π中間子原子精密分光による原子核中のカイラル凝縮定量評価

Quantitative evaluation of chiral condensate in nuclear medium via precision spectroscopy of pionic atoms

RIKEN Nishina Center

Kenta Itahashi

for piAF collaboration

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nature physics

T. Nishi, K.I. *et al.*

Article

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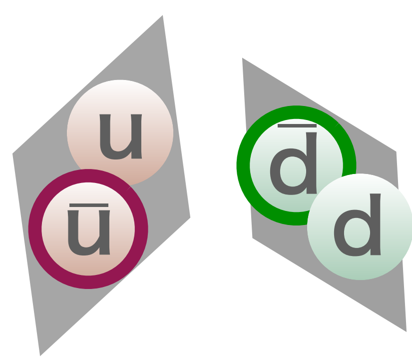
Chiral symmetry restoration at high matter density observed in pionic atoms

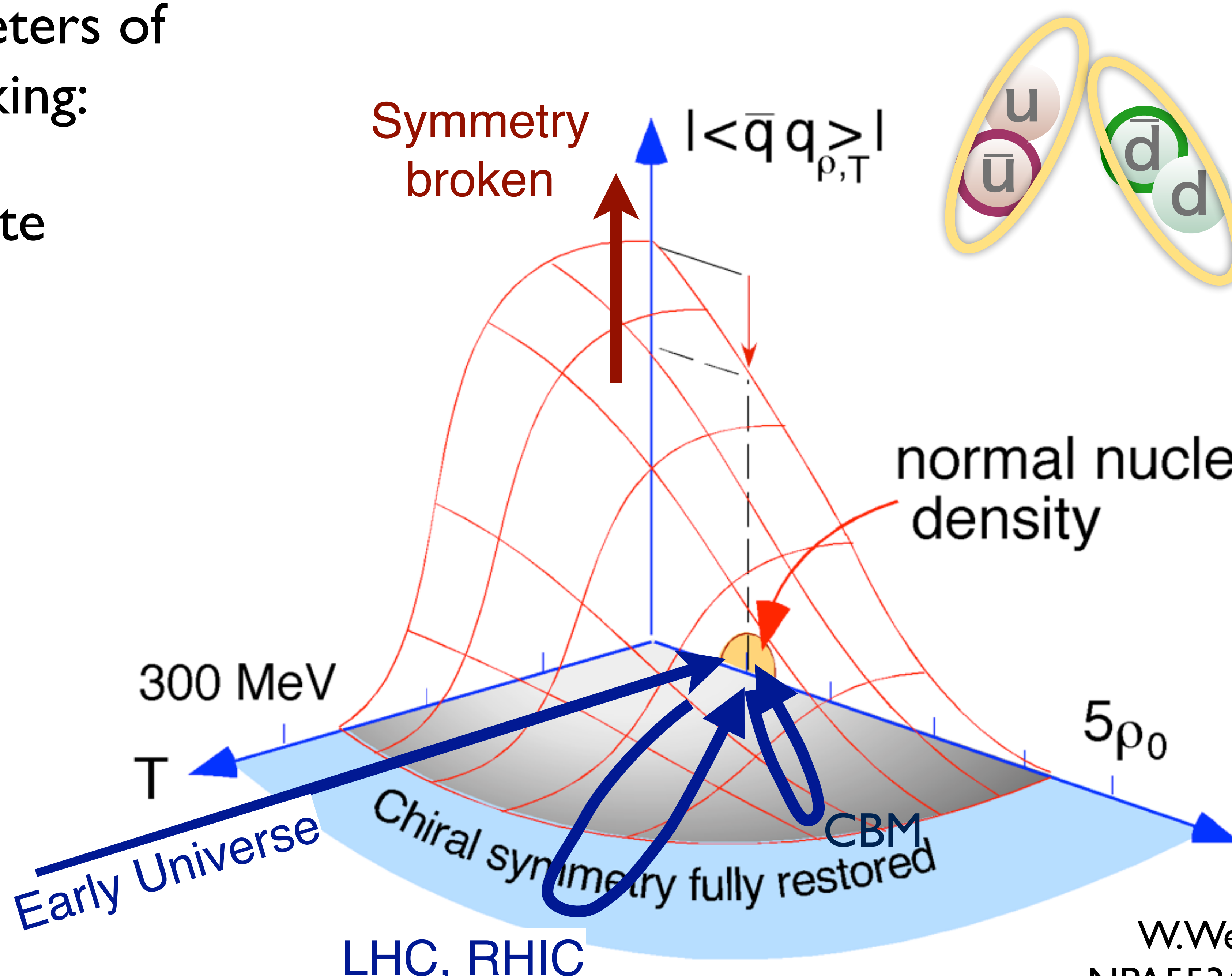
Nature Physics 19, 788-793(2023)
DOI: 10.1038/s41567-023-02001-x

Chiral condensate, order parameter of chiral symmetry

One of order parameters of
χ-symmetry breaking:

Chiral condensate

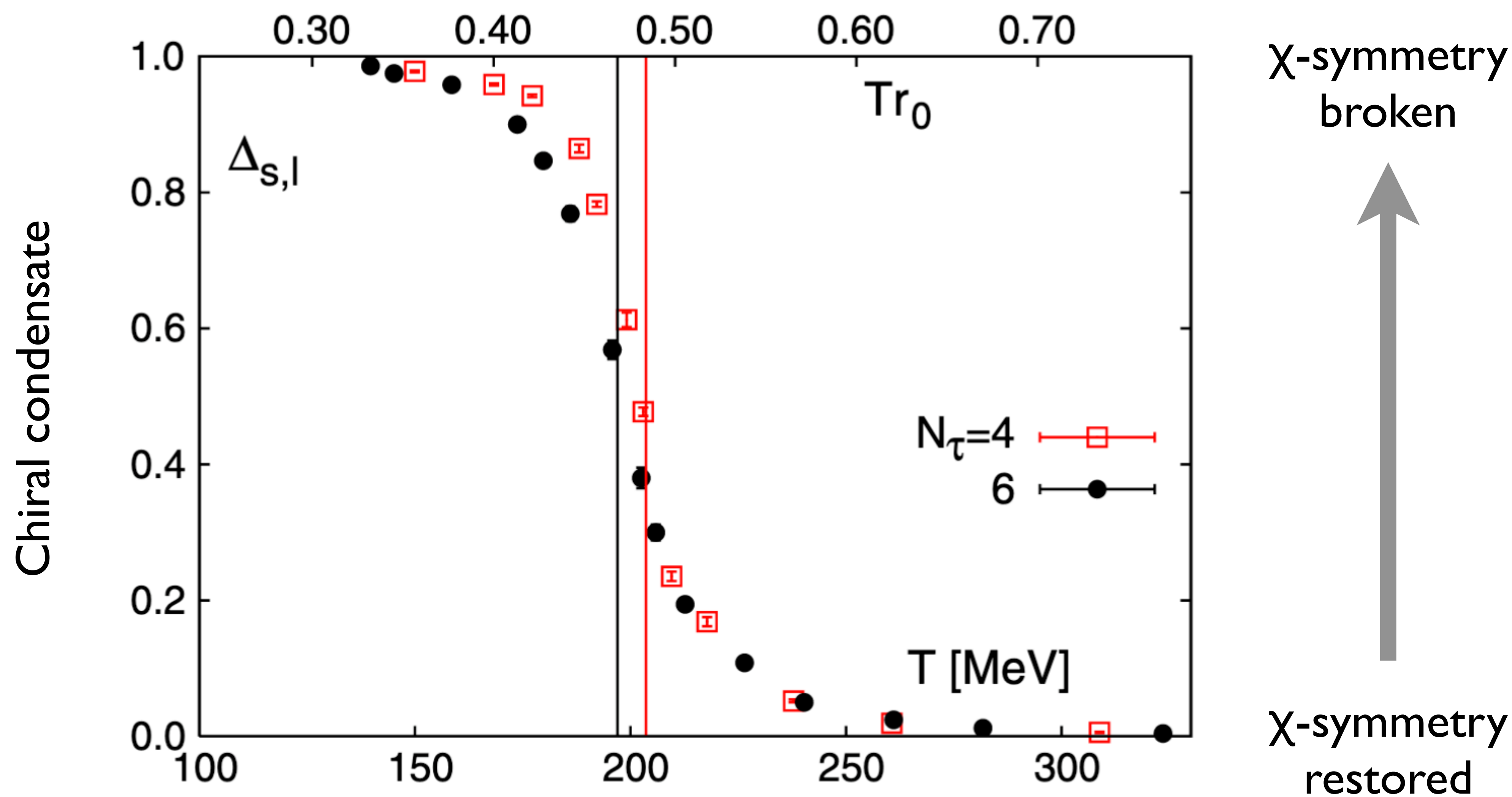




W.Weise,
NPA553(93)59.

Analysis of material properties
of QCD vacuum

Lattice QCD calculated T dependence of chiral condensate

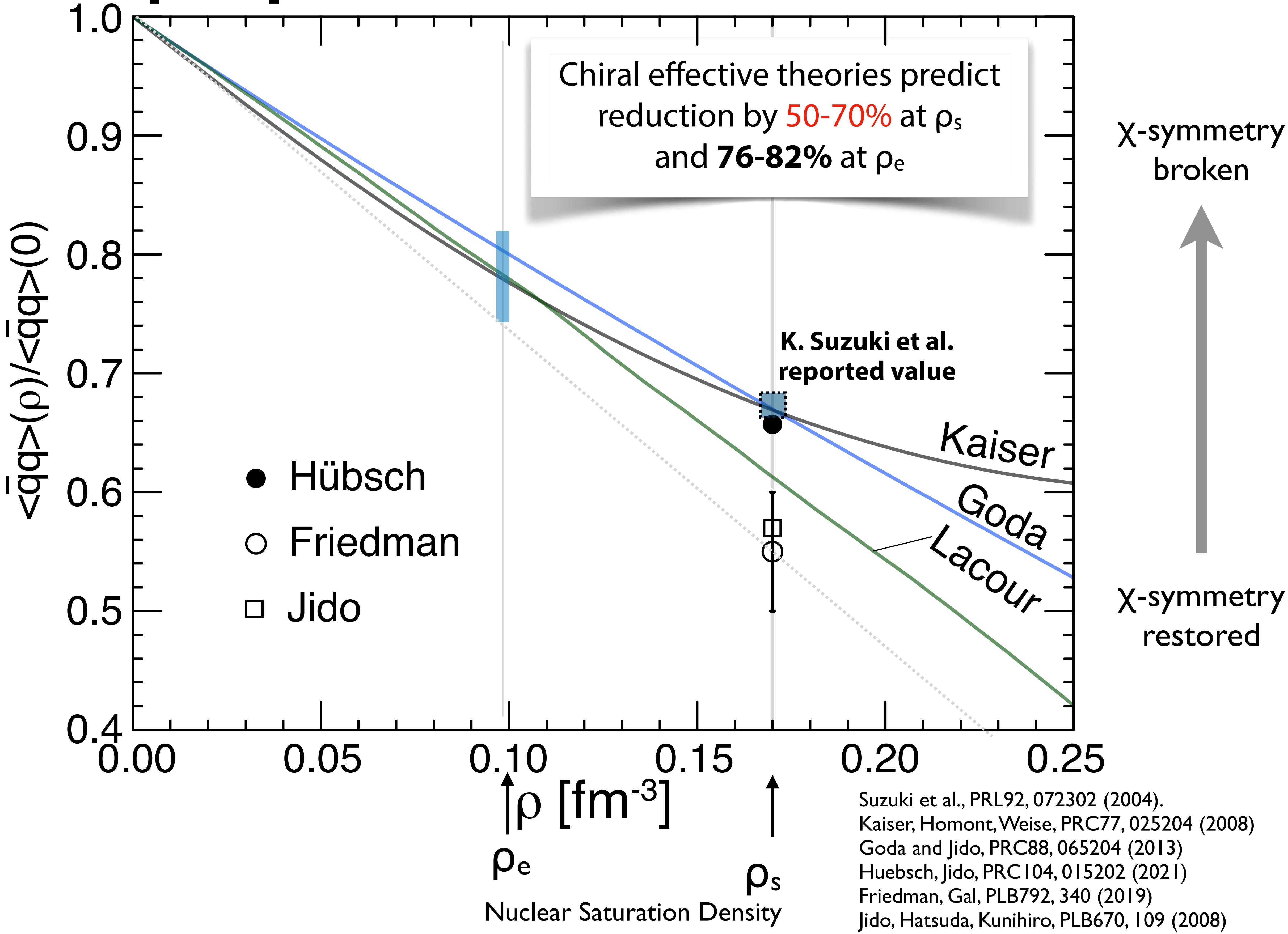


Temperature dependence of the chiral condensate from lattice QCD with 2 + 1 quark flavours and almost physical quark masses

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

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

ρ dependence of chiral condensate



Suzuki et al., PRL92, 072302 (2004).
Kaiser, Homont, Weise, PRC77, 025204 (2008)
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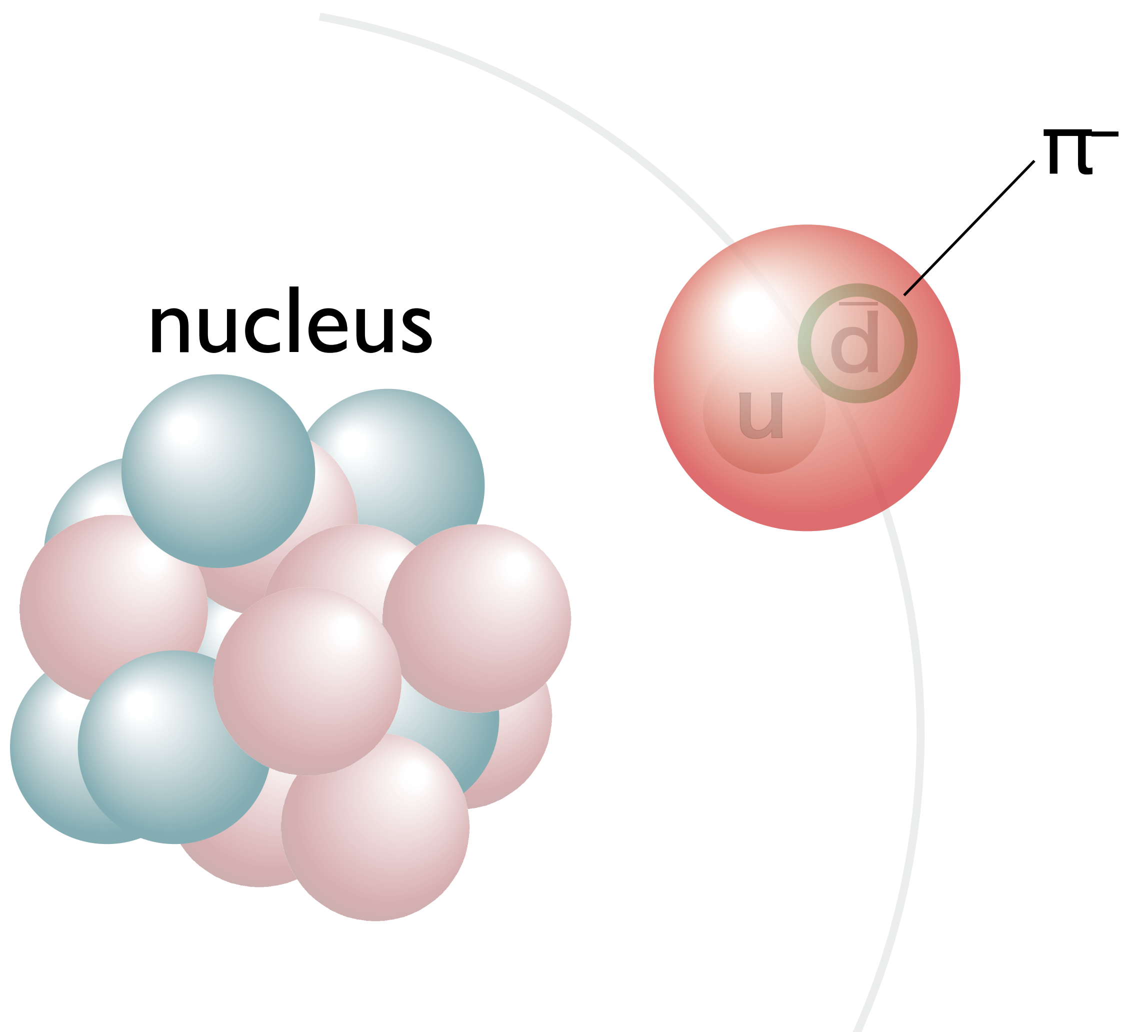
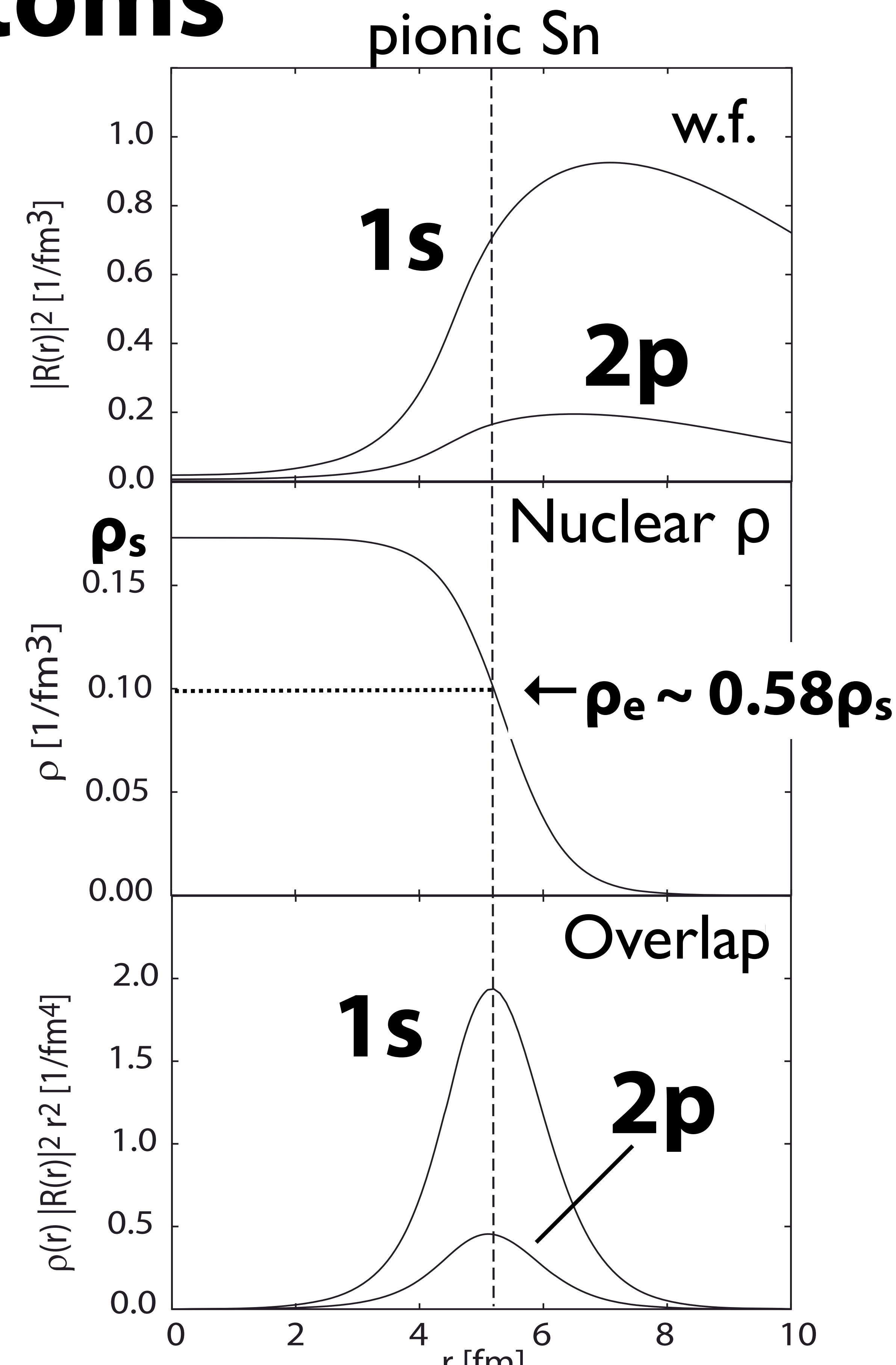
Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (2010)

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 $\rho_e \sim 0.58\rho_s$

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

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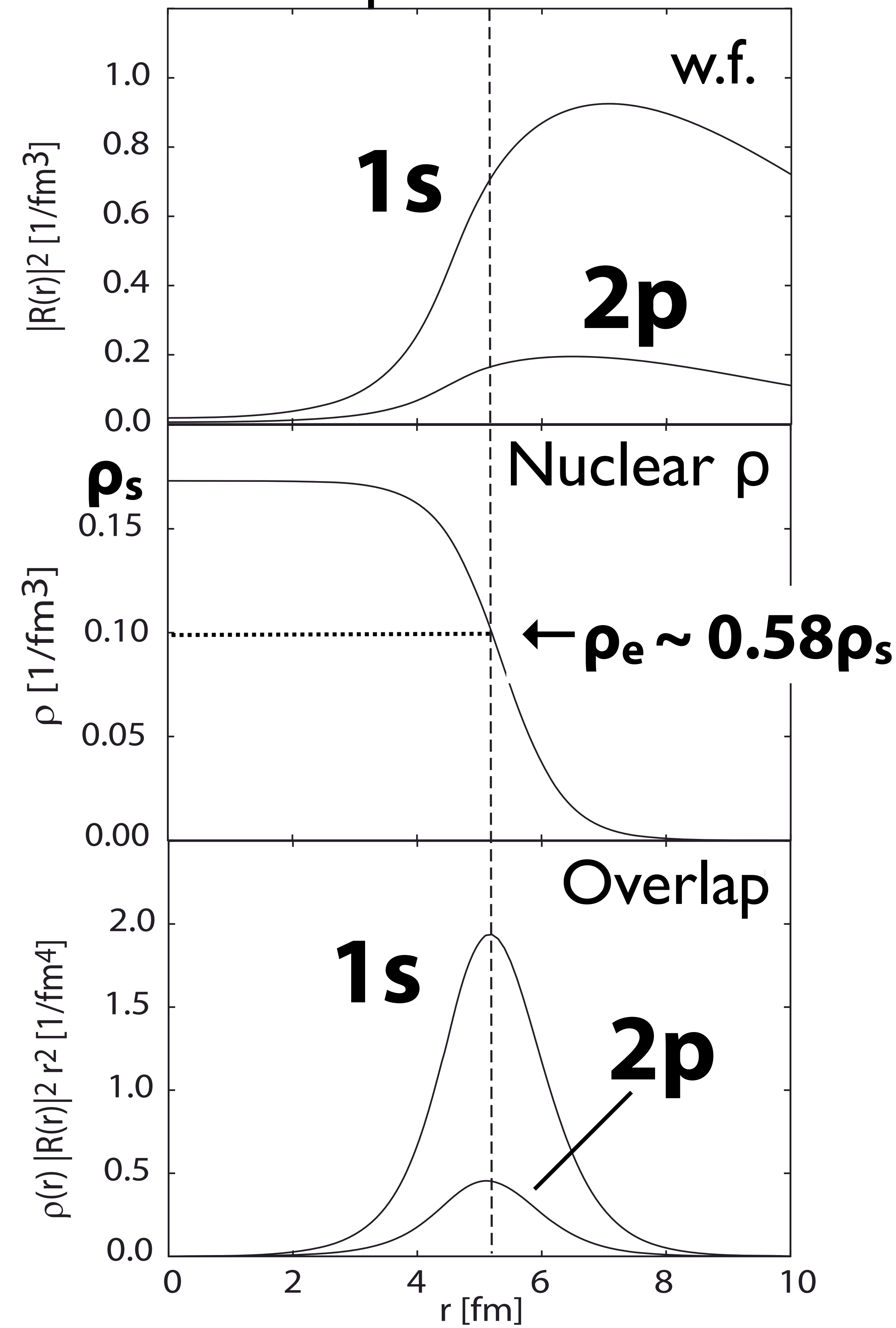

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In-medium Glashow-Weinberg relation

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

$\gamma = 0.184 \pm 0.003$

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

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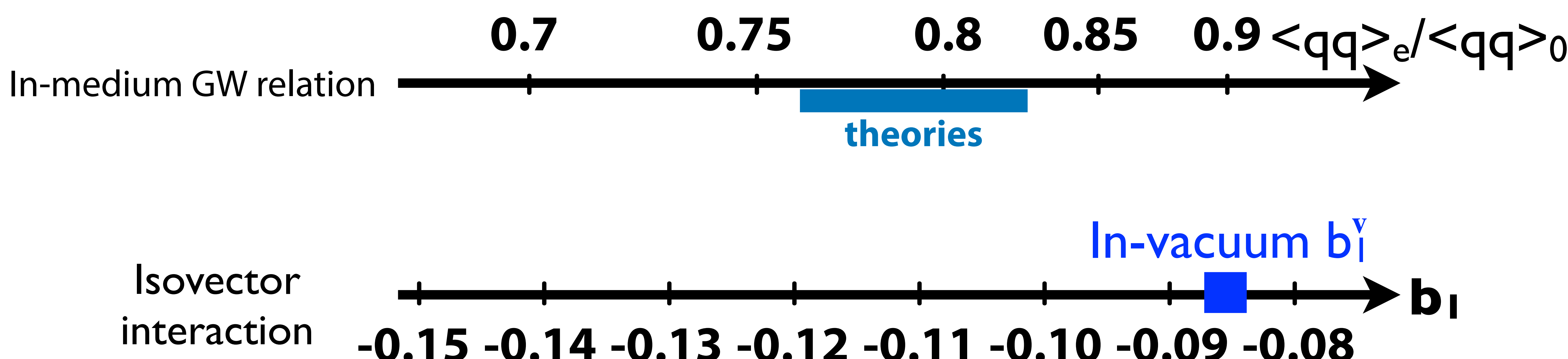
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)

Pionic hydrogen and deuterium

$b_1^{\mathrm{v}} = 0.0866 \pm 0.0010$

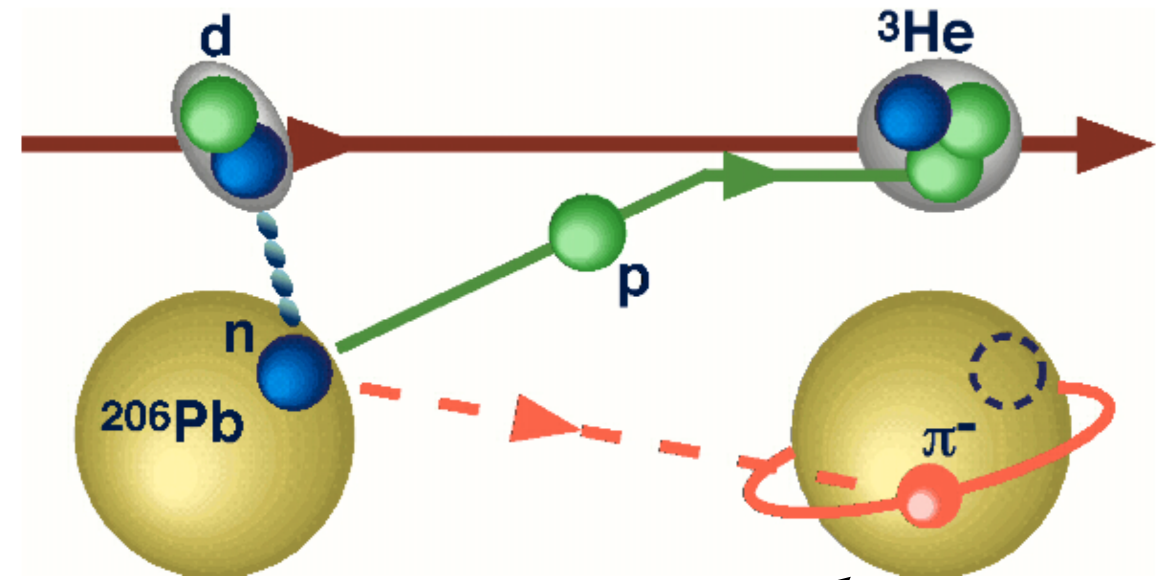
Hirtl et al., EPJA57, 70 (2021)



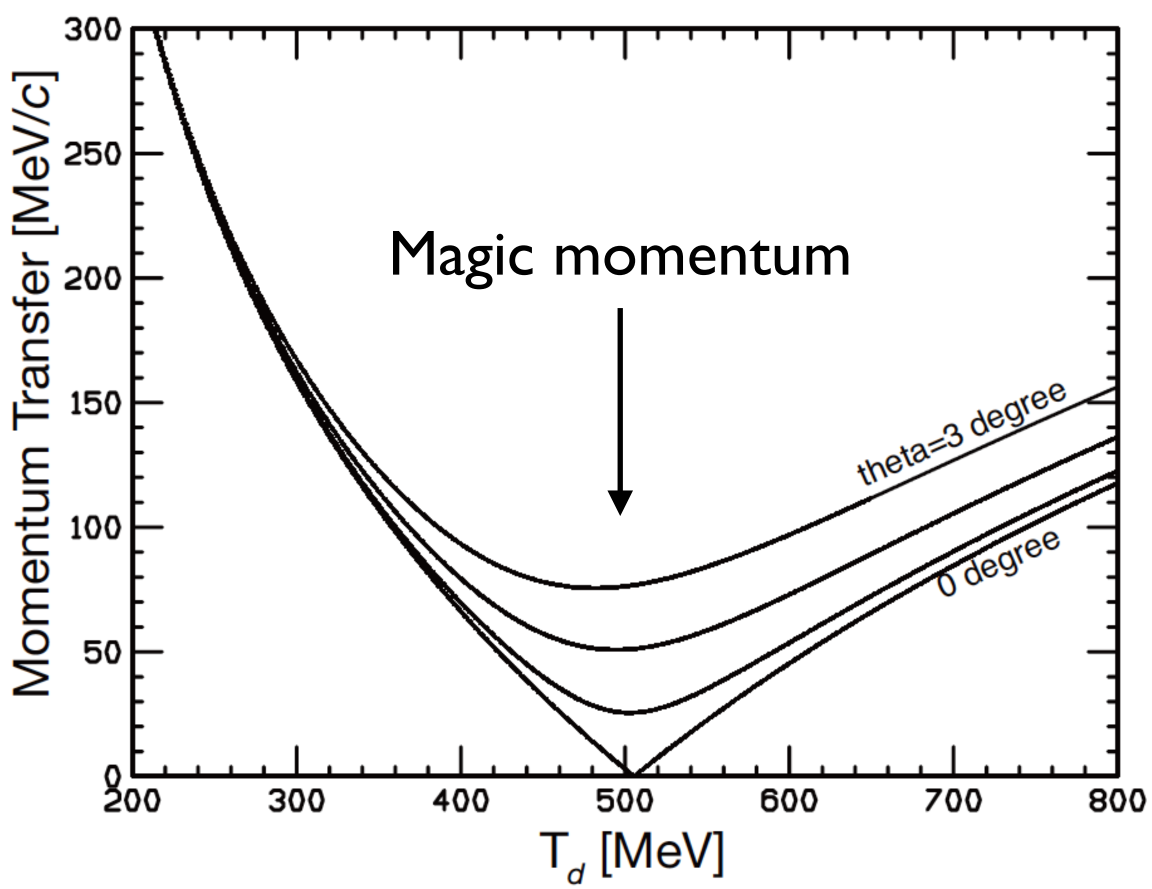
Spectroscopy of pionic atoms in (*d*,^{3}He) reactions

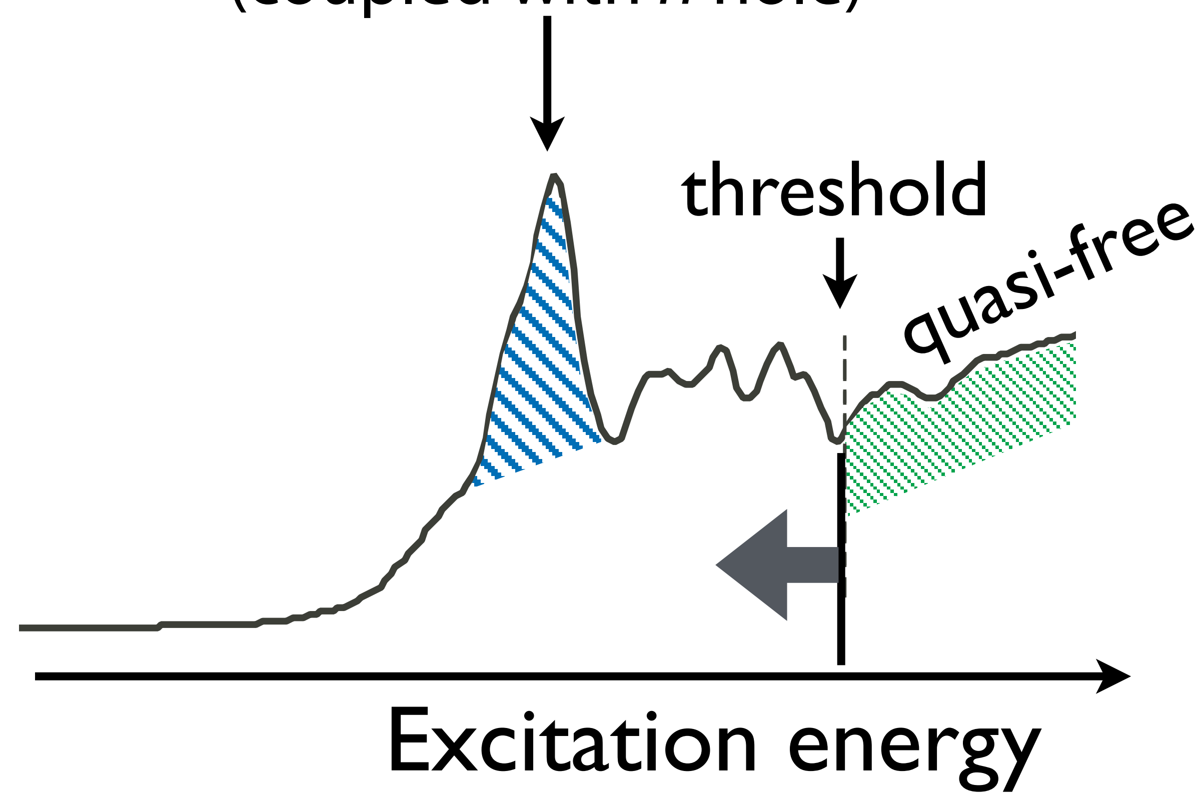
Missing mass spectroscopy to measure excitation spectrum of pionic atoms

Direct production of pionic atoms

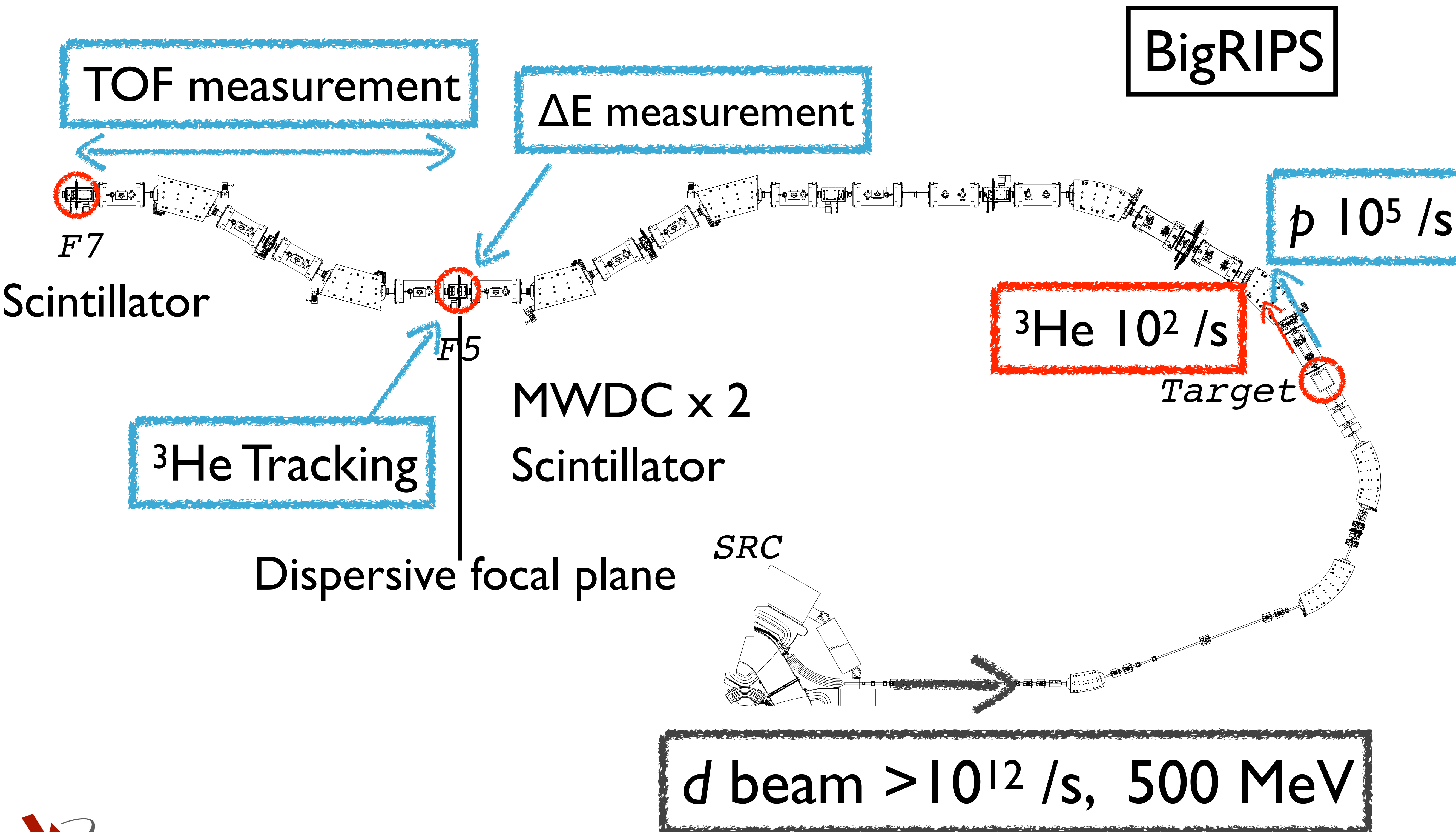


Momentum transfer





(d,^{3}He) Reaction Spectroscopy in RIBF



Kenta Itahashi, RIKEN

Pionic ^{121}Sn atom

Pilot run

15 hours DAQ in 2010

First simultaneous 1s and 2p observation

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

Resolution 394 keV (FWHM)

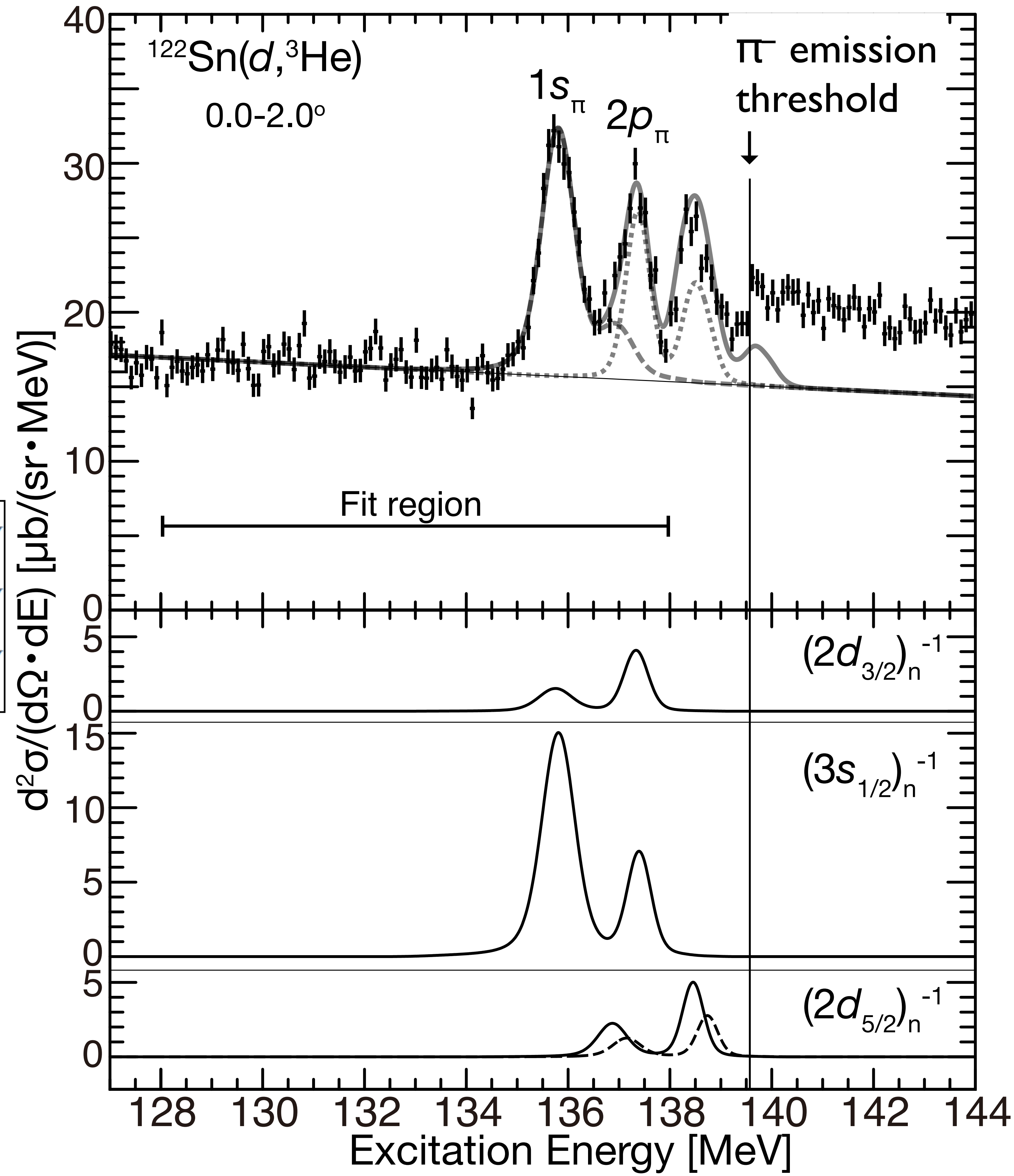
Theories

B_{1s}= 3.787–3.850 MeV

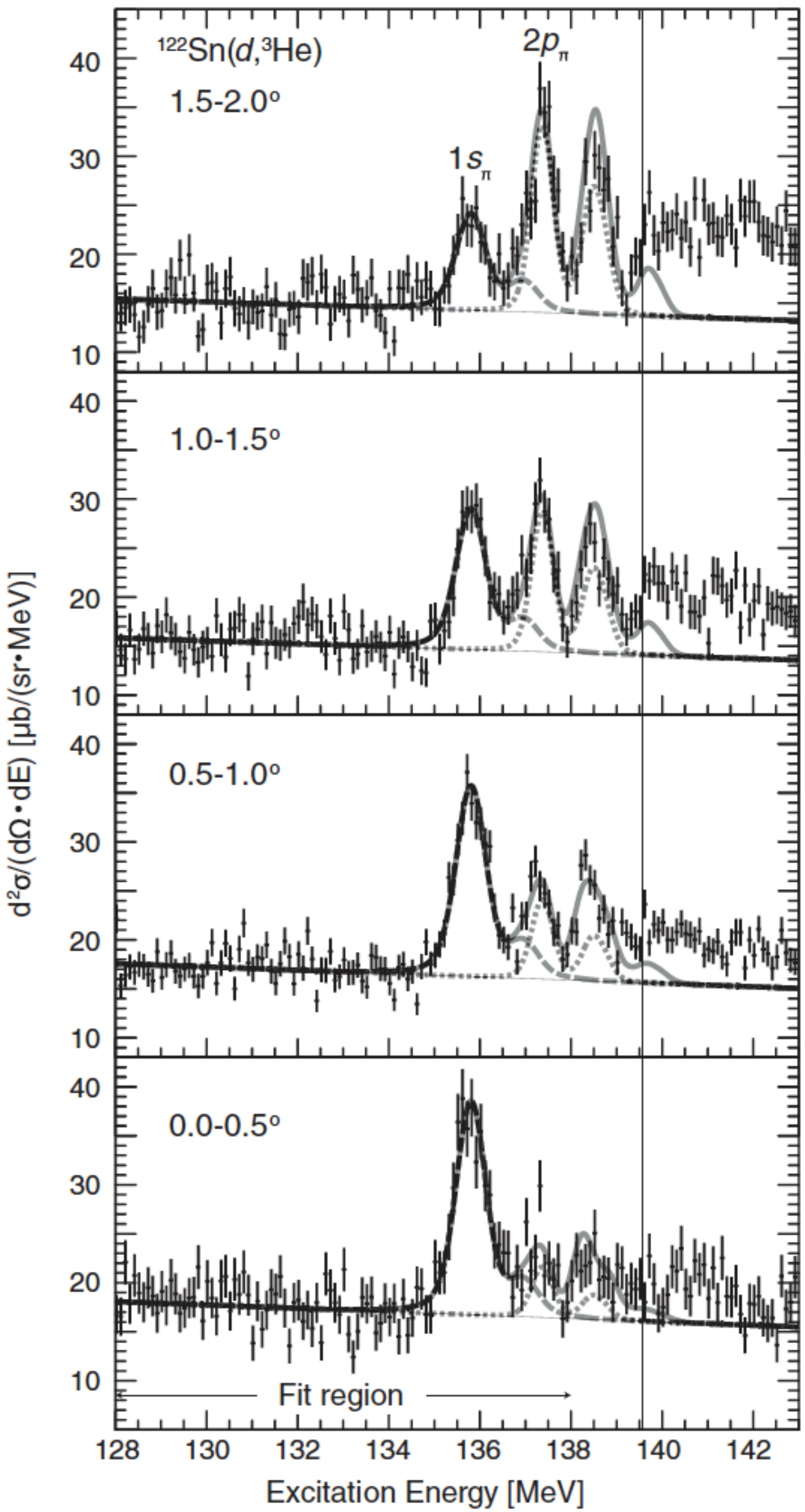
Γ_{1s}= 0.306–0.324 MeV

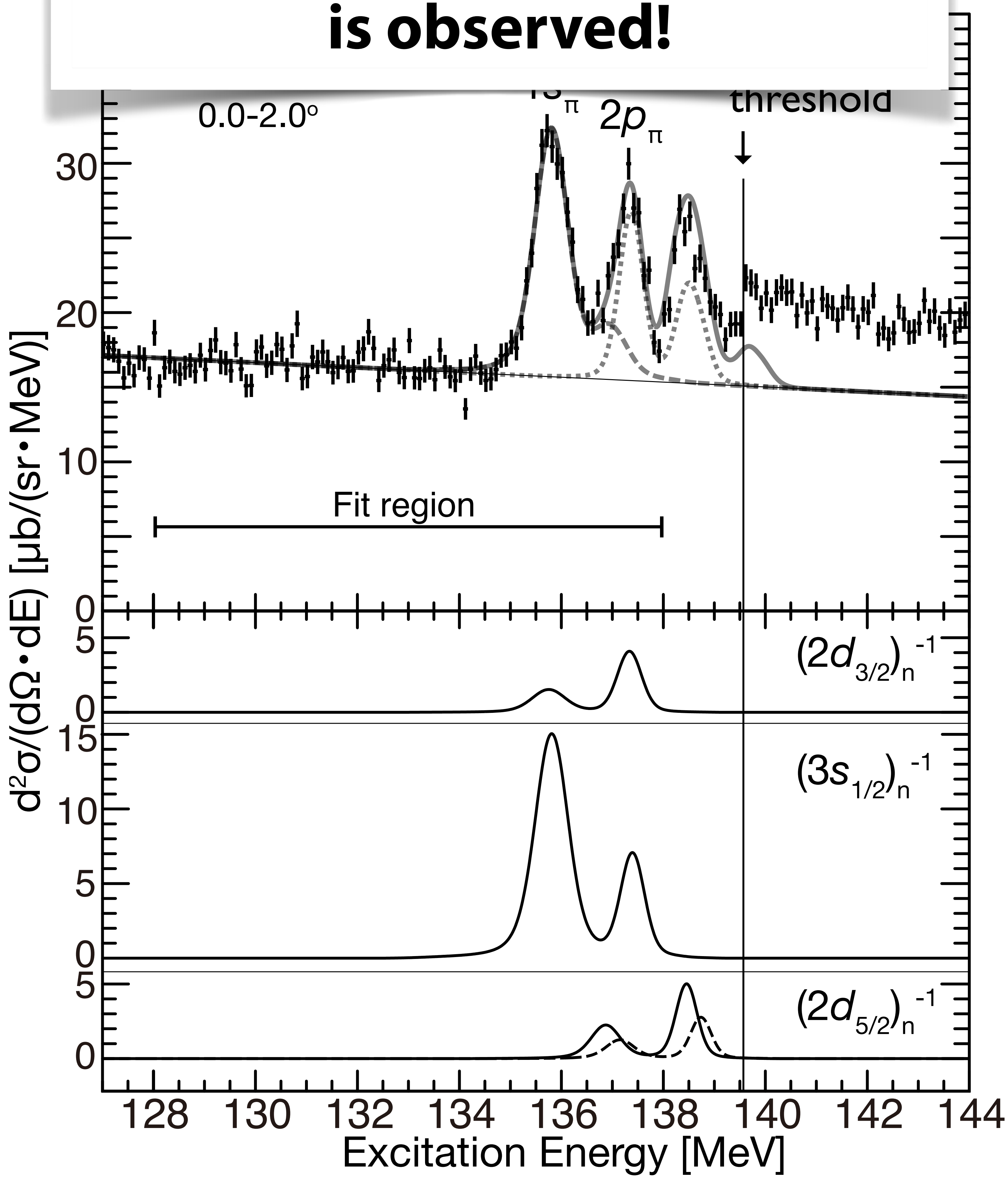
B_{2p}= 2.257–2.276 MeV

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



Scattering angle dependence is observed!





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$\Gamma_{1s} = 0.252 \pm 0.0$ … $_{-0.070}$ …

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

However, precision was not enough…

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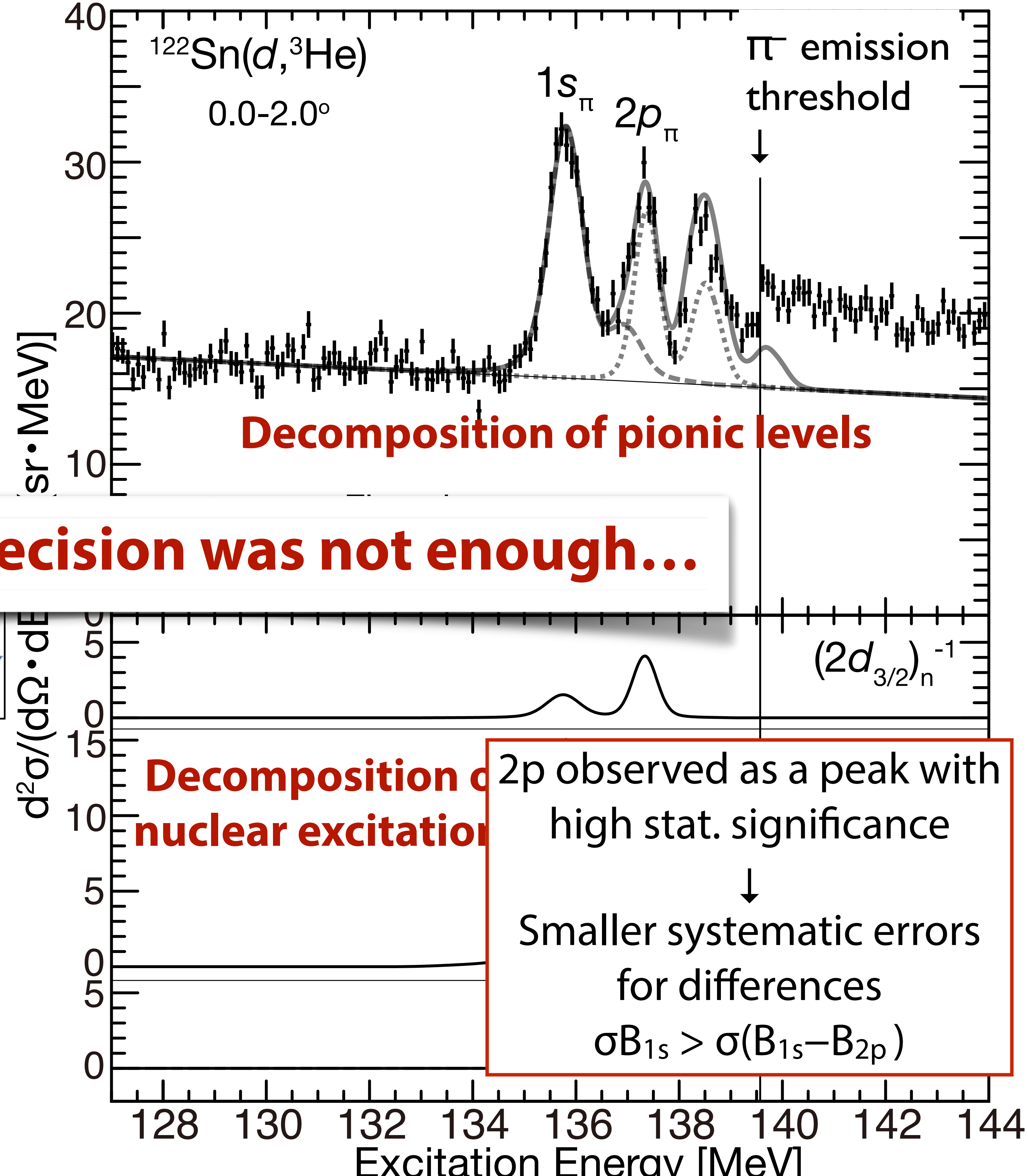


2p observed as a peak with high stat. significance

↓

Smaller systematic errors for differences

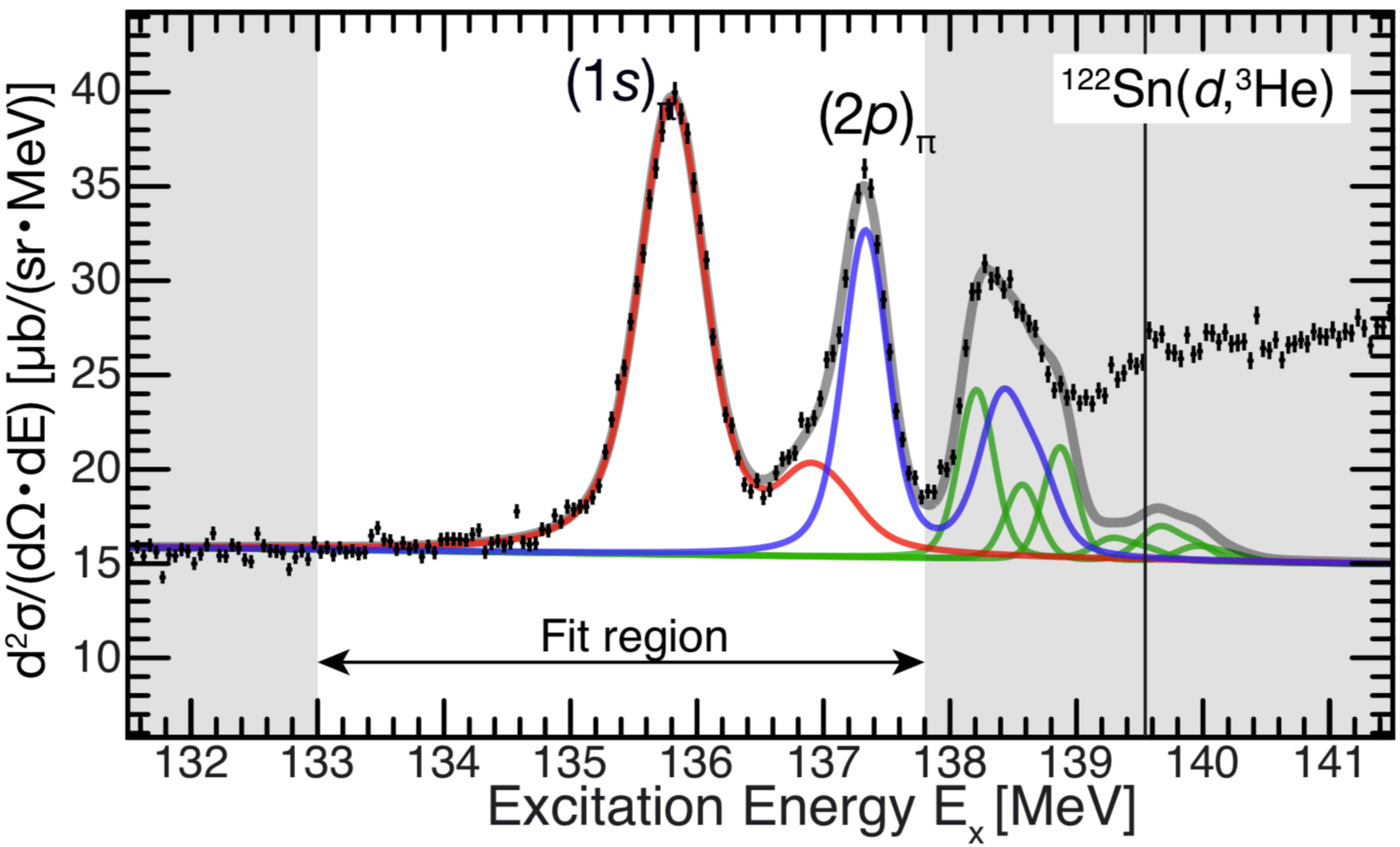
$\sigma B_{1s} > \sigma(B_{1s} - B_{2p})$

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]



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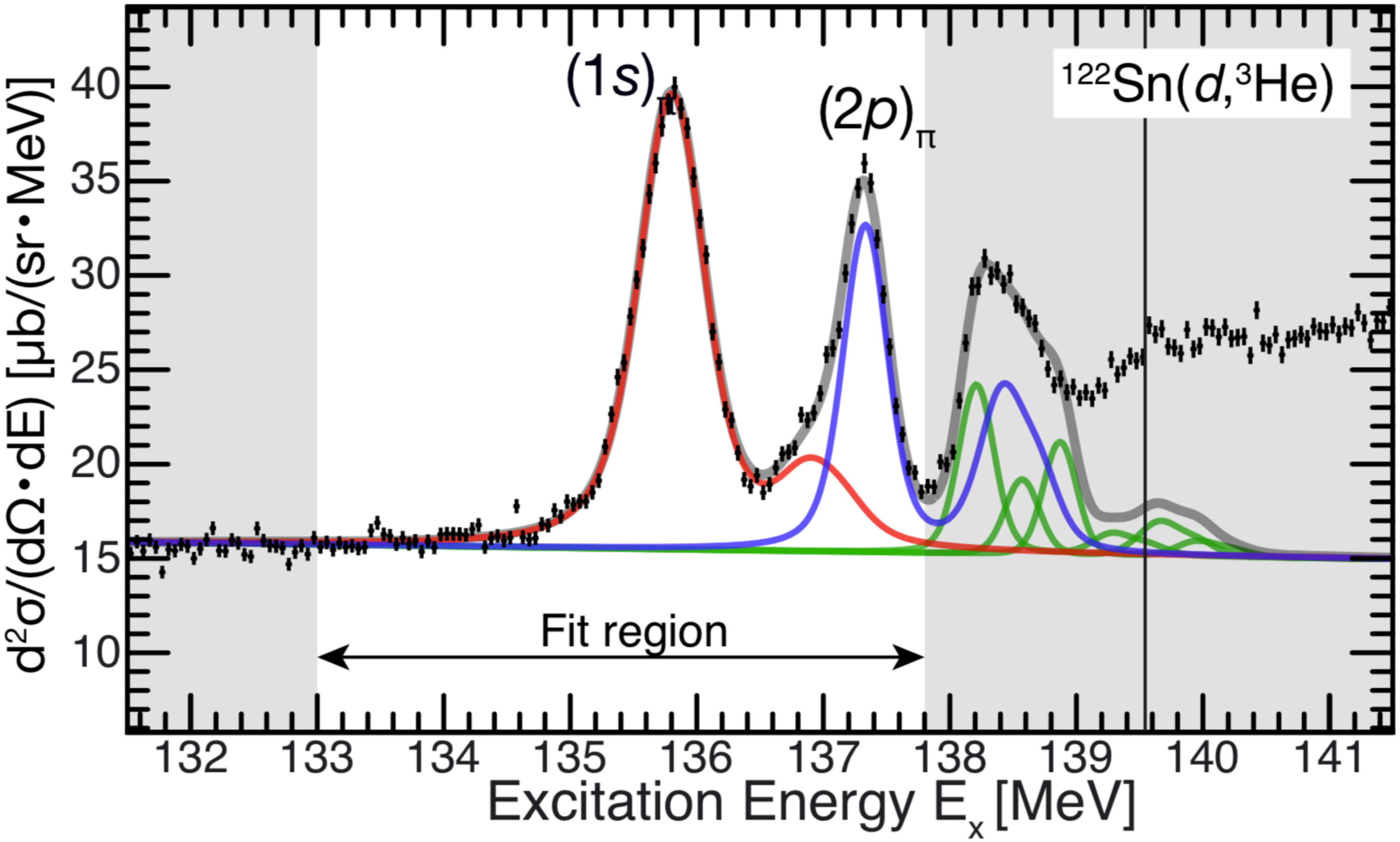

	[keV]	Statistical	Systematic
$B_\pi(1s)$	3831	±3	+78 − 76
$B_\pi(2p)$	2276	±3	+84 − 83
$B_\pi(1s) - B_\pi(2p)$	1555	±4	±12
$\Gamma_\pi(1s)$	316	±12	+36 − 39
$\Gamma_\pi(2p)$	164	±17	+41 − 32
$\Gamma_\pi(1s) - \Gamma_\pi(2p)$	152	±20	+28 − 36

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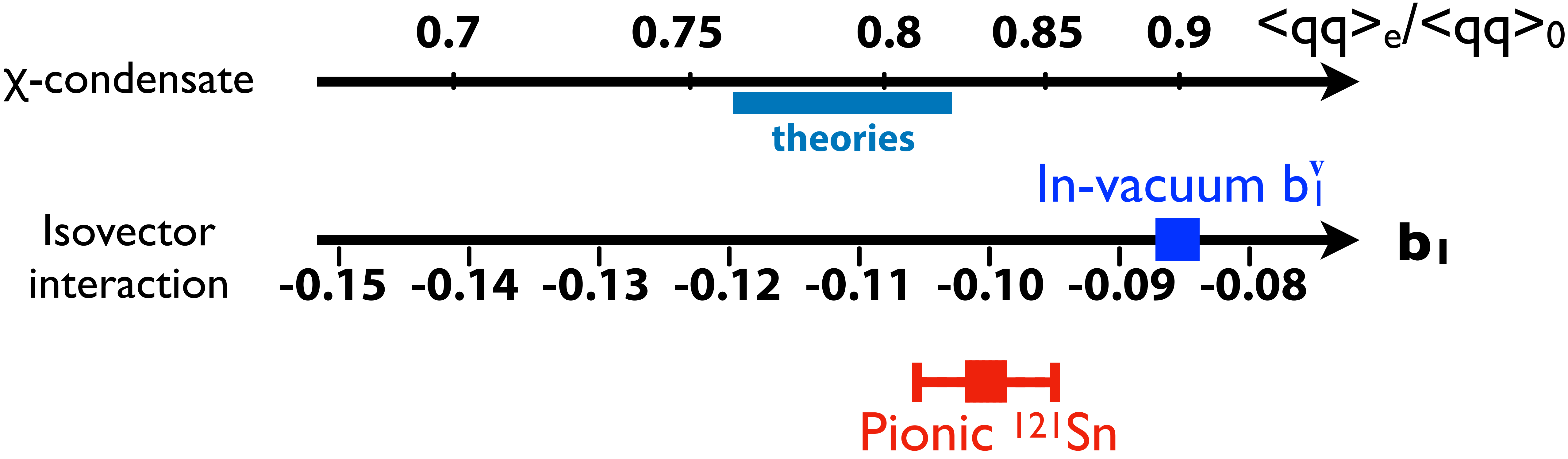
↓
Smaller systematic errors for differences
$\sigma B_{1s} > \sigma(B_{1s} - B_{2p})$

Best resolution 287 keV (FWHM)

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

Deduced b_1 from pionic Sn spectrum



b_1 = -0.1005 is deduced

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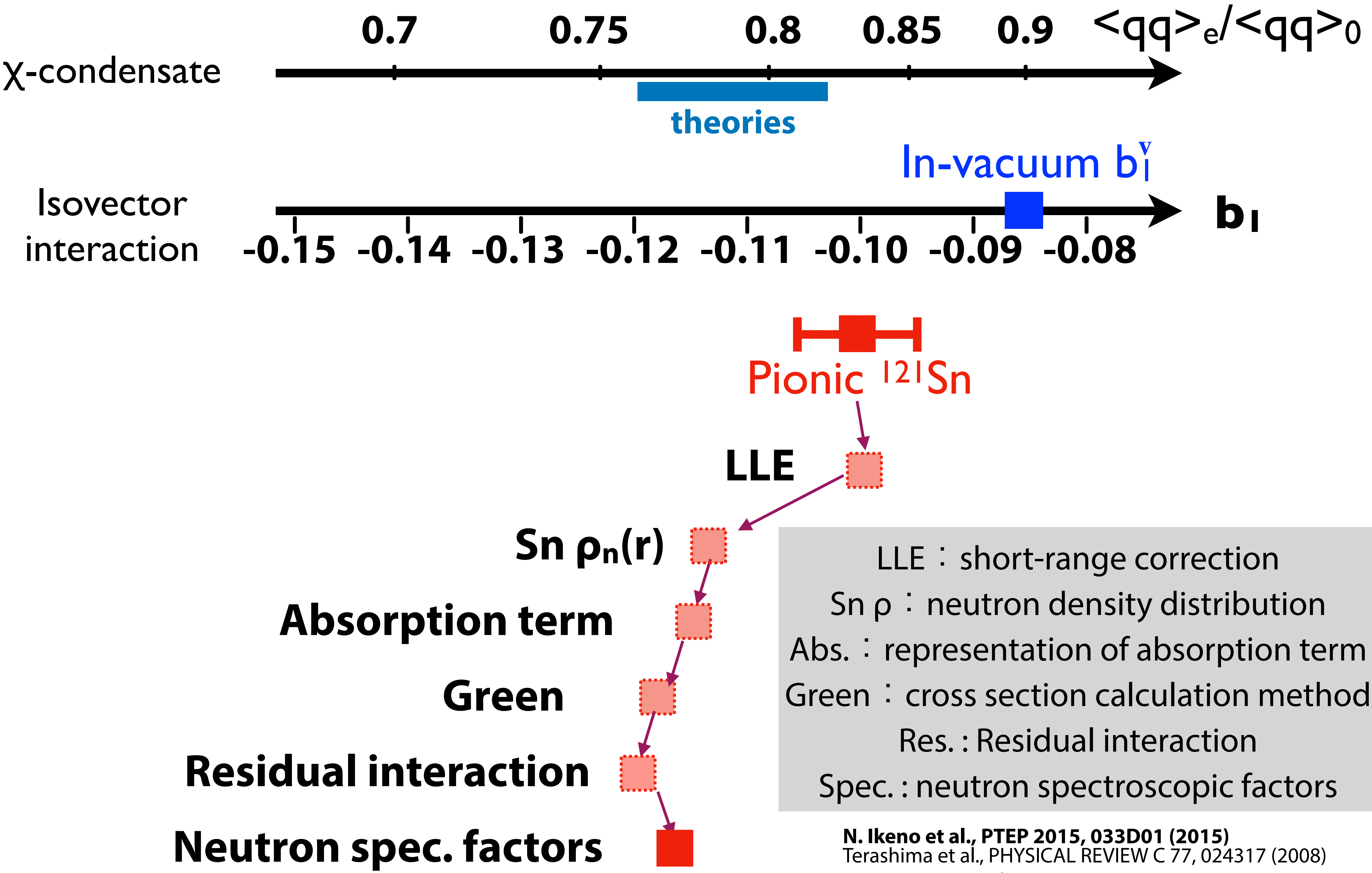
Nishi, KI et al., Nat. Phys. (2023)

Deduced b_1 with corrections



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

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

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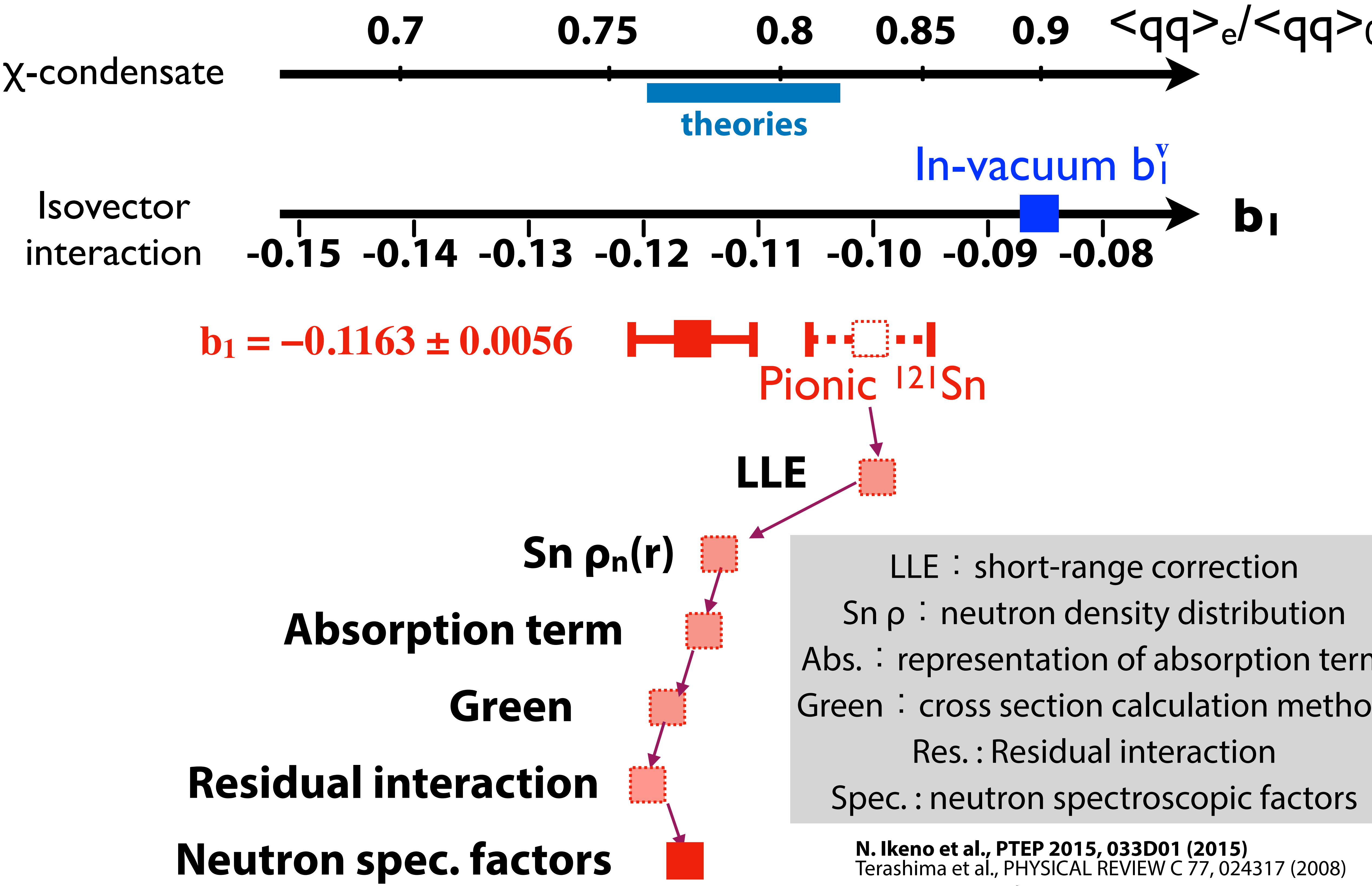
Deduced b_1 with corrections



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

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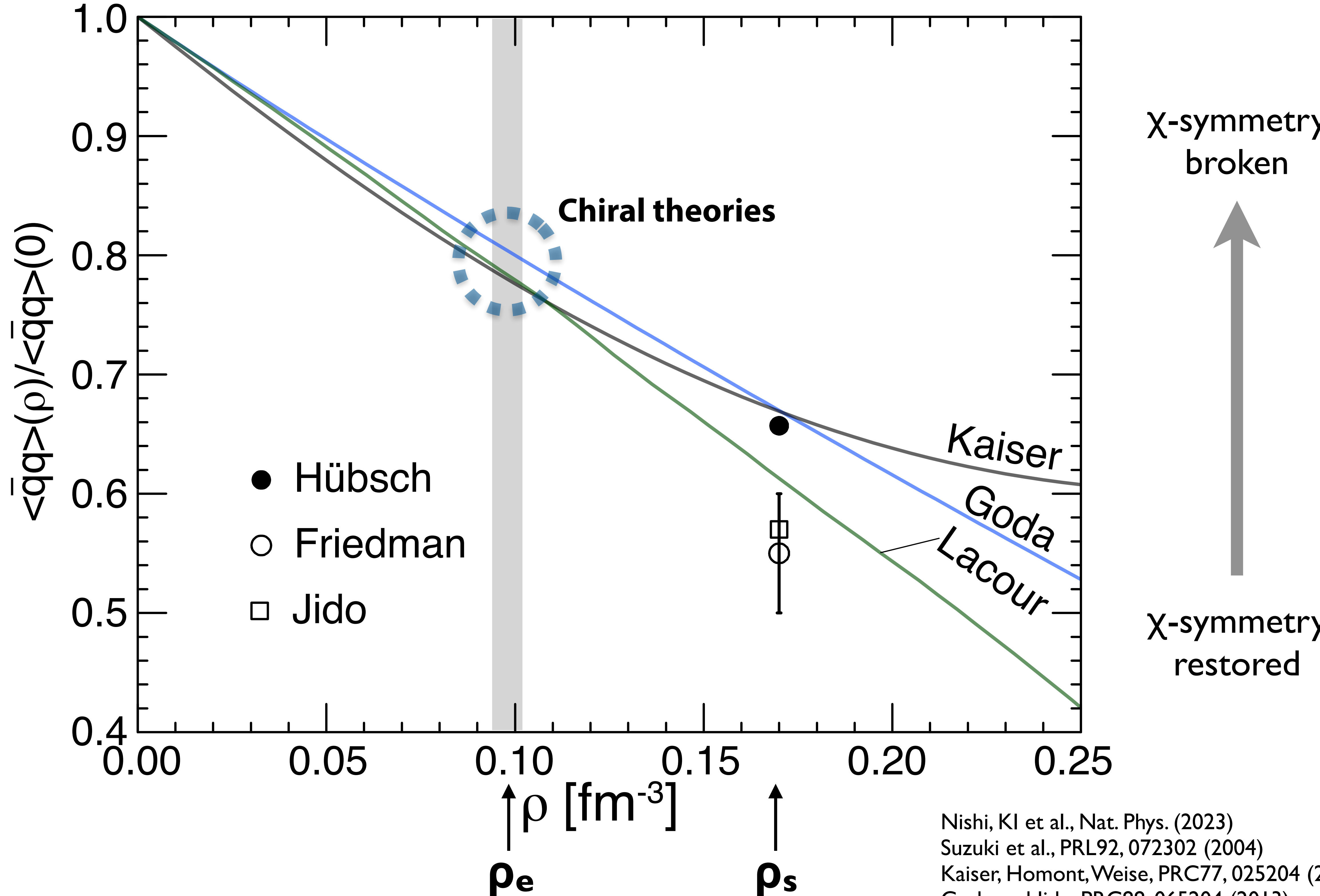
Result: deduced chiral condensate



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Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (201

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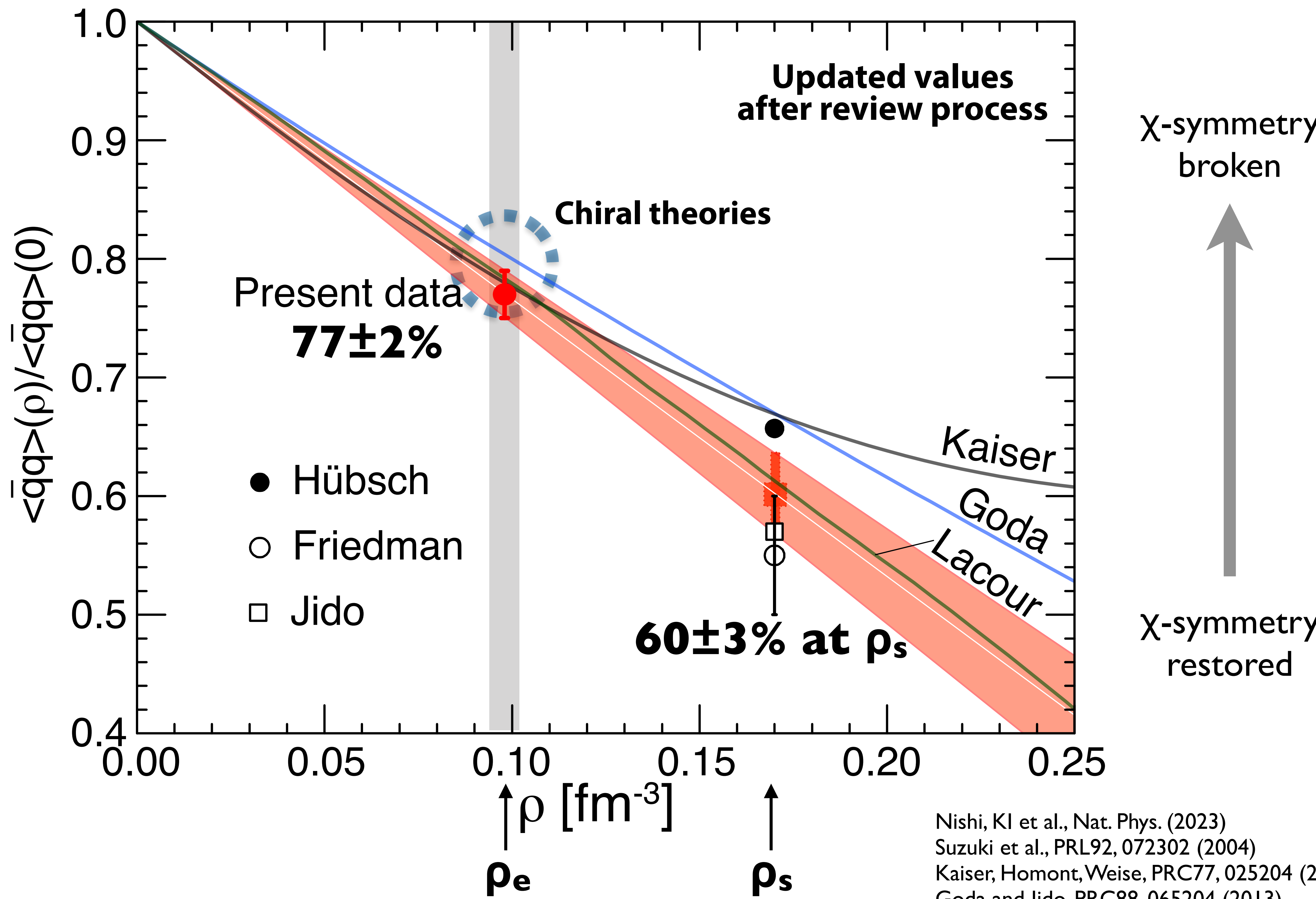

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Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (201

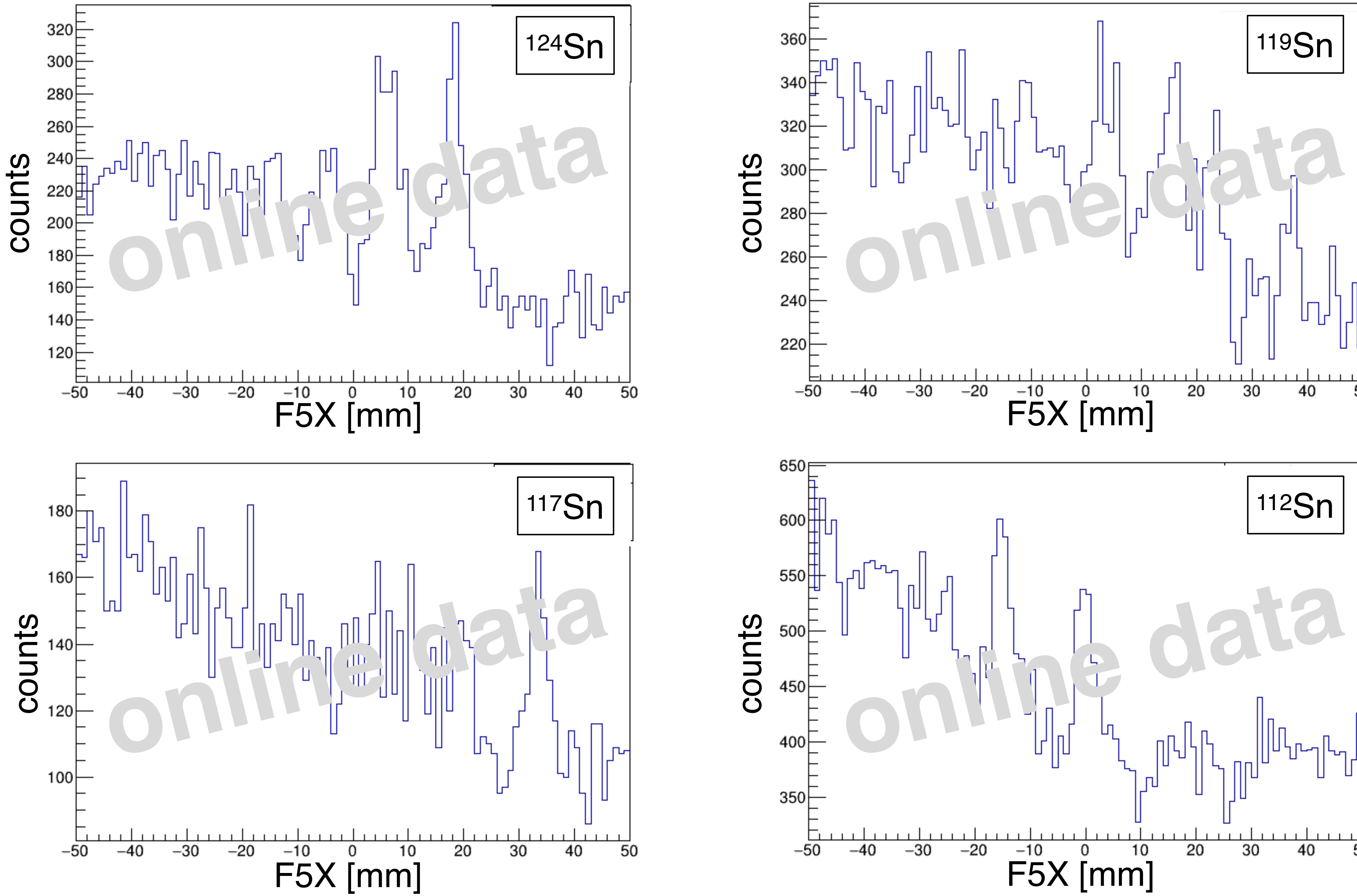
Analysis is ongoing for RIBF-135

Systematic spectroscopy of pionic Sn isotopes

for higher precision <qq> deduction

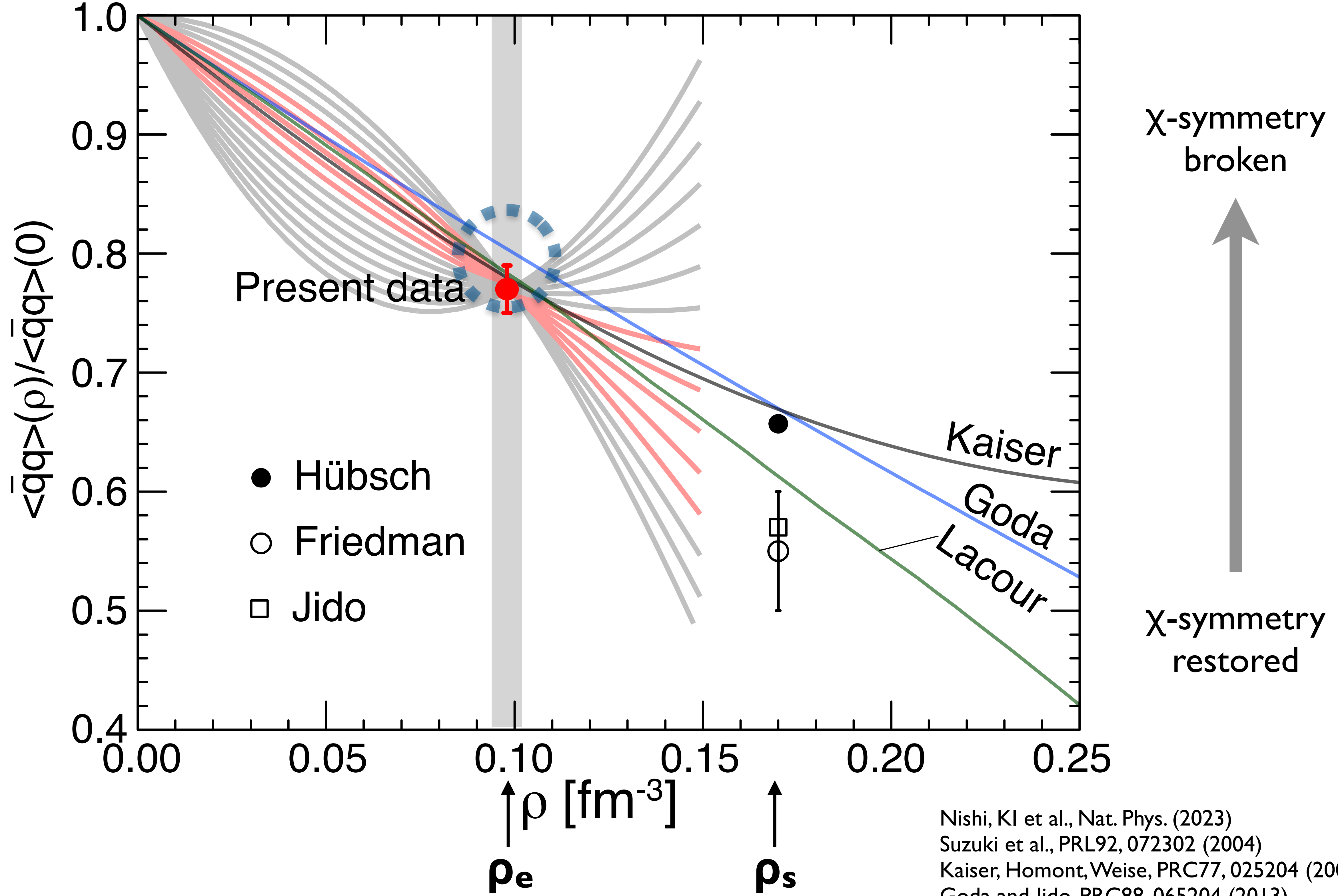
a	Ba	Ba	Ba	Ba	Ba	Ba	Ba	Ba	Ba	Ba	Ba	Ba	Ba	Ba
16	117	118	119	120	121	122	123	124	125	126	127	128	129	130
s	Cs	Cs	Cs	Cs	Cs	Cs	Cs	Cs	Cs	Cs	Cs	Cs	Cs	Cs
15	116	117	118	119	120	121	122	123	124	125	126	127	128	129
e	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe
14	115	116	117	118	119	120	121	122	123	124	125	126	127	128
I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
13	114	115	116	117	118	119	120	121	122	123	124	125	126	127
e	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te
12	113	114	115	116	117	118	119	120	121	122	123	124	125	126
b	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb
11	112	113	114	115	116	117	118	119	120	121	122	123	124	125
n	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn
10	111	112	113	114	115	116	117	118	119	120	121	122	123	124
n	In	In	In	In	In	In	In	In	In	In	In	In	In	In
09	110	111	112	113	114	115	116	117	118	119	120	121	122	123

RIBF-135 (2021) for **higher precision** <qq> deduction



D-candidate: S.Y. Matsumoto

New plan for d<qq>/dρ at ρ_e



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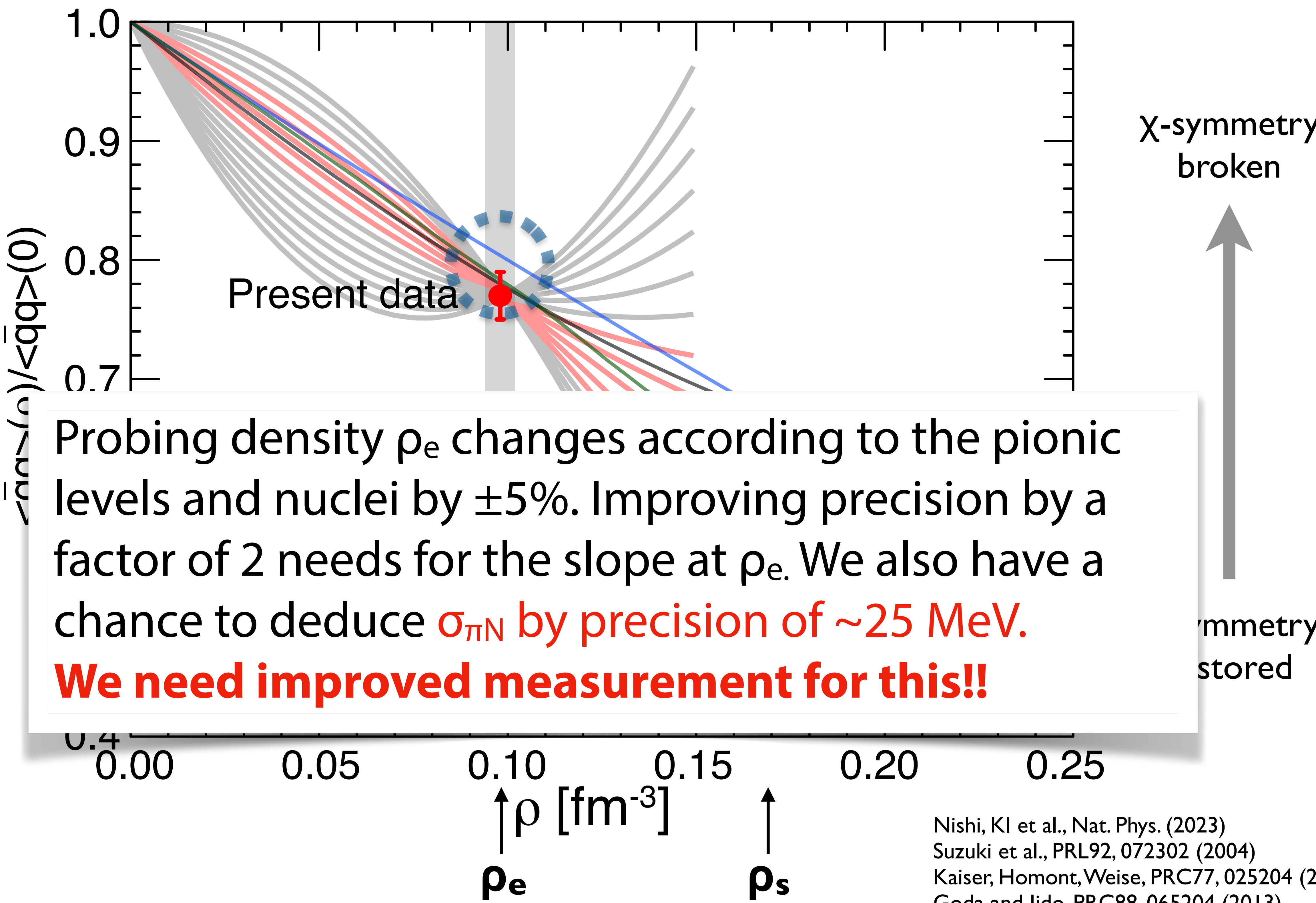

Probing density ρ_e changes according to the pionic levels and nuclei by ±5%. Improving precision by a factor of 2 needs for the slope at ρ_e. We also have a chance to deduce $\sigma_{\pi N}$ by precision of ~25 MeV.

We need improved measurement for this!!

Nishi, KI et al., Nat. Phys. (2023)
Suzuki et al., PRL92, 072302 (2004)
Kaiser, Homont, Weise, PRC77, 025204 (2008)
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Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (2010

Experimental deduction of $\sigma_{\pi N}$

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

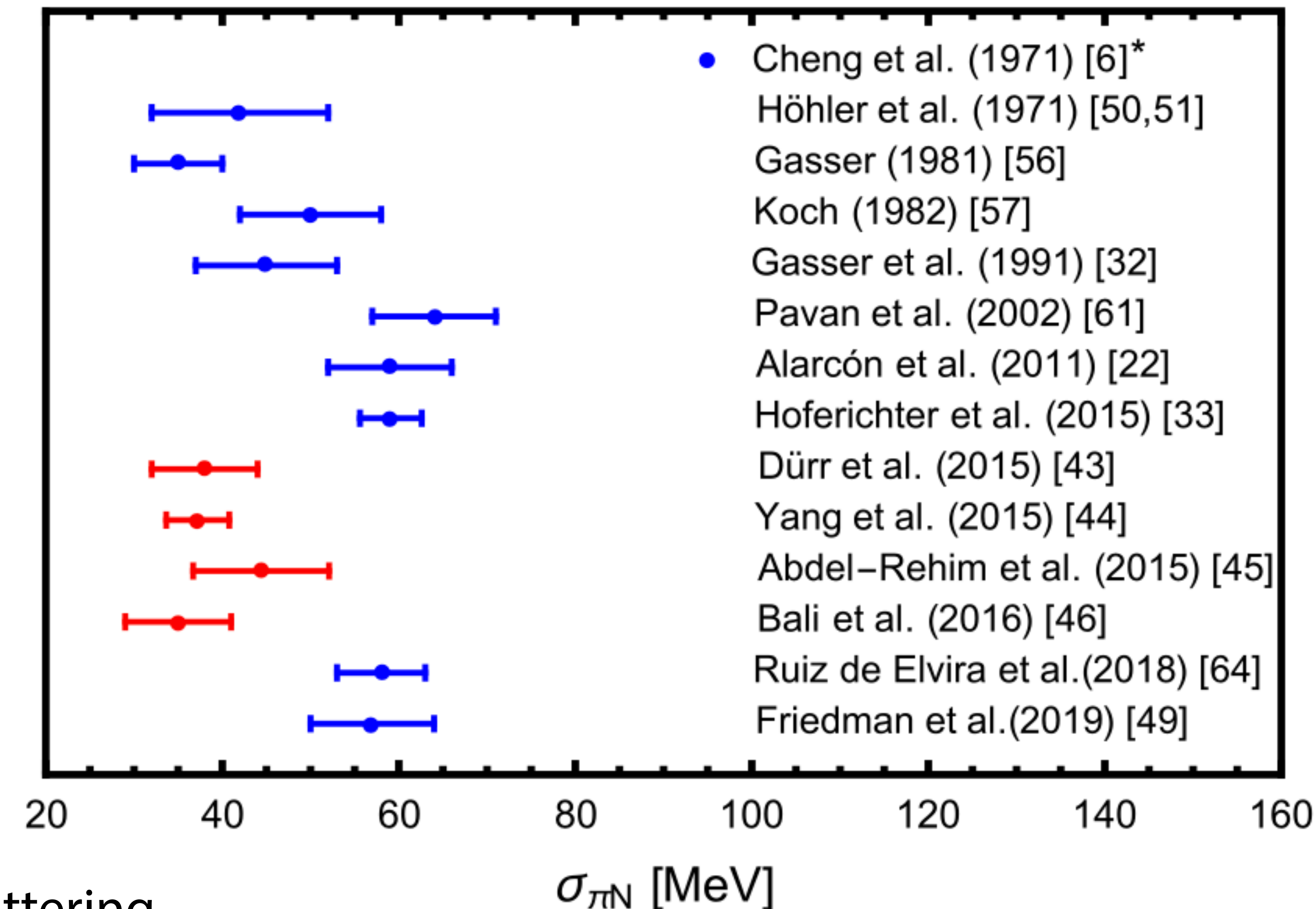
quark contribution to nucleon mass

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

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 $\rho=0$

Previous values of $\sigma_{\pi N}$



piN scattering
Lattice QCD
Chiral effective theory…

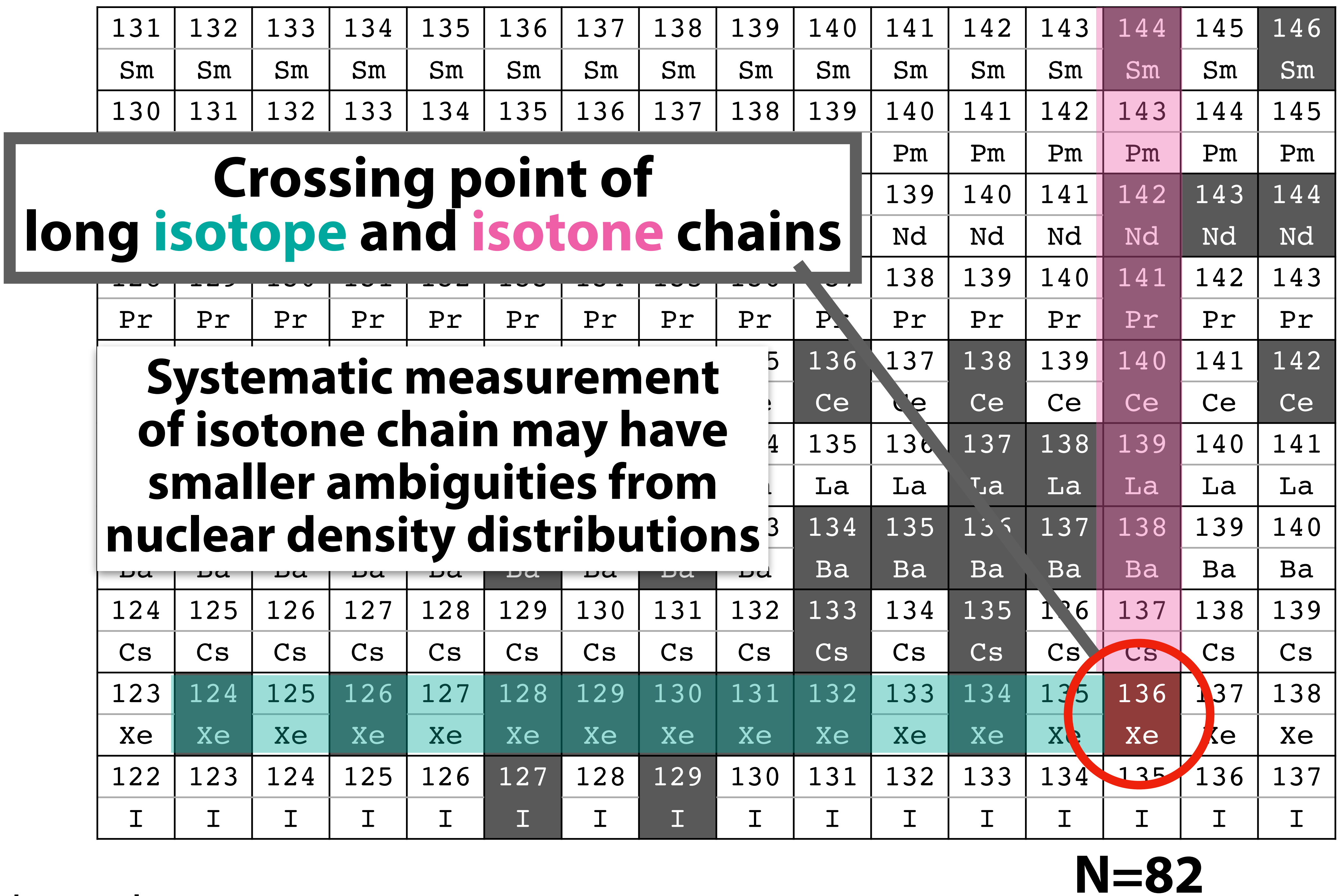
Alarcon, EPJ Spec. Top. (2021) 230:1609–1622
https://doi.org/10.1140/ep js/s11734-021-00145-6

Next experiment RIBF-214

PAC approval with rank A

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

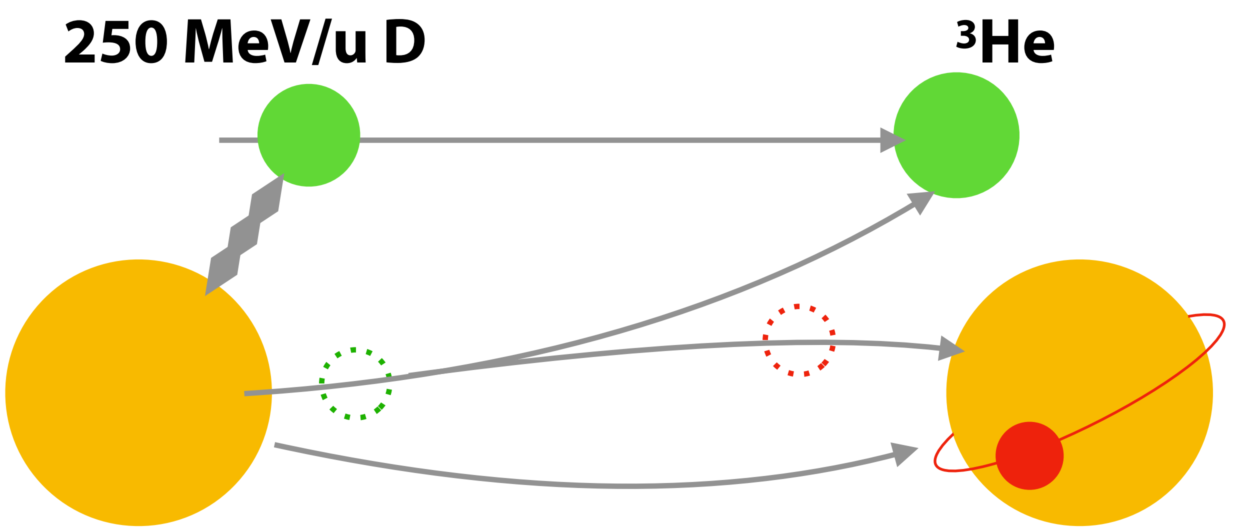
Inverse kinematics for higher precision!



KI, Y.K.Tanaka et al.

First application of
inverse kinematics reactions

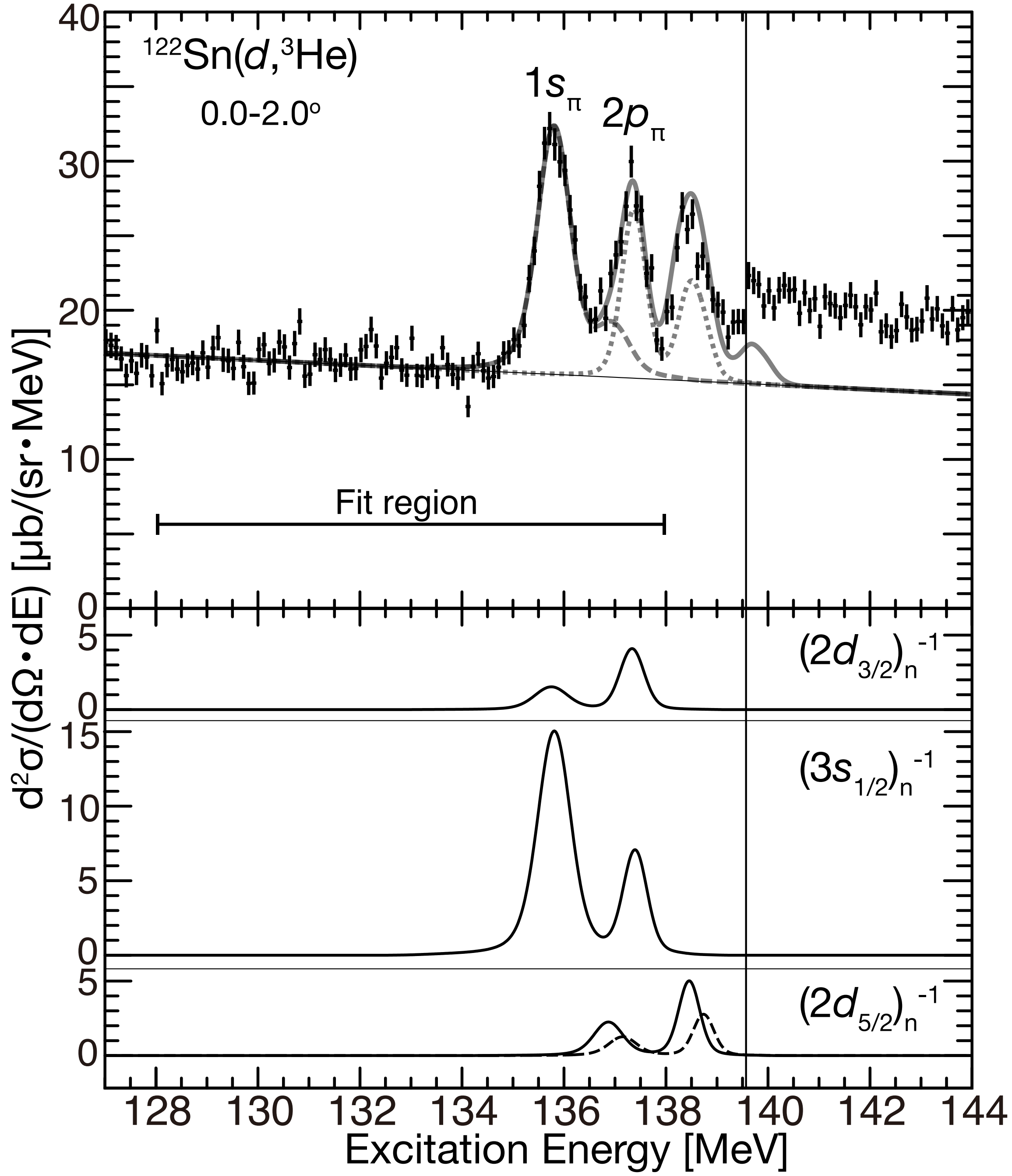
Normal kinematics (d,^{3}He) reactions



pionic atom coupled with a neutron hole

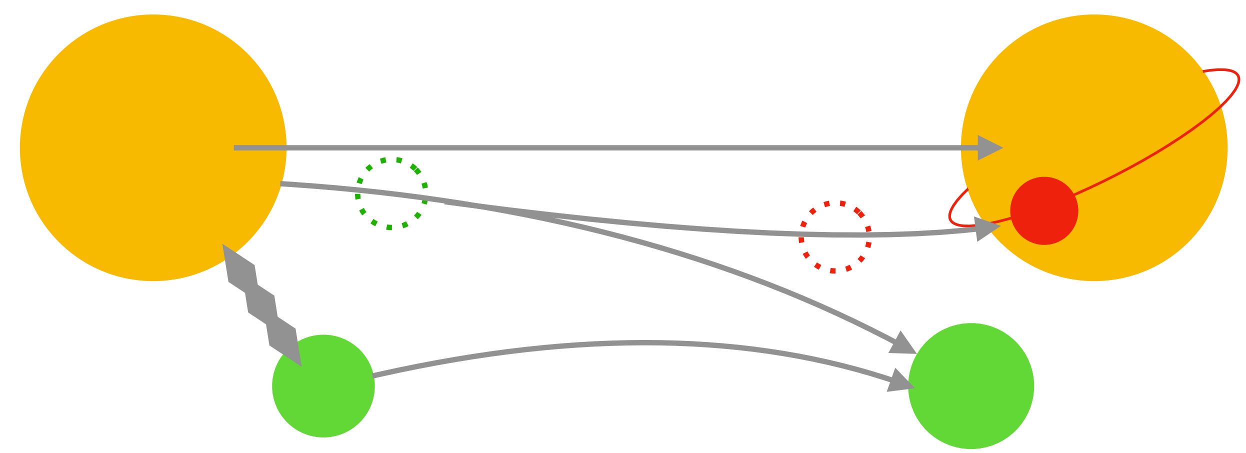
- **We measure ^{3}He energy for missing-mass and deduce mass of reaction product.**
- **This method can be applied to pionic RI spectroscopy**

RIBF-27 (2010)

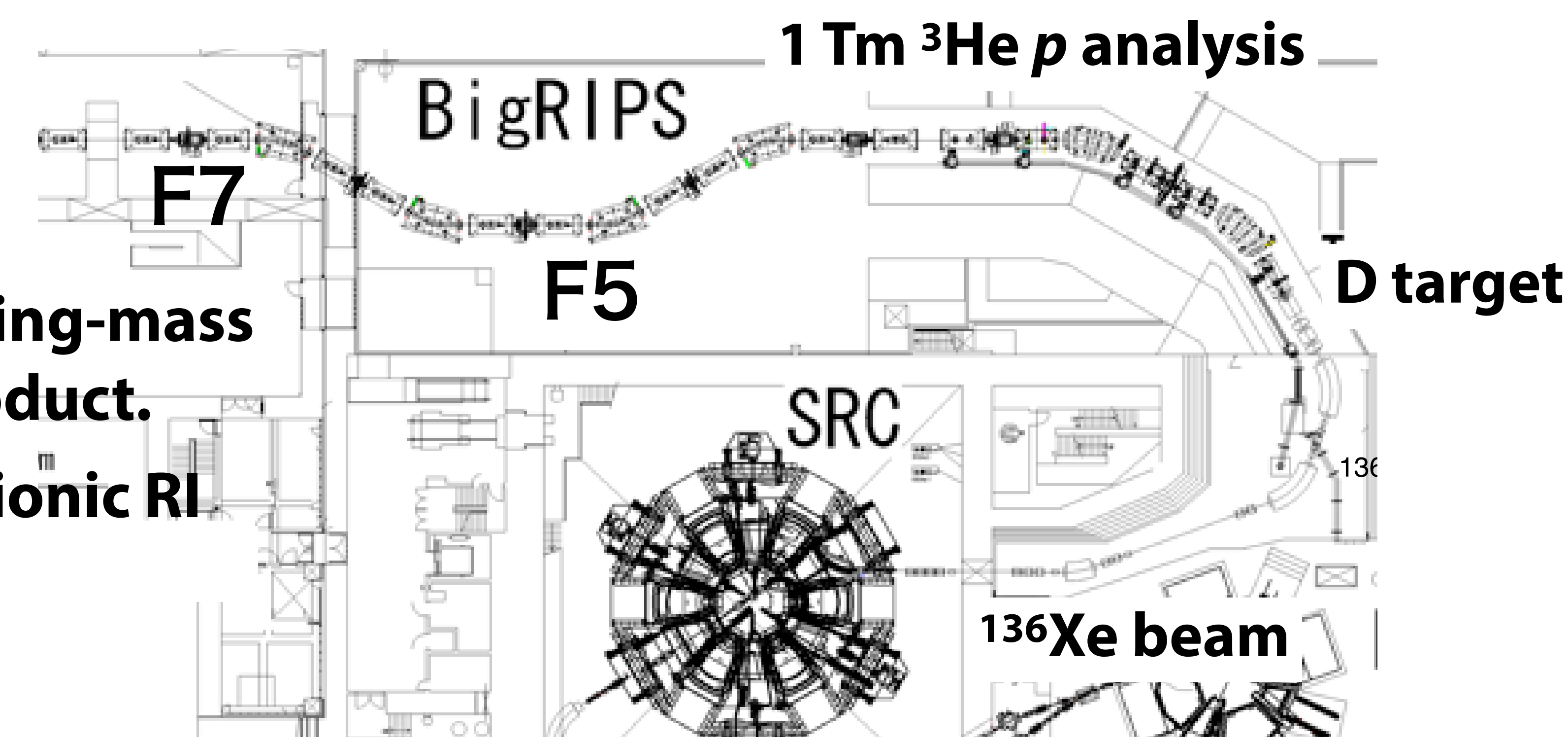


T. Nishi et al., PRL **120**, 152505 (2018)

First application of
inverse kinematics reactions



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



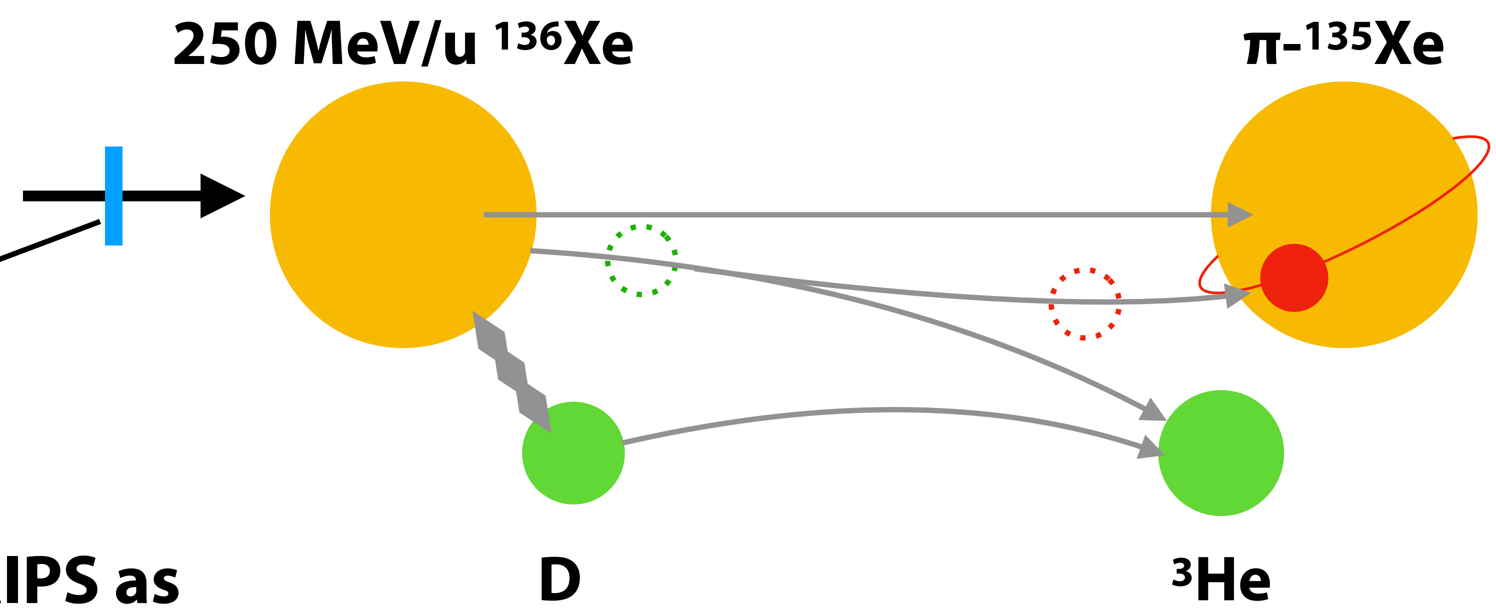
- **We measure ^{3}He energy for missing-mass and deduce mass of reaction product.**
- **This method can be applied to pionic RI spectroscopy**

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%



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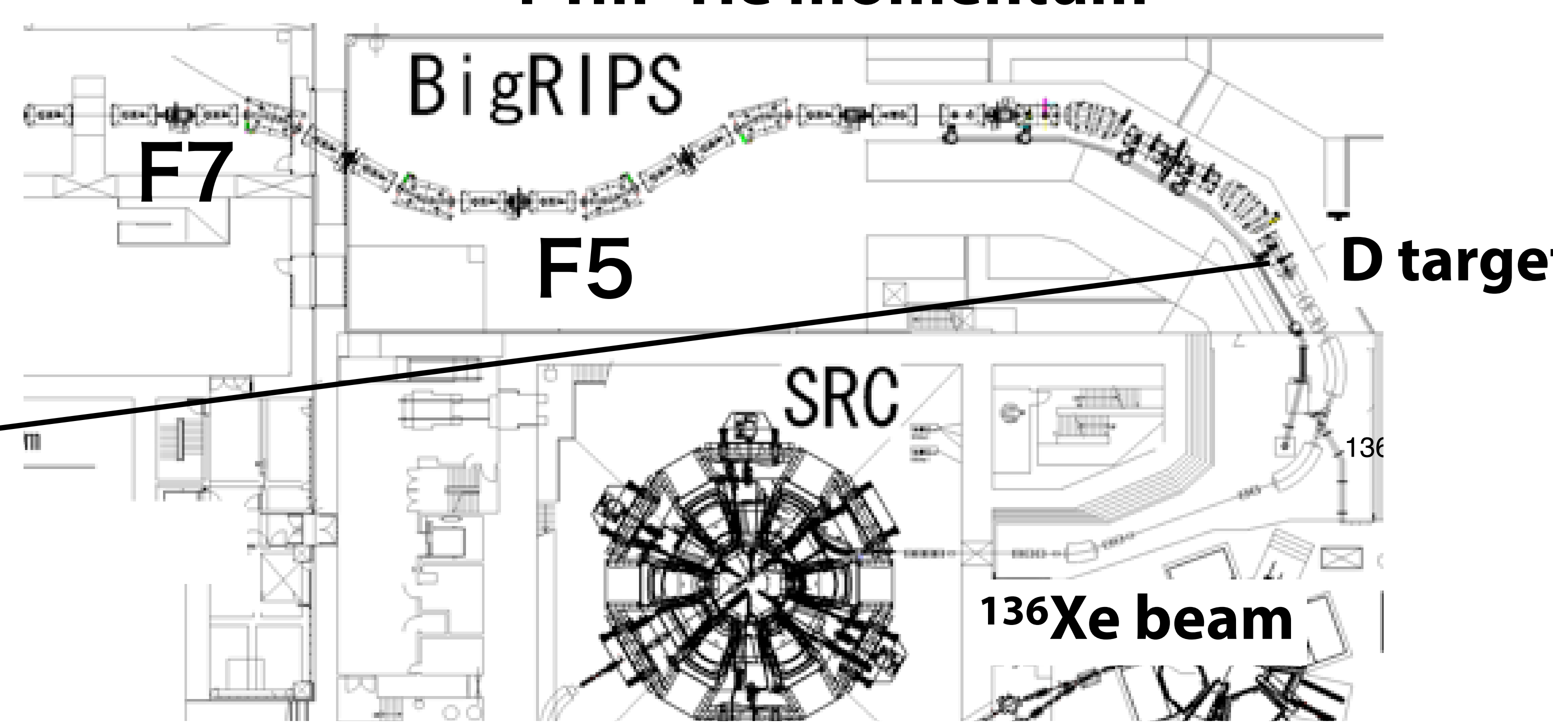
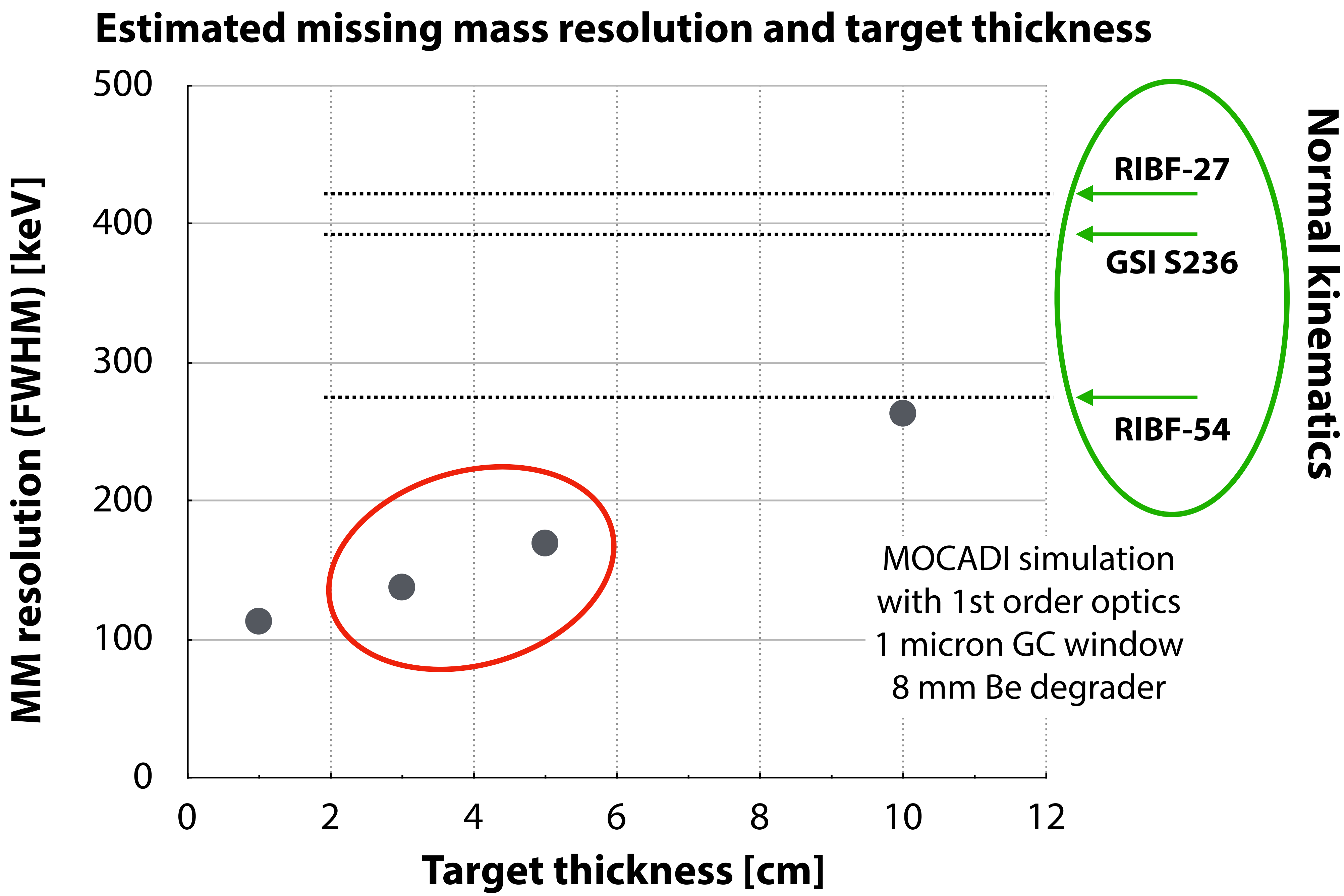
BigRIPS as spectrometer to measure ~1 Tm ^{3}He momentum



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

Missing mass resolution can be improved!

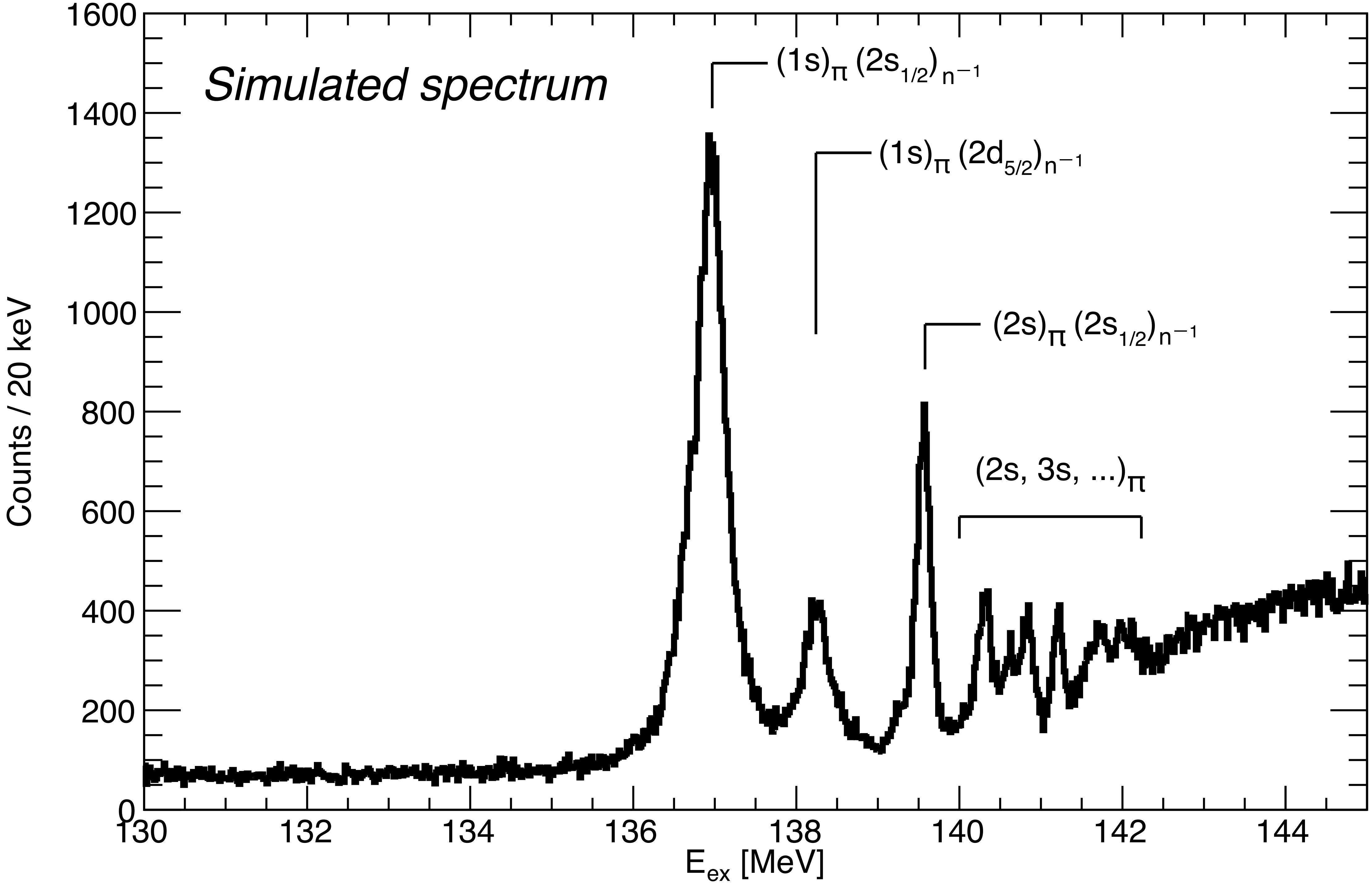


Unprecedented resolution can be achieved
→ Important for resolving higher orbitals and determine the widths

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



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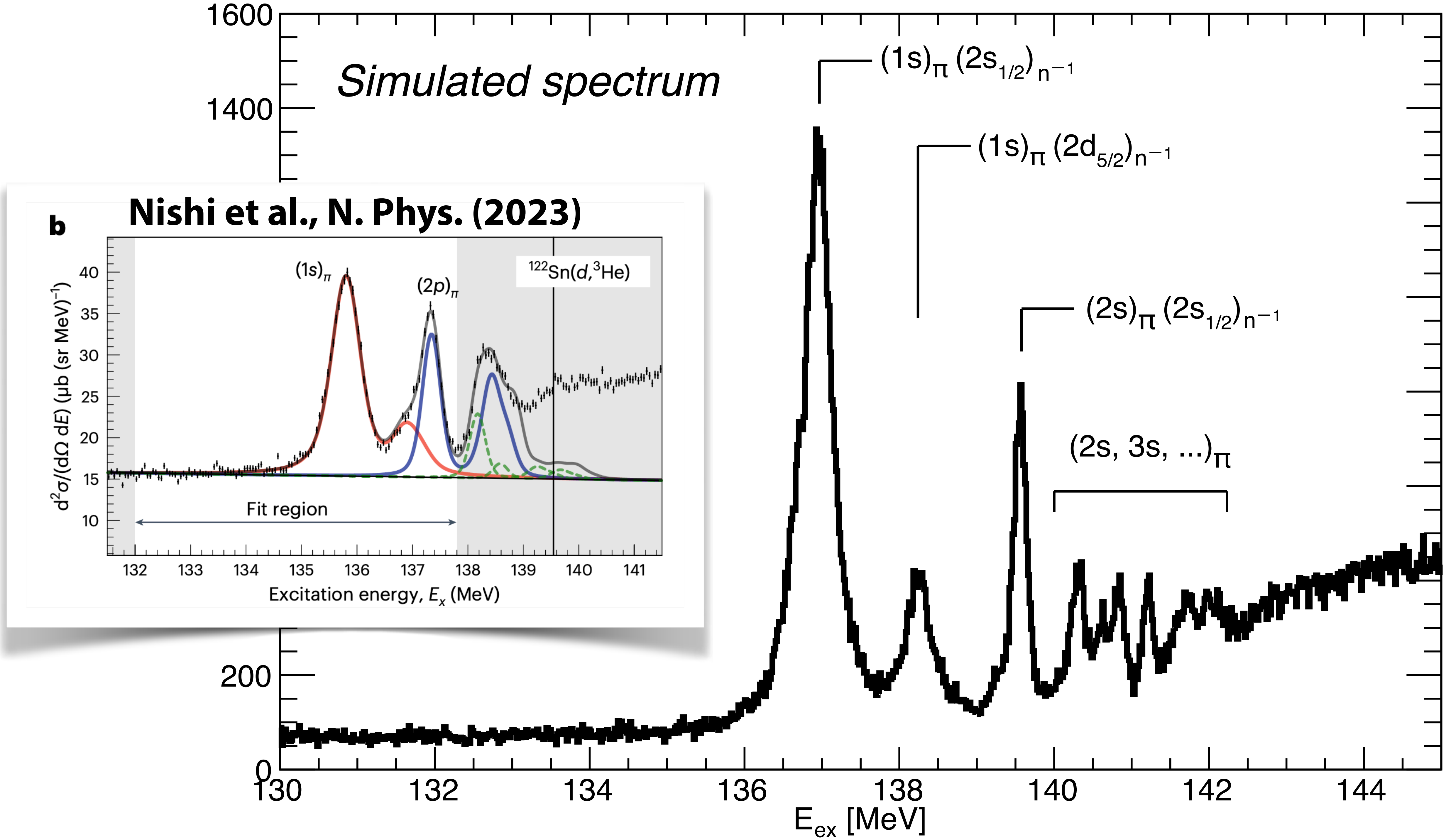

Summary

- 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, which may lead to pionic RI. Resolution will be further improved. Now, we are aiming at the πN σ term.