Formation of Mesic Nuclei

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Int. Sympo. on Mesic Nuclei, 16June2010
Jagiellonian Univ., Krakow, Poland

Outline of this talk

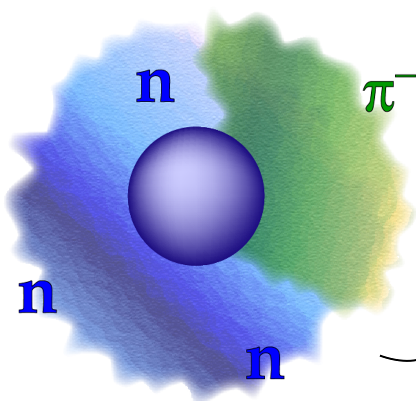
- 1 Introduction
- 2 Eta-Nucleus System ….. Interaction Based on Chiral Models
  ….. Formation by (pi, N) reaction
- 3 Eta'(958) -Nucleus System ….. Intro. & (pi,N) formation
- 4 Photon Induced (gamma, p) reaction
- 5 Preliminary results for d+d →4He + eta reaction
- 6 Summary

Introduction and Motivation

➢ 1. Exotic Many Body Physics

- Exotic Nuclei
  (Neutron Rich , Proton Rich,
  Mesic Atoms and Mesic Nuclei, …)
- Strangeness
  (Hyper Nucleus, kaonic Nucleus, …)

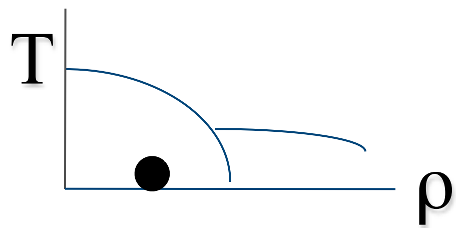
Ex.)



Pionic Atoms in halo nuclei
Co-existence of Pion-Neutron-halo

➢ 2. Hadron Physics at finite density

- High T, High ρ ,QGP ······· Heavy Ion Collision(RHIC)
- Low T, $\rho \sim \rho_0$, ······· Hadron in Nucleus



Fundamental theory (QCD)

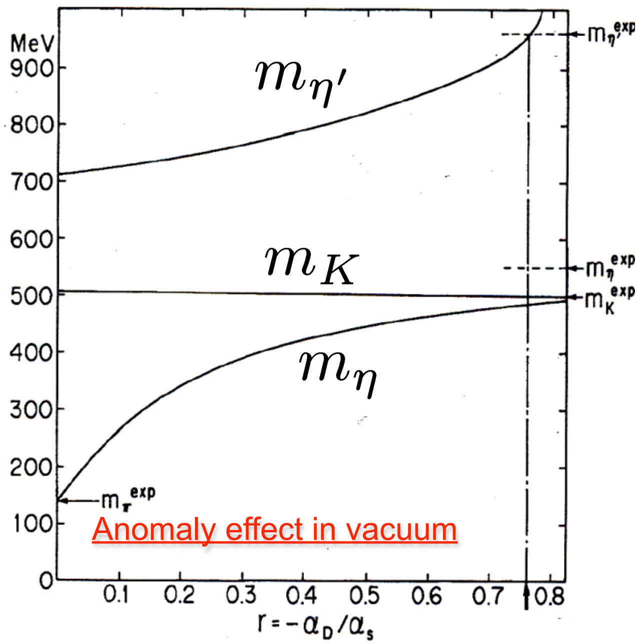
↔ Effective theory

↔ Hadron property at finite ρ

↔ Infinite System ⟺ Finite System

↔ Mesic Atoms and Mesic Nuclei

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



The NJL Model : $J^p = 0^-$

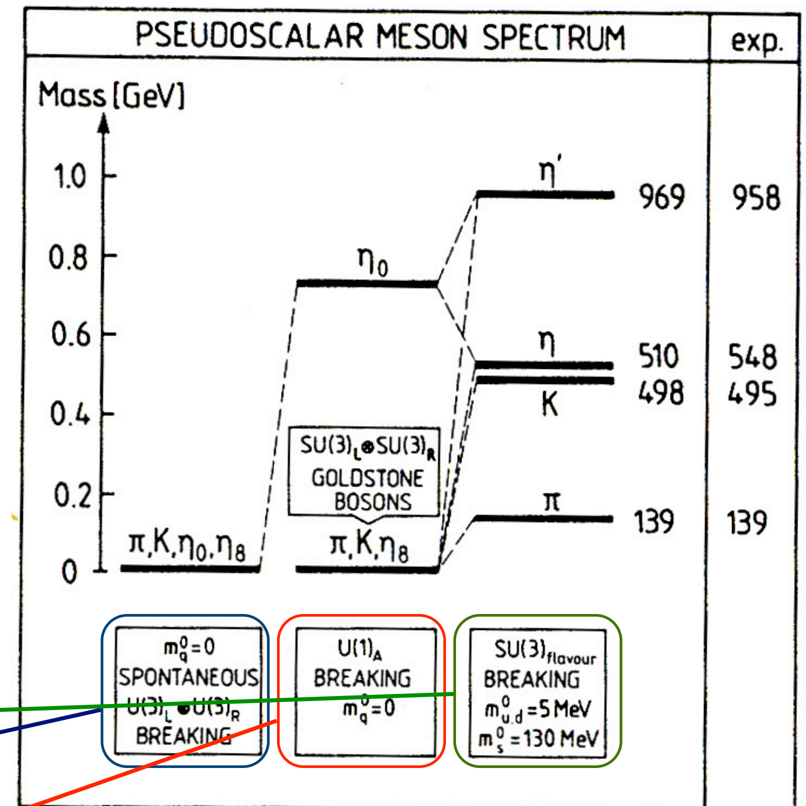


Fig. 10. *Pseudoscalar meson spectrum from the NJL model (Klimt et al. 1990), showing the chiral and flavour symmetry breaking pattern. Calculated and experimental masses are given in MeV.*

- Higgs mechanism
- Spontaneous Chiral Symmetry Breaking
- $U_A(1)$ Anomaly Effect

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^+,π^+)] (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 ($\gamma + {}^3He \rightarrow \pi^0 + p + X$)
  COSY-GEM ($p + Al \rightarrow {}^3He + Mg\text{-}\eta$)
  WASA-at-COSY ($d + d \rightarrow {}^3He + p + \pi$)
  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] » $\mathrm{I} = 0,\ \mathrm{J}^{\mathrm{P}} = 0^-$

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

η-N system

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

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

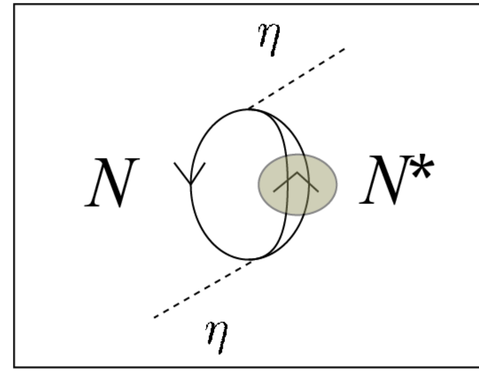
ηNN* system

-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 ~



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.Nagahiro, S.H. 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 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

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

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**

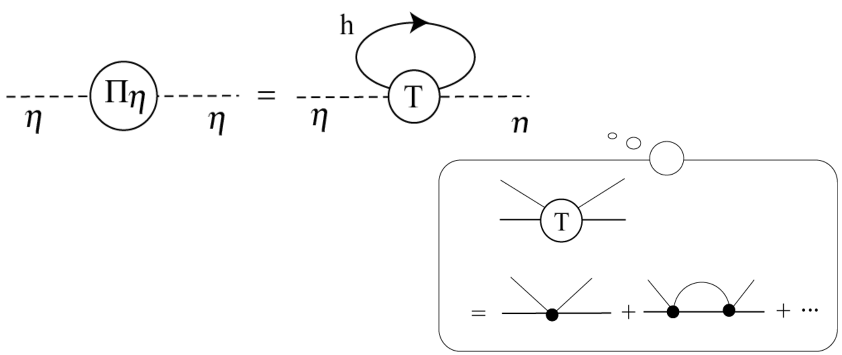
Chiral unitary model

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

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

A coupled channel Bethe-Salpeter eq.

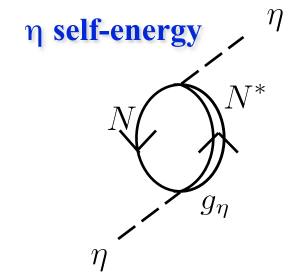
$$\{\pi^- p, \pi^0 n, \eta n, K^0\Lambda, K^+\Sigma^-, K^0\Sigma^0, \pi^0\pi^- p, \pi^+\pi^- n\}$$



* 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

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

potential nature at η threshold

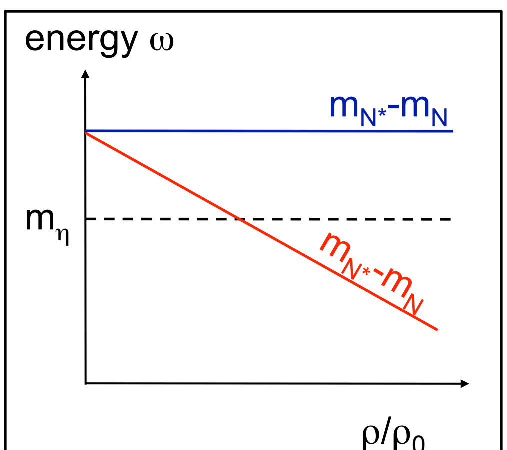
$$m_\eta - (m_{N^*} - m_N) < 0$$

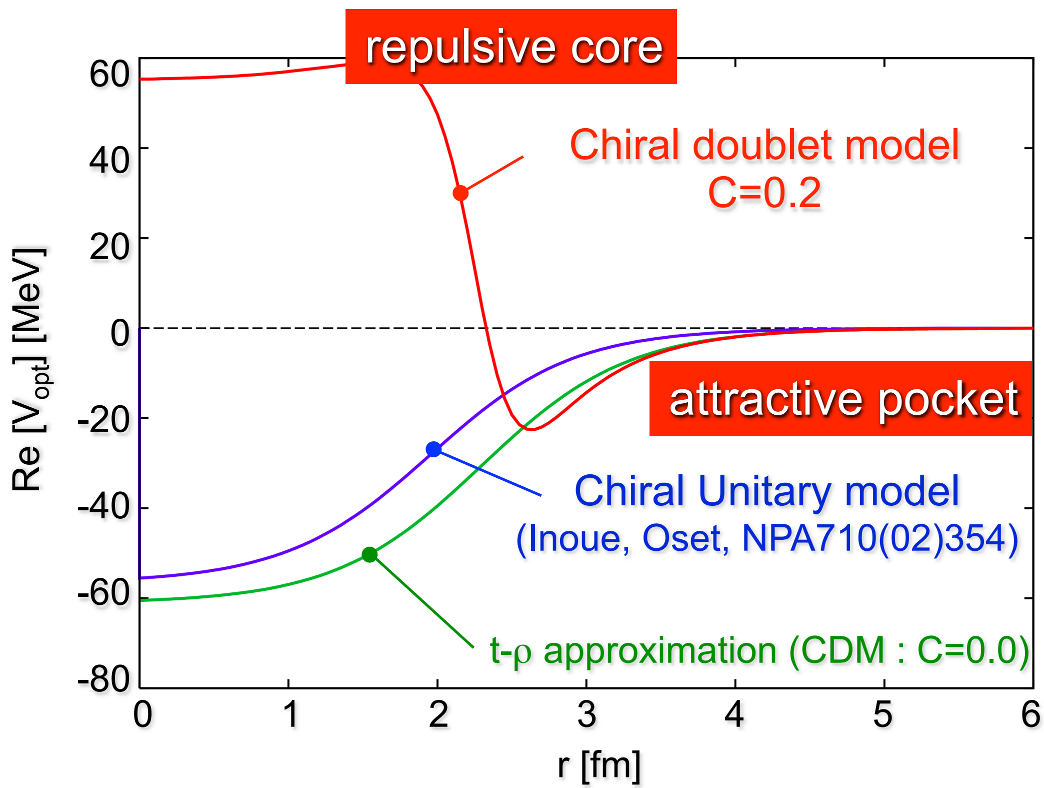
attractive

medium effect

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

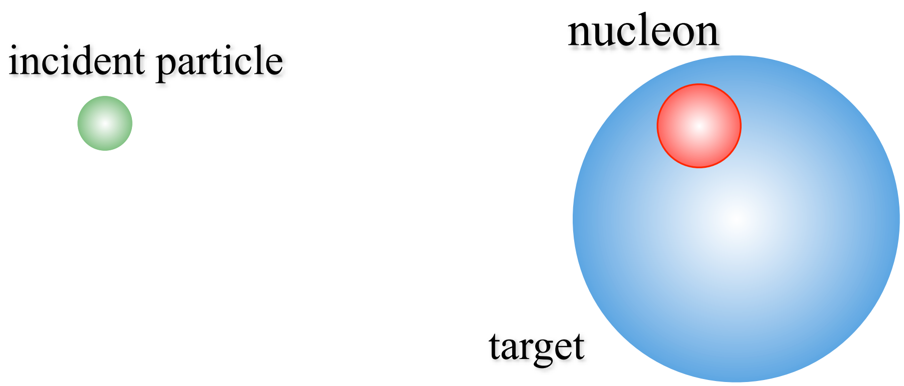
repulsive





•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**

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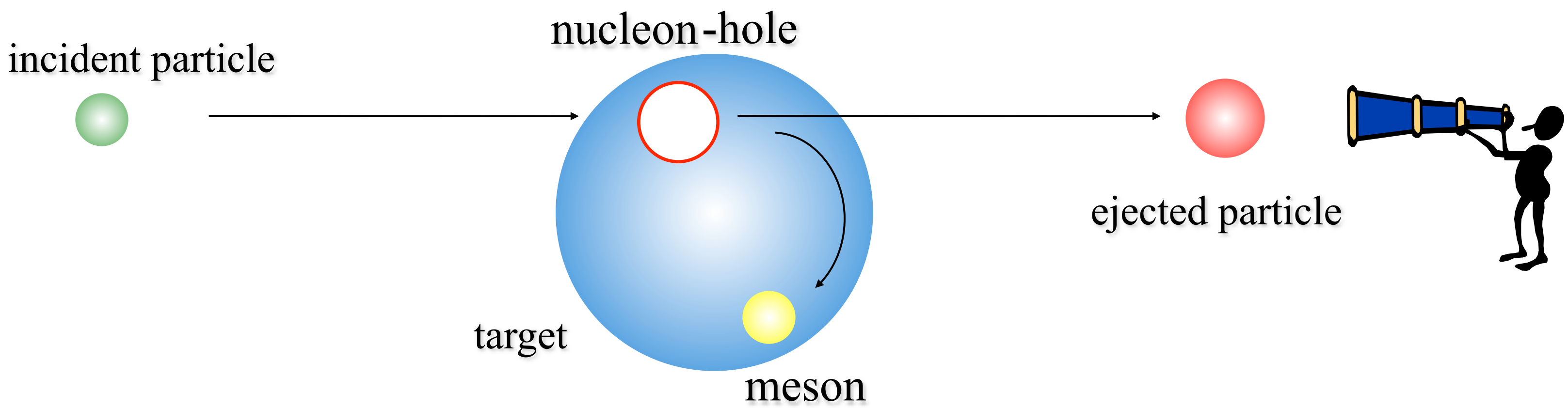

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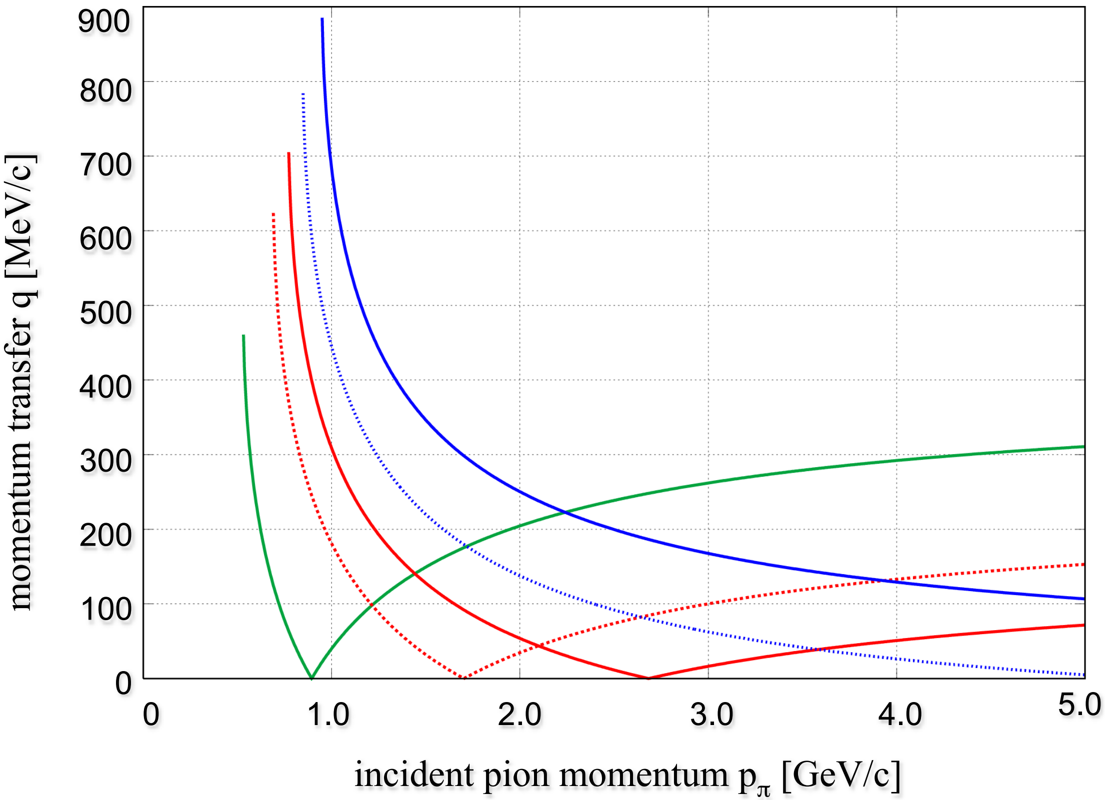
meson production in recoil-free kinematics

magic momentum in $^{12}C(\pi,N)$ reaction



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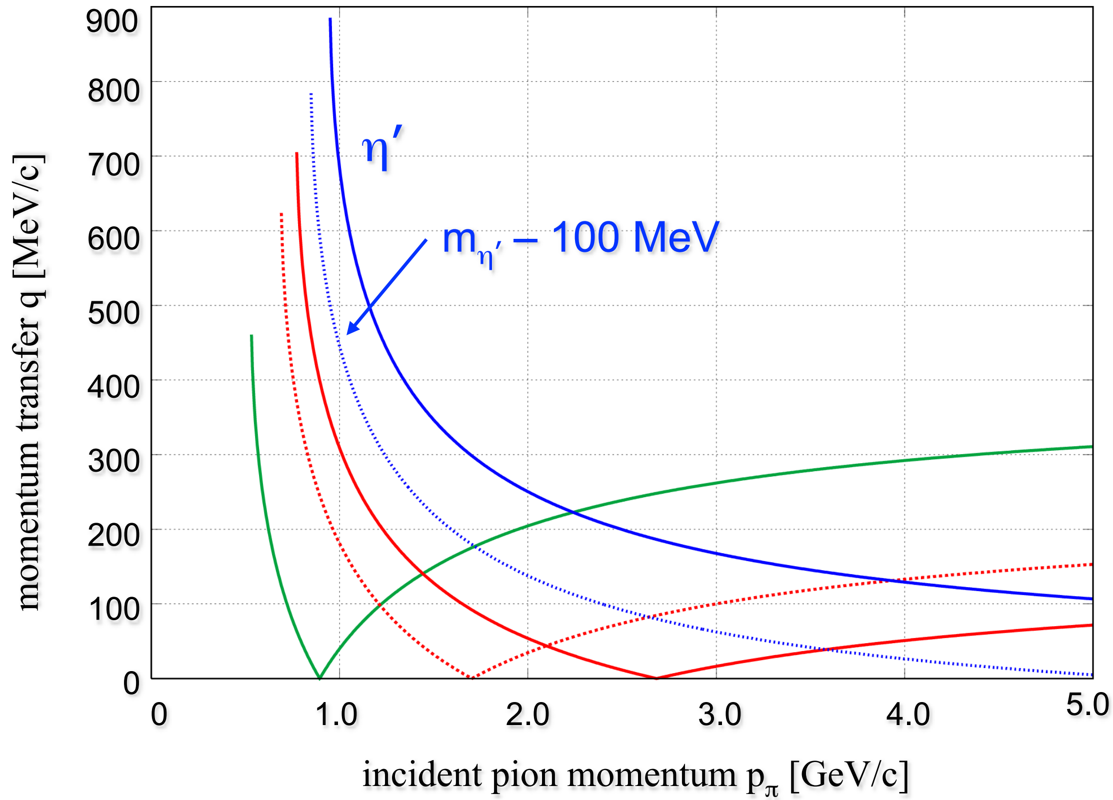

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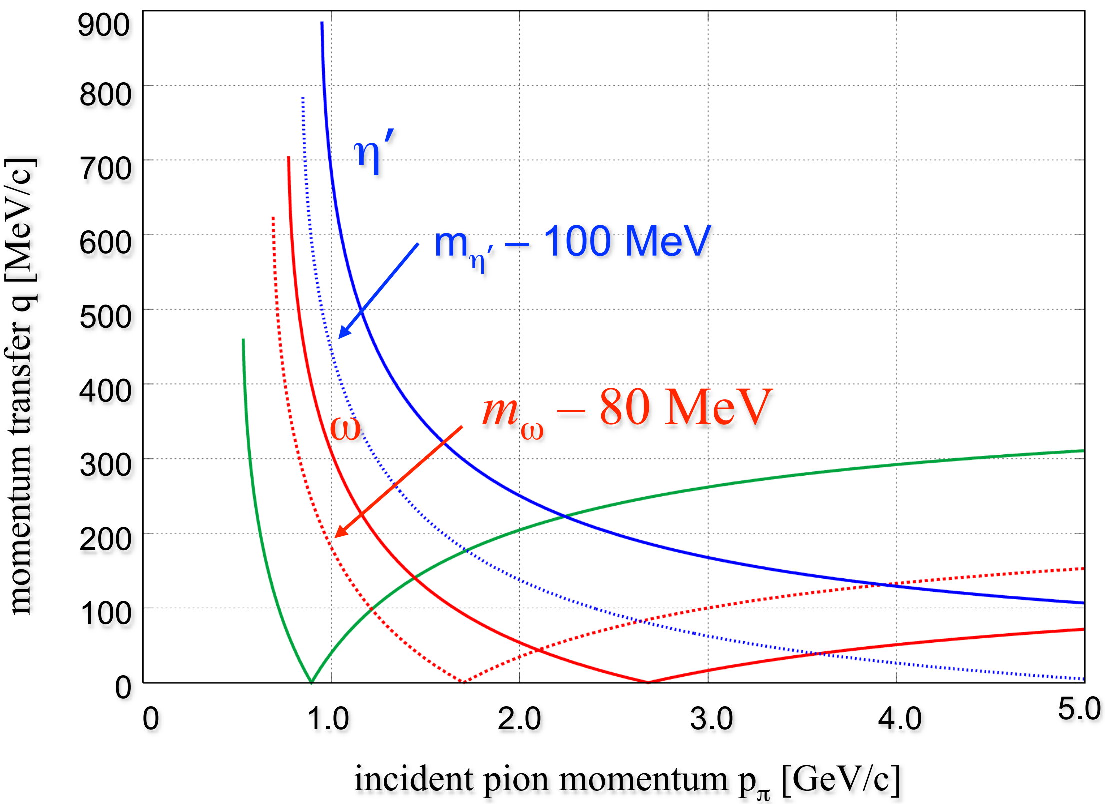

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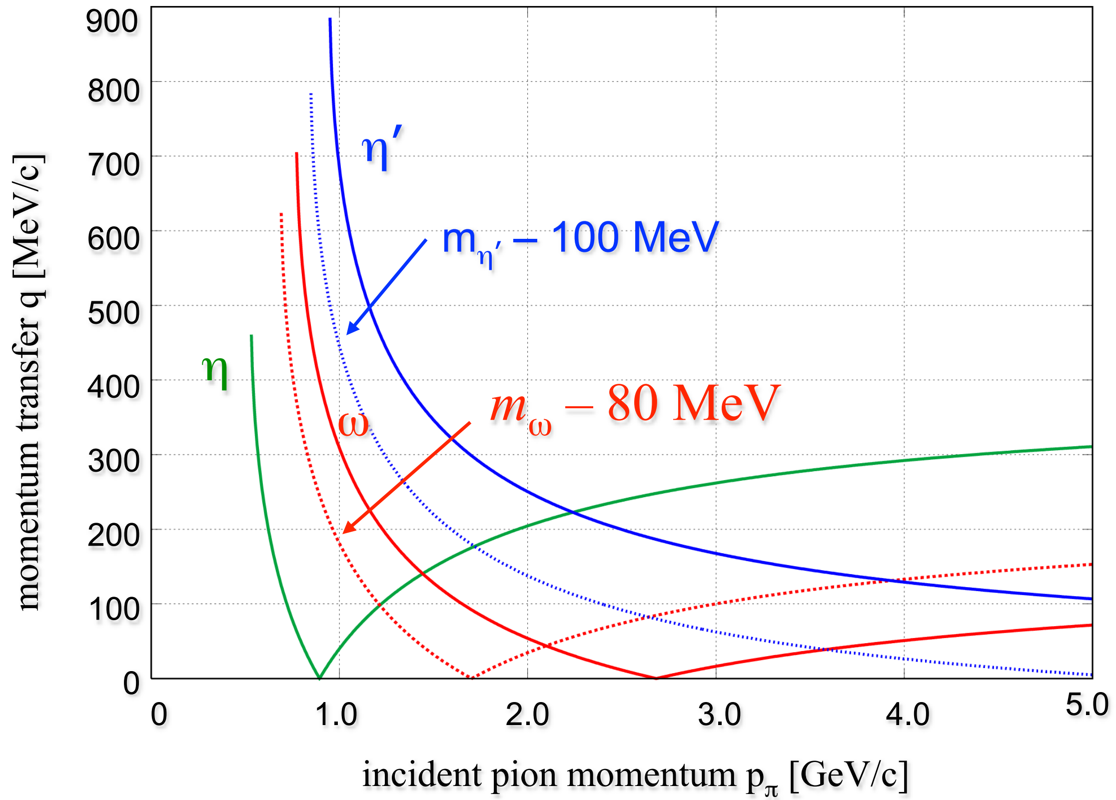

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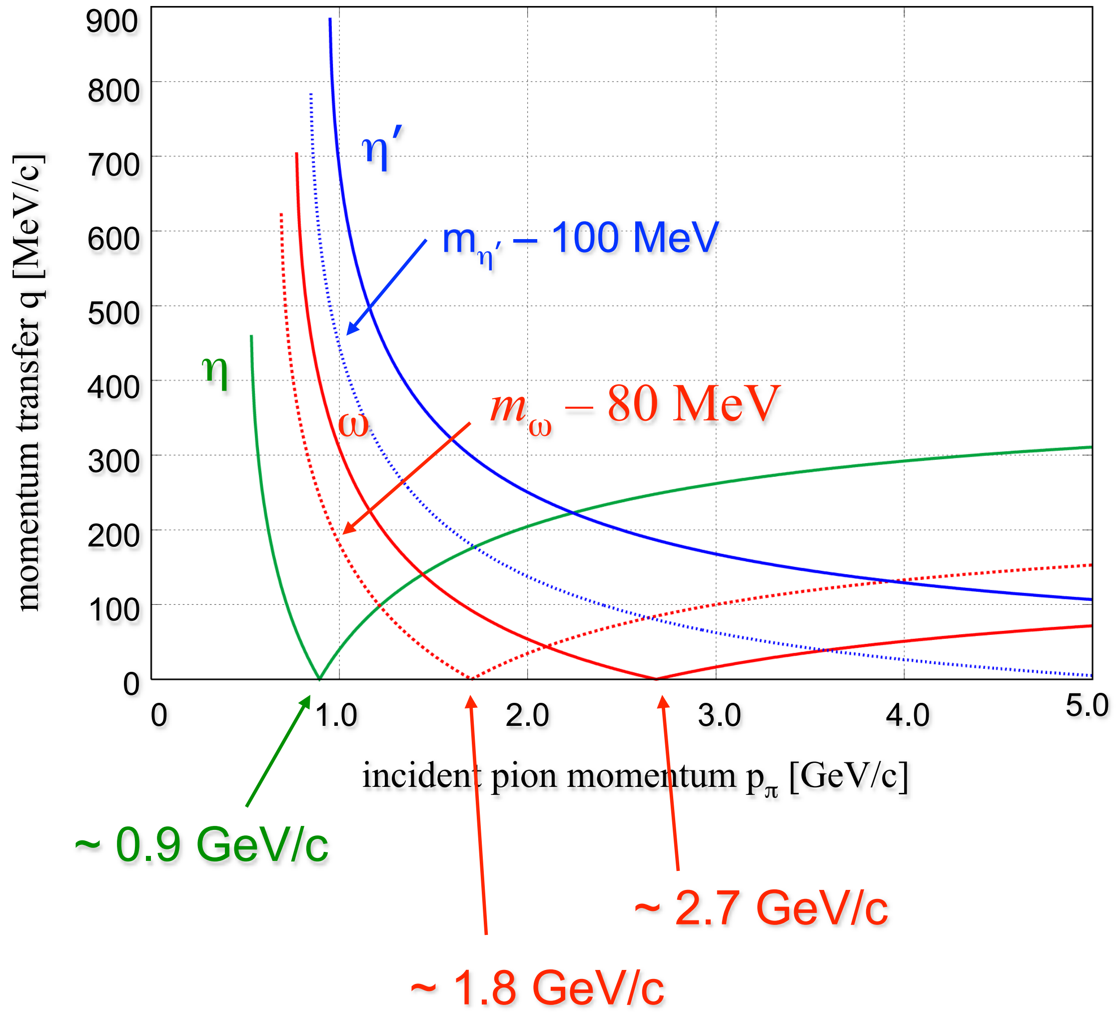


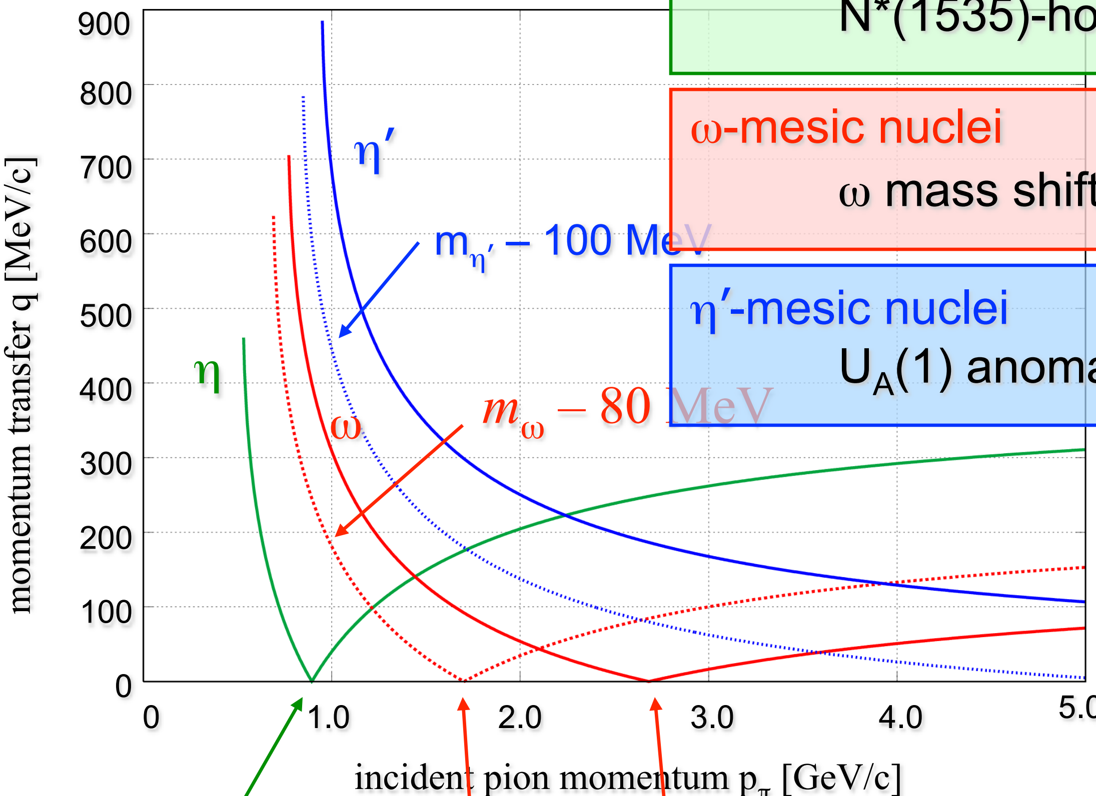
meson production in recoil-free kinematics

<u>magic momentum in ^{12}C(π,N) reaction</u>

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



~ 0.9 GeV/c

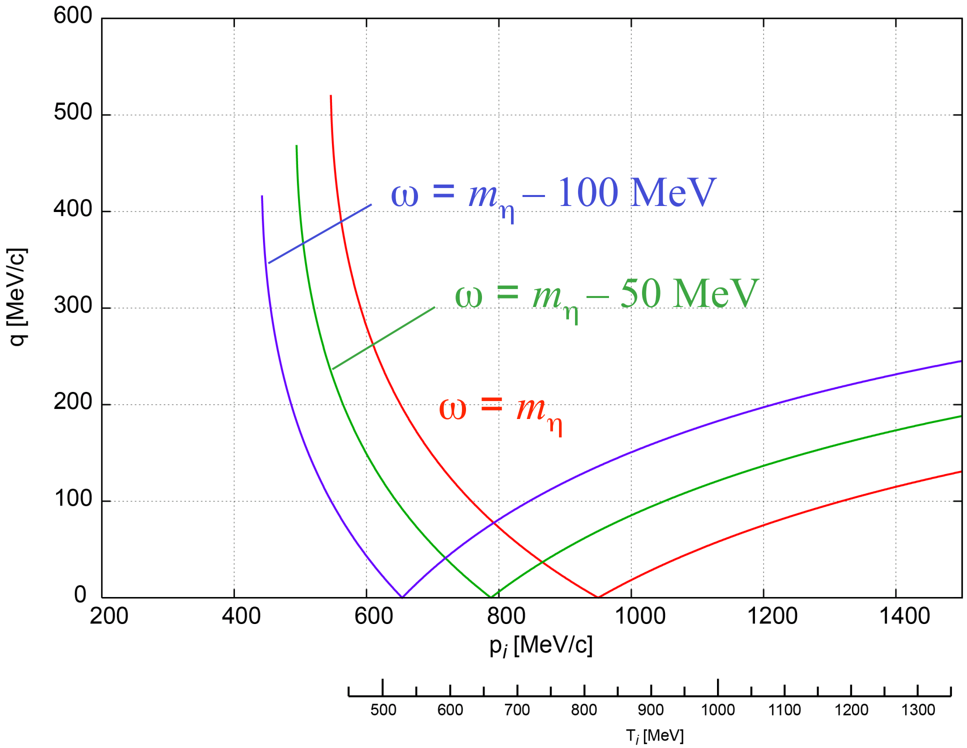
~ 2.7 GeV/c

~ 1.8 GeV/c

almost recoil-free production

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

Momentum transfer : forward proton angle



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

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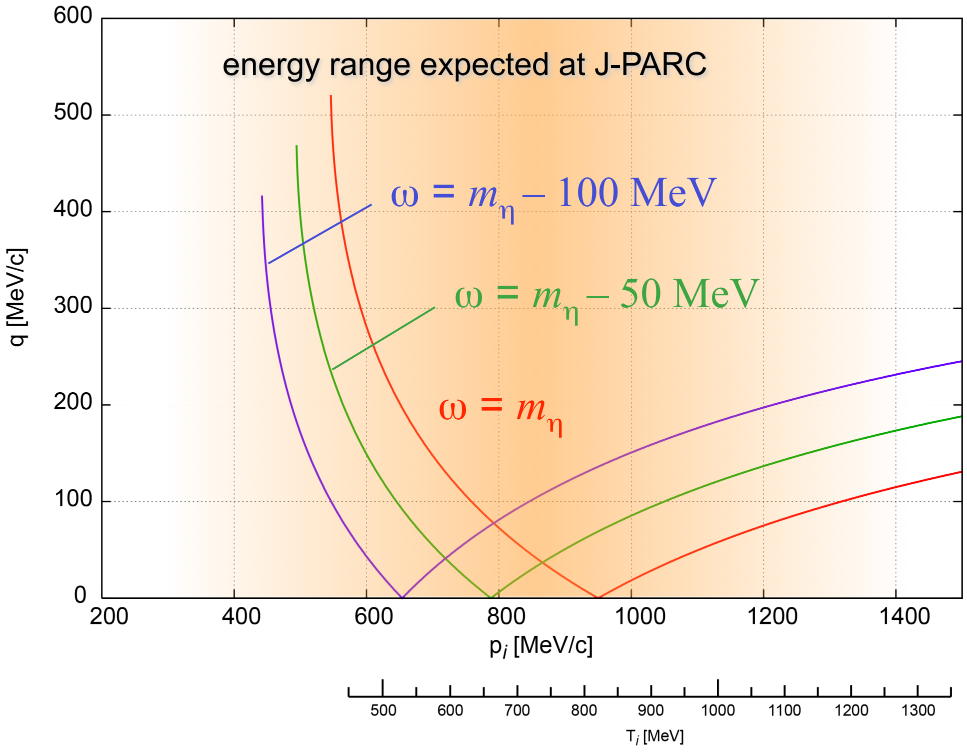

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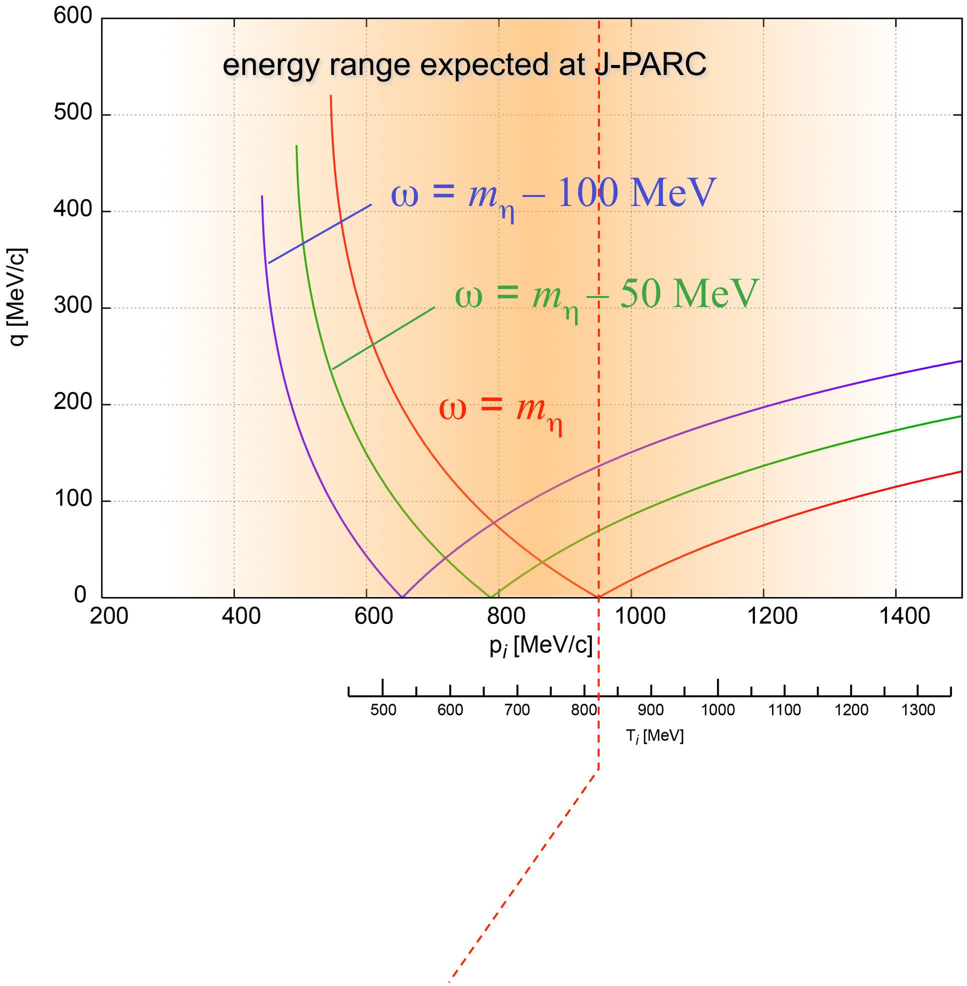
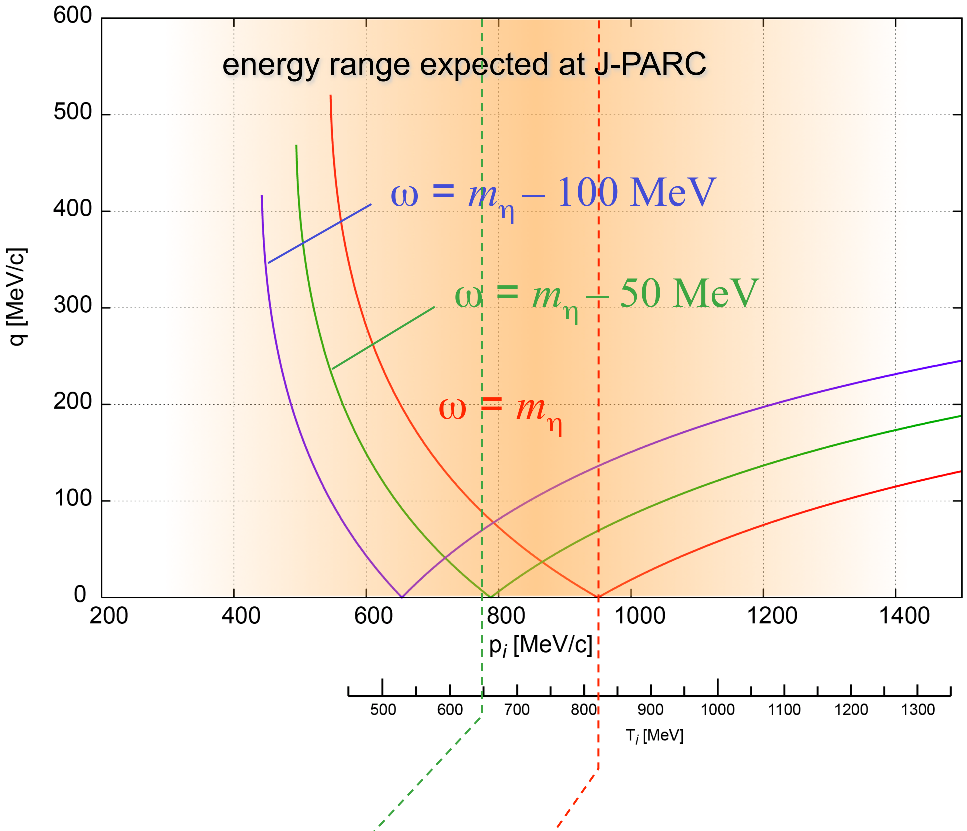


T_π = 820 MeV (p_π ~ 950 MeV/c)

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

Momentum transfer : forward proton angle

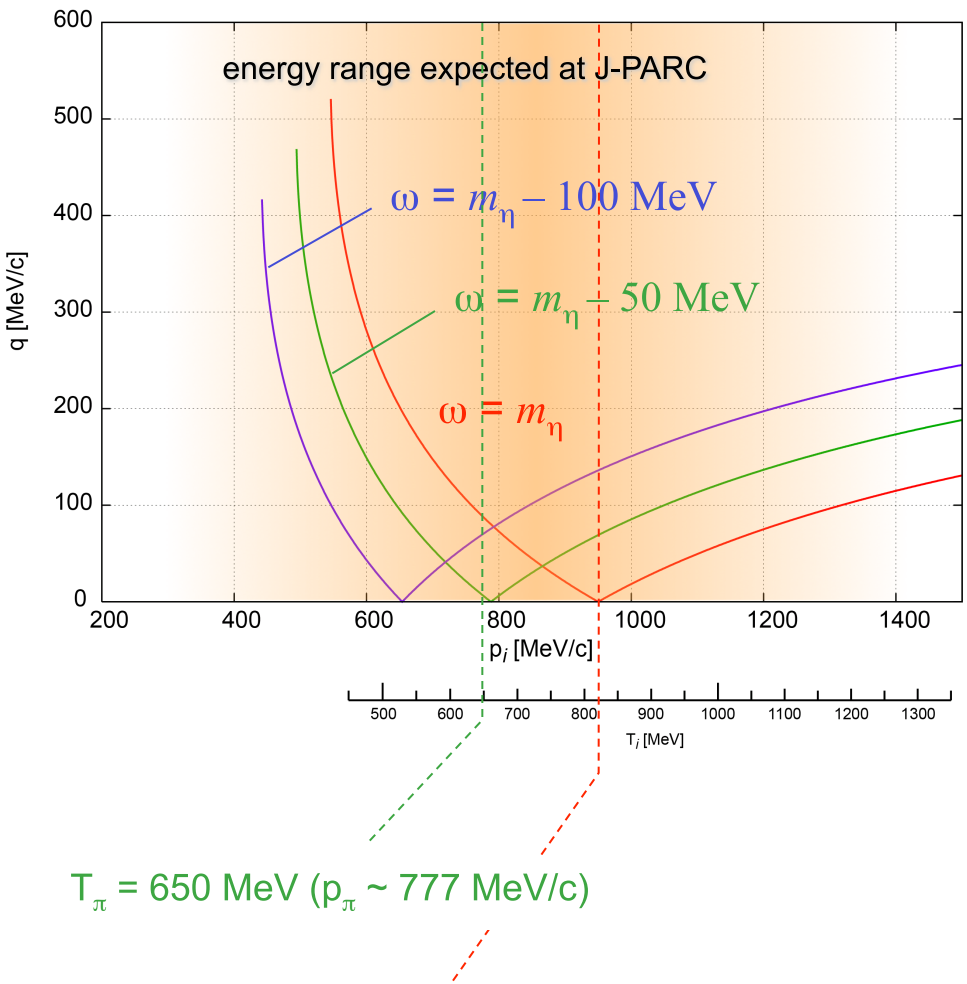


T_π = 650 MeV (p_π ~ 777 MeV/c)

T_π = 820 MeV (p_π ~ 950 MeV/c)

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

Momentum transfer : forward proton angle



T_π = 650 MeV (p_π ~ 777 MeV/c)

T_π = 820 MeV (p_π ~ 950 MeV/c)

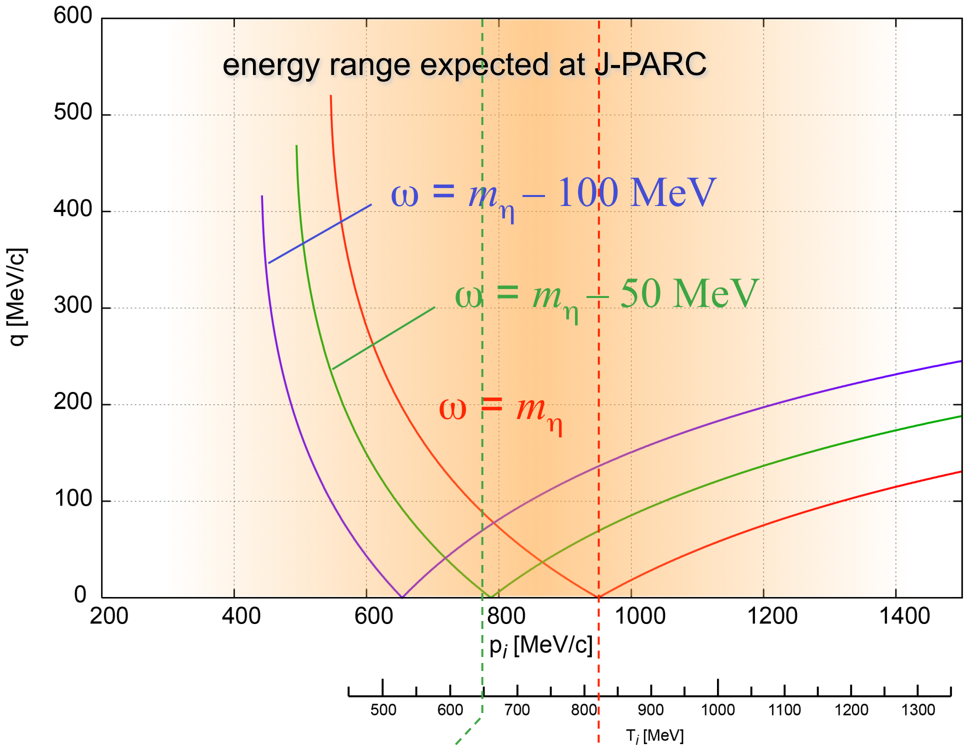
Elementary cross section

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

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

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

Momentum transfer : forward proton angle



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Elementary cross section

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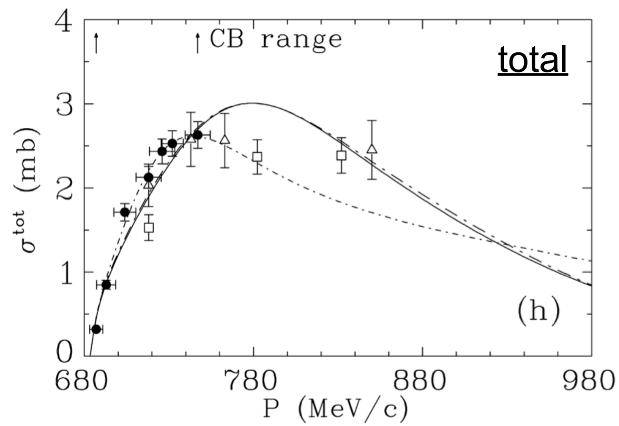
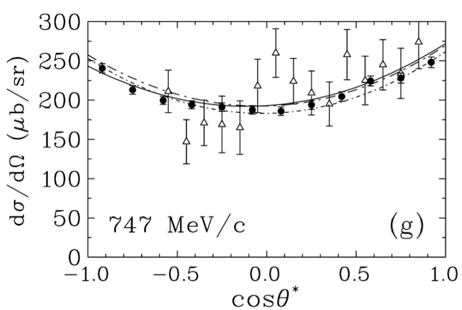
Total cross section



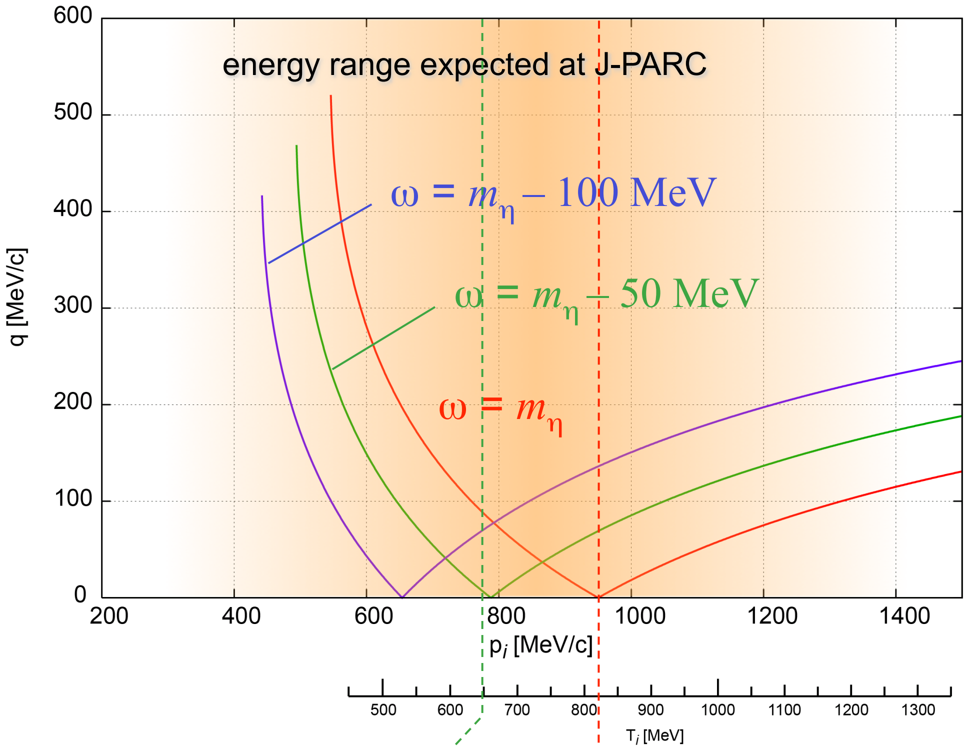
Angular distribution

~ Nearly flat



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

<u>Momentum transfer : forward proton angle</u>



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

T_π = 820 MeV (p_π ~ 950 MeV/c)

<u>Elementary cross section</u>

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

$$\downarrow$$

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

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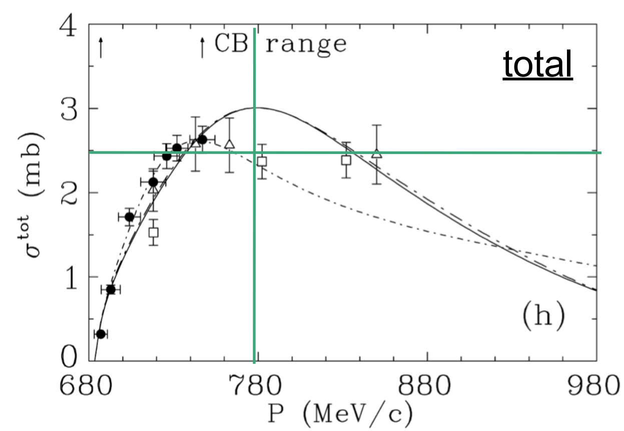
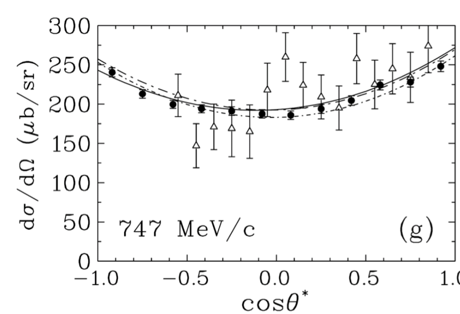
<u>Total cross section</u>

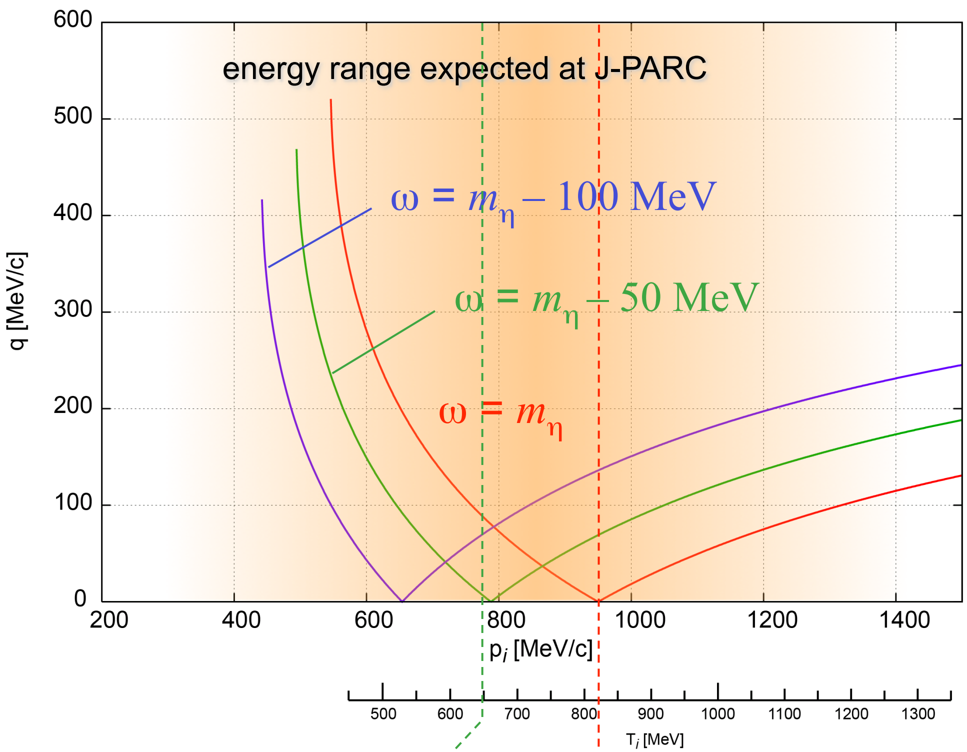


<u>Angular distribution</u> ~ Nearly flat



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

Momentum transfer : forward proton angle



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

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

Elementary cross section

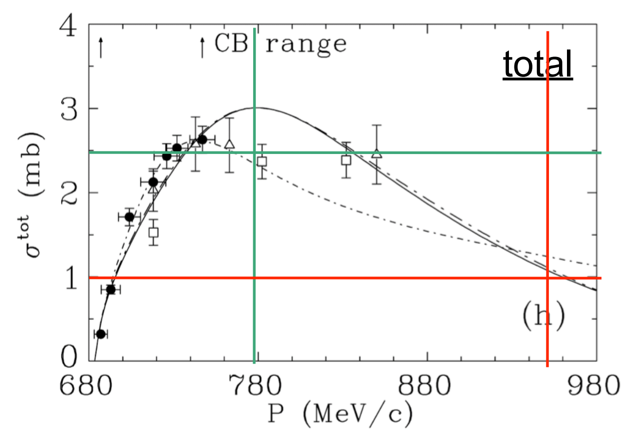
$$\pi^- p \rightarrow \eta n$$

$$\downarrow$$

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

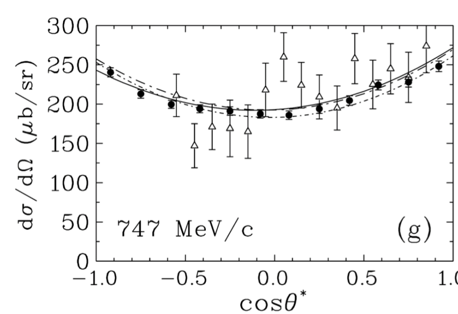
S.Prakhov *et al.*, [Crystal Ball Collaboration] PRC72,015203 (2005).

Total cross section



Angular distribution

~ Nearly flat



Formulation : $\pi + A \rightarrow p + (A\text{-}1)_\eta$

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

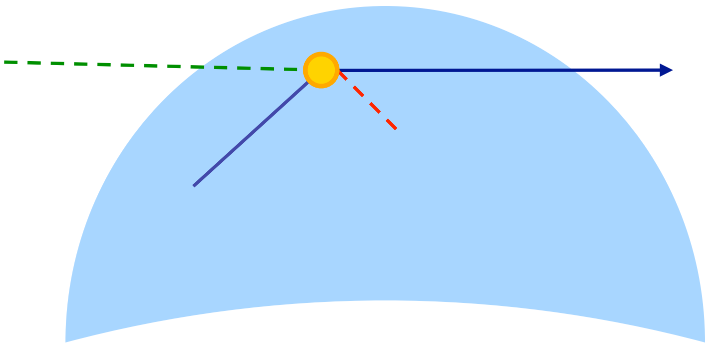
impulse approximation

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

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

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

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



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

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

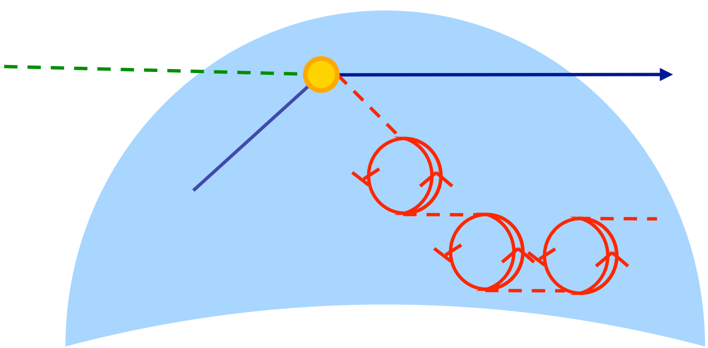
S.Prakhov *et al.*,
[Crystal Ball Collaboration]
PRC72,015203 (2005).

nuclear response function

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

Green's function

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



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 π⁺ + n → p + η

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

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

nuclear response function

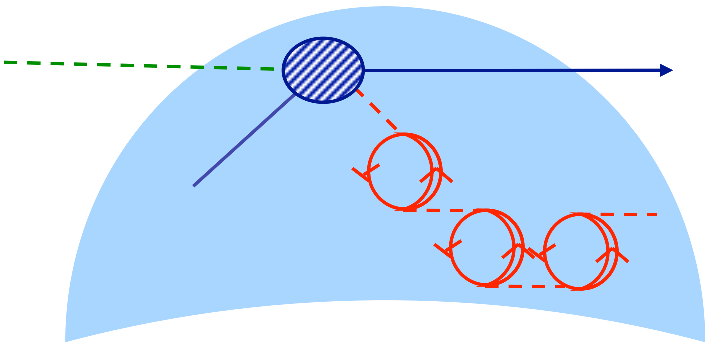
$$S(E) = -\frac{1}{\pi} Im \sum_f \mathcal{T}_f^\dagger G(E) \mathcal{T}_f$$

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

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



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

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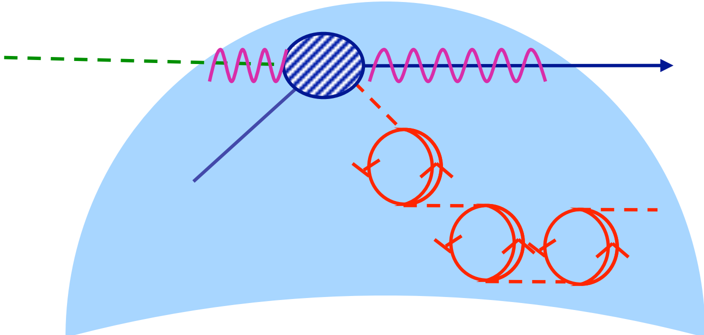


Distortion factor : flux reduction due to absorption

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

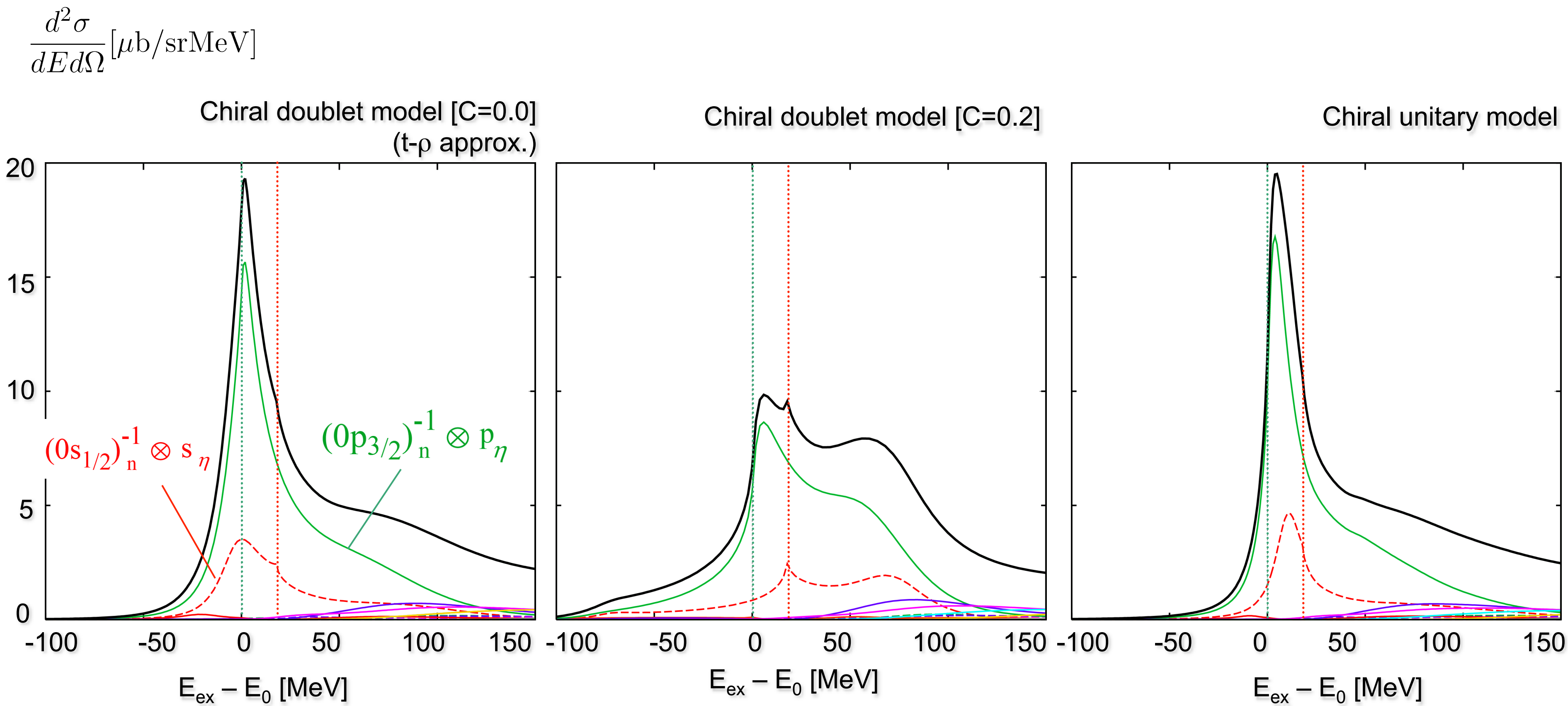
eikonal approximation

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

(π^+,p) spectra : ^{12}C target : Green function method

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

recoilless at η threshold



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

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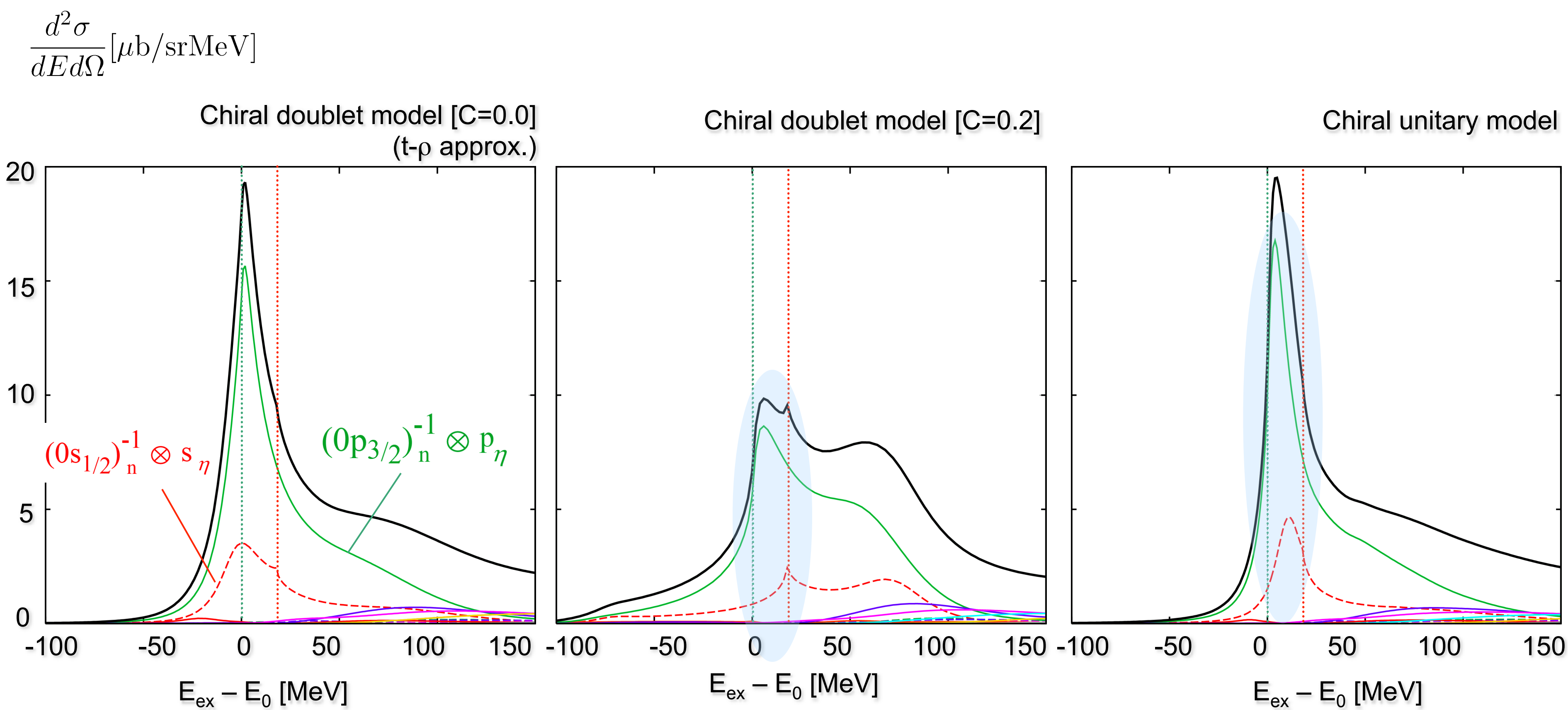

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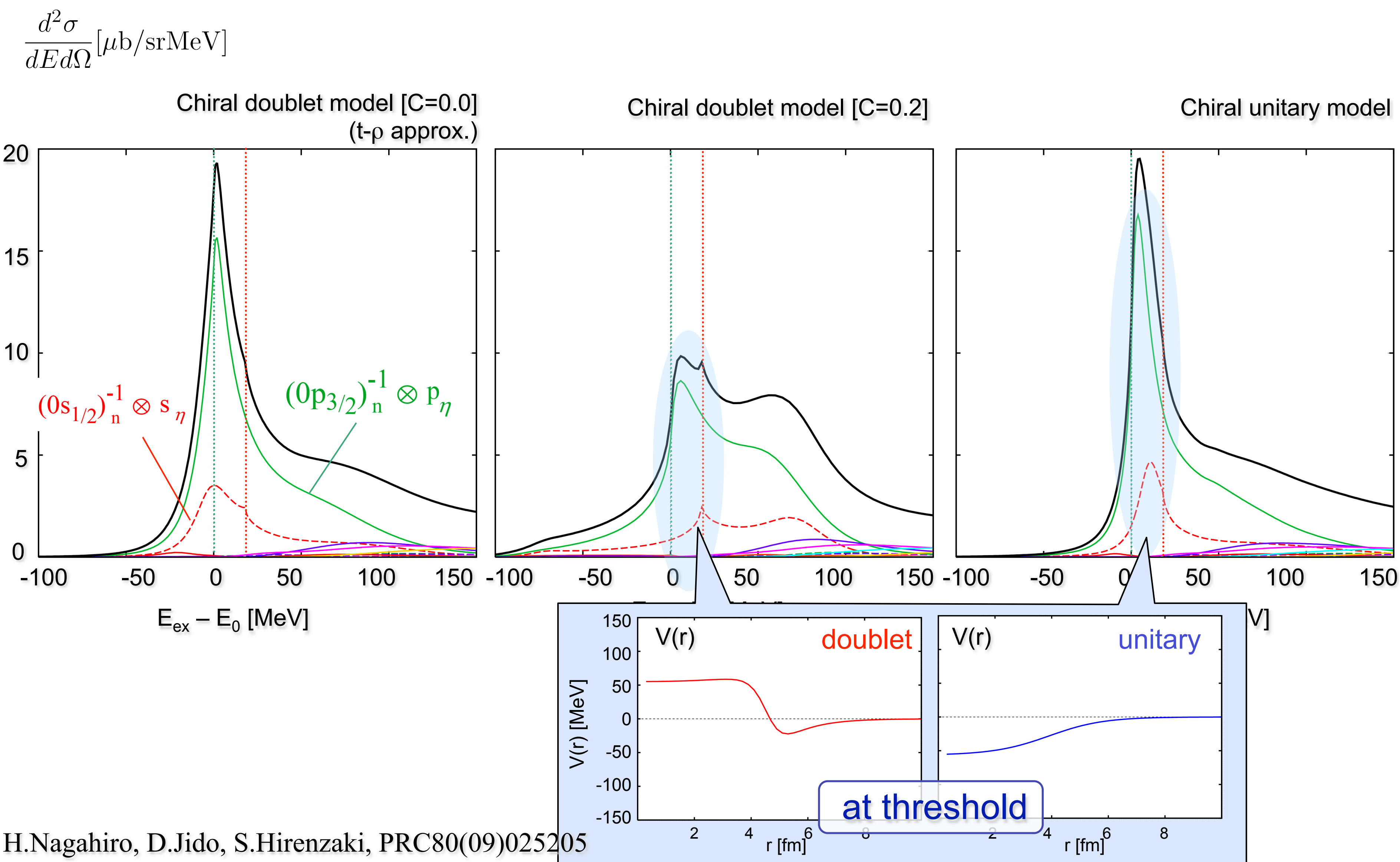

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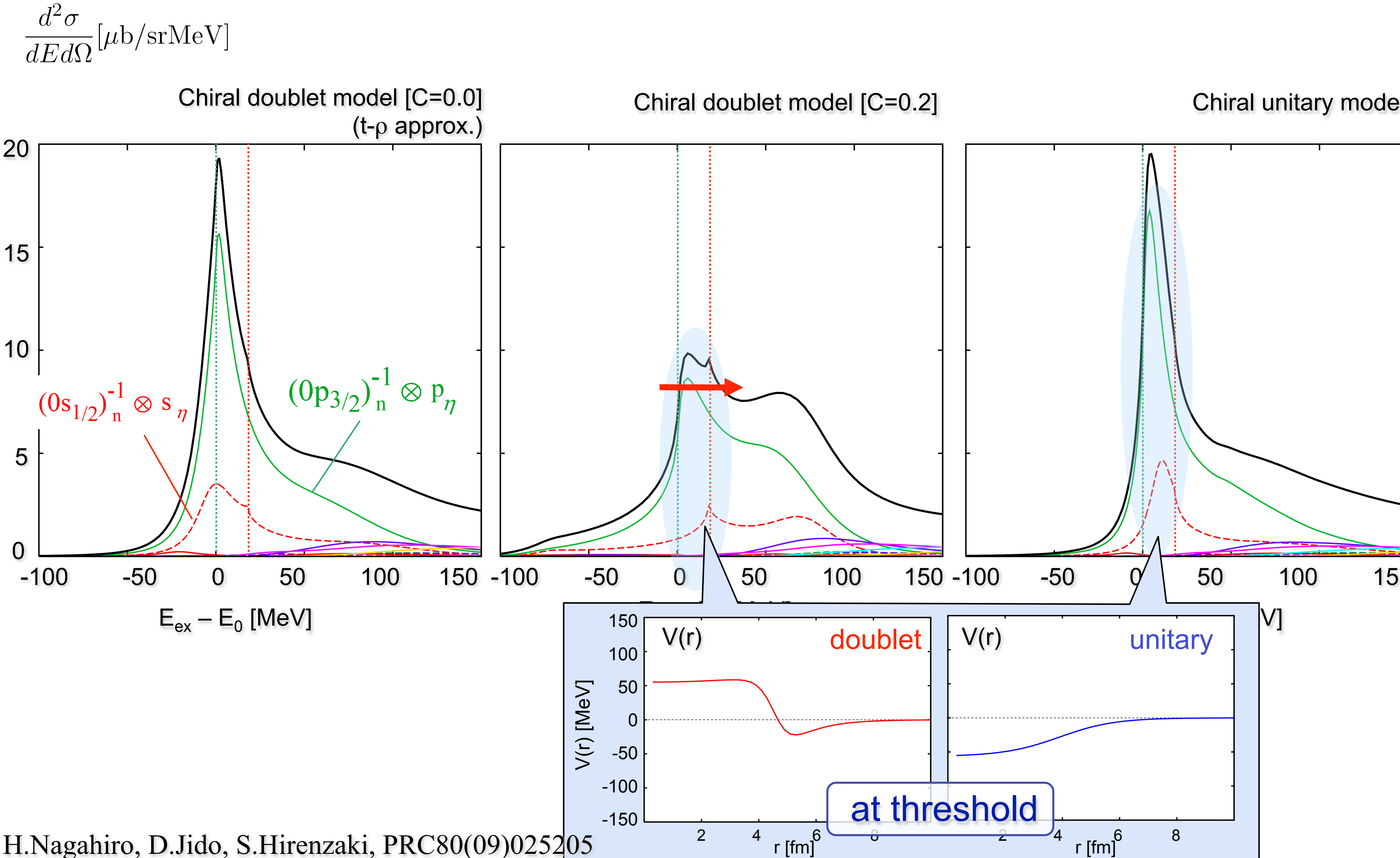

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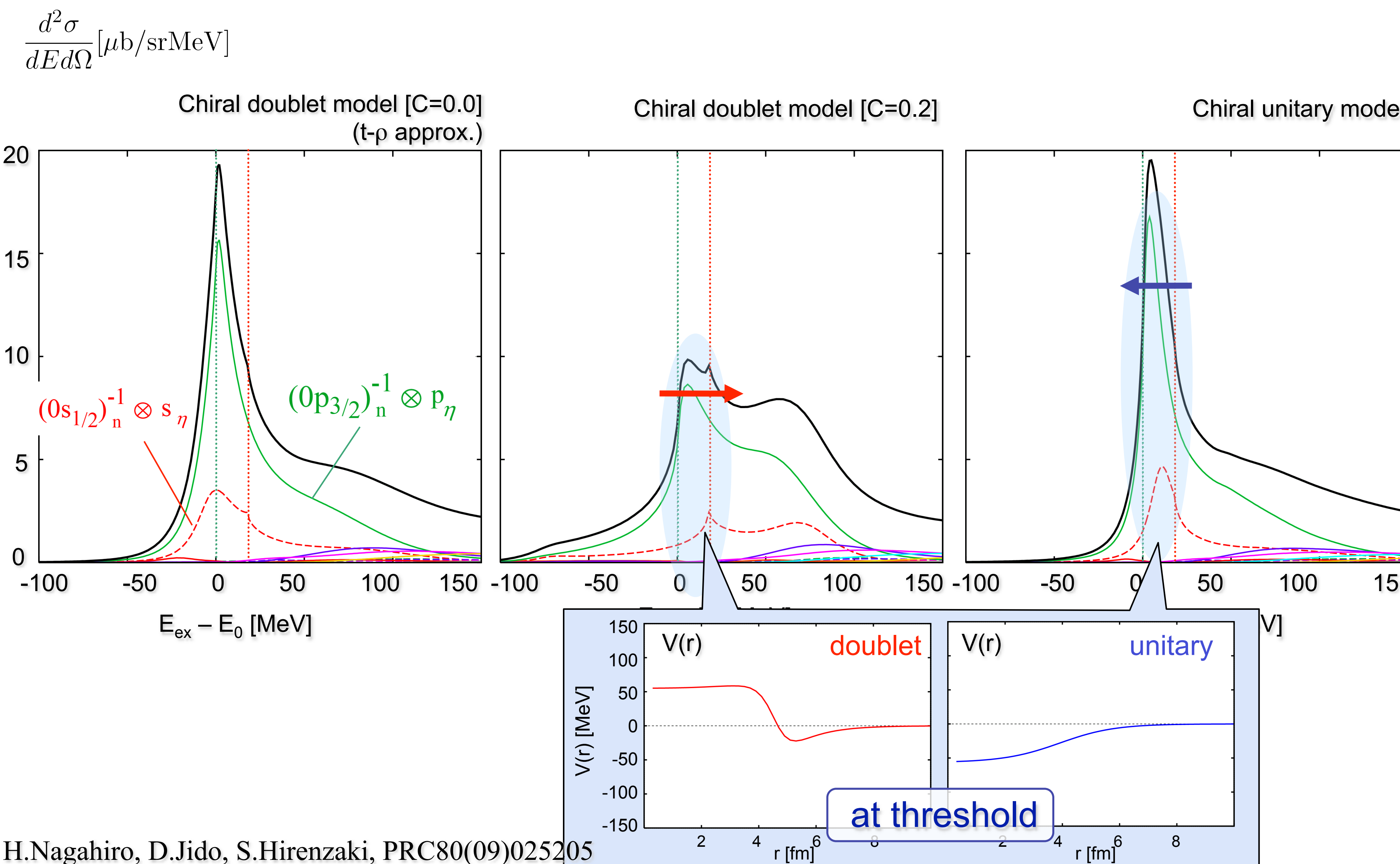

H.Nagahiro, D.Jido, S.Hirenzaki, PRC80(09)025205

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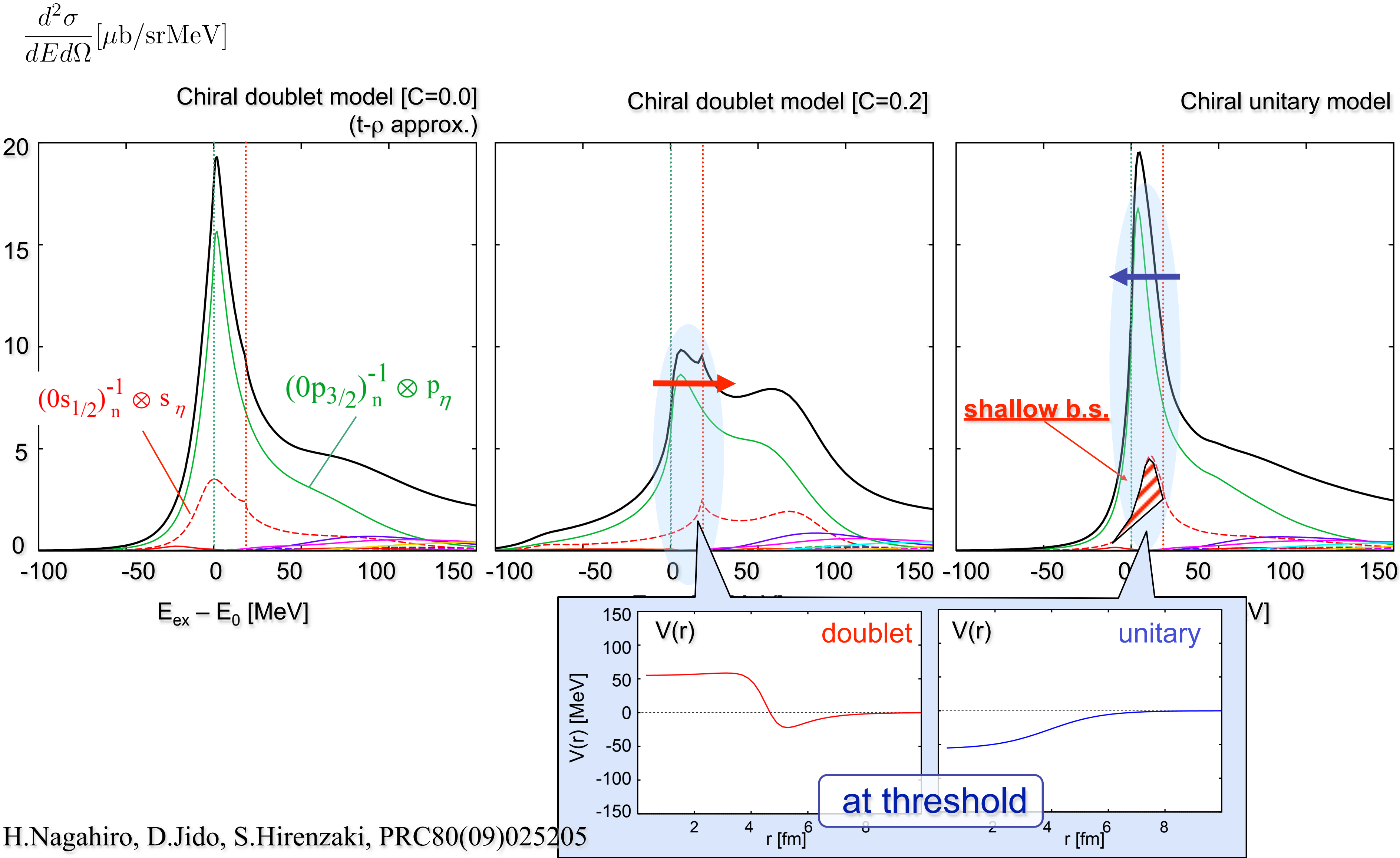
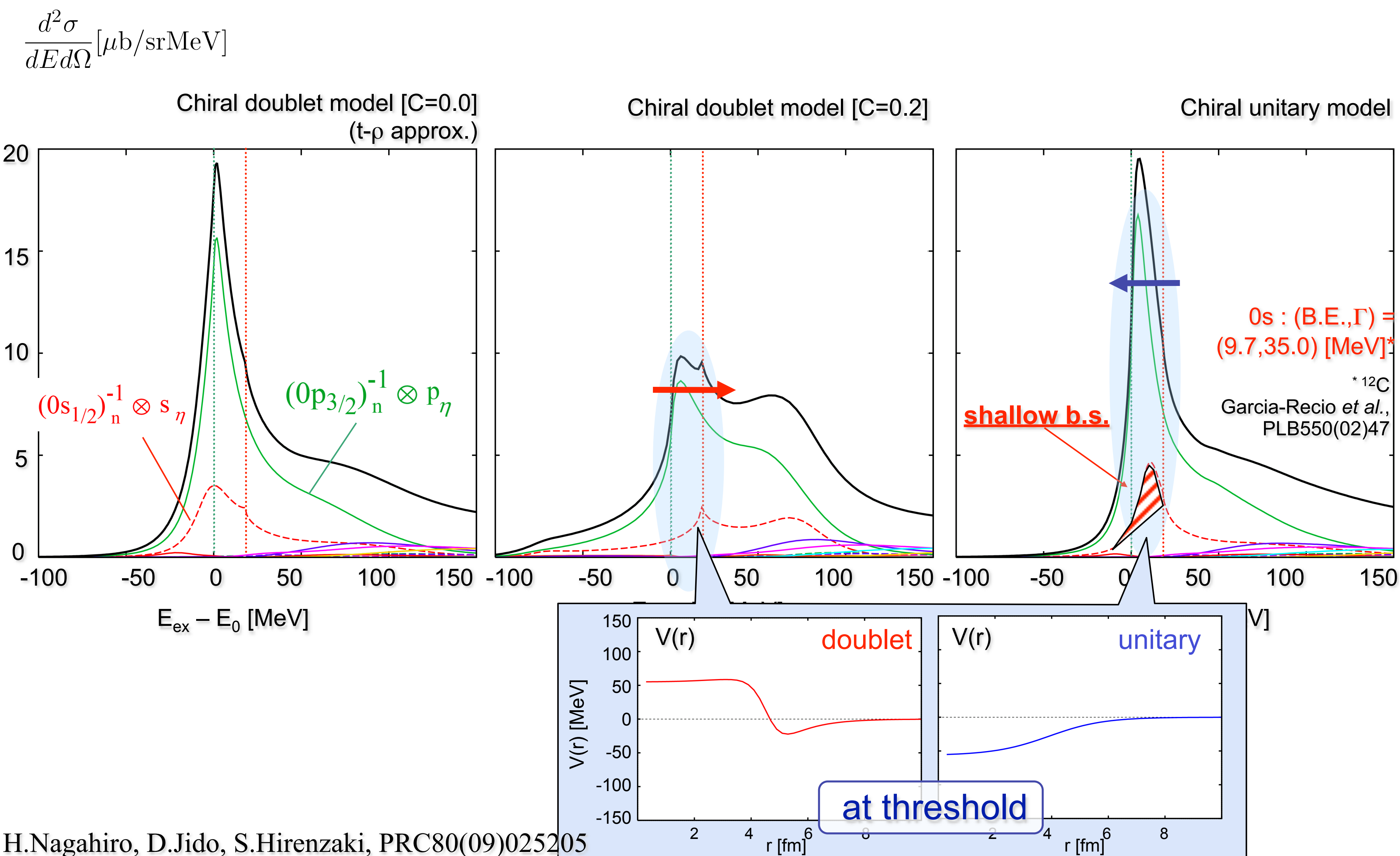


H.Nagahiro, D.Jido, S.Hirenzaki, PRC80(09)025205

(π⁺,p) spectra : ¹²C target : Green function method

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

recoilless at η threshold



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

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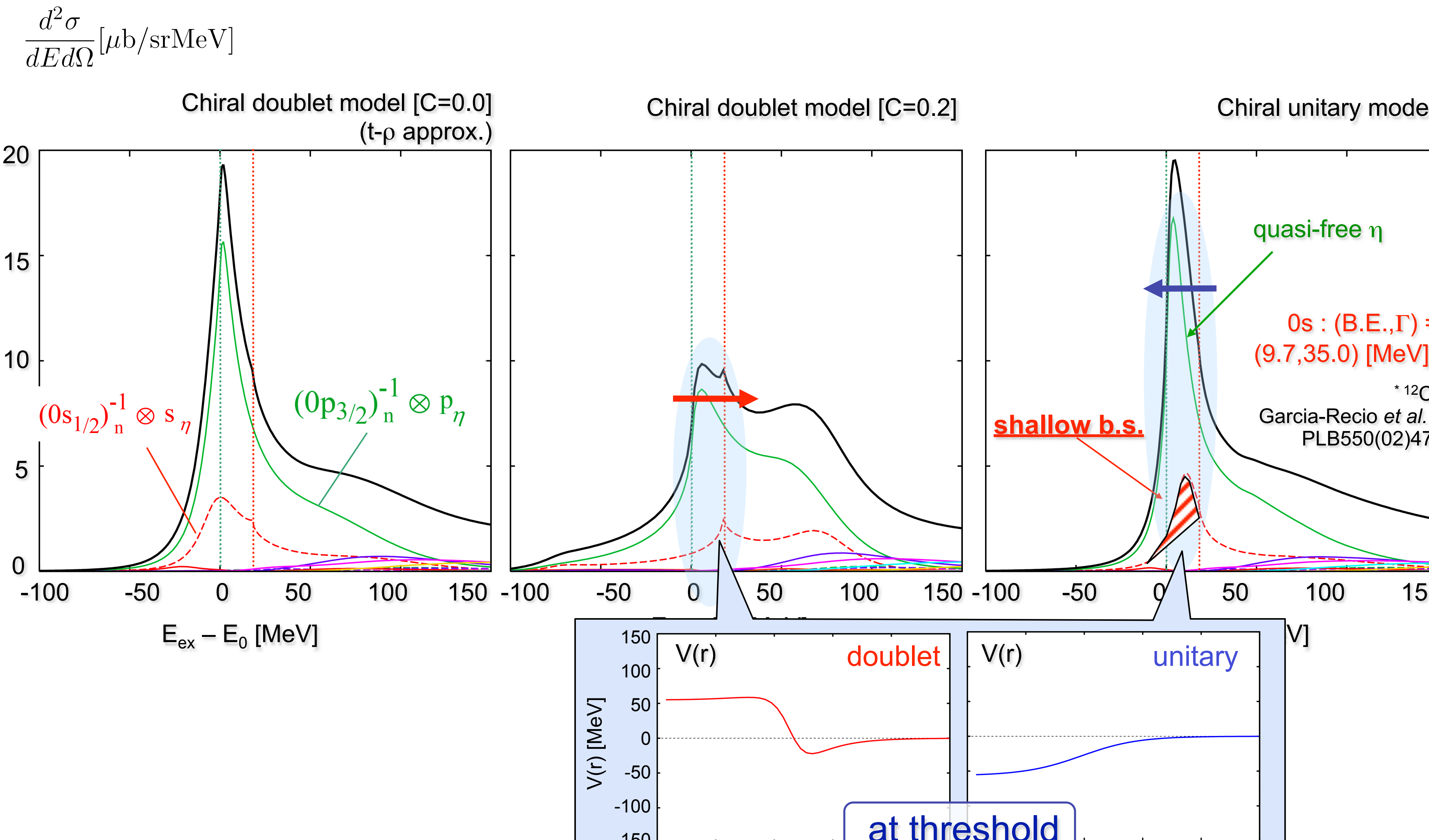

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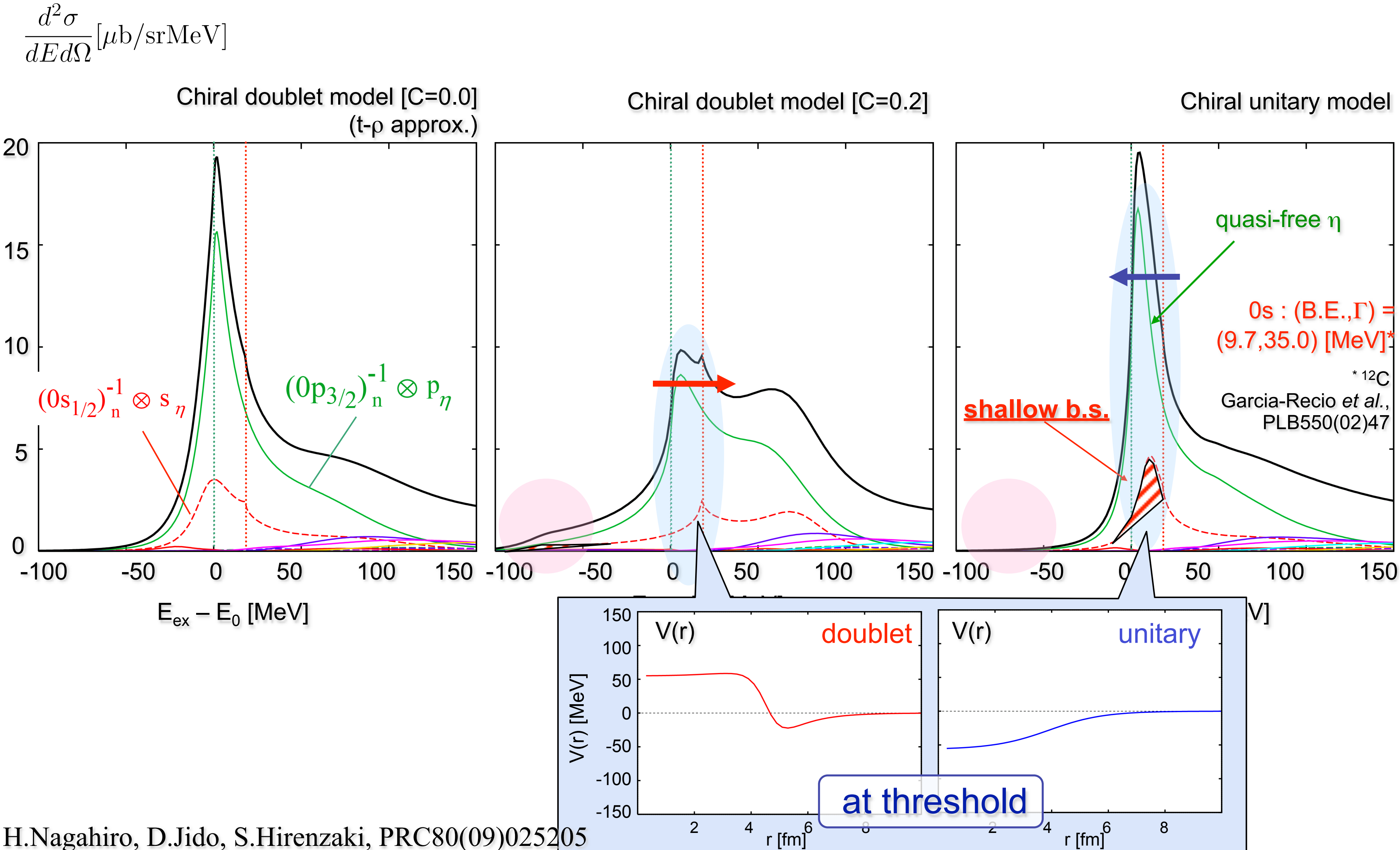
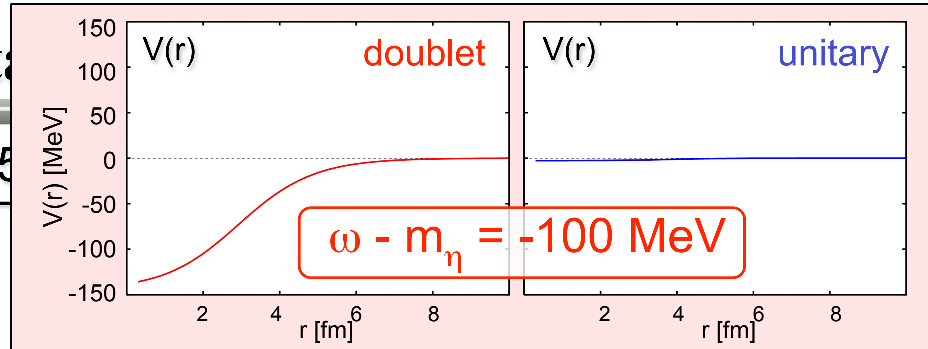
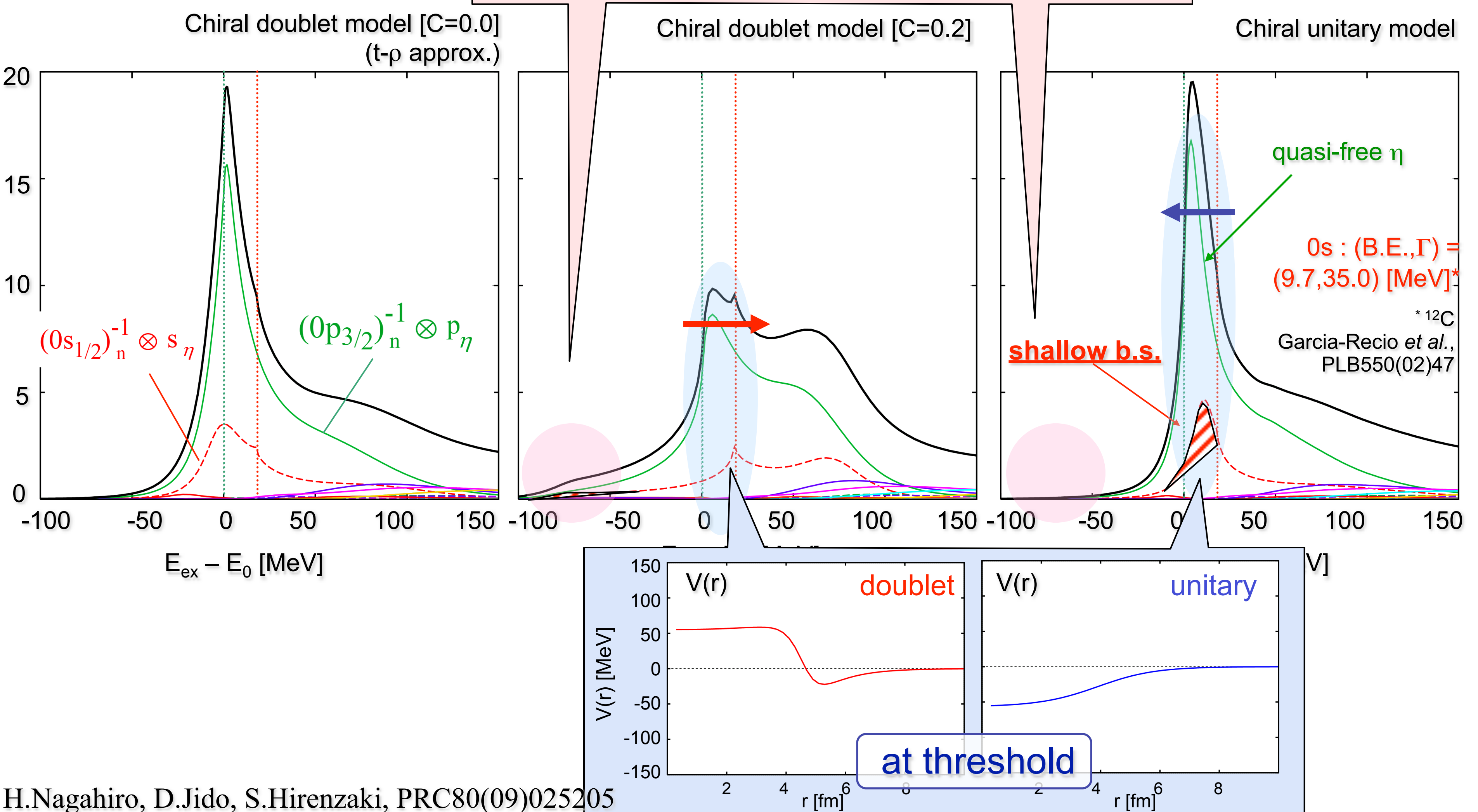


H.Nagahiro, D.Jido, S.Hirenzaki, PRC80(09)025205

(π^+,p) spectra : ^{12}C t…

T_π = 820 MeV (p_π = 95…





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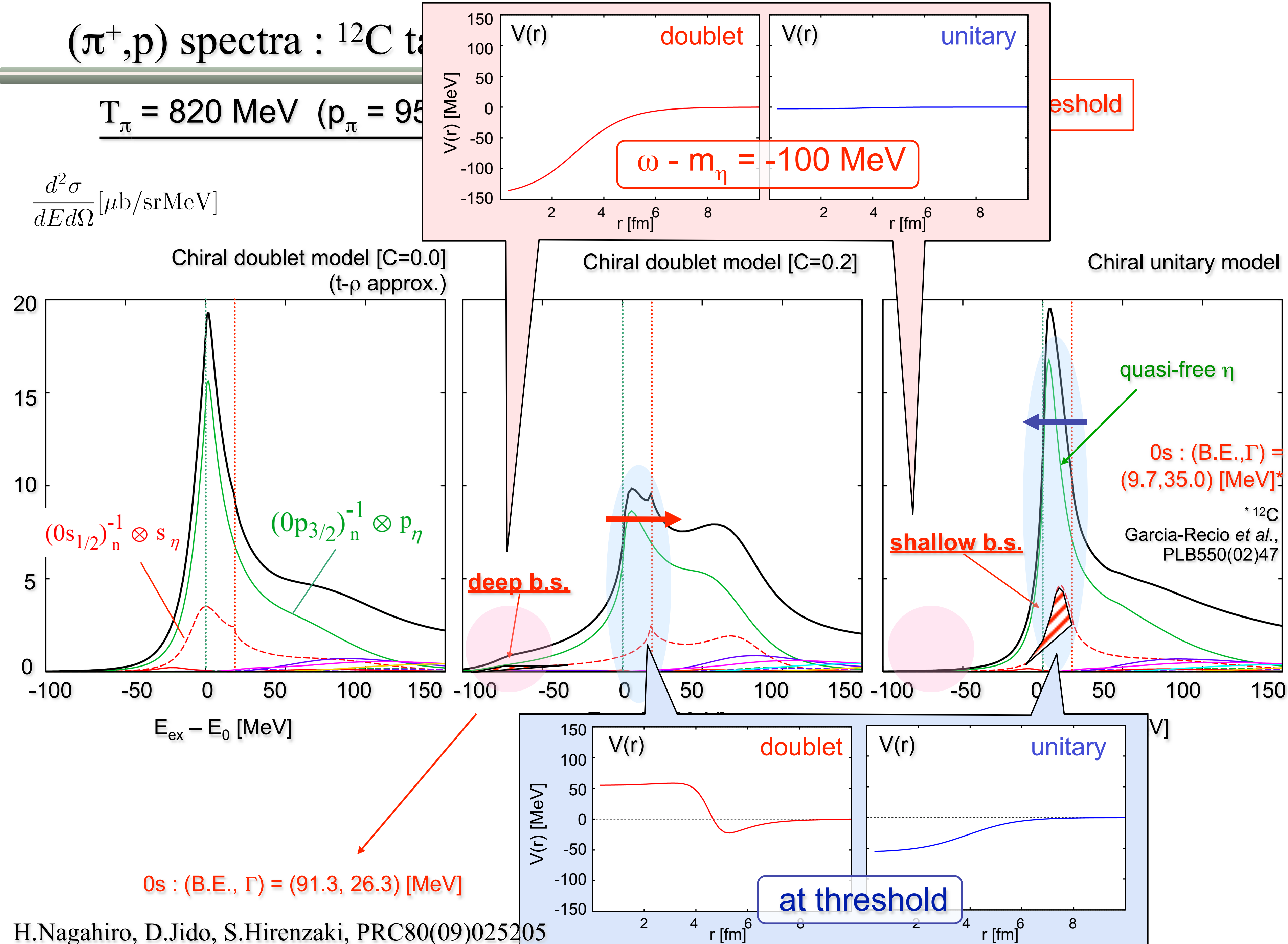

H.Nagahiro, D.Jido, S.Hirenzaki, PRC80(09)025205

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

- Chrien et al., PRL60(1988)2595
  - » p_π = 800 MeV/c : proton angle : **15 deg. (Lab.)**
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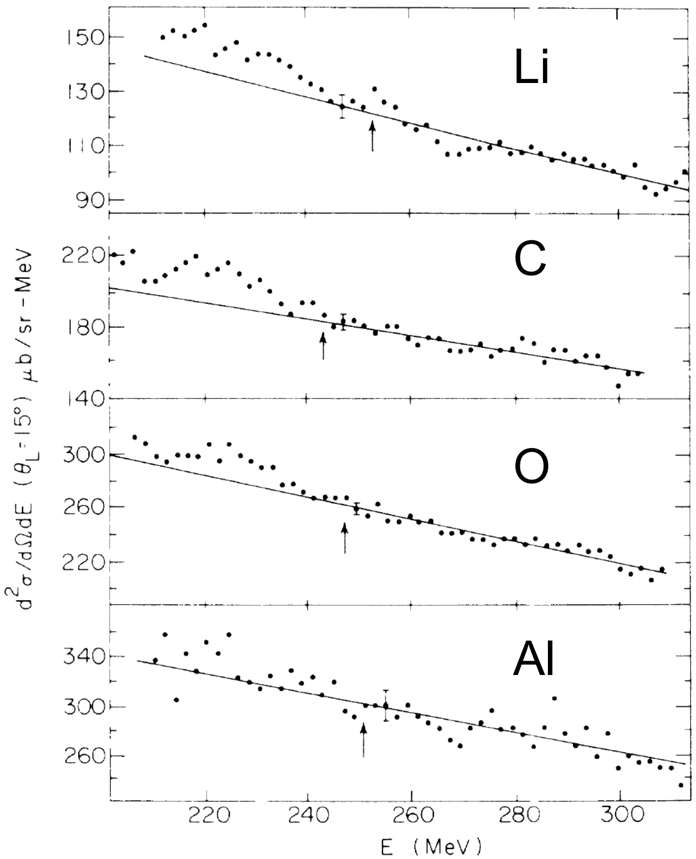
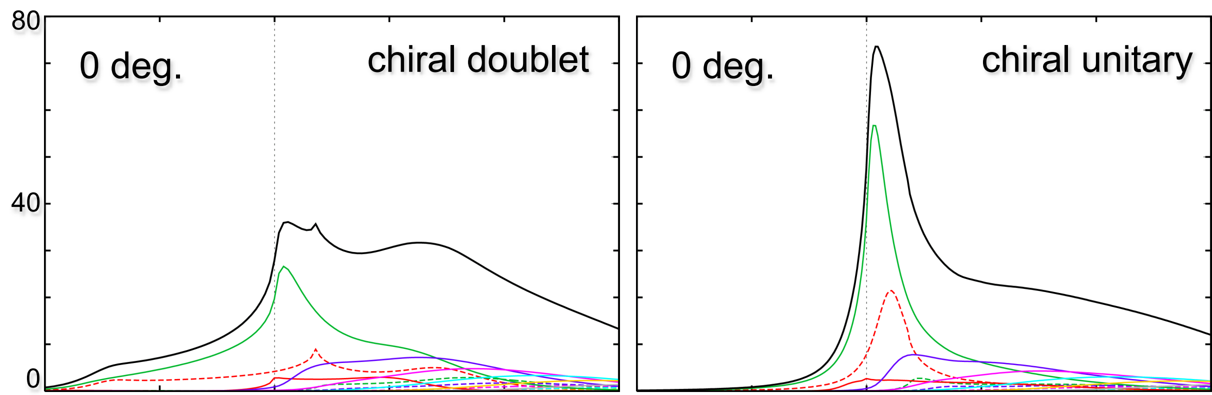
→ negative results (bound state peak was not observed)

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





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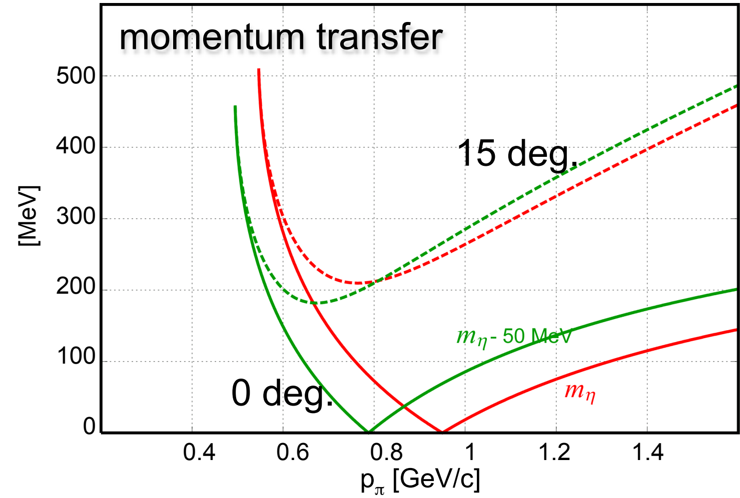

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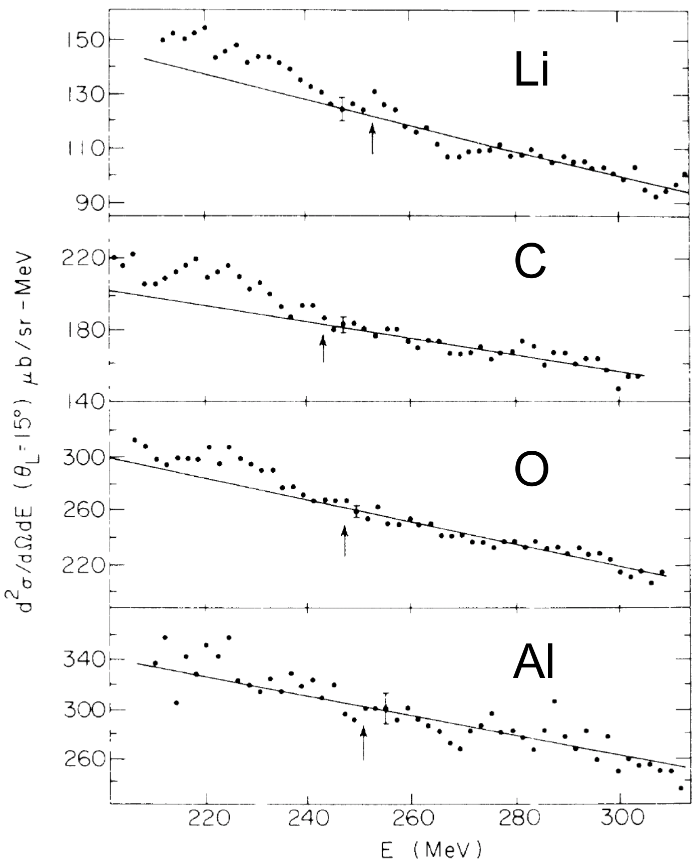

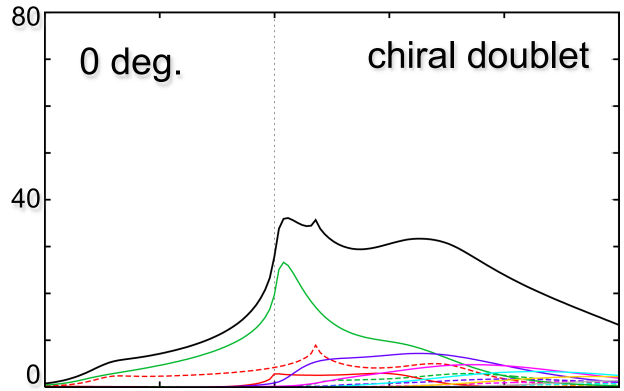

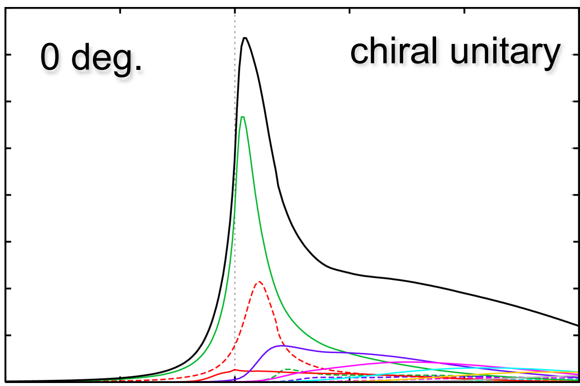

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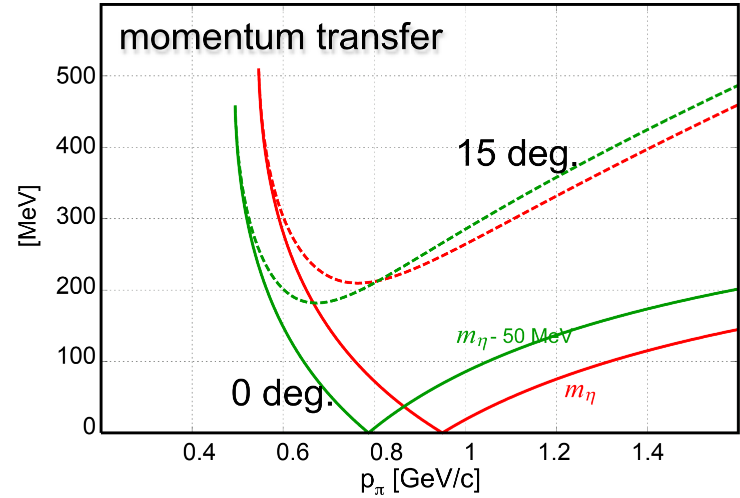

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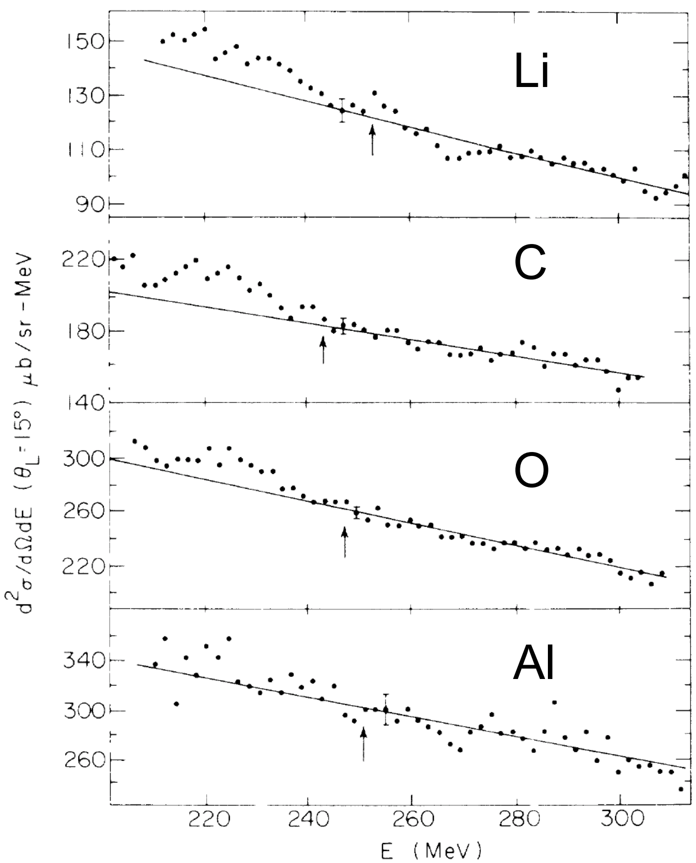

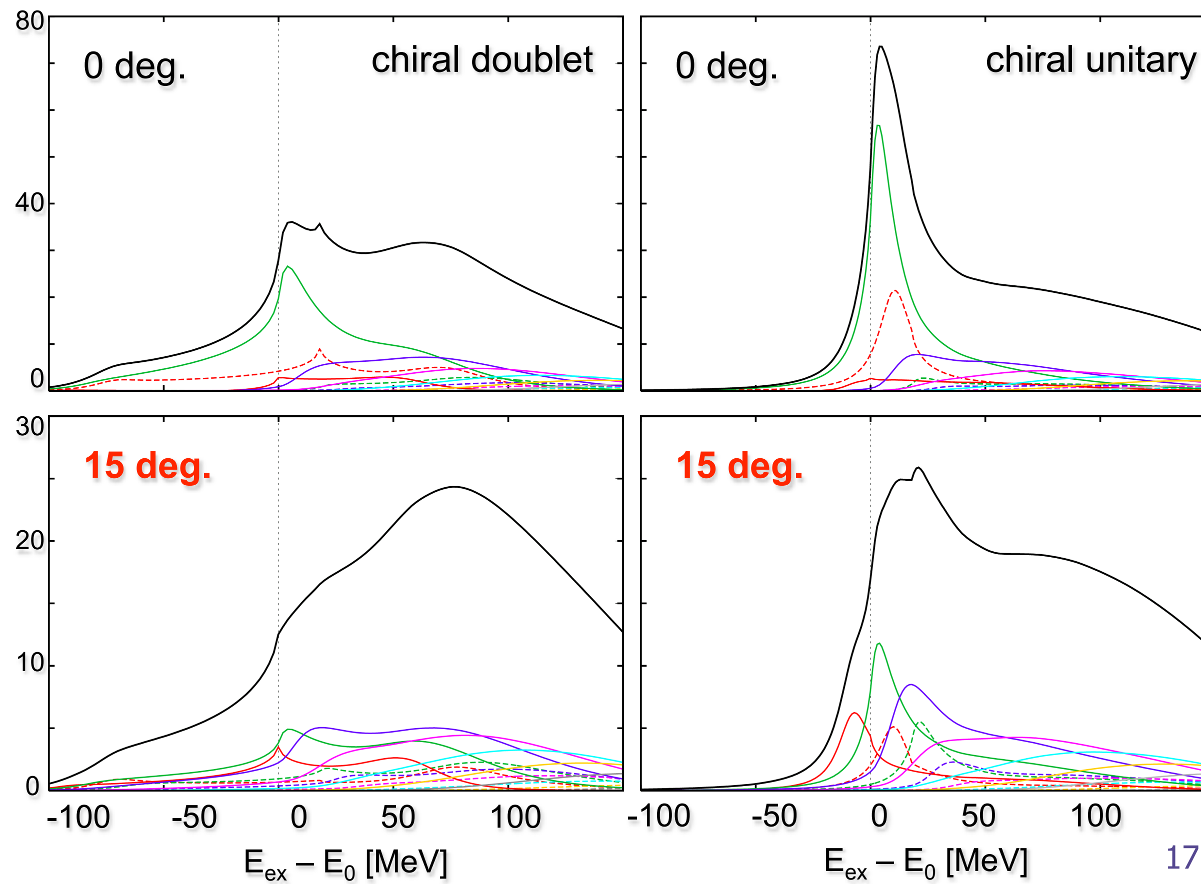

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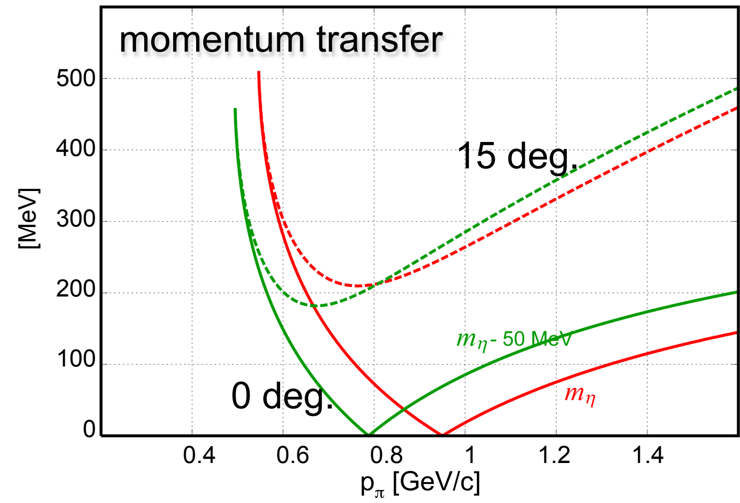

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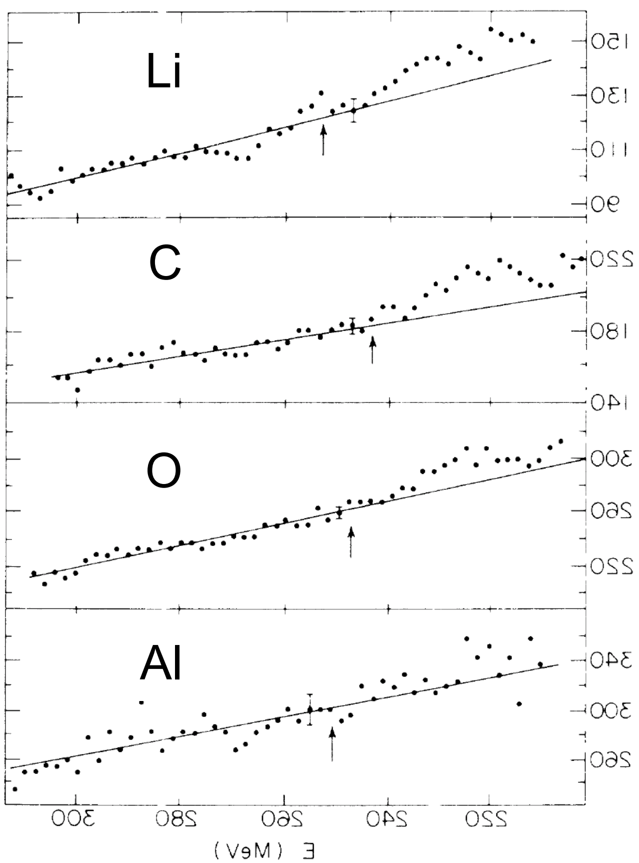

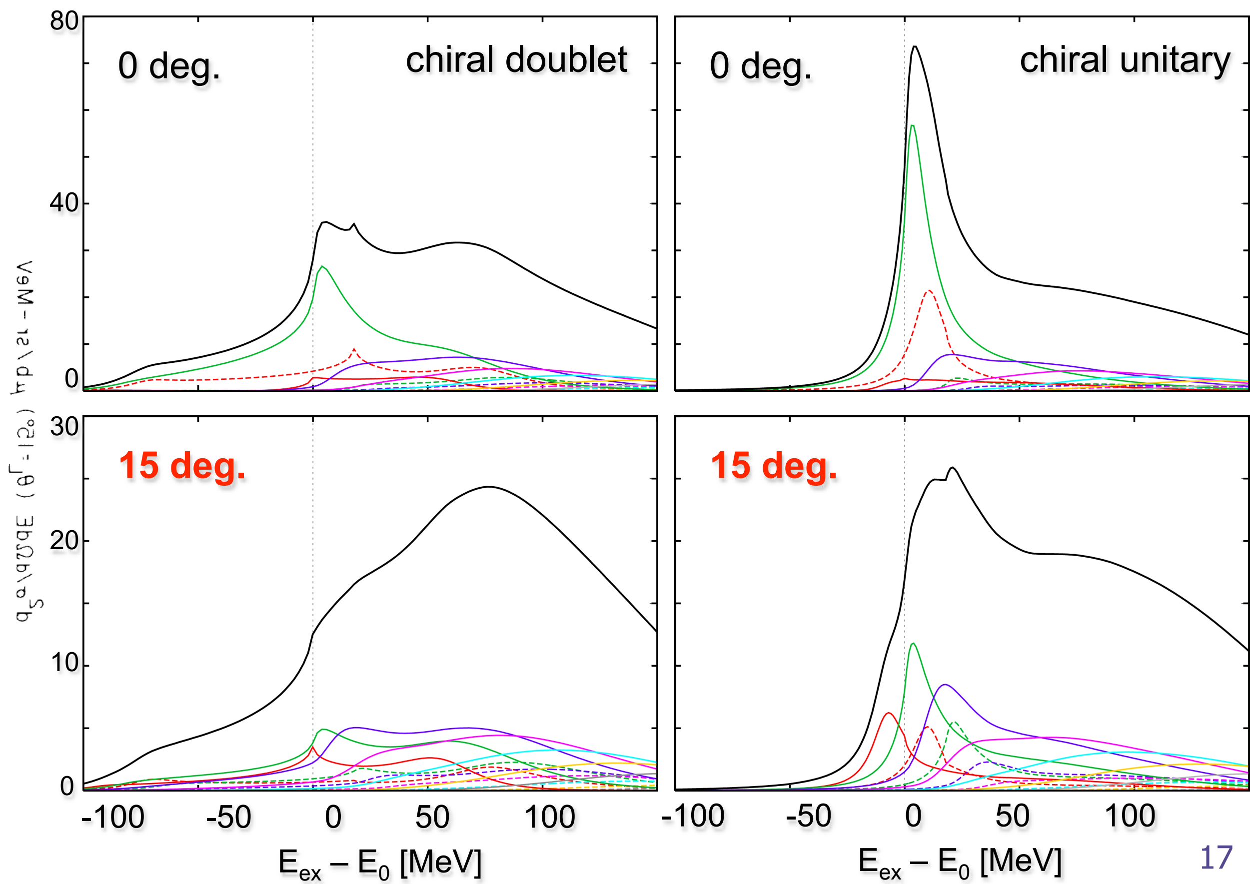

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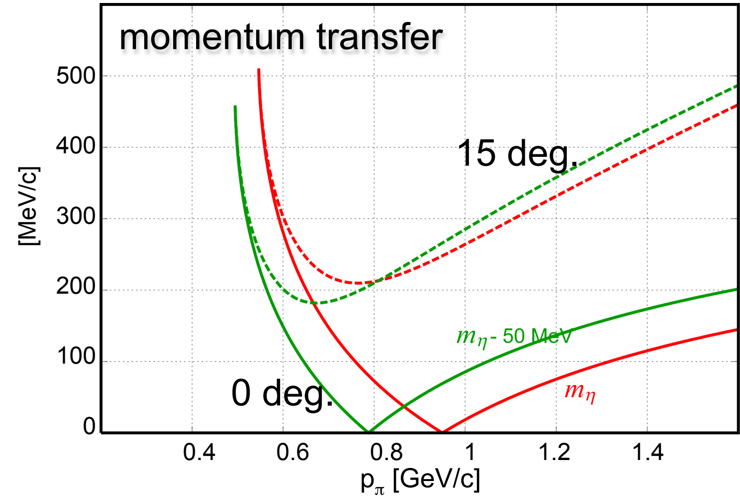

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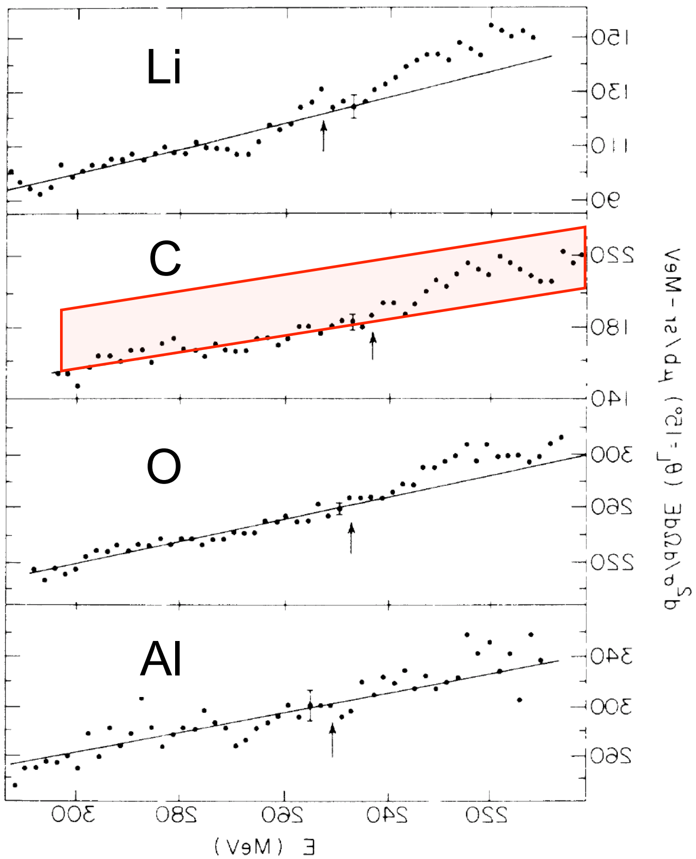

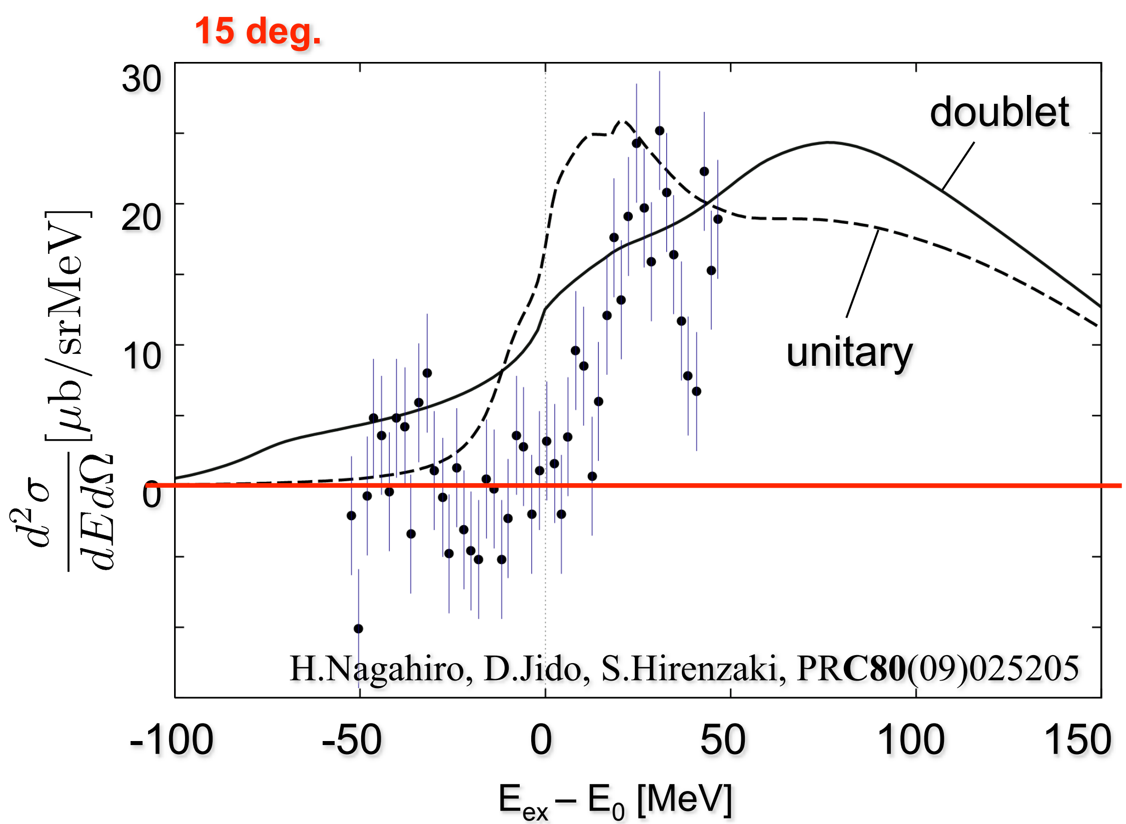

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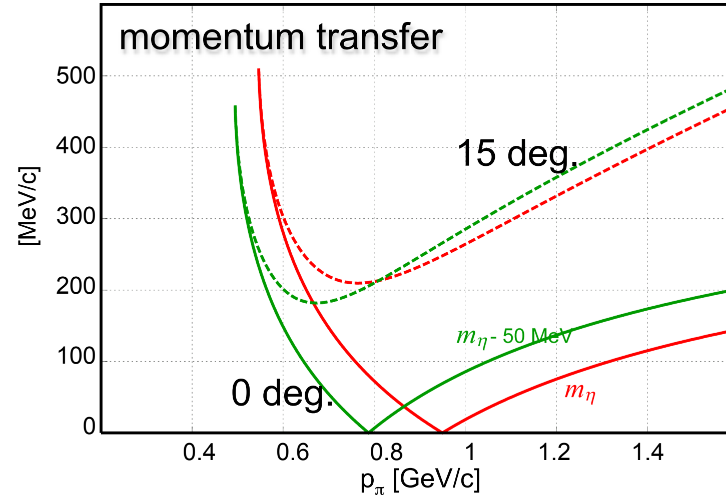

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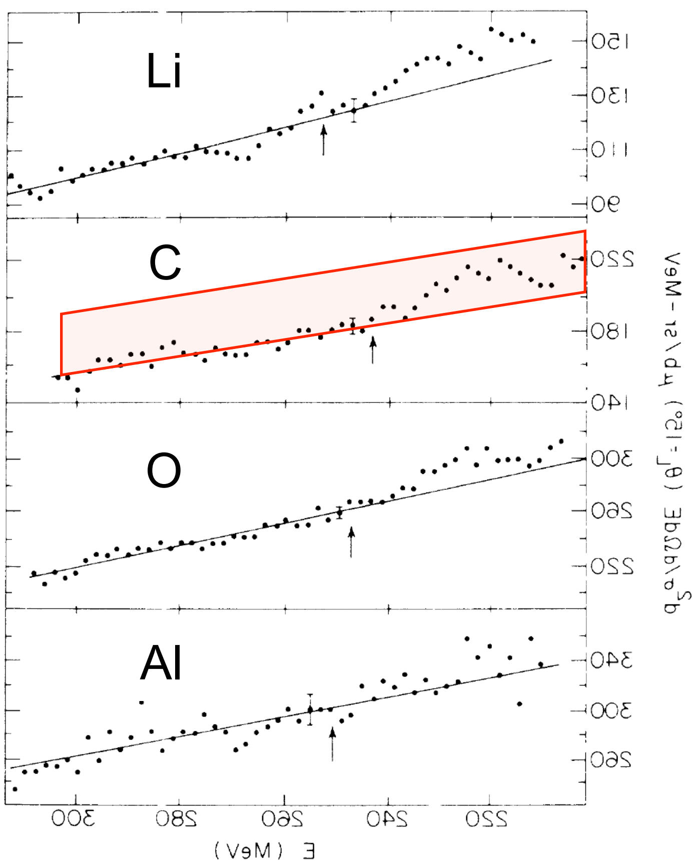

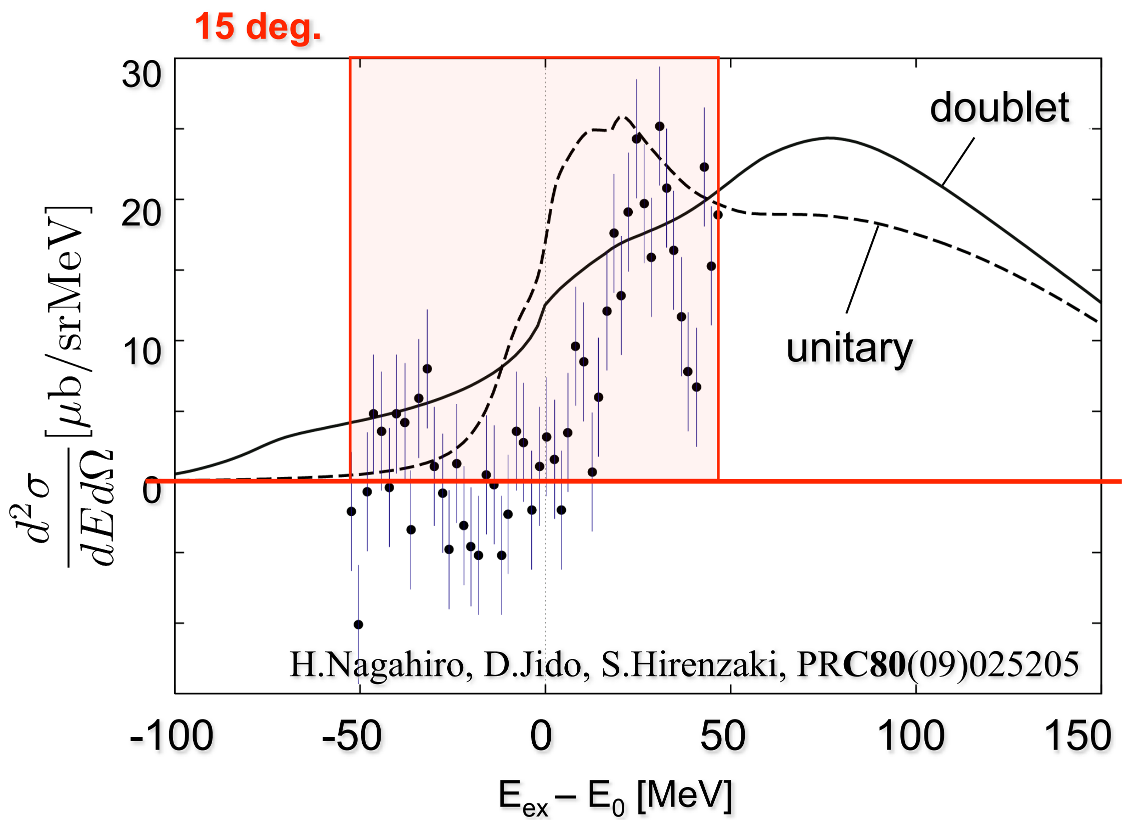

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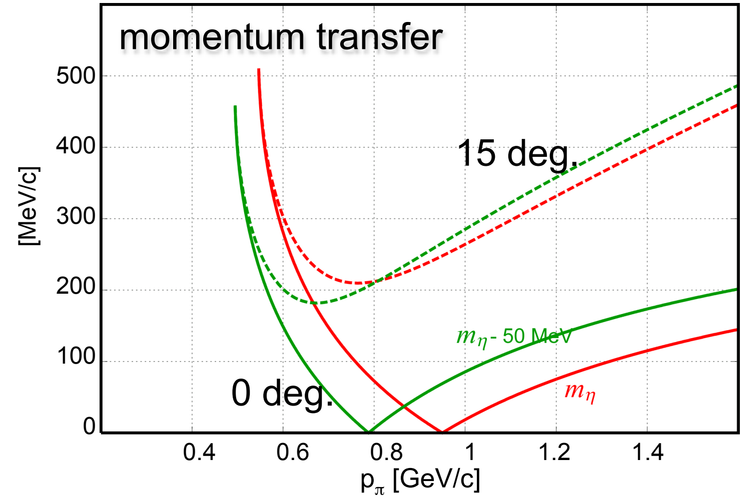

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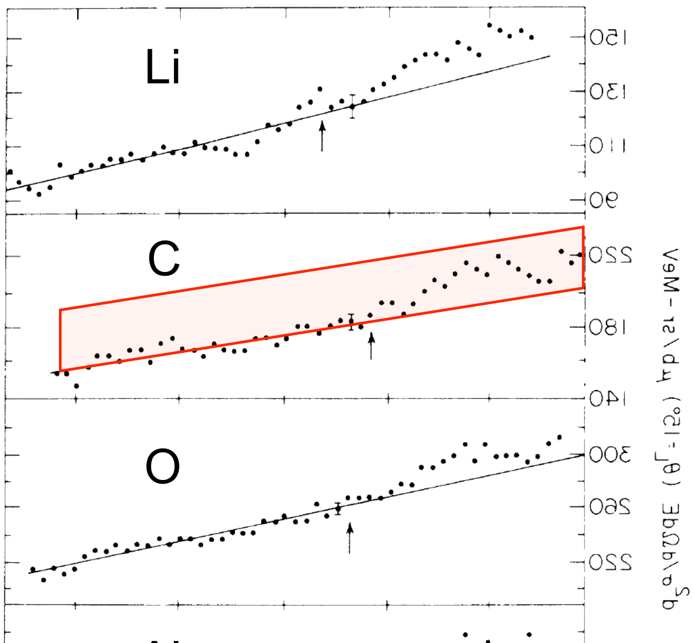
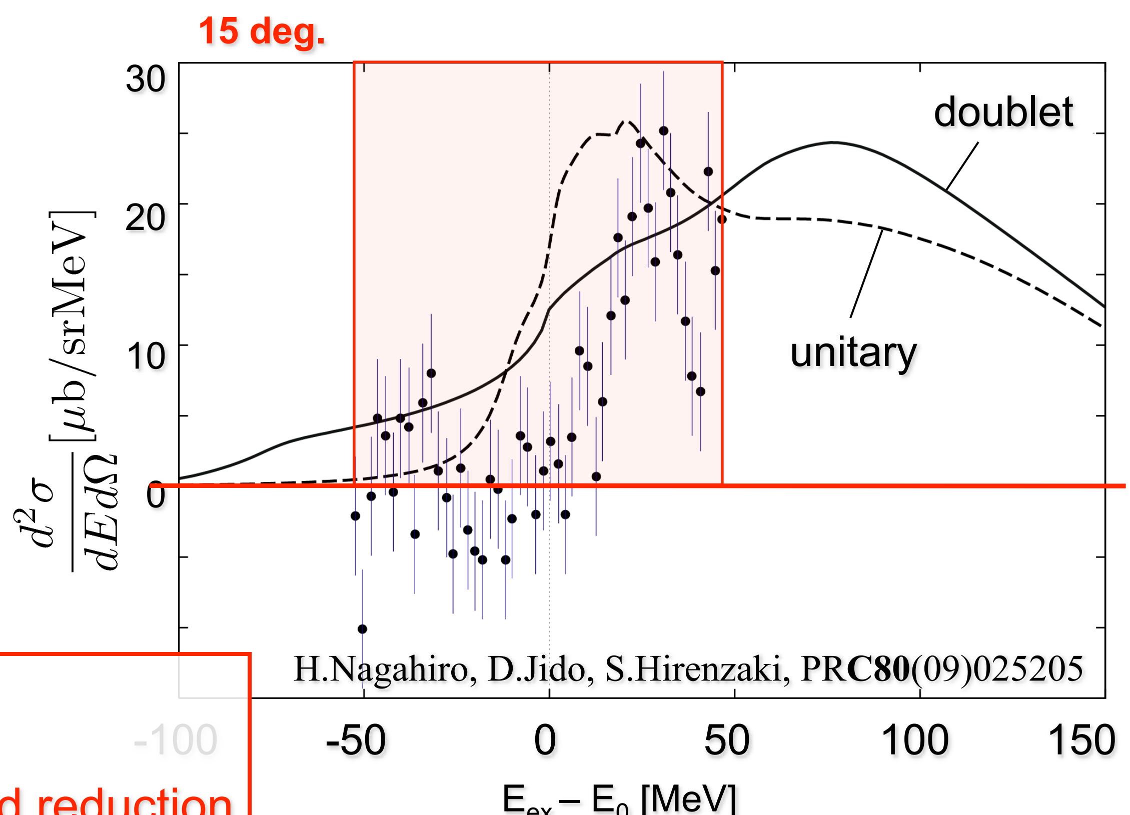
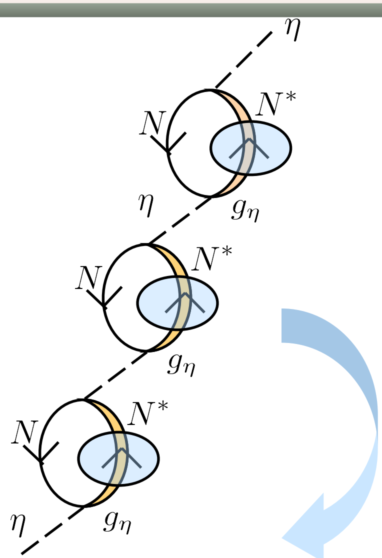


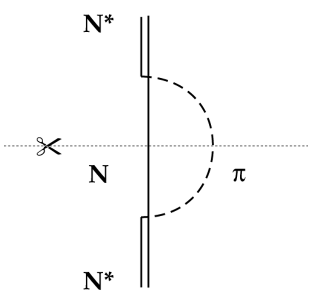


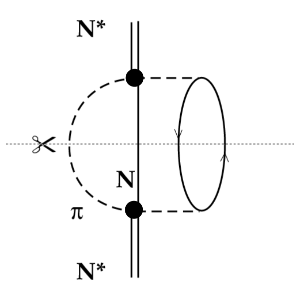
- wider energy range
- proton angle = 0 degree
- S/N ~ 1/10 → need background reduction

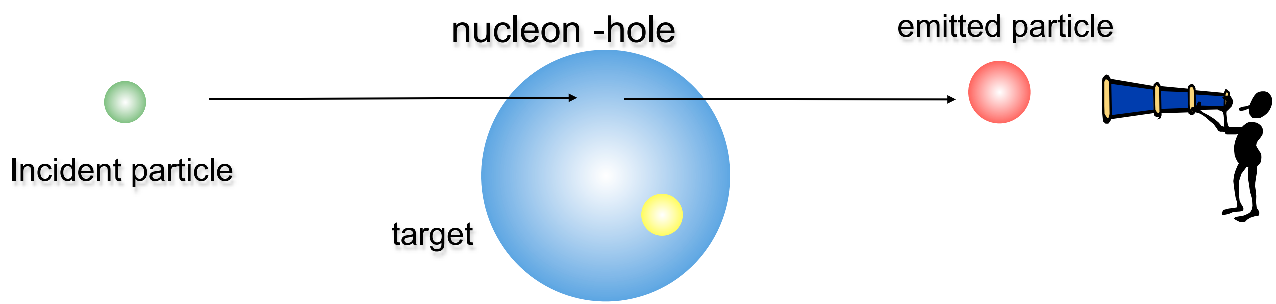
background reduction : coincidence measurement



N* width in CDM

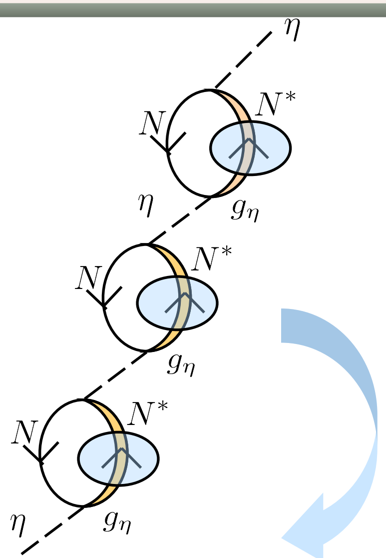




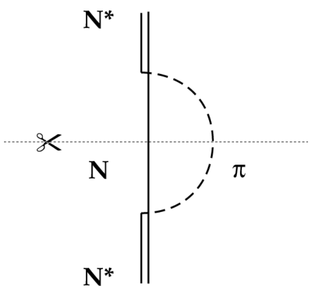


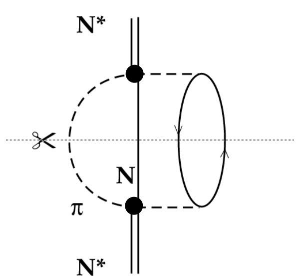
K.Itahashi, H.Fujioka, S.Hirenzaki, D.Jido, H.Nagahiro, Letter of Intent for J-PARC 2007

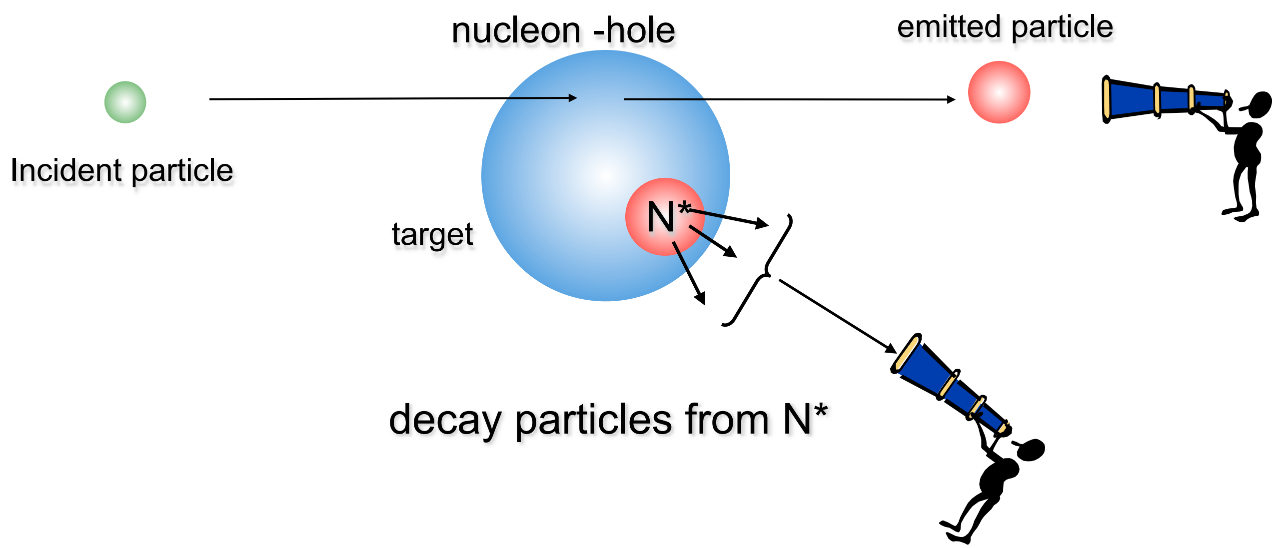
background reduction : coincidence measurement



N* width in CDM







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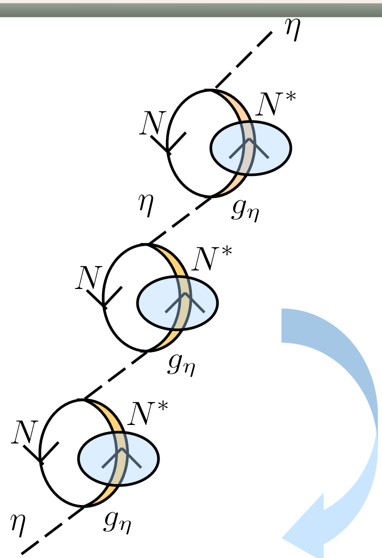
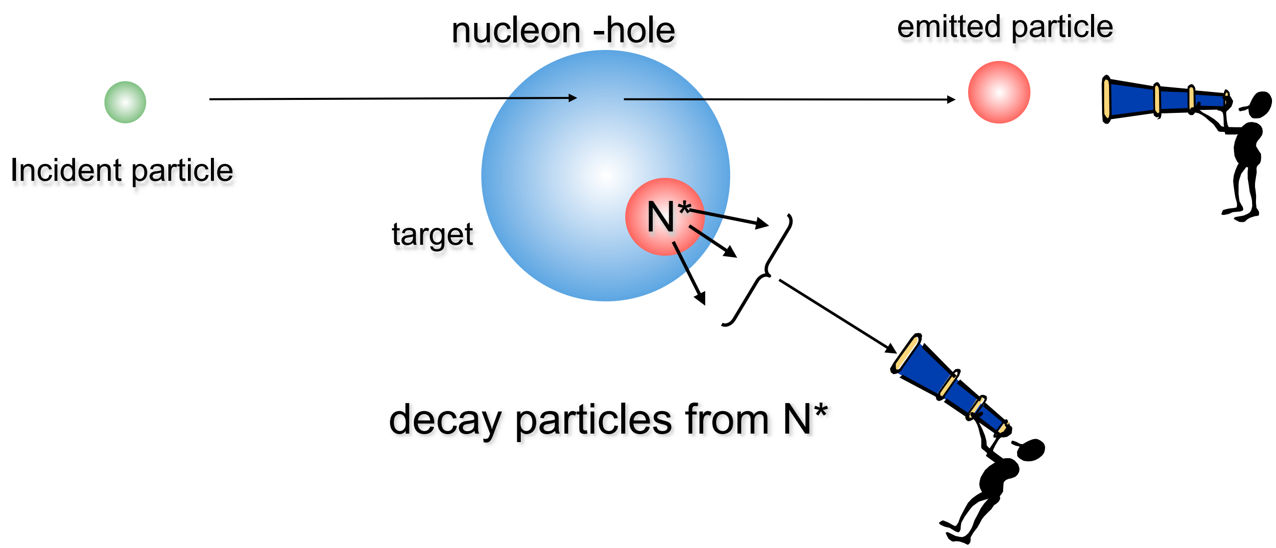
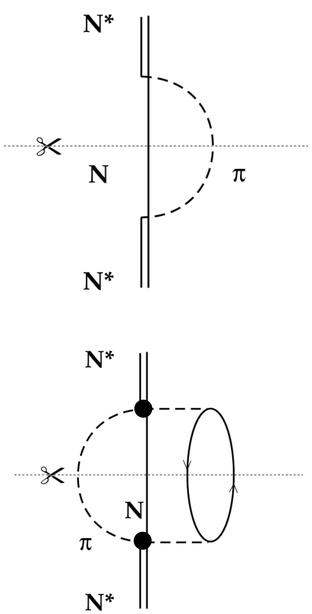
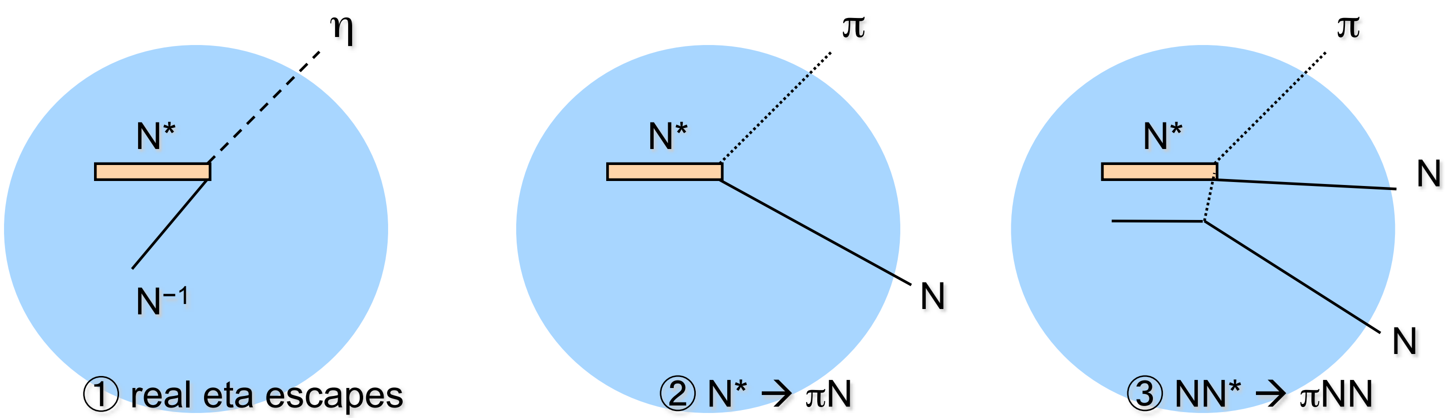


N* width in CDM





final states we considered

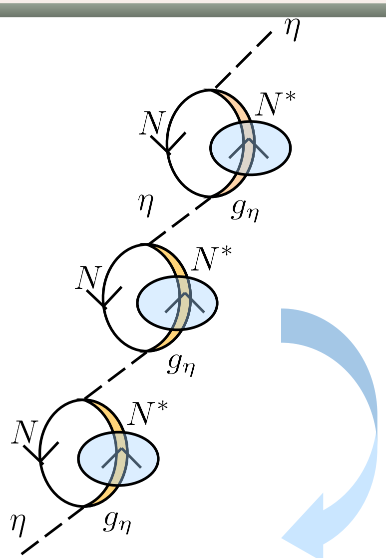


① real eta escapes (escape part)

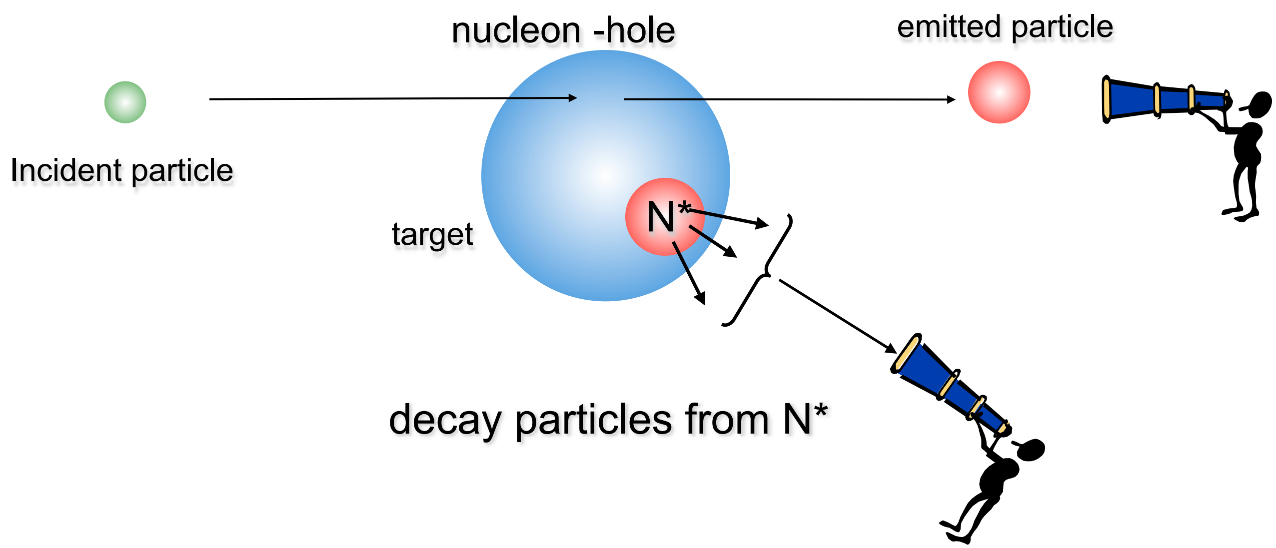
② N* → πN (conversion part)

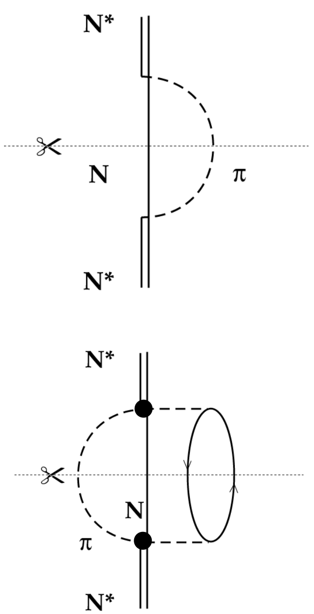
③ NN* → πNN (conversion part)

background reduction : coincidence measurement

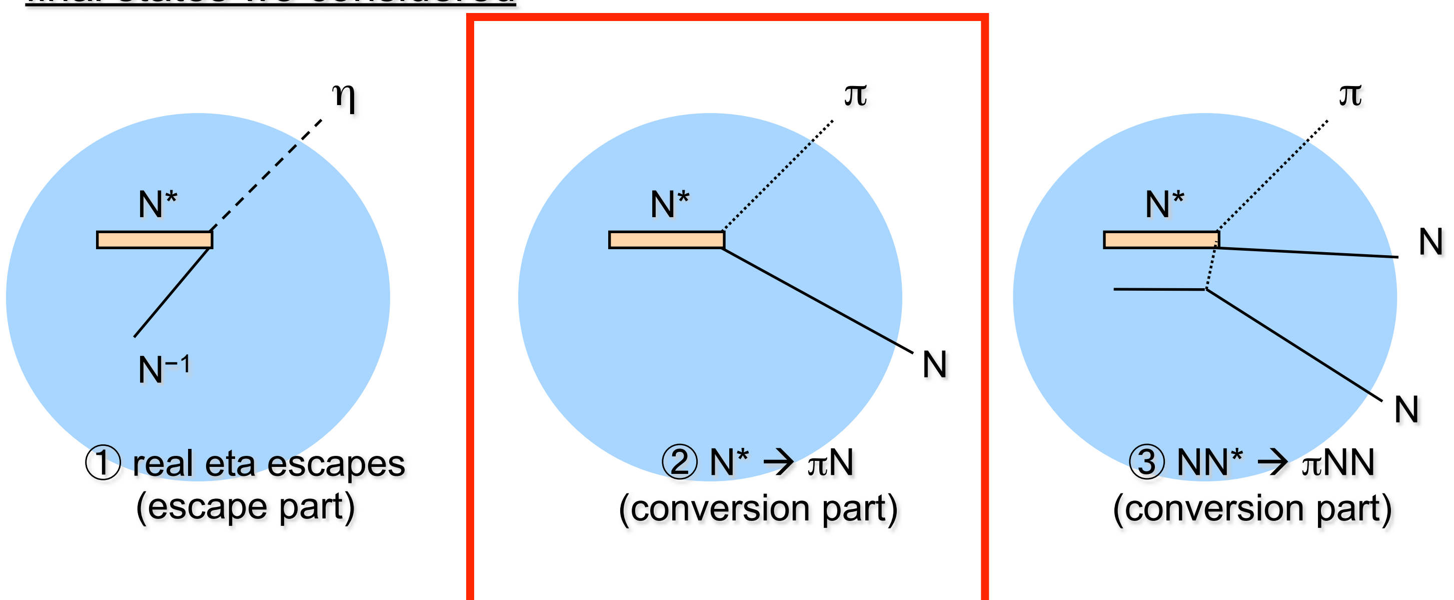


N* width in CDM





final states we considered



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:

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

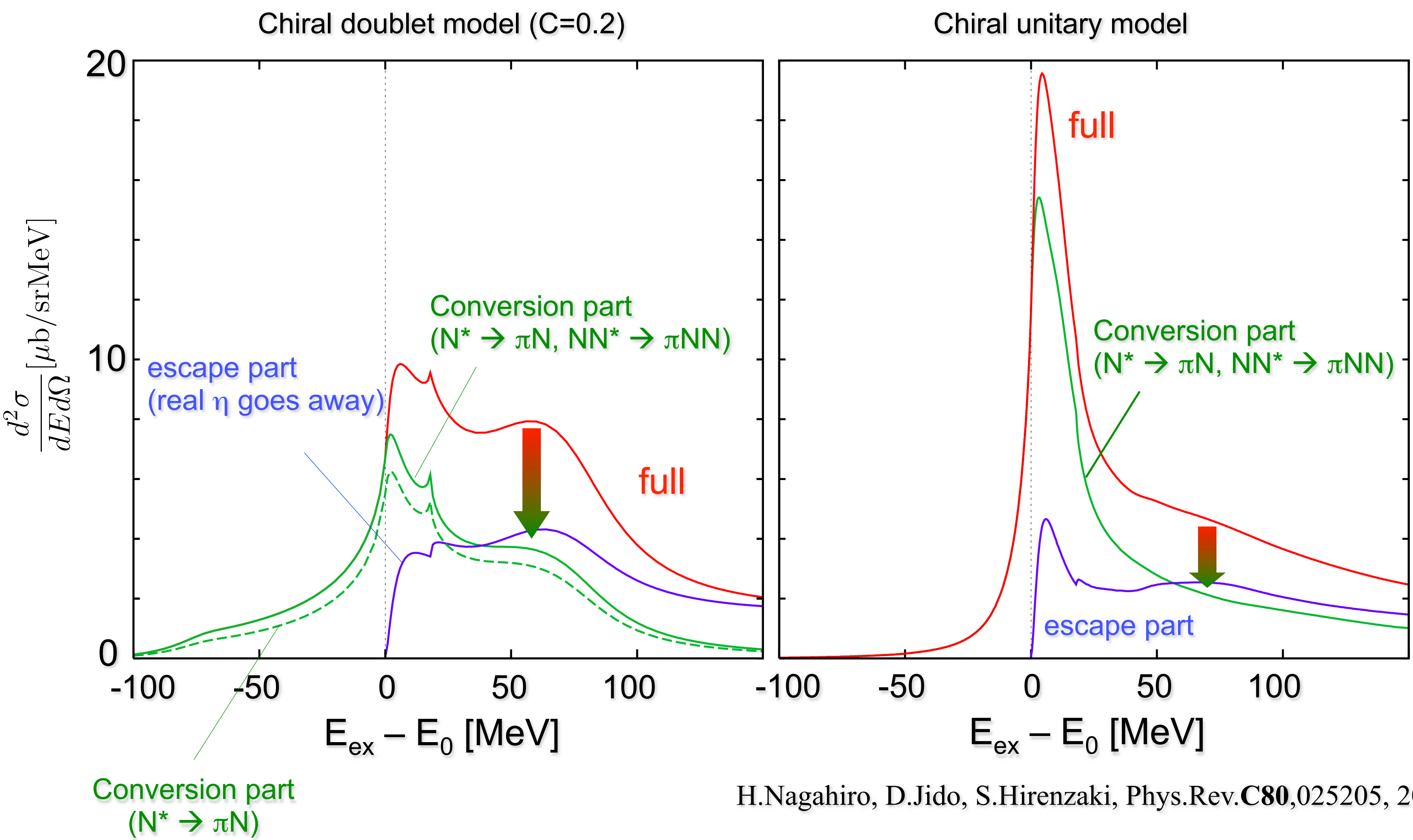
$$= -\sum_\alpha \mathrm{Im} \int \mathrm{d}\boldsymbol{r}\, \mathrm{d}\boldsymbol{r}'\, f_\alpha^*(\boldsymbol{r}') G(E - \varepsilon_\alpha; \boldsymbol{r}', \boldsymbol{r}) f_\alpha(\boldsymbol{r})\,, \tag{12}$$

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

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

[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

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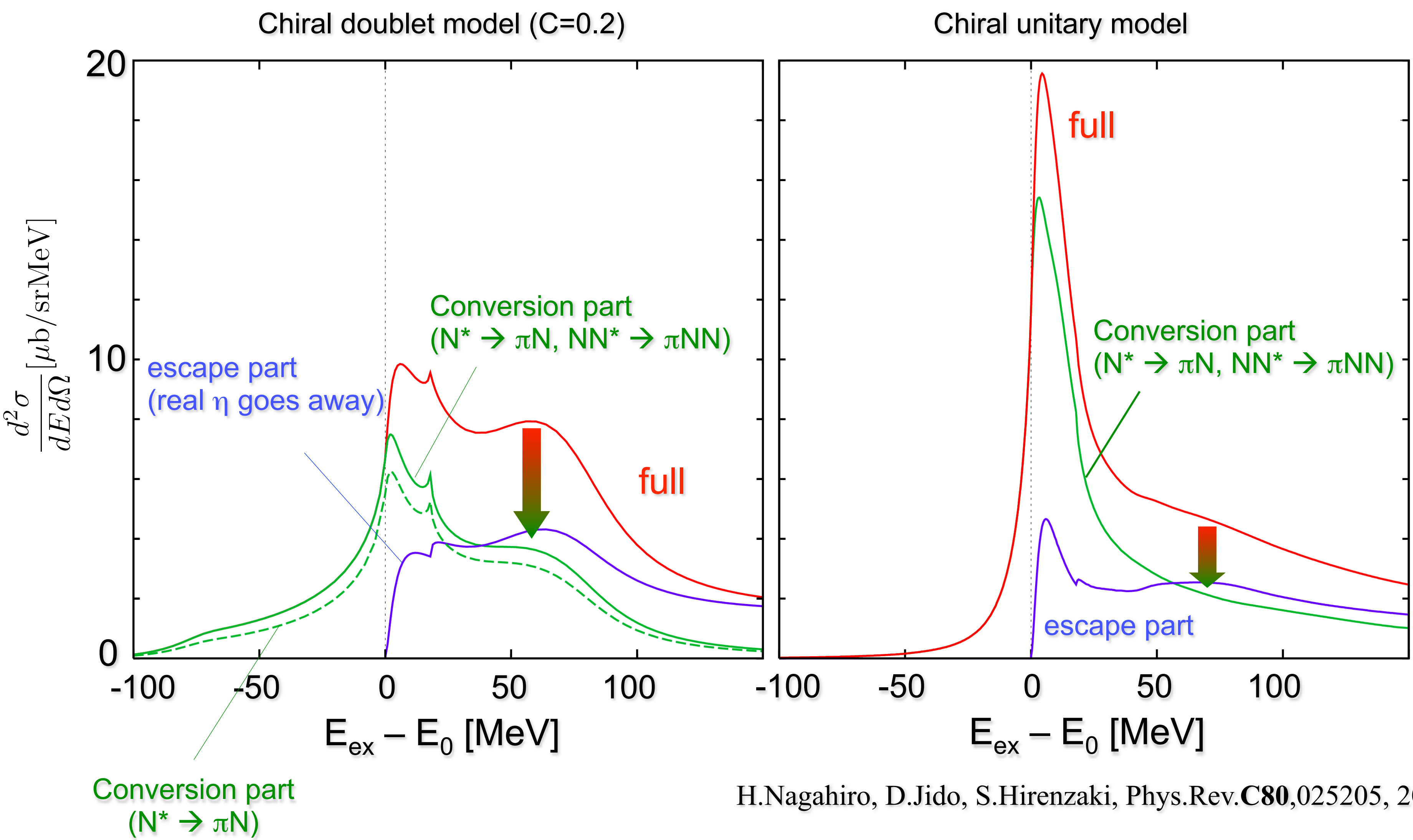

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future work : estimation of absolute value of background

η′(958) mesic nuclei formation

H.Nagahiro., S. H, PRL94(05)232503

H. Nagahiro, M. Takizawa and S. H, PRC74(06)045203

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  - » many theoretical works
    - › in vacuum / at finite temperature / at finite density
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$$\mathcal{L} = \bar{q}(i\,\partial\!\!\!/ - m)q + \frac{g_s}{2}\sum_a \left[(\bar{q}\lambda_a q)^2 + (i\bar{q}\lambda_a\gamma_5 q)^2\right] + g_D\left[\det \bar{q}_i(1-\gamma_5)q_j + h.c.\right]$$

explicit breaking the $U_A(1)$ sym.

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

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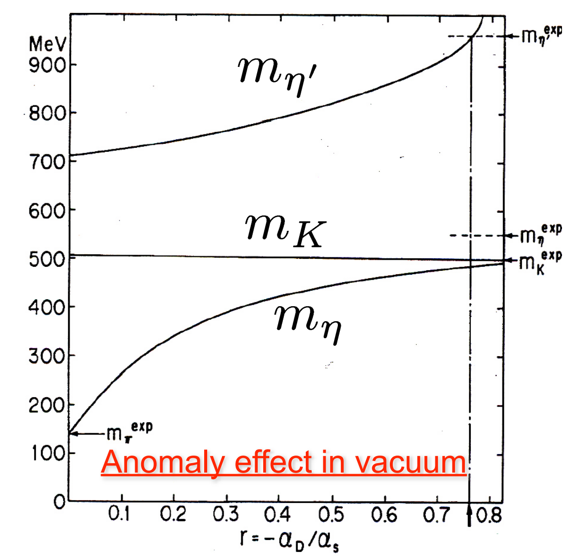

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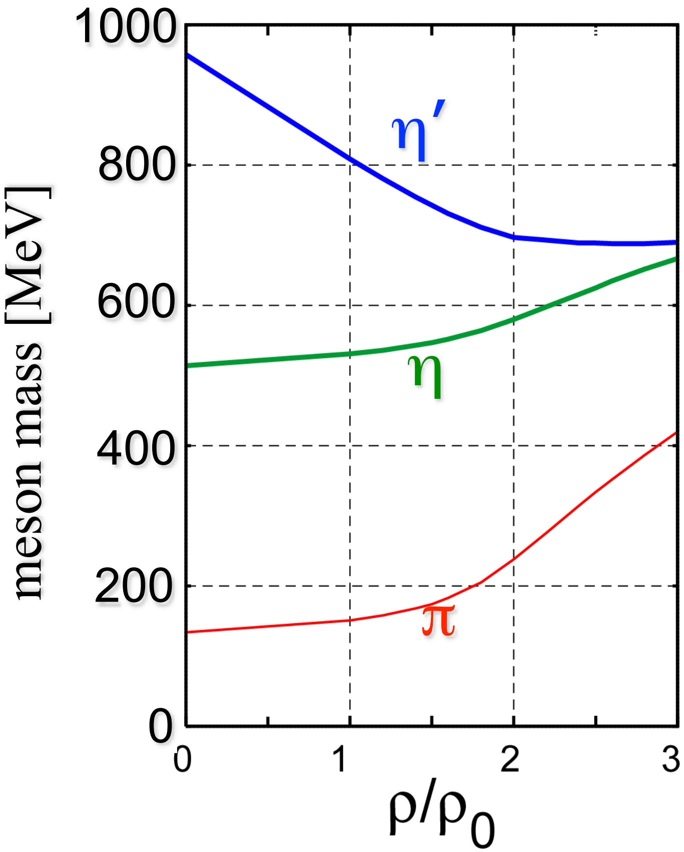

parameters (in vacuum)

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

Λ = 602.3 [MeV]
$g_S \Lambda^2$ = 3.67
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$m_{u,d}$ = 5.5 [MeV]
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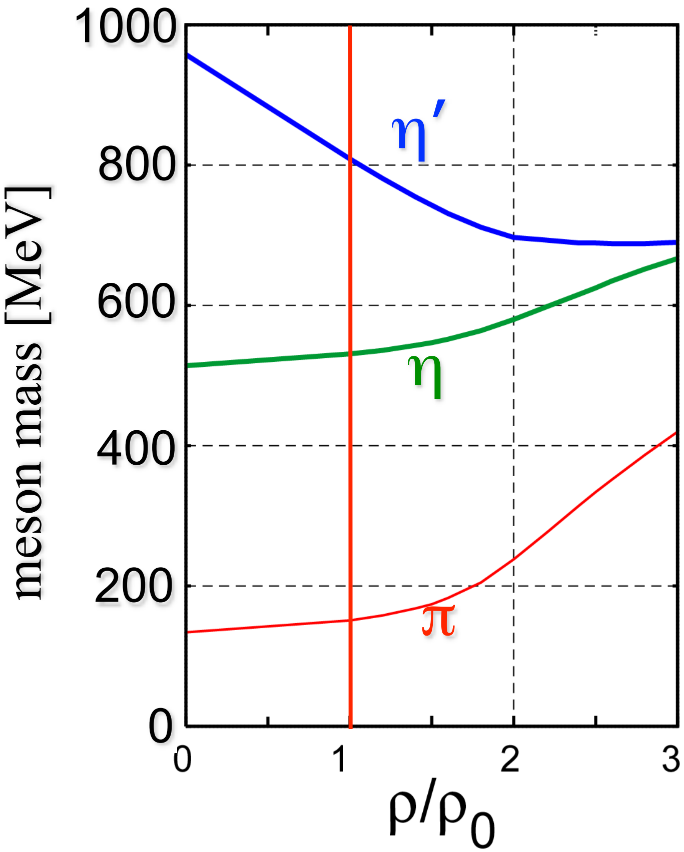

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$\Delta m_\eta \sim +20$ MeV @ ρ_0

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

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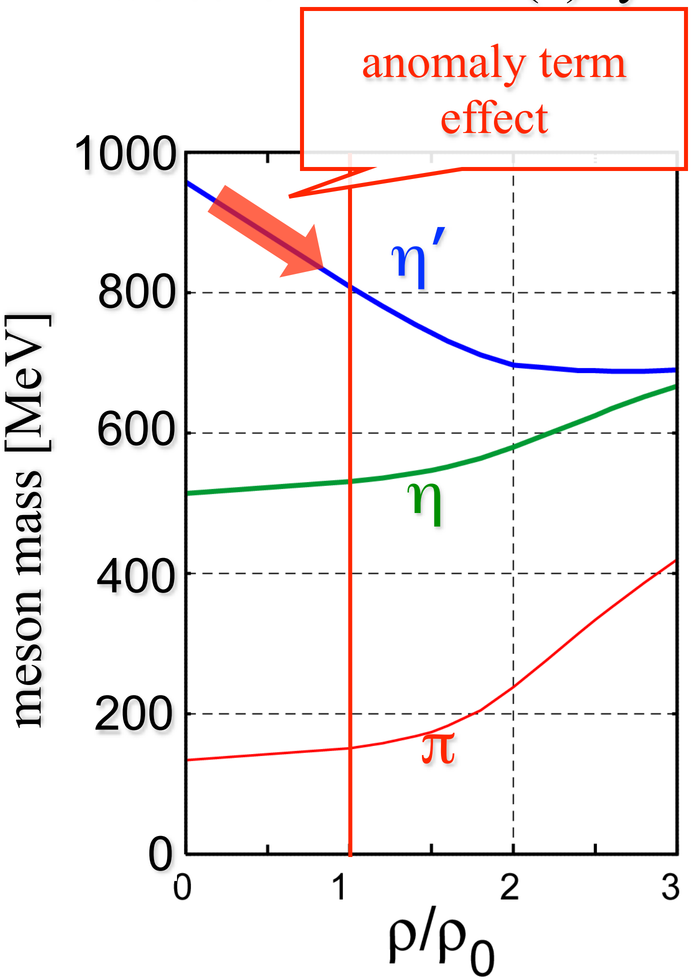

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η′(958) mesic nuclei by (π,N) reaction

- Potential description

Real Part V_0 … evaluated by possible η′ mass shift at ρ_0

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

Imaginary part W_0 … *unknown* → 20 MeV, *for example*

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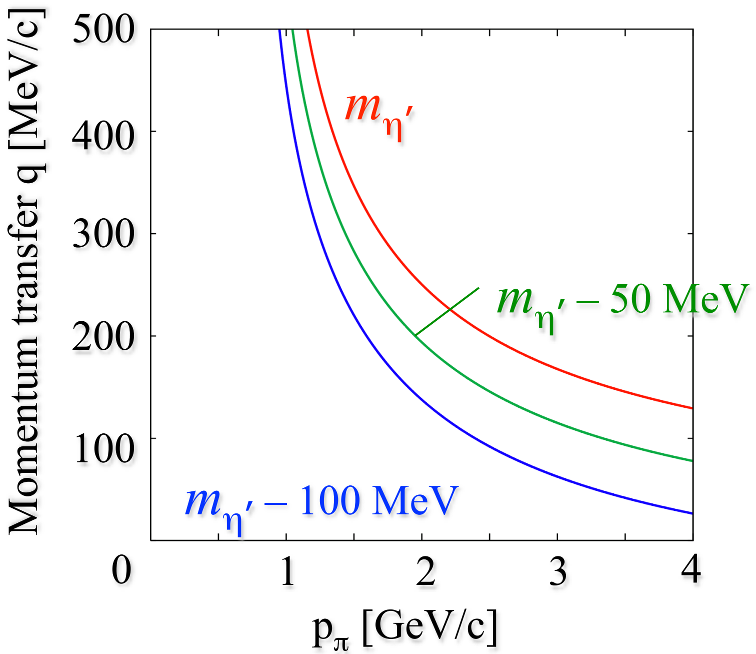

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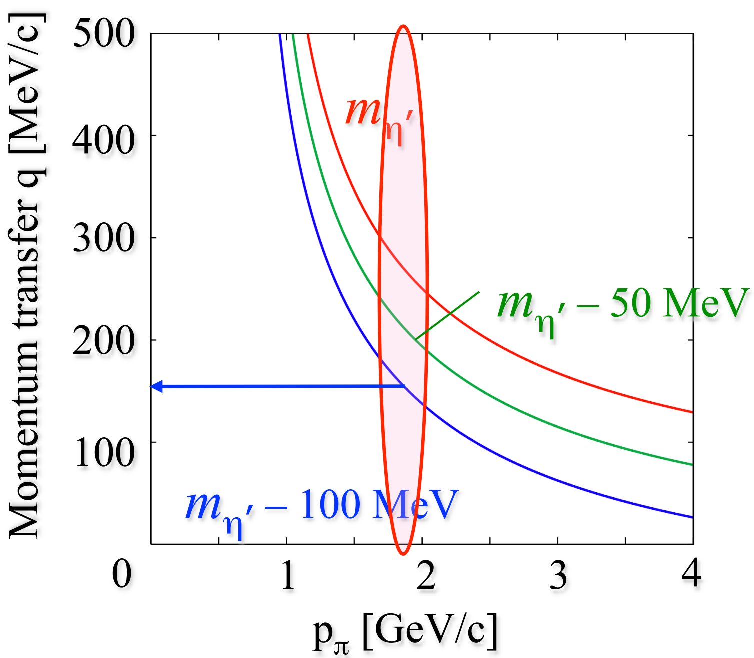

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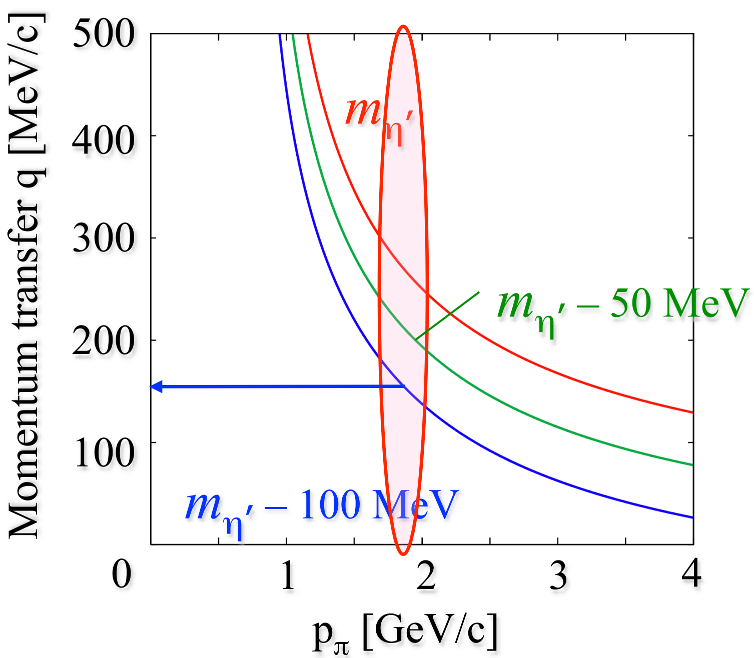

elementary cross section $\pi^+ n \to \eta' p$

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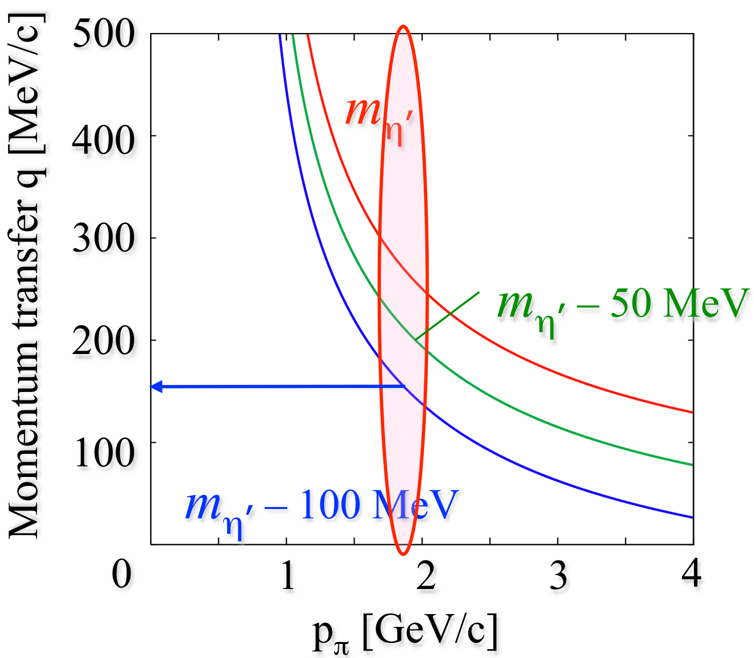

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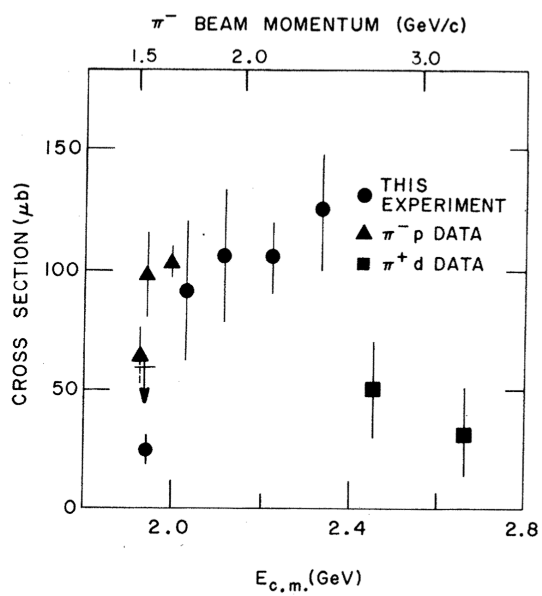

R.K.Rader *et al.*, PRD6(72)3059

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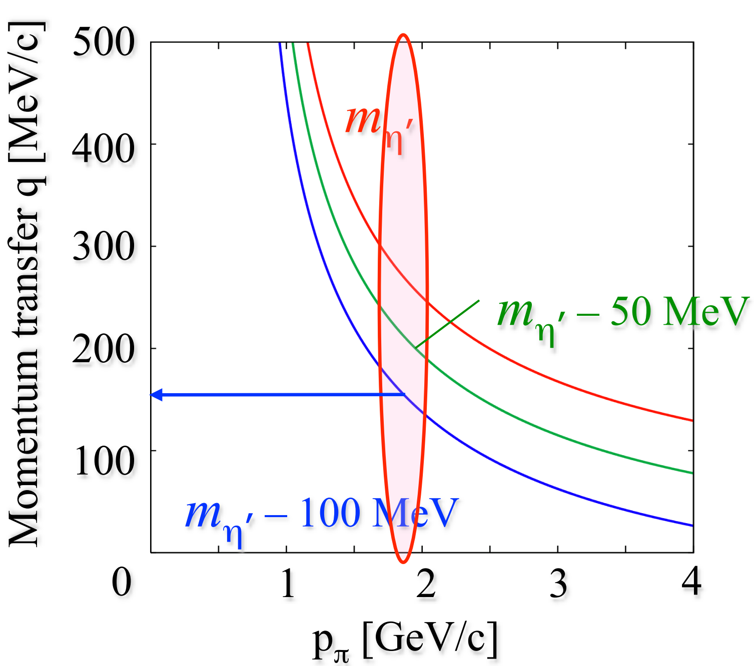

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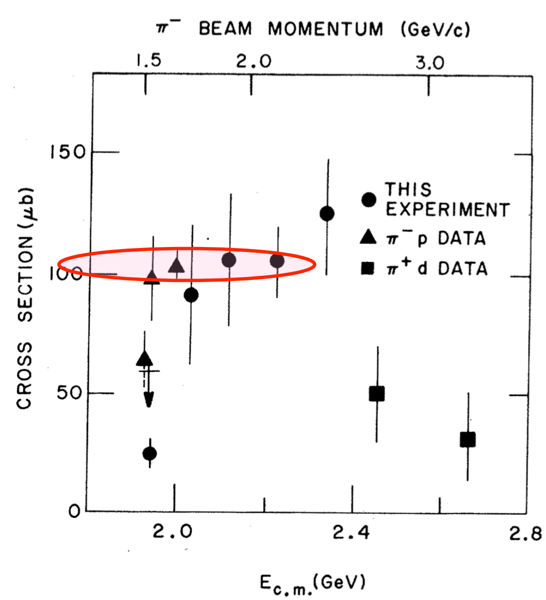


R.K.Rader *et al.*, PRD6(72)3059

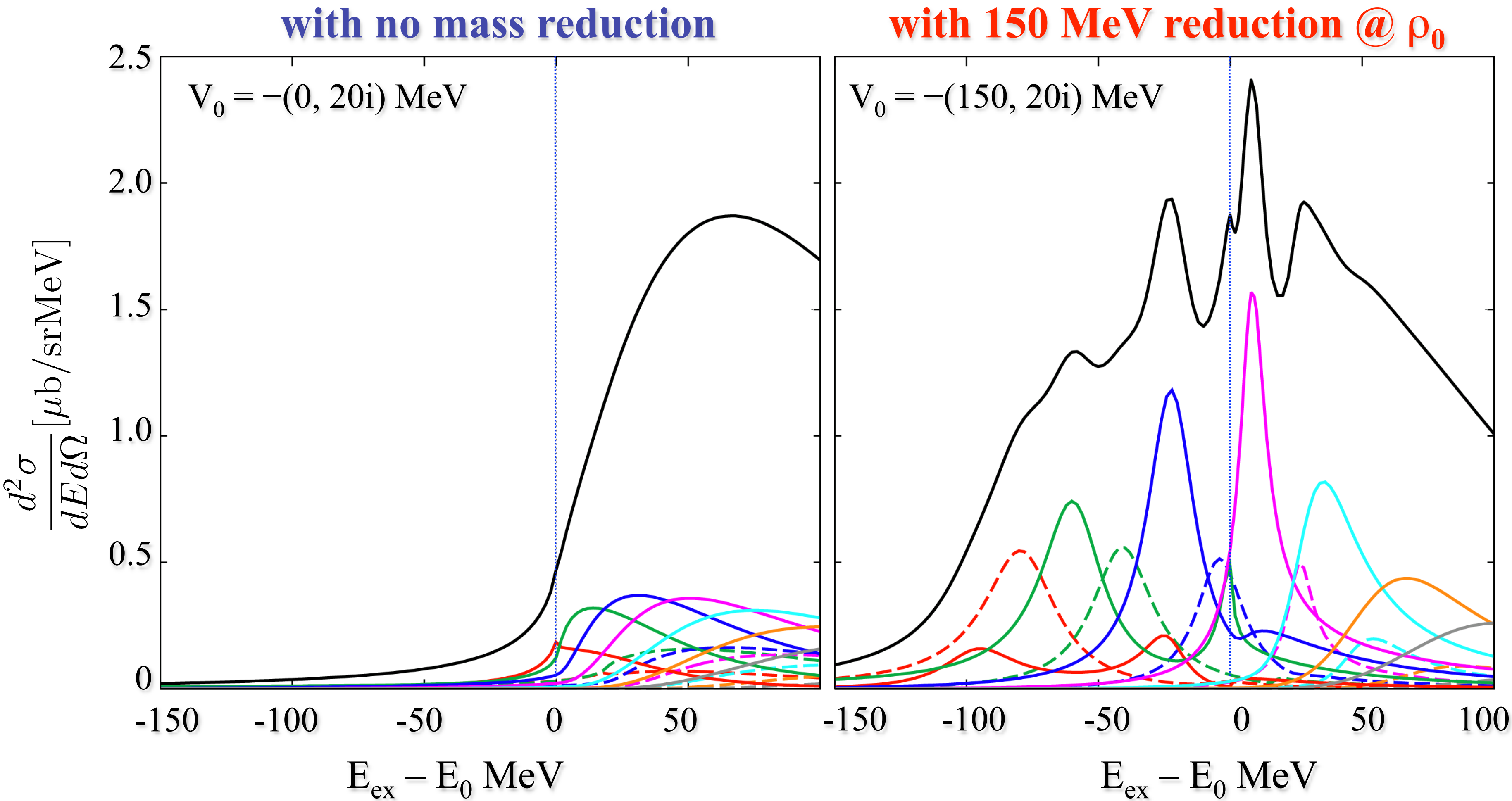
$\sigma(\pi^+ n \rightarrow \eta' p) \sim 100\ \mu b$

$$\left(\frac{d\sigma}{d\Omega}\right)^{Lab.} = 10 \sim 100 \mu\text{b/sr}$$

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

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

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



Photon Induced reaction case

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Nuclear Physics A 761 (2005) 92–119
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NUCLEAR PHYSICS A

Formation of mesic nuclei by (γ, p) reactions

H. Nagahiro [a,*], D. Jido [b,1], S. Hirenzaki [c]

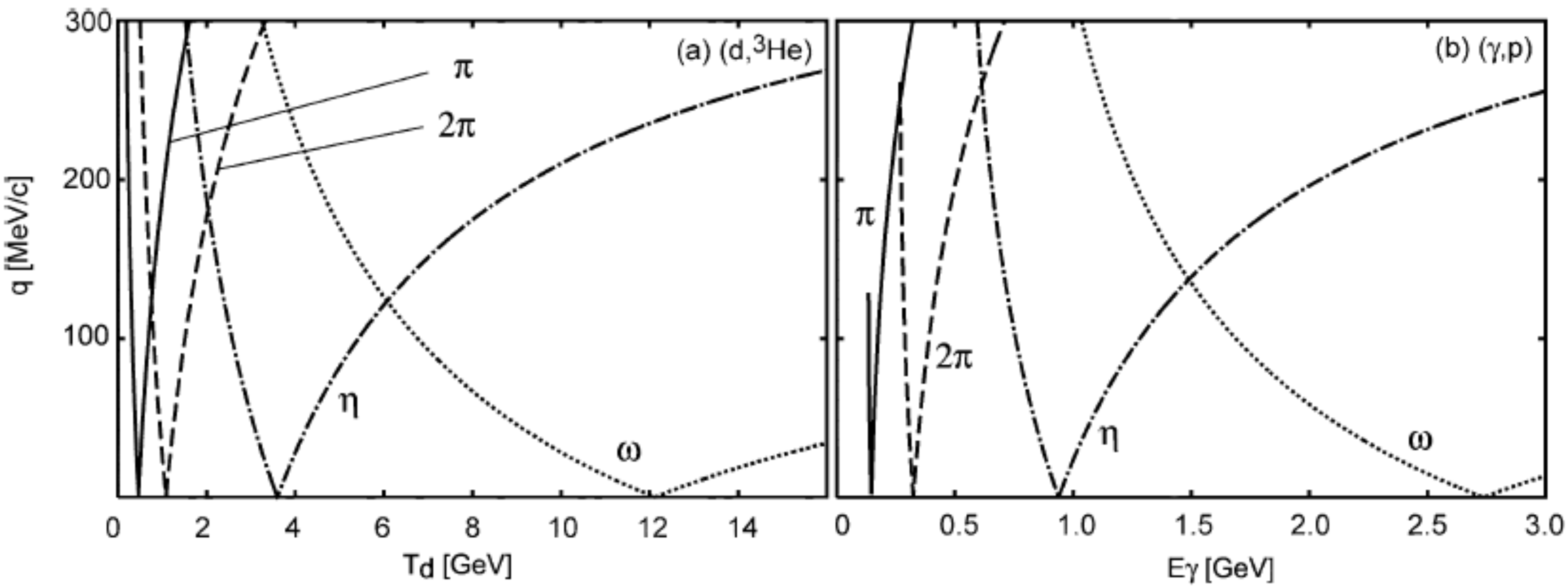
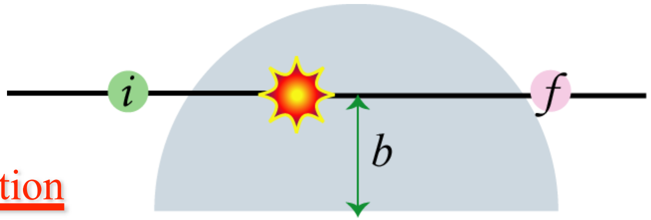


Fig. 5. Momentum transfer q is shown as a function of (a) the incident deuteron kinetic energy T_d in the $(d, {}^3\text{He})$ reaction, and (b) the incident γ energy E_γ in the (γ, p) reaction. The solid line shows the momentum transfer of the pion production case, and other lines show those of two pions, the η meson and the ω meson production cases as indicated in the figure.

“Transparency” of (γ,p) reaction

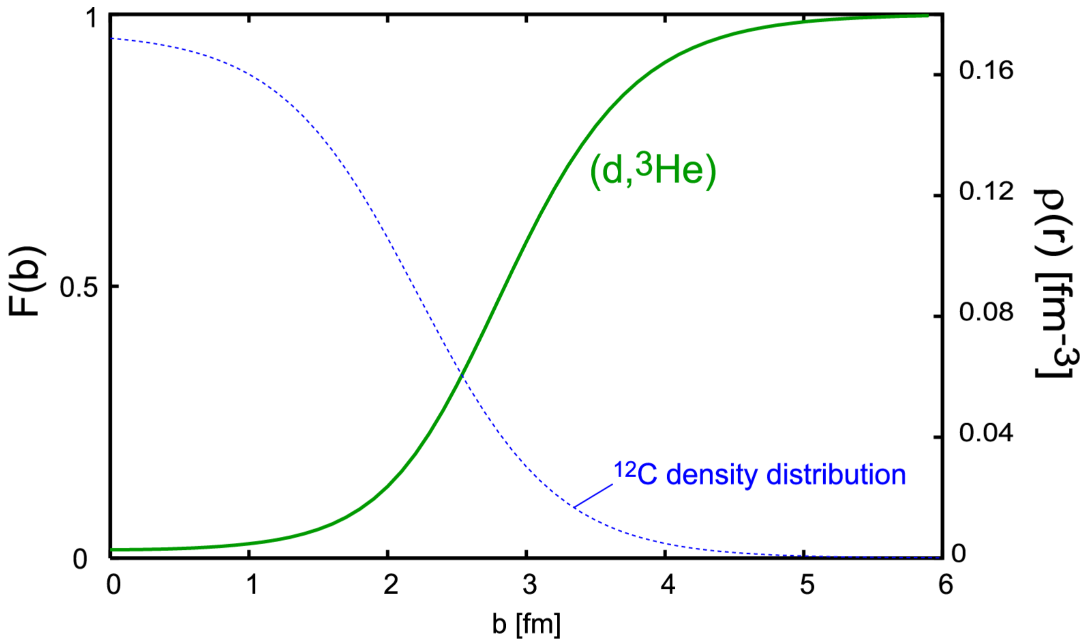
Eikonal approximation

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



Distortion Factor reduction of the flux due to absorption

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



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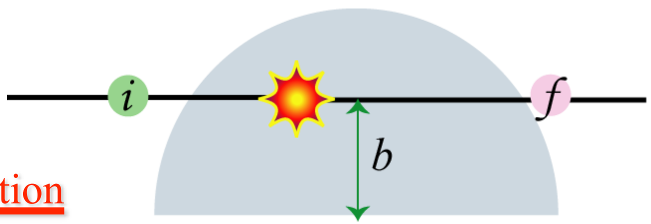

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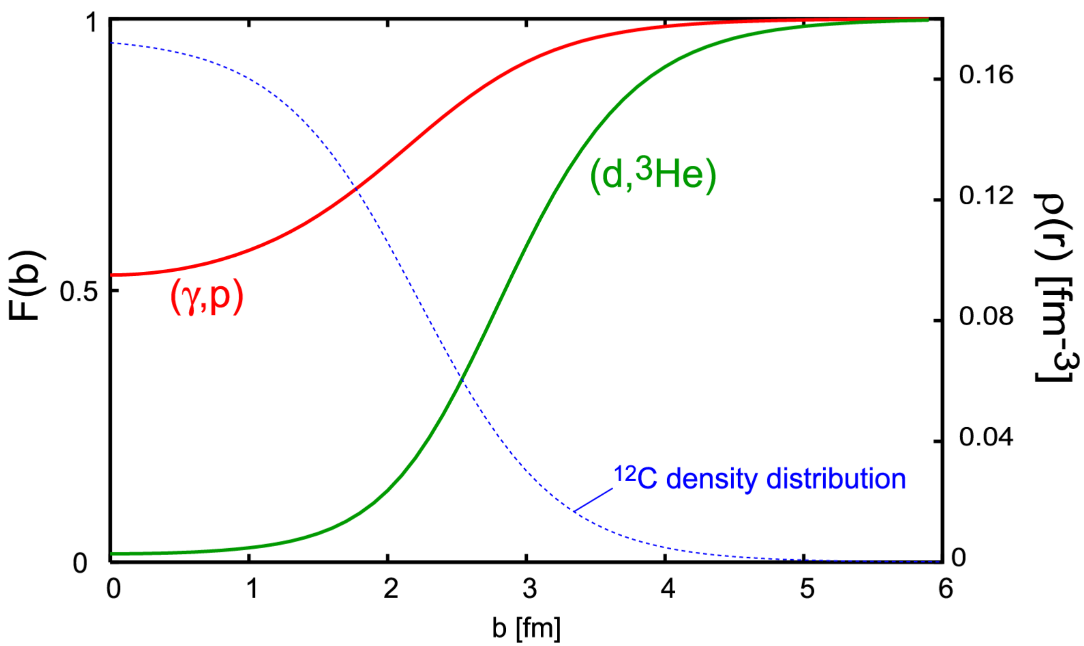

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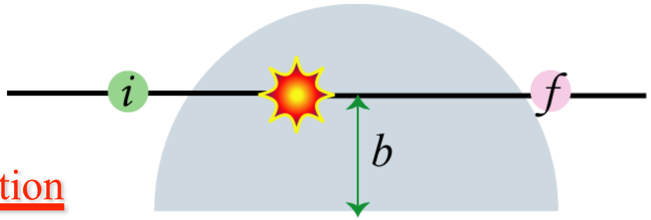

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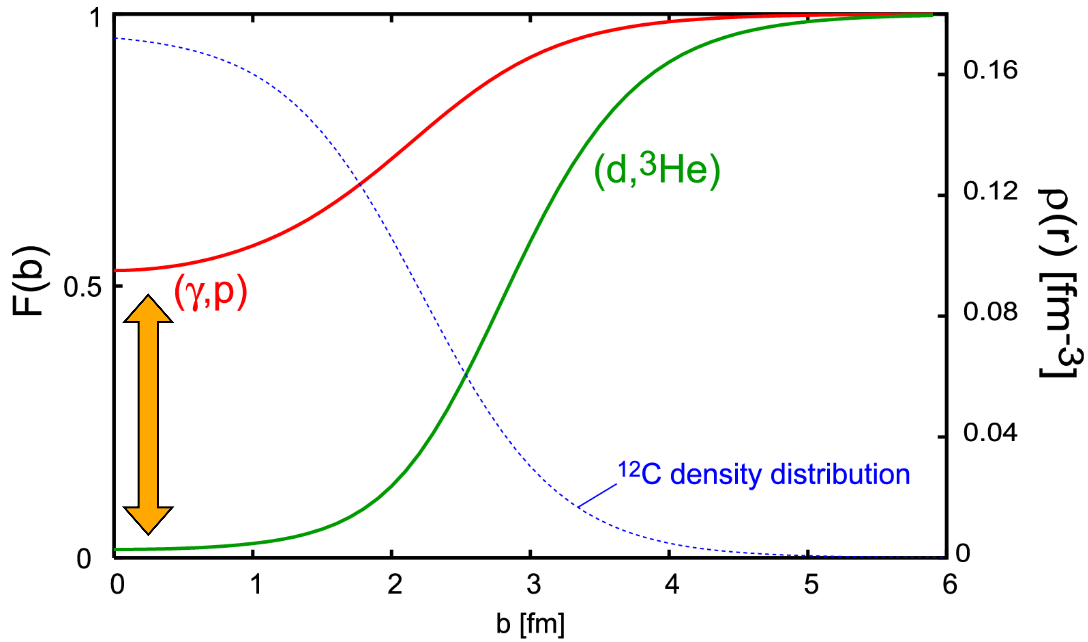

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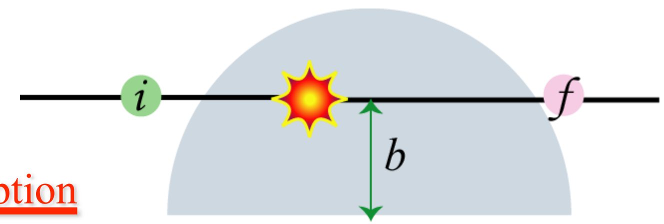

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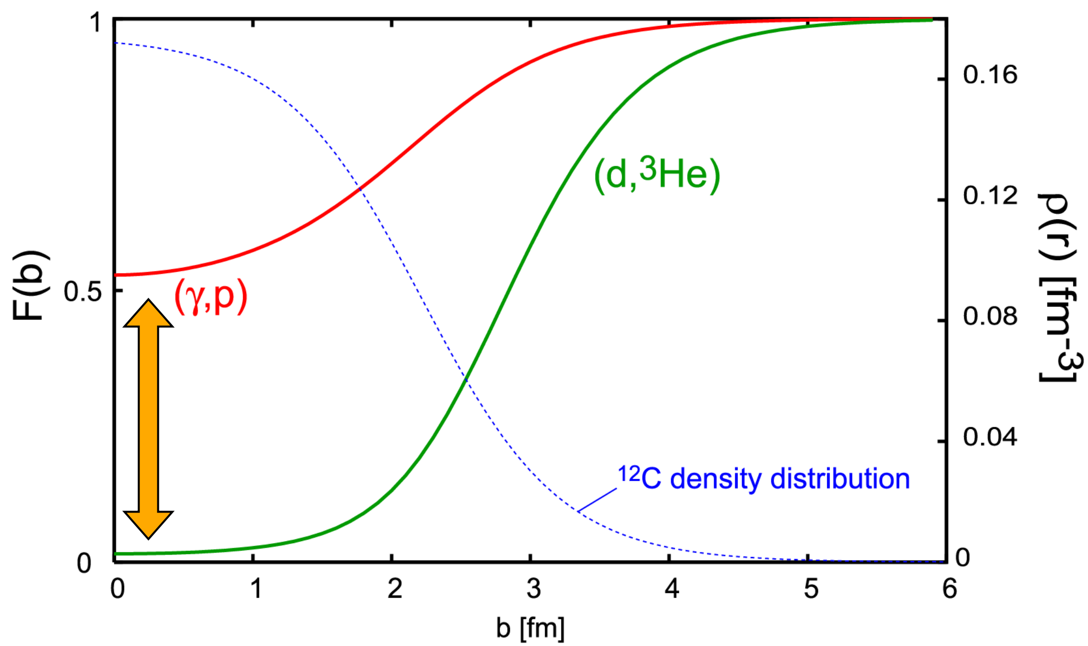
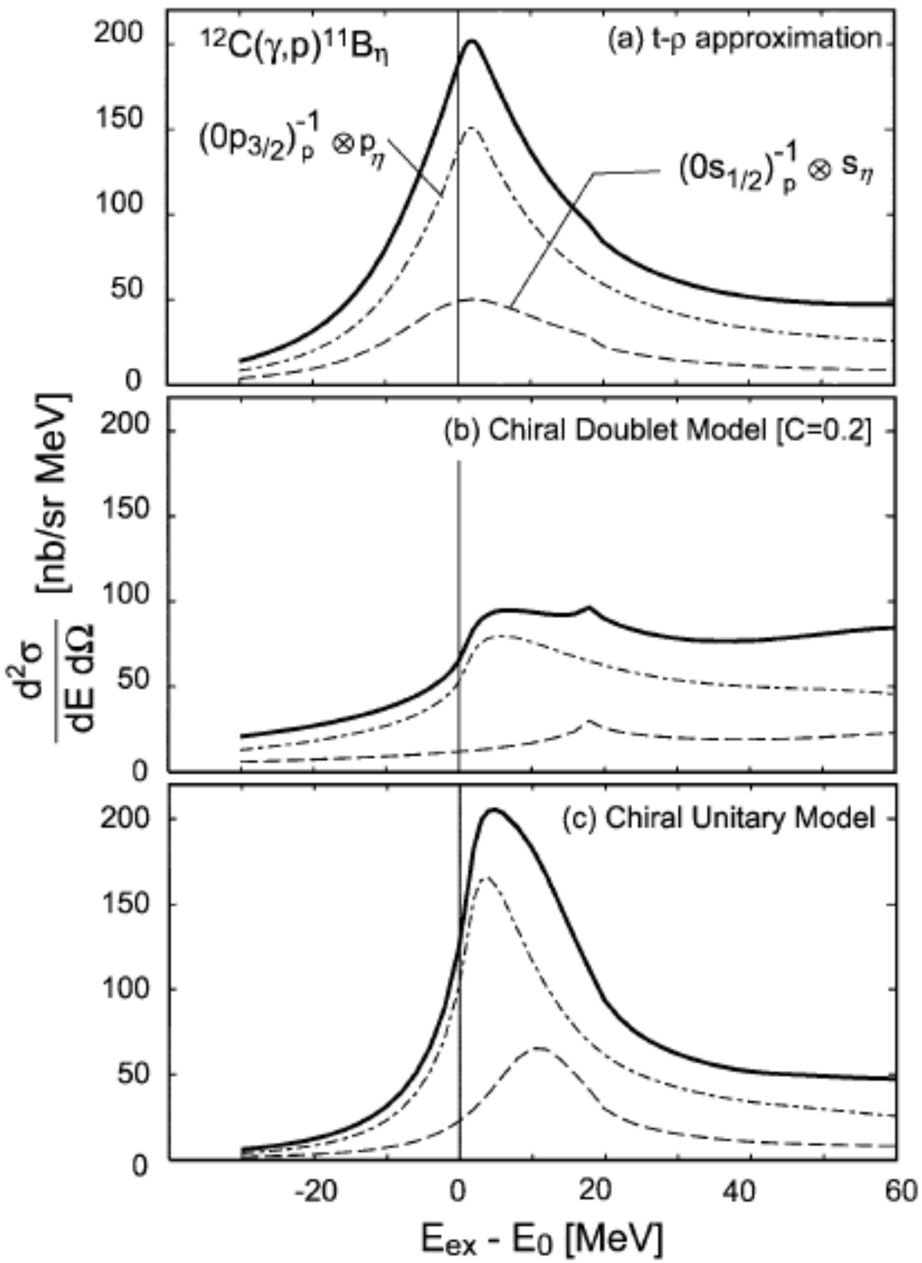
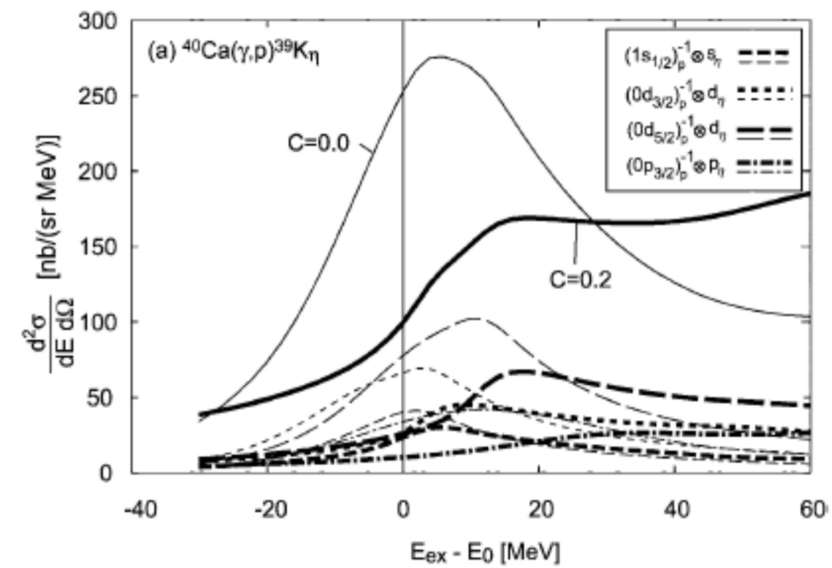


(γ,p) reaction : smaller distortion effect

more sensitive to the optical potential
at the interior of the nucleus



* E=950MeV
* C and Ca target
* Chiral Doublet C=0, 0.2
* Ciral Unitary



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

(COSY Proposal)
(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 $d\ d \rightarrow {}^4\text{He}\ \eta$

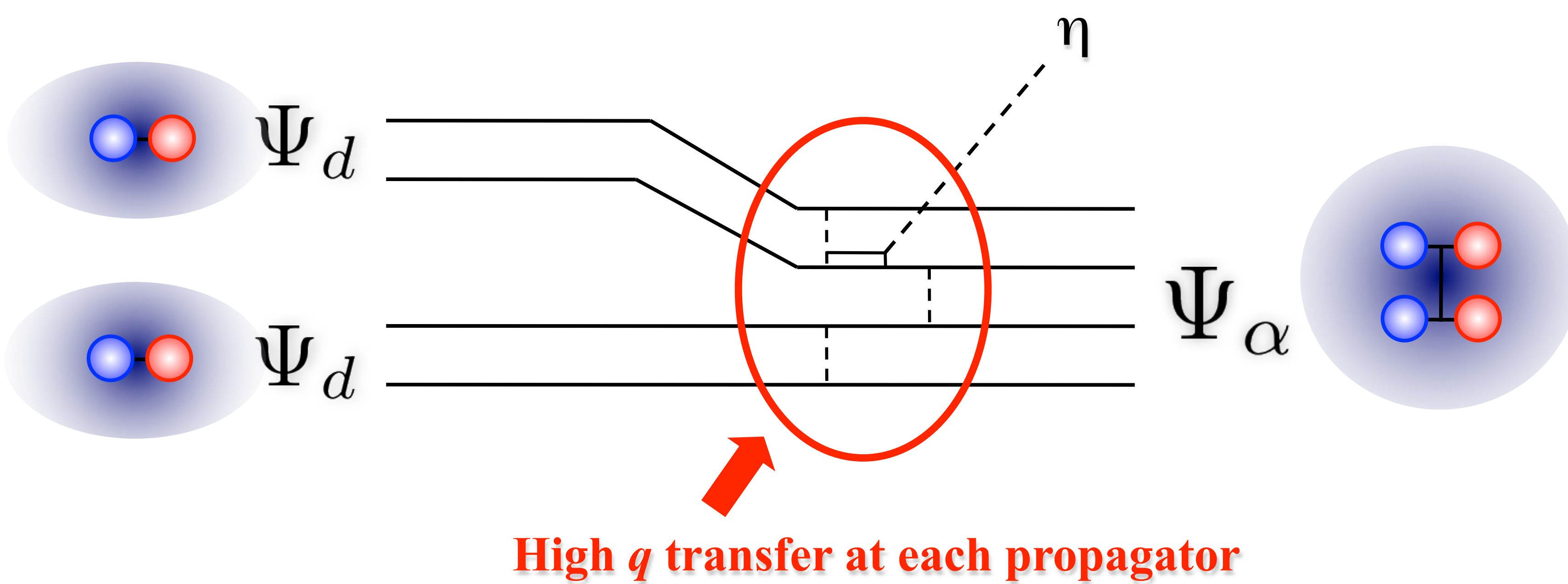
- Simple spectral structure for light systems

- System consists of

  2 Nucleon + 2 Nucleon → 4 Nucleon + 1 meson

Some remarks

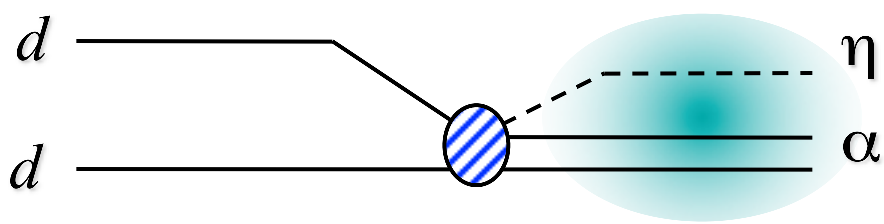
- Transition (η-production) part



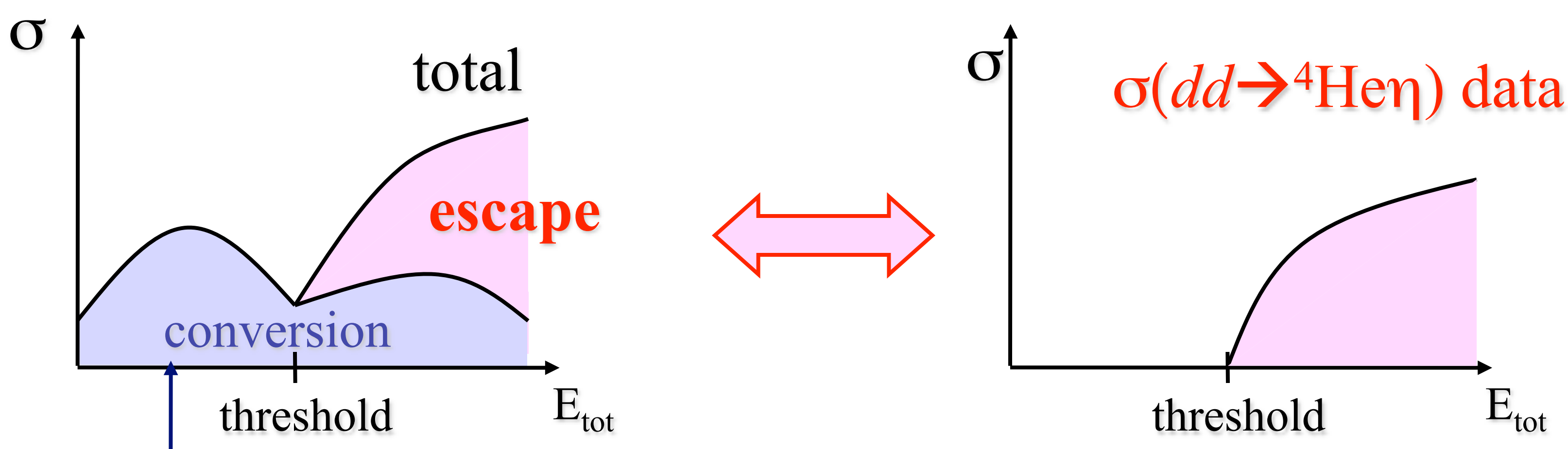
⟶ Parameterize this part. Fix by η production data

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

Schematic picture

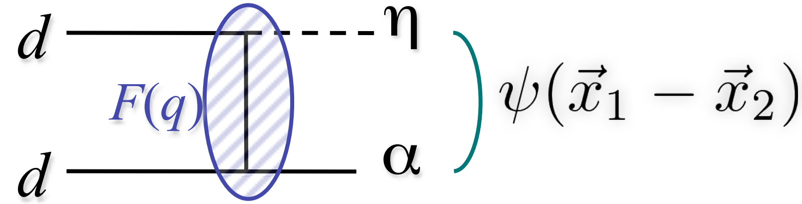


Green function method
with η-α optical potential



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

Scattering Amplitude



$$S = (i)^2 \int d^4x_1 d^4x_2 \sqrt{\frac{M_f}{E_f}} \frac{1}{\sqrt{V}} e^{iE_f T} e^{-\vec{p}_f \cdot \vec{R}} \psi^*(\vec{x}_1 - \vec{x}_2)$$

$$\times \int \frac{d^4q}{(2\pi)^4} iF(q) e^{iq\cdot(x_1 - x_2)} \sqrt{\frac{M_d}{E_1}} \frac{1}{\sqrt{V}} e^{-ip_1 \cdot x_1} \sqrt{\frac{M_d}{E_2}} \frac{1}{\sqrt{V}} e^{-ip_2 \cdot x_2}$$

$$\sigma_{\text{tot}} = 4\pi \frac{M_d^2}{\lambda^{1/2}(s, M_d^2, M_d^2)} \frac{M_f}{E_f}$$

$$\times \left(-\frac{1}{\pi}\right) \frac{1}{(2\pi)^6} \Im \int d\vec{r}_1 d\vec{r}_2 f(\vec{r}_1) e^{-i\vec{p}_2 \cdot \vec{r}_1} G(E_i; \vec{r}_1, \vec{r}_2) f^*(\vec{r}_2) e^{i\vec{p}_2 \cdot \vec{r}_2}$$

$$\sigma_{\text{conv}} = 4\pi \frac{M_d^2}{\lambda^{1/2}(s, M_d^2, M_d^2)} \frac{M_f}{E_f} \left(-\frac{1}{\pi}\right) \frac{1}{(2\pi)^6} \int d\vec{r}_1 d\vec{r}_2 d\vec{r}_3 f(\vec{r}_1) e^{-i\vec{p}_2 \cdot \vec{r}_1}$$

$$\times G(E_i; \vec{r}_1, \vec{r}_2) \Im V_{\text{opt}}(\vec{r}_2) G(E_i; \vec{r}_2, \vec{r}_3) f^*(\vec{r}_3) e^{i\vec{p}_2 \cdot \vec{r}_3}$$

$F(q)$ ($f(r)$:r-space representation)… Assumed to be Gaussian

A Theoretical Model for

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

3 parameters in this model

- η-α optical potential

$$V_{\text{opt}} = (V_0 + iW_0)\frac{\rho_\alpha(r)}{\rho_\alpha(0)}$$

- η production part *dd* → ^{4}Heη

$$F(q) = N \exp\left[-\frac{p^2}{p_0^2}\right]$$

Exp. Data of *dd* → ^{4}Heη

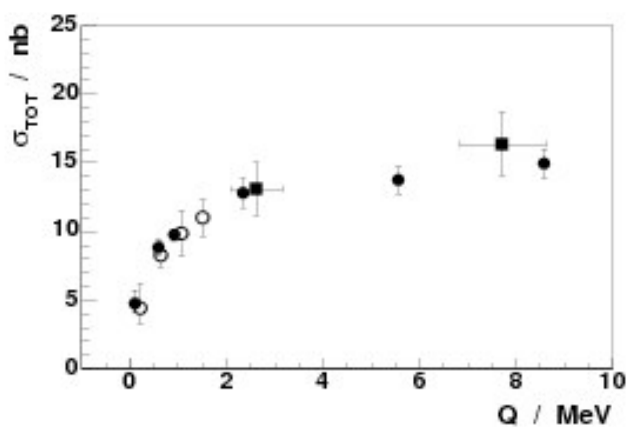


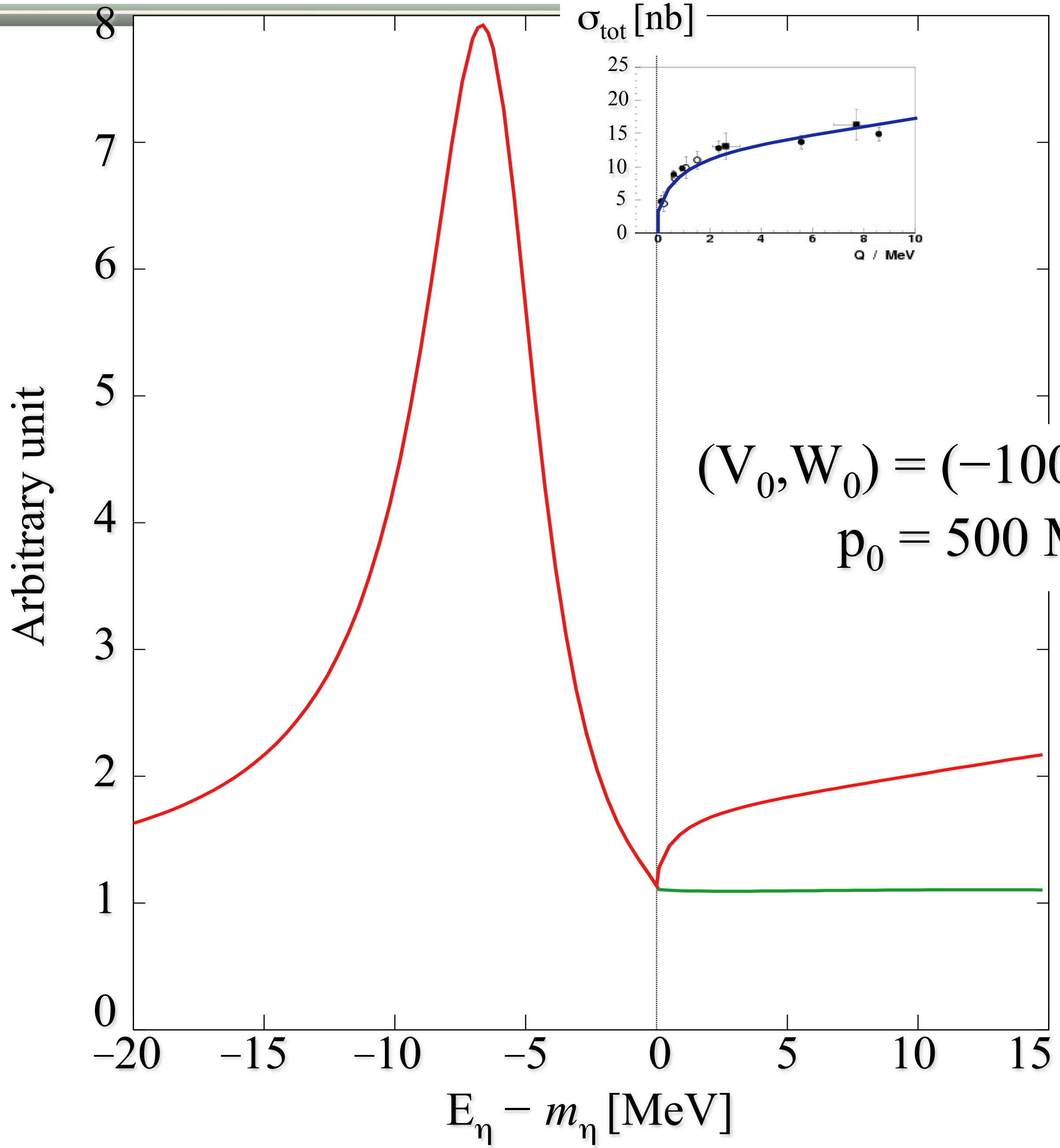
Fig. taken from NFQCD10@YITP, 2010 slide by S. Schadmand

R.Frascaria et al., Rhys.Rev.C50 (1994) 573,

N. Wills et al., Phys. Lett. B 406 (1997) 14,

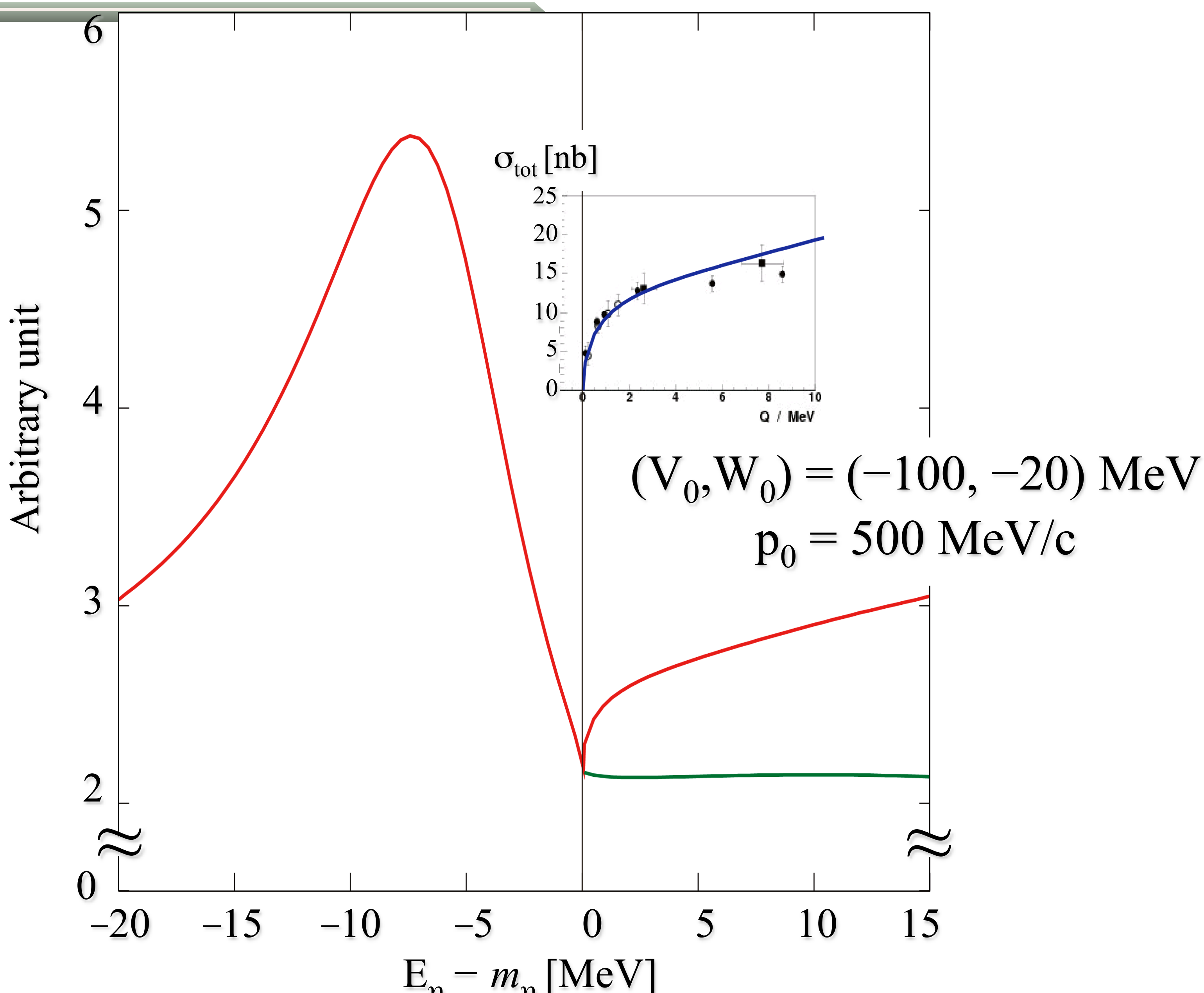
A. Wronska et al., Acta. Phys. Pol. 56 (2006) 279.

Numerical Results

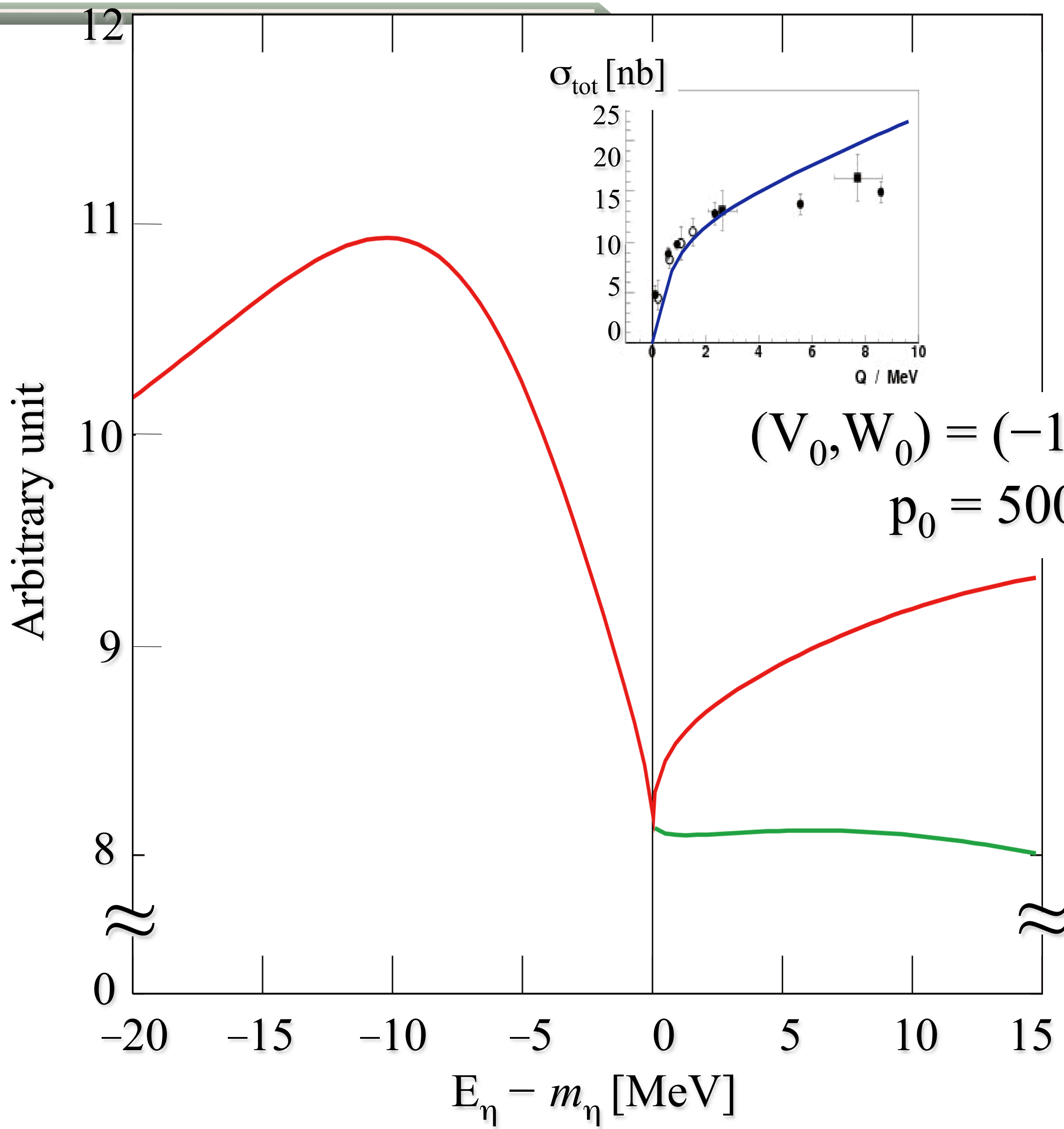


$(V_0, W_0) = (-100, -10)$ MeV
$p_0 = 500$ MeV/c

Numerical Results



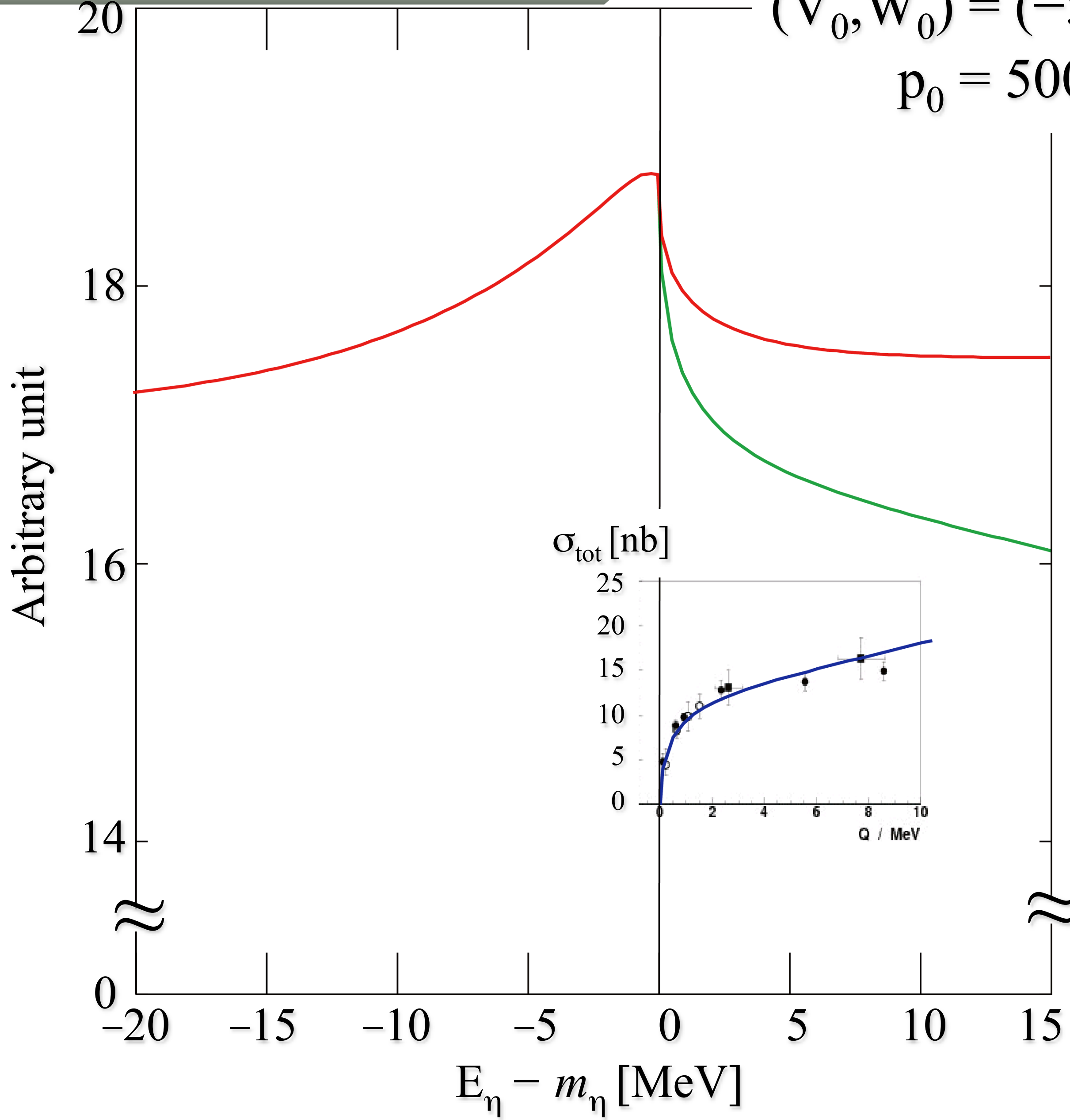
Numerical Results



$(V_0, W_0) = (-100, -40)$ MeV
$p_0 = 500$ MeV/c

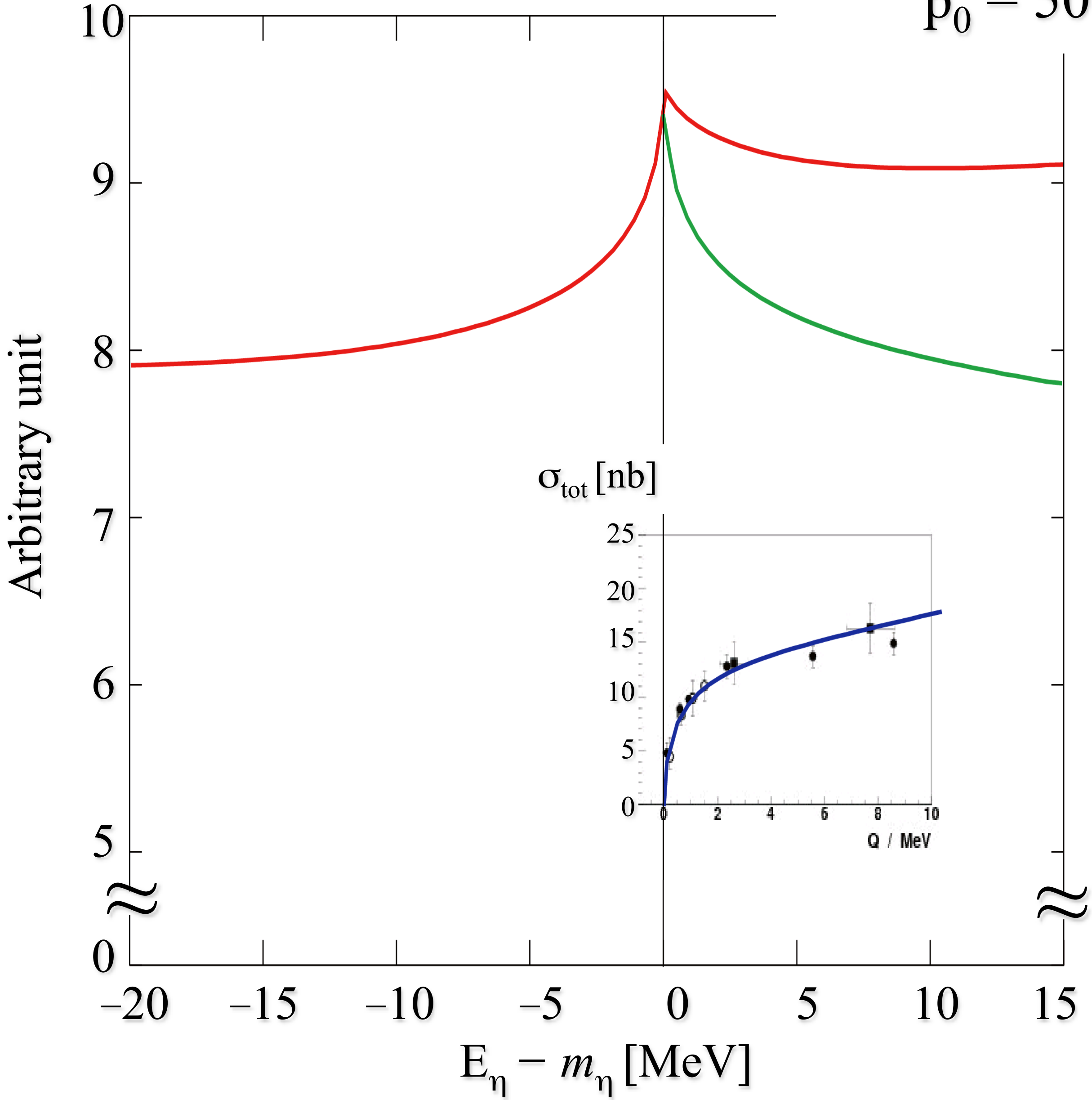
Numerical Results

$(V_0, W_0) = (-50, -40)$ MeV
$p_0 = 500$ MeV/c

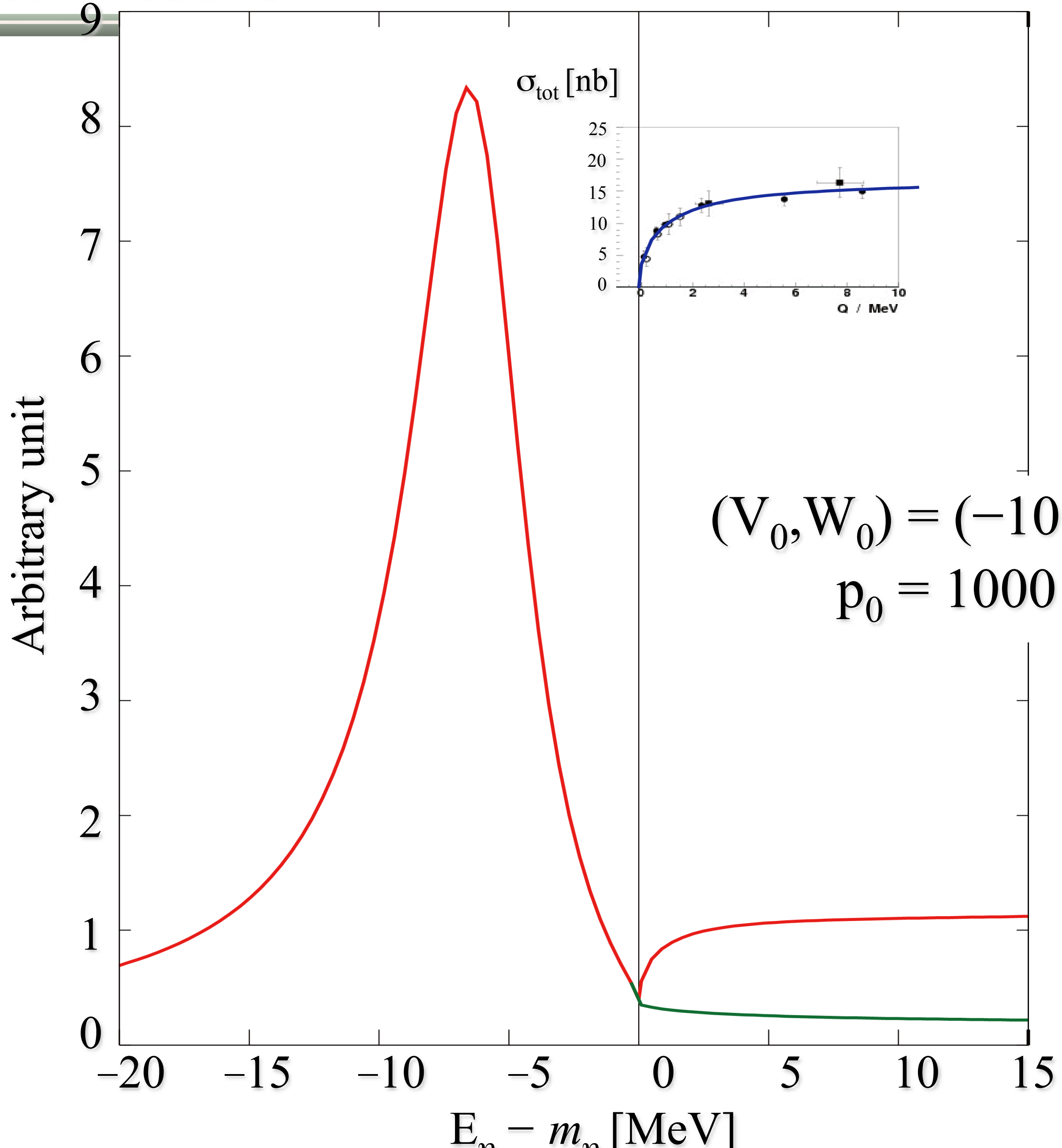


Numerical Results

$(V_0, W_0) = (-30, -20)$ MeV
$p_0 = 500$ MeV/c

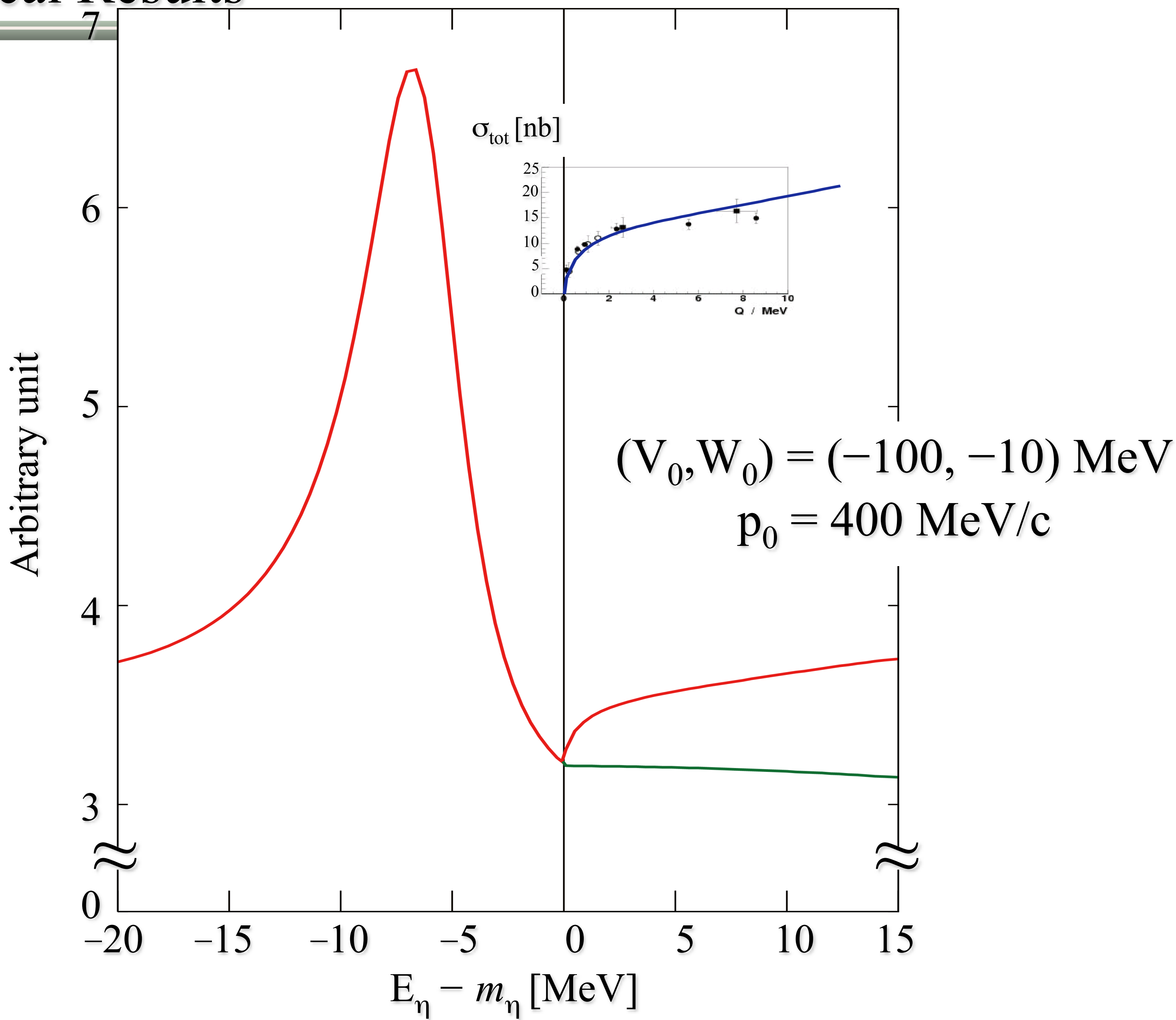


Numerical Results



$(V_0, W_0) = (-100, -10)$ MeV
$p_0 = 1000$ MeV/c

Numerical Results

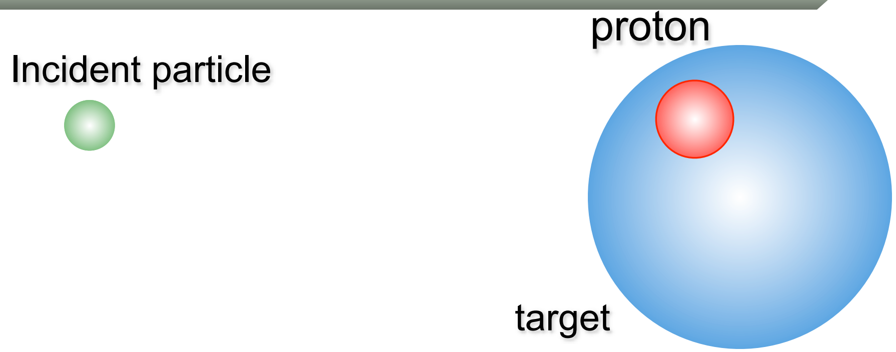


Summary

- Recent results on Formation of η & η'(958) mesic nucleus
  - » (π,p) reaction, (gamma, p) reaction
  - » d + d → (^{4}He-η) → p + π^- + 3He reaction
- Some indications by different Chiral models

  for η by (π,p) reaction
- New Experiments
  - » Fujioka, Itahashi, … @ J-PARC
  - » d + d ; COSY Proposal 186.2

Missing mass spectroscopy / reaction parameters



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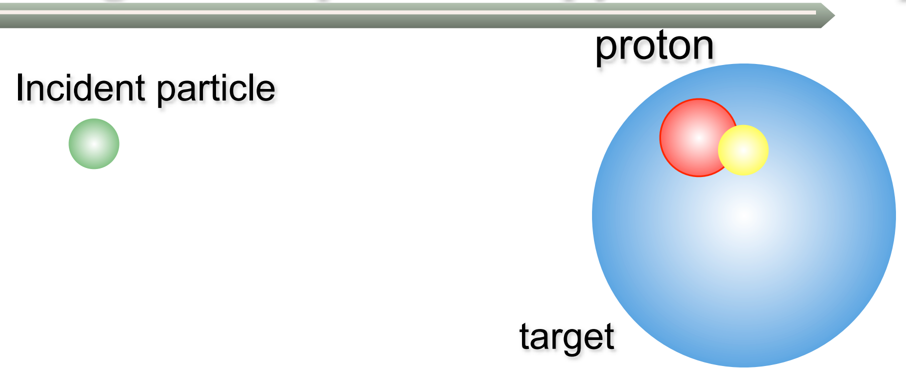

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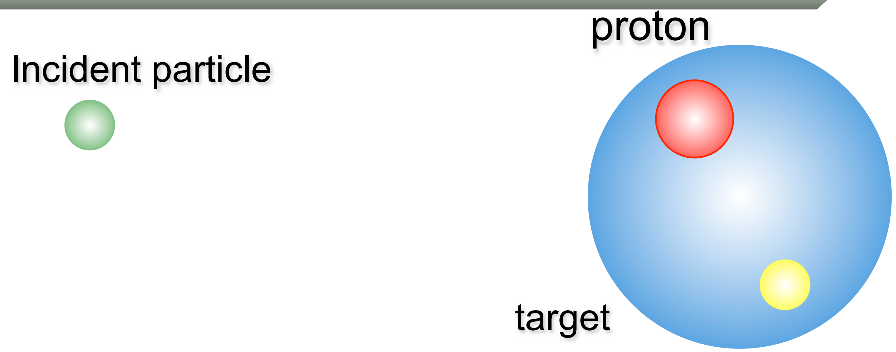

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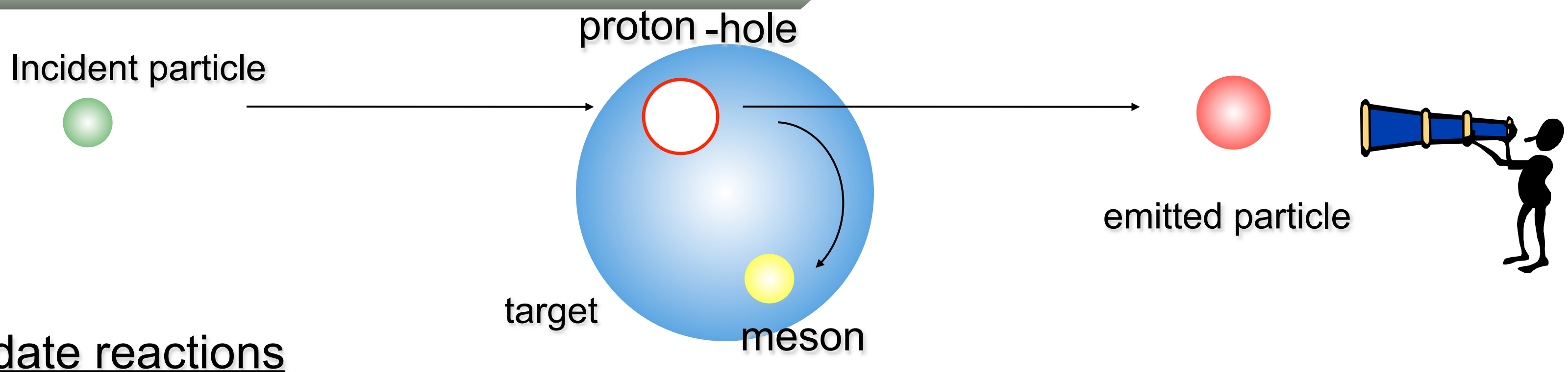
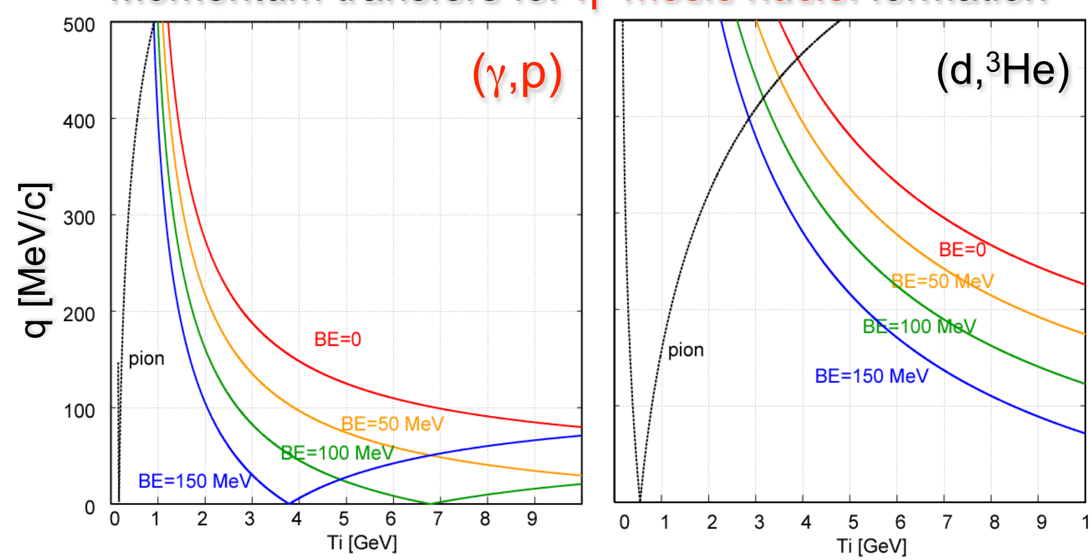


<u>candidate reactions</u>

ex.) (d,^{3}He) reaction … π atom formation, η-mesic nuclei @ GSI

(γ,p) reaction … smaller distortion effect, nearly recoilless for heavy η'

Momentum transfers for η'-mesic nuclei formation



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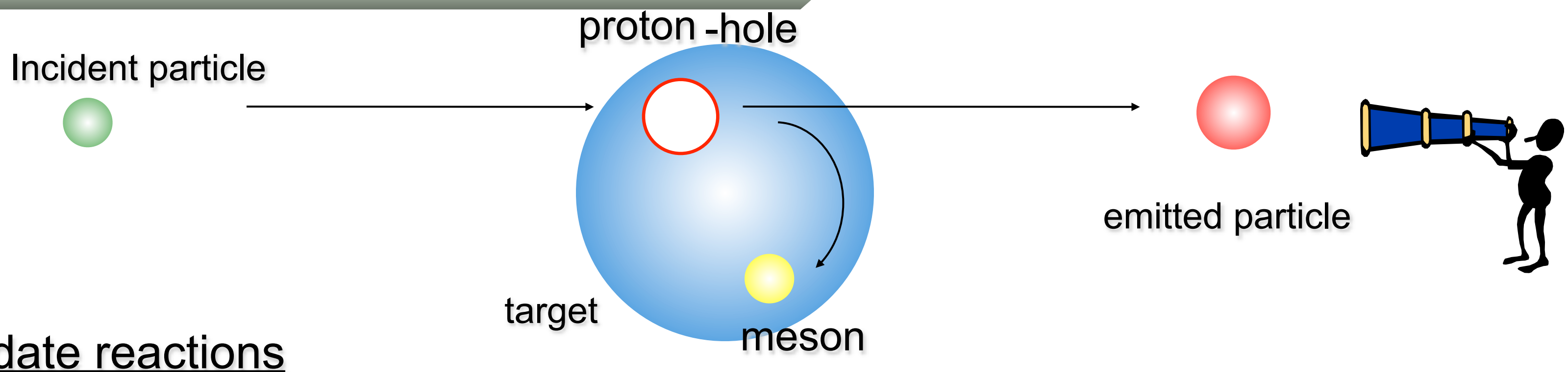

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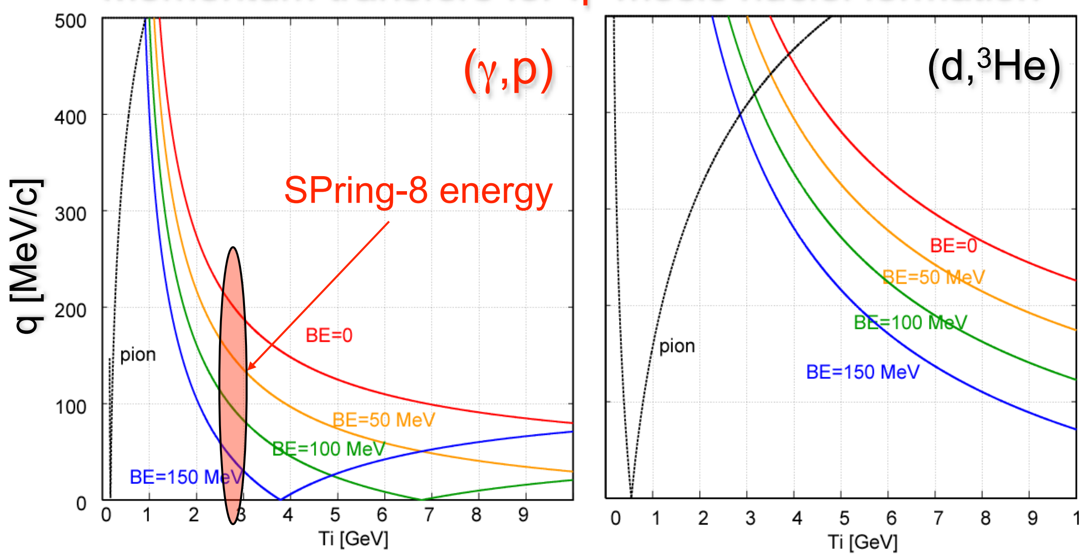

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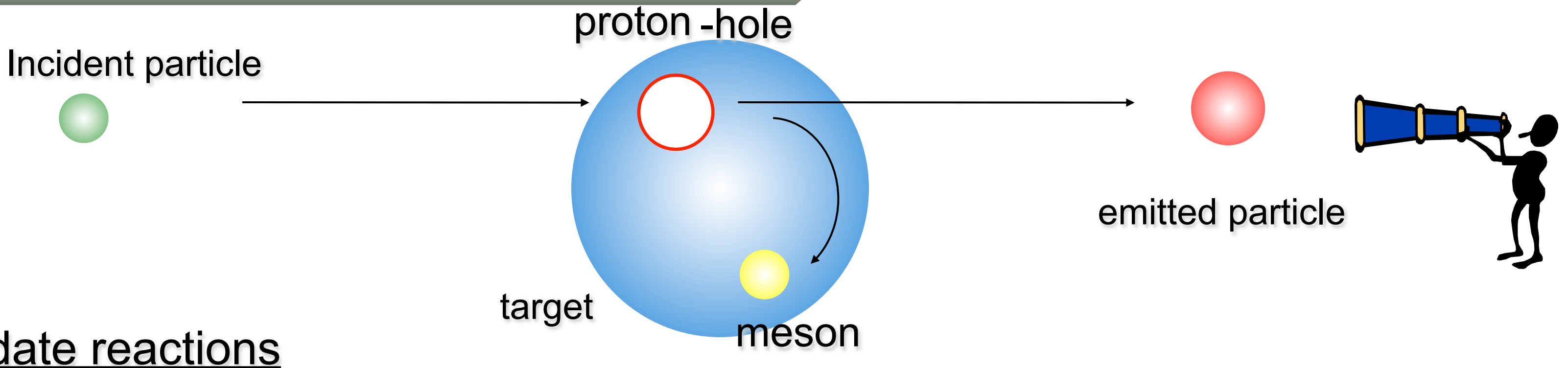


candidate reactions

ex.) (d,^{3}He) reaction … π atom formation, η-mesic nuclei @ GSI

(γ,p) reaction … smaller distortion effect, nearly recoilless for heavy η′

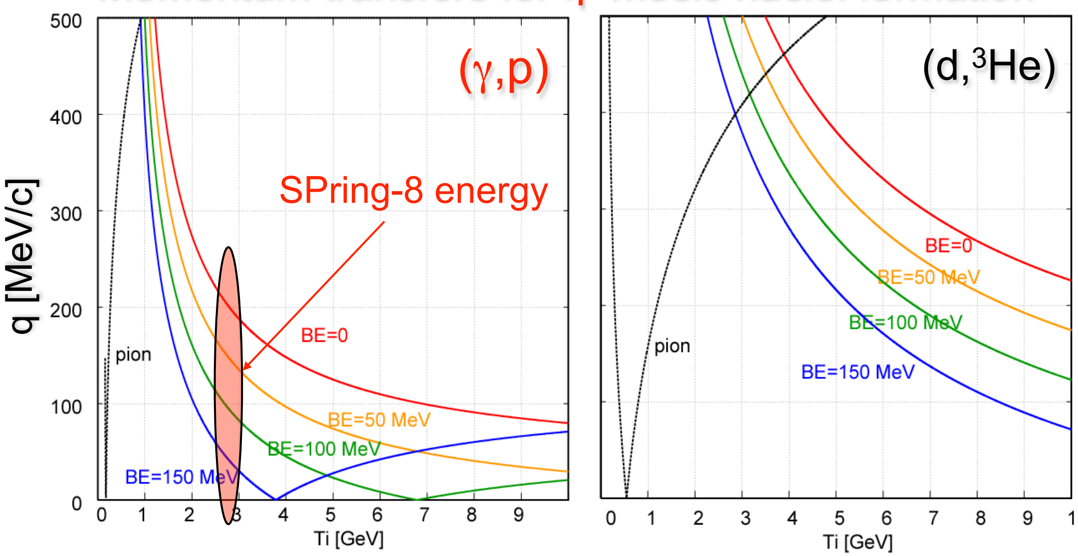
Reaction parameters

- (γ,p) reaction Eγ=2.7 GeV
- target : ^{12}C
- forward : θ_p = 0 deg.
- elementary cross section for γ+p → η′+p

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

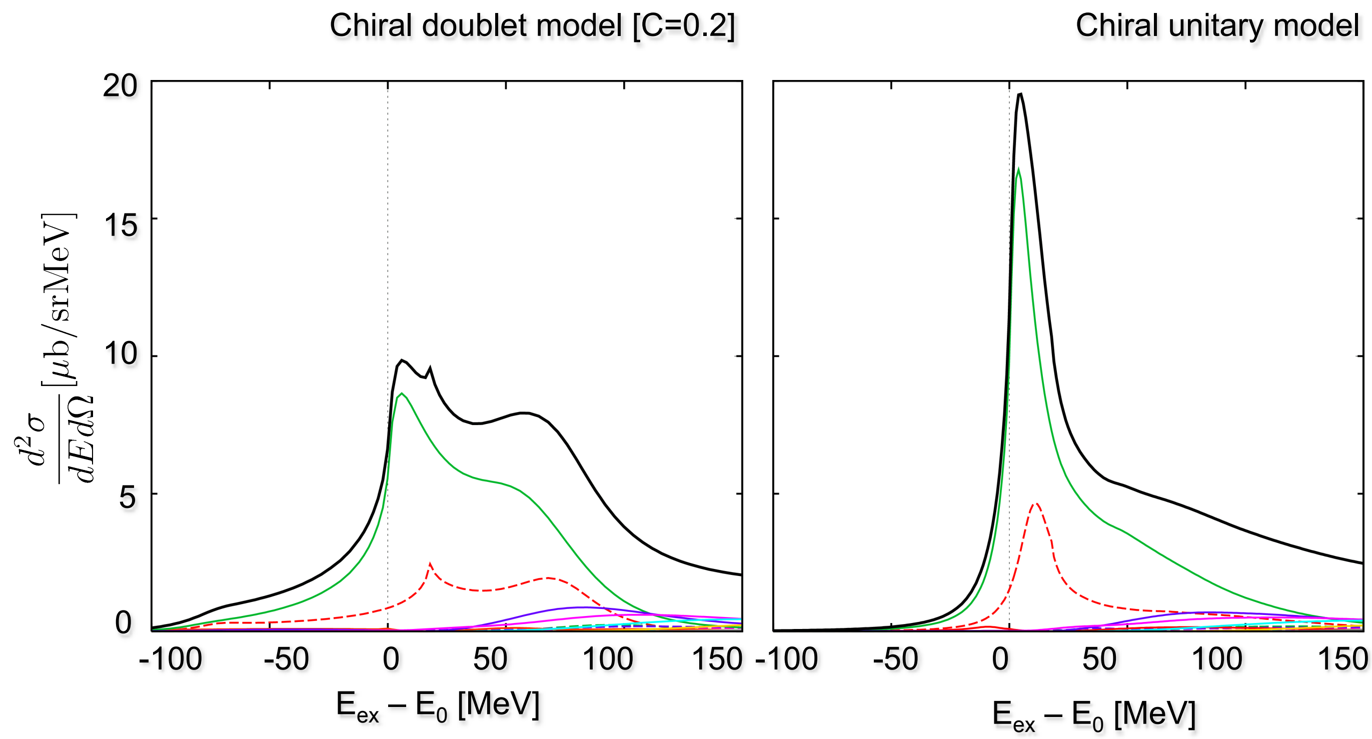
[SAPHIR collaboration, PLB444(98)555-562
Chiang, Yang, PRC68(03)045202]

Momentum transfers for η′-mesic nuclei formation



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

T_π = 820 MeV (p_π = 950 MeV/c)



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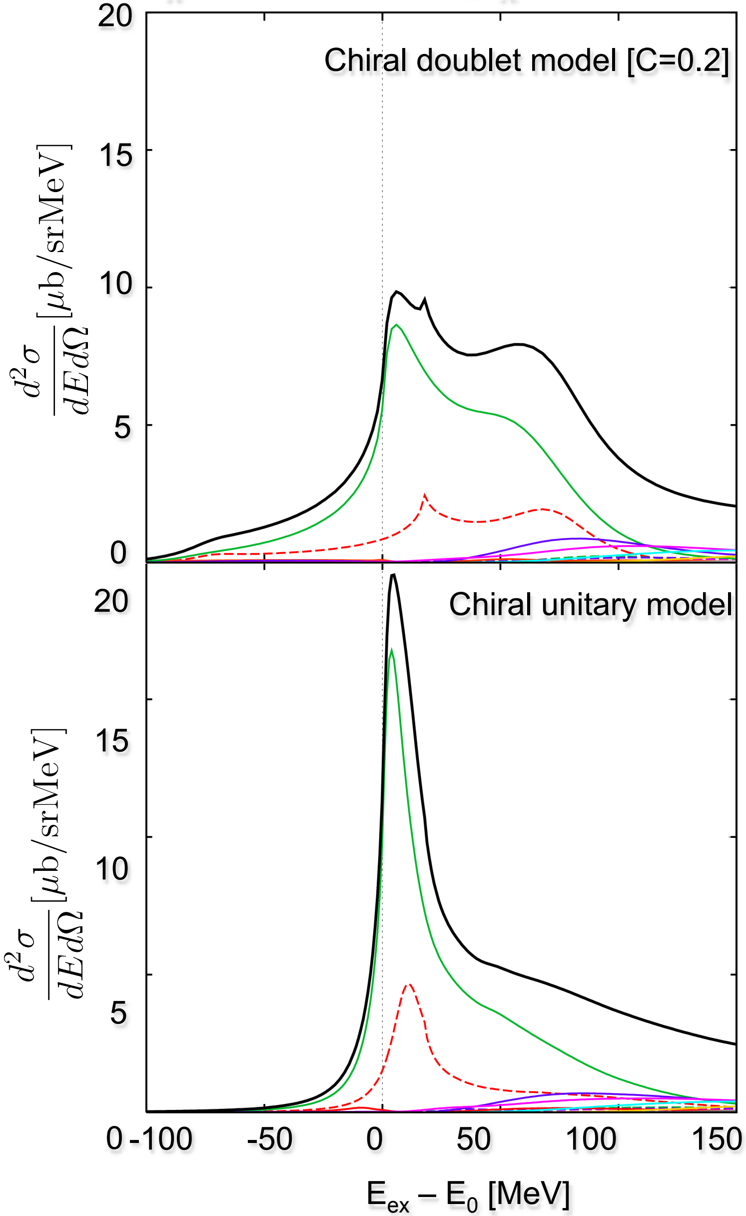

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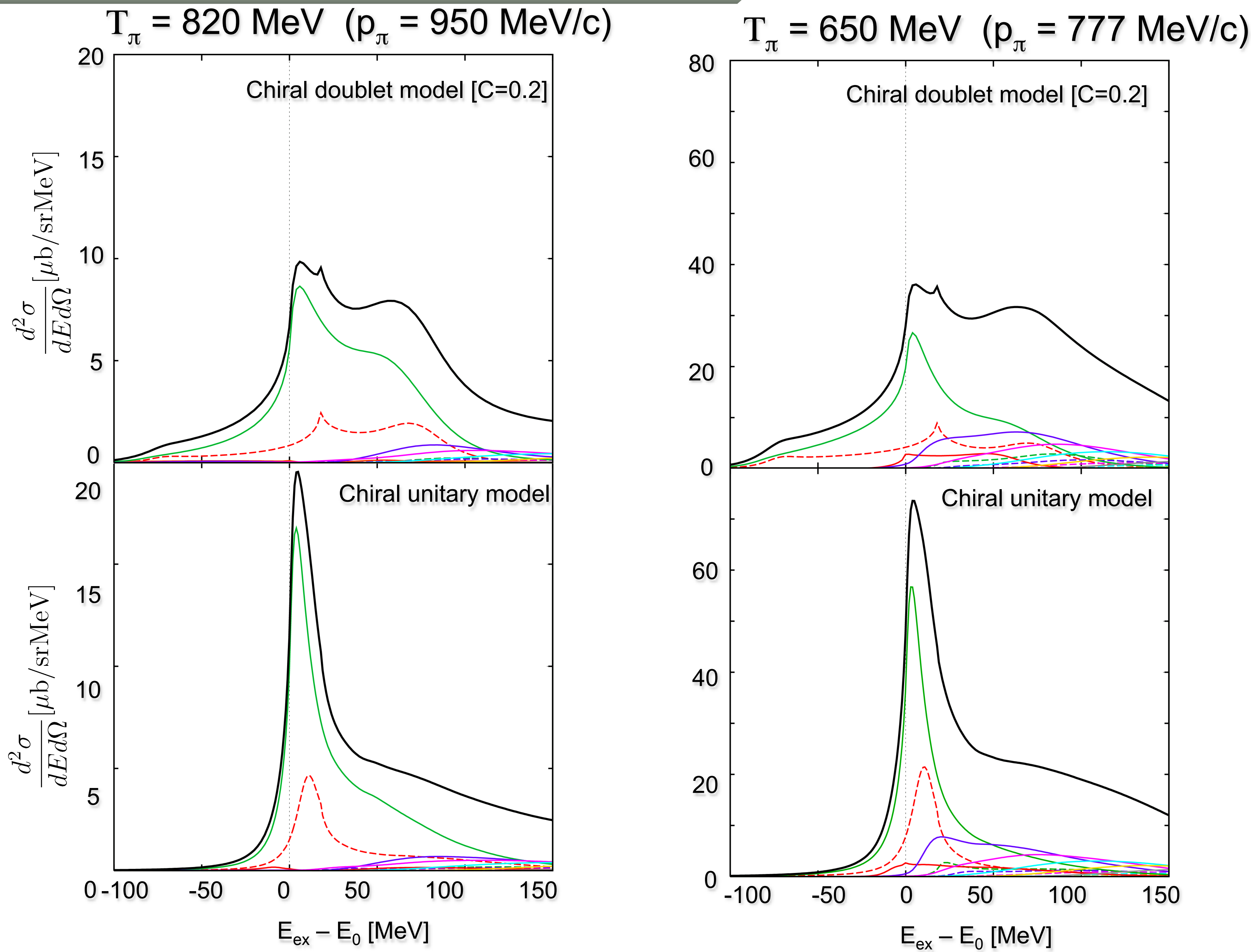

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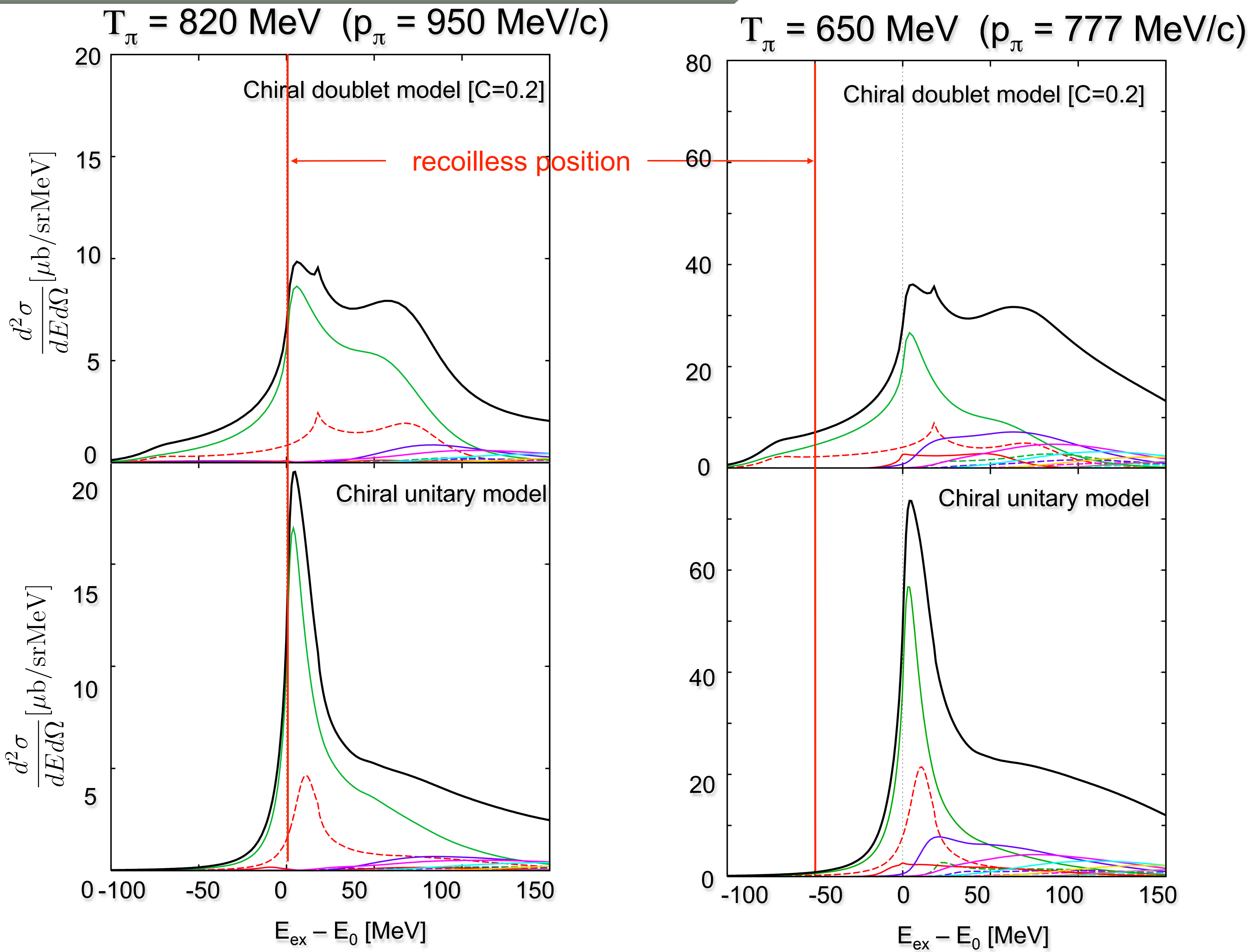

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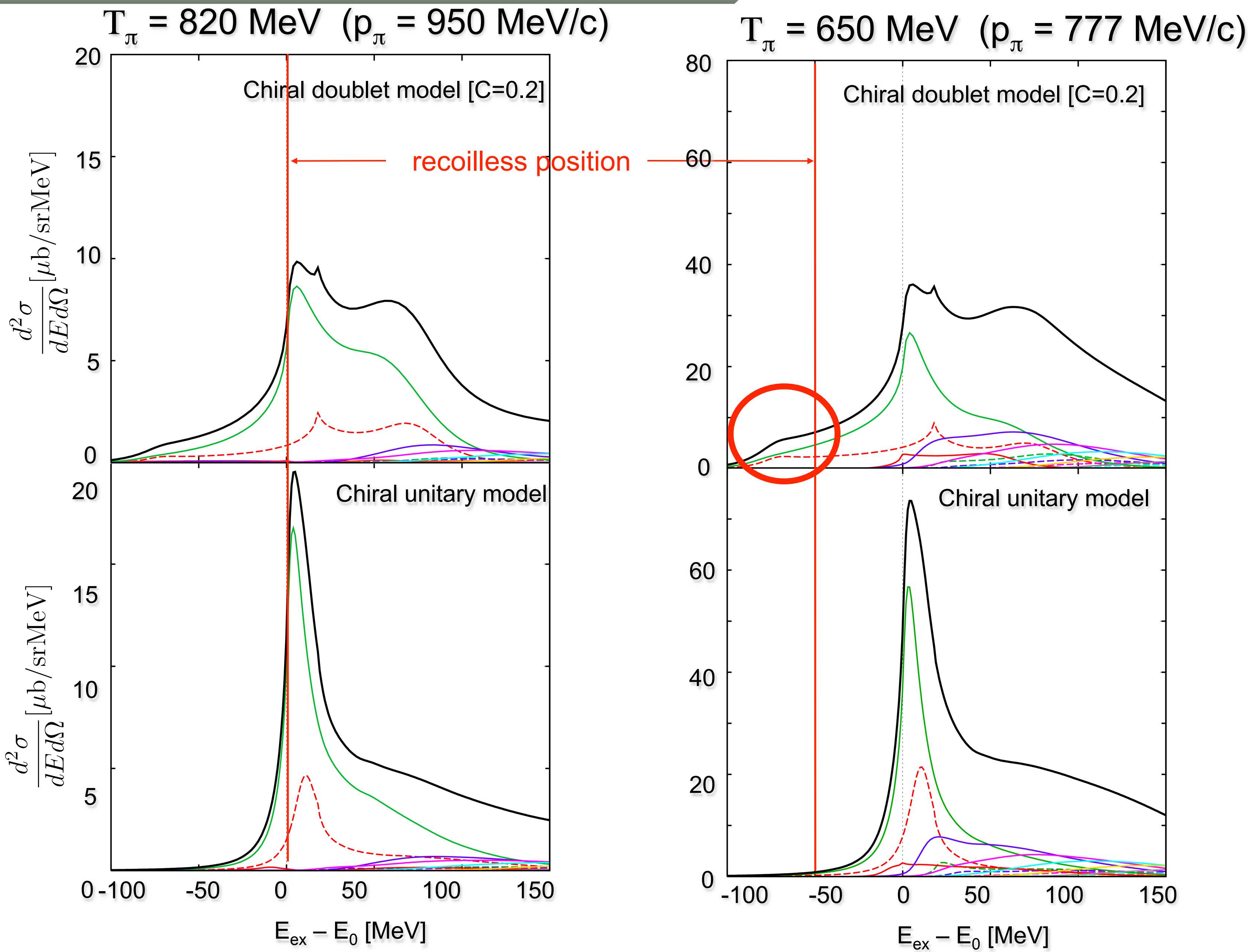
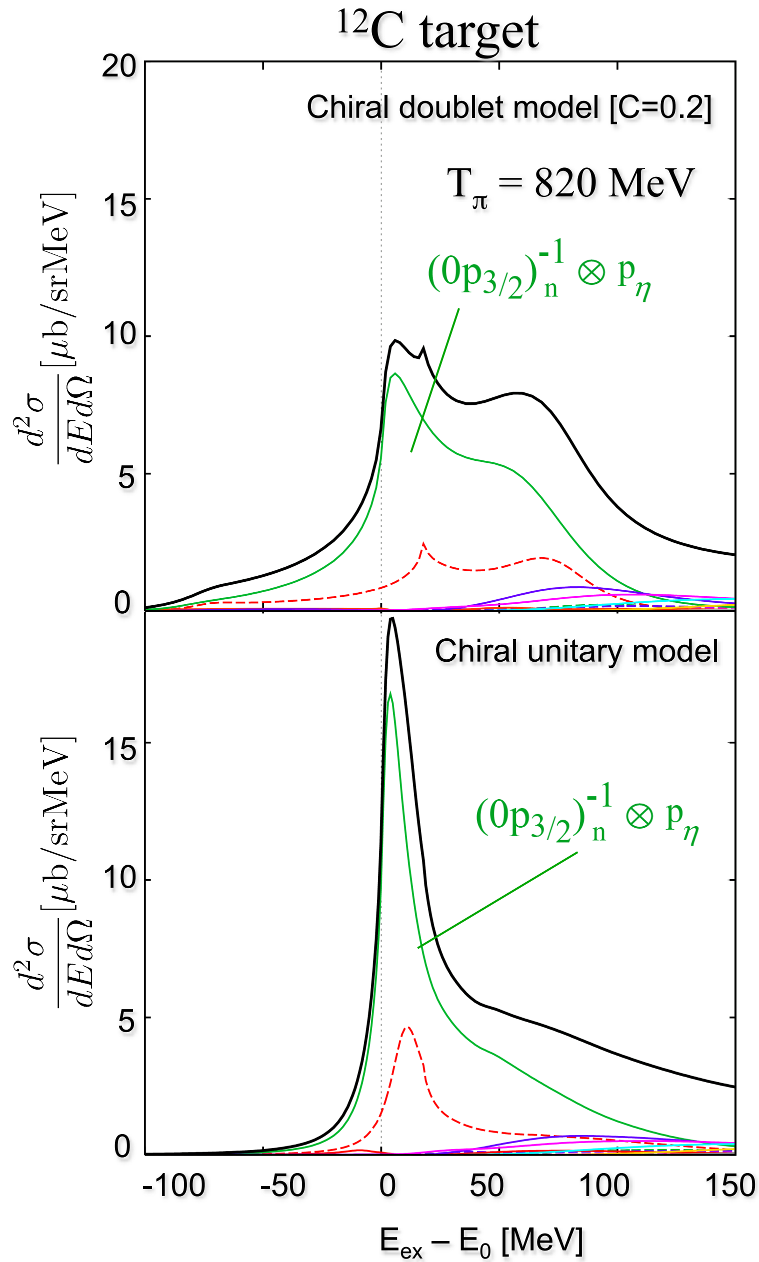


Target dependence : (π^-, n) spectrum (proton picked up)



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