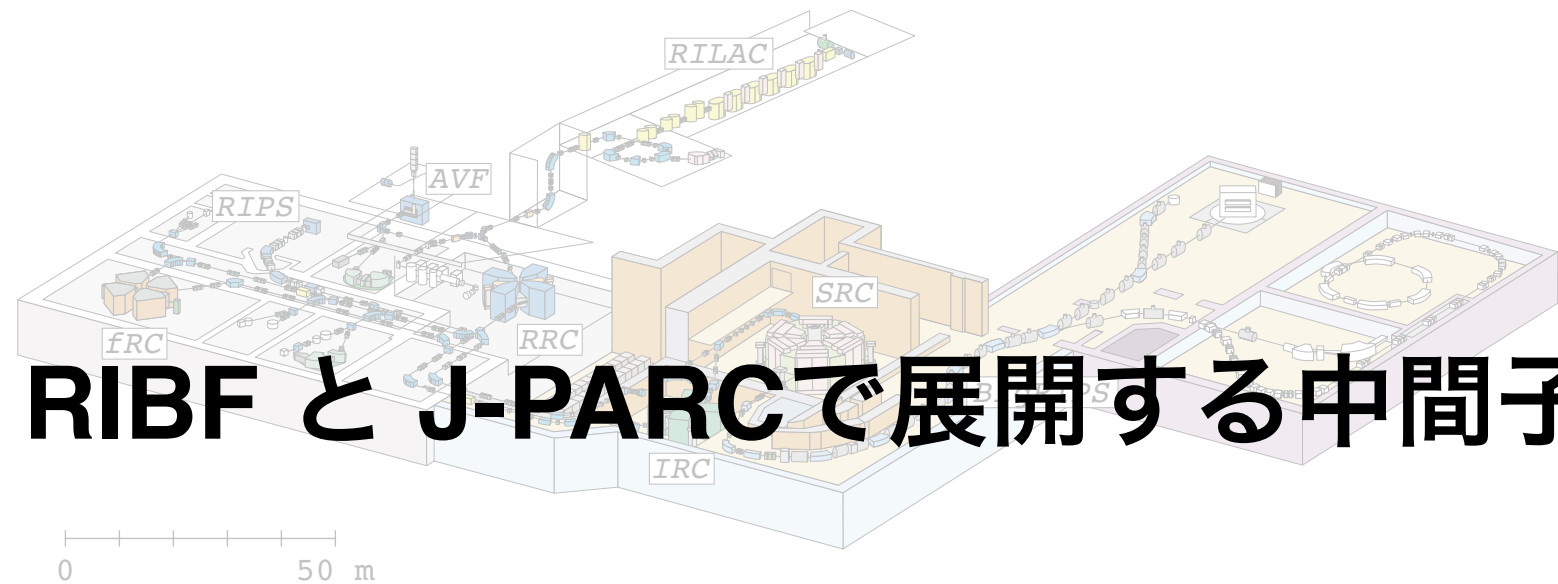
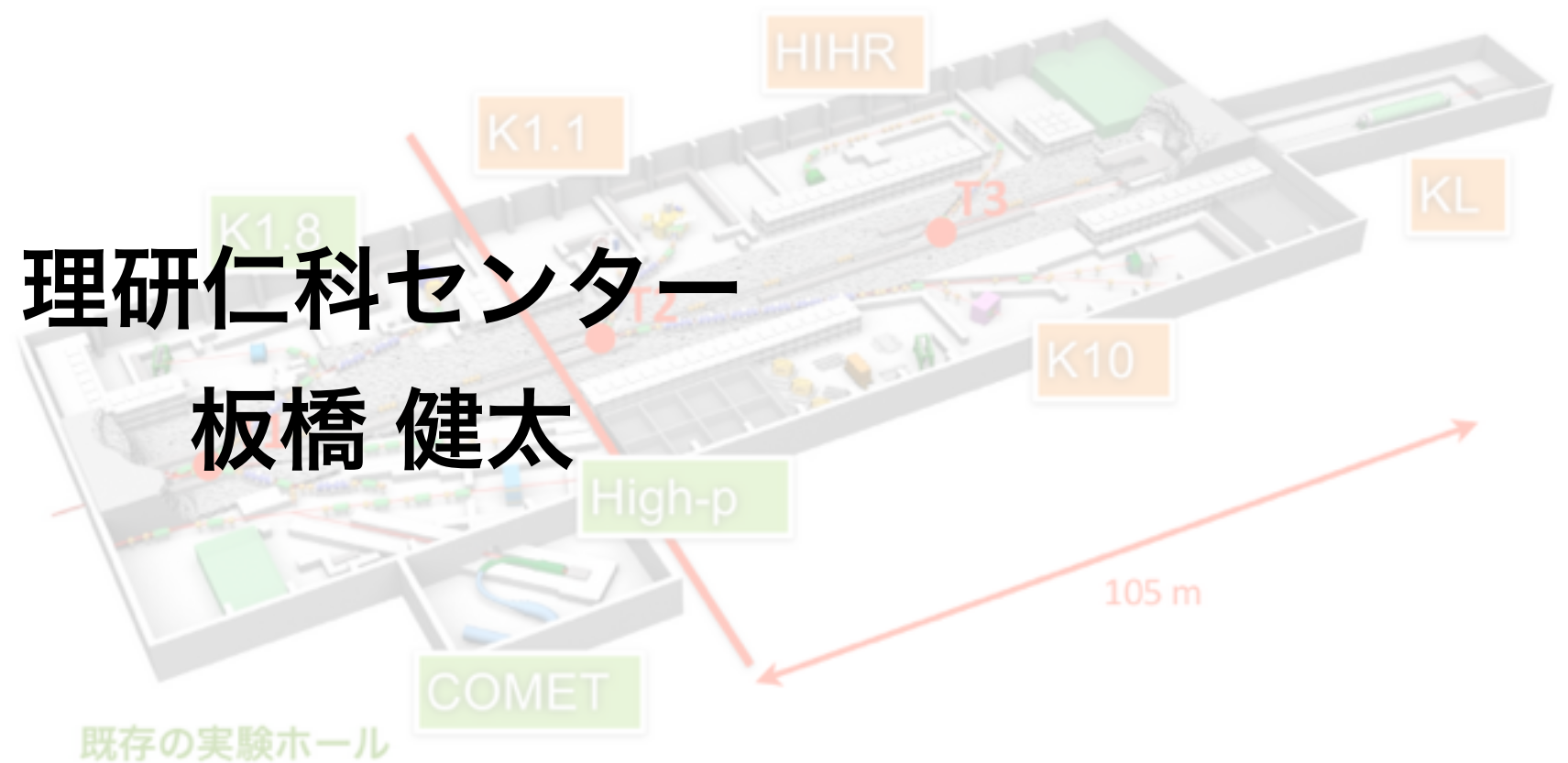


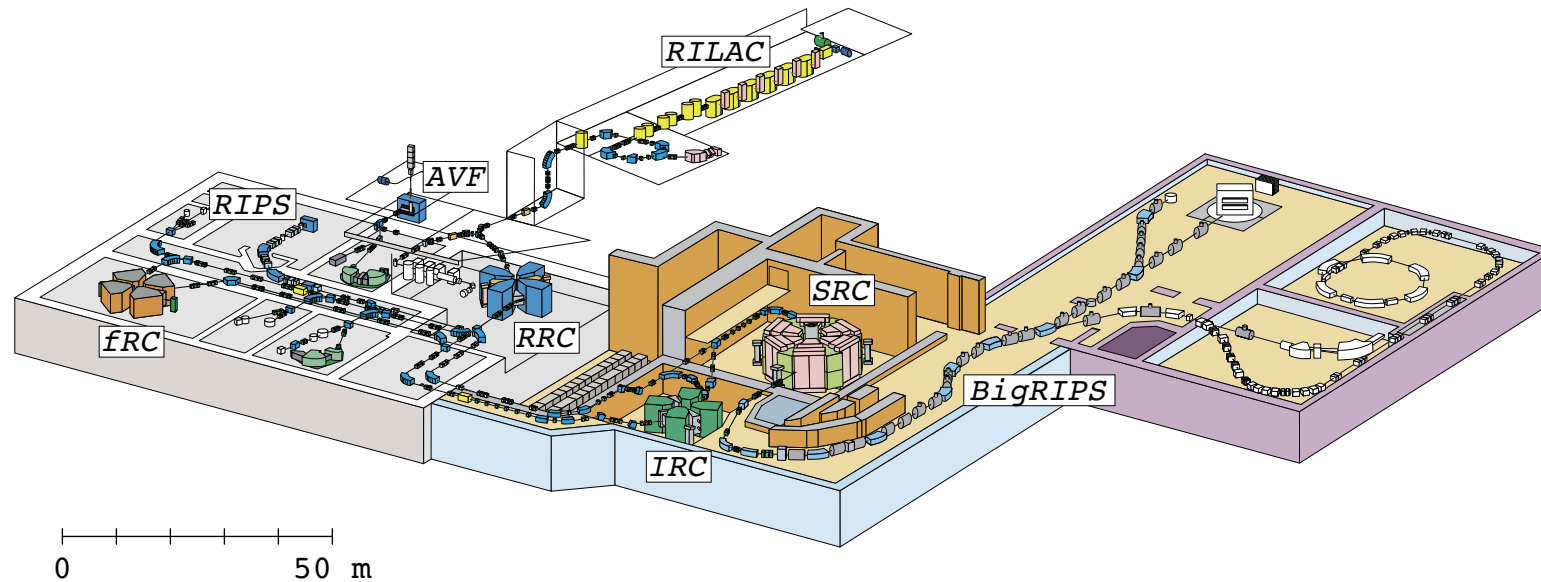


RIBF と J-PARCで展開する中間子-原子核束縛系の研究



理研仁科センター
板橋 健太

RIBF & J-PARC



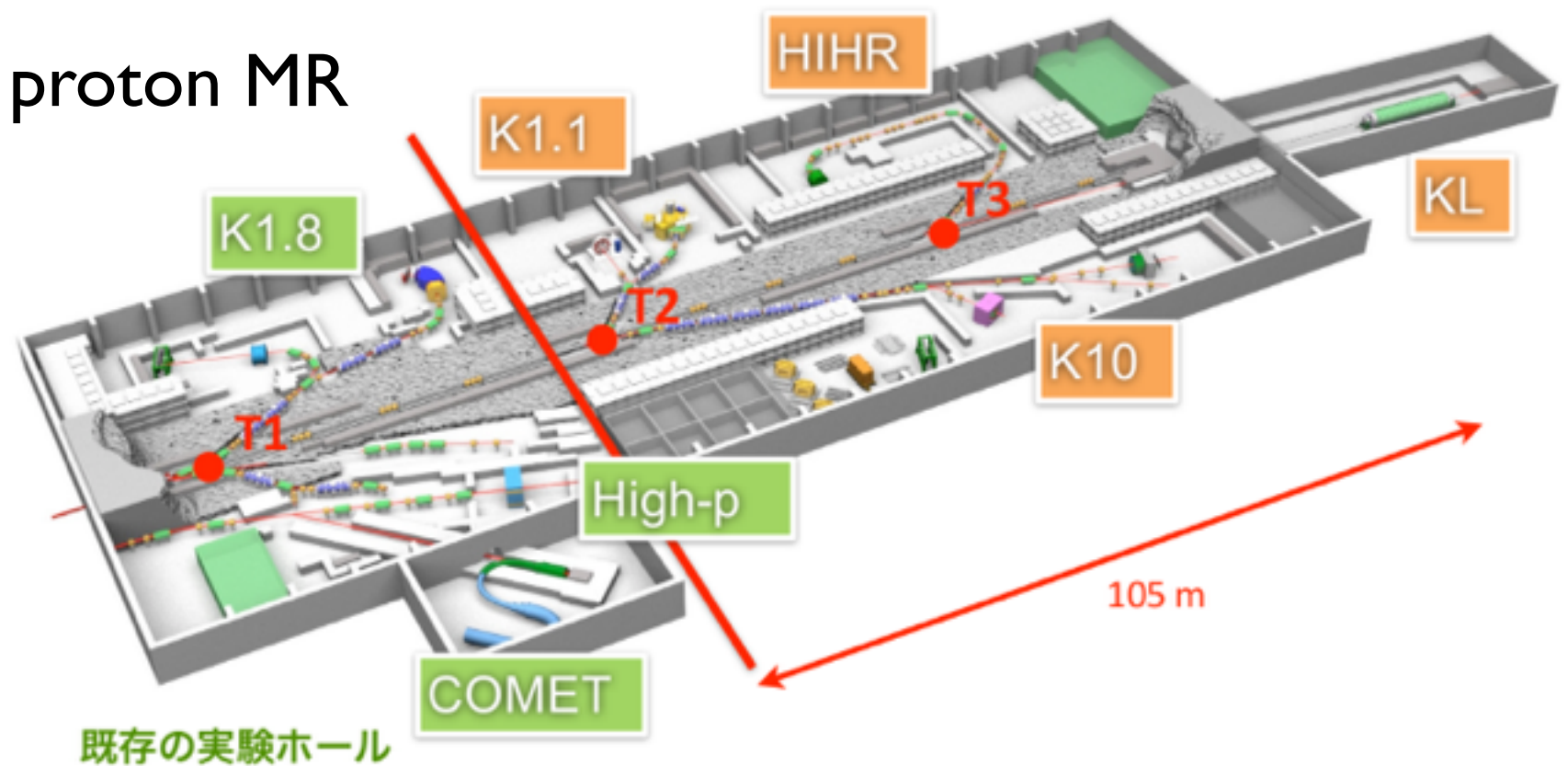
SRC
 $< 1 \text{ p}\mu\text{A}$
 $D \sim {}^{238}\text{U}$
 300-400 MeV/u
 pionic atoms

30 GeV proton MR

Kaonic nuclei
 Kaonic atoms
 η, η' -nuclei

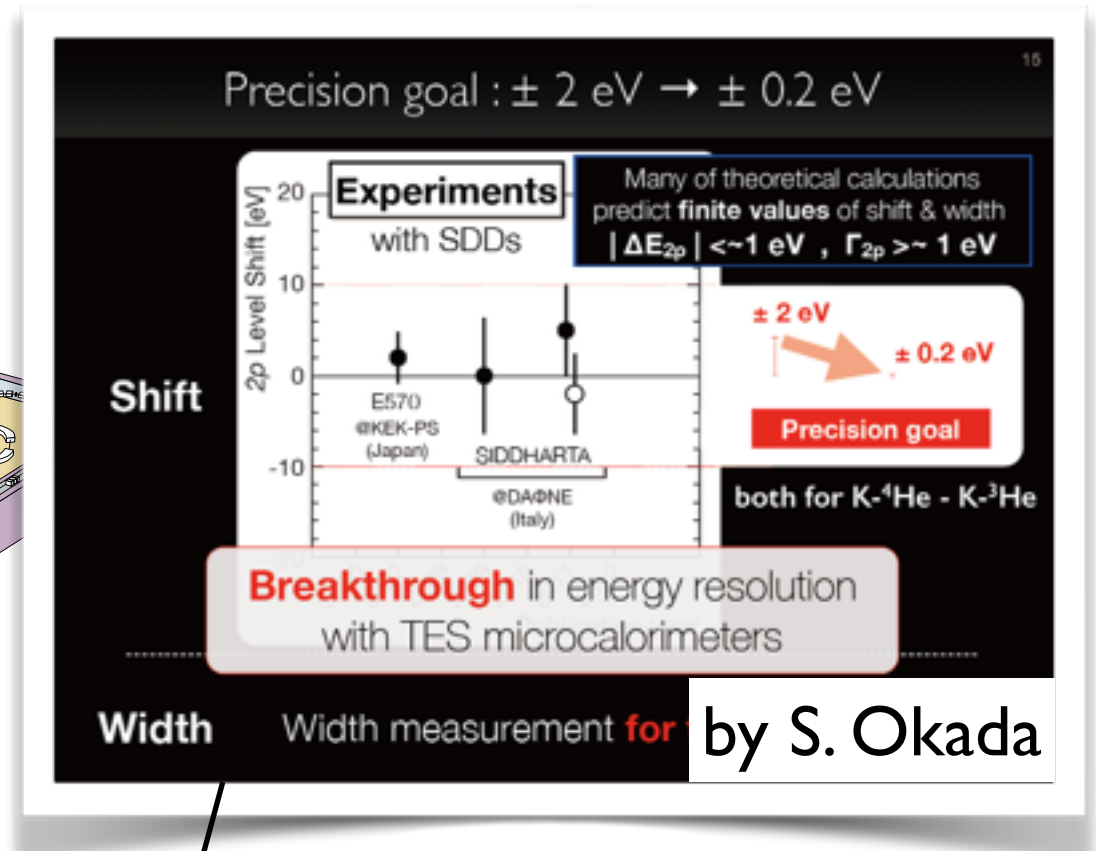
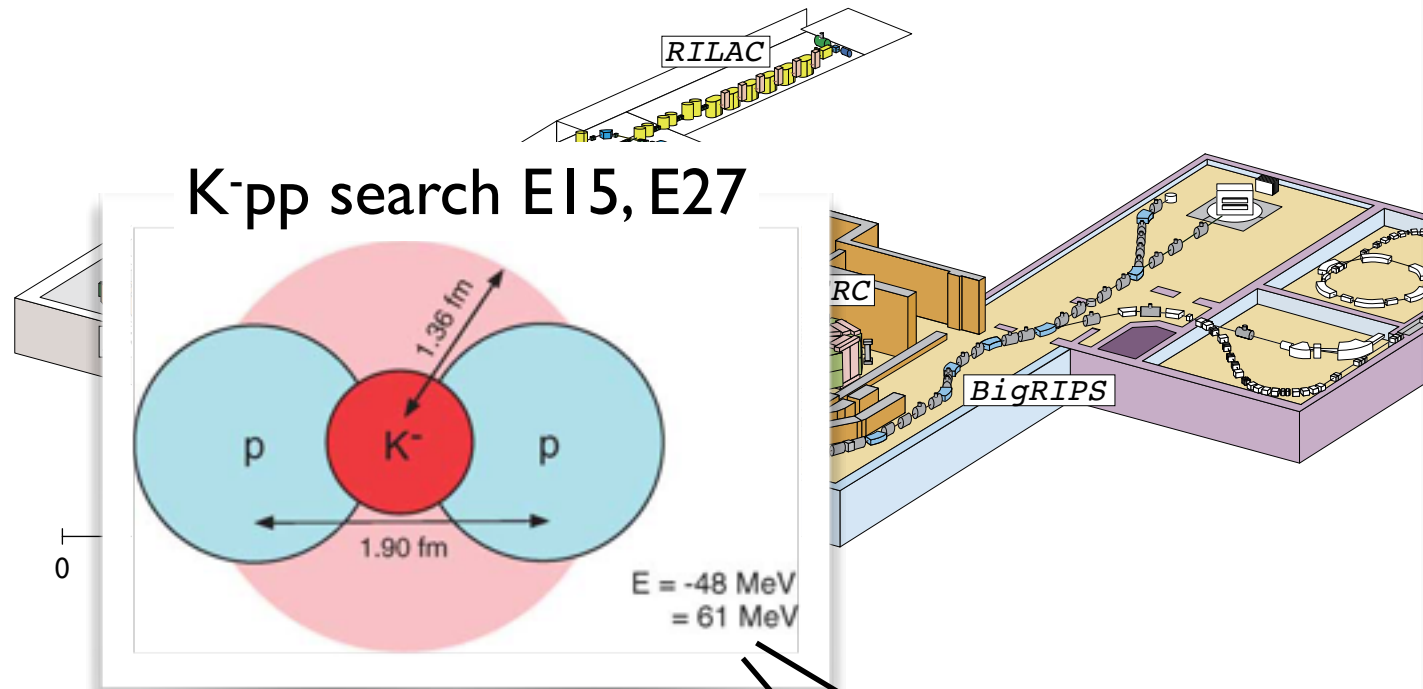
その他にも

Hyper nuclei
 $\Xi, \Lambda\Lambda \dots$



Kenta Itahashi, RIKEN

RIBF & J-PARC

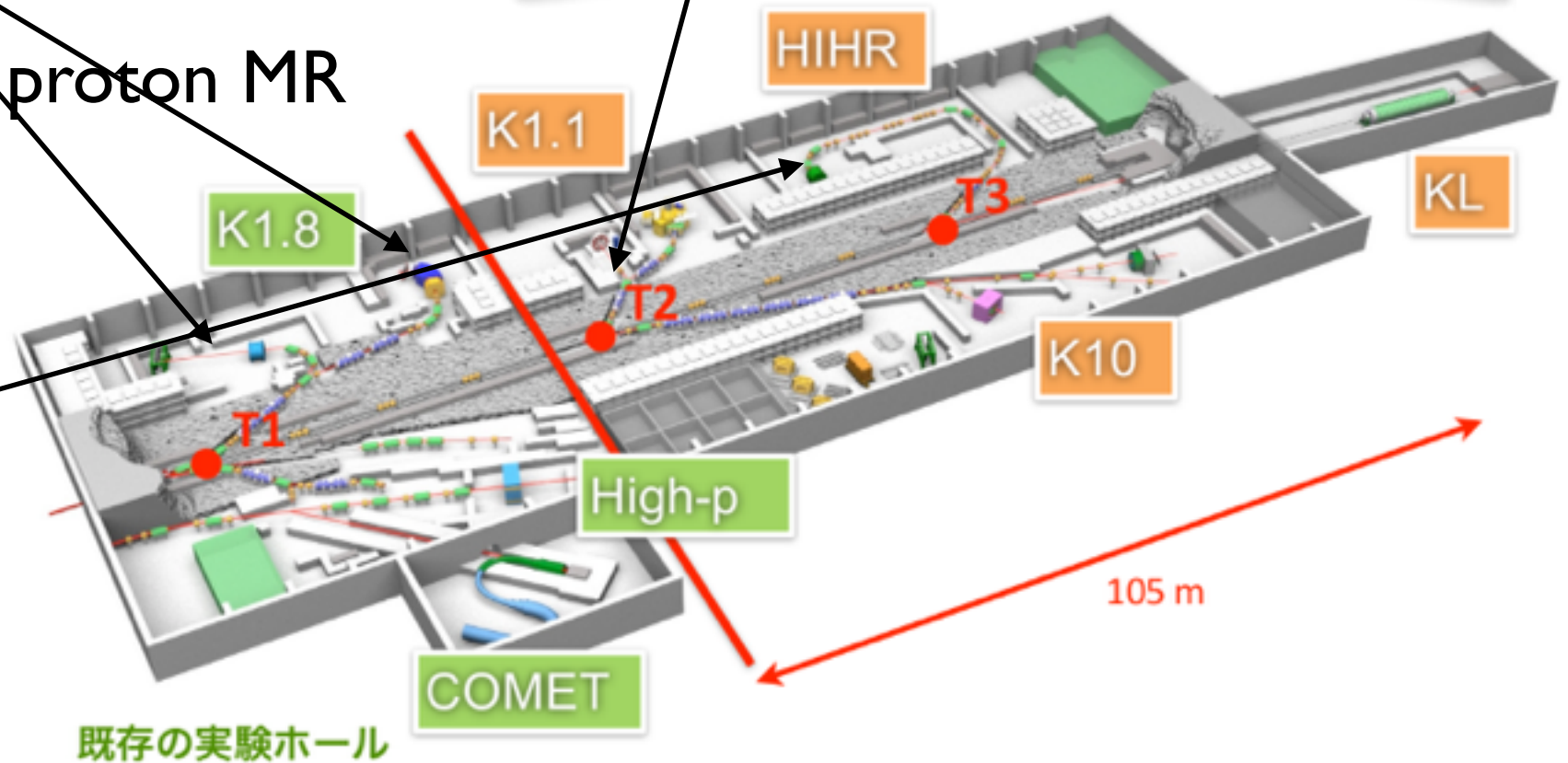


30 GeV proton MR

Kaonic nuclei
Kaonic atoms
 η , η' -nuclei

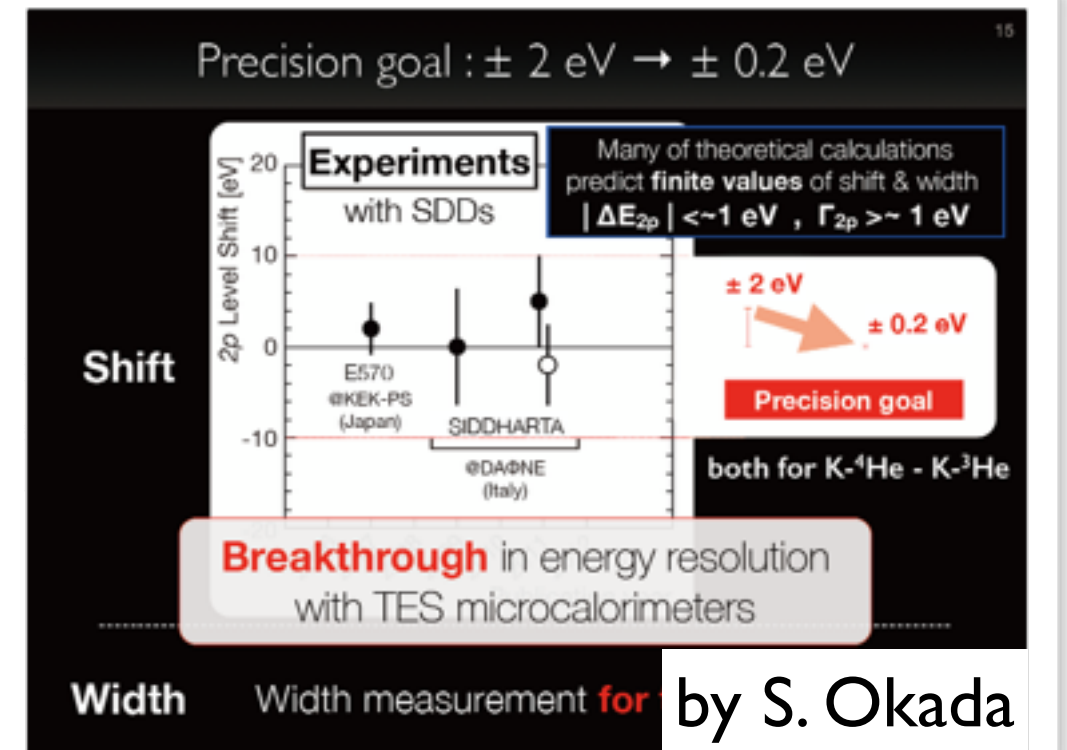
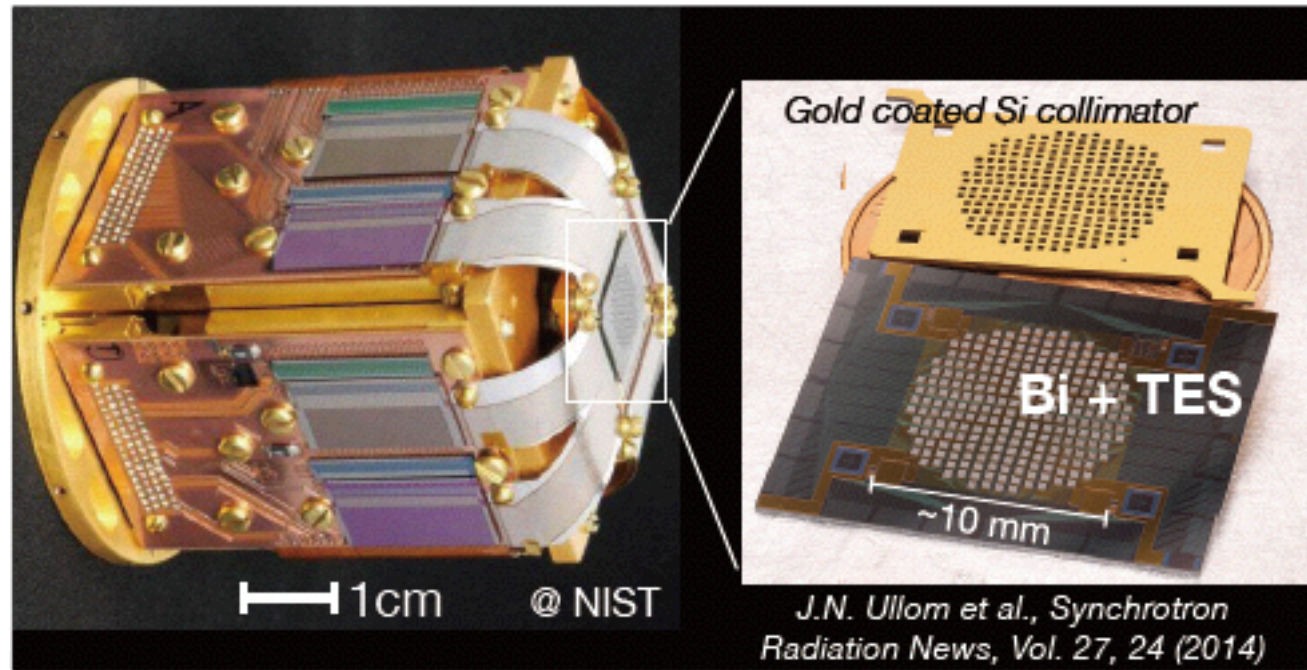
その他にも

Hyper nuclei
 Ξ^- , $\Lambda\Lambda$...



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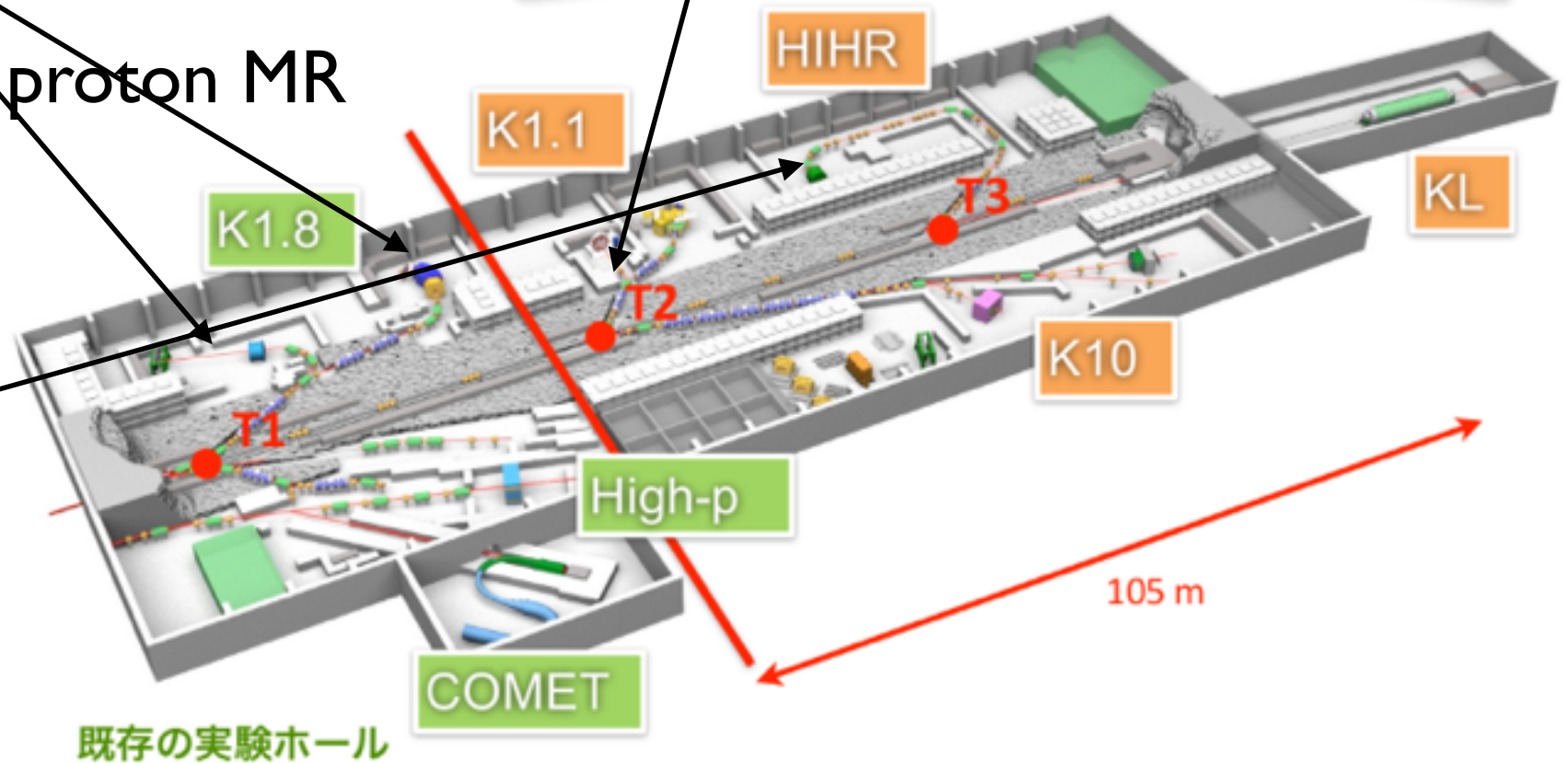
RIBF & J-PARC



30 GeV proton MR

Kaonic nuclei
Kaonic atoms
 η, η' -nuclei

その他にも
Hyper nuclei
 $\Xi, \Lambda\Lambda \dots$



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RIBF と J-PARCで展開する中間子-原子核束縛系の研究

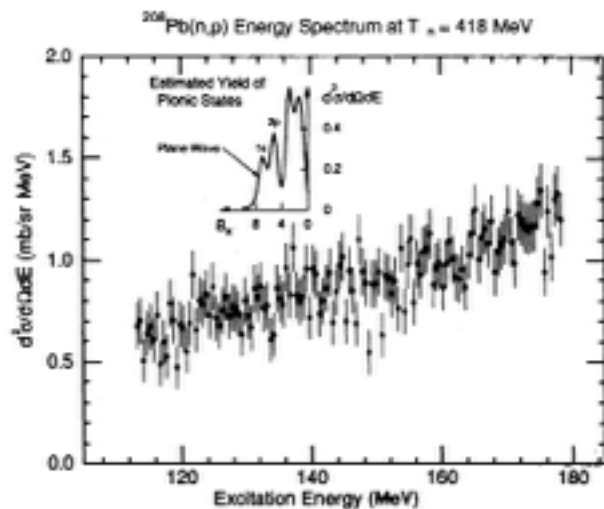
pionic atoms / RIBF

η, η' -nuclei / J-PARC

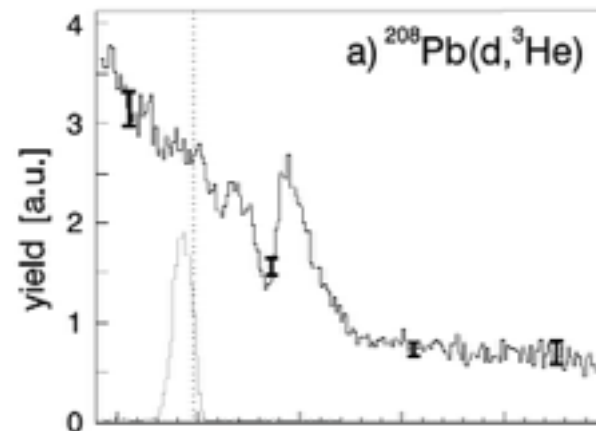
RIBF と J-PARCで展開する中間子-原子核束縛系の研究

pionic atoms

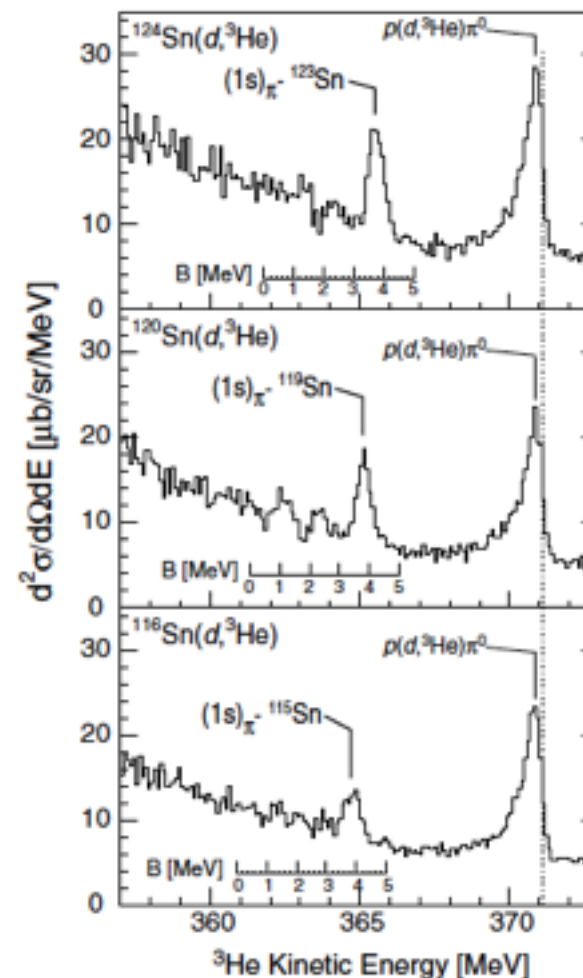
TRIUMF → (Saclay →) GSI → RIBF



(n,p)



(d, ^3He) 発見



系統的測定

Iwasaki et al., PRC 43

Yamazaki et al., Z. Phys A355

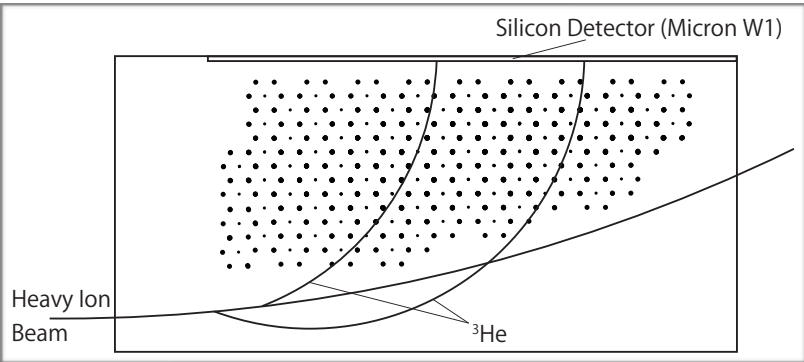
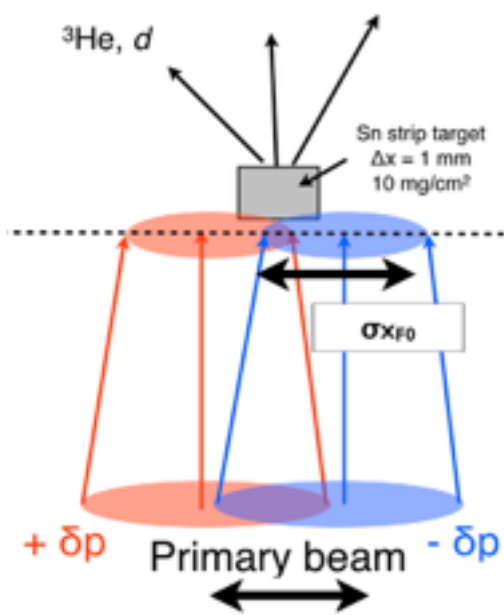
Suzuki et al., PRL 92

T. Nishi et al., to be submitted

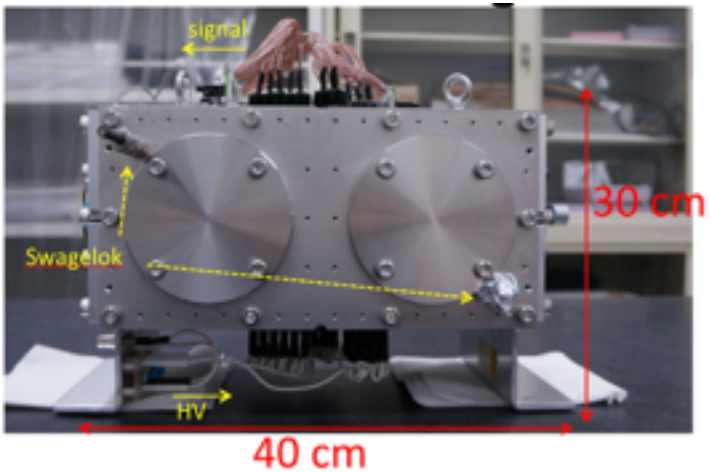
RIBF と J-PARCで展開する中間子-原子核束縛系の研究

pionic atoms

RIBF54R I



RIBF135



RIBF54R I

114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130
Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se
113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129
Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te
112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128
Te	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	127
Sb	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	126
Sn	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	125
In	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	124
Cd	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	123
Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag
106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122
Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd

RIBF135

さらなる

系統的

π中間子

高精度測定

高精度測定

高精度測定

不安定核原子

RIBF と J-PARCで展開する中間子-原子核束縛系の研究

η, η' -nuclei / J-PARC

LETTER OF INTENT FOR J-PARC

SPECTROSCOPY OF η MESIC NUCLEI BY (π^- , n) REACTION AT RECOILLESS KINEMATICS

K. Itahashi^{a1}, H. Fujioka^{b2}, S. Hirenzaki^c, D. Jido^d, and H. Nagahiro^e.

^a *RIKEN Nishina Center, RIKEN, 351-0198 Saitama, Japan*

^b *Department of Physics, The University of Tokyo, 113-0033 Tokyo, Japan*

^c *Department of Physics, Nara Women's University, 630-8506 Nara, Japan*

^d *Yukawa Institute for Theoretical Physics, Kyoto University, 606-8502 Kyoto, Japan*

^e *Research Center for Nuclear Physics (RCNP), Osaka University, 567-0047 Osaka, Japan*

EXPRESSION OF INTEREST

SPECTROSCOPY OF η/η' MESIC NUCLEI AT HIHR BEAMLINE

H. Fujioka¹, K. Itahashi²

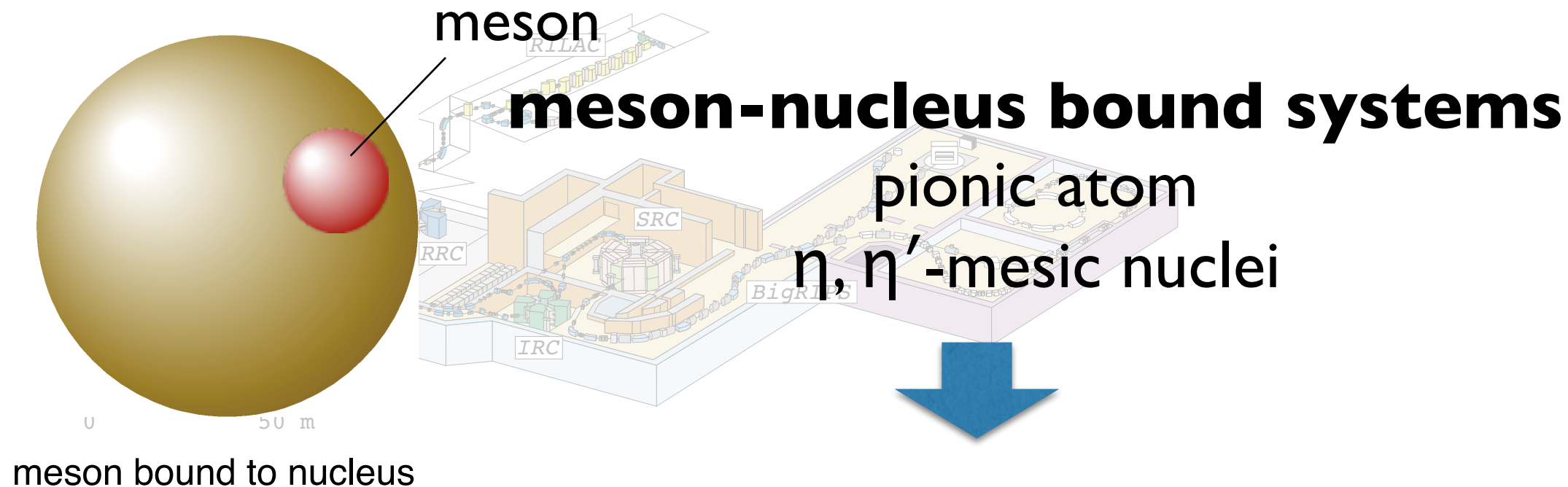
¹ *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

² *Nishina Center for Accelerator-Based Science, RIKEN, Saitama 351-0198, Japan*

η, η' -mesic nuclei を π beam で
生成・探索・分光

η -mesic nuclei @ ELPH, FAIR
 η' -mesic nuclei @ CB, SPring-8, FAIR

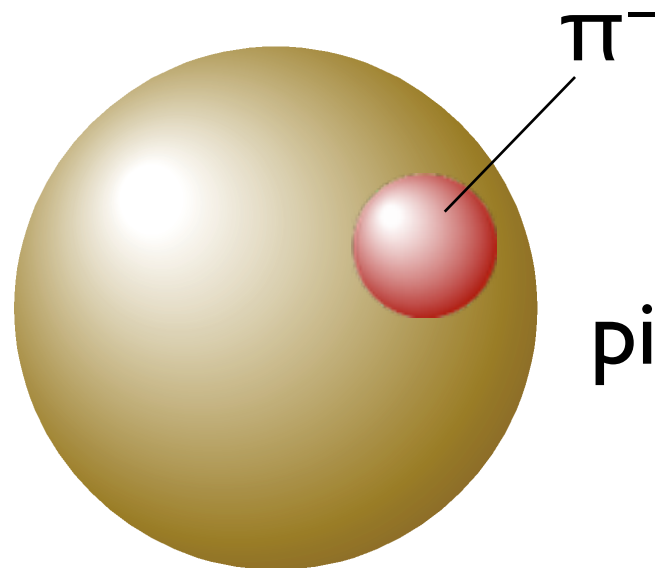
Spectroscopy of bound meson to nucleus



- meson-nucleus interaction
meson-nucleus potential
- meson properties in nuclei
Mass modification of meson

Low energy QCD and structure of vacuum

Pionic Atoms and piA interaction



pionic atoms
π bound to nucleus

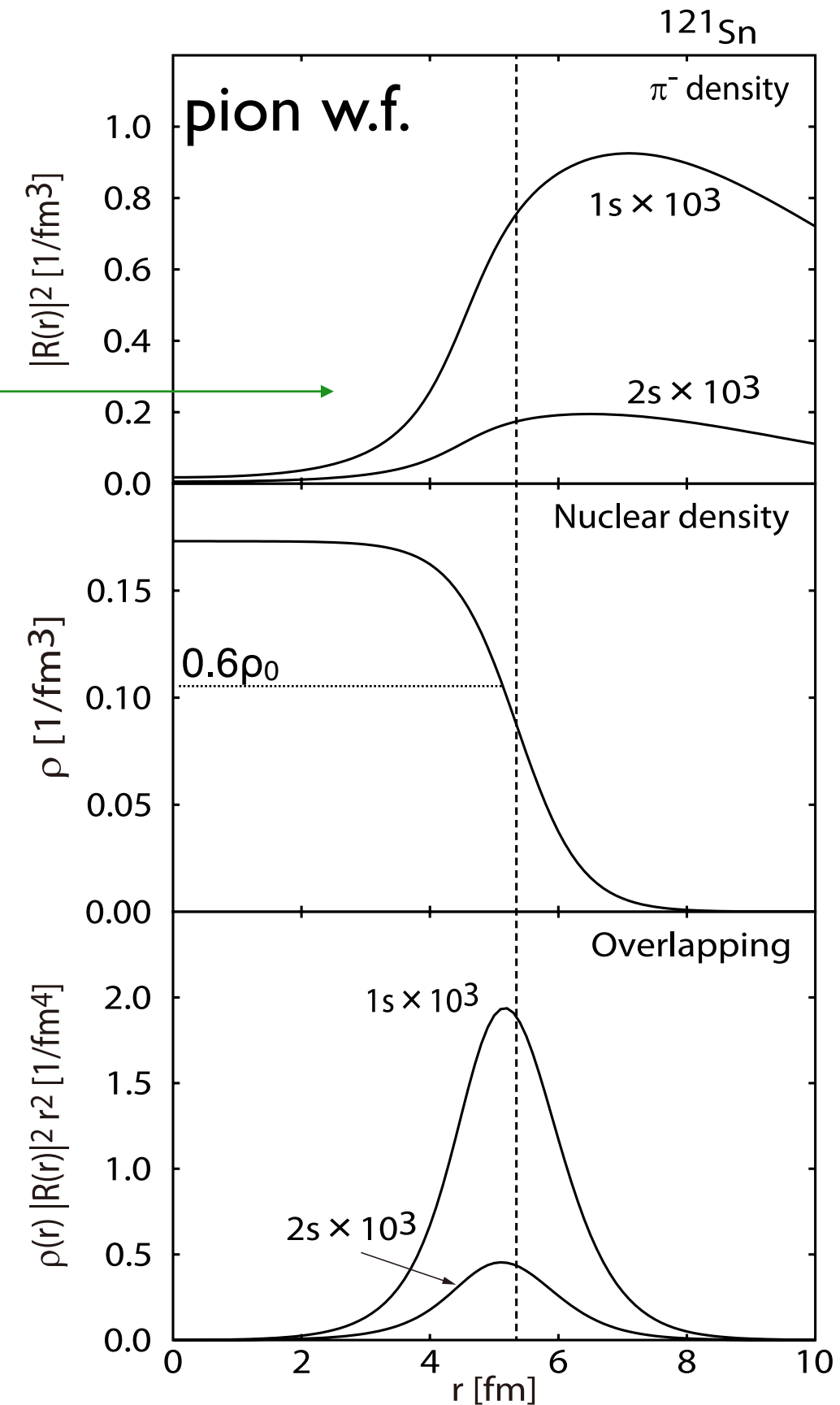
pion wave function locates
at vicinity of nucleus



Sensitivity to
π-nucleus s-wave potential

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

for $\rho_e = 0.6 \rho_0$



Chiral symmetry at finite density

Jido, Hatsuda, Kunihiro, Phys.Lett.B670:109-113,2008.
Kolomeitsev, Kaiser, Weise, Phys. Rev. Lett. 90(2003)092501

M. Gell-Mann et al., PRL75(1968)2195.

Gell-Mann-Oakes-Renner relation

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

f_π : pion decay constant

Y.Tomozawa, NuovoCimA46(1966)707.

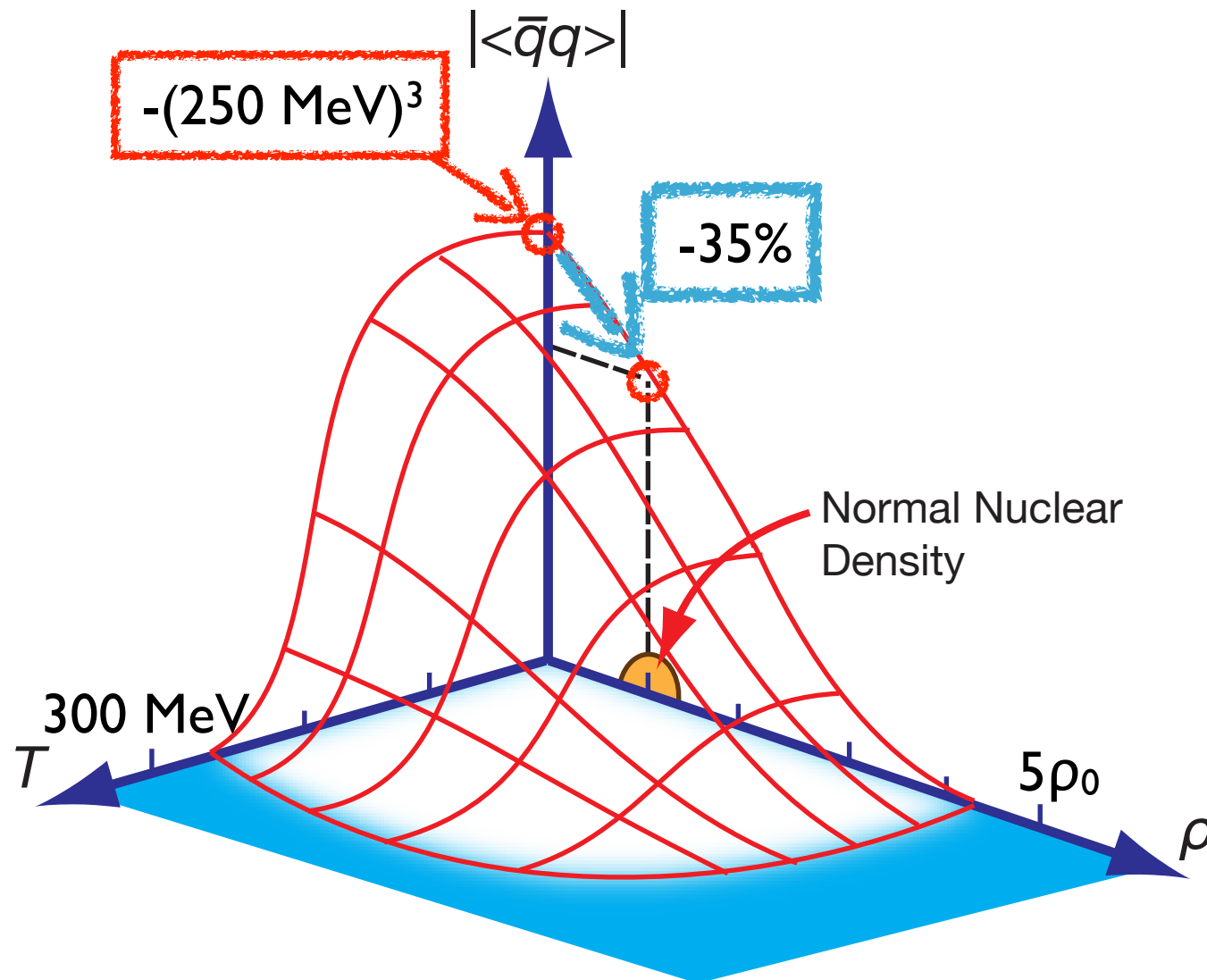
S.Weinberg, PRL17(1966)616.

Tomozawa-Weinberg relation

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

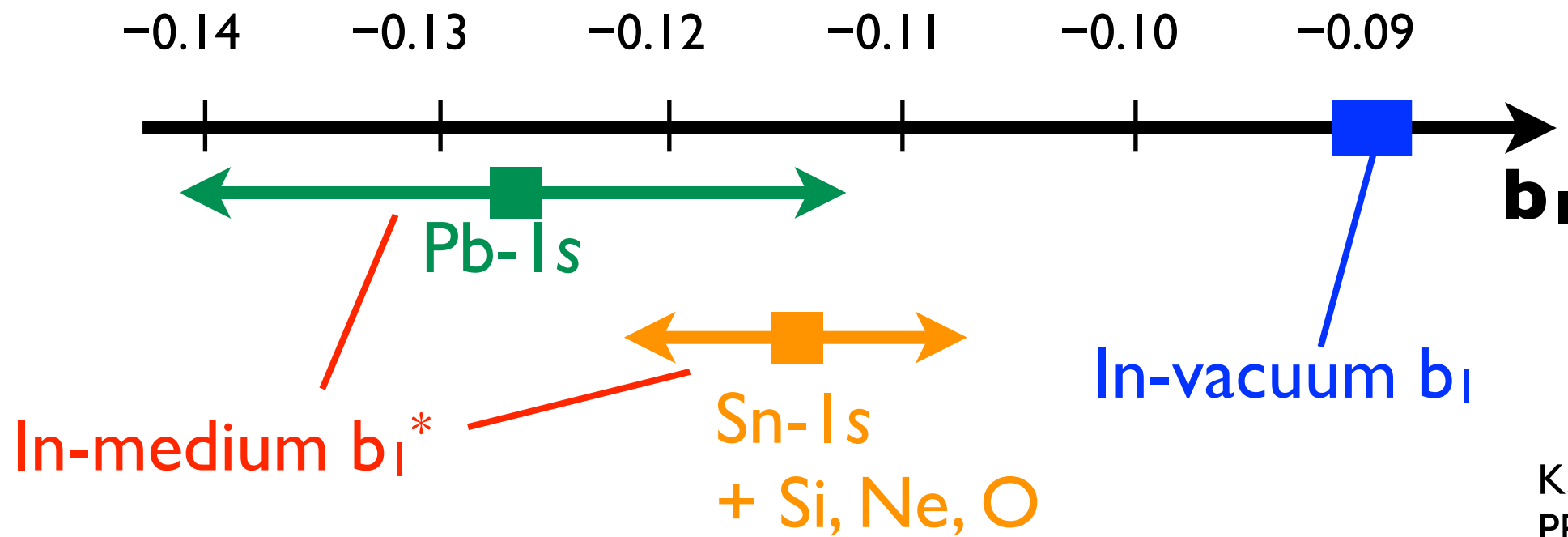
b_1 : isovector πN scattering length

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



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Present b_1 precision



b_1^* still has a large error

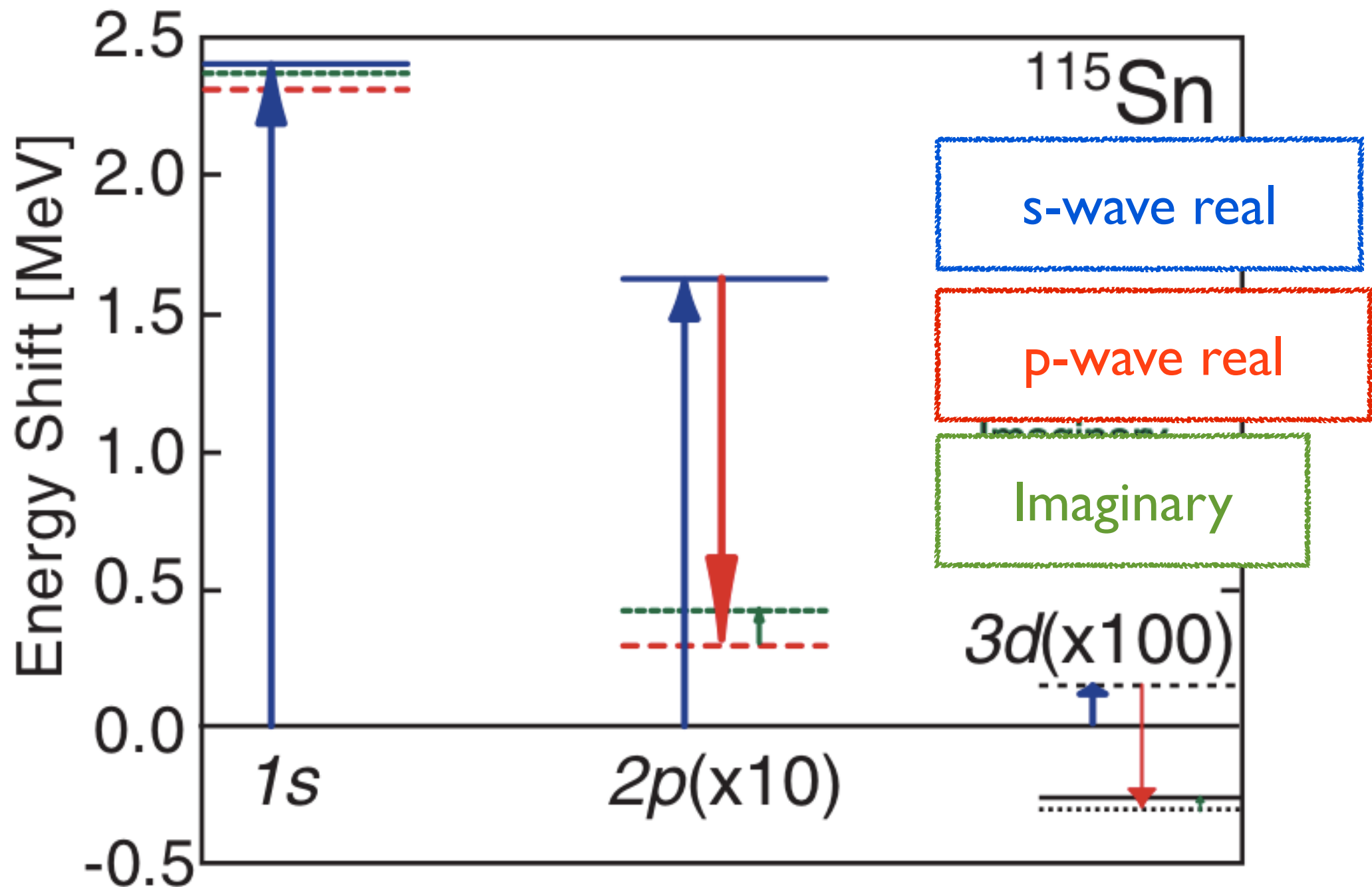
$$V_{s\text{-wave}} = b_0 \rho + \mathbf{b_1} (\rho_n - \rho_p) + B_0 \rho^2$$

← spectroscopy of pionic atoms

In-medium b_1 is calculated based on deeply bound pionic states data combined with light spherical pionic atom data.

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Strong interaction effect on pionic states



B_{2p} is stable against ambiguities of s-wave interaction

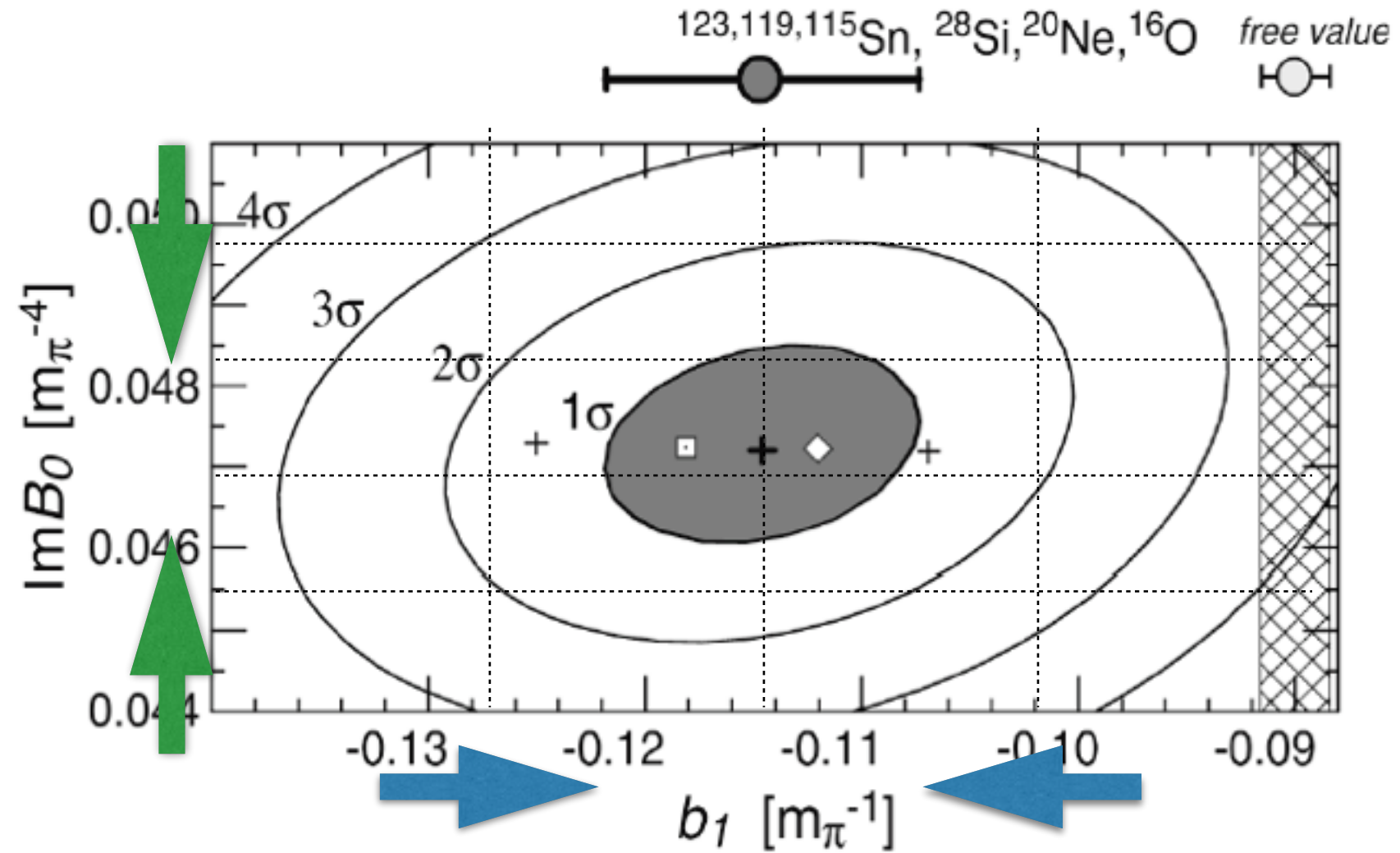
Present b_1 precision

Γ_{1s} [MeV]

^{115}Sn 0.441 ± 0.087
 ^{119}Sn 0.326 ± 0.080
 ^{123}Sn 0.341 ± 0.072

B_{1s} [MeV]

^{115}Sn 3.906 ± 0.024
 ^{119}Sn 3.820 ± 0.018
 ^{123}Sn 3.744 ± 0.018



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

$$\rho_e = 0.6 \rho_0$$

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

In-medium b_1 is calculated based on deeply bound pionic states data combined with light spherical pionic atom data.

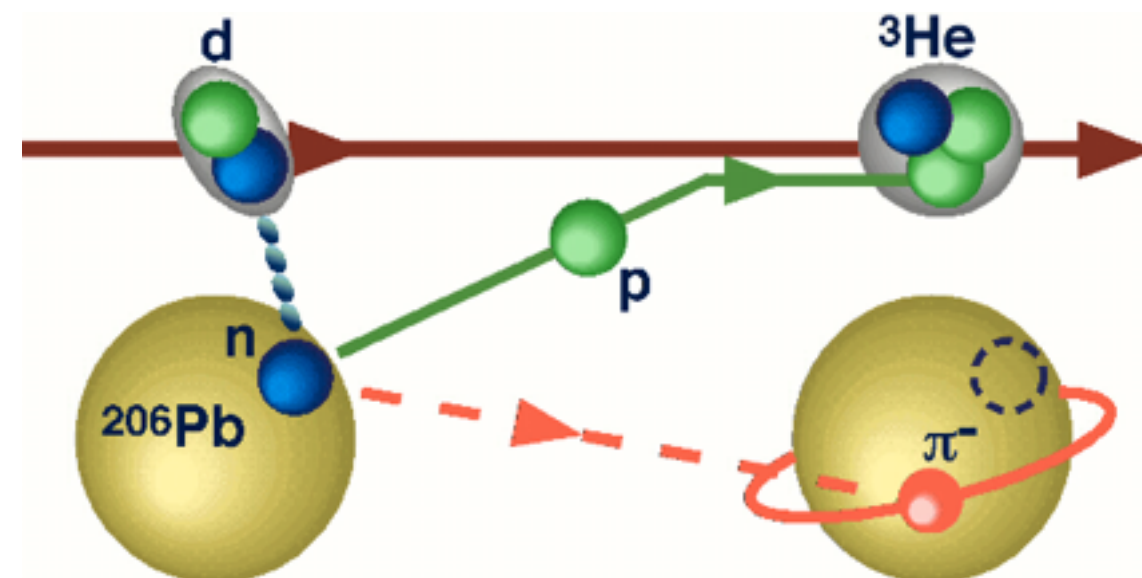
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Spectroscopy of pionic atoms

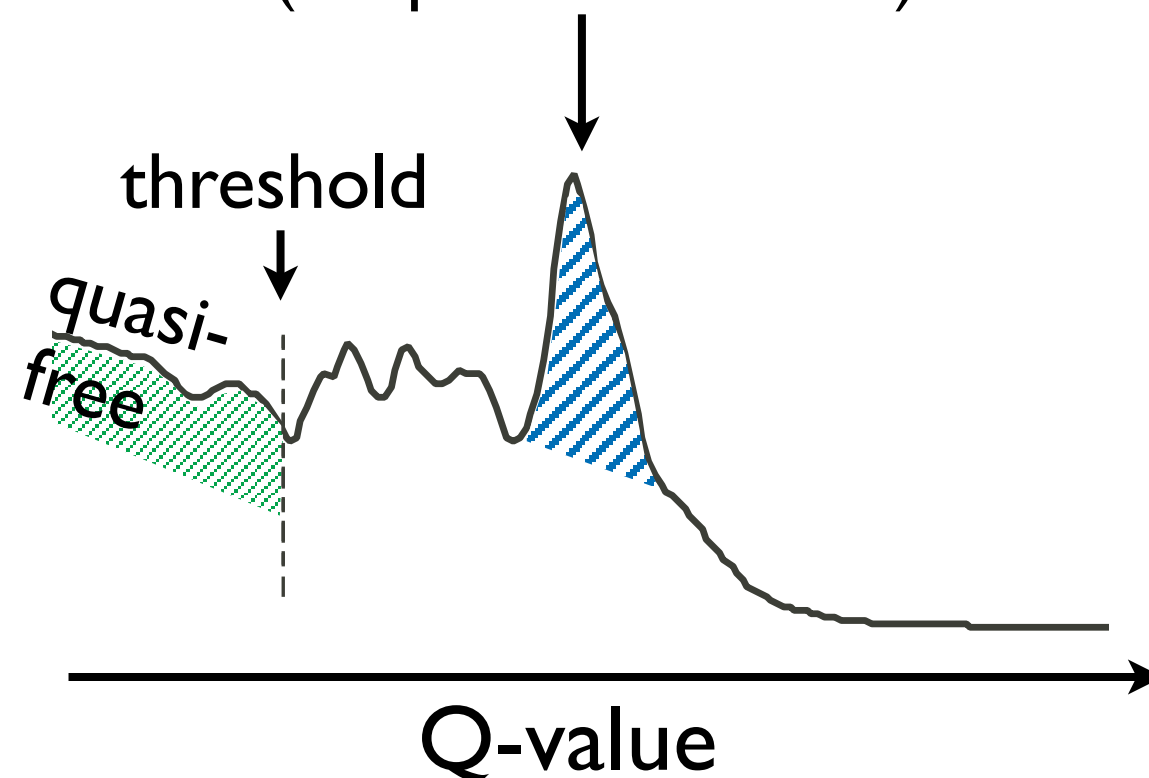
Direct production
in $(d, {}^3\text{He})$ nuclear reaction

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

We are aiming at
300 keV (FWHM) resolution.
(prev. 400 keV)

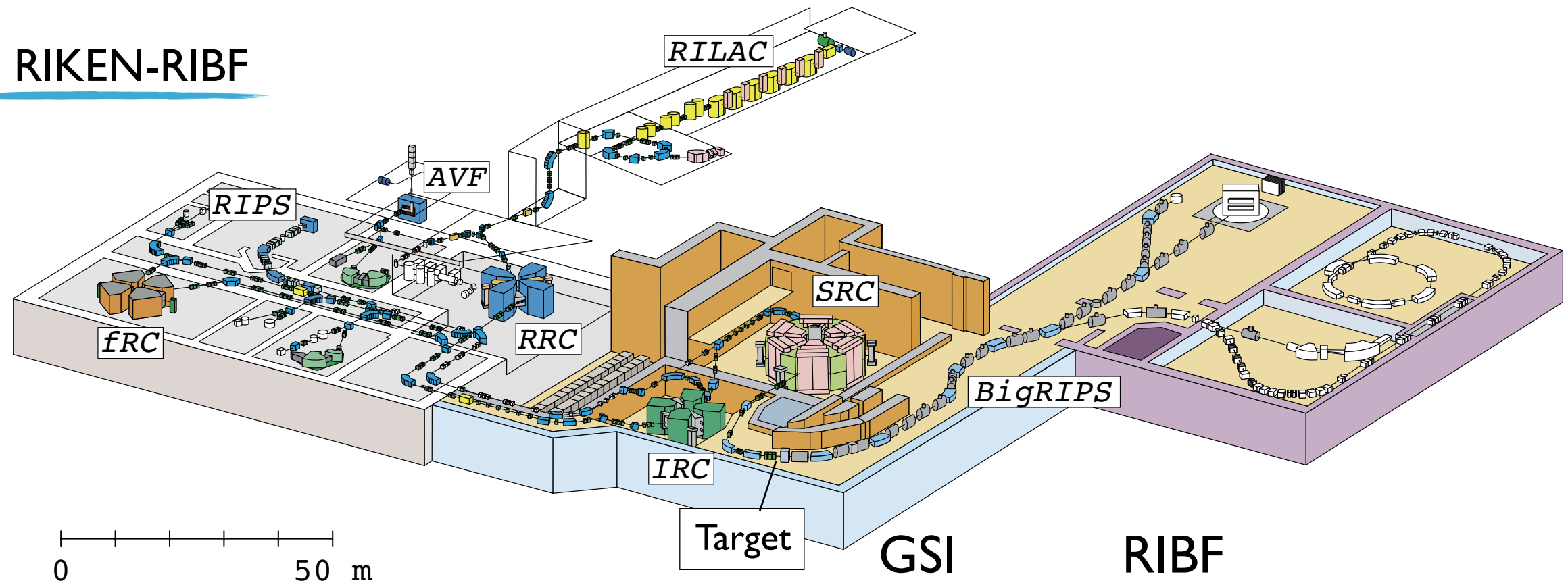


Pion bound state
(coupled with n hole)



Precision spectroscopy at RI Beam Factory

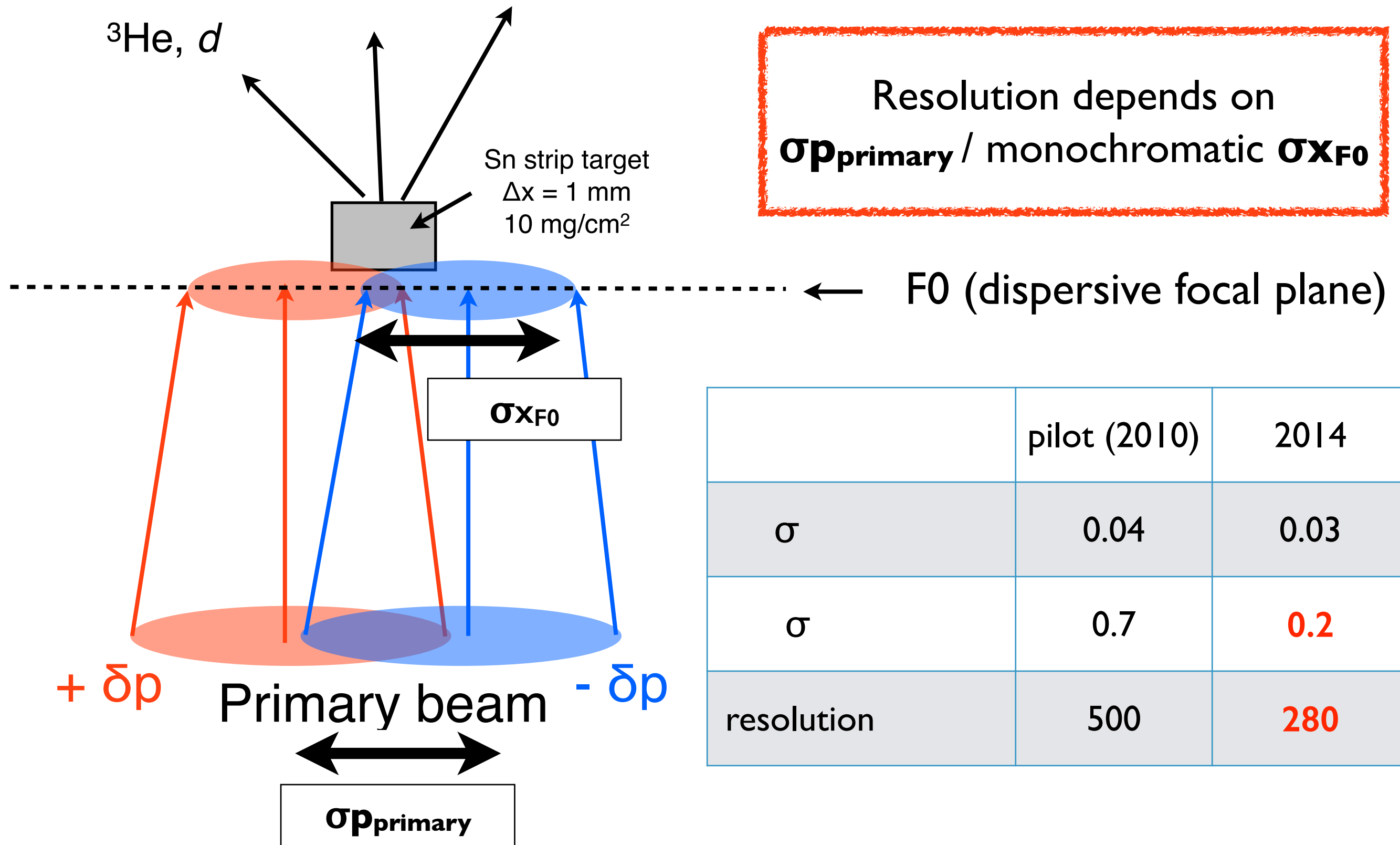
RIKEN-RIBF



	GSI	RIBF
d beam Intensity	10	10
Target	20 mg/cm	10 mg/cm
Δ	0.03%	0.06%
Resolution (FWHM)	400 keV	< 300 keV
Acceptance (mrad)	15H, 10V	40H, 60V

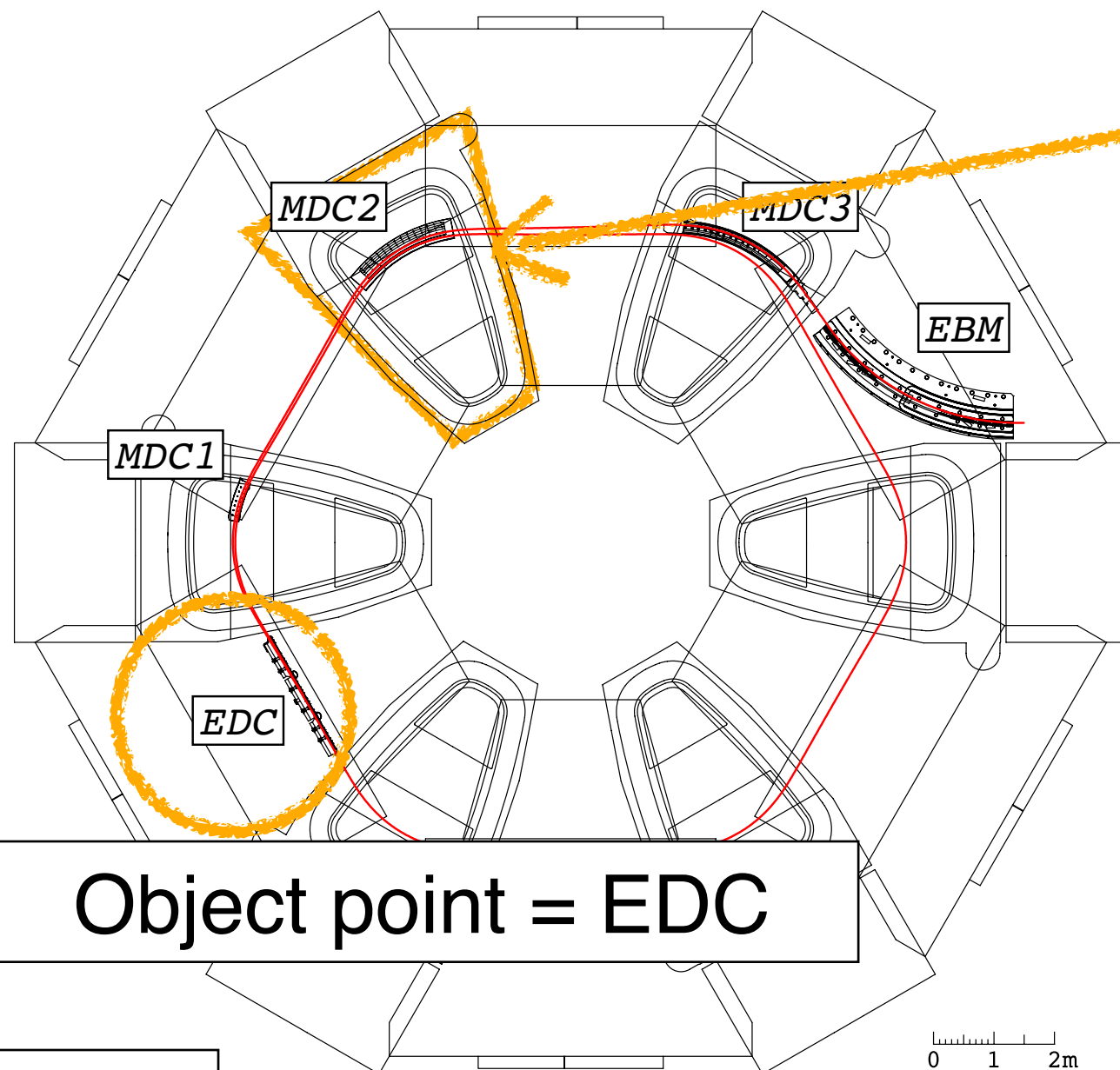
Resol. Matching

Resolution improvement

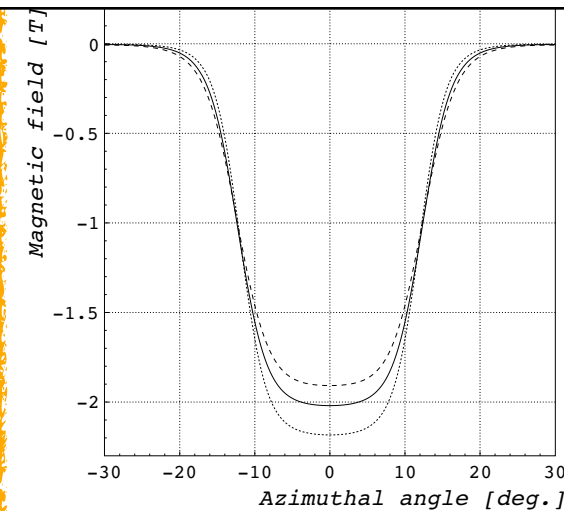


Optics

Dispersion matching using primary beam



magnetic field in the magnet



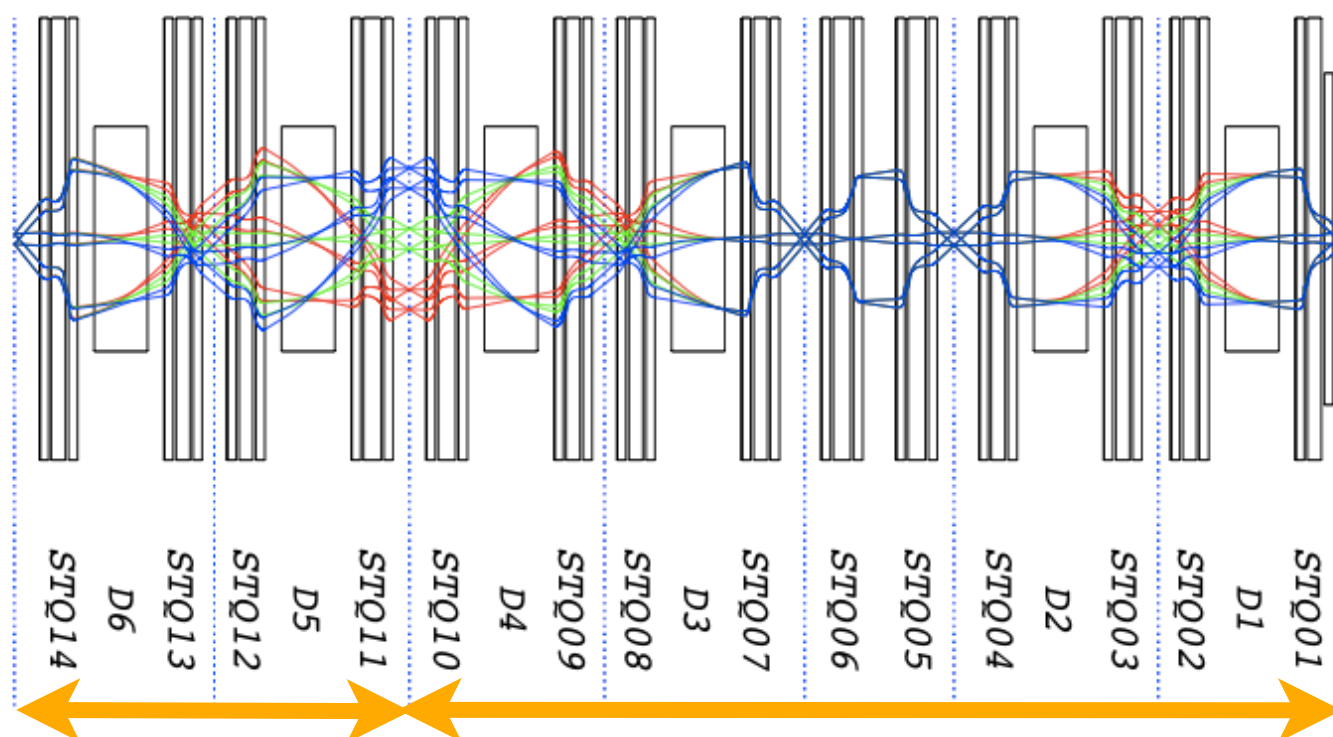
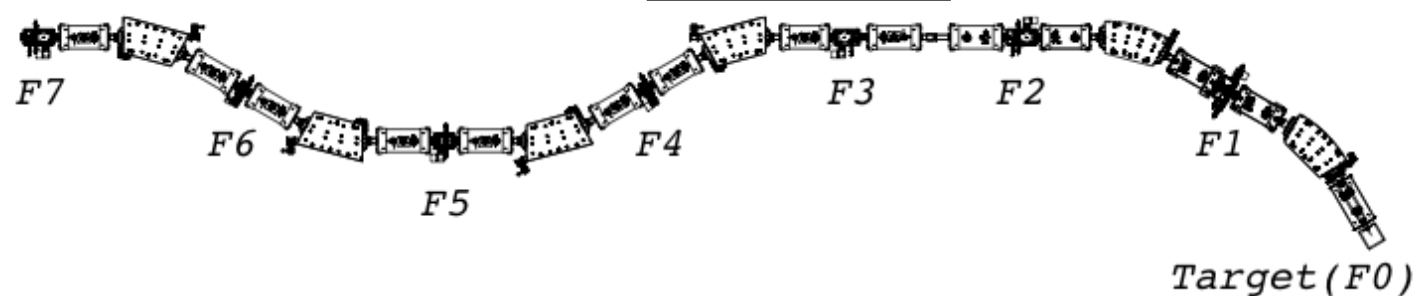
calculate the transfer matrix
using Runge-Kutta method

$$\begin{pmatrix} (x|x) & (x|a) & (x|y) & (x|b) & (x|\delta) \\ (a|x) & (a|a) & (a|y) & (a|b) & (a|\delta) \\ (y|x) & (y|a) & (y|y) & (y|b) & (y|\delta) \\ (b|x) & (b|a) & (b|y) & (b|b) & (b|\delta) \end{pmatrix}_{\text{EDC} \rightarrow \text{EBM}}$$

$$= \begin{pmatrix} -1.00 & -3.35 & 0.0 & 0.0 & 76.9 \\ 0.30 & -0.01 & 0.0 & 0.0 & -25.4 \\ 0.0 & 0.0 & -1.03 & -1.75 & 0.0 \\ 0.0 & 0.0 & -0.09 & -1.12 & 0.0 \end{pmatrix}$$

Optics

BigRIPS

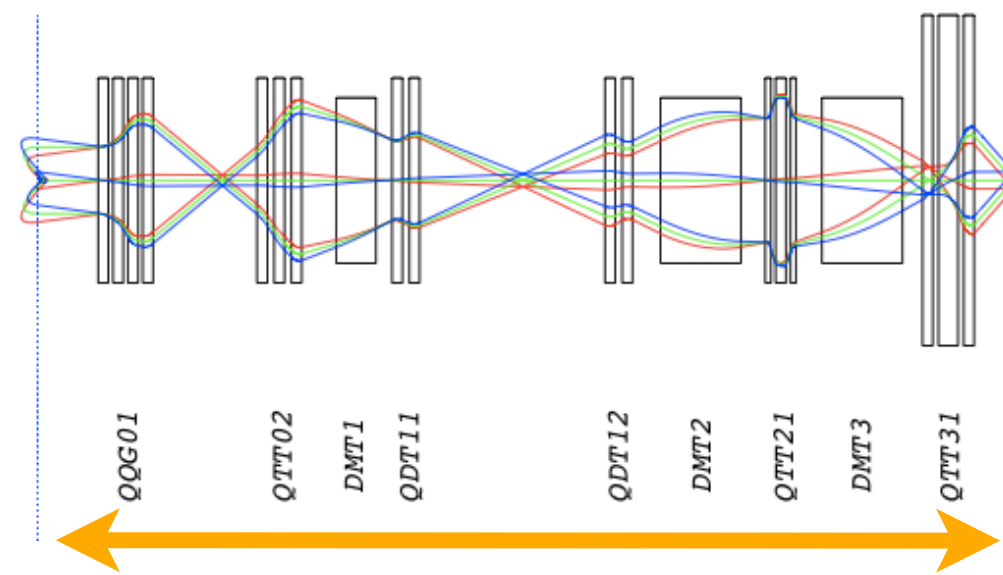
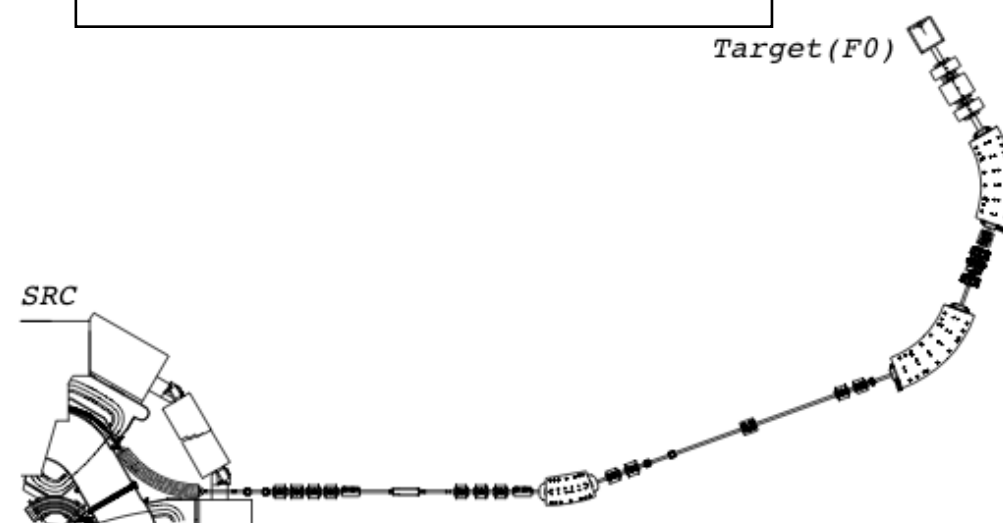


pID

Q analysis

dispersion: 62 mm/%

Beam Transfer line



dispersion matching

η, η' -mesic nuclei spectroscopy with pion beam

EXPRESSION OF INTEREST

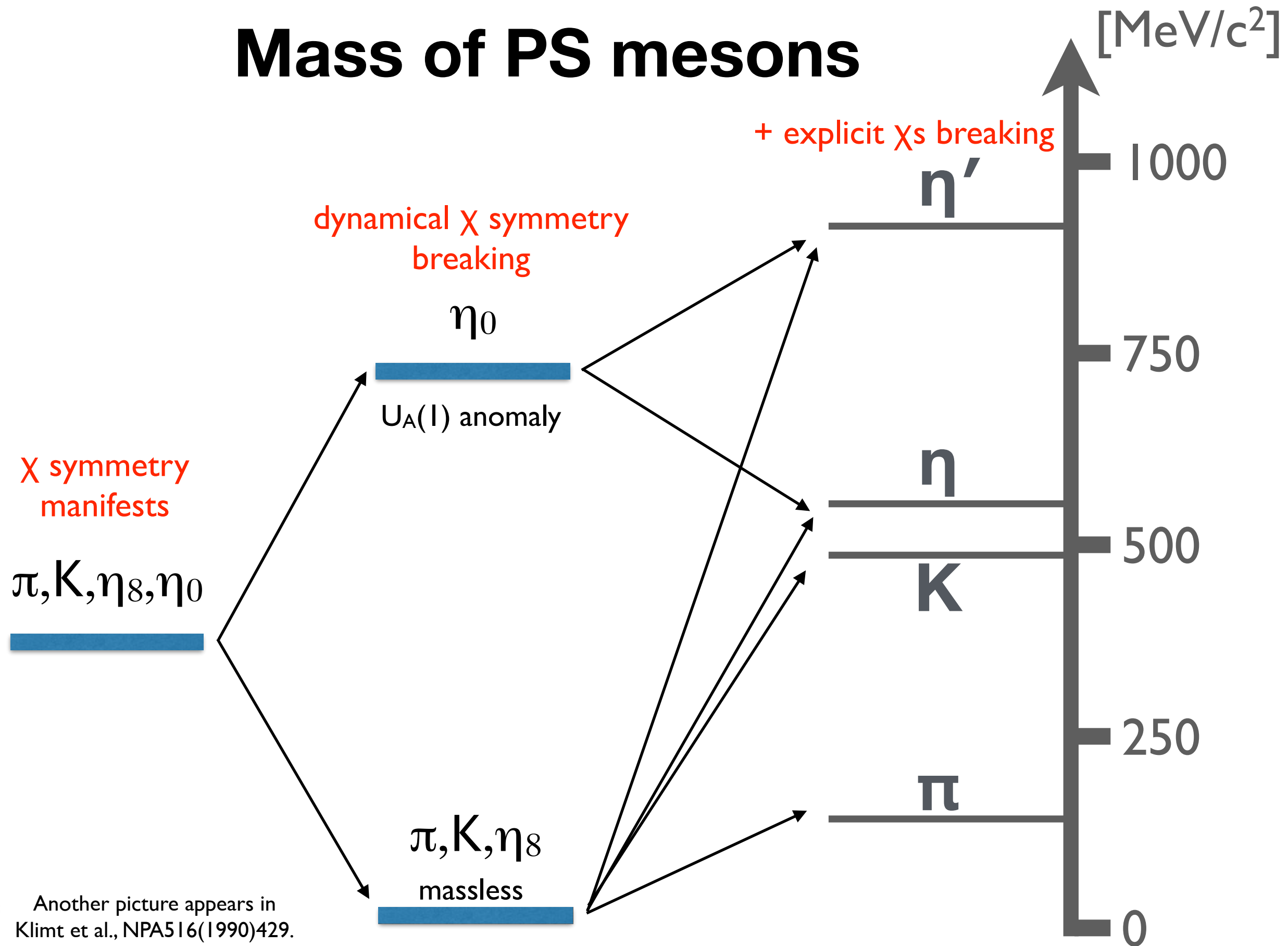
SPECTROSCOPY OF η/η' MESIC NUCLEI AT HIHR BEAMLINE

H. Fujioka¹, K. Itahashi²

¹ *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

² *Nishina Center for Accelerator-Based Science, RIKEN, Saitama 351-0198, Japan*

Mass of PS mesons

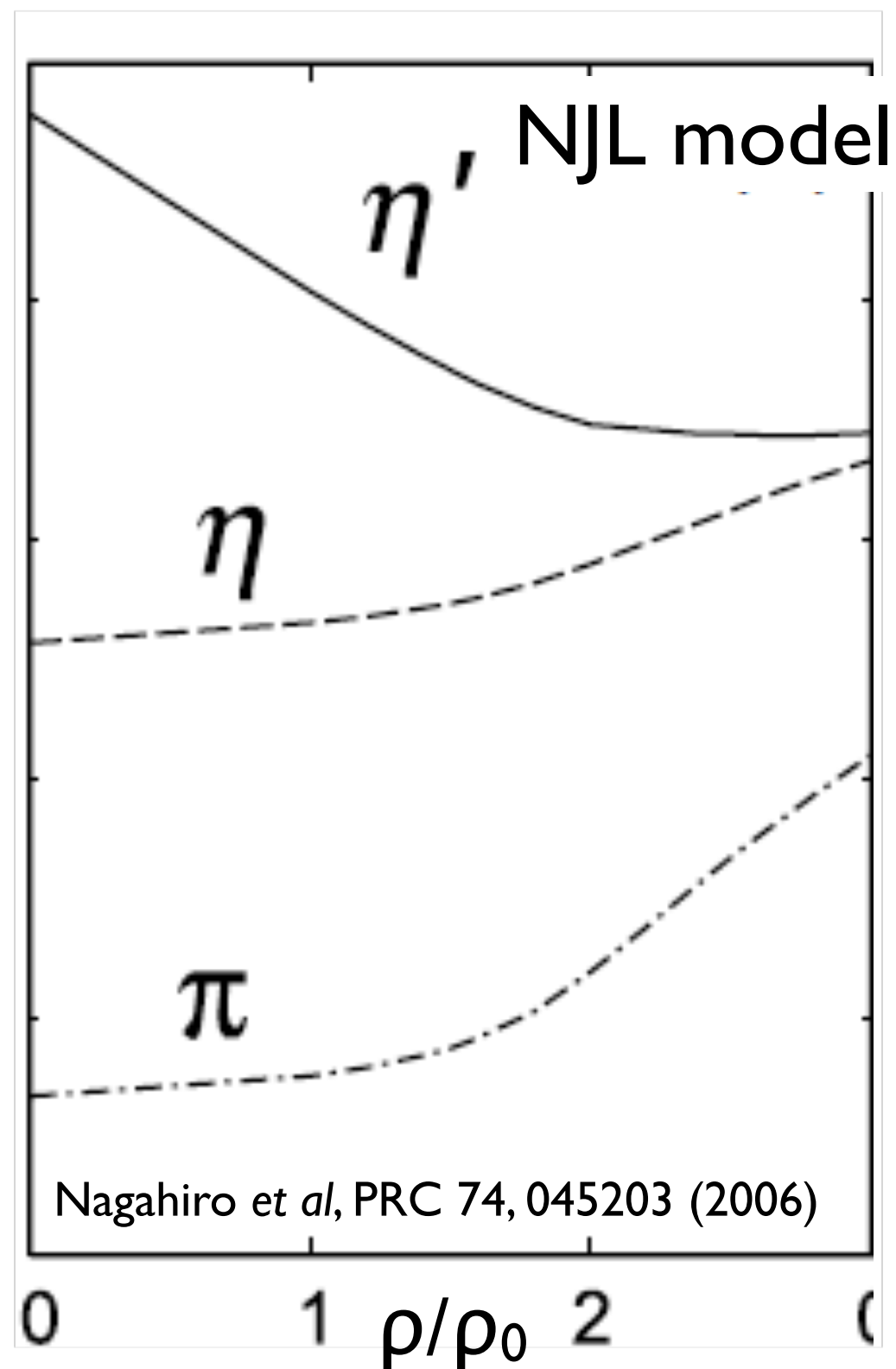
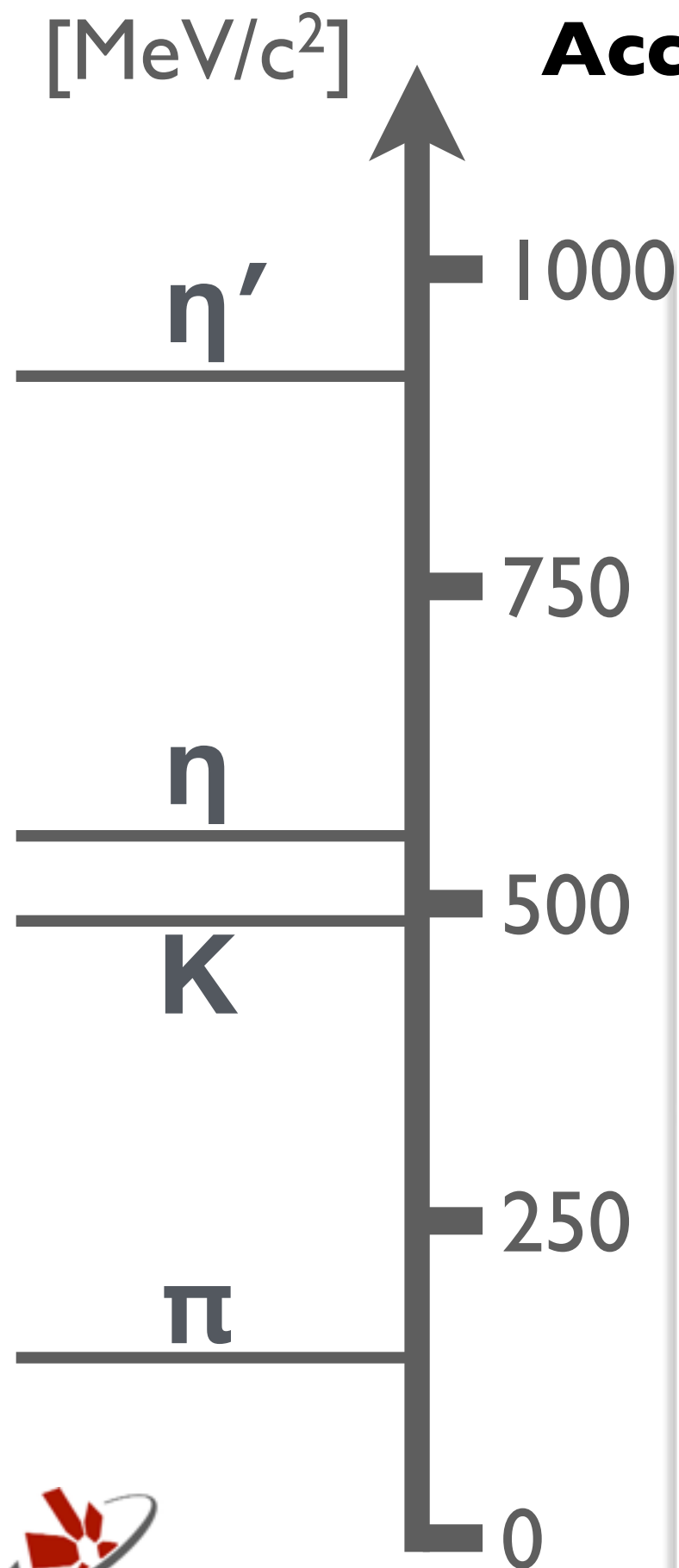


Another picture appears in
Klimt et al., NPA516(1990)429.

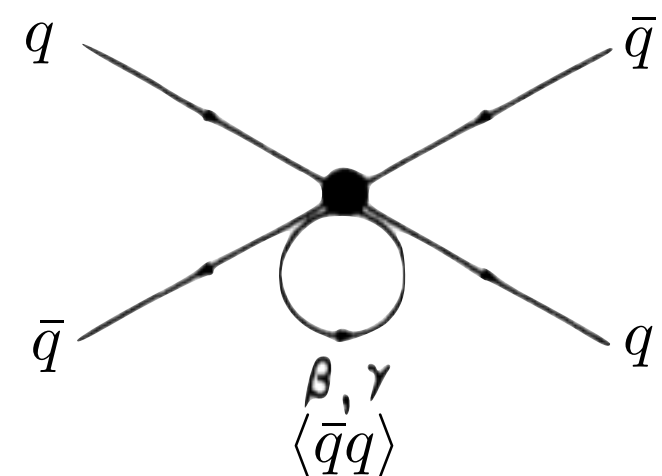
Kenta Itahashi, RIKEN

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

Access to structure of vacuum



$U_A(1)$ symmetry breaking
term of effective Lagrangian



time

Kobayashi-Maskawa-
't Hooft-type interaction

Kobayashi, Maskawa, PTP44(70)1422

't Hooft, PRD14(76)3432.

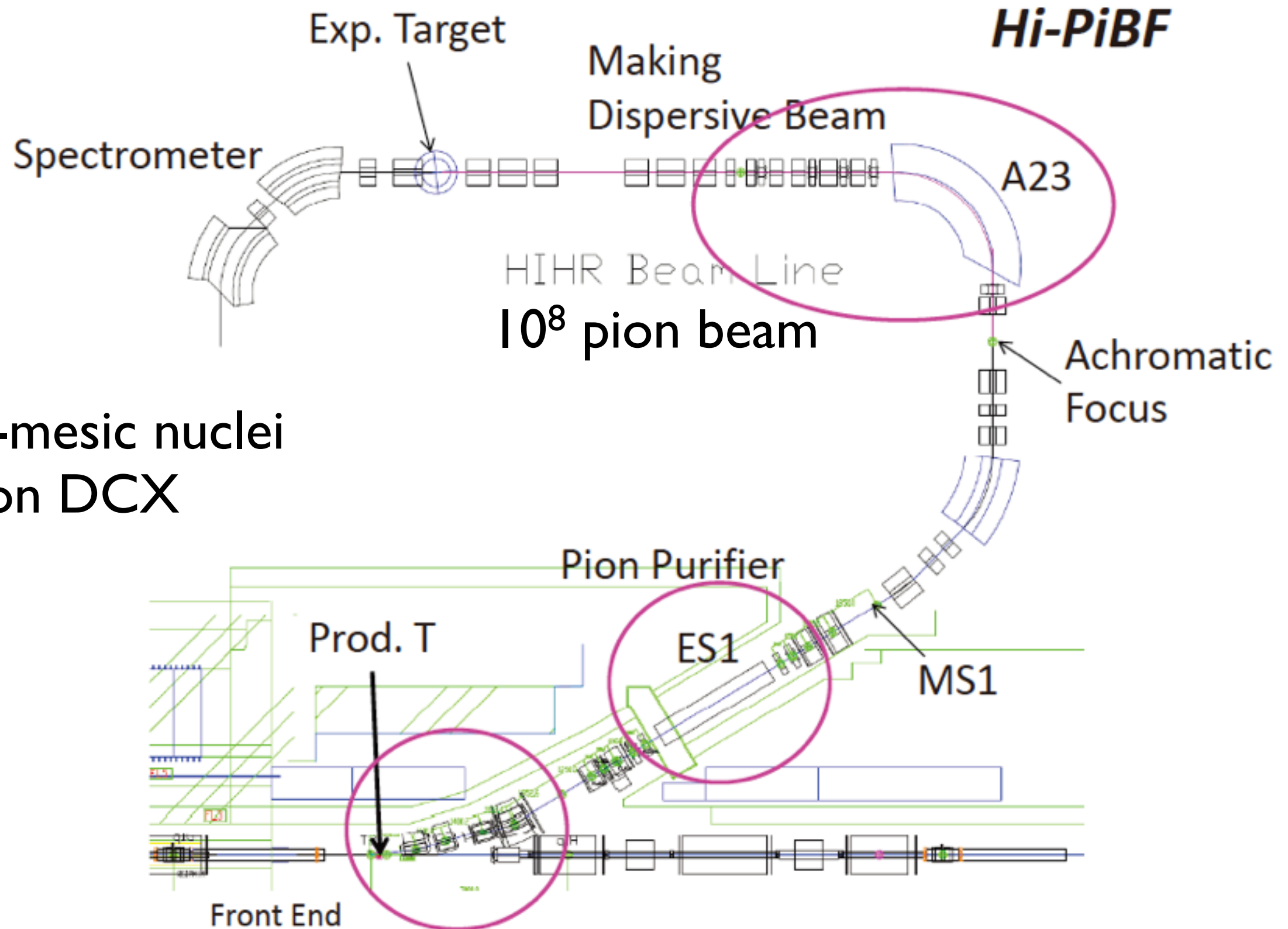
T. Kunihiro, Phys. Lett. B219(89)363.

Klimt, Lutz, Vogl, Weise, NPA516(90)429.

Jido, Nagahiro, Hirenzaki,
PRC85(2012)032201(R)

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

Pion induced reaction spectroscopy



η, η' -mesic nuclei
 ^4n pion DCX

from H. Noumi

Theoretical models for η -mesic nuclei

η -nucleus interaction ~ N^* dominance model ~

optical potential

$$V_{\text{opt}} = \frac{g_\eta^2}{2\mu} \frac{\rho}{\omega - (m_{N^*}(\rho) - m_N(\rho)) + i\Gamma_{N^*}(s; \rho)/2} + (\text{cross term})$$

potential nature

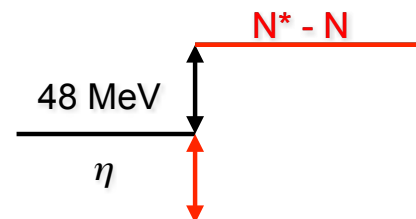
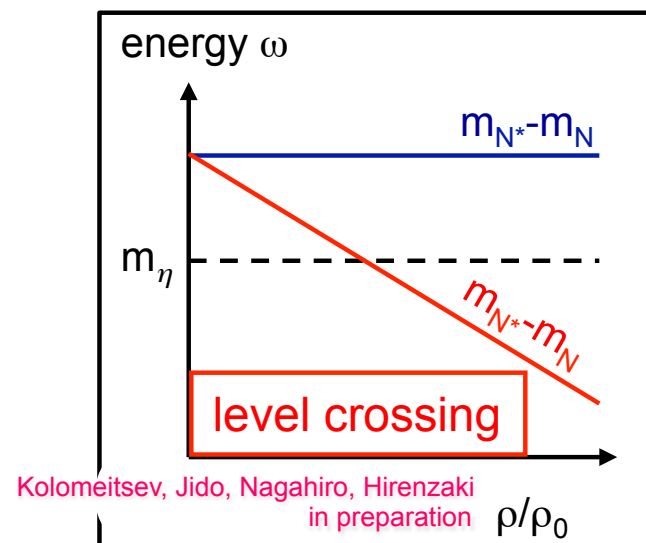
$$m_\eta - (m_{N^*} - m_N) < 0$$

attractive

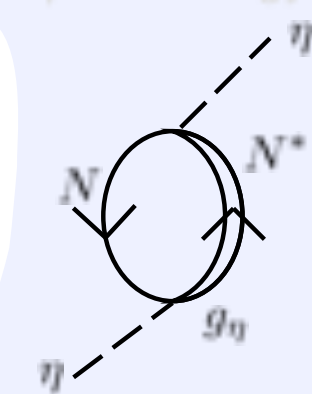
medium effect

$$m_\eta - (m_{N^*}(\rho) - m_N(\rho)) > 0$$

repulsive



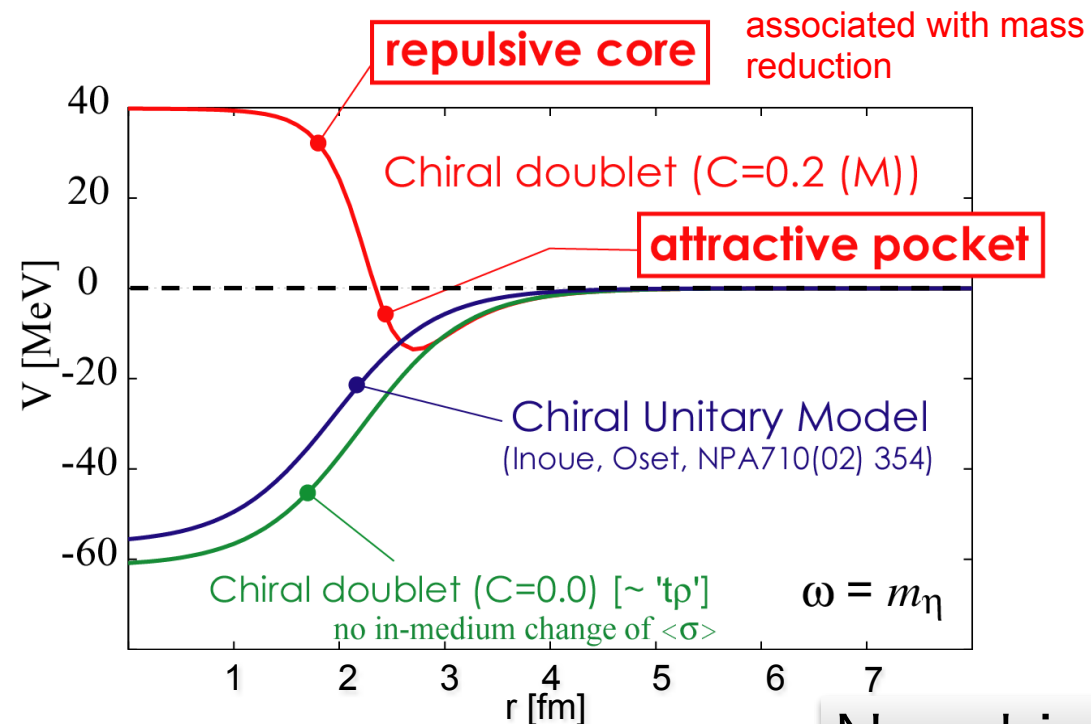
η self-energy



Chiang, Oset, Liu PRC44(1991)738

Jido, Nagahiro, Hirenzaki, PRC66(2002)045202

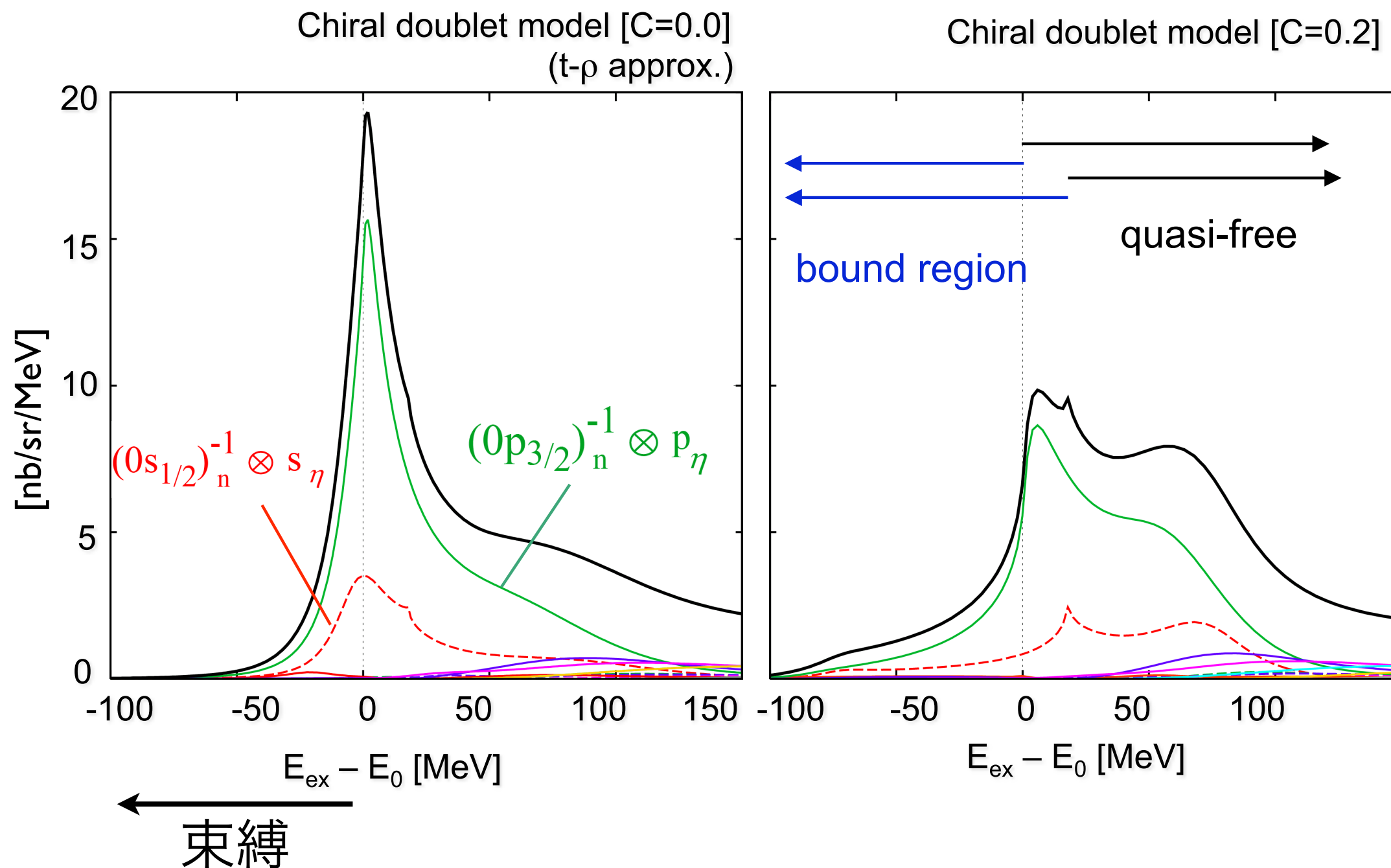
$$g_\eta \simeq 2.0 \quad (\Gamma_{N^* \rightarrow \eta N} \simeq 75 \text{ MeV})$$



Nagahiro @ 鳥羽

η -mesic nuclei spectroscopy with pion beam

$^{12}\text{C}(\pi, N)$ @ 950 MeV/c

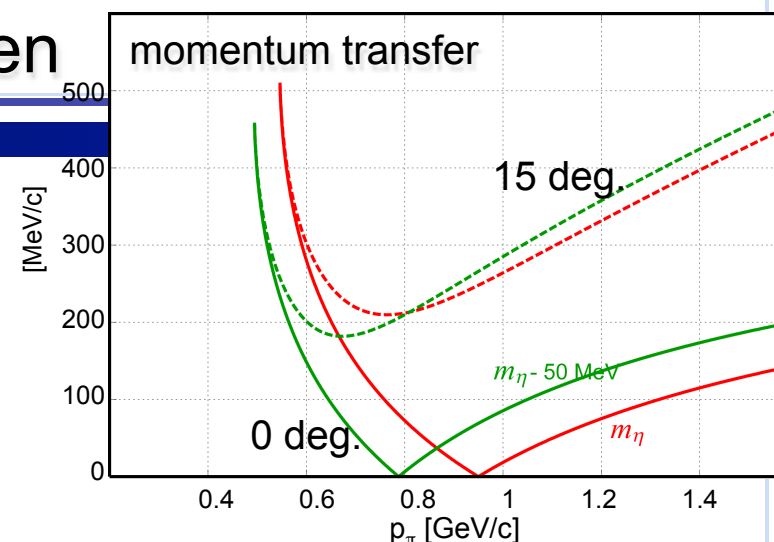


Nagahiro@鳥羽

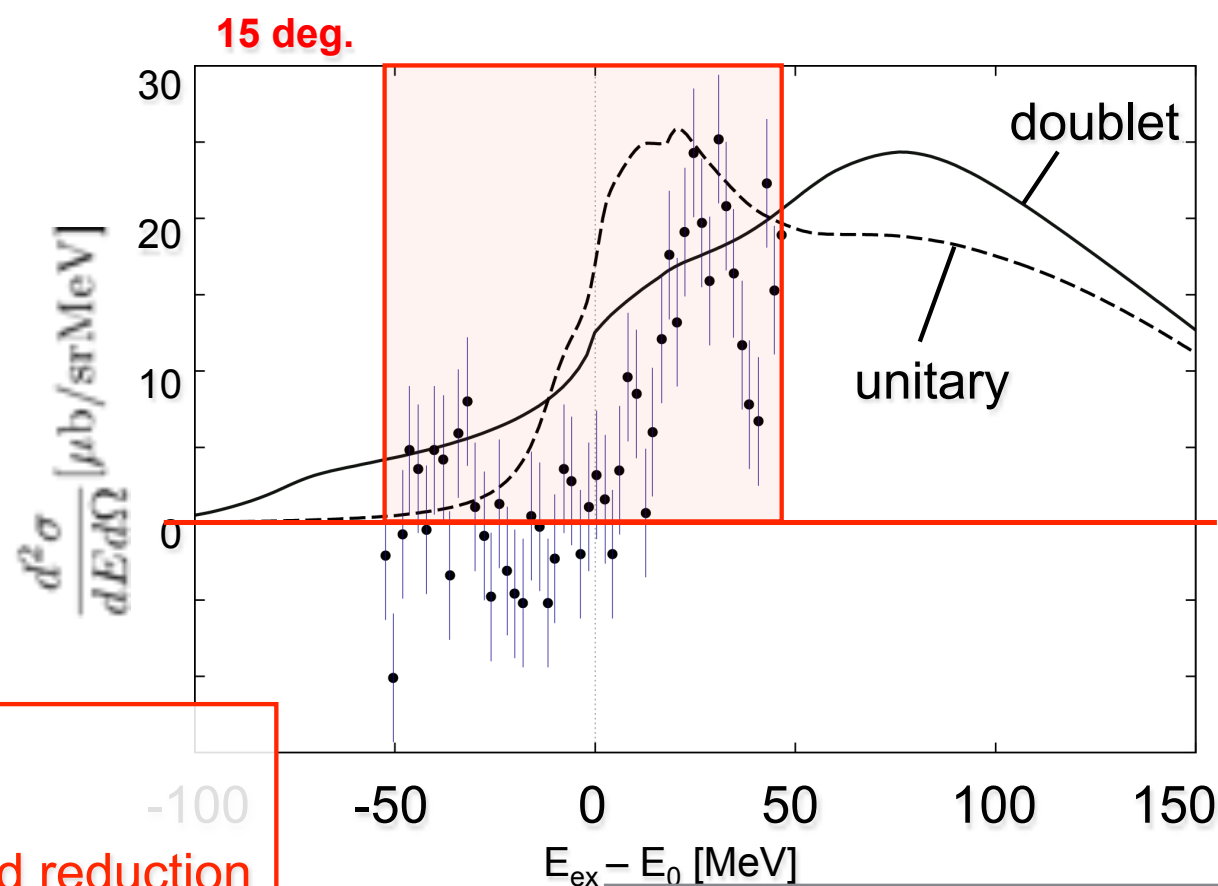
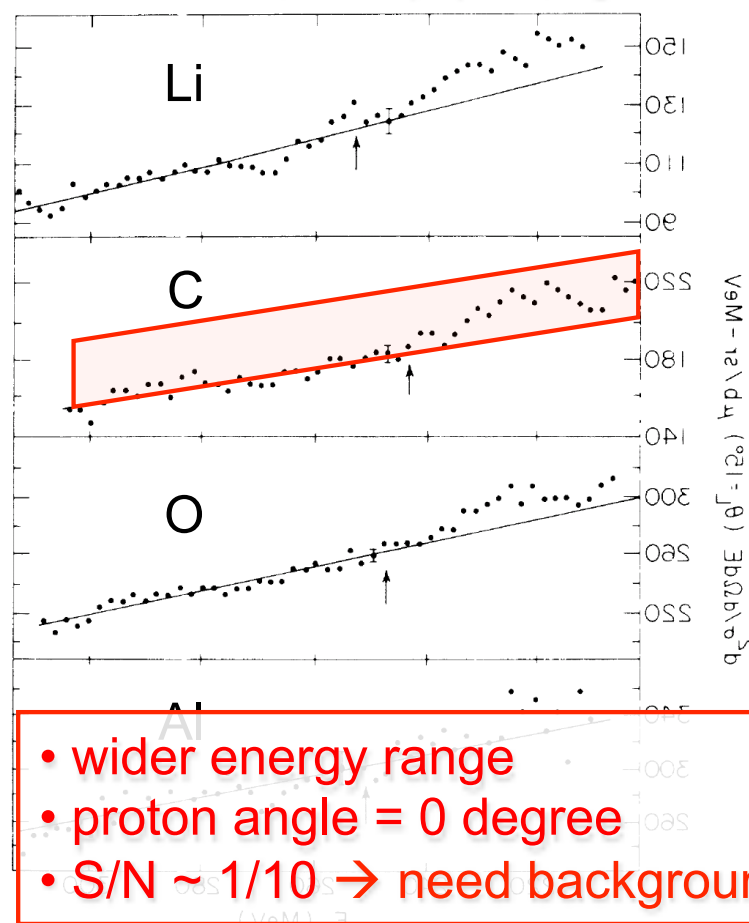
η -mesic nuclei spectroscopy with pion beam

(π^+, p) spectra : experiment at Brookhaven

- Chrien et al., PRL60(1988)2595
 - » $p_\pi = 800 \text{ MeV/c}$: proton angle : **15 deg. (Lab.)**
 - » search for predicted narrow bound state by Liu, Haider, PRC34(86)1845
 - negative results (bound state peak was not observed)



Chrien et al., PRL60(88)2595, Fig.1



Nagahiro@鳥羽(2007.3)

η -mesic nuclei spectroscopy with pion beam

Another earlier experiment

LAMPF $^{16}\text{O}(\pi^+, p)$ with p and π near 4π -BGO near TA

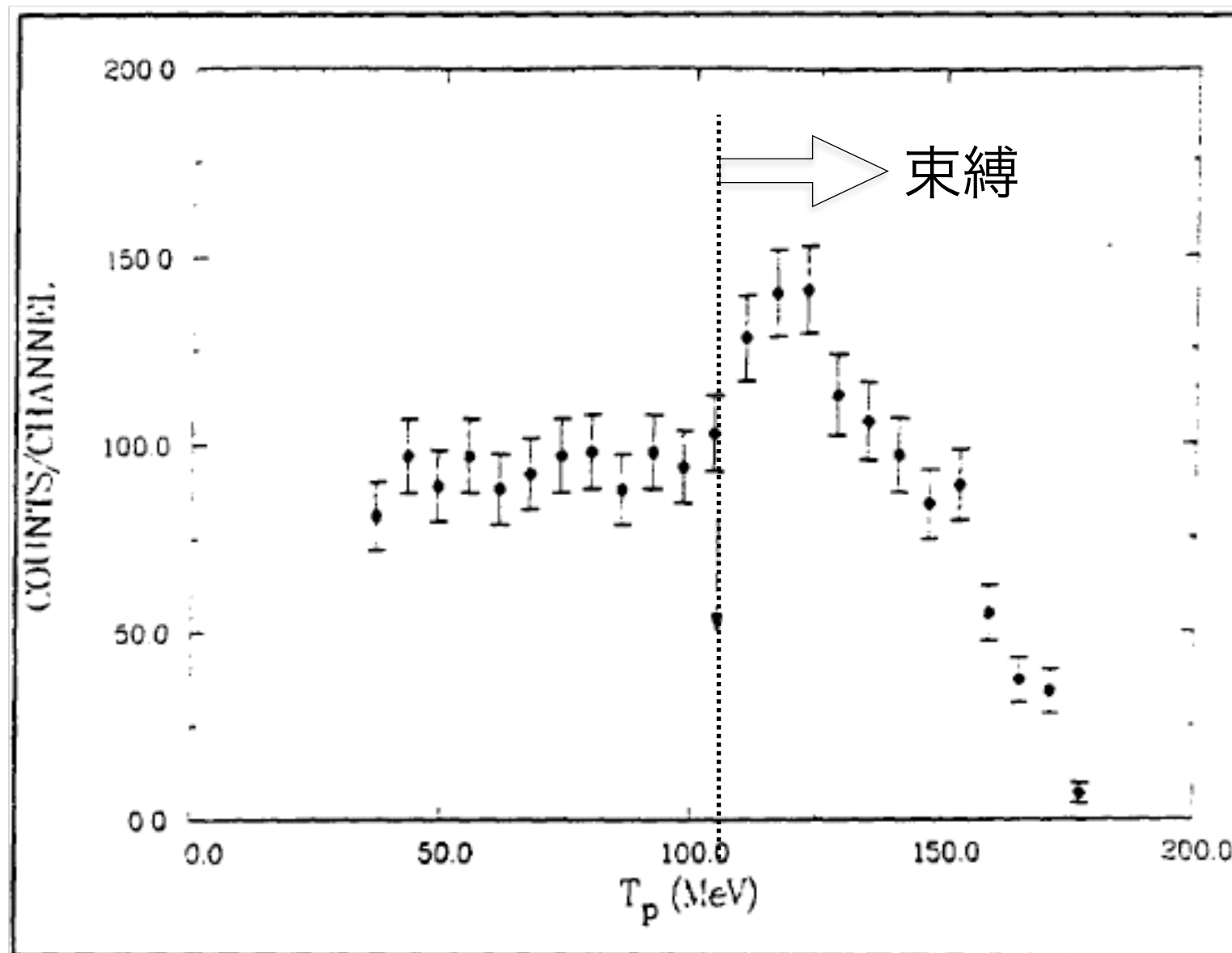
EXPERIMENT 1022 — P3.
East

Search for Nuclear Bound States of the Eta Meson

George Mason Univ., Los
Alamos, College of
William & Mary, Louisiana
State Univ., Virginia State
Univ.

Spokesmen: B. J. Lieb (George
Mason Univ.) and L. C. Liu
(Los Alamos)

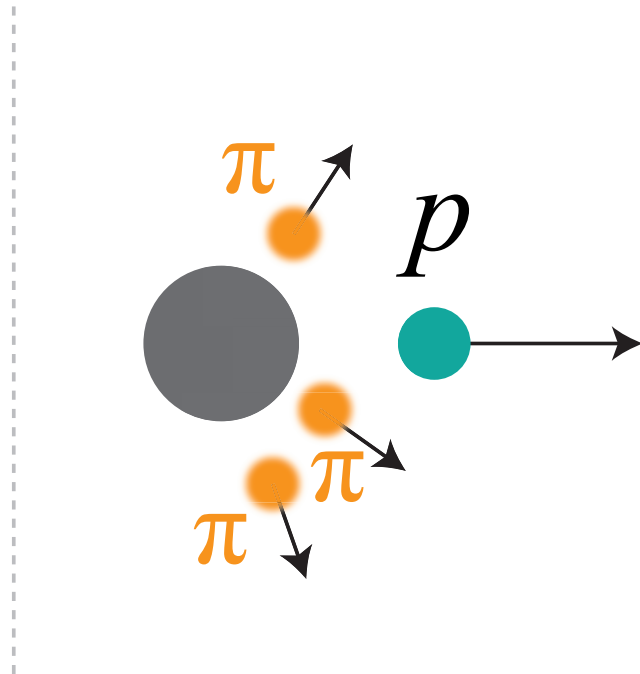
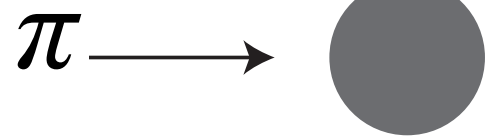
Participants: E. Cheung, B. J.
Dropesky, R. Estep, A. Fazely,
H. O. Funsten, N. L. Fuqua, Q.
Halder, B. J. Lieb, L. C. Liu,
C. Lyndon, J. MacKenzie, G.
L. Morris, C. F. Perdrisat, V.
Punjabi, C. Stronach, and P.
Ulmer



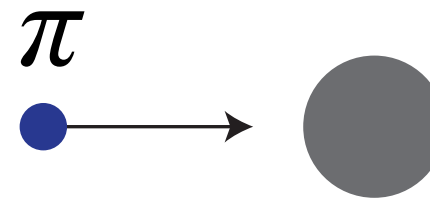
(unpublished)

Principles of Semi **Exclusive** Measurement

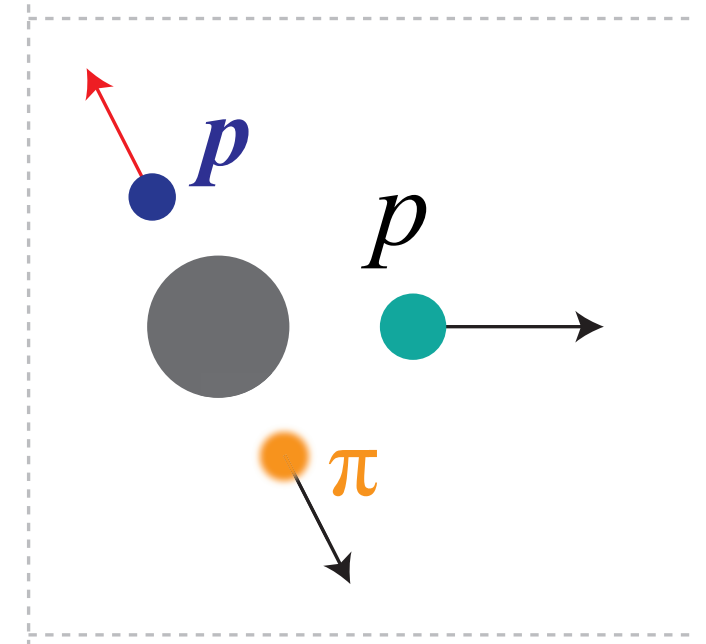
Background



Signal



$N\eta \rightarrow N^* \rightarrow p\pi$



η -mesic nuclei spectroscopy with pion beam

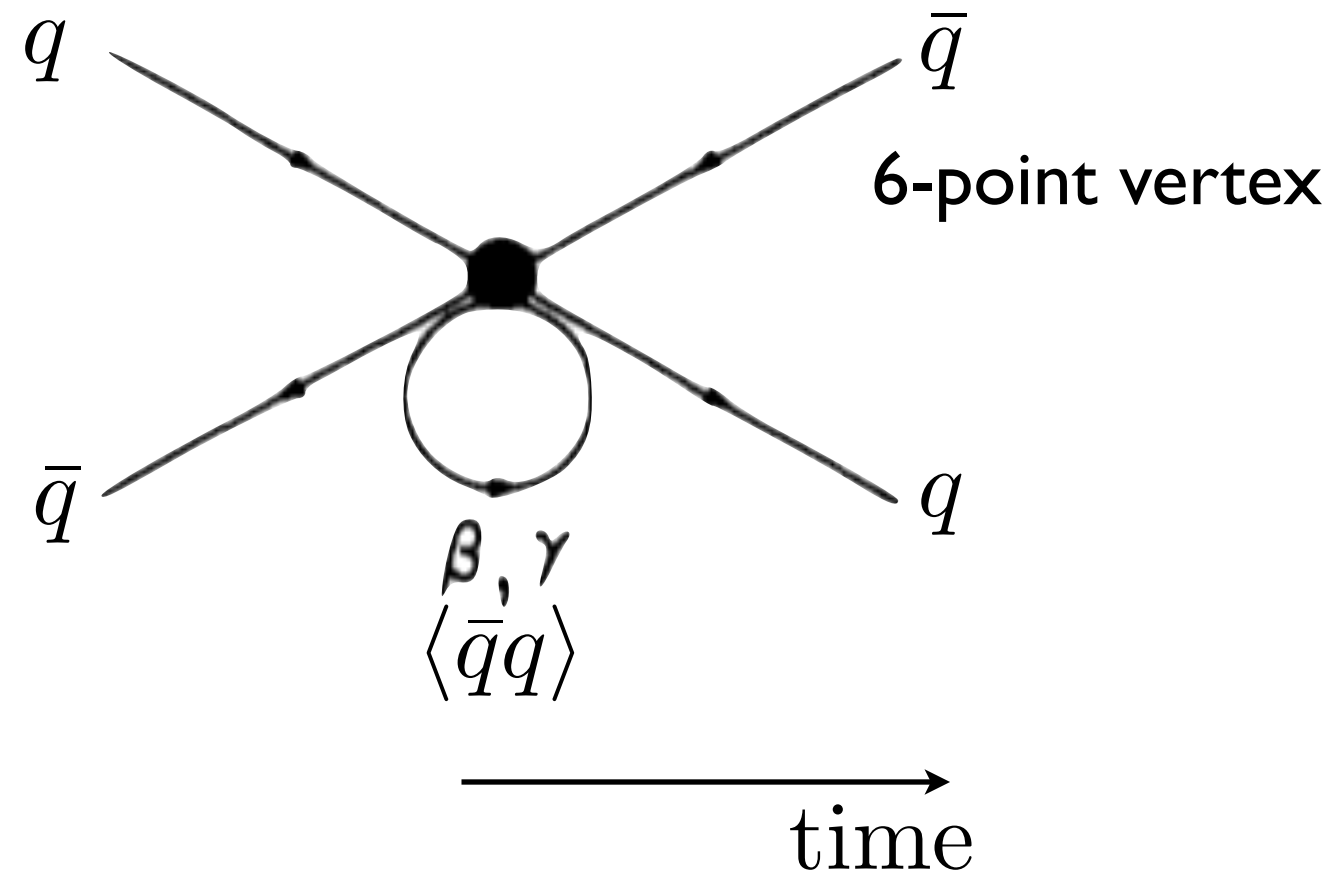
Possible experiments at J-PARC

ビーム	π^-	π^+
素過程	$p(\pi^-)$	$n(\pi^+)$
分光方法	Missing Mass	
測定方法	中性子TOF	Spectrometer/TOF
分解能	$\sim 20 \text{ MeV}/c$	$< 20 \text{ MeV}/c$

$p + \pi^-$ 測定を考えると
 π^+ のほうが有利かもしれない

Large η' mass can be explained

$U_A(1)$ symmetry breaking term of effective Lagrangian



Kobayashi-Maskawa-'t Hooft-type interaction

Kobayashi, Maskawa, PTP44(70)1422

't Hooft, PRD14(76)3432.

T. Kunihiro, Phys. Lett. B219(89)363.

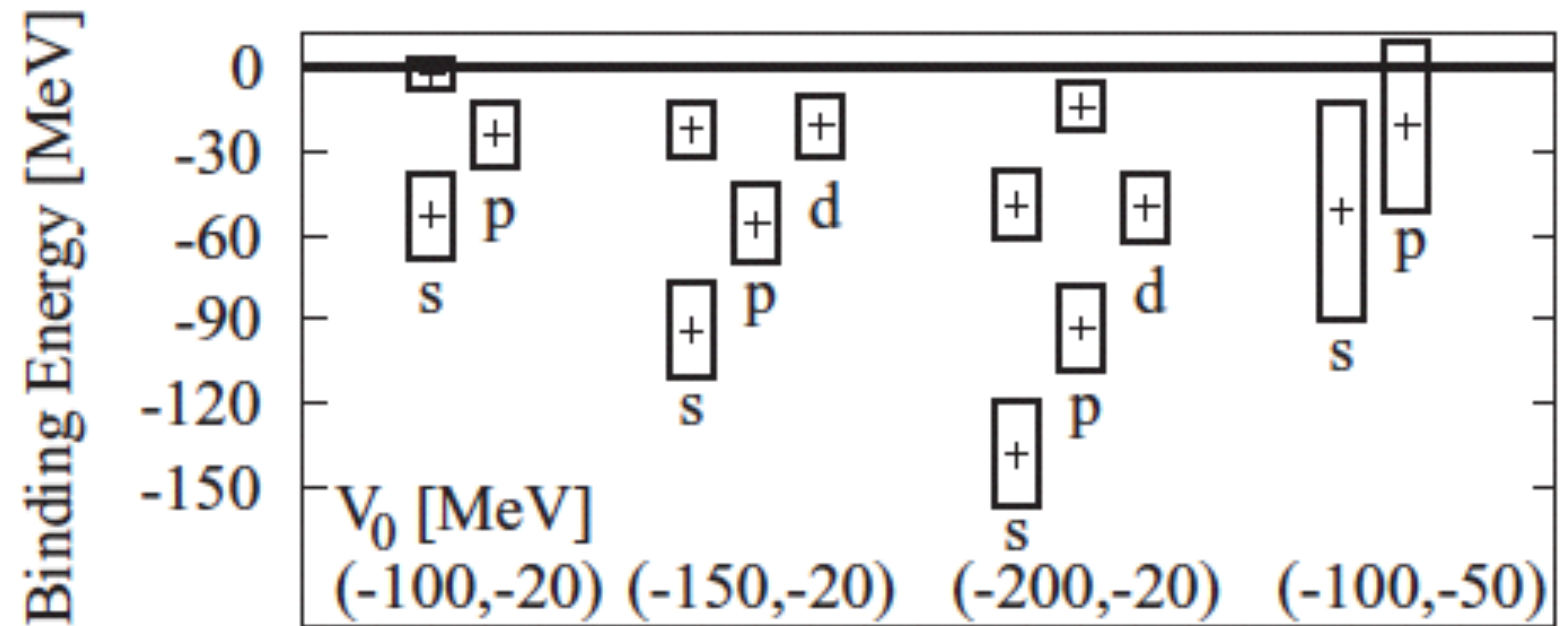
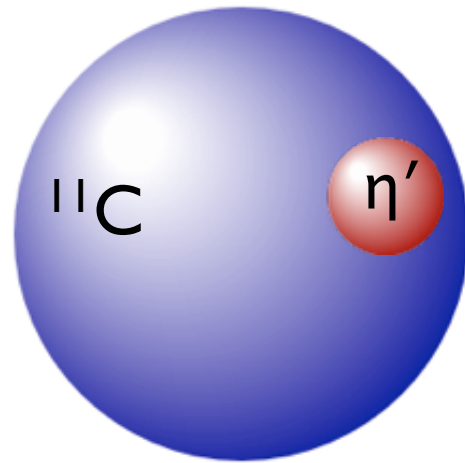
Klimt, Lutz, Vogl, Weise, NPA516(90)429.

Jido, Nagahiro, Hirenzaki,
PRC85(2012)032201(R)

Jido et al., NPA 914 (2013) 354

Kenta Itahashi, RIKEN

η' - nucleus energy levels



η' - ^{12}C levels with various potential assumptions

Level spacings < widths

→ observation of discrete levels

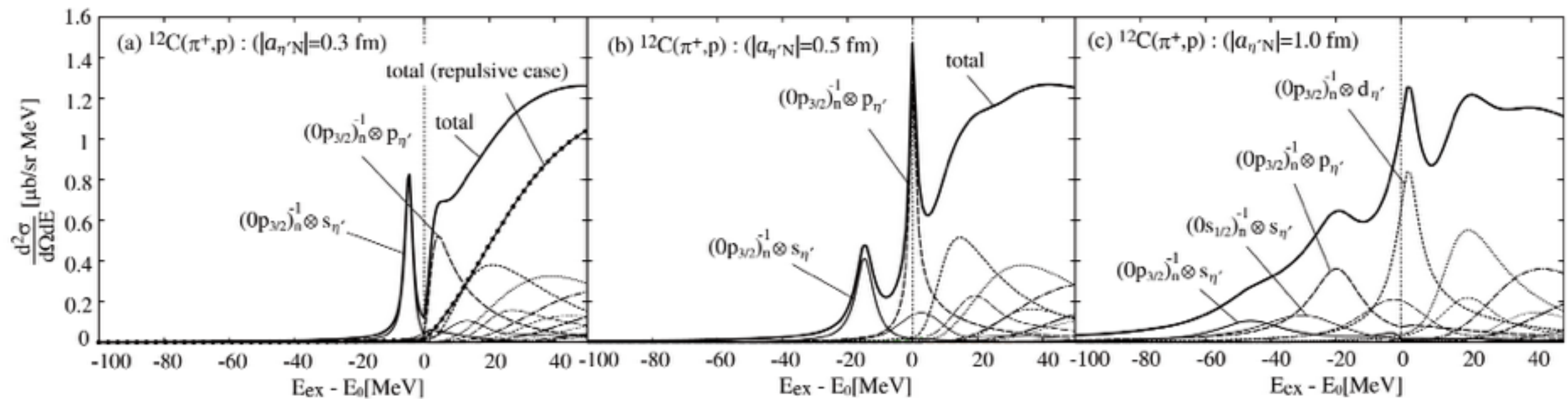
PHYSICAL REVIEW C 85, 032201(R) (2012)

Nuclear bound state of η' (958) and partial restoration of chiral symmetry in the η' mass

Daisuke Jido,¹ Hideko Nagahiro,² and Satoru Hirenzaki²

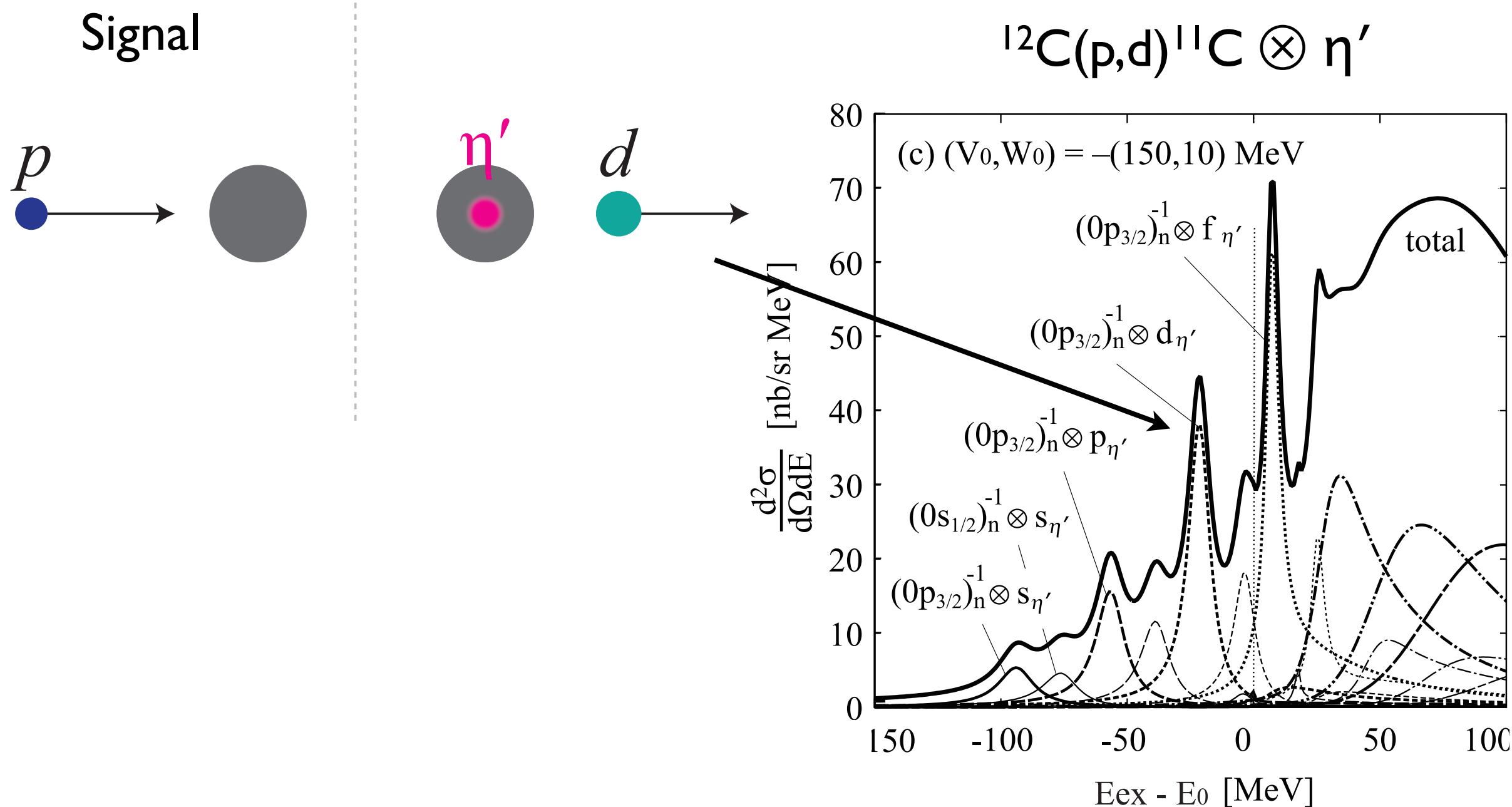
η' -mesic nuclei spectroscopy with pion beam

$^{12}\text{C}(\pi^+, p)$



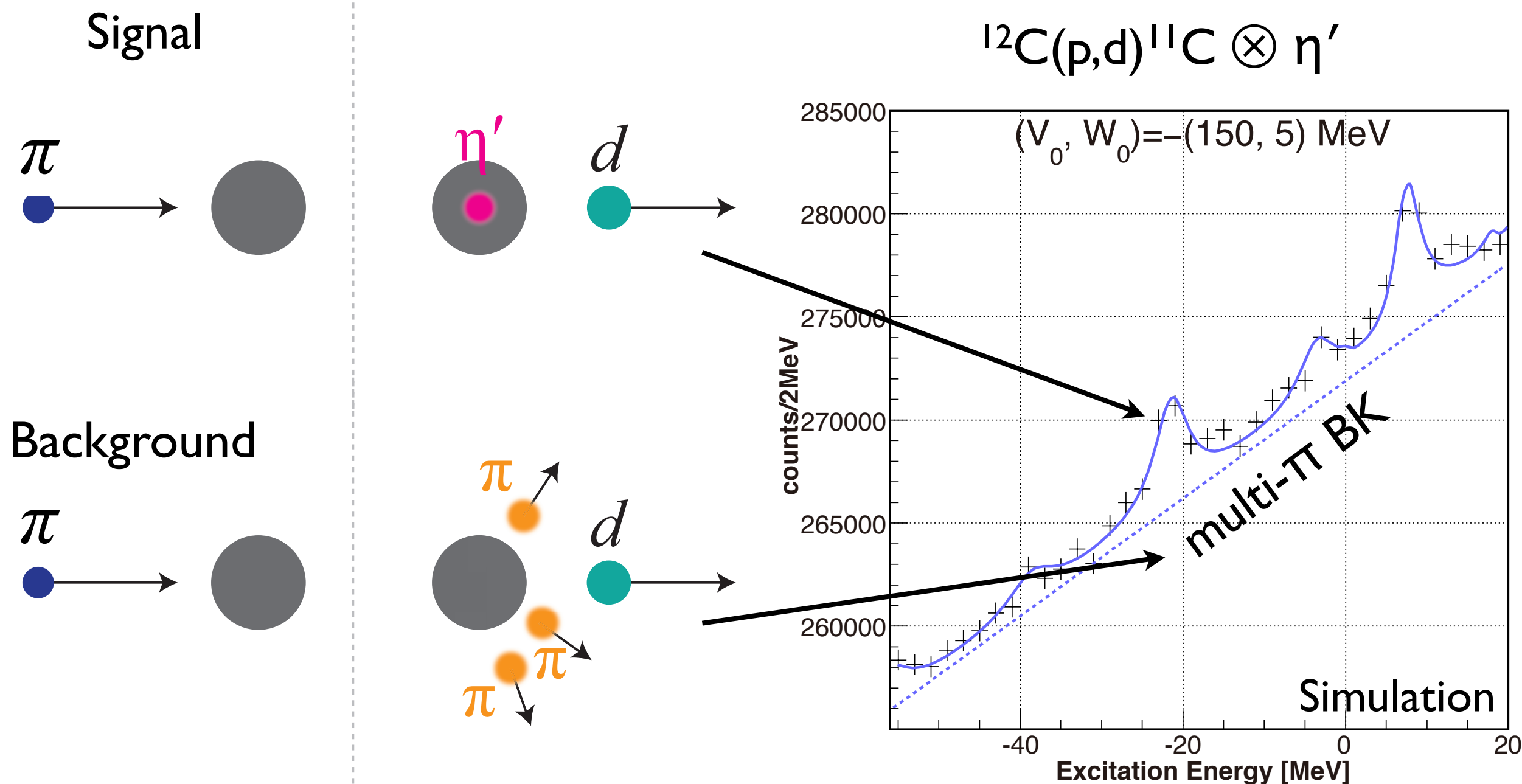
Nagahiro, NPA914

Spectrum in **Inclusive** Measurement at GSI



Nagahiro et al., PRC87(13)045201.

Spectrum in **Inclusive** Measurement



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

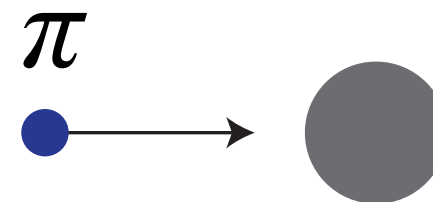
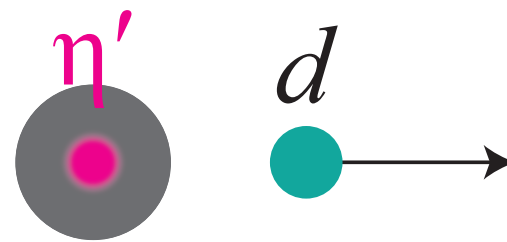
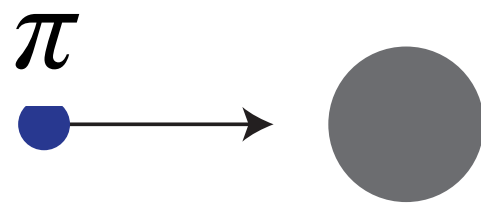
Principles of Exclusive Measurement

NUSTAR 2015

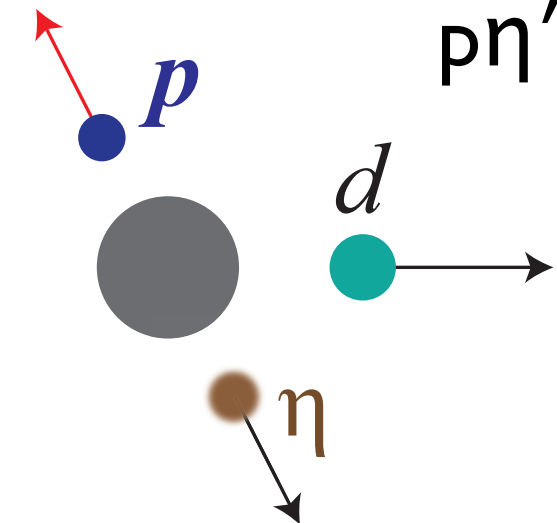
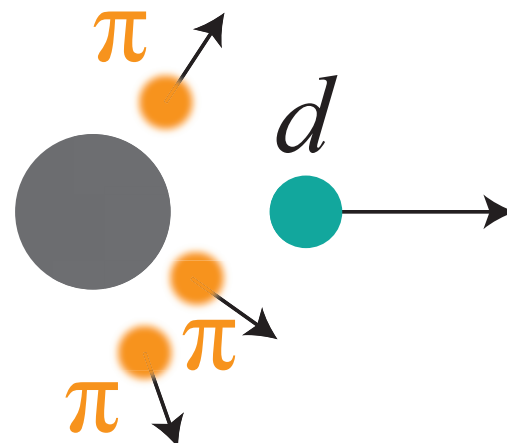
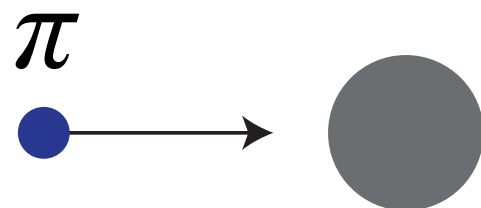
$$p\eta' \rightarrow p\eta$$

Signals

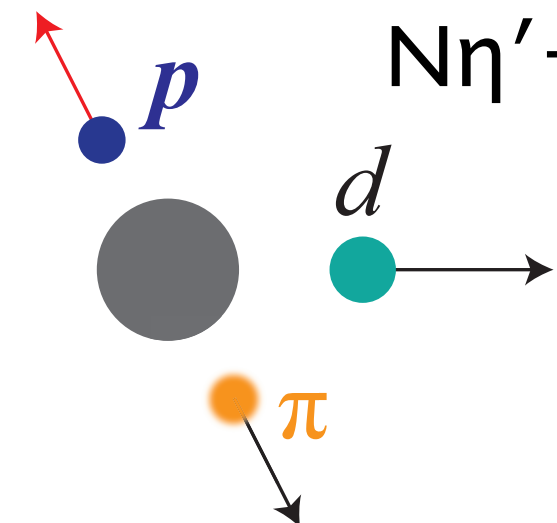
Signal



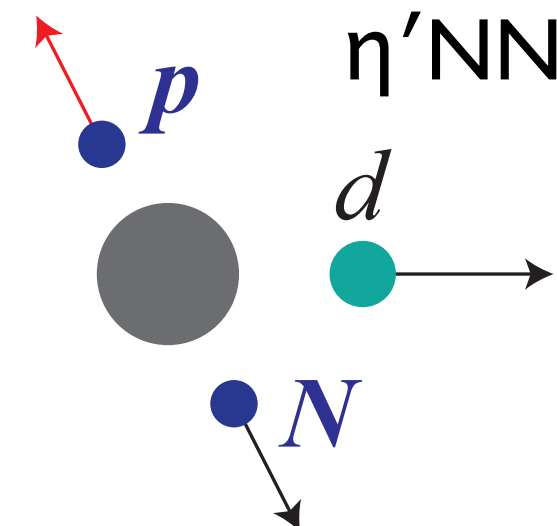
Background



$$N\eta' \rightarrow p\pi$$



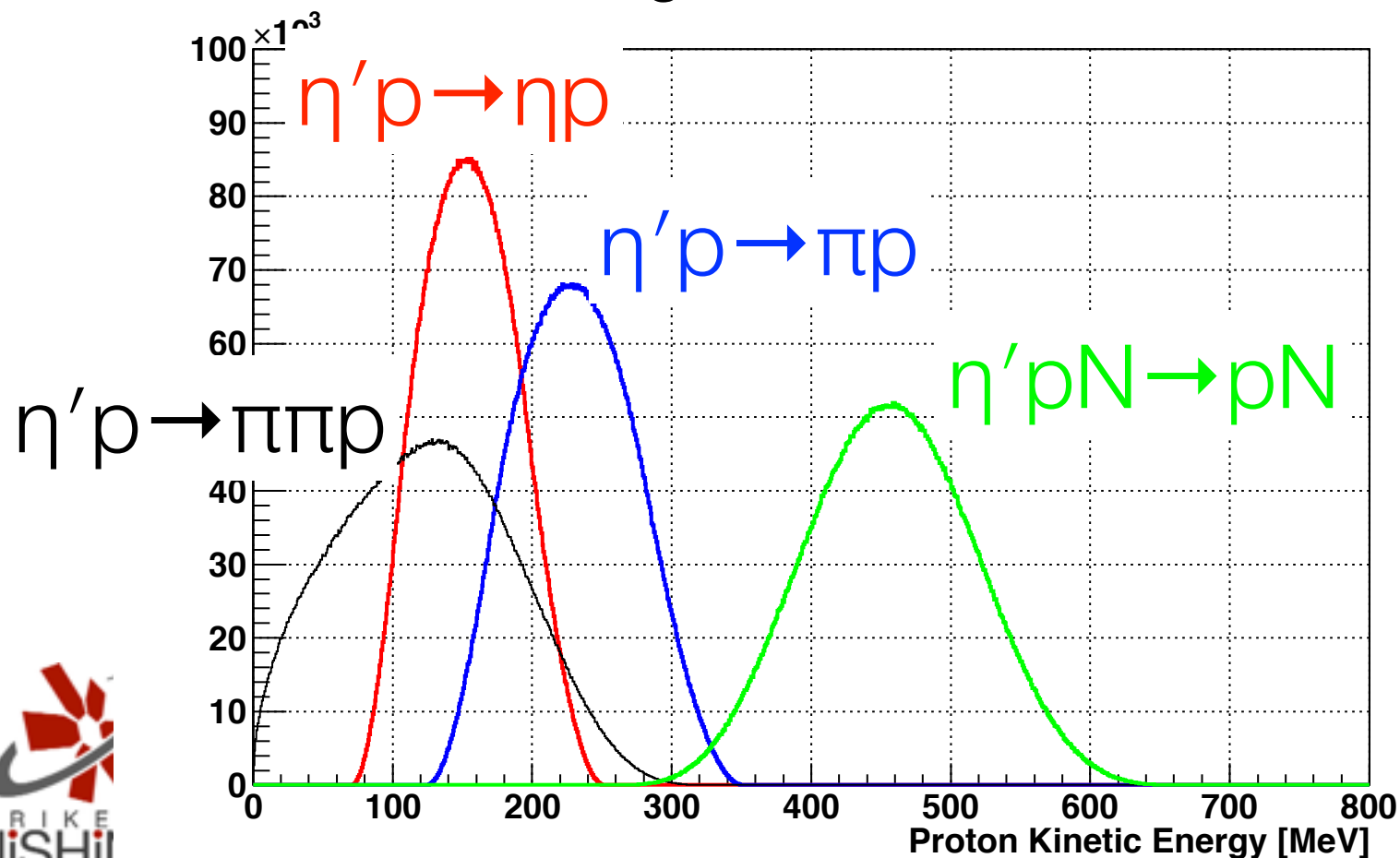
$$\eta' NN \rightarrow pN$$



Principles of **Exclusive** Measurement

Tagging high-momentum protons
(300-600 MeV)

Y.K. Tanaka and Y. Higashi

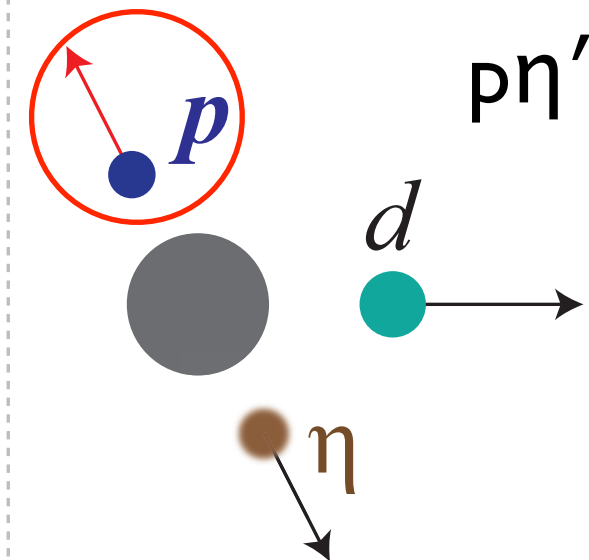


Signals

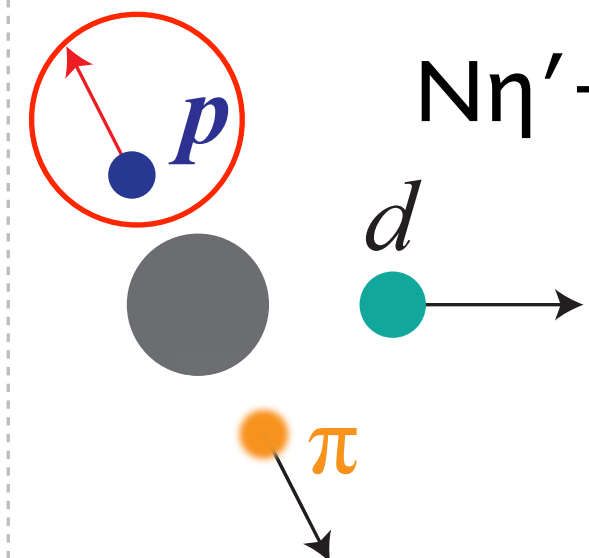
π

NUSTAR 2015

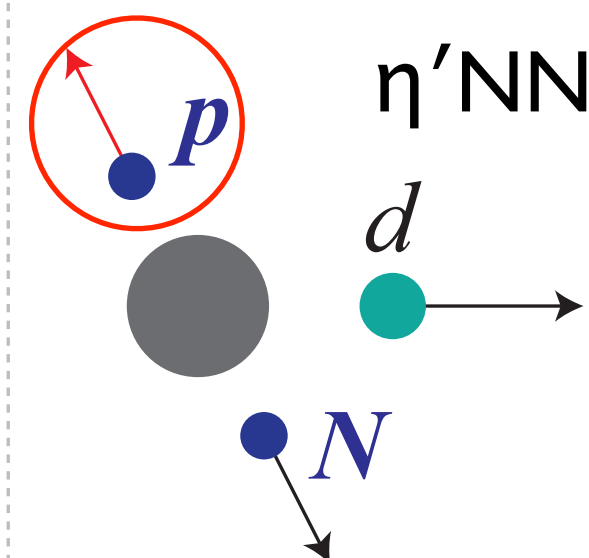
$p\eta' \rightarrow p\eta$



$N\eta' \rightarrow p\pi$



$\eta' NN \rightarrow pN$

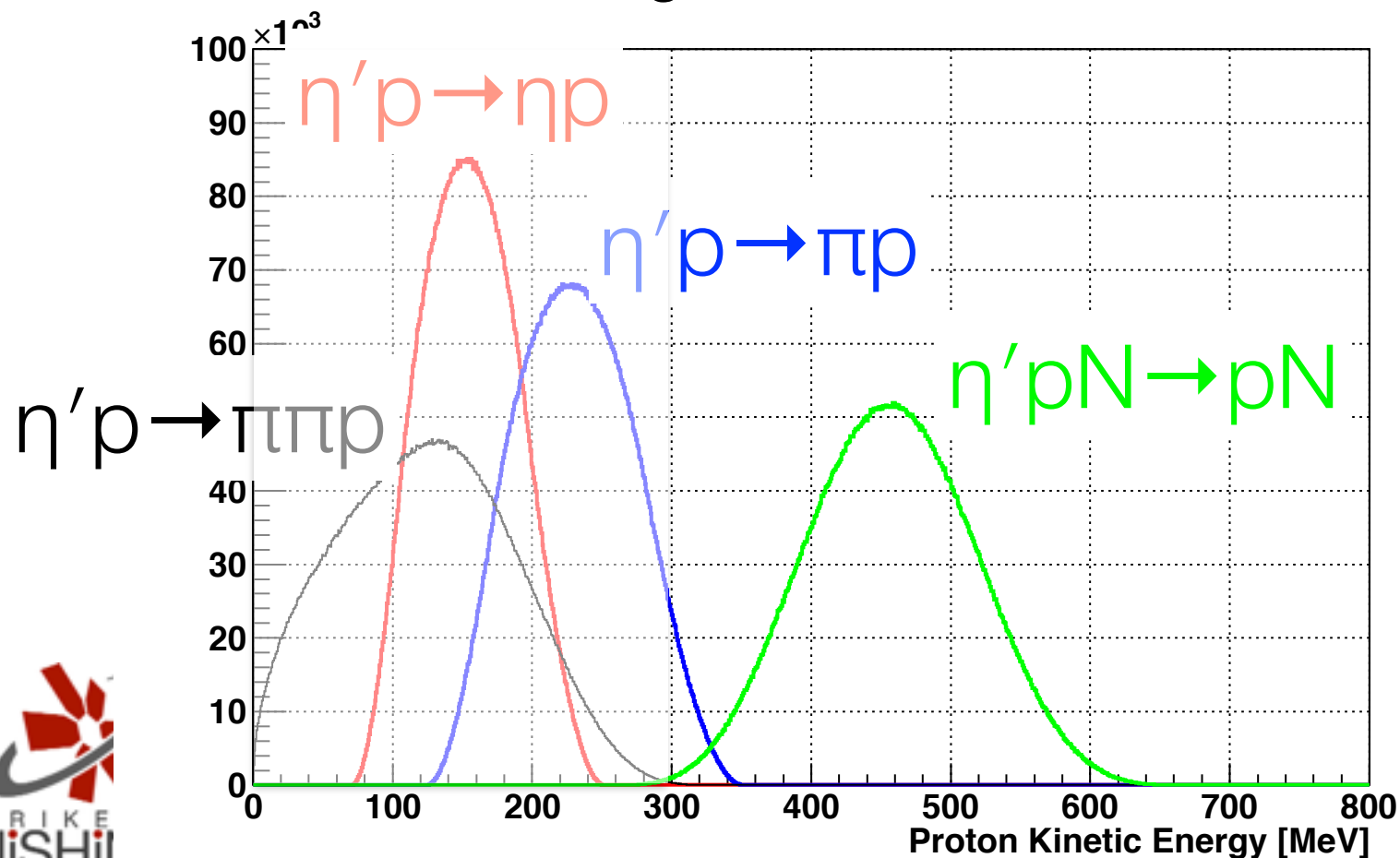


Principles of **Exclusive** Measurement

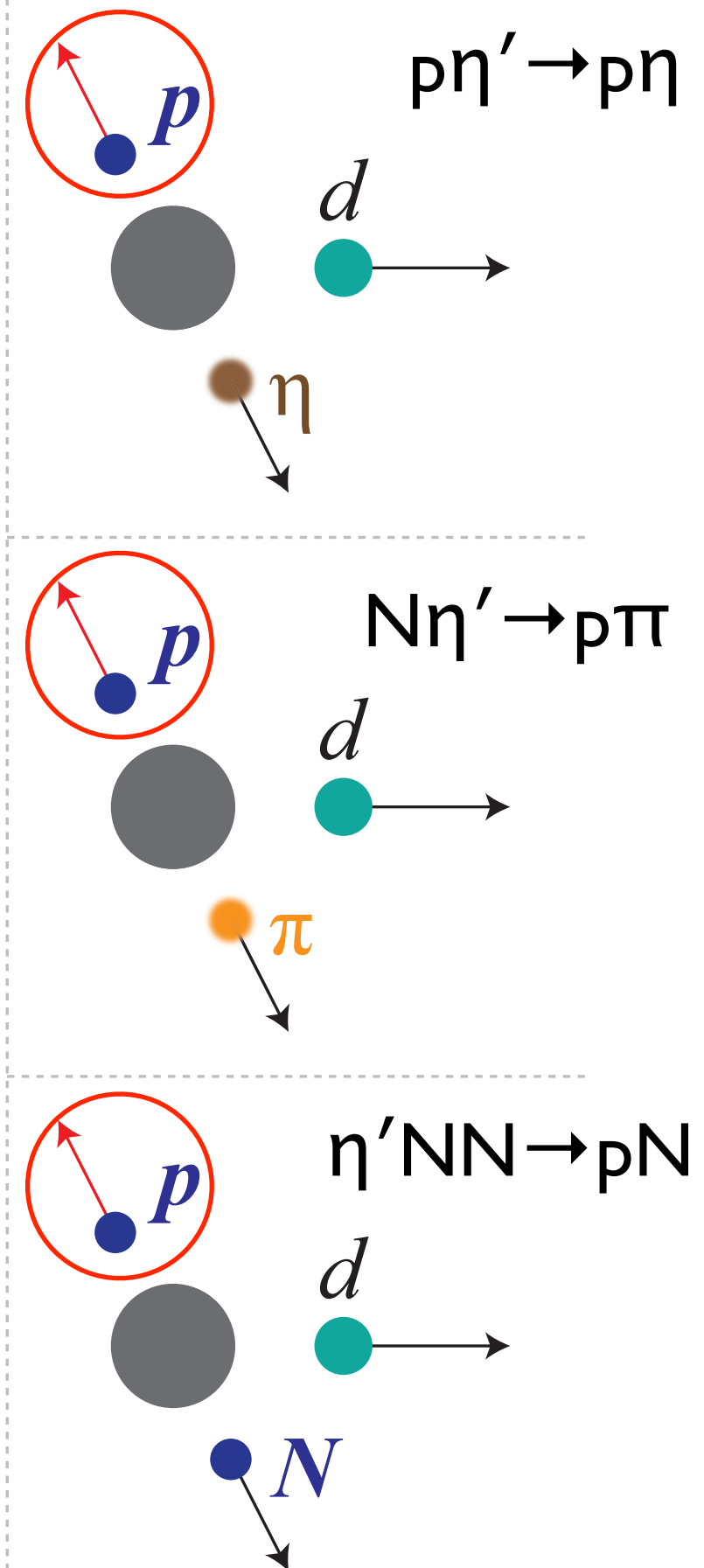
Tagging high-momentum protons
(300-600 MeV)

intra-nuclear cascade code $\rightarrow$
S/N improves by $f \sim 100$

Y.K. Tanaka and Y. Higashi



Signals



Summary

- Spectroscopy of meson bound states provides information on meson properties in medium and fundamental information on non-trivial structure of vacuum
- Pionic atoms provided quantitative evaluation of chiral symmetry restoration in medium.
- η -mesic nuclei may provide information on chiral symmetry in the baryon sector thru strong coupling with $N^*(1535)$
- η' -mesic nuclei may provide information on $U_A(1)$ anomaly