YITP workshop on

Hadron in Nucleus

31 Oct. – 2 Nov. 2013, Maskawa Hall, Kyoto University

$\eta'(958)$-nucleus bound states and their formations by missing mass spectroscopies

Hideko NAGAHIRO (Nara Women's University)

PRiME

H. Nagahiro, D.Jido, H. Fujioka, K.Itahashi, S. Hirenzaki, PRC87(13)045201 [(p,d) theo.]

Itahashi, Fujioka, Geissel, Hayano, Hirenzaki, Itoh, Jido, Metag, Nagahiro, Nanova, Nishi, Okochi, Outa, Suzuki, Tanaka, Weick, PTP128(12)601, [(p,d) exp. @GSI]

H. Nagahiro, S. Hirenzaki, E. Oset, A. Ramos, PLB709(12)87, [chiral unitary, (π,N)]

D. Jido, H. Nagahiro, S. Hirenzaki, PRC85(12)032201(R) [χsym vs. $m_{\eta'}$, (π,N)]

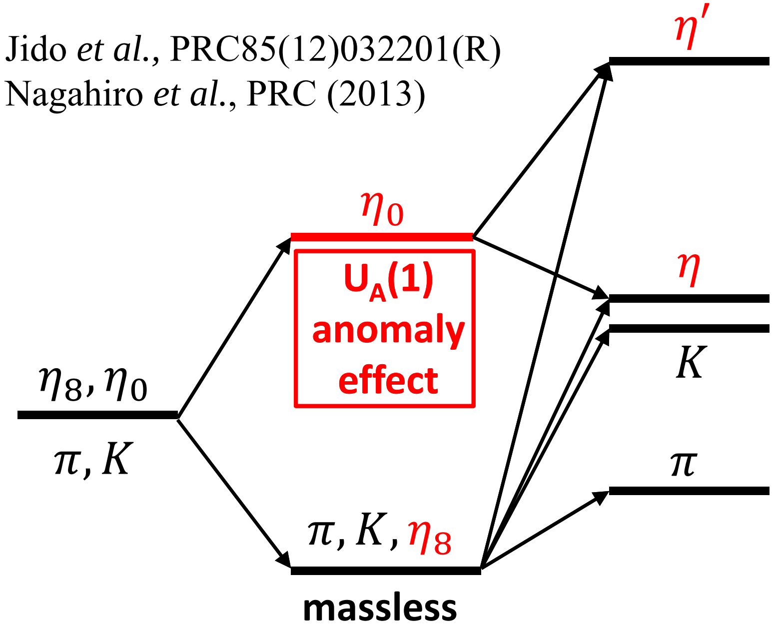
H.Nagahiro, M.Takizawa, S. Hirenzaki, PRC74(06)045203 [NJL, (γ,p)]

H. Nagahiro, S. Hirenzaki, PRL94(05)232503 [(γ,p)]

Heavy mass of the $\eta'(958)$ meson

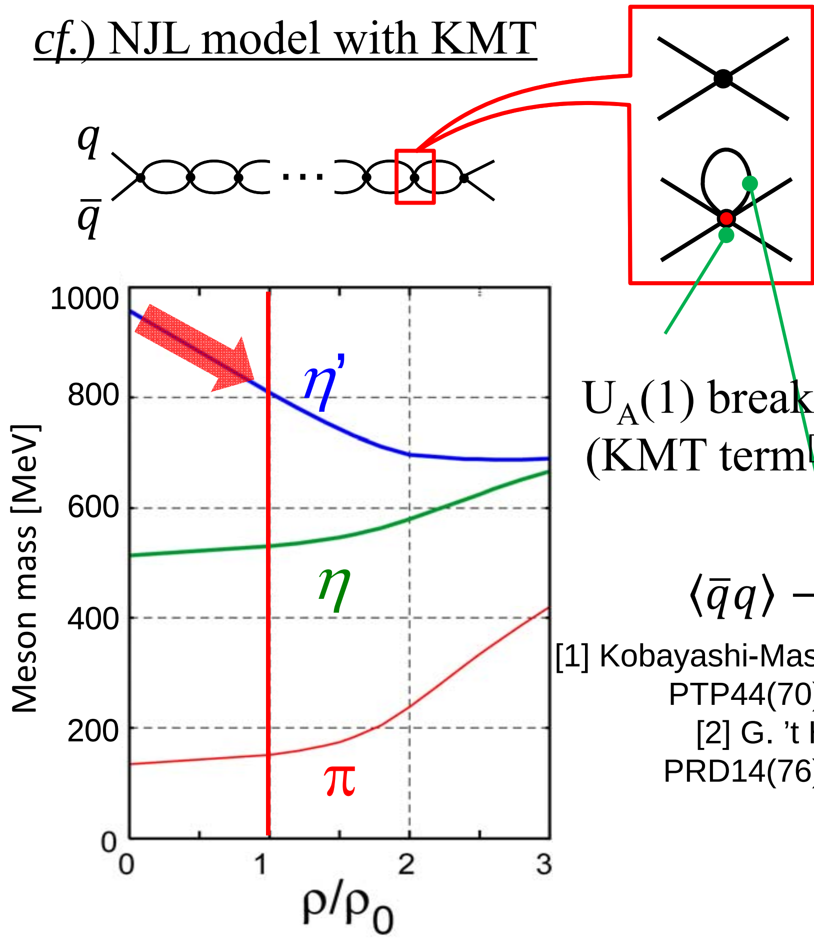
schematic view of the mass of π, K, η & η'

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



$U_A(1)$ breaking (KMT term[1,2])

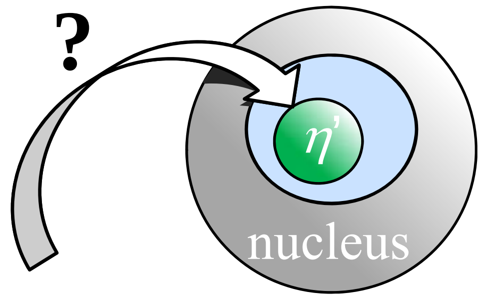
$\langle \bar{q}q \rangle \to 0$

[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

η' property in medium



→ Phenomenologically poorly understood

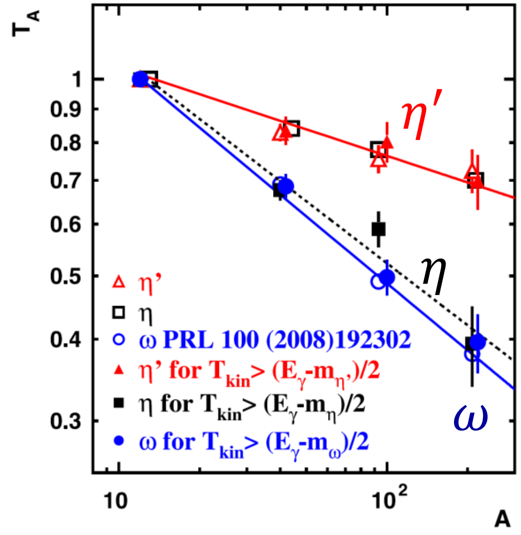
✓ **small scattering length ?**

$|\mathrm{Re}\, a_{\eta' N}| < 0.8$ fm, [$pp \to pp\eta'$@ COSY, Moskal *et al.*, PLB474(00)416]

$|a_{\eta' N}| \sim 0.1$fm, [… , Moskal *et al.*, PLB482(00)356]

[estimated from FSI on $pp \to pp\eta'$ observed at COSY]

M.Nanova *et al.*, PLB710(12)600



✓ **smaller absorption width in medium ?**

$\Gamma_{\eta'}(\rho_0; \langle|\vec{p}_{\eta'}|\rangle \sim 1\mathrm{GeV}/c) \sim 15 - 25\ \mathrm{MeV}@\rho_0,$

CBELSA/TAPS [M.Nanova *et al.*, PLB710(12)600]

[estimated transparency ratio $\gamma A \to \eta' X$]

✓ **mass reduction in finite T/ρ?**

$\Delta m \sim -150$ MeV @ ρ_0 [NJL model w/ KMT interaction]

$\Delta m \sim -200$ MeV ? *in finite T* [in Au+Au collisions at RHIC]

[experimentally observed enhanced production of soft pions
Interpreted as mass reduction of η' in the hot medium [Csorgo et al., PRL105(10)182301]]

Our strategy for studying the η' properties

- **Possible η' bound states and their formation**
  - » with missing mass spectroscopy : (γ,p), (π,N), (p,d), …
    - › H.N., S.Hirenzaki, PRL94 (05) 232503
    - › H.N., M.Takizawa, S.Hirenzaki, PRC74 (06)045203
    - › … and references in title page !

→ $\Gamma_{\eta'}$ in-medium strongly affects its observation possibilities

Experimental information [CBELSA/TAPS [M.Nanova *et al.*, PLB710(12)600]

$\Gamma_{\eta'} \sim 15 - 25$ MeV@ρ_0 [estimated transparency ratio $\gamma A \to \eta' X$]

phenomenological approach [H.N., S. Hirenzaki, E. Oset, A, Ramos, PLB]

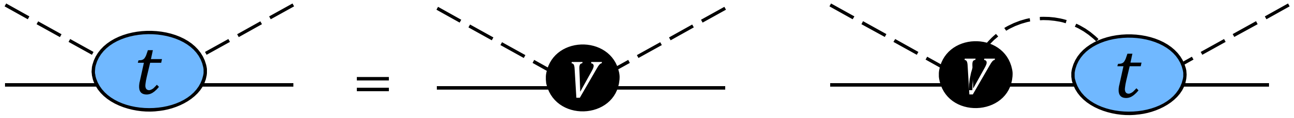
Based on : Coupled-channel calculation [Oset-Ramos, PLB704(11)334]

P-B (πN, ηN, KΛ, KΣ + η'N)+ V-B (K*Λ, K*Σ) + η_0B

Phenomenological approach for $\eta' N$ interaction

Oset-Ramos, PLB704(11)334

Unitarized scattering amplitude by coupled-channel BS eq.



Interaction kernel V

(1) Weinberg-Tomozawa interaction : pseudoscalar-baryon (PB) channel

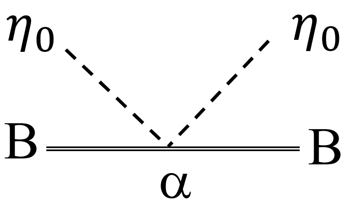
$\pi N, \eta N, K\Lambda, K\Sigma$ $+ \boldsymbol{\eta' N}$ by the η - η' mixing

their result : $|a_{\eta' N}| = 0.01$ fm $\Leftrightarrow$ $|a_{\eta' N}| \sim 0.1 - 0.8$ fm [PLB'00]

(2) Vector meson-baryon (VB) channel

their result : $|a_{\eta' N}| = 0.03$ fm

(3) **coupling of the singlet component of pseudoscalar to baryons**



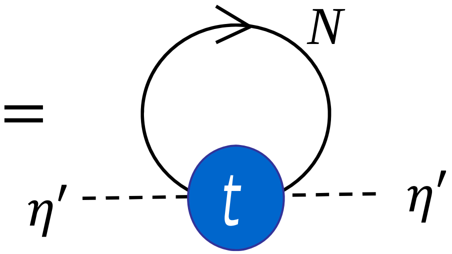
$$\mathcal{L}_{\eta_0 B} \propto \eta_0^2 \langle \partial_\mu \bar{B} \gamma^\mu B - \bar{B} \gamma^\mu \partial_\mu B \rangle$$

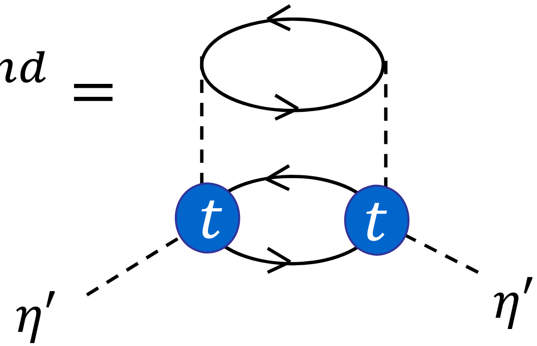
Borasoy , PRD61(00)014011
Kawarabayashi-Ohta, PTP66(81)1789

α … free parameter $\rightarrow |a_{\eta' N}| = 0.1$ fm

phenomenological estimation for $V_{\eta'}^{opt}$

Optical potential $V_{\eta'}$ [H.N., S. Hirenzaki, E. Oset, A. Ramos, PLB709(12)87]

$V_{\eta'}^{1st} =$ 

$V_{\eta'}^{2nd} =$ 

We consider only the **attractive** case & **energy-independent** potential.

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

in unit of MeV

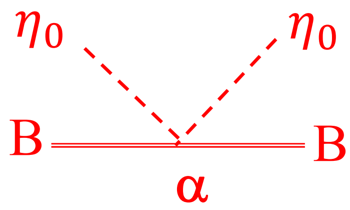
α	$\lvert a_{\eta' N}\rvert$ fm	$V_{\eta'}^{1st}(\rho_0)$	$V_{\eta'}^{2nd}(\rho_0)$	$V_{\eta'}^{total}(\rho_0)$
-0.193	0.1	$-8.6-1.7i$	$-0.1-0.1i$	$\mathbf{-8.7-1.8}\boldsymbol{i}$
-0.834	0.3	$-26.3-2.1i$	$-0.6-0.9i$	$\mathbf{-26.8-3.0}\boldsymbol{i}$
-1.79	0.5	$-43.8-3.0i$	$-1.3-2.5i$	$\mathbf{-44.1-5.5}\boldsymbol{i}$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

Re V $\gg$ Im V

phenomenological estimation for $V_{\eta'}^{opt}$

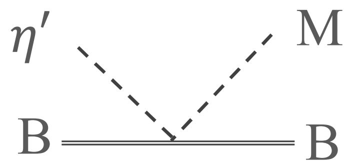
<u>The reason why Re V ≫ Im V in coupled channel calculation</u>

Kawarabayashi-Ohta, PTP66(81)1789
Borasoy , PRD61(00)014011



→ gives attraction

WT interaction for η'



→ **width [small]**

<u>This interaction …</u>

- ✓ *resembles* that of the anomaly effect discussed by D. Jido PRC85(12)
- ✓ seems to **dominate** the $\eta' N$ interaction
- ✓ contributes mostly to the ***η′* elastic channel** & barely to the **inelastic channel**

<u>ongoing work [A. Hinata (NaraWU) *et al.*]</u>

- ✓ **energy-dependence of $V_{\eta'}$** :
  we discuss over <u>a wide energy range</u> (deep bound state ↔ $a_{\eta' N}$ at threshold)
- ✓ possible ***α*** value evaluated from, ex.) $\pi N \rightarrow \eta' N$ cross section

formation by (p,d) reaction @ GSI (→ Y.K.Tanaka's talk)

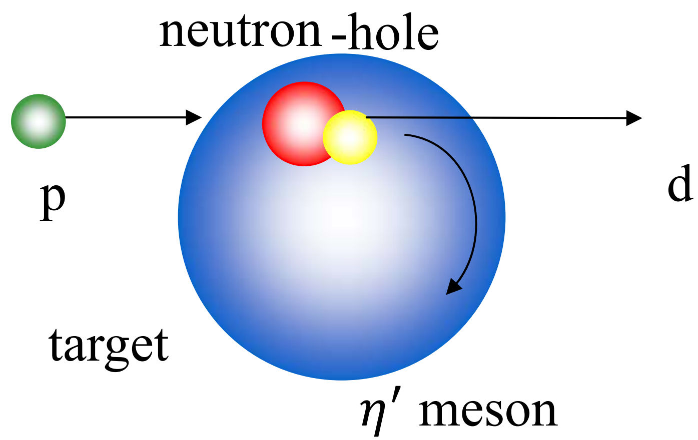
<u>missing mass spectroscopy</u>

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

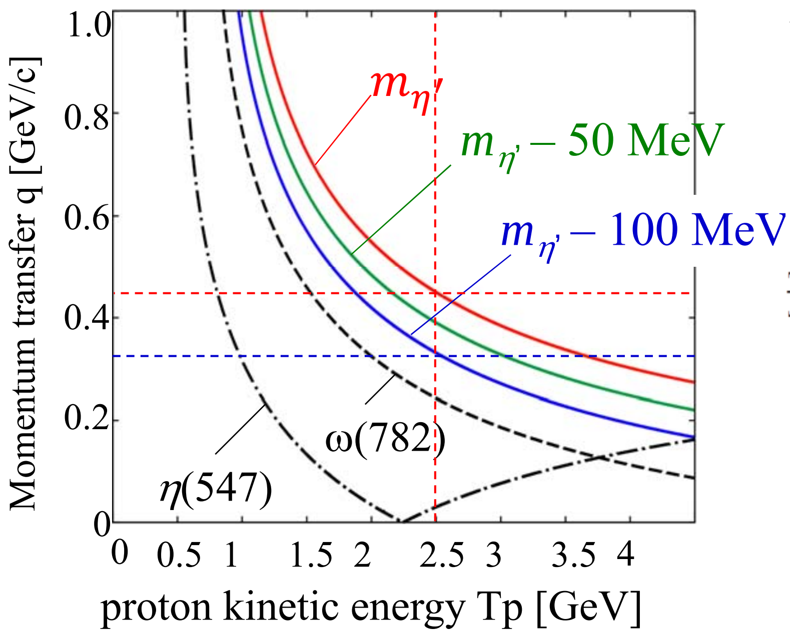
proton kinetic energy $T_p = 2.5$ GeV

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

forward reaction : $\theta_d = 0$ deg.

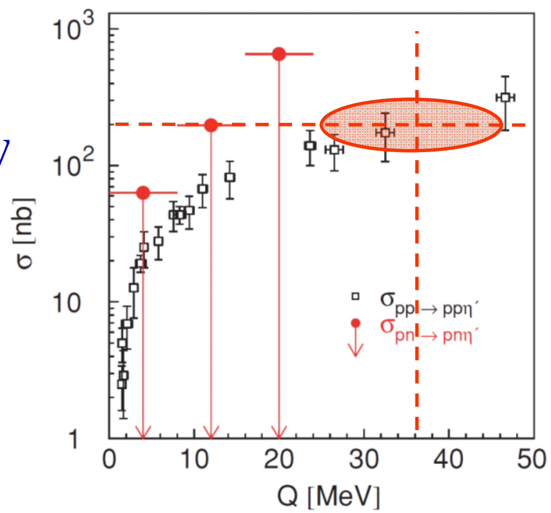


momentum transfer



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

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



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

↓

assumptions

↓

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

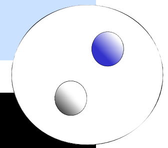
Itahashi *et al.*, PTP128(12)601
K.Nakayama in private comm.

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

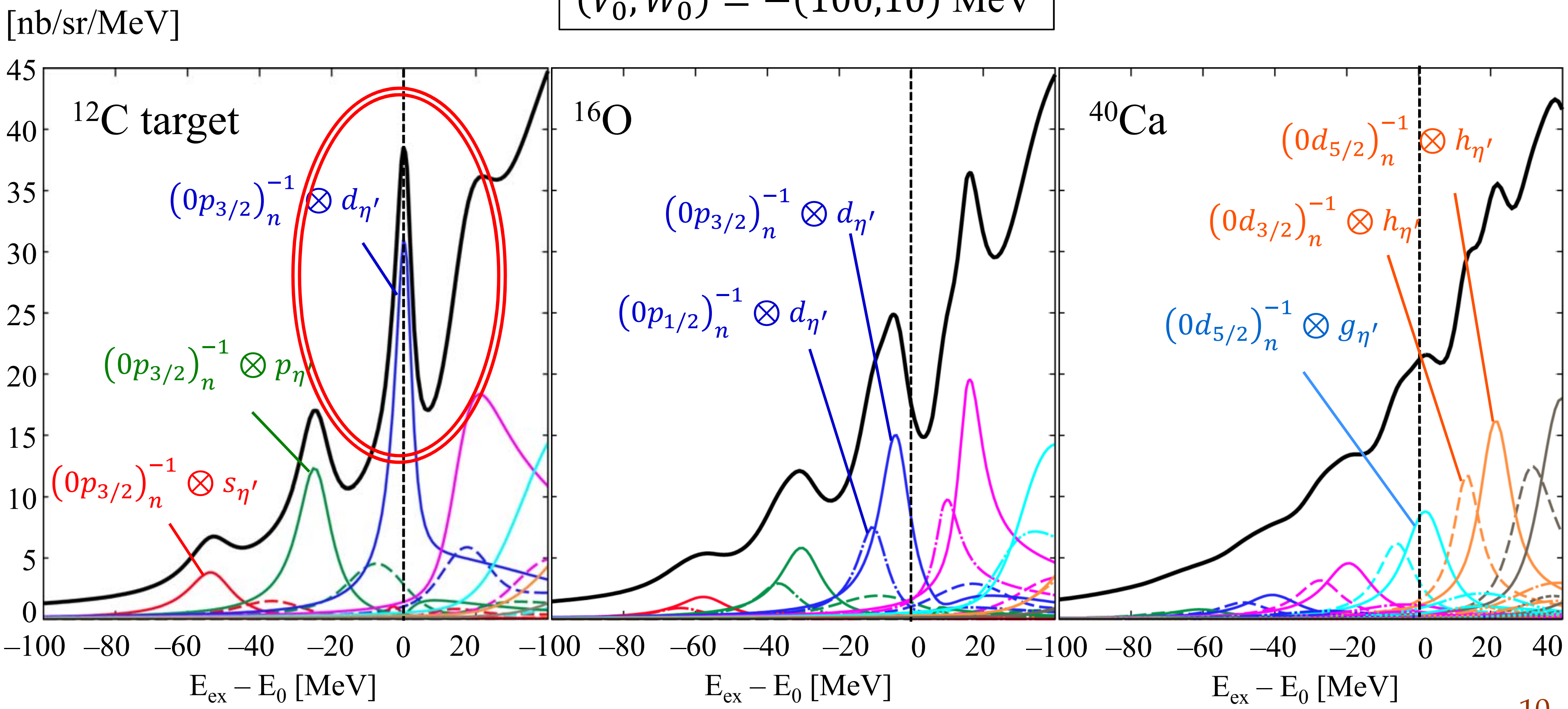
target-nucleus dependence : **strong attraction** case

light nucleus ⟷ **heavy nucleus**

less (shallow) η' bound states
less hole-states
✓ simpler structure

many (deeper) η' bound states
many hole-states
✓ complex structure

$(V_0, W_0) = -(100,10)$ MeV



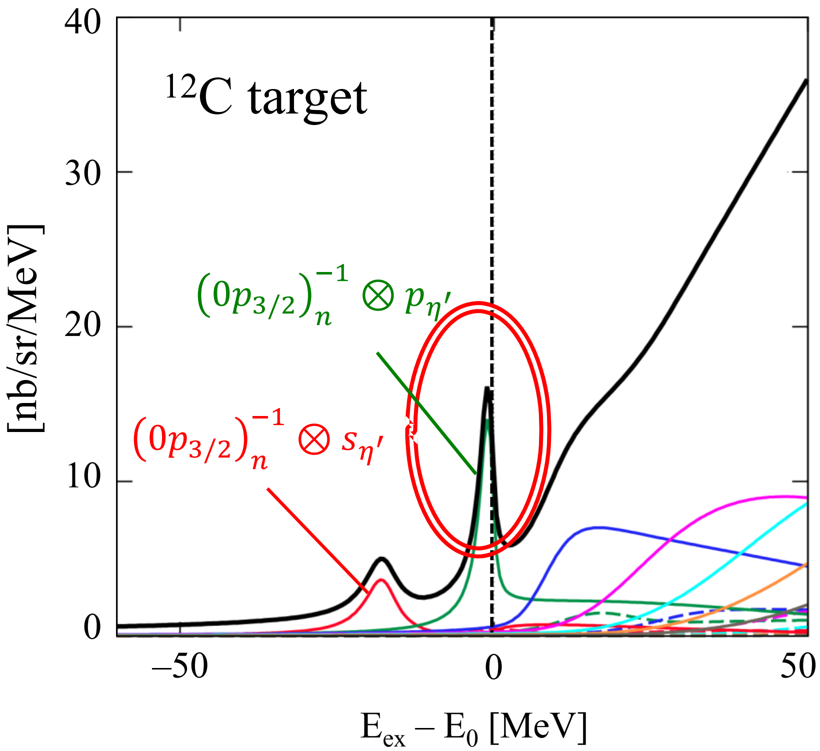
target-nucleus dependence : **shallower case**

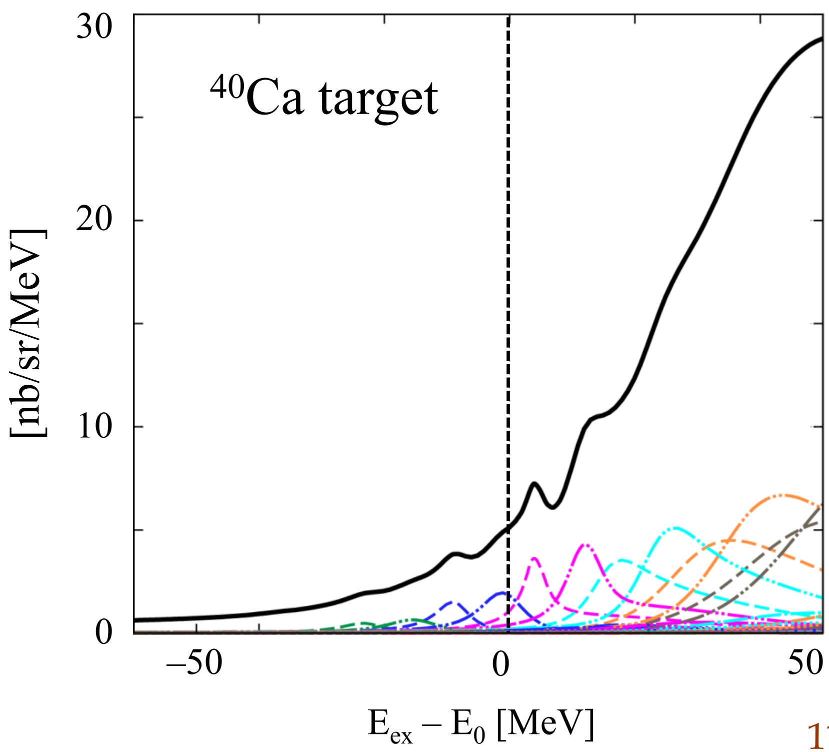
light nucleus ⟷ **heavy nucleus**

less (shallow) η' bound states
less hole-states
✓ simpler structure

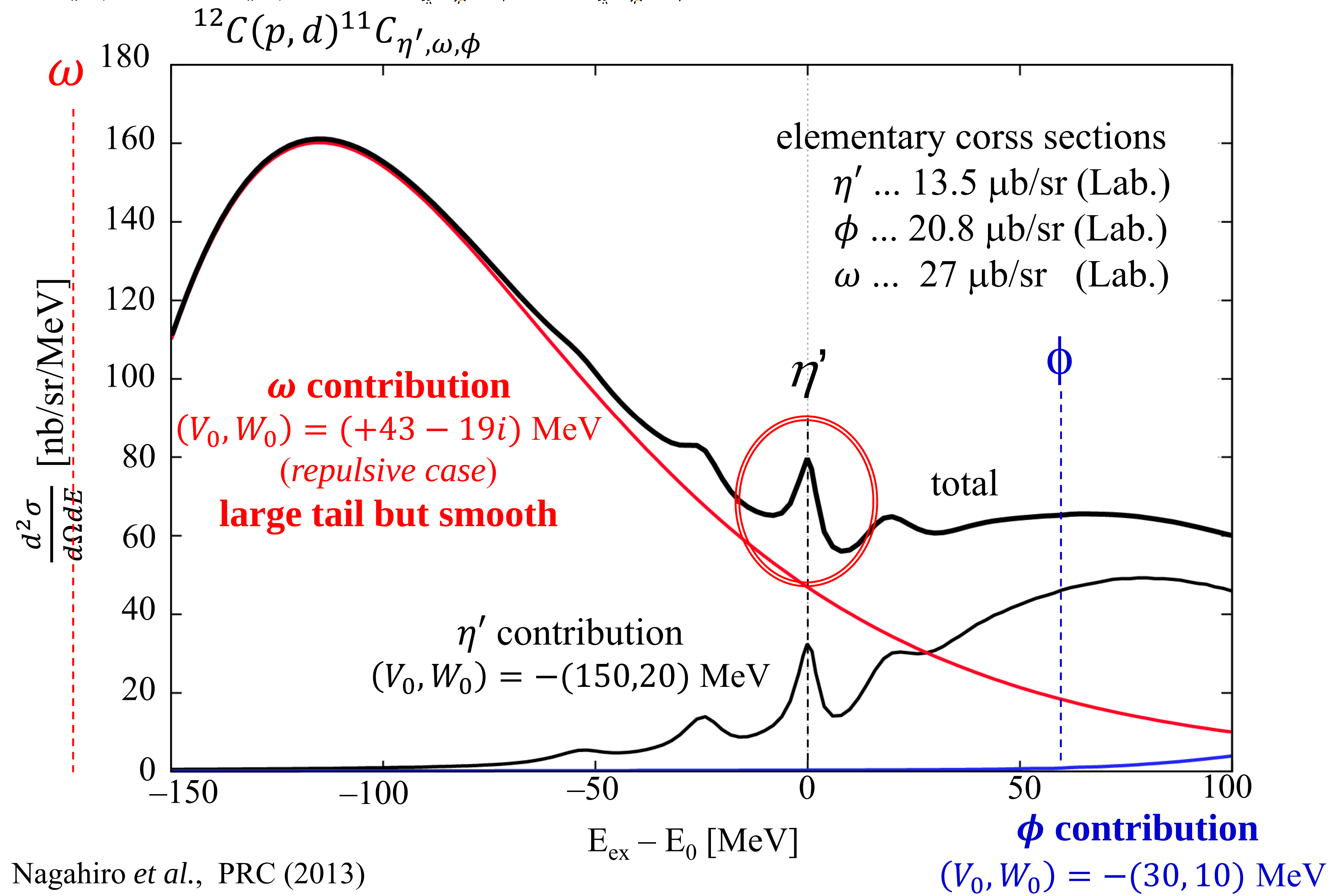
many (deeper) η' bound states
many hole-states
✓ complex structure

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





Contributions from ω and ϕ mesons

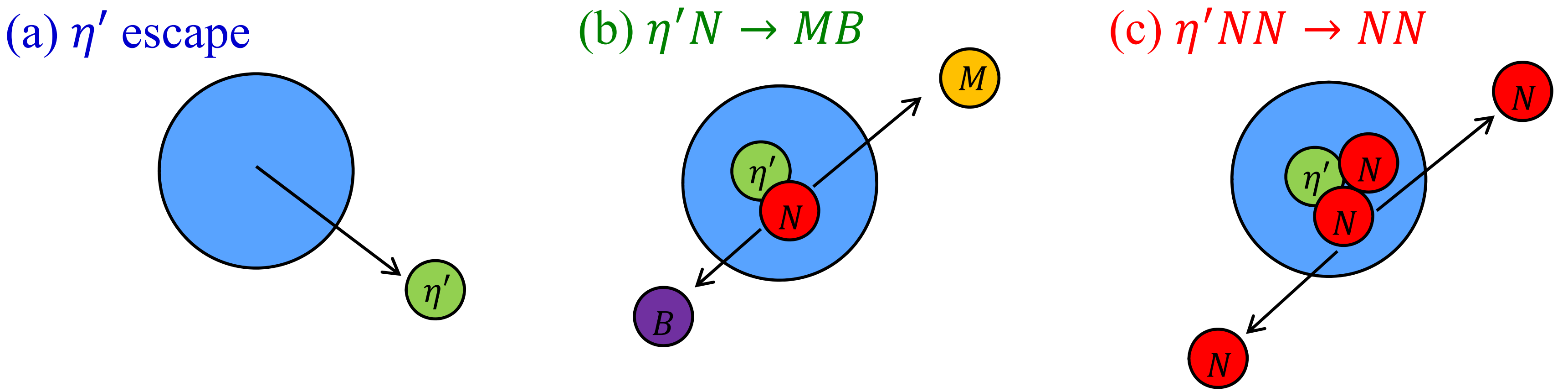


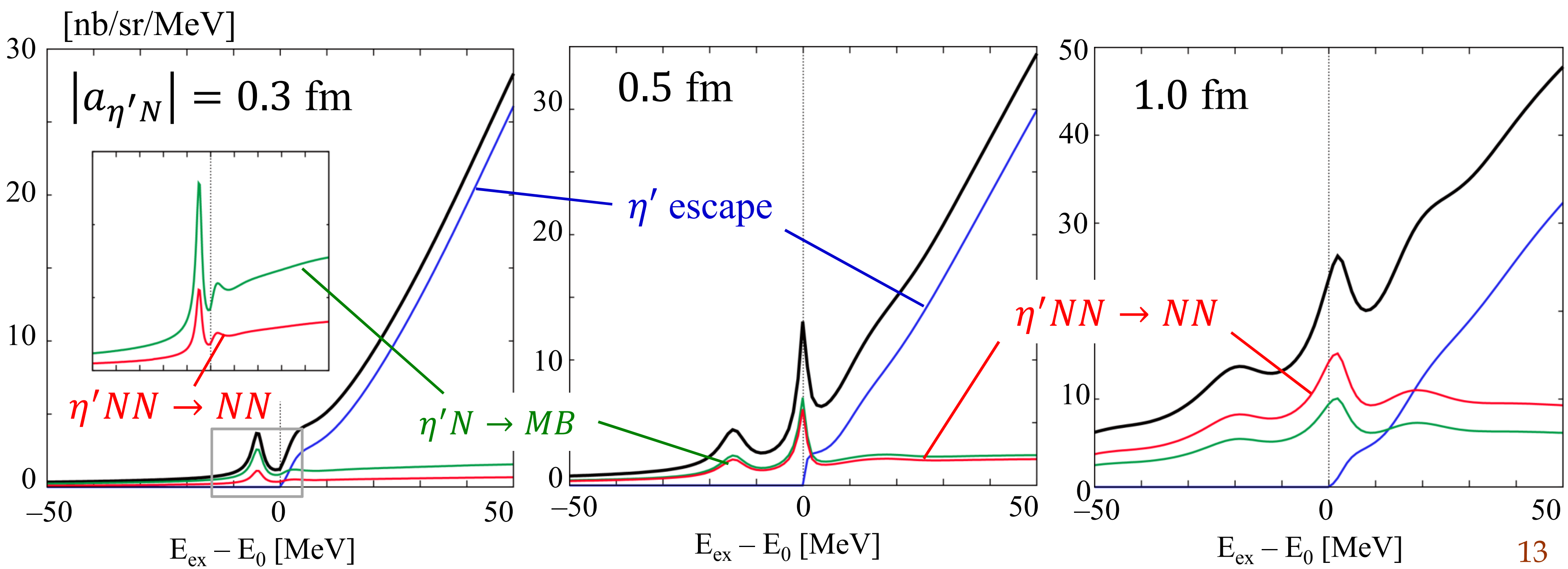
Nagahiro *et al.*, PRC (2013)

decomposition into different final states

Based on the coupled-channel cal.

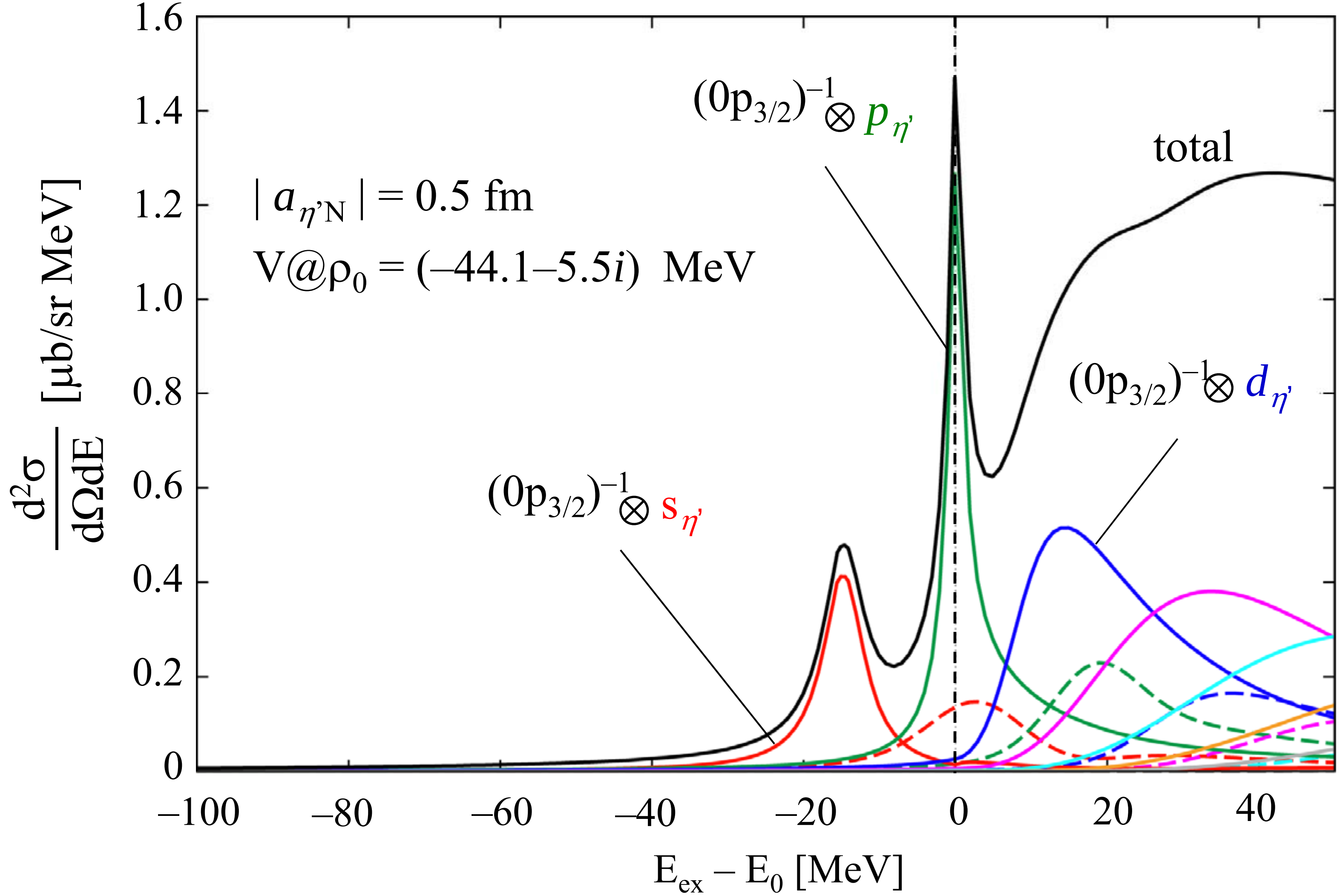
<u>three final states</u>





(π,N) and (γ,N) reactions are also possible

cf. $^{12}C(\pi^-, n)$ reaction with p_π=1.8 GeV/c



H. Nagahiro *et al.*, PLB

Briefly about *on-going* theoretical works :

We are now revisiting the $\eta' N$ scattering and η'-nucleus optical potential $V_{\eta'}$

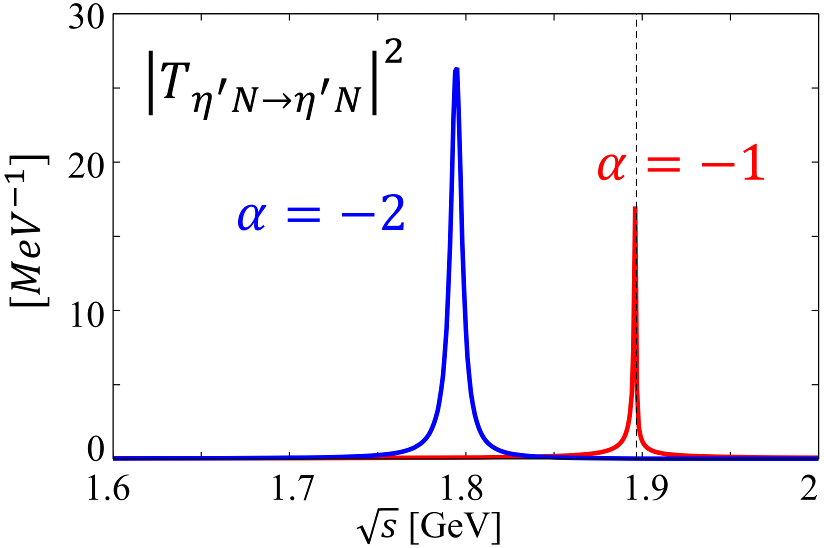
- ✓ different model for **vector-meson-baryon** channel (K.P. Khemchandani, PRD84)
- ✓ trying to extract **possible α value**

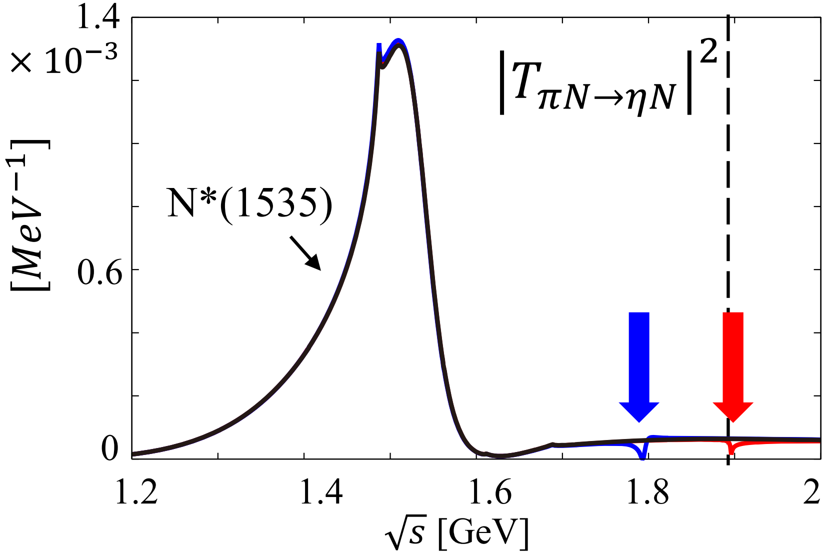
  → $\eta' N$ scattering length, $\pi N \to \eta' N$ production, η' transparency ratio, …
  & also η'-mesic nuclei formation, … Sakamoto, Kiyomura (Nara WU)

- ✓ considering "possibility to have $\eta' N$ bound state"

  → subtraction const. positive → negative value ($\Lambda \sim 1$GeV)
  (Oset-Ramos, PLB) (Hinata *et al.*)

Calculations by A. Hinata (w/o VB channels)





Summary : η'(958)-meson-nucleus bound system

Partial restoration of Chiral sym and $U_A(1)$ anomaly effect
in the viewpoint of mesic-nuclei

(possible) large mass reduction **without** large absorption

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

special feature of η'
- ✓ attraction from contact interaction
- ✓ smaller inelastic channel

possibilities to observe bound state peaks

ongoing theoretical works in NaraWU

estimate possible α (strength of singlet meson-baryon int.)

$\leftrightarrow$ transparency ratio of η'

$\leftrightarrow$ $\pi N \to \eta' N$ cross section

$\leftrightarrow$ $\eta' N$ scattering length and so on…