Meson Properties from Mesic Atoms and Mesic Nuclei

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Nara Women's University,

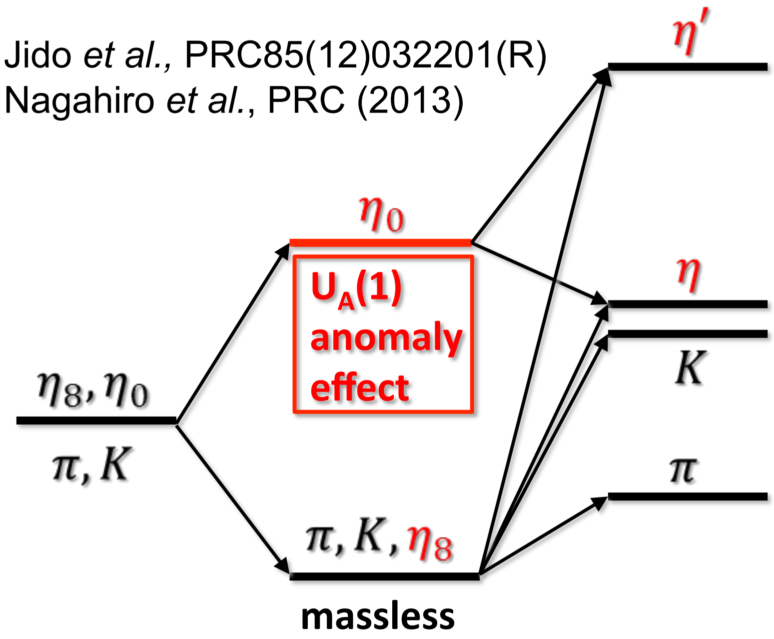
13th Int. Workshop Meson Production, Properties and Interaction (MESON2014)

Krakow, Poland, May 29 – June 3, 2014

Meson mass spectrum and Symmetry Breaking Pattern (PS)

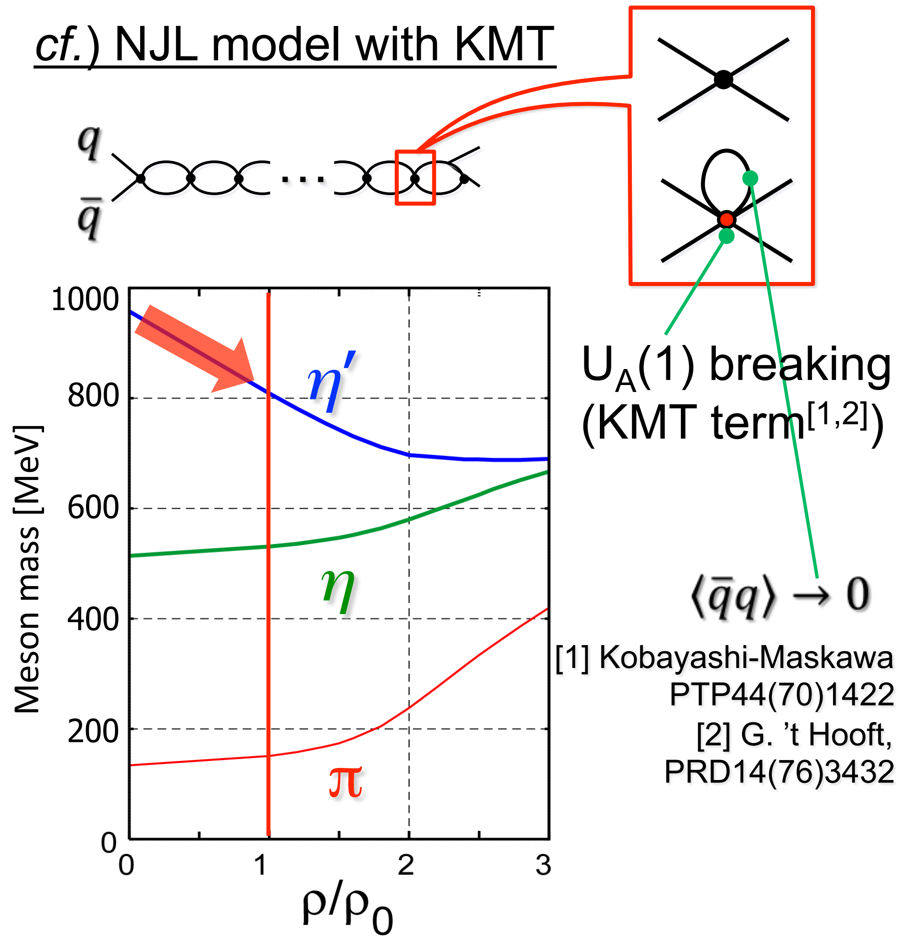
schematic view of the mass of π, K, η & η'

Jido *et al.*, PRC85(12)032201(R)
Nagahiro *et al.*, PRC (2013)



$m_q, m_s = 0$	$m_q, m_s = 0$	$m_q, m_s \neq 0$
$\langle \bar{q}q \rangle = 0$	$\langle \bar{q}q \rangle \neq 0$	$\langle \bar{q}q \rangle \neq 0$
ChS manifest	**dynamically broken**	**dyn. & explicitly broken**

cf.) NJL model with KMT



[1] Kobayashi-Maskawa PTP44(70)1422
[2] G. 't Hooft, PRD14(76)3432

$\Delta m \sim -150$ MeV @ ρ_0

Costa *et al.*,PLB560(03)171,
Nagahiro-Takizawa-Hirenzaki, PRC74(06)045203

Meson in Nucleus (related topics)

- Deeply Bound Pionic Atoms
- $\eta'(958)$ anomaly effect @ finite density, Exp. Plan

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- Vector Mesons at finite density ϕ, ω

  mass shift, width and up dated QCD sum rule

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  mass shift, width and up dated QCD sum rule

- Heavy Q mesons in Nucleus
- ……….

$\eta'(958)$ mesic nucleus

H.Nagahiro, S.Hirenzaki, Phys.Rev.Lett.94 (2005)232503
H.Nagahiro, M.Takizawa, S.Hirenzaki, Phys.Rev.C74 (2006)045203
D. Jido, H. Nagahiro, S. Hirenzaki, Phys.Rev.C 85, 032201 (R) (2012)
H. Nagahiro, S. Hirenzaki, E. Oset, A. Ramos, Phys. Lett. B 709 (2012) 87-92

K. Itahashi, H. Fujioka, H. Geissel, R. S. Hayano, S Hirenzaki, S. Itoh, D. Jido, V. Metag, H. Nagahiro, M. Nanova, T. Nishi, K. Okochi, H. Outa, K. Suzuki, Y. K. Tanaka, H. Weick, Prog. Theor. Phys. 128 (2012) 601-613.

H. Nagahiro, D. Jido, H. Fujioka, K. Itahashi, S. Hirenzaki, Phys. Rev. C 87, 045201 (2013).

Introduction

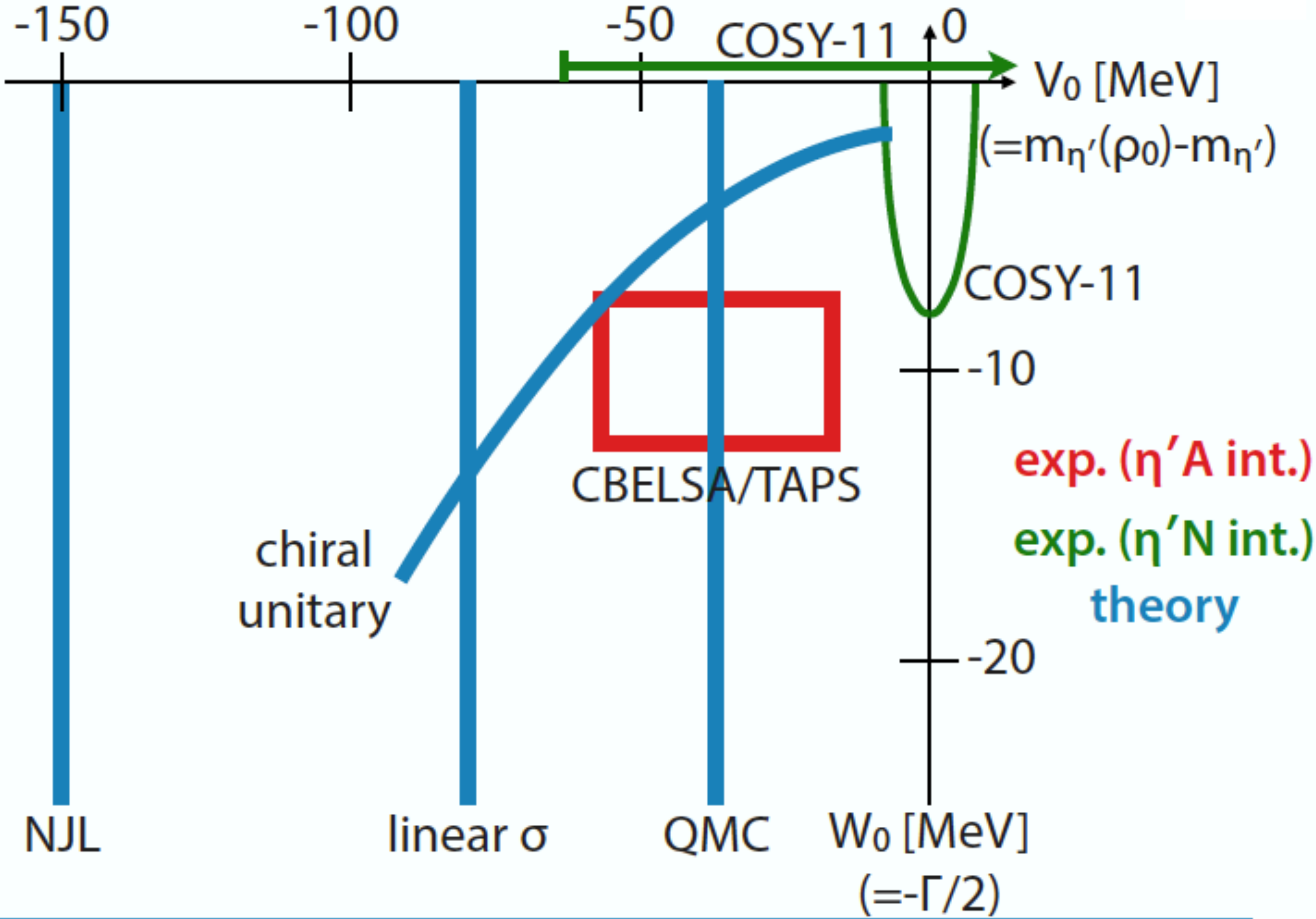
- η'(958) meson …close connections with $U_A(1)$ anomaly
  - Theoretical works
    - the effects of the $U_A(1)$ anomaly on η' properties
    - at finite temperature/density
      - T. Kunihiro, PLB219(89)363
      - R.D.Pisarski, R.Wilczek, PRD29(84)338
      - Y. Kohyama, K.Kubodera and M.Takizawa, PLB208(1988)165
      - K.Fukushima, K.Onishi, K.Ohta, PRC63(01)045203
      - P. Costa *et al.*,PLB560(03)171, hep-ph/0408177

      etc…
    - the possible **character changes of η' at $\rho \neq 0$**
  - Poor experimental information

    on the $U_A(1)$ anomaly at finite density

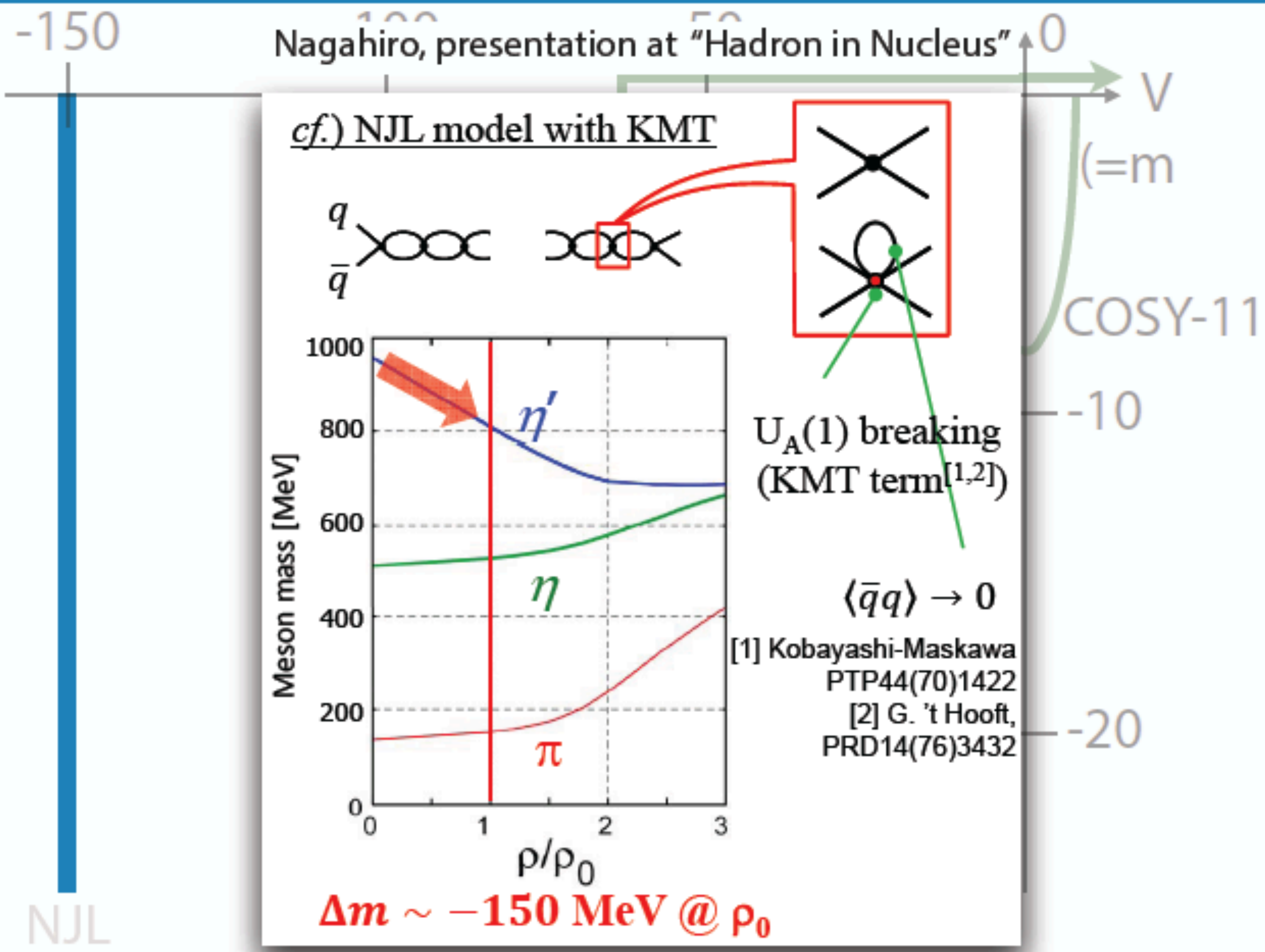
- Proposal for the study of the η'-mesic nuclei
  - $U_A(1)$ anomaly effect in medium from the "mesic nuclei"
  - the η' properties at finite density

η′ optical potential: state of the art



Nambu–Jona-Lasinio model

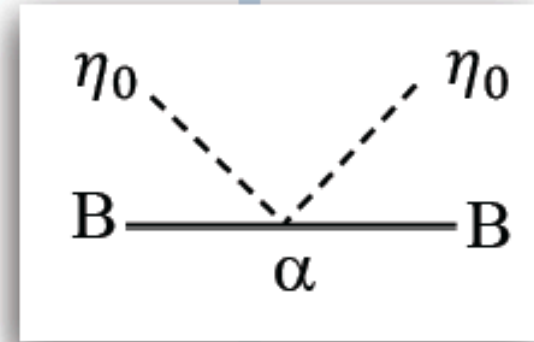
Nagahiro, presentation at "Hadron in Nucleus"

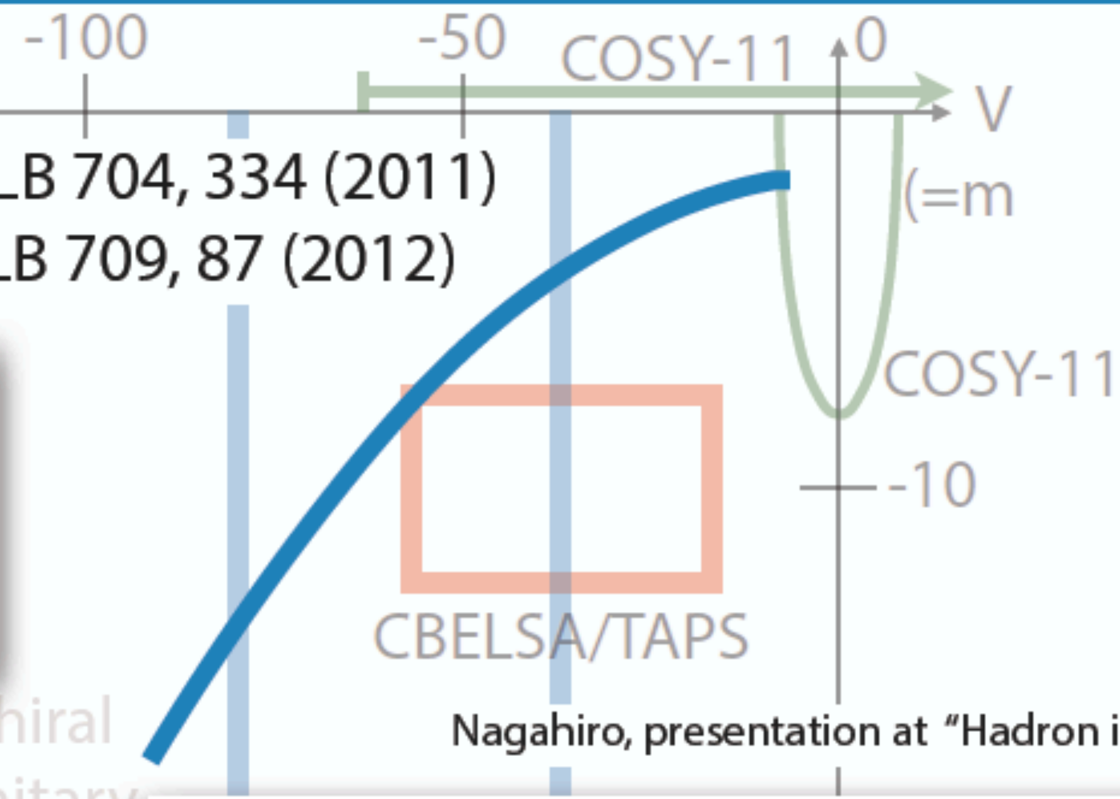


Nagahiro et al., PRC 76, 045203 (2006)

chiral unitary model

Oset and Ramos, PLB 704, 334 (2011)
Nagahiro et al., PLB 709, 87 (2012)





Nagahiro, presentation at "Hadron in Nucleus"

Re $V_{\eta'}$ and Im $V_{\eta'}$ with various α values

in unit of MeV

α	$\lvert a_{\eta' N}\rvert$ fm	$V^{1st}_{\eta'}(\rho_0)$	$V^{2nd}_{\eta'}(\rho_0)$	$V^{total}_{\eta'}(\rho_0)$
−0.193	0.1	$-8.6-1.7i$	$-0.1-0.1i$	$-8.7-1.8i$
−0.834	0.3	$-26.3-2.1i$	$-0.6-0.9i$	$-26.8-3.0i$
−1.79	0.5	$-43.8-3.0i$	$-1.3-2.5i$	$-44.1-5.5i$
−9.67	1.0	$-87.7-6.9i$	$-4.1-10.4i$	$-91.8-17.2i$

- An important piece of

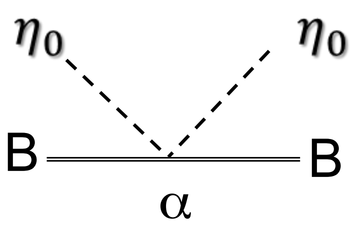
E. Oset, A. Ramos, PLB704(11)334

H.Nagahiro, S. H., E. Oset, A. Ramos, PLB709(12)87

Coupling of the singlet component of pseudoscalar to baryons

Borasoy , PRD61(00)014011
S. Bass, Phys.Lett. B463 (1999) 286
Kawarabayashi-Ohta, PTP66(81)1789

This interaction
*seems to dominate the eta'-N interaction
*contributes mostly to the elastic channel & barely to the inelastic channel

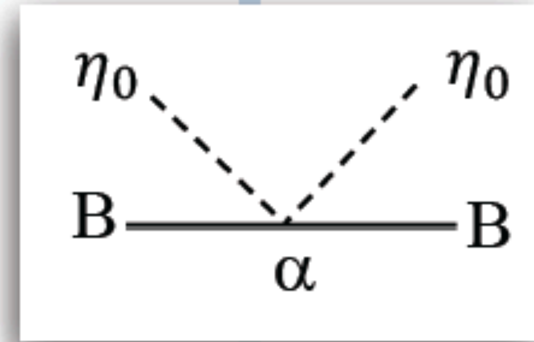


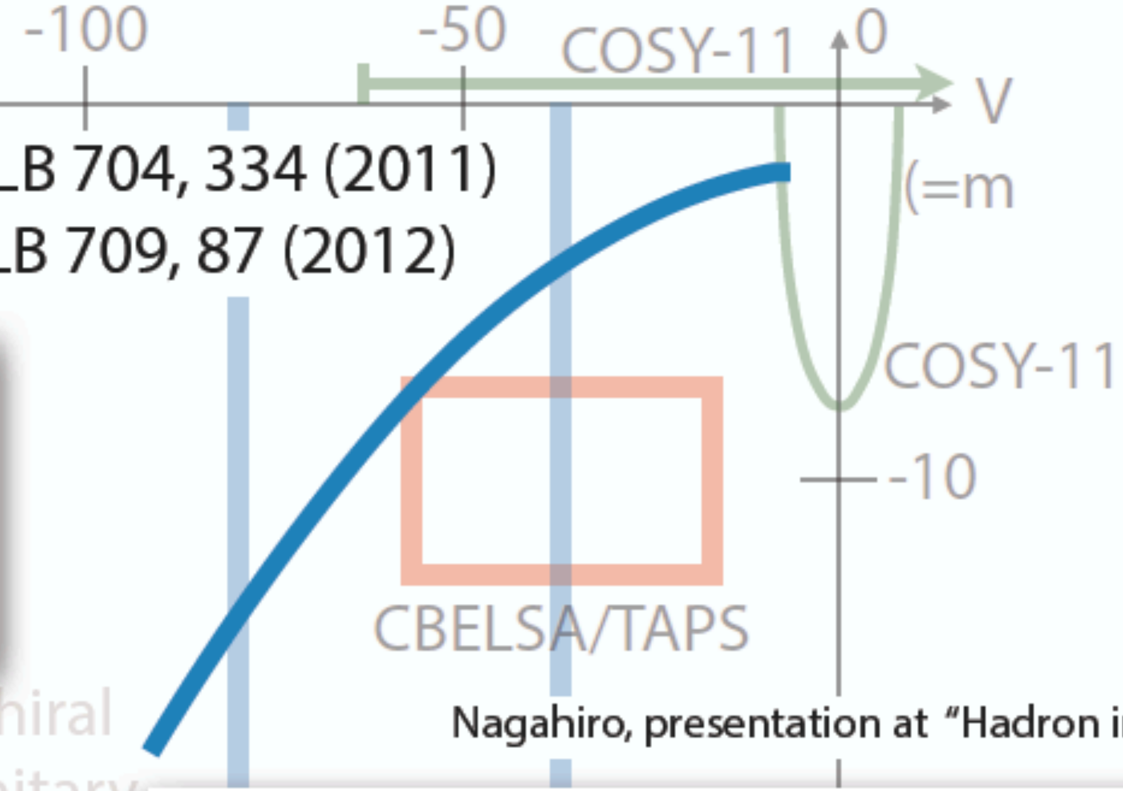
$$\mathcal{L}_{\eta_0 B} \propto \eta_0^2 \langle \partial_\mu \bar{B} \gamma^\mu B - \bar{B} \gamma^\mu \partial_\mu B \rangle$$

α … free parameter

chiral unitary model

Oset and Ramos, PLB 704, 334 (2011)
Nagahiro et al., PLB 709, 87 (2012)





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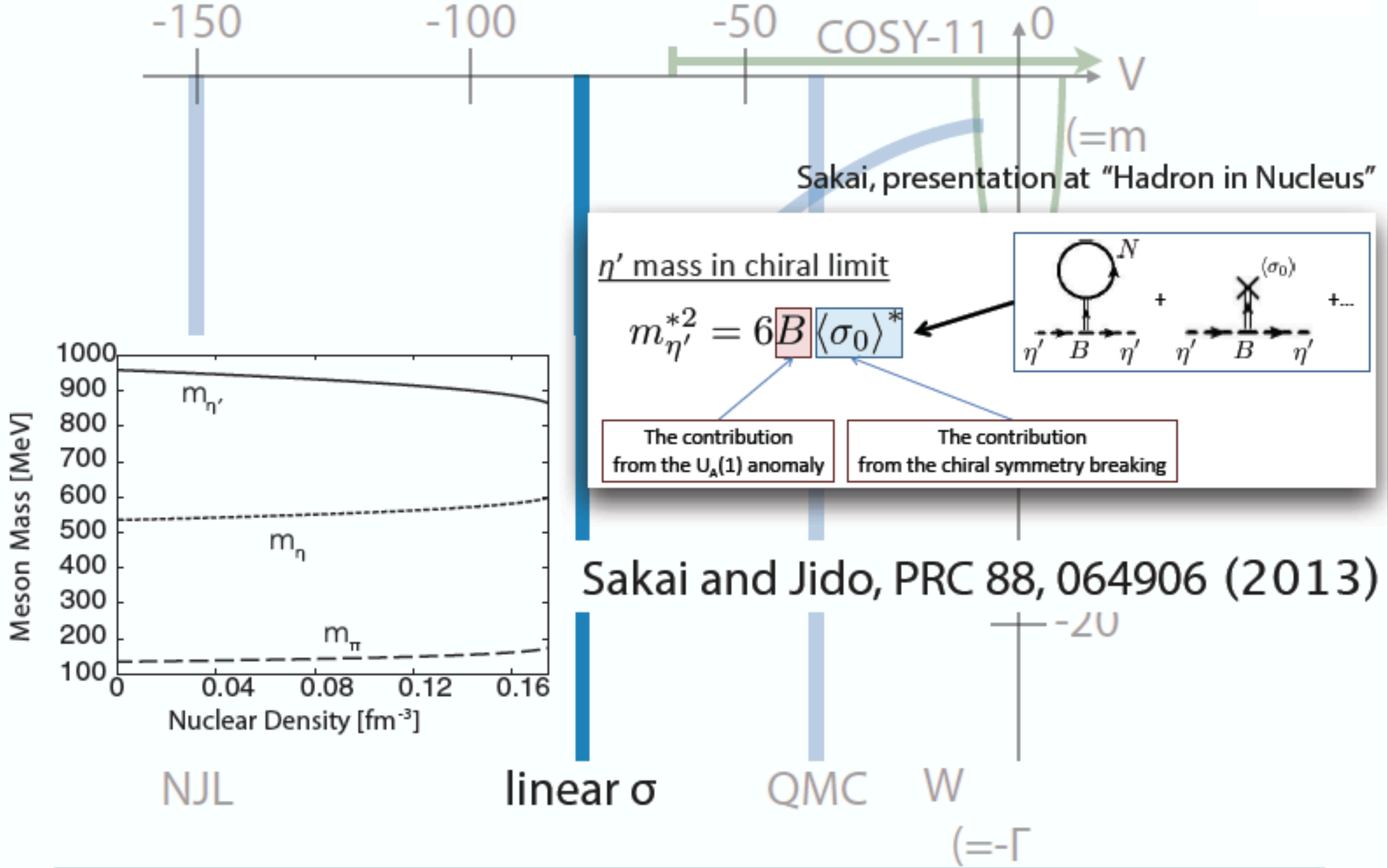
linear sigma model



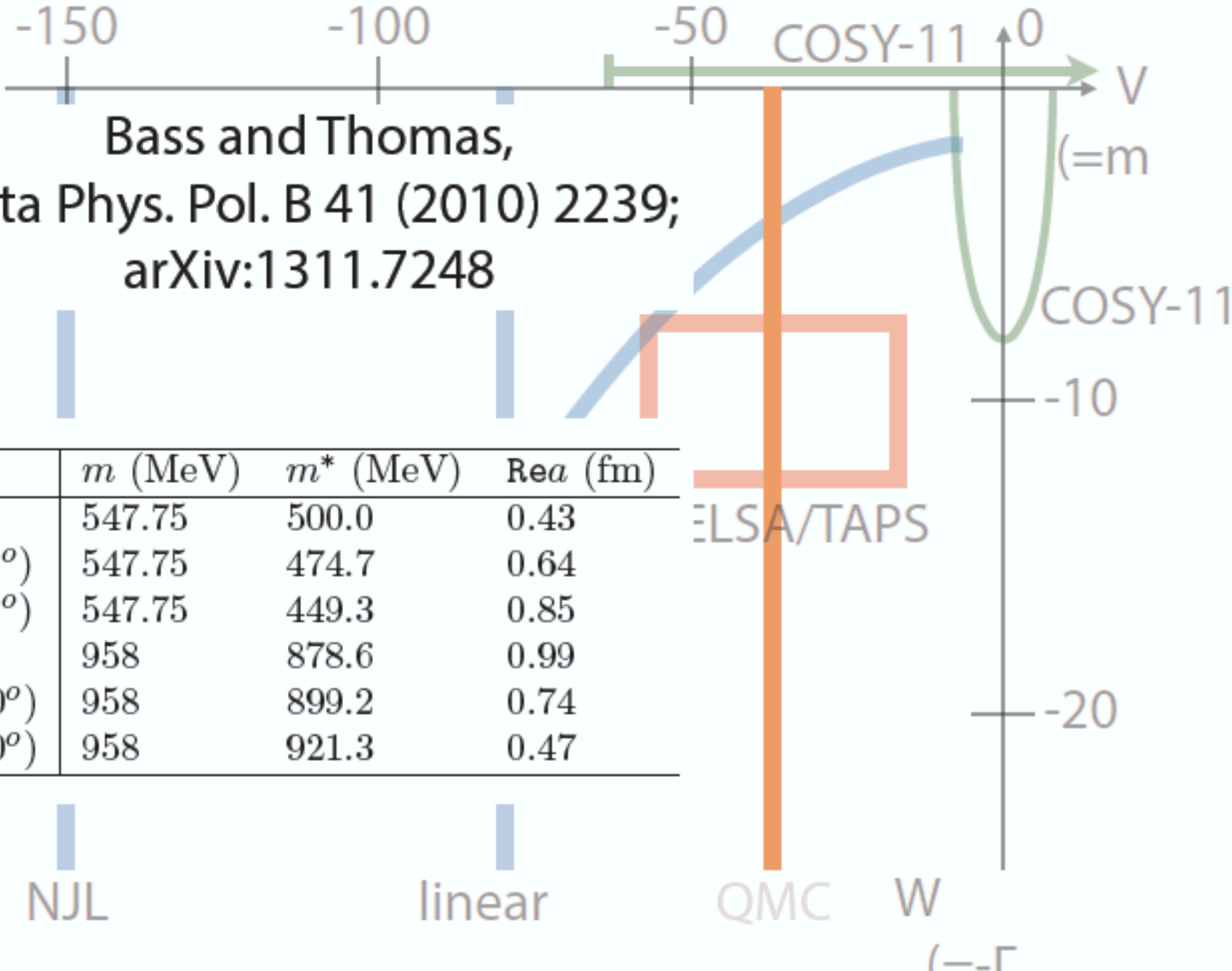
Sakai, presentation at "Hadron in Nucleus"

η′ mass in chiral limit

$$m_{\eta'}^{*2} = 6B\langle\sigma_0\rangle^*$$

Sakai and Jido, PRC 88, 064906 (2013)

quark-meson coupling model



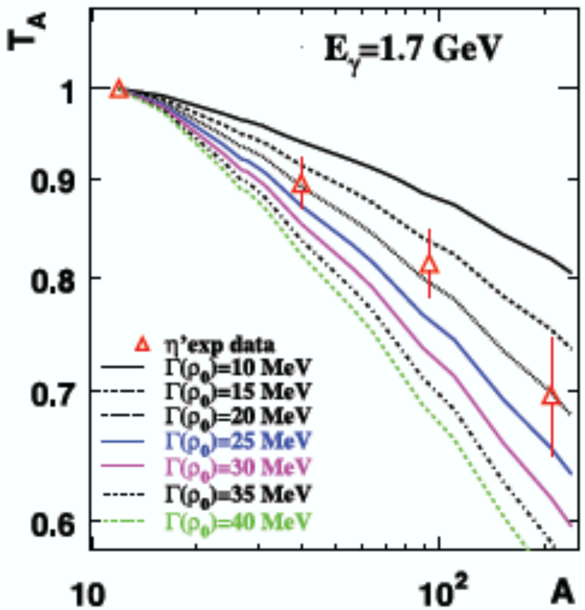
Bass and Thomas,
Acta Phys. Pol. B 41 (2010) 2239;
arXiv:1311.7248

	m (MeV)	m^* (MeV)	Rea (fm)
η_8	547.75	500.0	0.43
η (-10^o)	547.75	474.7	0.64
η (-20^o)	547.75	449.3	0.85
η_0	958	878.6	0.99
η' (-10^o)	958	899.2	0.74
η' (-20^o)	958	921.3	0.47

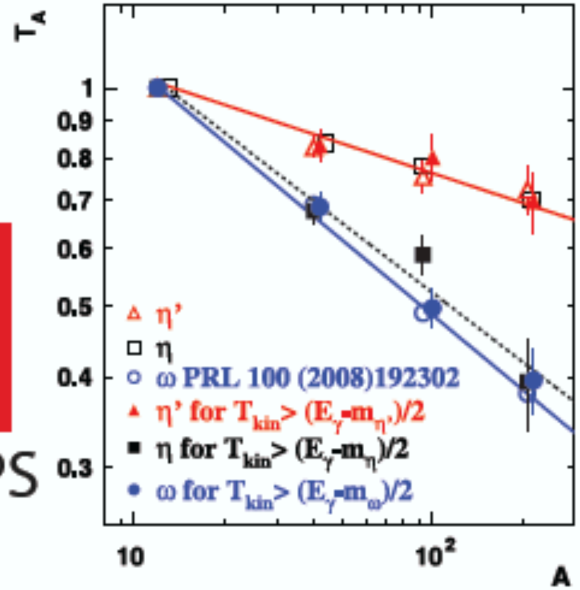
transparency ratio measurement

transparency ratio

$$T_A = \frac{\sigma(\gamma A \to \eta' X)}{A \cdot \sigma(\gamma N \to \eta' X)}$$



CBELSA/TAPS



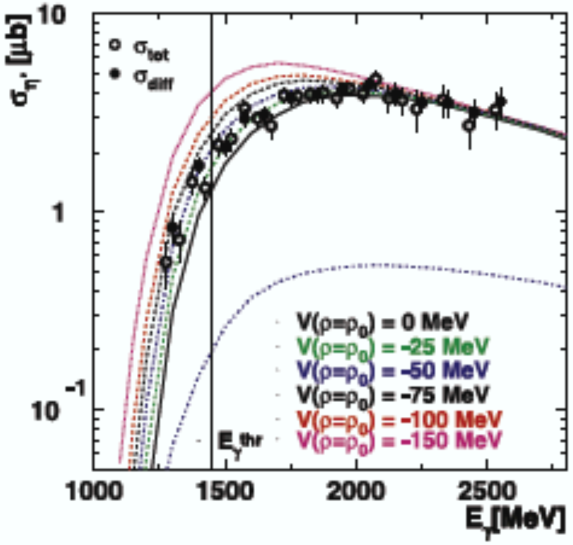
→ Γ=15–25MeV at $\rho=\rho_0$

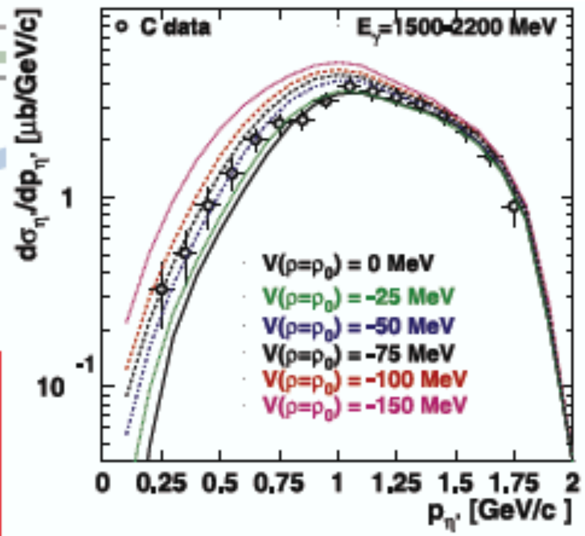
for $\langle p_{\eta'} \rangle \sim$1.05GeV/c

NJL linear QMC W (=-Γ

Nanova et al., PLB 710, 600 (2012)

excitation function and momentum distribution





$V_0=-(40\pm6)$ MeV

CBELSA/TAPS

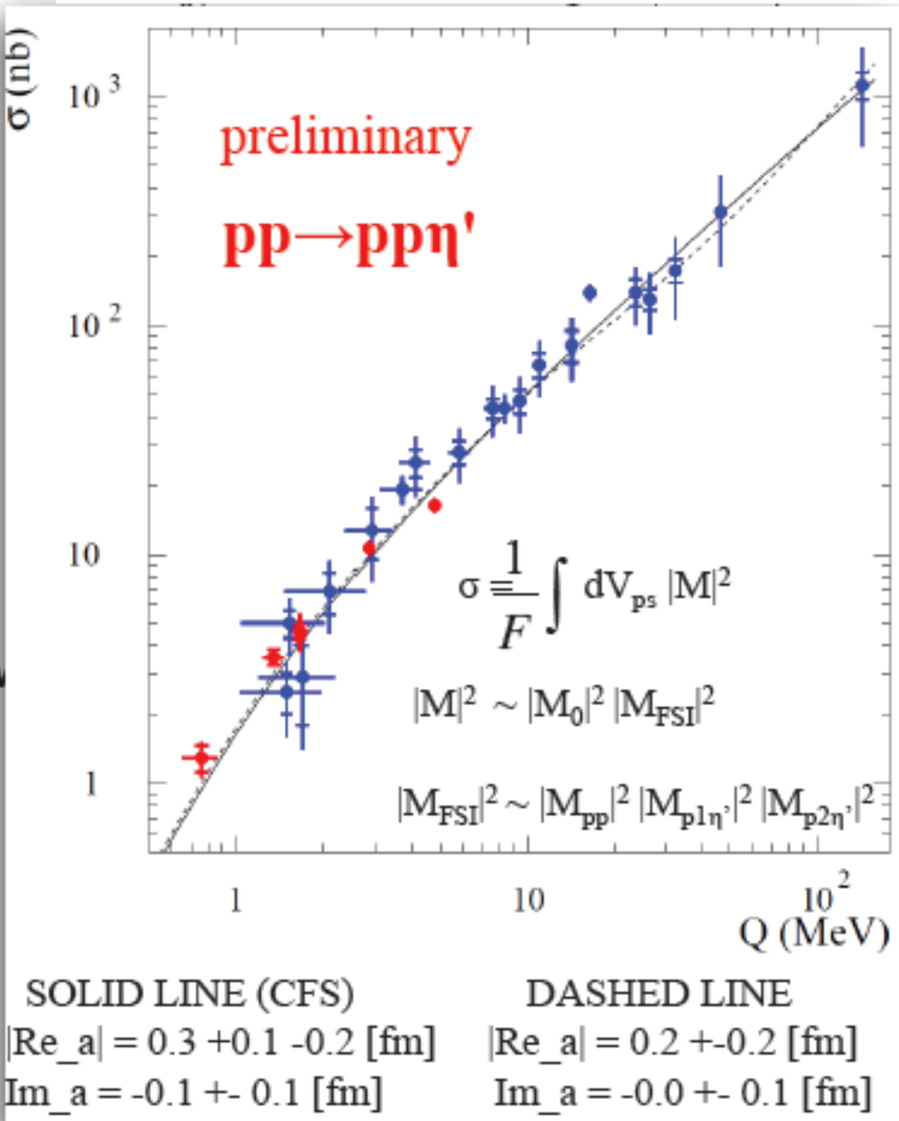
$V_0=-(32\pm11)$ MeV

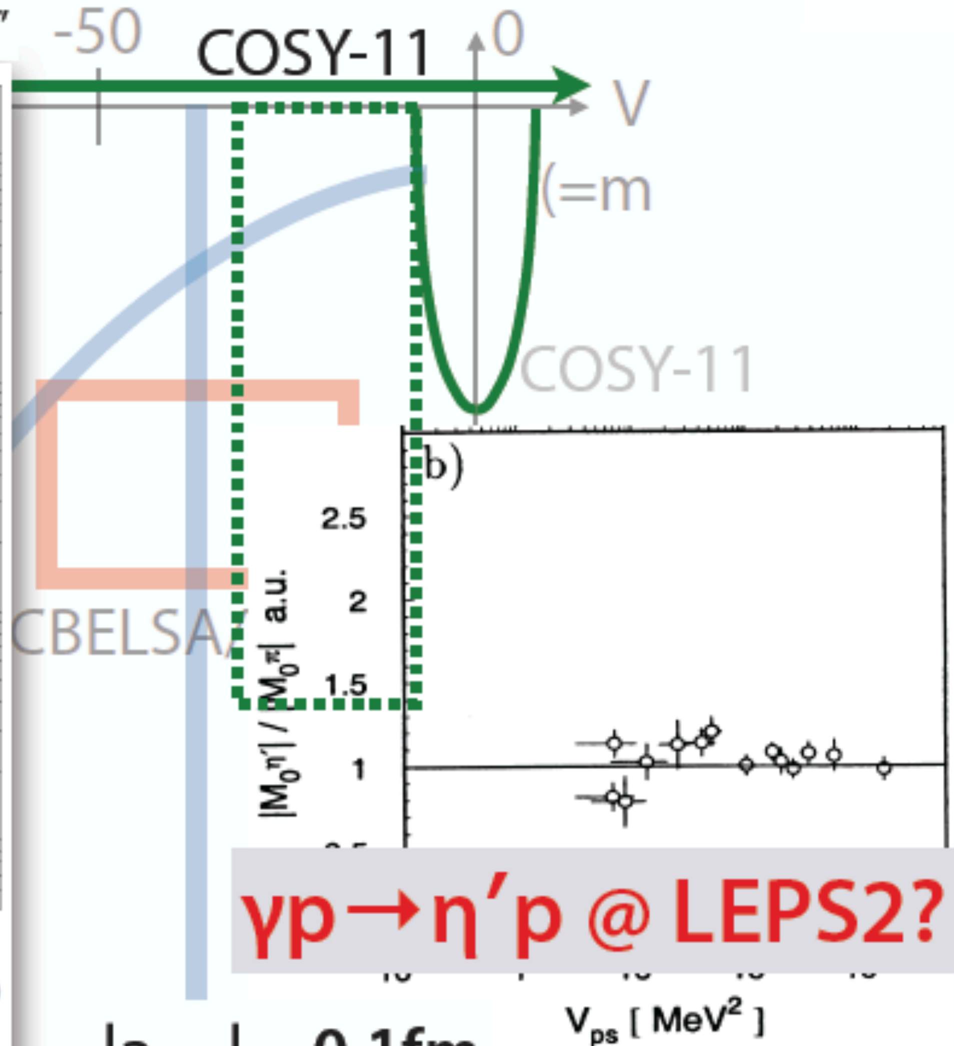
$V_0=-(37\pm10_{stat}\pm10_{syst})$ MeV

Nanova et al., PLB 727, 417 (2013)

elementary process : pp→ppη′

Moskal, presentation at "Hadron in Nucleus"





γp→η′p @ LEPS2?

$|a_{\eta' N}| \sim 0.1$fm

Moskal et al., PLB 482, 356 (2000)

COSY-11 New Result

arXiv:1404.5436v1 [nucl-ex] 22 Apr 2014

Determination of the η'-proton scattering length in free space

E. Czerwiński,[1,*] P. Moskal,[1] M. Silarski,[1] S. D. Bass,[2] D. Grzonka,[3] B. Kamys,[1] A. Khoukaz,[4] J. Klaja,[1] W. Krzemień,[1] W. Oelert,[5] J. Ritman,[3] T. Sefzick,[3] J. Smyrski,[1] A. Täschner,[4] M. Wolke,[6] and M. Zieliński[1]

[1] *Institute of Physics, Jagiellonian University, PL-30-059 Cracow, Poland*
[2] *Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences, Boltzmanngasse 3, A 1090 Vienna, Austria*
[3] *Institute for Nuclear Physics and Jülich Center for Hadron Physics, Research Center Jülich, D-52425 Jülich, Germany*
[4] *IKP, Westfälische Wilhelms-Universität, D-48149 Münster, Germany*
[5] *Johannes Gutenberg-Universität Mainz, 550099 Mainz, Germany*
[6] *Department of Physics and Astronomy, Uppsala University, SE-751 20 Uppsala, Sweden*

(Dated: April 23, 2014)

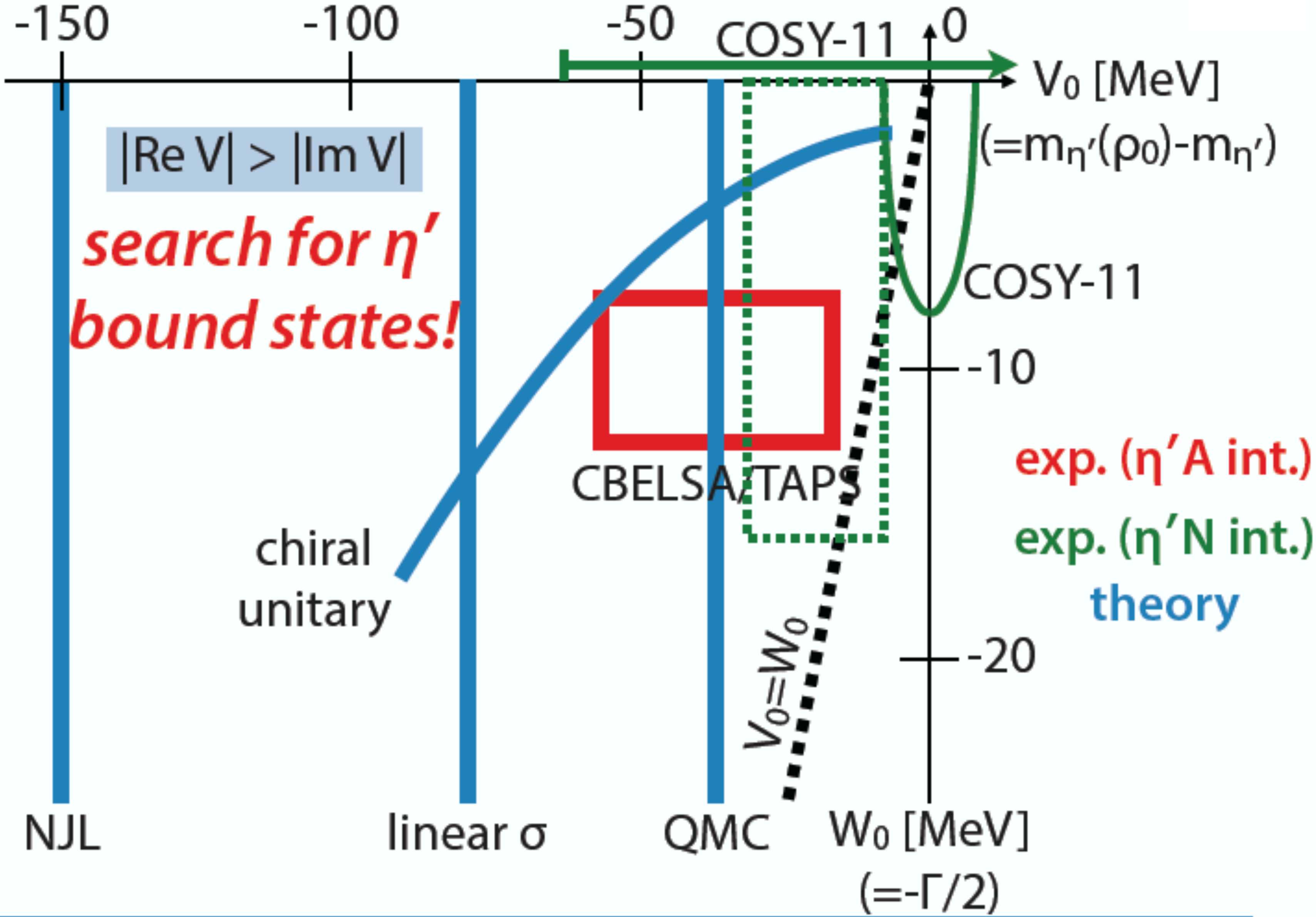
Taking advantage of both the high mass resolution of the COSY–11 detector and the high energy resolution of the low-emittance proton-beam of the Cooler Synchrotron COSY we determine the excitation function for the $pp \to pp\eta'$ reaction close-to-threshold. Combining these data with previous results we extract the scattering length for the η'-proton potential in free space to be $\mathrm{Re}(a_{p\eta'}) = 0 \pm 0.43$ fm and $\mathrm{Im}(a_{p\eta'}) = 0.37\ ^{+0.40}_{-0.16}$ fm.

$$\mathrm{Re}(a) = 0 \pm 0.43\mathrm{fm}$$

$$\mathrm{Im}(a) = 0.37 + 0.40 - 0.16\mathrm{fm}$$

Talk by Dr. *Eryk Czerwiński* in this confrence

η′ optical potential: state of the art



Formation by (p,d) reaction

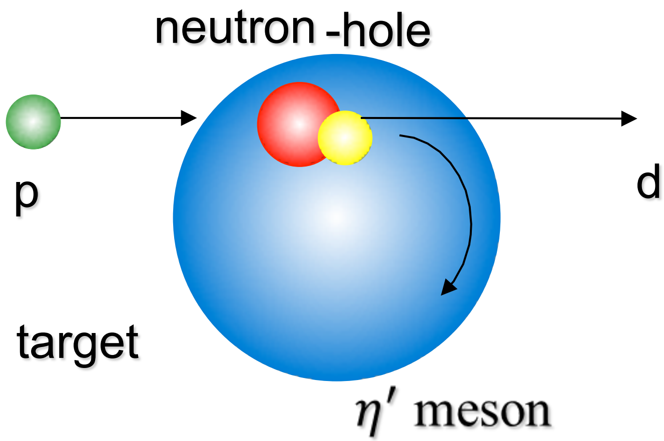
<u>missing mass spectroscopy</u>

K. Itahashi, H. Fujioka *et al.*, PTP128(12)601

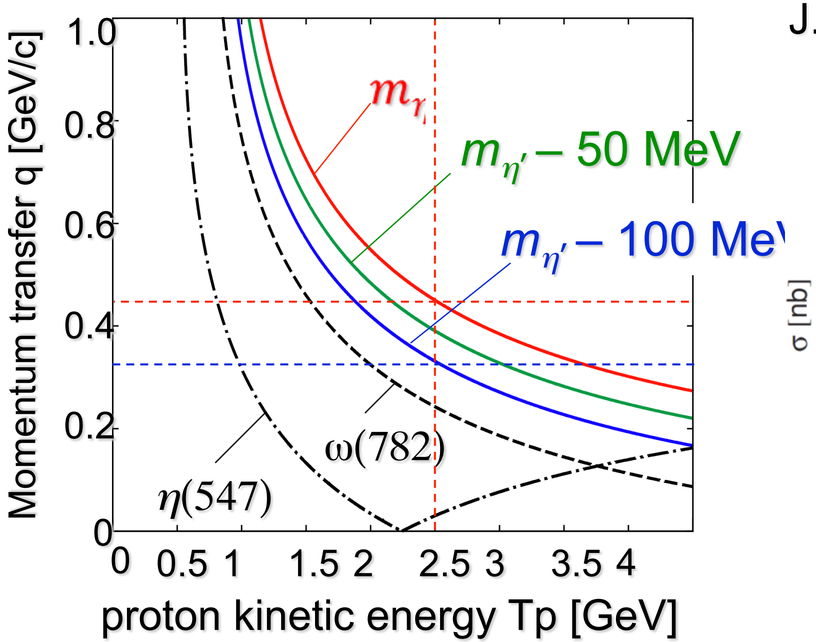
proton kinetic energy $T_p = 2.5$ GeV

target : ^{12}**C**, (^{16}O, ^{40}Ca)

forward reaction : $\theta_d = 0$ deg.

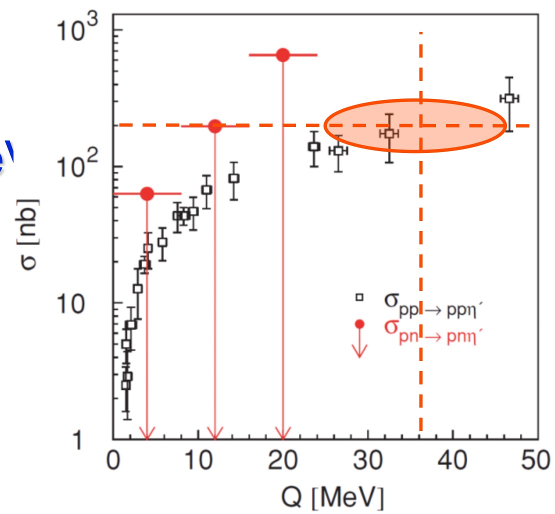


momentum transfer



elementary cross section $pn \to \eta' d$ ***No information***

J.Klaja et al., PRC81(10)035209 (COSY)



$\sigma_{pp\to pp\eta'}$

↓

assumptions

↓

$$\left(\frac{d\sigma}{d\Omega}\right)^{lab}_{pn\to\eta' d} = 30\ \mu b/sr$$

K.Nakayama in private comm
Itahashi *et al.*, PTP128(12)601

Green's function method

Ref. O.Morimatsu and K. Yazaki, NPA435(1985)727-737

where $\varepsilon_\alpha = E_\alpha - E_i$ is the nucleon separation energy for the state $|\alpha\rangle$, and G is the Green function for the optical potential U, satisfying the equation

$$G = G_0 + G_0 U G \tag{10}$$

with G_0 denoting the free Green function for Σ.

Taking the imaginary part of eq. (10), we obtain the following identity:

$$\mathrm{Im}\, G = (1 + G^+ U^+)\, \mathrm{Im}\, G_0 (1 + UG) + G^+\, \mathrm{Im}\, UG\,. \tag{11}$$

The first term on the r.h.s. of eq. (11) represents the contribution from the escape of the Σ from the nucleus, while the second term is due to the conversion of the Σ into Λ because the imaginary part of U is due to this conversion effect. Let us define the following quantities:

$$S_{\mathrm{tot}}(E) = -\tilde{f}\, \mathrm{Im}\, Gf$$

$$= -\sum_\alpha \mathrm{Im} \int \mathrm{d}\boldsymbol{r}\, \mathrm{d}\boldsymbol{r}'\, f_\alpha^*(\boldsymbol{r}') G(E - \varepsilon_\alpha; \boldsymbol{r}', \boldsymbol{r}) f_\alpha(\boldsymbol{r})\,, \tag{12}$$

➔ $$S_{\mathrm{esc}}(E) = -\tilde{f}(1 + G^+ U^+)\, \mathrm{Im}\, G_0 (1 + UG) f\,, \tag{13}$$

➔ $$S_{\mathrm{con}}(E) = -\tilde{f} G^+\, \mathrm{Im}\, UGf\,. \tag{14}$$

target-nucleus dependence { merit / demerit } to see peaks

light nucleus ⟷ **heavy nucleus**

light nucleus	heavy nucleus
less (shallow) η' bound states	many (deeper) η' bound states
less hole-states	many hole-states
✓ simpler structure	✓ complex structure

observed spectrum ⊗

η' bound states : $(V_0, W_0) = -(100, 10)$ MeV case

^{11}C	^{15}O	^{39}Ca
s, p	s, p, d	s, p, d, f, g

one neutron-hole state (excited states of daughter nucleus)

hole	ΔS_p	Γ	hole	ΔS_p	Γ	hole	ΔS_p	Γ
$0p_{3/2}$	–	–	$0p_{1/2}$	–	–	$0d_{3/2}$	–	–
$0s_{1/2}$	18	12	$0p_{3/2}$	6.3	0	$1s_{1/2}$	3.2	7.7
			$0s_{1/2}$	29	19	$0d_{5/2}$	8	3.7
						$0p_{1/2}$	25	21.6
						$0p_{3/2}$	25	21.6
						$0s_{1/2}$	48	30.5

^{12}C(p,d)^{11}C η': strong attraction $(V_0, W_0) = -(100,10)$ MeV

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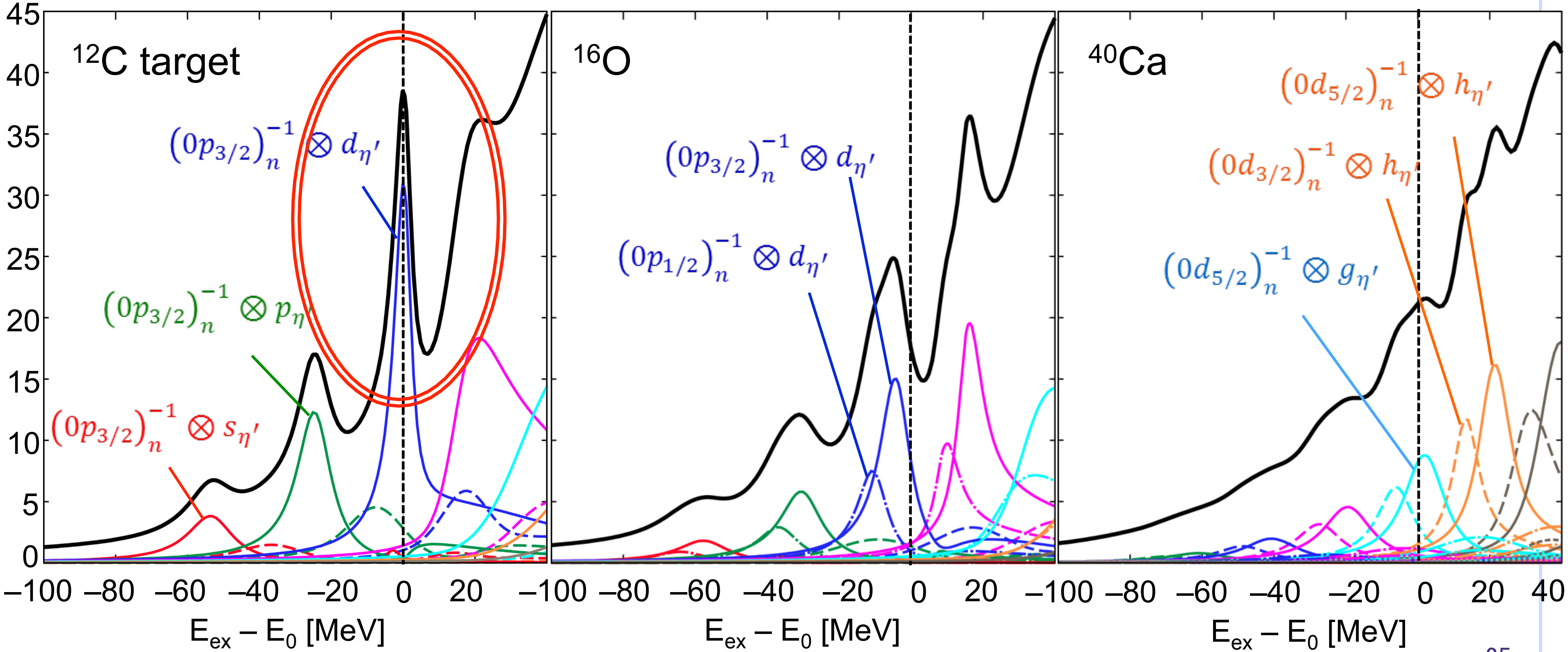

$^{12}C(p,d)^{11}C\,\eta'$: shallower case $(V_0, W_0) = -(50,5)$ MeV

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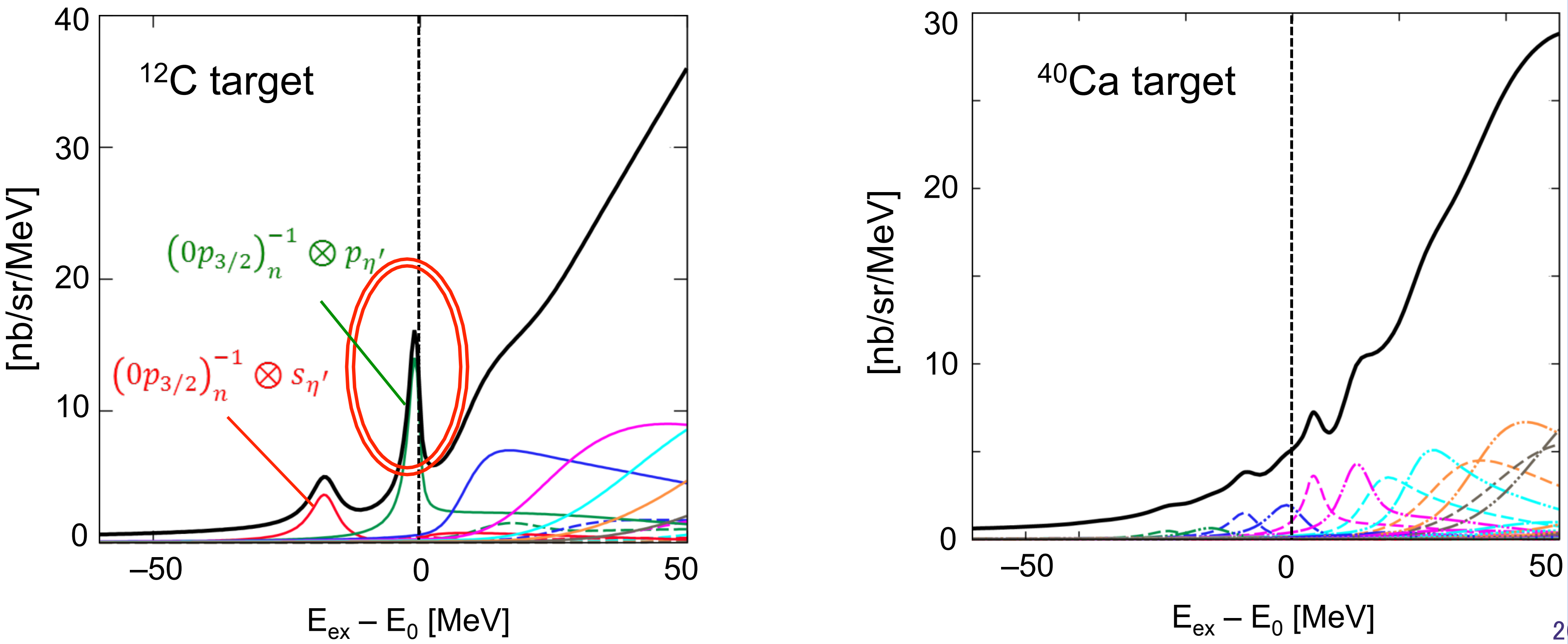
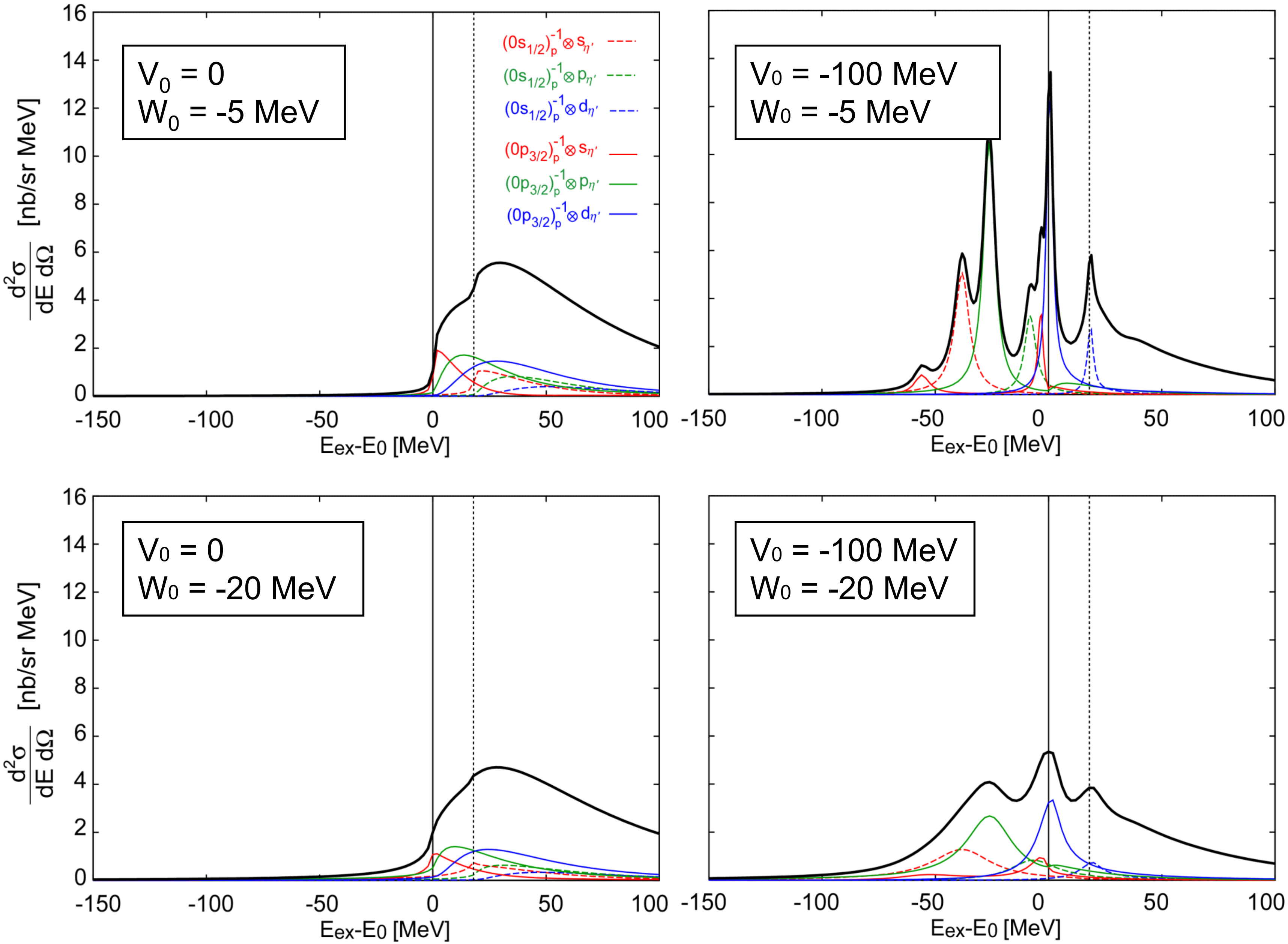
Shallower case : $(V_0, W_0) = -(50,5)$ MeV



Numerical Results : $^{12}C(\gamma,p)^{11}B_{\eta'}$

H.Nagahiro, S.Hirenzaki,
Phys.Rev.Lett.94 (2005)232503

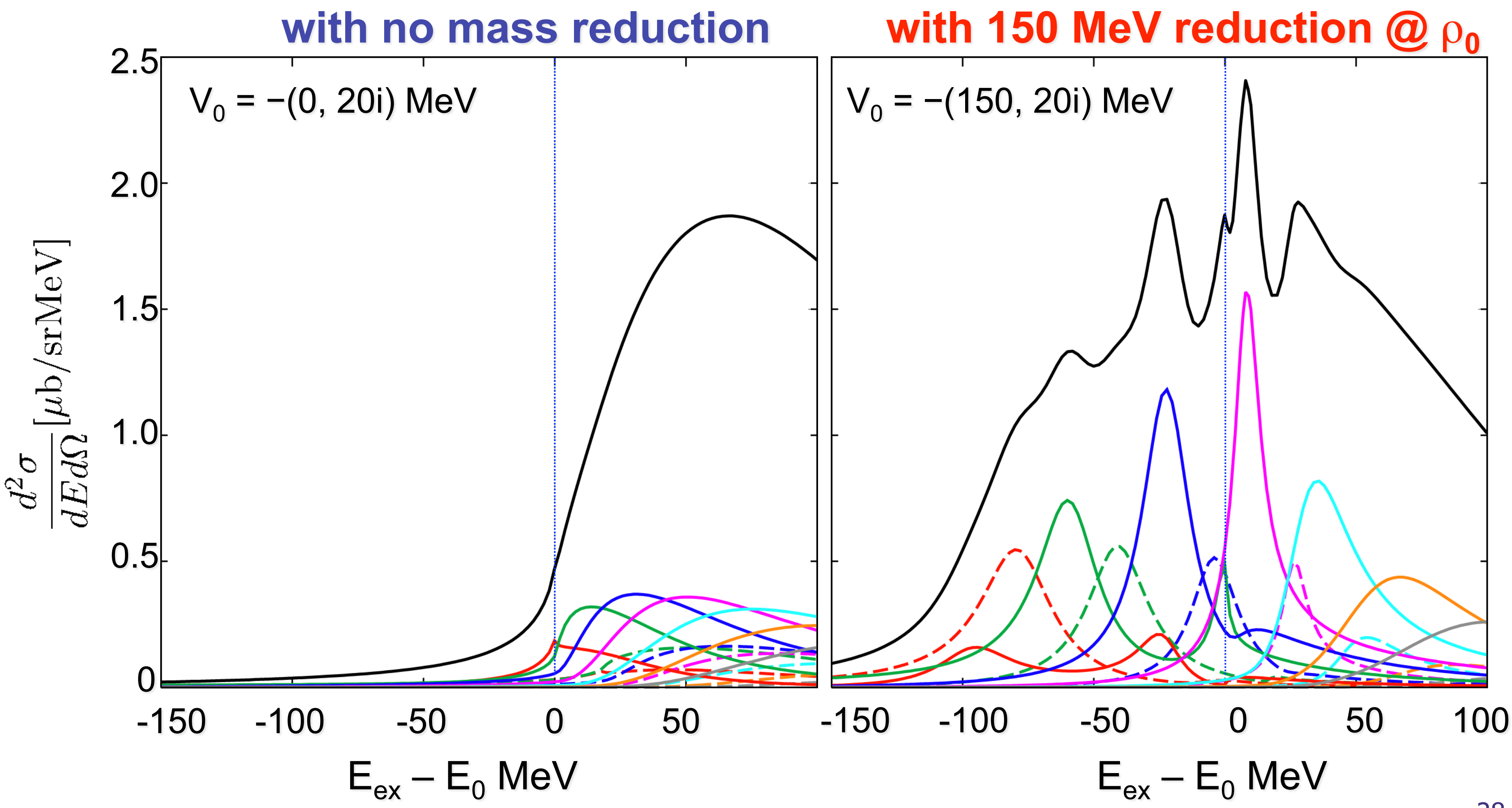


η'-mesic nuclei formation spectra : ^{12}C target : (π^+,p)reaction@JPARC

- p_π = 1.8 GeV/c
- proton angle = 0 deg.

$\left(\frac{d\sigma}{d\Omega}\right)^{Lab.} = 100\mu\text{b/sr}$ case

By H. Nagahiro
PTP Suppl. 186(2010)316.



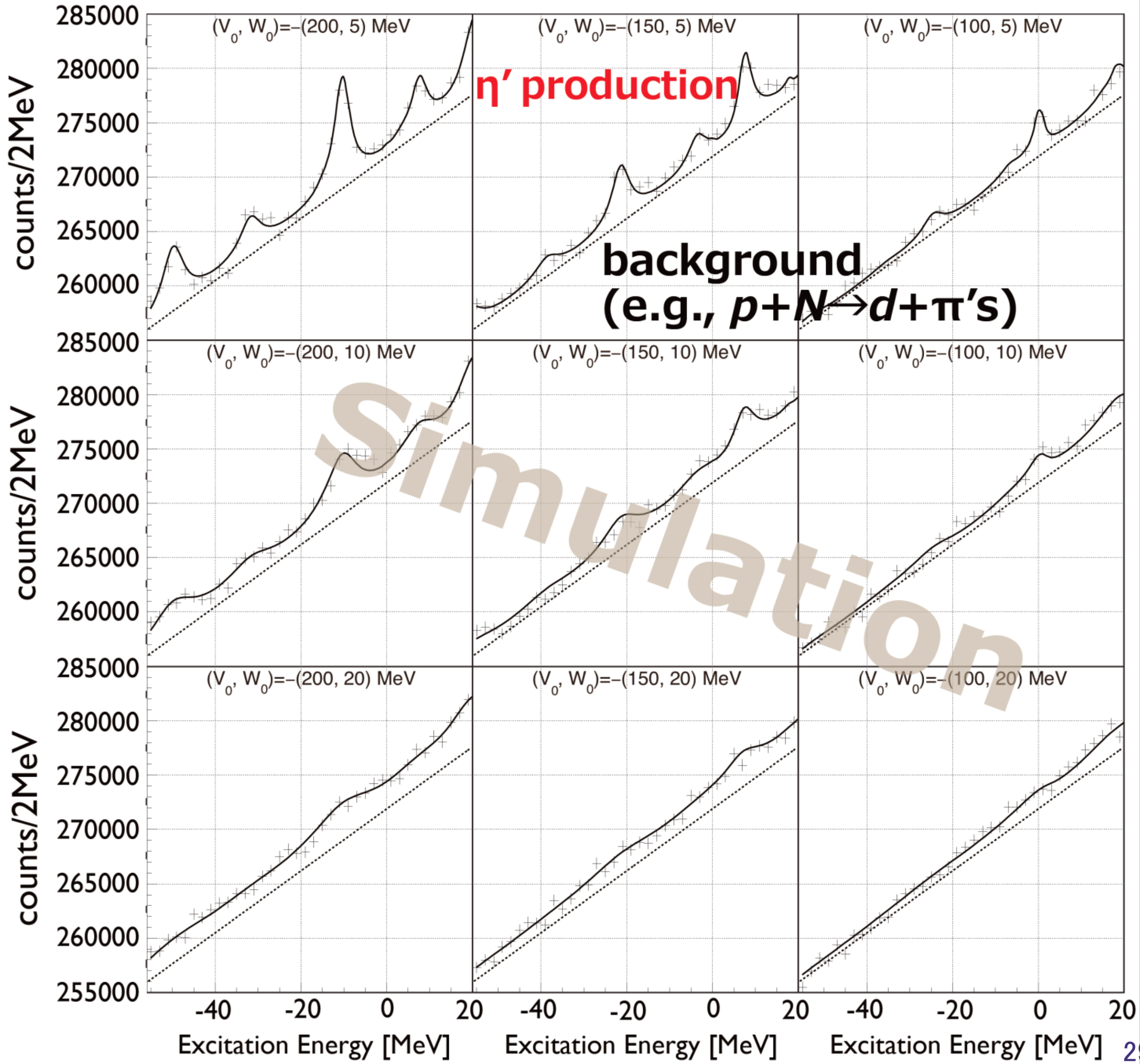
Experimental plan at GSI

- 1st Step : Inclusive measurement of (*p,d*) reaction with FRS at GSI

Simulation of spectra

- $\eta' \times$ C formation and background processes

- 4.5 days DAQ assumed



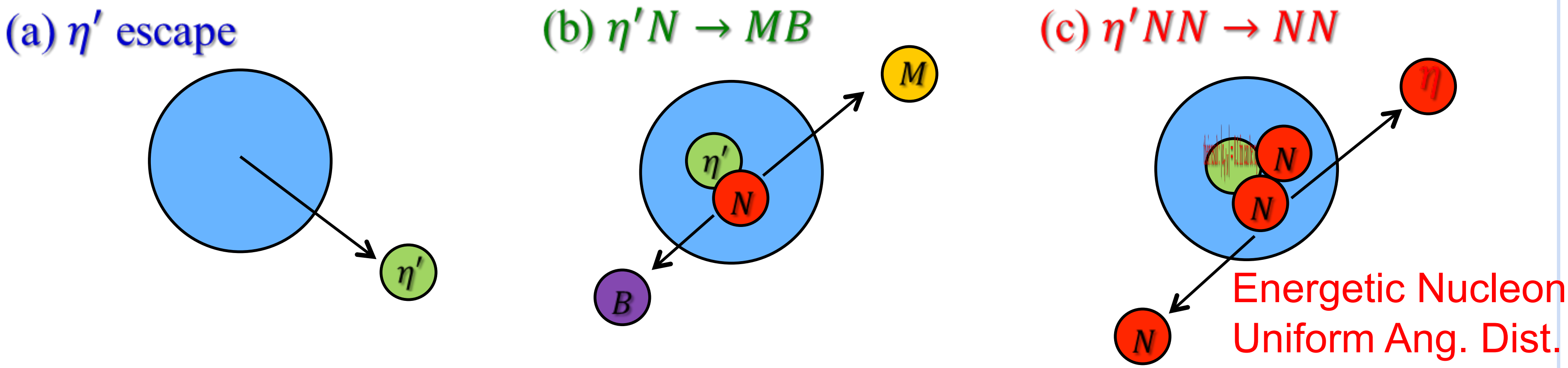
K. Itahashi, H. Fujioka, H. Geissel, R. S. Hayano, S Hirenzaki, S. Itoh, D. Jido, V. Metag, H. Nagahiro, M. Nanova, T. Nishi, K. Okochi, H. Outa, K. Suzuki, Y. K. Tanaka, H. Weick,

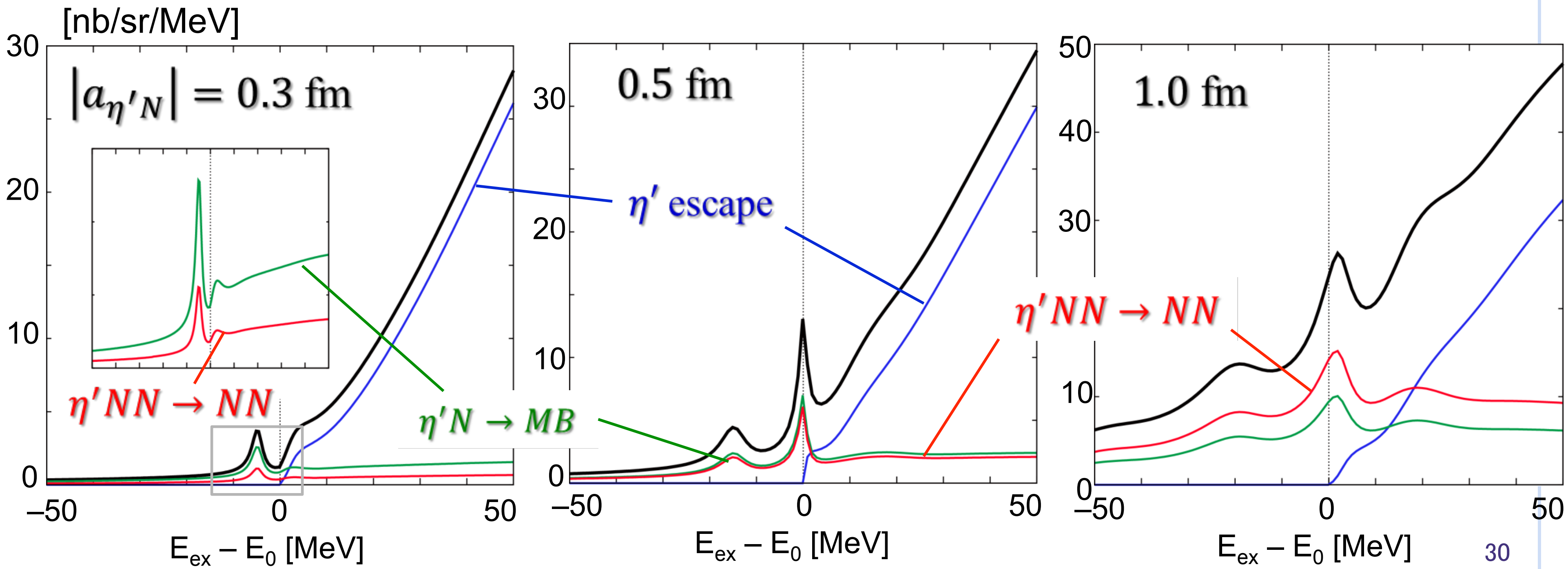
Prog. Theor. Phys. 128 (2012) 601-613.

Decomposition into different final states (based on chiral unitary model)

Nagahiro et al., PRC 87, 045201 (2013)

<u>three final states</u>

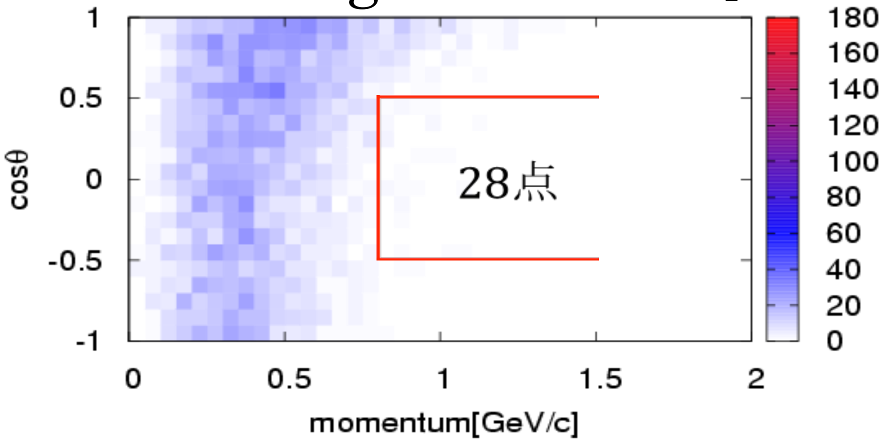




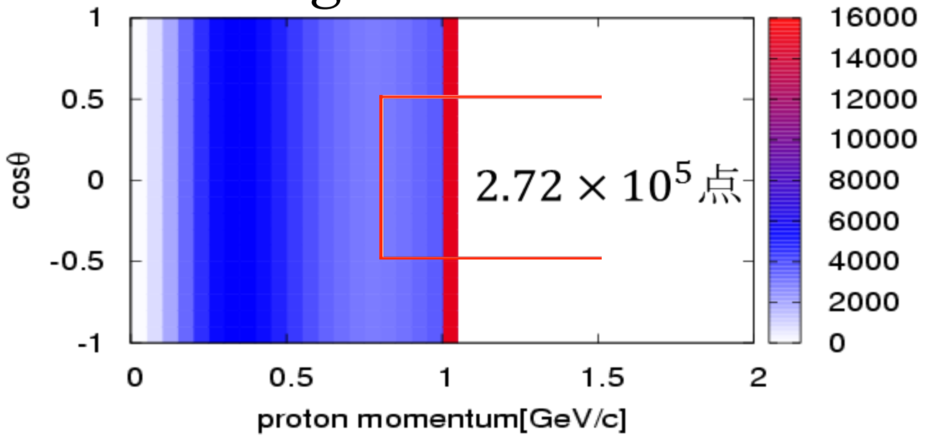
Proton emission from 2N abs.

JAM simulation program
(Y. Nara et al, PRC 61, 024901 (00))

Background (3712points)



Signal (1.0×10^6点)



	Inclusive(*p*,*d*) $\frac{d\sigma}{d\Omega_d}$ ※1		proton cut $\frac{d\sigma}{d\Omega_d}$ ※2
Background	990 [μb/sr]	→ $\times\frac{28}{3712}$ →	7.5 [μb/sr]
Signal	1.1 [μb/sr]	→ $\times\frac{2.72\times10^5}{1.0\times10^6}$ →	0.23 [μb/sr]
S/N比	1.1×10^{-3}	⇨	4.0×10^{-2}

(Results by Y. Higashi)

S/N Improvement (×36)

η'(958)-meson-nucleus bound system

$U_A(1)$ anomaly effect at finite density
in the viewpoint of mesic-nuclei

large mass reduction   **without** large absorption

$$\mathrm{Re}V \gg \mathrm{Im}V$$

special feature of η' ??

- ✓ attraction from 'elastic' interaction
- ✓ smaller inelastic channel

possibilities to observe bound state peaks

➔ Experiment

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➔ Experiment

Recent Activities on Pionic Atoms

= GSI $\longrightarrow$ RIBF/RIKEN (Next talk)

N. Ikeno , J. Yamagata-Sekihara, H. Nagahiro and S. Hirenzaki, PTEP(2013) 063D01
N. Ikeno, H. Nagahiro and S. Hirenzaki, EPJA47 (2011) 161
N. Ikeno, R. Kimura, J. Yamagata-Sekihara, H. Nagahiro, D. Jido, K. Itahashi, L. S. Geng and S. Hirenzaki, PTP126 (2011) 483

Introduction

Deeply bound pionic atom

… Useful system to study pion properties at finite density and partial restoration of chiral symmetry

Current status

- (d,^{3}He) reaction in $^{116, 120, 124}$Sn:
  Observation of pionic 1s states
- Pion-Nucleus optical potential

$$2\mu V^s_{\rm opt} = -4\pi[\varepsilon_1\{b_0\rho(r) + b_1\delta\rho(r)\} + \varepsilon_2 B_0\rho^2(r)]$$

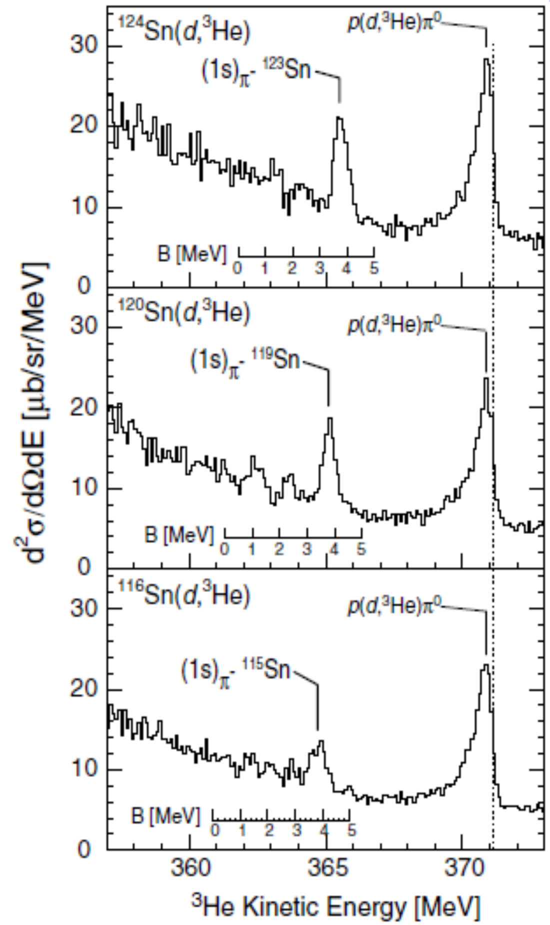
- GOR relation + Tomozawa-Weinberg

$$\frac{\langle\bar{q}q\rangle_\rho}{\langle\bar{q}q\rangle_0} \simeq \frac{f_\pi^{*2}}{f_\pi^{2}} \simeq \frac{b_1^{\rm free}}{b_1^*(\rho)} = 0.78 \pm 0.05 \ @\ \rho \simeq 0.6\rho_0$$

$$\sim 0.67 \ @\ \rho = \rho_0$$

Theoretical basis
Kolomeitsev, Kaiser, Weise, PRL90(2003)092501
Jido, Hatsuda, Kunihiro, PLB 670(2008)109

K. Suzuki *et al.*, PRL92(2004)072302



What's next ?

Interests

$\bar{q}q$ condensate: beyond the linear density approx. (ex.) Goda, Jido)

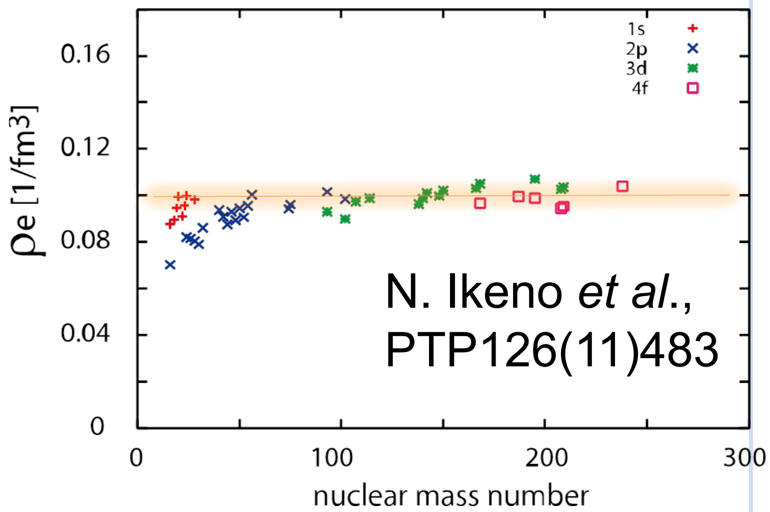
: in asymmetric (n or p rich) Nuclear Matter

➔ Aspects of symmetry in "various circumstances"

Difficulties for precise studies

= Limited sensitivity of known atomic pion to $\rho \simeq 0.6\rho_0$ (Seki-Masutani)

= Uncertainties of Neutron density distribution



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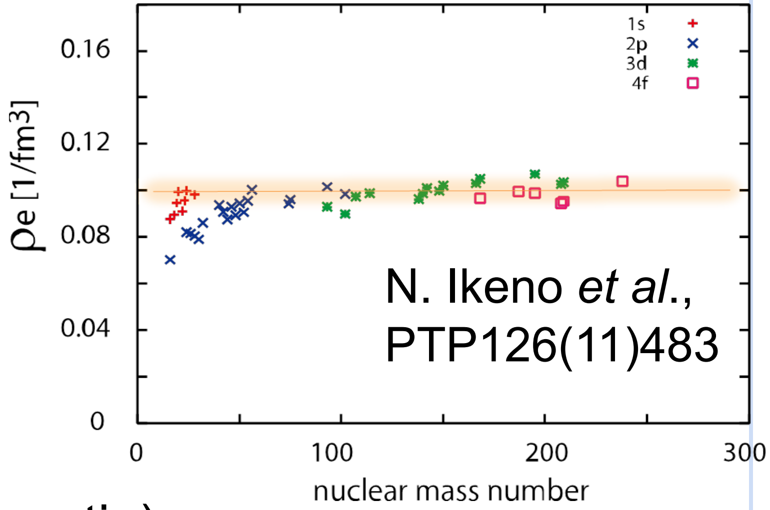
How we can..

= Several atomic states data (ex. 1s, 2s, 2p) in each nucleus
(=> possible reduction of systematic errors)



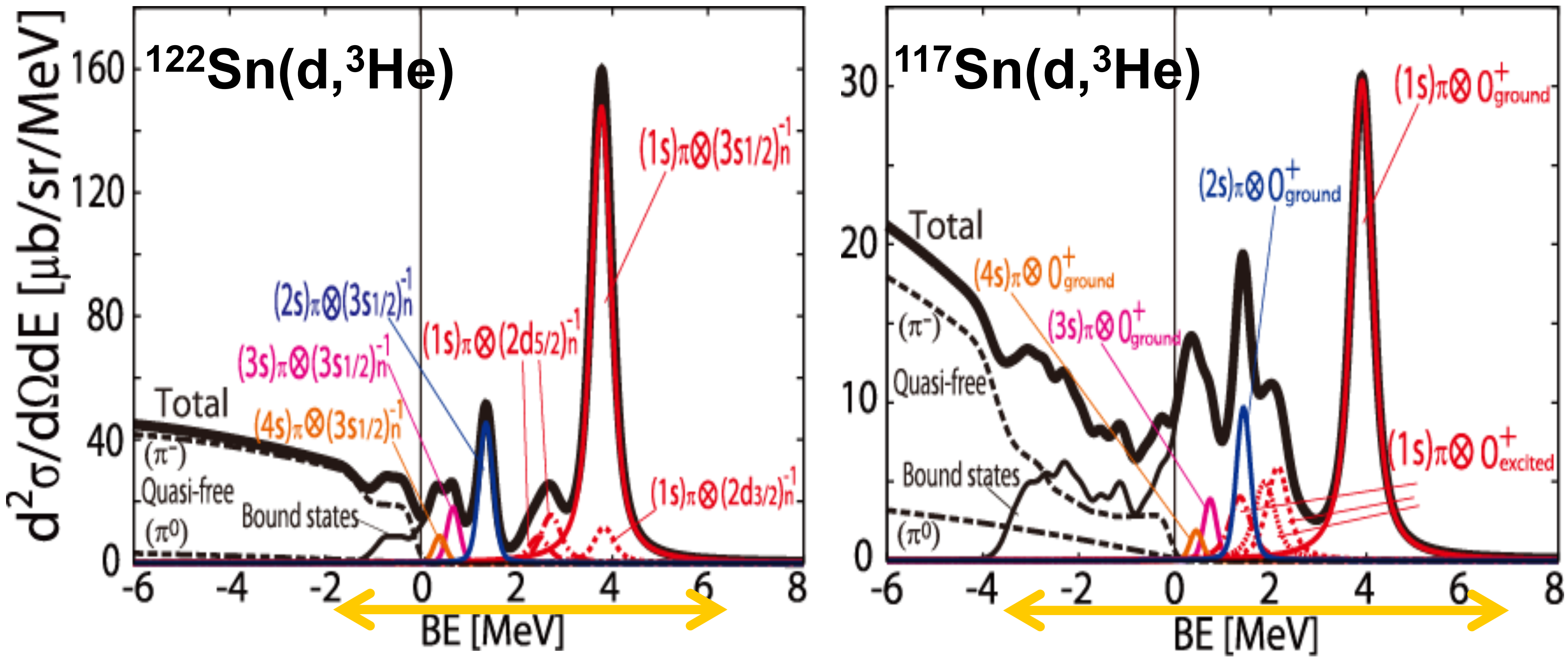
= Systematic 'precise' observation for various nucleus ***including unstable nuclei***
(=> observation of various effective ρ and p/n ratio)

= Odd-n nuclear target to avoid residual interaction effects

Some Numerical Results (by N. Ikeno)

0 degree

Even target: ^{122}Sn (0^+) | **Odd target: ^{117}Sn $(1/2^+)$**



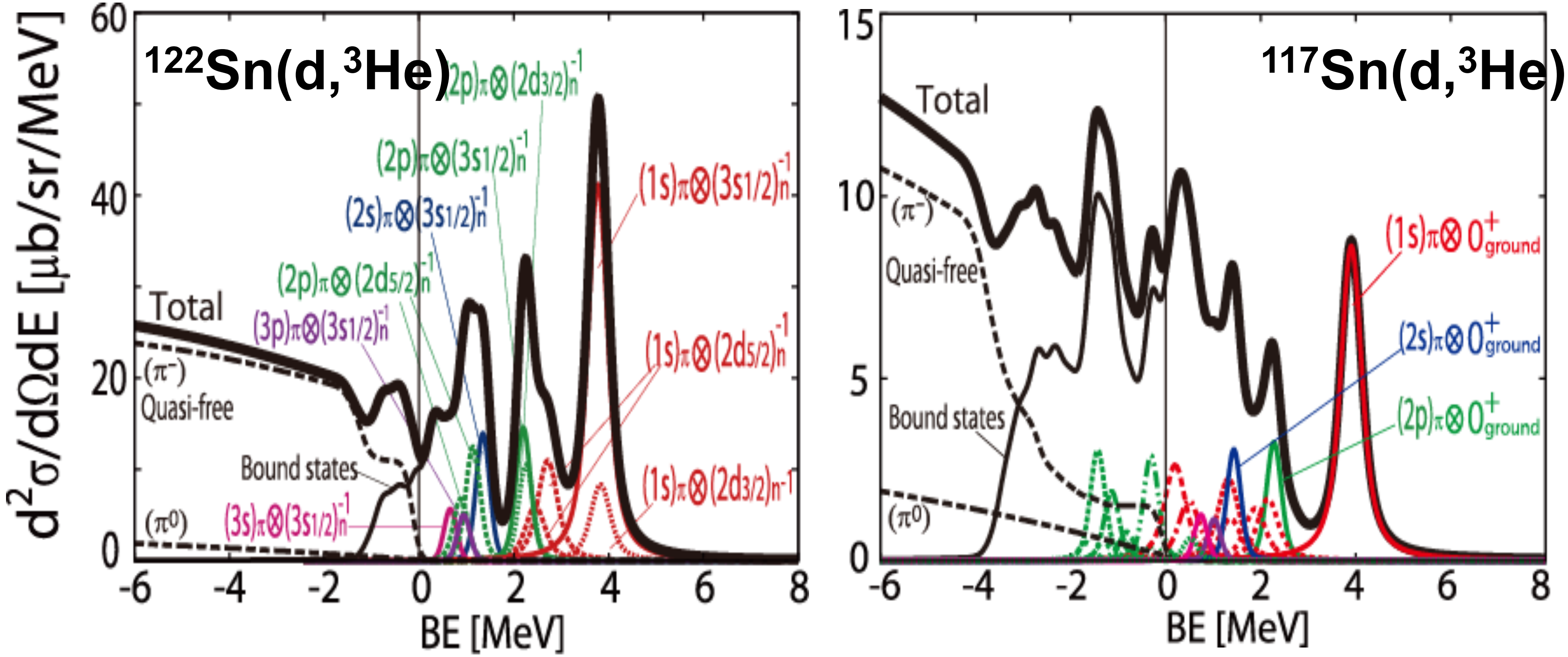
- Pionic 1s state formation with neutron s-hole state
- Spectrum of $^{117}Sn(d,^3He)$ is spread over wider energy range.
- Cross section of $^{117}Sn(d,^3He)$ is smaller.
- Pionic 1s and 2s states can be observed

Some Numerical Results (by N. Ikeno)

2 degree

Even target: ^{122}Sn (0^+)

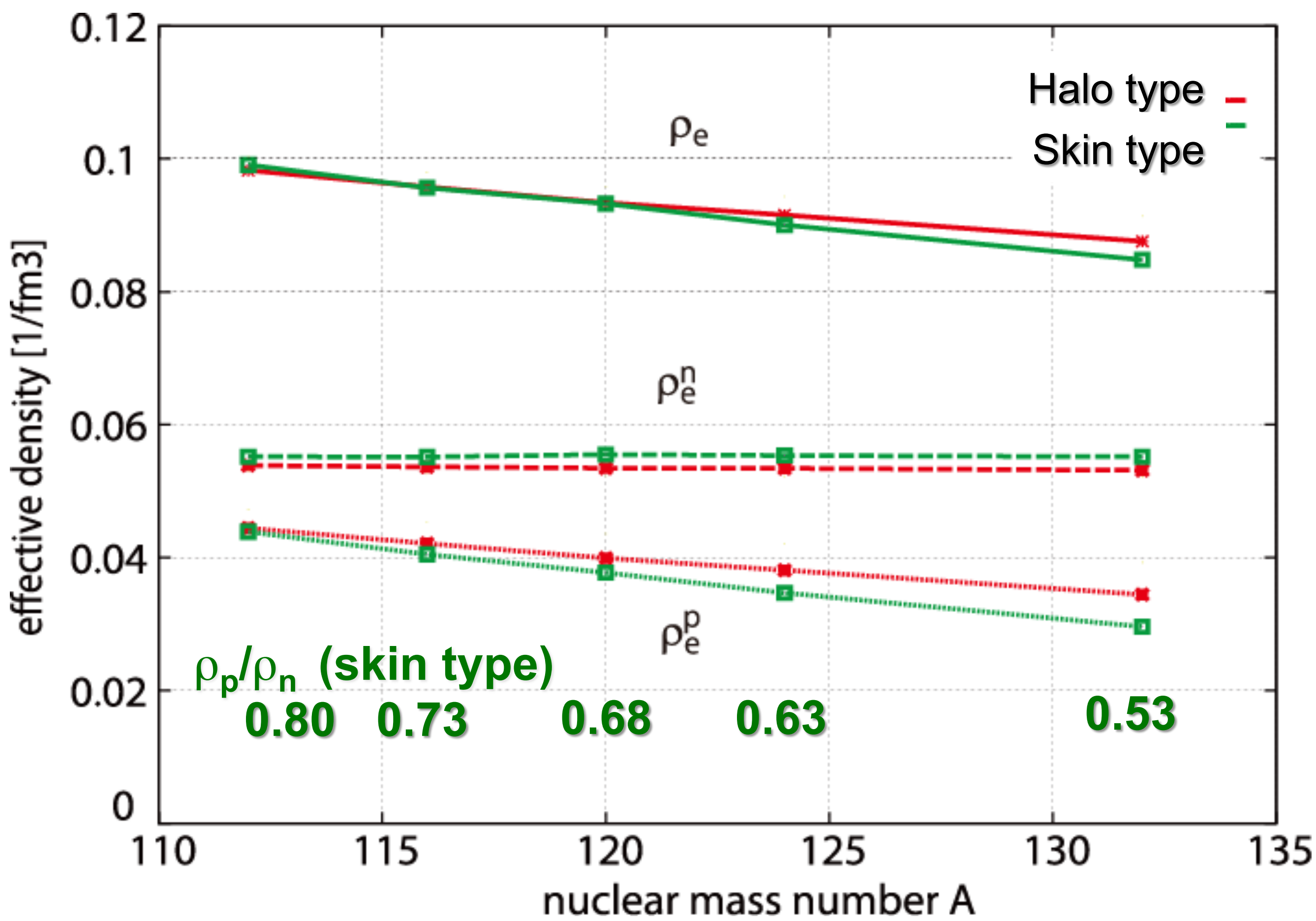
Odd target: ^{117}Sn ($1/2^+$)



- Pionic *2p* state contributions become relatively larger.

Expected effective density seen by pion

- Pionic atom 1s state in 112-132Sn



Evaluation by N. Ikeno

Relatively large variation of ρ_p/ρ_n ratio

Summary

- Meson property at finite density,
  Mesic atoms and Mesic nuclei

- $\eta'(958)$: Anomaly effect at finite density

- Pionic atom: for getting deeper insights

= information at various ρ and ρ_p/ρ_n ratio

= Pionic atom in various nucleus including unstable nuclei

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- Meson property at finite density,

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  ➔Exotic many body with exotic structure ?