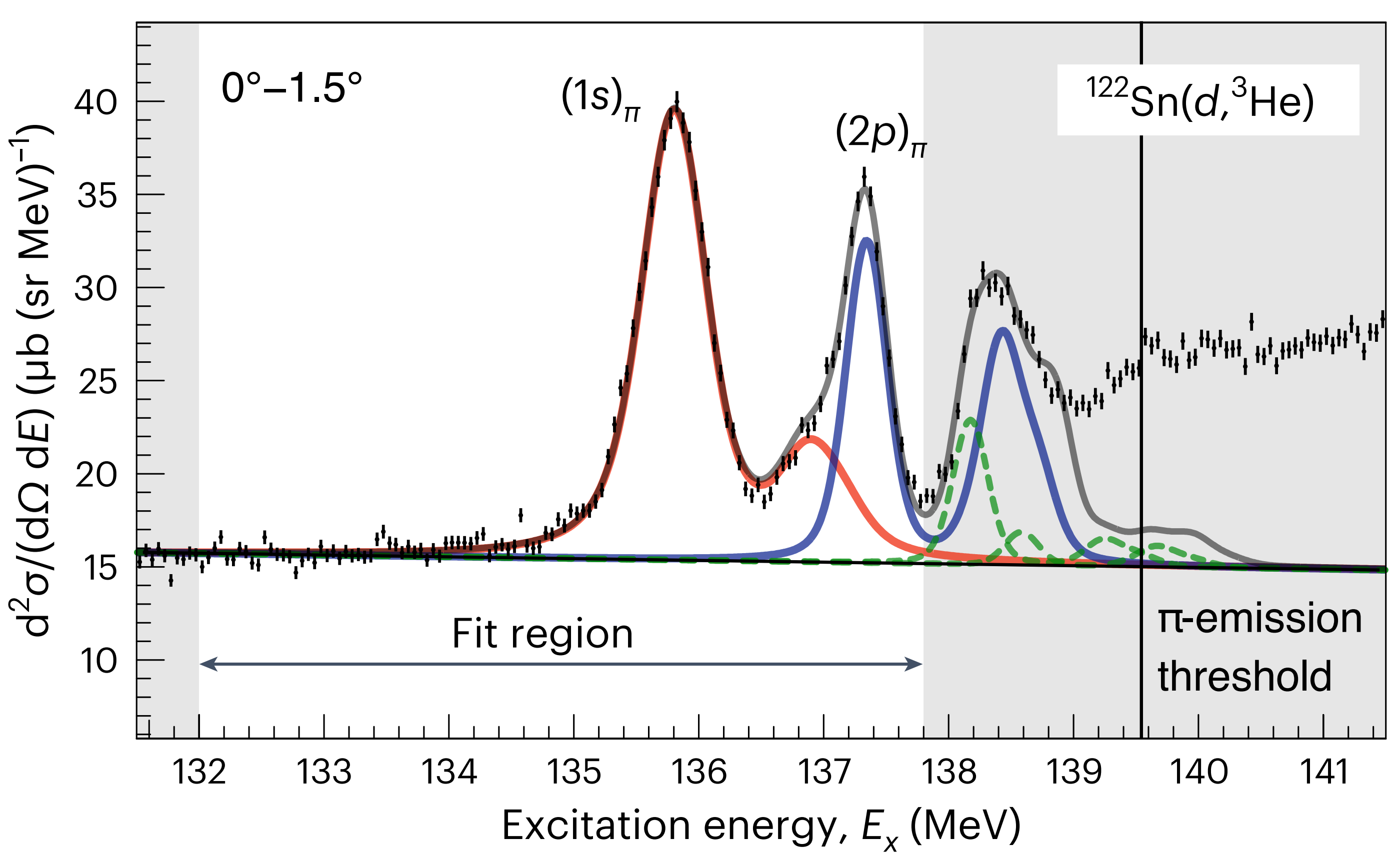
π-^{121}Sn excitation spectrum – Experiment in 2014 –

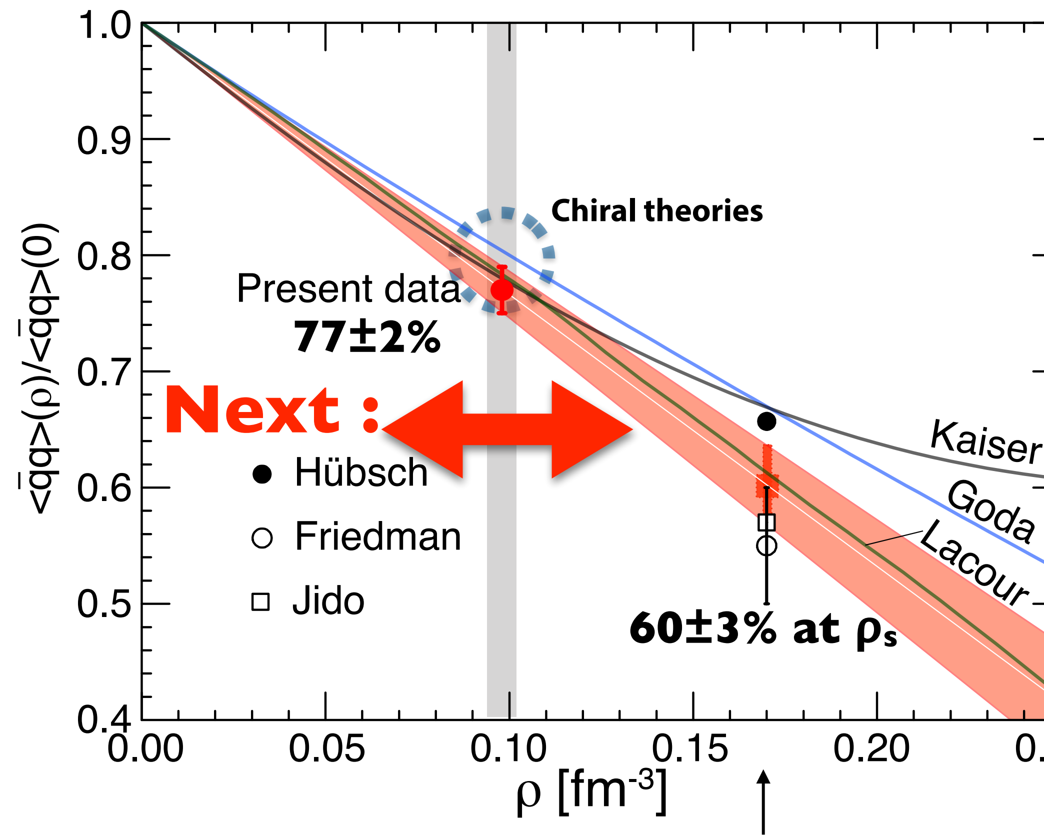


T. Nishi, K. Itahashi, et al.,
Nature Phys. 19, 788 (2023).

1s and 2p states observed simultaneously with high-statistics

π-[121]Sn excitation spectrum – Experiment in 2014 –





chiral symmetry broken

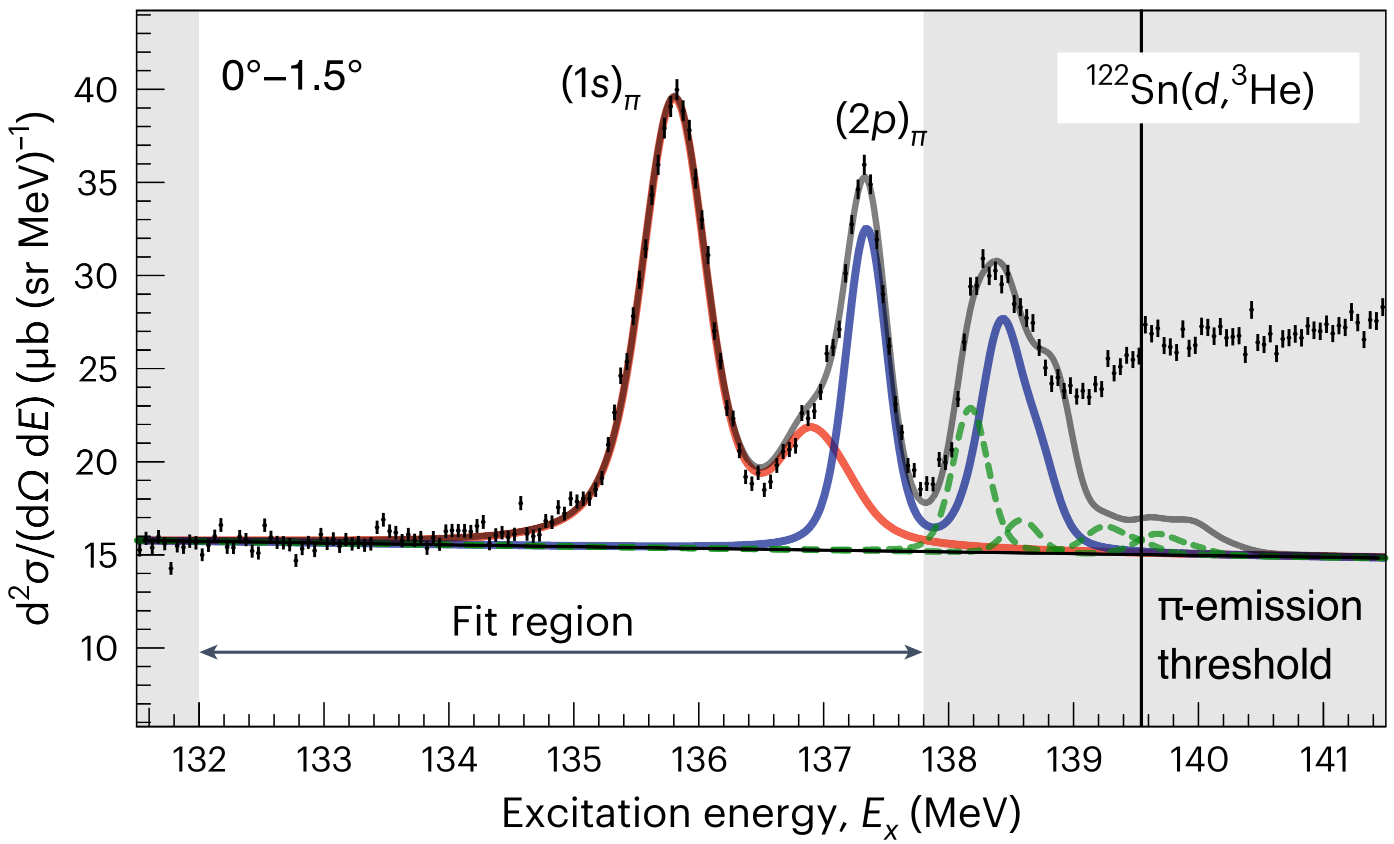
restored

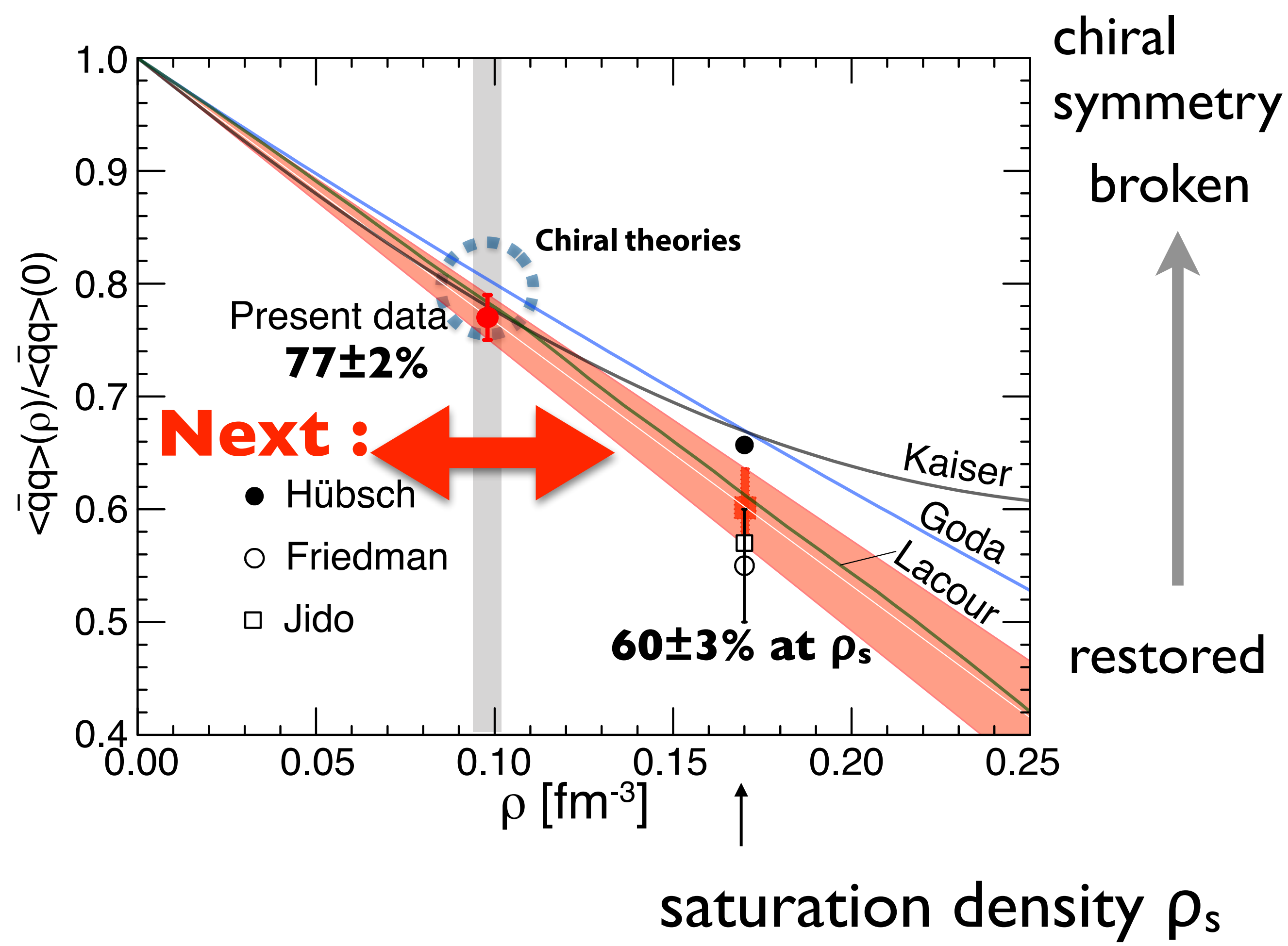
saturation density ρ_s

T. Nishi, K. Itahashi, et al.,

Nature Phys. 19, 788 (2023).

π-^{121}Sn excitation spectrum – Experiment in 2014 –





T. Nishi, K. Itahashi, et al.,

Nature Phys. 19, 788 (2023).

<u>Achieved resolution :</u>

Total (FWHM) : 290 keV

ΔP_{beam} contribution : 220 keV

<u>Dispersion matching condition :</u>

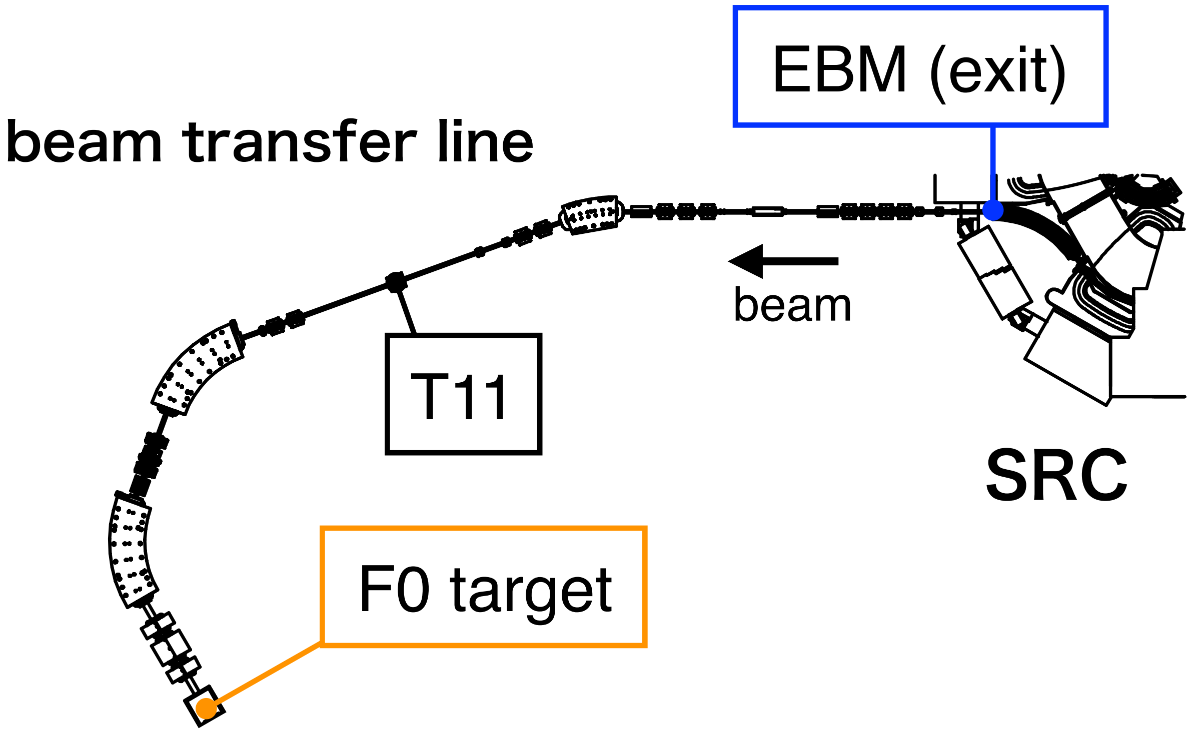
(X|δ) at F0 target ~ 28 mm/% (deduced)

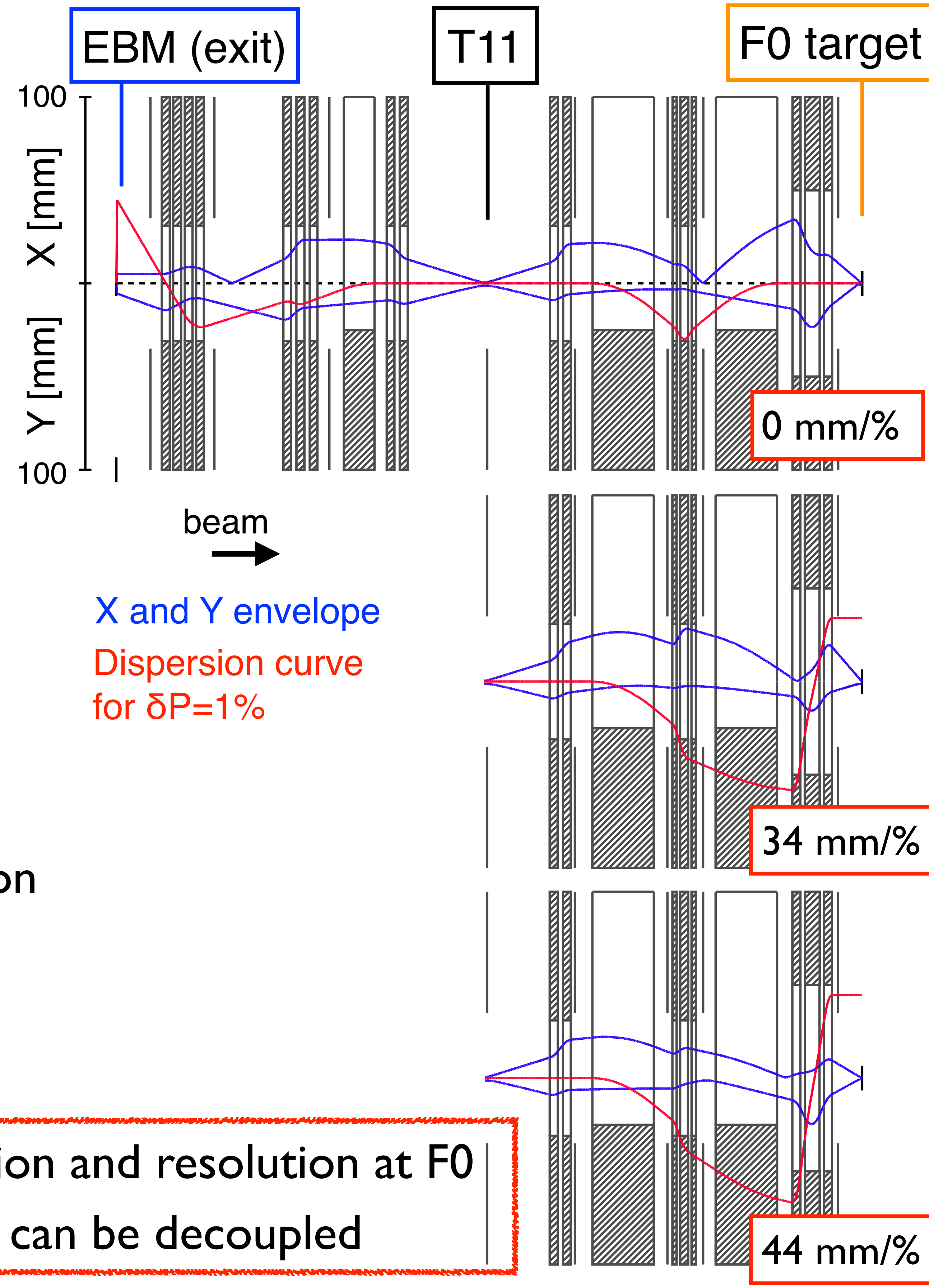
44 mm/% (for matching)

→ Dispersion matching partially achieved in the first experiments

Estimation of dispersion from accelerator seems to have uncertainties

Redesign ion optics of beam transfer line





◇ aim at T11 achromatic focus / waist

◇ use EBM (exit) - T11 section to compensate uncertainty from SRC beam phase space

◇ T11 - F0 section to produce desired dispersion

  * $(X|\delta) = 0$ (for tuning)
  * $(X|\delta) = 34$ mm/% (for C=1.00, DGTGR)
  * $(X|\delta) = 44$ mm/% (for C=1.31, π-atom)

◇ Straightforward adjustment of dispersion and resolution at F0

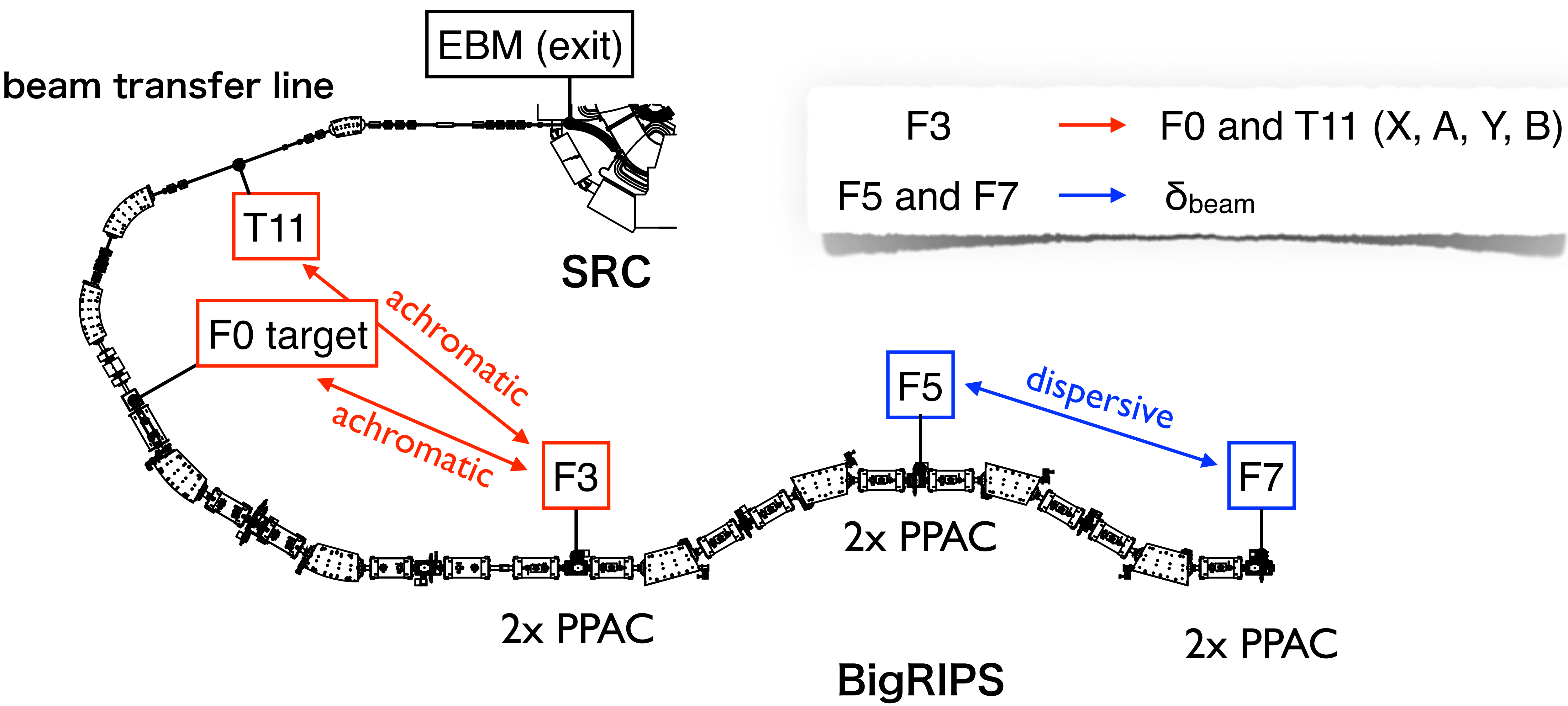
◇ Dispersion tuning and (X & Y) tuning can be decoupled

Next approach : Trace-back method

Measurement-based approach

◇ Measurement and tuning of beam at upstream beam transfer line are needed

◇ Use data of downstream focal planes to deduce F0 and T11 phase space



Test of trace-back method with ^{18}O beam in 2018

◇ BigRIPS optics tuning and matrix measurements

◇ T11-F0 achromatic optics tuning and matrix measurements

◇ T11-trace-back method to deduce primary beam phase space at T11

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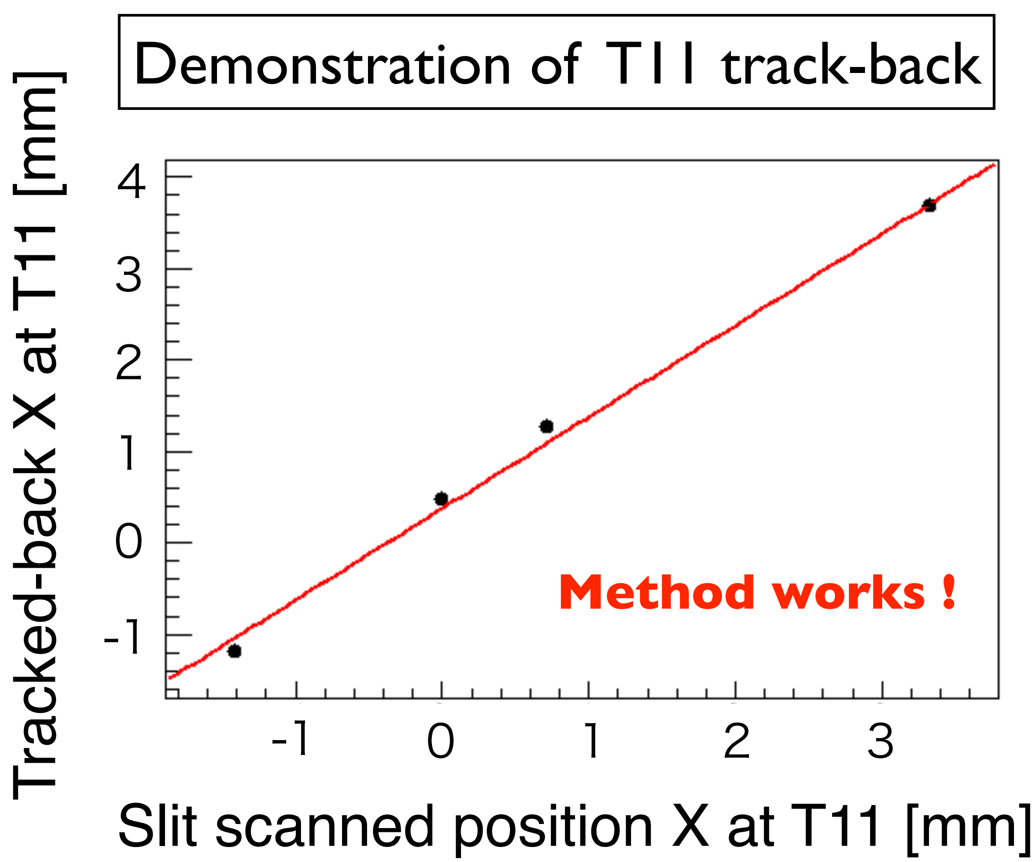
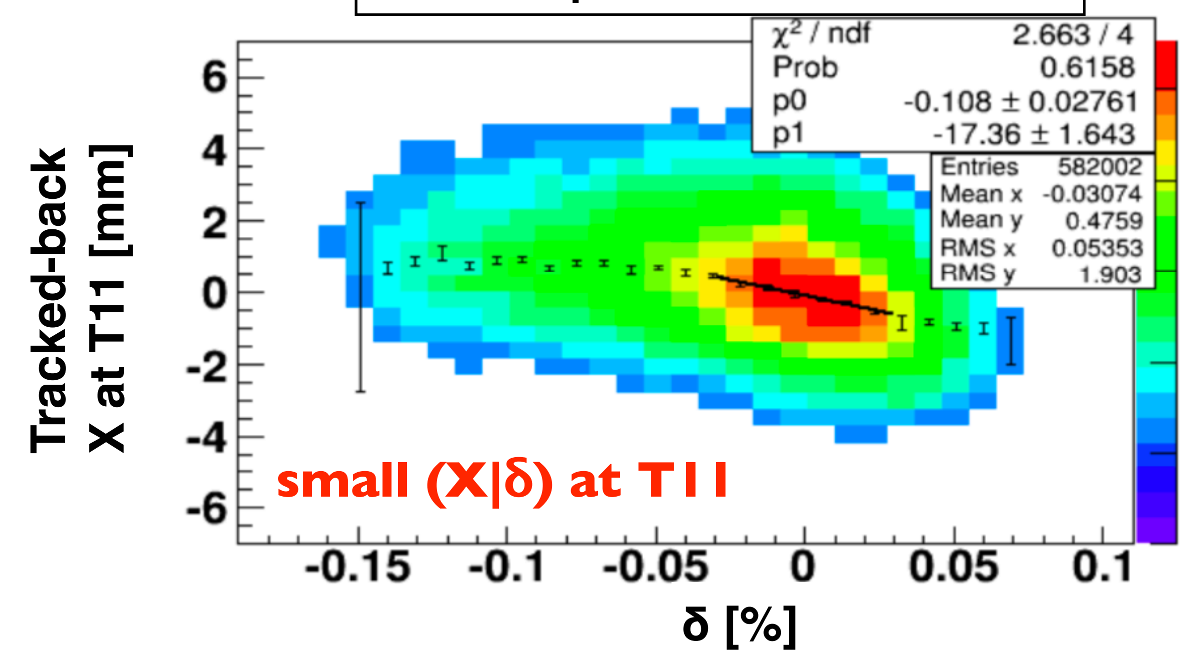
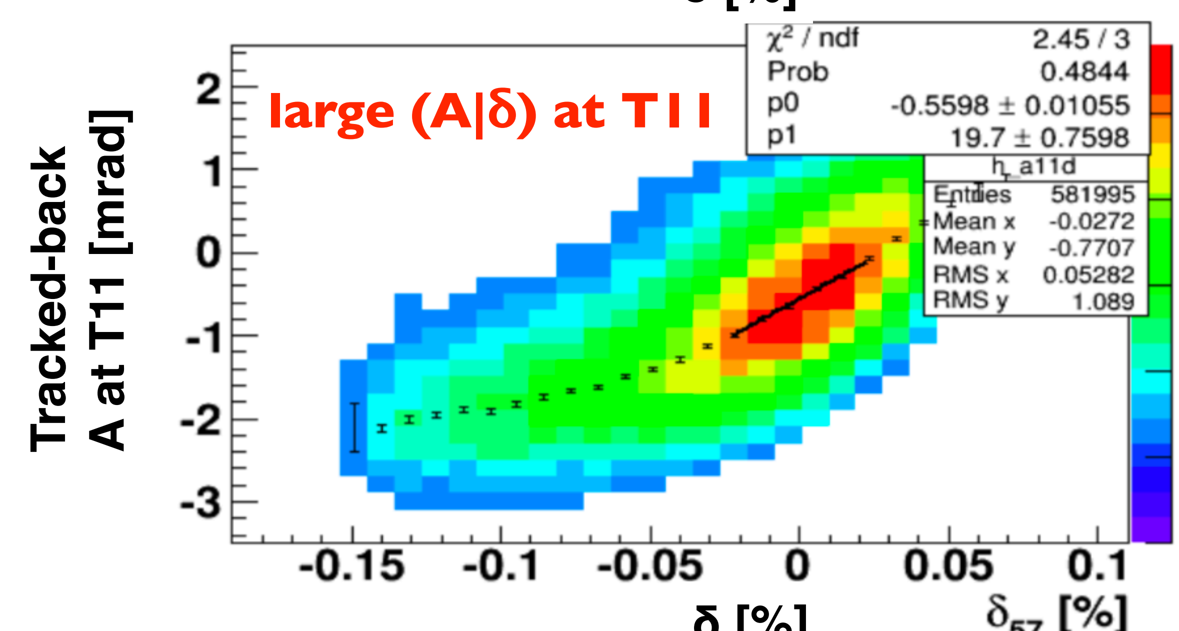


S. Y. Matsumoto

T11 dispersion estimation





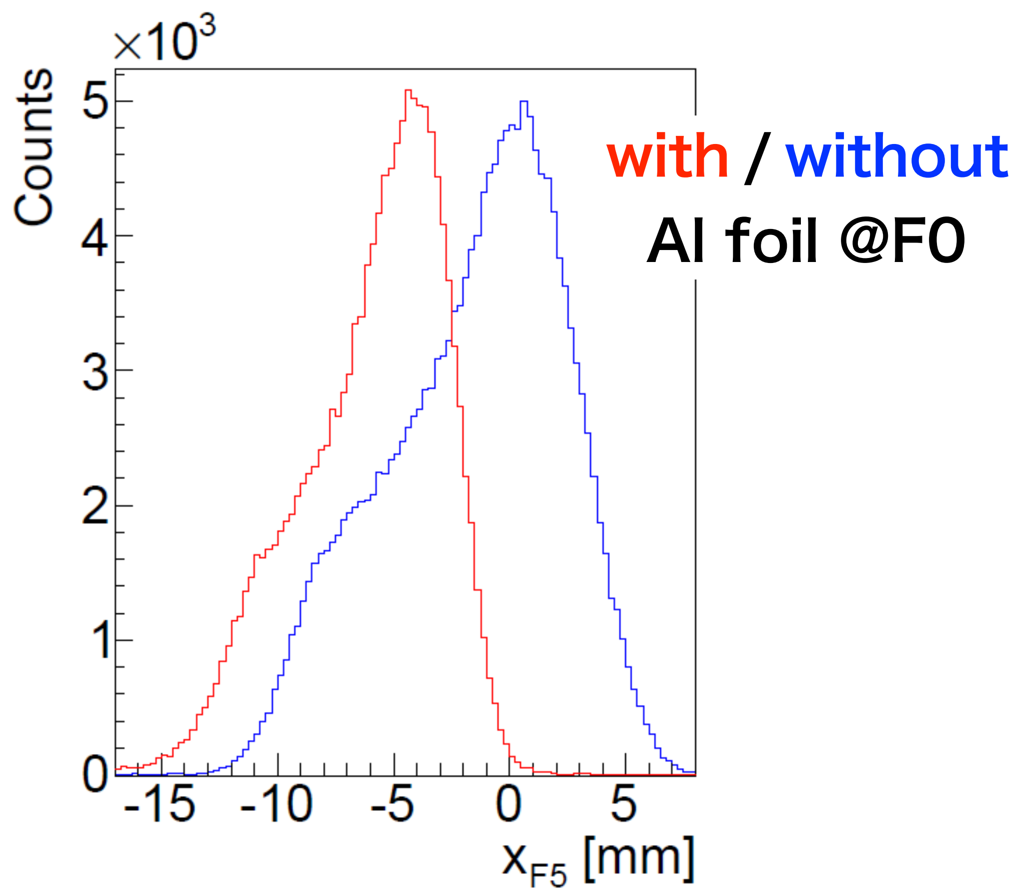
Test of trace-back method with ^{18}O beam in 2018

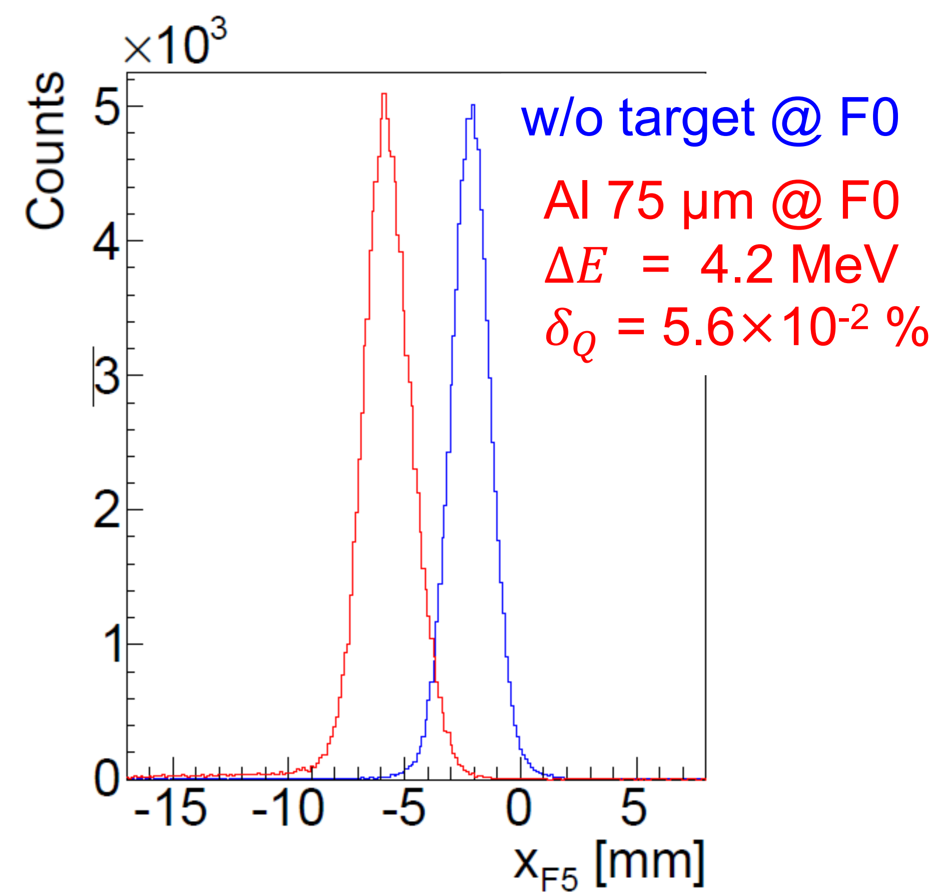
Demonstration of dispersion matching by ΔE spectroscopy

◇ ΔE measurement of Al 75 μm at F0 target

◇ C = 1.00 → $(X|\delta)_{SRC\text{-}F0}$ = 34 mm/% is required

Without dispersion matching $(X\|\delta)_{SRC\text{-}F0} = 0$	With dispersion matching $(X\|\delta)_{SRC\text{-}F0} \sim$ 34 mm/%





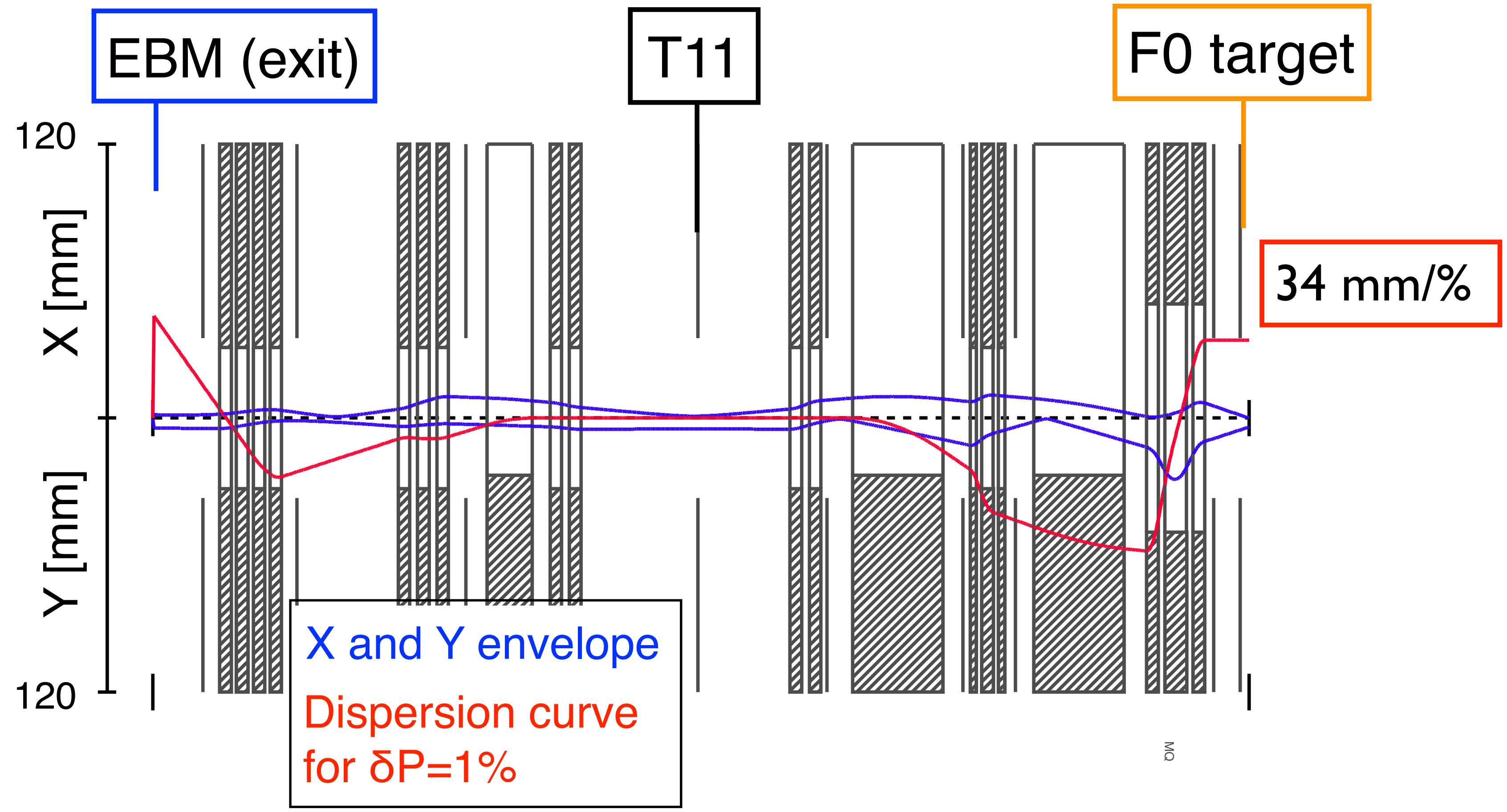
S. Y. Matsumoto et al.,
RIKEN Accel. Prog. Rep. 52 (2019) 135

Corresponding resolving power $P/\Delta P_{FWHM} \sim 3100$

DGTGR and π-atom experiments in 2021

^{12}C beam @ 250MeV/u
(DGTGR, 2021 May)

Trace-back +
T11→EBM matrix



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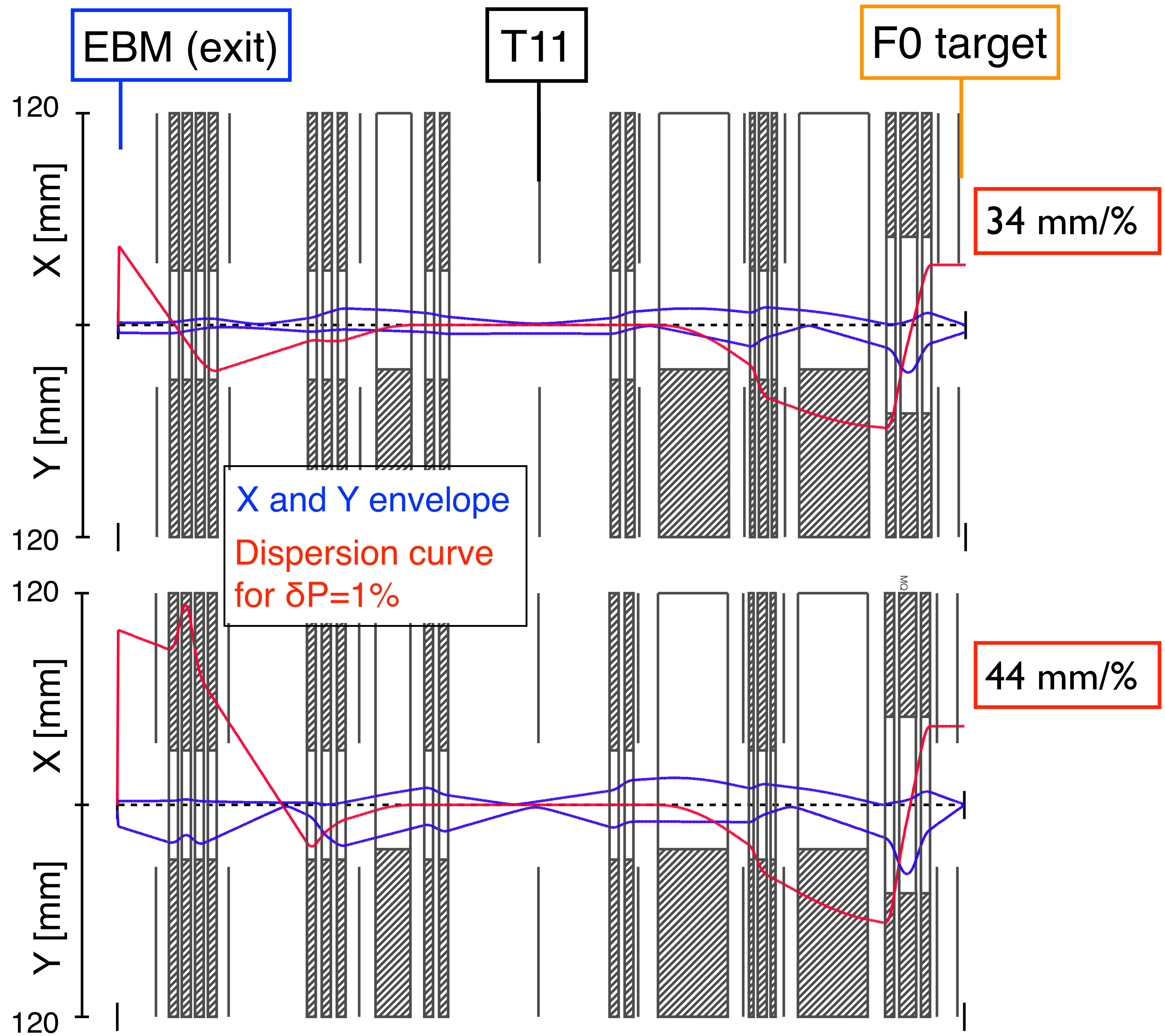

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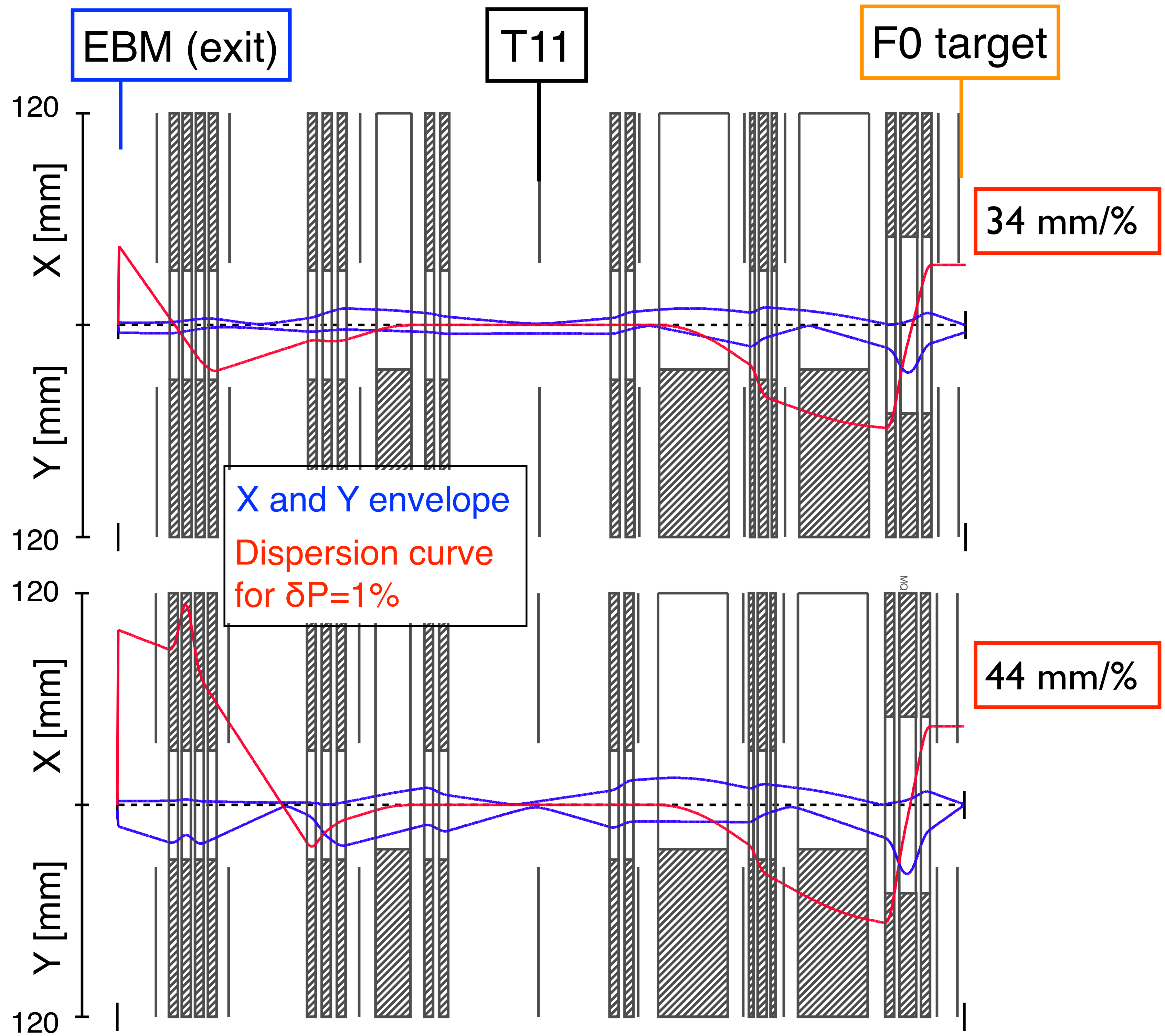
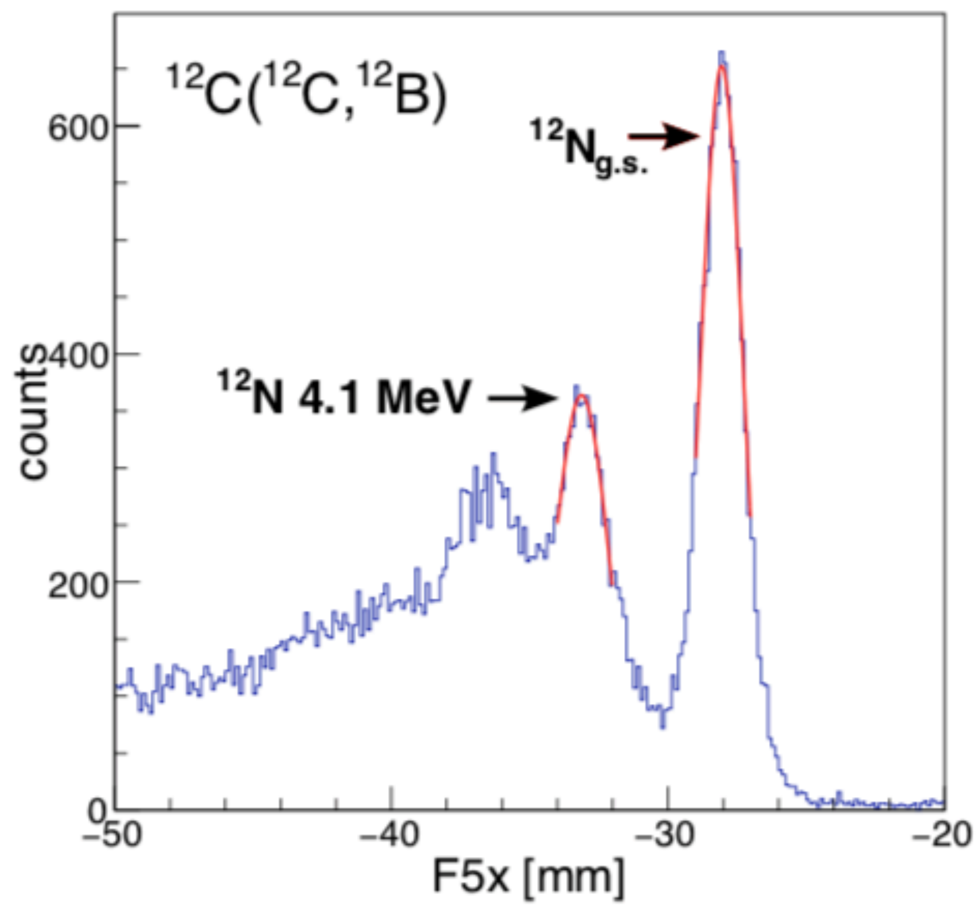


- ◇ Different dispersion curves at SRC exit were observed for different beams !
- ◇ For each experiment, T11 was tuned to be achromatic, and F0 with desired dispersion

DGTGR and π-atom experiments in 2021

^{12}C beam @ 250MeV/u
(DGTGR, 2021 May)

Calibration with single-charge exchange reaction

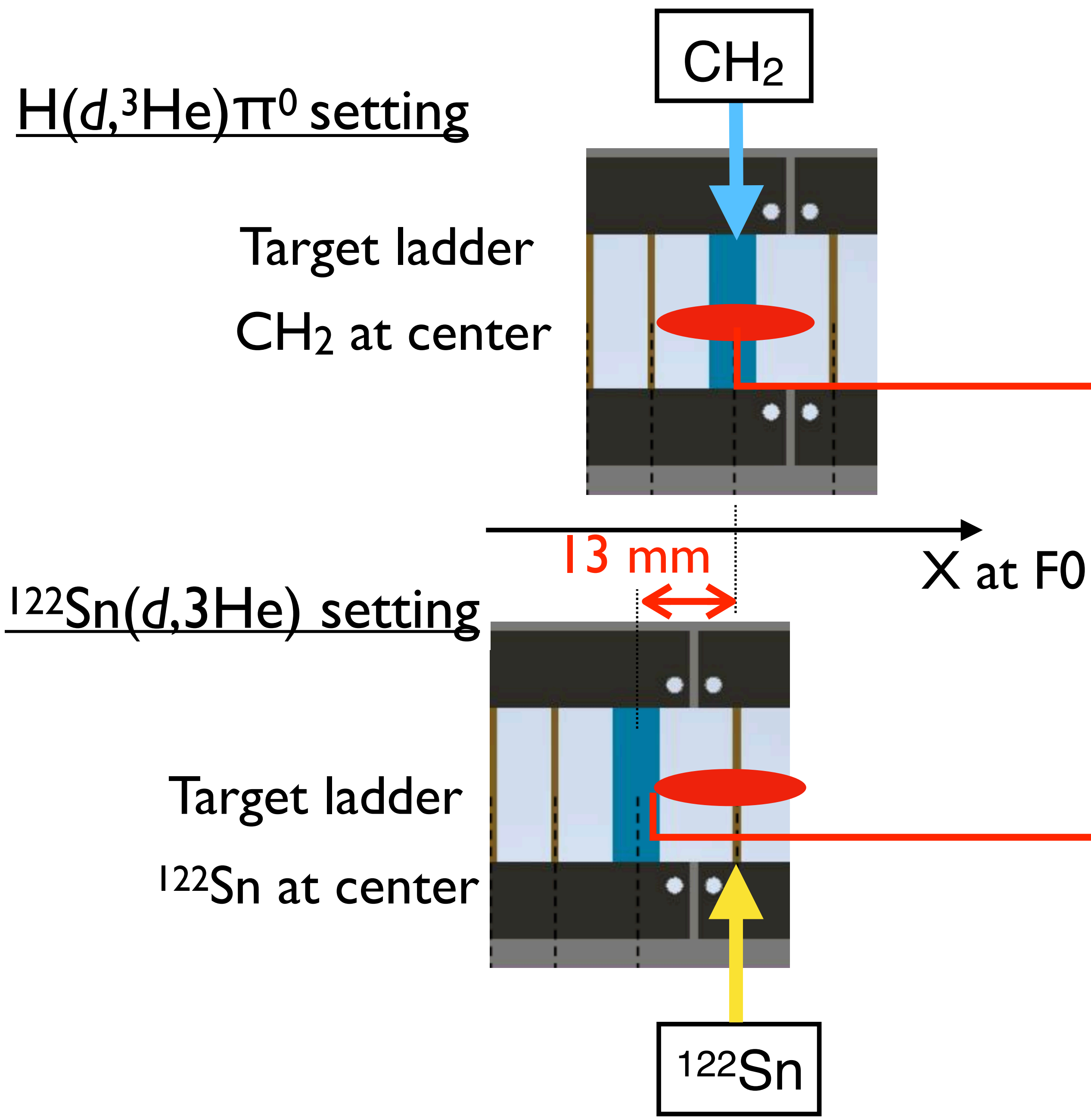


A. Sakaue, PhD thesis, Kyoto Univ.(2025)

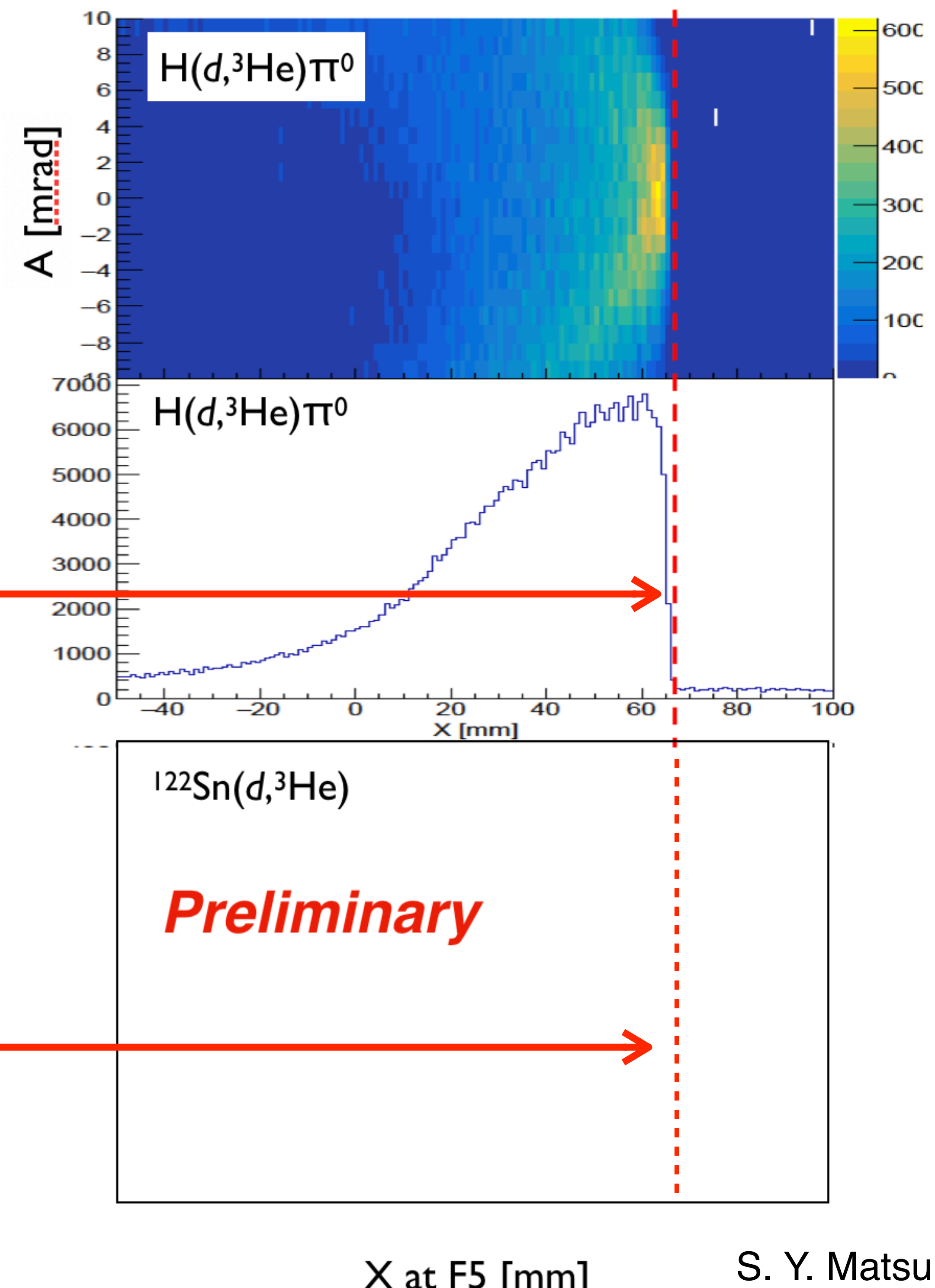
◇ Excitation energy resolution (FWHM) ~ 1.5 MeV
◇ Corresponding resolving power $P/\Delta P_{\mathrm{FWHM}}$ ~ 3600

DGTGR and π-atom experiments in 2021

d beam @ 250MeV/u
(π-atom, 2021 June)



Evidence of dispersion matching



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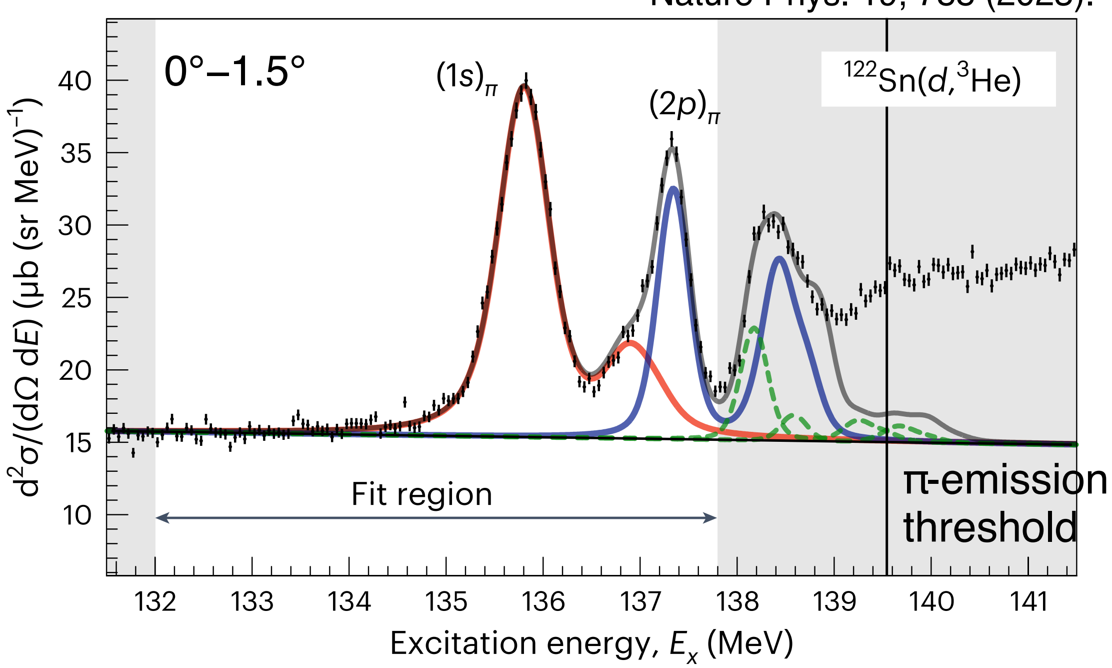
Effects of shifted X and δ of the beam at F0 compensate !

DGTGR and π-atom experiments in 2021

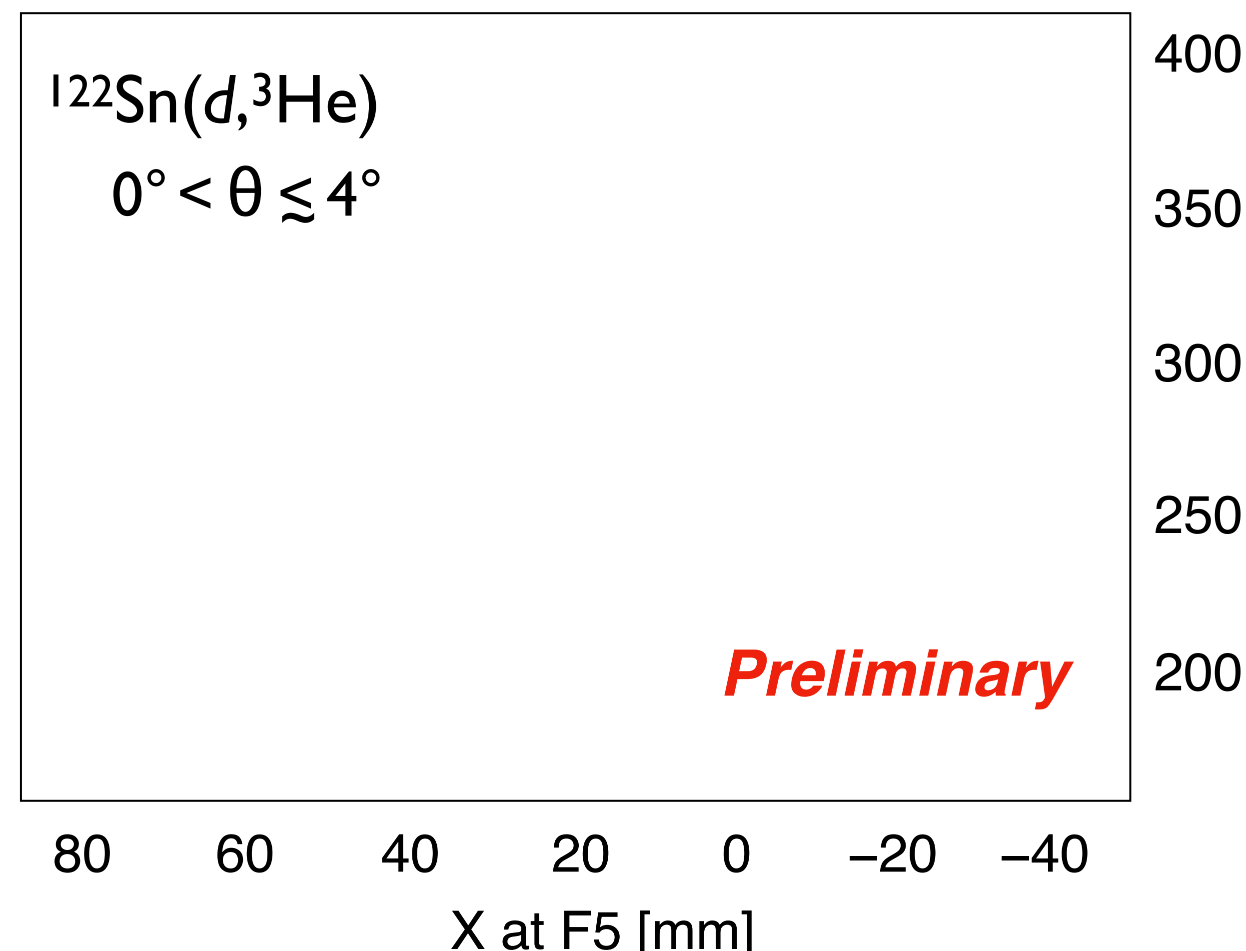
d beam @ 250MeV/u
(π-atom, 2021 June)

2014 experiment

Nature Phys. 19, 788 (2023).



2021 experiment



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- ◇ Narrower peaks and more sub-components are observed !
- ◇ Detailed analysis is in progress

Summary and future prospects

- We have developed dispersion-matched SRC + BigRIPS ion optics for precision missing-mass spectroscopy with reactions using primary beams. We established its tuning procedure with a trace-back method.

- Two experiments have been successfully performed in 2021 :
  - Spectroscopy of deeply-bound pionic atoms with ^{A}Sn(d,^{3}He) reaction
  - Study of double Gamow-Teller giant resonances with ^{48}Ca(^{12}C, ^{12}Be(0^{+}_{2})) reaction

- For the future, we will continue application of the dispersion-matching method to further studies of π-atom and DGTGR.

  e.g., DGTGR with ^{136}Xe target,

  π-atom with Z=50, 54 isotope, N=82 isotone

- We are also developing π-atom spectroscopy in inverse kinematics
  - $\partial E_{ex}/\partial P_{beam} \sim 0$ due to kinematics
  - Explore possibilities of producing variety of pionic atoms