Formation of η Mesic Nucleus

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@ Meson2010, Krakow, Poland

Outline of this talk

- 1 Introduction
- 2 Eta-Nucleus Interaction…. Based on Chiral Models
- 3 Formation of eta mesic nucleus by (pi, N) reaction
- 4 Preliminary results for d+d reaction
- 5 Summary

Introduction and Motivation

- Interests of Mesic Nucleus

  1. Exotic Many Body Physics

     … Physics of ‘Impurities’ and ‘Asymmetry’

  2. Hadron Physics at finite density

     … Possible connections to

     symmetries of strong interaction

Introduction and Motivation

- Mesons in nuclei and main interest
  - » Pionic Atom … fpi at finite density (Toki, Yamazaki,Hayano, Itahashi, Suzuki,,,)
  - » K-atom & nuclei … deeply bound nuclear state ? (Yamagata-Sekihara)
  - » η-mesic nuclei … N*(1535) in medium (Nagahiro, Jido,,,)
  - » η'-mesic nuclei … $U_A(1)$ anomaly in medium (Nagahiro, Takizawa)
  - » Phi –mesic nuclei … mass shift, OZI rule (Yamagata-Sekihara, Cabrera, Vicente-Vacas)
  - » ω-mesic nuclei ... bound state ? mass shift ? (Kaskulov, Nagahiro, Oset)
  - » σ-mesic nuclei … $m_\sigma \sim 2m_\pi$ enhancement ? (Nagahiro, Hatsuda, Kunihiro)
  - » --------
  - » Θ^+ in medium … S=+1 hypernuclei $[(K^+,\pi^+)]$ (Nagahiro, Oset, Vicente-Vacas)

Introduction of η-mesic nuclei

Motivation and our aim

» η-N system … strongly couples to the **N*(1535) resonance**

→ **η-mesic nuculei … doorway to in-medium N*(1535)**

» **N*(1535)** … a candidate of the chiral partner of nucleon

→ **chiral symmetry for baryons**

Many works for η mesic nuclei from 1980's

- Theor.
  - Liu, Haider, PRC34(1986)1845
  - Kohno, Tanabe, PLB231(1989)219; NPA519(1990)755
  - Garcia-Recio, Nieves, Inoue, Oset PLB550(02)47
  - C. Wilkin, T. Ueda, S. Wycech, ……
- Exp.
  - Chrien *et al.*, PRL60(1988)2595
  - TAPS@MAMI ($\gamma + {}^3\text{He} \rightarrow \pi^0 + p + X$)
  - COSY-GEM ($p + \text{Al} \rightarrow {}^3\text{He} + \text{Mg-}\eta$)
  - WASA-at-COSY ($d + d \rightarrow {}^3\text{He} + p + \pi$)
  - JPARC, ……

η-Nucleus system : Introduction

Our works for eta-mesic nuclei

- R.S. Hayano, S. Hirenzaki, A. Gillitzer, Eur. Phys. J. (99)
- D.Jido, H.Nagahiro and S.Hirenzaki, Phys.Rev.**C66**, 045202, 2002.
- H.Nagahiro, D.Jido, S.Hirenzaki, Phys.Rev.**C68**, 035205, 2003.
- H.Nagahiro, D.Jido and S.Hirenzaki, Nucl.Phys.**A761**,92, 2005.
- D.Jido, E.E.Kolomeitsev, H.Nagahiro, S.Hirenzaki, Nucl.Phys.**A811**:158, 2008.
- H.Nagahiro, D.Jido, S.Hirenzaki, Phys.Rev.**C80**,025205, 2009.

properties of eta meson

η meson

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

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

η-N system

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

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

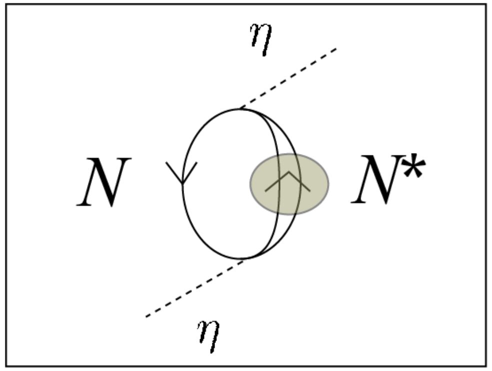
ηNN* system

-No I=3/2 baryon contamination
-Large coupling constant
-no suppression at threshold
(s-wave coupling)

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

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

η-Nucleus Interaction ~ N* dominance model ~



(Chiang, Oset, Liu PRC44(1991)738)
(D.Jido, H.Nagahiro, S.H. PRC66(2002)045202)

$g_\eta \simeq 2.0$

to reproduce the partial width
$\Gamma_{N^* \to \eta N} \simeq 75 \text{ MeV}$
at tree level.

optical potential

energy dependence

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

density-dependence

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 model for N and N*

Chiral doublet model

DeTar, Kunihiro, PRD39 (89)2805
Jido, Oka, Hosaka, Nemoto, PTP106(01)873
Jido, Hatsuda, Kunirhiro, NPA671(00)471

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

Lagrangian

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

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**

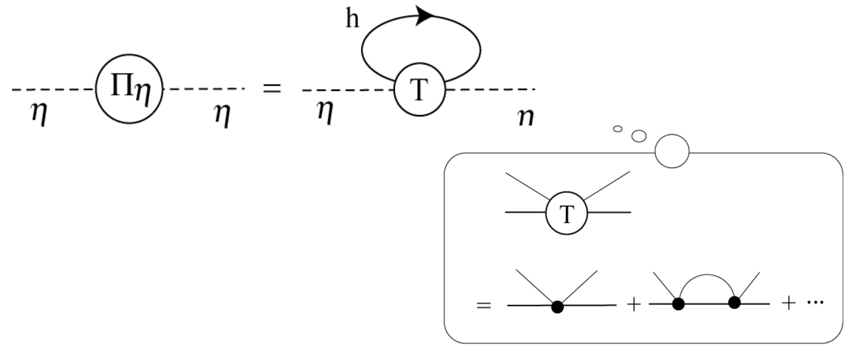
Chiral unitary model

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

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

A coupled channel Bethe-Salpeter eq.

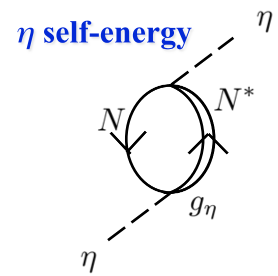
$$\{\pi^- p,\ \pi^0 n,\ \eta n,\ K^0\Lambda,\ K^+\Sigma^-,\ K^0\Sigma^0,\ \pi^0\pi^- p,\ \pi^+\pi^- n\}$$



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

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

η-nucleus interaction : potential descriptions



optical potential

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

potential nature at η threshold

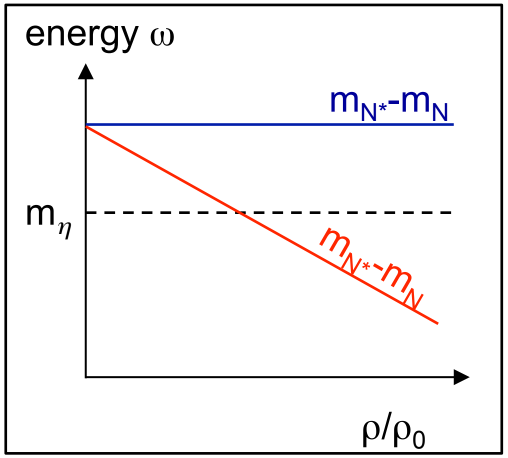
$$m_\eta - (m_{N^*} - m_N) < 0$$

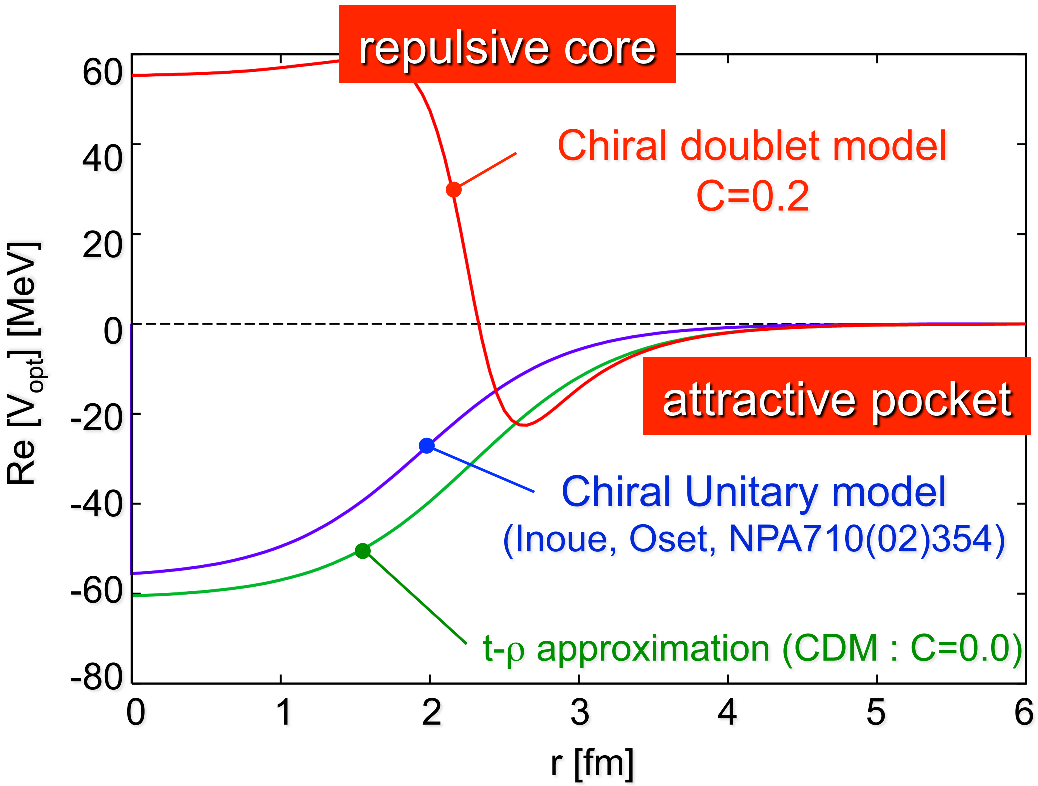
attractive

medium effect

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

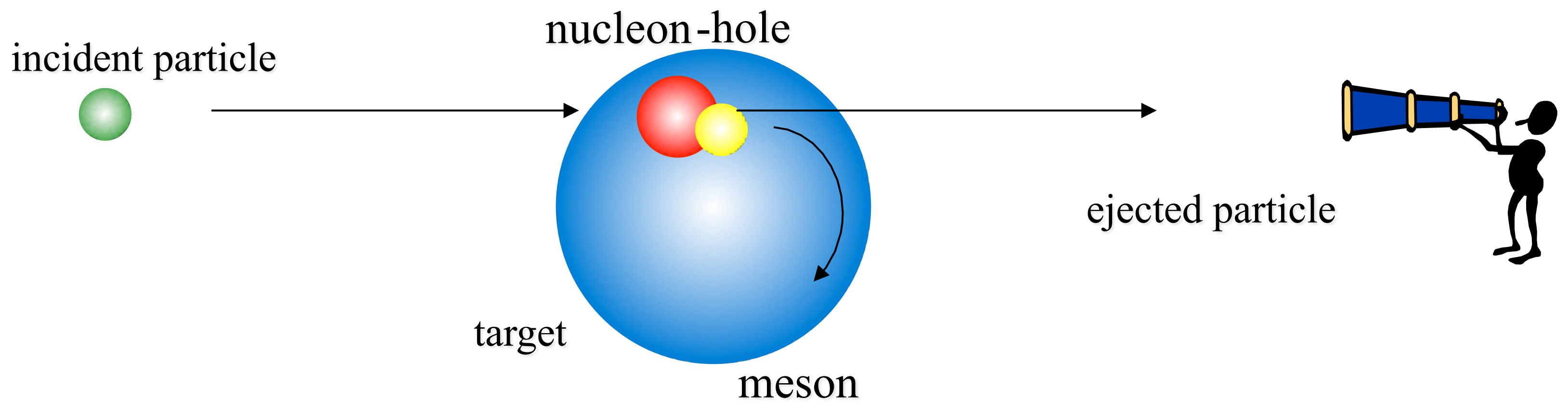
repulsive





•D.Jido, H.Nagahiro and S.Hirenzaki, PRC66(02)045202

Formation by the Missing mass spectroscopy



Candidate reactions for the mesic nuclei formation

» (d,^{3}He) reaction …established method π atom formation (96, 98, 01)

S.Hirenzaki, H.Toki, T.Yamazaki, PRC44(91)2472, …
K.Itahashi, *et al.*, PRC62(00)025202, …

» (γ,p) reaction … smaller distortion effect

M.Kohno, H.Tanabe PLB231(89)219
E.Marco, W.Weise, PLB502(01)59
H.Nagahiro, D.Jido, S.Hirenzaki, Nucl. Phys. **A761** (2005) 92-119 etc..

» **(π,N) reaction**

Chrien *et al.*, PRL60(1988)2595
Liu, Haider, PRC34(1986)1845
H.Nagahiro, D.Jido, S.Hirenzaki, PRC80(2009)025205, …

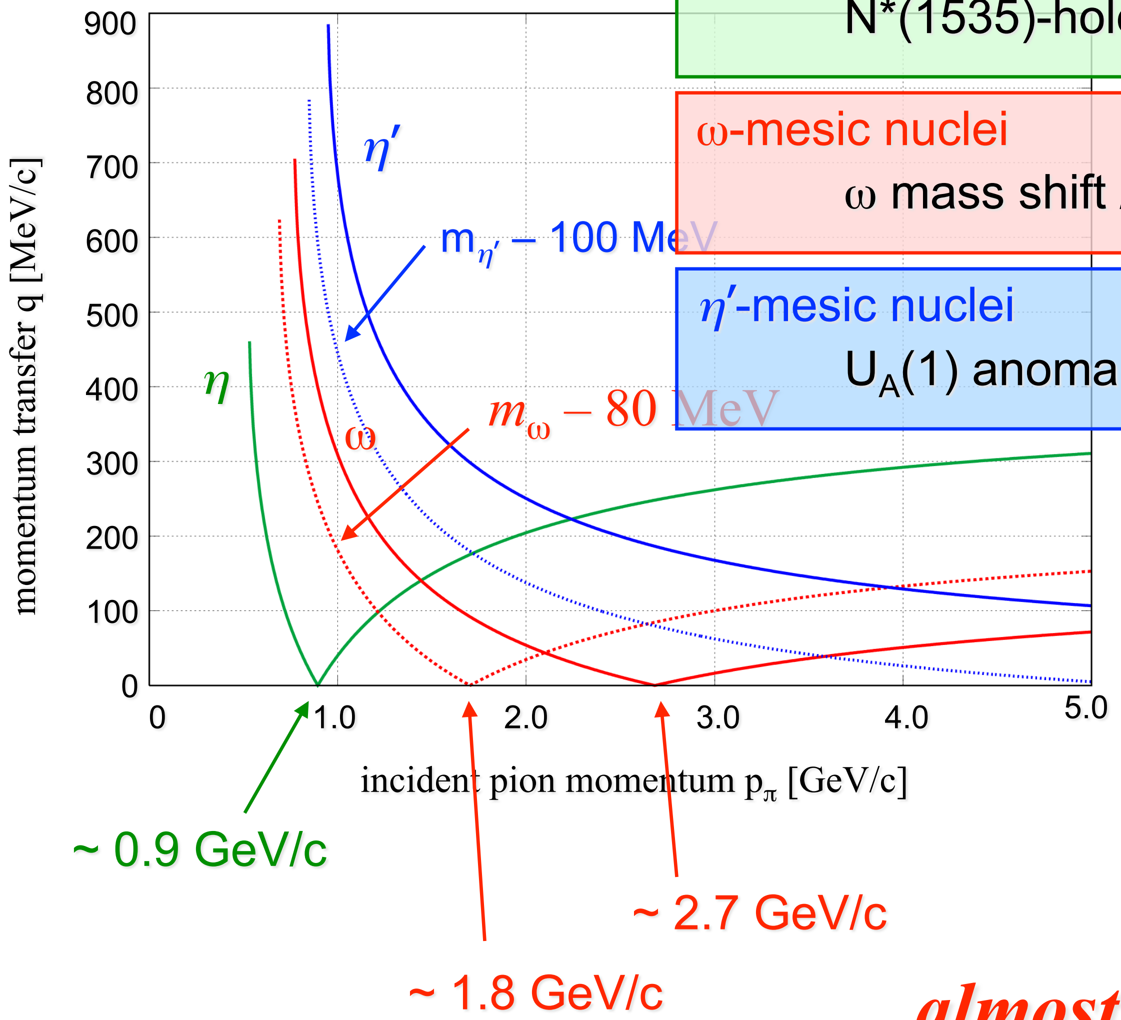
meson production in recoil-free kinematics

magic momentum in ^{12}C(π,N) reaction

η-mesic nuclei $p_\pi \sim 1$ GeV/c
N*(1535)-hole ... N*(1535) in medium

ω-mesic nuclei $p_\pi \sim 2\text{-}3$ GeV/c
ω mass shift / N(1520)-hole coupling

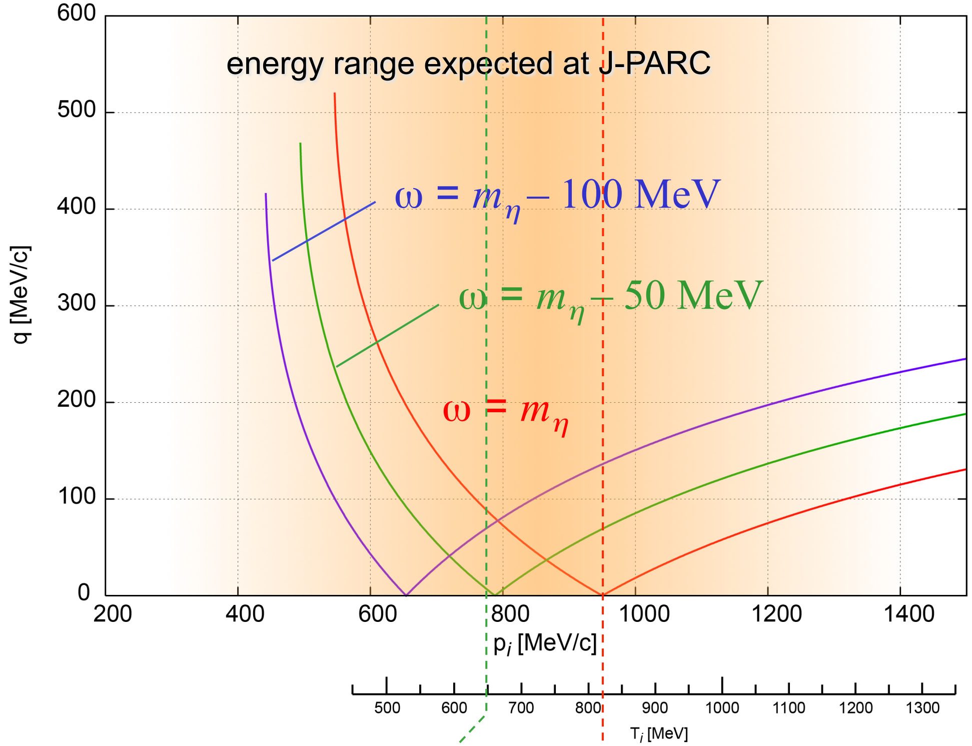
η'-mesic nuclei $p_\pi \sim 3\text{-}5$ GeV/c
$U_A(1)$ anomaly effect in medium



almost recoil-free production

$^{12}C(\pi^+,p)^{11}C_\eta$ reaction

Momentum transfer : forward proton angle



T_π = 650 MeV (p_π ~ 777 MeV/c) → $\left(\frac{d\sigma}{d\Omega}\right)^{Lab.} = 2.4\text{mb/sr}$

T_π = 820 MeV (p_π ~ 950 MeV/c) → $\left(\frac{d\sigma}{d\Omega}\right)^{Lab.} = 0.64\text{mb/sr}$

Elementary cross section

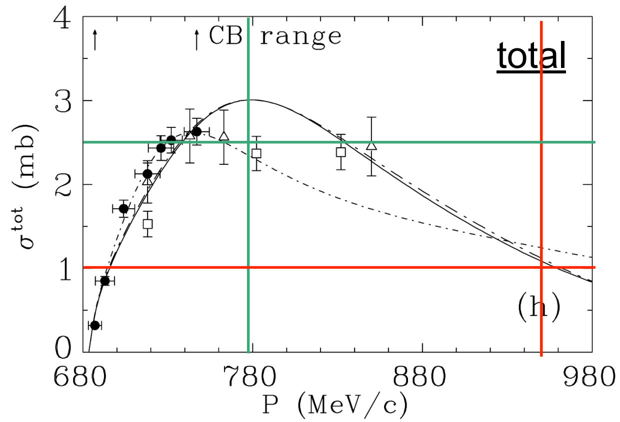
$$\pi^- p \to \eta n$$

$$\downarrow$$

$$\pi^+ n \to \eta p$$

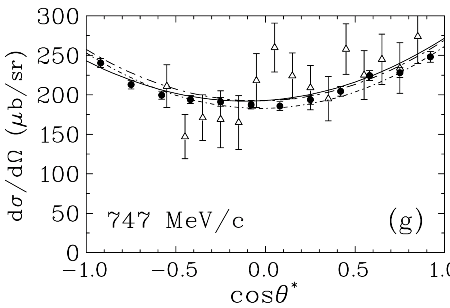
S.Prakhov *et al.*, [Crystal Ball Collaboration] PRC72,015203 (2005).

Total cross section



Angular distribution

~ Nearly flat



Formulation : π + A → p + (A-1)$_\eta$

Green's function method [Morimatsu, Yazaki NPA435(85)727, NPA483(88)493]

impulse approximation

$$\left(\frac{d^2\sigma}{d\Omega dE}\right) = \left(\frac{d\sigma}{d\Omega}\right)^{Lab.}_{n(\pi,p)\eta} \times S(E)$$

elementary cross section $\pi^+ + n \rightarrow p + \eta$

$$\left(\frac{d\sigma}{d\Omega}\right)^{Lab.} = 2.4\text{mb/sr}$$

S.Prakhov *et al.*,
[Crystal Ball Collaboration]
PRC72,015203 (2005).

nuclear response function

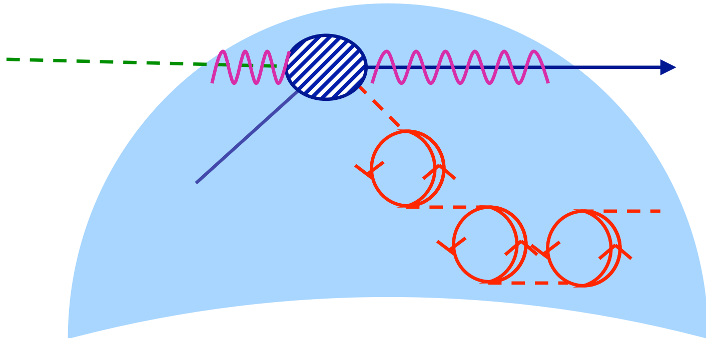
$$S(E) = -\frac{1}{\pi} Im \sum_f \mathcal{T}_f^\dagger G(E) \mathcal{T}_f$$

Green's function

$$G(E, \mathbf{r}, \mathbf{r}') = \langle p^{-1} | \phi_\eta(\mathbf{r}) \frac{1}{E - H_\eta + i\varepsilon} \phi_\eta^\dagger(\mathbf{r}') | p^{-1} \rangle$$

transition amplitude

$$\mathcal{T}_f(\mathbf{r}) = \chi_f^*(\mathbf{r}) \xi^*_{1/2, m_s} \left[Y^*_{\ell_\eta}(\hat{r}) \otimes \psi_{j_p}(\mathbf{r}) \right]_{JM} \chi_i(\mathbf{r})$$



Distortion factor : flux reduction due to absorption

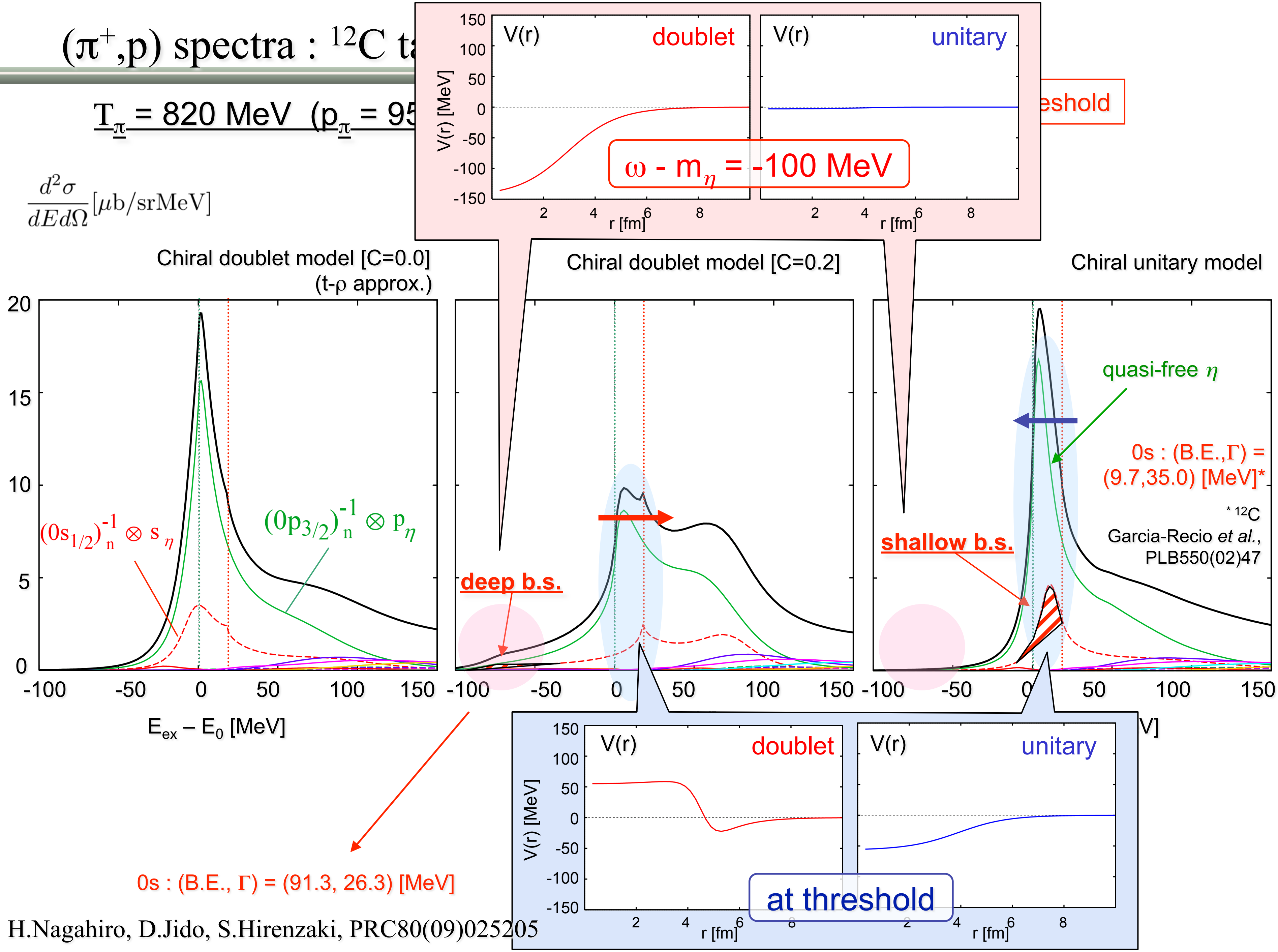
$$\chi_f^*(\mathbf{r})\chi_i(\mathbf{r}) = \exp[i\mathbf{q}\cdot\mathbf{r}] F(\mathbf{b})$$

eikonal approximation

$$F(b) = \exp\left[-\frac{1}{2}\sigma_{iN} \int_{-\infty}^{z} dz' \rho_A(z', b) - -\frac{1}{2}\sigma_{fN} \int_{z}^{\infty} dz' \rho_{A-1}(z', b) \right]$$

(π^+,p) spectra : ^{12}C ta

T_π = 820 MeV (p_π = 95

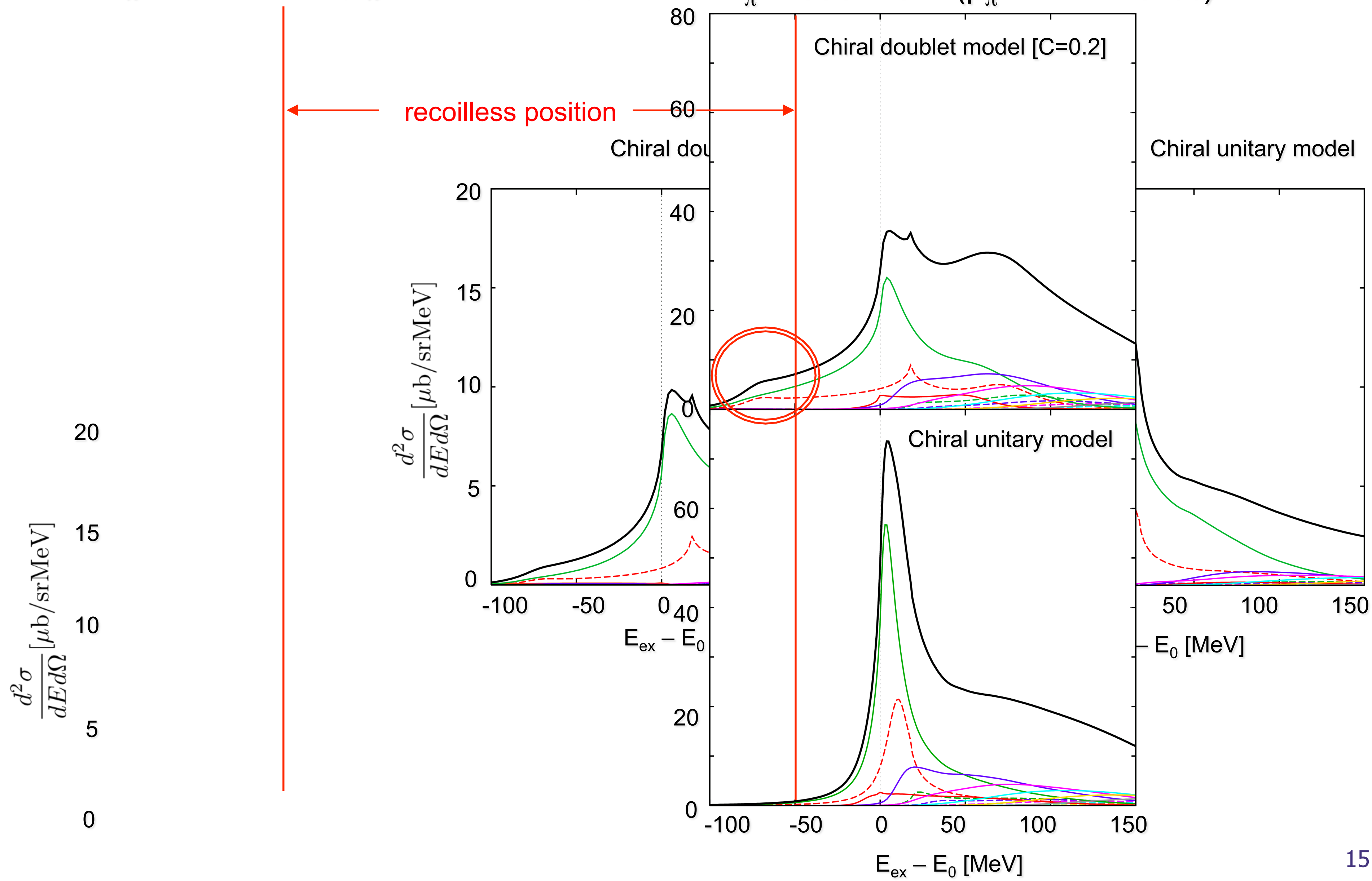


H.Nagahiro, D.Jido, S.Hirenzaki, PRC80(09)025205

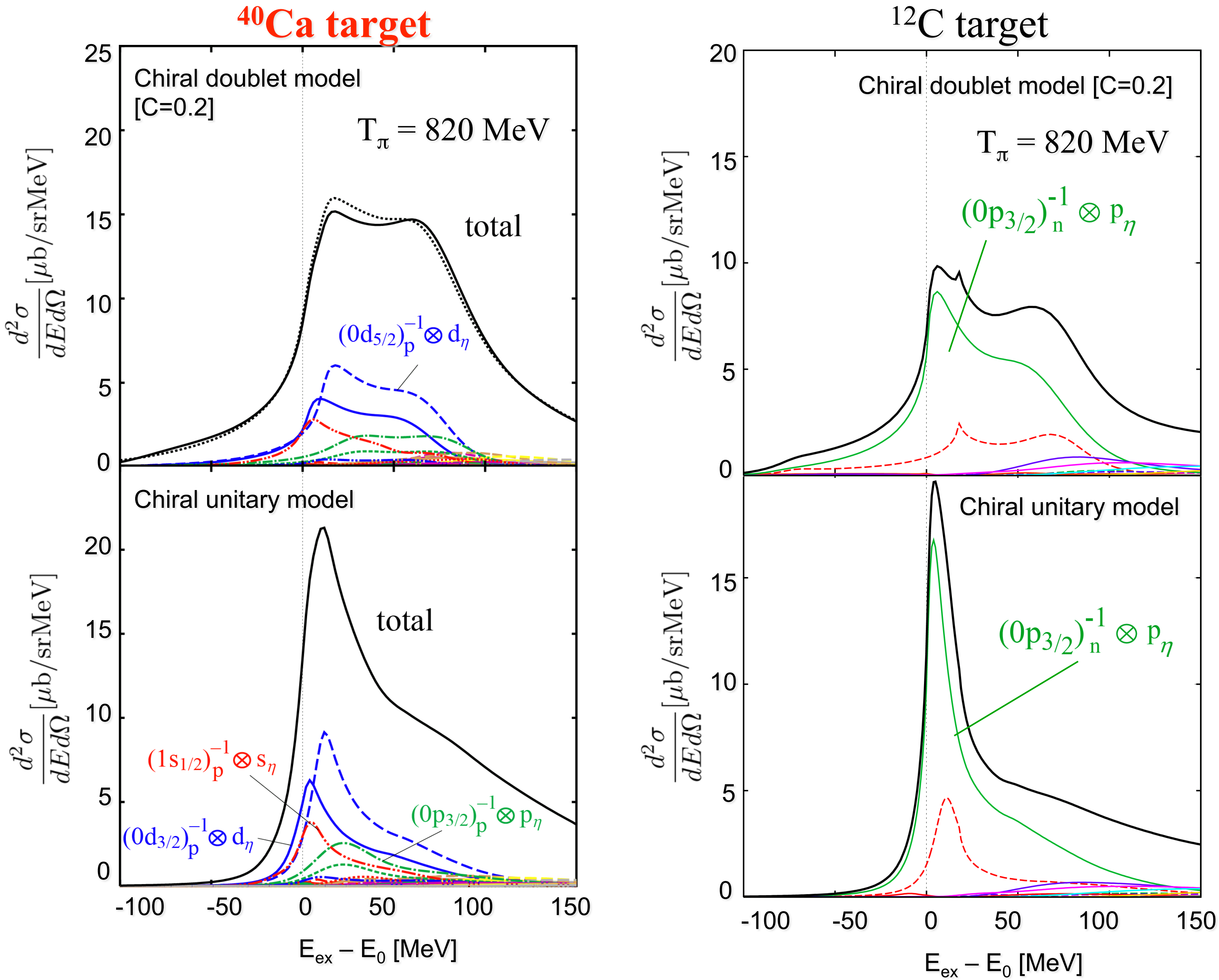
(π^+,p) spectra : ^{12}C target : incident energy dependence

T_π = 820 MeV (p_π = 950 MeV/c)

T_π = 650 MeV (p_π = 777 MeV/c)

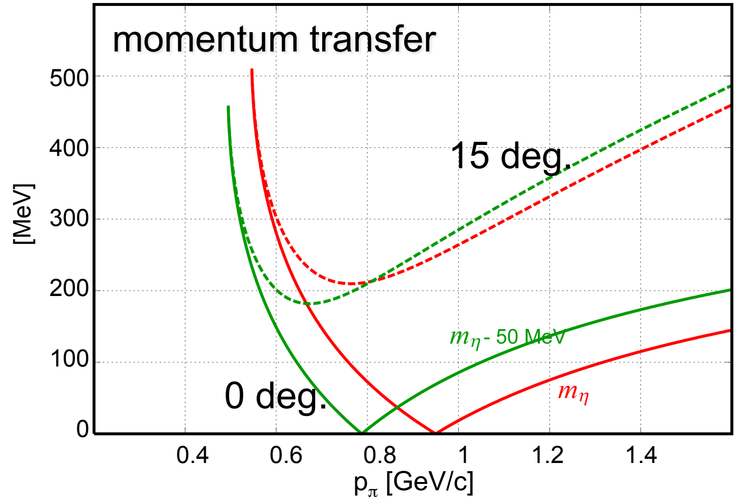


Target dependence : (π^-, n) spectrum (proton picked up)

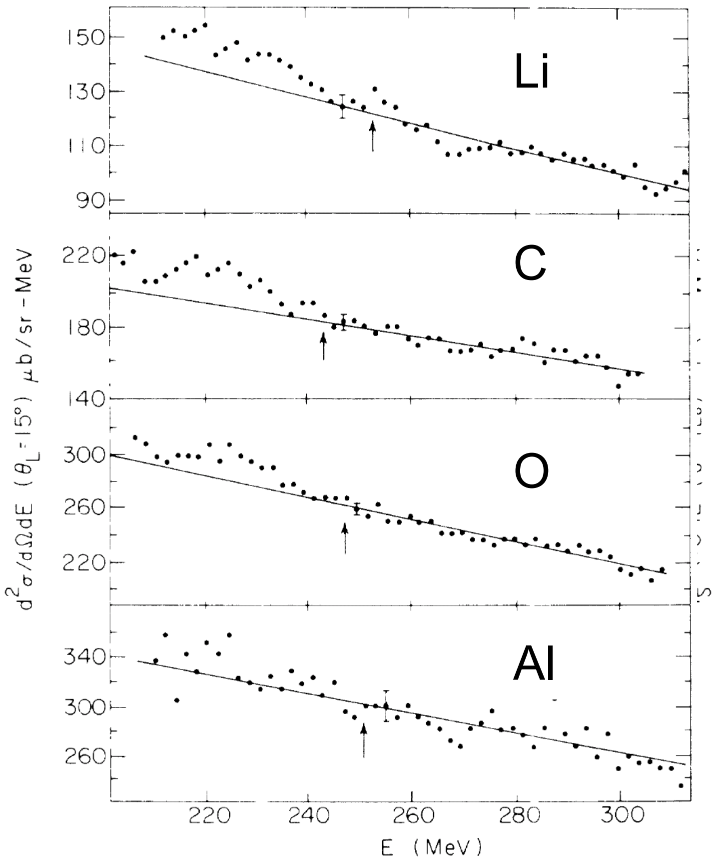


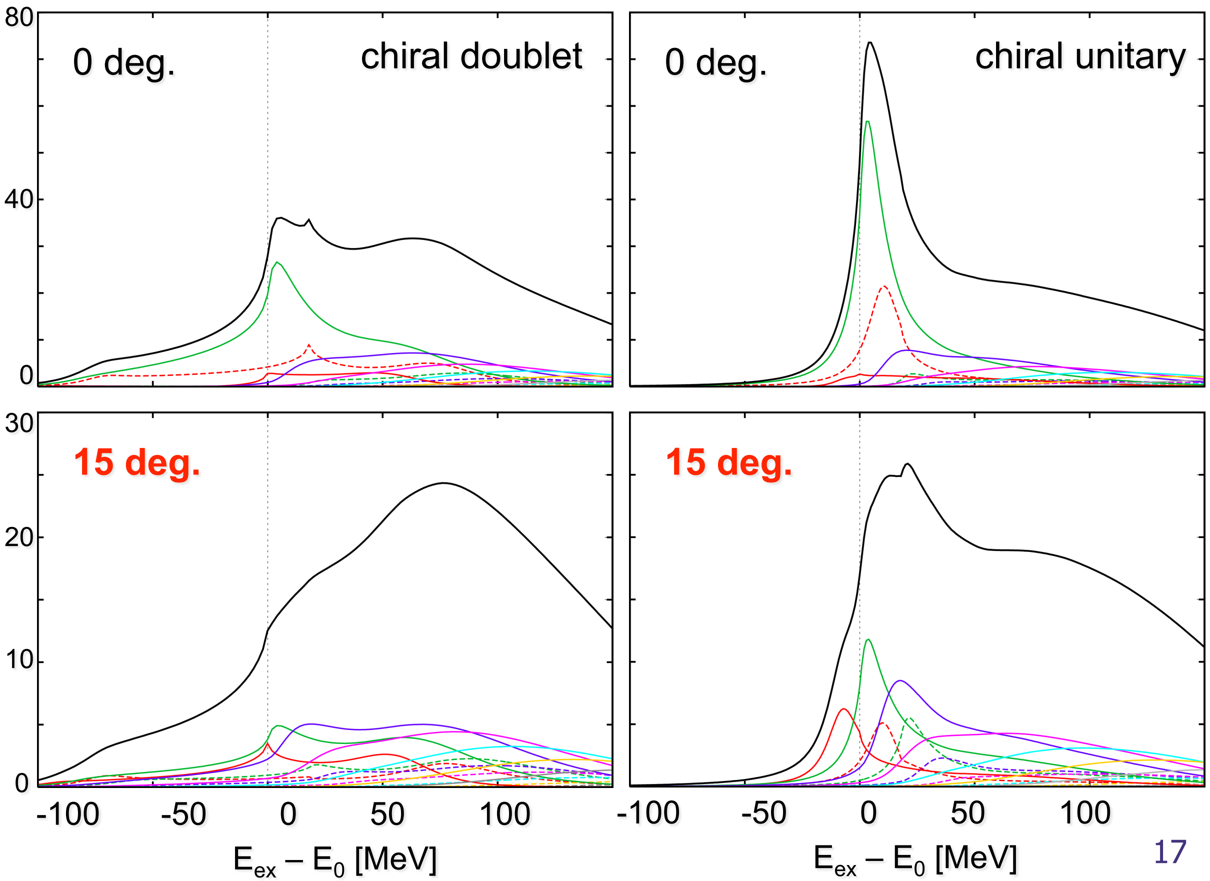
(π^+,p) spectra : experiment at Brookhaven

- Chrien et al., PRL60(1988)2595
  - » p_π = 800 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(1988)2595, Fig 1





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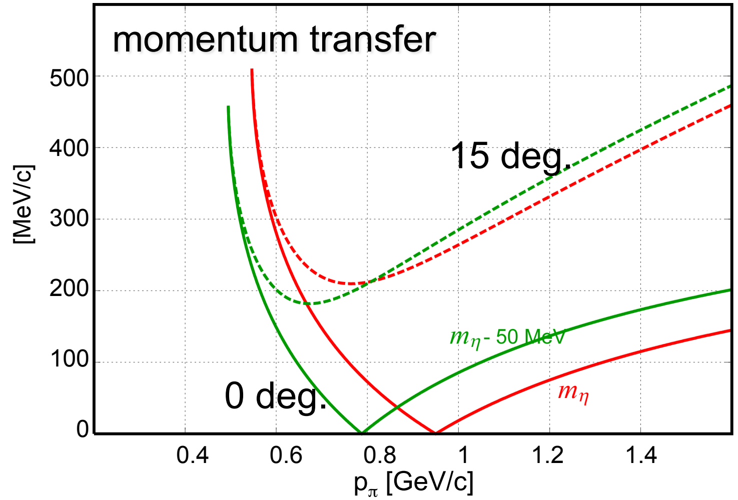
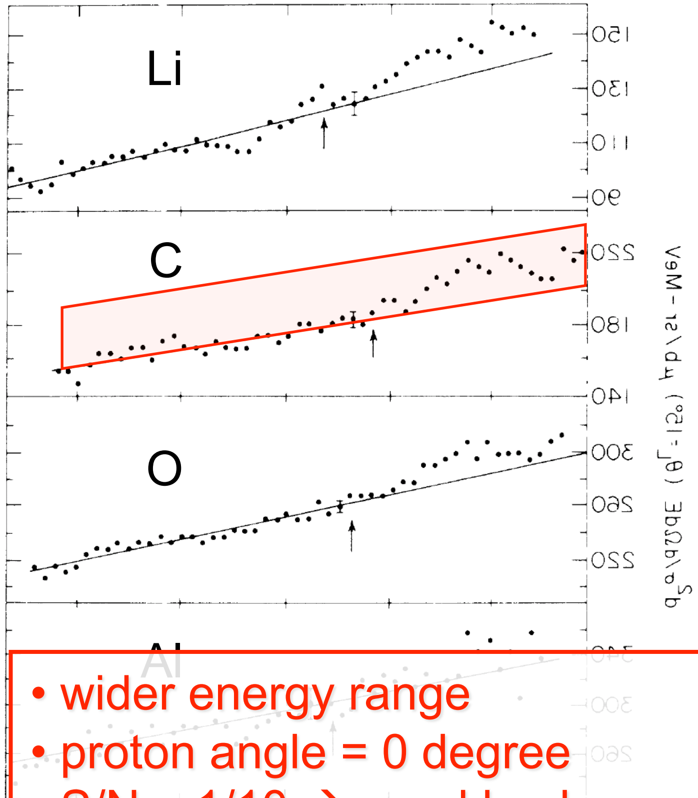
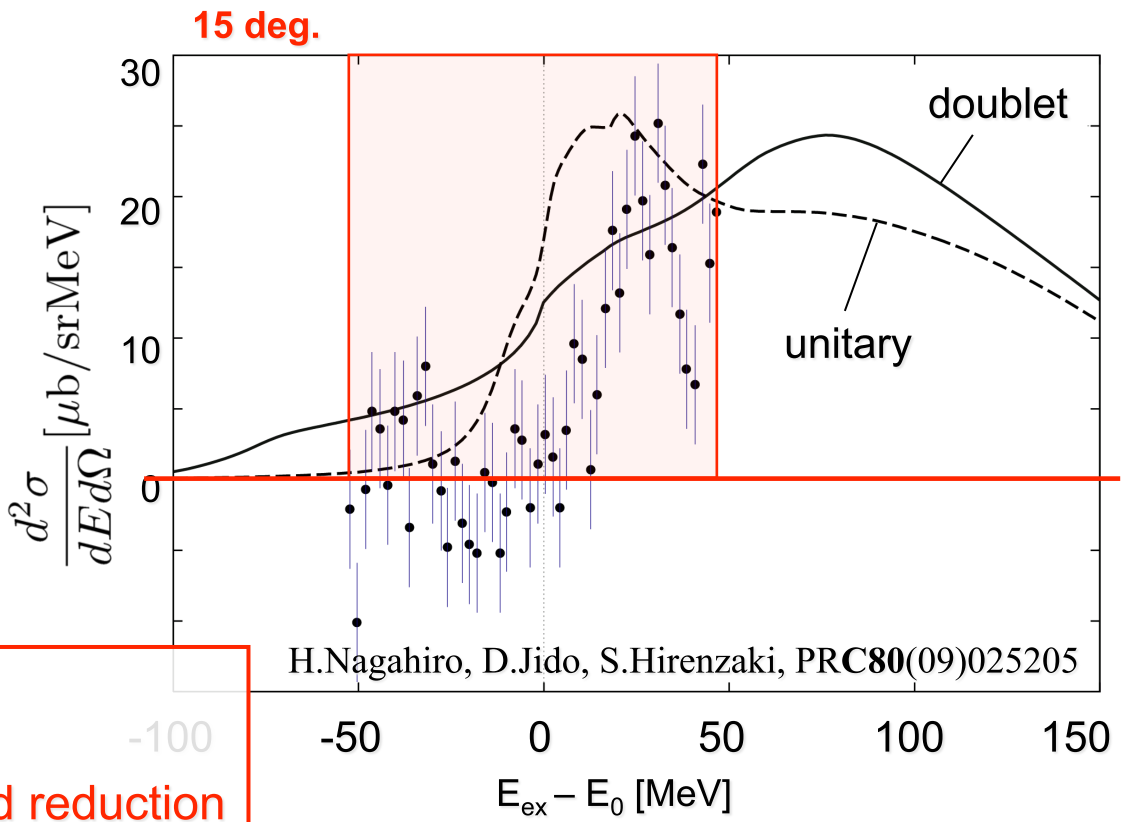


Chrien at al., PRL60(88)2595, Fig.1

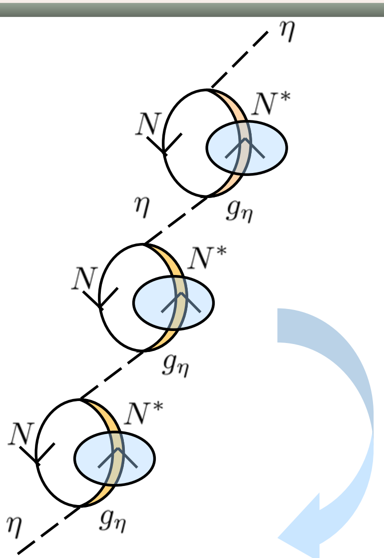




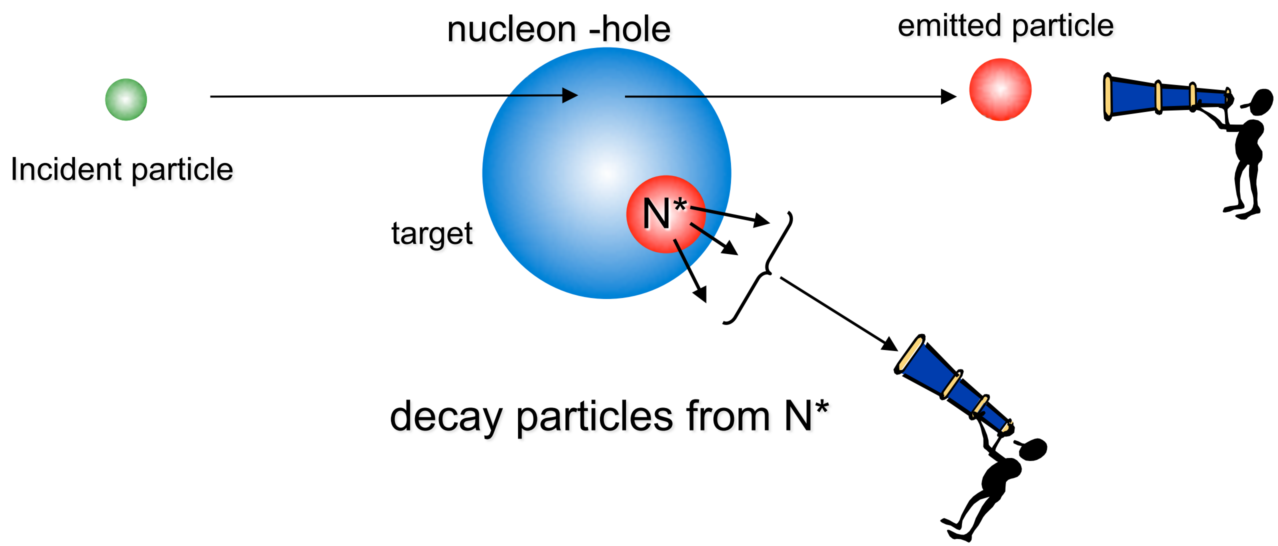
- wider energy range
- proton angle = 0 degree
- S/N ~ 1/10 → need background reduction

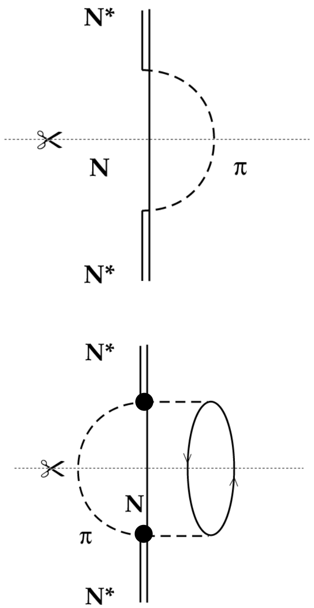
K.Itanashi, H.Fujioka, S.Hirenzaki, D.Jido, H.Nagahiro, Letter of Intent for J-PARC 2007

background reduction : coincidence measurement

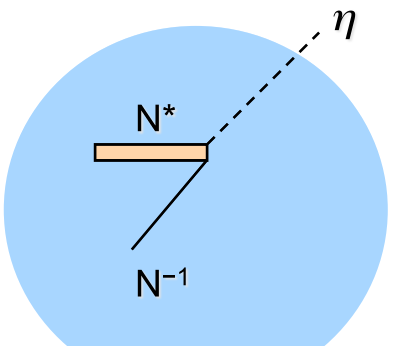


N* width in CDM

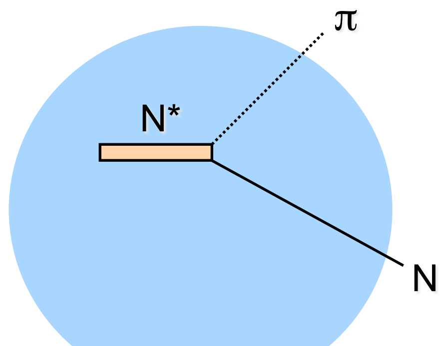




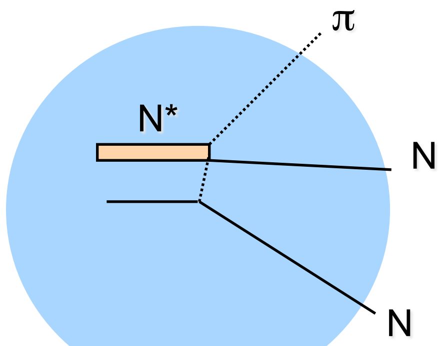
final states we considered



① real eta escapes
(escape part)



② N* → πN
(conversion part)



③ NN* → πNN
(conversion part)

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:

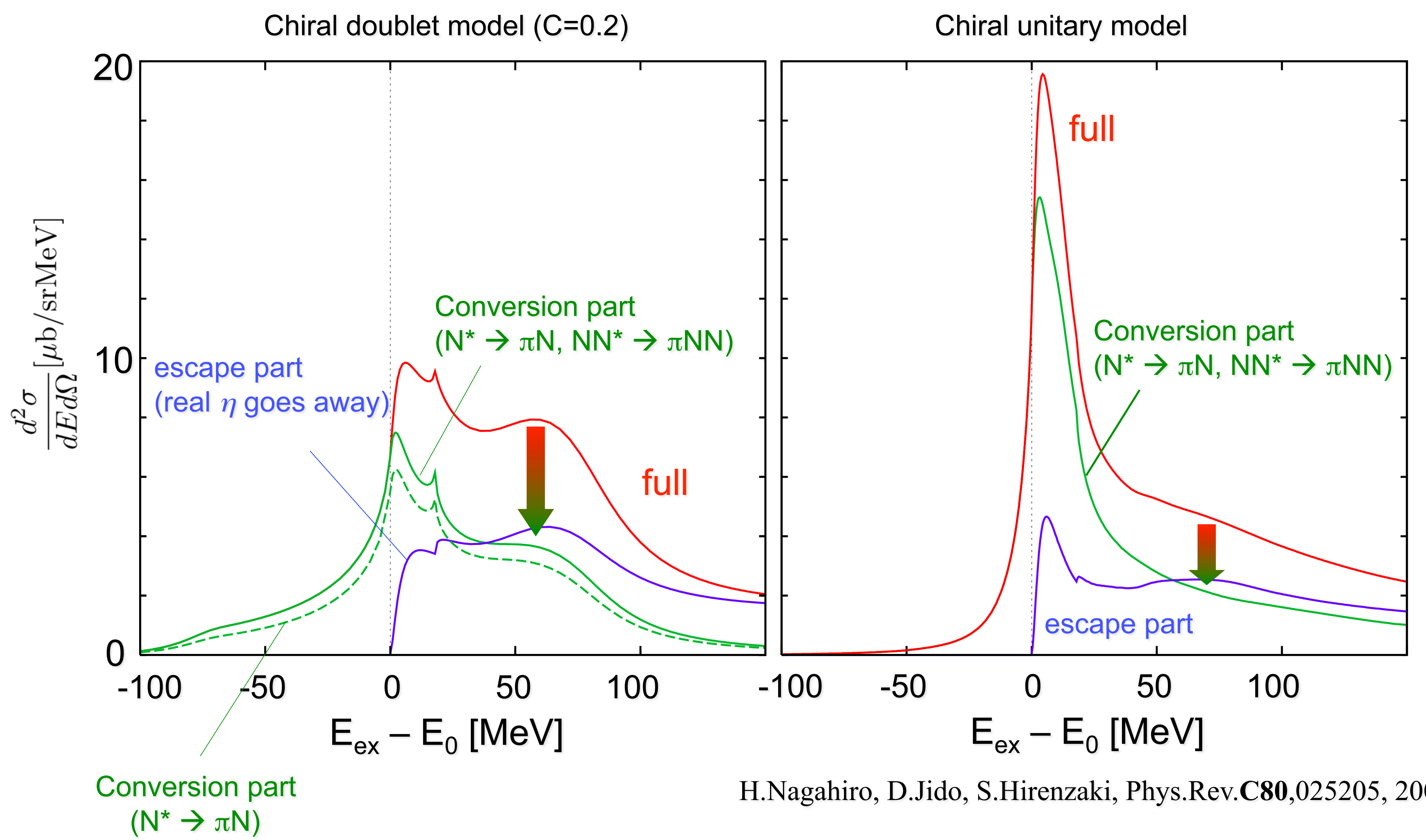
$$\begin{aligned} S_{\mathrm{tot}}(E) &= -\tilde{f}\, \mathrm{Im}\, Gf \\ &= -\sum_\alpha \mathrm{Im} \int \mathrm{d}\boldsymbol{r}\, \mathrm{d}\boldsymbol{r}'\, f_\alpha^*(\boldsymbol{r}') G(E - \varepsilon_\alpha; \boldsymbol{r}', \boldsymbol{r}) f_\alpha(\boldsymbol{r})\,, \end{aligned} \tag{12}$$

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

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

[Morimatsu, Yazaki NPA435(85)727, NPA483(88)493]

effect on "the signal" by coincidence measurement



H.Nagahiro, D.Jido, S.Hirenzaki, Phys.Rev.**C80**,025205, 2009

future work : estimation of absolute value of background

A Simple Theoretical Model for $d+d \to (^4\text{He-}\eta) \to p+\pi^- + ^3\text{He}$

(COSY Proposal 186.2)
(P.Moskal, arXiv:nucl-ex/09093979)

Some remarks

- Momentum transfer

  $p_d = 1.025$ GeV/c, $p_\alpha = p_\eta = 0$ at threshold in C.M.

- Data of $d\,d \rightarrow {}^4\text{He}\ \eta$

- Simple spectral structure for light systems

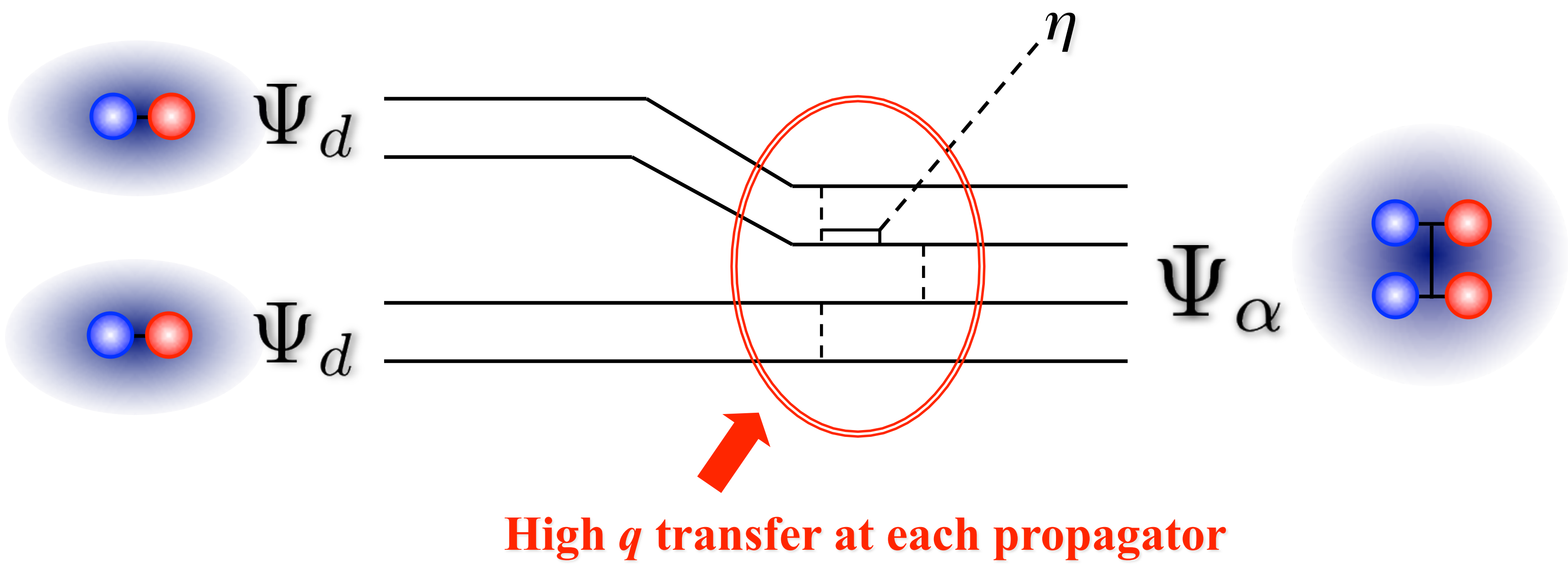
- System consists of

  2 Nucleon + 2 Nucleon → 4 Nucleon + 1 meson

A Simple Theoretical Model for $d + d \to ({}^4\text{He-}\eta) \to p + \pi^- + {}^3\text{He}$

Some remarks

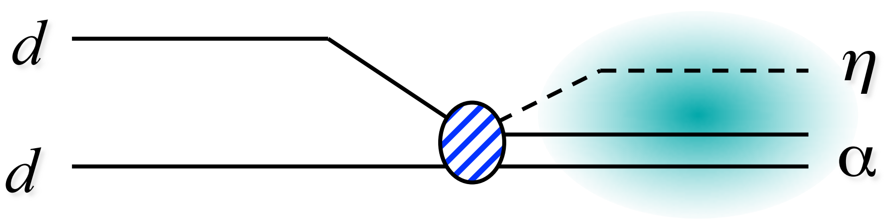
- Transition (η-production) part



$\longrightarrow$ Parameterize this part. Fix by η production data

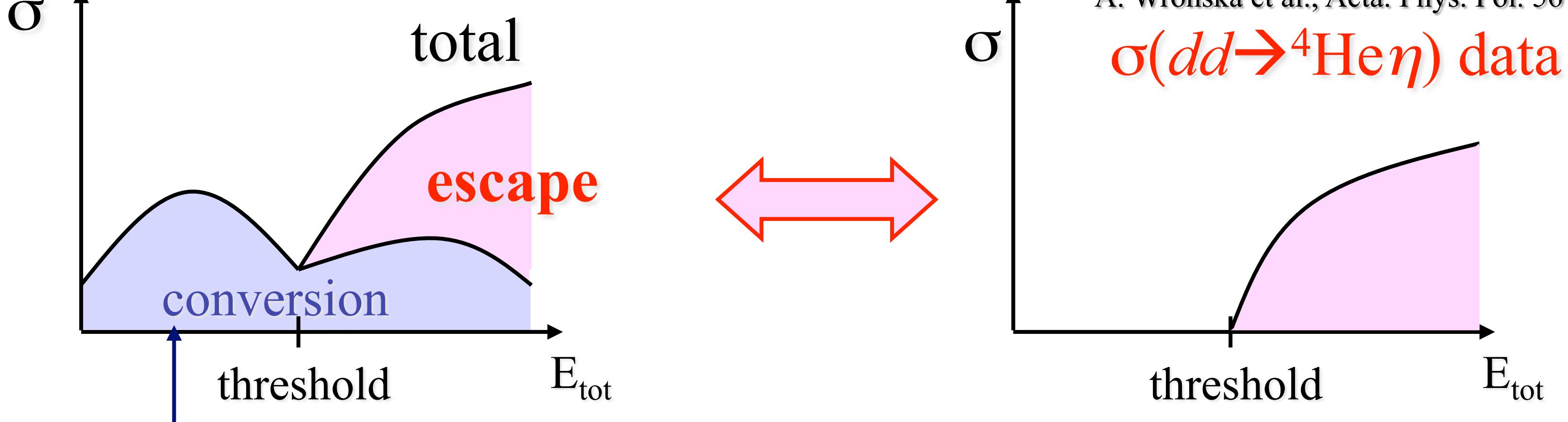
A Simple Theoretical Model for $d + d \rightarrow (^4\text{He-}\eta) \rightarrow p + \pi^- + ^3\text{He}$

Schematic picture



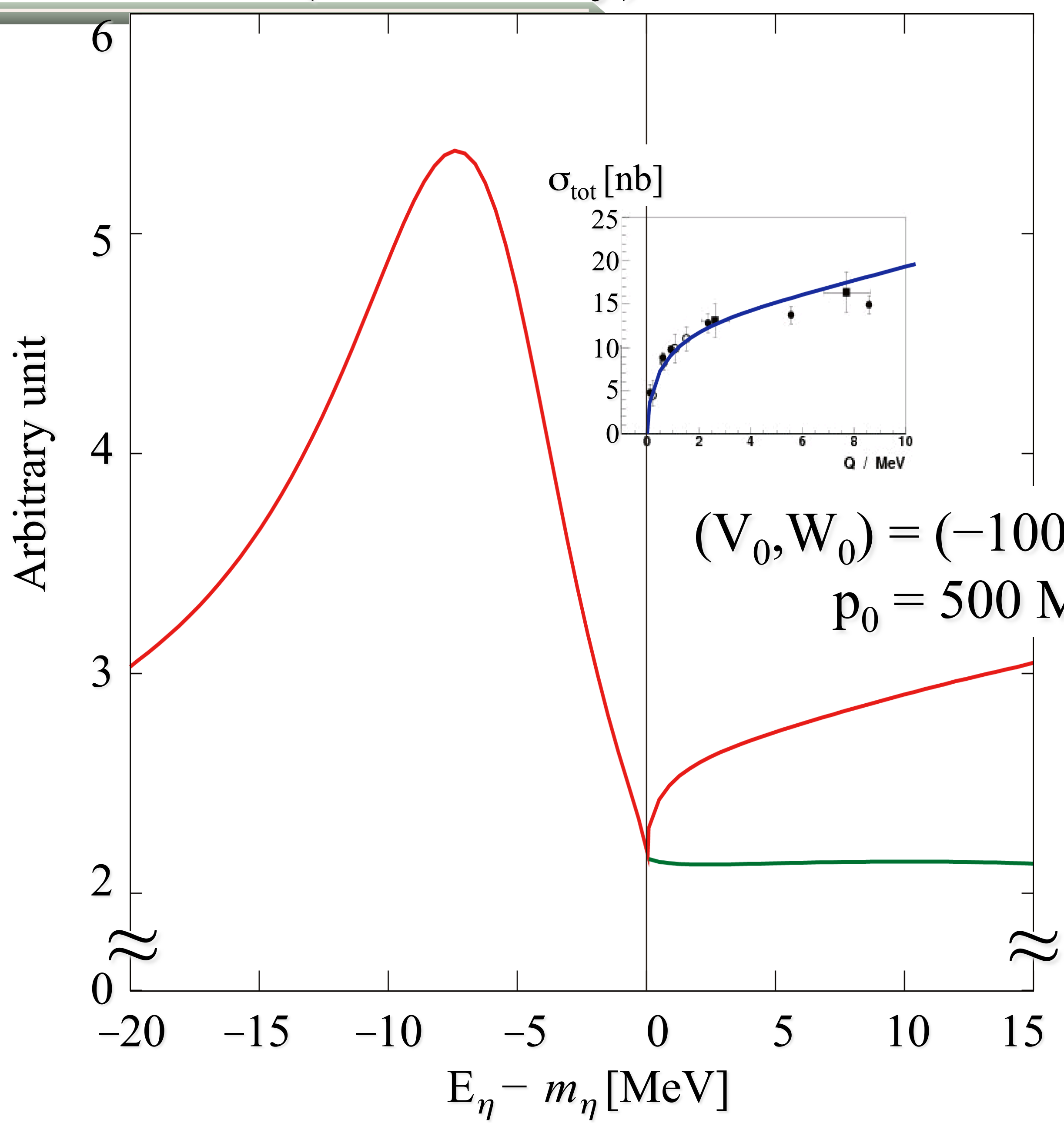
Green function method
with η-α optical potential

R.Frascaria et al., Rhys.Rev.C50 (1994) 573,
N. Wills et al., Phys. Lett. B 406 (1997) 14,
A. Wronska et al., Acta. Phys. Pol. 56 (2006) 279.



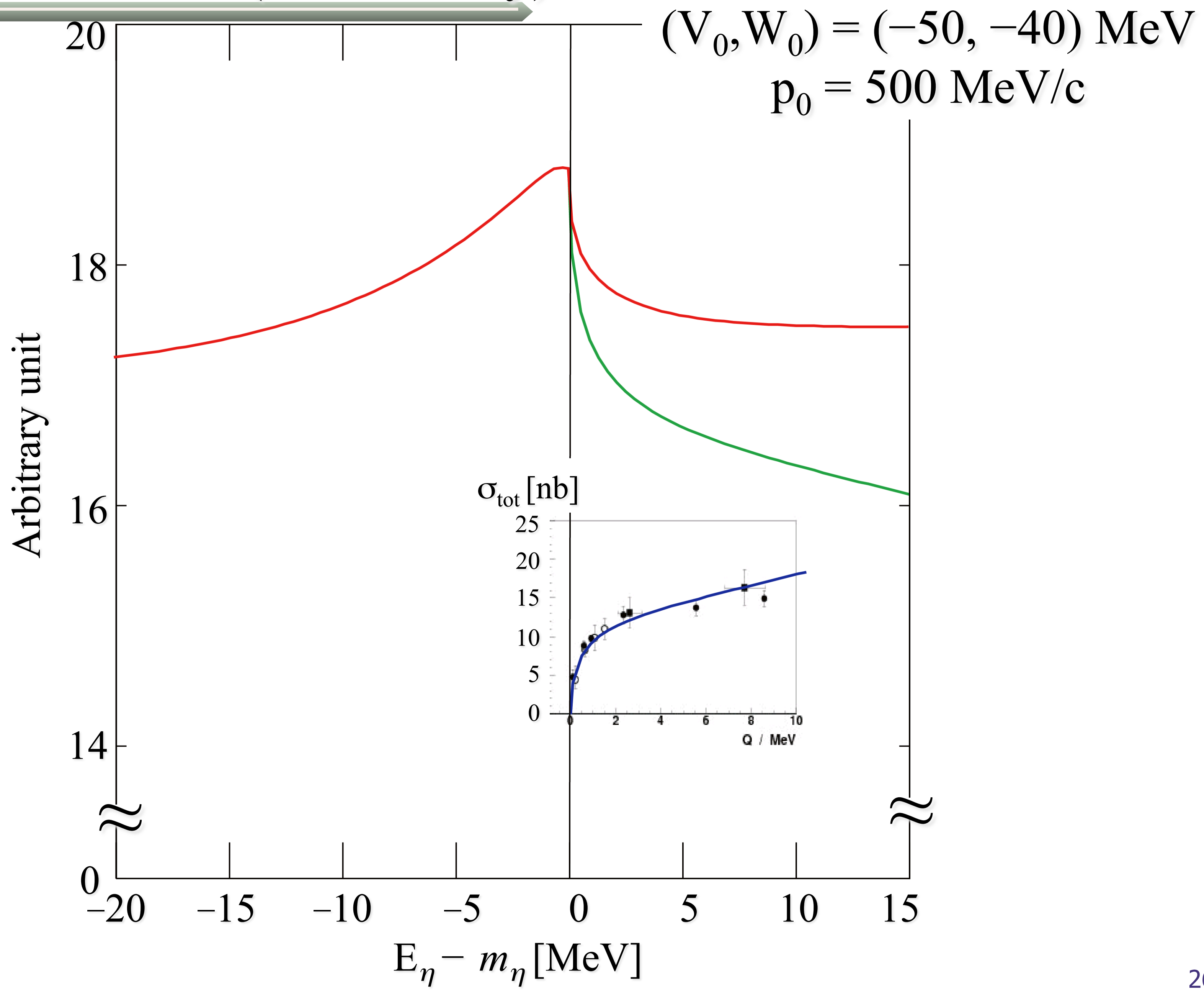
$$d + d \rightarrow (^4\text{He-}\eta) \rightarrow p + \pi^- + ^3\text{He}$$

Numerical Results (Preliminary)



$(V_0, W_0) = (-100, -20)$ MeV
$p_0 = 500$ MeV/c

Numerical Results(Preliminary)



Summary

- Recent results on Formation of η mesic nucleus
  - » (π,p) reaction
  - » d + d → (^{4}He-η) → p + π^- + 3He reaction

- Some indications by different Chiral models

  for (π,p) reaction

- New Experiments
  - » Fujioka, Itahashi, … @ J-PARC
  - » d + d ; COSY Proposal 186.2