Chiral symmetry in nuclear medium

observed in spectroscopy of pionic atoms

+ η′-mesic nuclei for $U_A(1)$ anomaly

RIKEN Nishina Center

Kenta Itahashi

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

Chiral symmetry in nuclear medium
observed in spectroscopy of pionic atoms

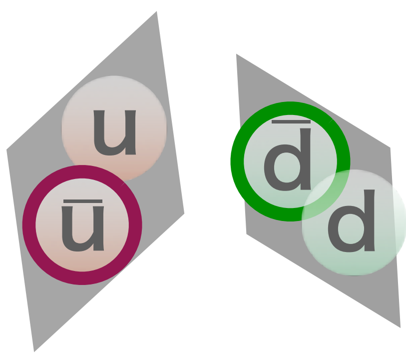
- **Dominant symmetry of the vacuum in low-energy region.**
- **Spontaneous breakdown due to non-perturbative strong interaction.**
- **Non-trivial structure of the QCD vacuum.**

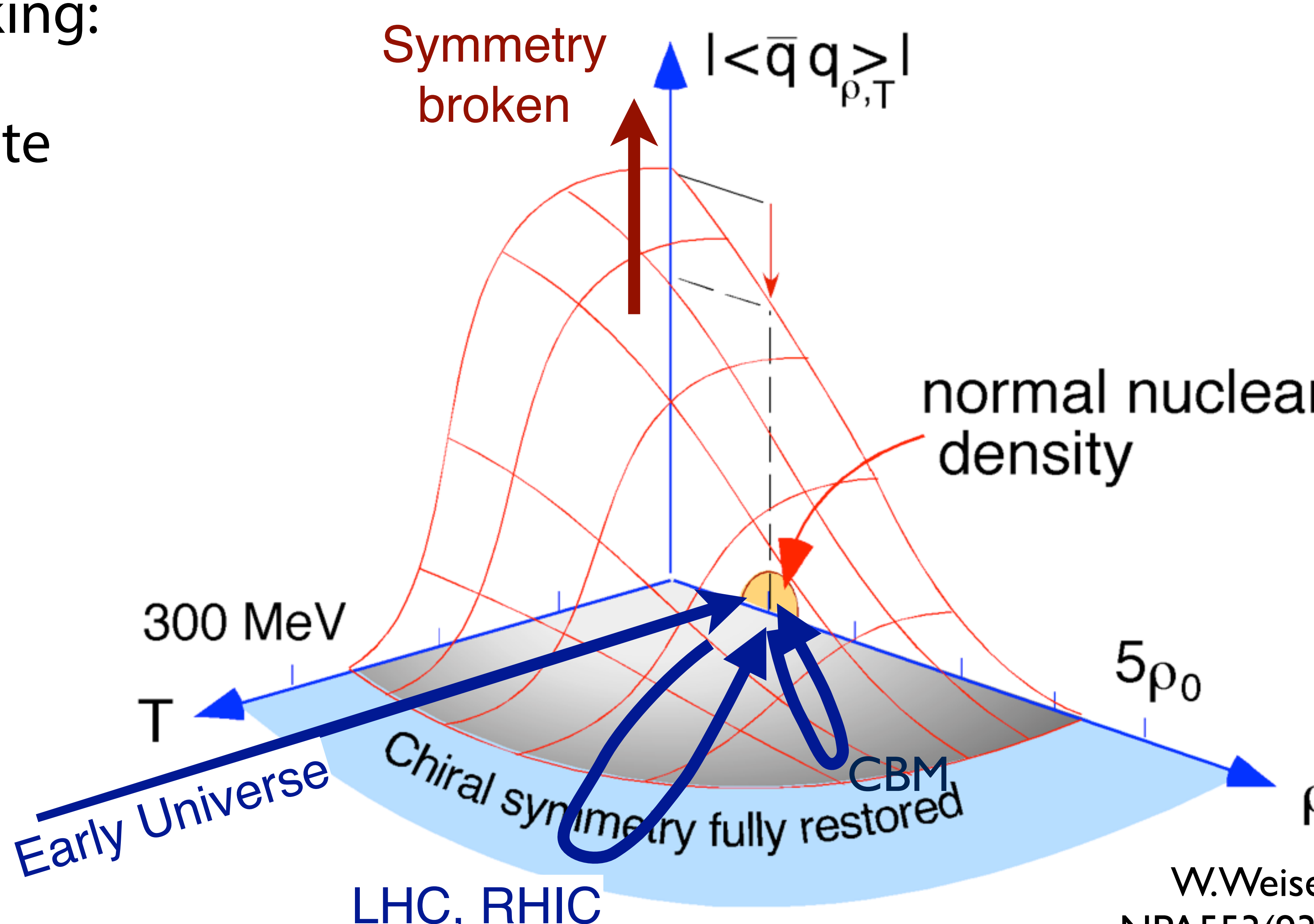
- Nature Physics **19**, 788 (2023)
  Article DOI: 10.1038/s41567-023-02001-x
- Nature Physics **19**, 764 (2023)
  News and Views "Modified in Medium"

Chiral condensate, order parameter of chiral symmetry

One of order parameters of χ-symmetry breaking:

Chiral condensate

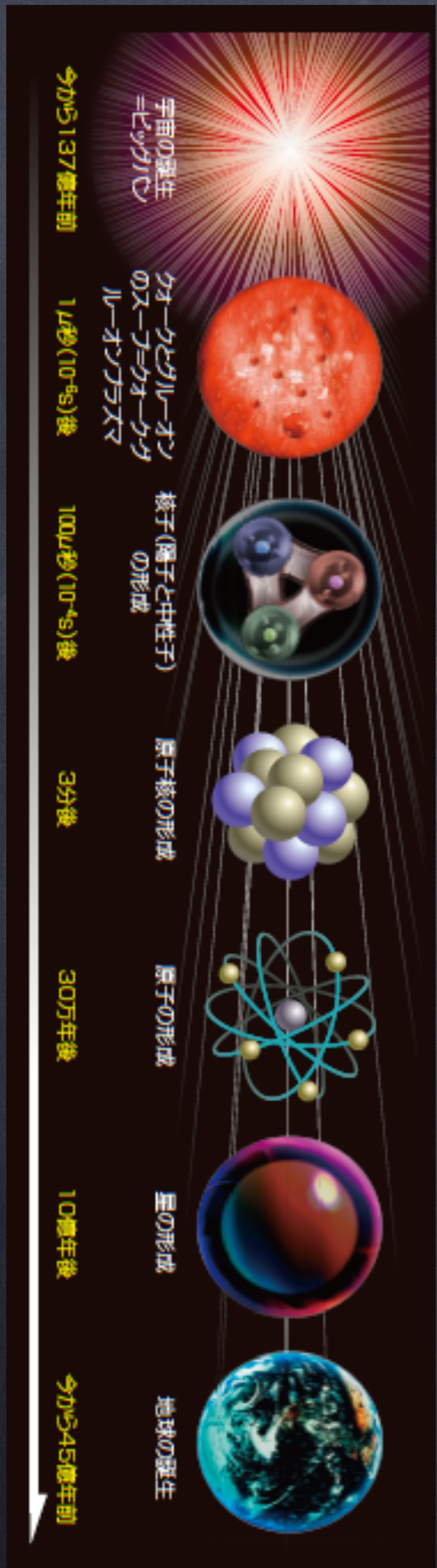




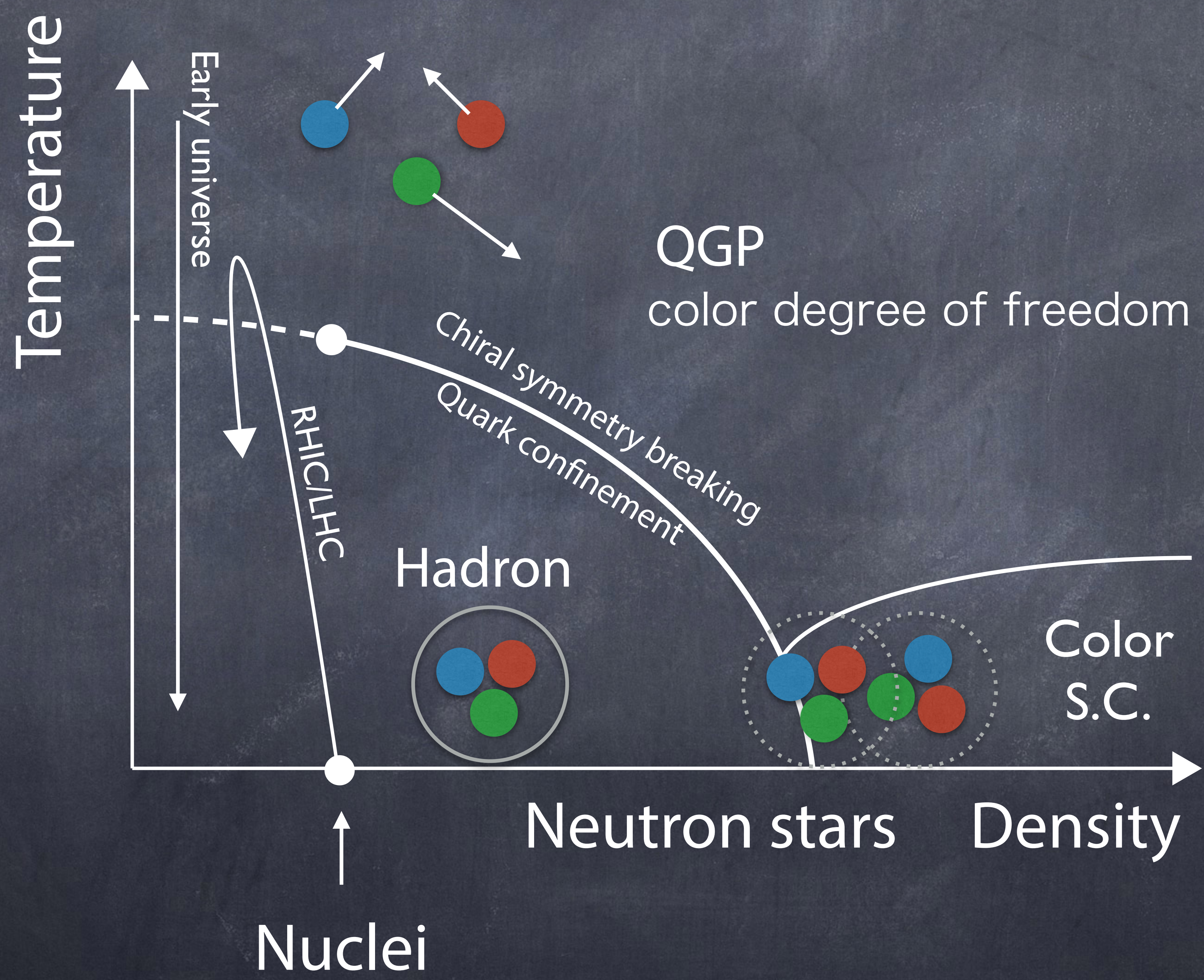
W.Weise, NPA553(93)59.

Analysis of material properties of QCD vacuum

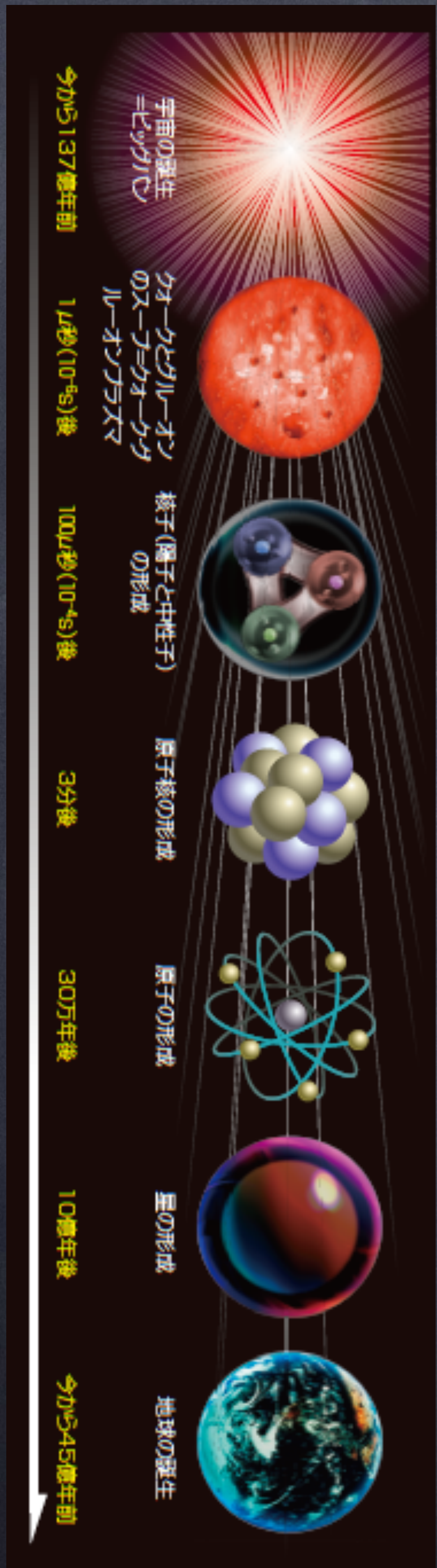
Material properties of vacuum



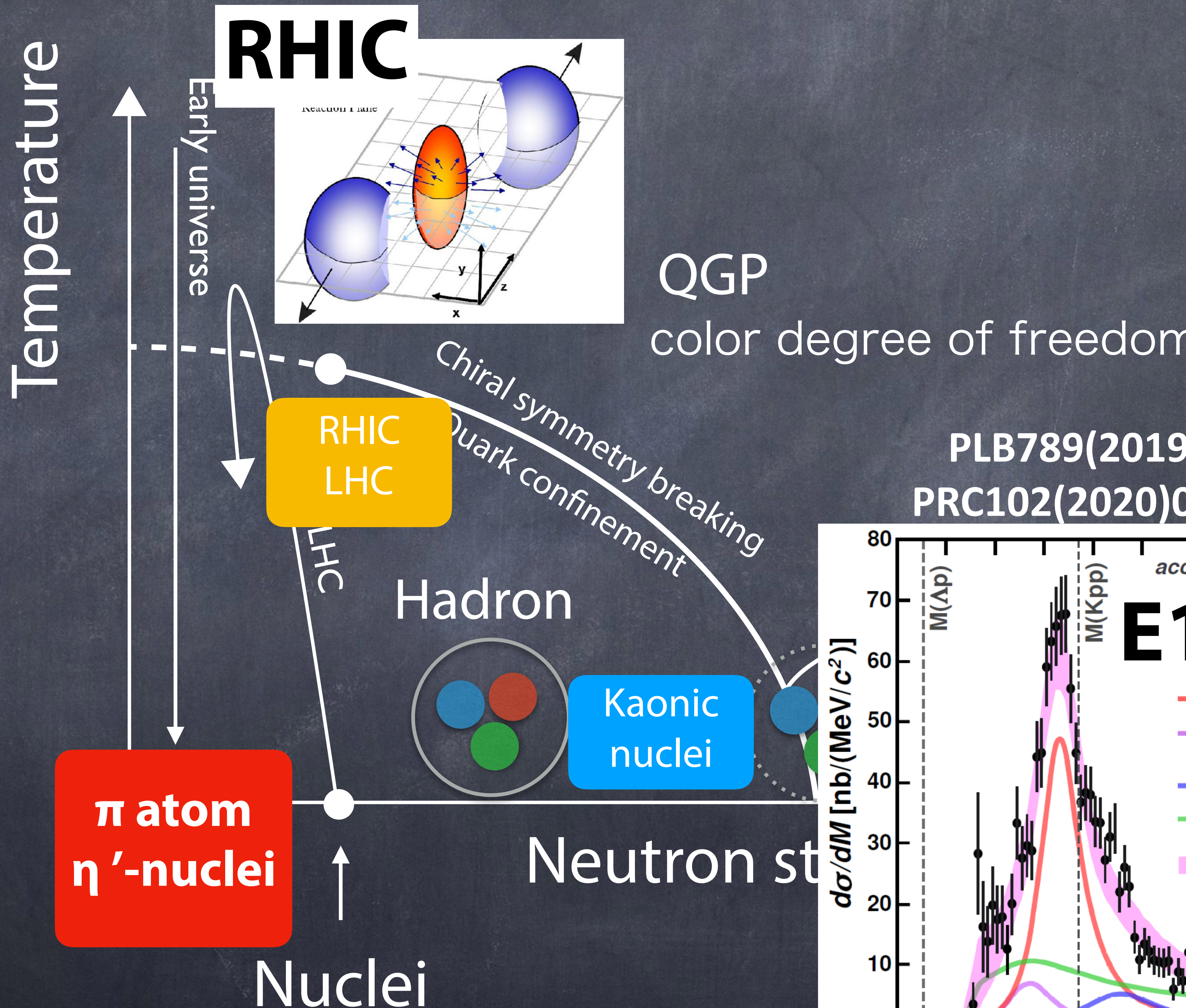
Properties of QCD vacuum
depend on temperature and matter-density



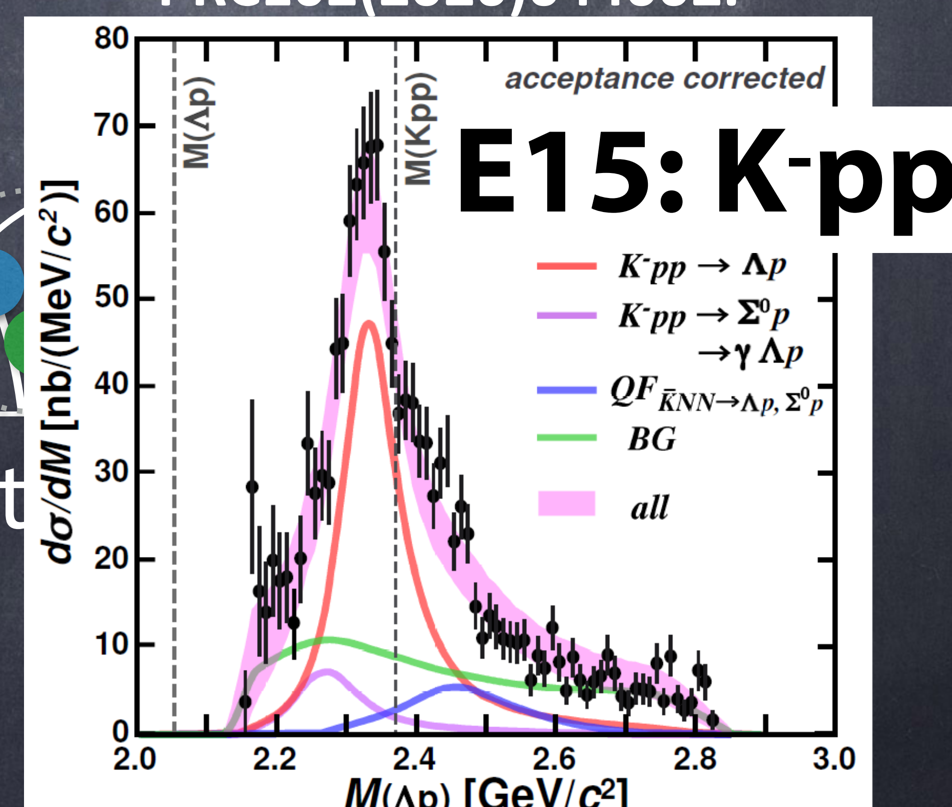
Material properties of vacuum



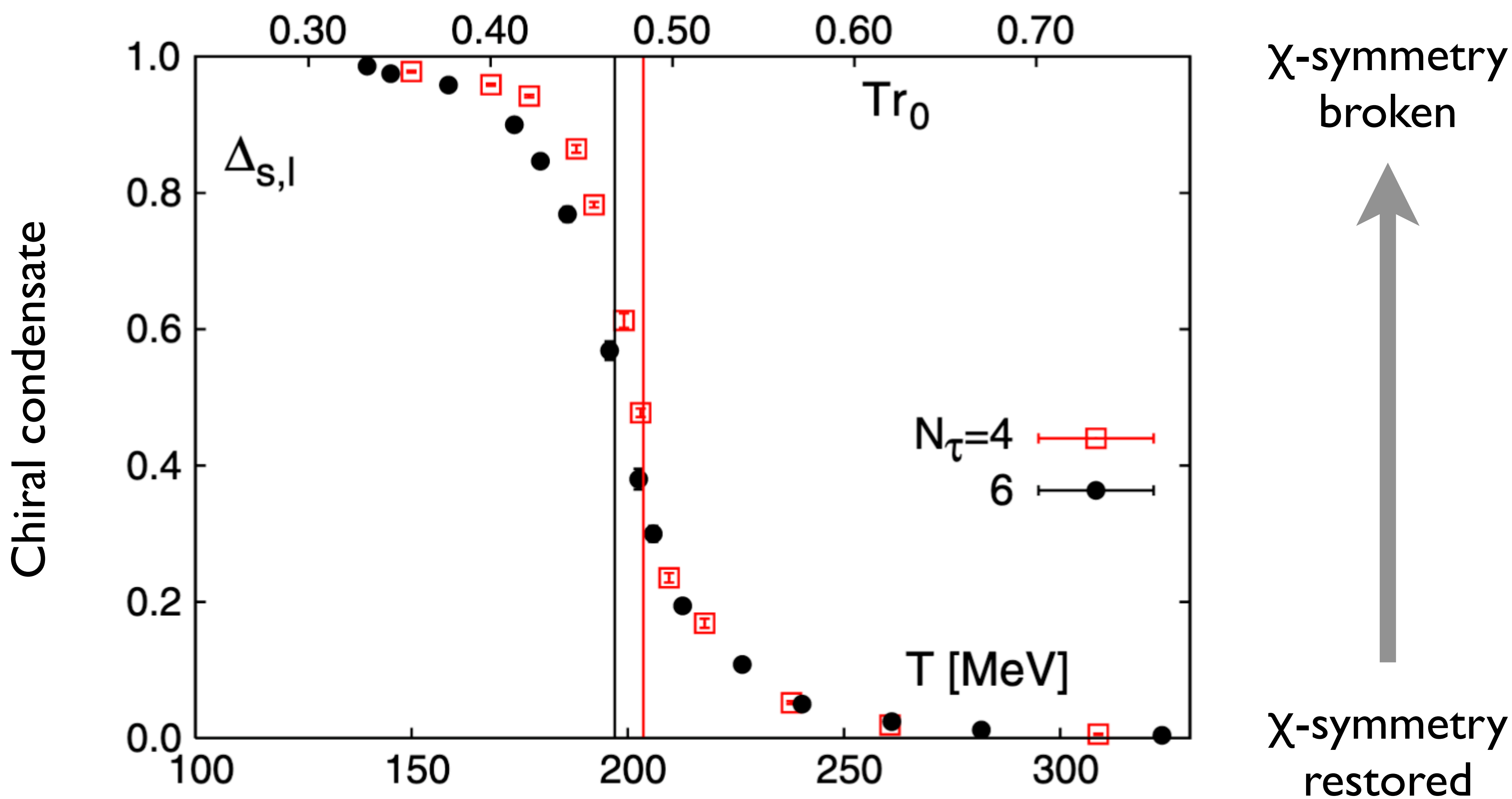
Properties of QCD vacuum
depend on temperature and matter-density



PLB789(2019)620.
PRC102(2020)044002.



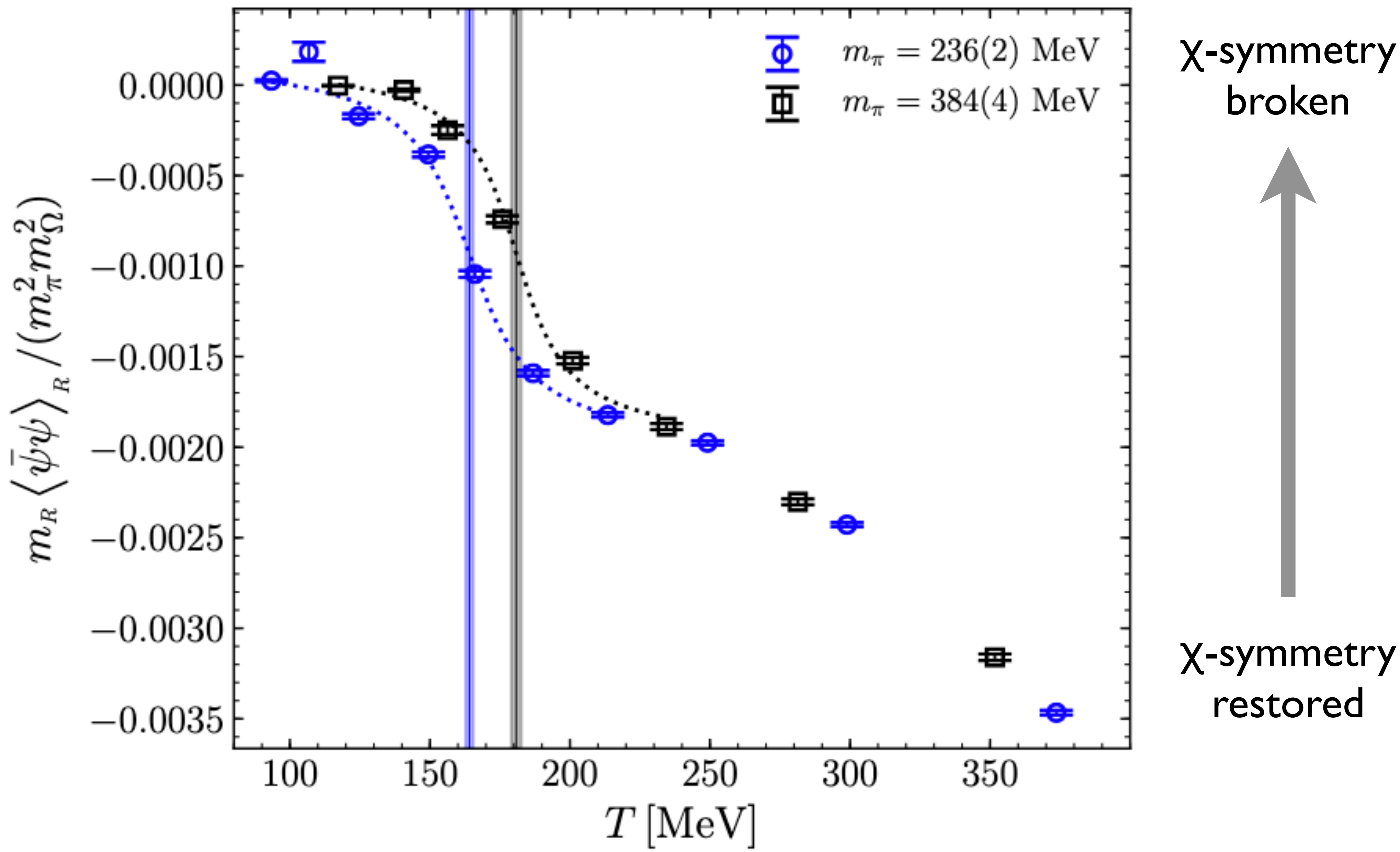
Lattice QCD calculated T dependence of chiral condensate



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.

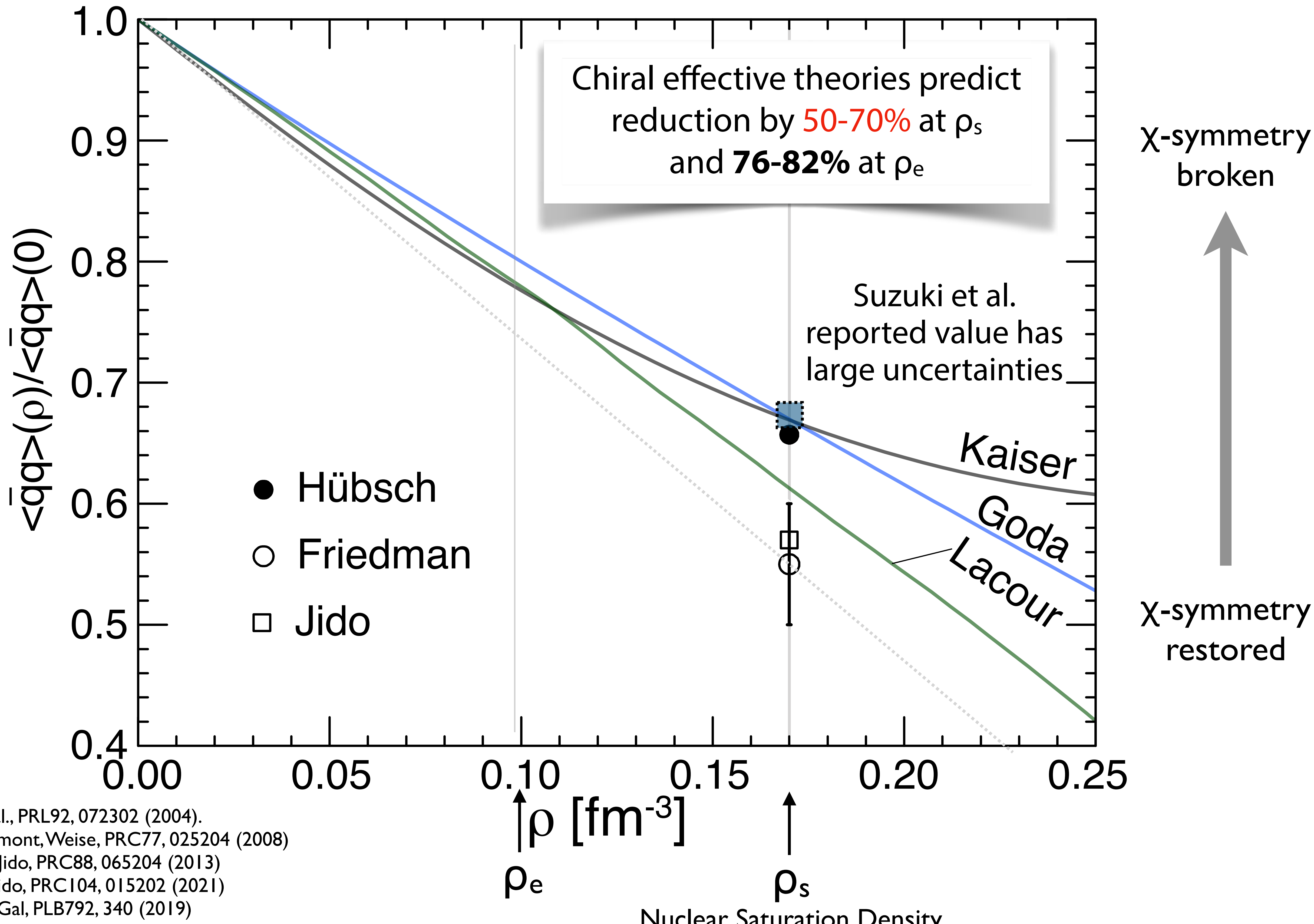
Lattice QCD calculated T dependence of chiral condensate



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

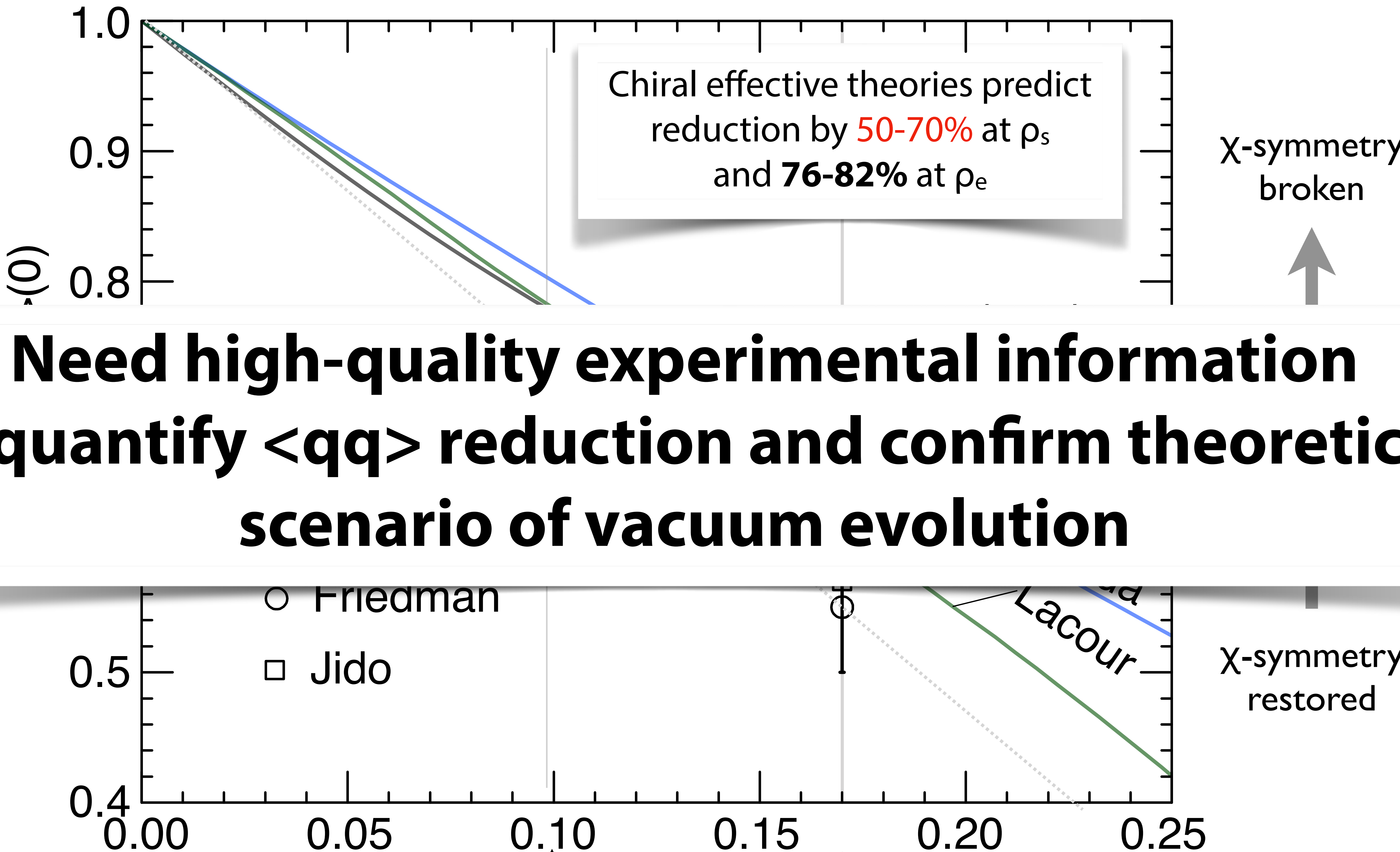
Jon-Ivar Skullerud
PRD105(2022)034504

ρ dependence of <q̄q> known so far



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)

ρ dependence of <q̄q> known so far



Need high-quality experimental information to quantify <qq> reduction and confirm theoretical scenario of vacuum evolution

ρ [fm^{-3}]

ρ_e

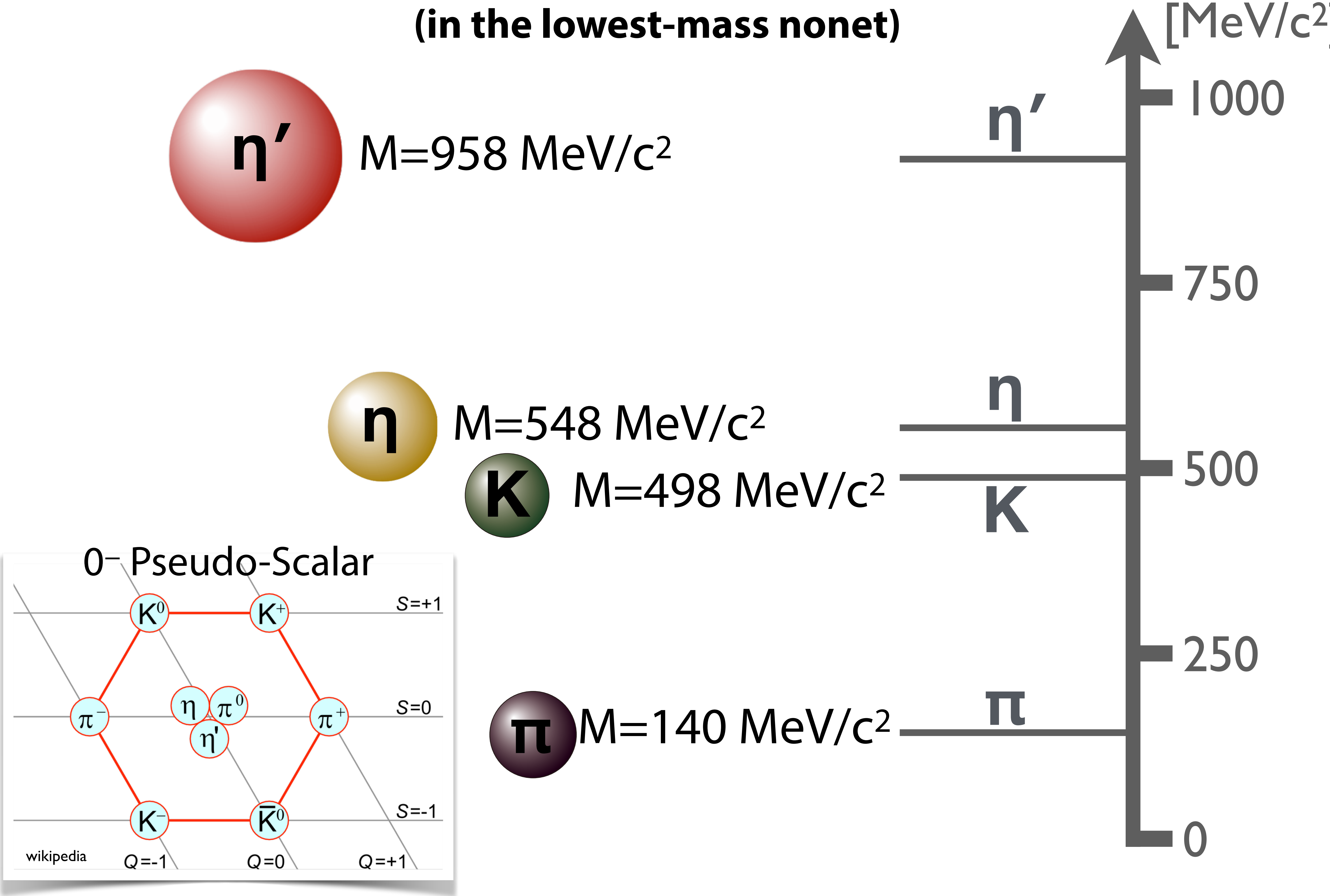
ρ_s

Nuclear Saturation Density

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)

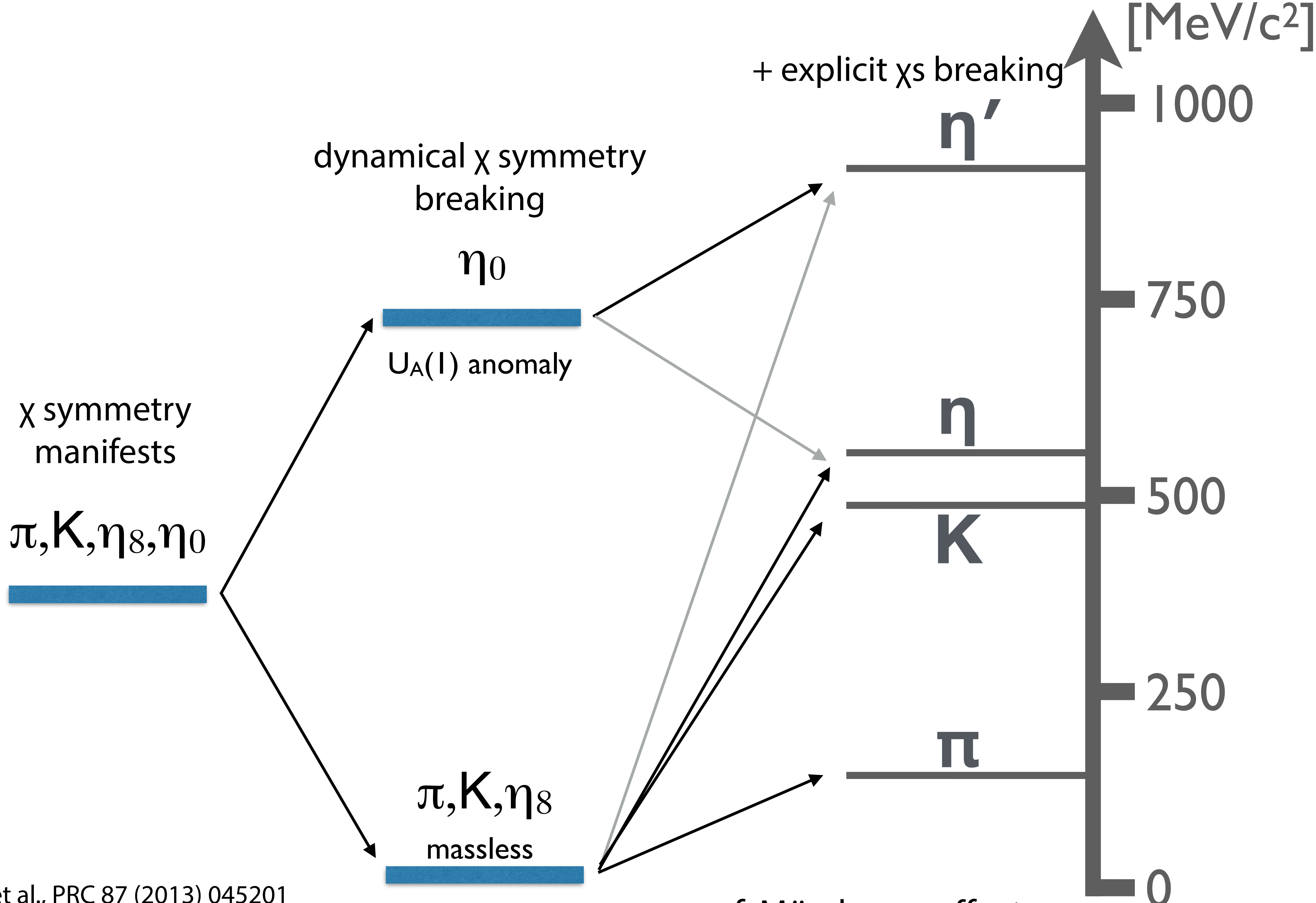
Pseudo-scalar mesons

(in the lowest-mass nonet)



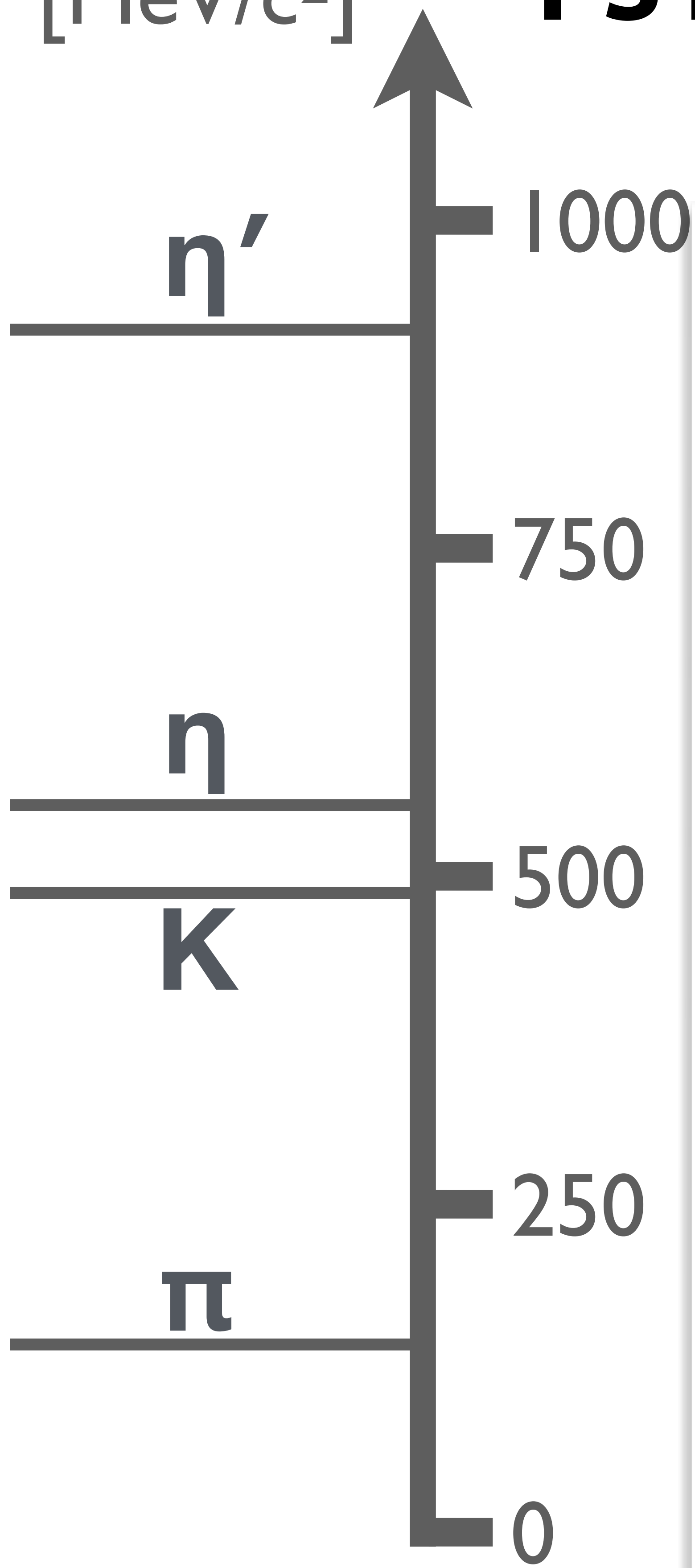
Masses of Pseudo-Scalar Mesons

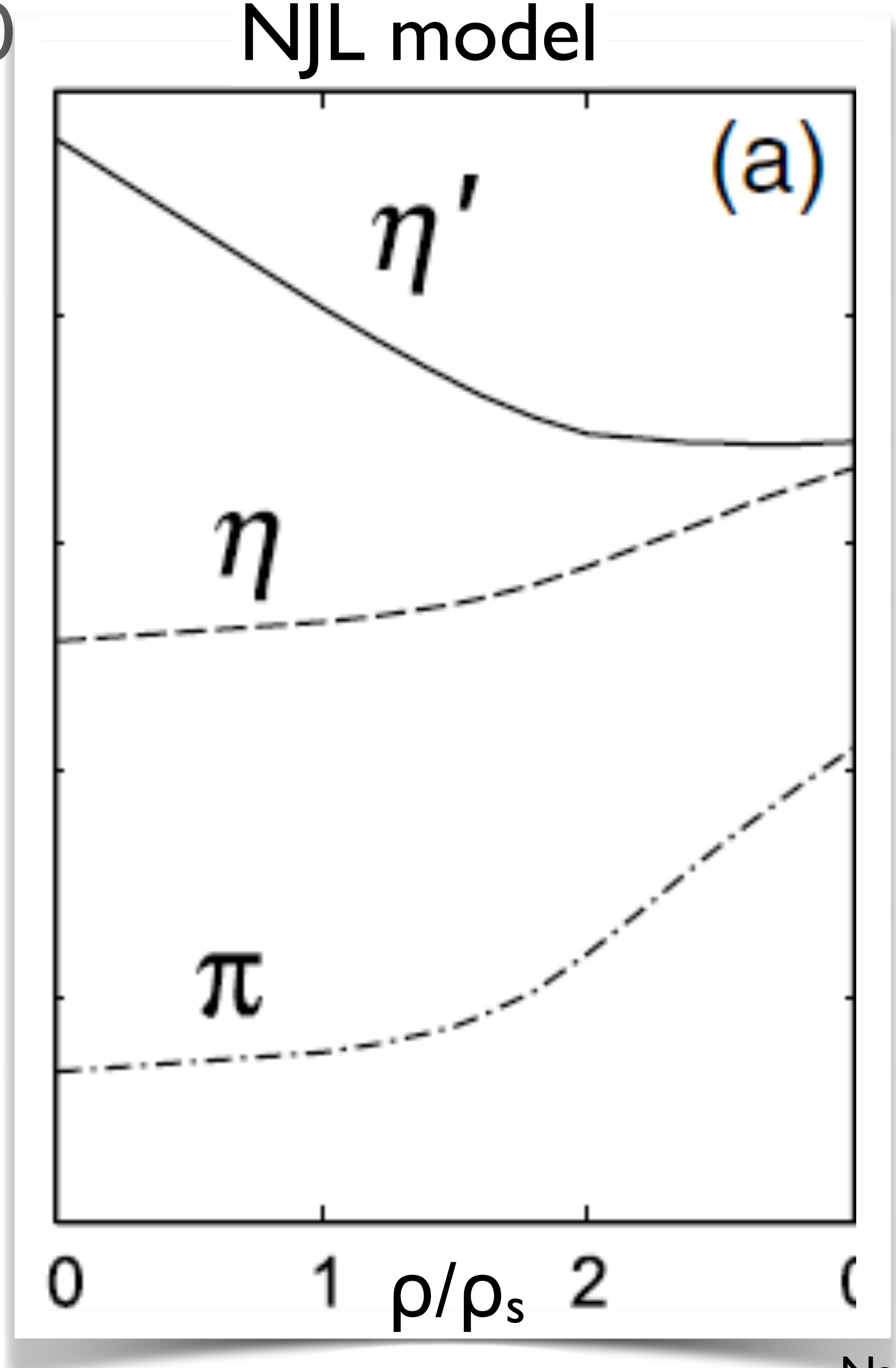
with various symmetry breaking patterns



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

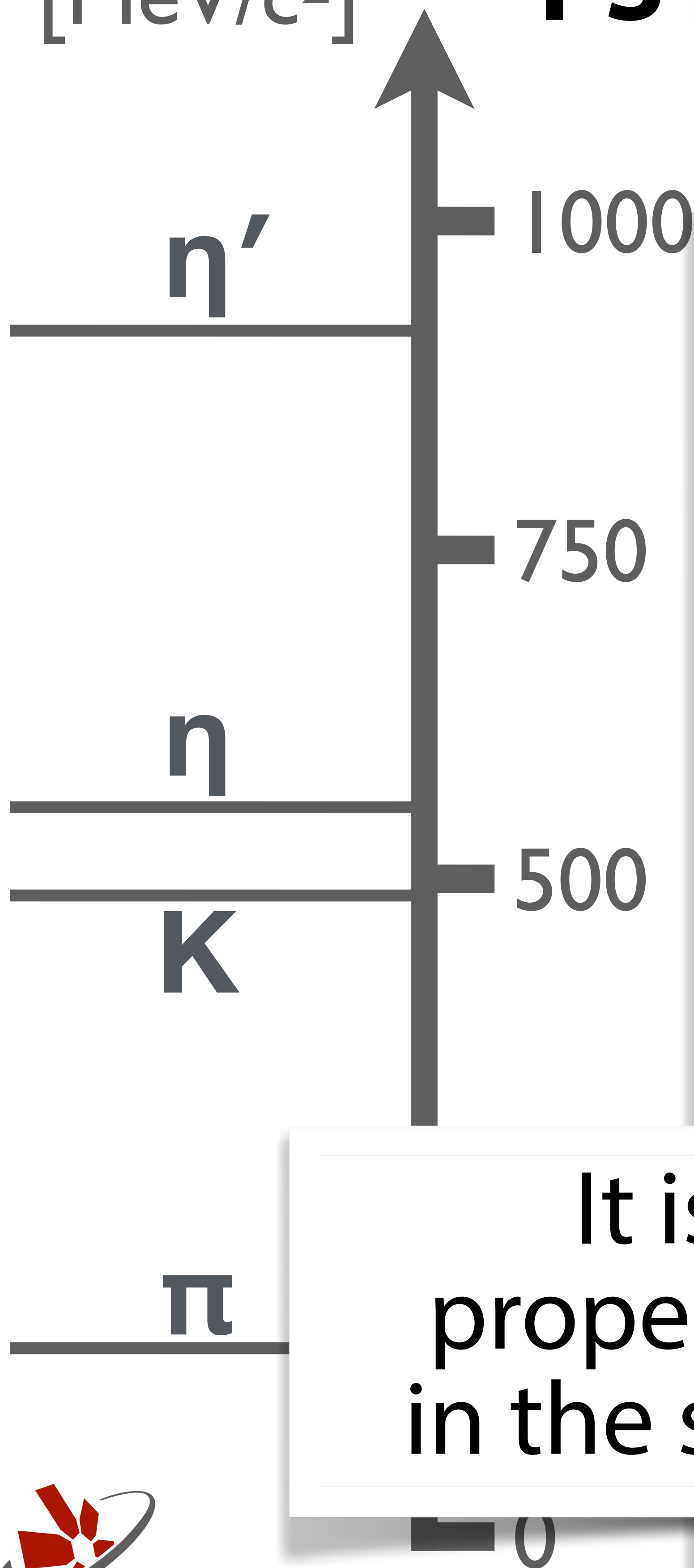
PS in high density medium

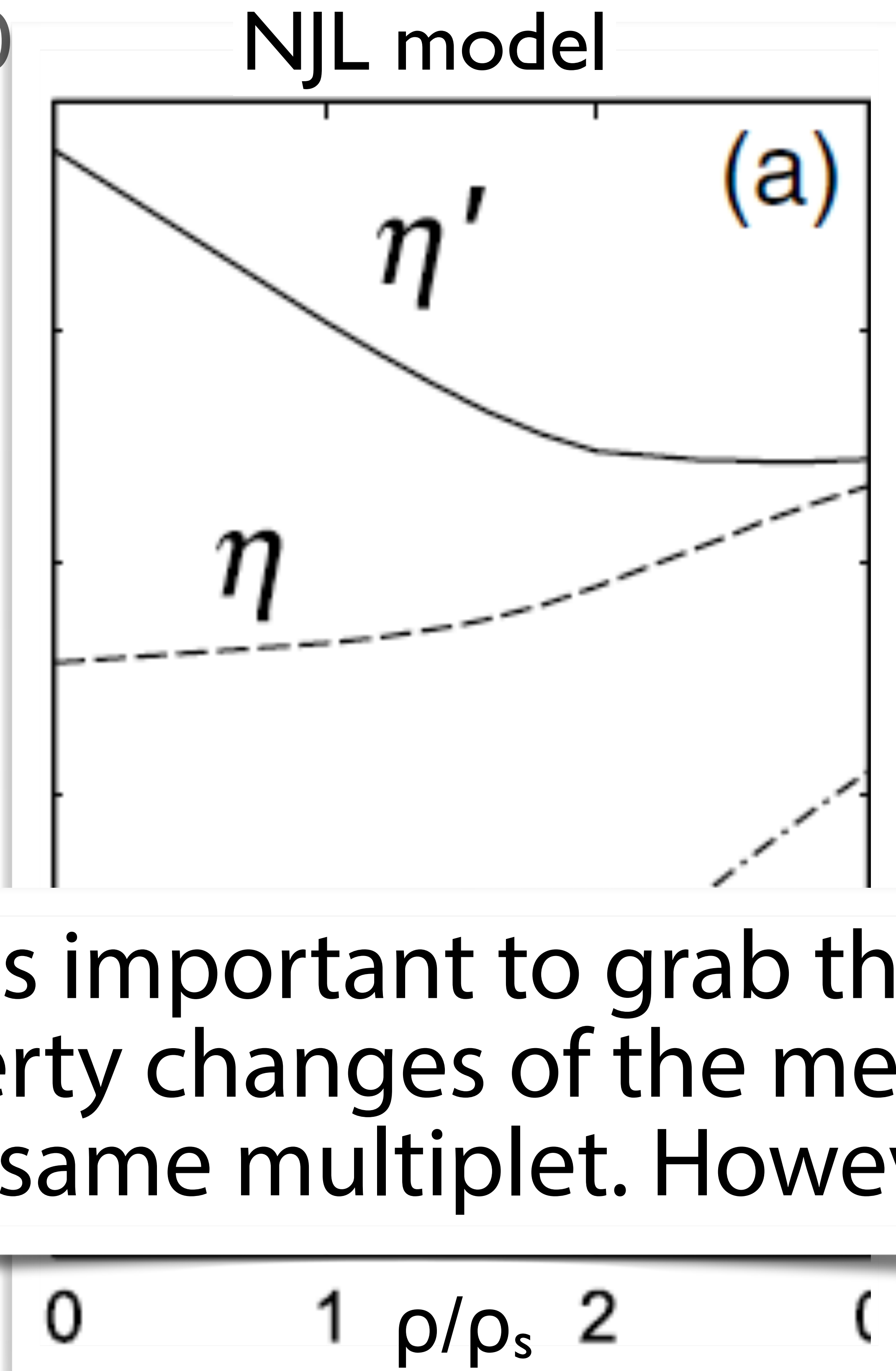




Nagahiro *et al*, PRC 74, 045203 (2006)

PS in high density medium





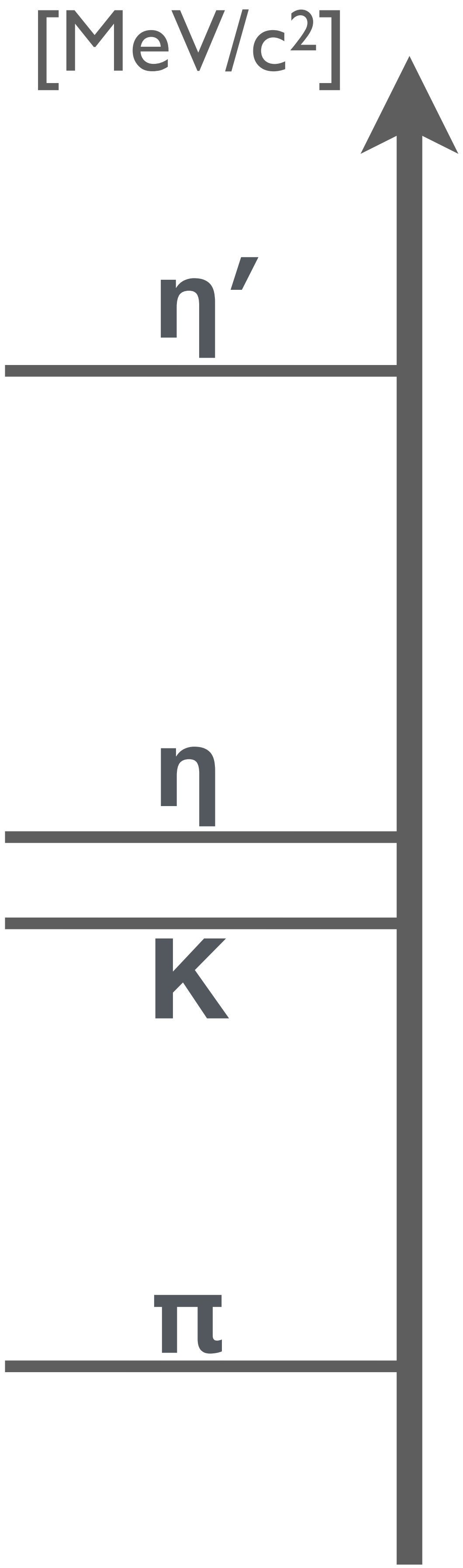
REMARK

⊿m between
η-η′, (σ, π)
(ρ, a_1) are important

It is important to grab the property changes of the mesons in the same multiplet. However…

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

Topics in mesic atoms/nuclei

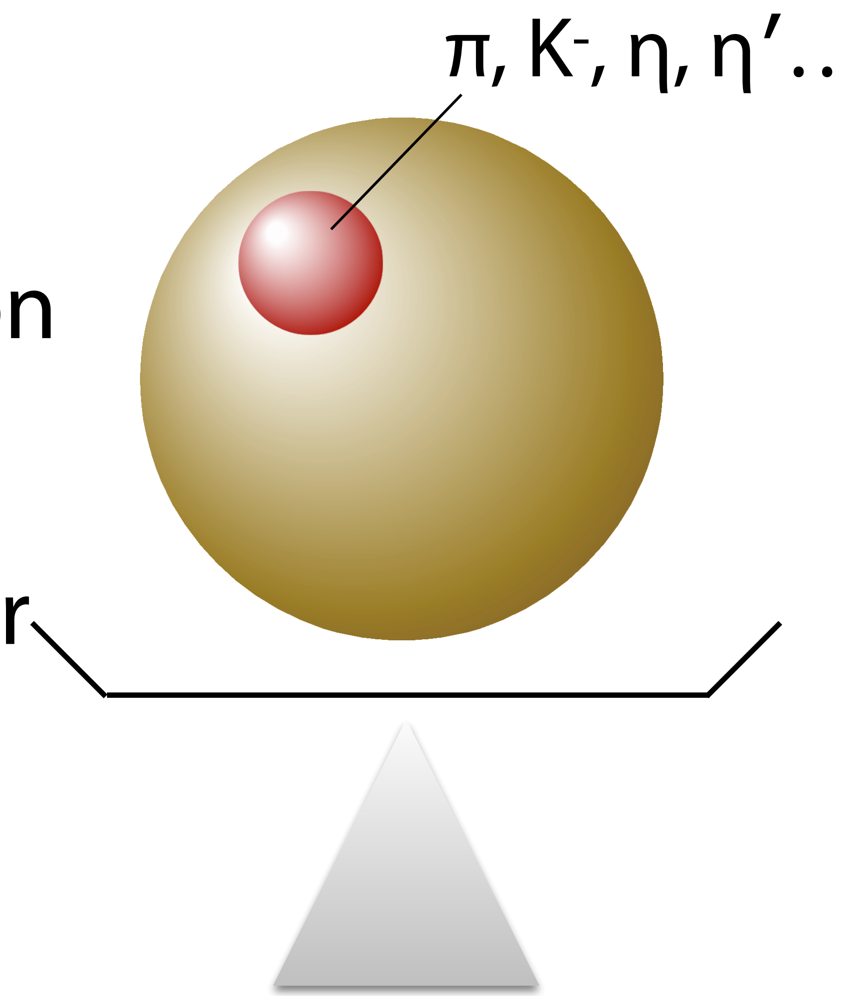


→ U$_A$(1) anomaly
gluon dynamics
instanton-induced interaction

Strong coupling to N*(1535)
→ χ-symmetry in baryon sector
→ Kaonic nuclei $\rho > \rho_0$
Λ(1405)
Relation to neutron stars

→ quantitative est. of chiral condensate
sensitivity to nuclear structure (neutron skins)

Hadrons as probes

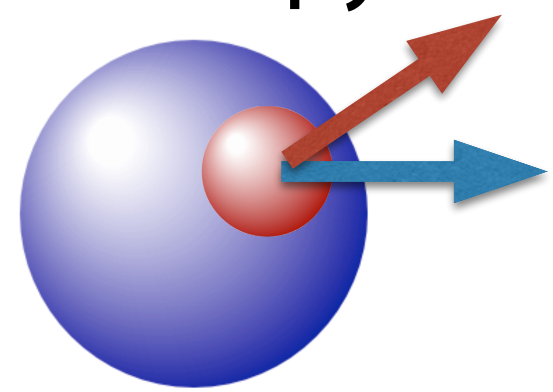


Experimental spectroscopy of meson in nuclear matter

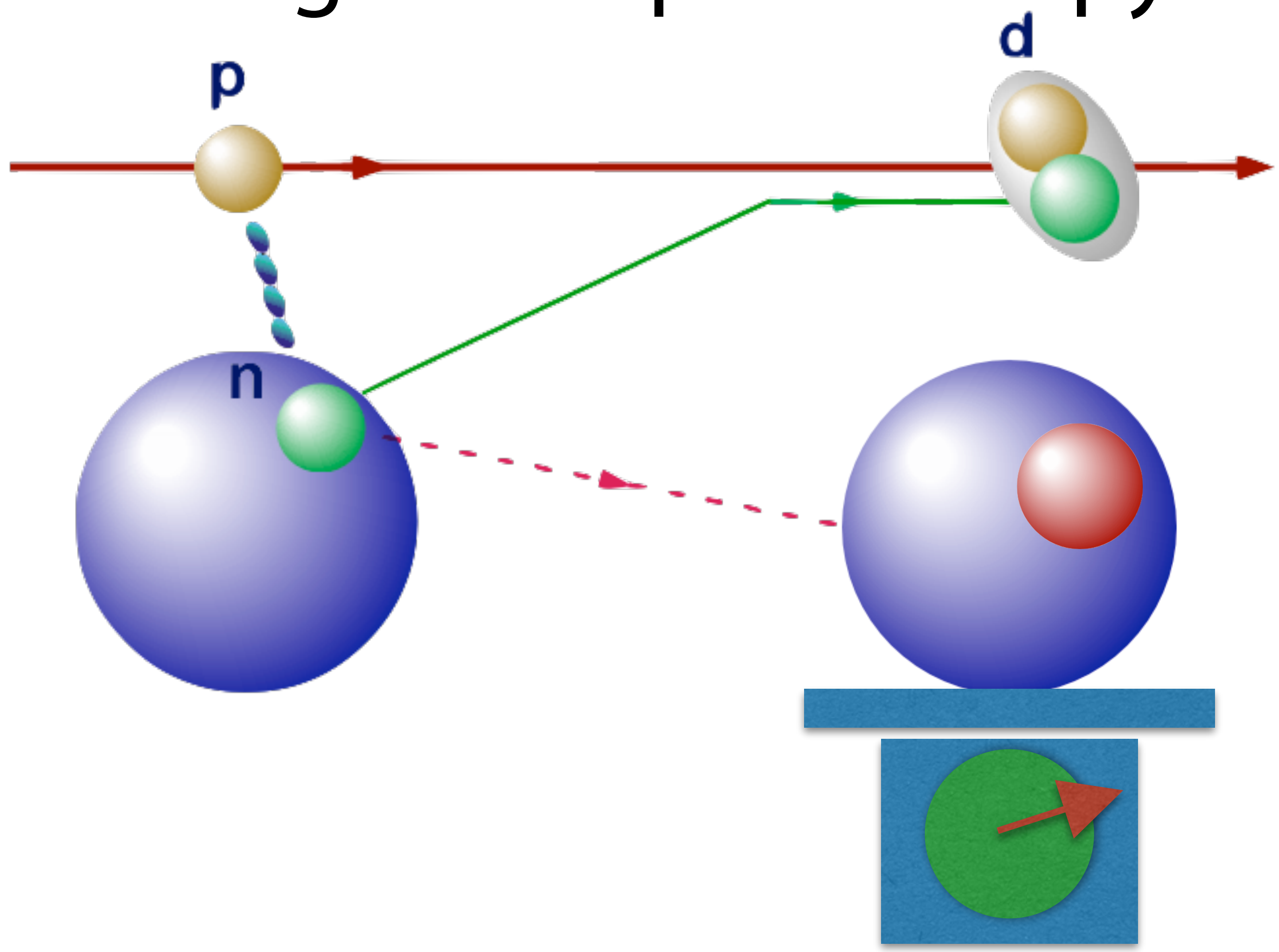
Experimental spectroscopy of meson in nuclear matter

Invariant mass spectroscopy

ex. $\phi \rightarrow e^{+}e^{-}$

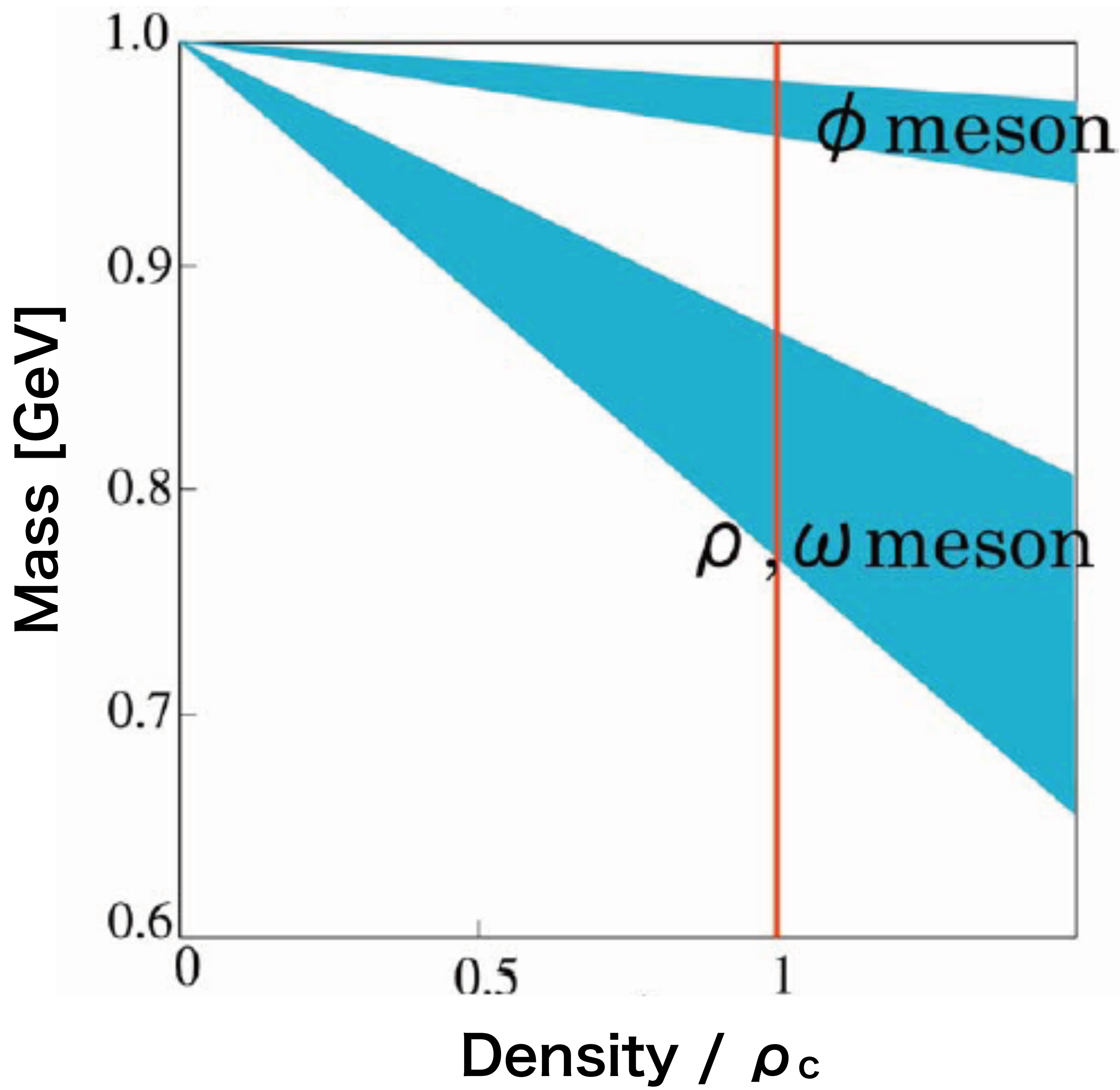


Missing mass spectroscopy



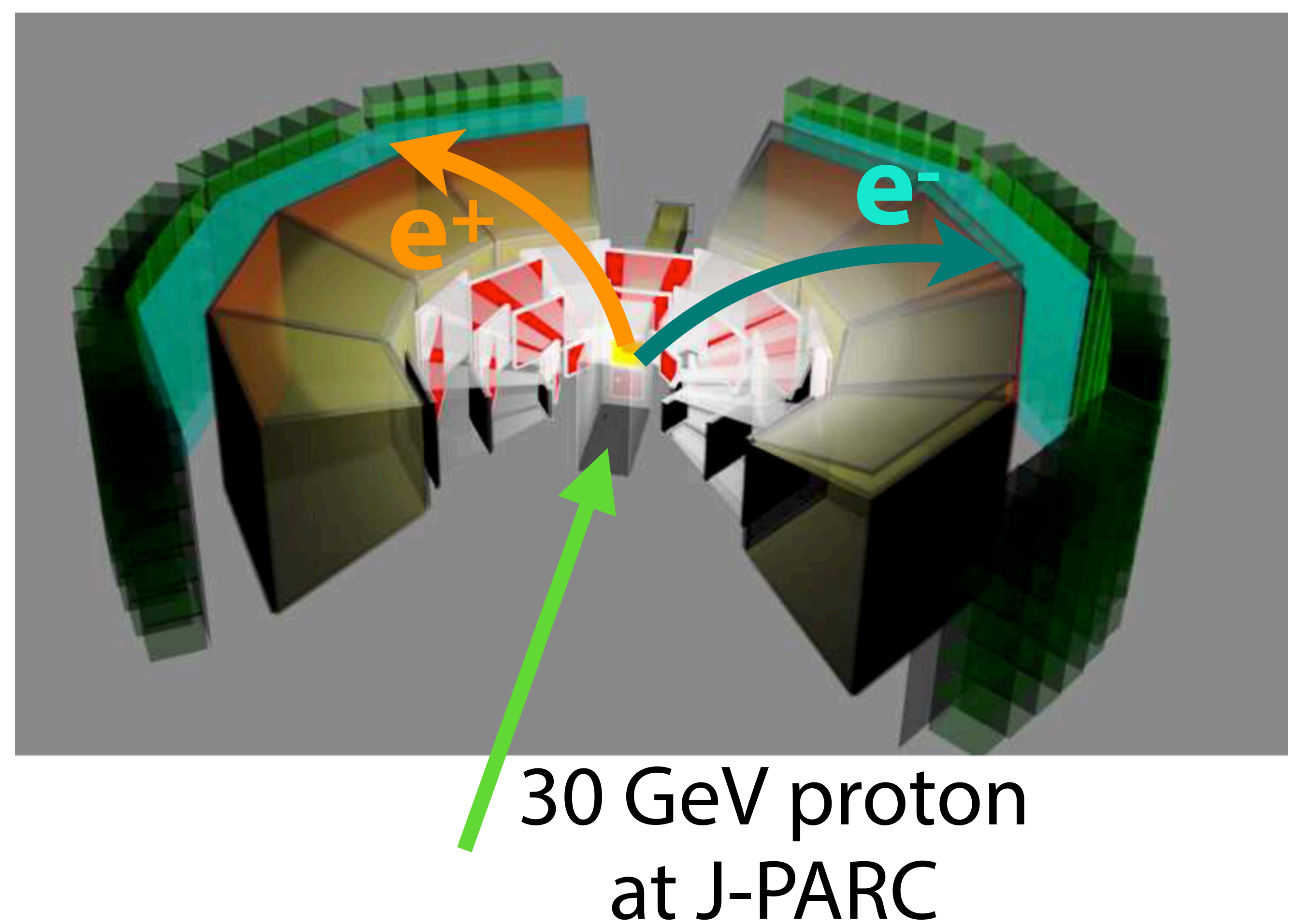
Meson masses and QCD medium effect

Vector meson mass modification (c.f. J-PARC E16)



p+A → ϕ in A

ϕ→e⁺e⁻



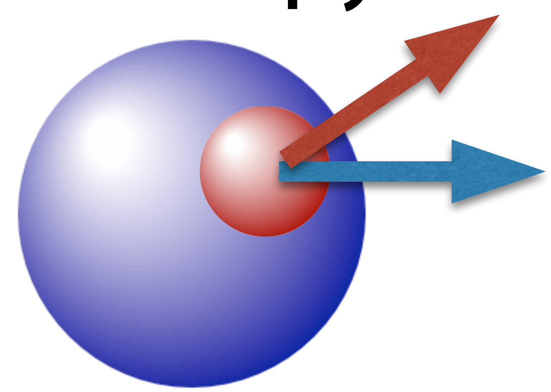
T.Hatsuda, S.H.Lee,
Phys. Rev. **C46** (1992) R34

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

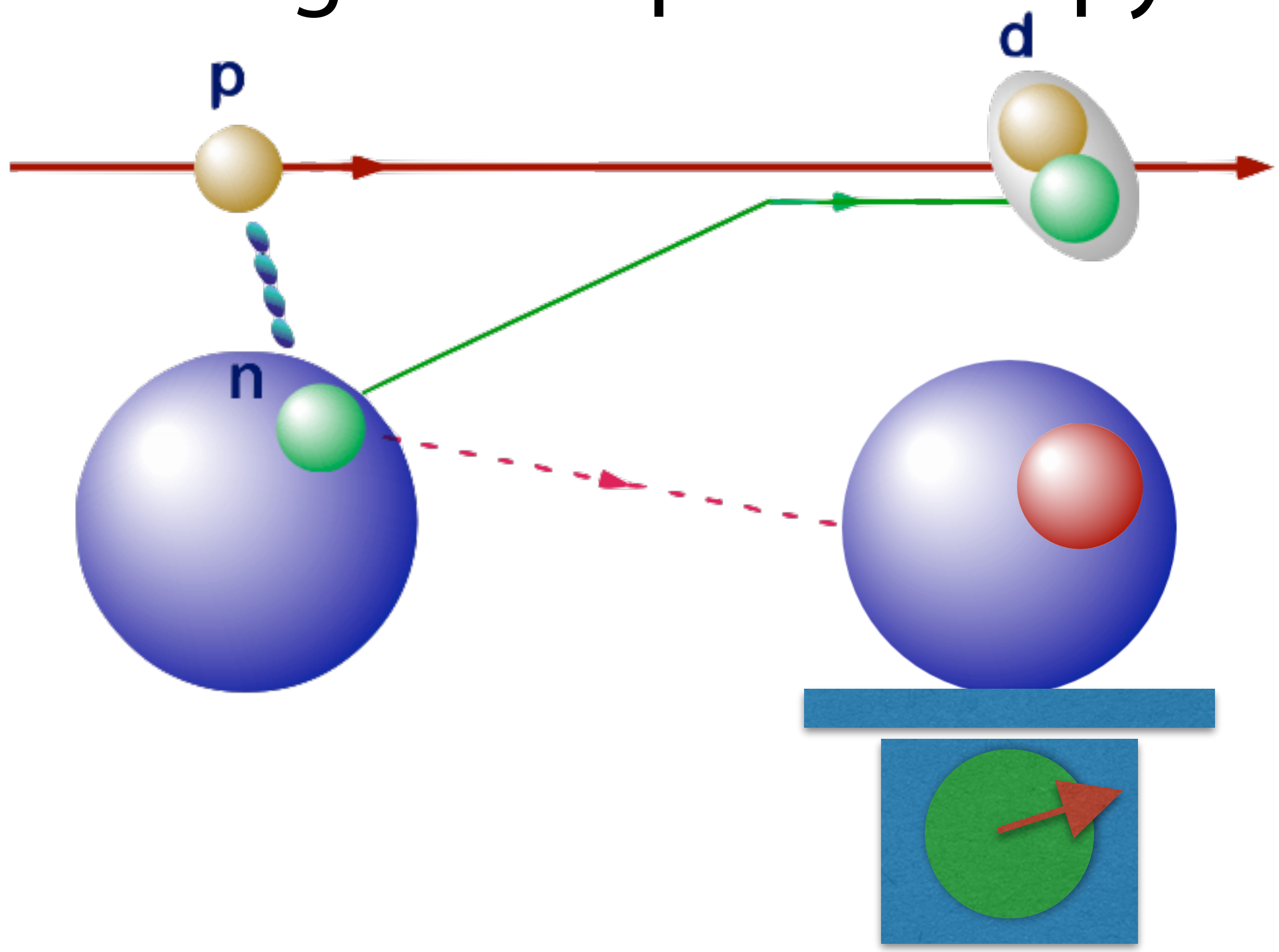
Experimental spectroscopy of meson in nuclear matter

Invariant mass spectroscopy

ex. $\phi \rightarrow e^+e^-$



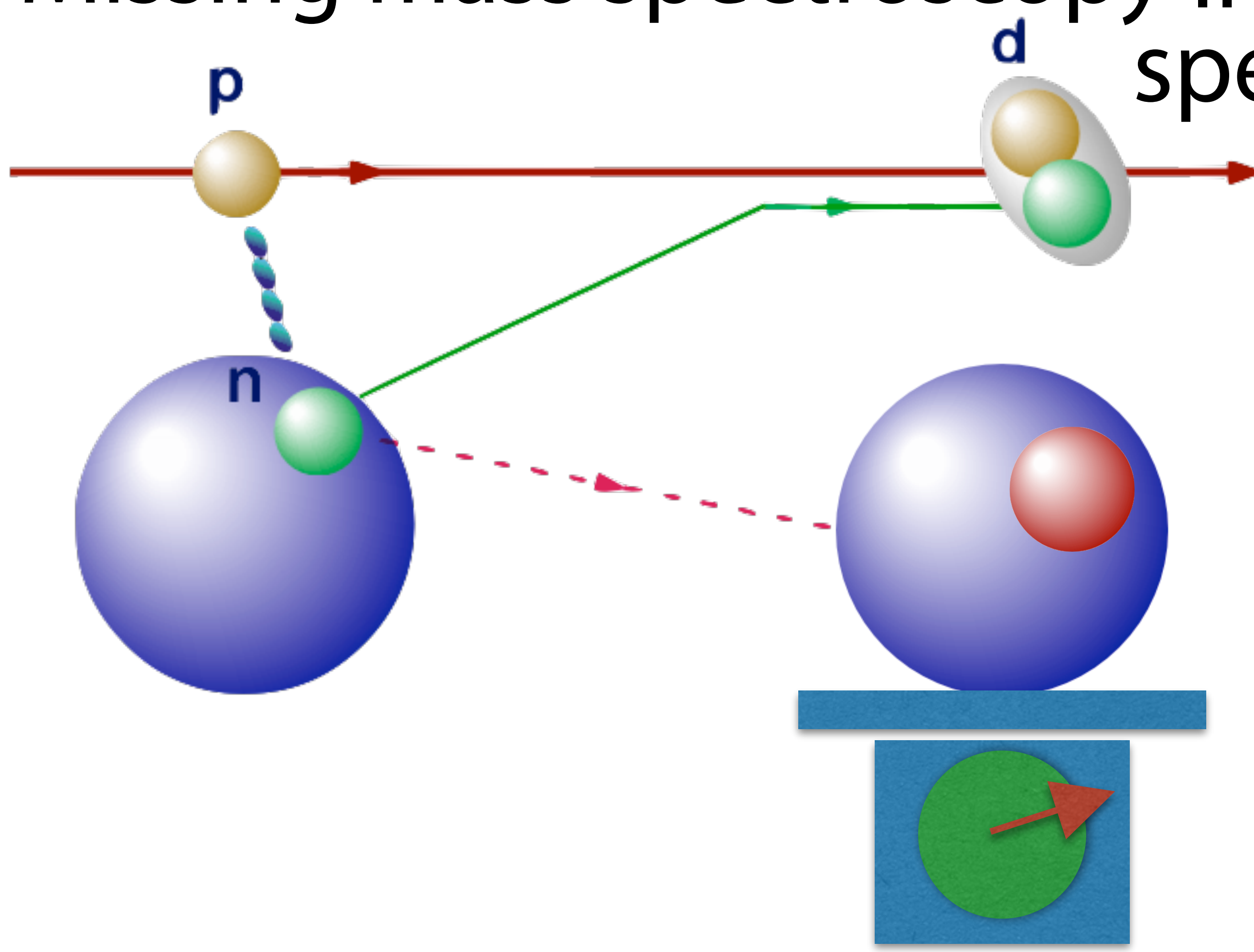
Missing mass spectroscopy



Experimental spectroscopy of meson in nuclear matter

- **Quantum object**
  including meson + nuclei
- **Lorentz invariant**
  isolated object in vacuum

Missing mass spectroscopy in reaction spectroscopy

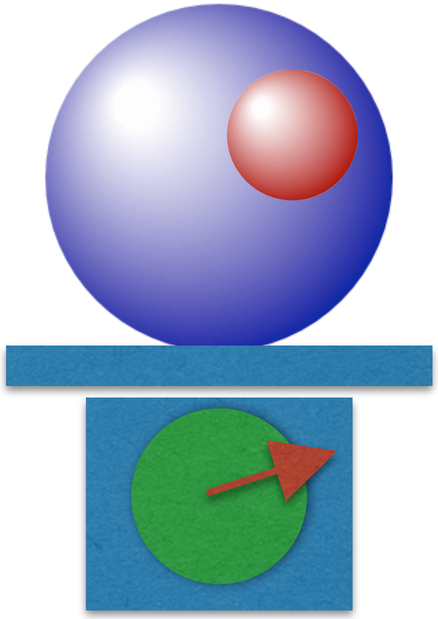


Experimental spectroscopy of meson in nuclear matter

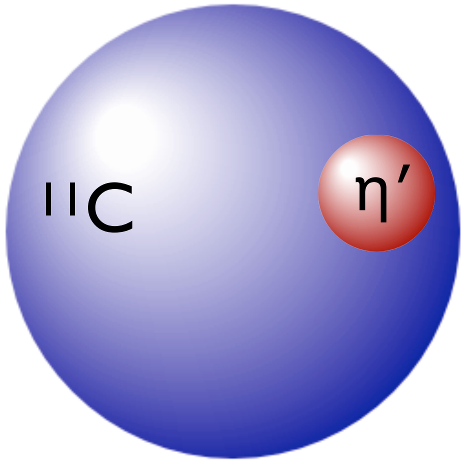
- **Quantum object**
  including meson + nuclei
- **Lorentz invariant**
  isolated object in vacuum

Missing mass spectroscopy in reaction spectroscopy

- **η′-mesic nuclei**
- **Pionic atoms**



Search for η′-mesic nuclei



System of an η′ meson and a nucleus bound by the strong interaction

Spectroscopy η′-mesic nuclei provides information of the strong interaction leading to understanding of the origin of the very large mass of η′ due to **U_A(1) anomaly**

η problem

Mass of η′ is much larger than quark model expectations

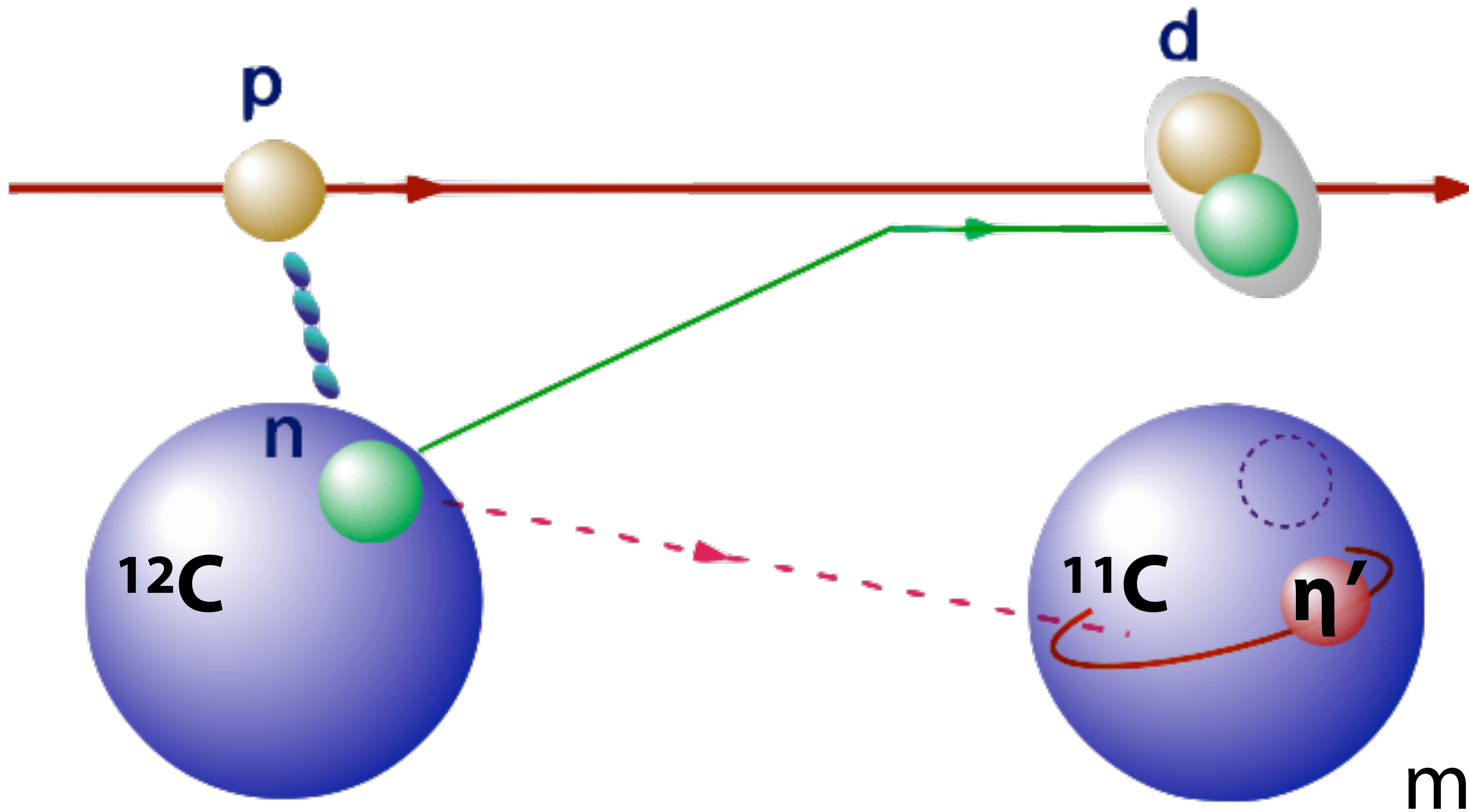
NiSHiNA CENTER

Jido et al., PRC85, 032201(R)(2012)

η′ Mesic Nuclei in (*p,d*) Reaction

Missing mass measurement of

(p,d) = η′ transfer + neutron pickup reaction

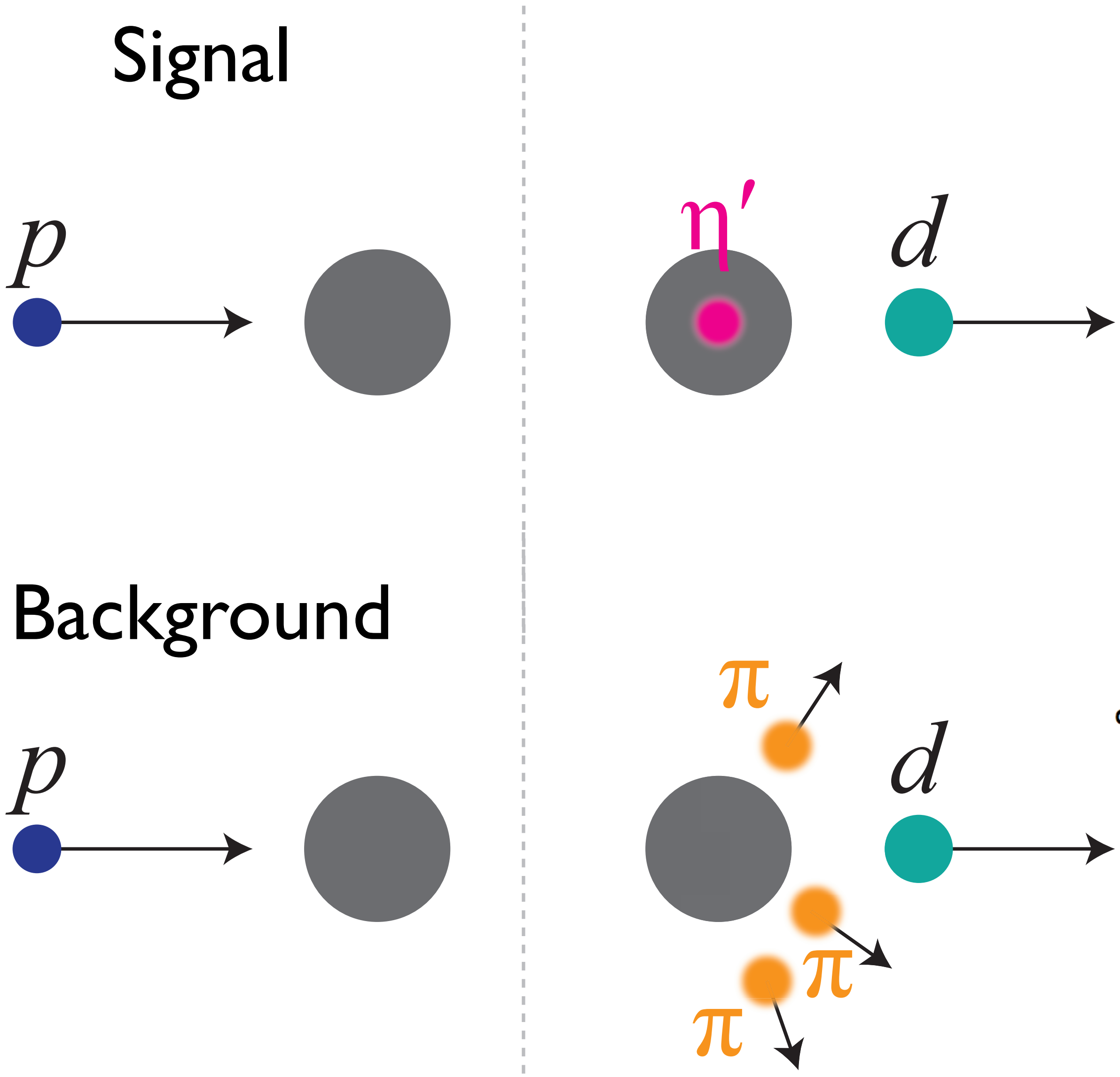


η′ × ¹¹C mesic nuclei

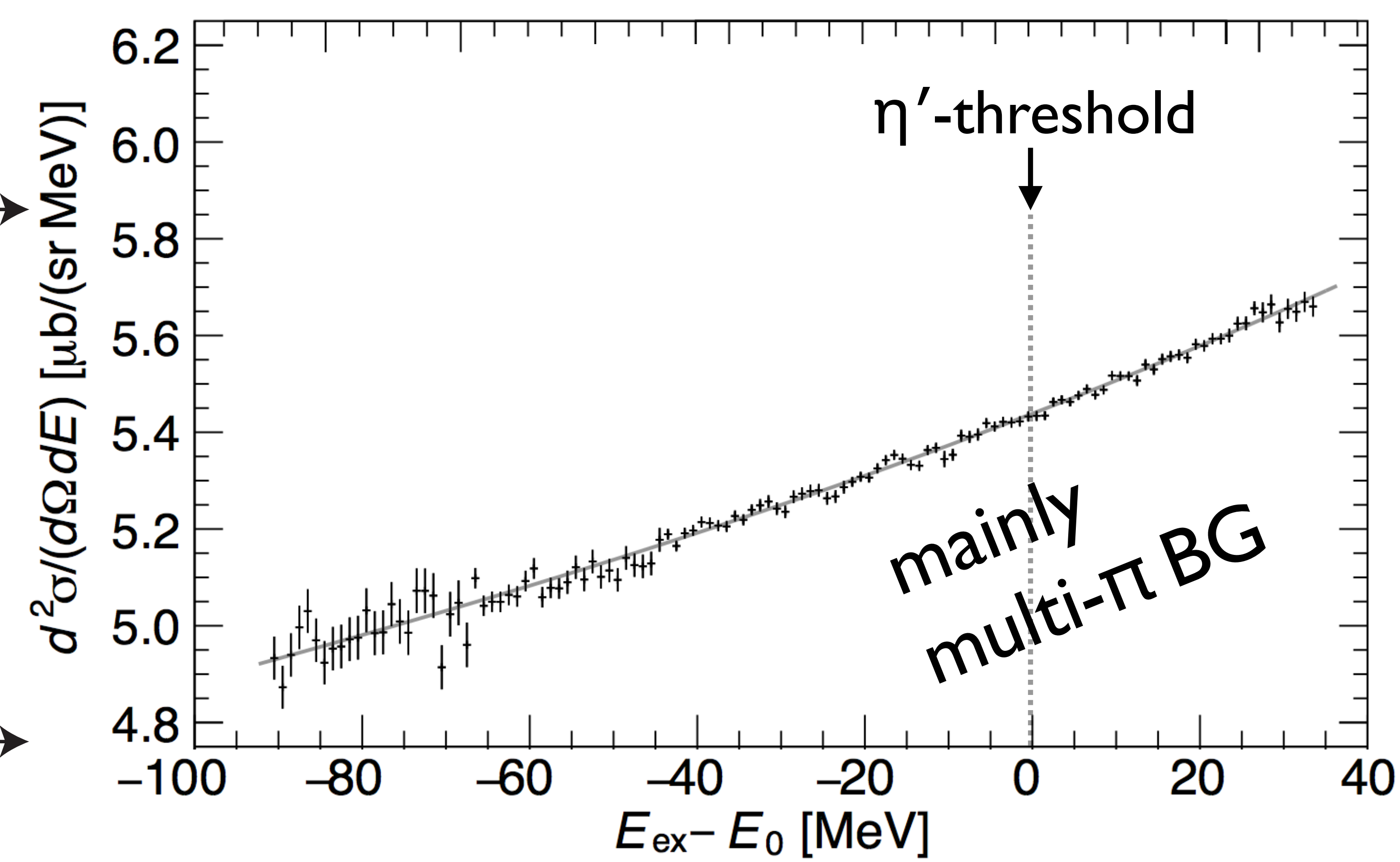
$T_p = 2.50$ GeV → q ~ 400 MeV/c

KI, Fujioka et al., PTP 128 (12) 601.

Step1: Missing-mass of (*p,d*) inclusive measurement



S437 ^{12}C(*p,d*) in 2014 at FRS/GSI



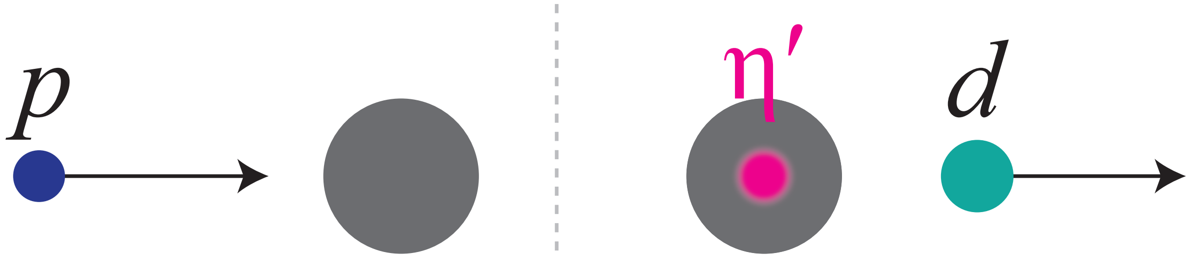
Y.K. Tanaka et al., Phys. Rev. Lett. **117**, 202501(2016)

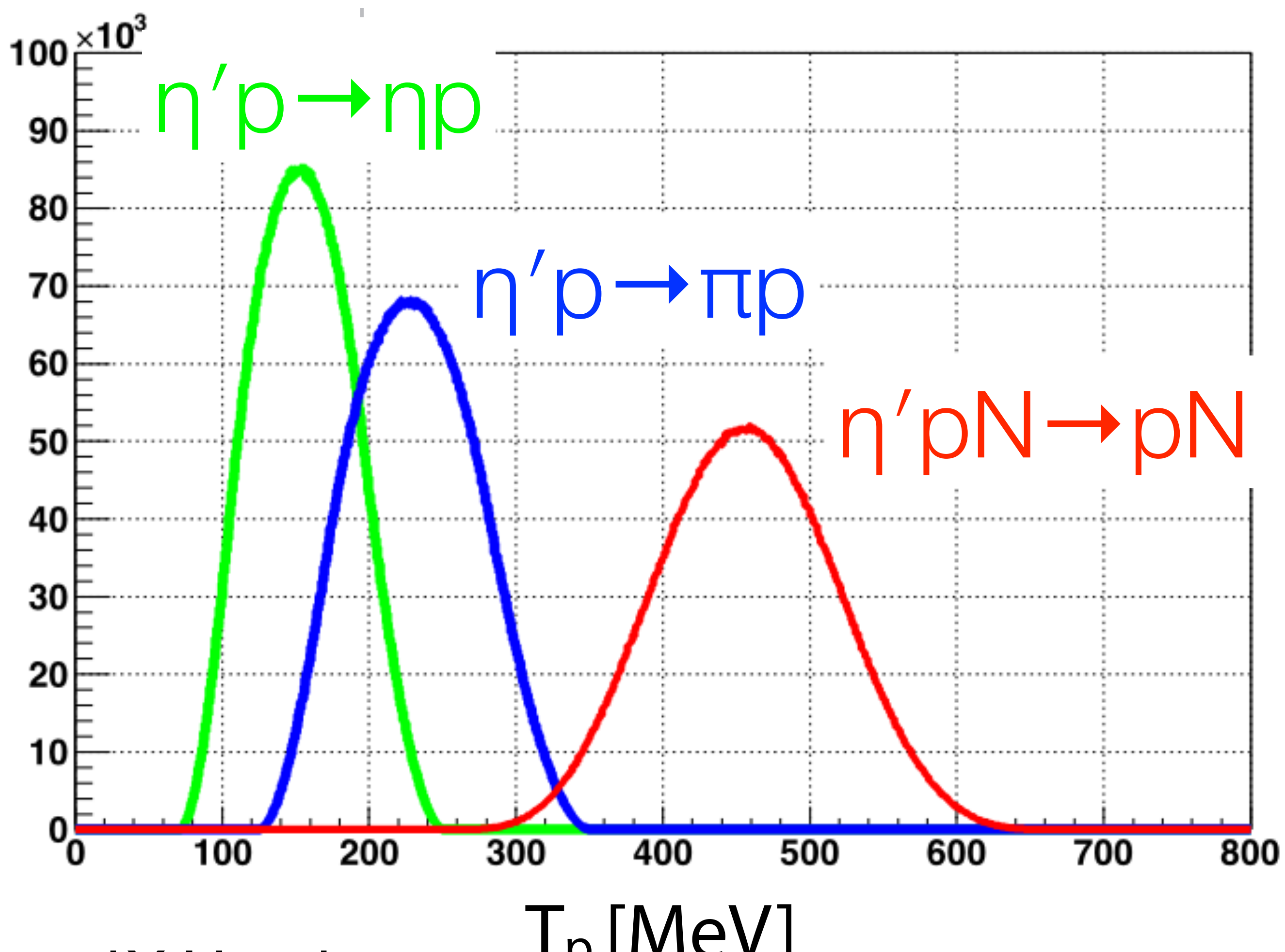
We achieved extremely high statistical sensitivity demonstrating very good performance of FRS.
But, no peak was observed. Major BG=multi π.
S/BG cross sections must be ~ 1/100

NiSHiNA CENTER

Step 2: Semi-exclusive measurement of $^{12}C(p,dp)$ reaction (GSI-S490, 2022)

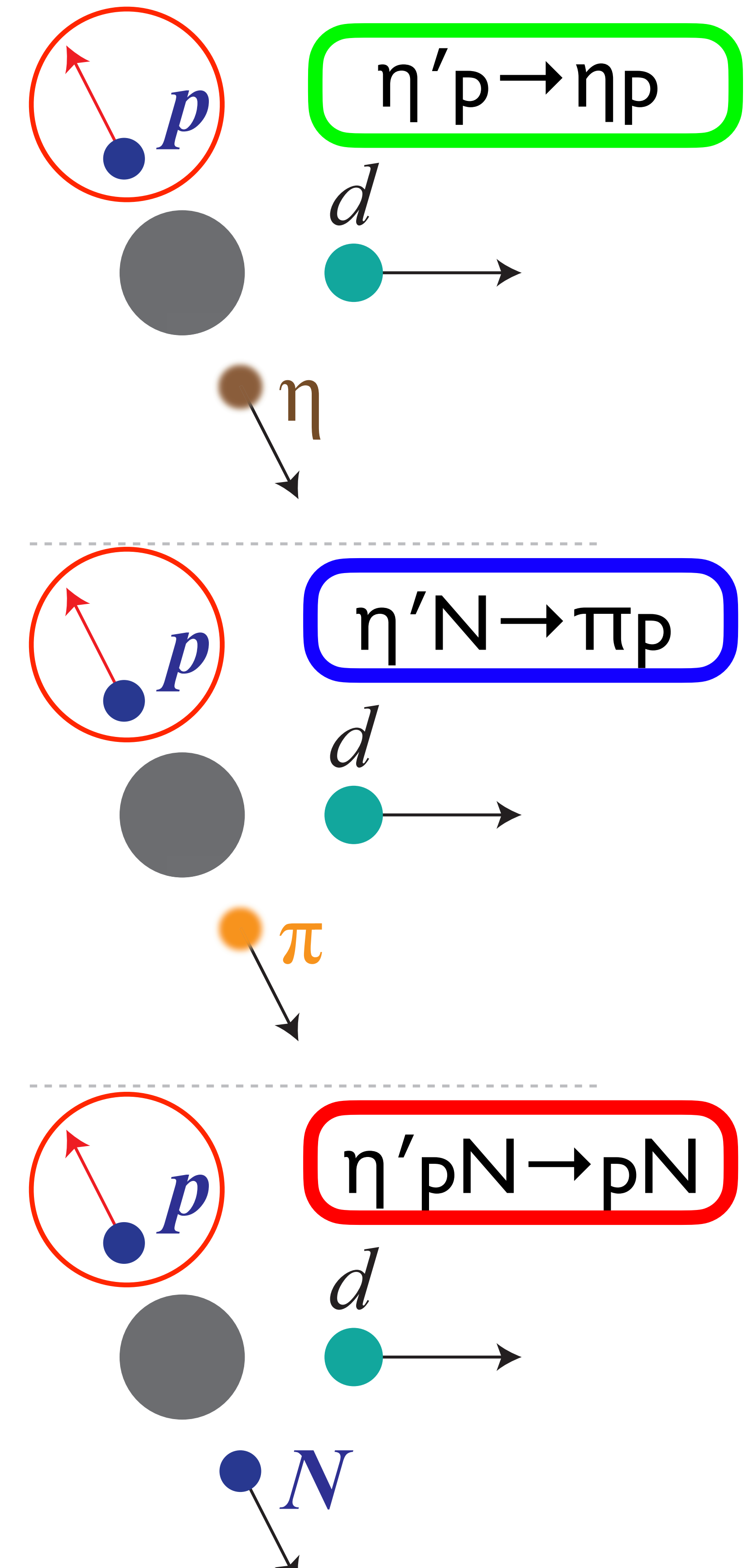
Signal





Y.K. Tanaka and Y. Higashi

3 major decay modes of η′-mesic nuclei

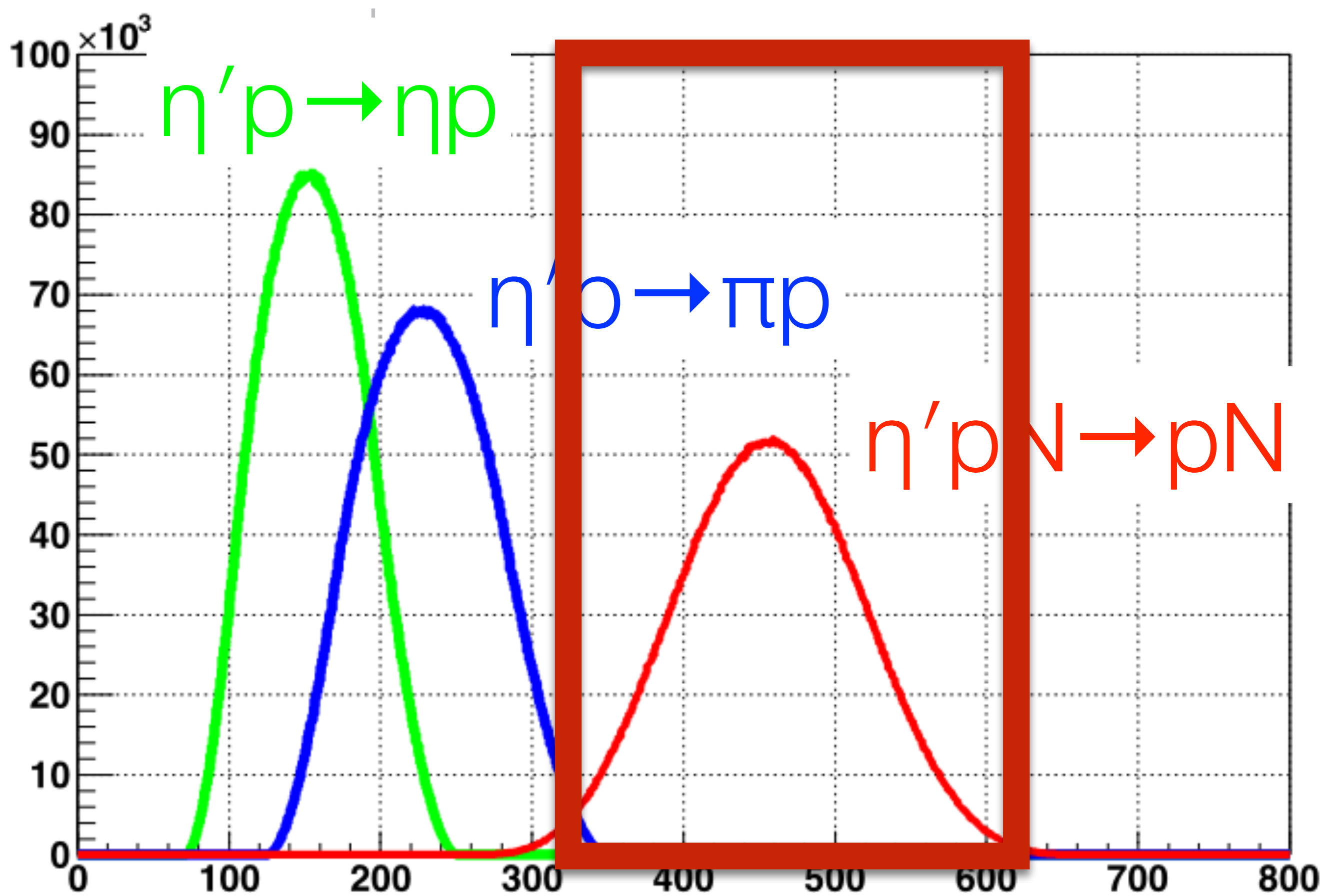


Other candidate channels: ωp or KΛ

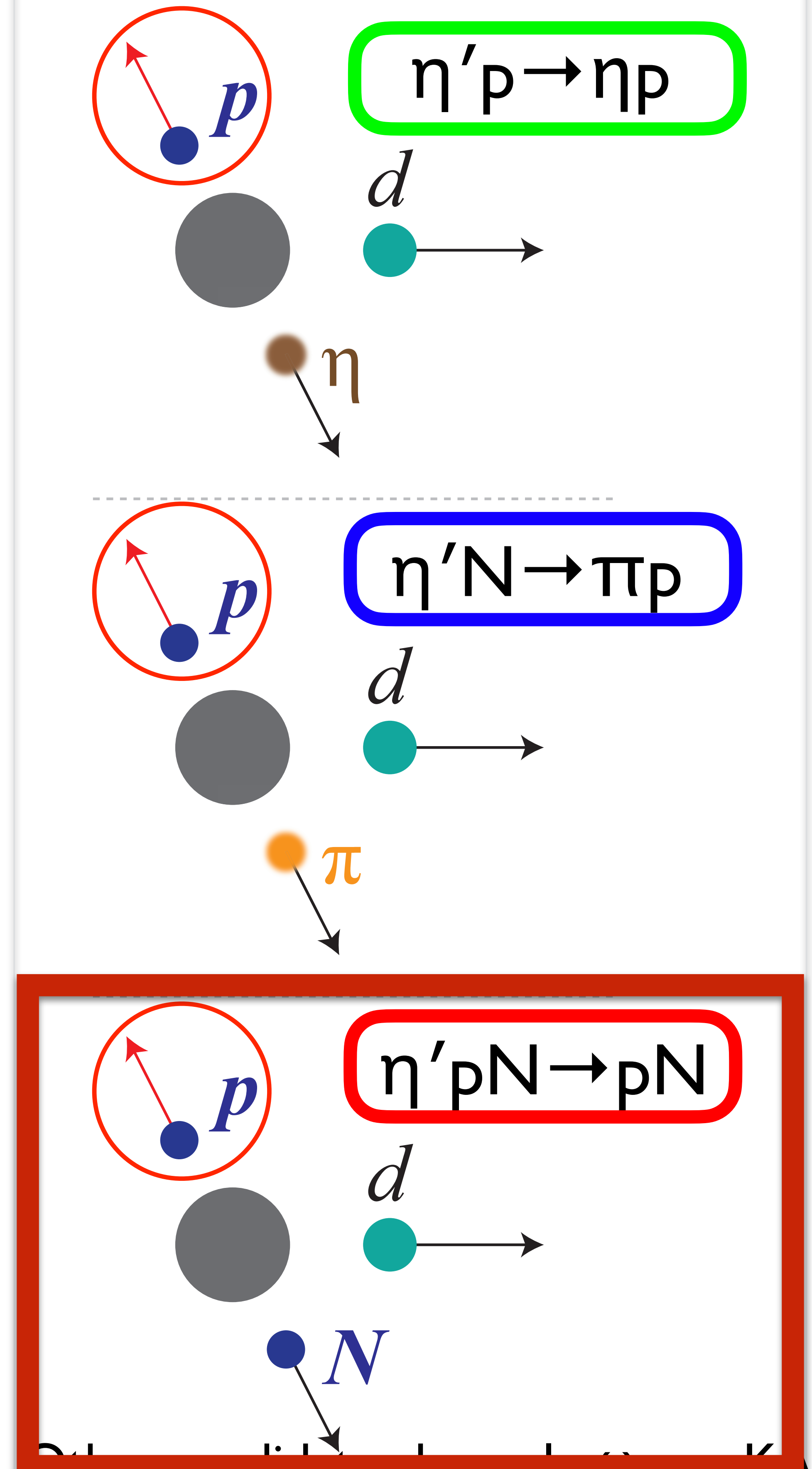
Step 2: **Semi-exclusive measurement of $^{12}C(p,dp)$ reaction (GSI-S490, 2022)**

p

Detect *p* (300-600 MeV) emitted in the decay of η′-nuclei for semi-exclusive measurement.
f ~ 100 improvement in S/BG

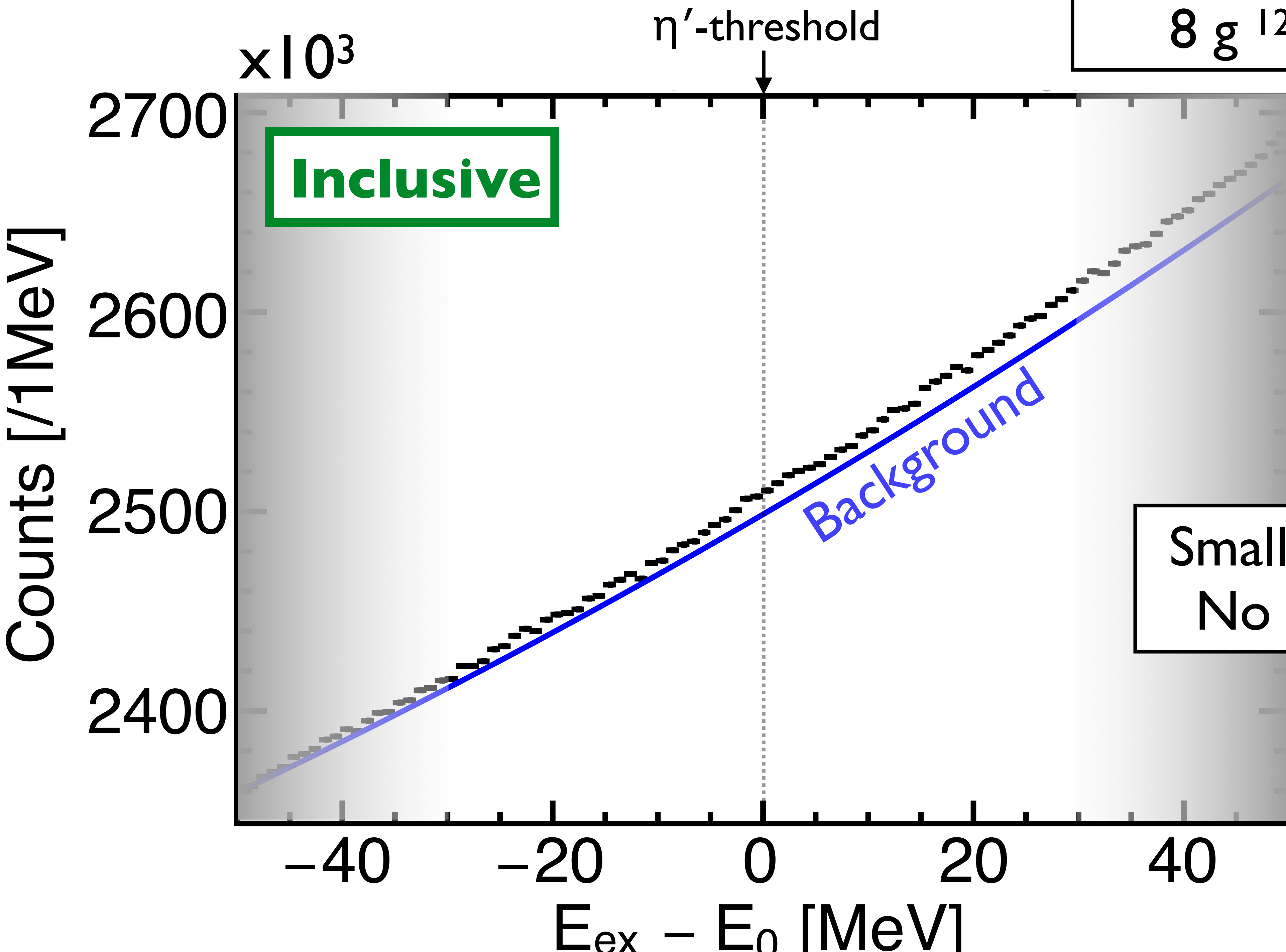


3 major decay modes of η′-mesic nuclei



Expected spectrum in 4 days of DAQ at FRS

T_p = 2.5 GeV, $^{12}C(p,d)$



p 2.5 GeV, 2.5x10⁸/s,
8 g ¹²C target

Small S/BG
No peak

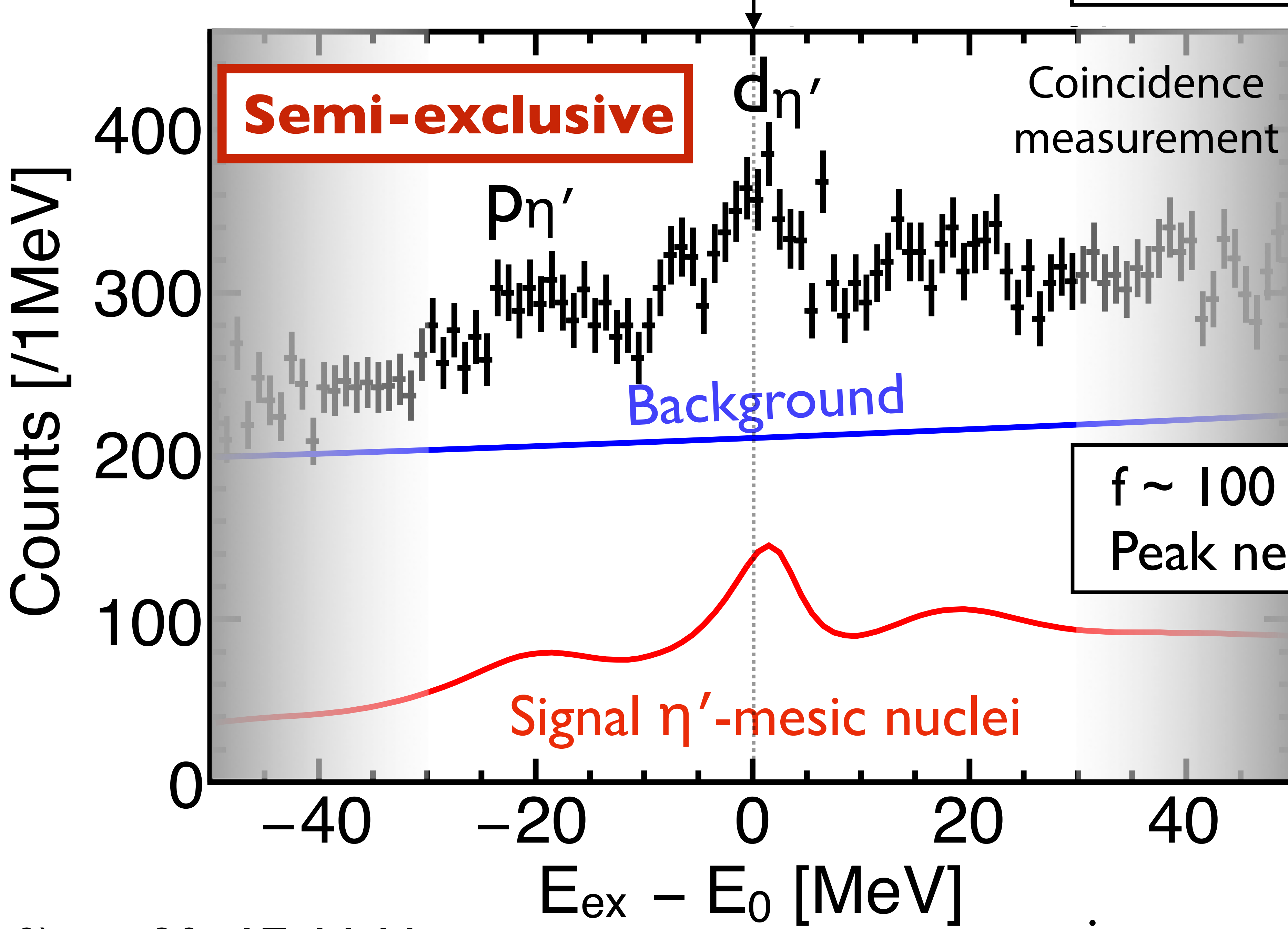
A: U(r=0) = −90−17i MeV
a parameter set of chiral unitary model

microscopic transport simulation

Expected spectrum in 4 days of DAQ at FRS

T_p = 2.5 GeV, $^{12}C(p,dp)$

p 2.5 GeV, 2.5x10^8/s, 8 g ^{12}C target

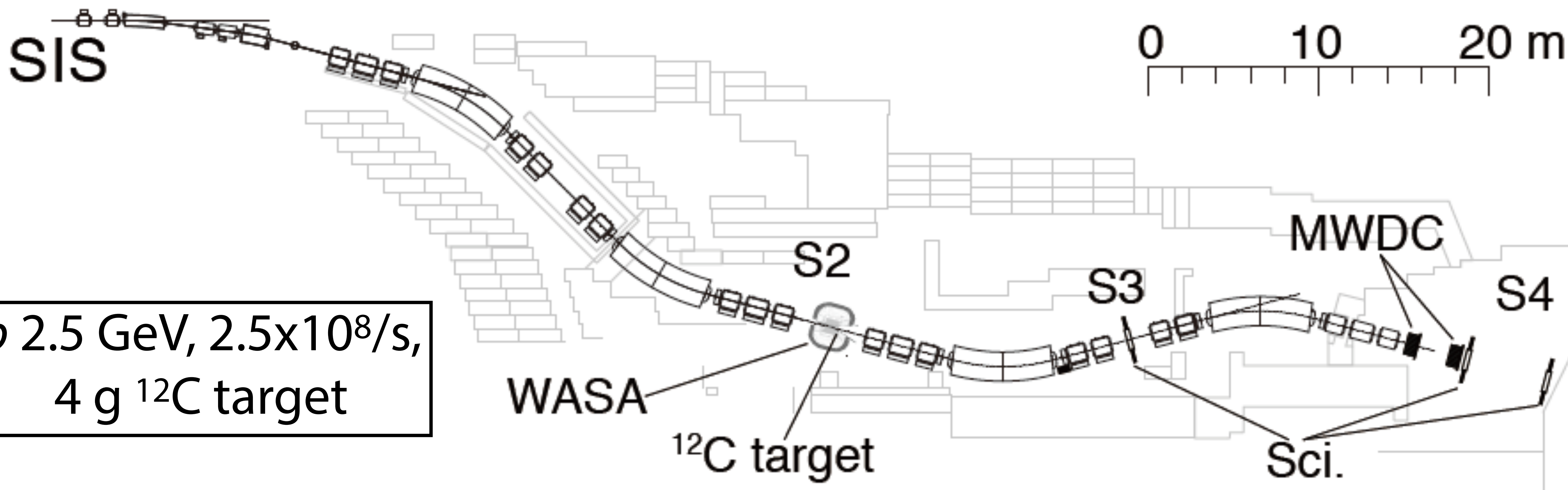


f ~ 100 better S/BG
Peak near threshold

A: U(r=0) = −90−17i MeV
a parameter set of chiral unitary model

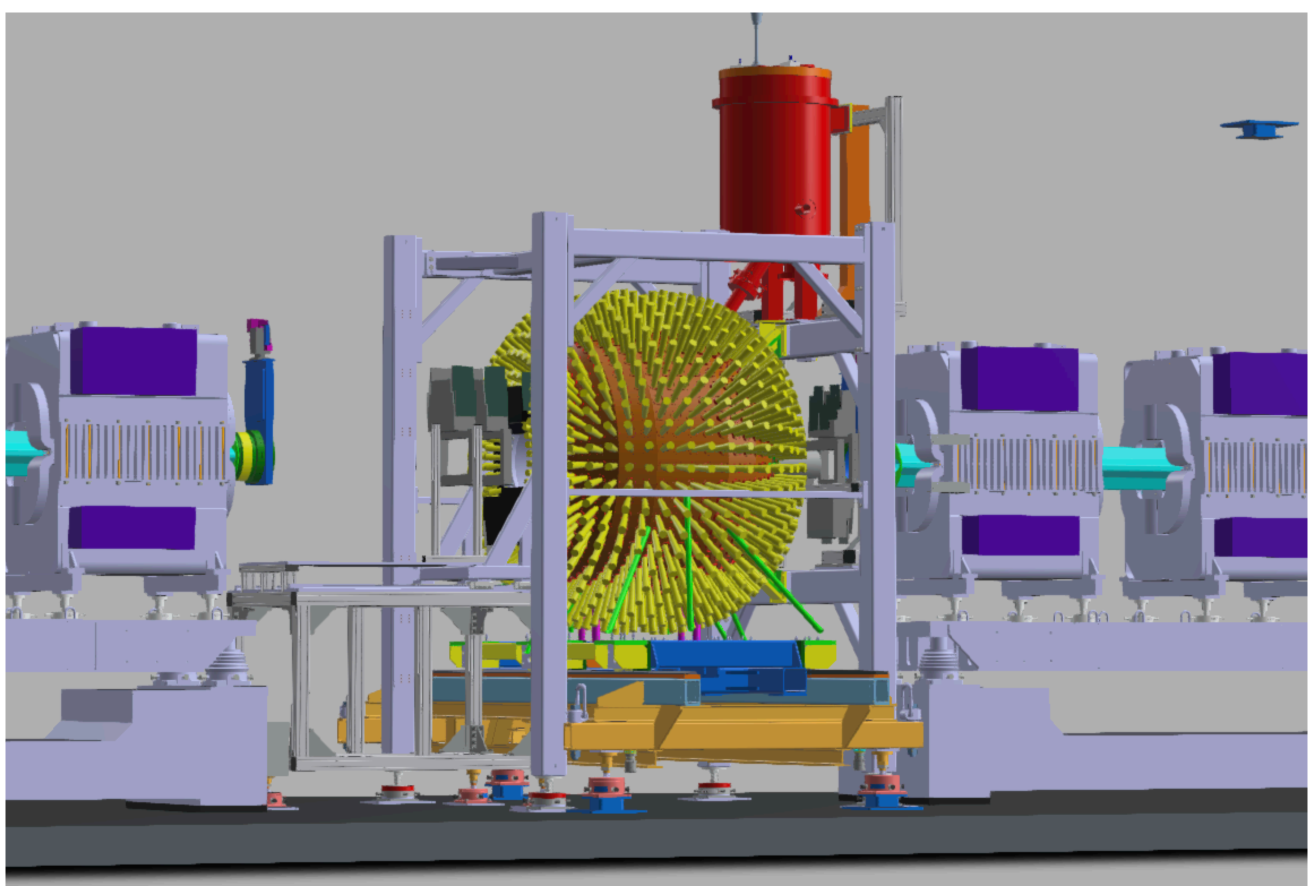
microscopic transport simulation

Experimental setup



p 2.5 GeV, 2.5x10^{8}/s,
4 g ^{12}C target

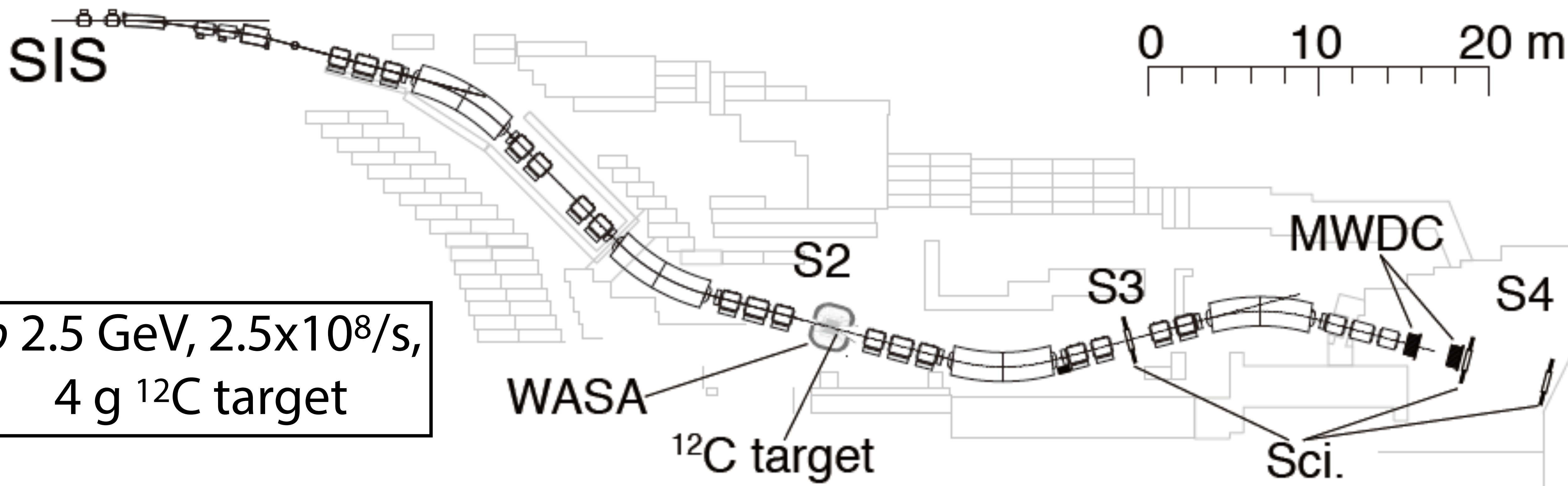
WASA in S2



FRS S2-S2: forward spectrometer with ~ 2.5 MeV energy resolution

WASA: η′NN→NN tagging

Experimental setup



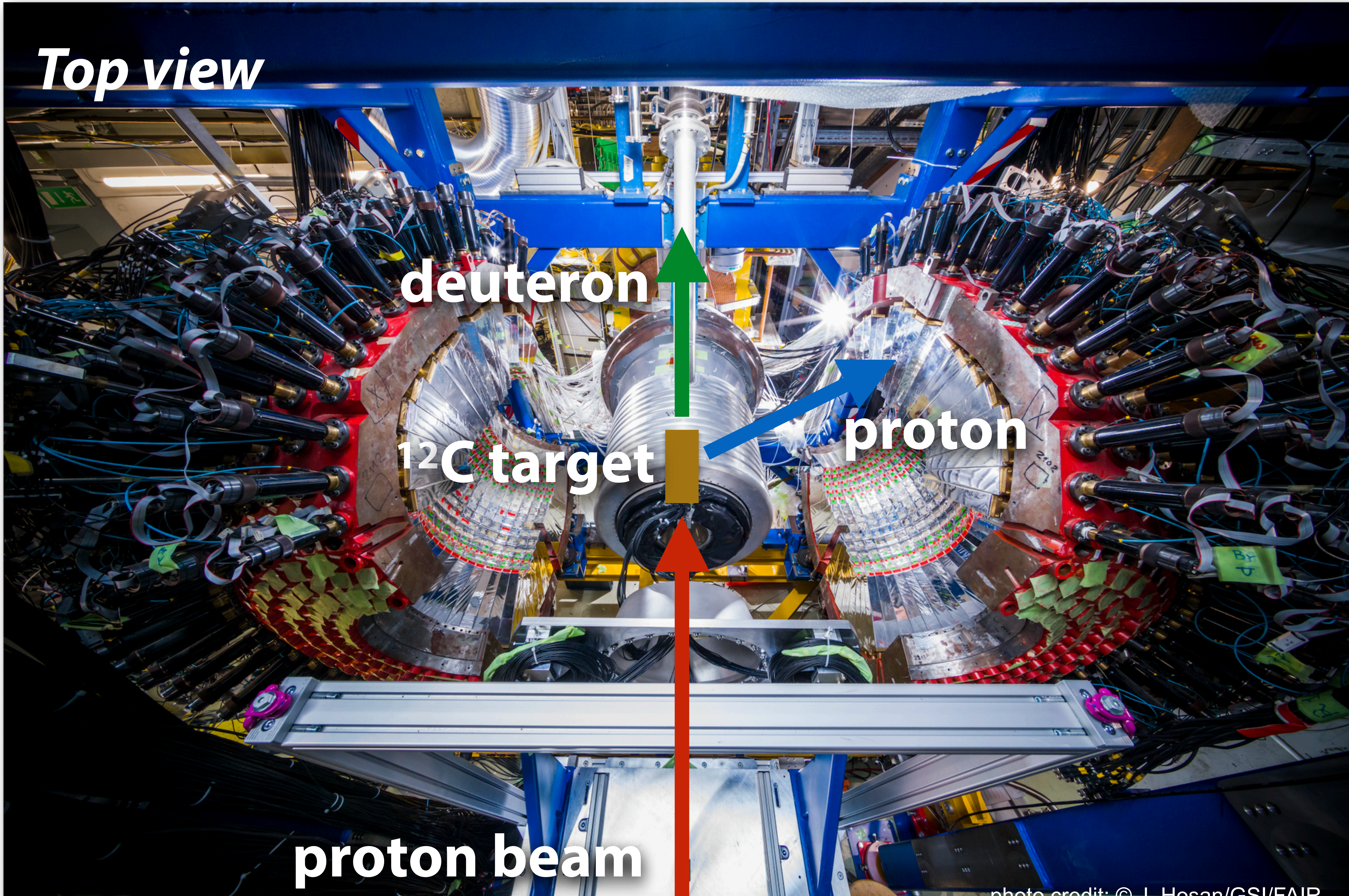
p 2.5 GeV, 2.5x10^{8}/s,
4 g ^{12}C target

Together with HypHI exp.

Expected rates
@S4
40 kHz (proton)
150 Hz (deuteron)
@WASA
10 MHz (pi)
25 MHz (proton)

Support from WASA-at-COSY
Esp. Prof. P. Moskal (Krakow)

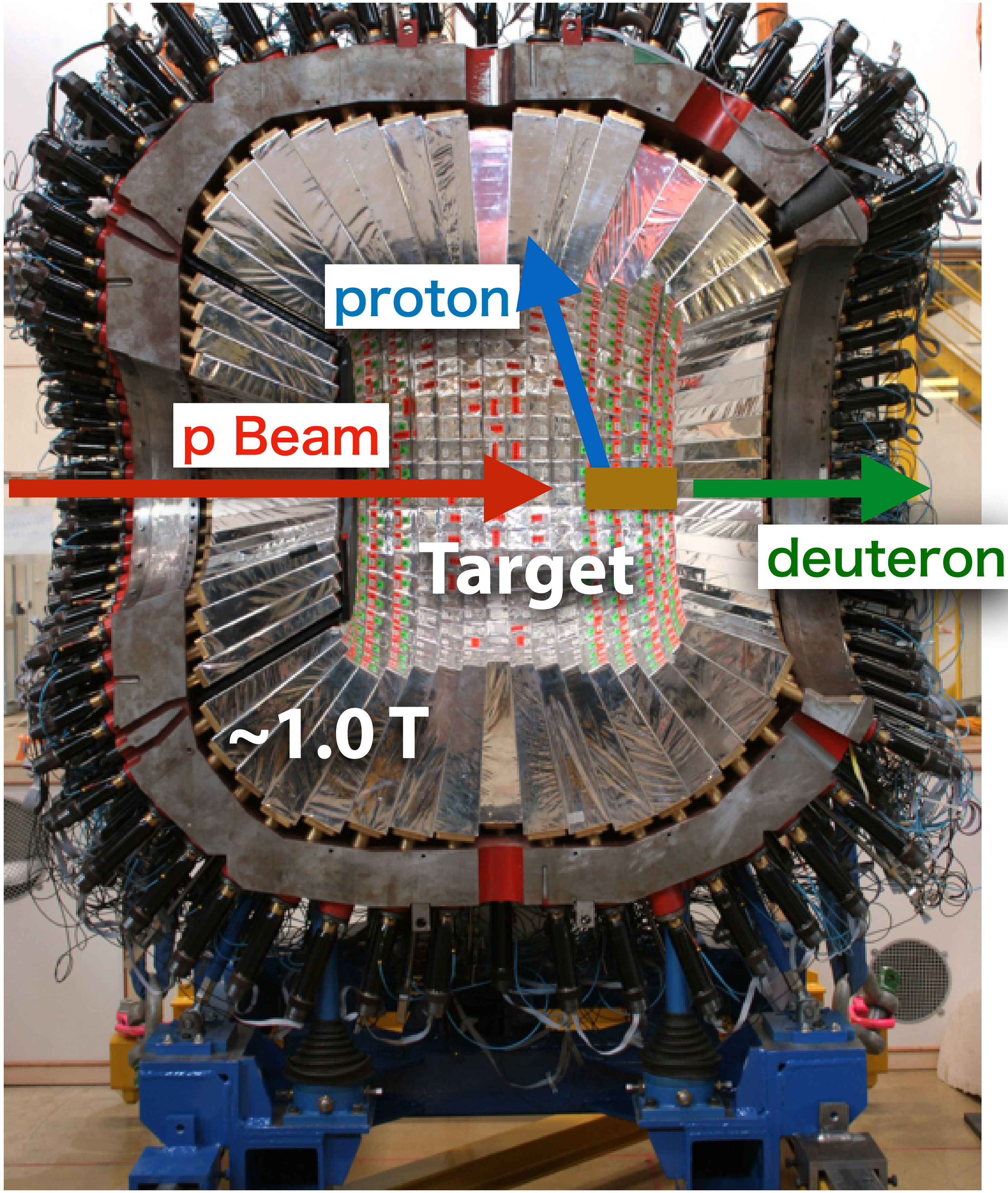
GSI-S490 WASA at FRS for η′mesic nuclei(2022)



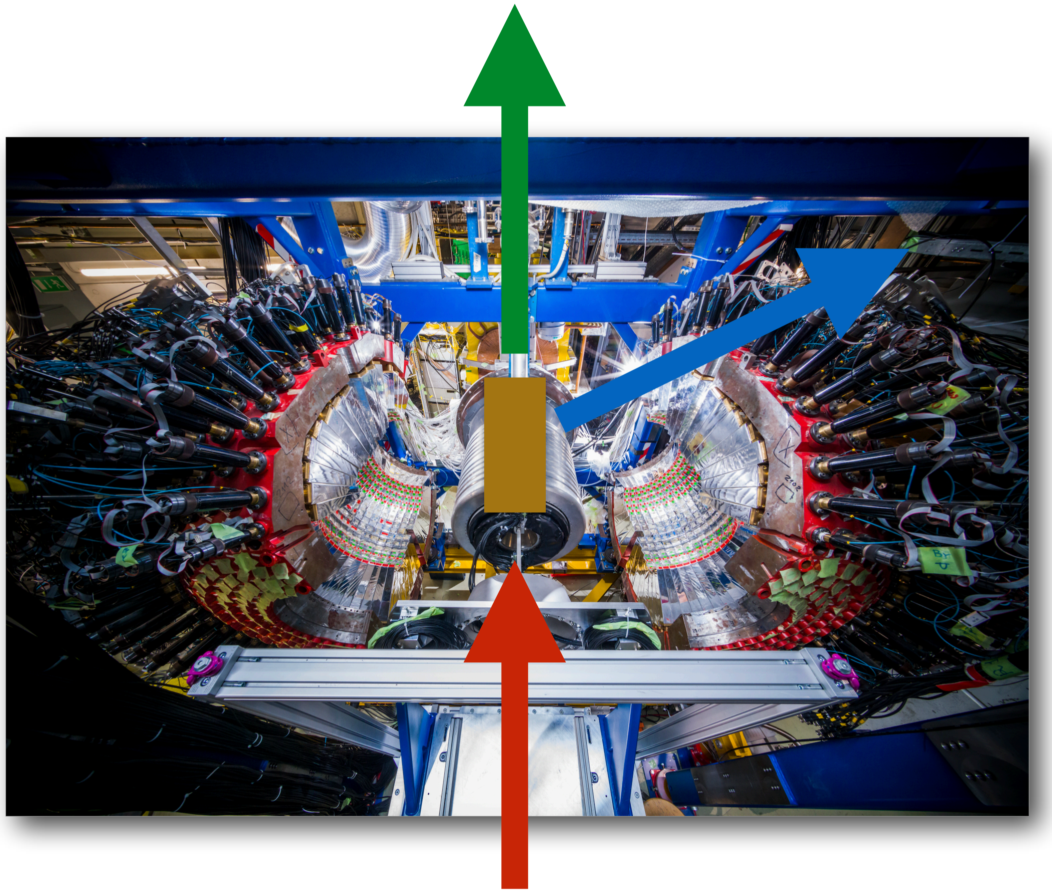
S490 Spokesperson: KI
co-Spokesperson: Y.K. Tanaka

D-candidate: R. Sekiya

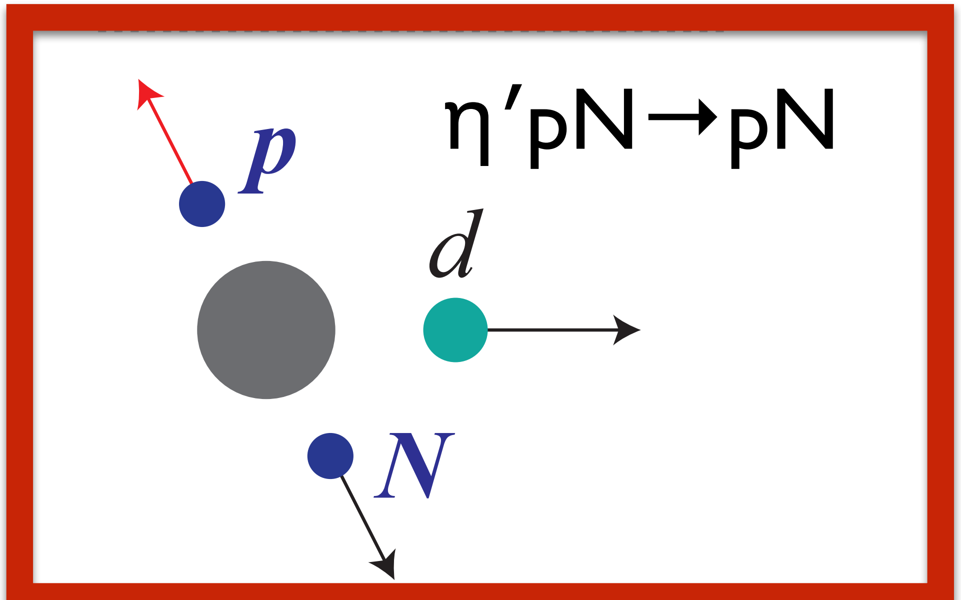
Detectors in WASA



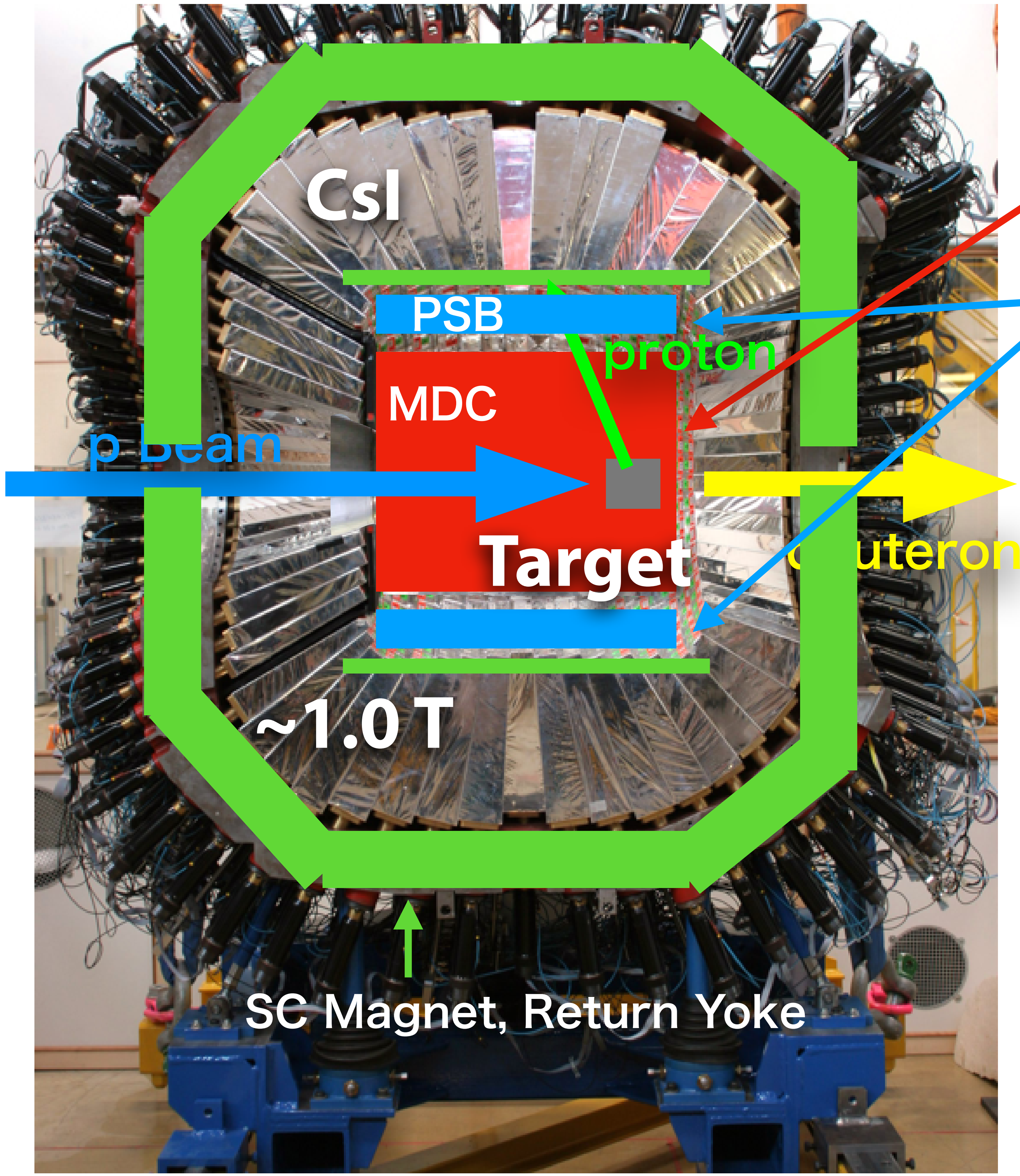
Cooperation with COSY-WASA collaboration



High energy proton tagging in coincidence with forward *d*



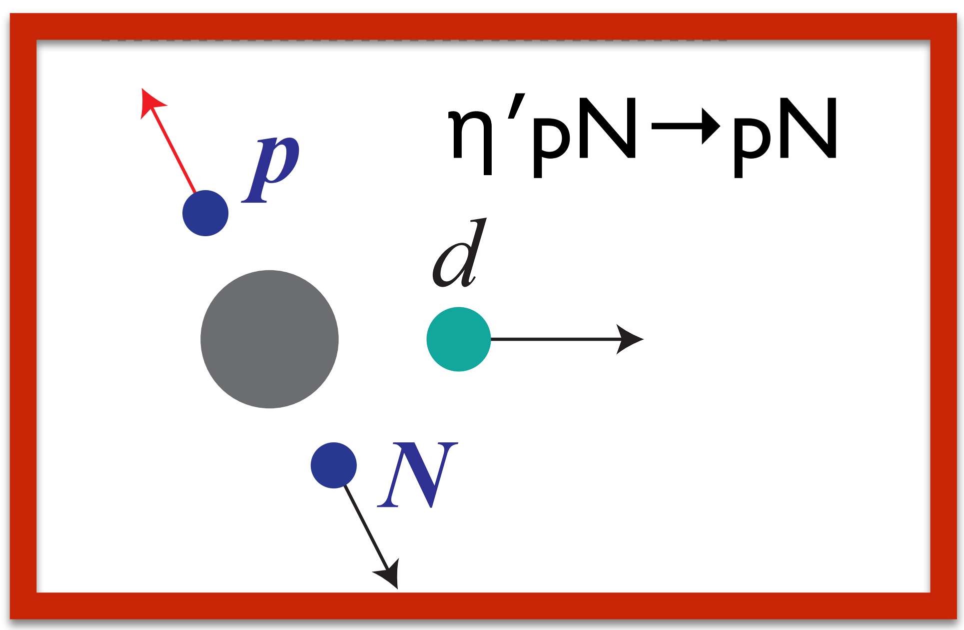
Detectors in WASA



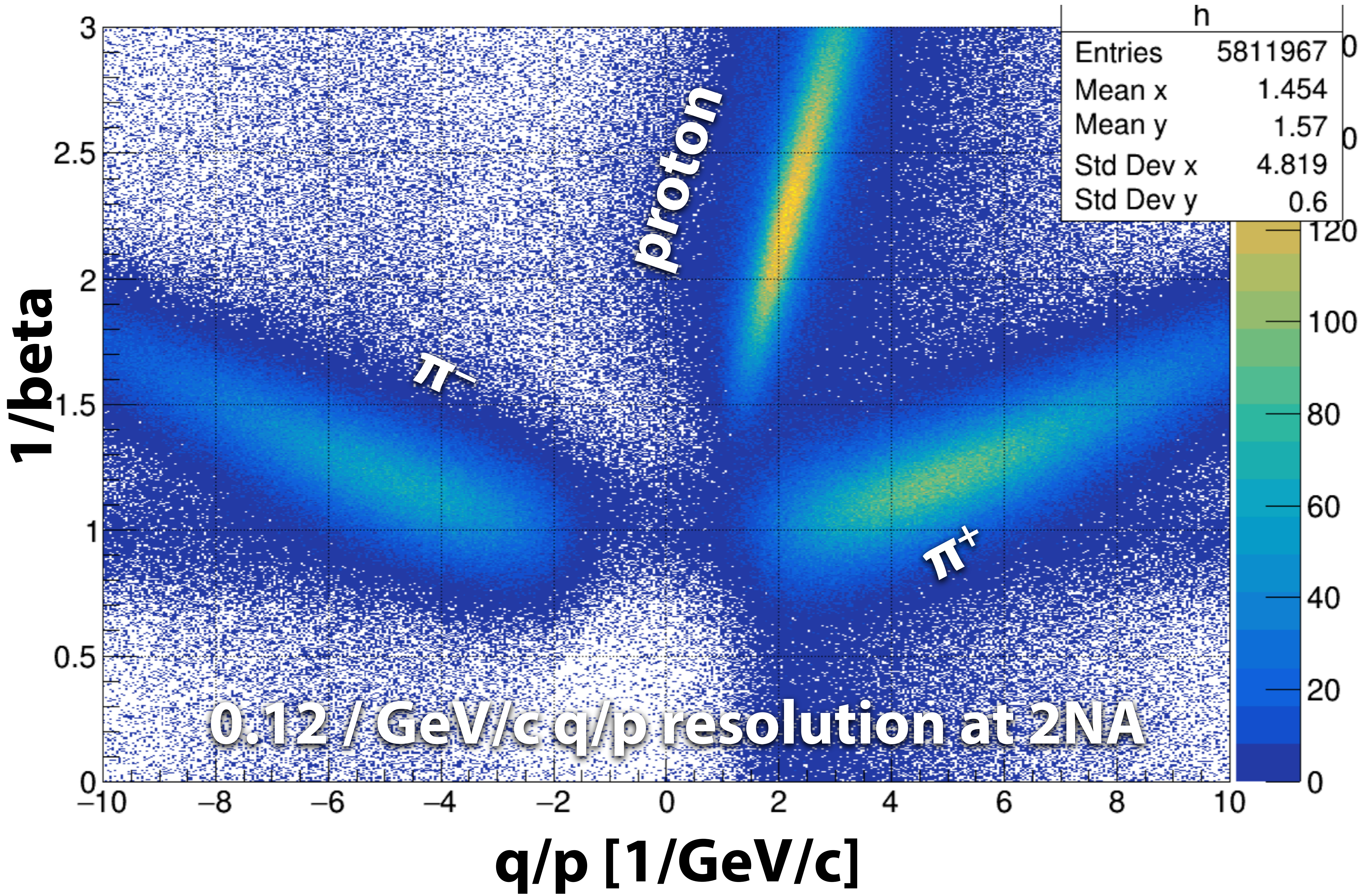
Cooperation with COSY-WASA collaboration

- **MDC (Mini Drift Chamber)**
  Charged particle tracking
- **PSB (Plastic Scintillator Barrel)**
  ΔE + Timing measurement
- **CsI**
  γ detection for calibration

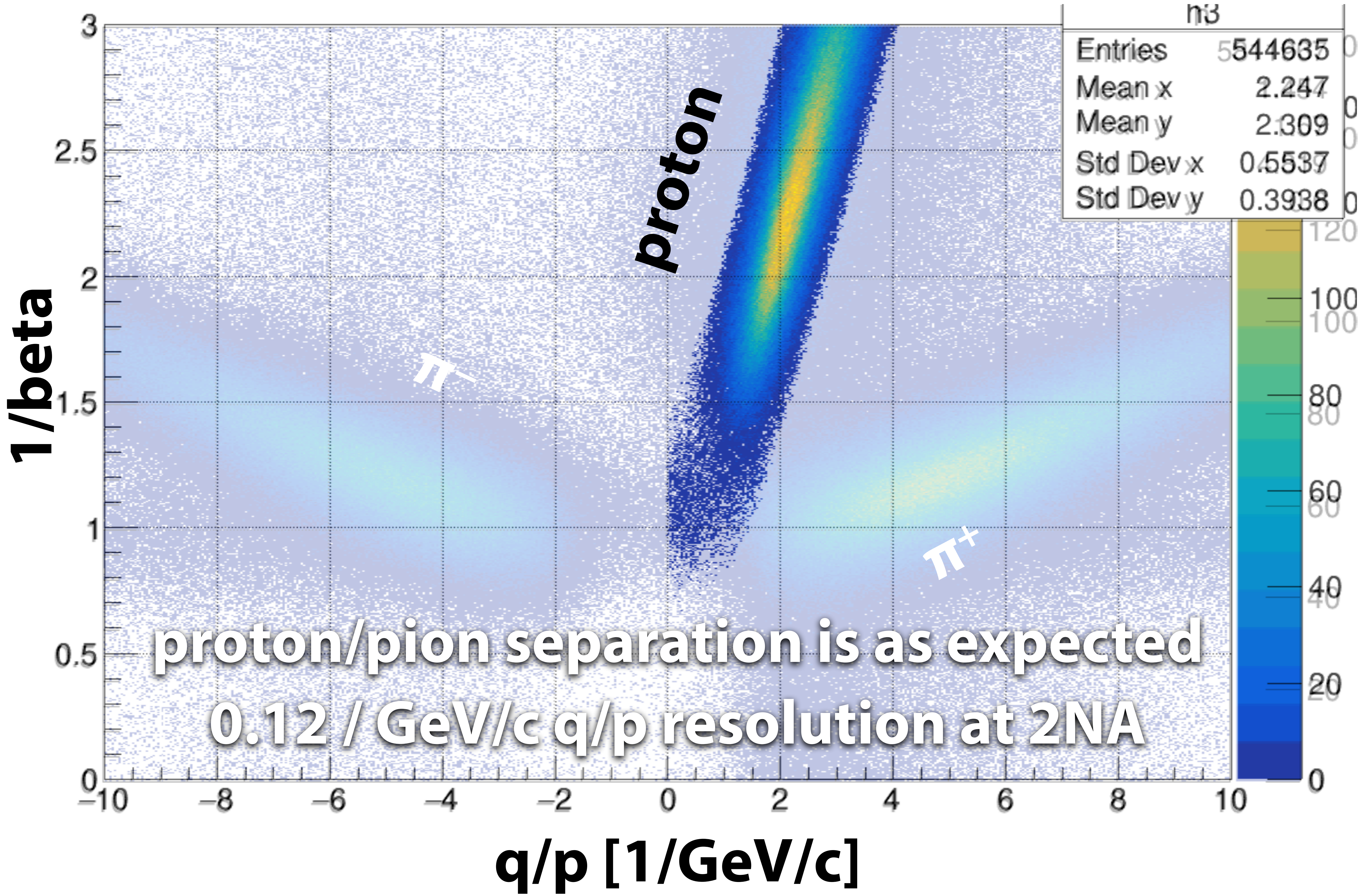
High energy proton tagging
in coincidence with forward *d*



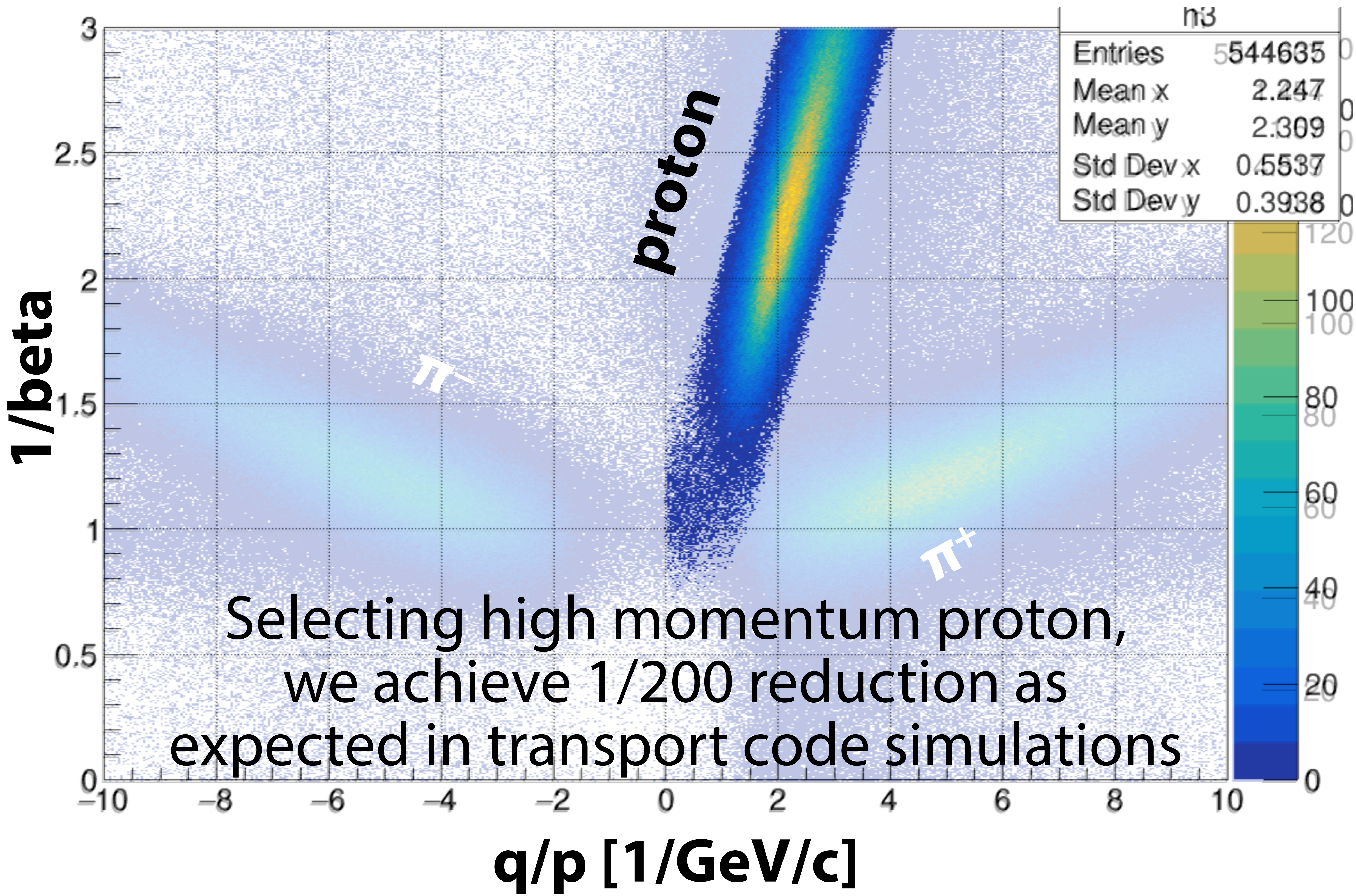
η′NN→NN tagging in WASA



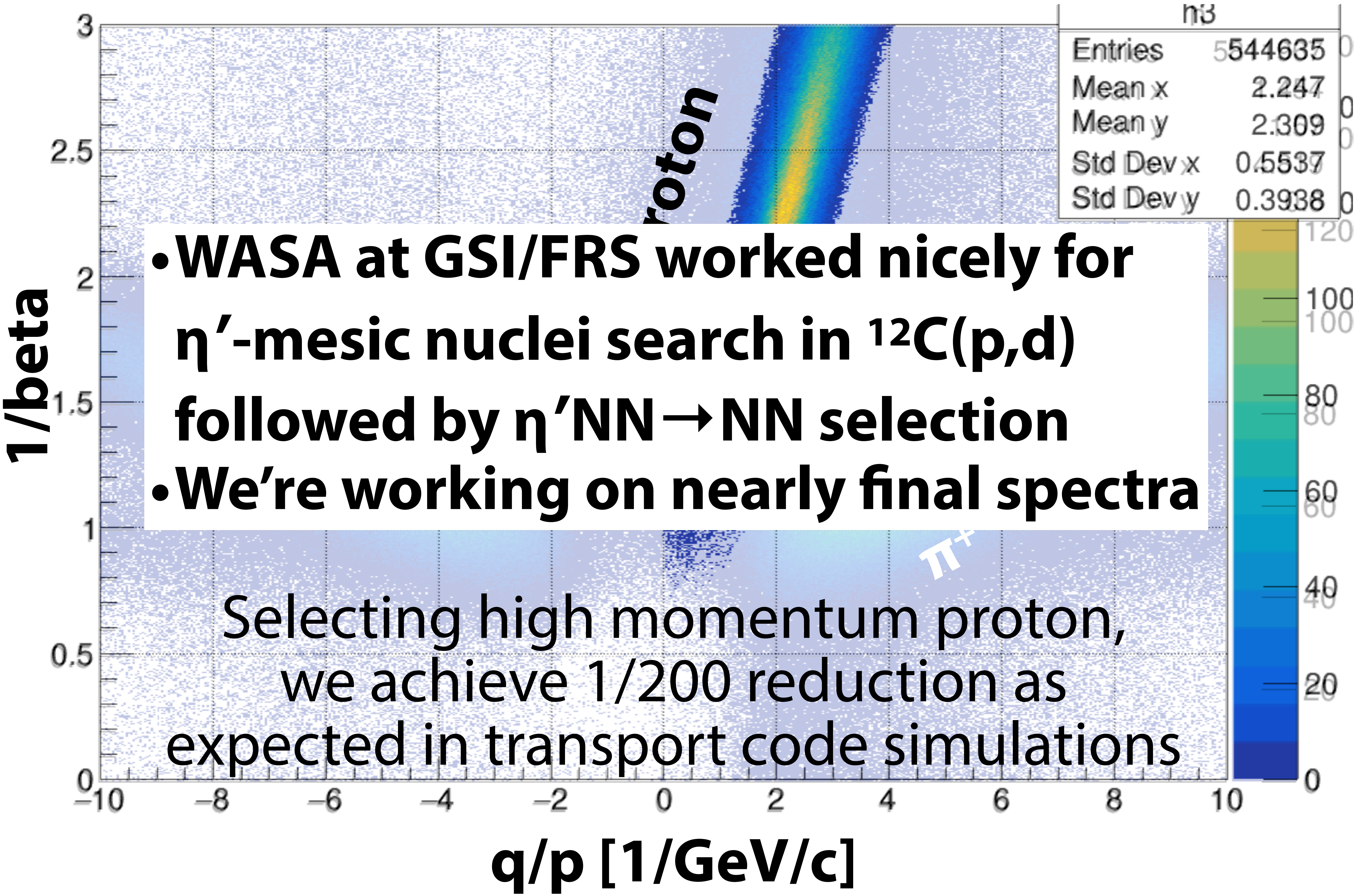
η′NN→NN tagging in WASA



η′NN→NN tagging in WASA



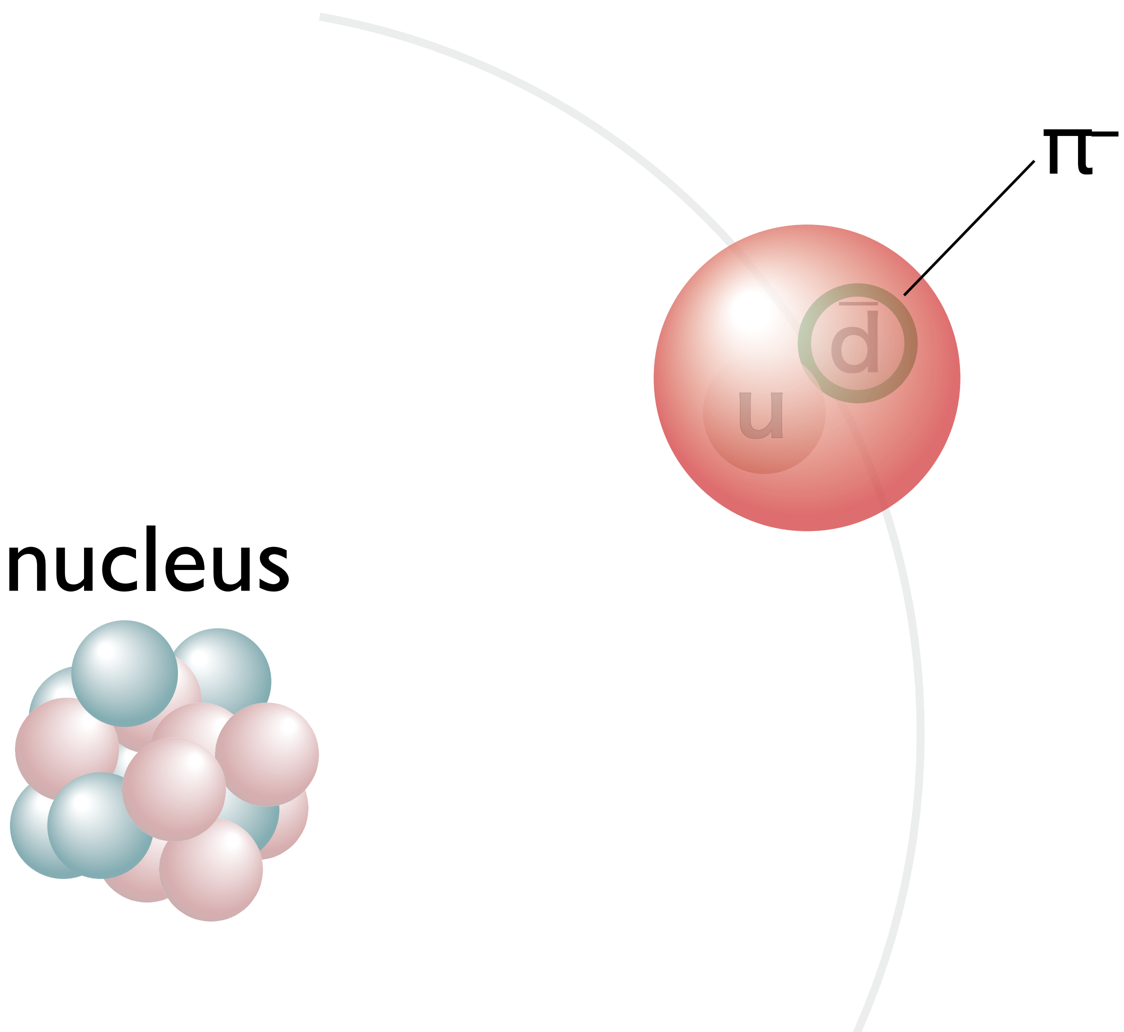
η′NN→NN tagging in WASA

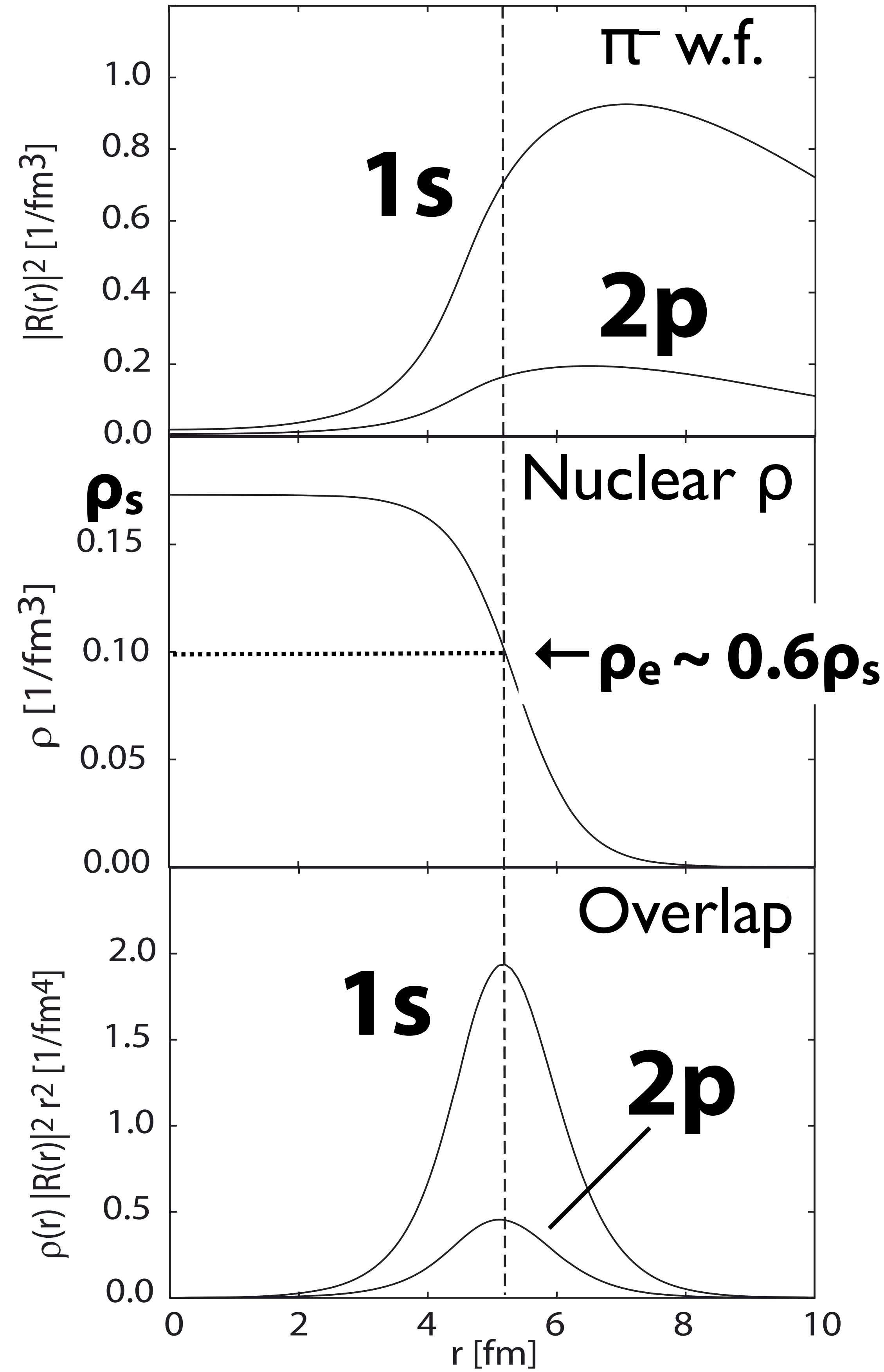


- **WASA at GSI/FRS worked nicely for η′-mesic nuclei search in ^{12}C(p,d) followed by η′NN→NN selection**
- **We're working on nearly final spectra**

Selecting high momentum proton, we achieve 1/200 reduction as expected in transport code simulations

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 $\rho_e \sim 0.6\rho_0$

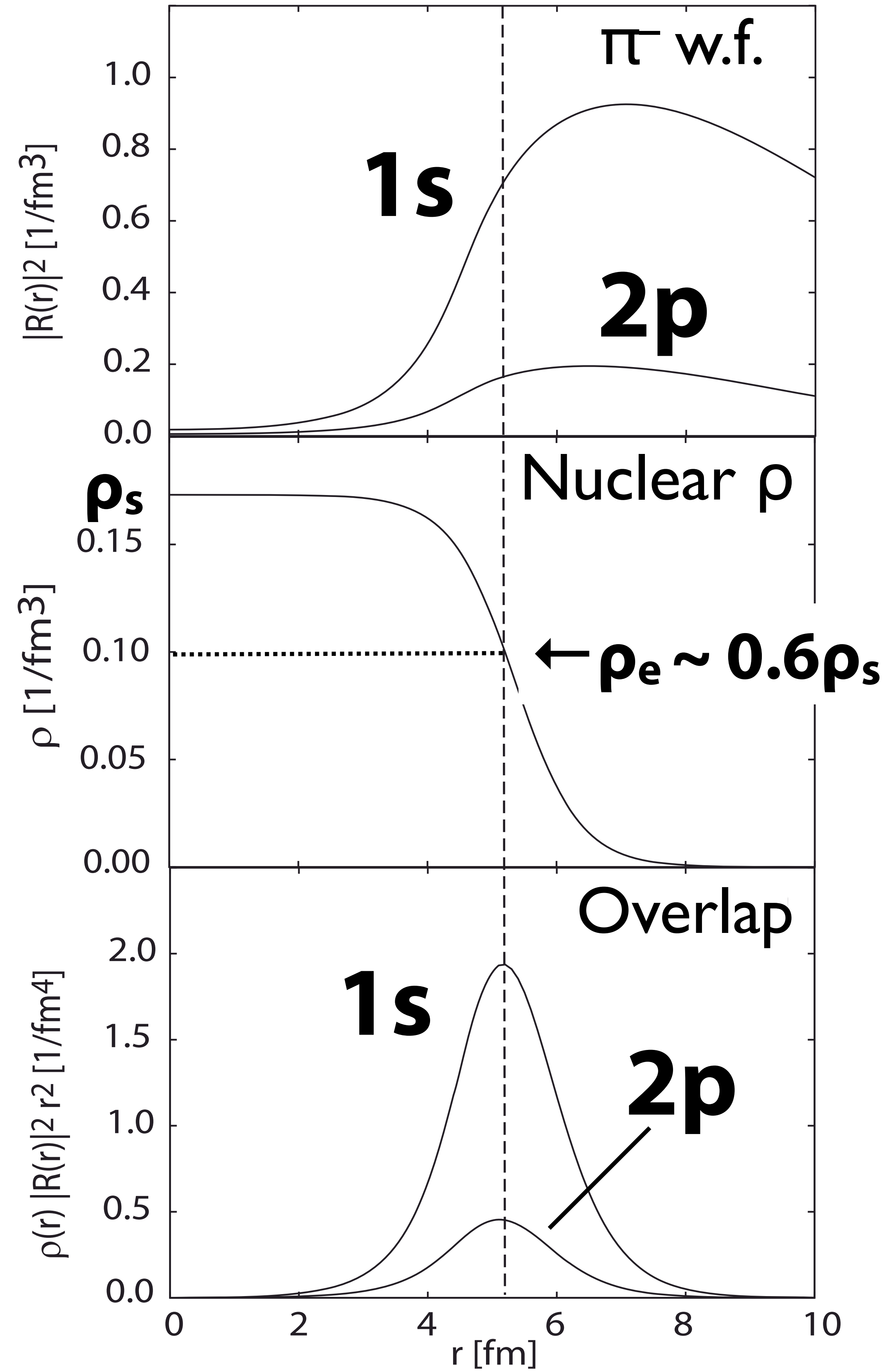
π-nucleus interaction is changed
for wavefunction renormalization
of medium effect

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 and chiral condensate

Overlap between
pion w.f. and nucleus
→ π works as a probe
at $\rho_e \sim 0.6\rho_0$

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

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)

Ericson-Ericson potential

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

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

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

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.

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

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

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

In-medium Glashow-Weinberg relation

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

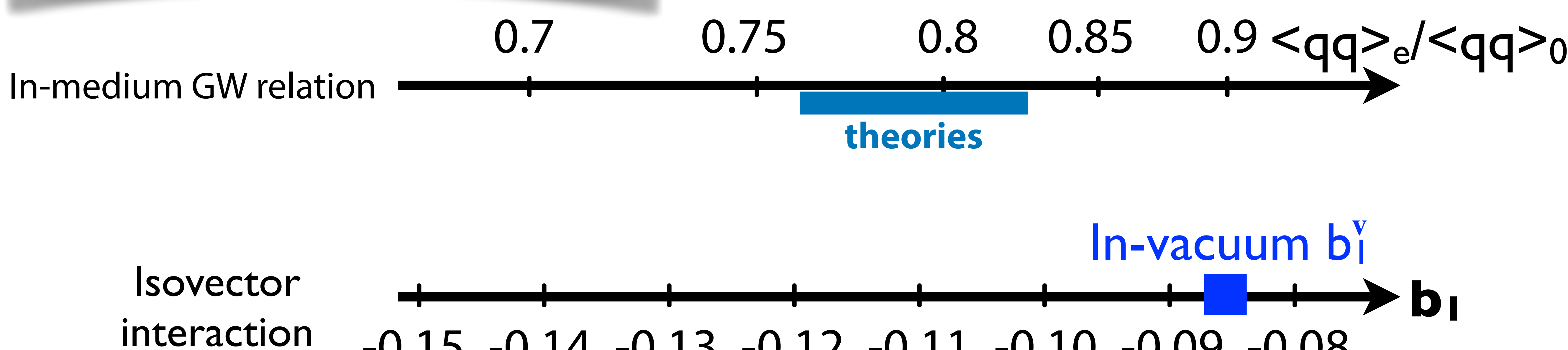
$\gamma = 0.184 \pm 0.003$

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

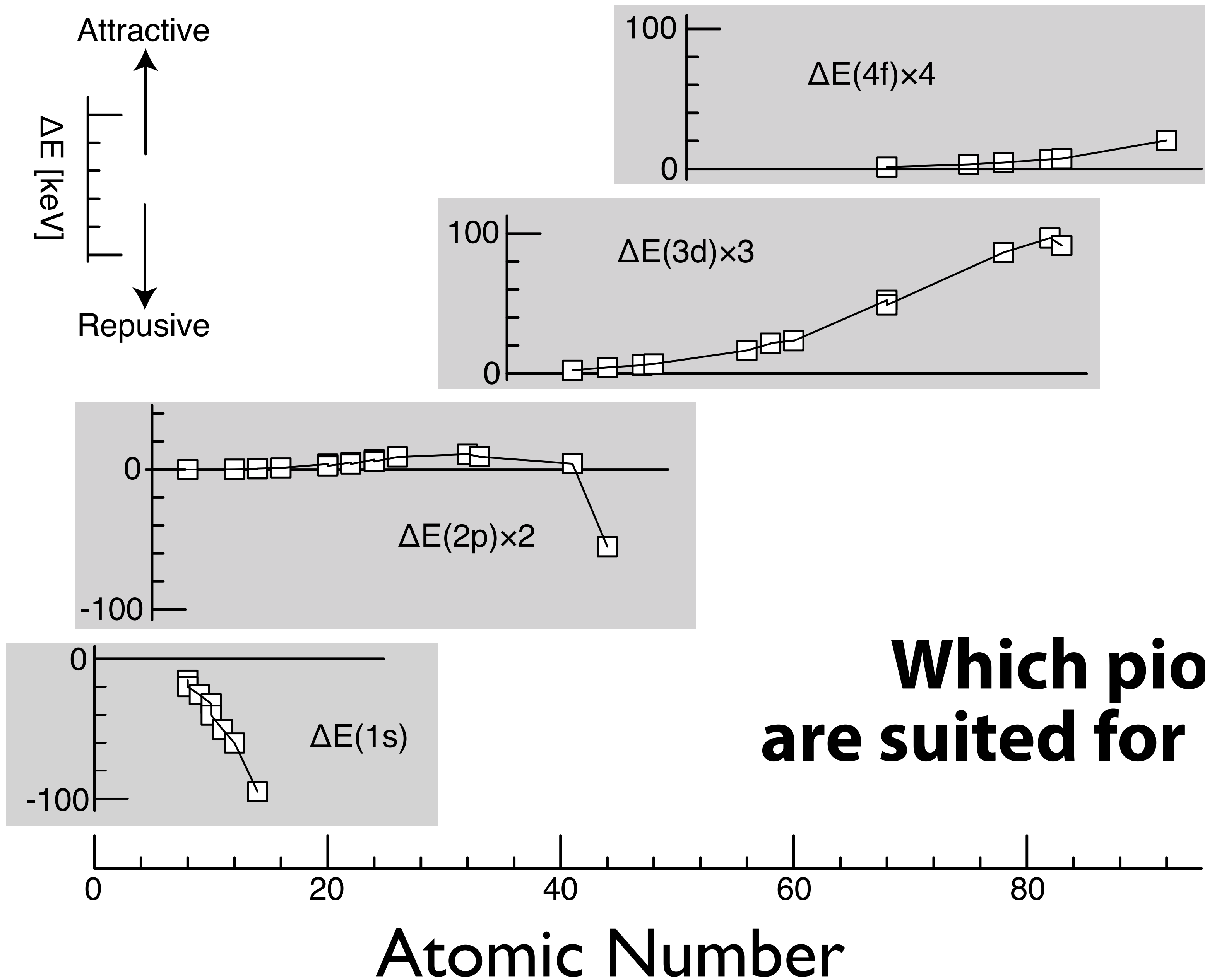
Pionic hydrogen and deuterium

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

Hirtl et al., EPJA57, 70 (2021)



Level shifts in pionic X-ray measurements



Which pionic atoms are suited for b_1 deduction?

Ericson-Ericson potential

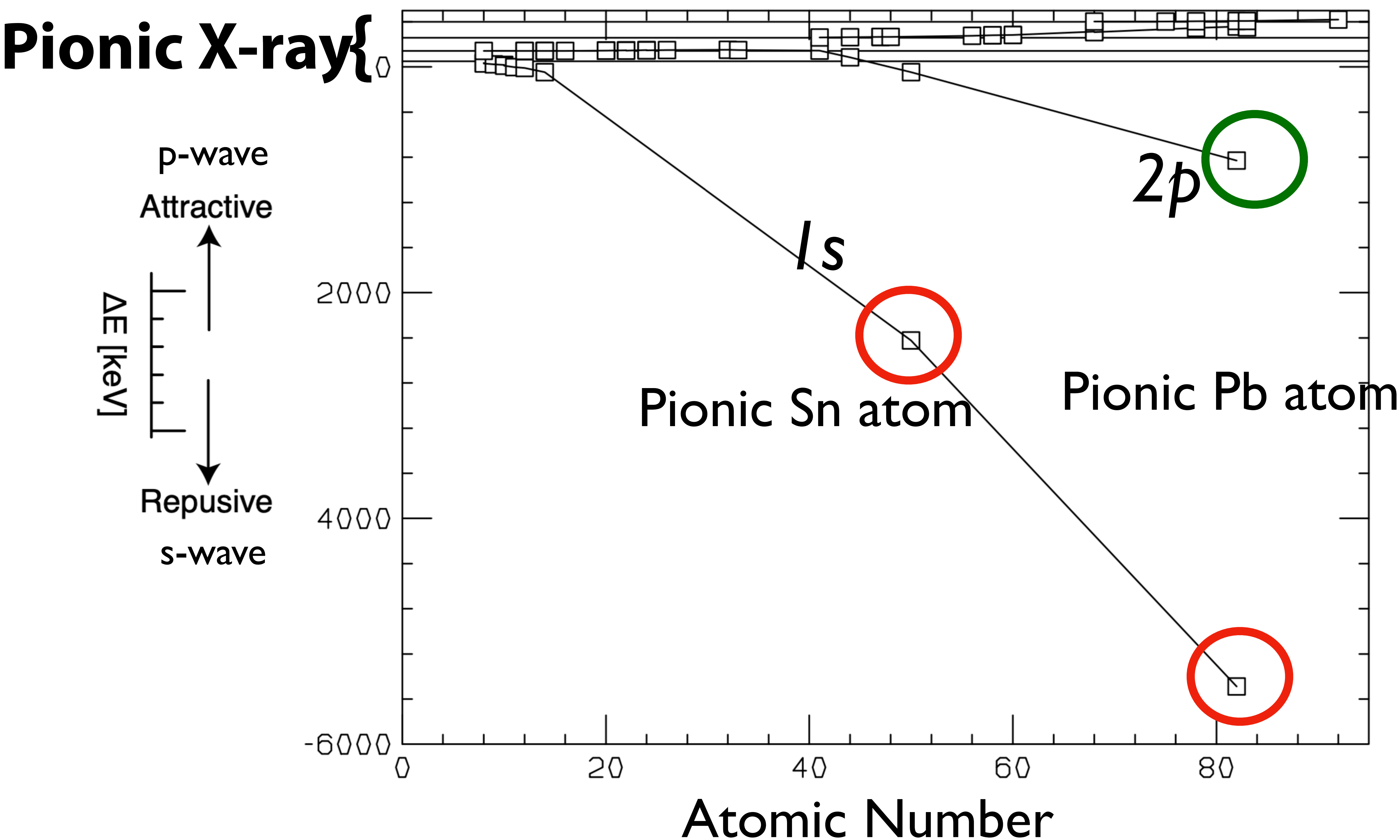
$$U_{opt}(r) = U_s(r) + U_p(r),$$

$$U_s(r) = b_0\,\rho + \mathbf{b_1}\,(\rho_n - \rho_p) + B_0\,\rho^2$$ → **s-wave = repulsive = negative shift**

$$U_p(r) = \frac{2\pi}{\mu}\vec{\nabla}\cdot[c(r) + \varepsilon_2^{-1}C_0\rho^2(r)]L(r)\vec{\nabla}$$ → **p-wave = attractive = positive shift**

Deeply bound pionic atoms

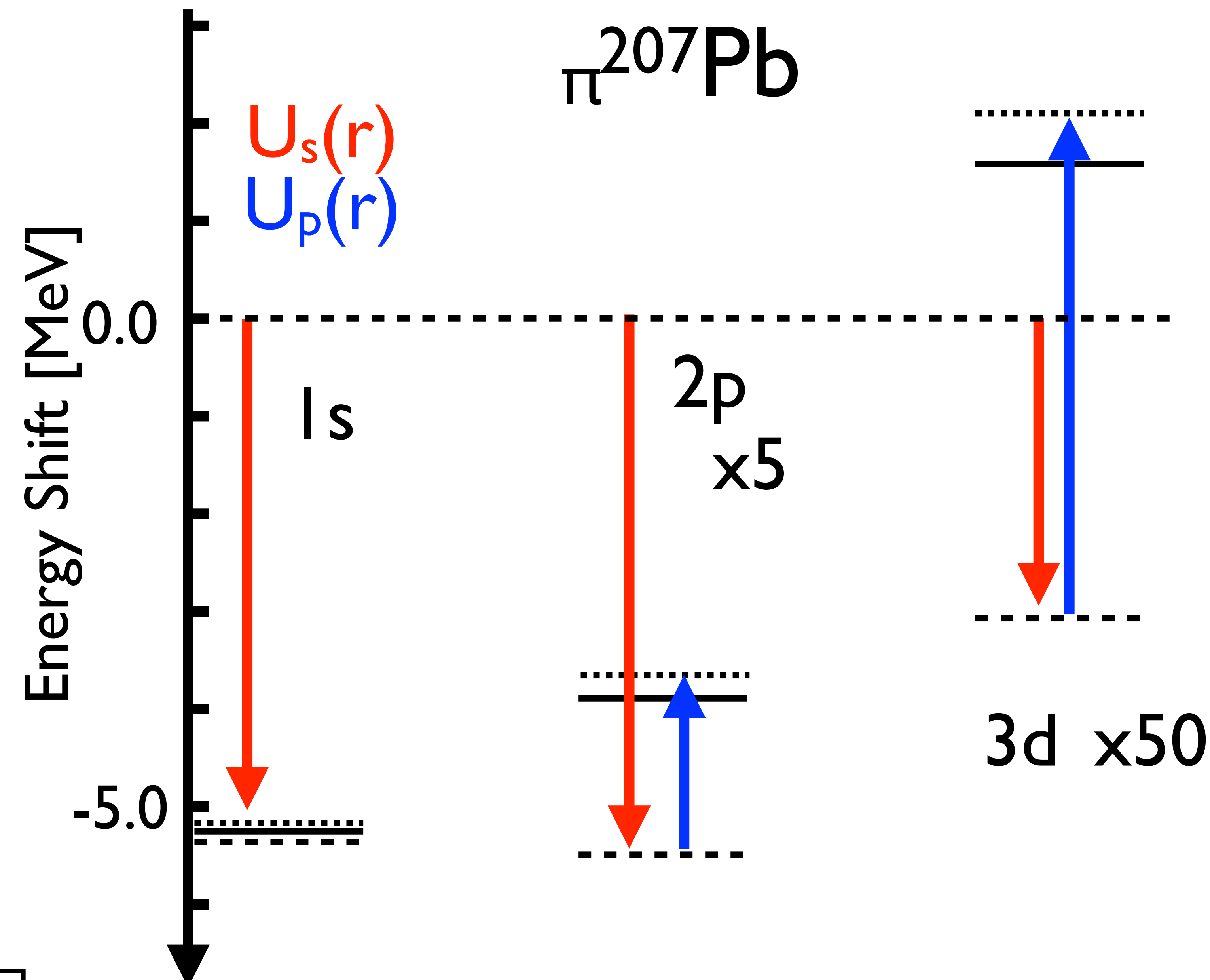
Level shifts



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

piA and π-nucleus interaction

Deeply bound states
are sensitive to s-wave
cf. Pionic X-rays are to p-wave



Ericson-Ericson potential

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

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

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

s-wave interaction is dominant in **<u>1s shift</u>**,
whereas p-wave is larger in 3d

PHYSICAL REVIEW C, VOLUME 62, 024606

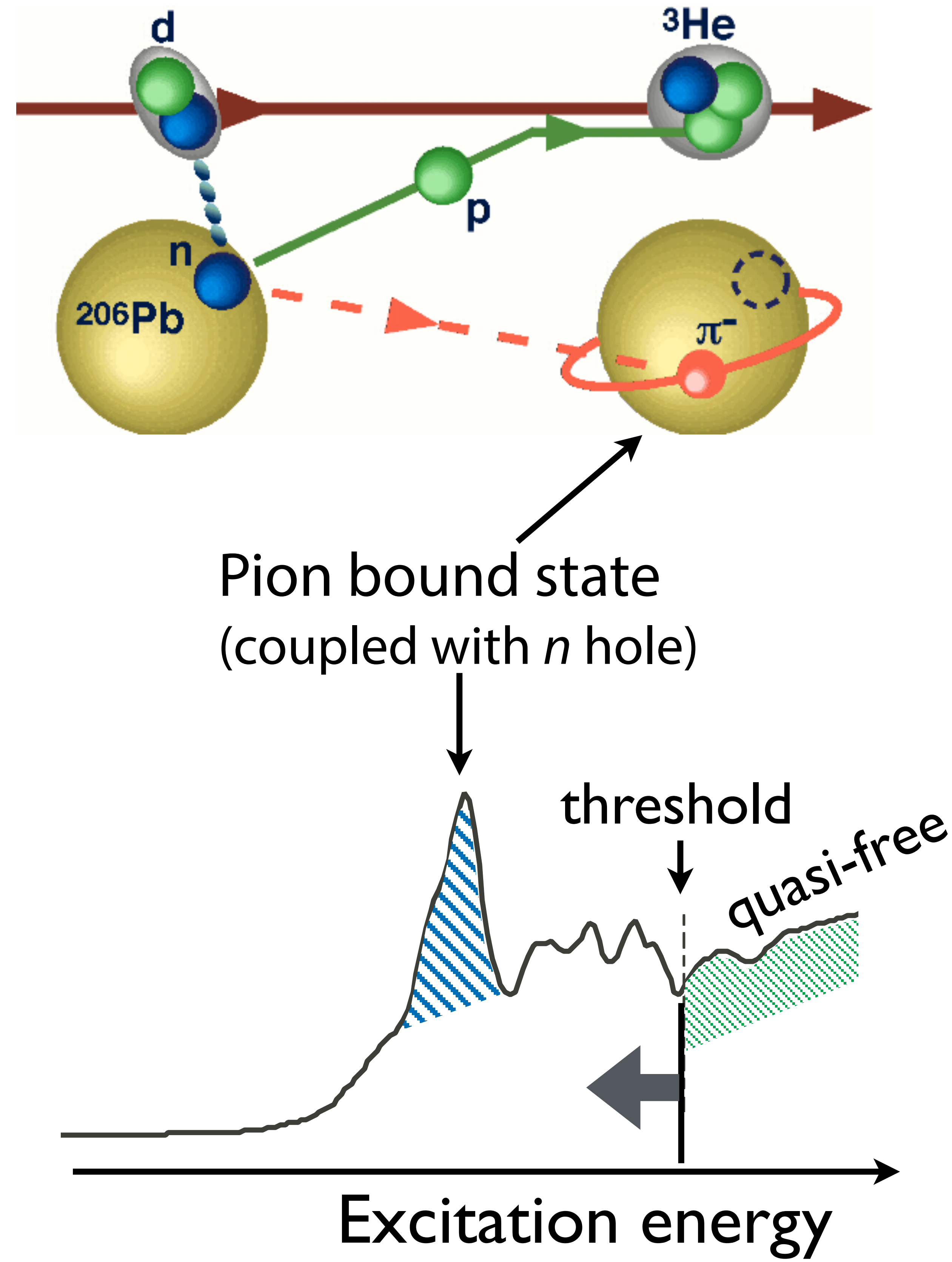
Isotope dependence of deeply bound pionic states in Sn and Pb

Y. Umemoto,[1] S. Hirenzaki,[1] K. Kume,[1] and H. Toki[2]

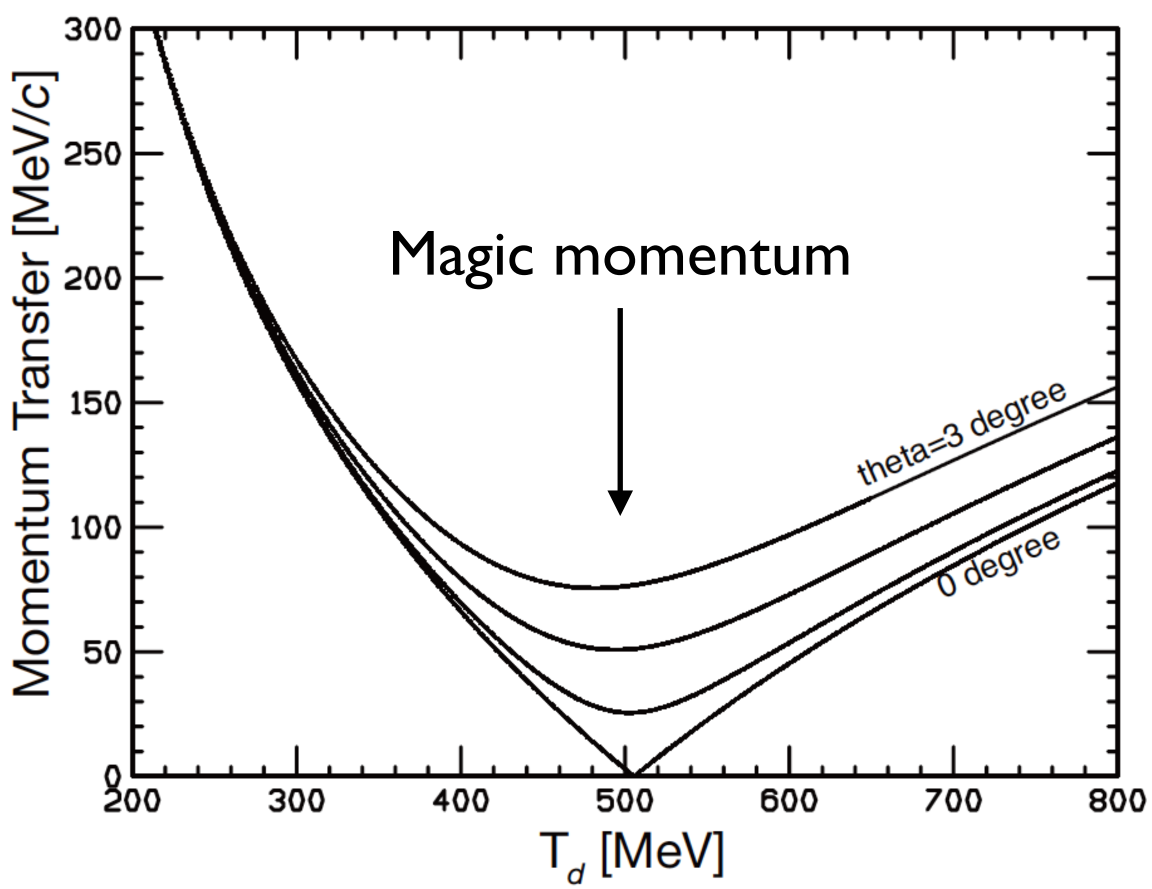
Spectroscopy of pionic atoms in (d,^{3}He) reactions

Missing mass spectroscopy to measure excitation spectrum of pionic atoms

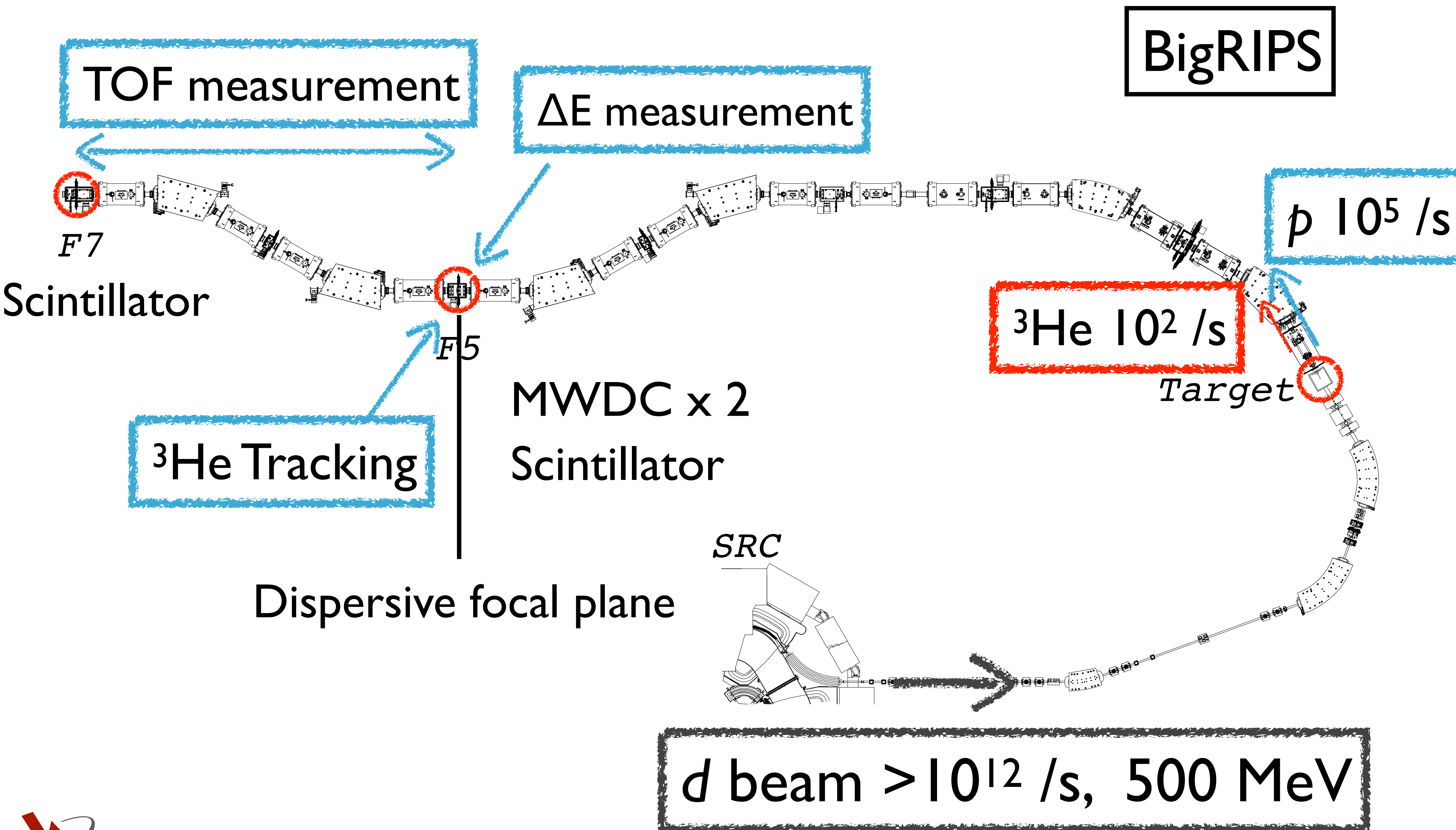
Direct production of pionic atoms



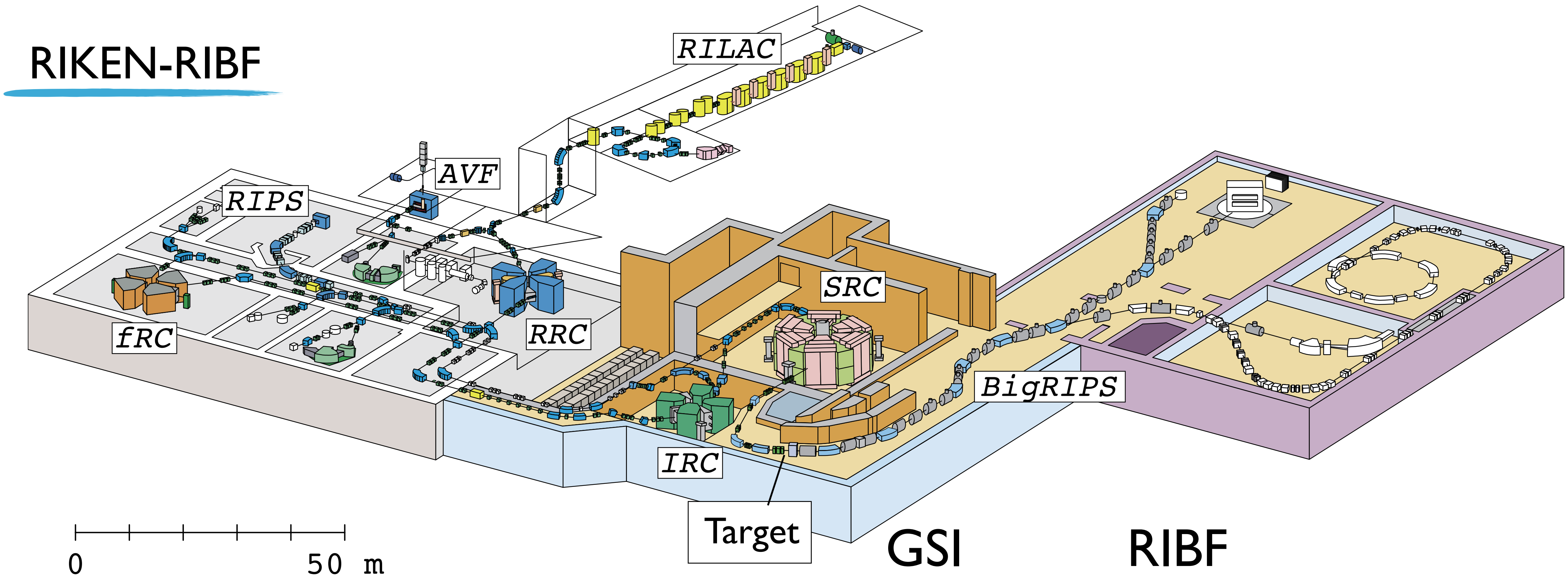
Momentum transfer



(d,³He) Reaction Spectroscopy in RIBF



RI Beam Factory

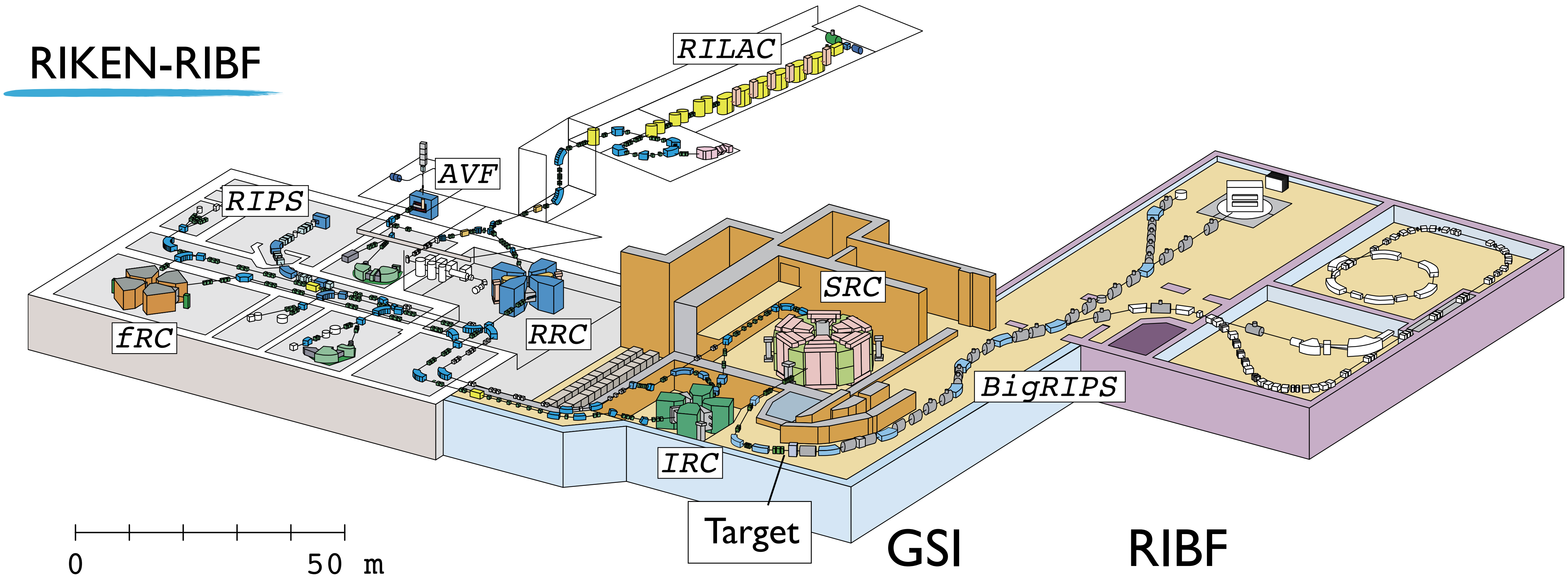


	GSI	RIBF
d beam Intensity	10^{11}/spill	>10^{12}/s
Target	20 mg/cm^2	10 mg/cm^2
$\Delta p_d/p_d$ (FWHM)	0.02%	0.06%
Resolution (FWHM)	400 keV	~1000 keV
Acceptance (mrad)	15H, 10V	40H, 60V

RIKEN NiSHiNA CENTER

Kenta Itahashi, RIKEN

RI Beam Factory



	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%	0.06%
Resolution (FWHM)	400 keV	~300 keV
Acceptance (mrad)	15H, 10V	40H, 60V

Dispersion matching

RIKEN NiSHiNA CENTER

Kenta Itahashi, RIKEN

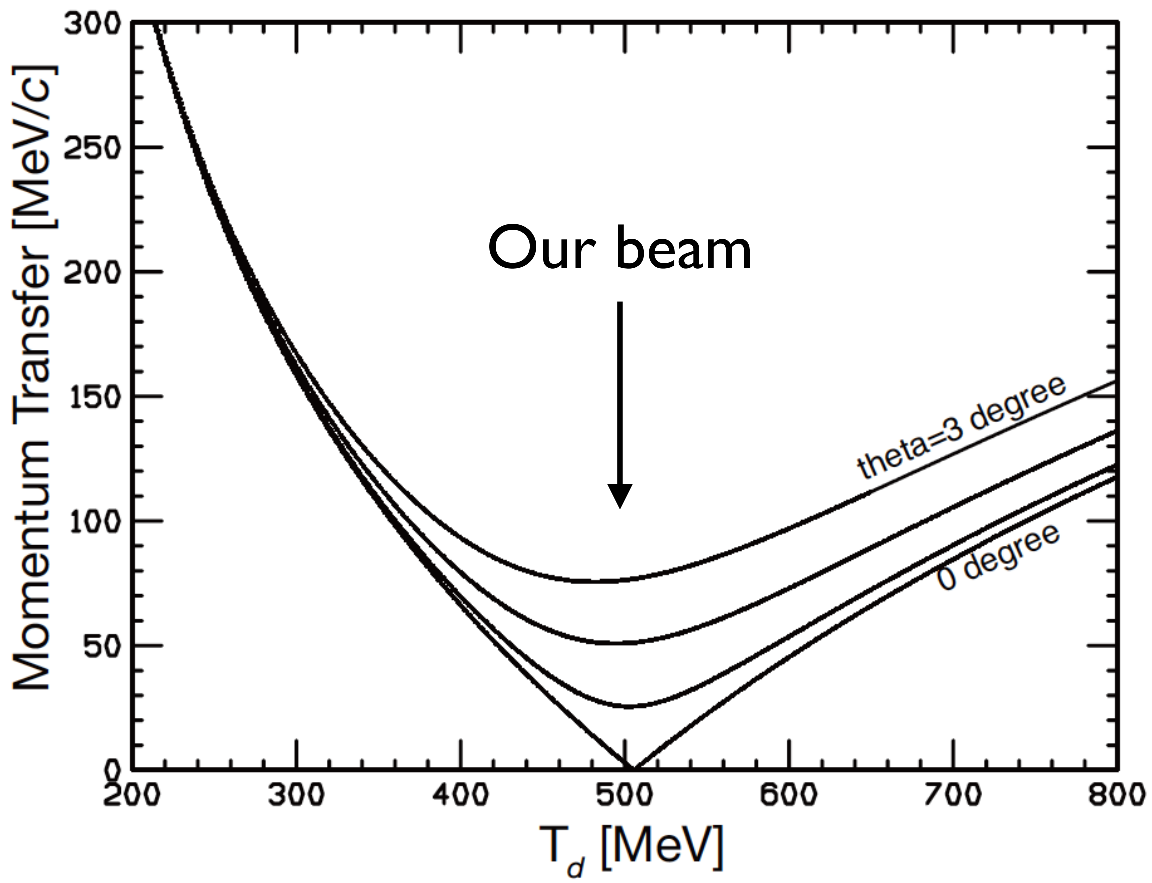
Pionic ^{121}Sn atom

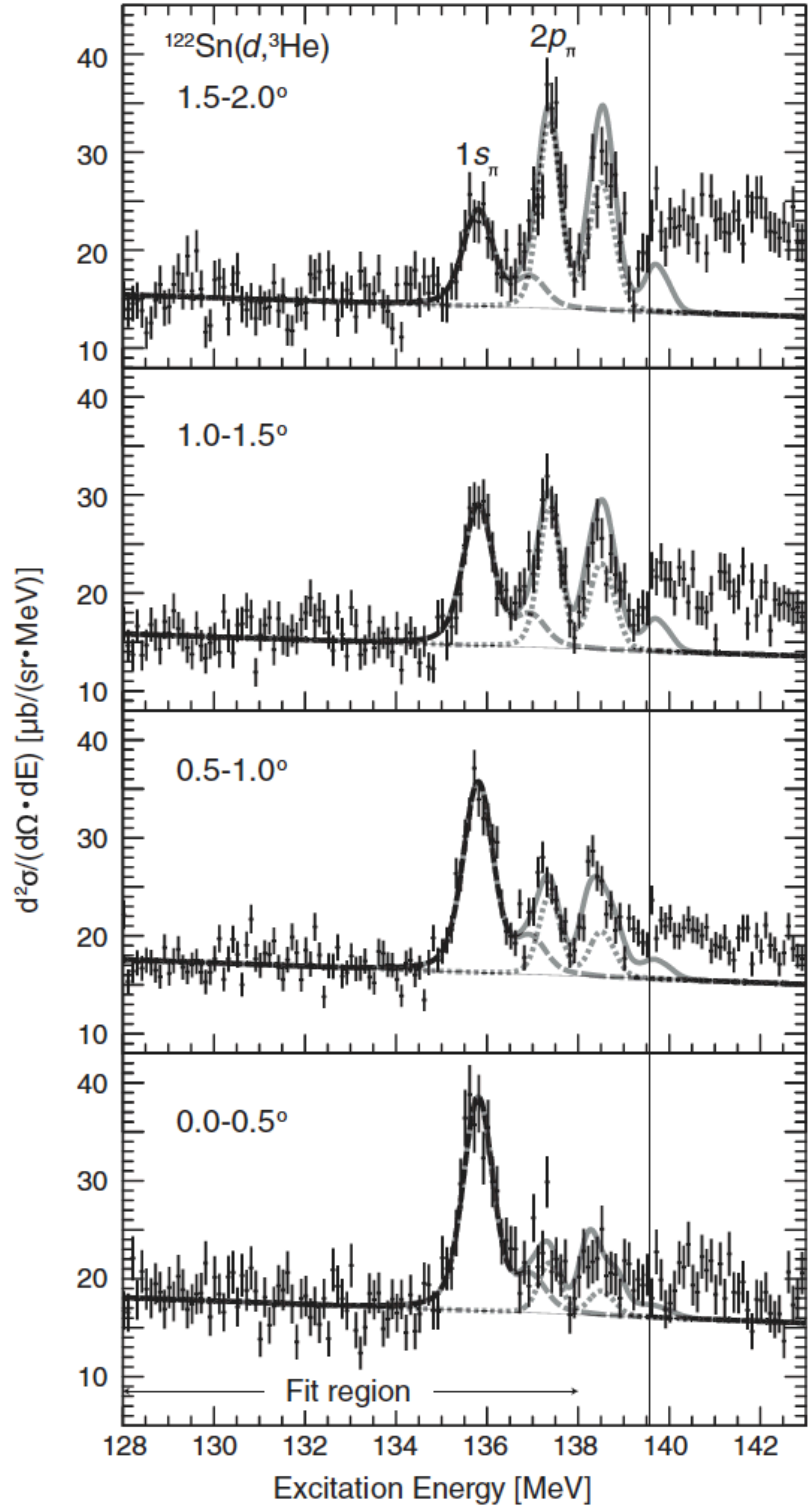
Pilot run

15 hours DAQ in 2010

First observation of θ dependence of π atom cross section

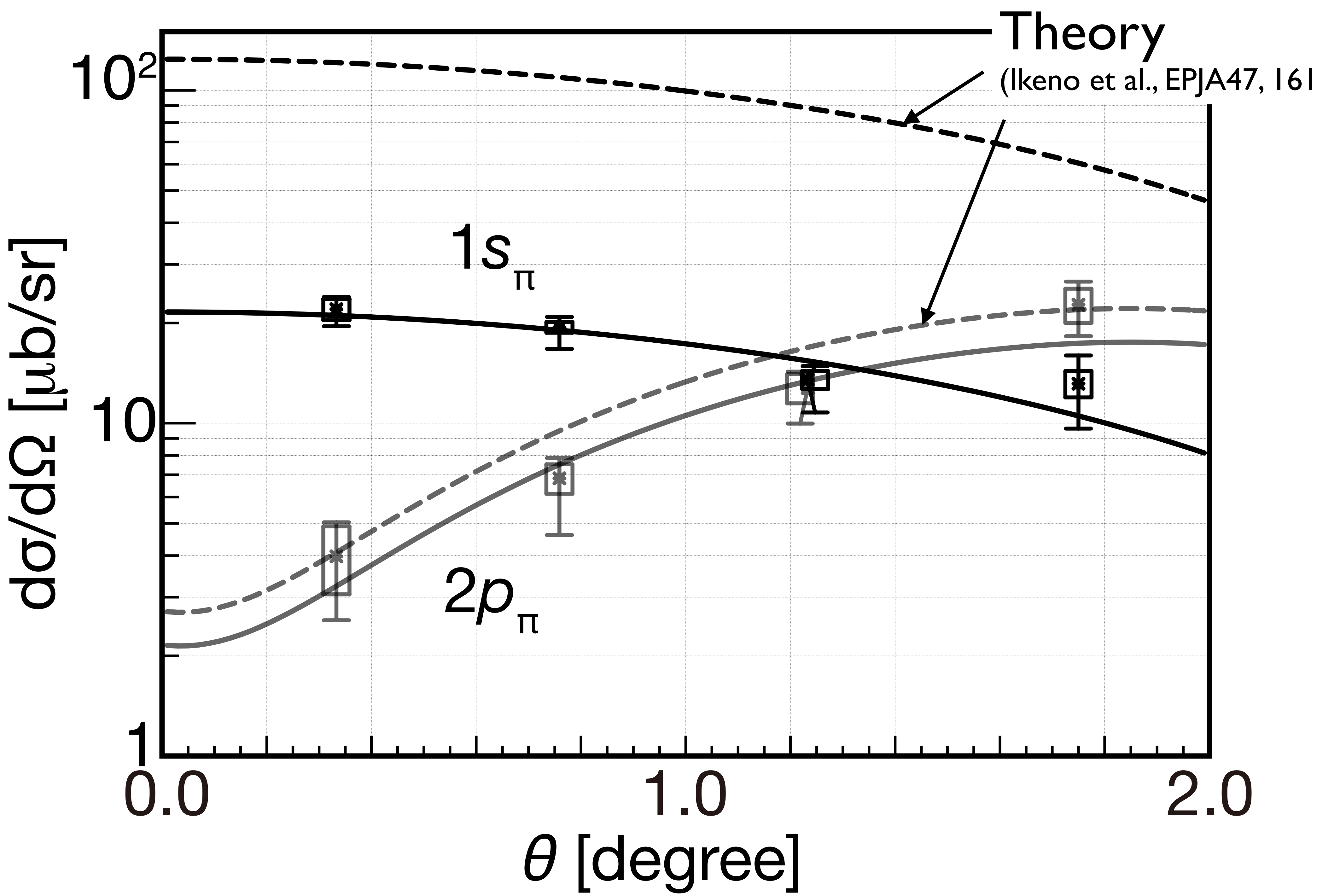
ΔL ~ R × q





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

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



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

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

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

Resolution 394 keV (FWHM)

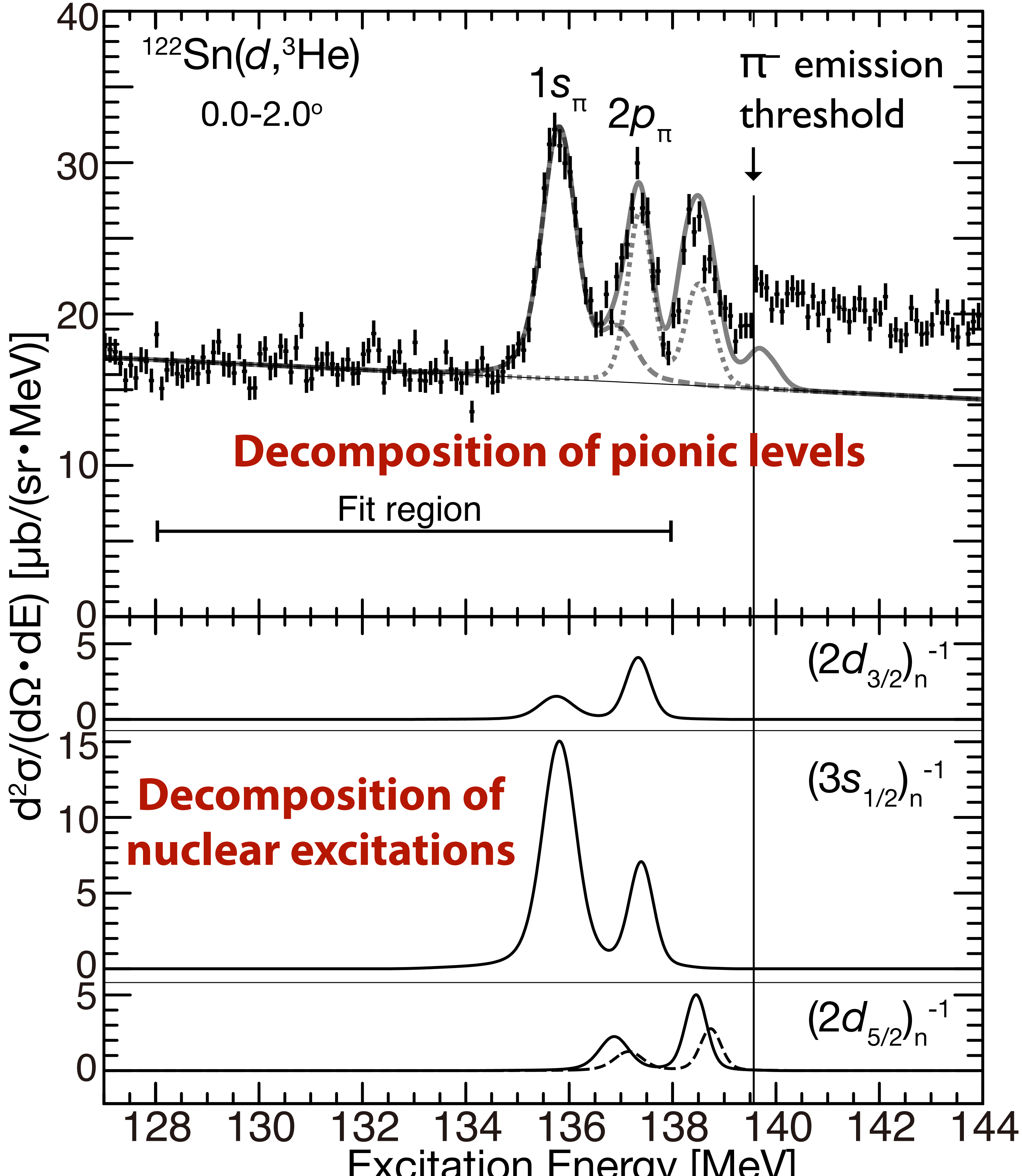
Theories

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

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

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

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

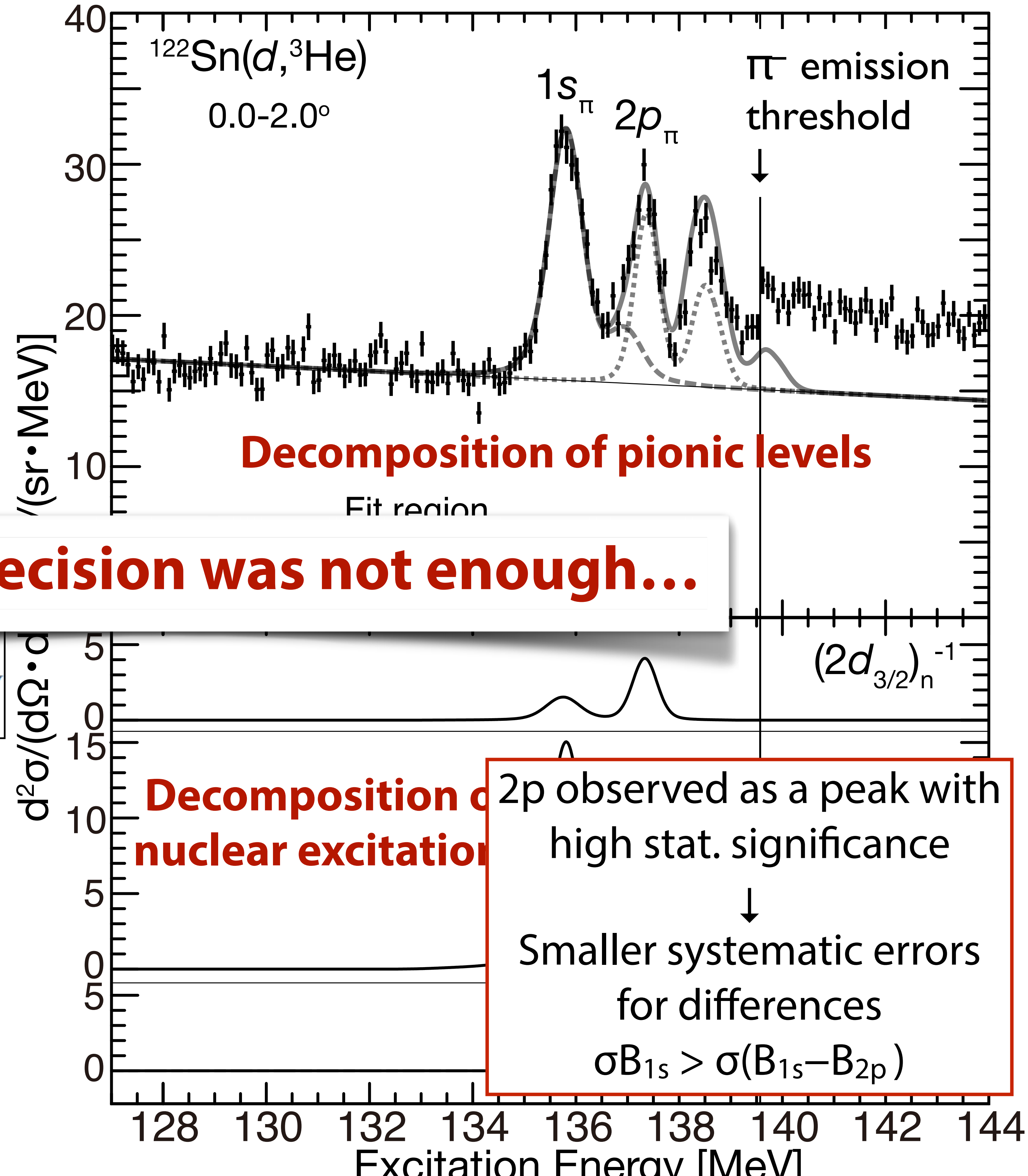
Resolution 394 keV (FWHM)

Theories

B_{1s}= 3.787–3.850 MeV

Γ_{1s}= 0.306–0.324 MeV

B_{2p}= 2.257–2.276 MeV



However, precision was not enough…

2p observed as a peak with high stat. significance

↓

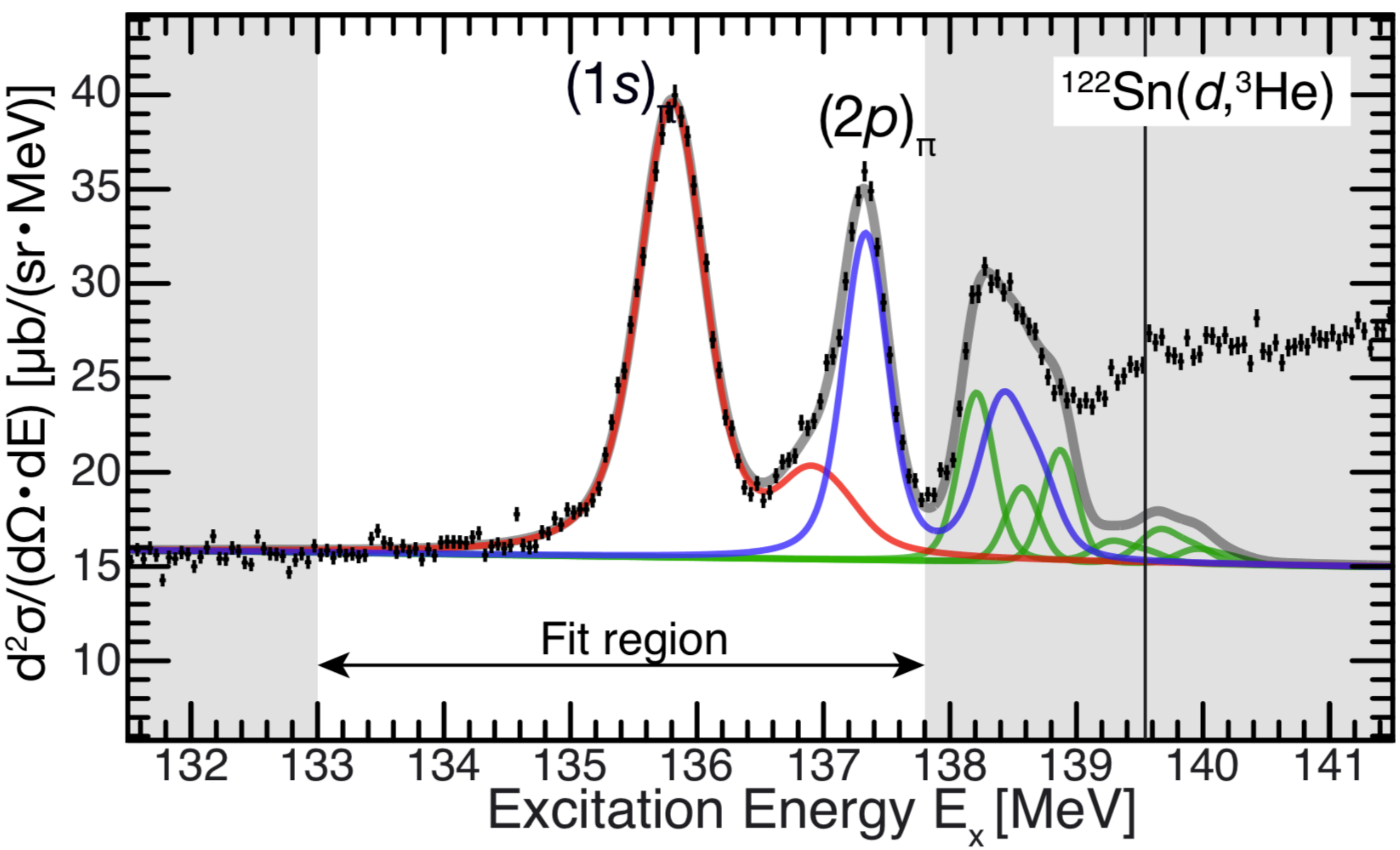
Smaller systematic errors for differences

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

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

Pionic atom unveils hidden structure of QCD vacuum

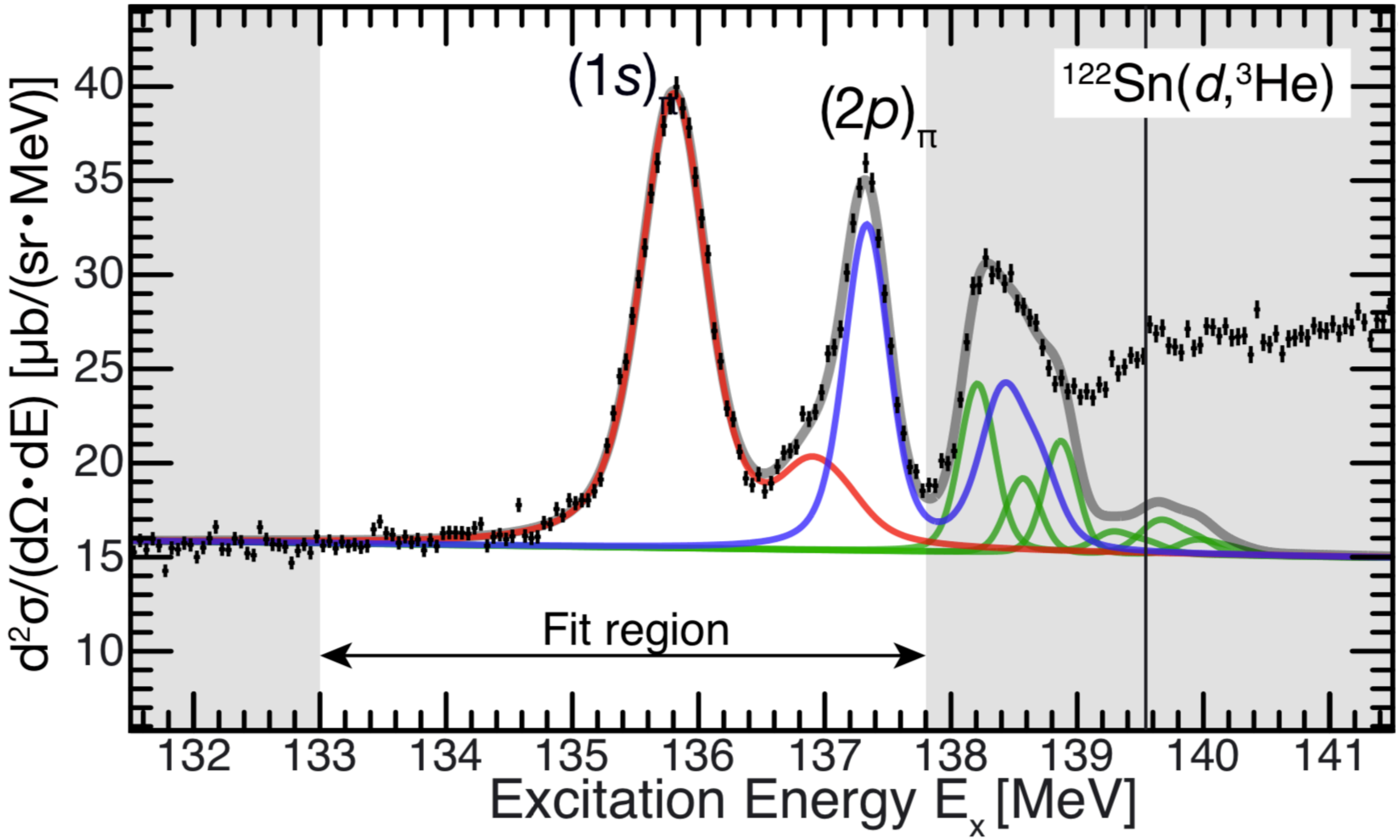
Takahiro Nishi[1], Kenta Itahashi[1,*] DeukSoon Ahn[1,2], Georg P.A. Berg[3], Masanori Dozono[1], Daijiro Etoh[4], Hiroyuki Fujioka[5], Naoki Fukuda[1], Nobuhisa Fukunishi[1], Hans Geissel[6], Emma Haettner[6], Tadashi Hashimoto[1], Ryugo S. Hayano[7], Satoru Hirenzaki[8], Hiroshi Horii[7], Natsumi Ikeno[9], 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]



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

Under review
arXiv: 2204.05568

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	$+28-36$

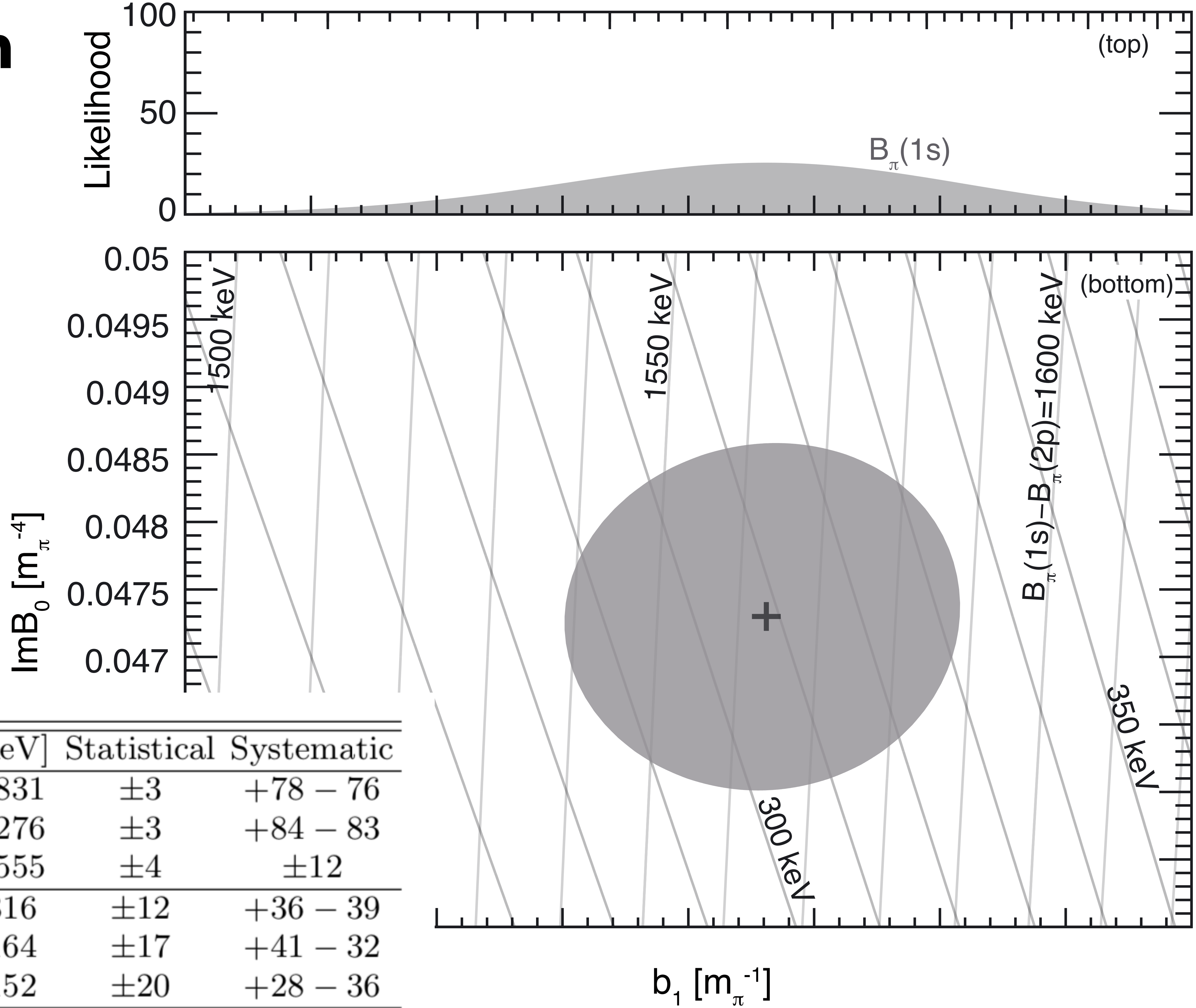
Best resolution 287 keV (FWHM)

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

Under review
arXiv: 2204.05568

b1 parameter Deduction

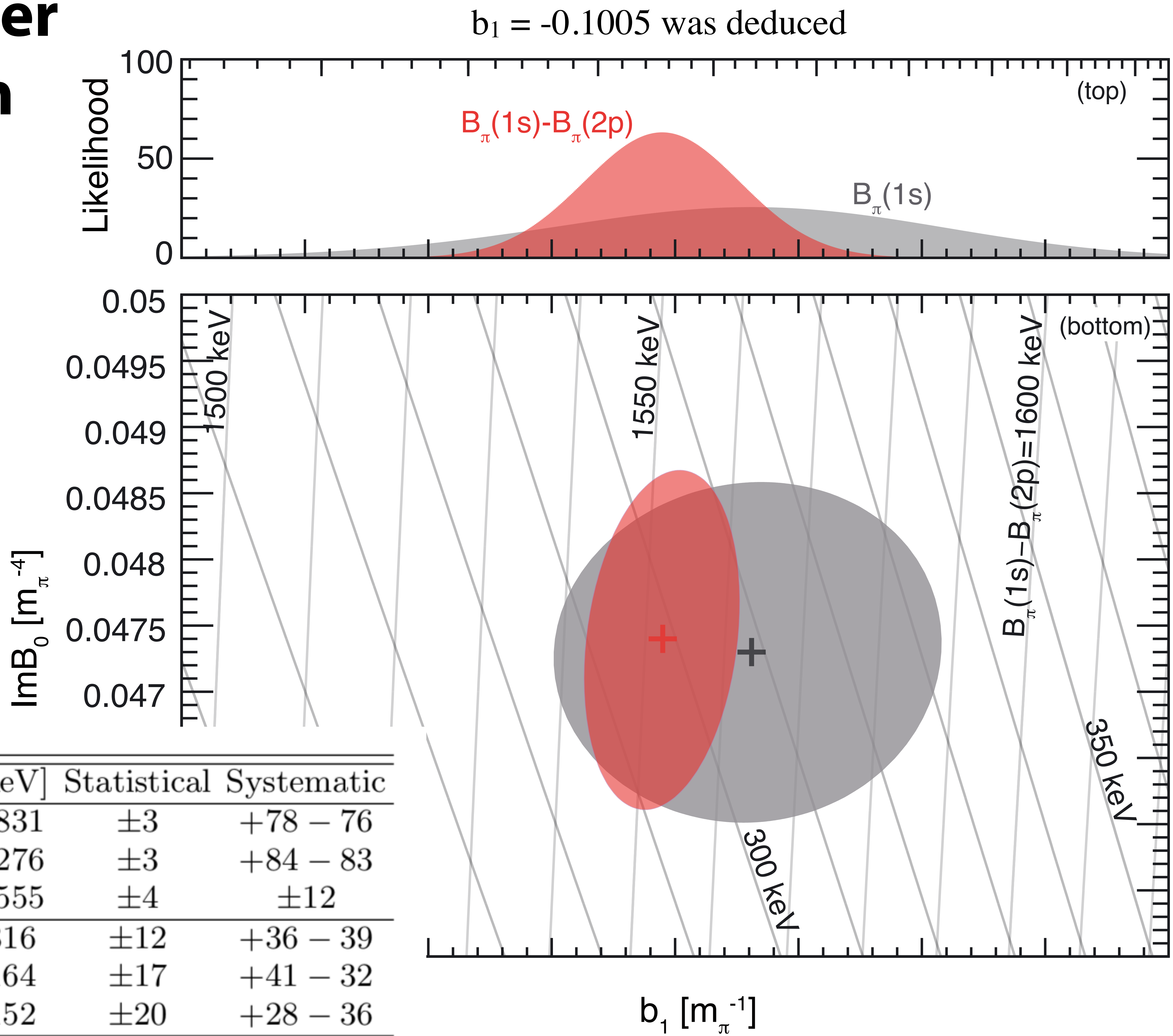
based on pionic C, N, O, and Sn atoms



	[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	$+28-36$

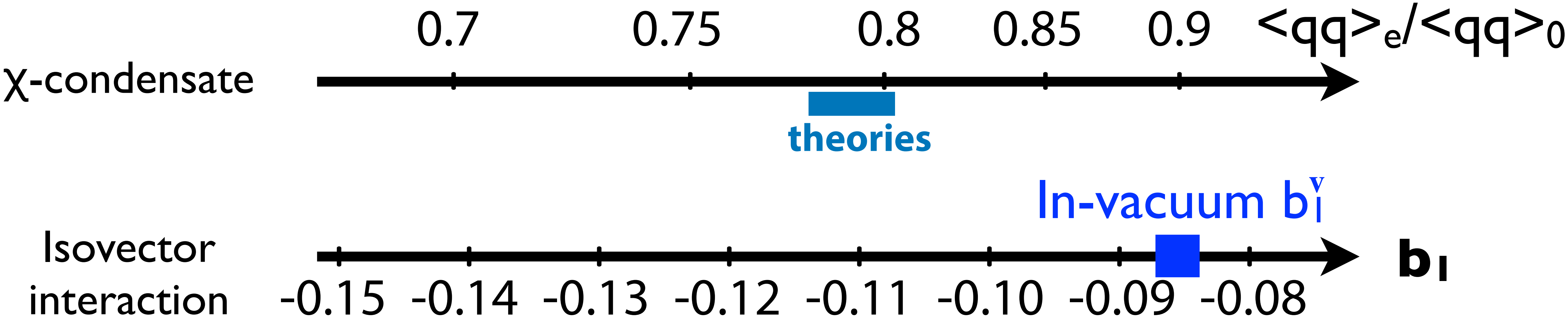
b1 parameter Deduction

based on pionic C, N, O, and Sn atoms



	[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	$+28-36$

Deduced b_1 and chiral condensate at ρ_e

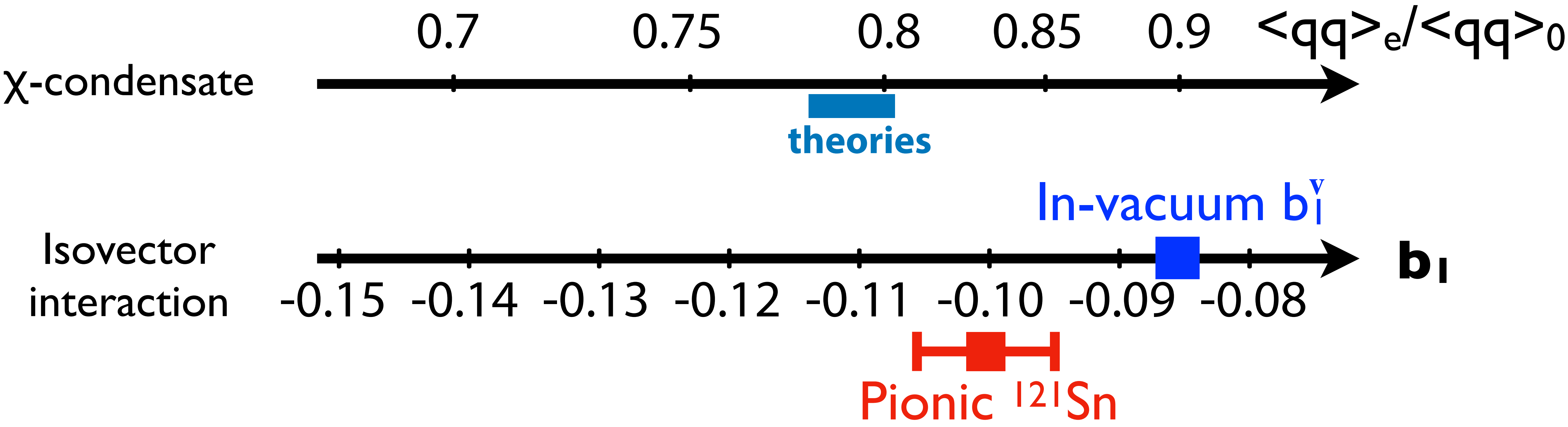


$b_1 = -0.1005$ was deduced

	[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	$+28-36$

Nishi, KI et al., arXiv: 2204.05568

Deduced b_1 and chiral condensate at ρ_e

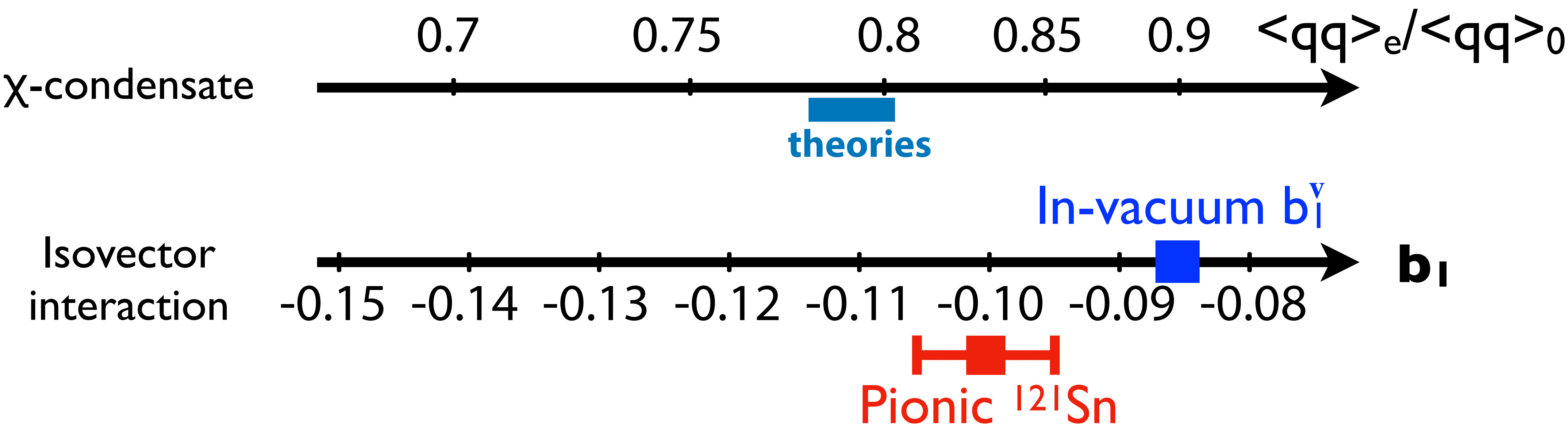


b_1 = -0.1005 was deduced

	[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	$+28-36$

Nishi, KI et al., arXiv: 2204.05568

Updated / newly introduced



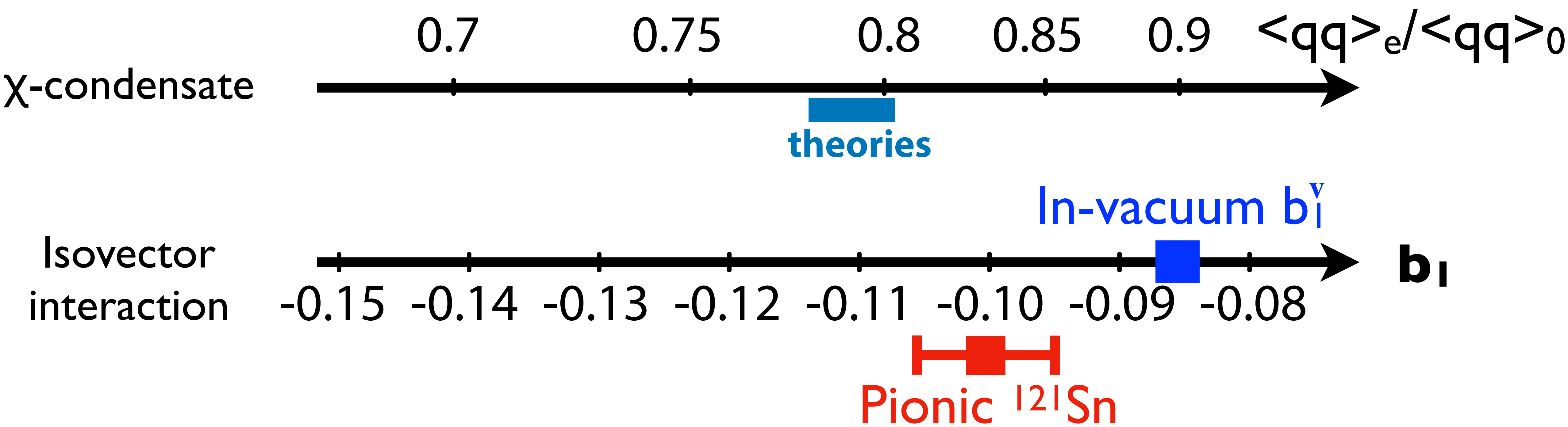
b_1 = -0.1005 was deduced

	[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	$+28-36$

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

Nishi, KI et al., arXiv: 2204.05568

Updated / newly introduced



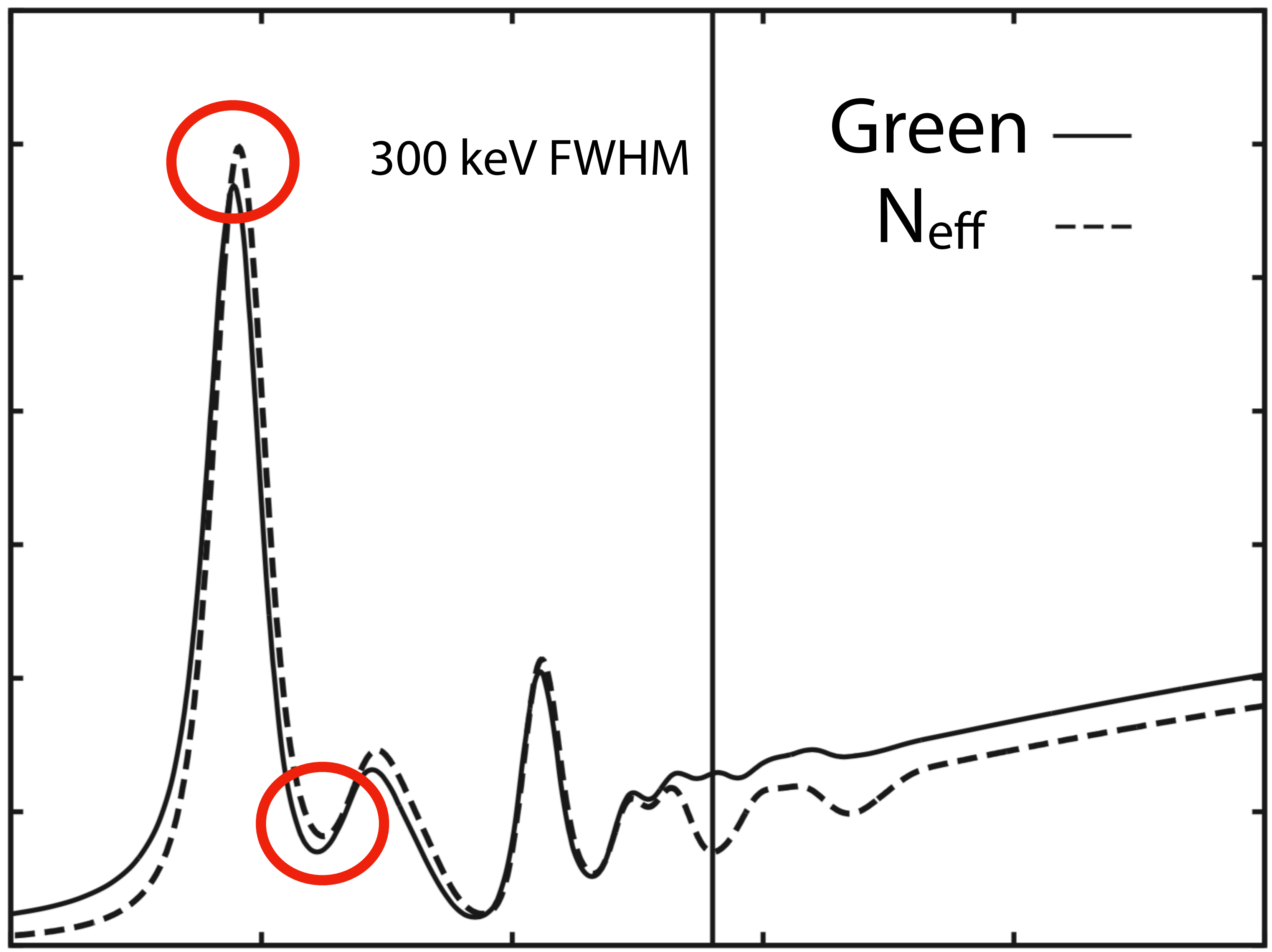
b_1 = -0.1005 was deduced

	[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	$+28-36$

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

Nishi, KI et al., arXiv: 2204.05568

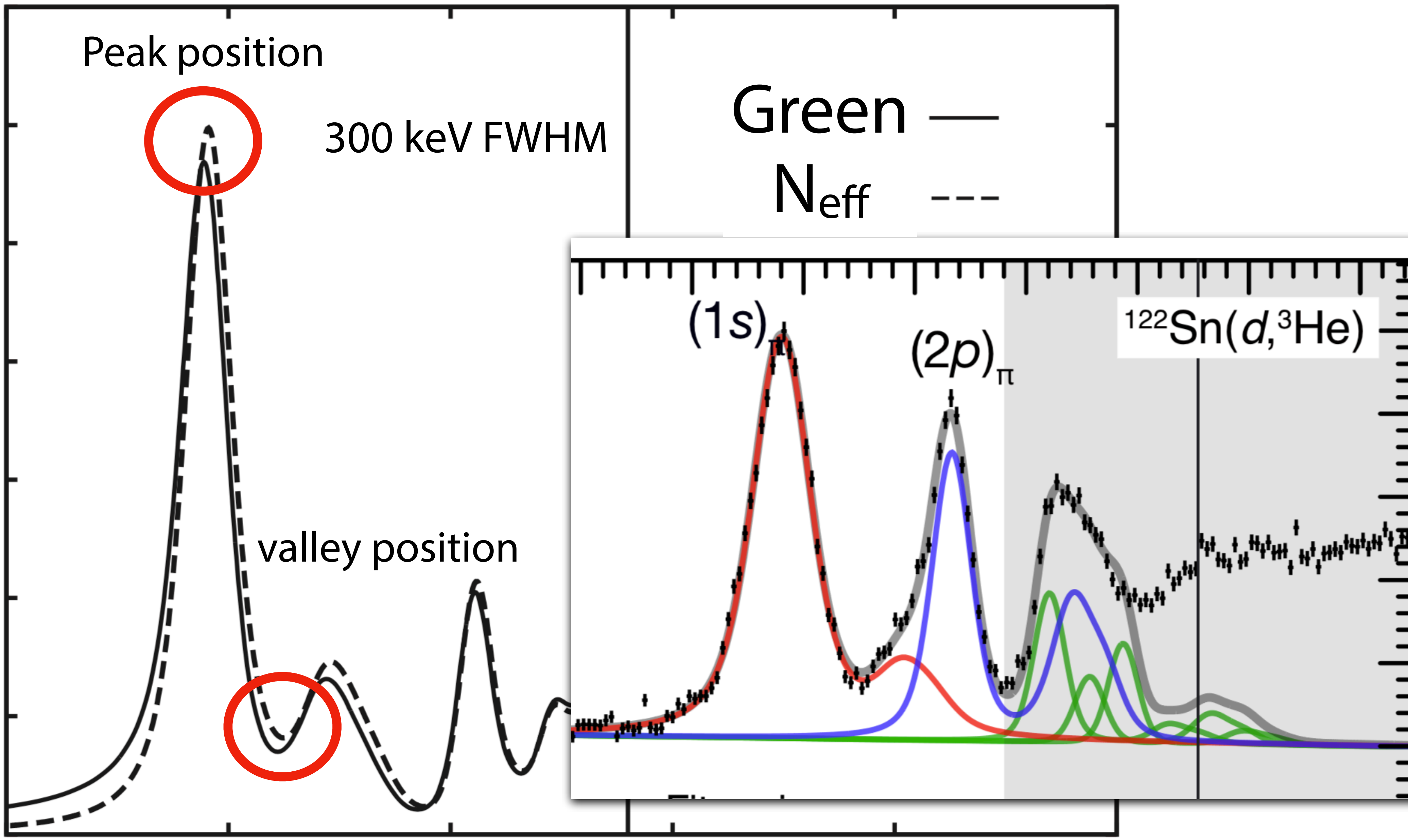
$^{122}Sn(d,^{3}He)$ spectra calculated with Neff and Green's function methods



Green's function method calculates slightly different spectral shapes from N_{eff} approach

N. Ikeno et al., PTEP 2015, 033D01 (2015)

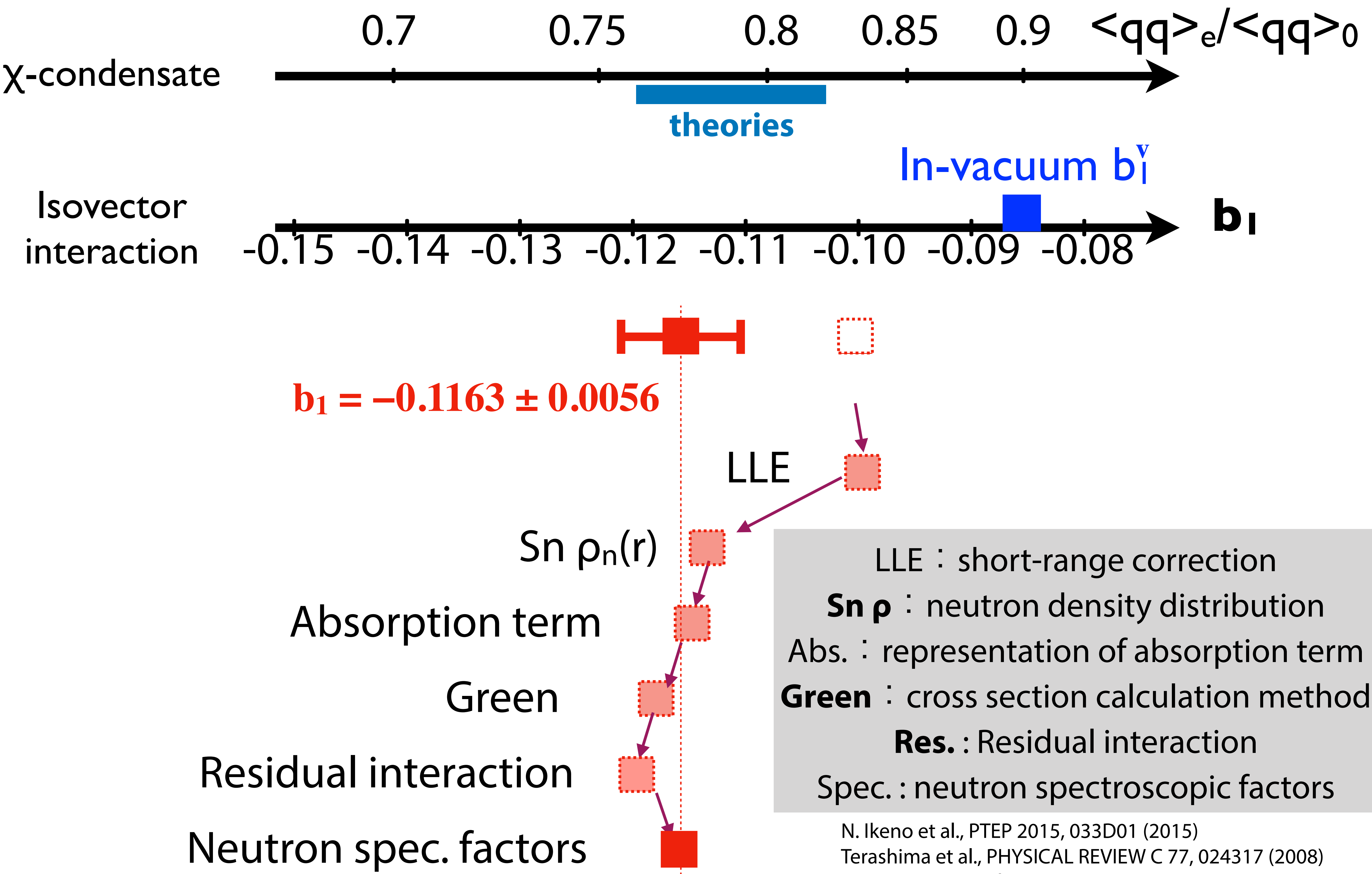
^{122}Sn(d,^{3}He) spectra calculated with Neff and Green's function methods



Green's function method calculates slightly different spectral shapes from N_{eff} approach

N. Ikeno et al., PTEP 2015, 033D01 (2015)

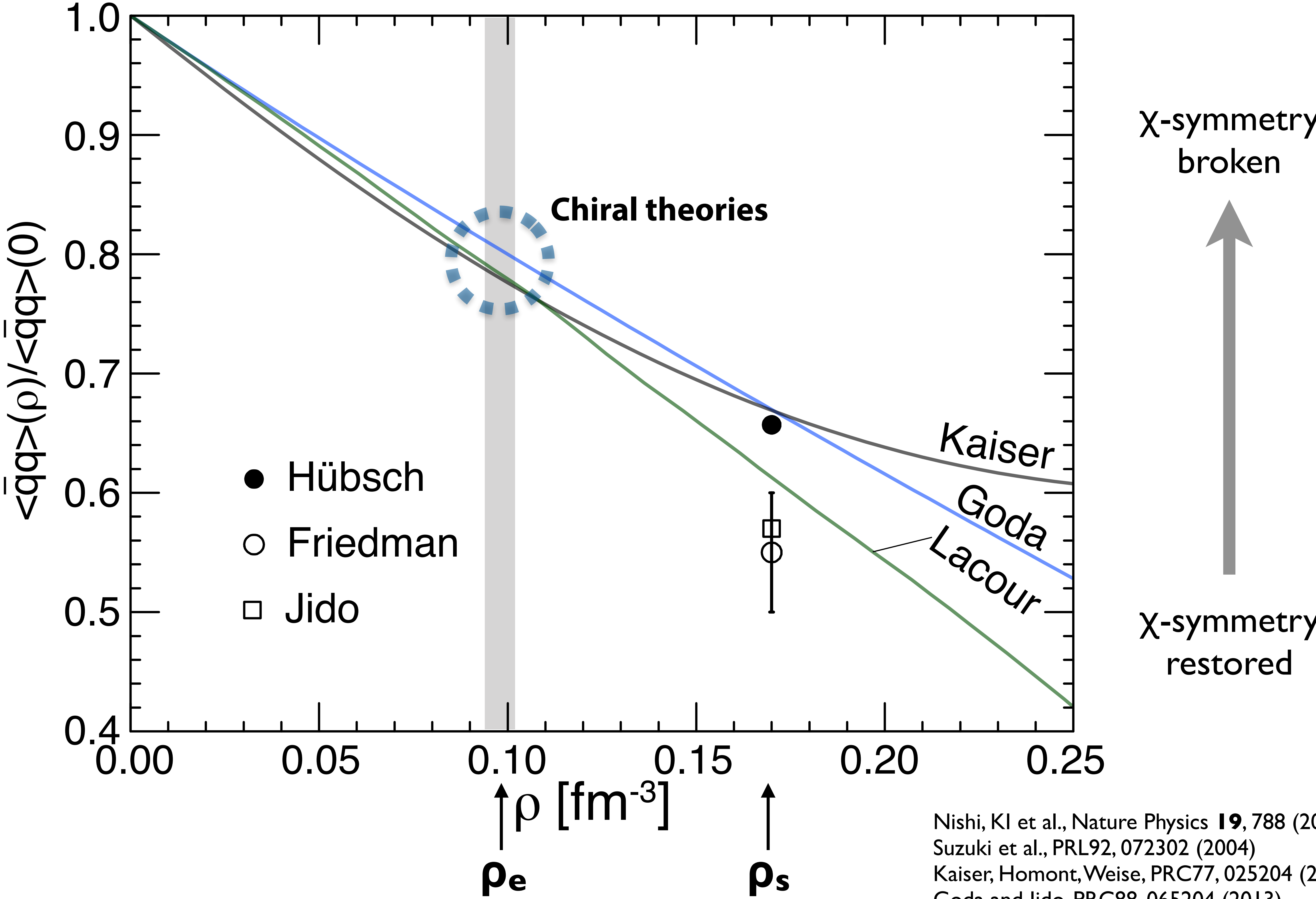
Deduced b_1 after all



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

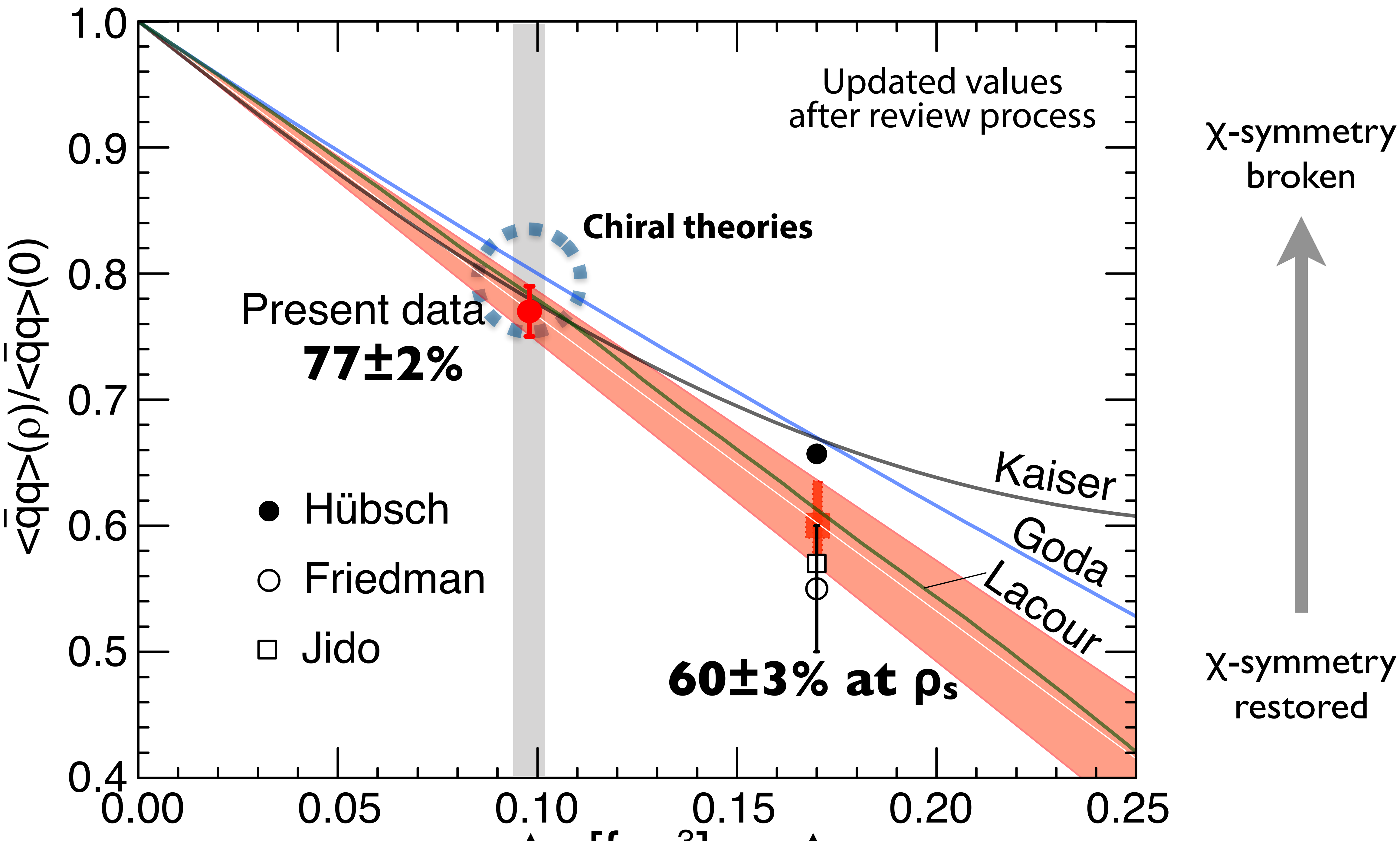
N. Ikeno et al., PTEP 2015, 033D01 (2015)
Terashima et al., PHYSICAL REVIEW C 77, 024317 (2008)
Nose-Togawa et al., PRC71, 061601(R) (2005)
Szwec et al., PRC104,054308

Result: deduced chiral condensate



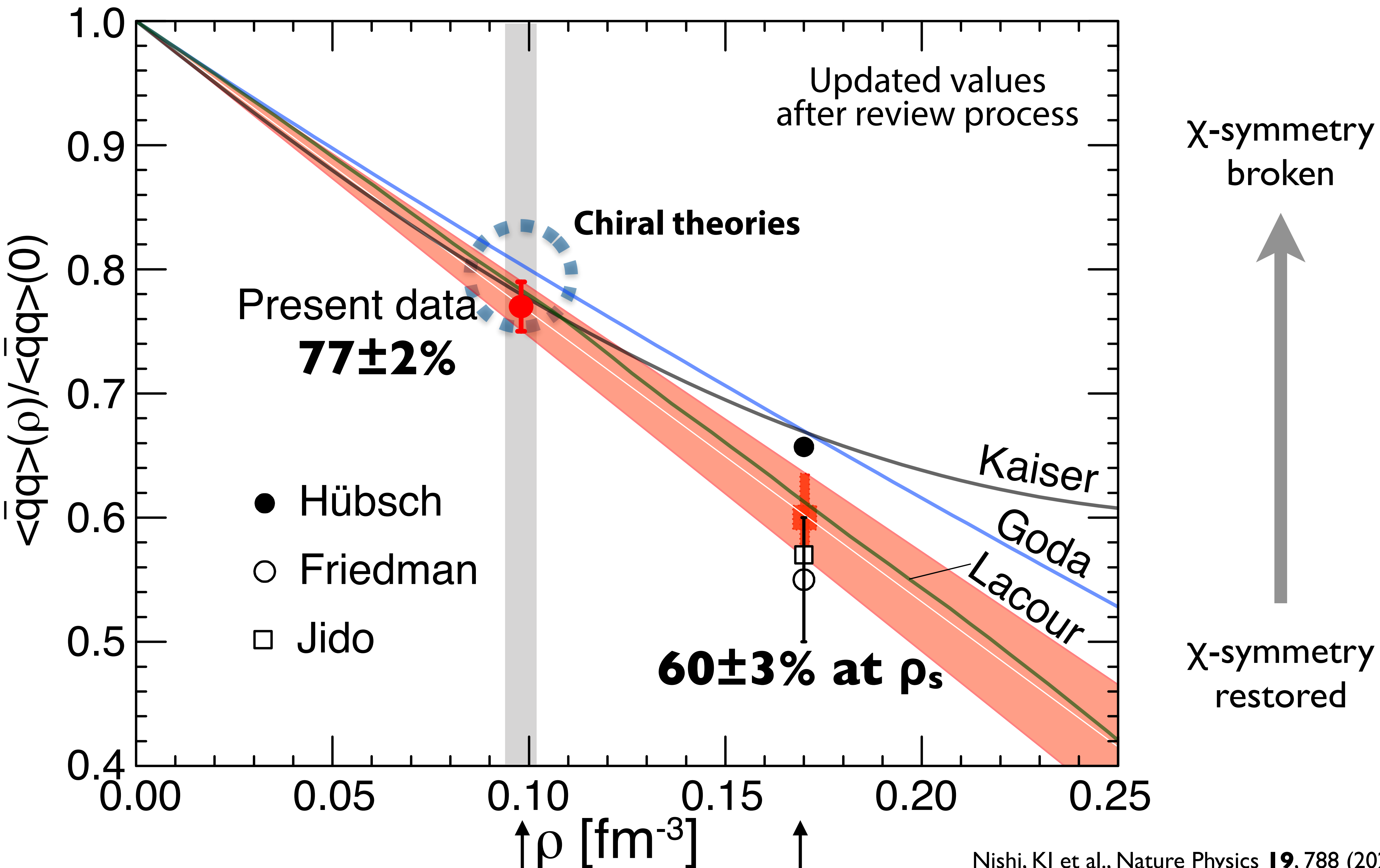
Nishi, KI et al., Nature Physics **19**, 788 (2023)
Suzuki et al., PRL92, 072302 (2004)
Kaiser, Homont, Weise, PRC77, 025204 (2008)
Goda and Jido, PRC88, 065204 (2013)
Huebsch, Jido, PRC104, 015202 (2021)
Friedman, Gal, PLB792, 340 (2019)
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)
Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (2010

Result: deduced chiral condensate



Nishi, KI et al., Nature Physics **19**, 788 (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

Result: deduced chiral condensate

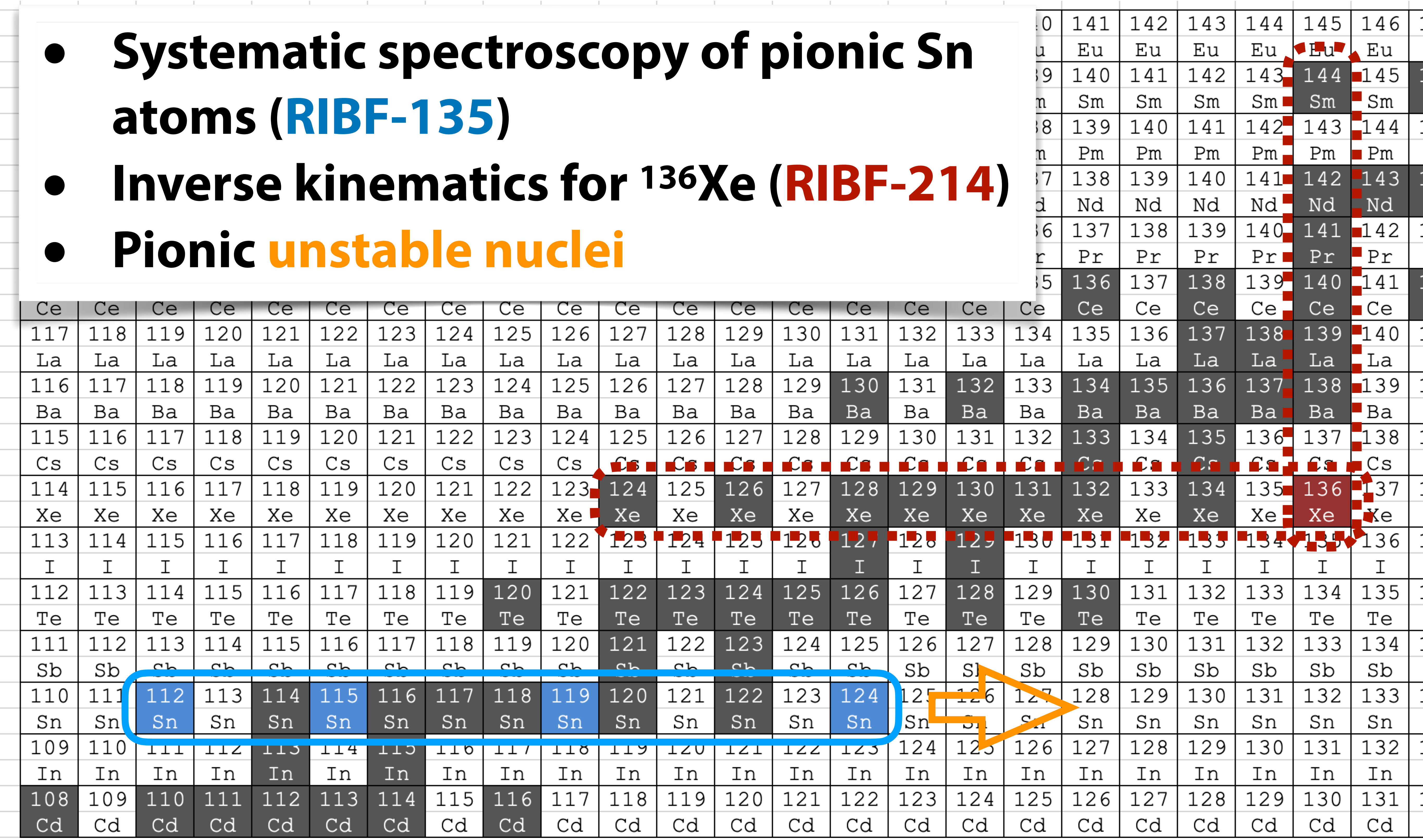


Nishi, KI et al., Nature Physics **19**, 788 (2023)
2008)
8)
Lacour, Oller, Meissner, J. Phys. G: 37, 125002 (2010

The experimental result shows good agreement with chiral perturbation theories

Next plans

- **Systematic spectroscopy of pionic Sn atoms (RIBF-135)**
- **Inverse kinematics for ^{136}Xe (RIBF-214)**
- **Pionic unstable nuclei**

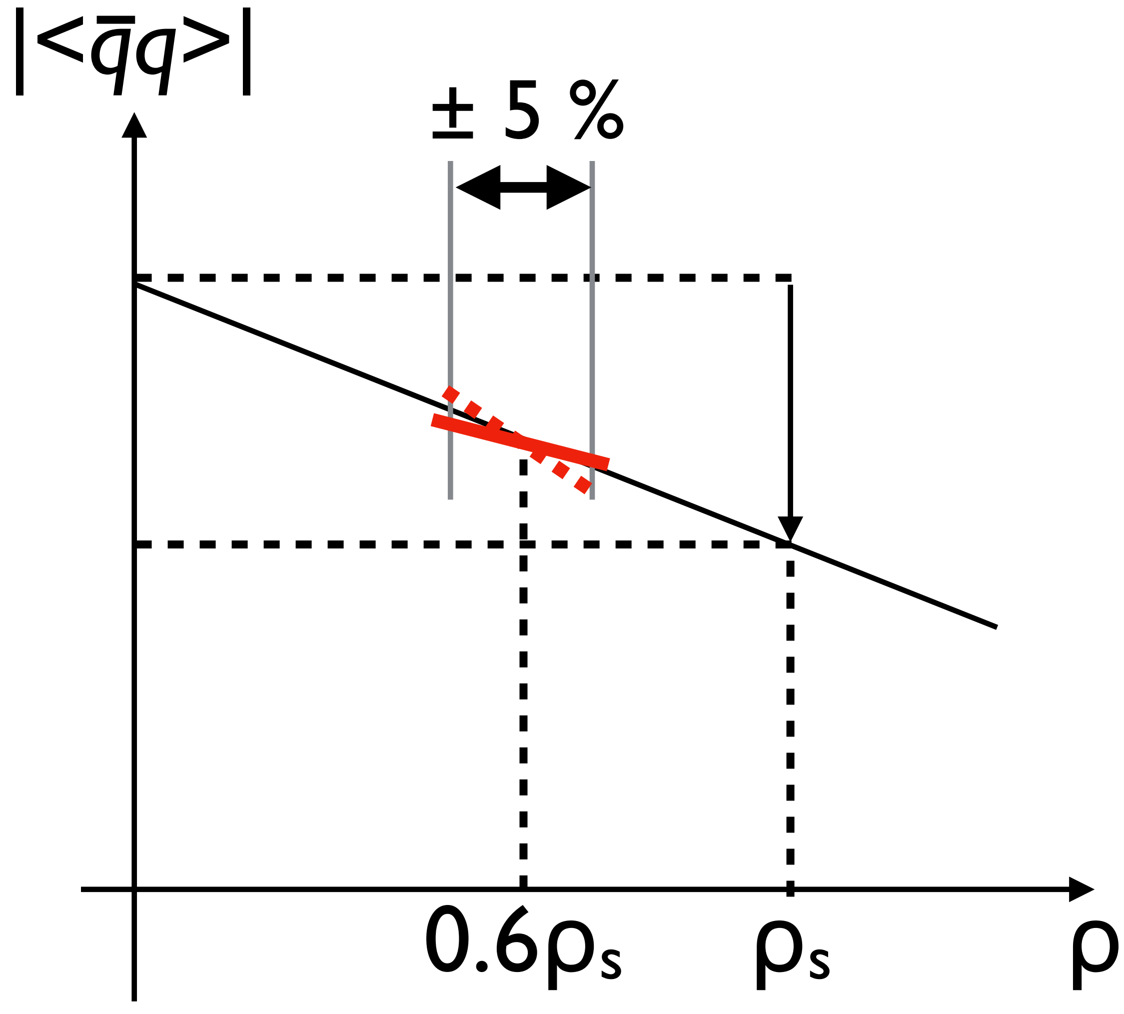


Density Dependence of Chiral Condensate

ρ derivative of <qq>= d<qq>/dρ can be studied by systematic spectroscopy of pionic Sn isotopes

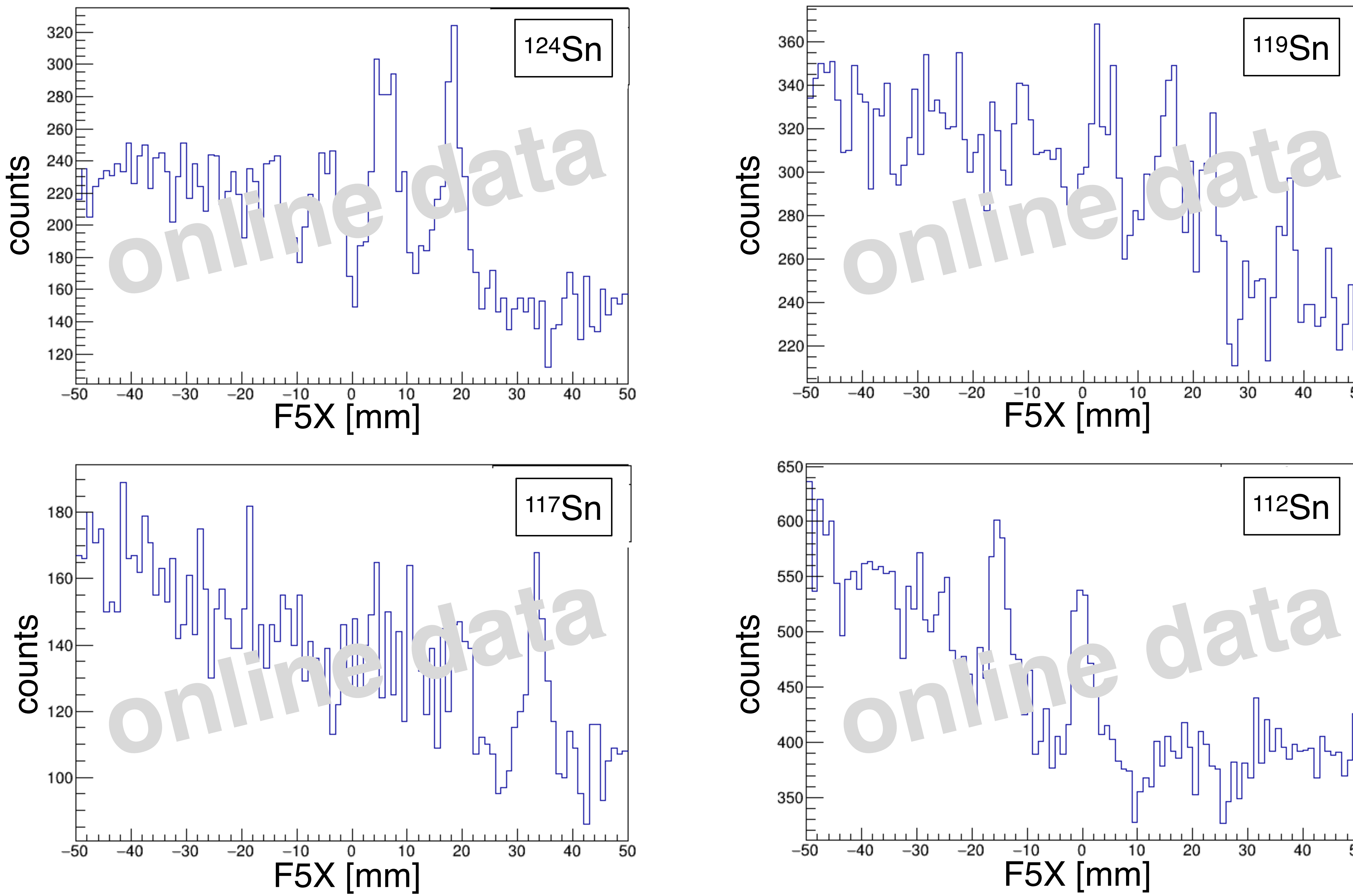
Densities probed by pionic Sn with wide range of A

Important for $\sigma_{\pi N}$ for investigation of origin of matter mass



Pionic atoms are known to probe ~$0.6\rho_s$

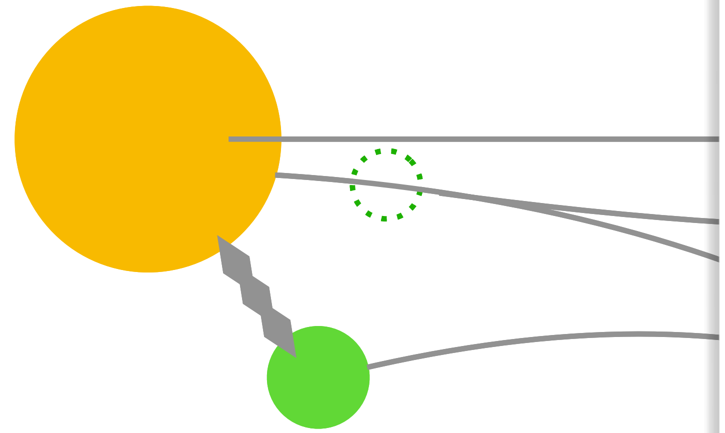
Systematic spectroscopy of pionic Sn isotopes
Successful measurement in RIBF-135 (2021)



First application of inverse

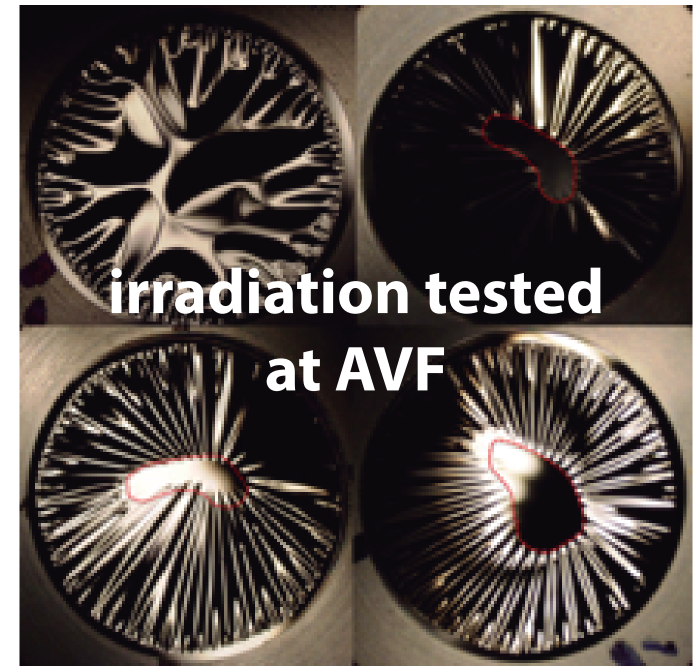
250 MeV/u ^{136}Xe

Inverse kinematics



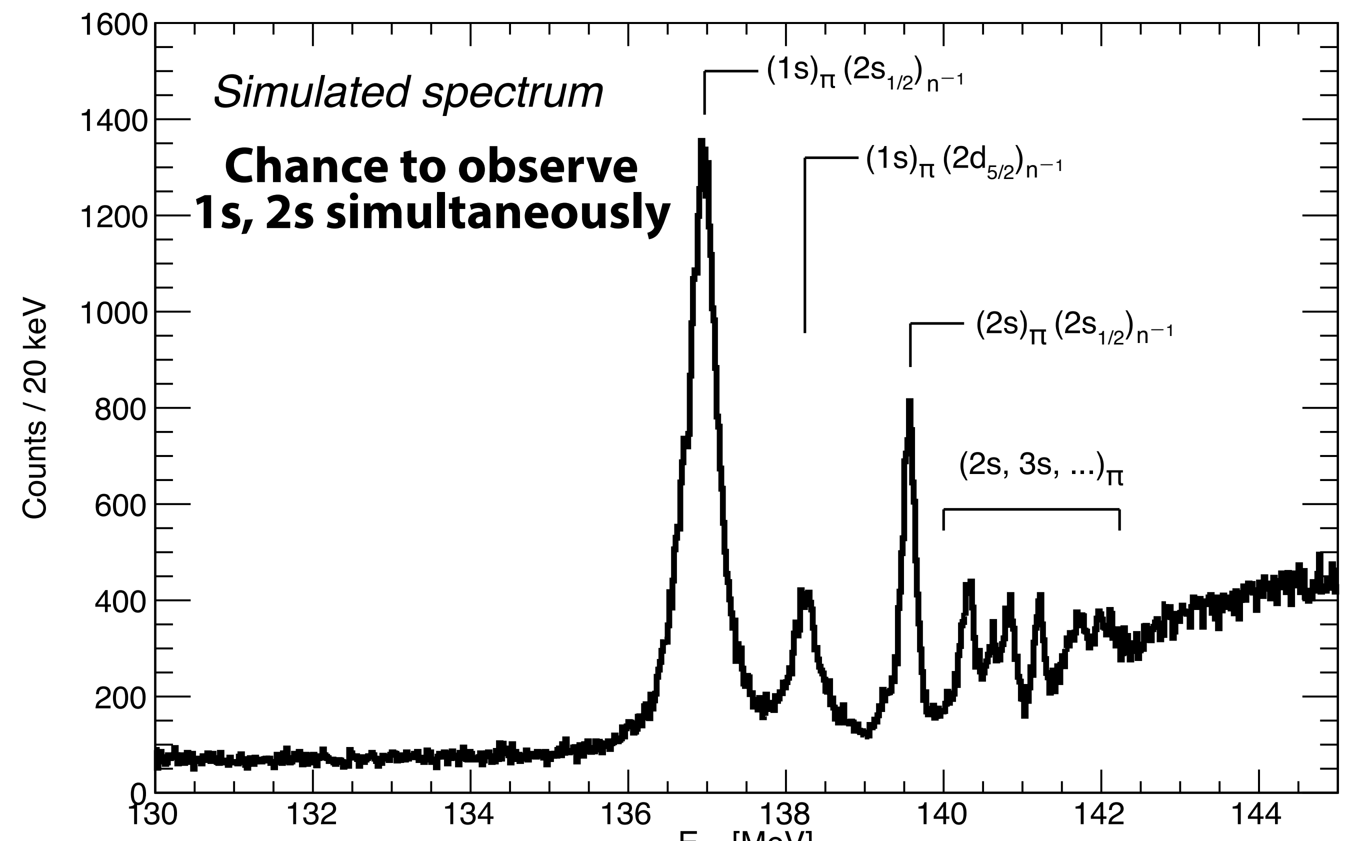
D

1-atm deuterium gas target with
1 μm **graphenic carbon** windows



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

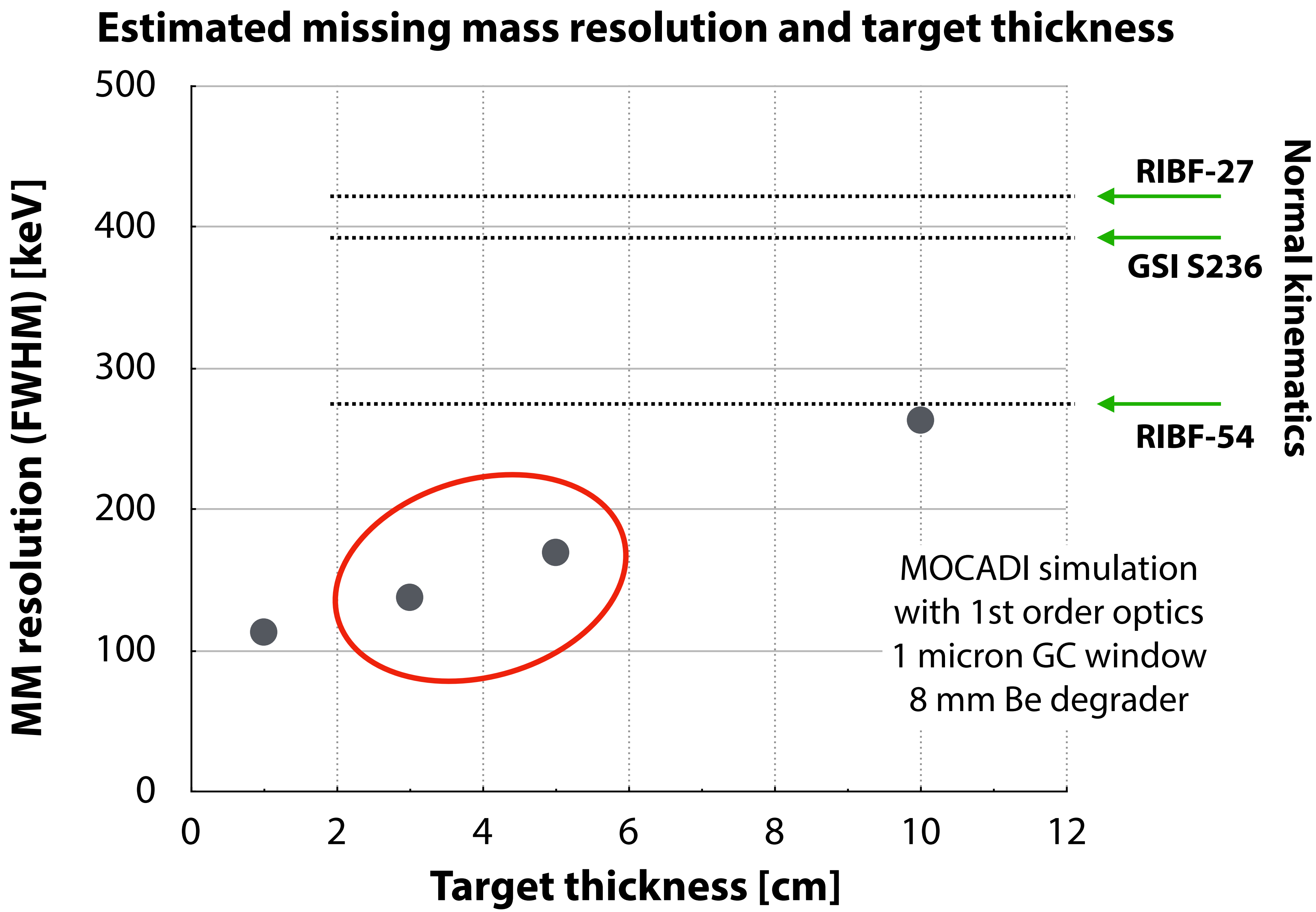
36 hours with 10^{10}/s ^{136}Xe beam



Advantages of inverse kinematics

1. **Unprecedented resolution**
   MM resolution does not depend on incident beam energy spread.
2. **Extension of piA across nuclear chart**
   Use of materials not suited for targets including **radio active nuclei.**

Unprecedented MM 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.

Summary

In-medium meson spectroscopy in missing-mass measurement of meson production reactions is a strong tool to investigate the structure/symmetry of the vacuum at finite ρ.

For η′-mesic nuclei search

- η′-mesic nuclei may give some hints of $U_A(1)$ quantum anomaly.
- We make use of $^{12}C(p,d)$ missing-mass measurement + η′NN→NN tagging.
- WASA at GSI/FRS worked as designed. Background is reduced by 1/200 as simulated.
- We are finalizing the analysis and working on the exclusive spectra.

For pionic atom spectroscopy

- We make use of Sn(d,^{3}He) missing-mass measurement for the pionic atoms.
- The binding energies and widths of the 1*s* and 2*p* states in ^{121}Sn were determined. Difference between the 1*s* and 2*p* values reduces the systematic errors drastically.
- We deduced pion-nucleus interaction after including recent updates. The interaction is modified for the w.f. renomalization of the medium effect.
- Chiral condensate at $\rho_e \sim 0.6\rho_0$ is evaluated to be reduced by a factor of 77±2%.
- We continue study for ρ dependence of <qbar q>. We plan measurement with "inverse kinematics" with better resolution, leading to future experiments of pionic unstable nuclei.