KEK研究会
『現代の原子核物理　ー多様化し進化する原子核の描像ー』

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高エネルギー加速器研究機構 素粒子原子核研究所

formation of η - and η'-mesic nuclei

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H.N., D.Jido and S.Hirenzaki, NPA761(05)92
H.N., D.Jido, S.Hirenzaki, PRC68(03)035205
D.Jido, H.N. and S.Hirenzaki, PRC66(02)045202

H.N., S. Hirenzaki, PRL94(05)232503
H.N., M.Takizawa and S. Hirenzaki, nucl-th/0606052

formation of η-mesic nuclei

properties of N*(1535) resonance in medium
Chiral doublet model
Chiral unitary model
(d,^{3}He), (γ,p) & (π^+,p) reactions

formation of η'-mesic nuclei

$U_A(1)$ anomaly effect in medium
Nambu-Jona-Lasinio model
(γ,p) reaction
η-, ω- & η'-mesic nuclei formations @ Eγ = 2.7 GeV

η-Nucleus system

D.Jido,H.Nagahiro,S.Hirenzaki, PRC66(02)045202,
H.Nagahiro,D.Jido,S.Hirenzaki, PRC68(03)035205,
H.Nagahiro., D.Jido, S.Hirenzaki, NPA761(05)92,
Kolomeitsev, Jido, Nagahiro, Hirenzaki, in preparation
Nagahiro, Jido, Hirenzaki, in progress

works for eta-mesic nuclei

» (π^+, p)
* Liu, Haider, PRC34(1986)1845
* Chiang, Oset, and Liu, PRC44(1988)738
* Chrien *et al.*, PRL60(1988)2595

» (d,^{3}He)
* Hayano, Hirenzaki, Gilltzer, Eur.Phys.J.A6(1999)99
* D. Jido, H.Nagahiro, S.Hirenzaki PRC66(2002)045202
* Exp. at GSI (Yamazaki, Hayano group)

» η-light nucleus system : TAPS @ MAMI (2004) (exp.), B.K.Jain *et al.*(thor.) etc…

» etc… (ex. (γ,η) @ 核理研, etc…)

properties of eta meson

eta meson

» $m_\eta = 547.3$ [MeV] » $\mathrm{I} = 0,\ \mathrm{J^P} = 0^-$

» $\Gamma = 1.18$ [keV] $(2\gamma,\ 3\pi^0,\ \pi^+\pi^-\pi^0, \cdots)$

$\eta N N^*$ system
- -No $I = \frac{3}{2}$ baryon contamination
- -Large coupling constant
- -no suppression at threshold (s-wave coupling)

$\mathcal{L}_{\eta N N^*} = g_\eta \bar{N} \eta N^* + h.c.$

eta-N system

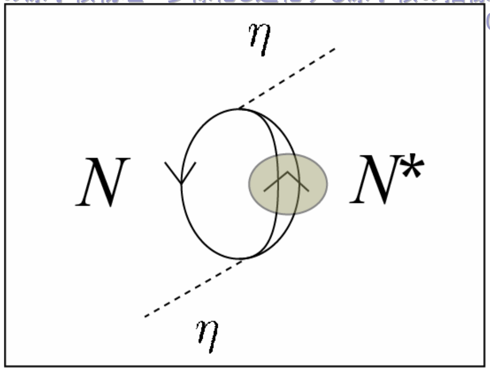
- **Strong Coupling to N*(1535),** $\mathrm{J^P} = \frac{1}{2}^-$

» $\Gamma_{\pi N} \sim \Gamma_{\eta N} \sim 75$[MeV]

eta-Nucleus system ⇒ **Doorway to N*(1535)**

η-Nucleus Interaction

~ N* dominance model ~



optical potential

energy dependence

$$V_{\rm opt} = \frac{g_\eta^2}{2\mu}\frac{\rho}{\omega + m_N(\rho) - m_{N^*}(\rho) + i\Gamma^*_N(s;\rho)/2}$$

density-dependence

(Chiang, Oset, Liu PRC44(1991)738)

(D.Jido, H.N., S.Hirenzaki, PRC66(2002)045202)

$g_\eta \simeq 2.0$

to reproduce the partial width

$\Gamma_{N^*\to\eta N} \simeq 75$ MeV

at tree level.

potential nature

In free space $(V \sim t\rho)$

$$\omega + m_N - m_{N^*} < 0$$ → attractive

$$(m_\eta + m_N - m_{N^*} \sim -50\text{MeV})$$

General feature

medium effect

m_N & m_{N^*} change ??

$$\omega + m_N(\rho) - m_{N^*}(\rho) > 0 \ ?$$ → **Repulsive ??**

N & N* properties in medium evaluated by two kinds of Chiral Models

Chiral models for N and N*

Chiral doublet model

DeTar, Kunihiro, PRD39 (89)2805
Jido,Nemoto,Oka,Hosaka, NPA671(00)471
Jido, Hatsuda, Kunihiro, PRL84(00)3252
Jido, Oka, Hosaka, PTP106(01)873
etc.

Extended SU(2) Linear Sigma Model for N and N*

Lagrangian

$$\mathcal{L} = \sum_{j=1,2} [\bar{N}_j i \not\partial N_j - g_j \bar{N}_j (\sigma + (-)^{j-1} i\gamma_5 \vec{\tau}\cdot\vec{\pi}) N_k] - m_0 (\bar{N}_1 \gamma_5 N_2 - \bar{N}_2 \gamma_5 N_1)$$

Physical fields

$$\begin{pmatrix} N \\ N^* \end{pmatrix} = \begin{pmatrix} \cos\theta & \gamma_5 \sin\theta \\ -\gamma_5 \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \end{pmatrix}$$

N* : chiral partner of nucleon

Mass difference

$$m^*_N(\rho) - m^*_{N^*}(\rho) = (1 - C\frac{\rho}{\rho_0})(m_N - m_{N^*})$$

* C~0.2 :the strength of the Chiral restoration at the nuclear saturation density

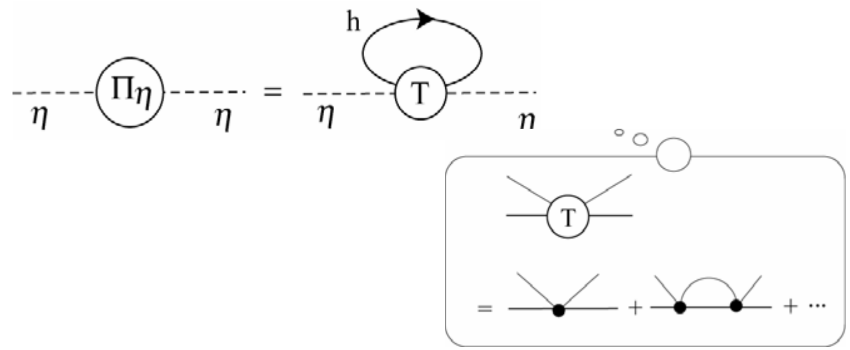
*** reduction of mass difference**

Chiral unitary model

Kaiser, Siegel, Weise, PLB362(95)23
Waas, Weise, NPA625(97)287
Garcia-Recio, Nieves, Inoue, Oset, PLB550(02)47
Inoue, Oset, NPA710(02) 354
etc.

A coupled channel Bethe-Salpeter eq.

$$\{\pi^- p, \pi^0 n, \eta n, K^0\Lambda, K^+\Sigma^-, K^0\Sigma^0, \pi^0\pi^- p, \pi^+\pi^- n\}$$

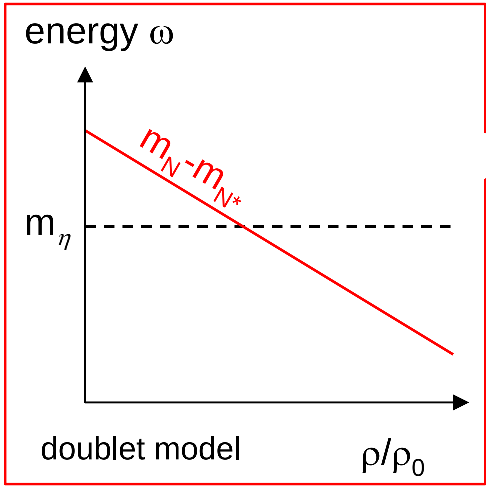


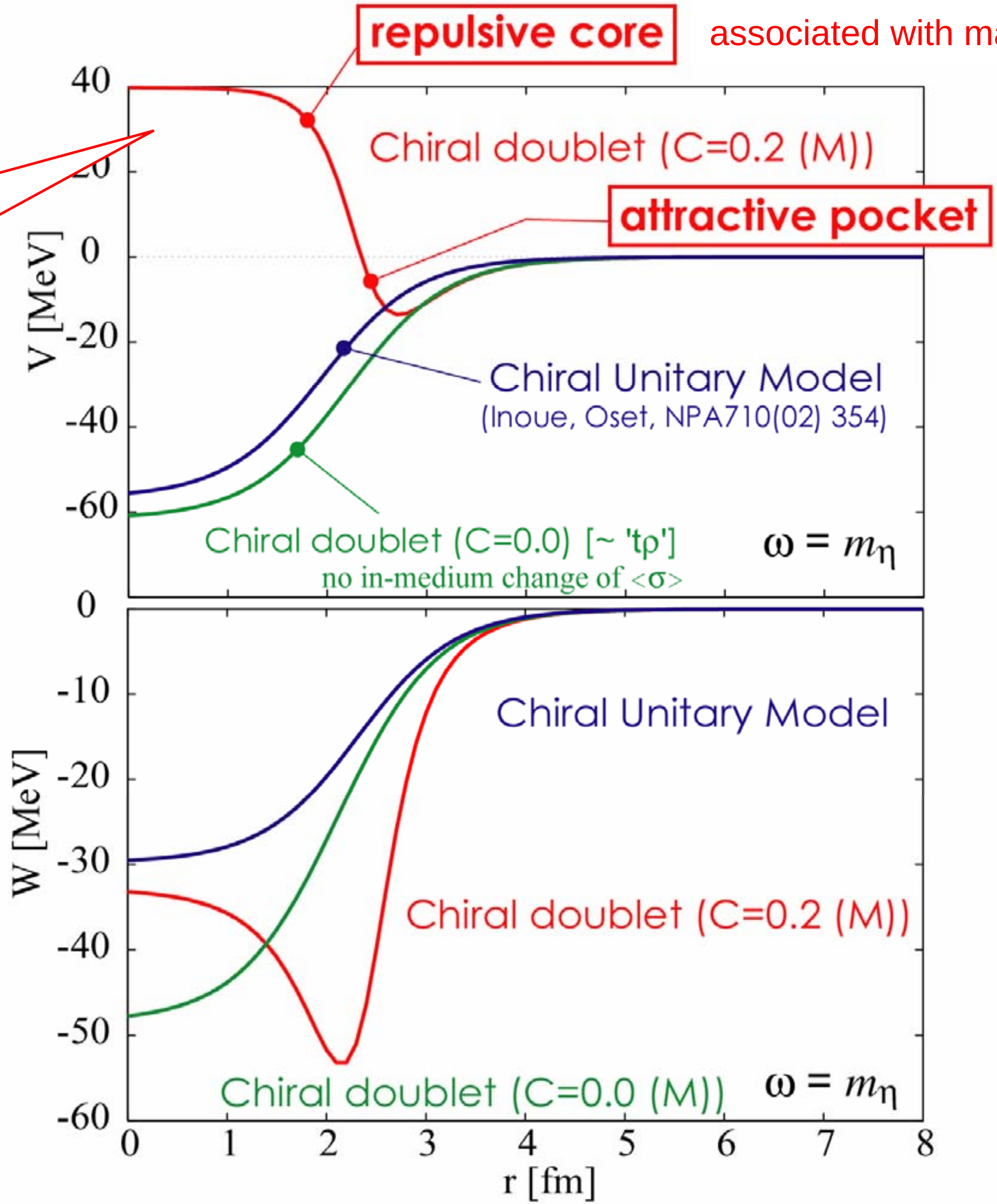
* the N* is introduced as **a resonance generated dynamically** from meson-baryon scattering.

*** No mass shift of N* is expected in the nuclear medium.**

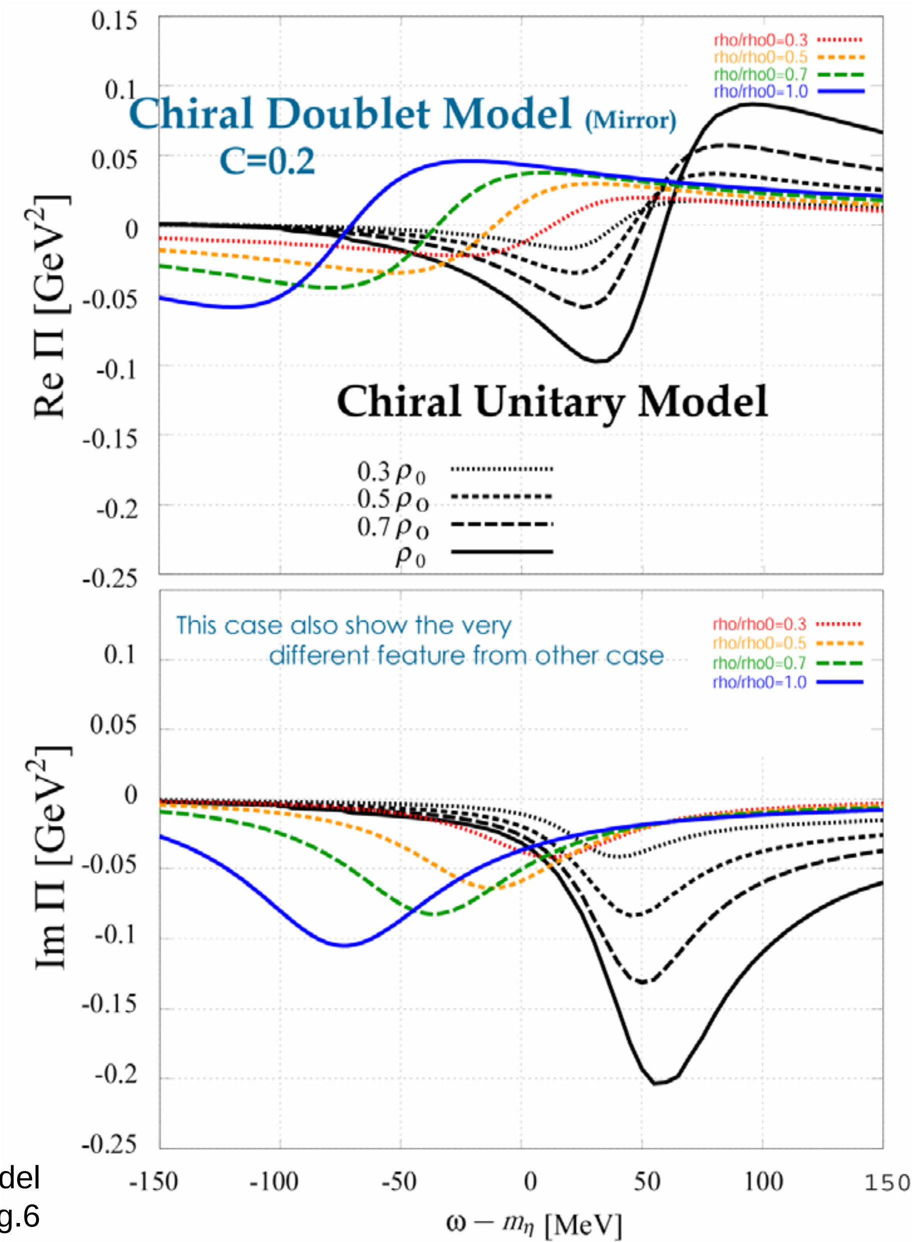
* In this study, we directly take the eta-self-energy in the ref.NPA710(02)354

η-Nucleus optical potential



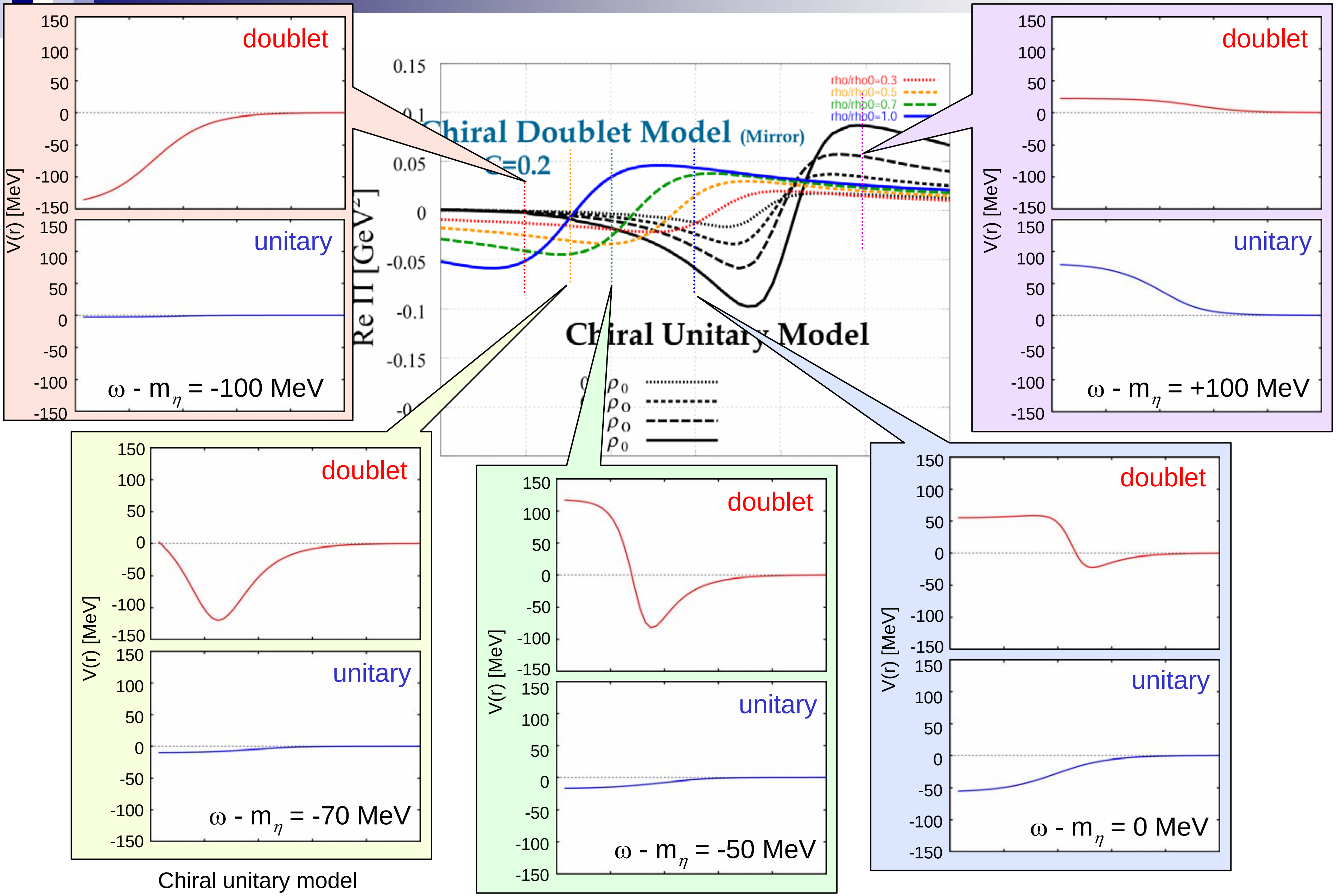


Energy dependence of the optical potentials



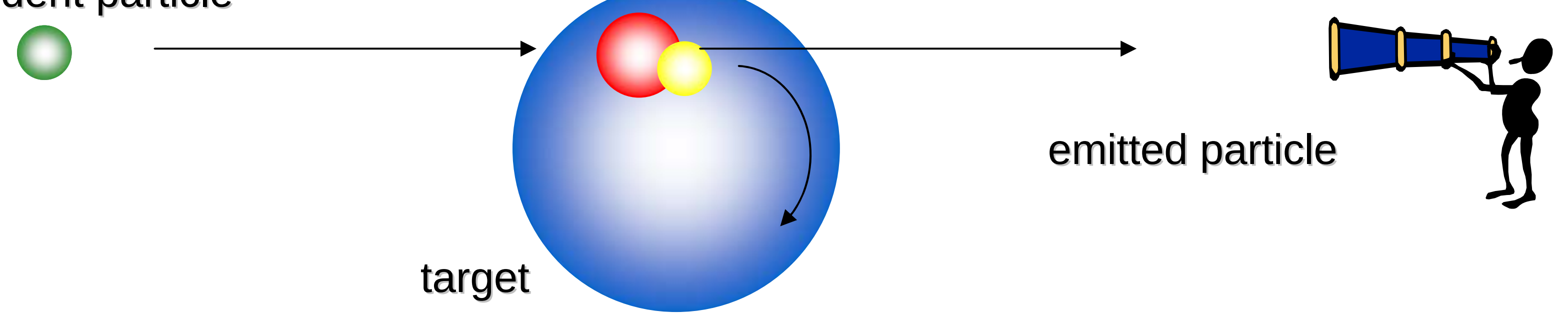
Chiral unitary model
Inoue, Oset, NPA710(02) 354, fig.6

Energy dependence of the optical potentials



Chiral unitary model
Inoue, Oset, NPA710(02) 354, fig.6

Missing mass spectroscopy : one proton pick-up

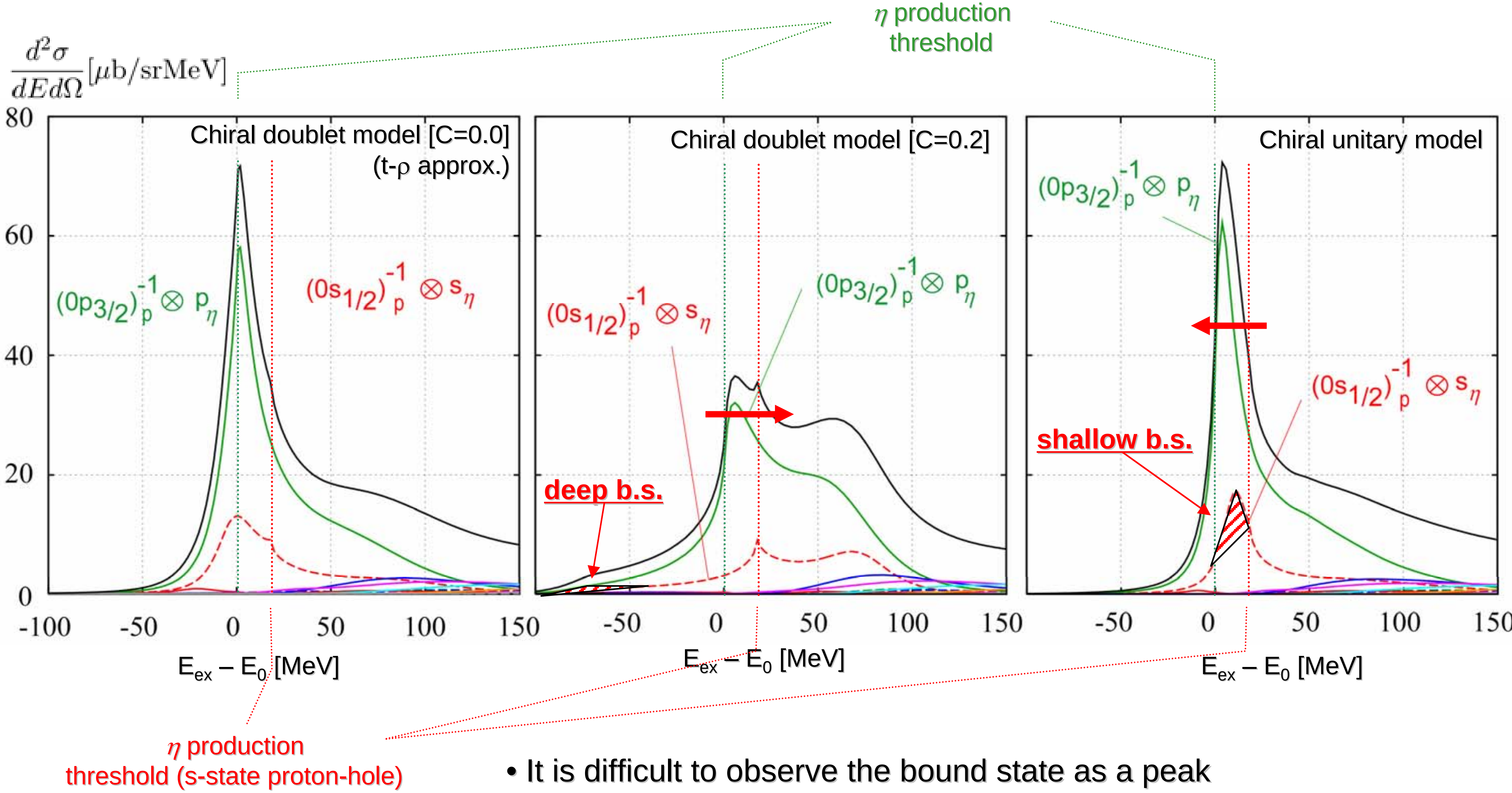


- $(d,^3He)$: established by studies of pionic atom formation
  - theory … S.Hirenzaki, H.Toki, T.Yamazaki, PRC44(91)2472, …
  - experiment … K.Itahashi et al., PRC62(00)025202, …
  - η-mesic nuclei formation : D.Jido,H.N.,S.Hirenzaki, PRC66(02)045202, H.N.,D.Jido,S.Hirenzaki, PRC68(03)035205.
- (γ,p) : smaller distortion effect
  - ω-nucleus … Marco, Weise, PLB502(01)59
  - π-atom … Hirenzaki, Oset, PLB527(02)69
  - η-mesic nuclei formation : H.N., D.Jido,S.Hirenzaki, NPA761(05)92.
- (π^+,p) : could be performed at J-PARC ?
  - secondary meson beam, π, K, …
    - Elementary cross section : $(d\sigma/d\Omega)$ ~ 2.4 mb/sr [Crystal Ball : Prakhov *et al.*, PRC72(05)015203]

(π^+,p) spectra : ^{12}C target

T_π = 820 MeV (p_π = 950 MeV/c) : θ = 0 deg. (Lab)

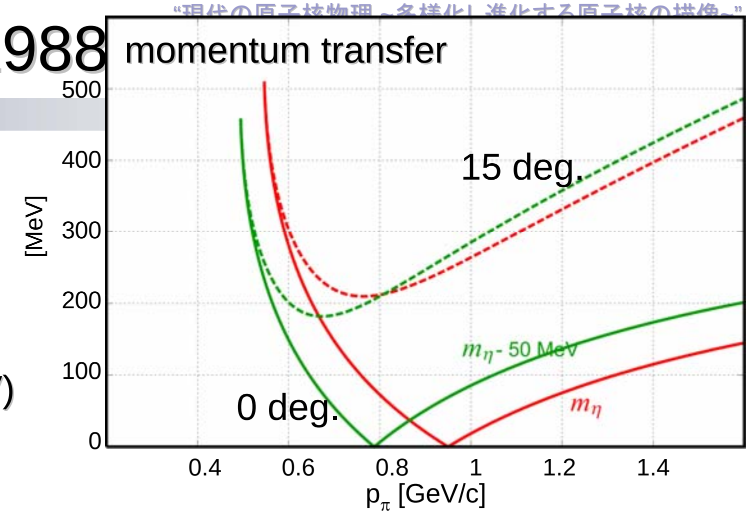
recoilless at η threshold



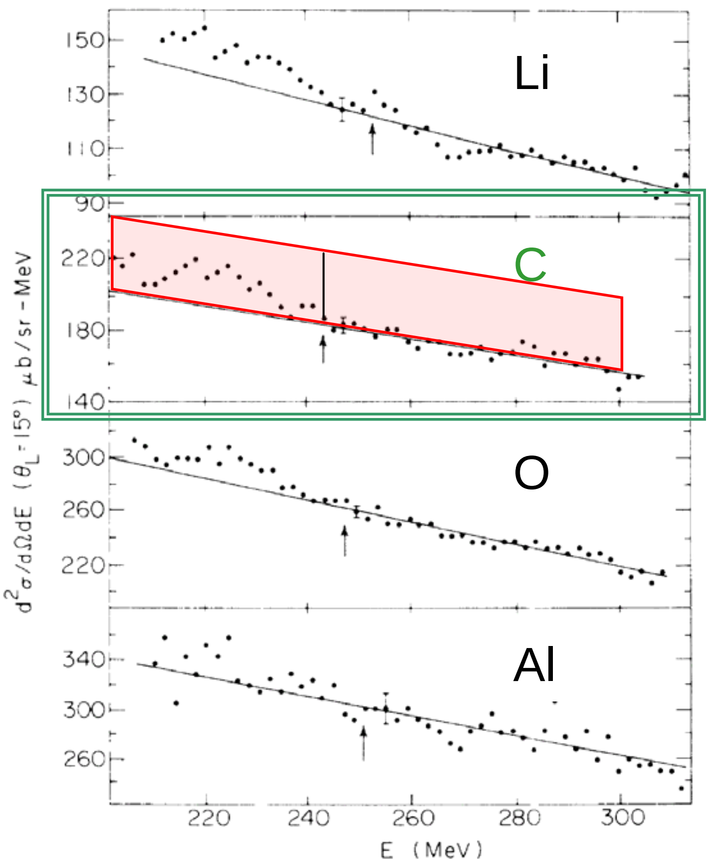
- It is difficult to observe the bound state as a peak
- We need to observe whole shape itself (not peak structures)

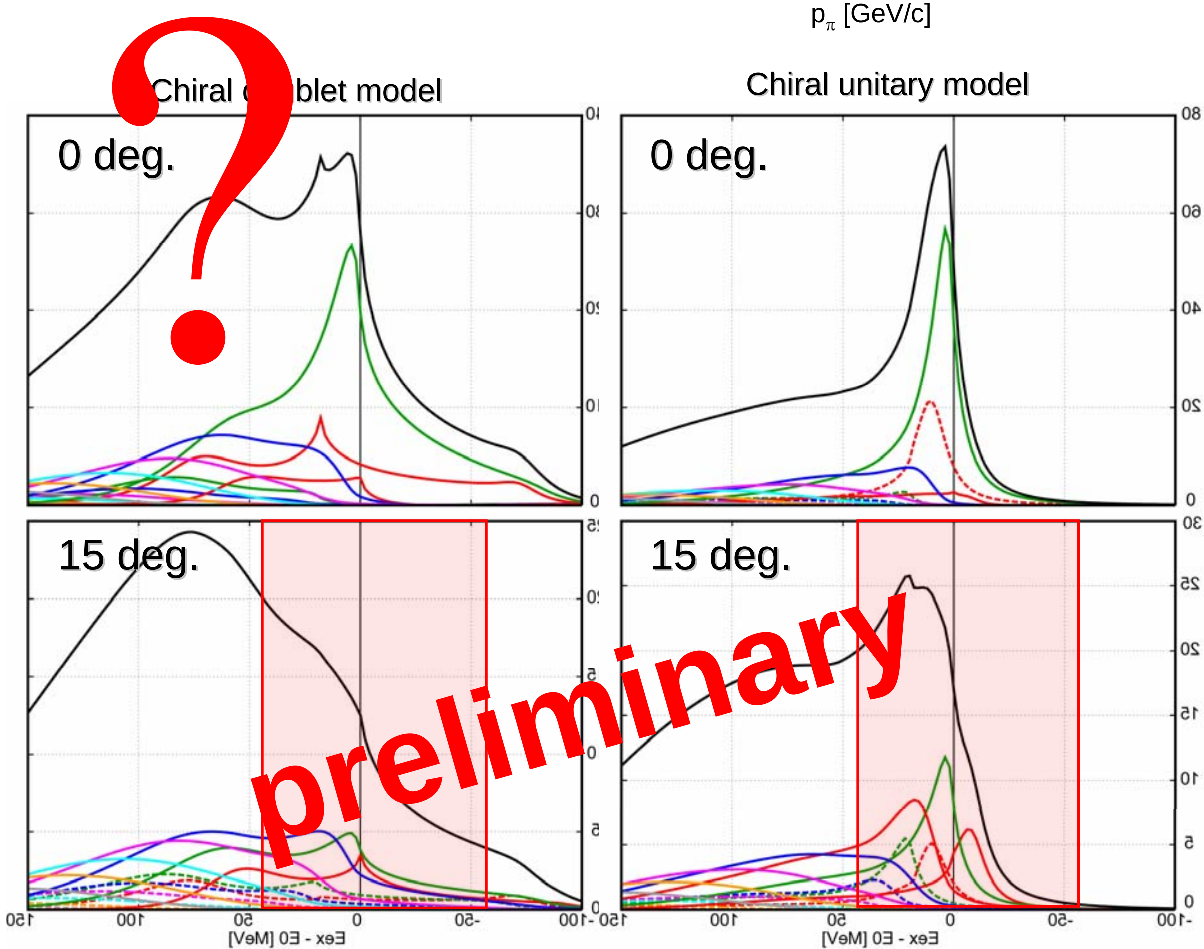
(π^+,p) spectra : past experiment in 1988

- Chrien et al., PRL60(1988)2595
  - p_π = 800 MeV/c
  - proton angle : 15 deg. (Lab.)
  - targets : Li, C, O, Al
  - search for predicted narrow bound state (ex. Γ ~ 10 MeV)
  - → negative results (bound state was not observed)



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





η'(958)-Nucleus system

H.N., S. Hirenzaki, Phys.Rev.Lett.**94**, 232503 (2005)
H.N., M.Takizawa and S. Hirenzaki, nucl-th/0606052

- η'(958) meson …close connections with U_A(1) anomaly
  - some 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'**
  - a poor experimental information on the U_A(1) anomaly at finite density

- proposal for the formation reaction of the η'-mesic nuclei using the **(γ,p) reactions**
  - U_A(1) anomaly in medium from the viewpoint of "mesic nuclei"
  - the η' properties, especially mass shift, at finite density

Model for η and η' meson in medium

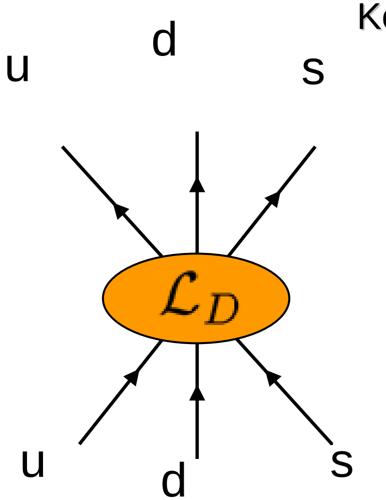
- **Nambu-Jona-Lasinio model** with the **KMT interaction**
  - unified treatment of the η and η' meson

$$\mathcal{L} = \bar{q}(i\,\partial\!\!\!/ - m)q + \frac{g_s}{2}\sum_{a=0}^{8}\left[(\bar{q}\lambda_a q)^2 + (i\bar{q}\lambda_a\gamma_5 q)^2\right]$$

$$+ g_D\left[\det \bar{q}_i(1-\gamma_5)q_j + h.c.\right]$$

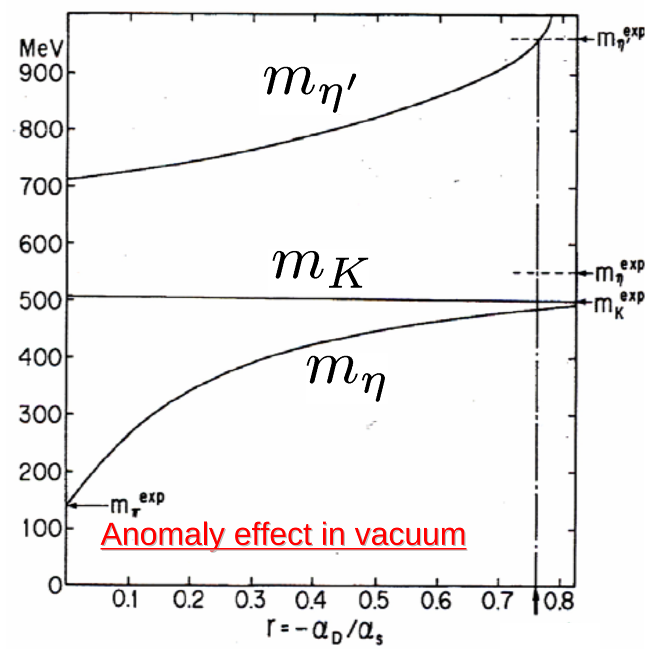
explicit breaking the $U_A(1)$ sym.

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



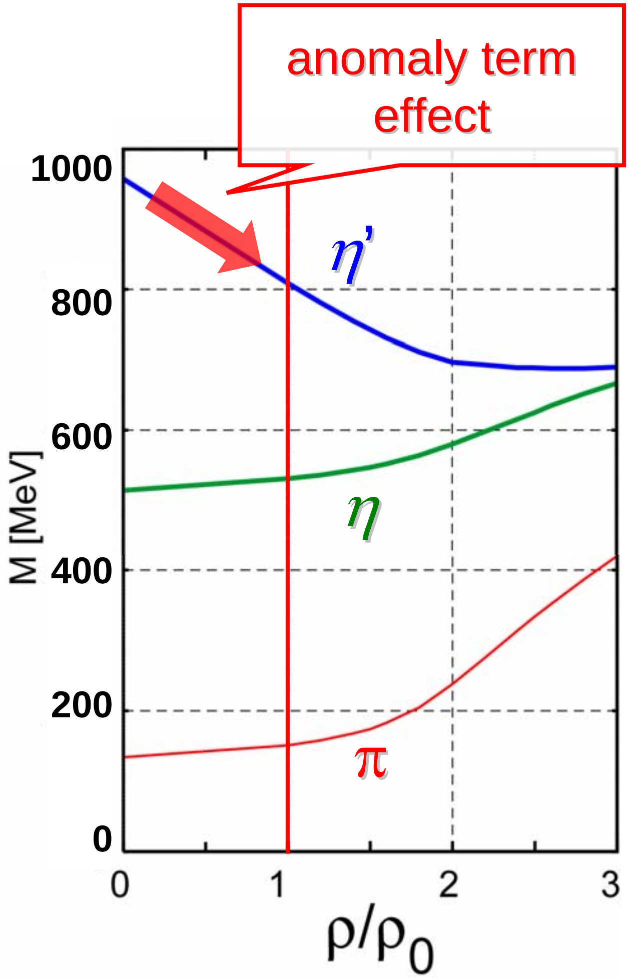
One can reproduce the heavy η' mass

Kunihiro, Hatsuda, PLB206(88)385, Fig.3



SU(2) symmetric matter $\rho_u = \rho_d, \ \rho_s = 0$

- we consider the SU(2) sym. matter as the sym. nuclear matter.



parameters (in vacuum)

P. Rehberg, et al., PRC53(96)410.

Λ = 602.3 [MeV]
$g_S \Lambda^2$ = 3.67
$g_D \Lambda^5$ = -12.36
$m_{u,d}$ = 5.5 [MeV]
m_s = 140.7 [MeV]

$M_{u,d}$ = 367.6 [MeV]
M_s = 549.5 [MeV]
$\langle \bar{u}u \rangle^{1/3}$ = -241.9 [MeV]
$\langle \bar{s}s \rangle^{1/3}$ = -257.7 [MeV]
$m_{\eta'}$ = 958 [MeV]
m_η = 514 [MeV]
m_π = 135 [MeV]

η and η' mass shifts @ ρ_0

$\Delta m_{\eta'} \sim -150$ MeV @ ρ_0

$\Delta m_{\eta} \sim +20$ MeV @ ρ_0

We can see the large medium effect even at normal nuclear density.

η- & η'-Nucleus optical potential

~ potential description

$$U(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$

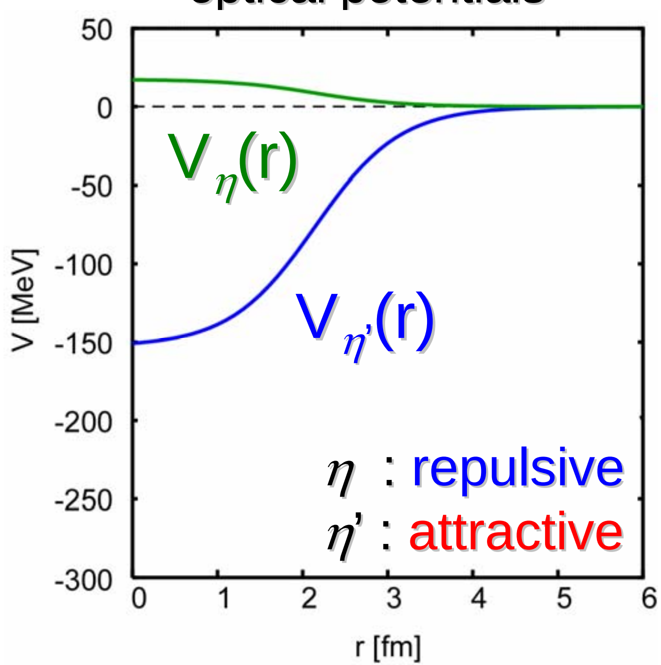
Real Part V_0

» evaluated by possible η, η' mass shift at ρ_0

$$m_{\eta'}^2 \to m_{\eta'}^2(\rho) = (m_{\eta'} + \Delta m_{\eta'}(\rho))^2 \sim m_0^2 + 2m_0\Delta m(\rho)$$

$$\Delta m(\rho) \to V(\rho(r)) = V_0\frac{\rho(r)}{\rho_0}$$

optical potentials



η- & η'-Nucleus optical potential

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$$m_{\eta'}^2 \to m_{\eta'}^2(\rho) = (m_{\eta'} + \Delta m_{\eta'}(\rho))^2 \sim m_0^2 + 2m_0\Delta m(\rho)$$

$$\Delta m(\rho) \to V(\rho(r)) = V_0 \frac{\rho(r)}{\rho_0}$$

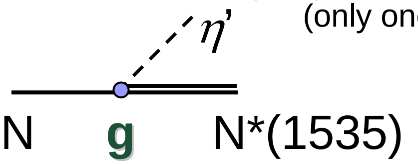
Imaginary Part W_0 for η'

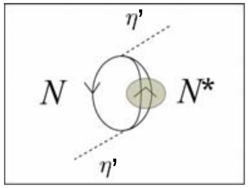
~ phenomenological estimation

» estimated from AIP Conf.Proc.717 (04)837(A.Sibirtsev,Ch.Elster, S.Krewald, J.Speth) analysis of $\gamma p \to \eta' p$ data

→ fix a coupling g

(only one resonance included)





› in analogy with Δ-hole model for the π-nucleus system

$$U \sim \frac{g^2}{2m_{\eta'}}\frac{\rho}{m_{\eta'} + M_N - M_{N^*} + i\Gamma_{N^*}/2} = (+77\text{ MeV},\ -8\text{ MeV}i)\frac{\rho}{\rho_0}$$

$$W_0 = -5,\ -20\text{ MeV (parameter)}$$

Imaginary Part for η

W_0 = - 40 MeV

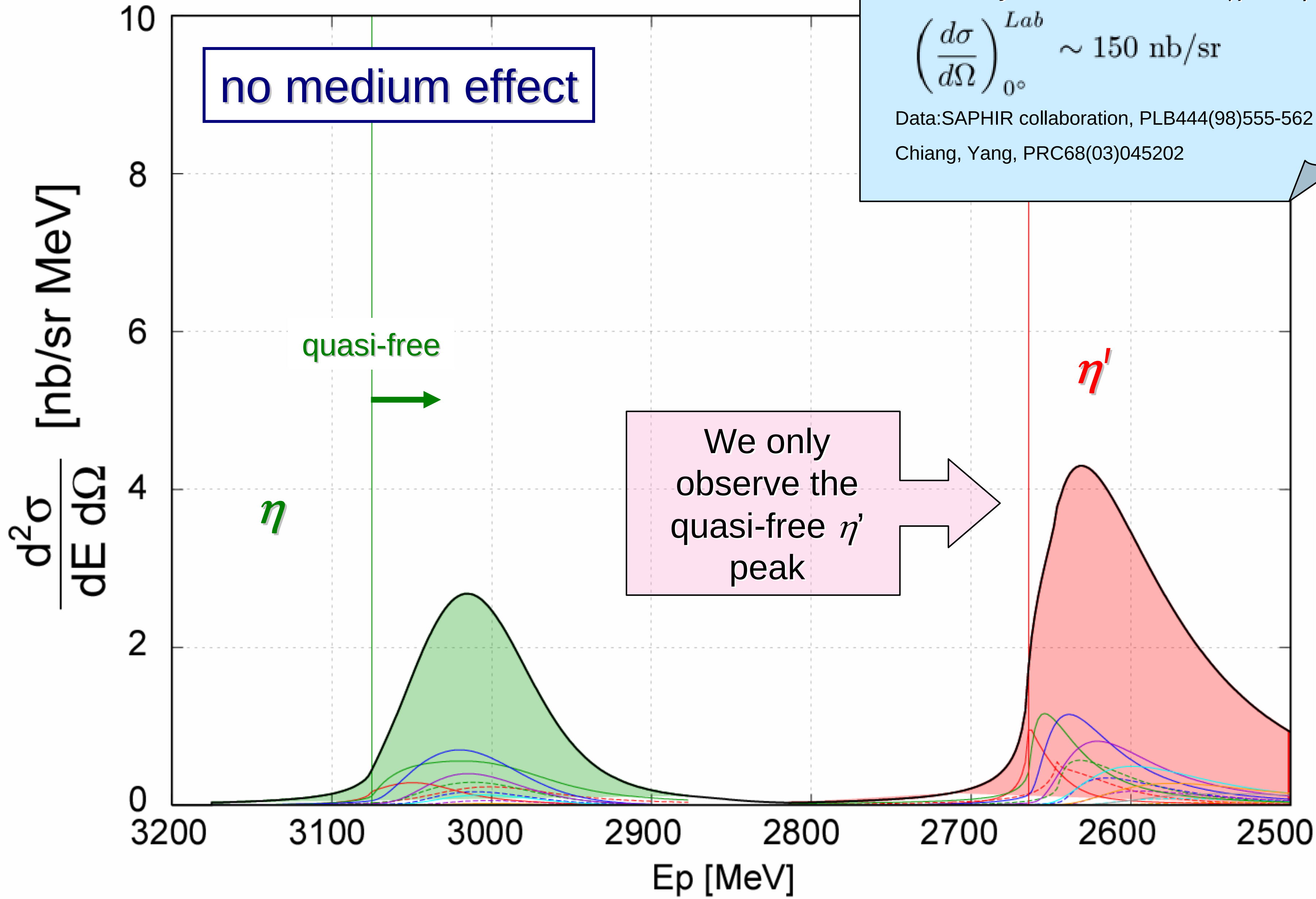
D.Jido,H.N.,S.Hirenzaki, PRC66(02)045202,
H.N.,D.Jido,S.Hirenzaki, PRC68(03)035205,

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

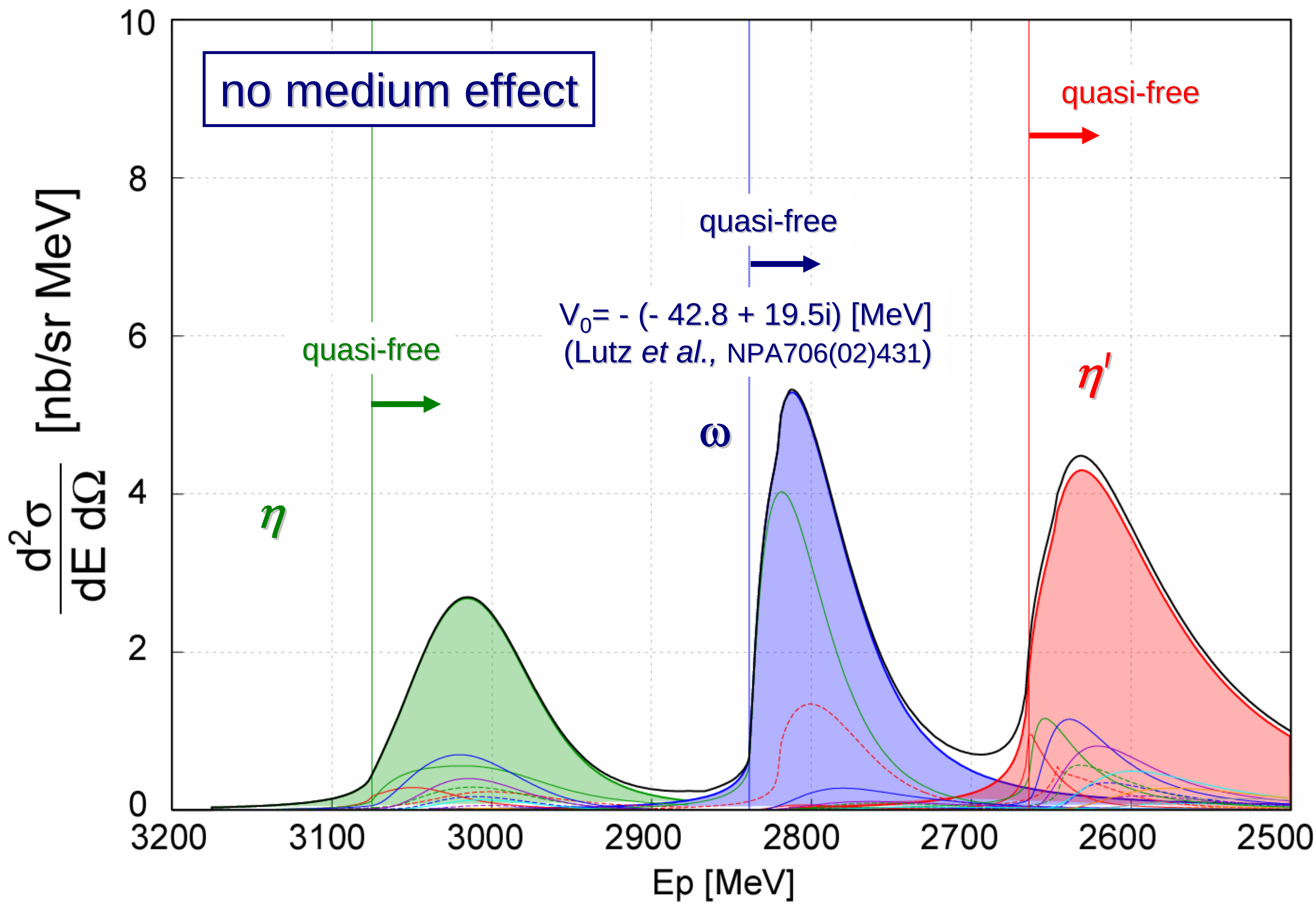
(γ,p) reaction @ Eγ=2.7 GeV
target … ^{12}C
Forward (θ ~ 0 deg.)
Elementary cross section for $\gamma p \rightarrow \eta' p$

$$\left(\frac{d\sigma}{d\Omega}\right)^{Lab}_{0^\circ} \sim 150\ \mathrm{nb/sr}$$

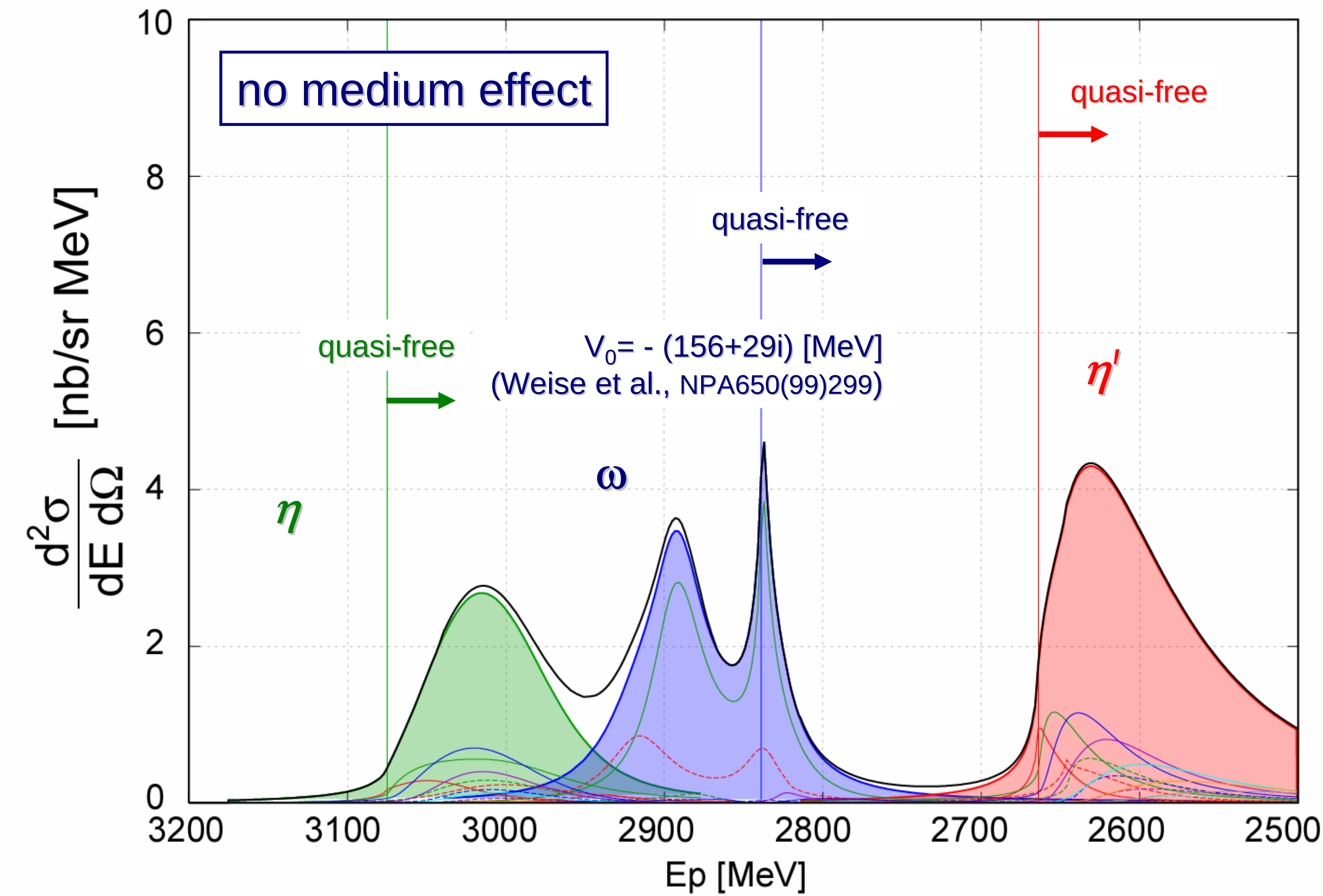
Data:SAPHIR collaboration, PLB444(98)555-562
Chiang, Yang, PRC68(03)045202



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



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



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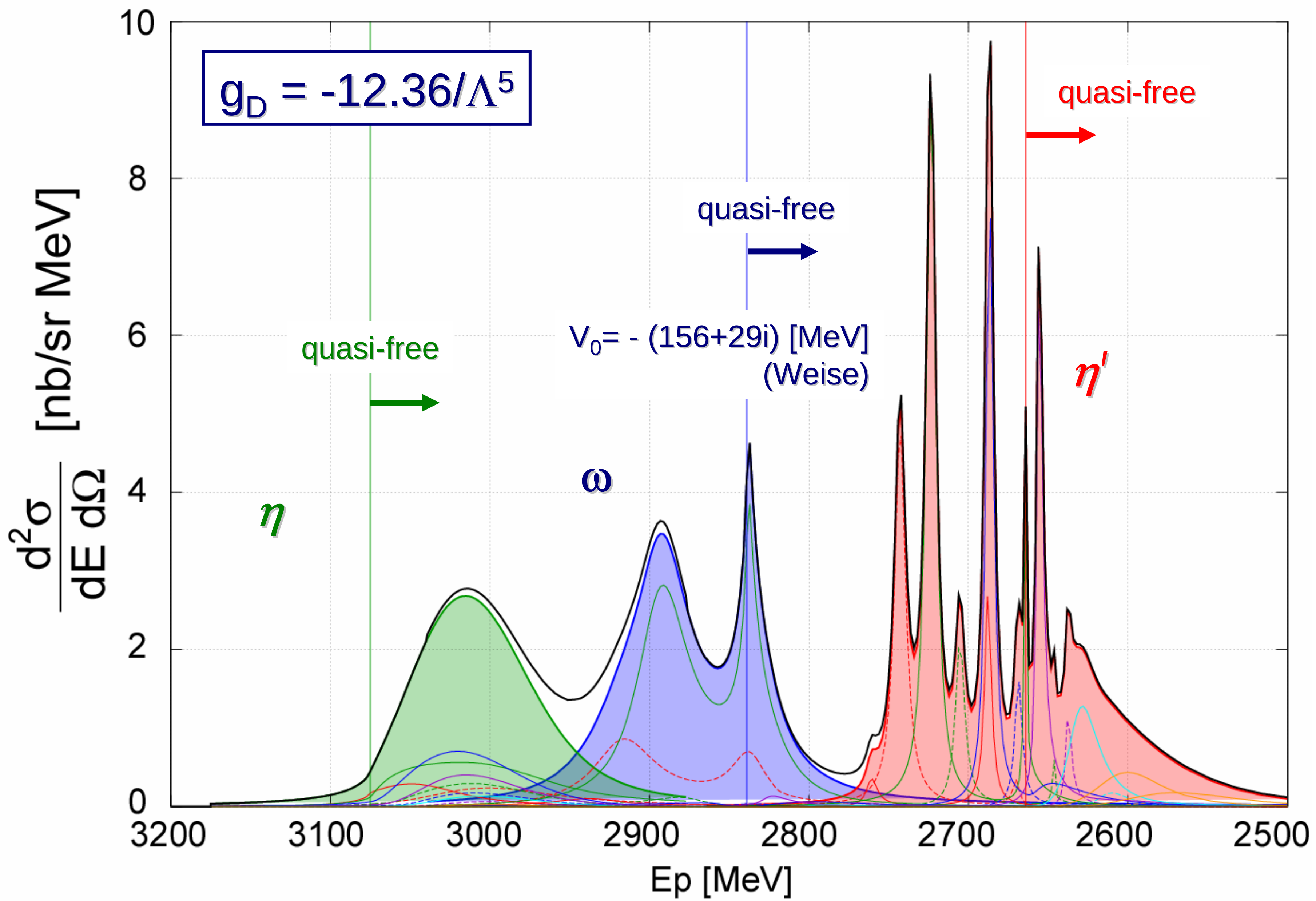

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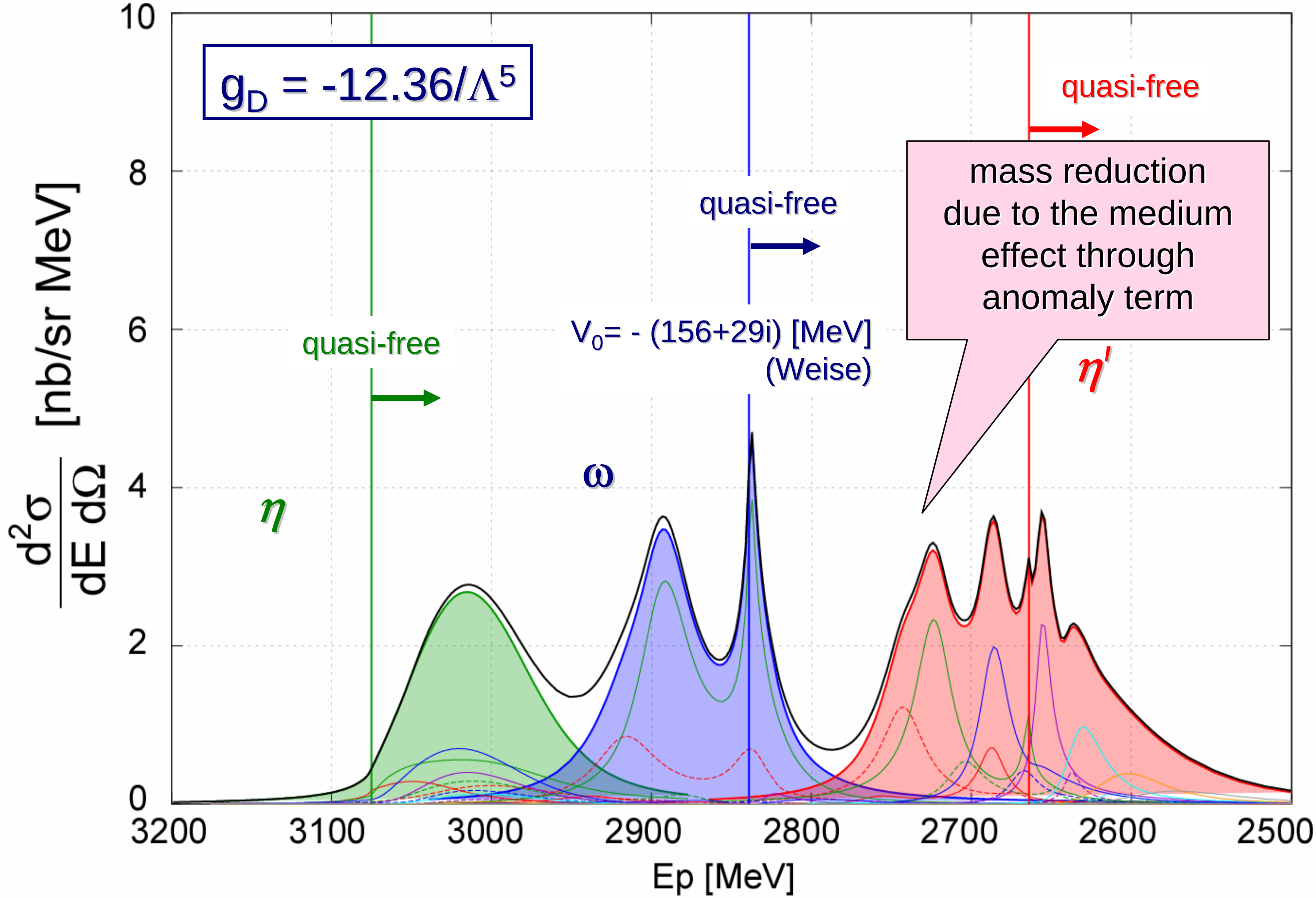

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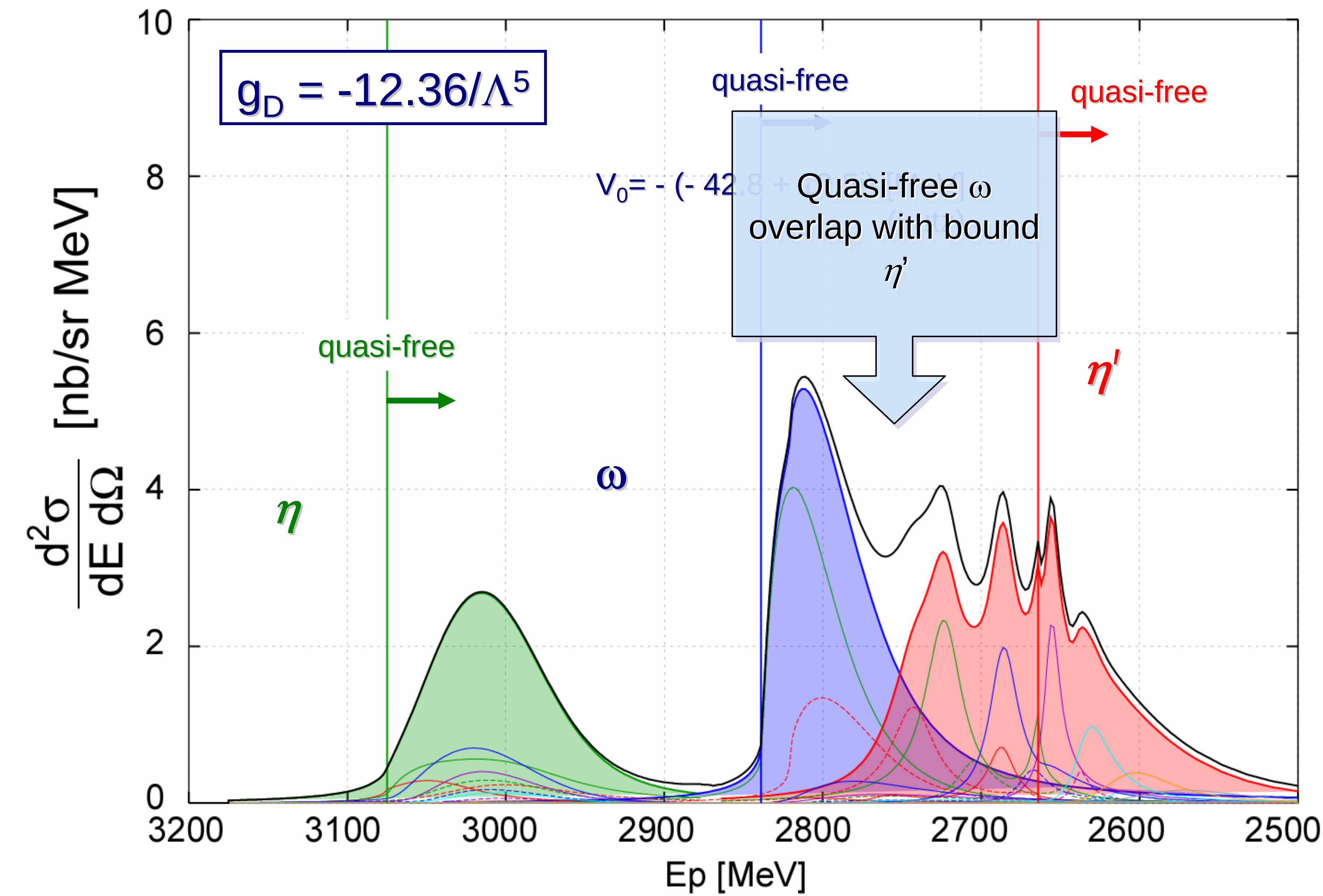

Summary

- Formations of mesic nuclei
  - in-medium properties of hadrons and QCD symmetries
  - **η -nucleus systems**
    - two different chiral models
      - different physical pictures of **the N*(1535) resonance**
  - **η'-nucleus systems**
    - New information on **the $U_A(1)$ anomaly at finite density**
- experiments
  - (d,^{3}He) experiment for η-nucleus system @ GSI (2005?6?)
    - Compare the spectra of (γ,p) and (d,^{3}He) : complementary information
  - (π^+,p) reaction for η-nucleus system
    - possible at J-PARC ?
  - (γ,p) reaction for the formation of ω-mesic nuclei @ SPring-8
    - information on η & η’ also expected
- Future works
  - η-mesic nuclei
    - (π^+,p) experiments by Chrien et al., (1988)
    - appropriate kinematical conditions
  - η’-mesic nuclei
    - relation with other models for η & η’