RCNP研究会
『核子と中間子の多体問題の統一的描像に向けて』
2007年12月15日

η中間子原子核生成と原子核媒質中のN*(1535)共鳴

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

- H.Nagahiro, D.Jido, S.Hirenzaki, *in preparation*
- D.Jido, E.E.Kolomeitsev, H.Nagahiro, S.Hirenzaki, *in preparation*
- K.Itanashi, H.Fujioka, S.Hirenzaki, D.Jido, H.Nagahiro, Letter of Intent for J-PARC, July 2007

Introduction : symmetries of QCD

non-trivial structure

$J^P = 0^-$

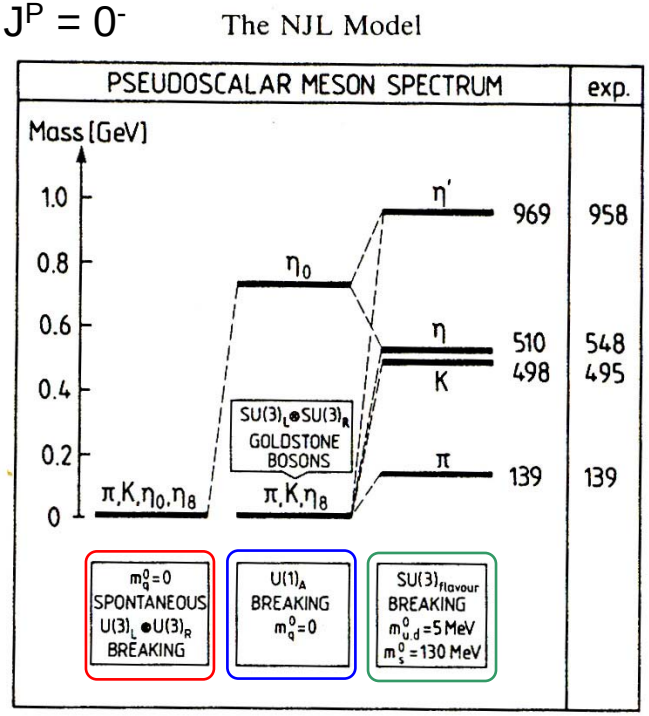
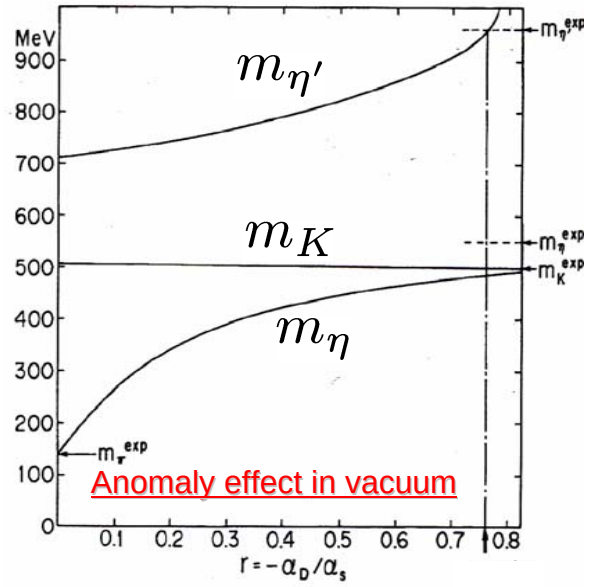


Fig. 10. *Pseudoscalar meson spectrum from the NJL model (Klimt et al. 1990), showing the chiral and flavour symmetry breaking pattern. Calculated and experimental masses are given in MeV.*

- spontaneous chiral symmetry breaking
- $U_A(1)$ anomaly effect
- Explicit symmetry breaking

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



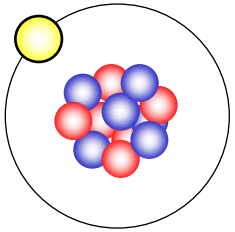
→ 環境を変えて応答をみる。

finite temperature and/or finite density

中間子 - 原子核束縛系

エキゾチック原子・原子核

中間子原子



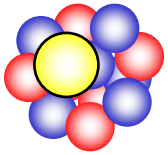
- クーロン力で束縛されている。
- 軌道は原子核に非常に近くなる。

→ 原子核表面付近の密度を感じる。

- 束縛された中間子は、原子核の外、表面付近に存在する。

→ 幅が狭い。

中間子原子核



- 強い相互作用で束縛される。

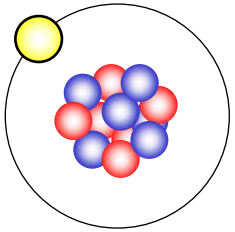
→ 幅が広い。

- 原子核の内部に存在する。

→ 原子核中心付近程度の密度を感じる。

エキゾチック原子・原子核

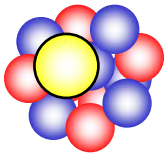
中間子原子



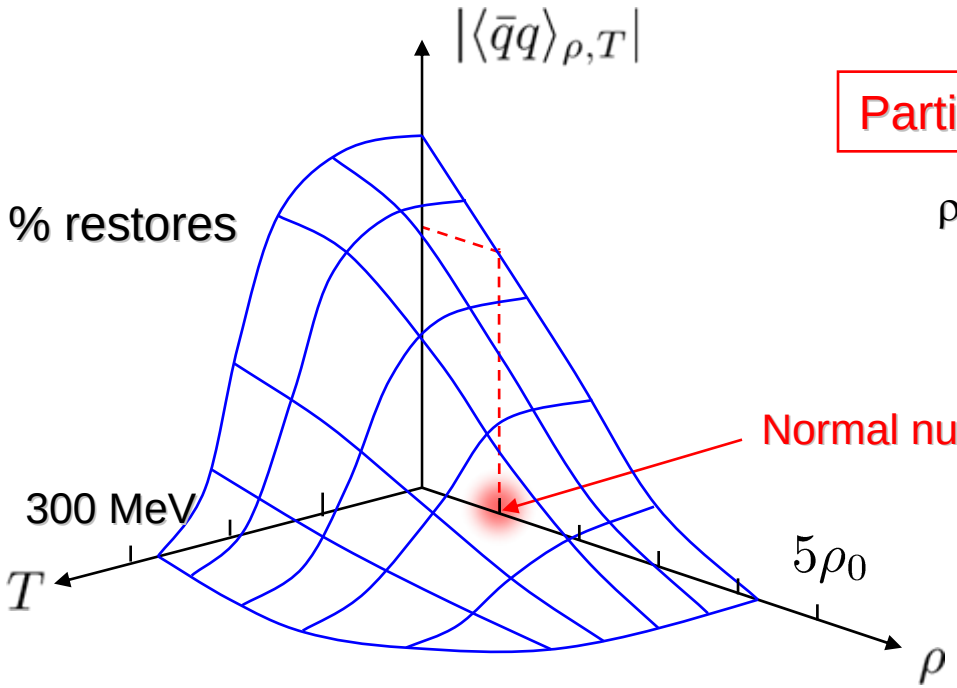
meson & baryon properties at
$\rho \sim \rho_0$?

$$\langle \bar{q}q \rangle = (1 - C\frac{\rho}{\rho_0})\langle \bar{q}q \rangle_0$$

中間子原子核



The quark condensate with finite T and ρ



T.Hatsuda, T.Kunihiro, PRL55(85)158
W. Weise, NPA553(93)59c

Partial restoration of chiral symmetry

ρ ~ ρ0 , T=0 での物理
←→ RHIC などの
高温高密度の物理と相補的

Various interesting

η 中間子原子核
- N*(1535) in medium

今日のお話

σ中間子原子核

Hirenzaki, H.N.,Hatsuda,Kunihiro NPA710(02)131
- 2π enhancement?

π 中間子原子
- deeply bound pionic atom
- missing repulsion
- f_π in medium ?

→ 木村さん's talk & 板橋さん's talk

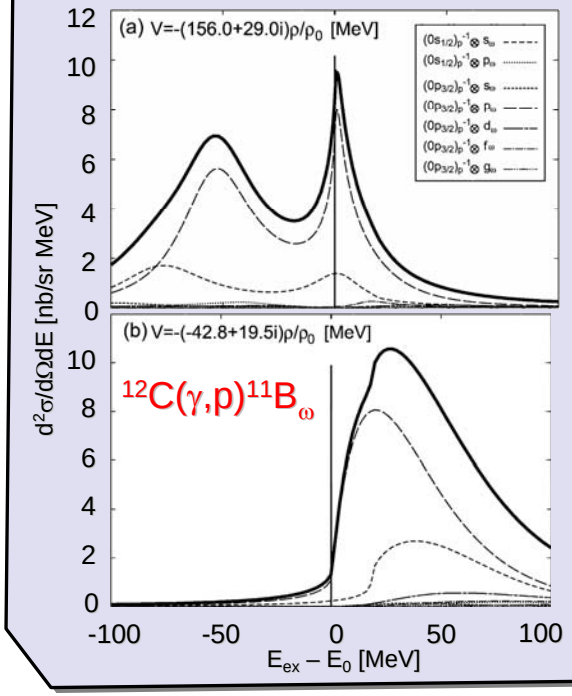
K中間子原子 &K中間子原子核
- deeply bound Kaonic nuclei ?
- deeply bound Kaonic Atom ?

→ 山縣さん's talk & 板橋さん's talk

ω 中間子原子核
- attraction ? repulsion ?

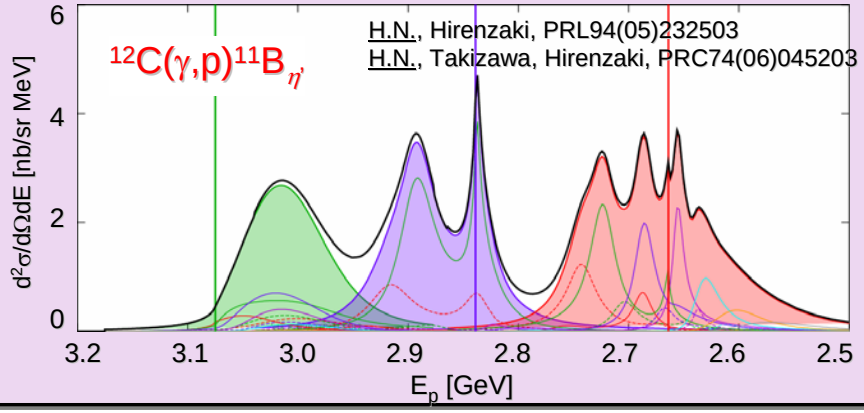
H.N., Jido, Hirenzaki, NPA761(05)92

Kaskulov,H.N.,Hirenzaki, Oset, PRC75(07)064616



φ 中間子原子核
- 引力？観測可能？ → 山縣さん's talk

η' 中間子原子核生成
- $U_A(1)$ anomaly effect at finite density



Introduction : η 中間子原子核

η 中間子原子核の研究

- (π^+,p) * Liu, Haider, PRC34(1986)1845 [theo]
  * Chiang, Oset, and Liu, PRC44(1988)738 [theo]
  * Chrien *et al.*, PRL60(1988)2595 [exp]
  * Kohno, Tanabe, PLB231(1989)219; NPA519(1990)755 [theo]
- $(d,^3He)$ * Hayano, Hirenzaki, Gilltzer, EPJ.A6(1999)99 [theo]
  * Jido, Nagahiro, Hirenzaki, PRC66(2002)045202 [theo]
  * Exp. at GSI (Yamazaki, Hayano group) 2005-6 [exp]
- (γ,p) * Nagahiro, Jido, Hirenzaki, NPA761(2005)92 [theo]
- η-^{3}He system : PRL92(04)252001:TAPS@MAMI [exp]

etc… (ex. (γ,η) @ Tohoku, etc …)

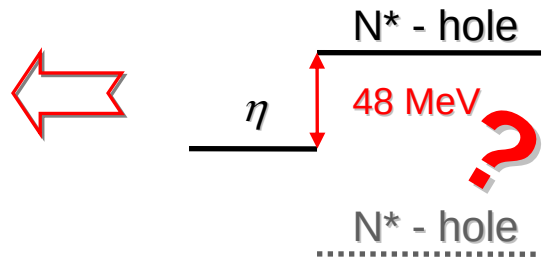
η 中間子-原子核の特徴

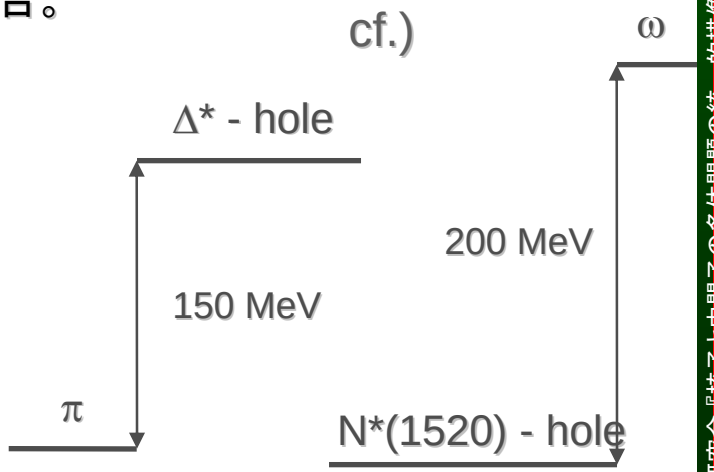
- η 中間子核子系 : **N*(1535) 共鳴状態**と選択的に強く結合。
  → η 中間子原子核ポテンシャルに影響。
- **準位が近い。** ⇒ **準位交差の可能性。**
  → N*(1535) の媒質効果が顕著に現れる。

何が起こる？

何で起きる？

何が見える？



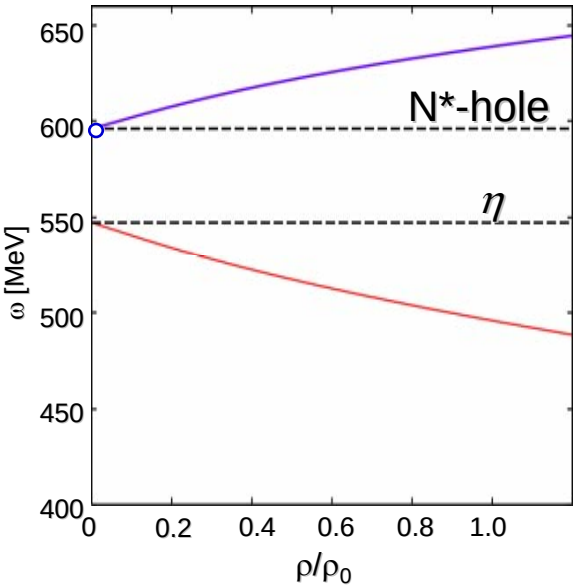


η と N*-hole mode の level crossing

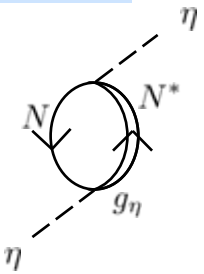
in-medium η propagator (infinite matter)

$$D_\eta(\omega, k) = \frac{1}{\omega^2 - k^2 - m_\eta^2 - \Pi_\eta(\omega, k)}$$

t-ρ approxiation



self-energy



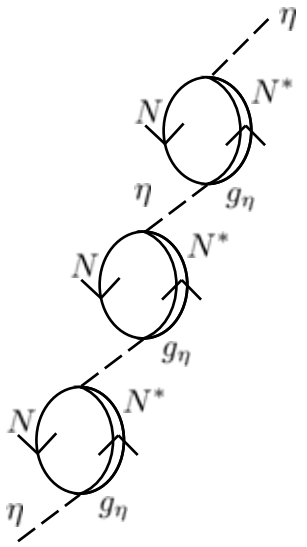
$\Pi_\eta(\omega, k)$

$g_\eta \simeq 2.0\,(\Gamma_{N^* \to \eta N} \simeq 75\ \mathrm{MeV})$

N* dominance

Chiang, Oset, Liu PRC44(1991)738
Jido, Nagahiro, Hirenzaki, PRC66(2002)045202

propagator (Green's function)



two branches

η meson branch and N*-h branch

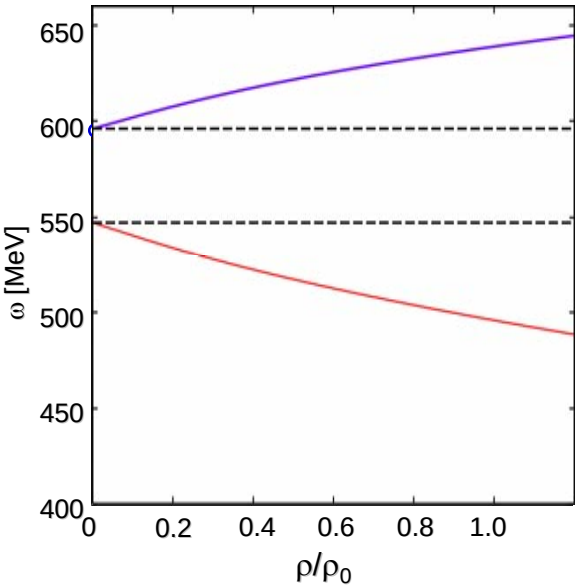
T. Waas, W. Weise, NPA 625 (1997) 287.
T.Inoue, E.Oset, NPA710(02)354

η と N*-hole mode の level crossing

in-medium η propagator (infinite matter)

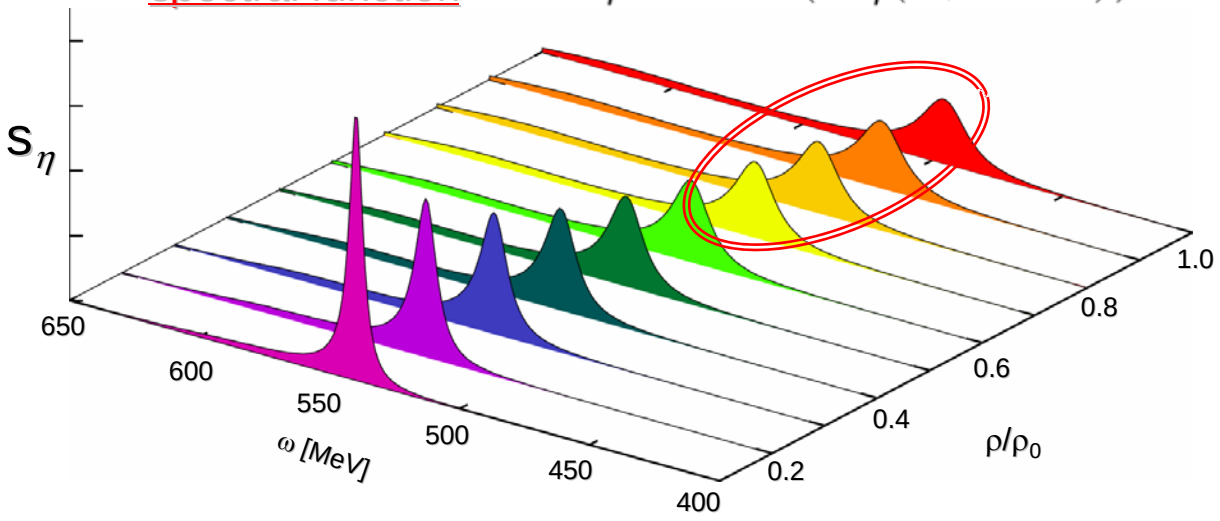
$$D_\eta(\omega, k) = \frac{1}{\omega^2 - k^2 - m_\eta^2 - \Pi_\eta(\omega, k)}$$

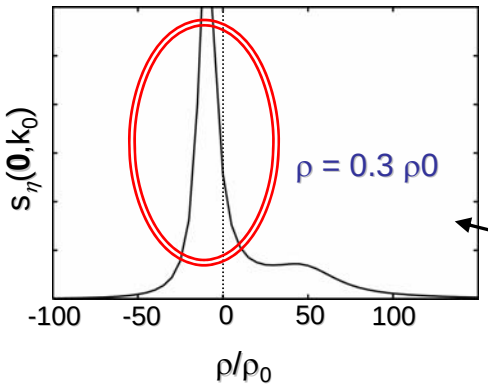
t-ρ approxiation



spectral function

$$S_\eta = -\mathrm{Im}(D_\eta(\omega, k=0))$$





T. Waas, W. Weise, NPA 625 (1997) 287.z

T. Inoue E.Oset, NPA710(02)354、Fig.8

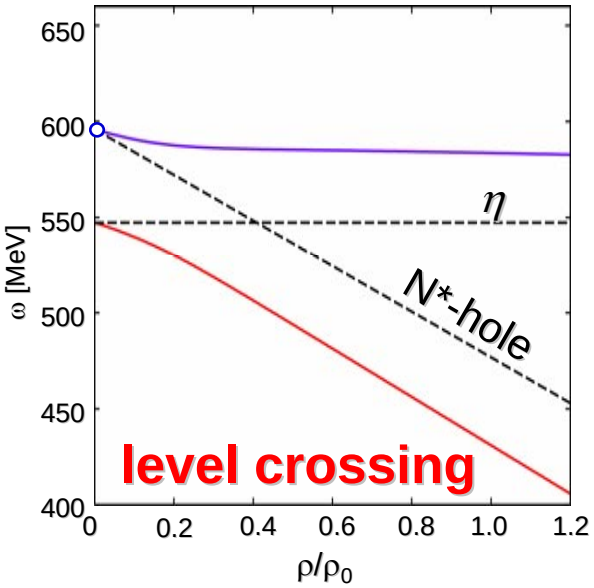
Chiral Unitary model

η と N*-hole mode の level crossing

in-medium η propagator (infinite matter)

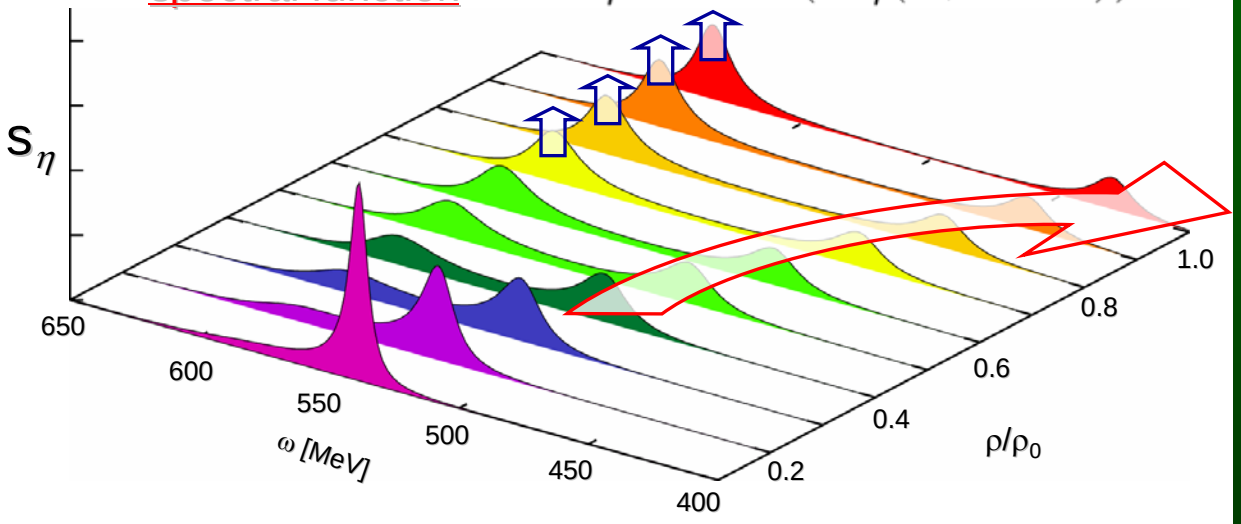
$$D_\eta(\omega, k) = \frac{1}{\omega^2 - k^2 - m_\eta^2 - \Pi_\eta(\omega, k)}$$

N*-hole mass reduction



spectral function

$$S_\eta = -\mathrm{Im}(D_\eta(\omega, k=0))$$



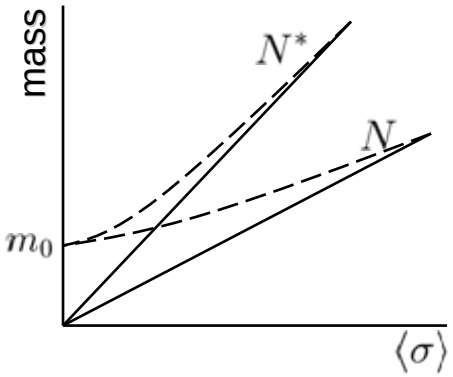
- level 反発 …
  - lower pole goes to down
    - → deeply bound η ?
- level mixing …
  - upper pole の高さ > lower pole の高さ

何が準位交差を引き起こしうるか？ … Chiral対称性の回復

Chiral doublet model

DeTar, Kunihiro PRD39(89)2805
Jido, Nemoto, Oka, Hosaka NPA671(00)471
Jido, Oka, Hosaka PTP106(01)873
Kim, Jido, Oka NPA640(98)77

N* : Chiral partner of nucleon



mass difference of N* and nucleon

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

C ~ 0.2 : strength of chiral restoration at the saturation density ρ_0

reduction of mass difference in the nuclear medium

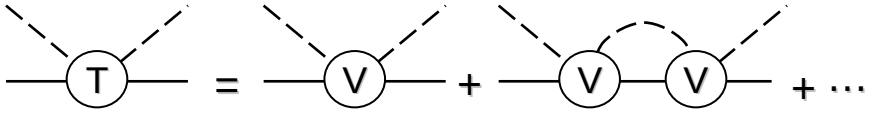
Chiral unitary model

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

N* : resonance dynamically generated
in meson-baryon scattering

→ quasi-bound state of $K\Sigma$

no Pauli blocking for Σ in nuclear medium

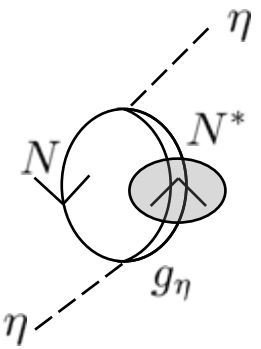


coupled channel Bethe-Salpater eq. in medium

No mass shifts of N* is expected in the nuclear medium

η-nucleus interaction : potential descriptions

η self-energy



Chiang, Oset, Liu PRC44(1991)738

Jido, Nagahiro, Hirenzaki, PRC66(2002)045202

$g_\eta \simeq 2.0\,(\Gamma_{N^* \to \eta N} \simeq 75\ \mathrm{MeV})$

optical potential

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

potential nature at η threshold

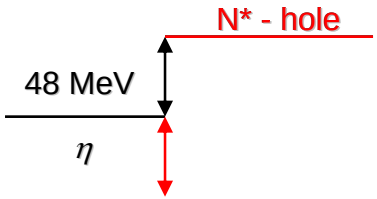
$$m_\eta - (m_{N^*} - m_N) < 0$$

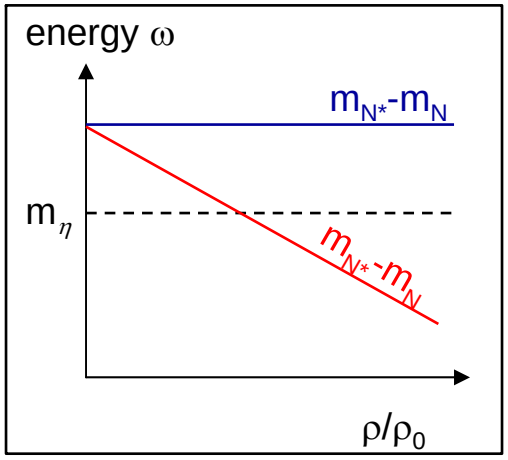
attractive

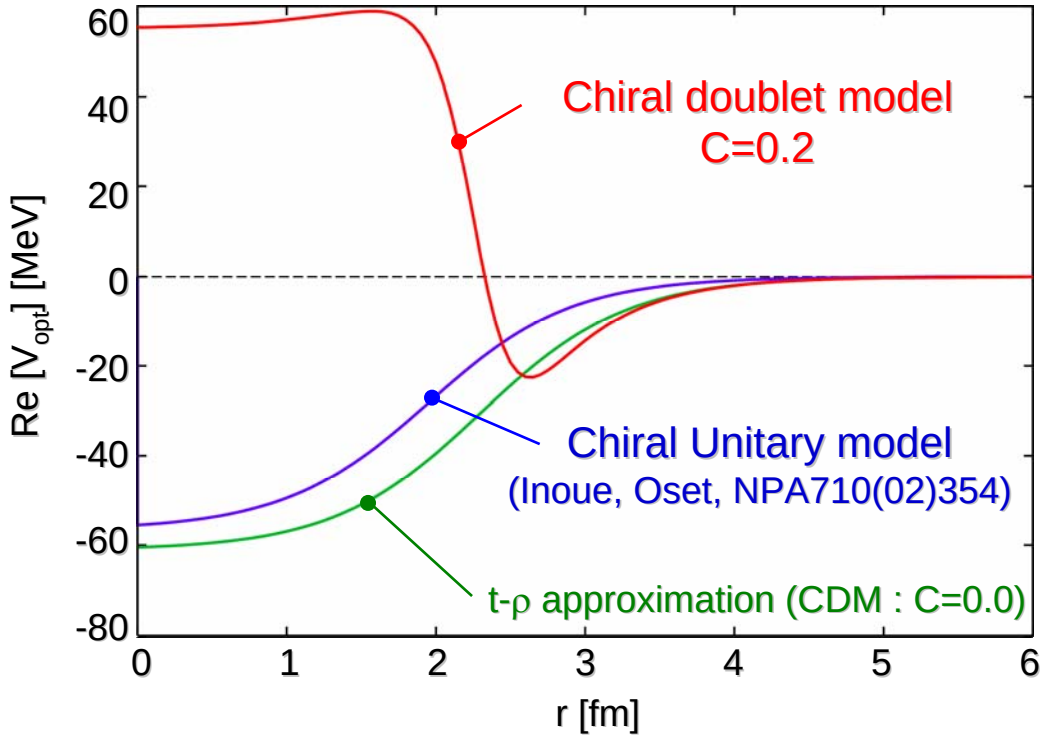
medium effect

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

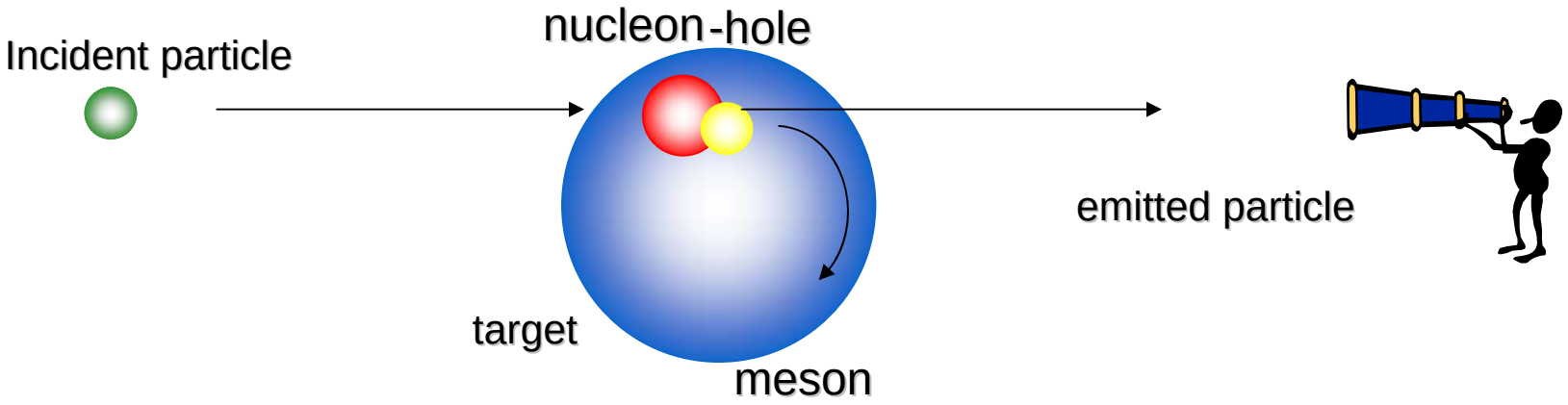
repulsive







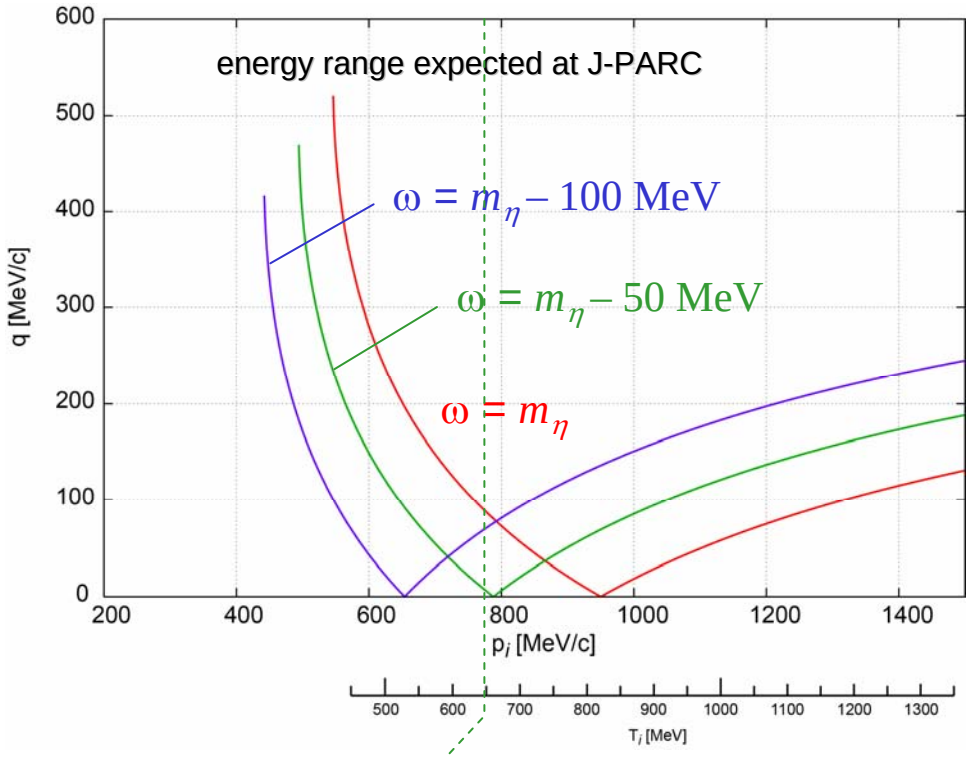
Missing mass spectroscopy : one nucleon pick-up



- (d,^{3}He) : 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 possible at J-PARC**
  - › **secondary meson beam, π, K, …**

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

momentum transfer : **forward proton angle (0 degree)**



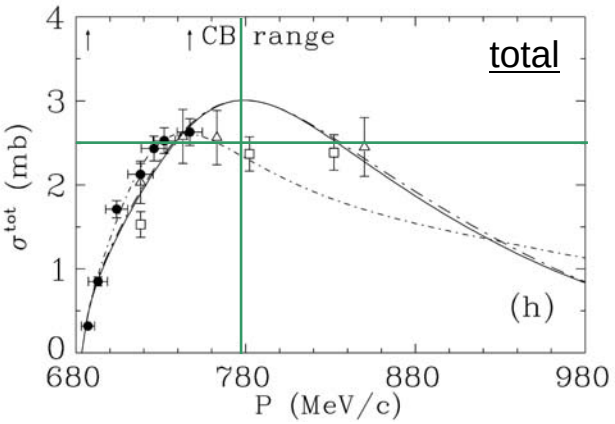
elementary cross section

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

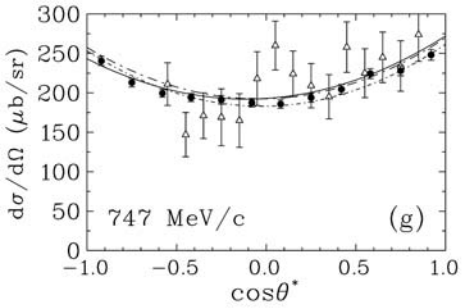
$$\pi^+ n \rightarrow \eta p$$

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

total cross section



角度分布 ~ flat



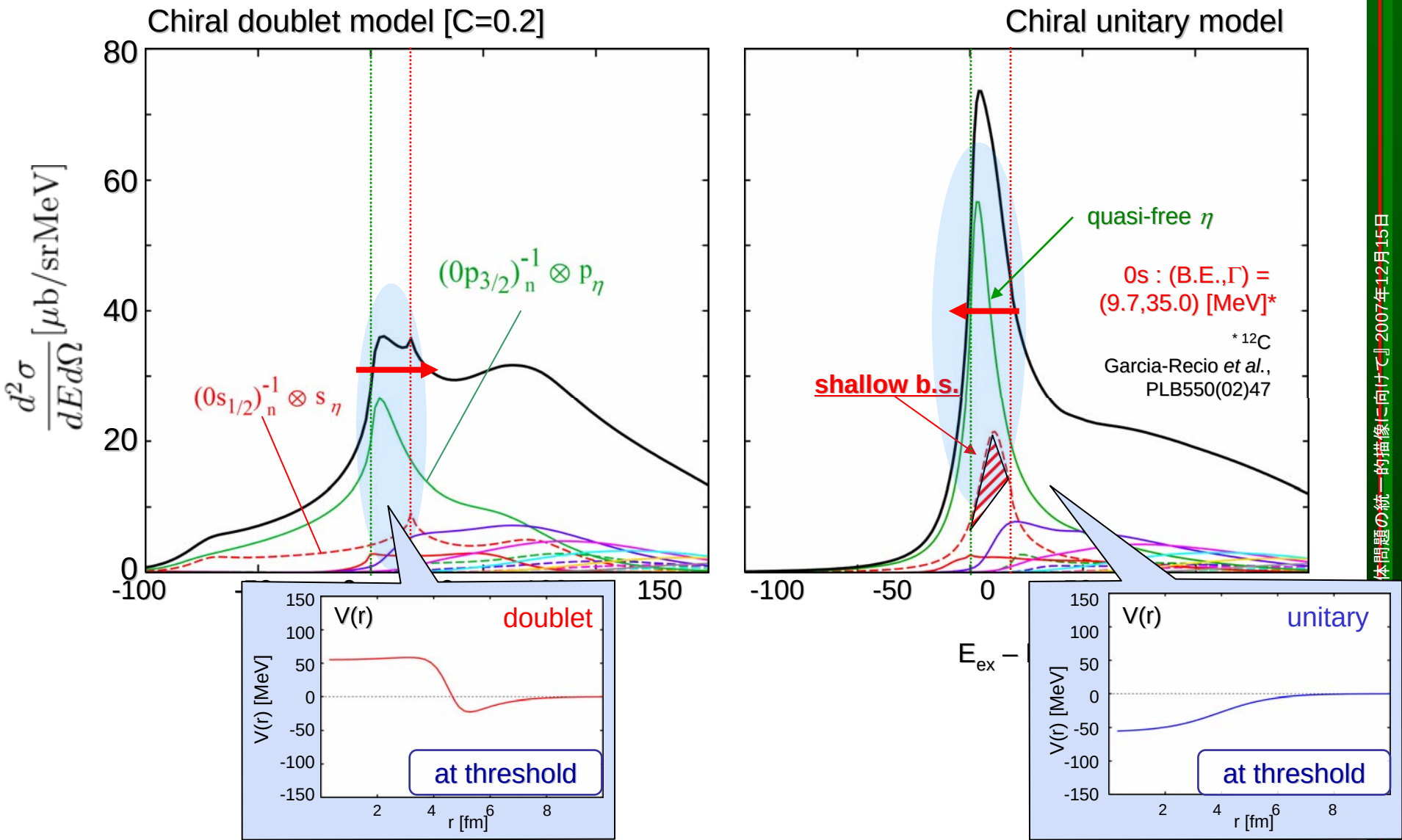
T_π = 650 MeV (p_π ~ 777 MeV/c) → $\left(\frac{d\sigma}{d\Omega}\right)^{Lab.} = 2.4\text{mb/sr}$

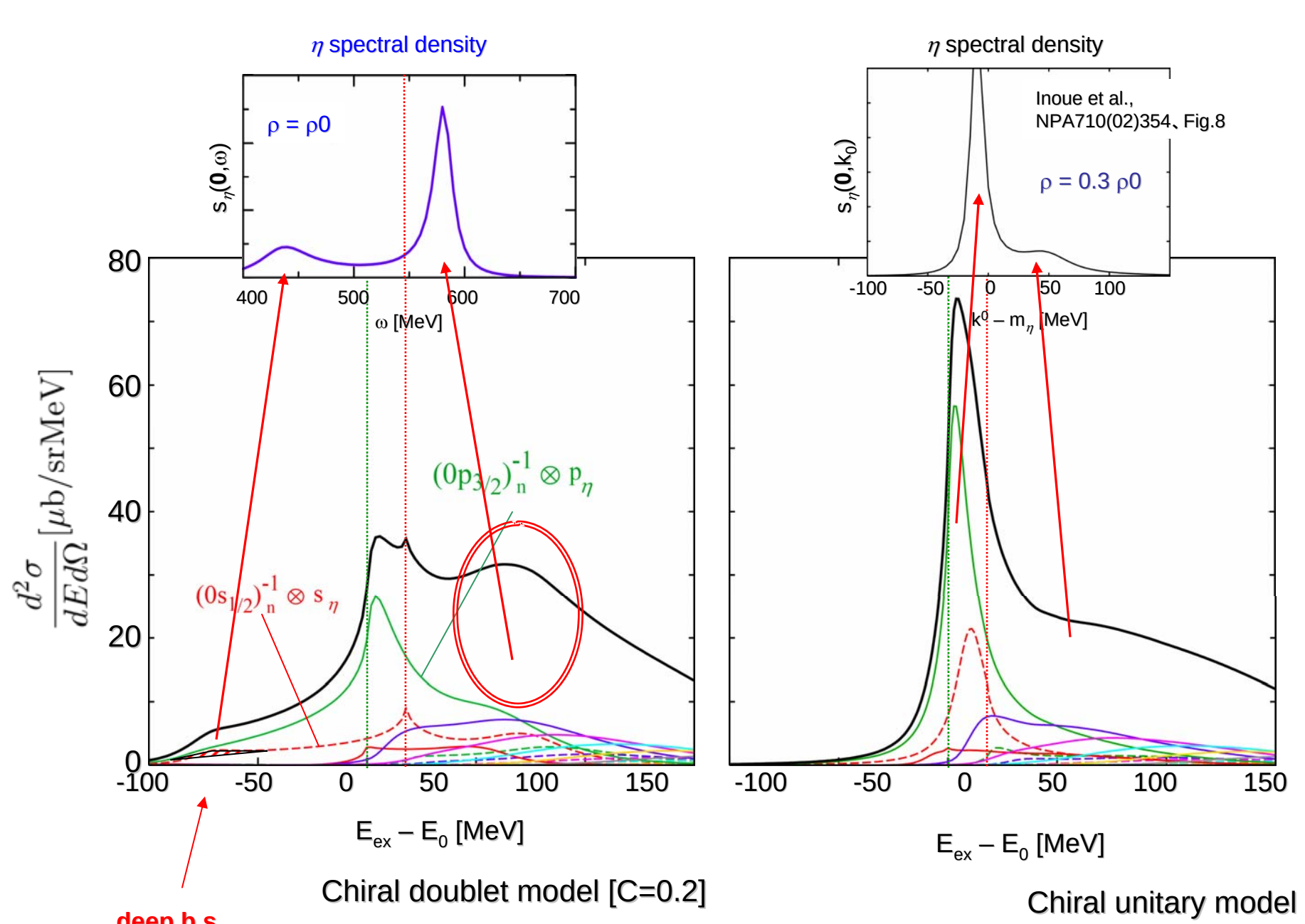
Green's function method

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

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

T_π = 650 MeV (p_π = 777 MeV/c) : θ = 0 deg. (Lab)



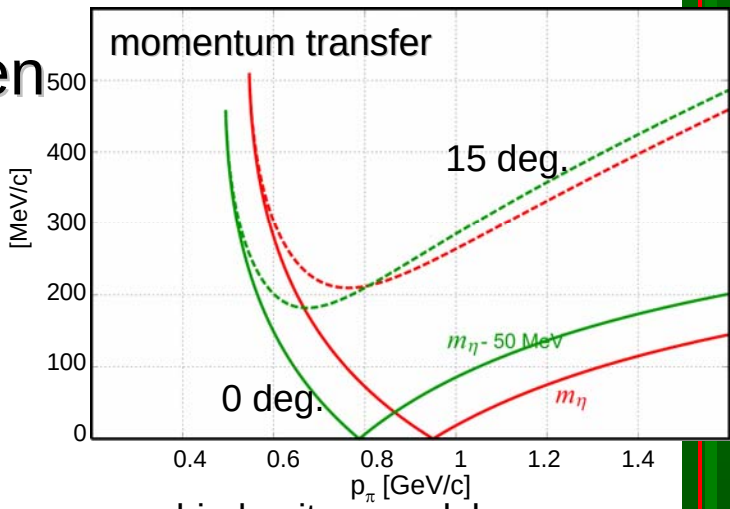

η spectral density
ρ = ρ0
$s_\eta(\mathbf{0},\omega)$
400
500
600
700
ω [MeV]
η spectral density
Inoue et al.,
NPA710(02)354、Fig.8
ρ = 0.3 ρ0
$s_\eta(\mathbf{0},k_0)$
-100
-50
0
50
100
$k^0 - m_\eta$ [MeV]
$\frac{d^2\sigma}{dEd\Omega}$ [μb/srMeV]
80
60
40
20
0
$(0p_{3/2})^{-1}_n \otimes p_\eta$
$(0s_{1/2})^{-1}_n \otimes s_\eta$
-100
-50
0
50
100
150
$E_{ex} - E_0$ [MeV]
Chiral doublet model [C=0.2]
deep b.s.
0s : (B.E., Γ) = (91.3, 26.3) [MeV]
$E_{ex} - E_0$ [MeV]
Chiral unitary model

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

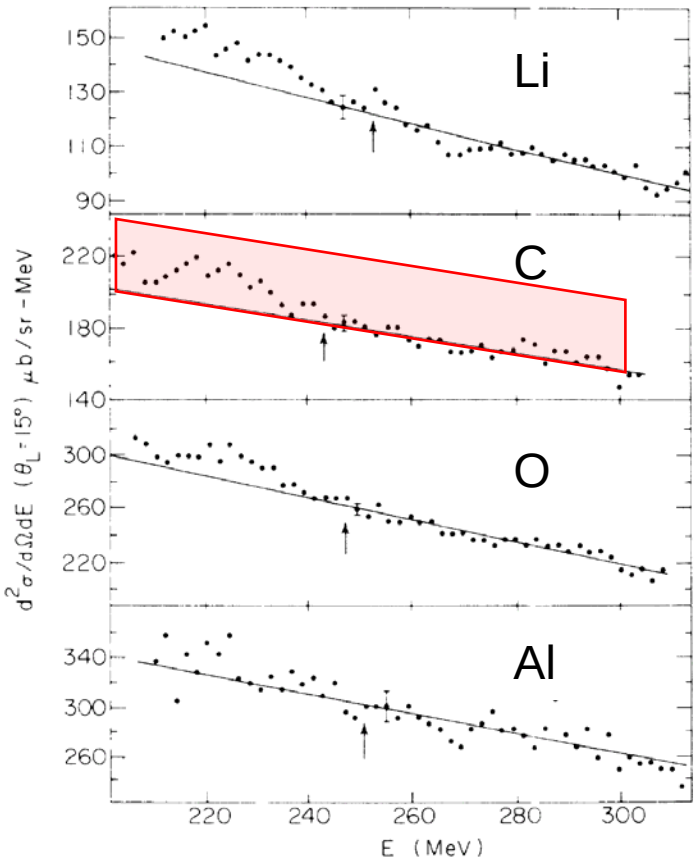
Chrien et al., PRL60(1988)2595

- p_π = 800 MeV/c : proton angle : **15 deg. (Lab.)**
- search for predicted narrow bound state by Liu, Haider, PRC34(86)1845

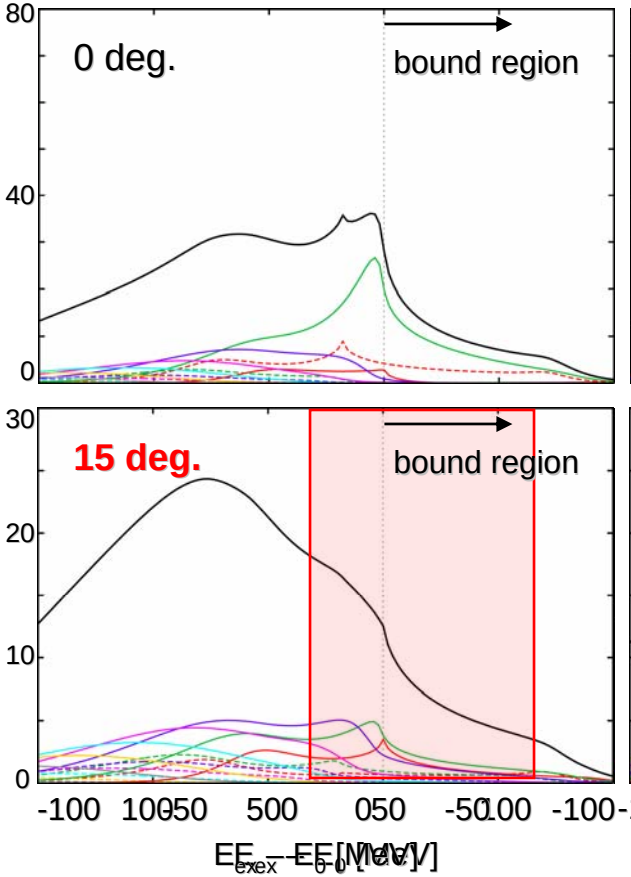
→ negative results (bound state was not observed)



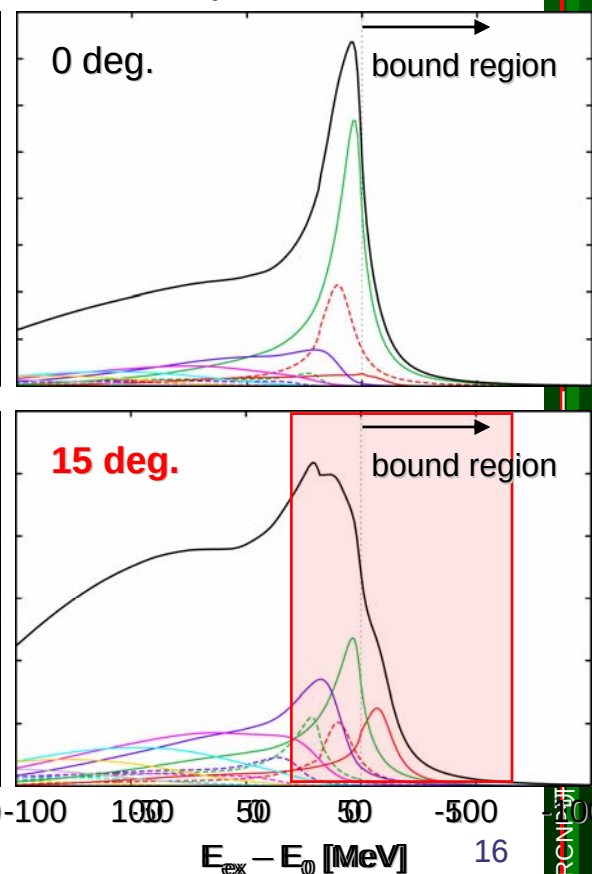
Chrien at al., PRL60(88)2595, Fig.1



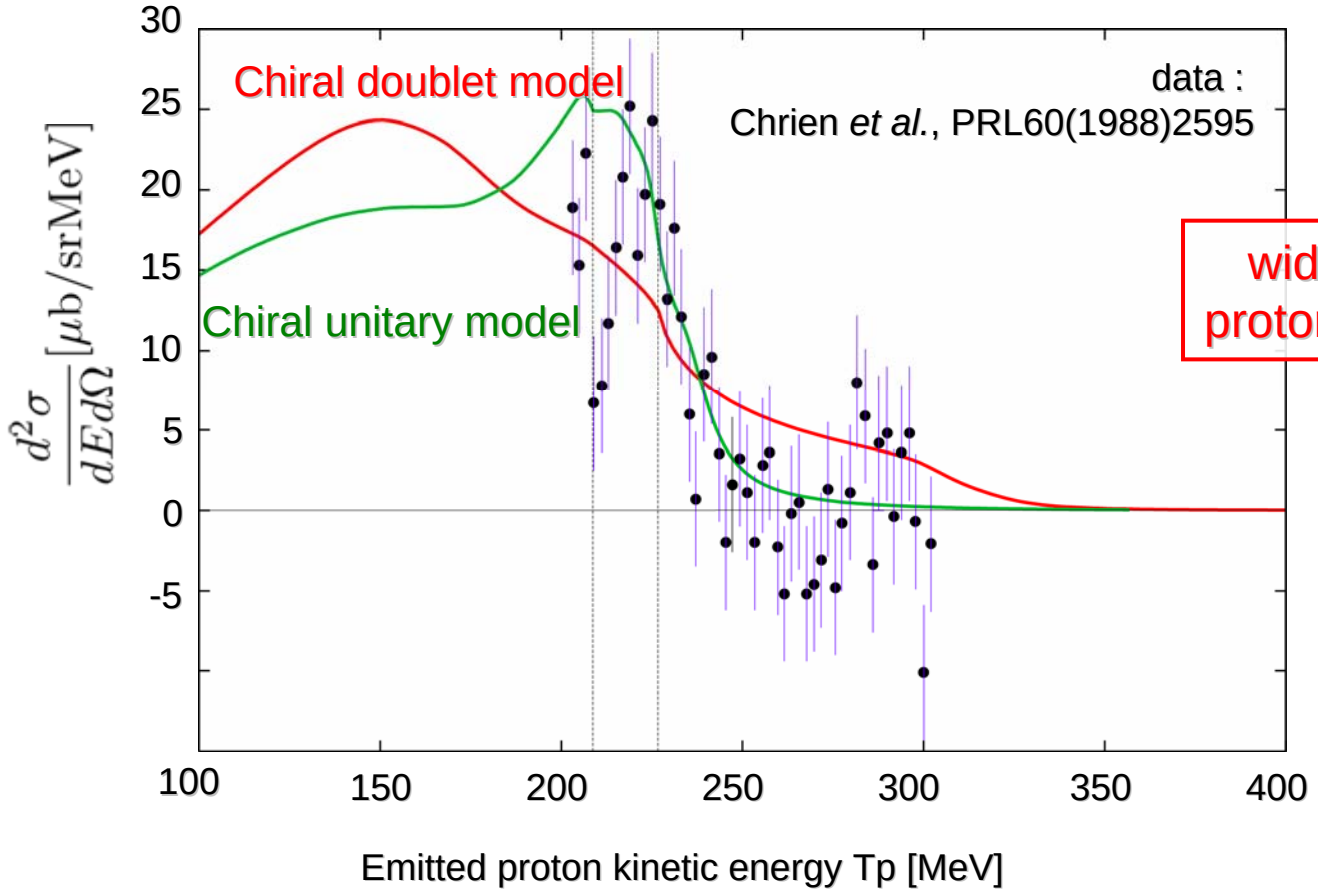
chiral doublet model



chiral unitary model



(π^+,p) spectra : comparison of our calc. with the exp. data



wider energy range
proton angle = 0 degree

- The experimental data is consistent with both model

→ This experimental set-up is not sensitive to N* in-medium

[M. Kohno, H. Tanabe, NPA519(90)755]

Discussion with Experimentalist [板橋(理研), 藤岡(東大)]

- The experiment can be performed at J-PARC.
  - » しかも economical
- (π^-,n) が (π^+,p) より望ましい
  - » $p_{\pi+} \sim p_p$: recoilless kinematics; $C_{\pi+} = C_p$: plus charge
    - → difficult to select emitted proton from large incident pion flux

★ calculation of (π^-,n) spectra

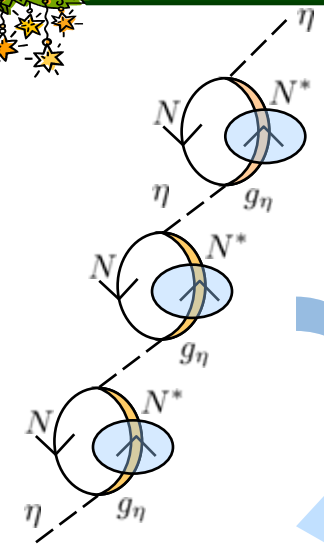
→ almost same with (π^+,p)

- 実験のエネルギー解像度 ~ 20 − 30 MeV
- 2π production から来る background
  - » 何らかの background 除去が重要
    - → N*(1535) からの崩壊粒子 Nπ を同時に測定する。

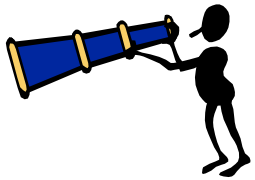
★ background の評価

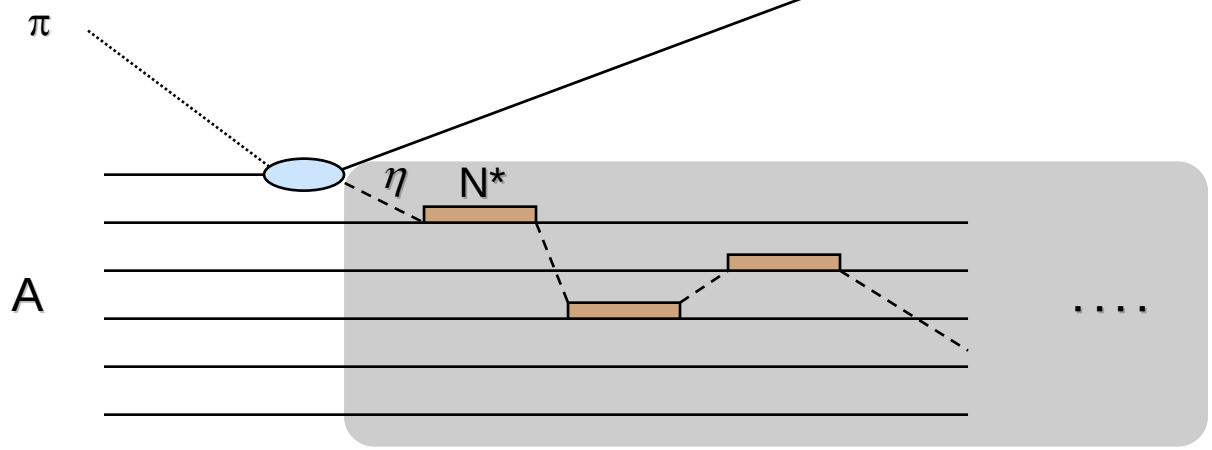
★ 終状態を指定したことによる signal への影響

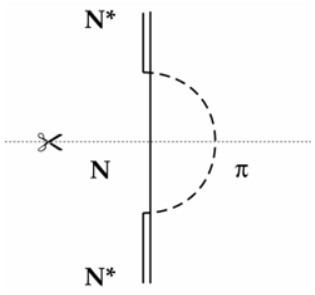
Background reduction : 終状態の指定

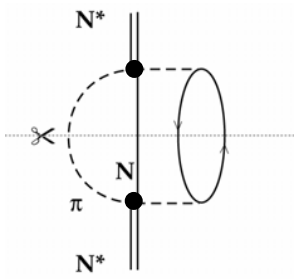


N* width in CDM

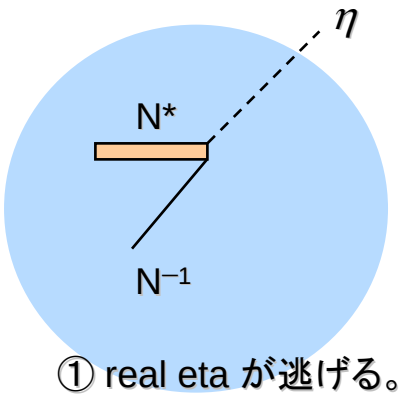




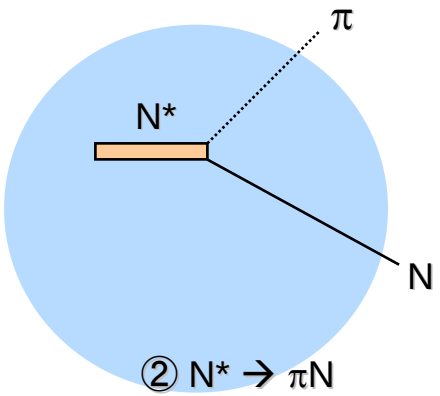




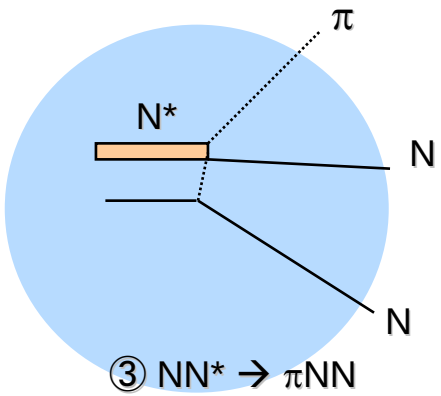
終状態



① real eta が逃げる。
(escape part)



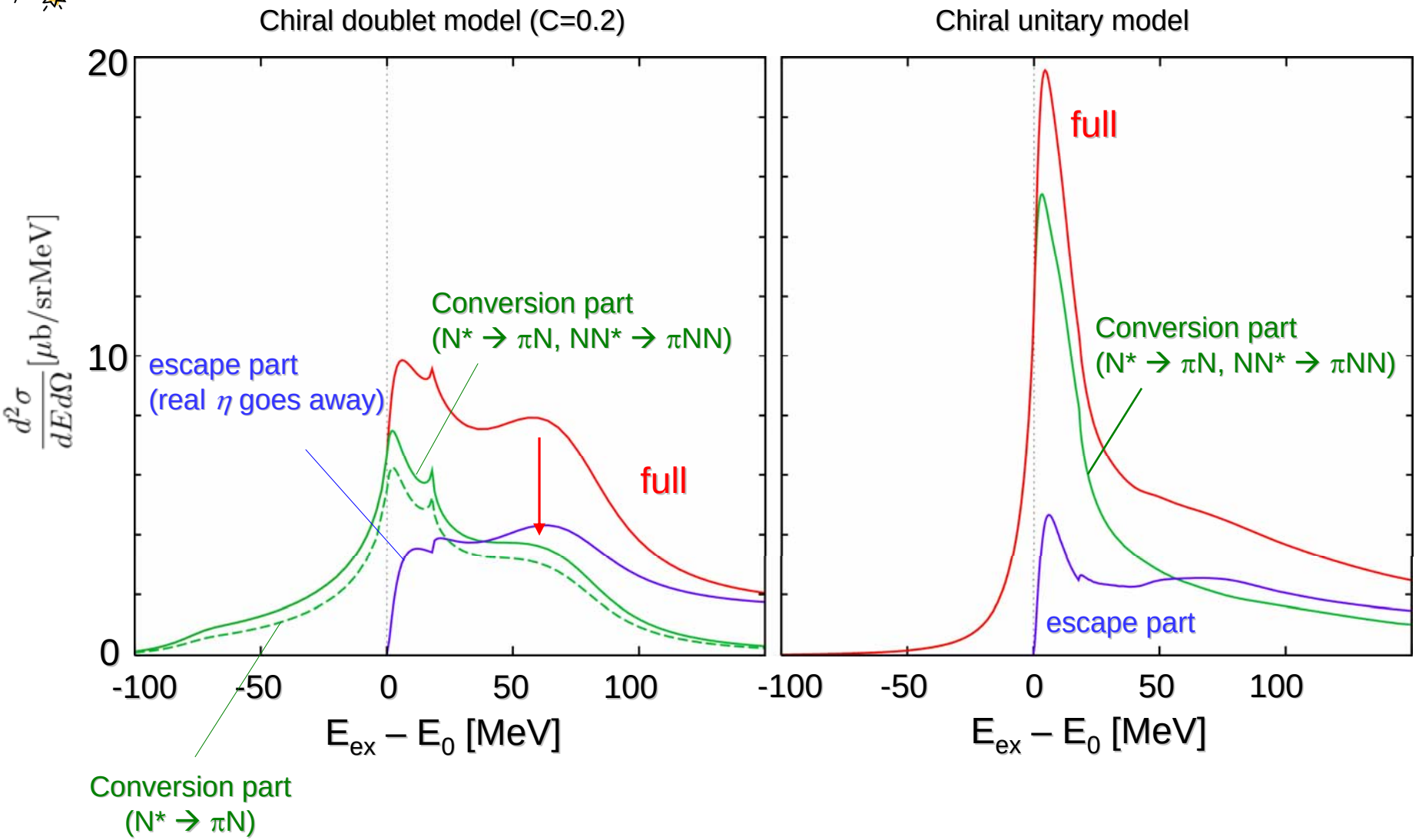
② N* → πN
(conversion part)



③ NN* → πNN
(conversion part)

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

終状態の指定による signal への影響



Summary

- η 中間子原子核生成反応
  - **媒質中でのN*(1535) resonance の性質**
  - η N と N* の 準位交差の可能性 ←→ **Chiral symmetry restoration** in-medium
    - N* が 核子のカイラルパートナーの候補 (Chiral Doublet model)
  - 準位交差が引き起こす現象
    - deeply bound η ? upper mode enhancement ?

- (π^+,p) 反応 (~(π^-, n))
  - incident pion kinetic energy
    - T_π = 820 MeV (p_π ~ 950 MeV/c) : recoilless at η threshold
    - T_π = 650 MeV (p_π ~ 777 MeV/c) : recoilless at η threshold – 50 MeV
  - Brookhaven(1988年)実験との比較。
    - 射出陽子の角度15° は適切か？
    - N* properties in-medium に sensitive ではない。
  - We should discuss the whole shape itself in the case that the imaginary part might be large
  - → 射出陽子の角度は 0度が好ましい。
  - N*(1535) への媒質効果は観測しうる。

- J-PARC で実験可能 : (π^-,n) reaction
  - 実験研究者 [板橋 (理研), 藤岡 (東大)]との具体的な議論中
  - background の評価