1st Hadron Spanish Network Days and Spanish-Japanese JSPS Workshop
Valencia, SPAIN, June 15-17, 2015

η'(958)-nucleon interaction and Possible bound state of η'(958)–N system

Hideko NAGAHIRO (Nara Women's University)

PRiME

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

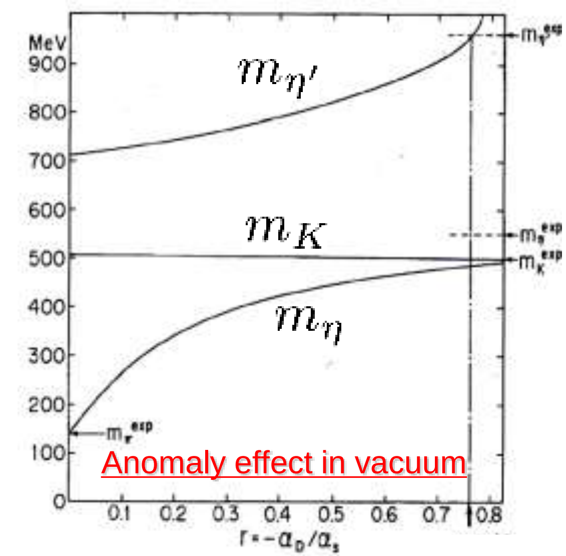
Itahashi, Fujioka, Geissel, Hayano, Hirenzaki, Itoh, Jido, Metag, Nagahiro, Nanova, Nishi, Okochi, Outa, Suzuki, Tanaka, Weick, PTP128(12)601, [(p,d) exp. @GSI]

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 $\eta'(958)$ mass

- $\eta'(958)$ meson … close connection to the $U_A(1)$ anomaly
  - » many theoretical works
    - › in vacuum / at finite temperature / at finite density
      - » R. D. Pisarski, R. Wilczek, PRD29(84)338
      - » T. Kunihiro, T. Hatsuda, PLB206(88)385 / T. Kunihi
      - » V. Bernard, R.L.Jaffe and U.-G.Meissner, NPB308(1
      - » Y. Kohyama, K.Kubodera and M.Takizawa, PLB208
      - » K. Fukushima, K.Onishi, K.Ohta, PRC63(01)045203
      - » P. Costa *et al.*,PLB560(03)171, PRC70(04)025204, e
  - » poor experimental information at finite density

Kunihiro, Hatsuda, PLB206(88)385



- $U_A(1)$ anomaly in medium from the viewpoint of "mes
  - » the η' properties, especially **mass shift**, at finite density

- **Nambu-Jona-Lasinio model** with the **KMT interaction**

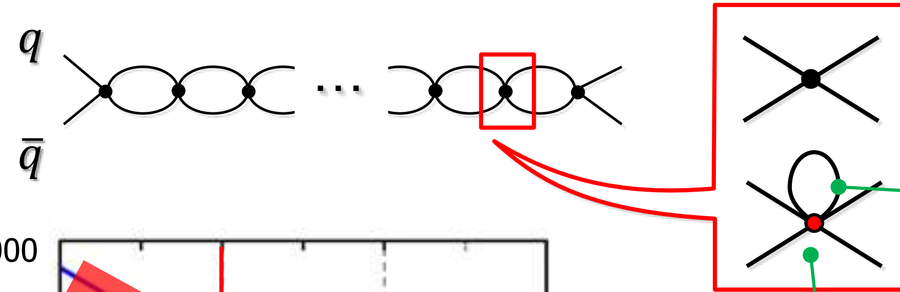
$$\mathcal{L} = \bar{q}(i\,\partial\!\!\!/ - m)q + \frac{g_s}{2}\sum_a\left[(\bar{q}\lambda_a q)^2 + (i\bar{q}\lambda_a\gamma_5 q)^2\right]$$
$$+ g_D\left[\det \bar{q}_i(1-\gamma_5)q_j + h.c.\right]$$

explicit breaking the $U_A(1)$ sym.

Kobayashi, Maskawa Prog.Theor.Phys.44, 1422 (70), G. 't Hooft, Phys.Rev.D14,3432 (76)

✓ in-medium η' mass reduction with NJL model

Kobayashi-Maskawa, PTP44(70)1422
G. 't Hooft, PRD14(76)3432
Kunihiro, Hatsuda, PLB206(88)385
Costa et al., PLB560(03)171
:



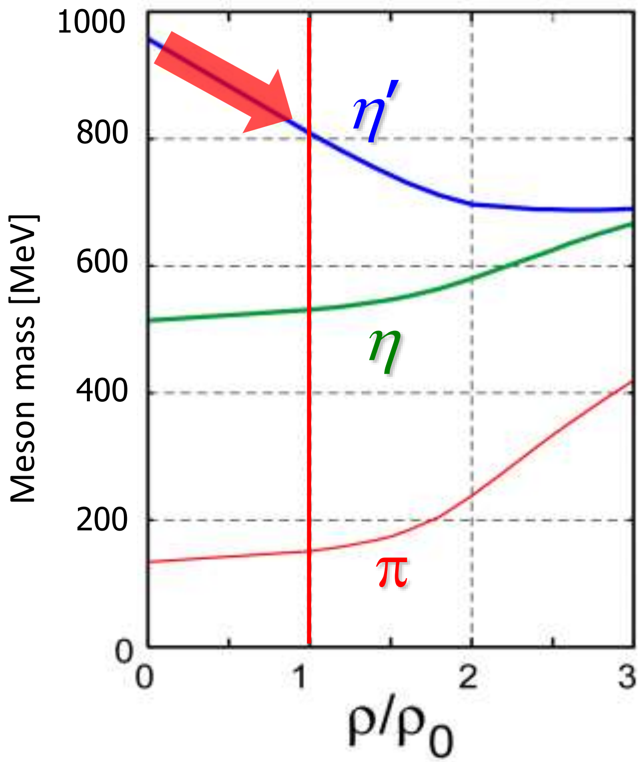
$\langle \bar{q}q \rangle \to$ small

partial restoration of chiral sym.

$U_A(1)$ breaking [KMT interaction]
(giving heavier mass for η')

$U_A(1)$ anomaly **effect** → small in medium

$$\Delta m_{\eta'} \sim -150 \text{ MeV @ } \rho_0$$



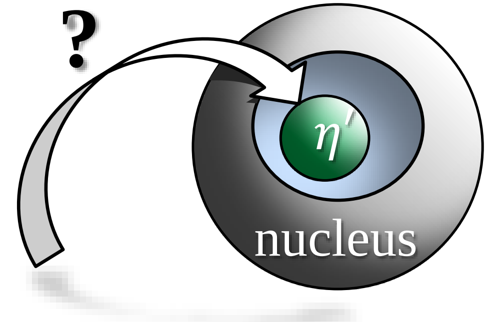
Costa *et al.*,PLB560(03)171,

Nagahiro-Takizawa-Hirenzaki,
PRC74(06)045203

cf.) $\Delta m_{\eta'} \sim -40$ - -80 MeV @ ρ_0
Quark-meson-coupling model,
S.Bass, A.Thomas, PLB634(06)368

cf.) $\Delta m_{\eta'} \sim -80$ MeV @ ρ_0
linear sigma model
S.Sakai, D.Jido, PRC88(13)064906

η' property in medium



→ Phenomenologically poorly understood

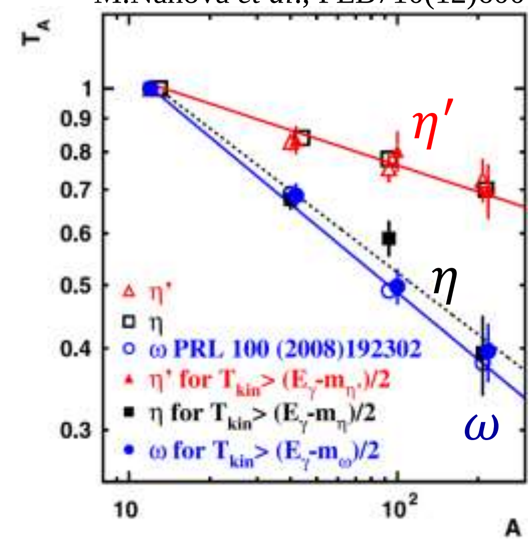
✓ **small scattering length ?**

$$Re(a_{\eta' p}) = 0 \pm 0.43\ \text{fm},\ \text{Im}(a_{\eta' p}) = 0.37\ {}^{+0.40}_{-0.16}\ \text{fm} \quad \text{in free space}$$

[E. Czerwinski *et al.*, (COSY-11) PRL113(14)062004]

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

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



✓ **smaller absorption width in medium ?**

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

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

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

✓ **real part of V_{opt} (not bound state observation)**

$$\text{Re}\,V(\rho_0) \sim -(37 \pm 10(stat) \pm 10(syst))\text{MeV}$$

CBELSA/TAPS [M. Nanova et al., PLB727(2013)417-423]

[photoroduction of η' off ^{12}C]

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]

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

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

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

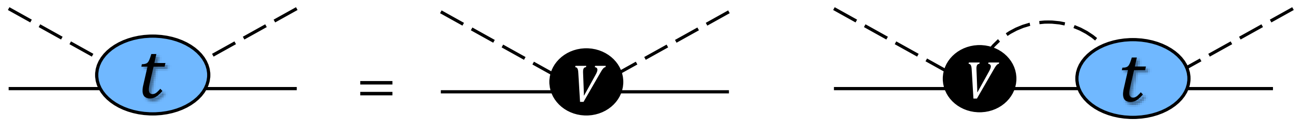
Based on : Coupled-channel calculation [Oset-Ramos, PLB704(11)334]

$$PB\ (\pi N, \eta N, K\Lambda, K\Sigma) + VB\ (K^*\Lambda, K^*\Sigma) + \eta_0 B$$

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

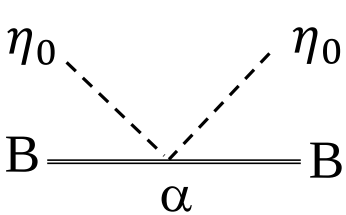
their result : $|a_{\eta' N}| = 0.01$ fm $\Leftrightarrow$ $|a_{\eta' N}| \sim 0.1 - 0.8$ fm [PLB'00]

(2) Vector meson-baryon (VB) channel ($K^*\Lambda, K^*\Sigma$)

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

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

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



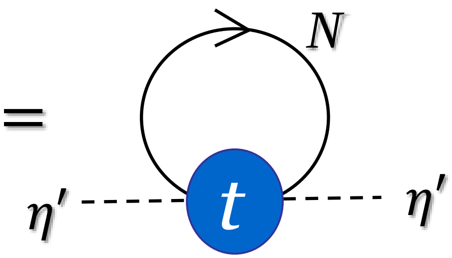
$$\mathcal{L}_{\eta_0 B} \propto \eta_0^2 \langle \partial_\mu \bar{B} \gamma^\mu B - \bar{B} \gamma^\mu \partial_\mu B \rangle$$

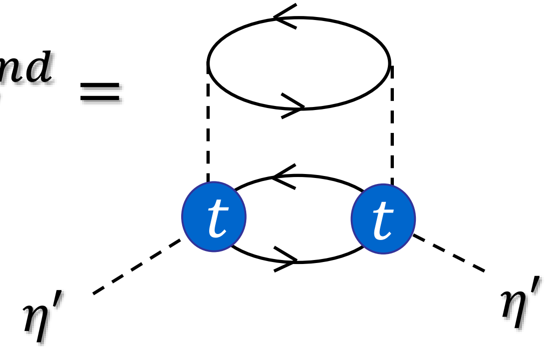
α … free parameter $\rightarrow |a_{\eta' N}| = 0.1$ fm

~ the det-int ($U_A(1)$ anomaly) in linear σ model [Sakai-Jido, PRC88(13)064906]

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

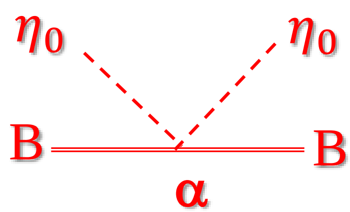
$\boldsymbol{\alpha}$	$\lvert a_{\eta' N}\rvert$ **fm**	$V_{\eta'}^{1st}(\rho_0)$	$V_{\eta'}^{2nd}(\rho_0)$	$V_{\eta'}^{total}(\rho_0)$
-0.193	0.1	$-8.6-1.7i$	$-0.1-0.1i$	$\boldsymbol{-8.7-1.8i}$
-0.834	0.3	$-26.3-2.1i$	$-0.6-0.9i$	$\boldsymbol{-26.8-3.0i}$
-1.79	0.5	$-43.8-3.0i$	$-1.3-2.5i$	$\boldsymbol{-44.1-5.5i}$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

Re $V \gg$ Im V

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

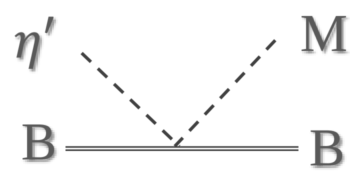
The reason why Re V $\gg$ Im V in coupled channel calculation

Kawarabayashi-Ohta, PTP66(81)1789, Borasoy , PRD61(00)014011
Sakai-Jido PRD88(13)064906, …



→ gives attraction

WT interaction for η'



→ **width [small]**

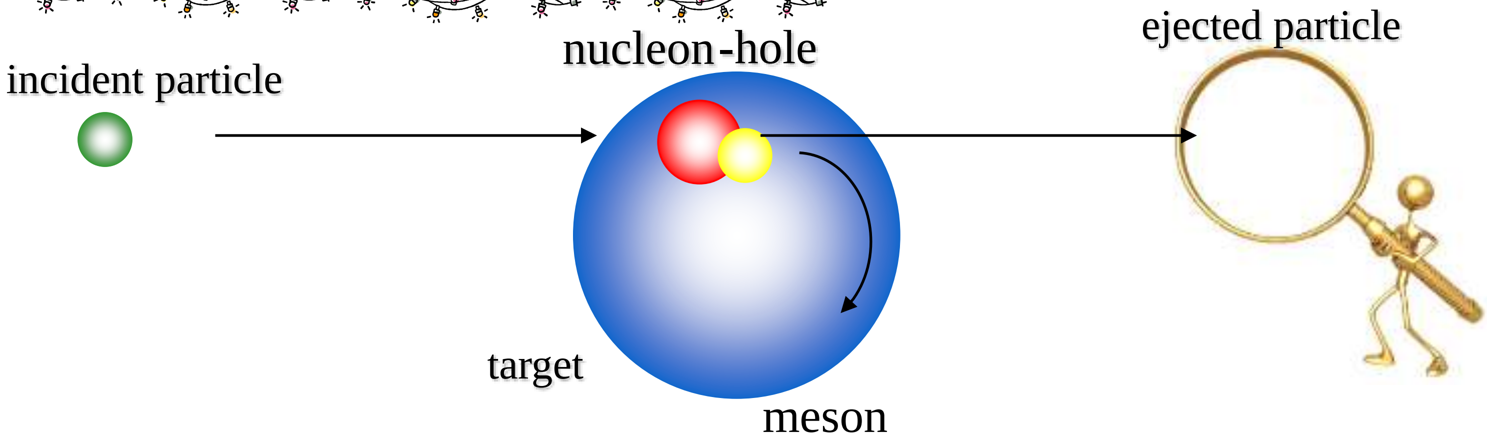
This interaction …

- ✓ represents the anomaly effect [S.Sakai, D.Jido, PRD88(13)064906]
- ✓ **dominate** the $\eta' N$ interaction
- ✓ contributes mostly to the **η' elastic channel** & barely to the **inelastic channel**

ongoing work **[→ Later]**

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

Missing mass spectroscopy



<u>one-nucleon picking-up</u>

» **(p,d) reaction @ GSI, August 2014**

Itahashi, Fujioka, Geissel, Hayano, Hirenzaki, Itoh, Jido, Metag, <u>Nagahiro</u>, Nanova, Nishi, Okochi, Outa, Suzuki, Tanaka, Weick, PTP128(12)601.
<u>Nagahiro</u>, Jido, Fujioka, Itahashi, Hirenzaki, PRC87(13)045201.

» **(γ,p) reaction @ SPring-8, TAPS, …**

Nagahiro-Hirenzaki, PRL94(05)232503, ···

» **(π,N) reaction @ J-PARC**

Nagahiro, Hirenzaki, Oset, Ramos, PLB

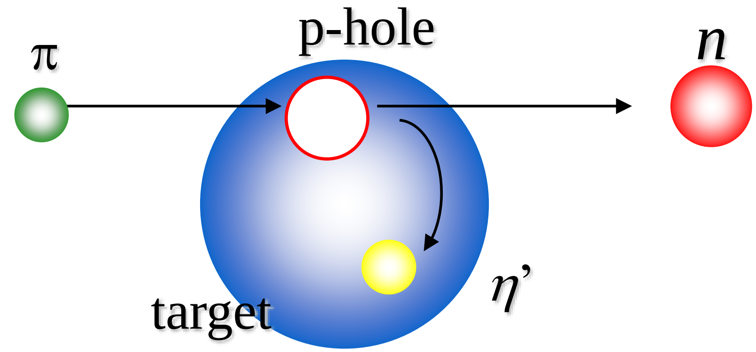
η'(958) mesic nuclei by (π^-,n) reaction

<u>missing mass spectroscopy</u>

π beam momentum p_π=1.8GeV/c

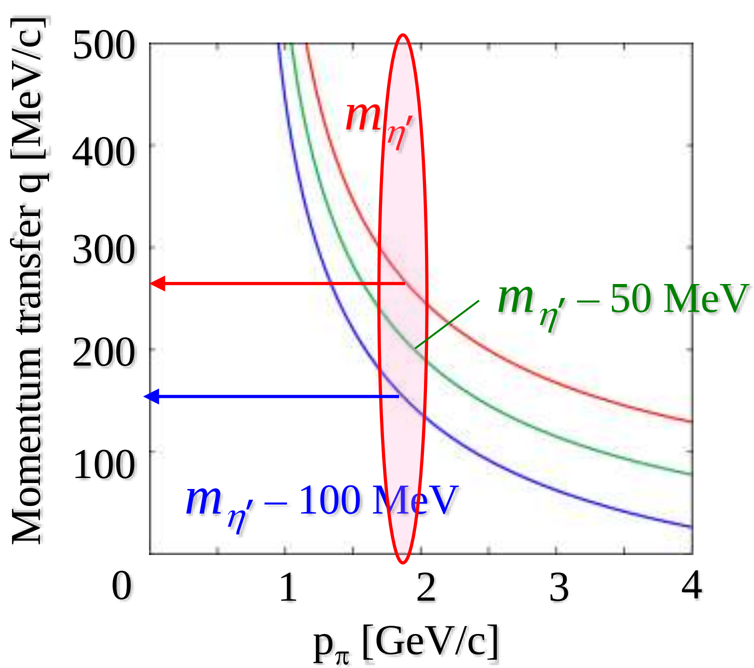
target : ^{12}C, ^{40}Ca

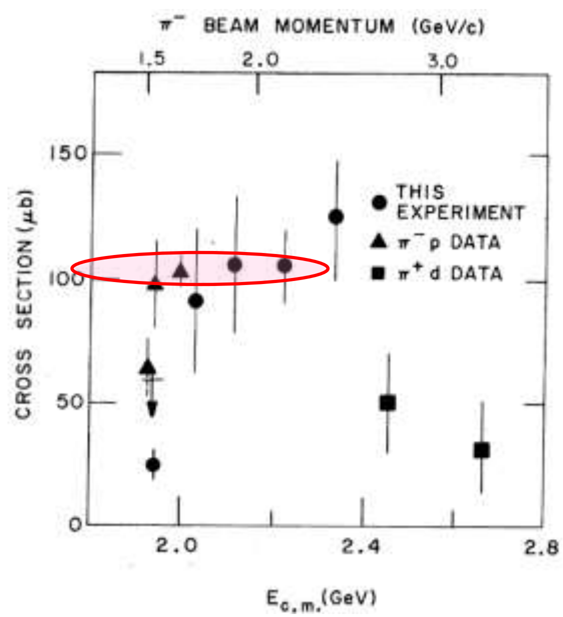
forward reaction : θ_n = 0 deg.



momentum transfer

elementary cross section $\pi^- p \rightarrow \eta' n$





R.K.Rader *et al.*, PRD6(72)3059

$\sigma(\pi^+ n \rightarrow \eta' p) \sim 100\ \mu b$

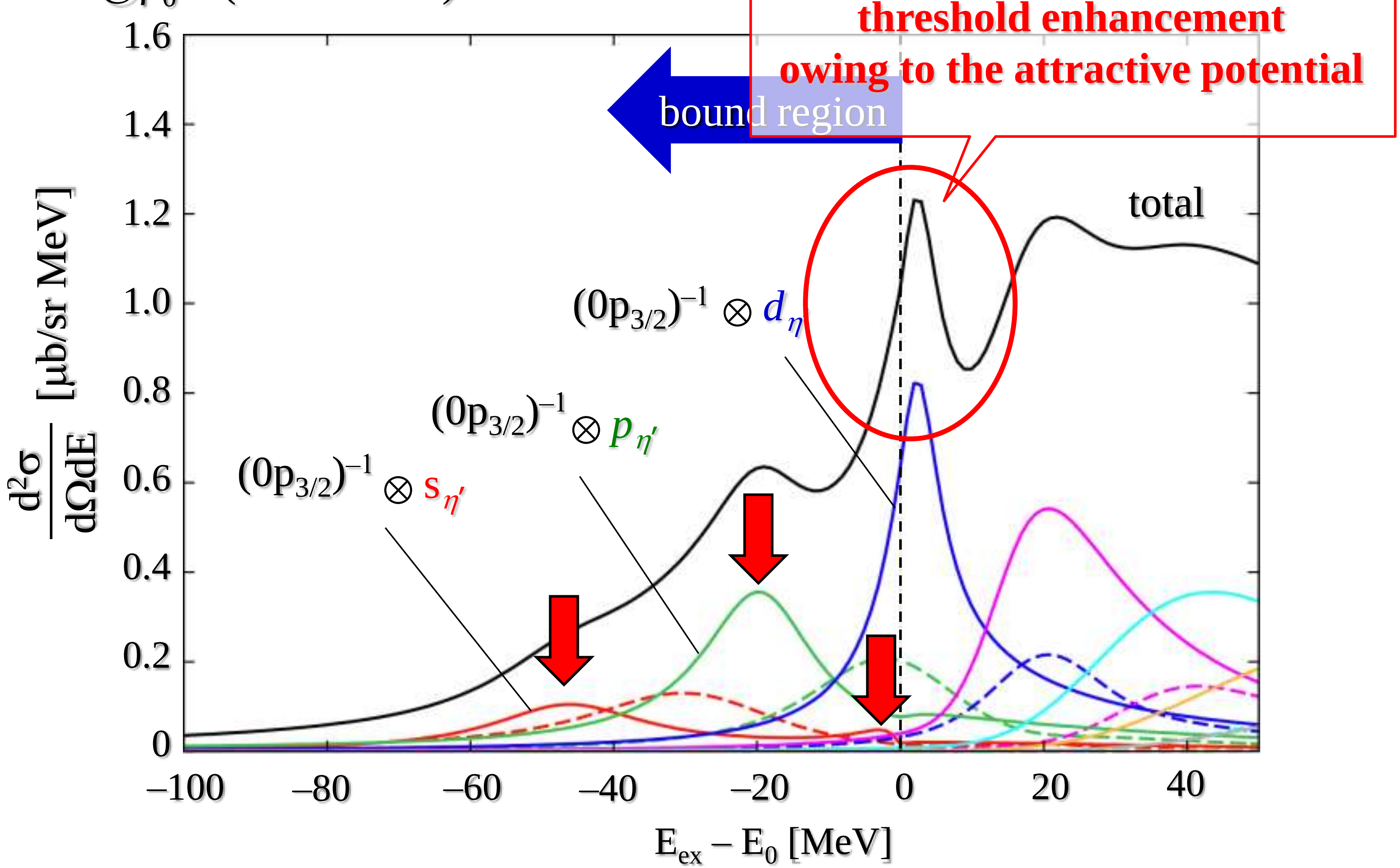
$$\left(\frac{d\sigma}{d\Omega}\right)^{\mathbf{Lab.}} \sim 100\ \mu b/sr$$

Numerical results $^{12}\mathrm{C}(\pi^-,\mathrm{n})^{11}\mathrm{C}_{\eta'}$

$|a_{\eta'N}| = 1.0$ fm

$V@\rho_0 = (-91.8-17.2i)$ MeV

	(BE. Γ)
0*s*	(−46.10, 23.34)
1*s*	(−0.29, 4.99)
0*p*	(−18.73, 15.78)



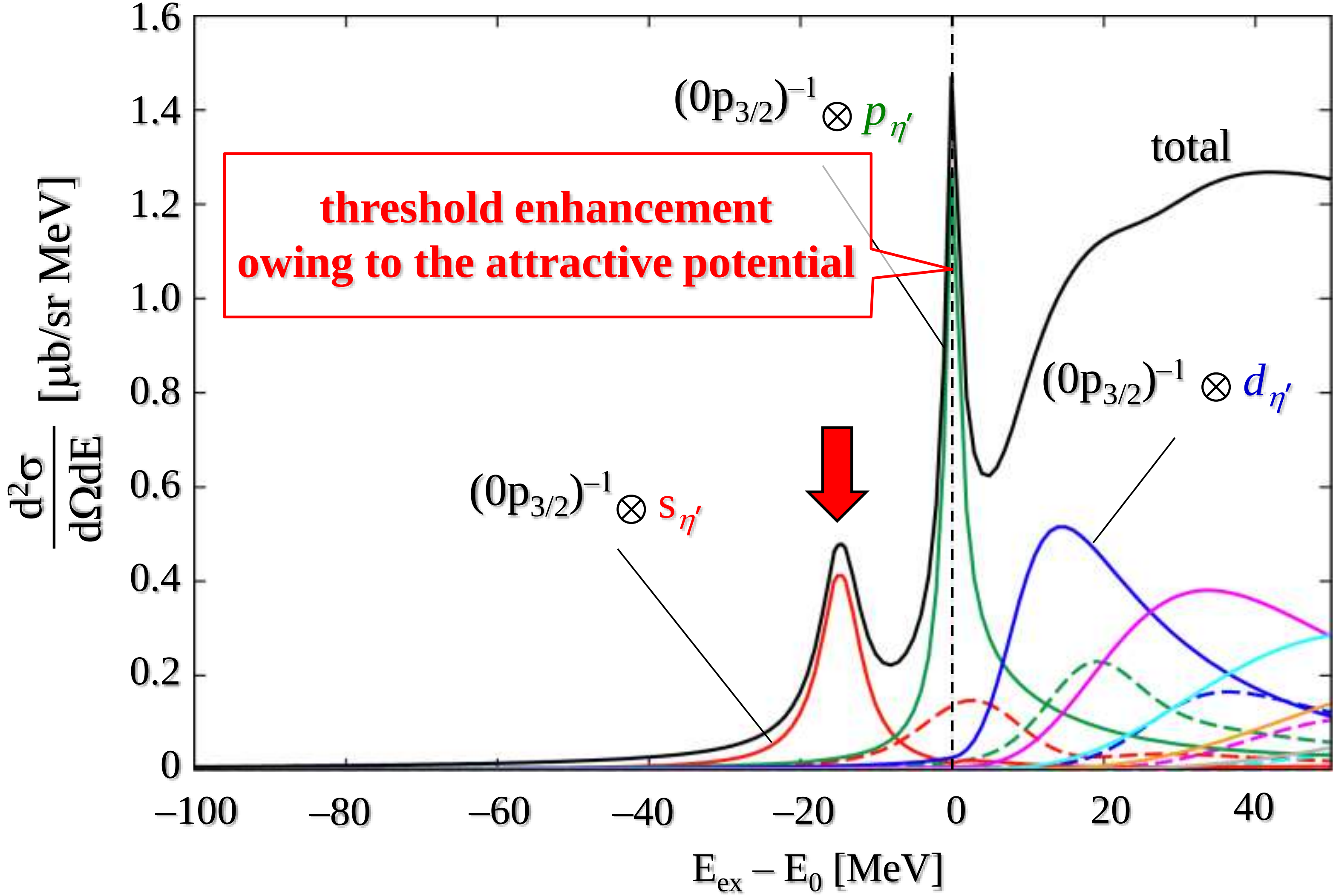
Numerical results $^{12}C(\pi^-,n)^{11}C_{\eta'}$

$|a_{\eta' N}| = 0.5$ fm

$V@\rho_0 = (-44.1-5.5i)$ MeV

(BE. Γ)

0s (−14.50, 5.95)



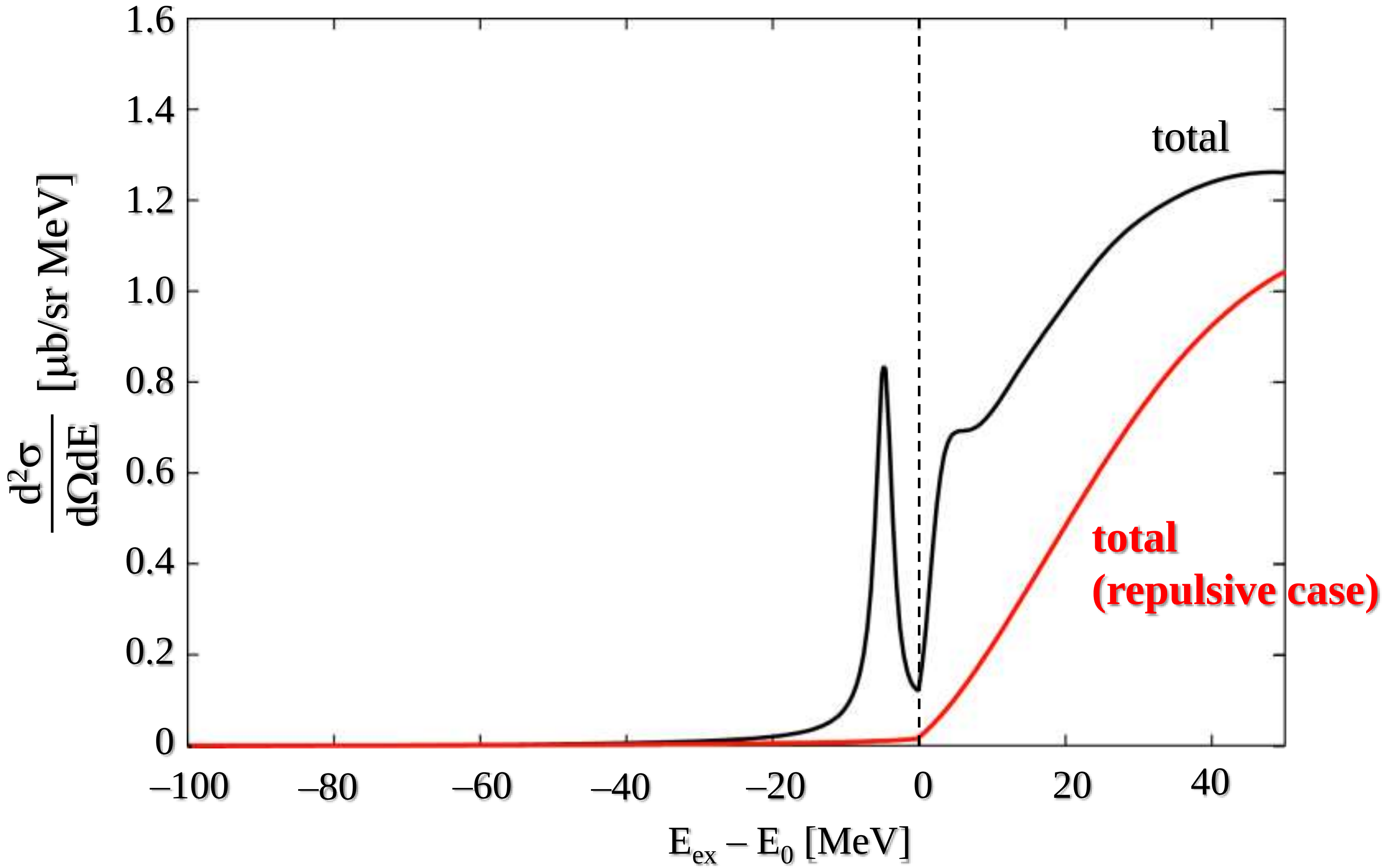
Numerical results $^{12}C(\pi^-,n)^{11}C_{\eta'}$

(BE. Γ)

$|a_{\eta' N}| = 0.3$ fm

$0s$ (−4.65, 2.55)

$V@\rho_0 = (-26.8-3.0i)$ MeV



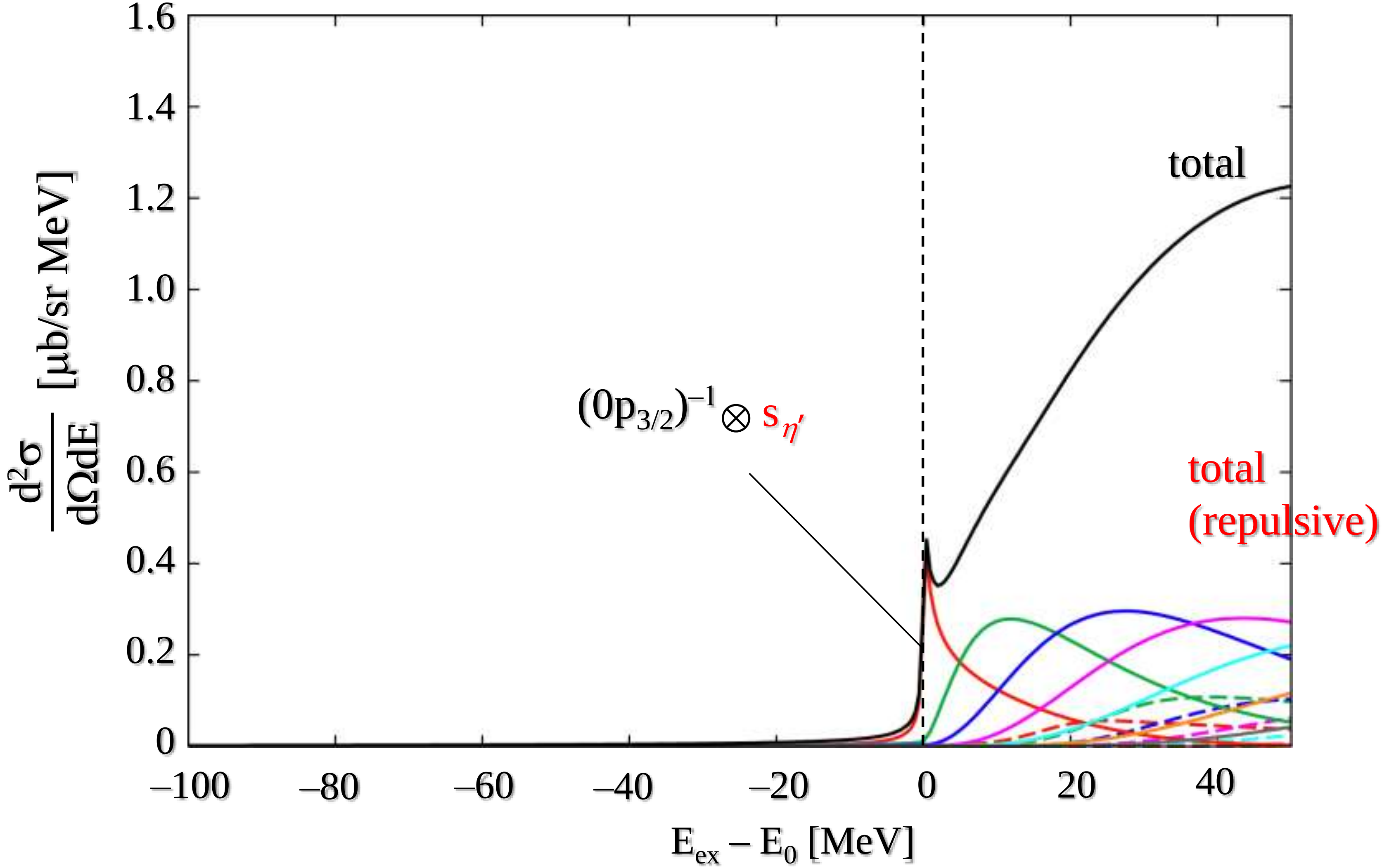
Numerical results $^{12}C(\pi^-,n)^{11}C_{\eta'}$

(BE. Γ)

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

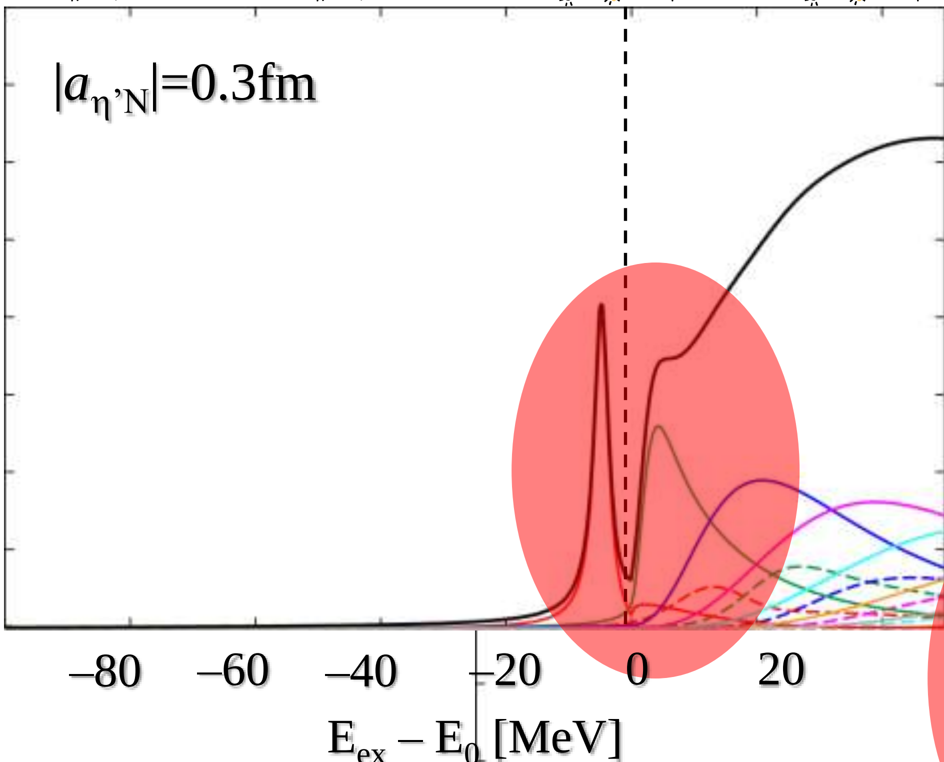
$V@\rho_0 = (-6.4-1.8i)$ MeV

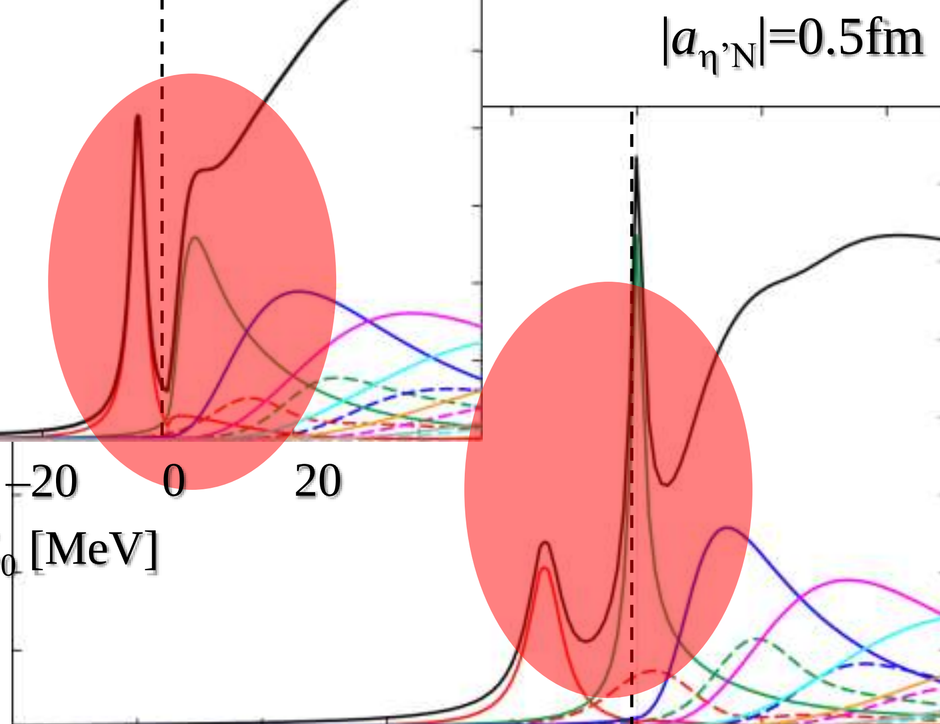
no bound state

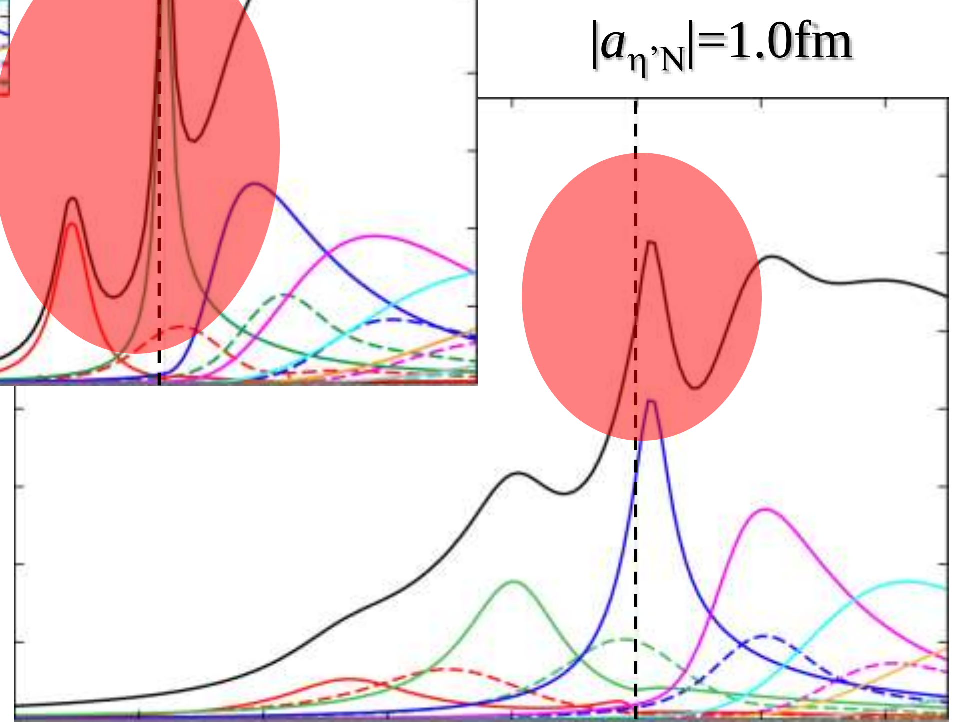


Structure around the η' threshold

similar spectra are expected in (p,d) @ GSI … will be coming soon (?)



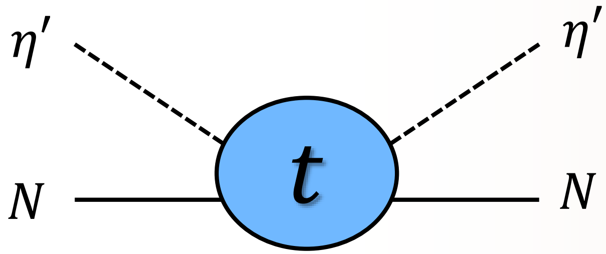




Momentum transfer ~ 200-300 MeV/c
is not so small for heavy η'
→ See the Next Miyatani's talk

Revisiting $\eta' N$ scattering amplitude considering a **possible $\eta' N$ bound state**

A. Hinata, A. Kiyomura, M. Sakamoto, H.N., S. Hirenzaki, in progress
(Nara Women's Univ.)



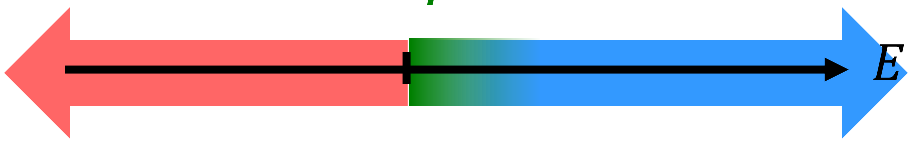
on-going theoretical works

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

- ✓ We have estimated Re($V_{\eta'}$) and Im($V_{\eta'}$) by using $T_{\eta' N \to \eta' N}$ [Oset-Ramos(2011)] **at $\eta' N$ threshold value**

$a_{\eta' N}$

bound state



η' production
η' transparency ratio
etc …

→ **Energy-dependence is important**

- ✓ **different model for vector-meson-baryon channel**

  [K. P. Khemchandani, A. Martinez Torres H. N. and A. Hosaka, PRD88(13)114016]

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

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

- ✓ trying to extract **possible α value**

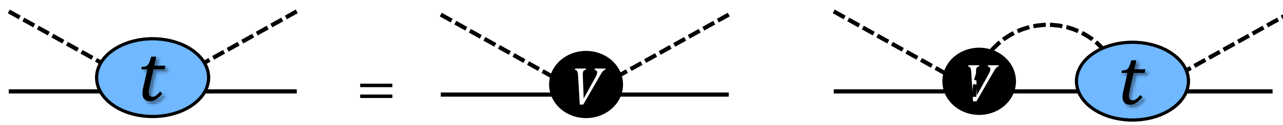
  → $\eta' N$ scattering length, $\pi N \to \eta' N$ production, η' transparency ratio, …
  & also η'-mesic nuclei formation, …

- ✓ **different model for vector-meson-baryon channel**

✓ different model for vector-meson-baryon channel

K. P. Khemchandani, A. Martinez Torres, H. N. and A. Hosaka, PRD88(13)114016

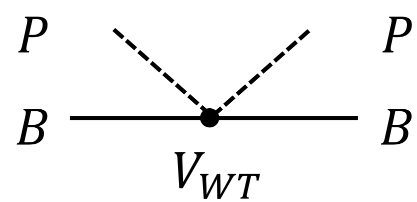
Unitarized scattering amplitude by coupled-channel BS eq.

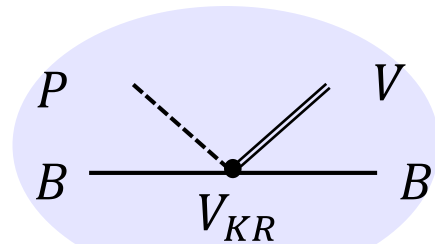


Interaction kernel V

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

$\pi N, \eta N, K\Lambda, K\Sigma$

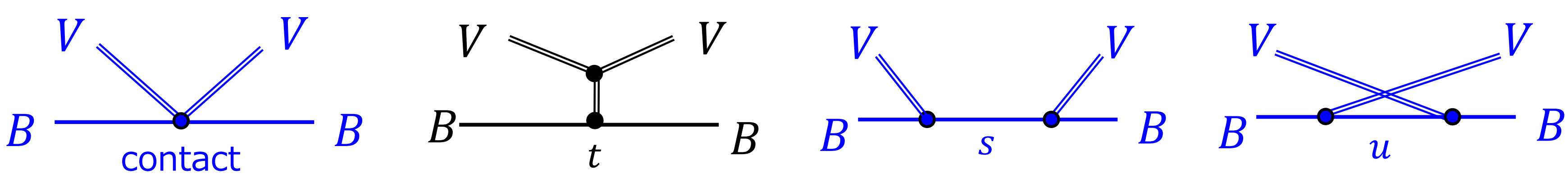




Kroll-Ruddermann $(\gamma p \to \pi p)$

(2) Vector meson-baryon (VB) channel

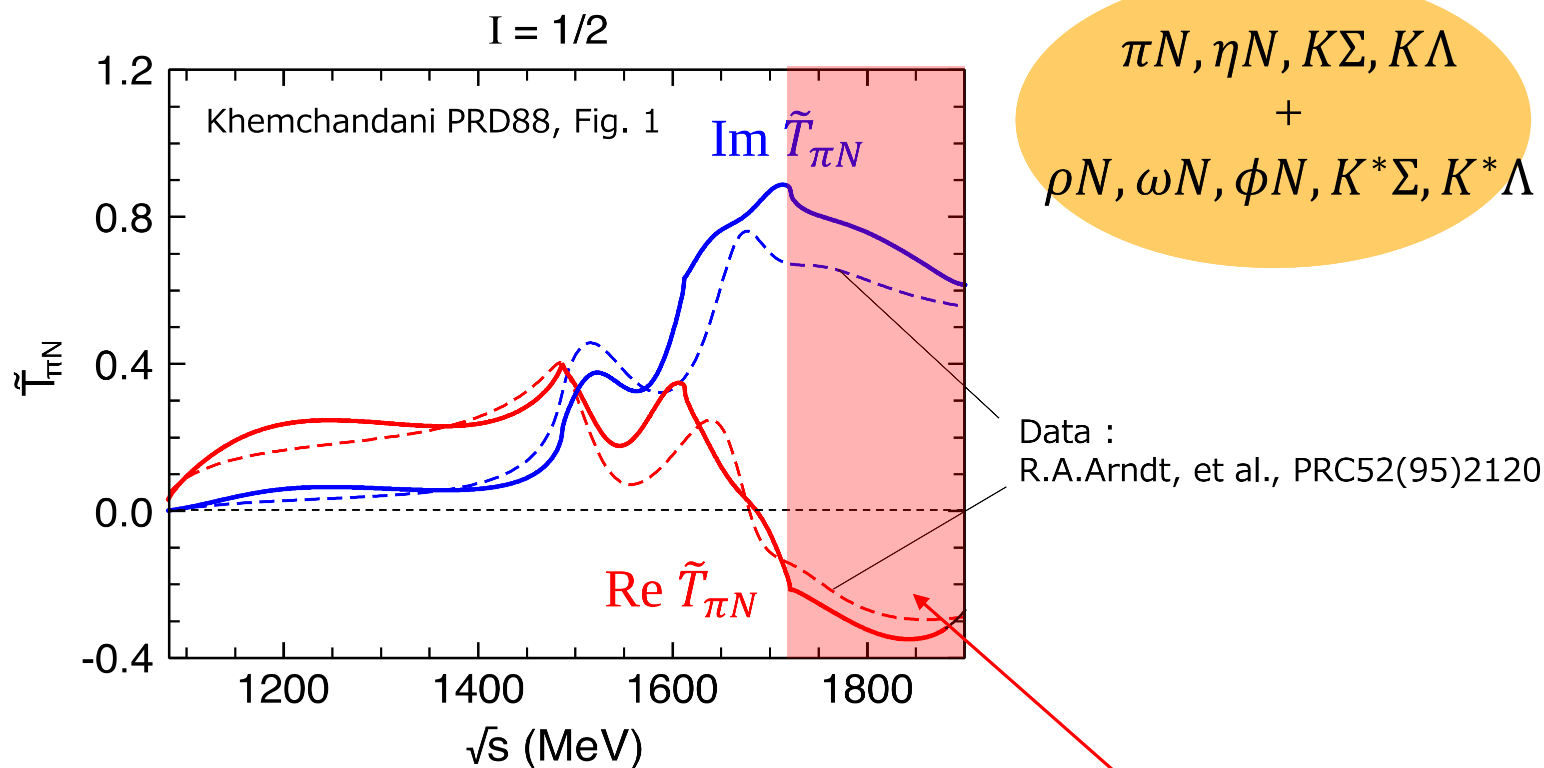
$\rho N, \omega N, \phi N, K^*\Sigma, K^*\Lambda$



✓ different model for vector-meson-baryon channel

K. P. Khemchandani, A. Martinez Torres, H. N. and A. Hosaka, PRD88(13)114016

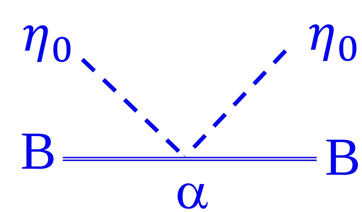
$\pi N, \eta N, K\Sigma, K\Lambda$
$+$
$\rho N, \omega N, \phi N, K^*\Sigma, K^*\Lambda$



$\pi N \to \pi N$ scattering amplitude … good agreement at $\sqrt{s} \sim 1.9$ GeV

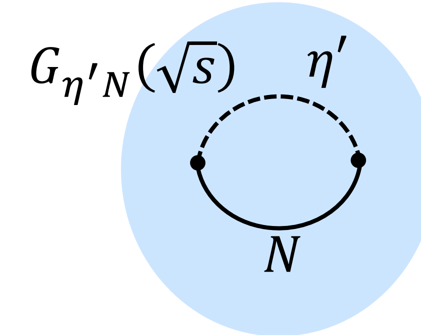
Hinata, Kiyomura, Sakamoto (Nara WU.)

→ we add $\eta' N$ channel in V_{WT} through η-η' mixing
and $V_{\eta_0 B}$ (singlet-η Baryon interaction) as well



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

→ subtraction const. positive → negative value (Λ~1GeV)



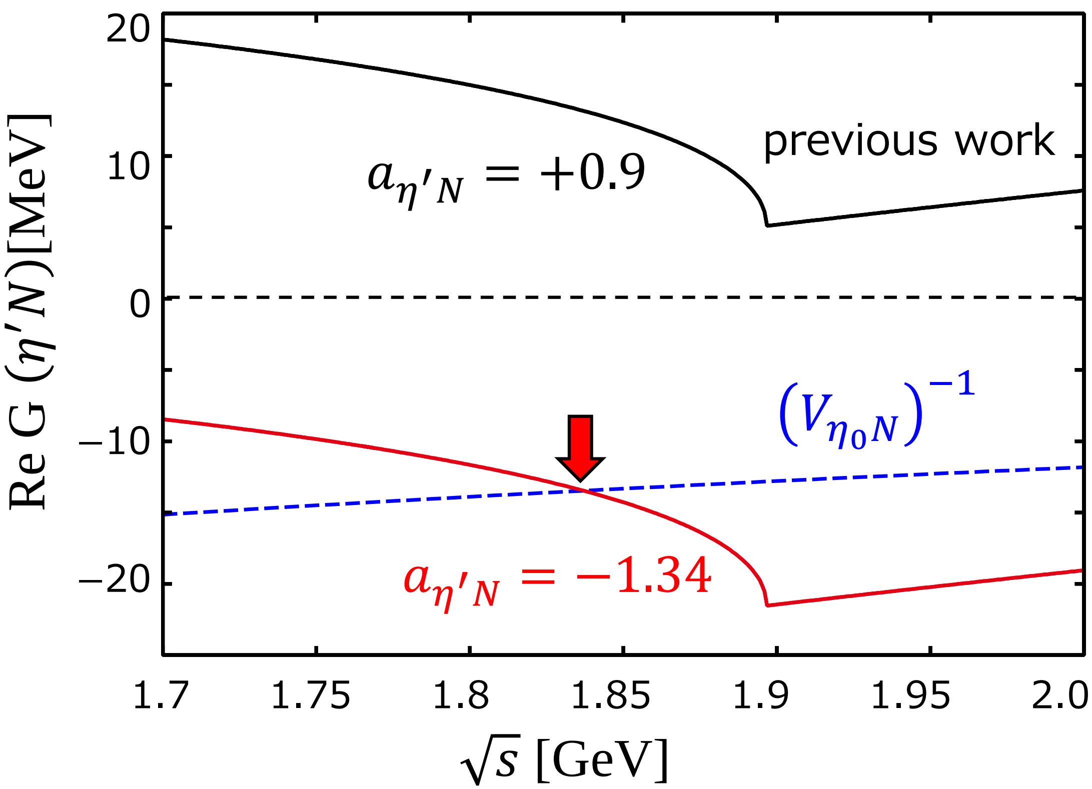
<u>subtraction constants for the loop function</u>

[Oset-Ramos-PLB, and our previous work]

$a_{\pi N}, a_{\eta N}, a_{K\Sigma}, a_{K\Lambda}$ $\boxed{a_{\eta' N} = a_{\eta N} = 0.9}$ ➡ $\boxed{a_{\eta' N} = -1.34}$

→ to reproduce $N^*(1535)$ (Inoue et al., PRC65)

$\Lambda \sim 1$ GeV/c

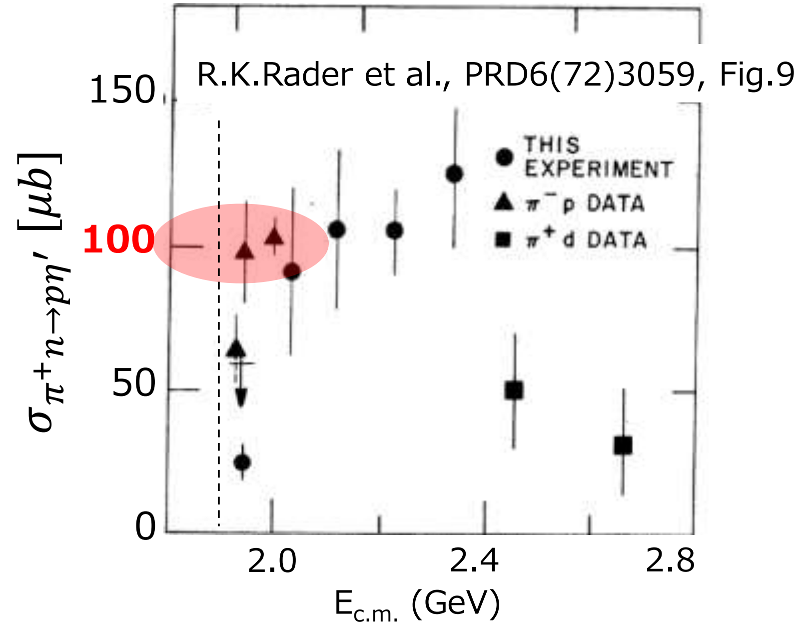


$$\left(V_{\eta_0 N}\right)^{-1} - G(\sqrt{s}) = 0$$

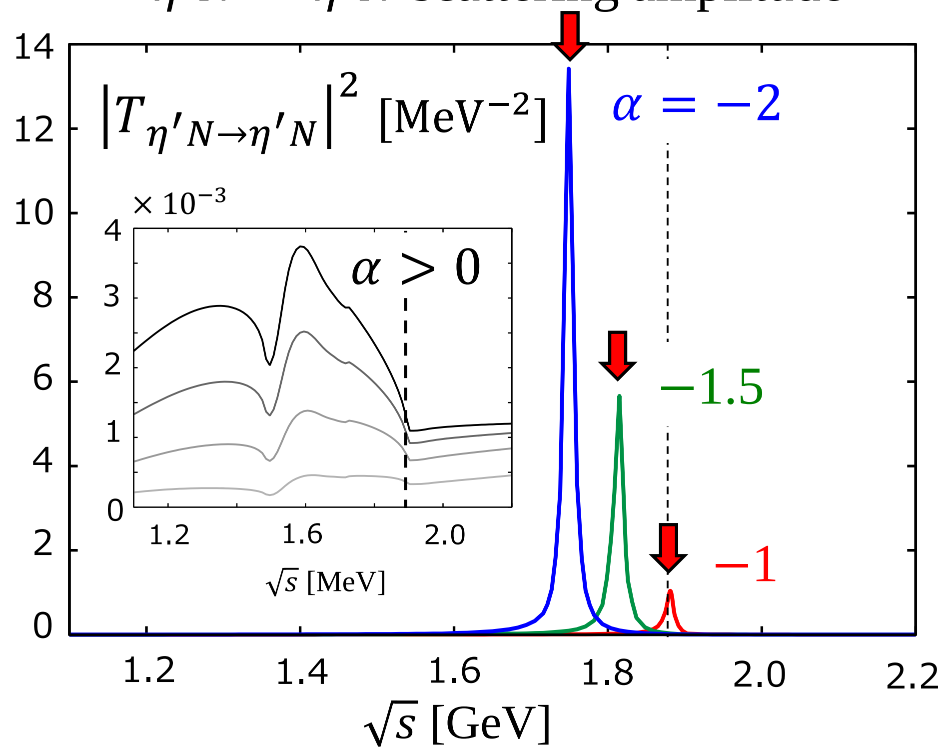
→ $\eta' N$ bound state due to $\eta_0 B$ coupling ?

$\eta' N$ bound state and $\sigma_{\pi N \to \eta' N}$

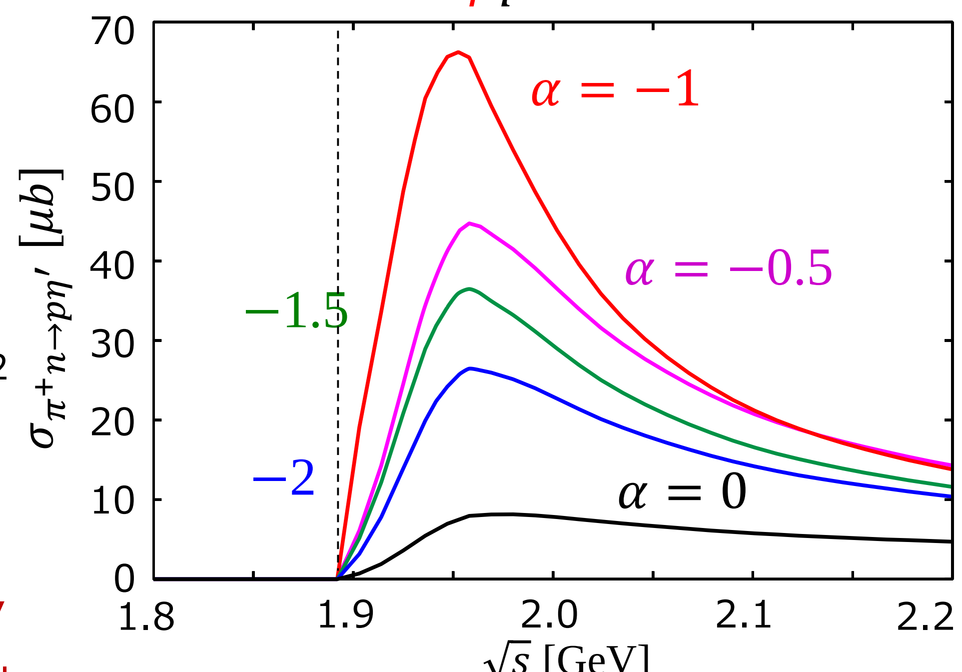
by Hinata, Kiyomura, Sakamoto [Nara WU.]

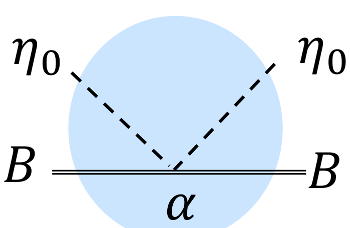


$\eta' N \to \eta' N$ scattering amplitude



$\pi^+ n \to \eta' p$ cross section





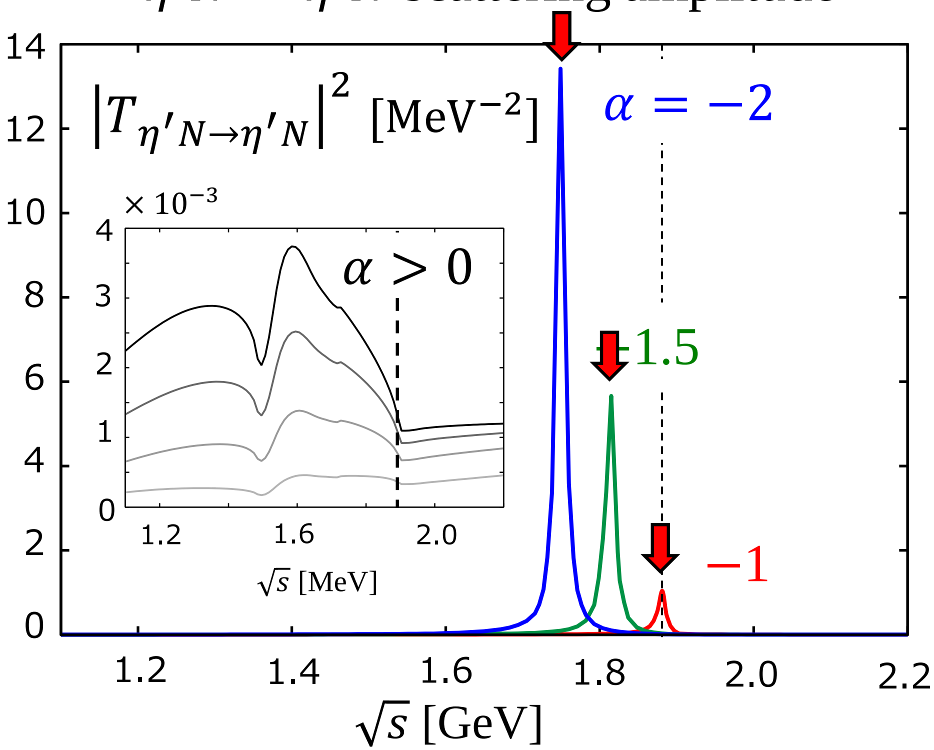
$\eta' N$ bound state

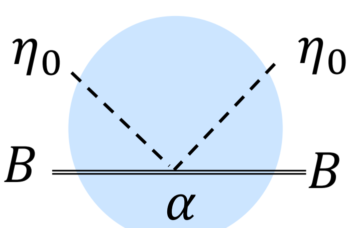
cf.) S. Sakai and D. Jido, PRC88(13)064906, based on linear σ model

$\eta' N$ scattering length

✔ **small scattering length**

$\eta' N \to \eta' N$ scattering amplitude

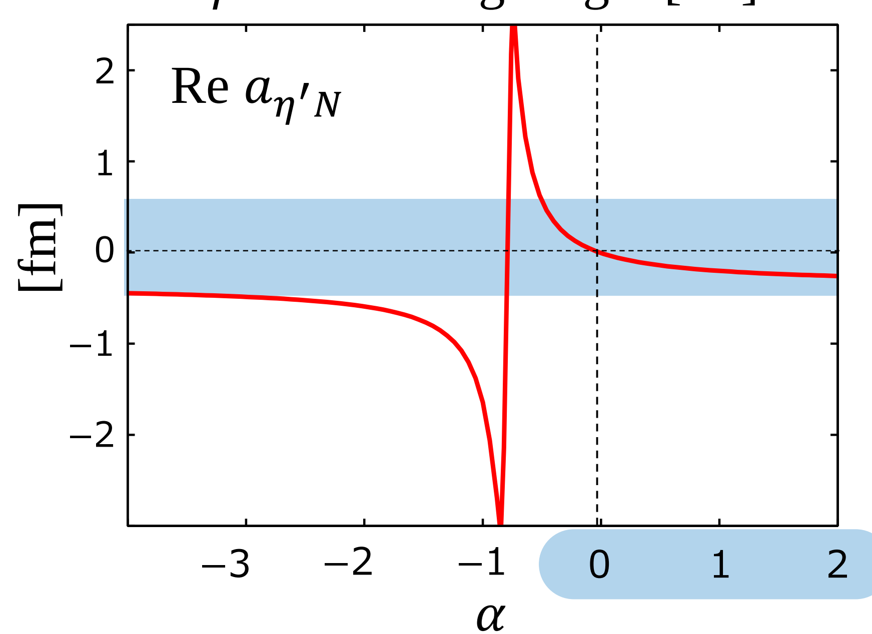




$$Re(a_{\eta' p}) = 0 \pm 0.43 \text{ fm}$$
$$\mathrm{Im}(a_{\eta' p}) = 0.37 \,{}^{+0.40}_{-0.16} \text{ fm}$$

[E. Czerwinski *et al.*, (COSY-11), PRL113(14)062004]

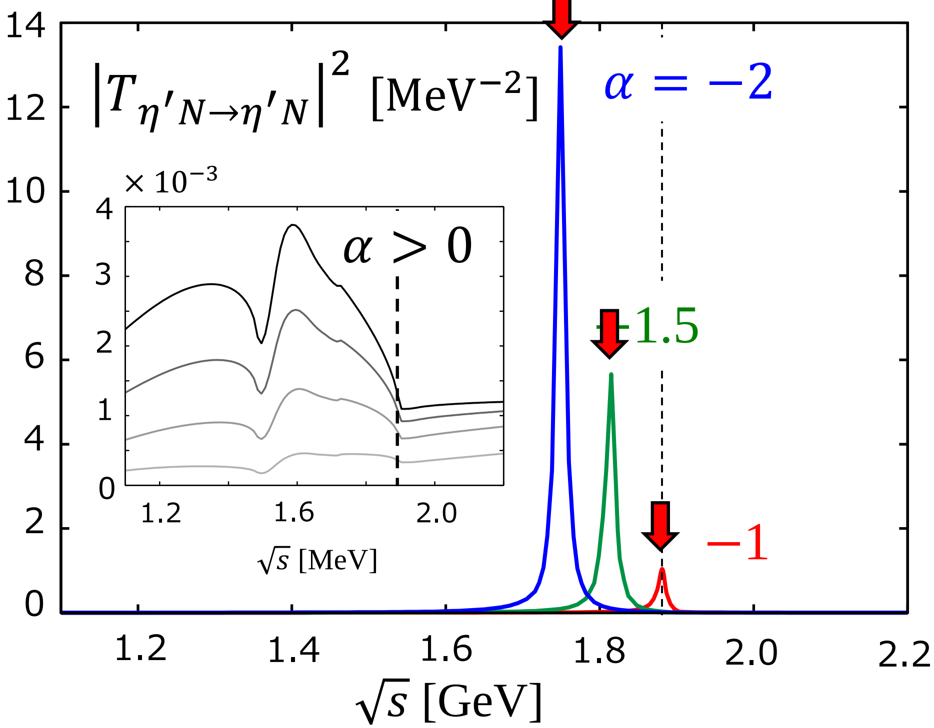
$\eta' N$ scattering length [fm]



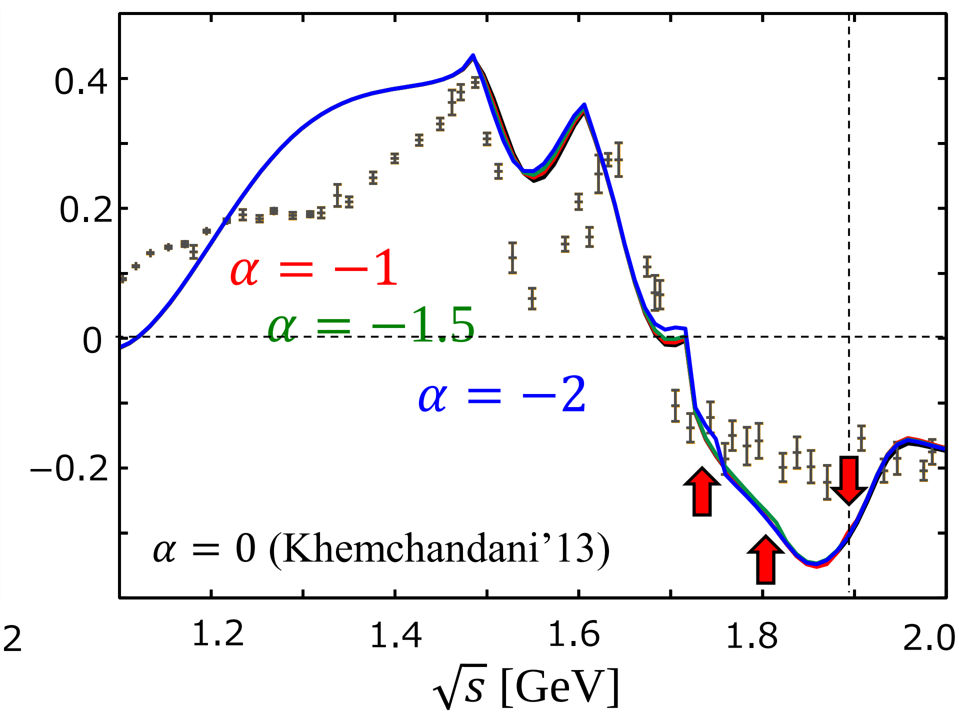
πN scattering amplitudes

by Hinata, Kiyomura, Sakamoto [Nara WU.]

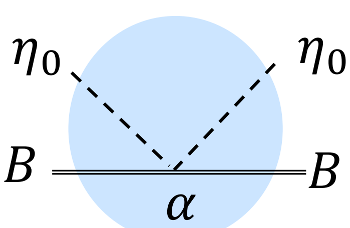
$\eta' N \to \eta' N$ scattering amplitude



πN amplitude (real part)



data : CNS, http://gwdac.phys.gwu.edu/

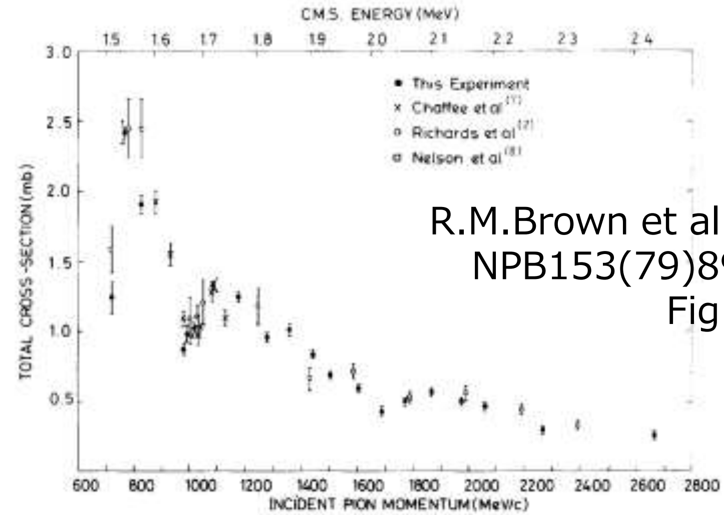


such a "narrow N^*" exists ??

… at least it does not couple to πN due to its singlet char.

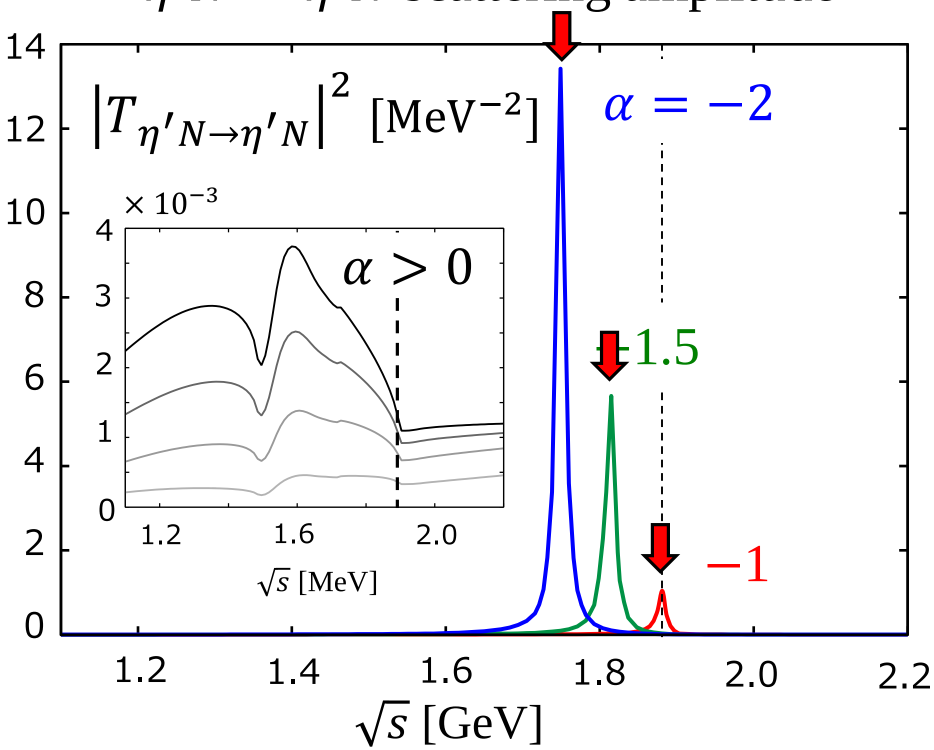
$\sigma_{\pi N \to \eta N}$ cross section

by Hinata, Kiyomura, Sakamoto [Nara WU.]

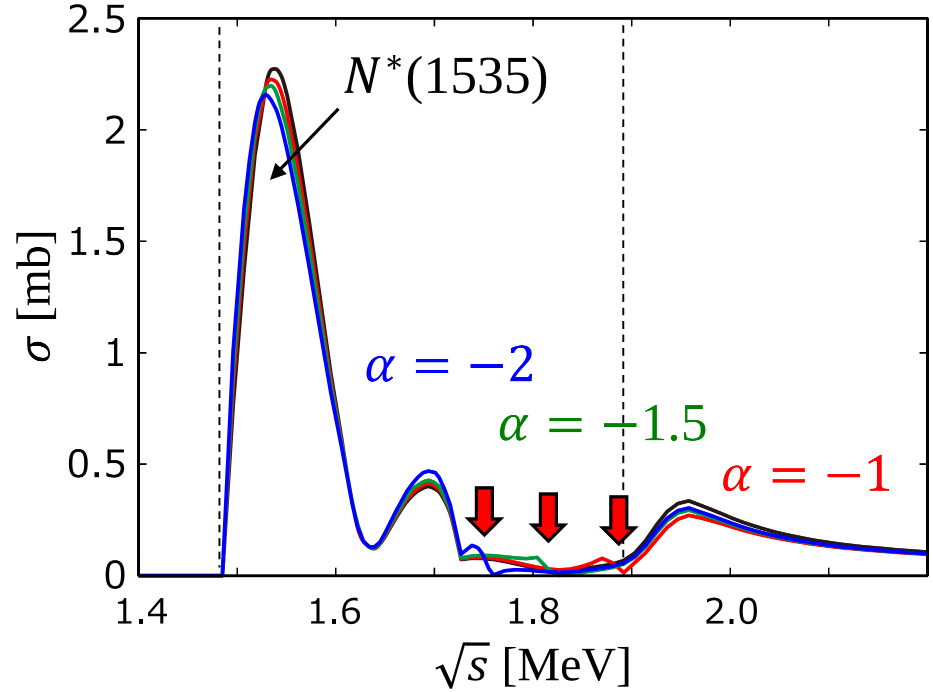


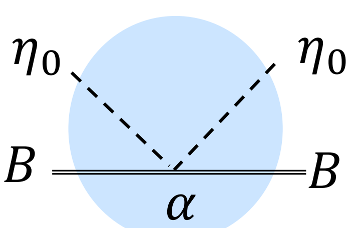
R.M.Brown et al., NPB153(79)89, Fig.9

$\eta' N \to \eta' N$ scattering amplitude



$\pi^- p \to \eta n$ cross section





$\eta' N$ b.s. cannot be seen in η production

$\eta' N$ bound state ⟺ η'-nucleus bound state ?

- ✓ $\pi N \to \eta' N$ is **sensitive** to $V_{\eta_0 B}$ interaction (α), where, however, the $\eta' N$ bound state cannot be reached (above the threshold)

- ✓ The $\eta' N$ bound state **does not appear** in the π or η production, because it couples to $\eta' N$ channel selectively due to its singlet character.

- ✓ The large $\pi N \to \eta' N$ production prefers the **attractive $V_{\eta_0 B}$**, while the small scattering length prefers **zero or repulsive $V_{\eta_0 B}$** .

- ✓ $\eta' N$ b.s. must play an **important role in η'-nucleus** optical potentials, which gives **strong energy dependence**.

$\eta' N$ b.s. can be found as (deeply) η'-nucleus bound state ?

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 & unique feature of η'
different from η, ω, ϕ-mesic nuclei

ongoing theoretical works in NaraWU

- ✓ Considering $\eta' N$ bound state
- ✓ estimate possible α (strength of singlet meson-baryon int.)
  - $\leftrightarrow$ transparency ratio of η'
  - $\leftrightarrow$ $\pi N \rightarrow \eta' N$ cross section
  - $\leftrightarrow$ $\eta' N$ scattering length and so on…