Precision Spectroscopy of Pionic Atoms at RIBF

and Deduction of Chiral Condensate at Nuclear Density

RIKEN Nishina Center
Kenta Itahashi

published 2023/3

nature physics **T. Nishi, K.I. et al., Nat. Phys. 19, 788(2023)**

Article https://doi.org/10.1038/s41567-023-02001-x

Chiral symmetry restoration at high matter density observed in pionic atoms

- Nature Physics **19**, 788 (2023/3/23)
  Article DOI: 10.1038/s41567-023-02001-x
- Nature Physics **19**, 764 (2023/3/23)
  News and Views "Modified in Medium"

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プレスリリース

Nature Physics **19**, 764 (2023/3/23)
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Nuclear physics

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Sean Freeman

Nature Physics 19, 764–765 (2023) | Cite this article

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The strong interaction is modified in the presence of nuclear matter. An experiment has now quantified with high precision and accuracy the reduction of the order parameter of the system's chiral symmetry, which is partially restored.

The vacuum state of quantum chromodynamics (QCD) sounds dull, boring and empty. However, due to the strength of the strong force underlying QCD, it turns out to be extremely complex and is teeming with pairs of virtual particles that cannot be directly observed.

理化学研究所

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2023年3月27日
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“π”で探る真空の秘密
－真空に隠された構造「クォーク凝縮」の精密測定に成功－

理化学研究所（理研）仁科加速器科学研究センター 加速器基盤研究部の西 隆博 研究員、中間子科学研究室の板橋 健太 専任研究員（開拓研究本部 岩崎中間子科学研究室 専任研究員）、奈良女子大学 理学部 数物科学科の比連崎 悟 教授、鳥取大学 農学部 生命環境農学科の池野 なつ美 講師、大阪大学 核物理研究センター 核物理理論研究部門の野瀬-外川 直子 協同研究員らの国際共同研究グループは、π（パイ）中間子[1]が原子核に束縛されたπ中間子原子の精密測定を行い、真空が空っぽの空間ではなく、見えない構造を隠し持つことを示す実験結果を得ることに成功しました。

一般に真空は、「空（から）」の空間を意味しますが、現代物理学の理論によると、宇宙がビッグバン以降広がりながら冷えていく過程で、クォーク[2]と反クォーク[2]の対が空間に凝縮（クォーク凝縮[3]）し、真空を満たした状態です。この理論は物質の質量の起源に関する基礎的理論である一方、実験的な実証が課題でした。クォーク凝縮は直接には観測できませんが、環境の温度や物質密度によって変化し、クォーク凝縮の量が変化したことの影響は

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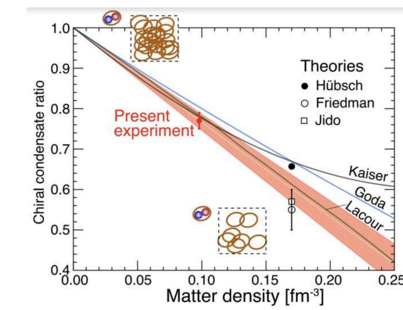
APRIL 14, 2023 FEATURE | Editors' notes

New experimental evidence of the restoration of chiral symmetry at high matter density

by Ingrid Fadelli , Phys.org



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Nishina Center

nta Itahashi

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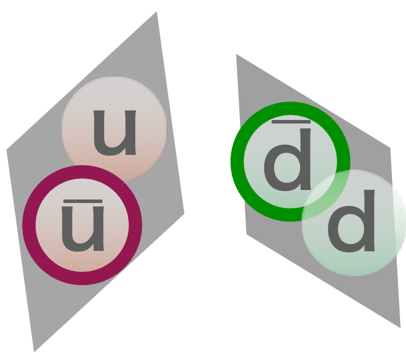
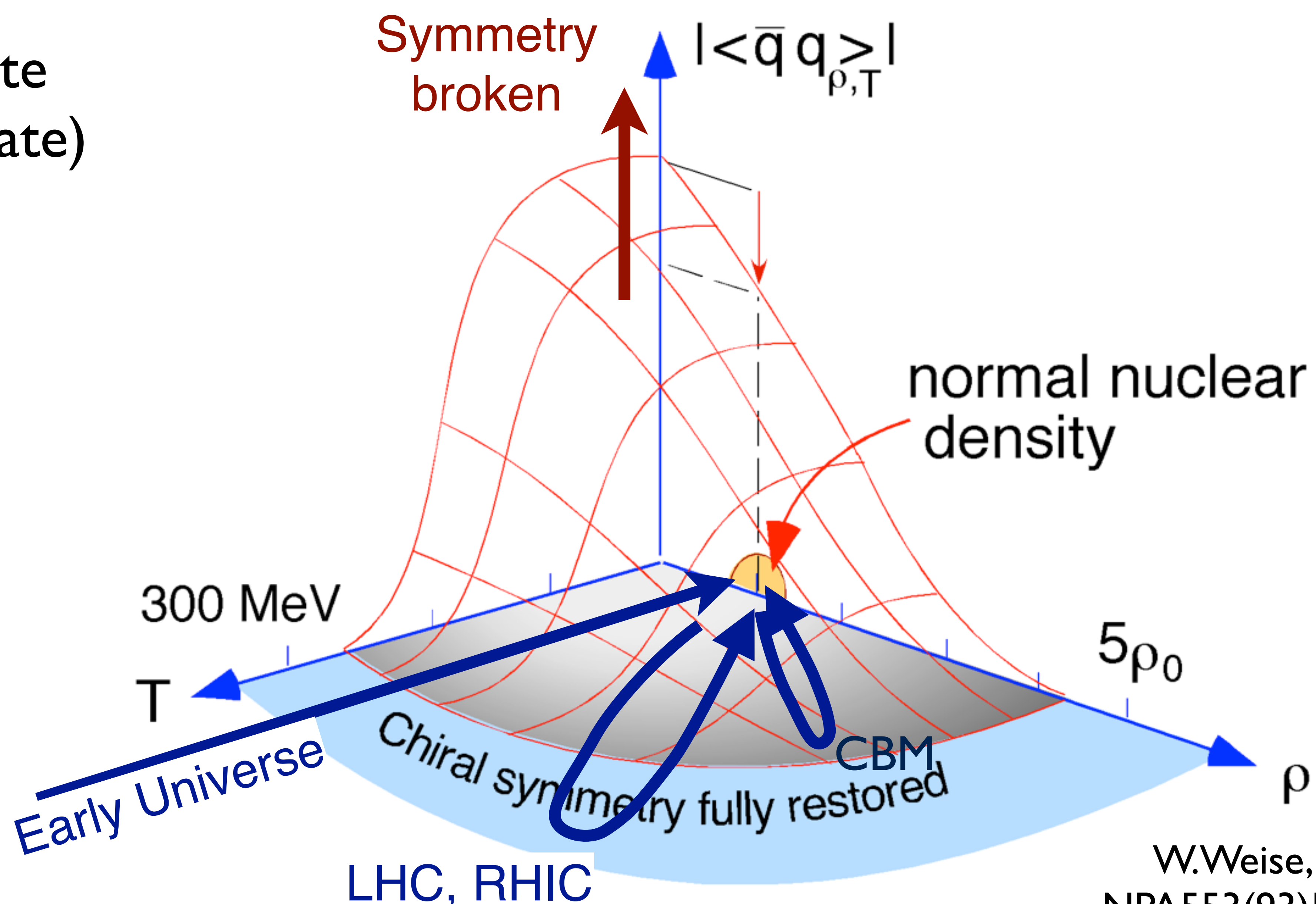
Chiral Condensate

Order parameter of chiral symmetry depends on T and ρ

Chiral condensate
(= quark condensate)

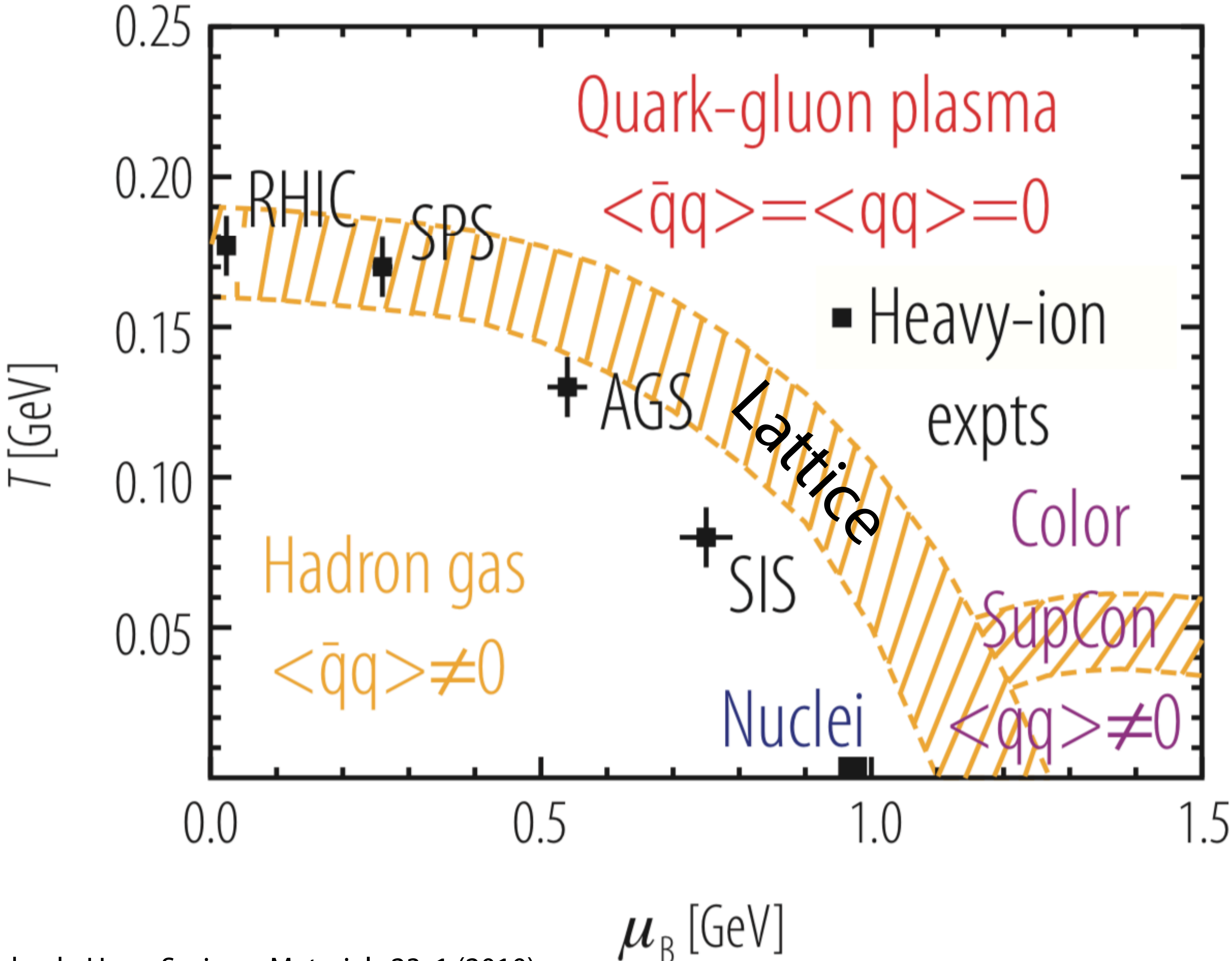




W.Weise, NPA553(93)59.

Analysis of material properties of QCD vacuum

QCD phase and chemical freezeout points

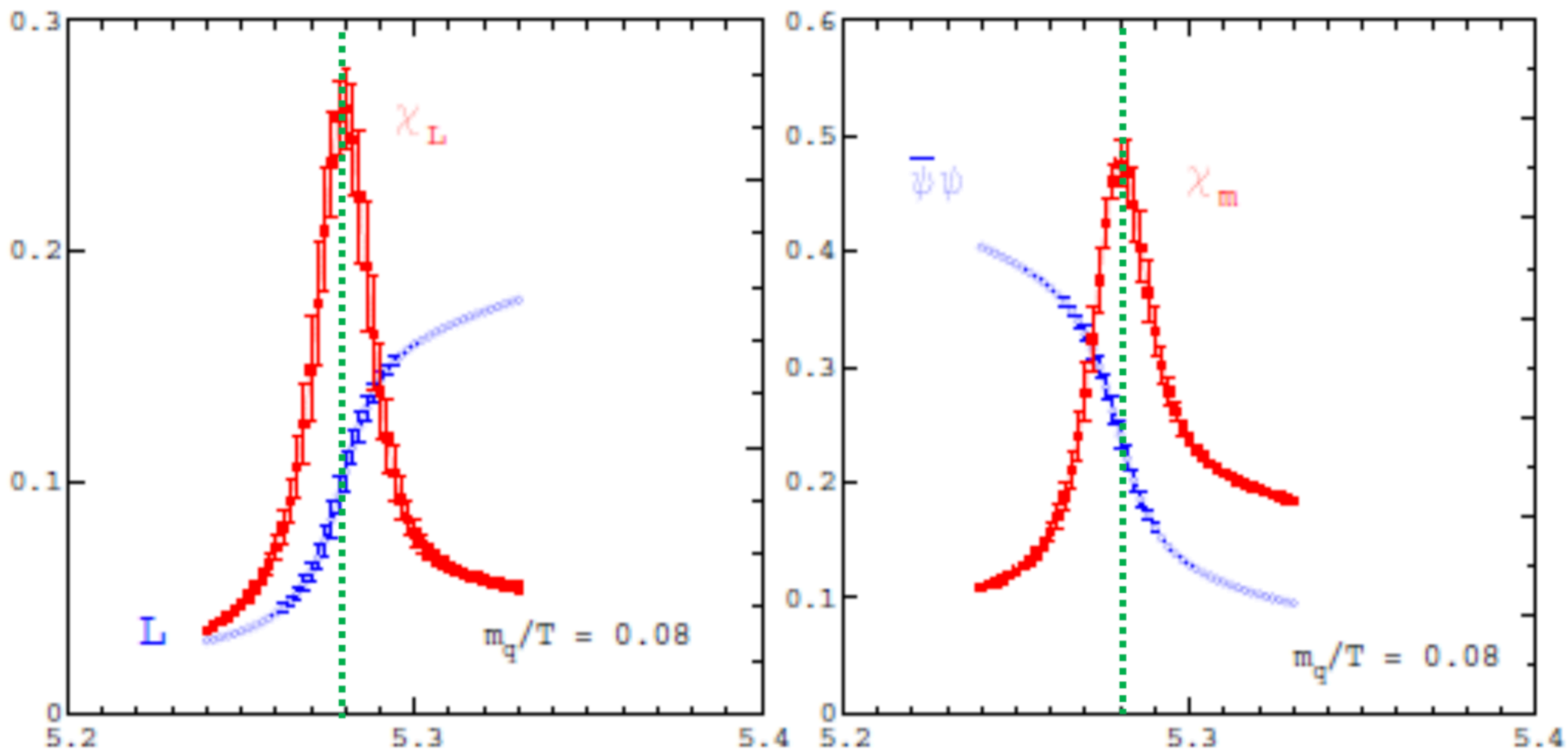


Rapp, Wambach, Hees, SpringerMaterials 23, 1 (2010)
P. Braun-Munzinger et al., QGP3, 491 (2004)

Chiral transition & Quark confinement

Correlation between Confinement and CSB is suggested by
Simultaneous Phase Transition of
Deconfinement and Chiral Restoration.

Lattice QCD results at finite temperature F. Karsch, Lect. Notes Phys. (2002)



Polyakov Loop **<P>** Chiral Condensate **<$\bar{q}$q>**

Color Confinement Chiral Symmetry Breaking

Fig. 2. Deconfinement and chiral symmetry restoration in 2-flavour QCD: Shown is $\langle L \rangle$ (left), which is the order parameter for deconfinement in the pure gauge limit ($m_q \to \infty$), and $\langle \bar{\psi}\psi \rangle$ (right), which is the order parameter for chiral symmetry breaking in the chiral limit ($m_q \to 0$). Also shown are the corresponding susceptibilities as a function of the coupling $\beta = 6/g^2$.

H. Suganuma, JPS symposium (2010)

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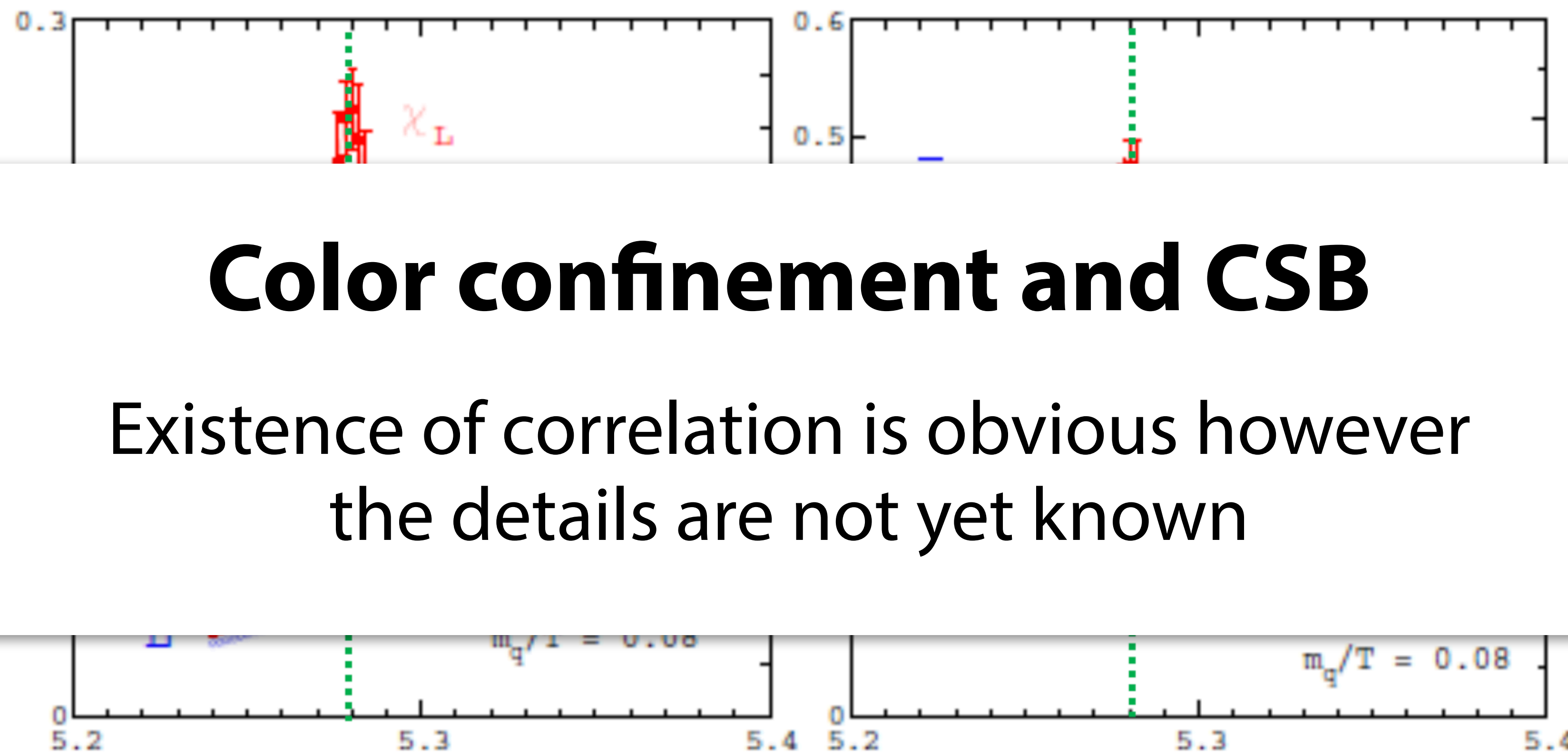


Color confinement and CSB

Existence of correlation is obvious however
the details are not yet known

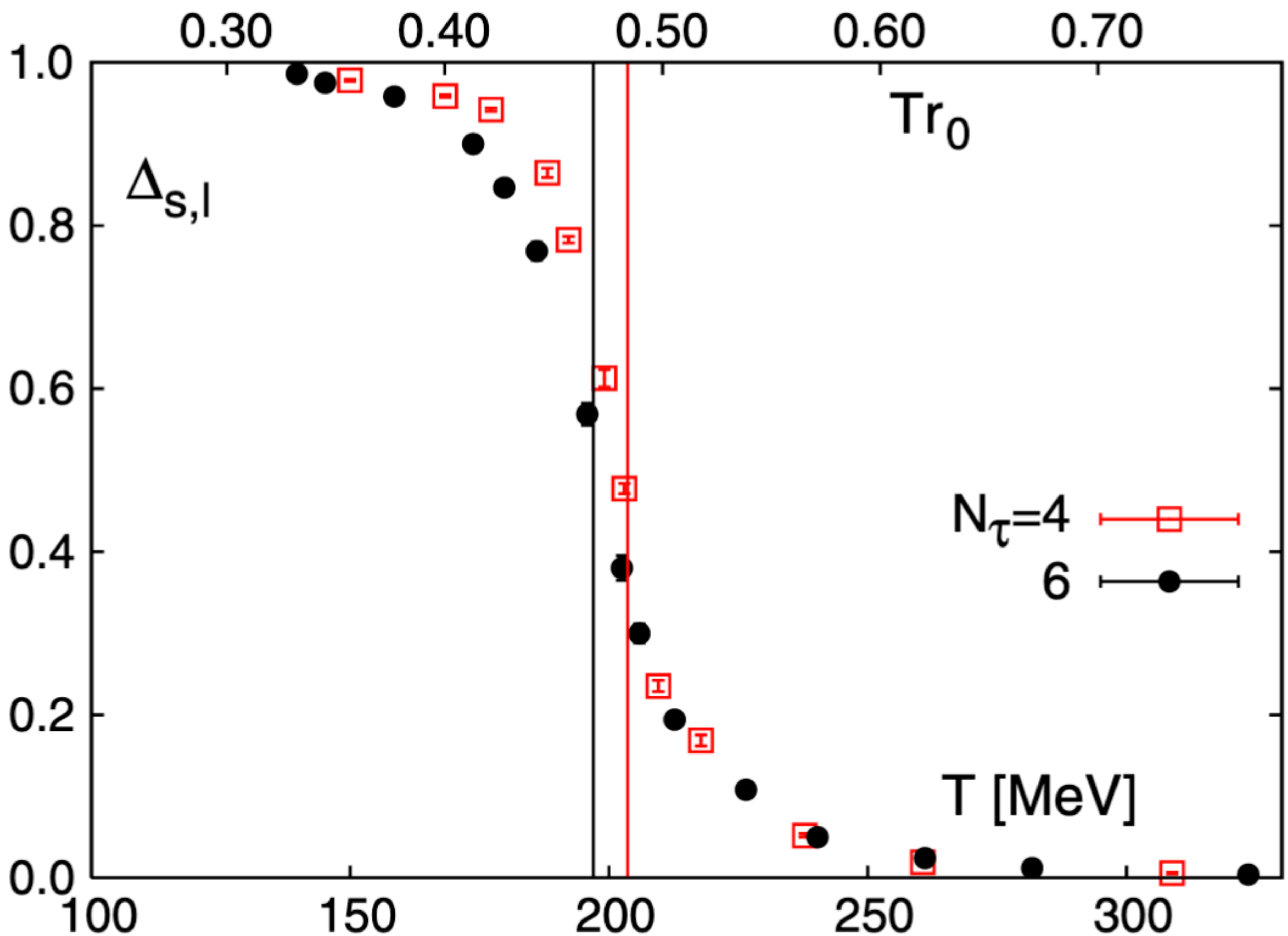
Polyakov Loop $\langle P \rangle$ — Color Confinement

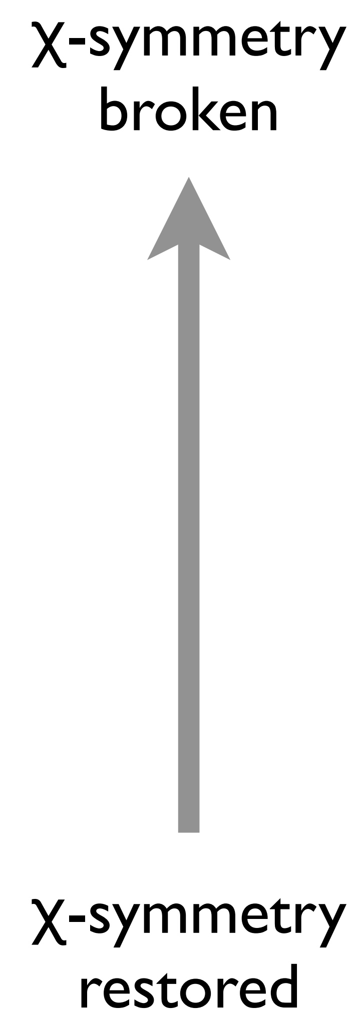
Chiral Condensate $\langle \bar{q}q \rangle$ — Chiral Symmetry Breaking

Fig. 2. Deconfinement and chiral symmetry restoration in 2-flavour QCD: Shown is $\langle L \rangle$ (left), which is the order parameter for deconfinement in the pure gauge limit ($m_q \to \infty$), and $\langle \bar{\psi}\psi \rangle$ (right), which is the order parameter for chiral symmetry breaking in the chiral limit ($m_q \to 0$). Also shown are the corresponding susceptibilities as a function of the coupling $\beta = 6/g^2$.

H. Suganuma, JPS symposium (2010)

Lattice QCD calculated T dependence of chiral condensate

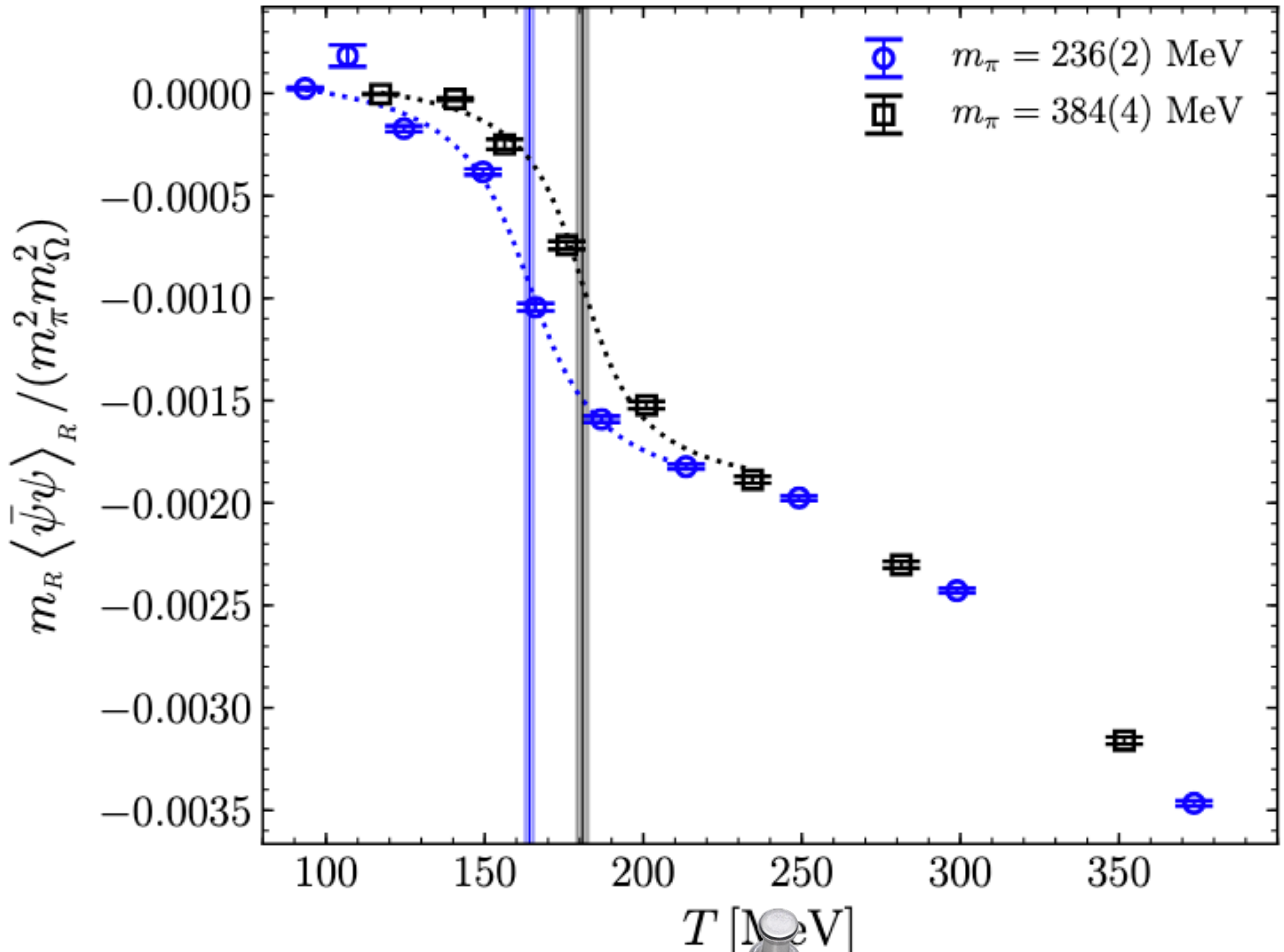


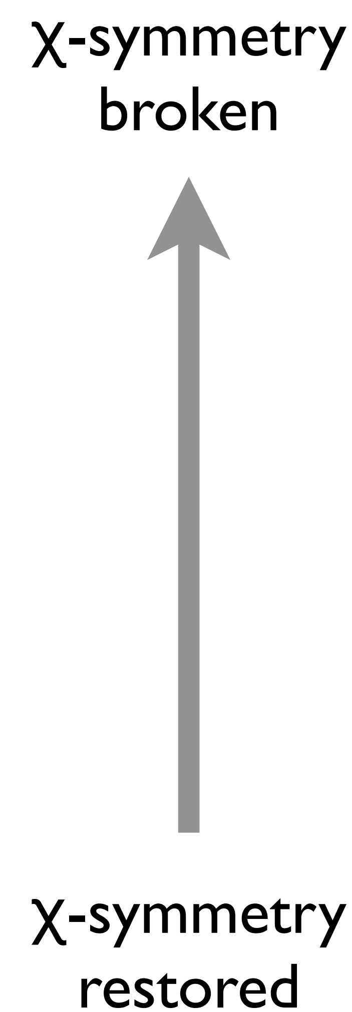


Temperature dependence of the chiral condensate from lattice QCD with 2 + 1 quark flavours and almost physical quark masses

M. Cheng et al., Phys. Rev. D77(2008), 014511.

Lattice QCD calculated T dependence of chiral condensate

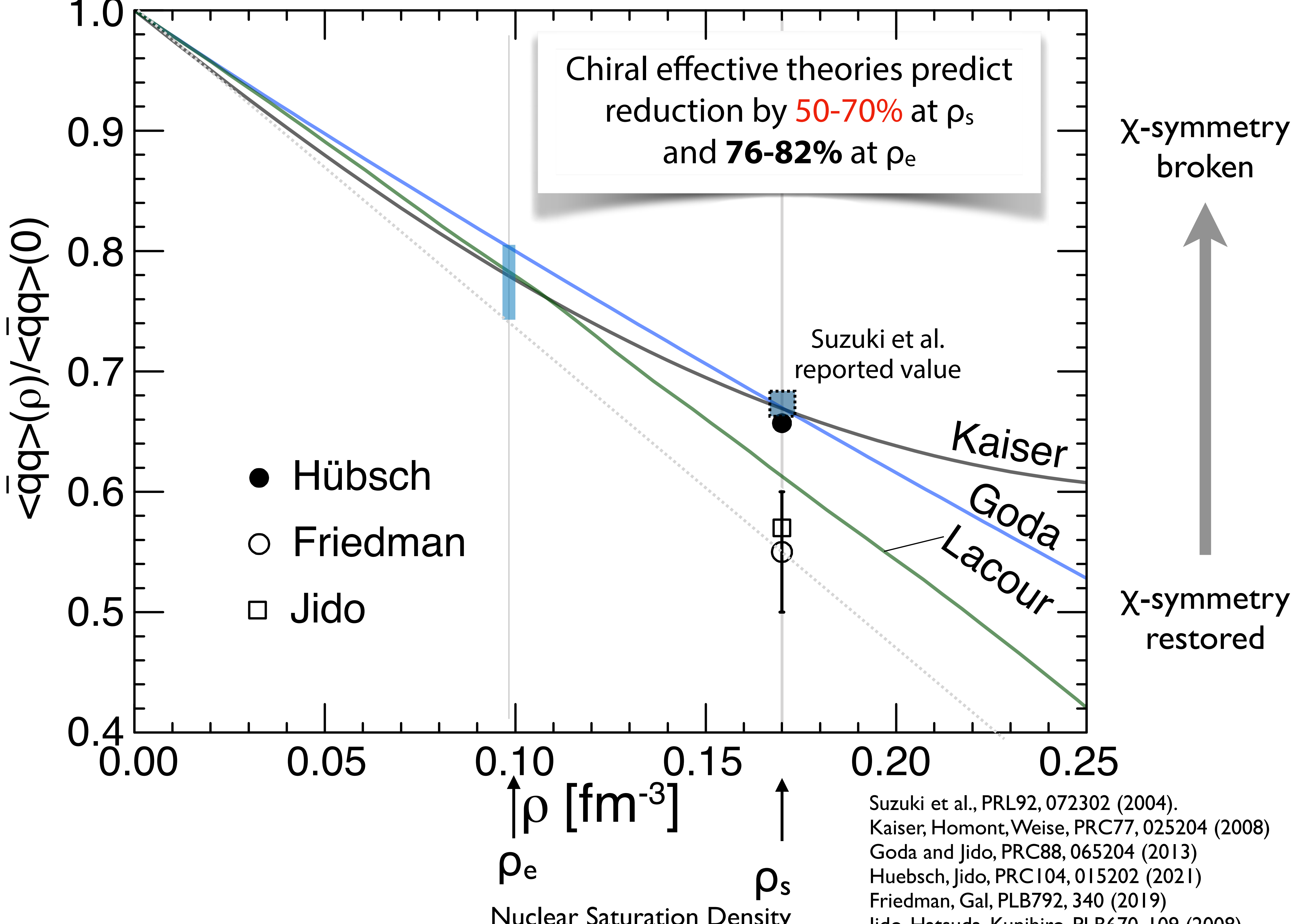




Remark: sign problem makes it difficult for lattice to approach non-zero ρ region

Jon-Ivar Skullerud
PRD105(2022)034504

ρ dependence of chiral condensate

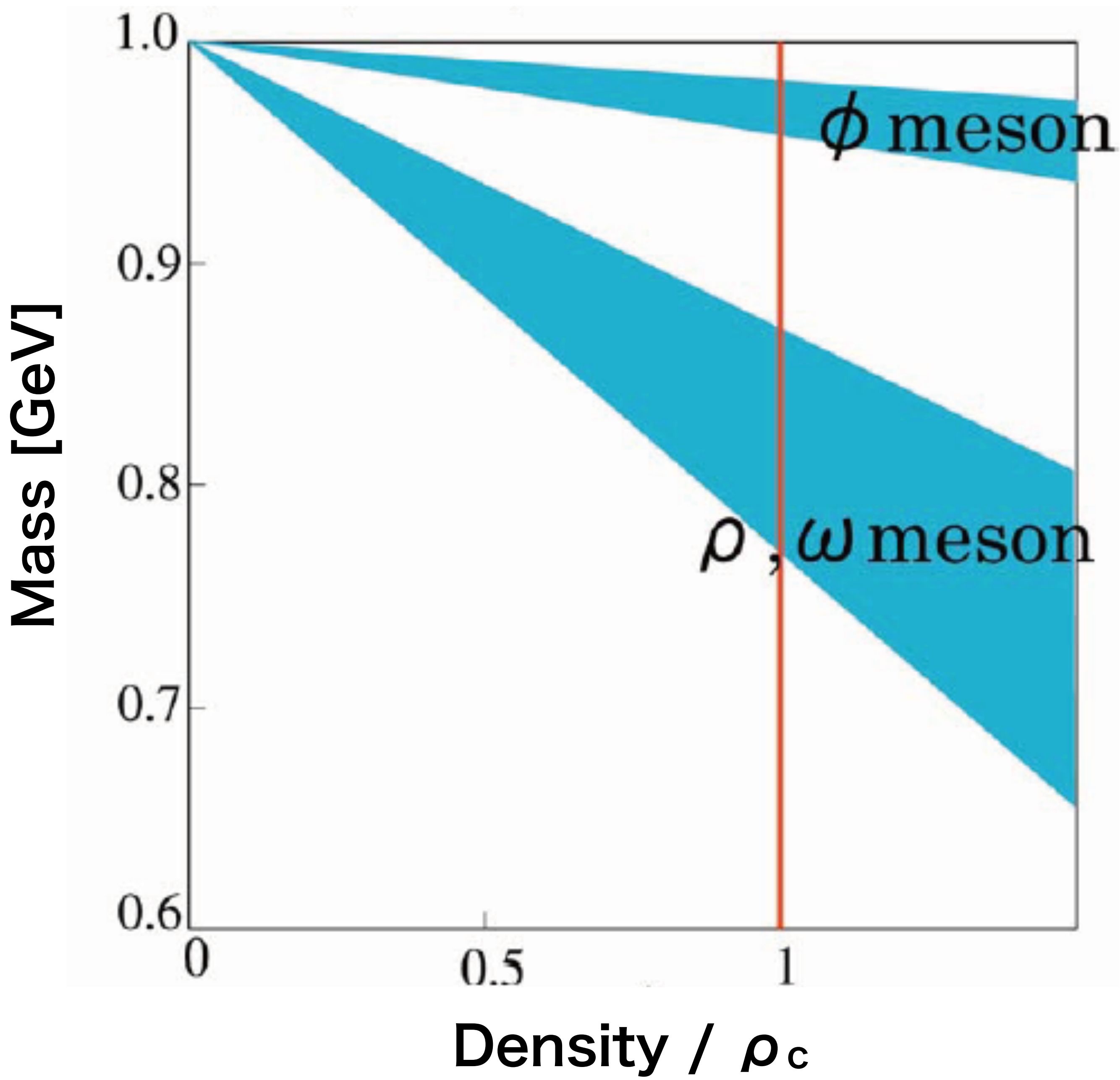


Suzuki et al., PRL92, 072302 (2004).
Kaiser, Homont, Weise, PRC77, 025204 (2008)
Goda and Jido, PRC88, 065204 (2013)
Huebsch, Jido, PRC104, 015202 (2021)
Friedman, Gal, PLB792, 340 (2019)
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)
Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (2010)

Meson masses and QCD medium effect

Vector meson mass modification in QCD sum rule

(J-PARC E16)



$\phi(1020)$ $I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1019.455 \pm 0.020$ MeV (S = 1.1)
Full width $\Gamma = 4.26 \pm 0.04$ MeV (S = 1.4)

$\phi(1020)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
K^+K^-	(48.9 ± 0.5) %	S=1.1	127
$K^0_L K^0_S$	(34.2 ± 0.4) %	S=1.1	110
$\ell^+\ell^-$	—		510
e^+e^-	$(2.954 \pm 0.030) \times 10^{-4}$	S=1.1	510
$\mu^+\mu^-$	$(2.87 \pm 0.19) \times 10^{-4}$		499

$\rho(770)$ [h] $I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 775.49 \pm 0.34$ MeV
Full width $\Gamma = 149.1 \pm 0.8$ MeV
$\Gamma_{ee} = 7.04 \pm 0.06$ keV

$\omega(782)$ $I^G(J^{PC}) = 0^-(1^{--})$

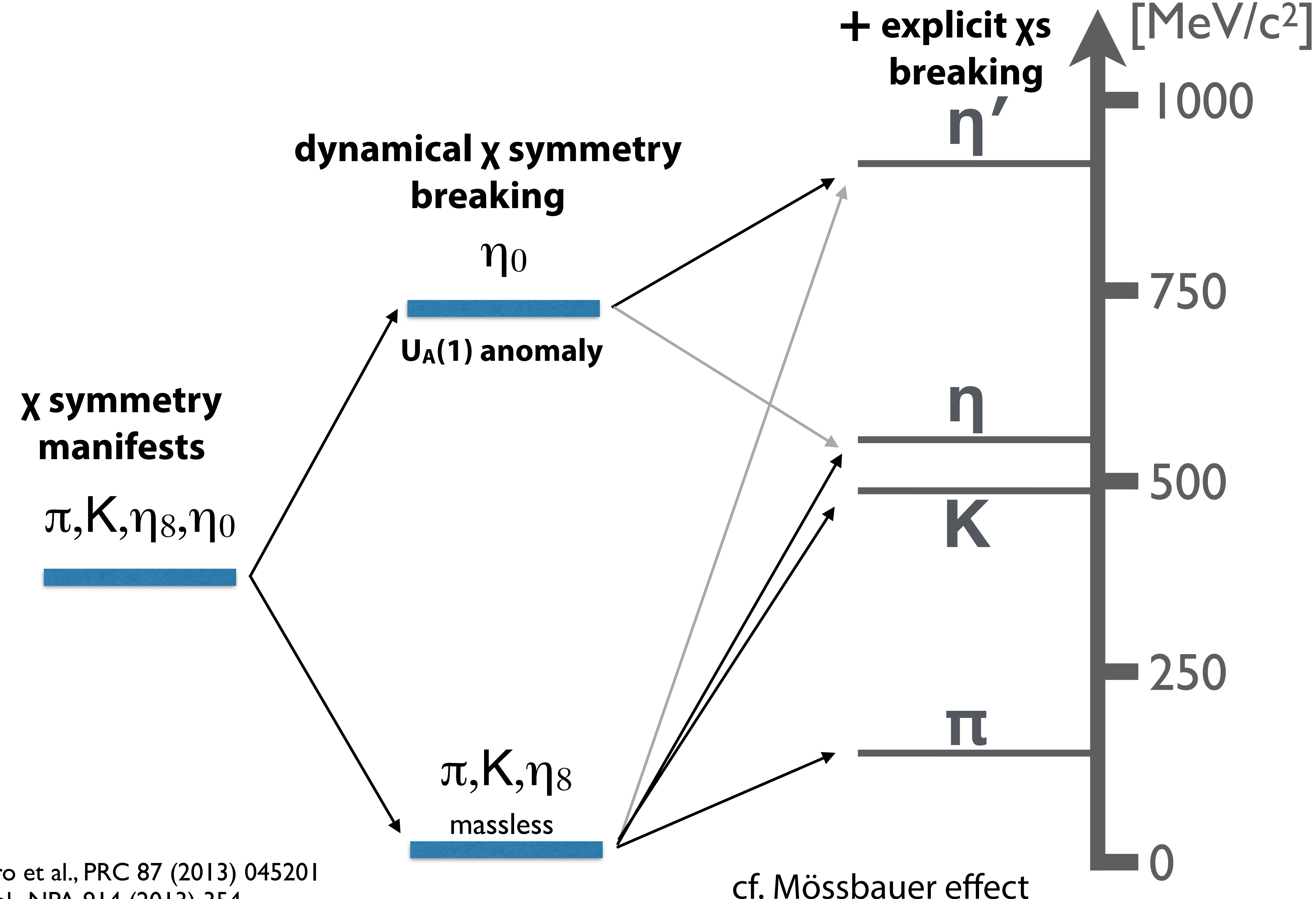
Mass $m = 782.65 \pm 0.12$ MeV (S = 1.9)
Full width $\Gamma = 8.49 \pm 0.08$ MeV
$\Gamma_{ee} = 0.60 \pm 0.02$ keV

*T.Hatsuda, S.H.Lee, Phys. Rev. **C46** (1992) R34*

Brown,Rho(1991), Hatsuda,Lee(1992)
Klingle,Keiser,Weise(1997),etc.

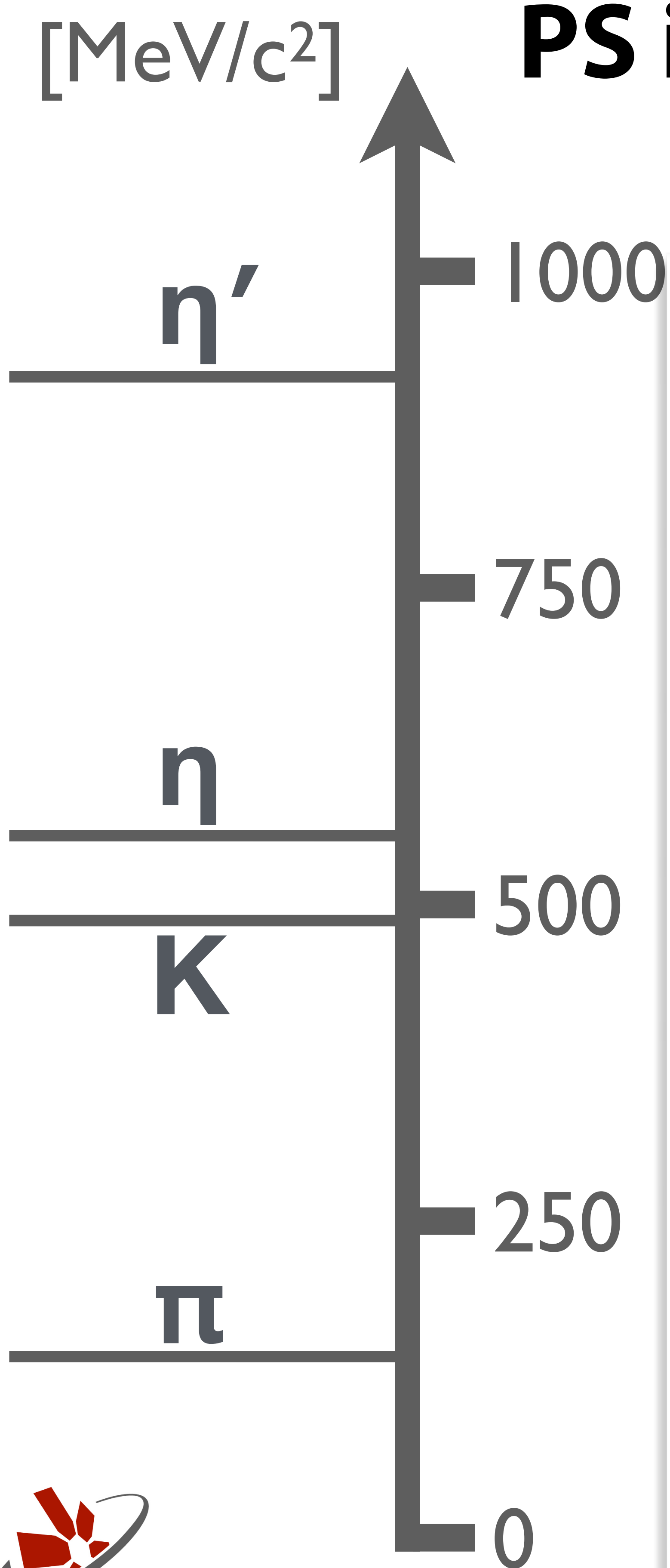
Masses of Pseudo-Scalar Mesons

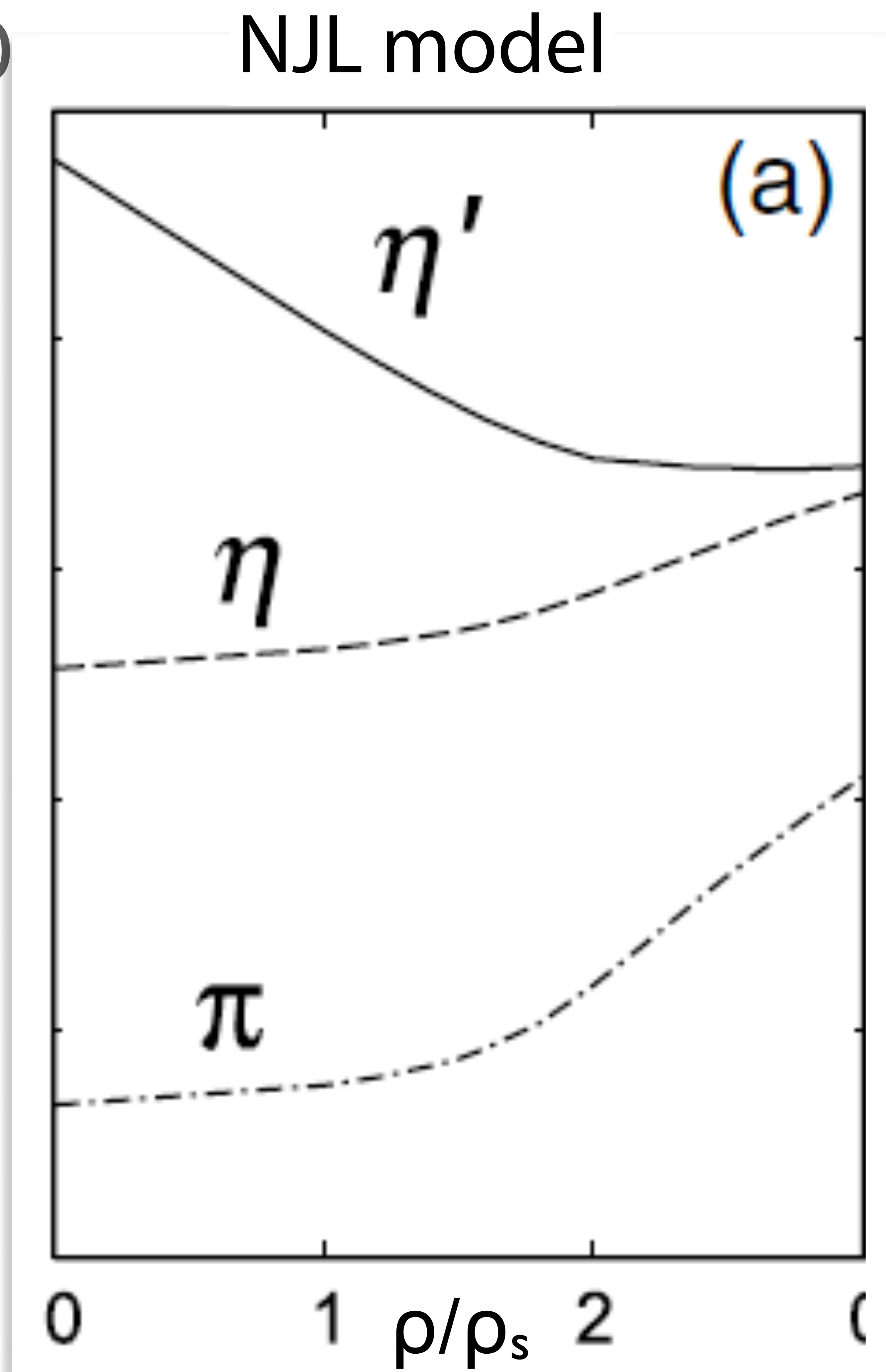
with various symmetry breaking patterns



Nagahiro et al., PRC 87 (2013) 045201
Jido et al., NPA 914 (2013) 354

PS in high density medium





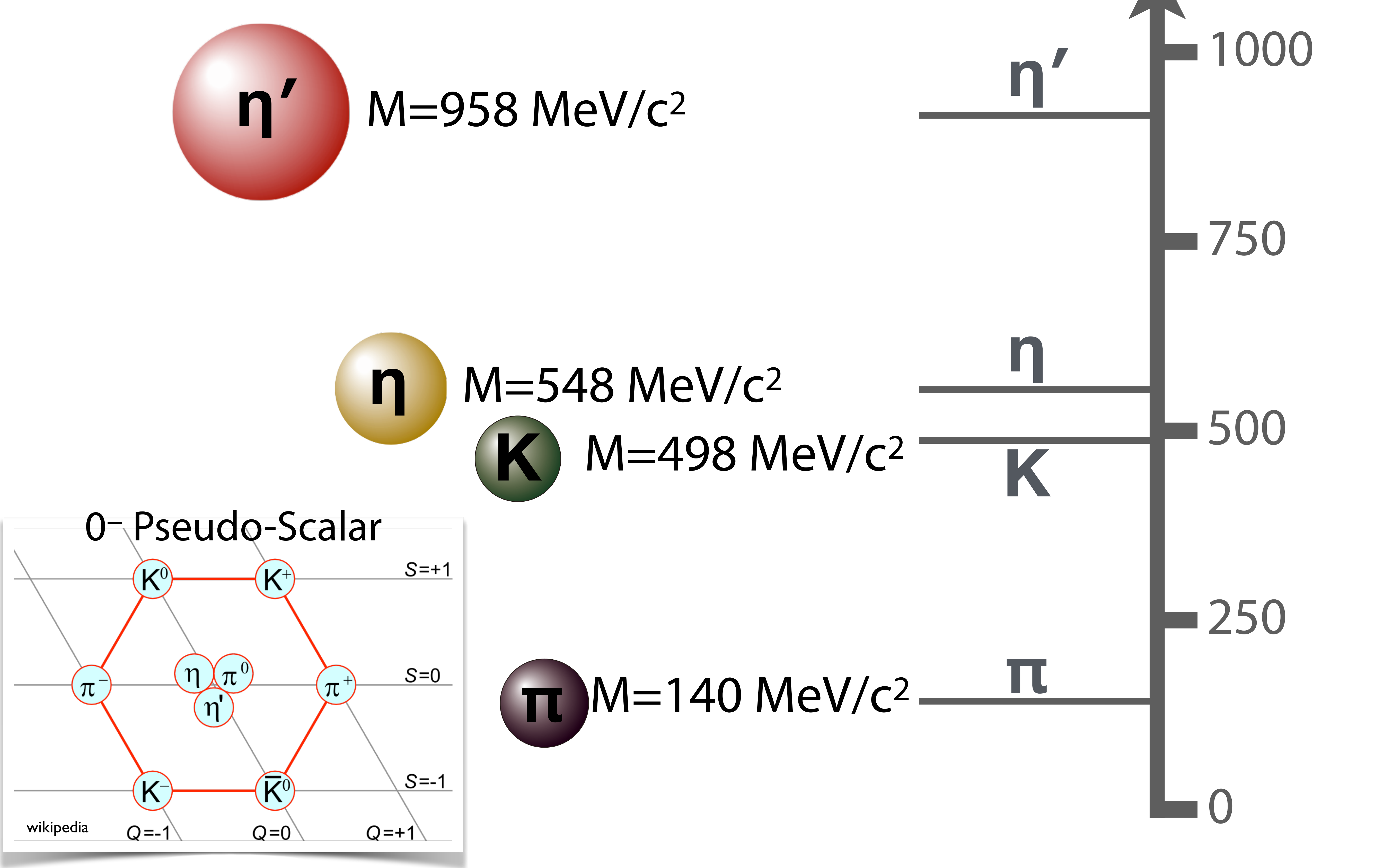
REMARK

Systematic measurement is important.

Nagahiro *et al*, PRC 74, 045203 (2006)

Pseudo-scalar mesons

(in the lowest-mass nonet)



Spectroscopy of *K⁻pp* bound states

2D Fit for the "$\bar{K}NN$" state

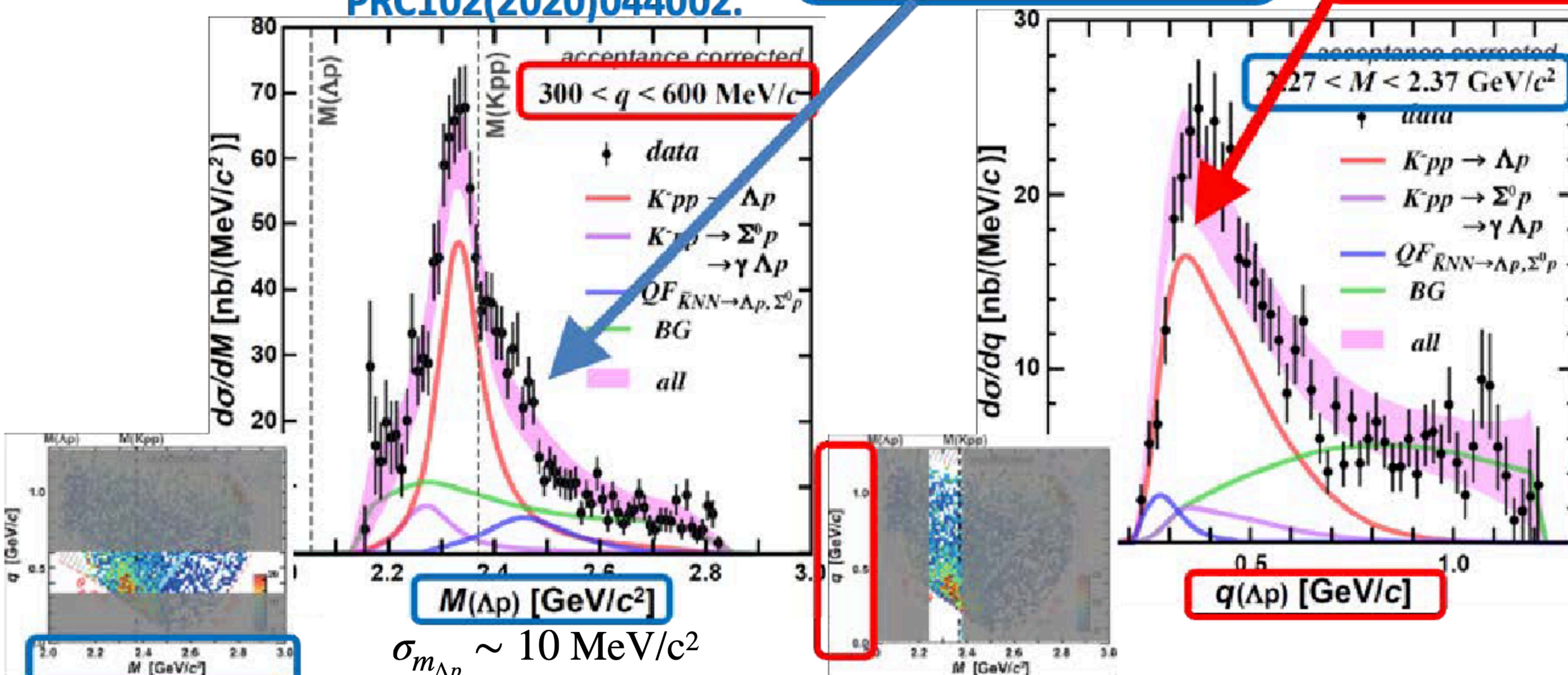
0.3 < q_x <0.6 GeV/c: Signals are well separated from other process

Fit with PWIA

$$\sigma(M,q) \propto \rho(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M-M_{Kpp})^2+(\Gamma_{Kpp}/2)^2} \times exp\left(-\frac{q^2}{{Q_{Kpp}}^2}\right)$$

phase space — Breit Wigner — form factor

PRC102(2020)044002.



$\sigma_{m_{\Lambda p}} \sim 10$ MeV/c²

B_{Kpp} ~ 40 MeV, Γ_{Kpp} ~ 100 MeV

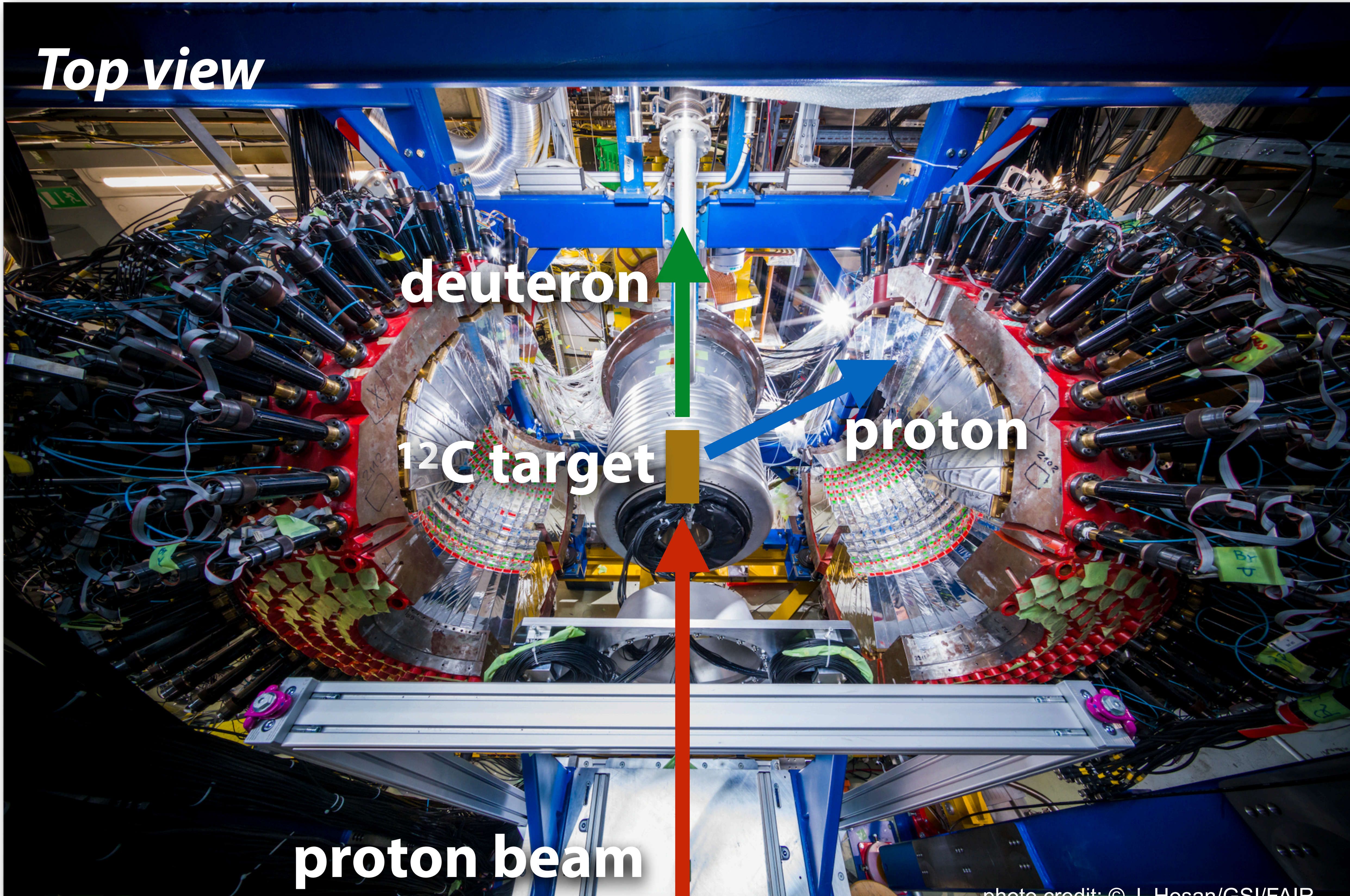
→ *large binding energy*

Q_{kpp} ~ 400 MeV (c.f. Q_{QF} ~ 200 MeV)

→ *wide momentum transfer*

T. Hashimoto, J-PARC Hadron 2023

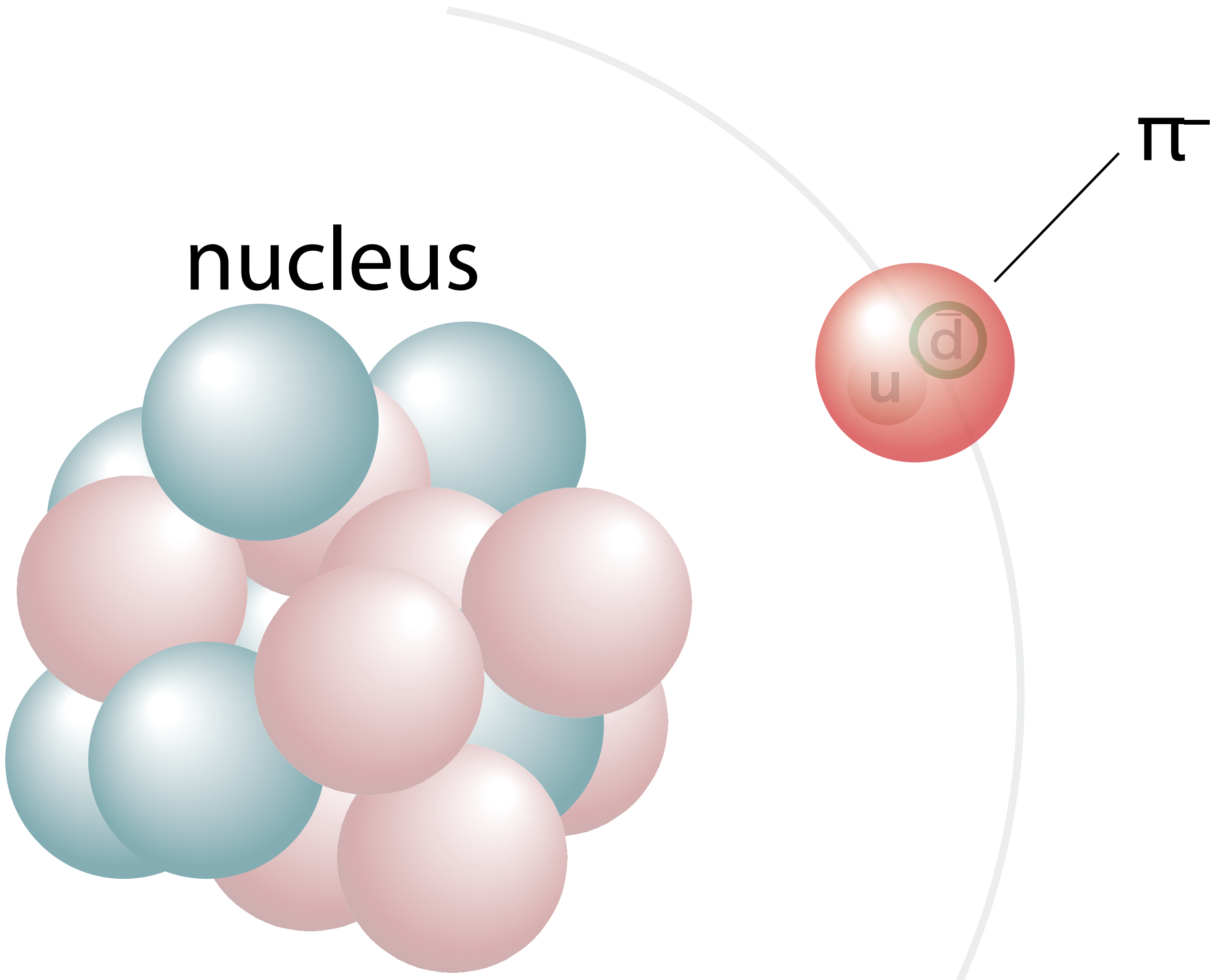
GSI-S490 WASA at FRS for η′mesic nuclei(2022)



S490 Spokesperson: KI
co-Spokesperson: Y.K. Tanaka

D-candidate: R. Sekiya

Pionic atoms

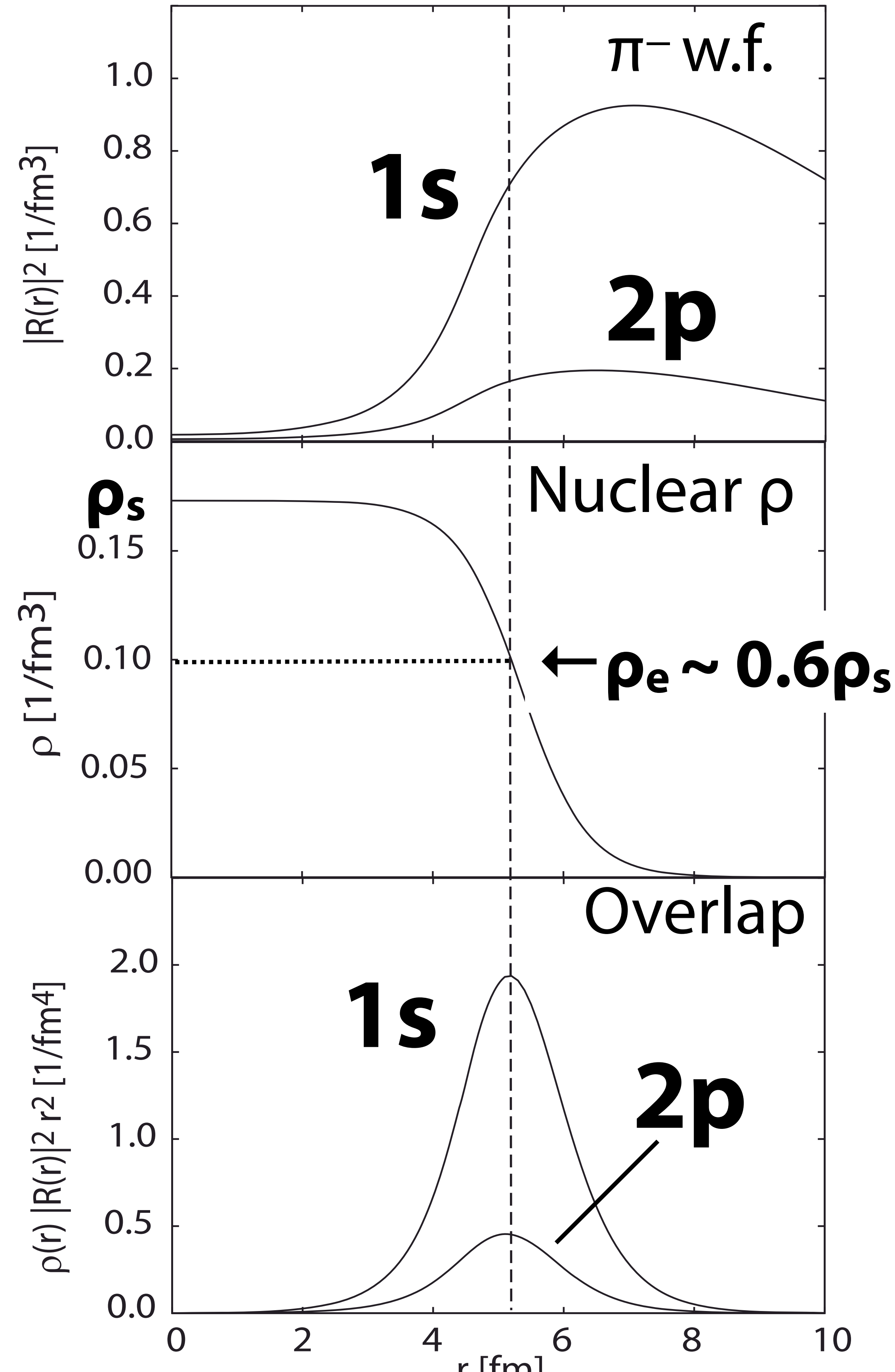


Ericson-Ericson potential

$$U_{\rm opt}(r) = U_s(r) + U_p(r),$$

$$U_s(r) = b_0\,\rho + \mathbf{b_1}\,(\rho_n - \rho_p) + B_0\,\rho^2$$

$$U_p(r) = \frac{2\pi}{\mu}\vec{\nabla}\cdot[c(r) + \varepsilon_2^{-1}C_0\rho^2(r)]L(r)\vec{\nabla}$$



Ikeno et al., PTP126 (2011) 483

Pion-nucleus interaction

Overlap between
pion w.f. and nucleus
→ π works as a probe
at $\rho_e \sim 0.6\rho_s$

π-nucleus interaction is changed
for wavefunction renormalization
of medium effect

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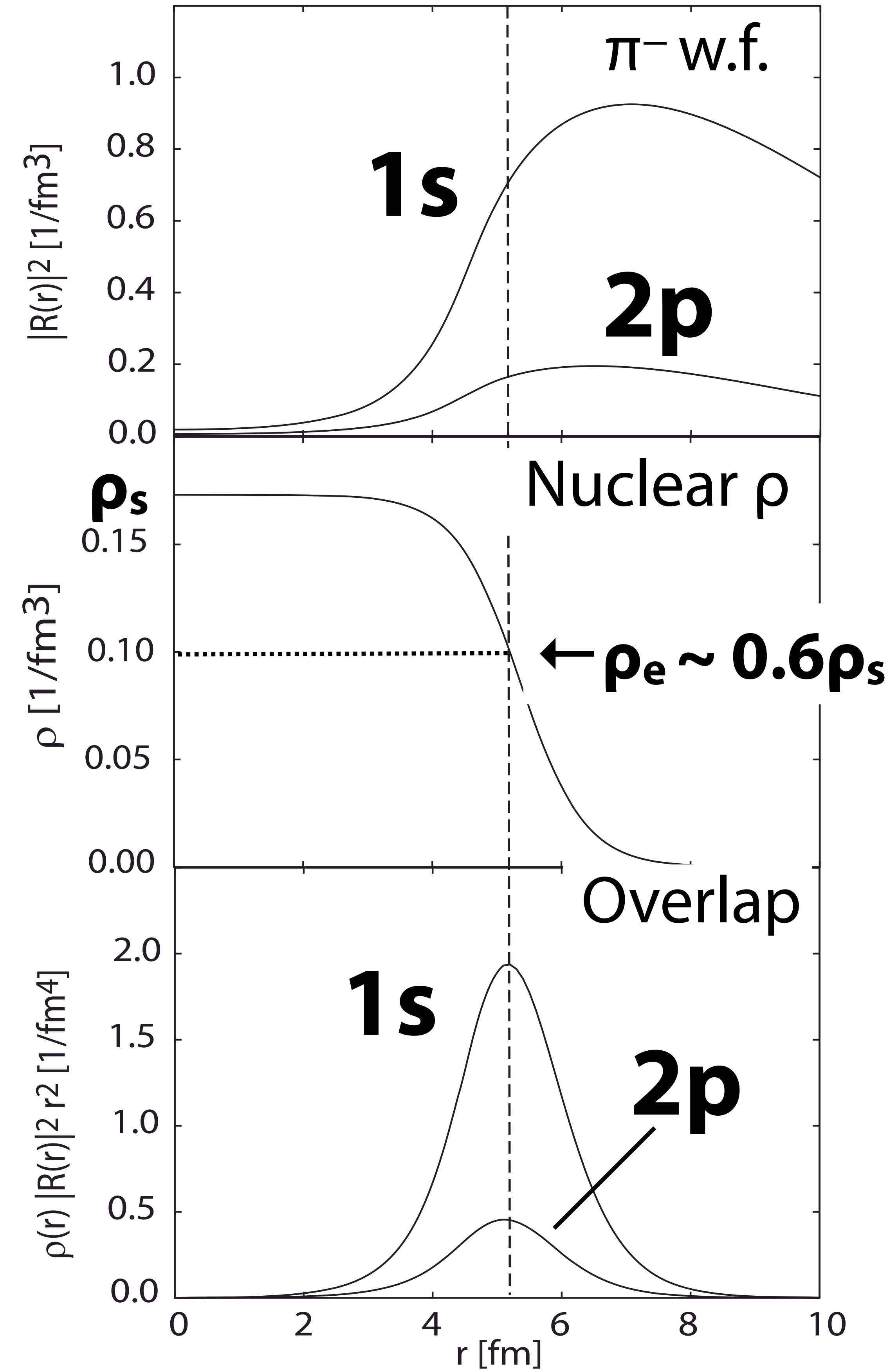

Ikeno et al., PTP126 (2011) 483

Pion-nucleus interaction and chiral condensate

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In-medium Glashow-Weinberg relation

$$\frac{\langle\bar{q}q\rangle^*}{\langle\bar{q}q\rangle} \simeq \left(\frac{b_1^{\mathbf{v}}}{b_1}\right)^{1/2}\left(1-\gamma\frac{\rho}{\rho_0}\right)$$

$\gamma = 0.184 \pm 0.003$

Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)

Pion-nucleus interaction and chiral condensate

Gell-Mann-Oakes-Renner relation

$$f_\pi^2 m_\pi^2 = -2m_q \langle \bar{q}q \rangle$$

Tomozawa-Weinberg relation

$$b_1 = -\frac{m_\pi}{8\pi f_\pi^2}$$

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

M. Gell-Mann *et al.*, PR175(1968)2195.
Y. Tomozawa, NuovoCimA46(1966)707.
S. Weinberg, PRL17(1966)616.

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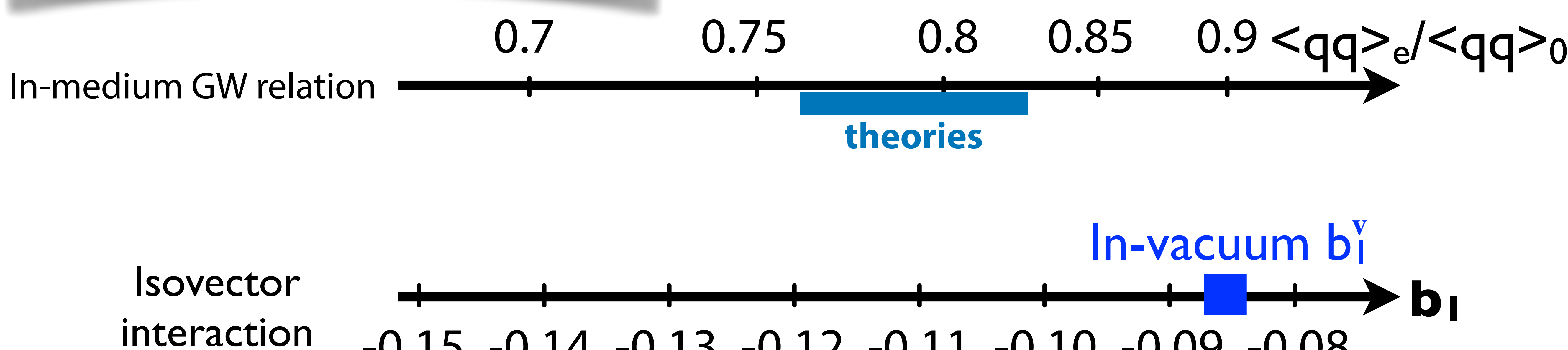
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)

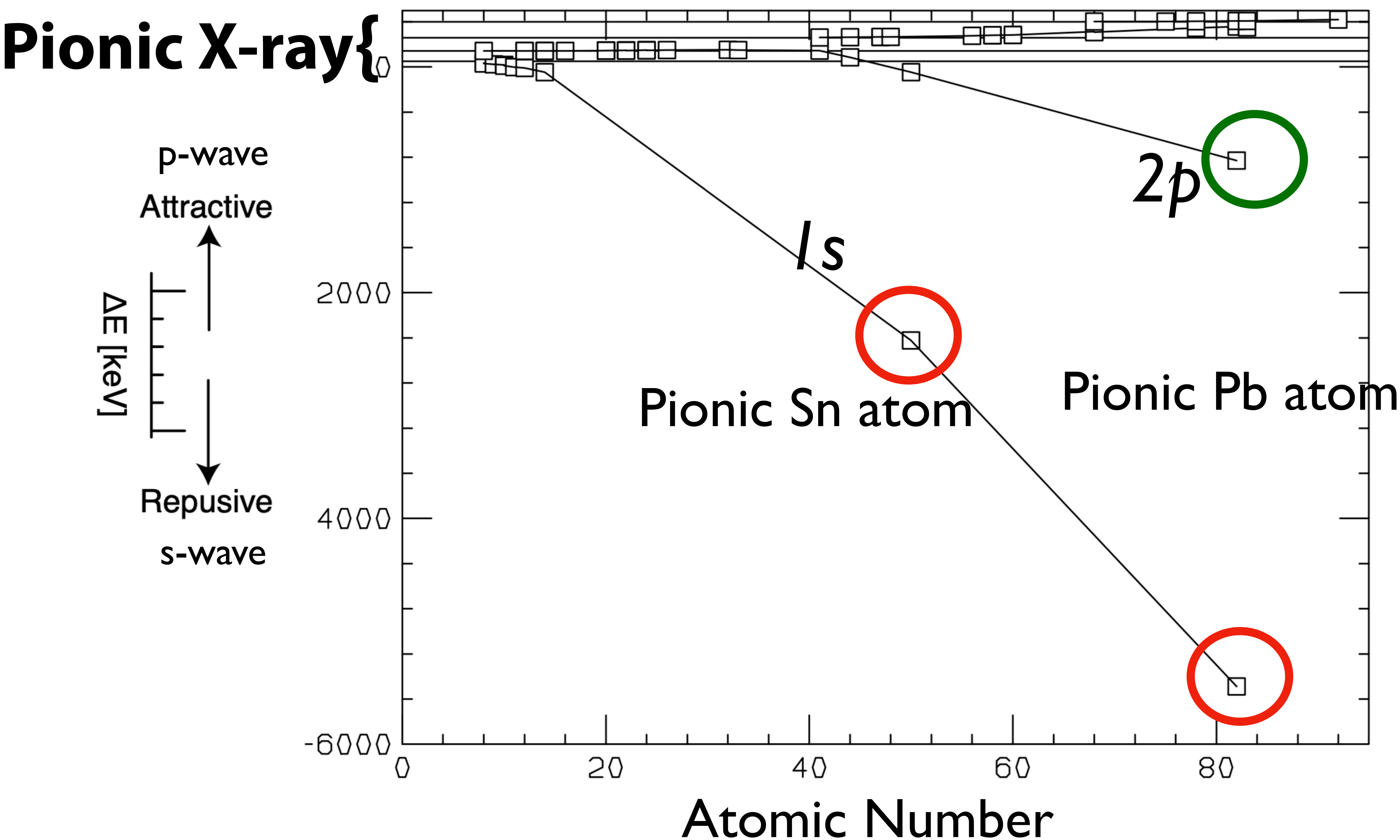
Pionic hydrogen and deuterium

$b_1^v = 0.0866 \pm 0.0010$

Hirtl et al., EPJA57, 70 (2021)



Deeply bound pionic atoms
Level shifts

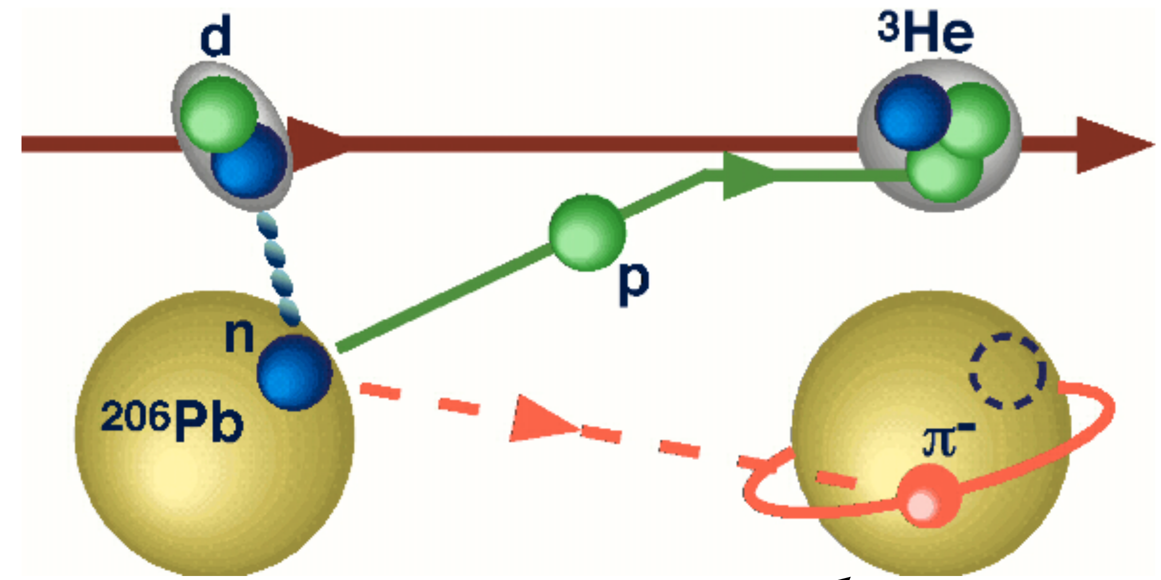


Deeply bound atoms have "super" repulsive shifts and provide *s*-wave information

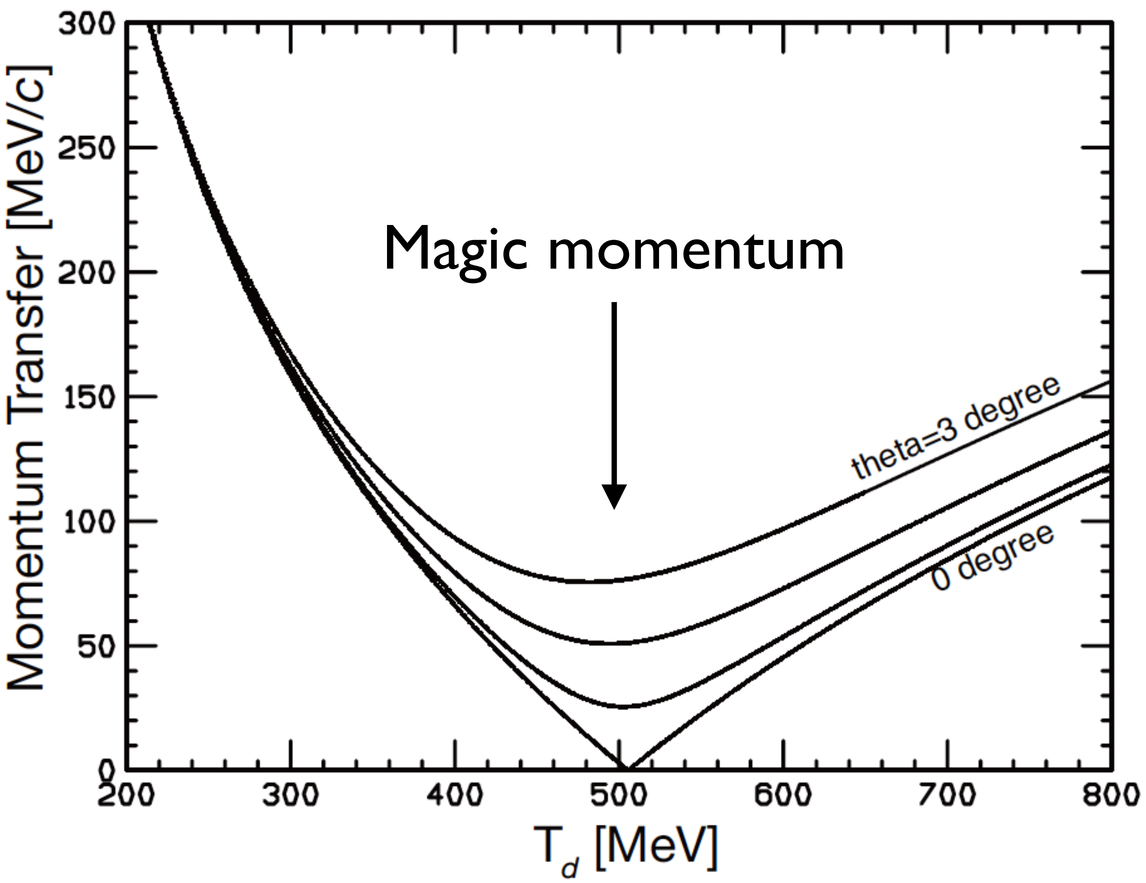
Spectroscopy of pionic atoms in (*d*,^{3}He) reactions

Missing mass spectroscopy to measure excitation spectrum of pionic atoms

Direct production of pionic atoms

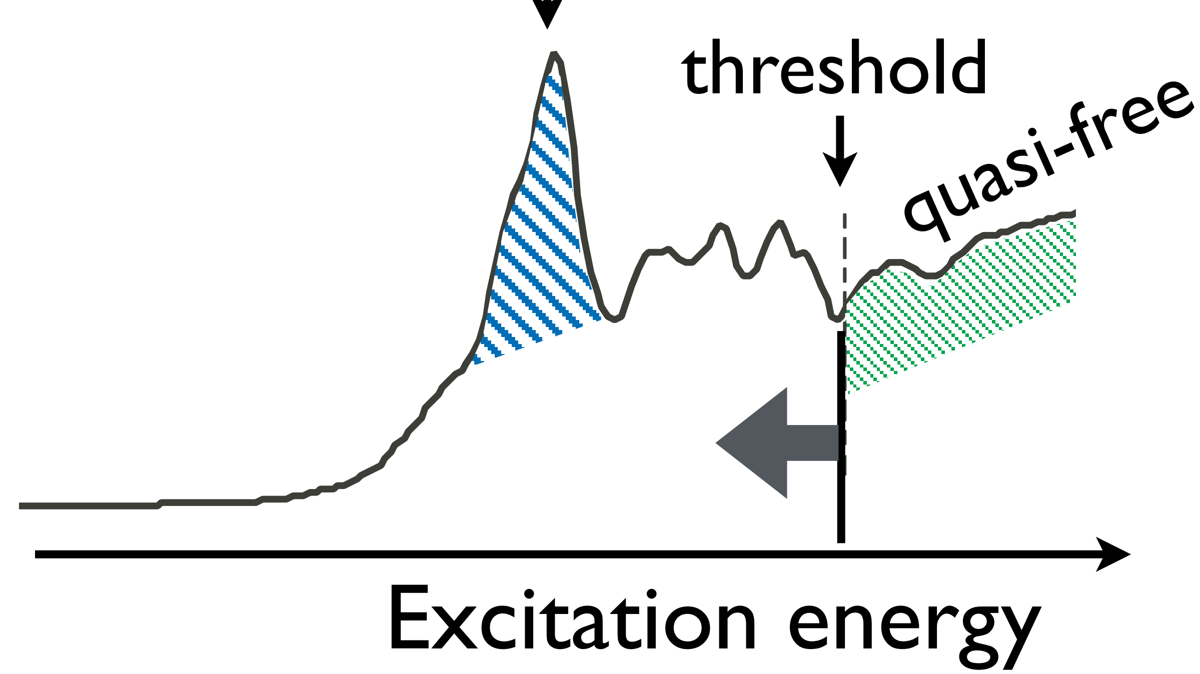


Momentum transfer

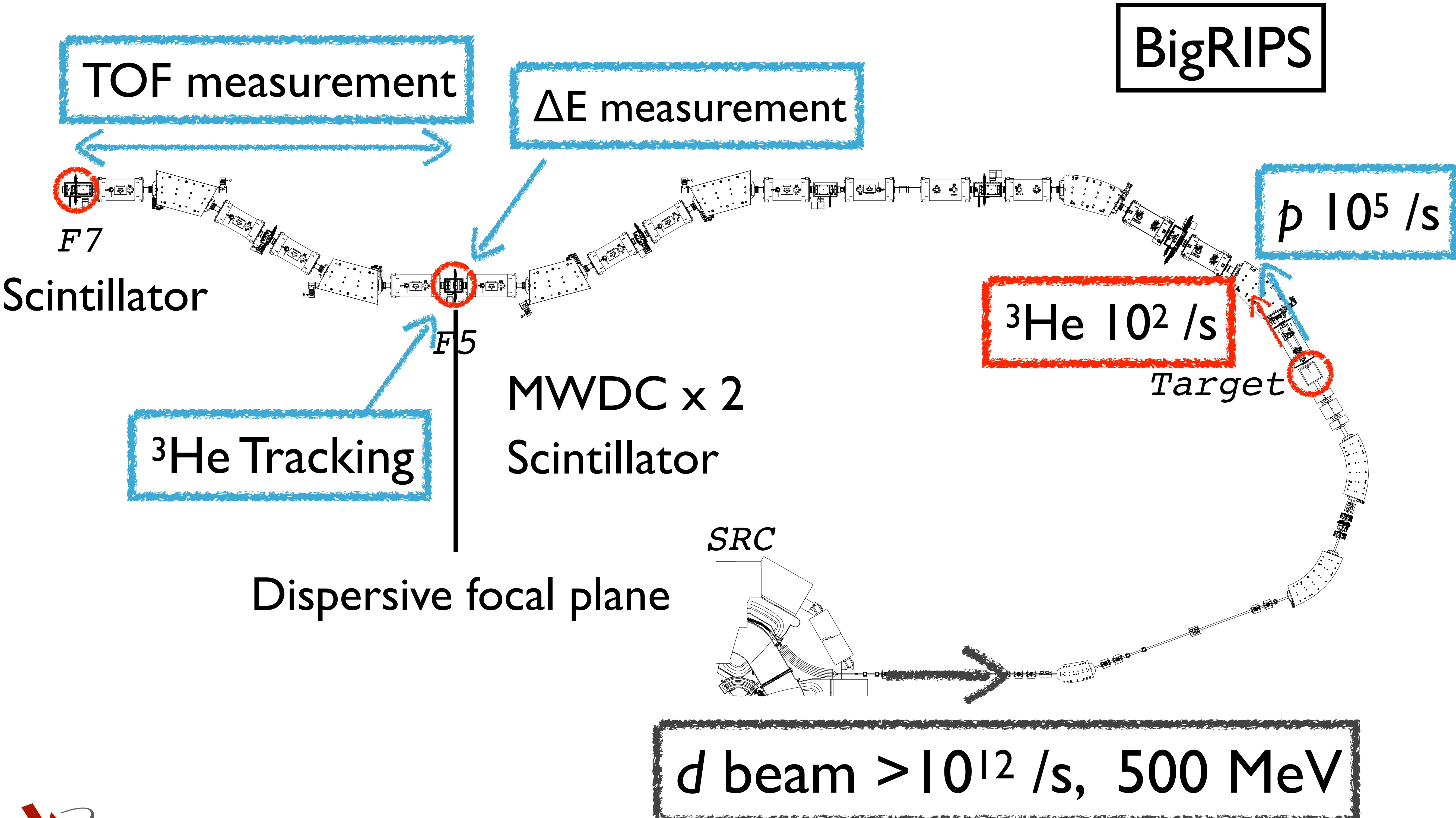


Pion bound state

(coupled with *n* hole)

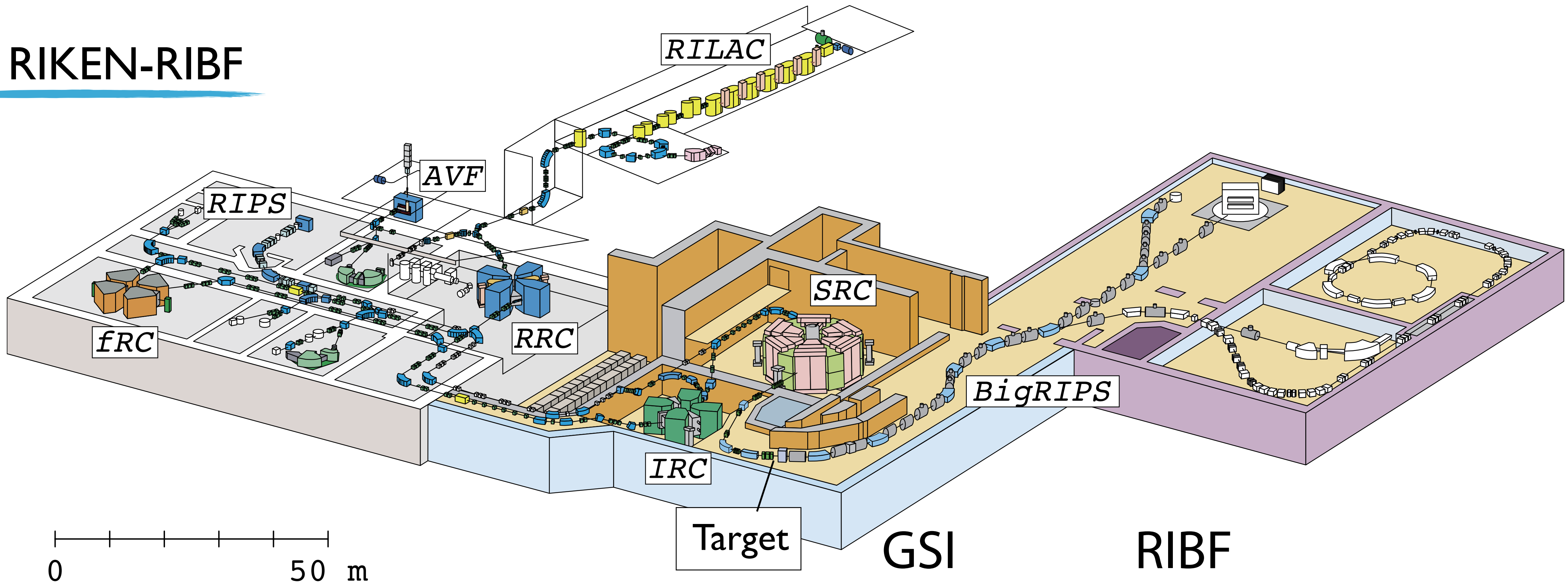


(d,³He) Reaction Spectroscopy in RIBF



RI Beam Factory

RIKEN-RIBF

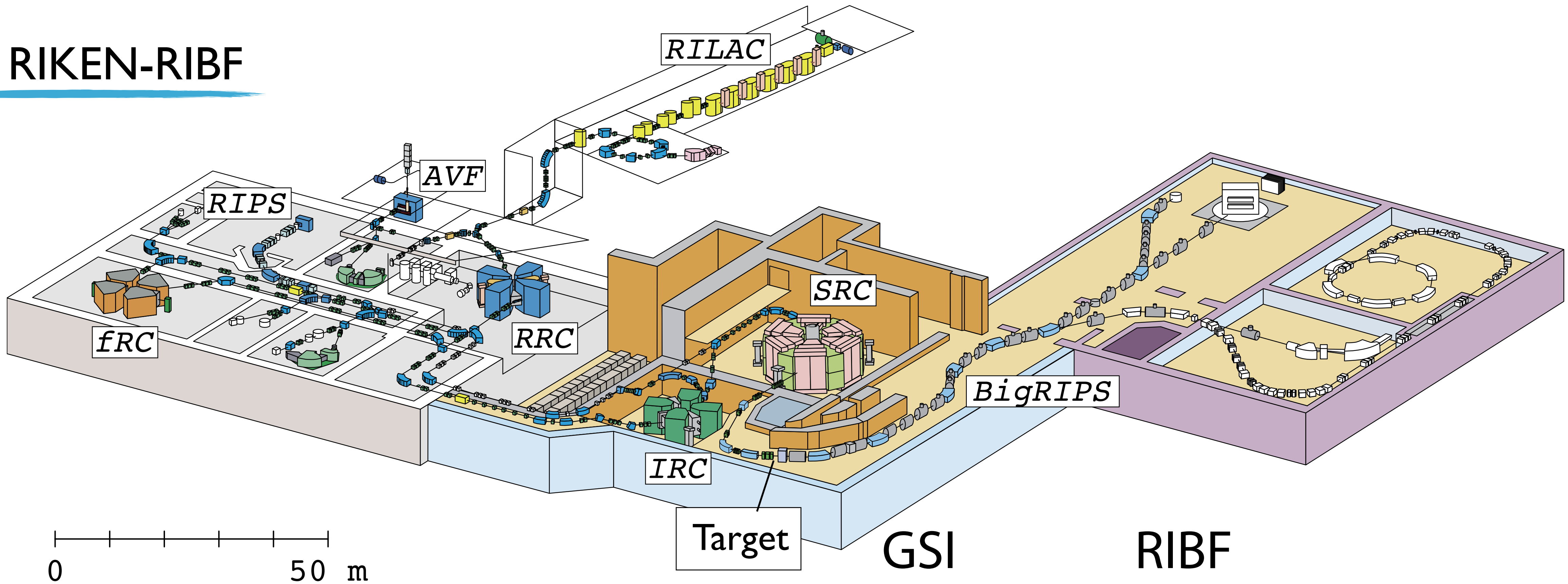


	GSI	RIBF
d beam Intensity	10^{11}/spill	>10^{12}/s
Target	20 mg/cm^2	10 mg/cm^2
$\Delta p_d/p_d$ (FWHM)	0.02%	0.04%
Resolution (FWHM)	400 keV	~800 keV
Acceptance (mrad)	15H, 10V	40H, 60V

×50!!

RI Beam Factory

RIKEN-RIBF



	GSI	RIBF
d beam Intensity	10^{11}/spill	>10^{12}/s
Target	20 mg/cm^2	10 mg/cm^2
$\Delta p_d/p_d$ (FWHM)	0.02%	0.04%
Resolution (FWHM)	400 keV	< 300 keV
Acceptance (mrad)	15H, 10V	40H, 60V

×50!!

SRC tuning + Dispersion matching required

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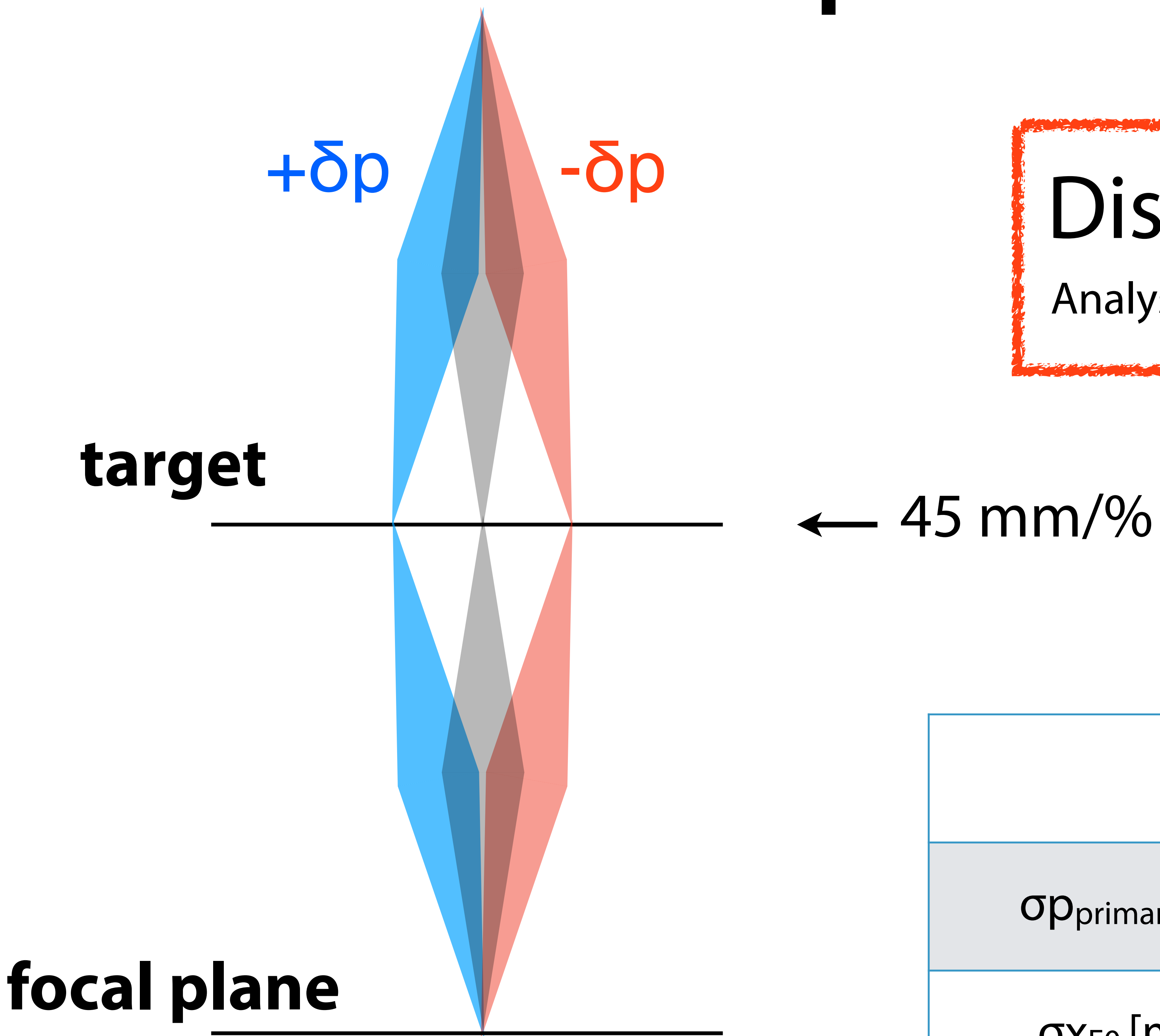
Resolution improvement technique



Dispersion matching

Analysis of beam energy in the beam line

	Pilot (2010)	Standard
$\sigma p_{primary}$ [%]	0.04	0.04
σx_{F0} [mm]	0.7	1
$resolution_{exp}$ [keV]	500	800

Dispersion matching of primary beam

Dispersion matching to eliminate contribution of beam momentum spread in spectral resolution

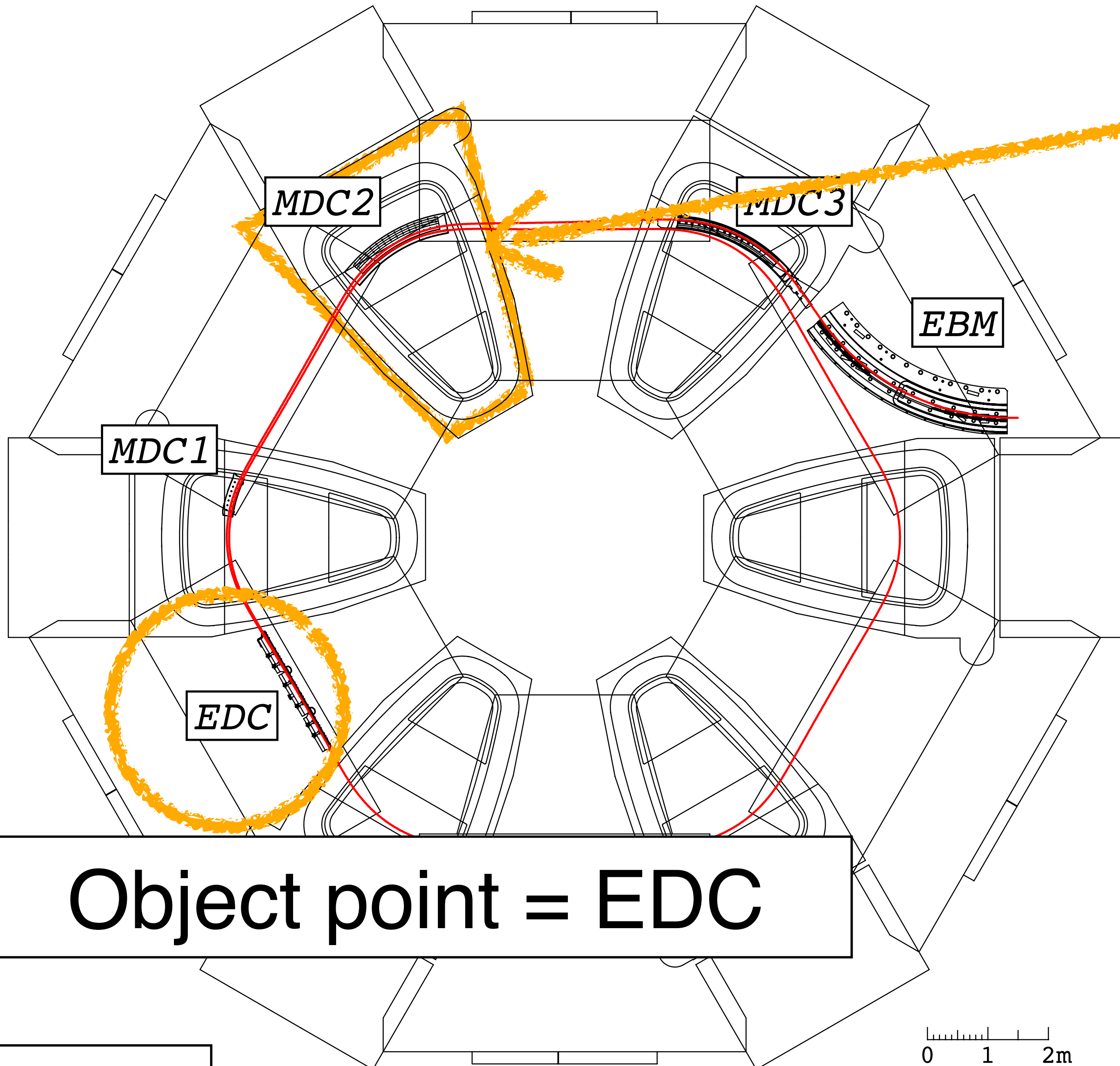
Spectrometer (BigRIPS) — reaction — SRC-BT Line (T-course)

$$\begin{pmatrix} x_{\text{F5}} \\ \theta_{\text{F5}} \\ \delta p_{\text{F5}} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{16} \\ S_{21} & S_{22} & s_{26} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & C \end{pmatrix} \begin{pmatrix} A_{11} & A_{12} & A_{16} \\ A_{21} & A_{22} & A_{26} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_0 \\ \delta p_0 \end{pmatrix}$$

*C: kinematical factor = 1.31

$$x_{\text{F5}} = \cdots + (S_{11} A_{16} + C S_{16}) \delta p_0$$

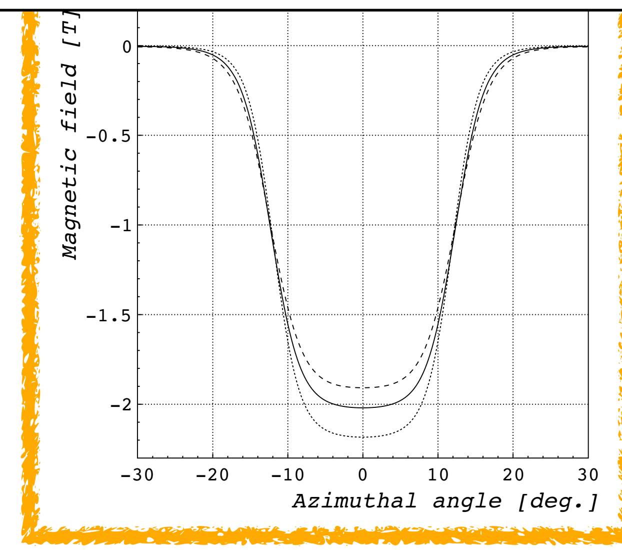
Dispersion matching of primary beam



Object point = EDC

SRC

magnetic field in the magnet

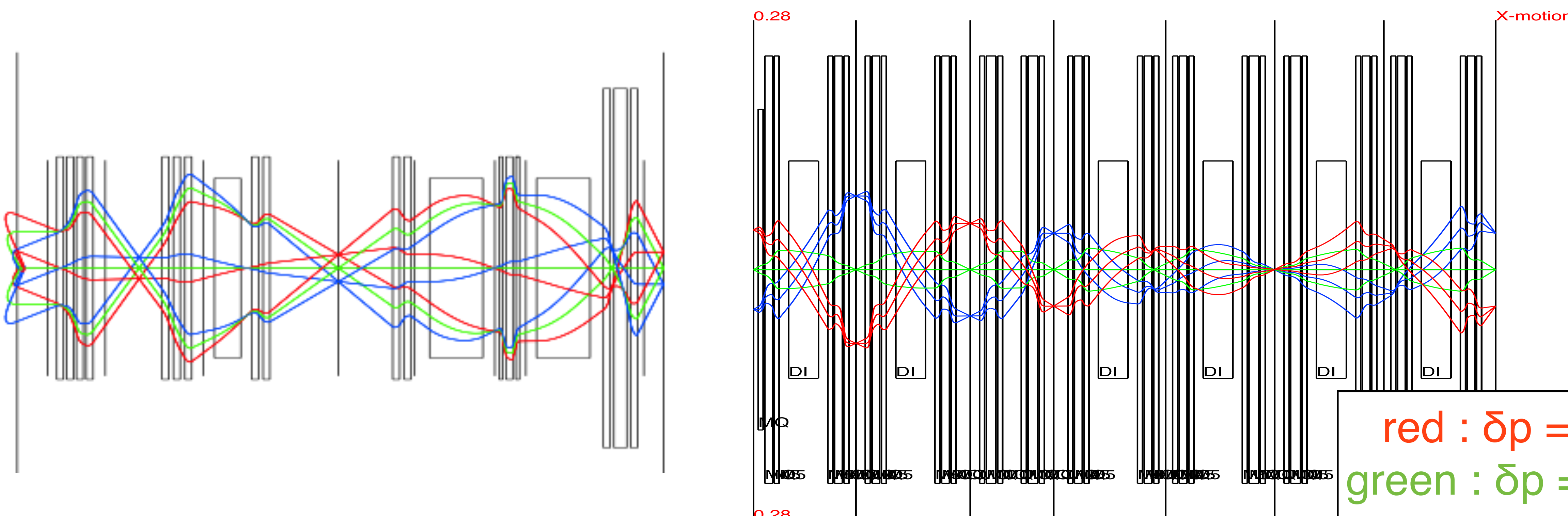


calculate the transfer matrix using Runge-Kutta method

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

Dispersion matching of primary beam

EBM **F0** **F3** **F5** **F7**



red : δp = +0.5%
green : δp = 0%
blue : δp = -0.5%

$$x_{\mathrm{F5}} = \cdots + (S_{11}A_{16} + CS_{16})\delta p_0$$

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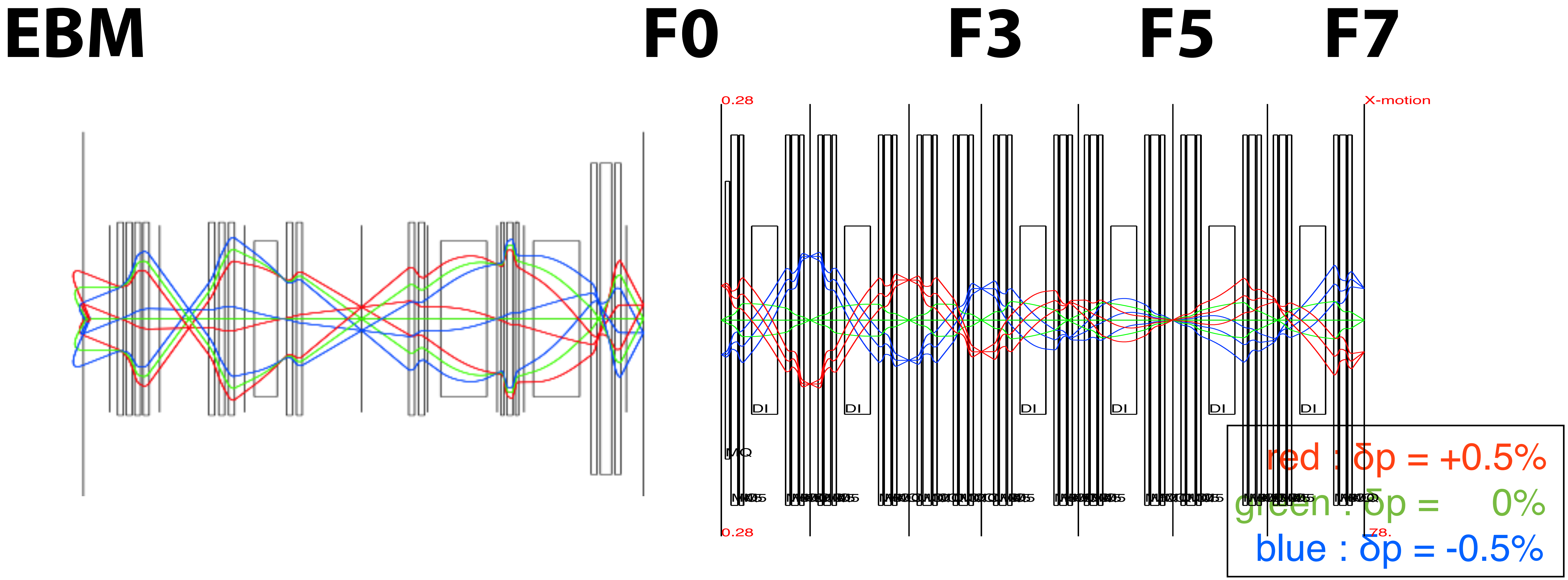
Dispersion matching of primary beam

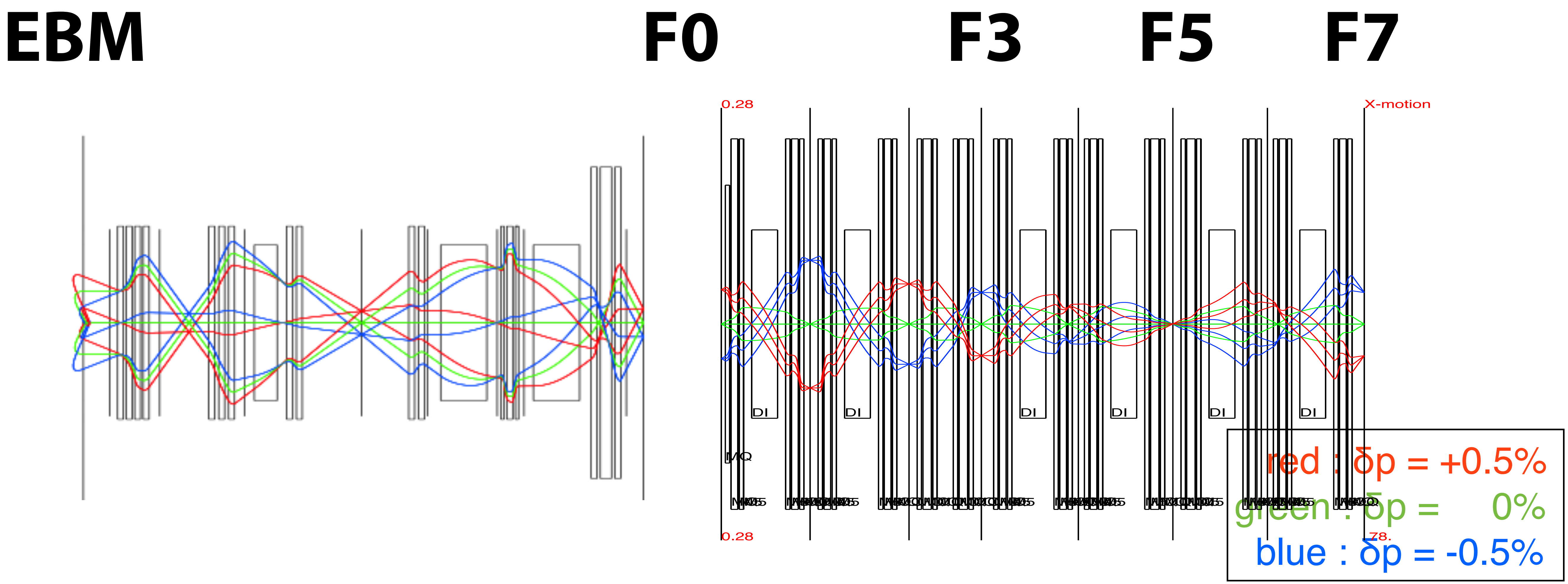


$$x_{F5} = \cdots + (S_{11}A_{16} + CS_{16})\delta p_0$$

magnification of BigRIPS

position at F0

Dispersion matching of primary beam



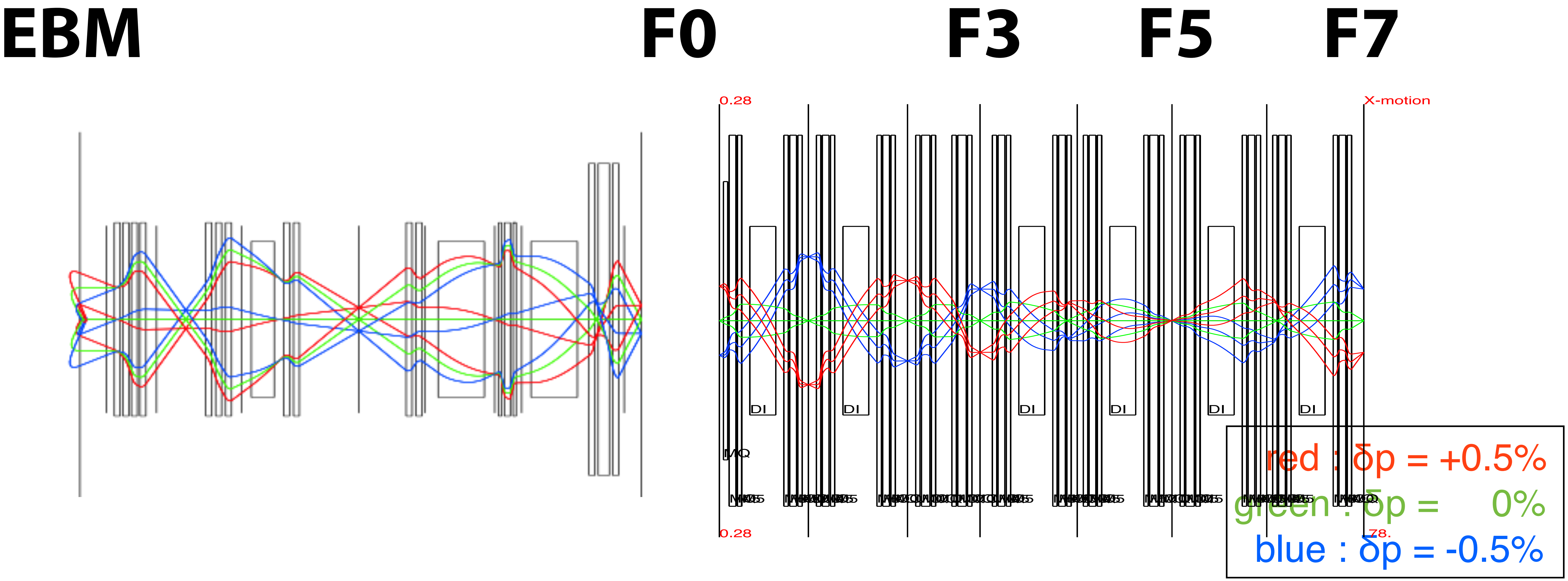
$$x_{F5} = \cdots + (S_{11}A_{16} + CS_{16})\delta p_0$$

Cancel out

design values: $S_{11} = -1.8$

$C = 1.31$ $S_{16} = 62$ mm/%

Dispersion matching of primary beam



$$x_{F5} = \cdots + (S_{11}A_{16} + CS_{16})\delta p_0$$

Cancel out

design values: S_{11} = -1.8 **A_{16} = 44.6 mm/%**

C = 1.31 S_{16} = 62 mm/%

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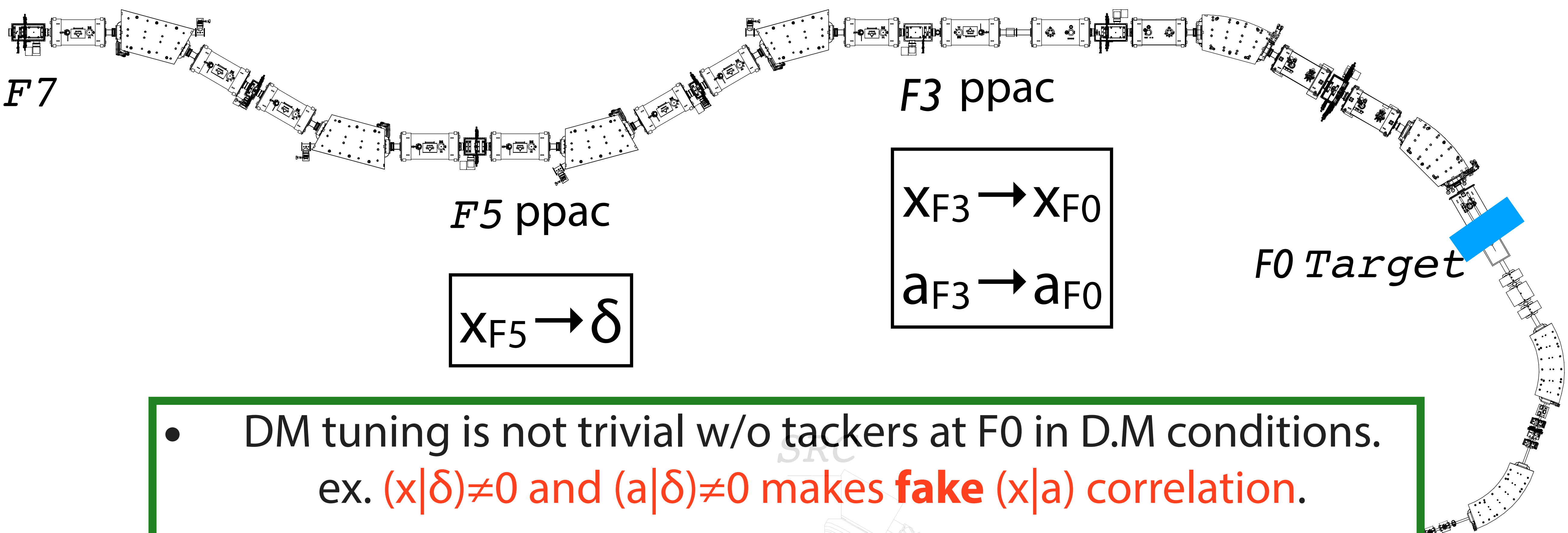
New Method for Dispersion Matching Tuning

Track back to F0 using F3 and F5 trackers

RIKEN-BigRIPS



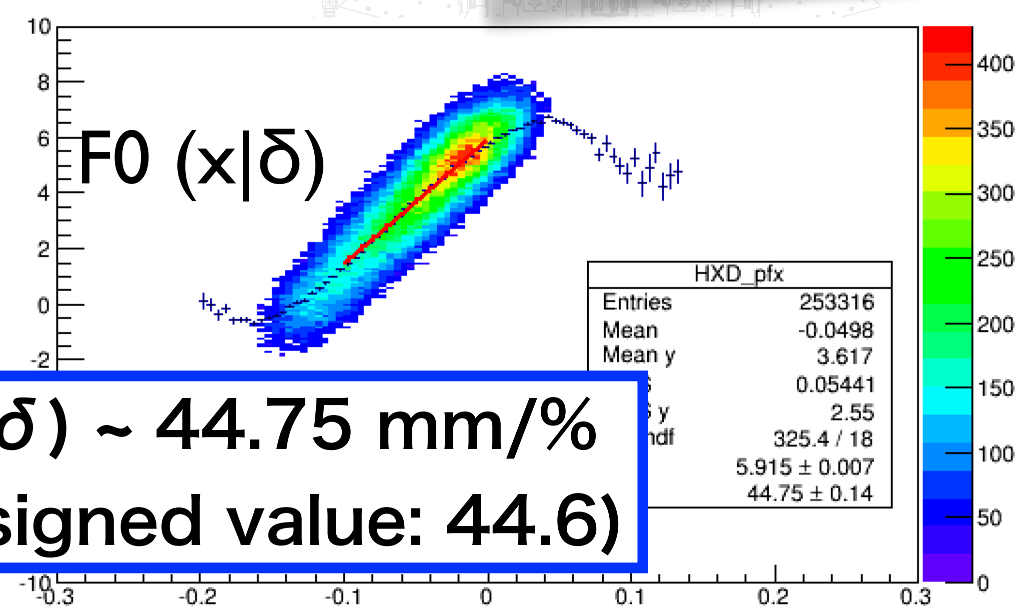
- DM tuning is not trivial w/o tackers at F0 in D.M conditions.
  ex. $(x|\delta)\neq0$ and $(a|\delta)\neq0$ makes **fake** $(x|a)$ correlation.
- We established a new method "Trace-back method" by taking point-to-point image at F3 and dispersion measurement at F5

New Method for Dispersion Matching Tuning

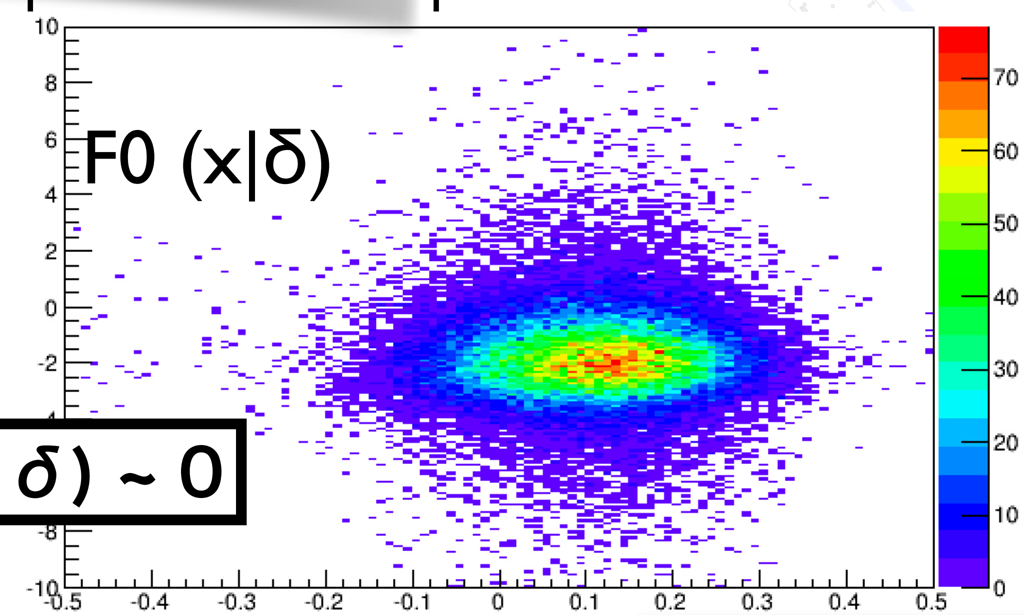
Track back to T11 using F3 and F5 trackers

RIKEN-BigRIPS

We have in our hands capability of freely tuning optical conditions at F0



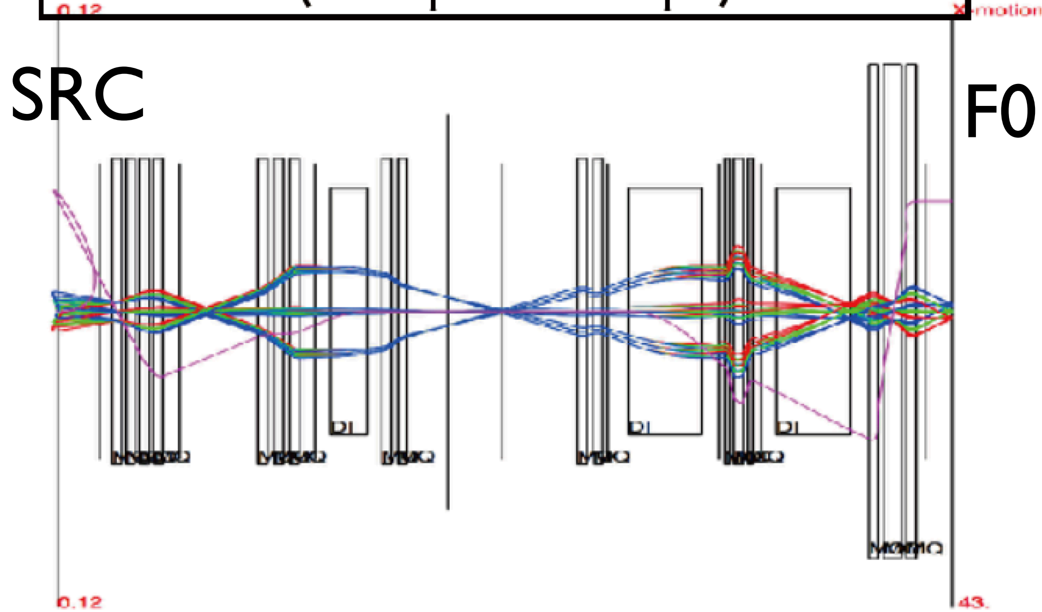
(x|δ) ~ 44.75 mm/%
(designed value: 44.6)

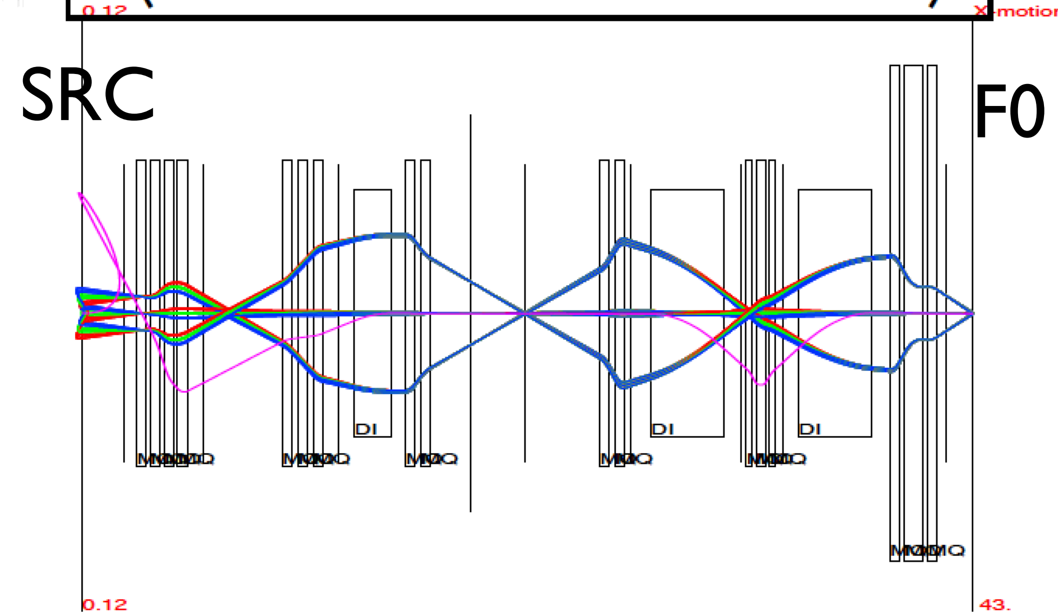


(x|δ) ~ 0

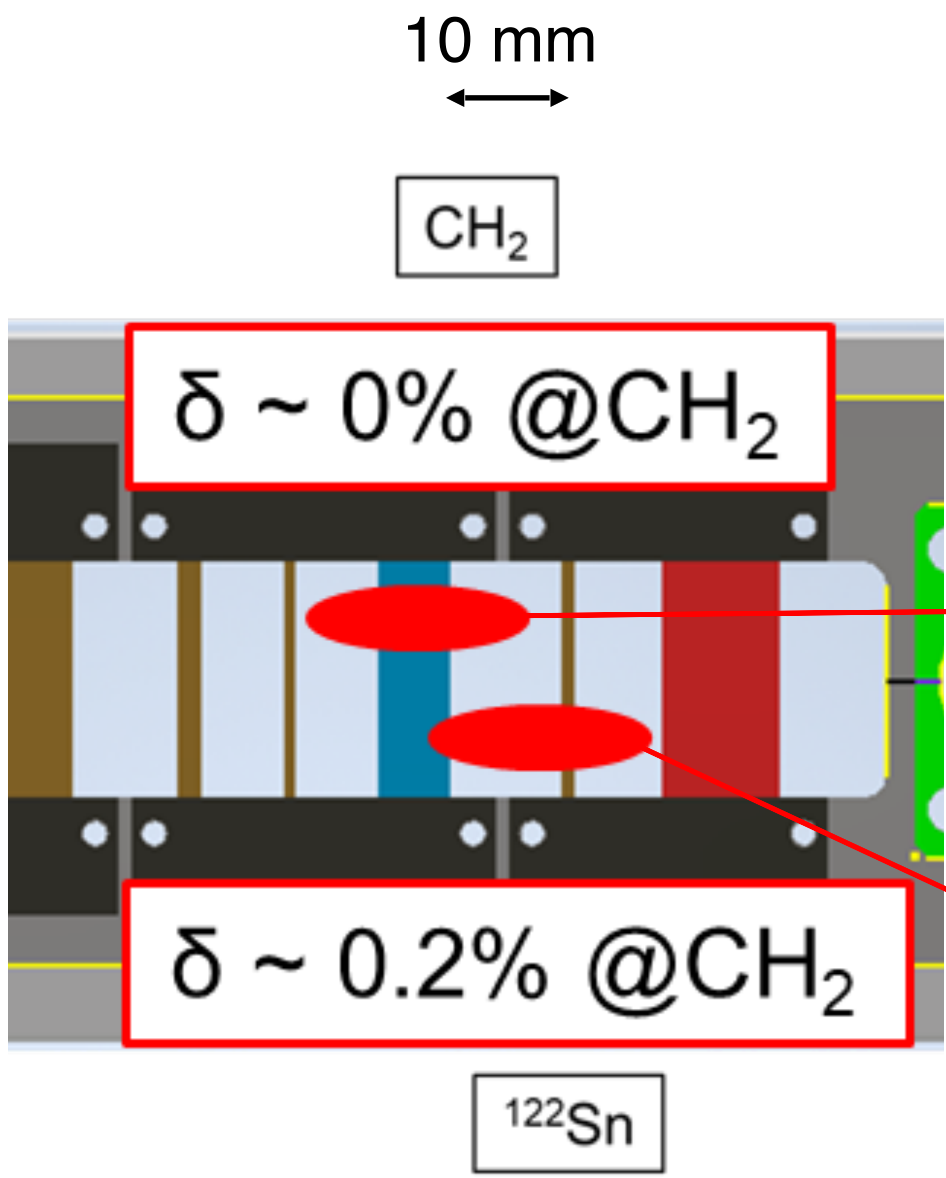
(x|δ) = 44.6 [mm/%]
(for piAF exp.)

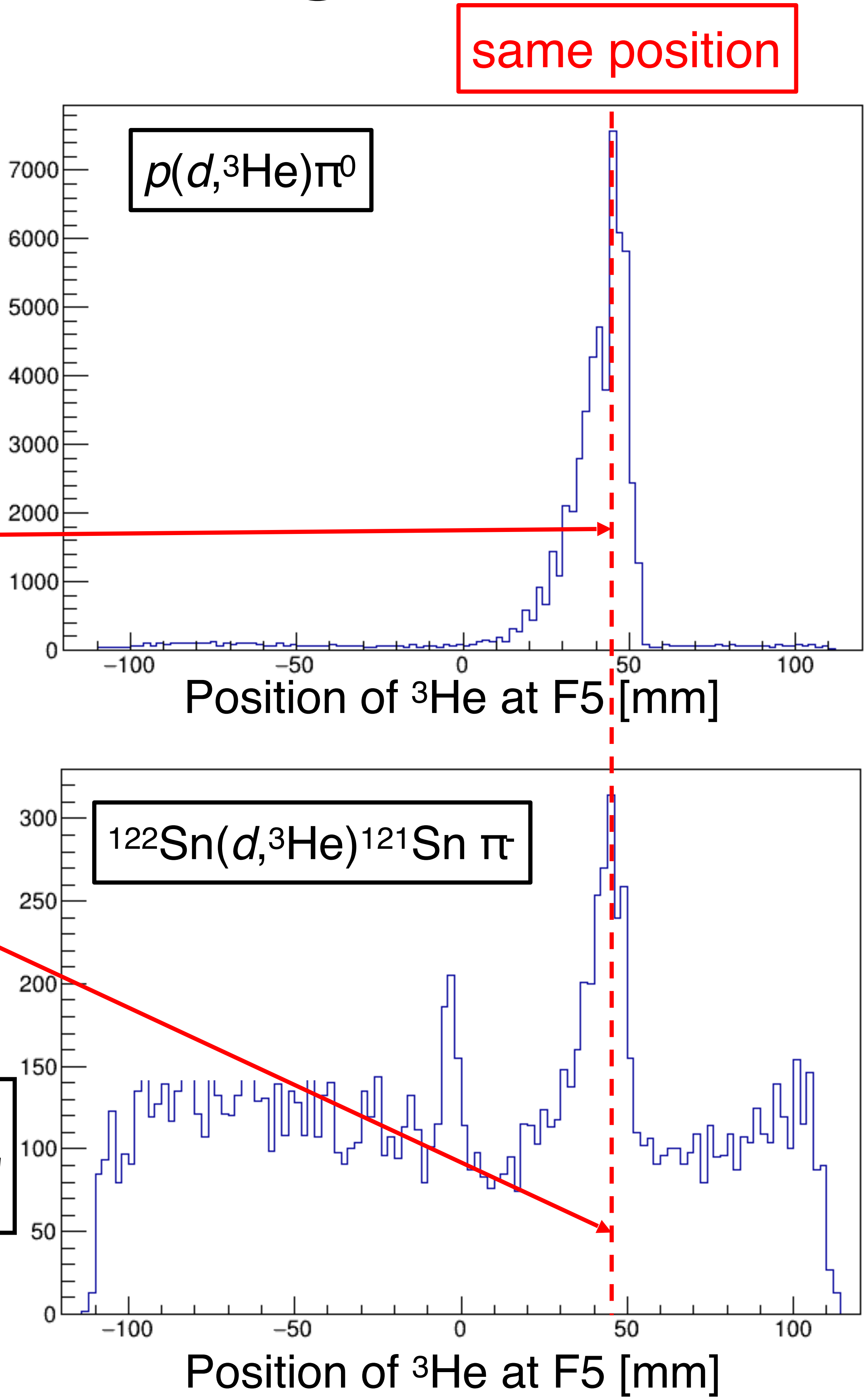
(x|δ) = 0 [mm/%]
(for achromatic condition)





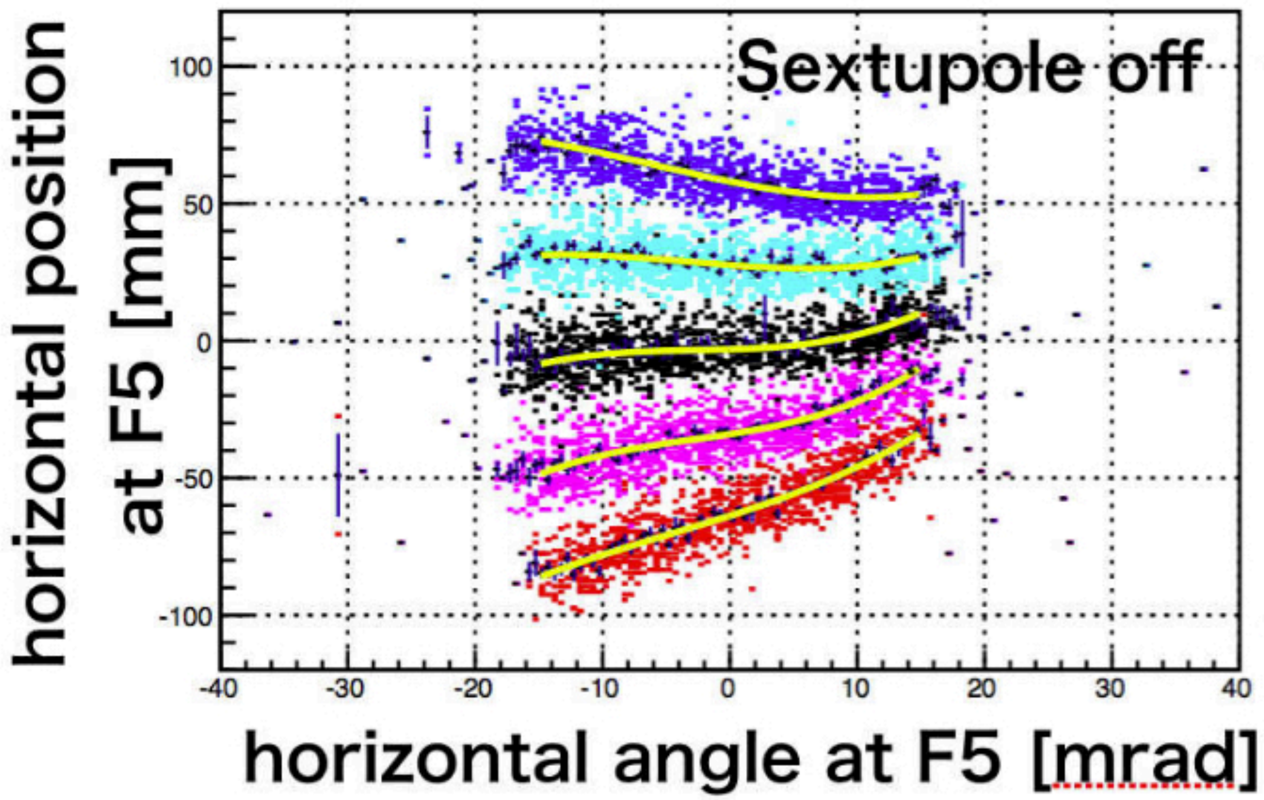
Improved dispersion matching in 2021





Even with 20mm displacement at TA, same position at F5 for same "physics"

Higher-order aberration corrections of BigRIPS as a spectrometer

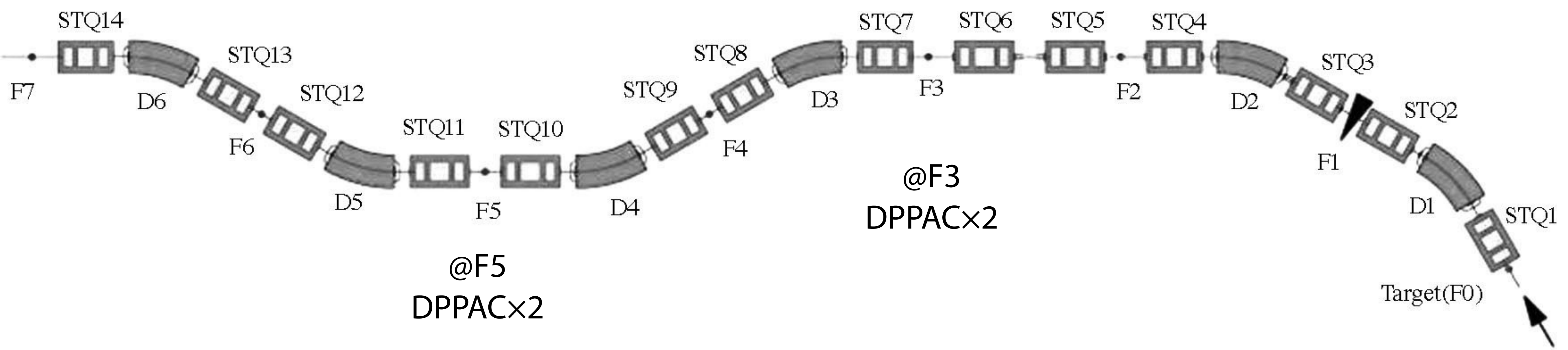


2nd (x|ad) and 3rd (x|aaa) order aberrations correction is required.

Higher-order aberration corrections

Primary beam : ^{18}O 230 MeV / u
target : 30mm Be
fragment : ^{9}C ~ 1kcps ($B\rho$=2.47 Tm)

@F7
PPAC
plastic scintillator

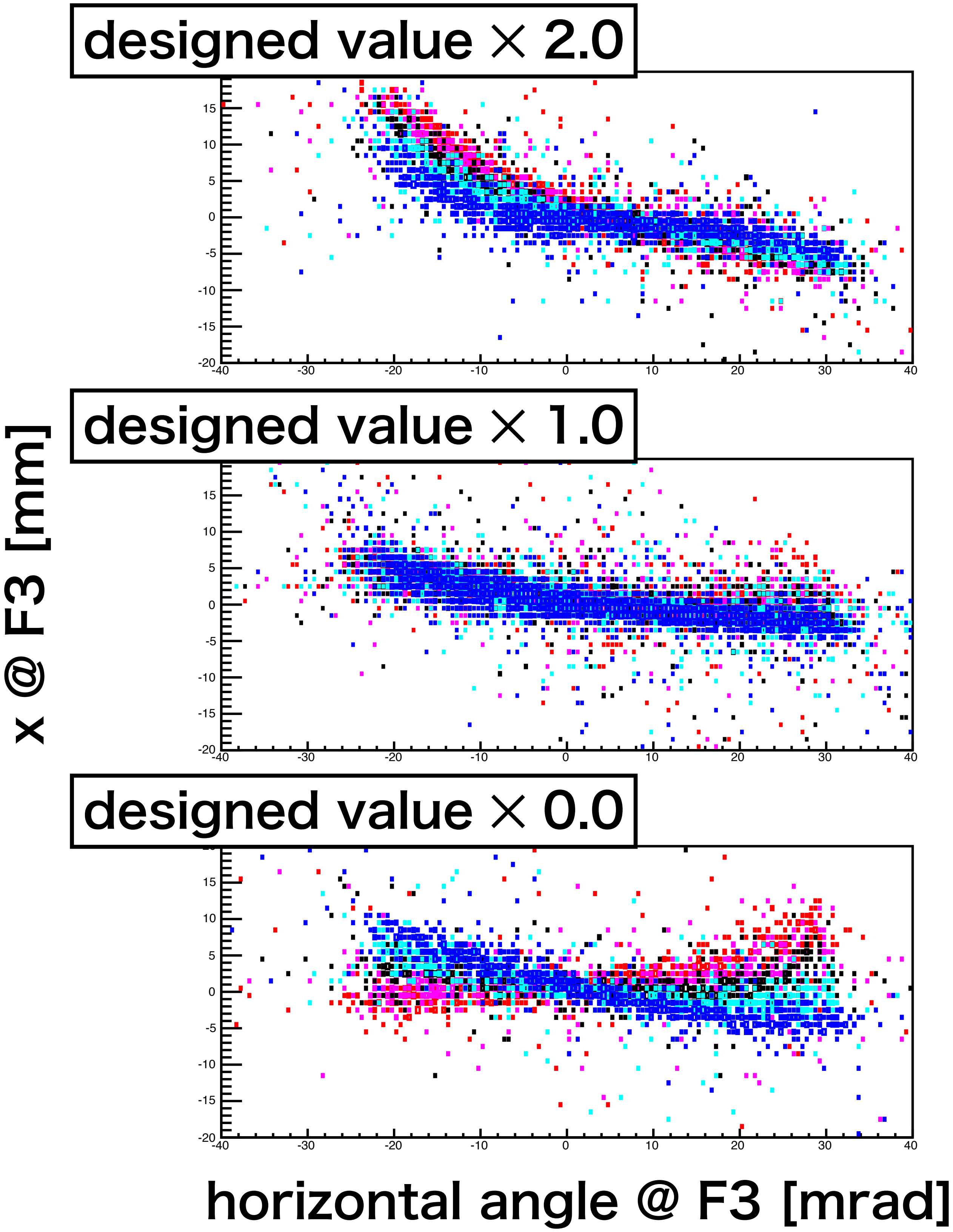


@F3
DPPAC×2

@F5
DPPAC×2

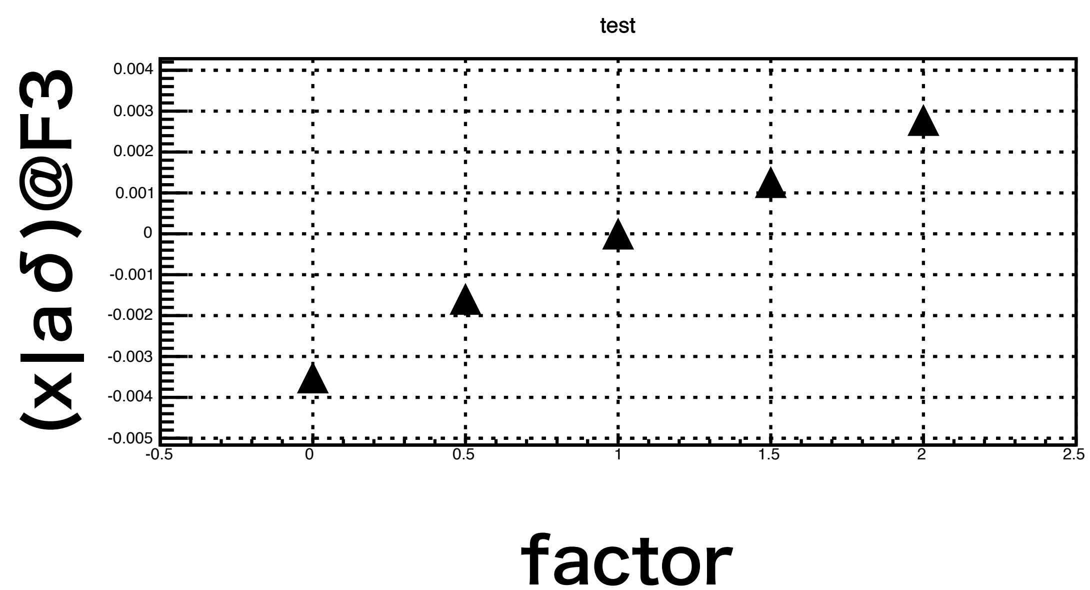
- ToF(F3-F7) : dE @F7 for PI
- Measure aberration at F3/F5 by selecting δ by ToF (RF-F7)
- Change SX settings respecting symmetry

Higher-order aberration measurement



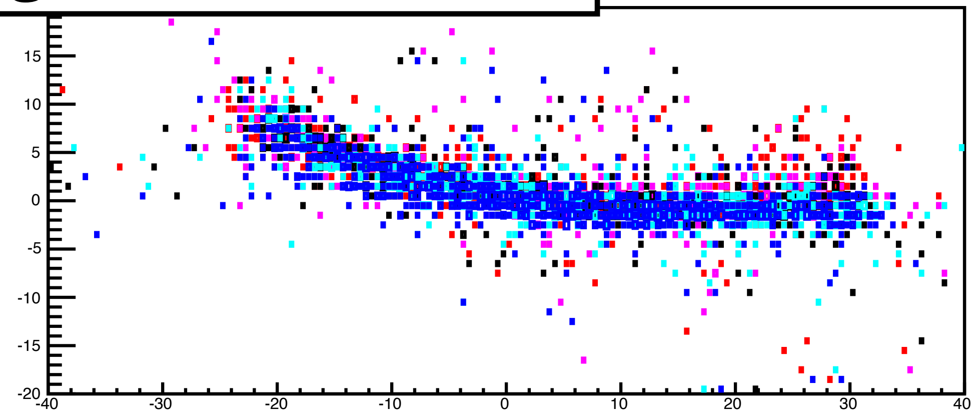
Chromatic aberration

(x|aδ)@F3
(SX 2, 3)

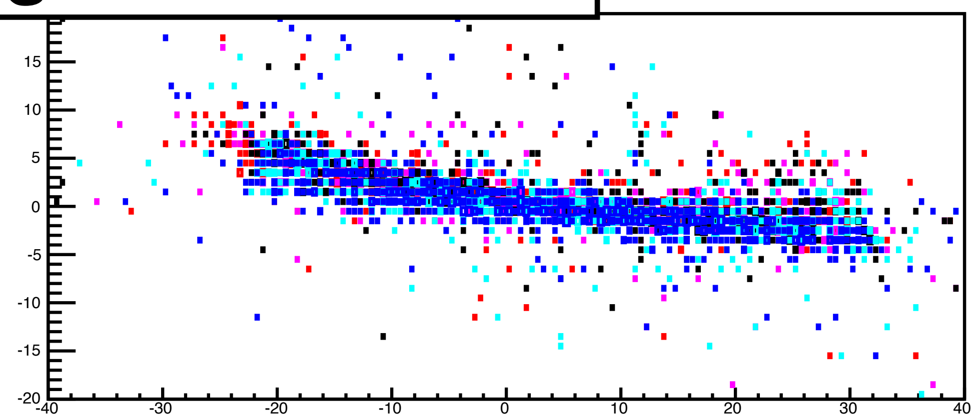


Higher-order aberration measurement

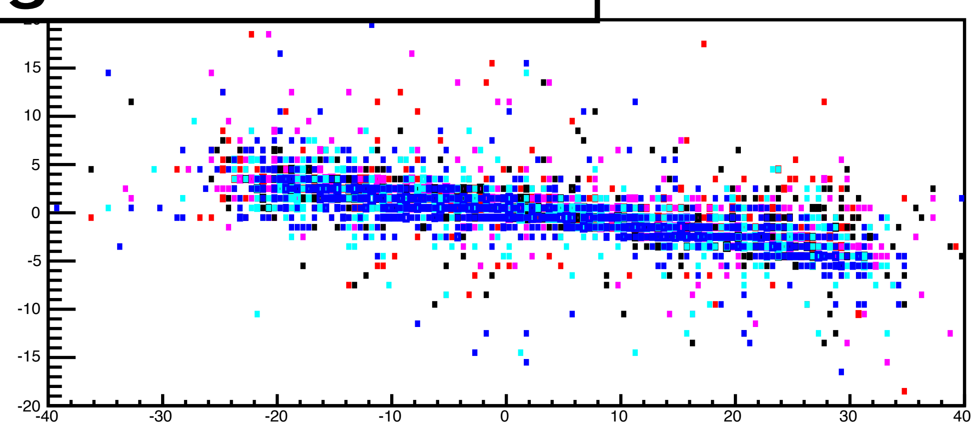
designed value × 2.0



designed value × 1.0



designed value × 0.0

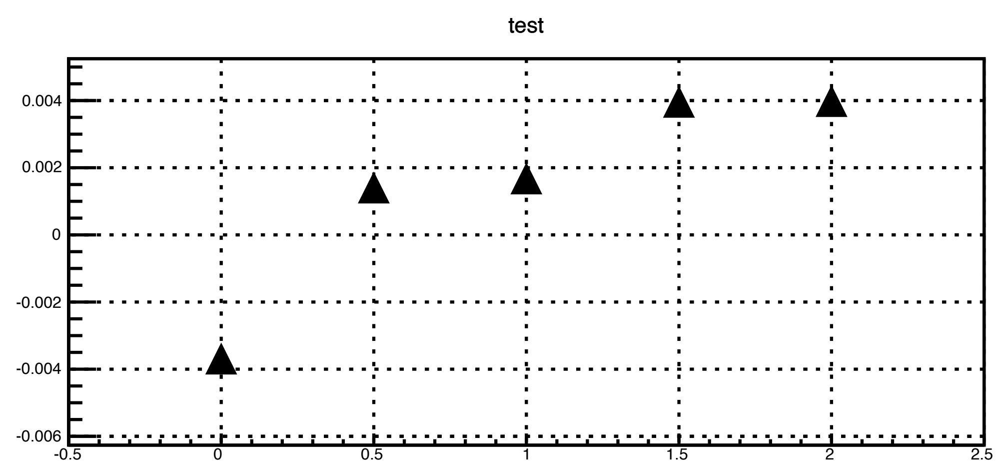


x @ F3 [mm]

horizontal angle @ F3 [mrad]

Field curvature

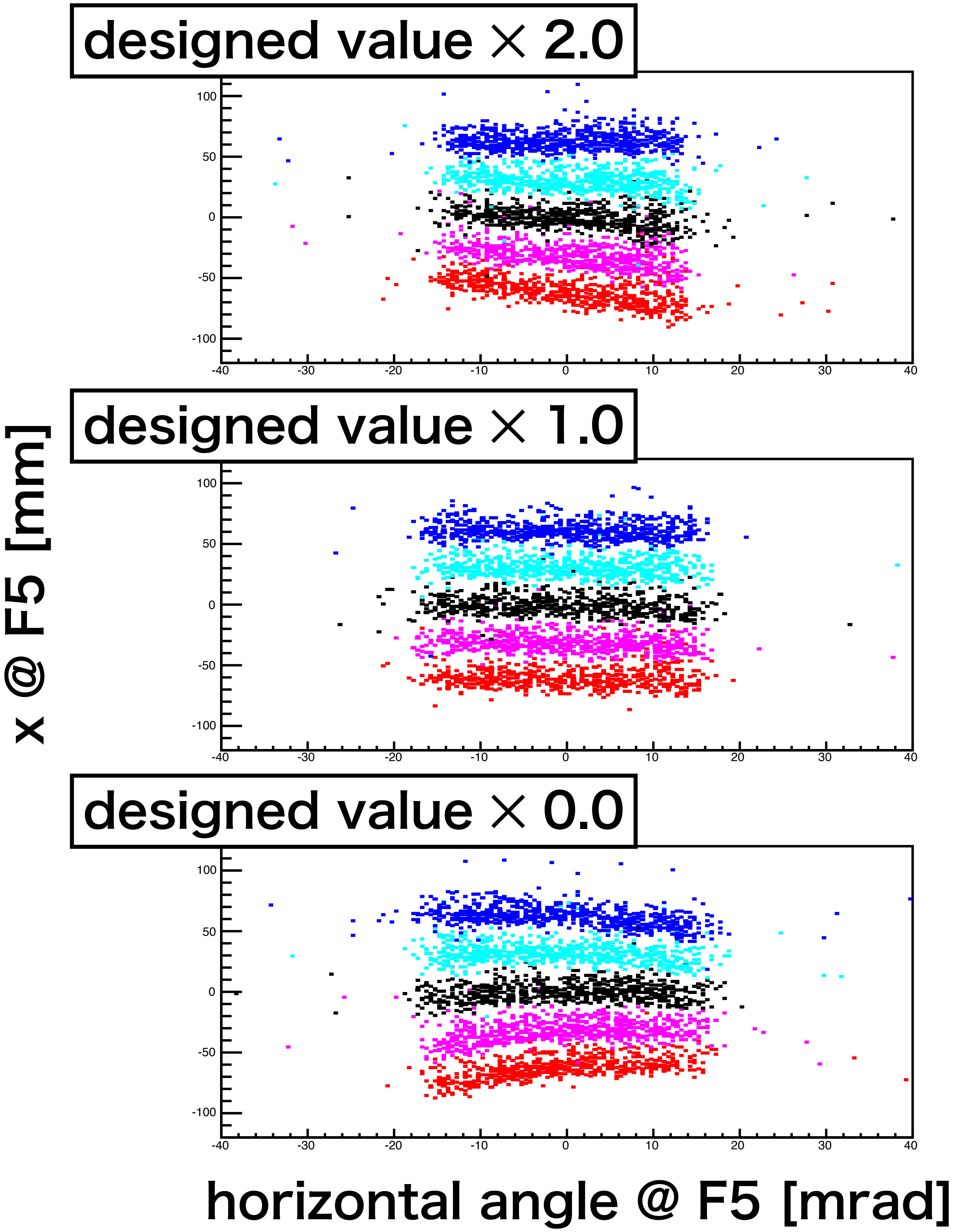
(x|aa)@F3
(SX 1, 4)



(x|aa)@F3

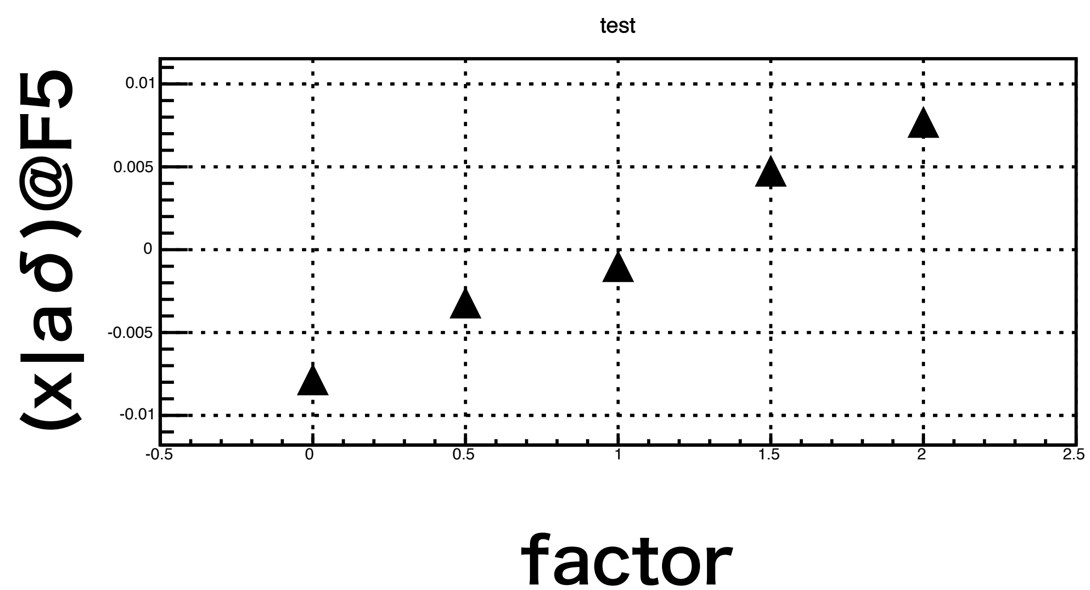
factor

Higher-order aberration measurement



Chromatic aberration

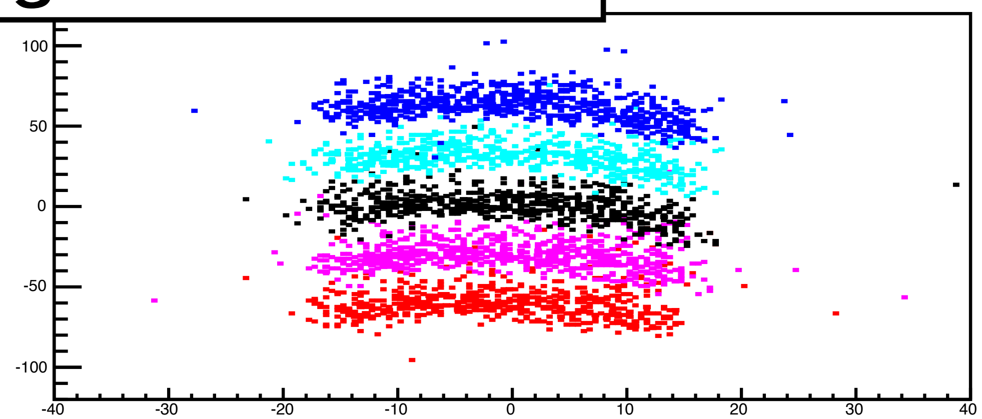
(x|aδ)@F5
(SX 7, 14)



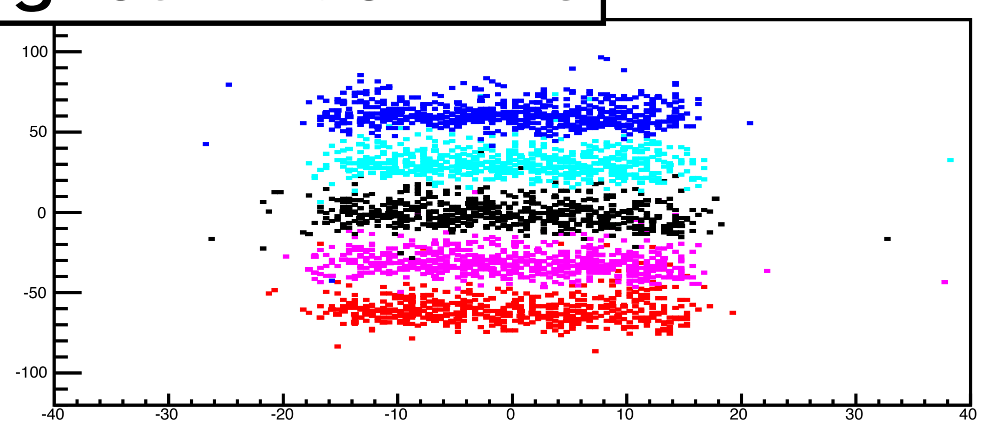
Higher-order aberration measurement

x @ F5 [mm]

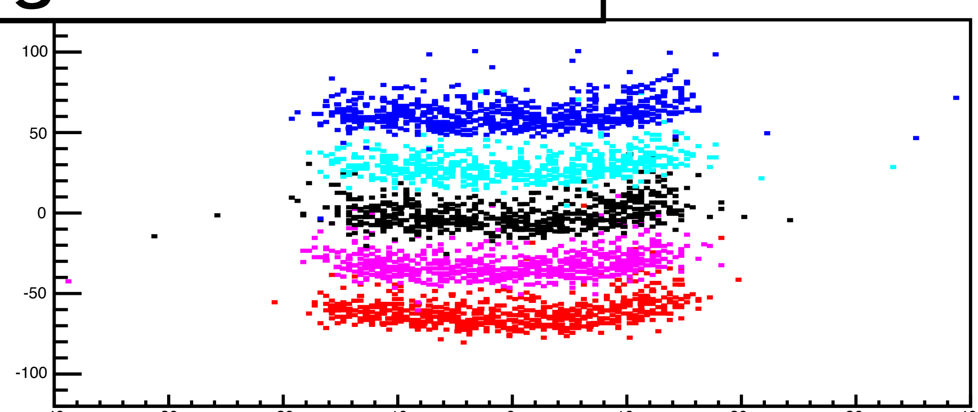
designed value × 2.0



designed value × 1.0



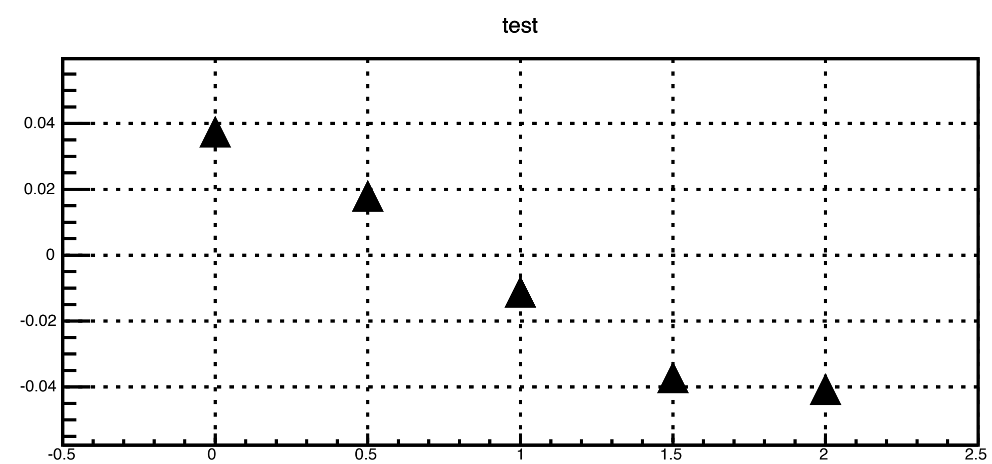
designed value × 0.0



horizontal angle @ F5 [mrad]

Field curvature

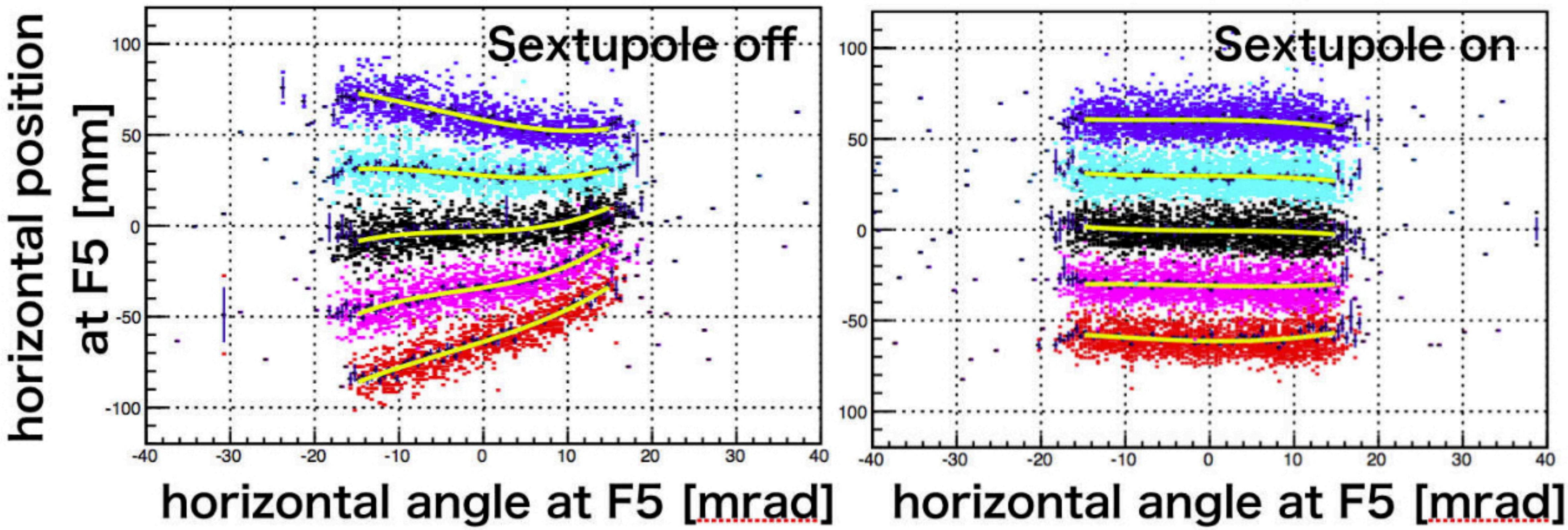
(x|aa)@F5
(SX 8, 9, 12, 13)



(x|aa)@F5

factor

Higher-order aberration corrections



We achieved reduction of 2nd (x|ad) and 3rd (x|aaa) order aberrations.

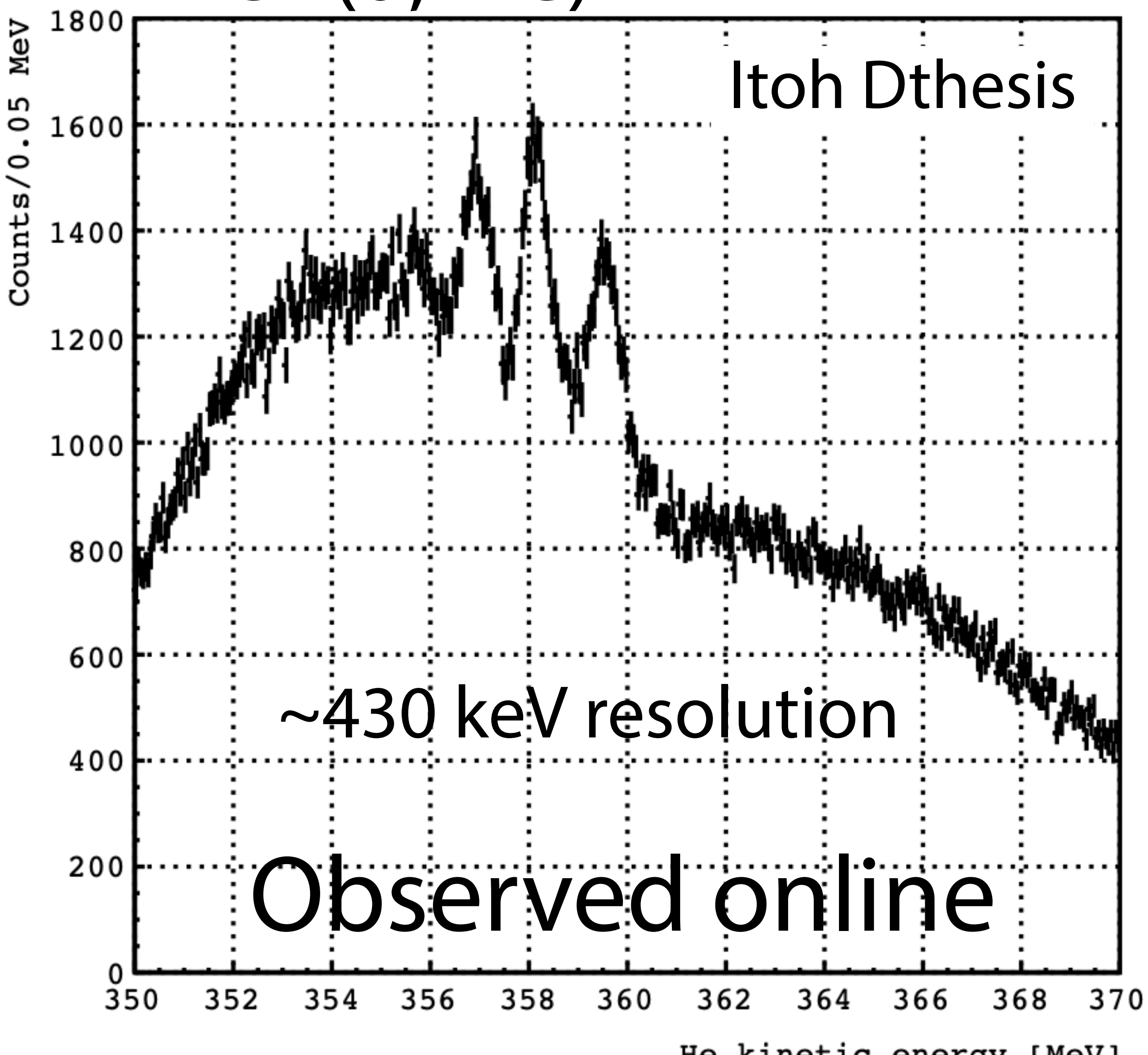
Ready for high resolution spectroscopy!!

Measured spectra, pion-nucleus interaction, and deduction of chiral condensate

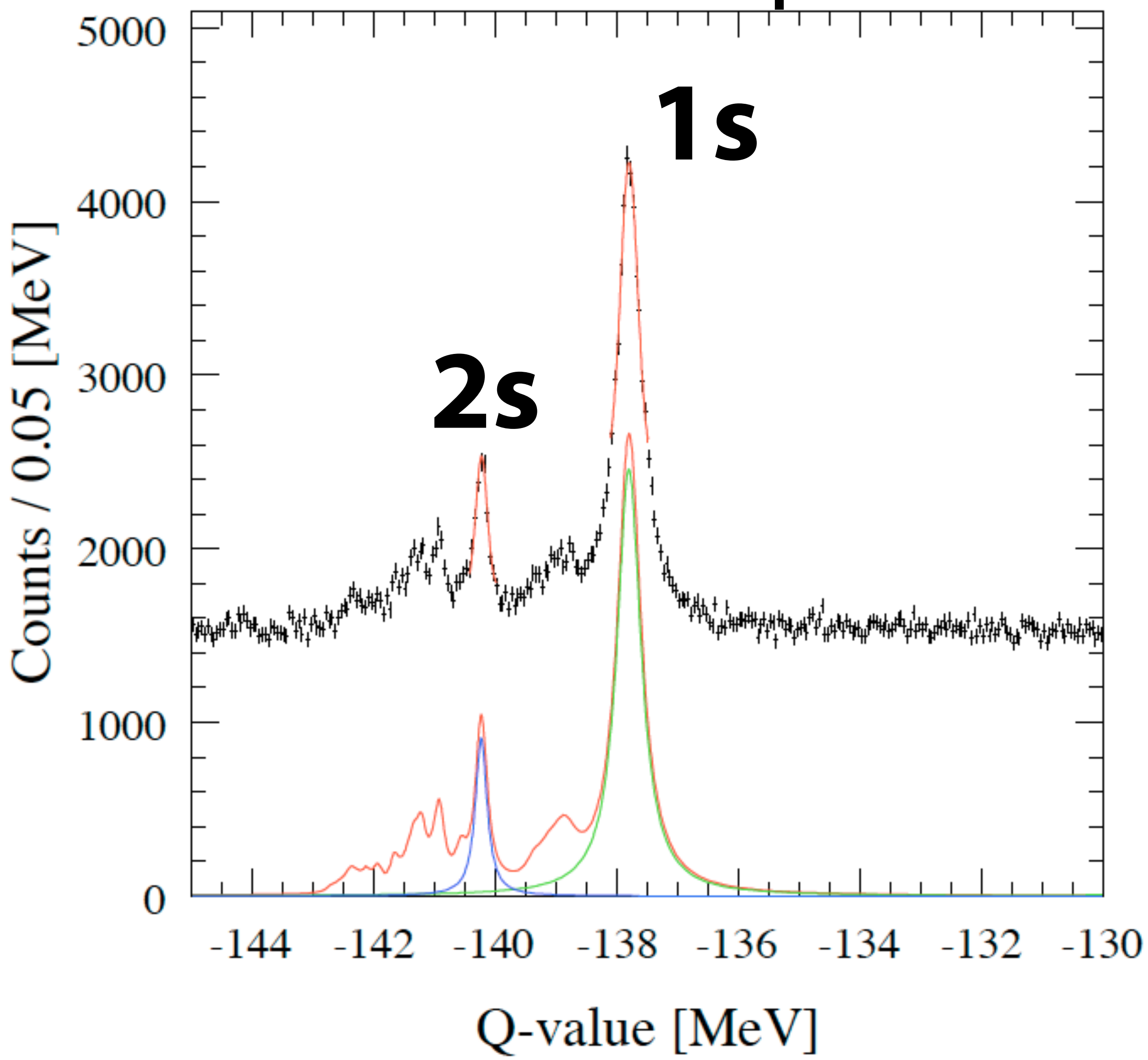
Pionic ^{121}Sn atom

Pilot run of ^{122}Sn(d,^{3}He)
15 hours DAQ in 2010

^{122}Sn(d,^{3}He)



Theoretical spectra

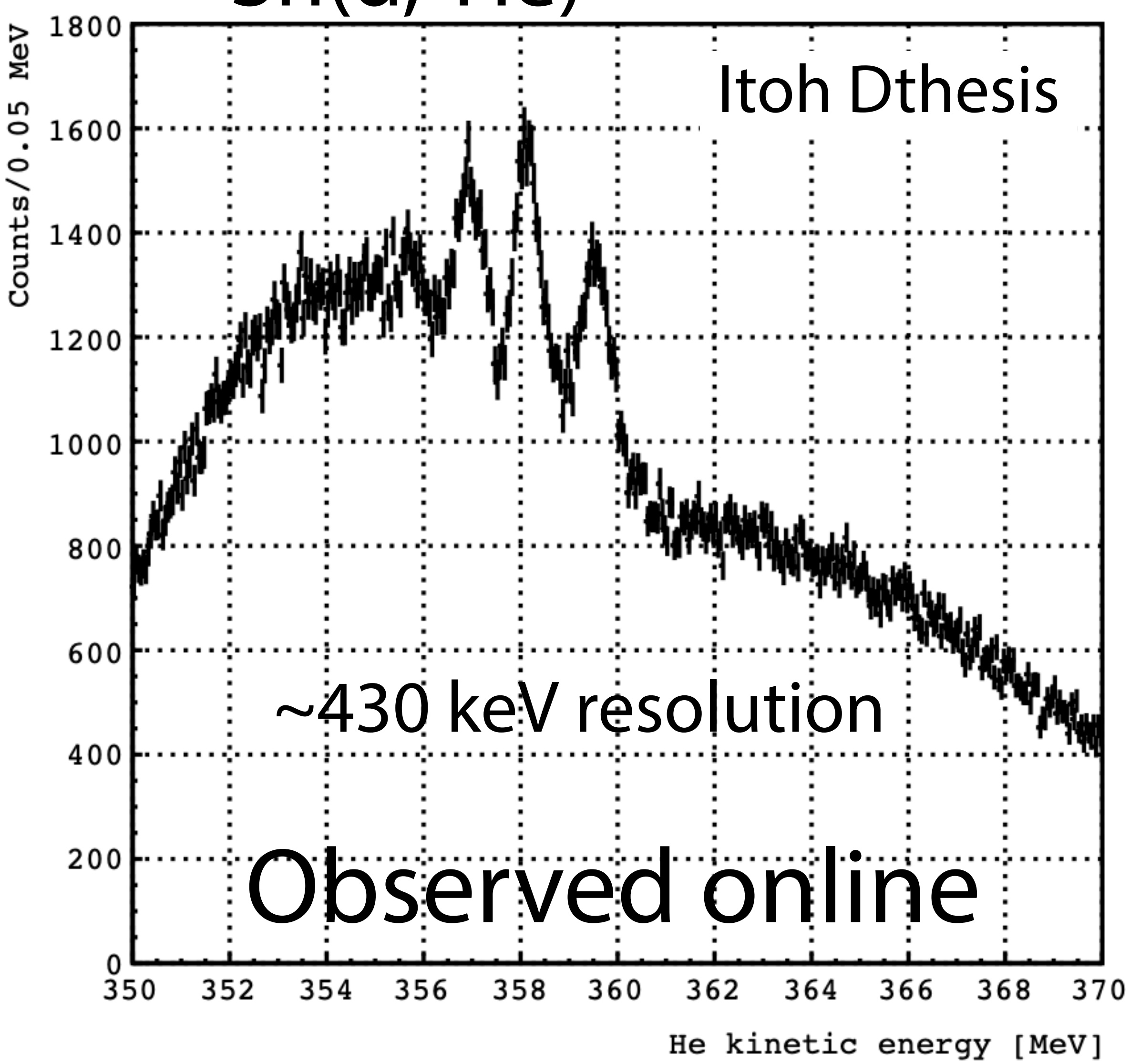


Ikeno, Hirenzaki

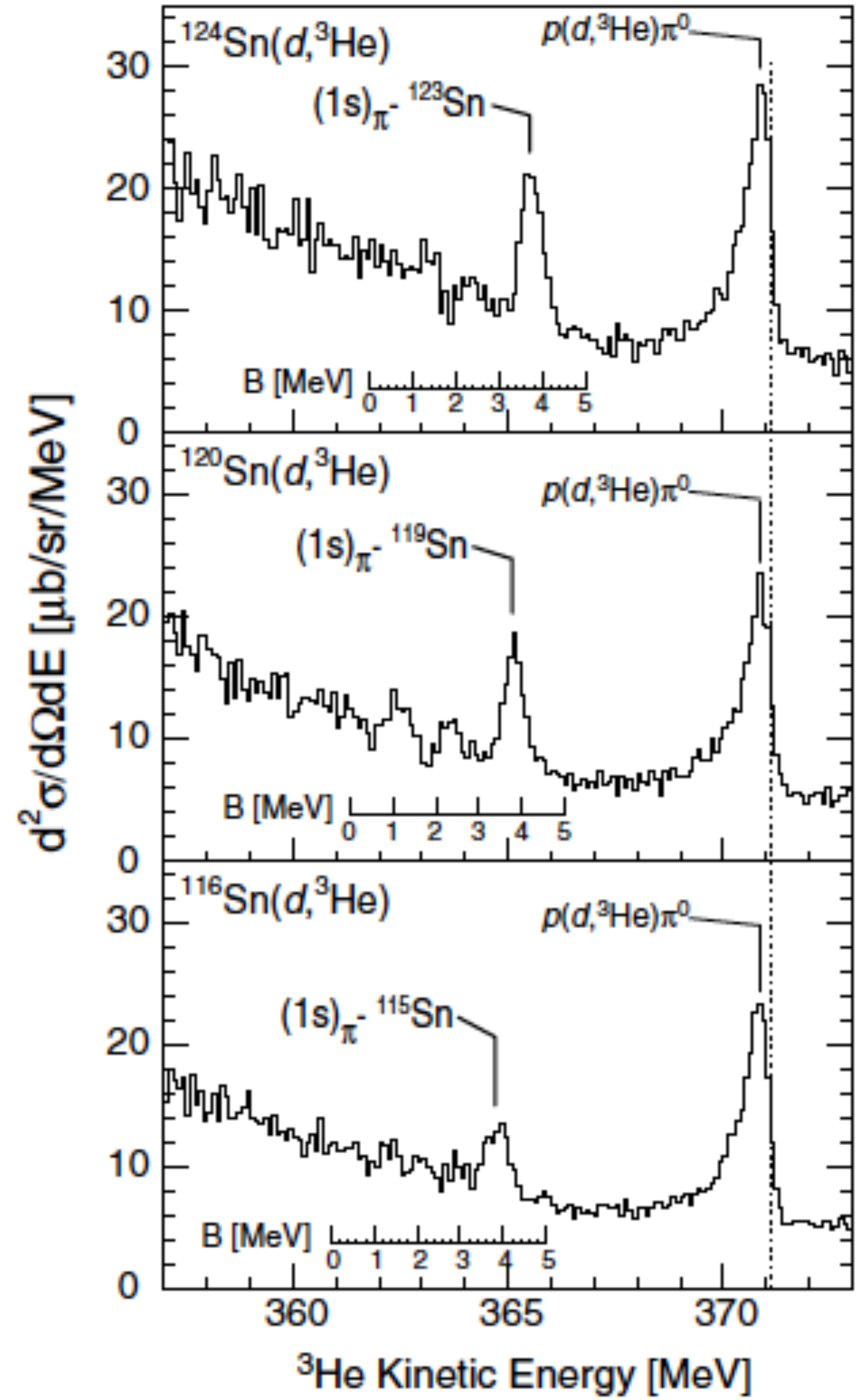
Pionic ^{121}Sn atom

Pilot run of $^{122}Sn(d,^{3}He)$
15 hours DAQ in 2010

$^{122}Sn(d,^{3}He)$



GSI ~30 days

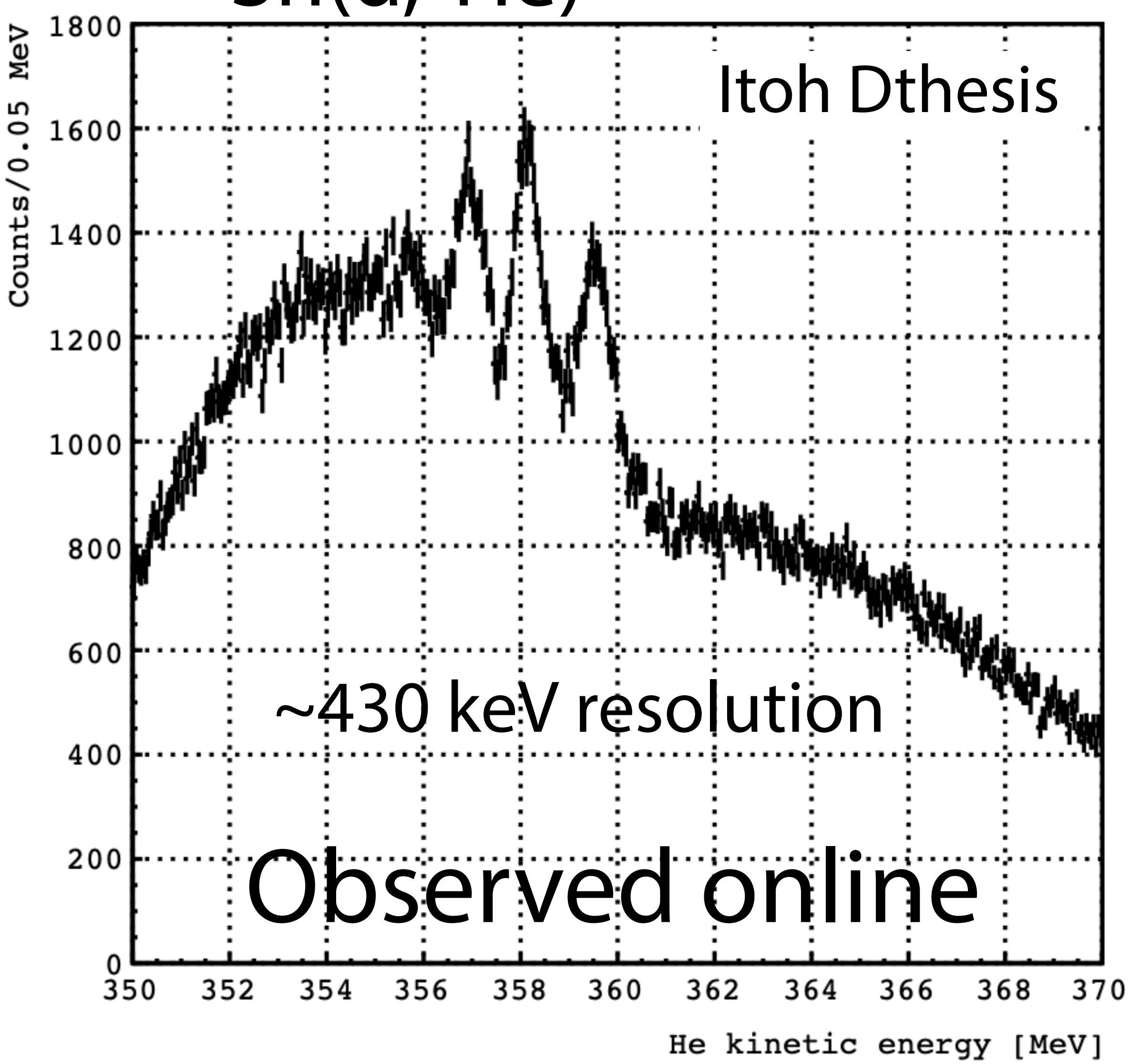


Suzuki et al., PRL 92

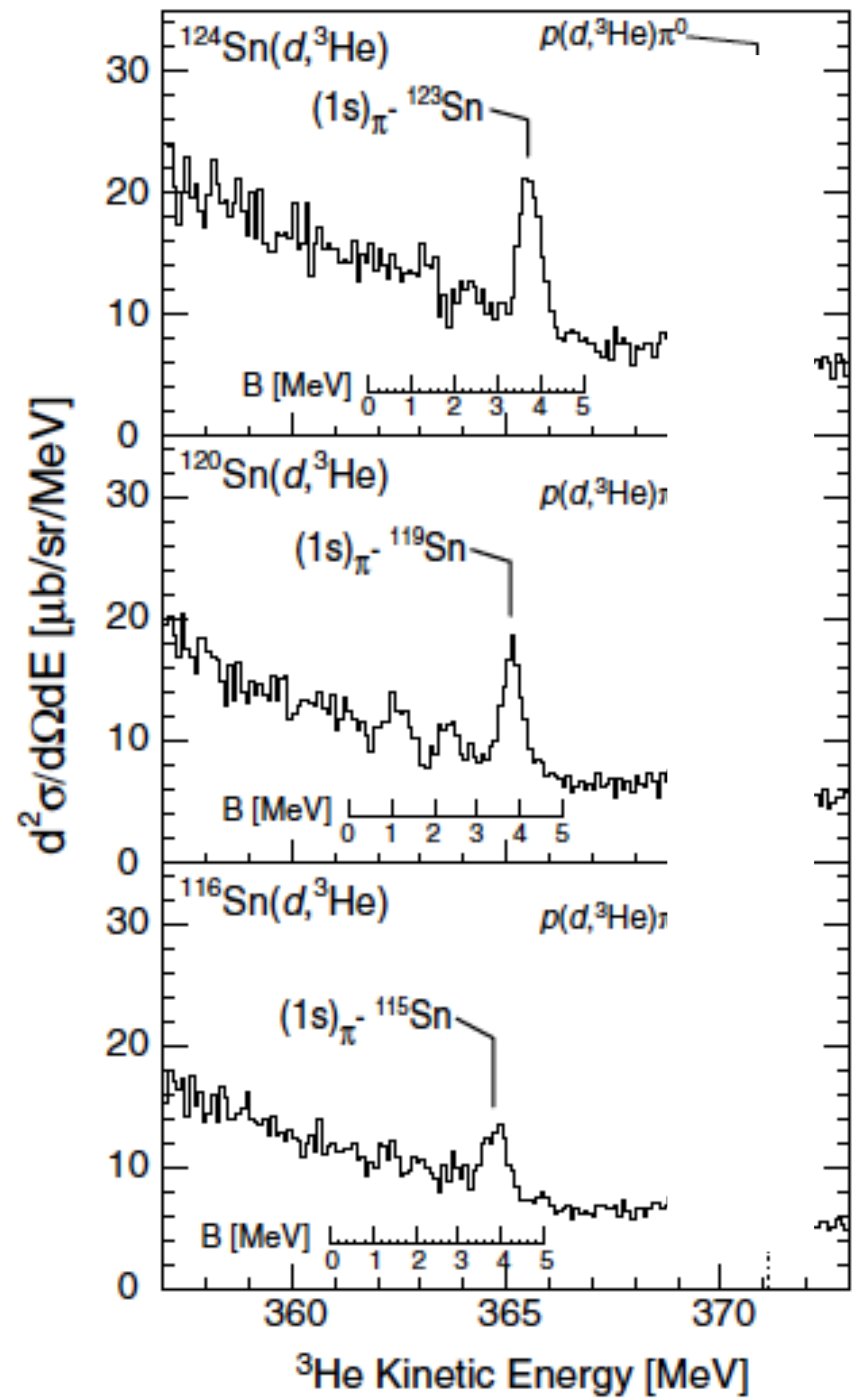
Pionic ^{121}Sn atom

Pilot run of ^{122}Sn(d,^{3}He)
15 hours DAQ in 2010

^{122}Sn(d,^{3}He)



GSI ~30 days



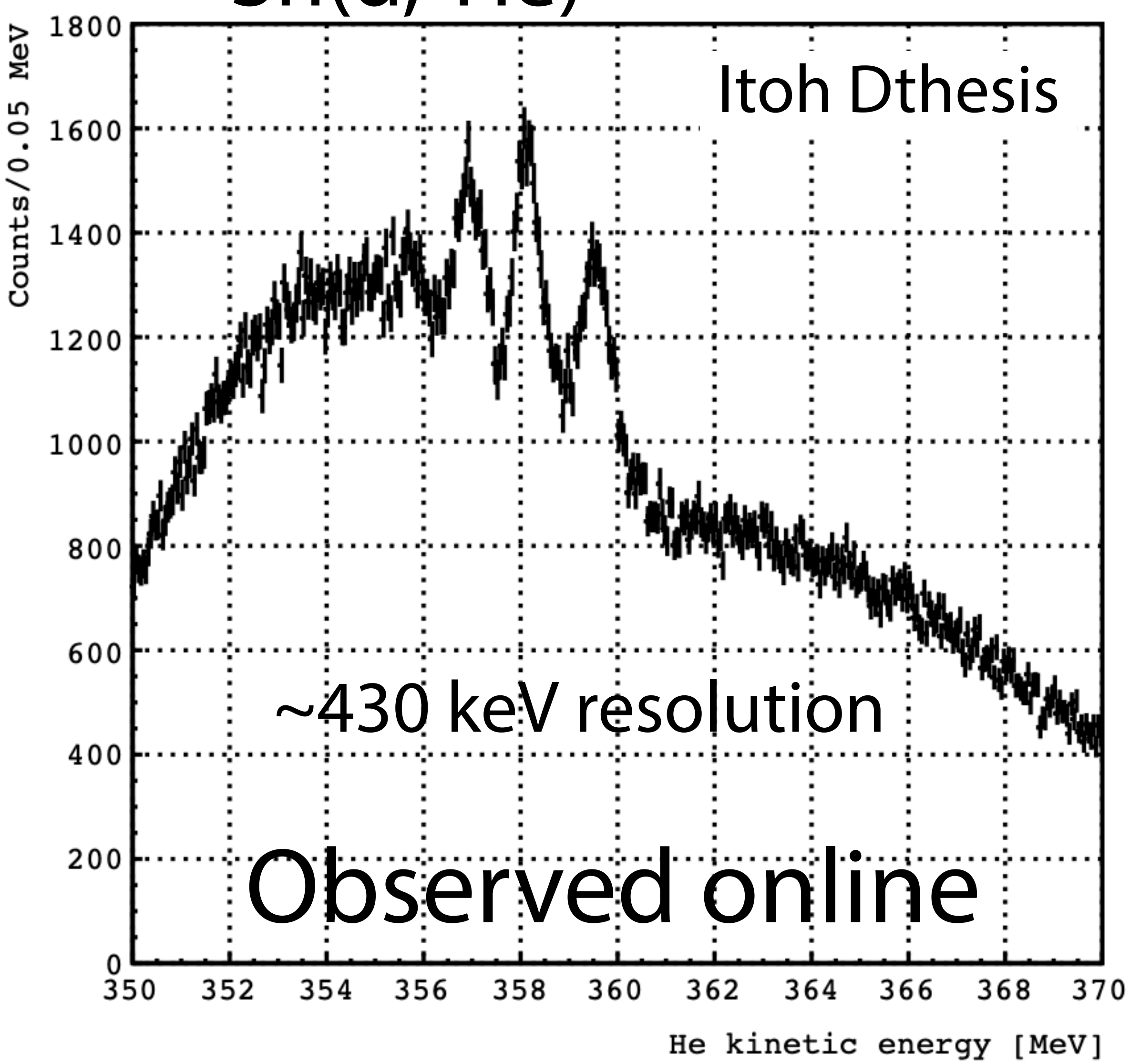
Suzuki et al., PRL 92

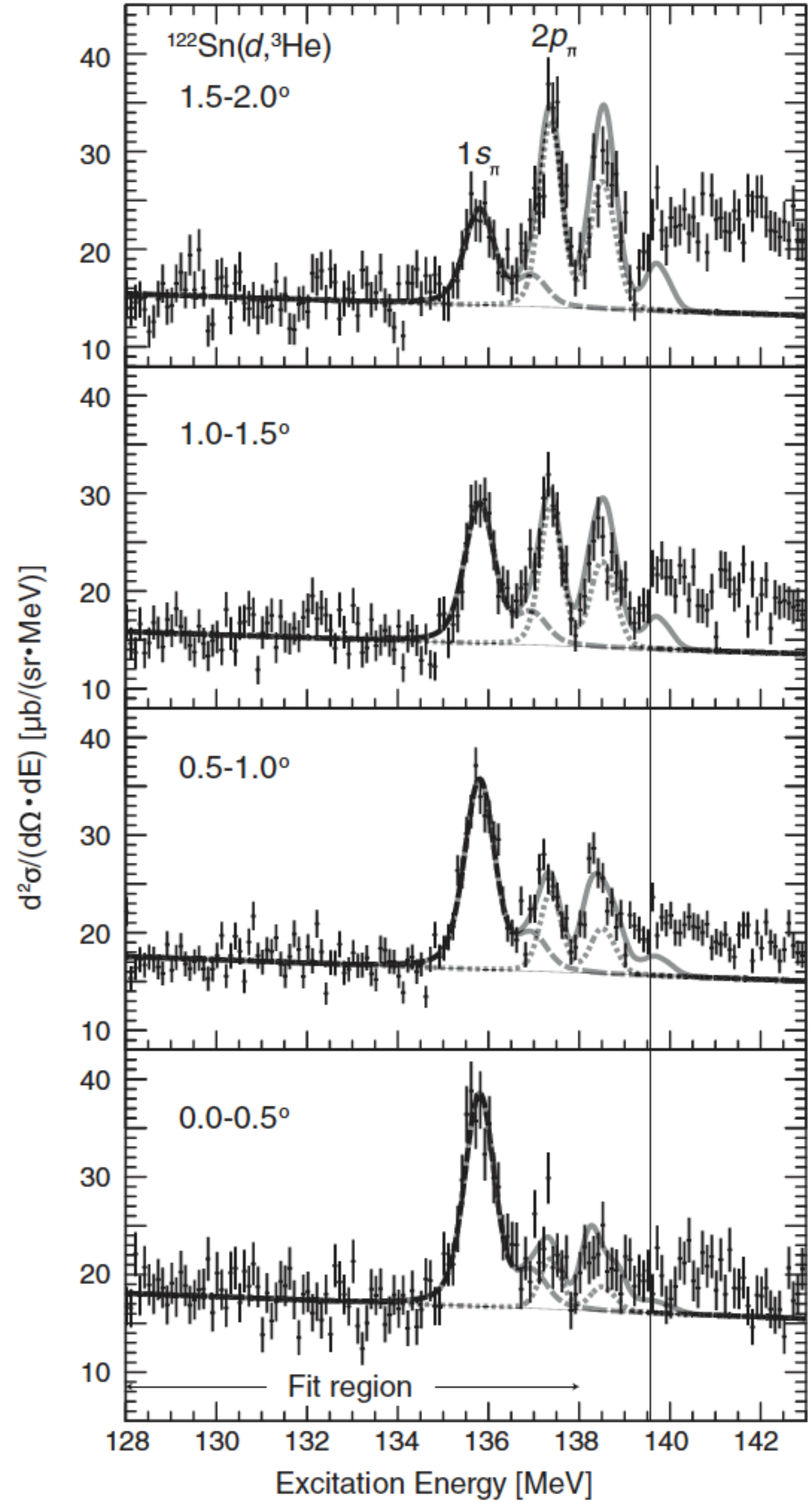
Pionic ^{121}Sn atom

Pilot run of $^{122}Sn(d,^3He)$
15 hours DAQ in 2010

First observation of
θ dependence of
π atom cross section

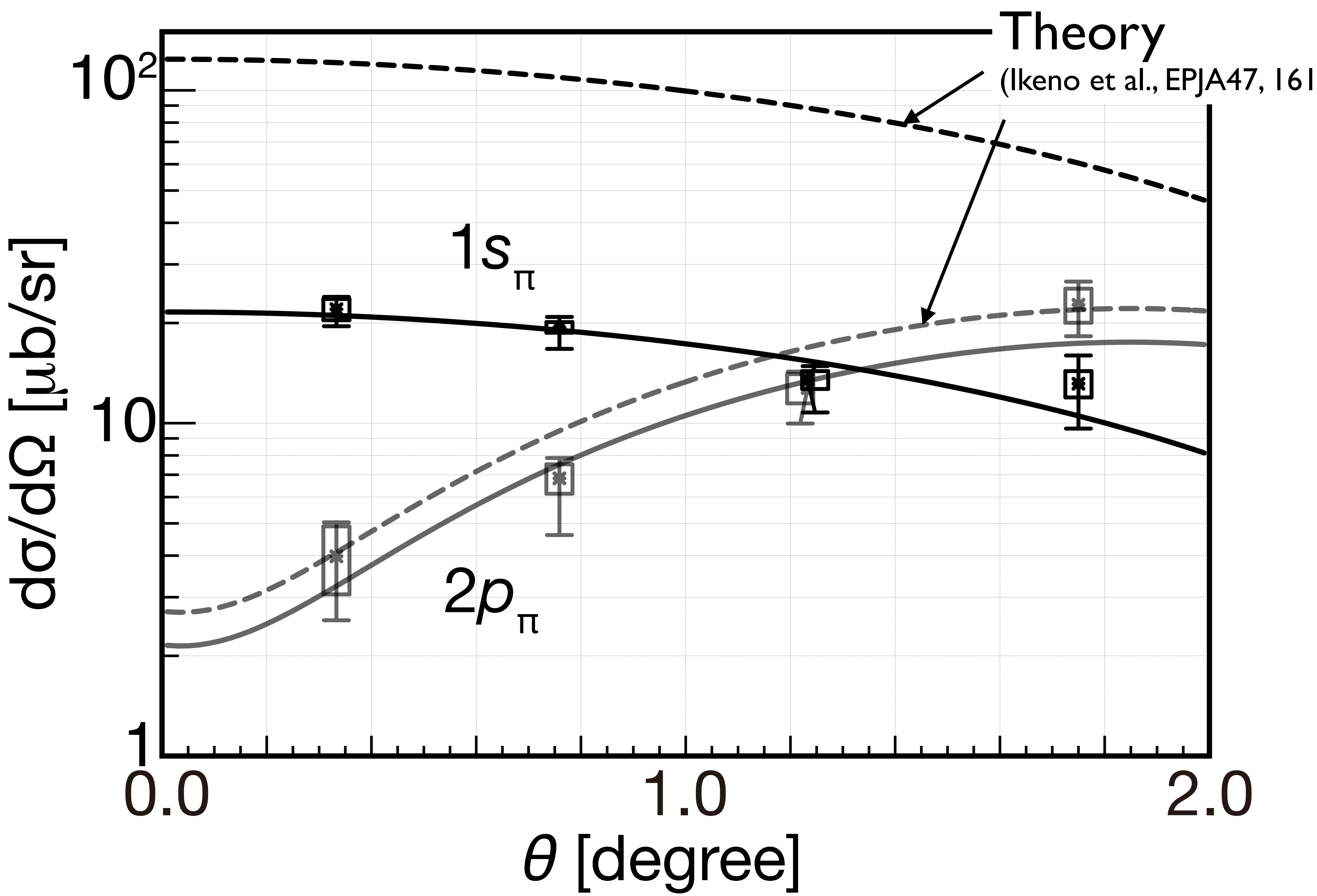
$^{122}Sn(d,^3He)$





T. Nishi KI et al., PRL120, 152505 (2018)

1s and 2p pionic atom cross sections in (d,^{3}He)



T. Nishi KI et al., PRL120, 152505 (2018)

θ dependence is well reproduced.
Theory calculates 5x larger cross section for 1s

Pionic ^{121}Sn atom

Pilot run

15 hours DAQ in 2010

First simultaneous 1s and 2p observation

$$B_{1s} = 3.828 \pm 0.013(\text{stat})^{+0.036}_{-0.033}(\text{syst})\ \text{MeV}$$
$$\Gamma_{1s} = 0.252 \pm 0.054(\text{stat})^{+0.053}_{-0.070}(\text{syst})\ \text{MeV}$$
$$B_{2p} = 2.238 \pm 0.015(\text{stat})^{+0.046}_{-0.043}(\text{syst})\ \text{MeV}$$

Resolution 394 keV (FWHM)

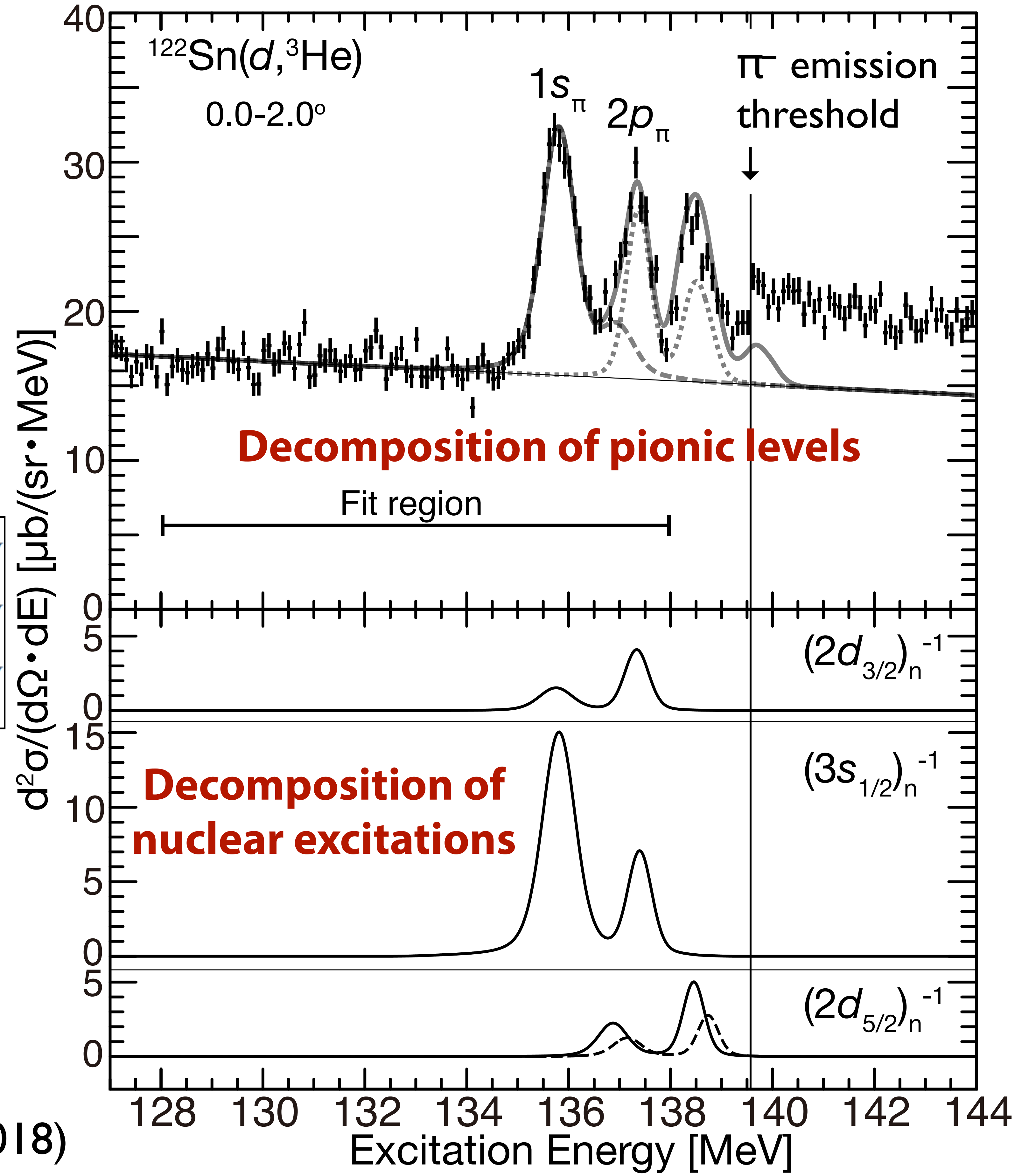
Theories

B_{1s}= 3.787–3.850 MeV

Γ_{1s}= 0.306–0.324 MeV

B_{2p}= 2.257–2.276 MeV

T. Nishi KI et al., PRL120, 152505 (2018)



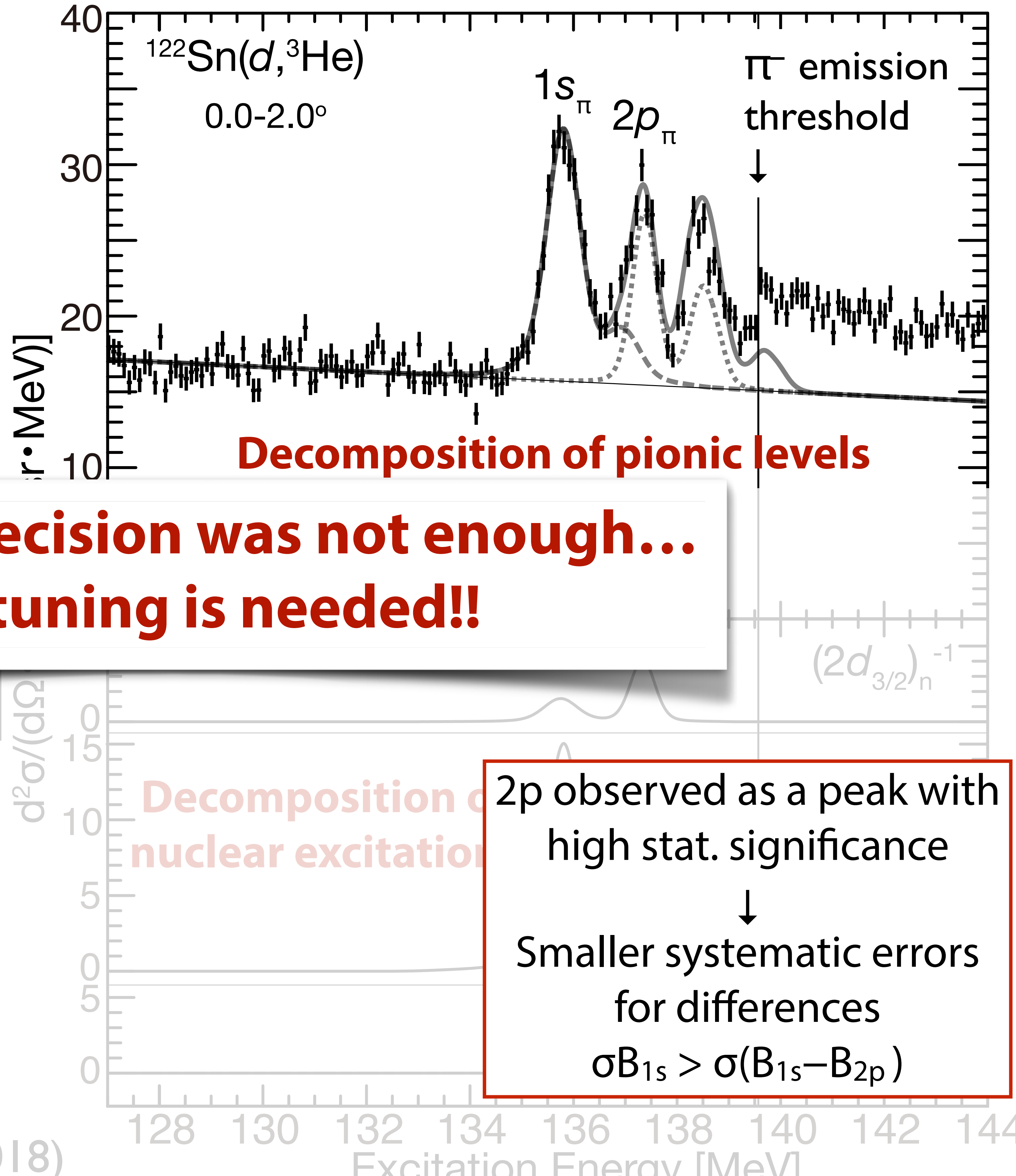
T. Nishi KI et al., PRL120, 152505 (2018)

Pionic ^{121}Sn atom

Pilot run

15 hours DAQ in 2010

First simultaneous 1s and 2p observation



However, precision was not enough…
DM tuning is needed!!

$B_{1s} = 3.828 \pm 0.0$

$\Gamma_{1s} = 0.252 \pm 0.0$

$B_{2p} = 2.238 \pm 0.015(\text{stat})^{+0.046}_{-0.043}(\text{syst})$ MeV

Resolution 394 keV (FWHM)

2p observed as a peak with high stat. significance
↓
Smaller systematic errors for differences
$\sigma B_{1s} > \sigma(B_{1s} - B_{2p})$

Theories

B_{1s}= 3.787–3.850 MeV

Γ_{1s}= 0.306–0.324 MeV

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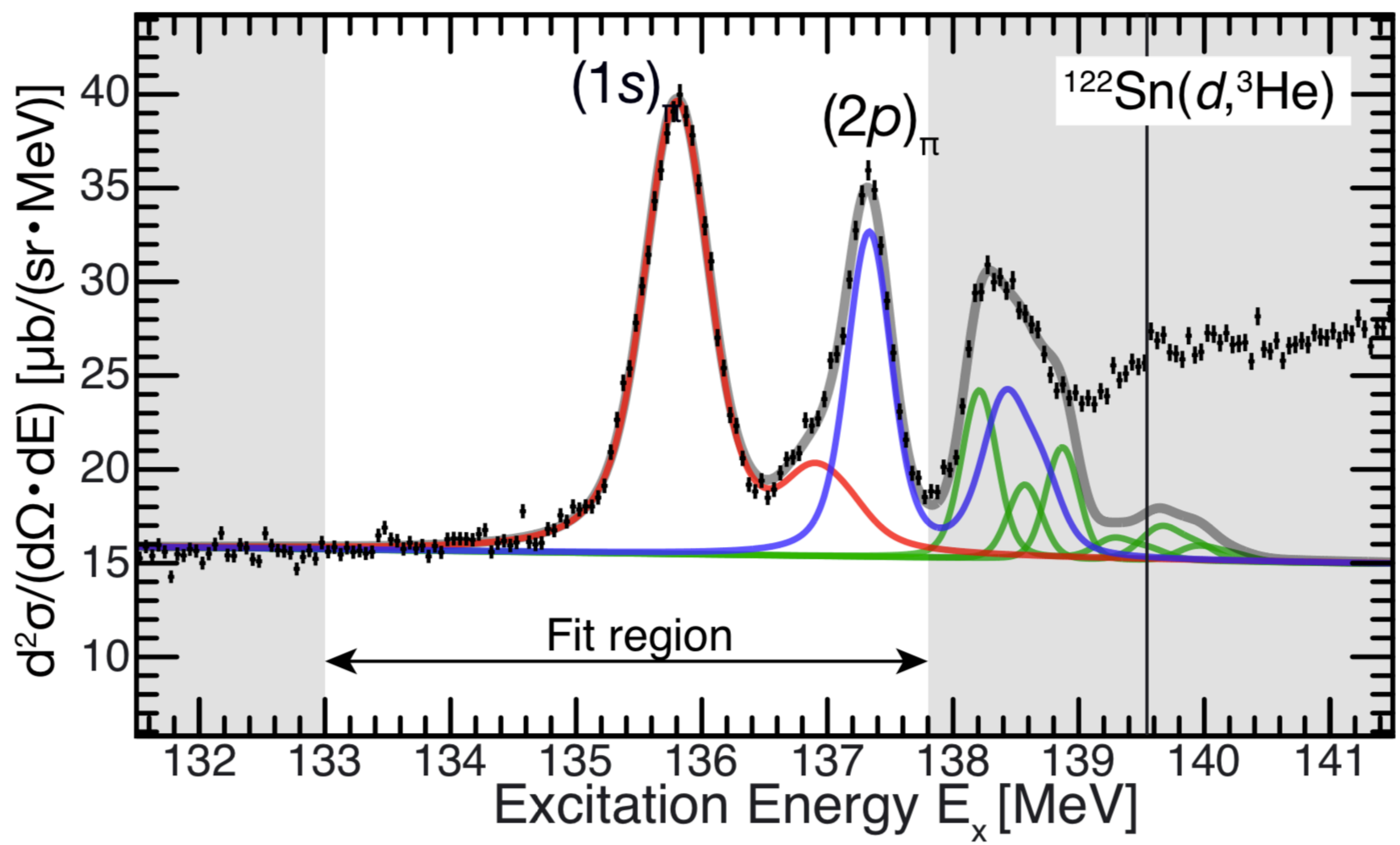
T. Nishi KI et al., PRL120, 152505 (2018)

High Precision Spectrum of $^{122}Sn(d,^{3}He)$ in 2014 run

Pionic atom unveils hidden structure of QCD vacuum

Takahiro Nishi[1], Kenta Itahashi[1,*] DeukSoon Ahn[1,2], Georg P.A. Berg[3], Masanori Dozono[1], Daijiro Etoh[4], Hiroyuki Fujioka[5], Naoki Fukuda[1], Nobuhisa Fukunishi[1], Hans Geissel[6], Emma Haettner[6], Tadashi Hashimoto[1], Ryugo S. Hayano[7], Satoru Hirenzaki[8], Hiroshi Horii[7], Natsumi Ikeno[9], Naoto Inabe[1], Masahiko Iwasaki[1], Daisuke Kameda[1], Keichi Kisamori[10], Yu Kiyokawa[10], Toshiyuki Kubo[1], Kensuke Kusaka[1], Masafumi Matsushita[10], Shin'ichiro Michimasa[10], Go Mishima[7], Hiroyuki Miya[1], Daichi Murai[1], Hideko Nagahiro[8], Megumi Niikura[7], Naoko Nose-Togawa[11], Shinsuke Ota[10], Naruhiko Sakamoto[1], Kimiko Sekiguchi[4], Yuta Shiokawa[4], Hiroshi Suzuki[1], Ken Suzuki[12], Motonobu Takaki[10], Hiroyuki Takeda[1], Yoshiki K. Tanaka[1], Tomohiro Uesaka[1], Yasumori Wada[4], Atomu Watanabe[4], Yuni N. Watanabe[7], Helmut Weick[6], Hiroki Yamakami[5], Yoshiyuki Yanagisawa[1], and Koichi Yoshida[1]

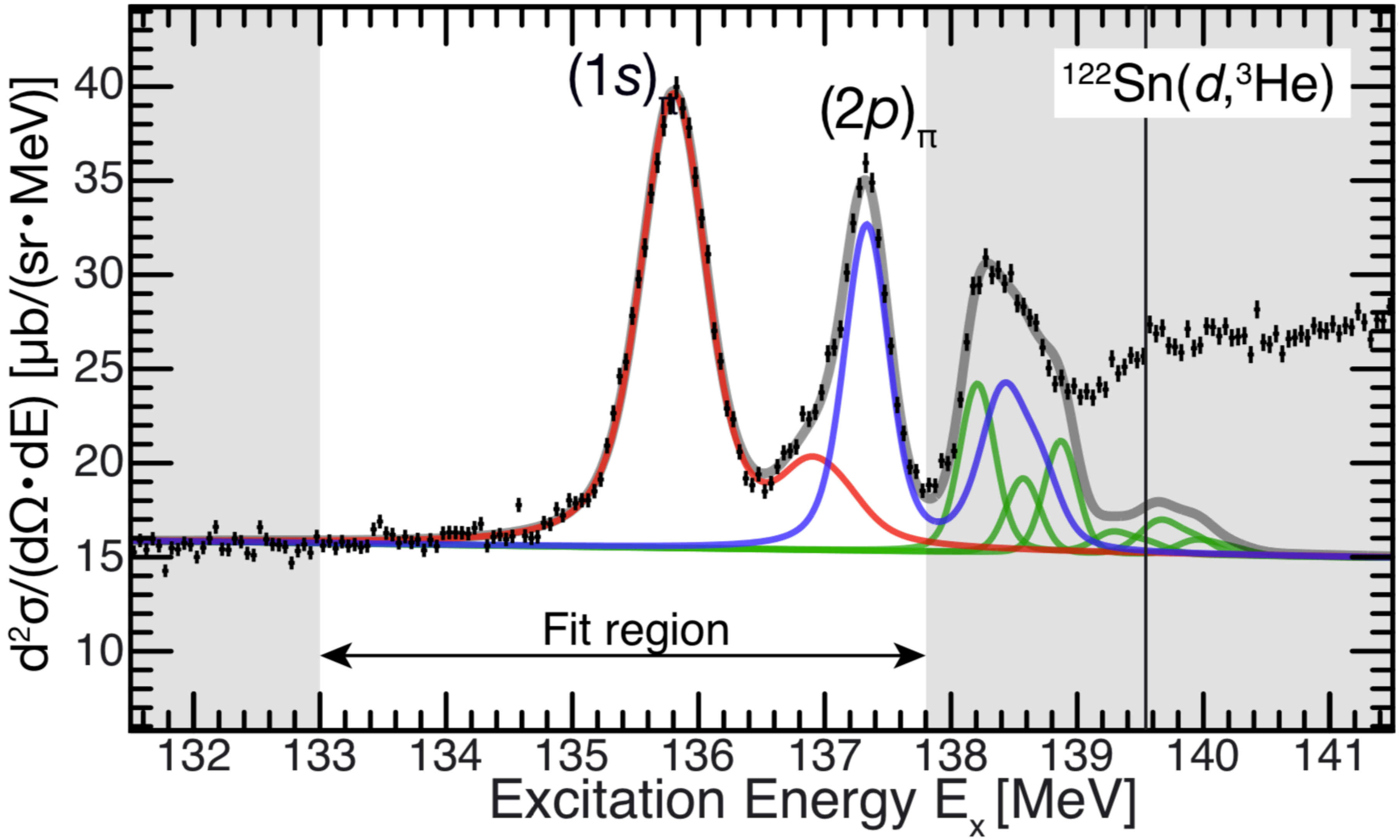


Optimized DM

2p observed as a peak with high stat. significance
↓
Smaller systematic errors for differences
$\sigma B_{1s} > \sigma(B_{1s} - B_{2p})$

Nature Physics **19**, 788 (2023/3/23)
Article DOI: 10.1038/s41567-023-02001-x

High Precision Spectrum of ^{122}Sn(d,^{3}He) in 2014 run



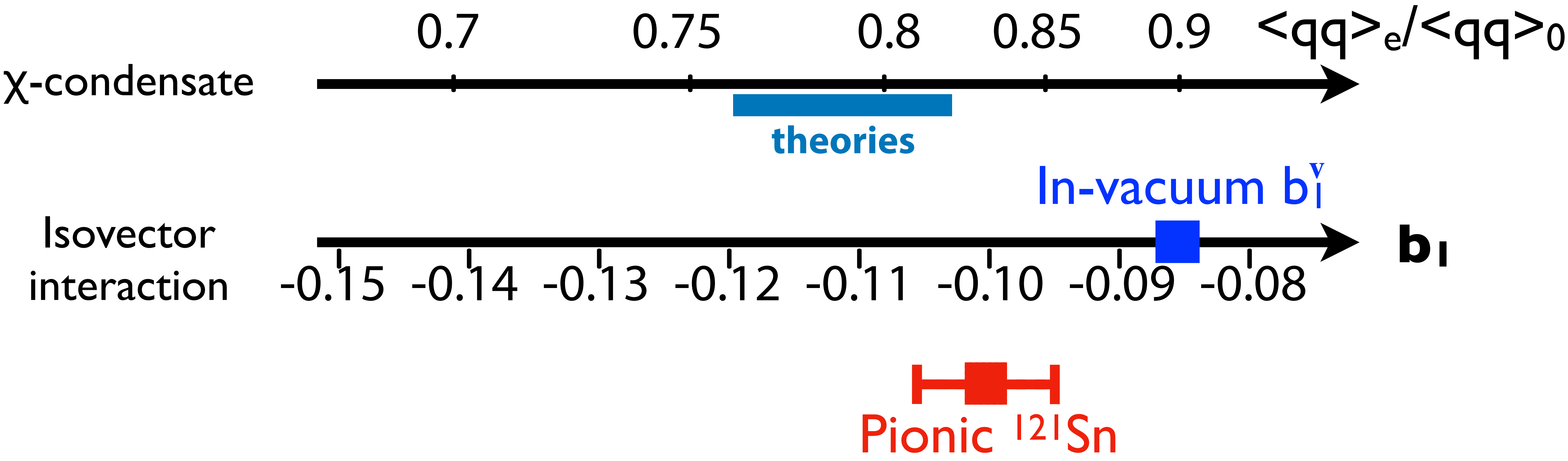
	[keV]	Statistical	Systematic
$B_\pi(1s)$	3831	± 3	$+78 - 76$
$B_\pi(2p)$	2276	± 3	$+84 - 83$
$B_\pi(1s) - B_\pi(2p)$	1555	± 4	± 12
$\Gamma_\pi(1s)$	316	± 12	$+36 - 39$
$\Gamma_\pi(2p)$	164	± 17	$+41 - 32$
$\Gamma_\pi(1s) - \Gamma_\pi(2p)$	152	± 20	$+28 - 36$

Best resolution 287 keV (FWHM)

2p observed as a peak with high stat. significance
↓
Smaller systematic errors for differences
$\sigma B_{1s} > \sigma(B_{1s} - B_{2p})$

Nature Physics **19**, 788 (2023/3/23)
Article DOI: 10.1038/s41567-023-02001-x

Deduced b_1 from pionic Sn spectrum



b_1 = -0.1005 is deduced

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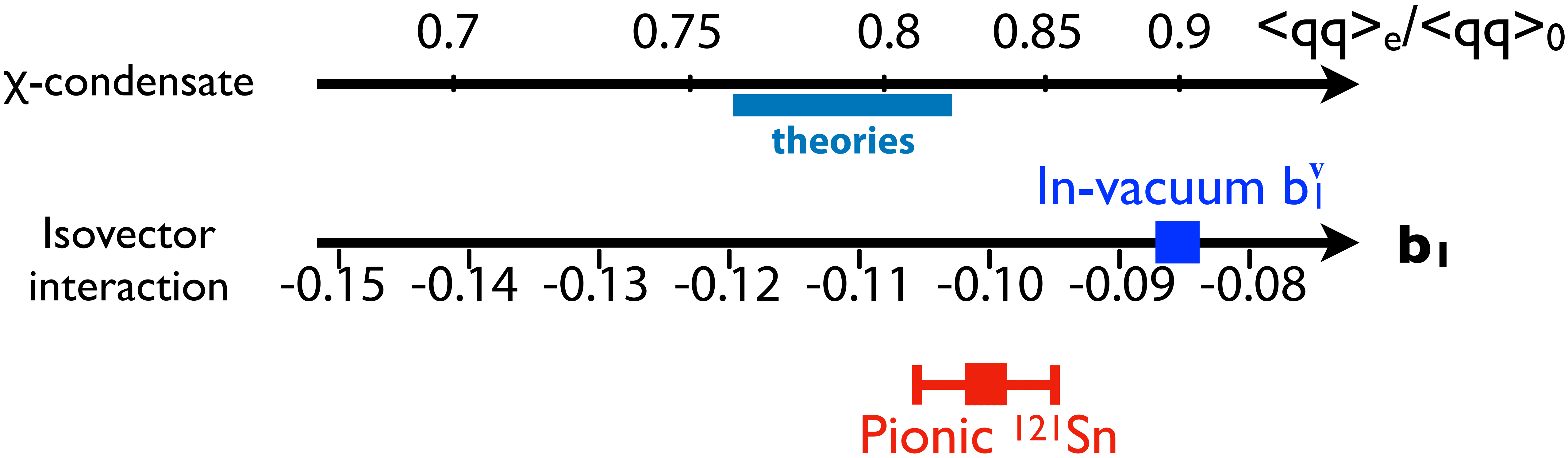
Nishi, KI et al., Nat. Phys. (2023)

Deduced b_1 from pionic Sn spectrum



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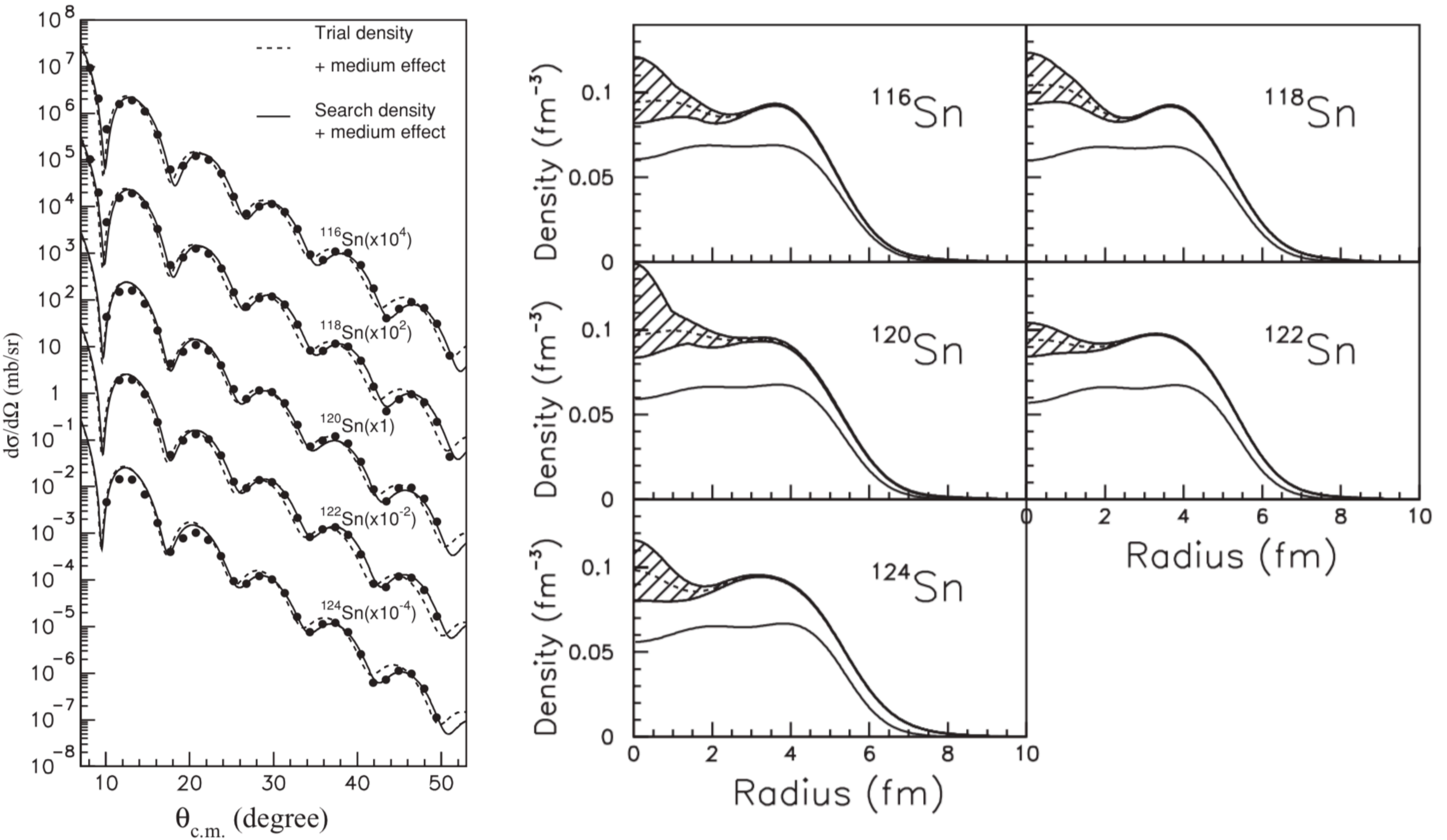
$\Gamma_\pi(1s)-\Gamma_\pi(2p)$	152	±20	$+28-36$

Nishi, KI et al., Nat. Phys. (2023)

LLE：short-range correction
Sn ρ：neutron density distribution
Abs.：representation of absorption term
Green：cross section calculation method
Res. : Residual interaction
Spec. : neutron spectroscopic factors

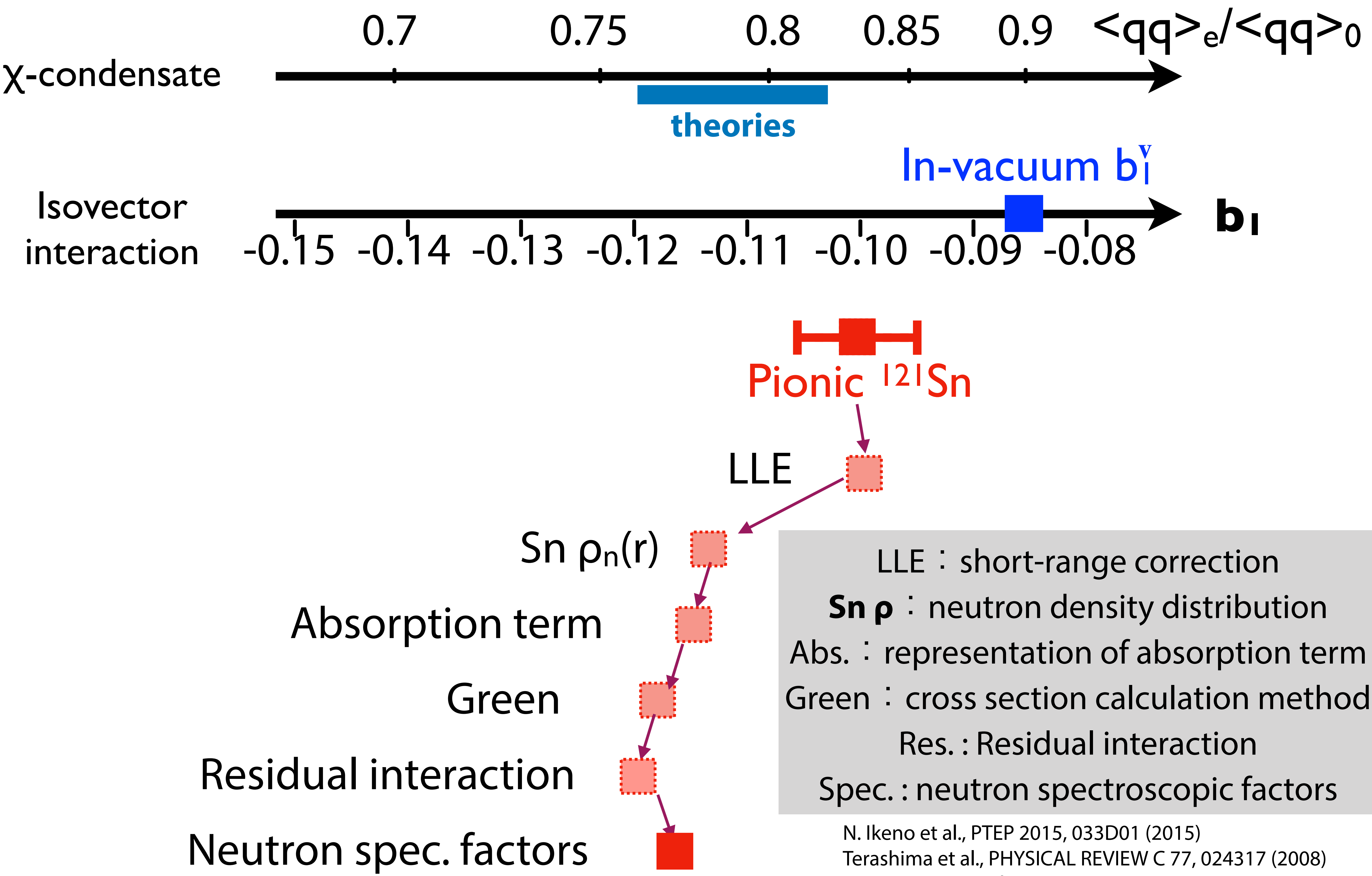
N. Ikeno et al., PTEP 2015, 033D01 (2015)
Terashima et al., PHYSICAL REVIEW C 77, 024317 (2008)
Nose-Togawa et al., PRC71, 061601(R) (2005)
Szwec et al., PRC104,054308 (2022)

Measured nuclear density distribution of Sn isotopes
Sn(p,p') reaction at RCNP, Osaka



Terashima, Sakaguchi *et al.*, PHYSICAL REVIEW C **77**, 024317 (2008)

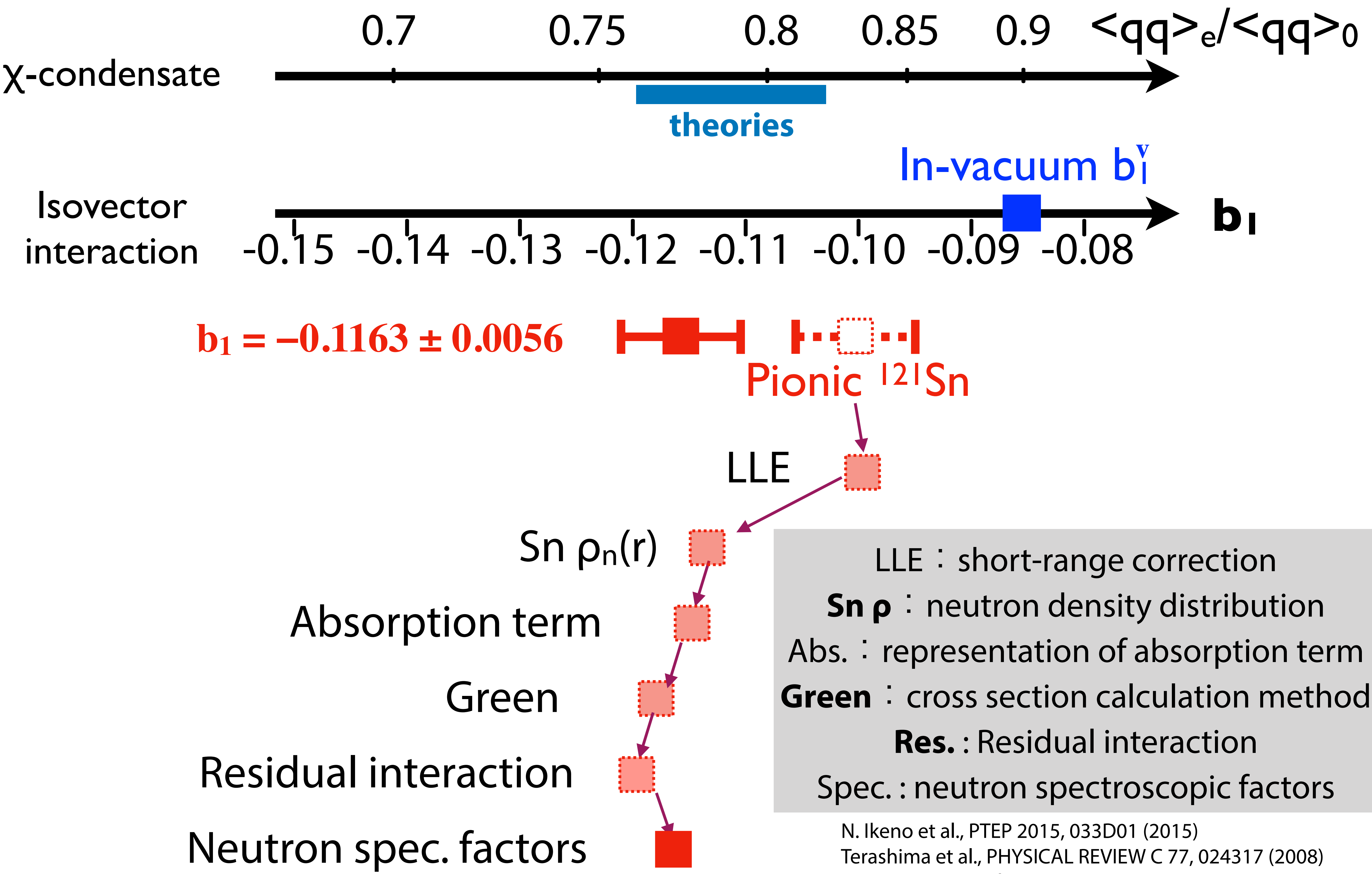
Deduced b_1 with corrections



N. Ikeno et al., PTEP 2015, 033D01 (2015)
Terashima et al., PHYSICAL REVIEW C 77, 024317 (2008)
Nose-Togawa et al., PRC71, 061601(R) (2005)
Szwec et al., PRC104,054308 (2022)

Nishi, KI et al., Nat. Phys. (2023)

Deduced b_1 with corrections

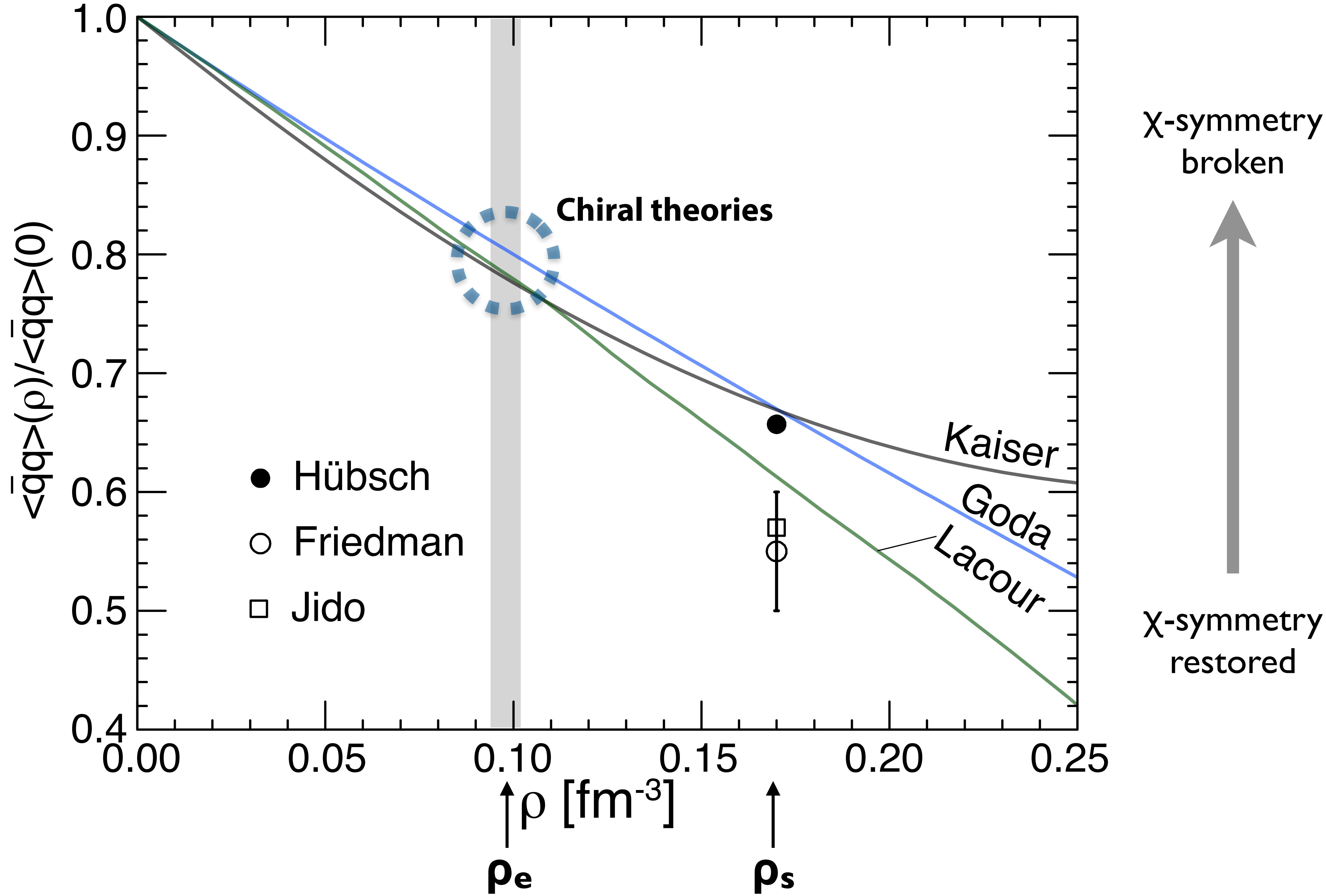


N. Ikeno et al., PTEP 2015, 033D01 (2015)
Terashima et al., PHYSICAL REVIEW C 77, 024317 (2008)
Nose-Togawa et al., PRC71, 061601(R) (2005)
Szwec et al., PRC104,054308 (2022)

Nishi, KI et al., Nat. Phys. (2023)

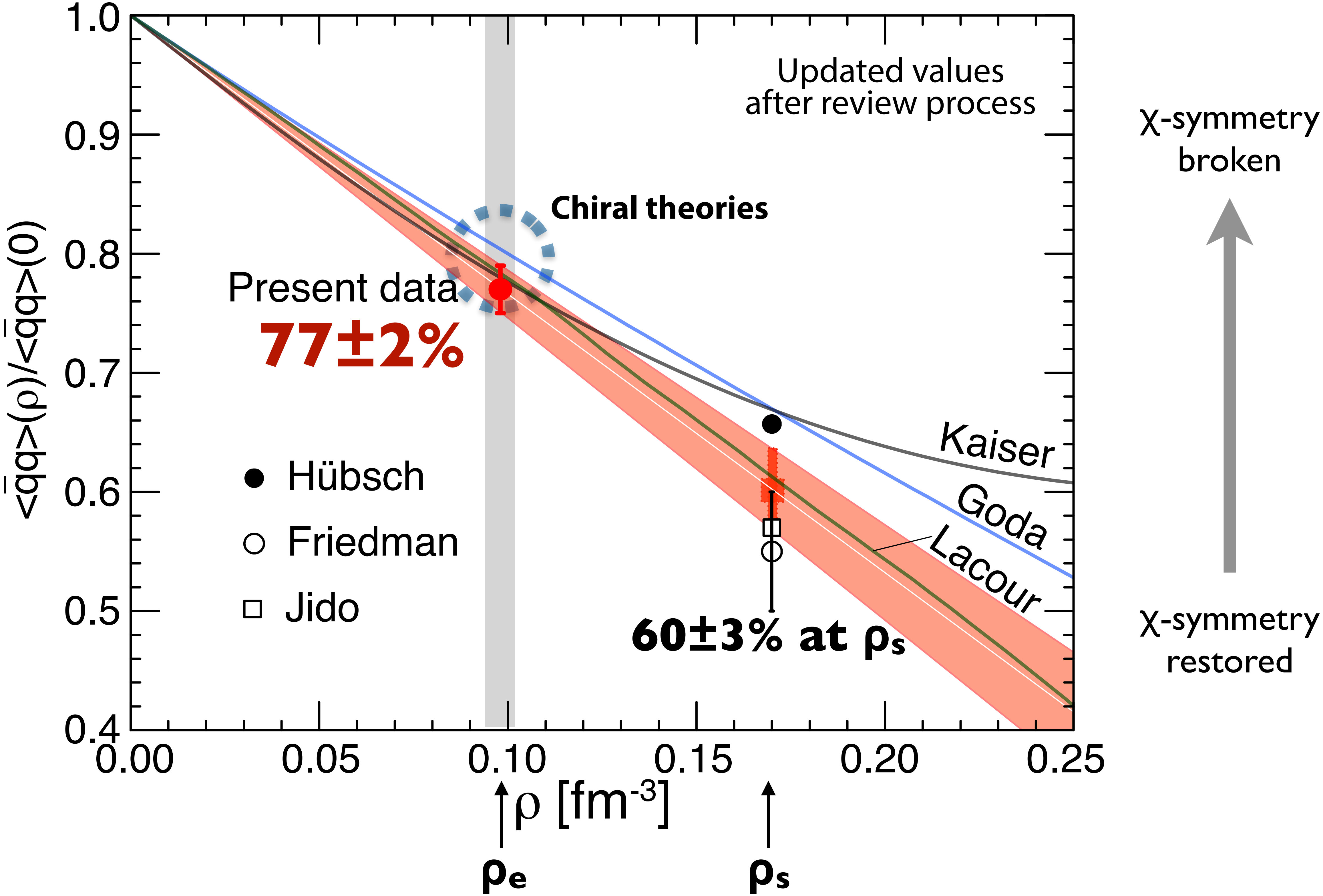
57

Result: deduced chiral condensate



Nature Physics **19**, 788 (2023/3/23)
Article DOI: 10.1038/s41567-023-02001-x

Result: deduced chiral condensate



Nature Physics **19**, 788 (2023/3/23)
Article DOI: 10.1038/s41567-023-02001-x

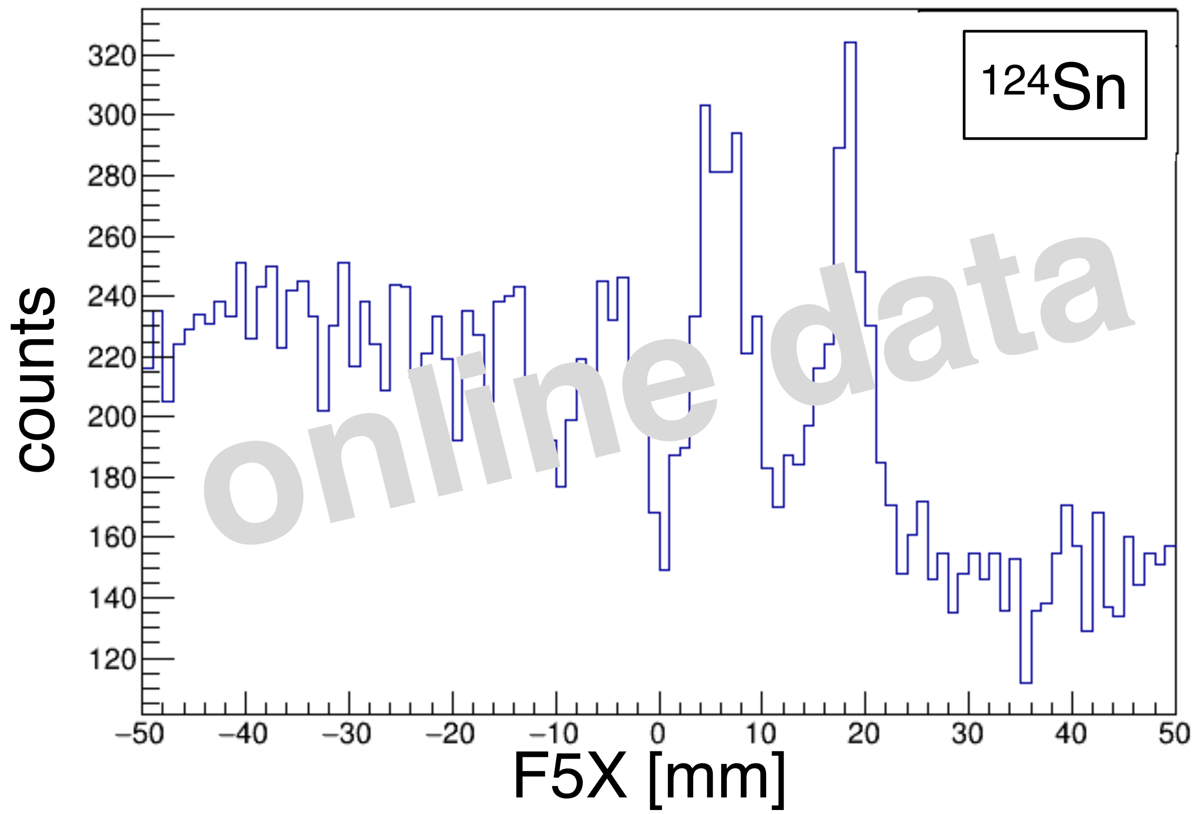
Next Experiments and Future plans

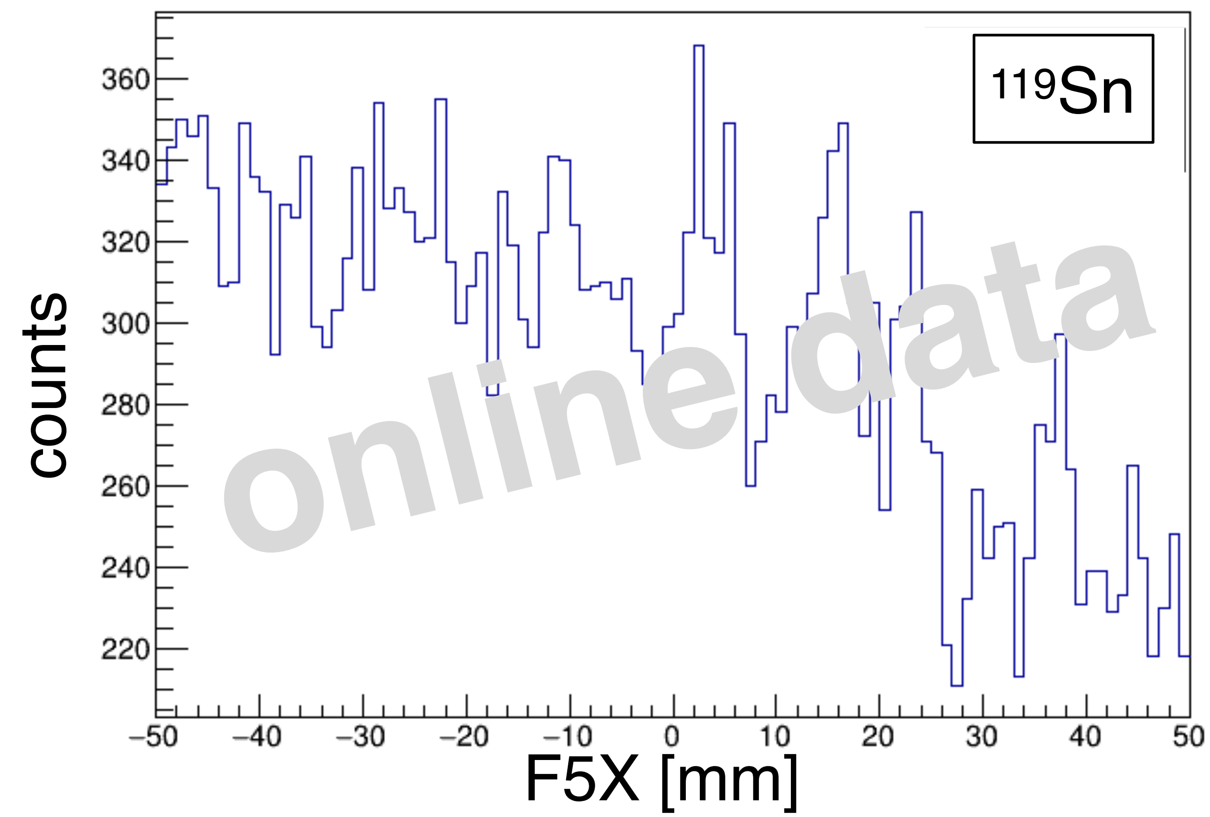
Systematic spectroscopy of pionic Sn isotopes
RIBF-135

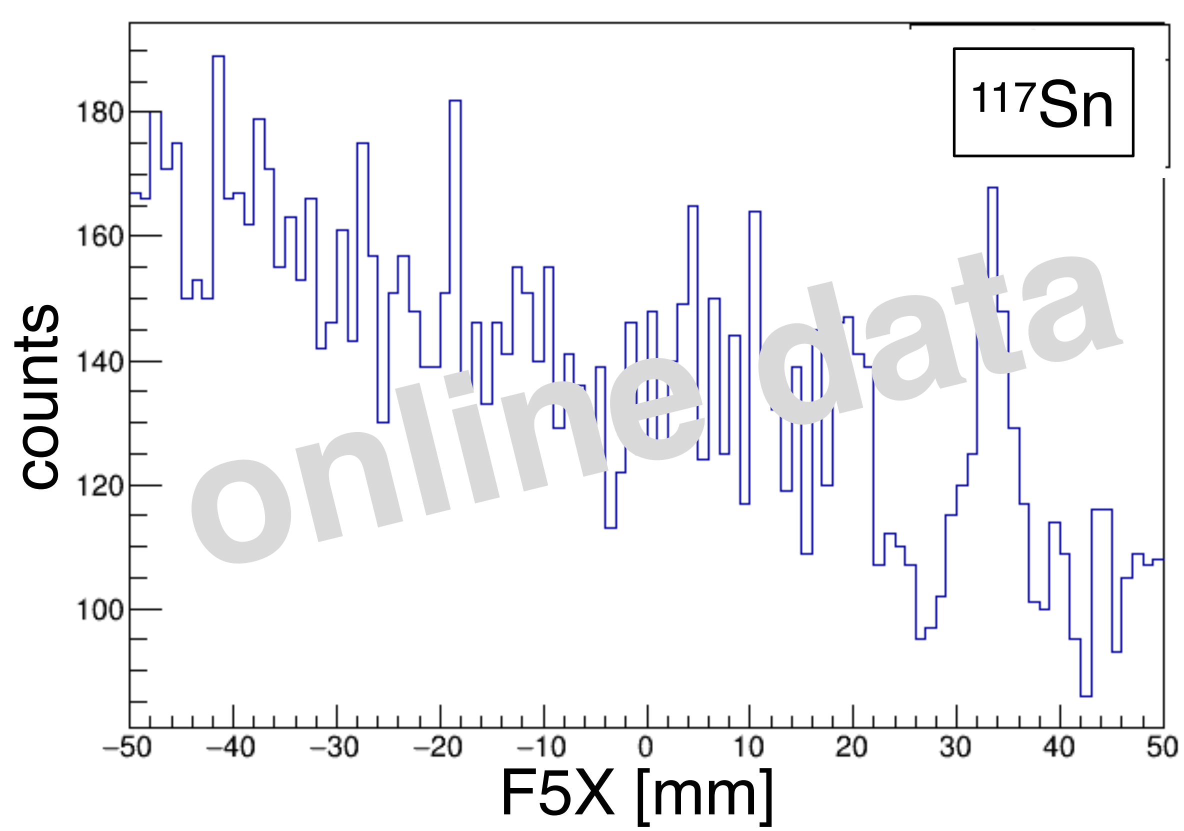
113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128
I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127
Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te
111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126
Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb
110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125
Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn
109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124
In	In	In	In	In	In	In	In	In	In	In	In	In	In	In	In
108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123
Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd
107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122
Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag

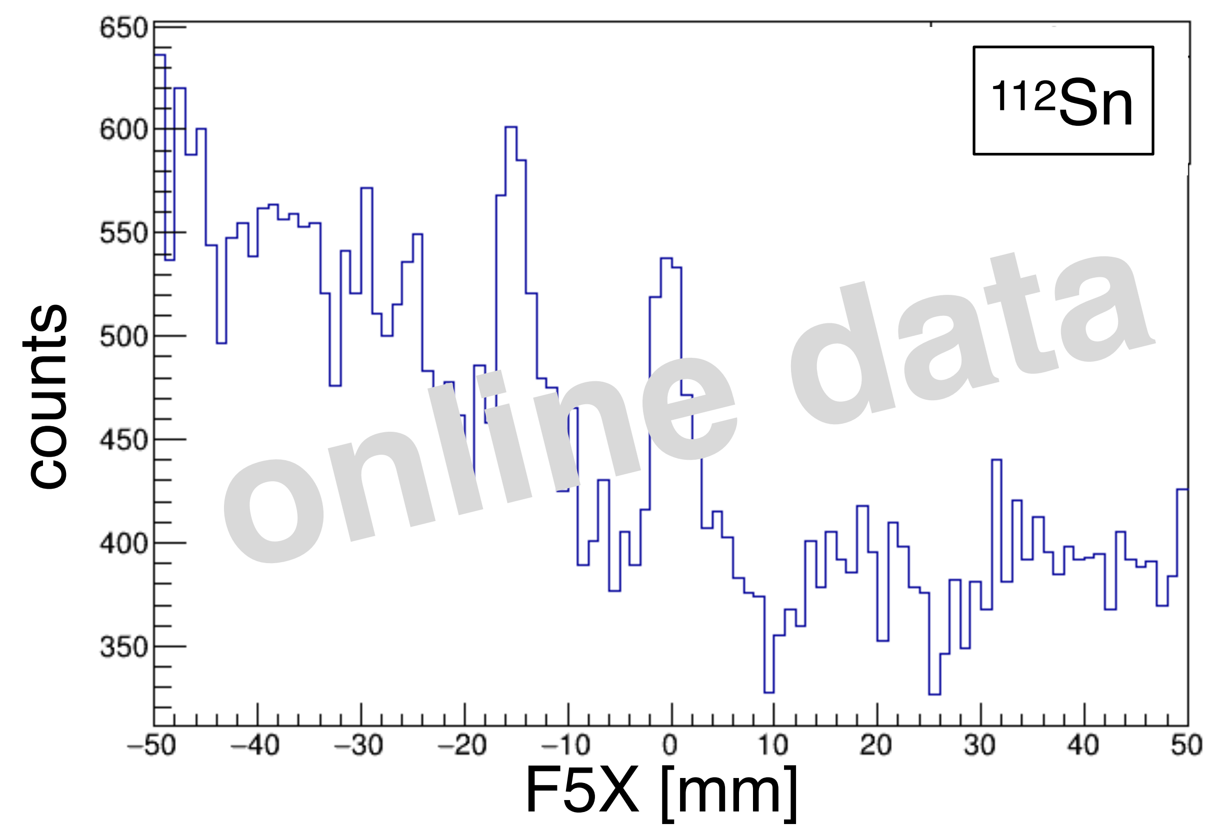
for better precision

Online spectra in RIBF-135 (2021)









D-candidate: S.Y. Matsumoto

Now, we are interested in $\sigma_{\pi N}$

$$\sigma_{\pi N} \equiv m_q/2m_N \Sigma_{u,d} < N|\bar{q}q|N >$$

quark contribution to nucleon mass

$$\frac{b_1^0}{b_1(\rho)} = \frac{<\bar{q}q>(\rho)}{<\bar{q}q>(0)} \simeq 1 - \frac{\rho\sigma_{\pi N}}{f_\pi^2 m_\pi^2}\left(1 - \frac{3k_F^2}{10M_N^2} + \frac{9k_F^4}{56M_N^4}\right) + O(\rho^2)$$

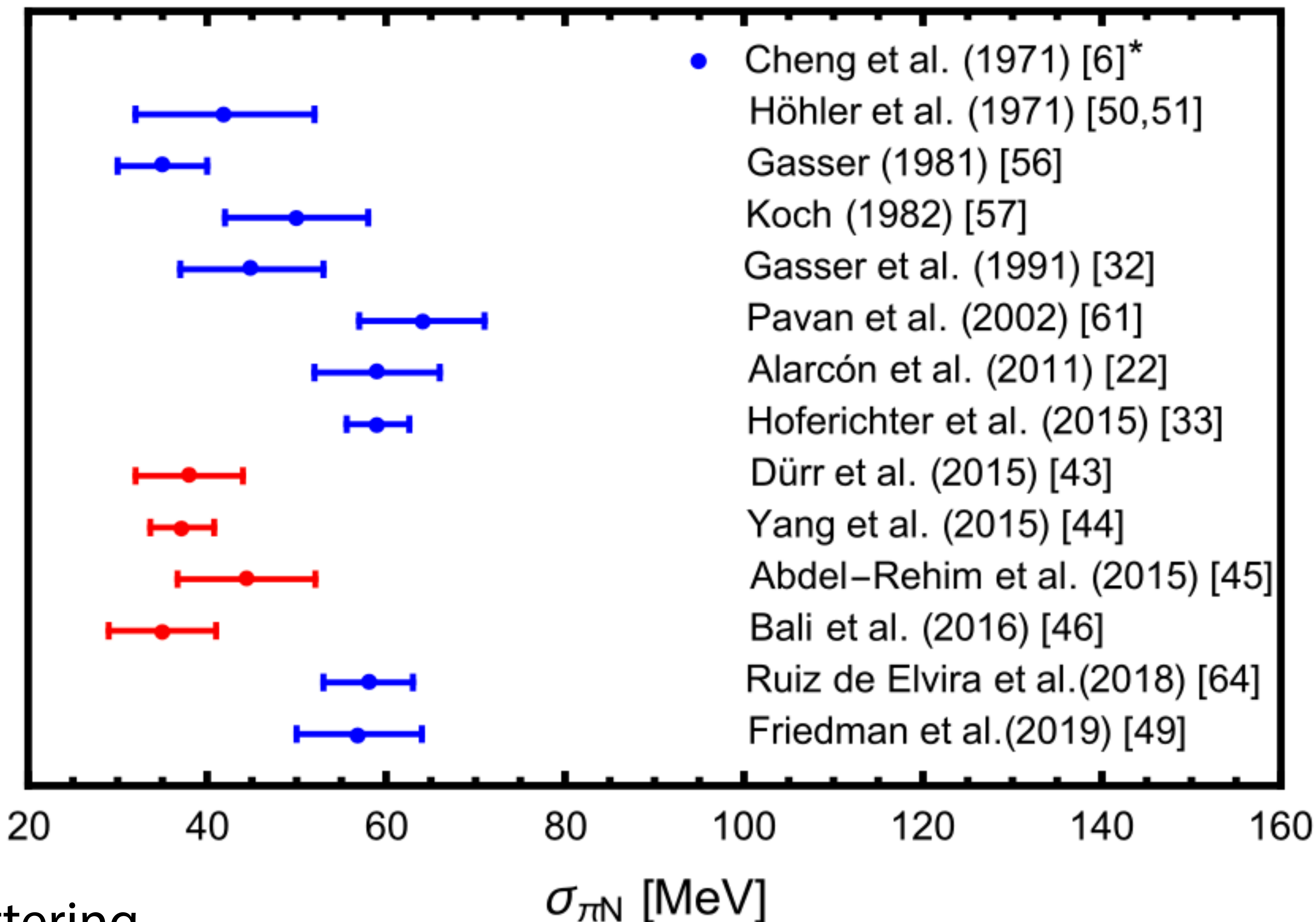
$$k_F = (3/2\pi^2\rho)^{1/3}$$

Kaiser et al., PRC77, 025204 (2008)
Gubler, Sato, PPNP106,1(2019)

Two approaches:

1. derivation from $b_1(\rho)$
   Ikeno et al., PTEP 2023, 033D03
2. determine $d<qq>/d\rho$ at ρ_e and extrapolate to $\rho=0$

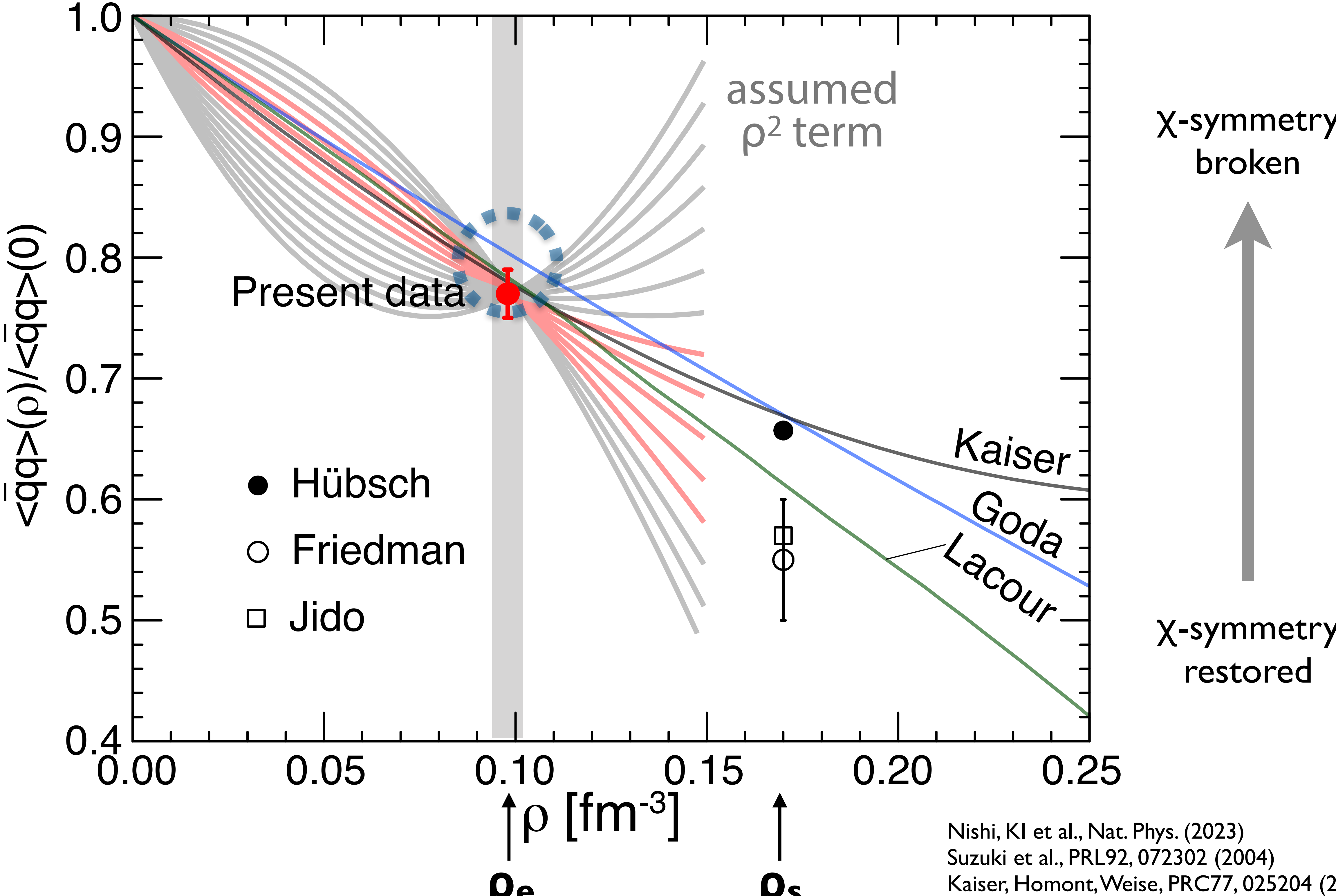
Now, we are interested in $\sigma_{\pi N}$



piN scattering
Lattice QCD
Chiral effective theory…

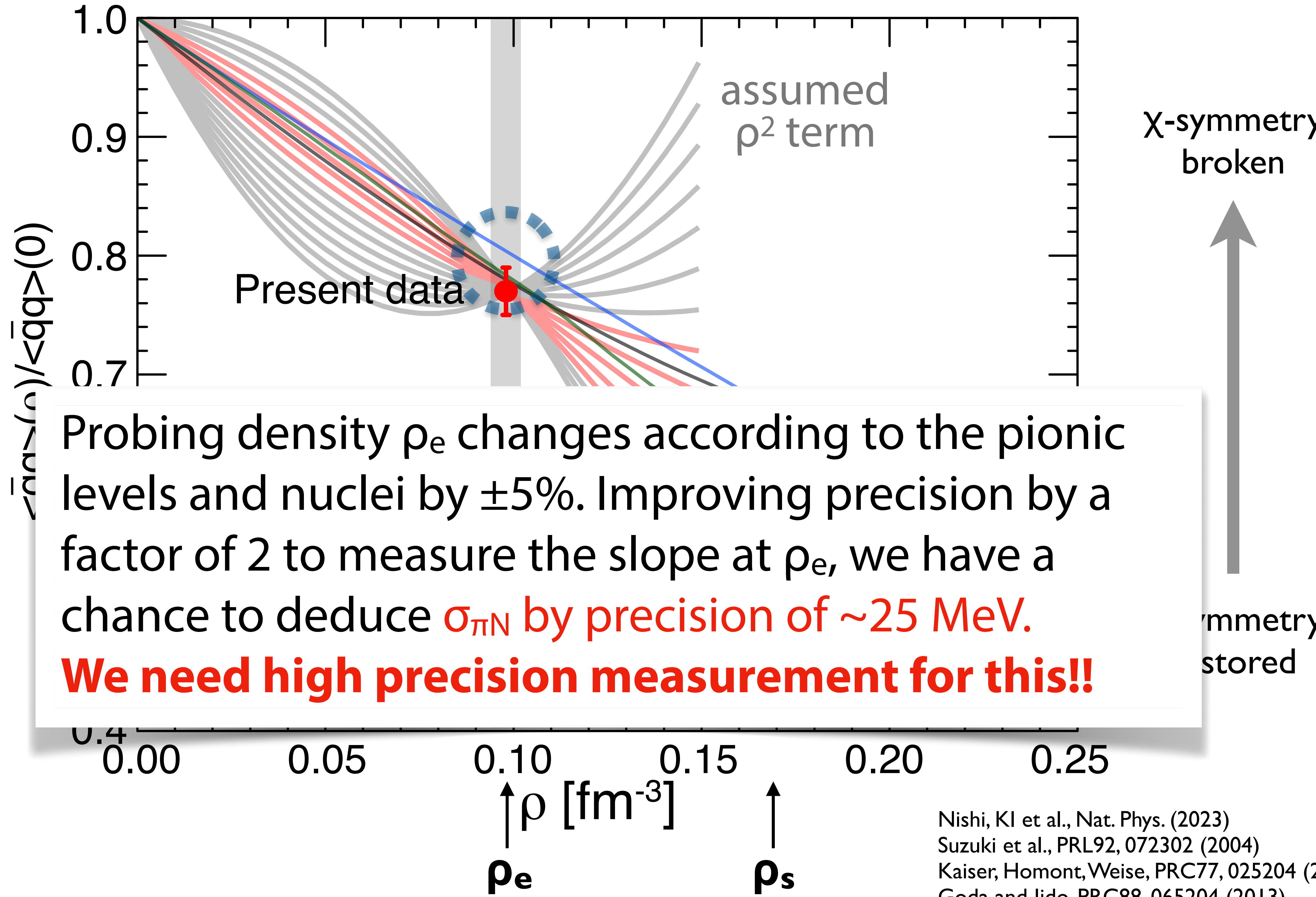
Alarcon, EPJ Spec. Top. (2021) 230:1609–1622
https://doi.org/10.1140/ep js/s11734-021-00145-6

New interest in $\sigma_{\pi N}$ term



Nishi, KI et al., Nat. Phys. (2023)
Suzuki et al., PRL92, 072302 (2004)
Kaiser, Homont, Weise, PRC77, 025204 (2008)
Goda and Jido, PRC88, 065204 (2013)
Huebsch, Jido, PRC104, 015202 (2021)
Friedman, Gal, PLB792, 340 (2019)
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)
Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (2010

New interest in $\sigma_{\pi N}$ term



Probing density ρ_e changes according to the pionic levels and nuclei by ±5%. Improving precision by a factor of 2 to measure the slope at ρ_e, we have a chance to deduce $\sigma_{\pi N}$ by precision of ~25 MeV.

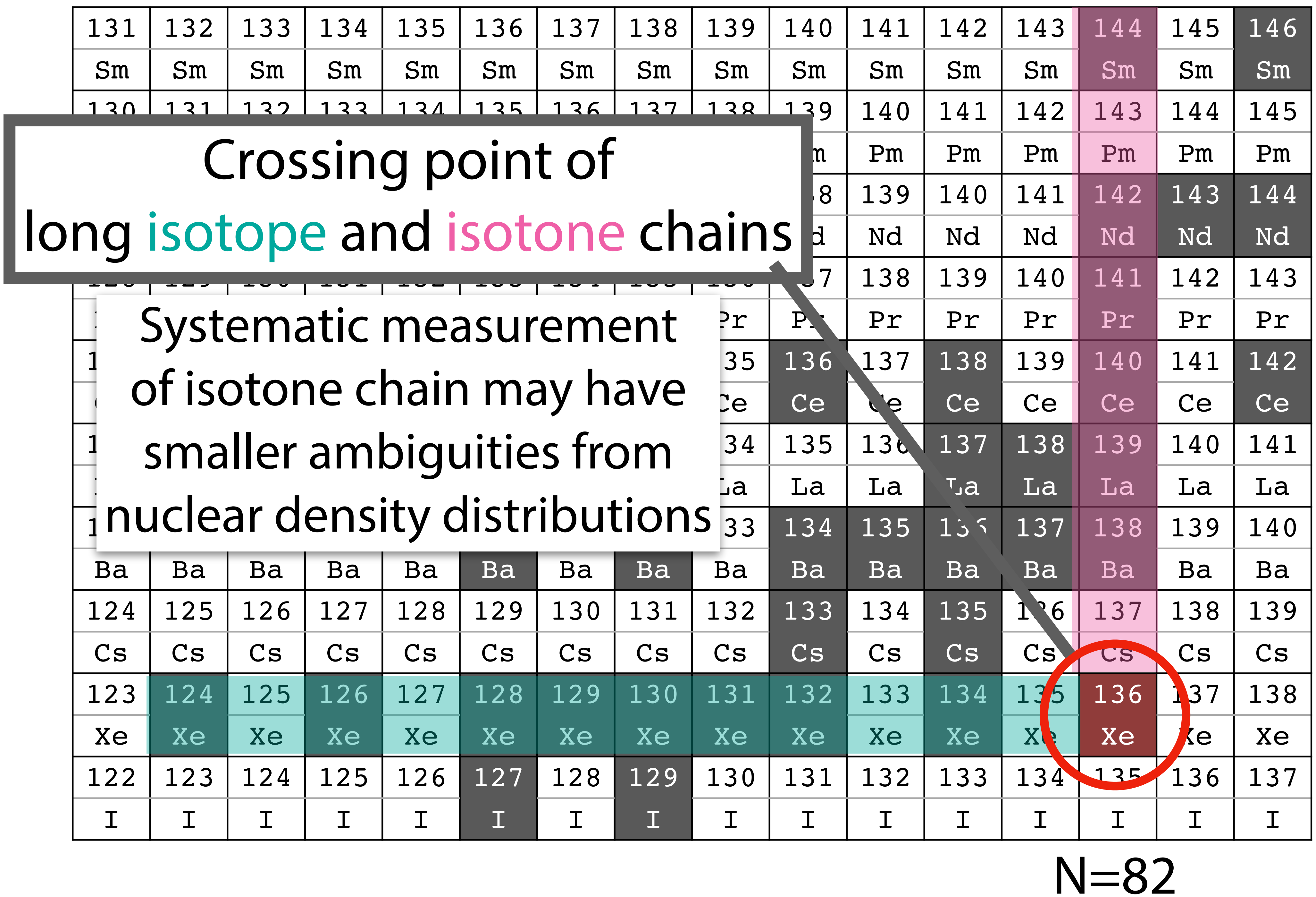
We need high precision measurement for this!!

Nishi, KI et al., Nat. Phys. (2023)
Suzuki et al., PRL92, 072302 (2004)
Kaiser, Homont, Weise, PRC77, 025204 (2008)
Goda and Jido, PRC88, 065204 (2013)
Huebsch, Jido, PRC104, 015202 (2021)
Friedman, Gal, PLB792, 340 (2019)
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)
Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (2010

Next Experiment RIBF-214

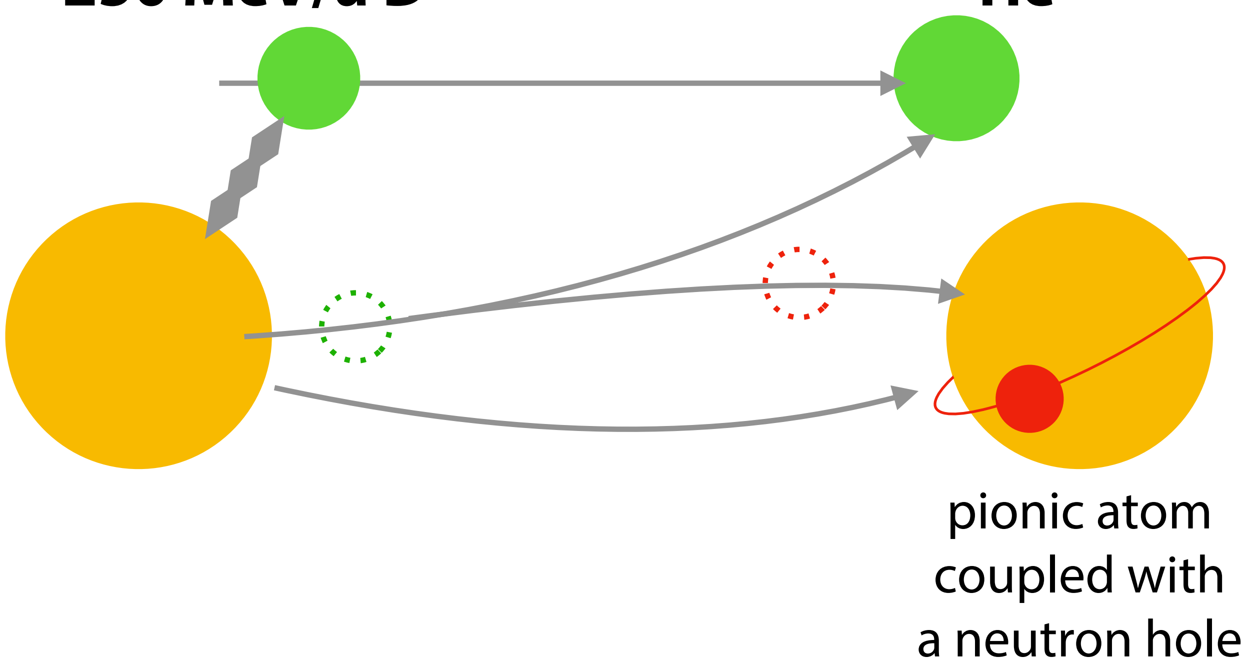
PAC approved with A

Proposing D(^{136}Xe,^{3}He) reaction at T = 250 MeV/u at RIBF



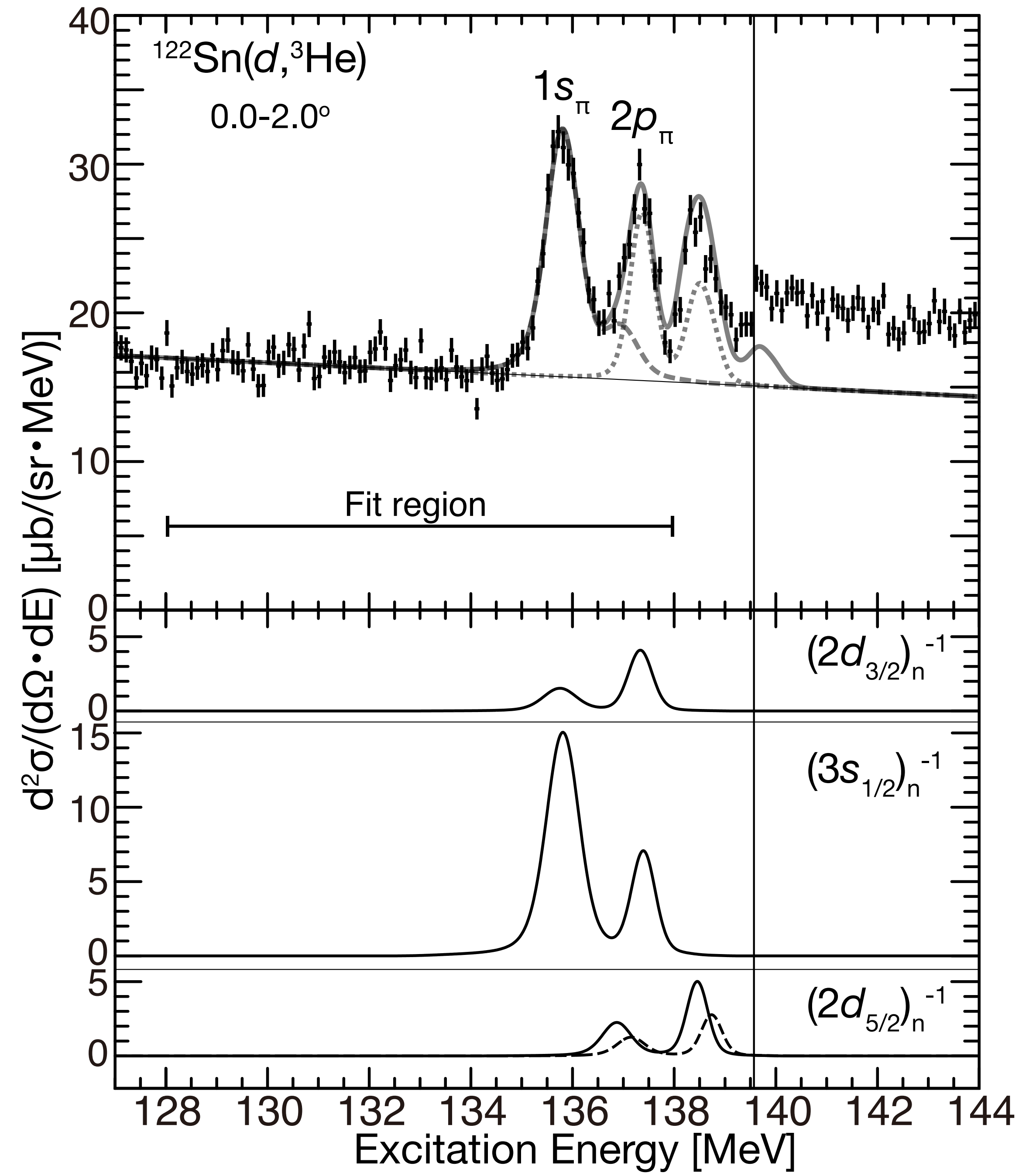
First application of inverse kinematics reactions

Normal kinematics $(d,^3He)$ reactions



We measure ^3He energy for missing-mass and deduce mass of reaction product

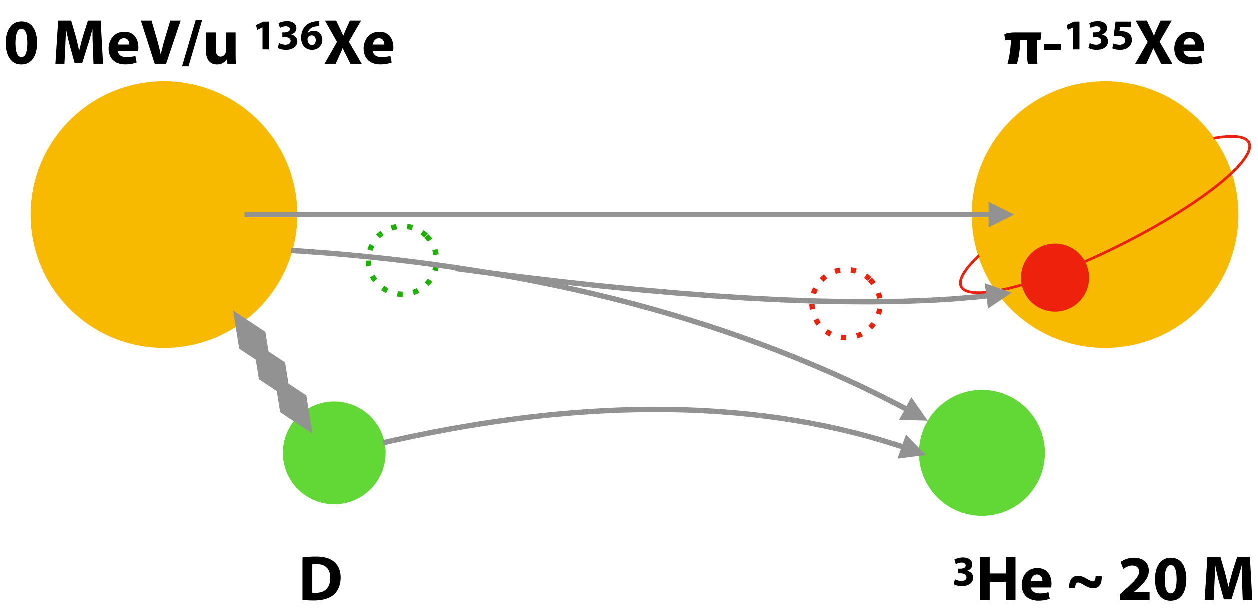
RIBF-27



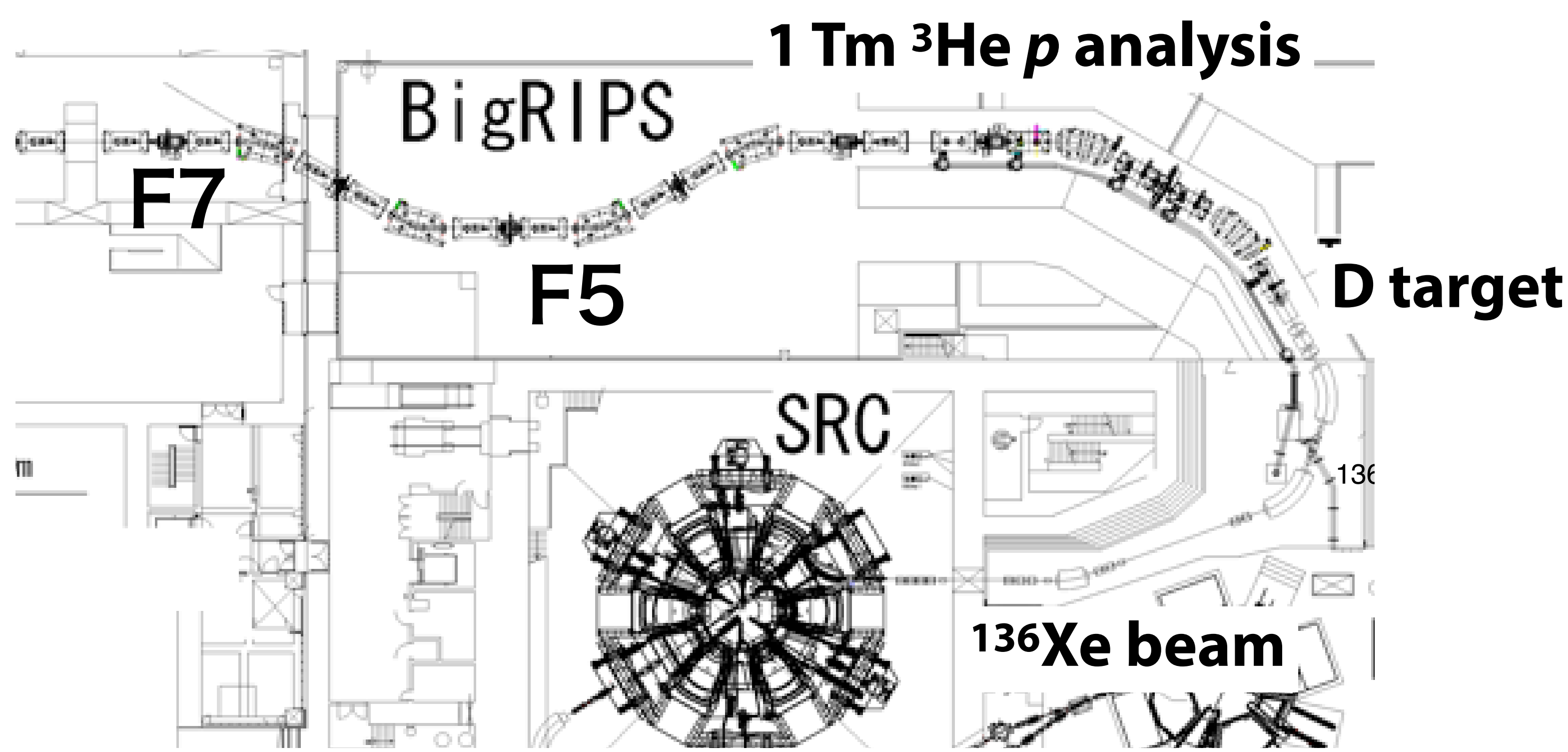
T. Nishi et al., PRL **120**, 152505 (2018)

First application of

inverse kinematics reactions



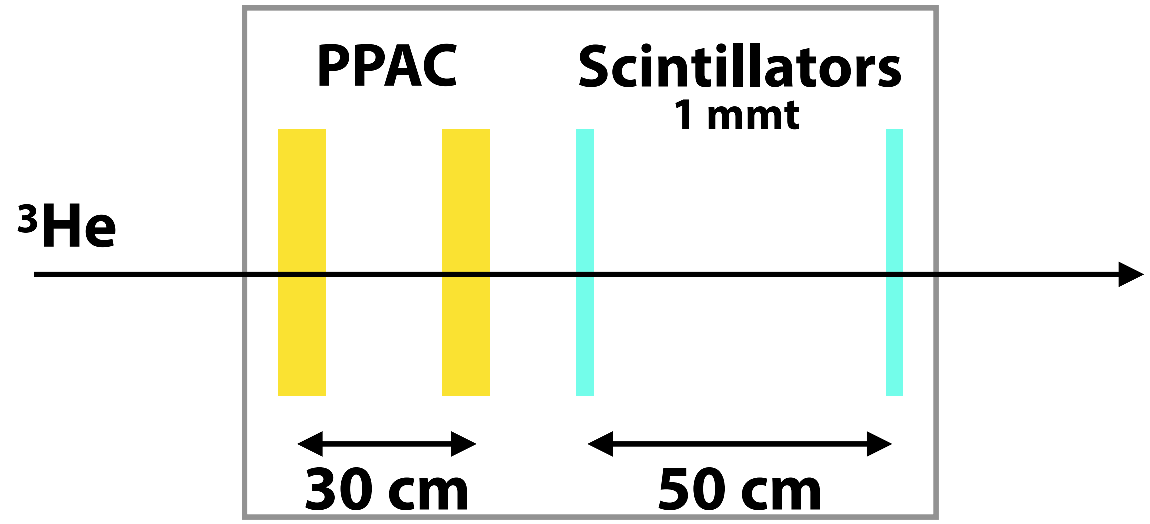
We make use of BigRIPS as spectrometer and deduce MM by ^{3}He momentum measurement

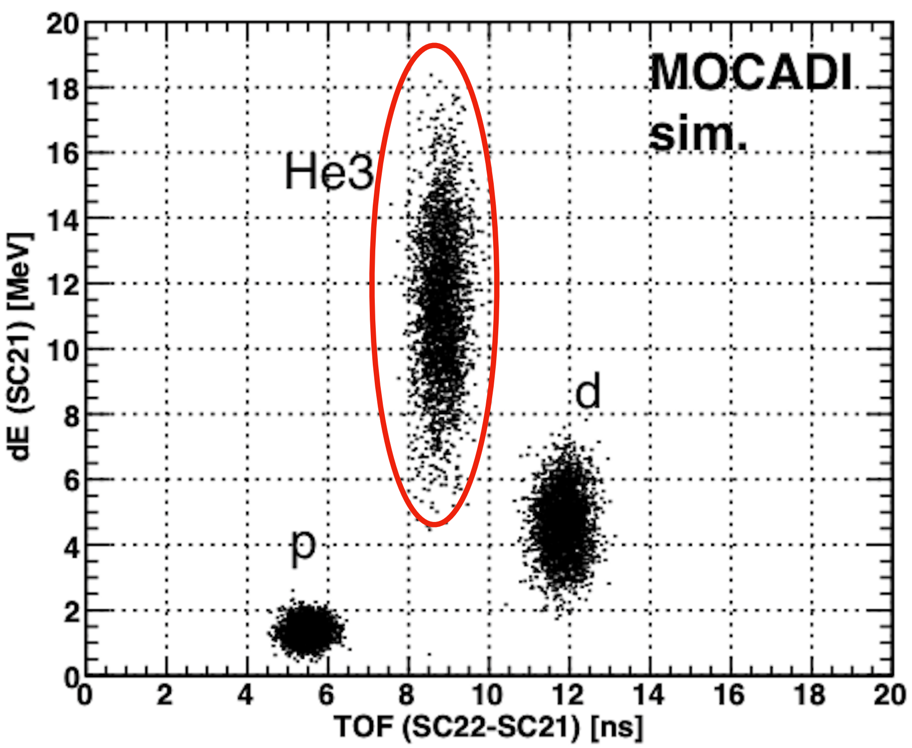


Experimental setup

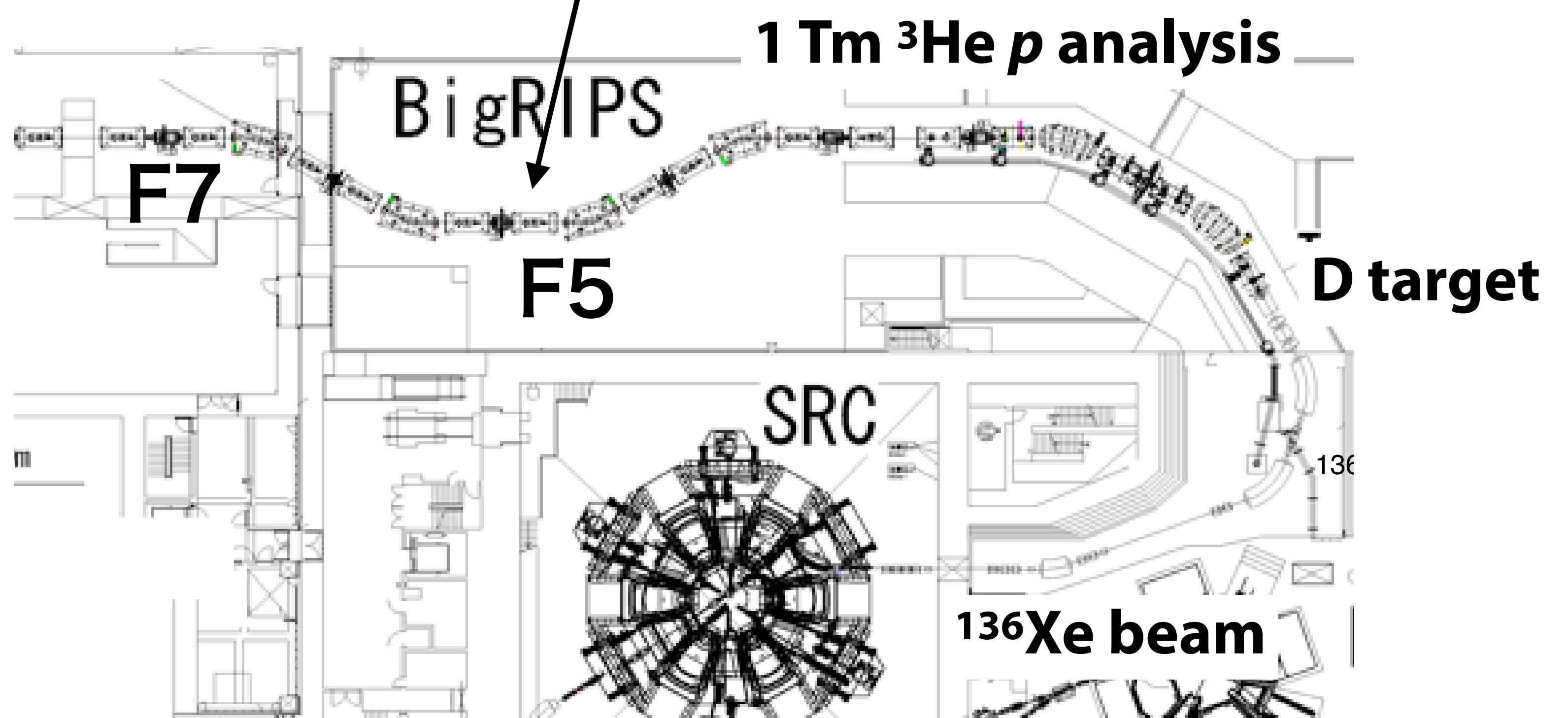
PPAC

F5





^{3}He trigger by ΔE (and TOF)

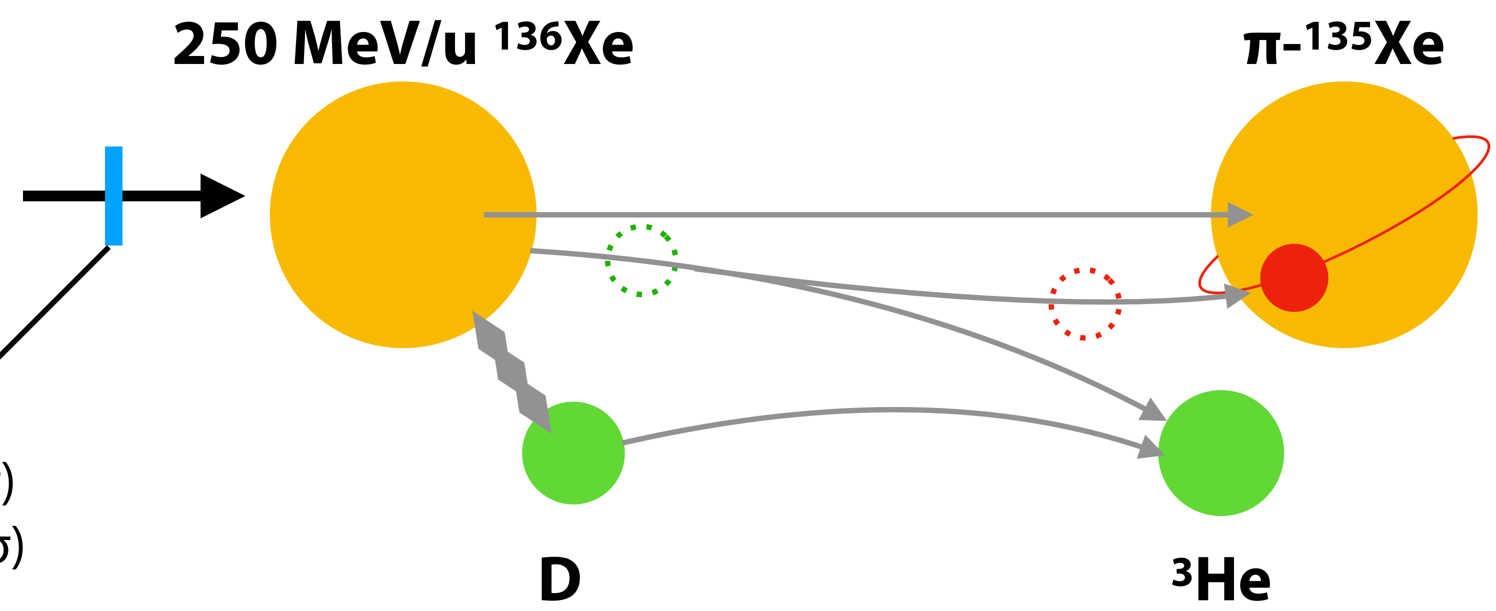


Experimental setup

NP2212-RIBF214

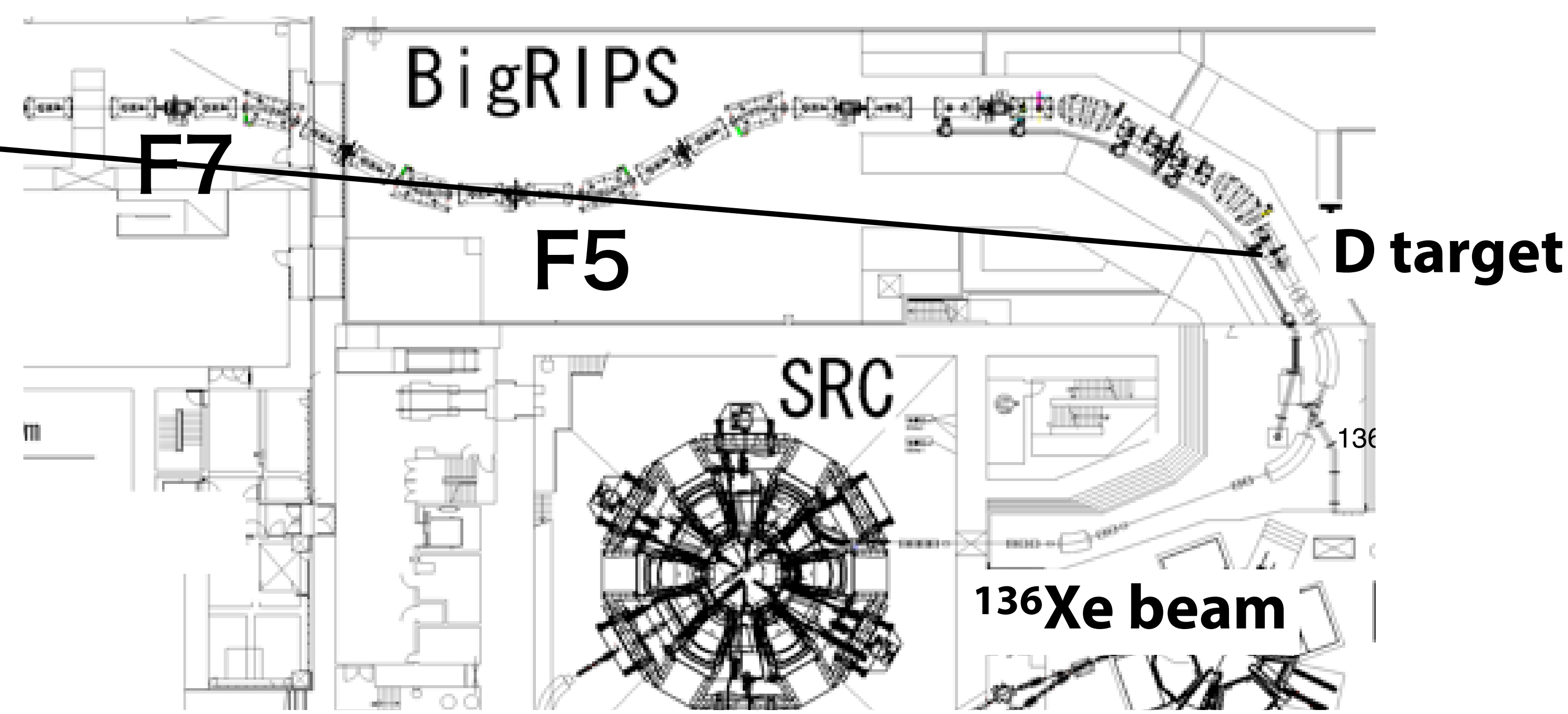
345 MeV/u ^{136}Xe beam
(RRC-fRC-IRC-SRC)

Be degrader 8.14 mm
Energy straggling = 0.2 MeV/u (σ)
Angular straggling = 1.15 mrad (σ)
Charge state stays by 92.5%



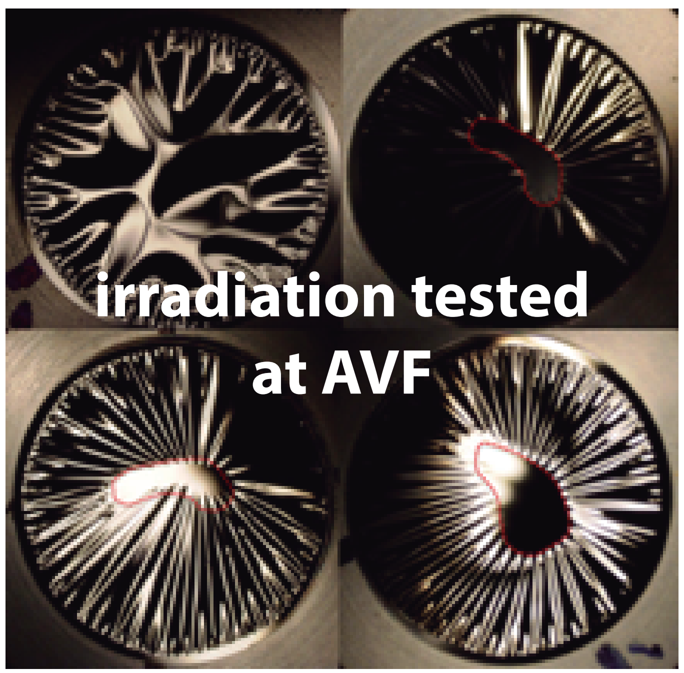
BigRIPS as spectrometer to measure ~1 Tm ^{3}He momentum

1-atm deuterium gas target at F0 with **thin membrane** windows



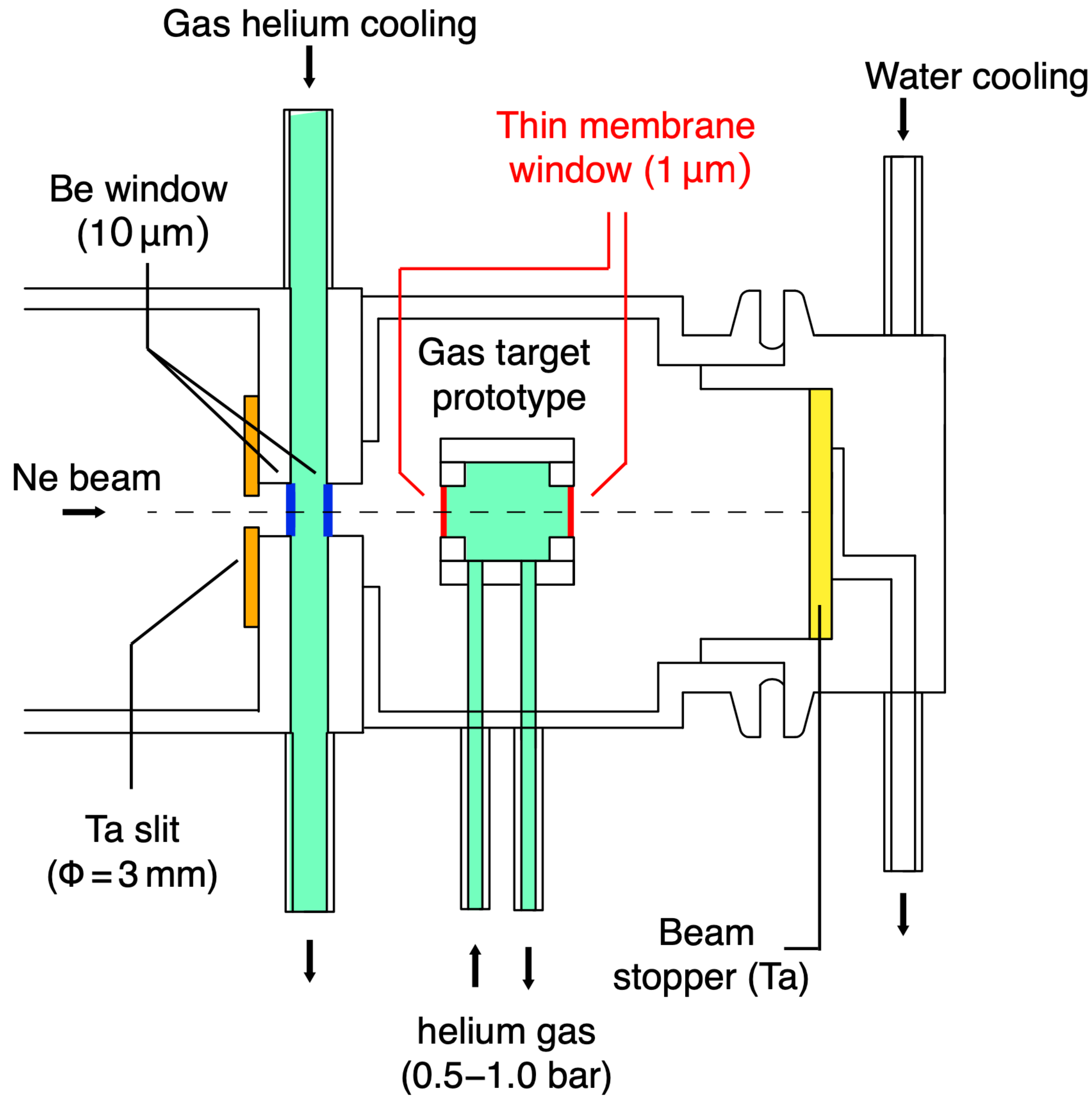
Deuterium gas target development

1 μm graphene foil
tested till breakdown
with 5 MeV Ne beam (2018)

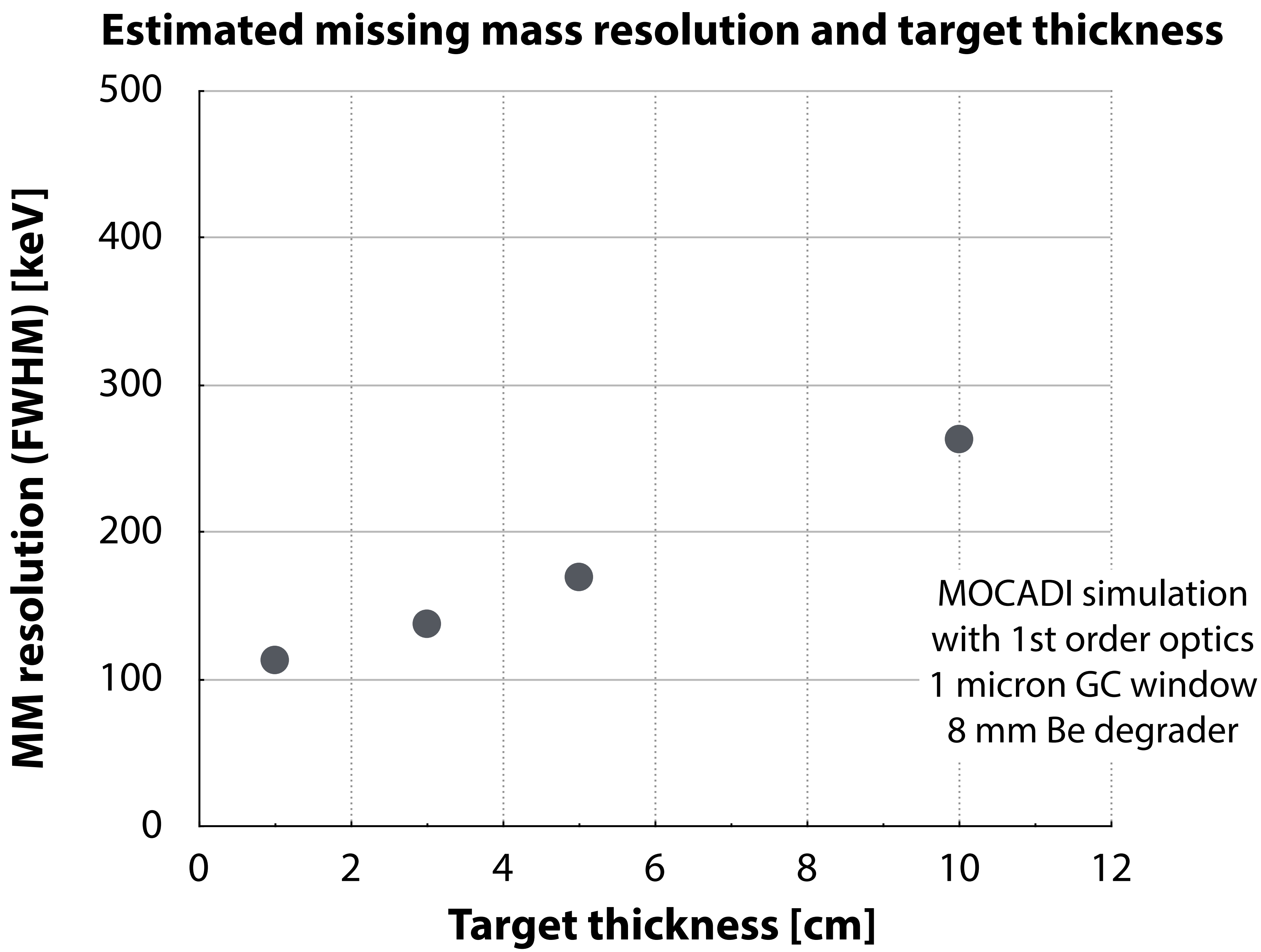


S. Purushothaman et al., APR **53**, 134 (2019)

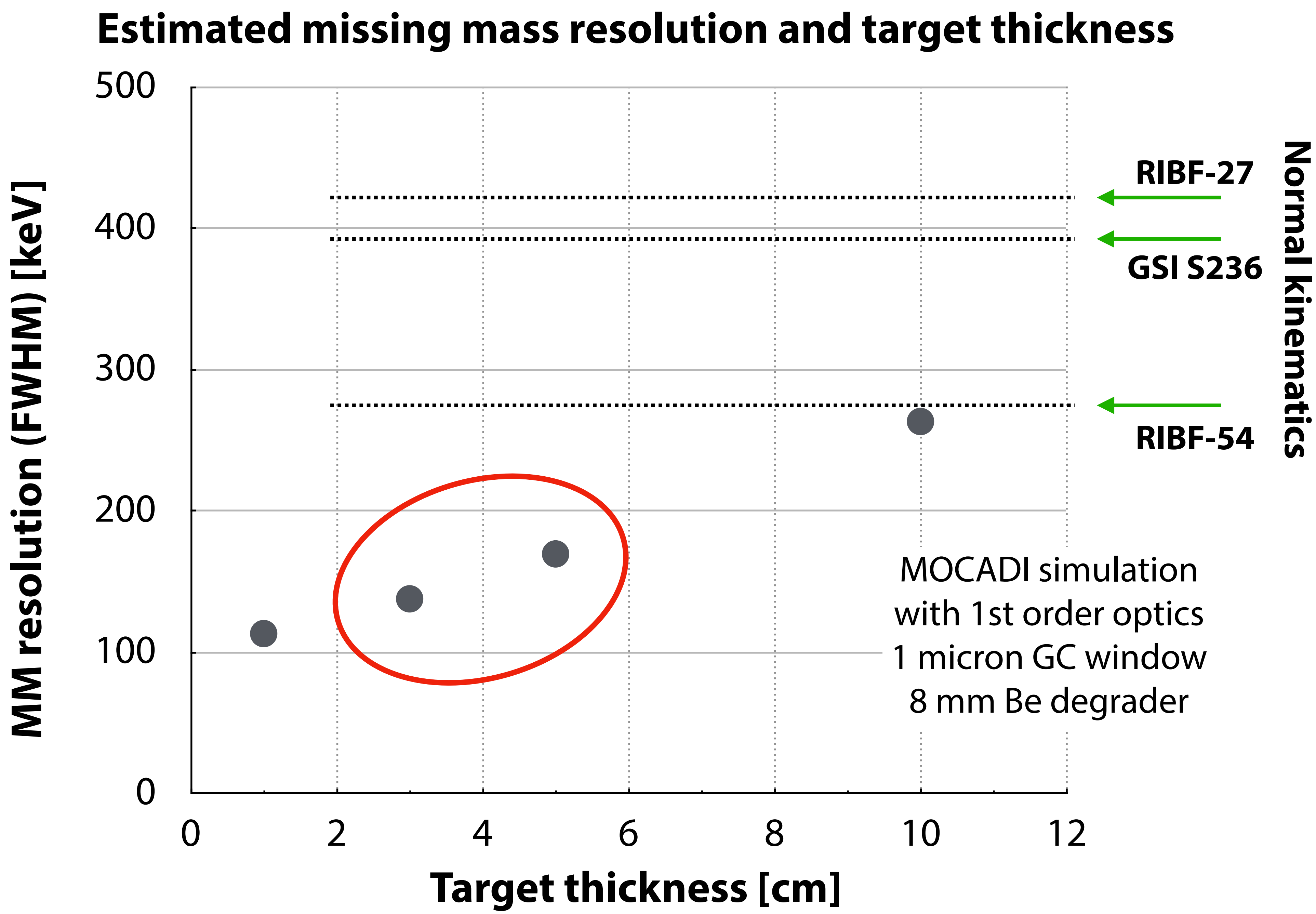
Beam test in 2024/4-5
to hold 0.5-1 atm He



Missing mass resolution



Missing mass resolution can be improved!

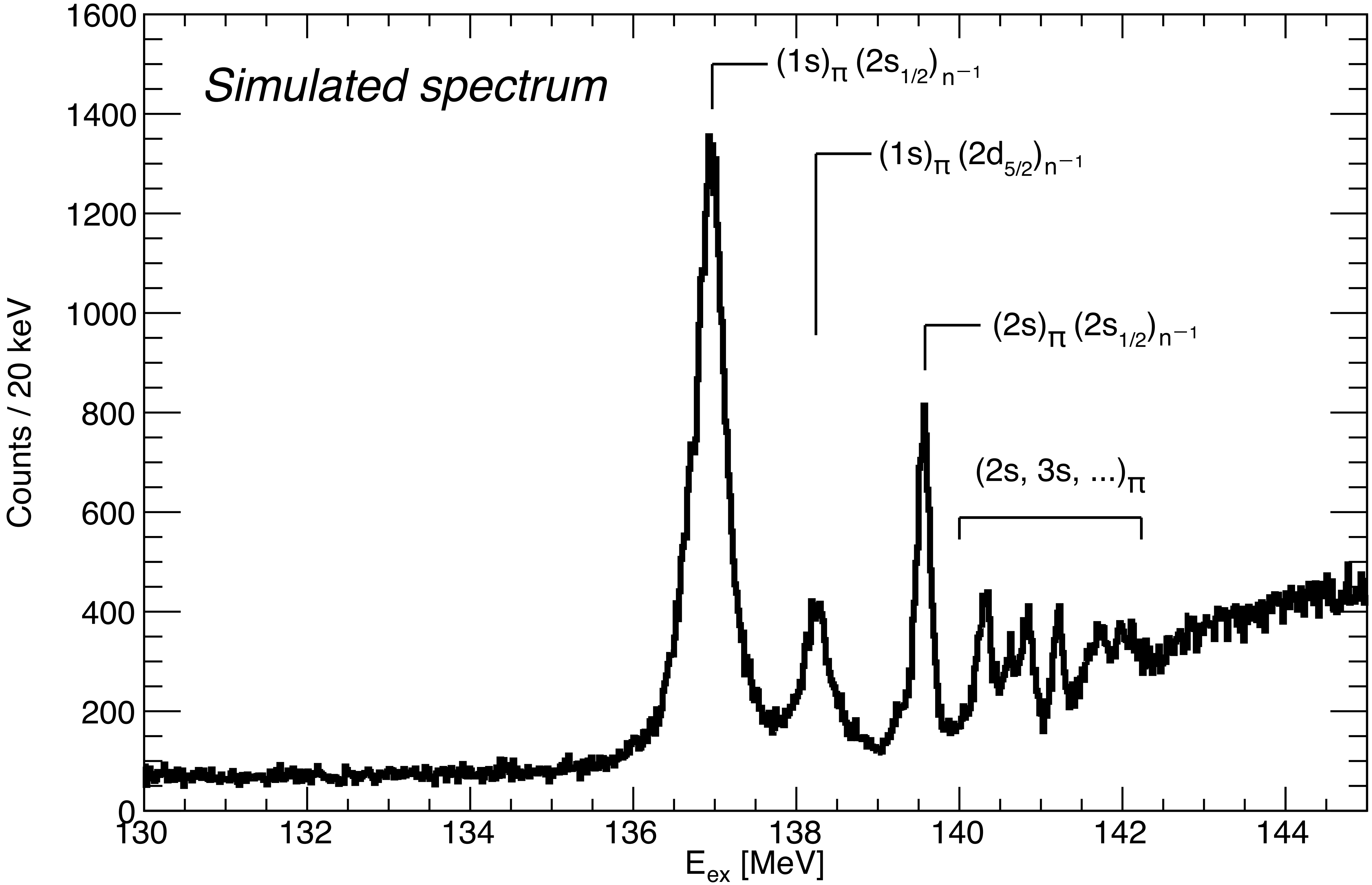


Unprecedented resolution can be achieved
→ Important for resolving higher orbitals and determine the widths

cf. For normal kinematics, resolution has been limited by beam properties.

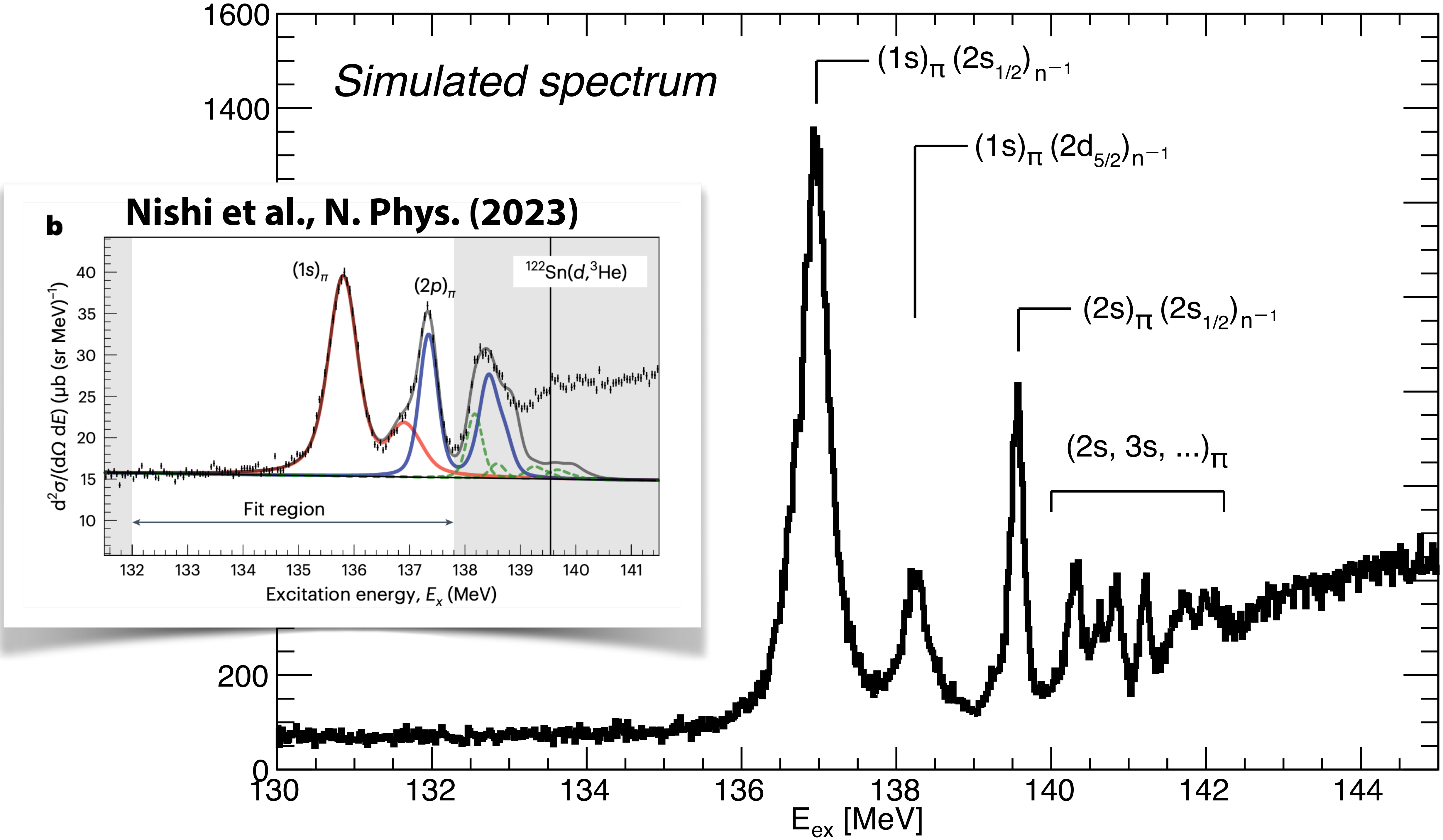
Striking spectrum with 150 keV resolution

36 hours with 10^{10}/s ^{136}Xe beam 4 cm target



Striking spectrum with 150 keV resolution

36 hours with 10^{10}/s ^{136}Xe beam 4 cm target



Summary

- Chiral condensate at ρ_e is evaluated to be reduced by 77±2%, which is linearly extrapolated to 60±3% at the nuclear saturation density.
- The binding energies and widths of the pionic 1*s* and 2*p* states in Sn121 were determined with high precision. Taking difference between the 1*s* and 2*p* values drastically reduces the systematic errors.
- Recent theoretical progress was adopted to the <qq> deduction, which directly relates the chiral condensate and the pion-nucleus interaction.
- We calculated various corrections for the first time and applied them. The corrections made substantial effects. After the corrections, the chiral condensate ratio was deduced with much higher reliability.
- For future, we are analyzing data of systematic study of pionic Sn isotopes to achieve higher precision <qq>.
- We also plan measurement in “inverse kinematics” reactions for pionic Xe 136. The resolution will be further improved. Now, we are aiming at determination of the πN σ term.