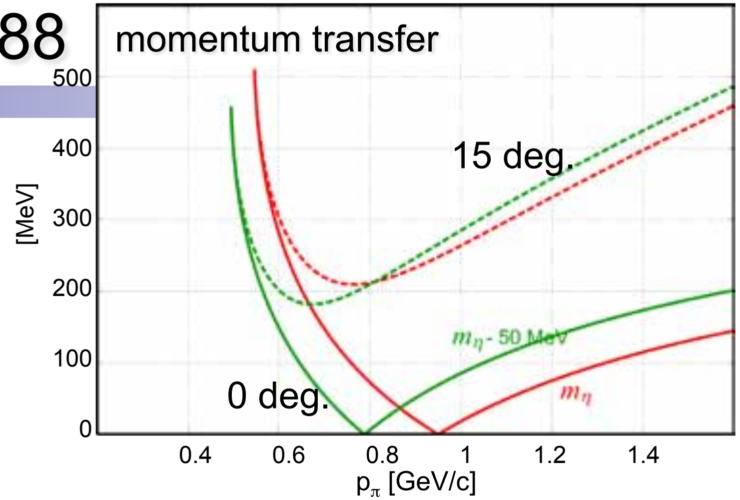
(π^+,p) spectra : past experiment in 1988



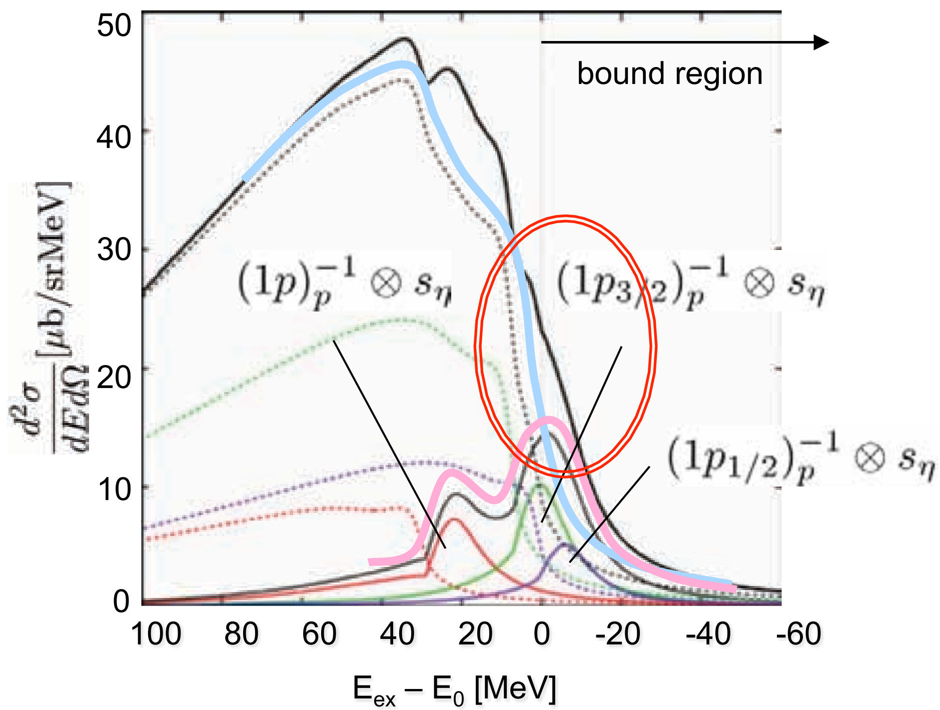
- quasi-free contribution
  - » virtual η absorption (due to Imaginary potential)
  - → Bound state peaks are masked
- ^{16}O neutron separation energy for each level
  - » 1p1/2
  - » 1p3/2
  - » 1s1/2

~ 6 MeV

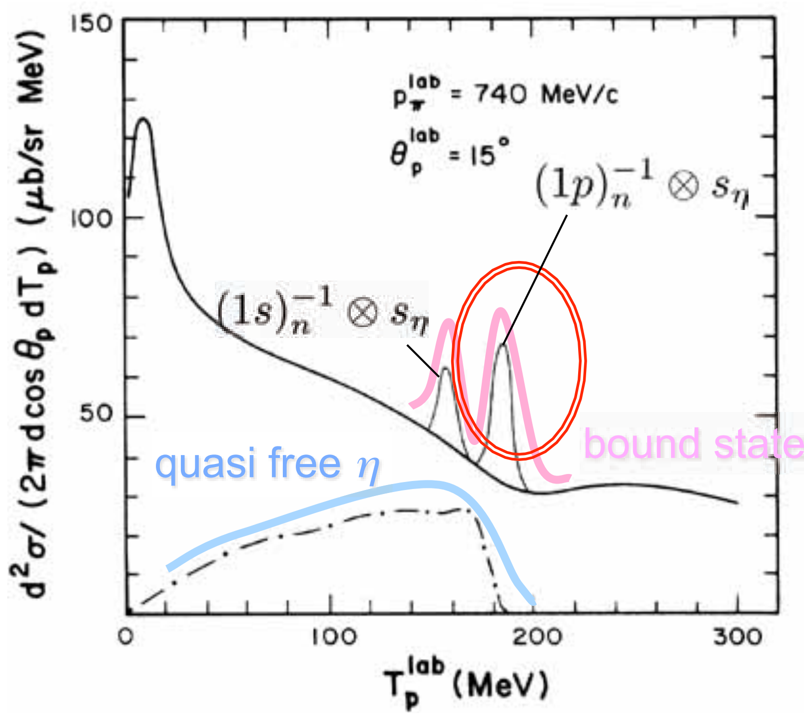
~ 23 MeV $(0.28 + 0.19i)$

Liu, Haider, PRC34(86)1845

green function method (V_0,W_0) = -(34,15) [MeV]

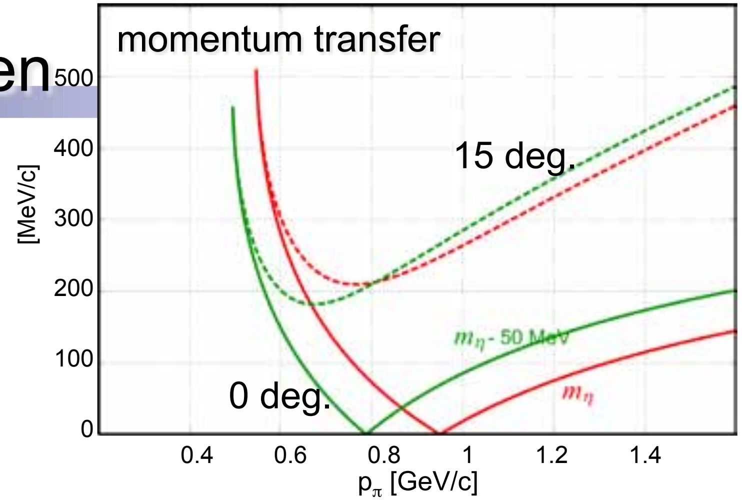


Liu, Haider, PRC34(86)1845, Fig.7



(B.E, $\Gamma/2$) = (2.65, 4.77) [MeV]

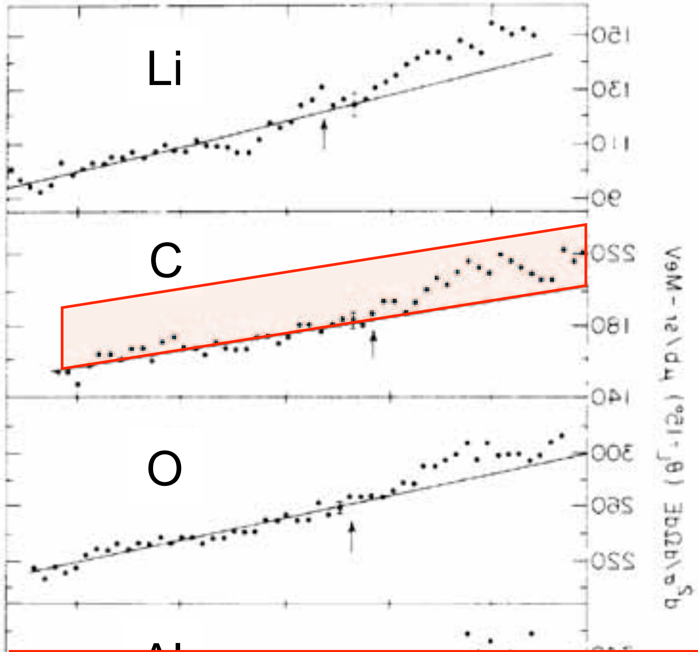
(π^+,p) spectra : experiment at Brookhaven



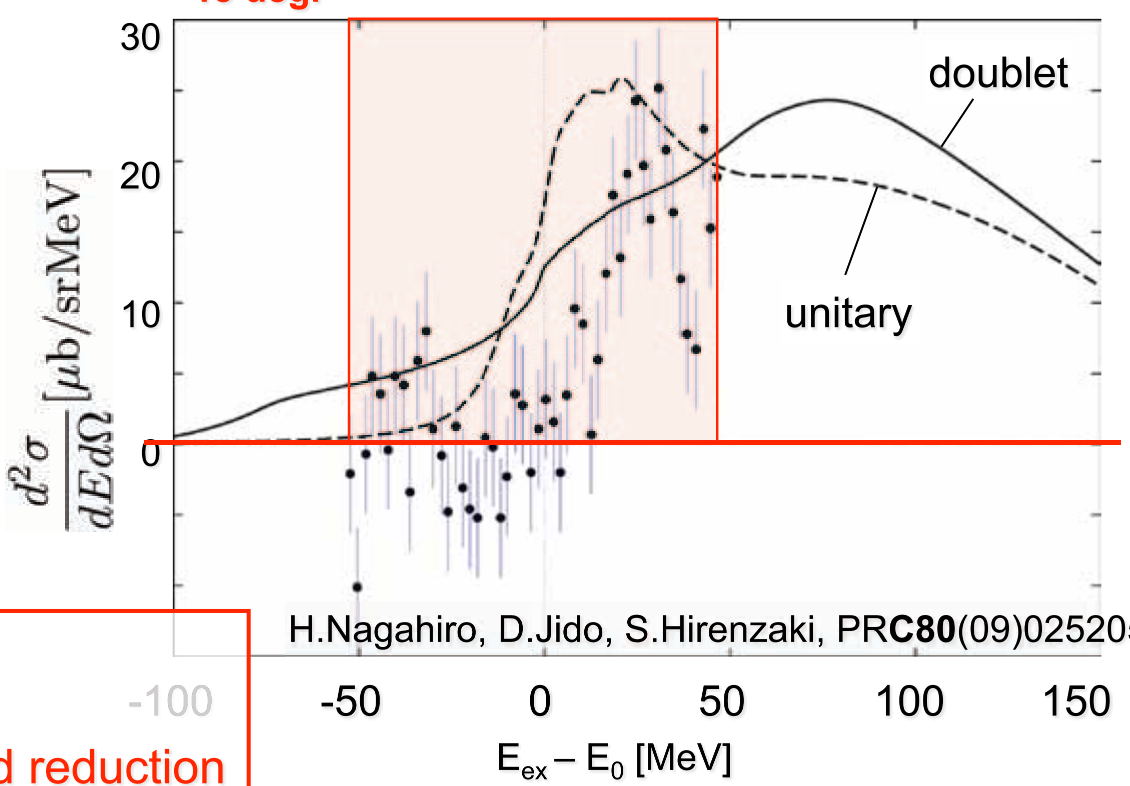
- Chrien et al., PRL60(1988)2595
  - » p_π = 800 MeV/c : proton angle : **15 deg. (Lab.)**
  - » search for predicted narrow bound state by Liu, Haider, PRC34(86)1845

→ negative results (bound state peak was not observed)

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



15 deg.

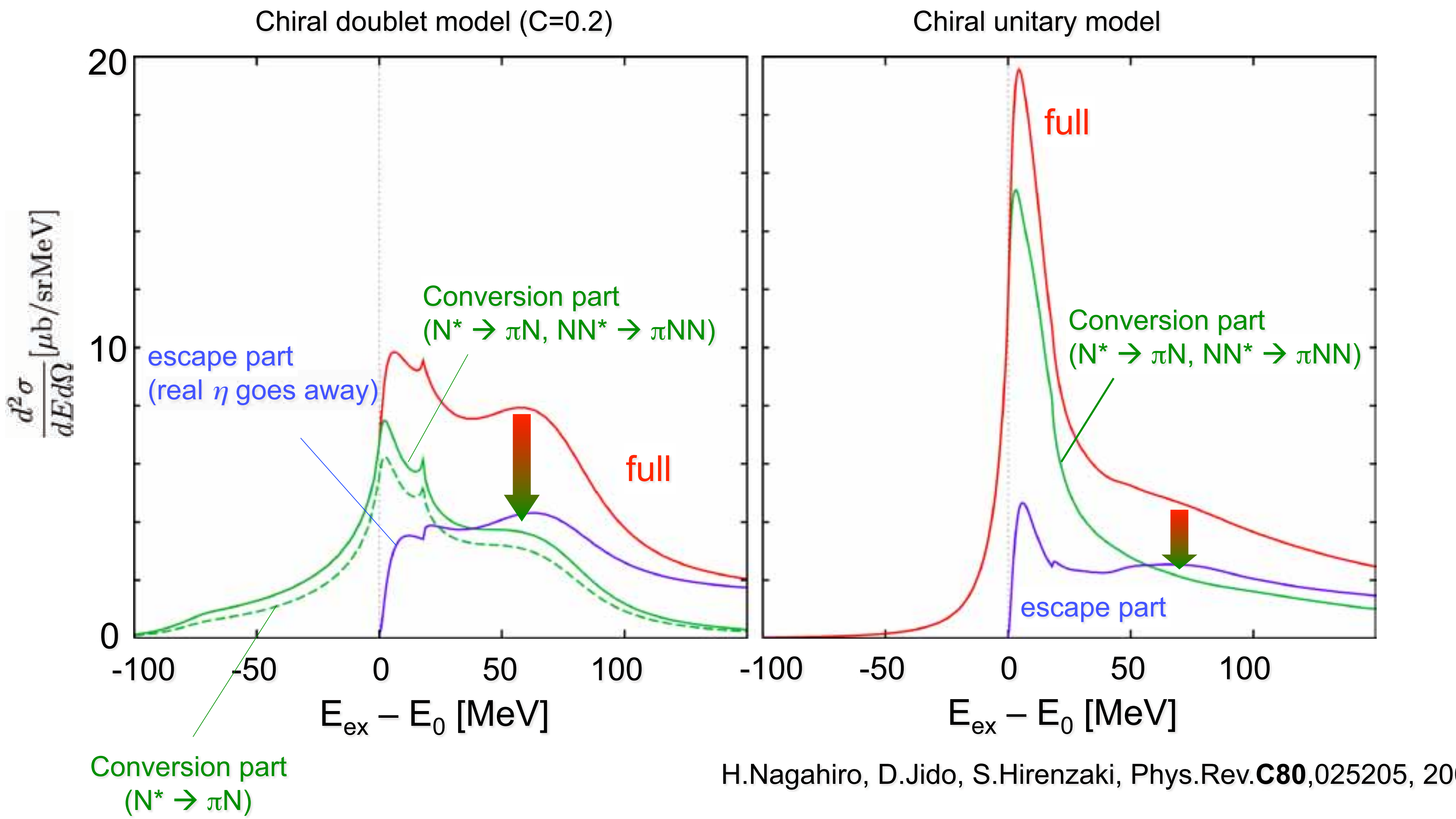


H.Nagahiro, D.Jido, S.Hirenzaki, PR**C80**(09)025205

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

effect on “the signal” by coincidence measurement

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



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

future work : estimation of absolute value of background

η'(958) in Nuclei

H.Nagahiro, S.Hirenzaki, Phys.Rev.Lett.94 (2005)232503
H.Nagahiro, M.Takizawa, S.Hirenzaki, Phys.Rev.C74 (2006)045203
D. Jido, H. Nagahiro, S. Hirenzaki, Phys.Rev.C 85, 032201 (R) (2012)
H. Nagahiro, S. Hirenzaki, E. Oset, A. Ramos, Phys. Lett. B 709 (2012) 87-92

K. Itahashi, H. Fujioka, H. Geissel, R. S. Hayano, S Hirenzaki, S. Itoh, D. Jido, V. Metag, H. Nagahiro, M. Nanova, T. Nishi, K. Okochi, H. Outa, K. Suzuki, Y. K. Tanaka, H. Weick, Prog. Theor. Phys. 128 (2012) 601-613.

H. Nagahiro, D. Jido, H. Fujioka, K. Itahashi, S. Hirenzaki,
Phys. Rev. C 87, 045201 (2013).

PRiME

Introduction

- 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' at $\rho \neq 0$**
  - » 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

Our motivation & present work

- a poor experimental information on the $U_A(1)$ anomaly at finite density

- η'(958)-mesic Nucleus formation reaction
  - $U_A(1)$ anomaly in medium
  - η, η' **mass shift** observation

  ⟹ new information on the properties of $U_A(1)$ anomaly ?

- We consider …
  - NJL Lagrangian + KMT term
  - η' spectra
  - η and η' in the same framework cf. chiral doublet, chiral unitary models.
  - η and η' mesic nuclei formation cross section

Model for η and η' meson in medium

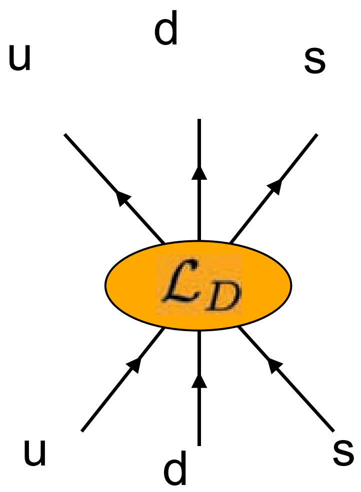
- **Nambu-Jona-Lasinio model** with the **KMT interaction**
  - » unified treatment of the η and η' meson

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

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

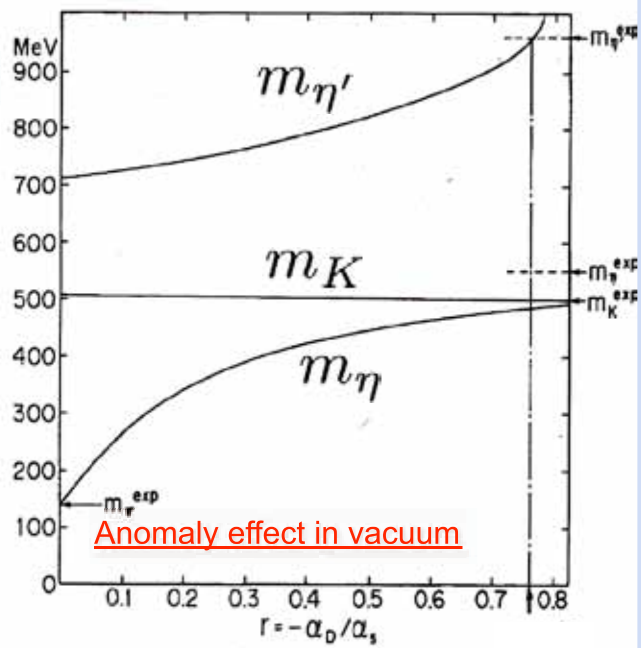
explicit breaking the $U_A(1)$ sym.

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



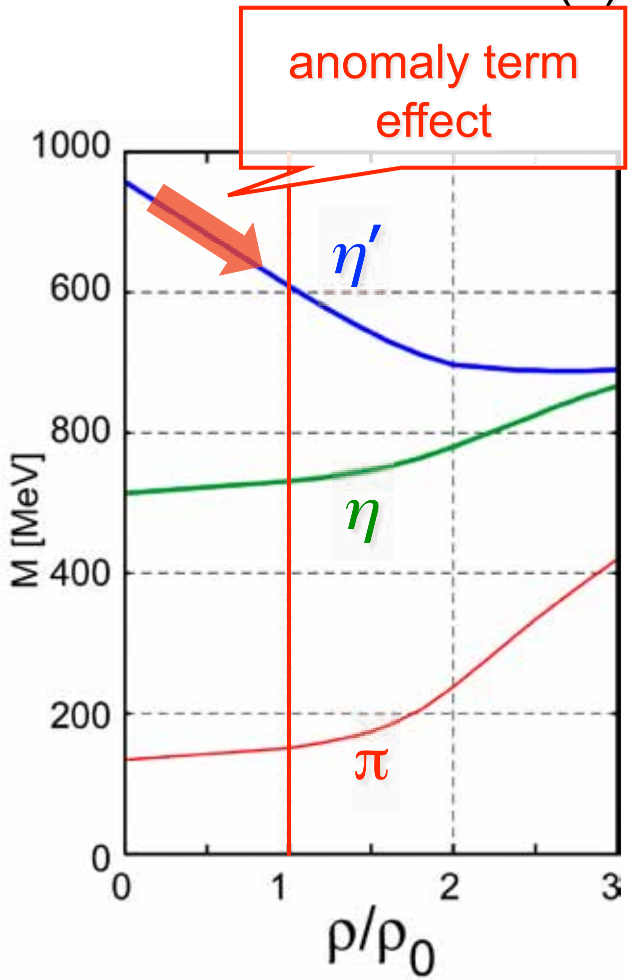
One can reproduce the heavy η' mass

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]

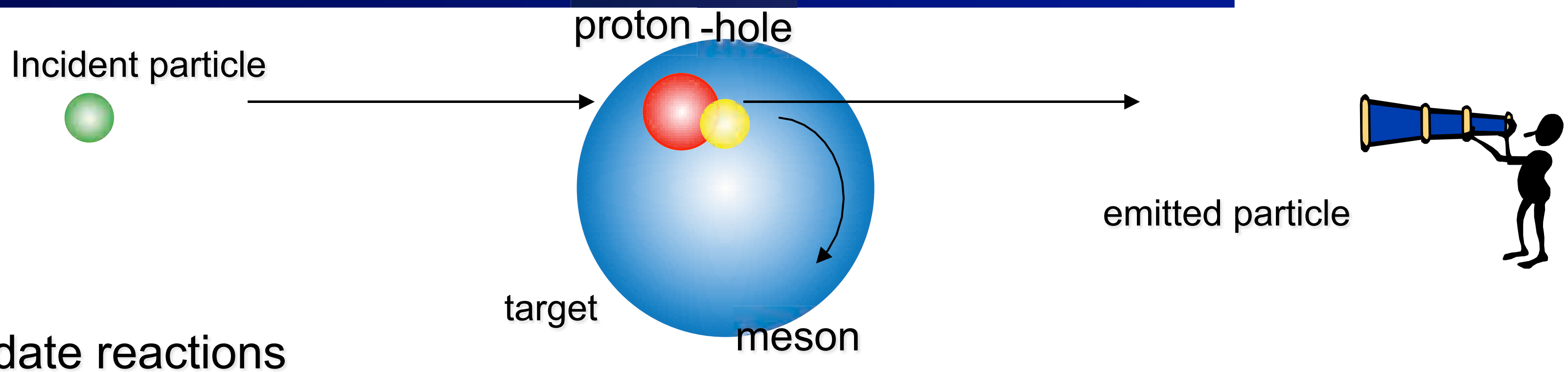
η and η' mass shifts @ ρ_0

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

$\Delta m_{\eta} \sim +20$ MeV @ ρ_0

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

Missing mass spectroscopy / reaction parameters



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'

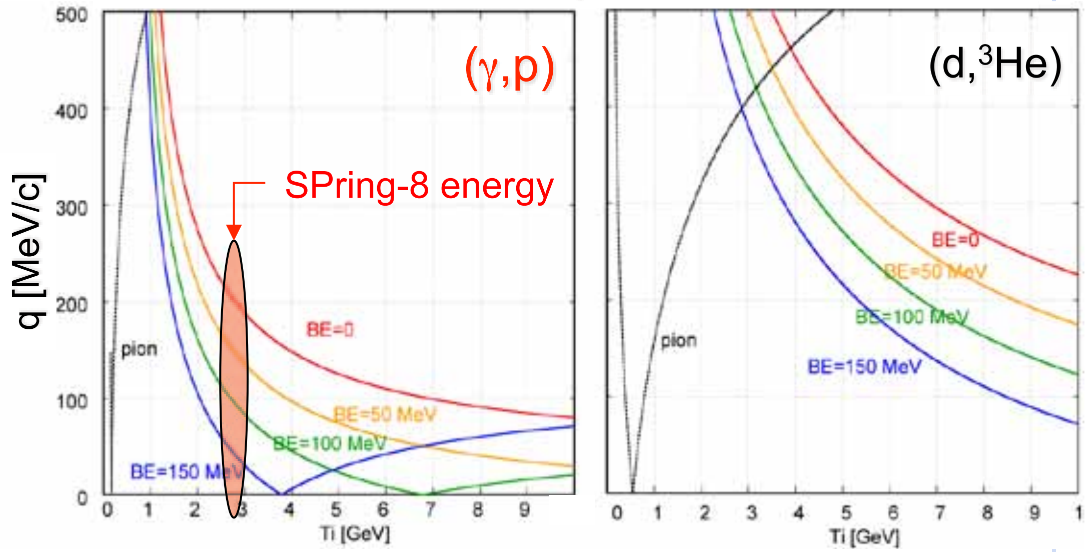
Reaction parameters

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

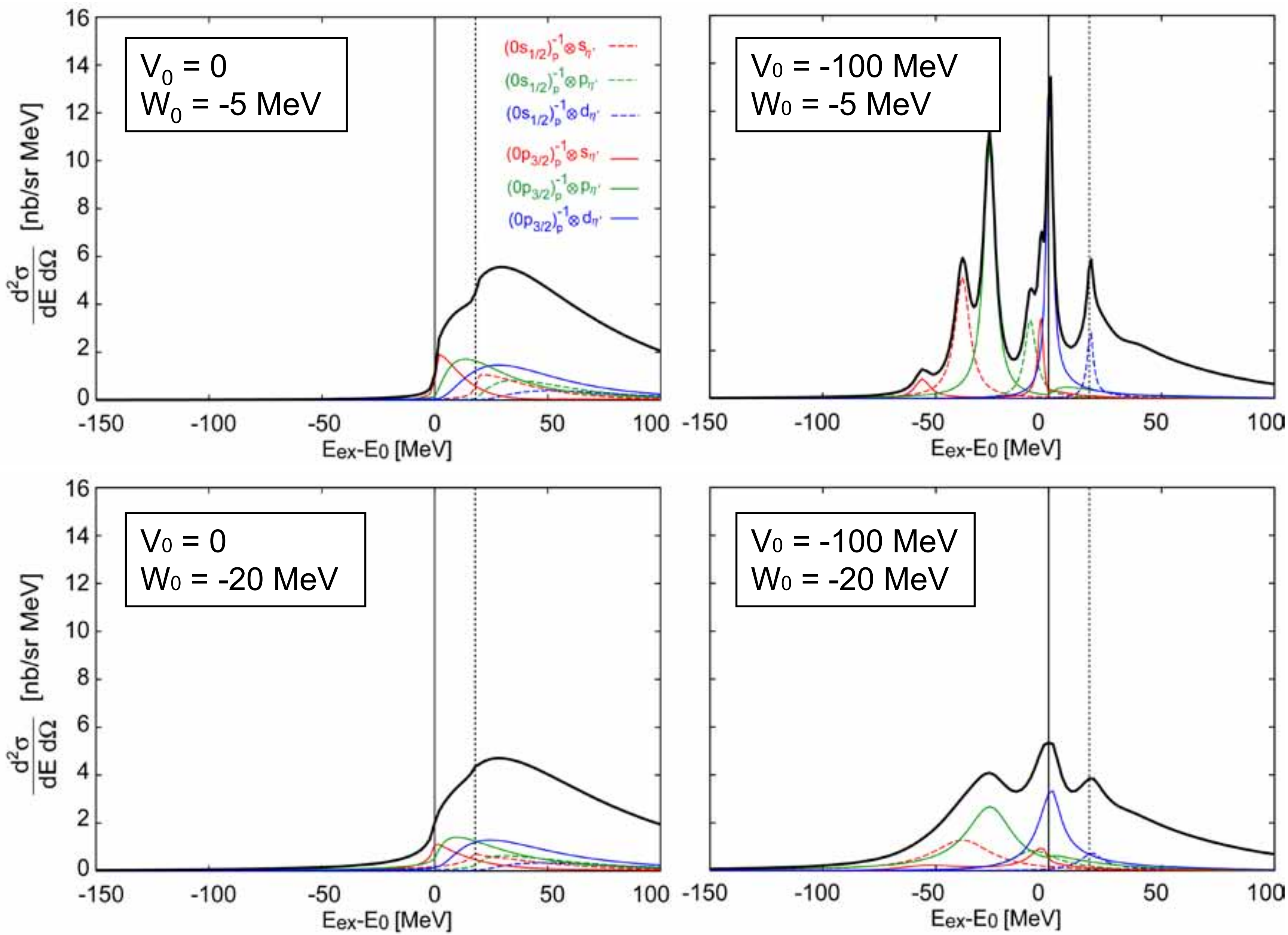
$$\left(\frac{d\sigma}{d\Omega}\right)^{Lab}_{0^\circ} \sim 150\ \mathrm{nb/sr}$$

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

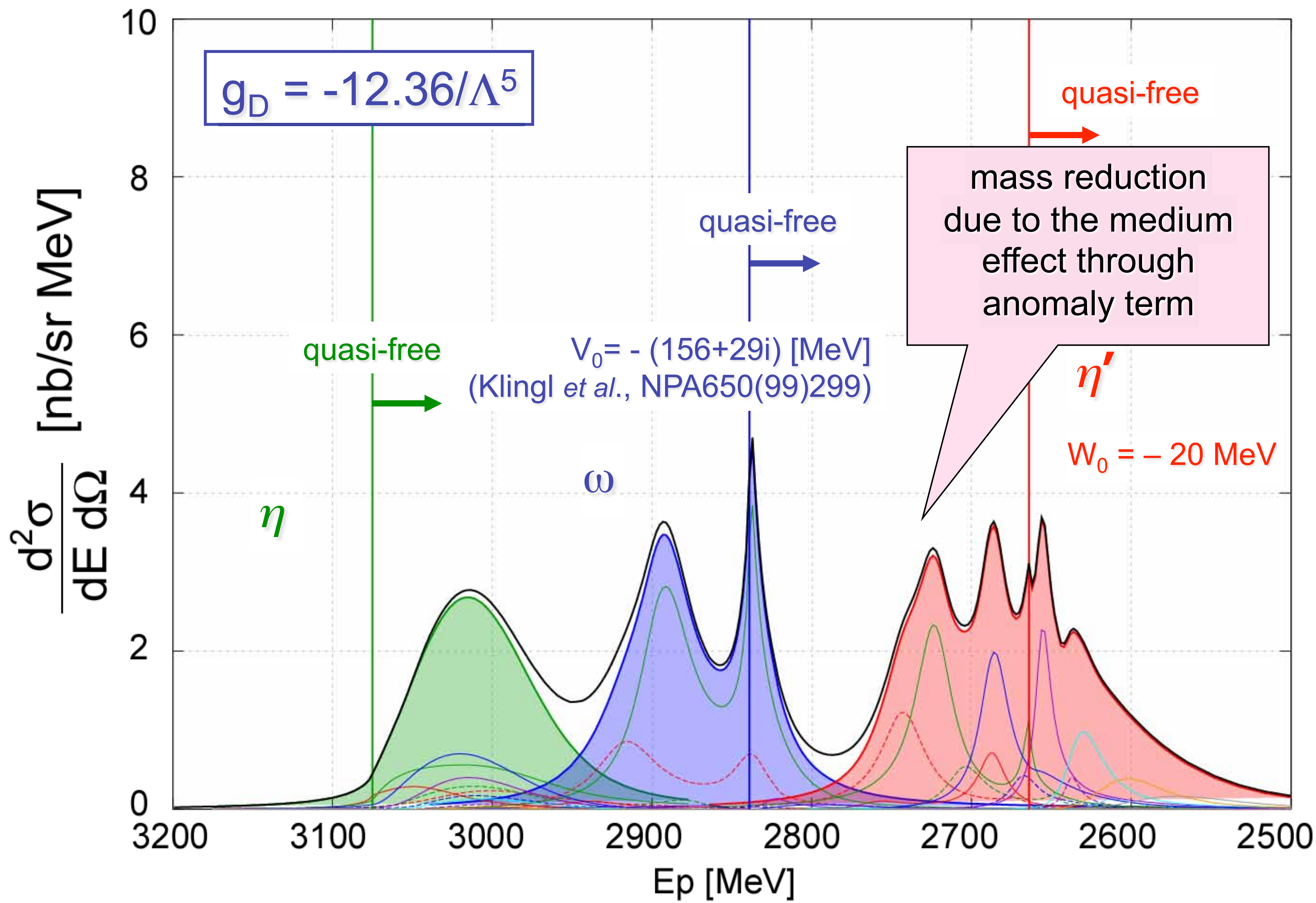
Momentum transfers for η'-mesic nuclei formation



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



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



ここまでの Summary

- $U_A(1)$ anomaly effect in finite density
  through the view point of **"mesic nuclei"**
  - possibility of observation of anomaly effects in-medium
  - η and η' mesic nuclei with NJL model
  - response to the environment change

- (γ,p) reaction for the mesic nuclei formation
  - Reasonably large cross sections predicted
    - S/N ~ 1/10 … N.Muramatsu, private communication
    - the experiment for the formation of ω-mesic nuclei
      @ SPring-8 ?
      - Information on η'-mesic nuclei also can be expected
- (pi, N) experiment for η mesic nuclei formation @ JPARC–by H. Nagahiro, recently
- Future
  - density dependence of g_D ?
  - Other treatment ? – beyond the NJL model
  - relation with other models for η & η'
    - chiral doublet model & chiral unitary approach for the η-mesic nuclei

2010年位から議論がまた盛んになって来た。。

Daisuke Jido, Hideko Nagahiro, Satoru Hirenzaki
‘Nuclear bound state of eta'(958) and partial restoration of chiral symmetry in the eta' mass’
arXiv:1109.0394, nucl-th

- 1. Some additional Remarks for Motivation
- 2. Current Status
- 3. Summary

『Meson Mass Reduction』

1, Mass reduction will be equivalent to attractive V in Eq. of Motion..

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

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

2, But " Attractive ➔ Mass reduction " is wrong. Ex.) Coulomb case.
Origin of the attraction is important.

$$p^2 + (m - \Delta m)^2 = (E + V)^2$$

$$\Rightarrow M_{\text{inv}}^2 = E^2 - p^2 \sim m^2 \left(1 - \frac{2}{m}(\Delta m + V)\right)$$

Invariant mass data ONLY at small kinetic energy

3, Thus, "exclusive" and/or "systematic" are important !
==> Bound state spectroscopies
(Quantum number selection rules, No vacuum background)

『η(958) Bound State』

3, Thus, “exclusive” and/or “systematic” are important !
==> Bound state spectroscopies
(Quantum number selection rules, No vacuum background)

4, For Bound State observation as peaks, however,

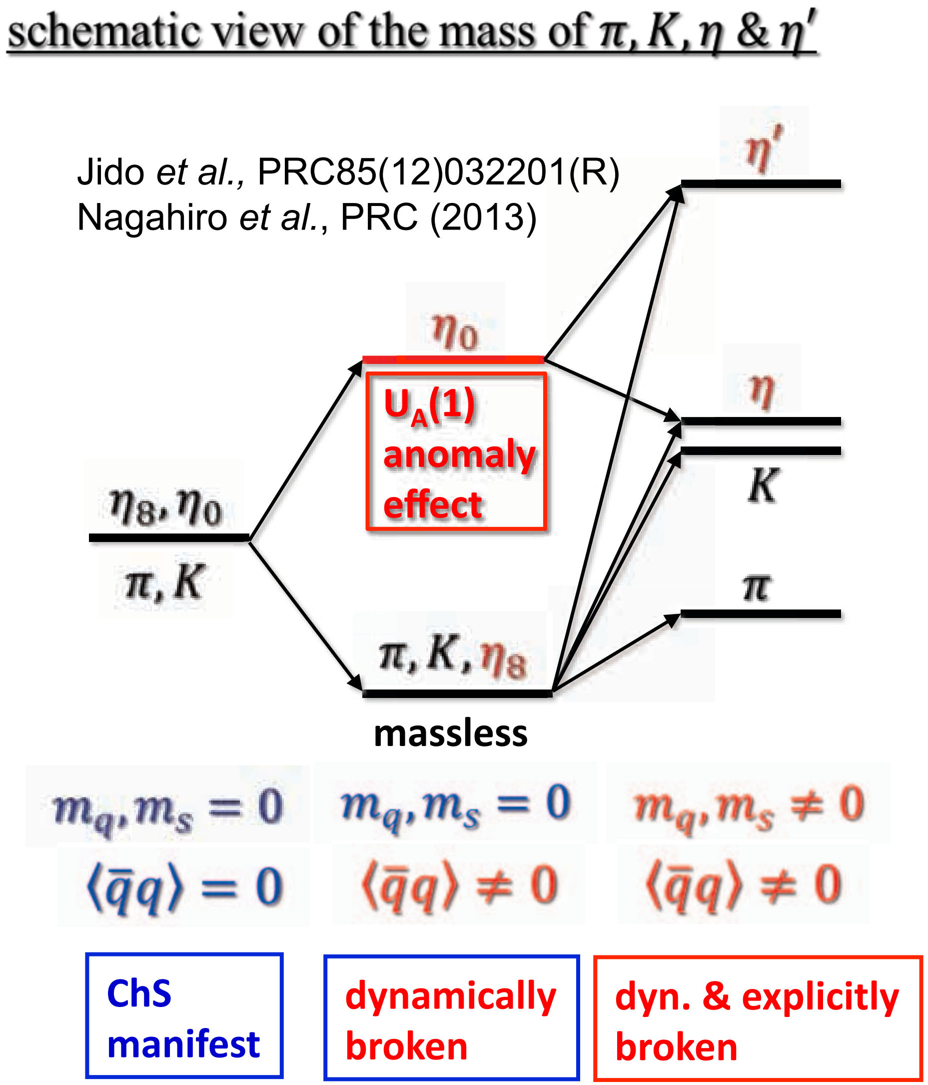
<u>ReV>ImV</u>

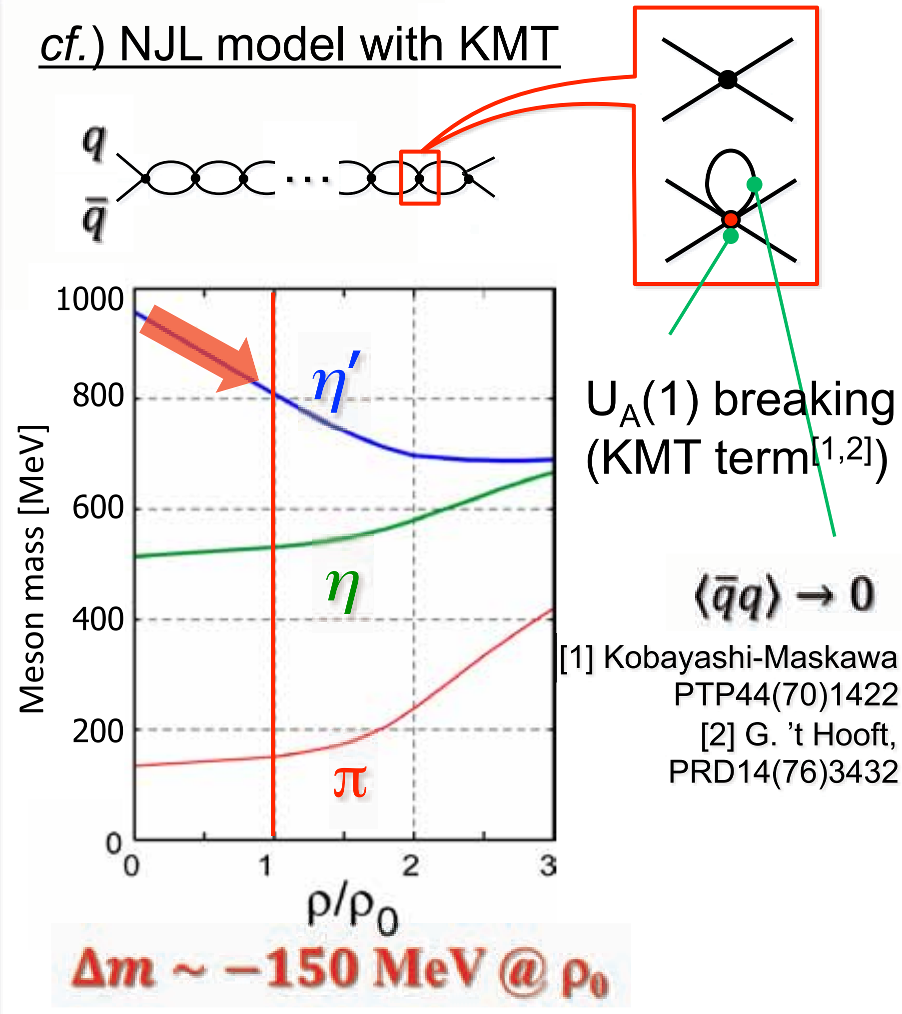
is important.

5, And <u>“clear (dominant) origin”</u> is important to deduce something.

6, η(958) seems interesting, in these senses.

Heavy mass of the η'(958) meson





Costa *et al.*,PLB560(03)171,
Nagahiro-Takizawa-Hirenzaki, PRC74(06)045203

Reported DATA

1. CBELSA/TAPS (transparency)
   by M. Nanova et al., Phys. Lett. B (2012), Prog. Part. Nucl. Phys. (2012)
   Γ (ρ_0, $\langle \vec{p}_{\eta'} \rangle \sim 1.05$ GeV/c) ~ 15 – 25 MeV (No string p-dependence)
   (Reasonally smaller than theoretically expected $\Delta m_{\eta'}$)

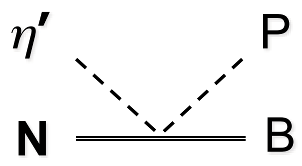
2 (1) COSY (final state interaction)
   by P. Moskal *et al*., Phys. Lett. B 482 (2000) 356.
   ABS($a_{\eta' p}$)~ 0.1 fm (V(ρ_0) ~ 10 MeV), sign is not known

2 (2) COSY (final state interaction)
   by P. Moskal *et al*., Phys. Lett. B 474 (2000) 416.
   ABS(RE ($a_{\eta' p}$))＜0.8 fm, sign is not known

3. RHIC: PHENIX/STAR (Low energy pion)
   by T. Csorgo *et al*., Phys. Rev. Lett. 105 (2010) 182301.
   $\Delta m_{\eta'}$ ~ 200 MeV (Roughly Consistent to NJL, but at different T)

η'N interaction : Chiral Unitary model : Oset-Ramos, PLB704(11)334

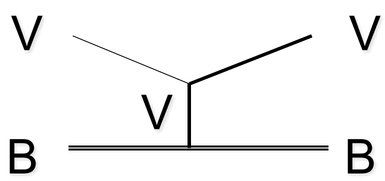
η'N → η'N, πN, ηN, KΛ, KΣ (PB) Weinberg-Tomozawa + **η -η' mixing**

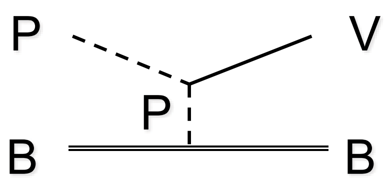


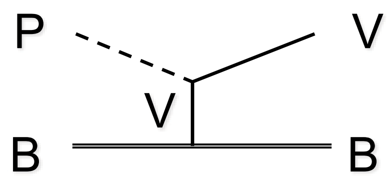
→ | $a_{\eta' N}$ | = 0.01 fm

cf. | $a_{\eta' N}$ | ~ **0.1** – 0.8 fm [Moscal:PLB'00]

η'N → vector-baryon (VB)

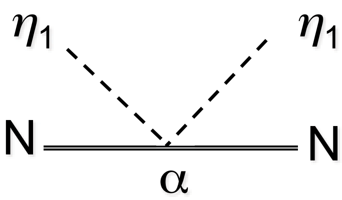






→ | $a_{\eta' N}$ | = 0.03 fm

η_1N → η_1N : singlet component – contribution to ELASTIC channel



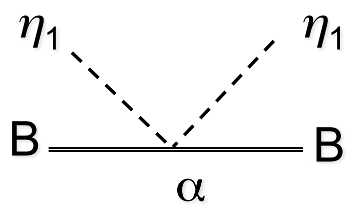
$$\mathcal{L}_{\eta_1 B} \propto \eta_1^2 \langle \partial_\mu \bar{B} \gamma^\mu B - \bar{B} \gamma^\mu \partial_\mu B \rangle$$

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

α … free parameter

→ | $a_{\eta' N}$ | = 0.1 fm

Calculated $V_{\eta'}^{opt}$ Nagahiro, Hirenzaki, Oset, Ramos, PLB709(2012)87



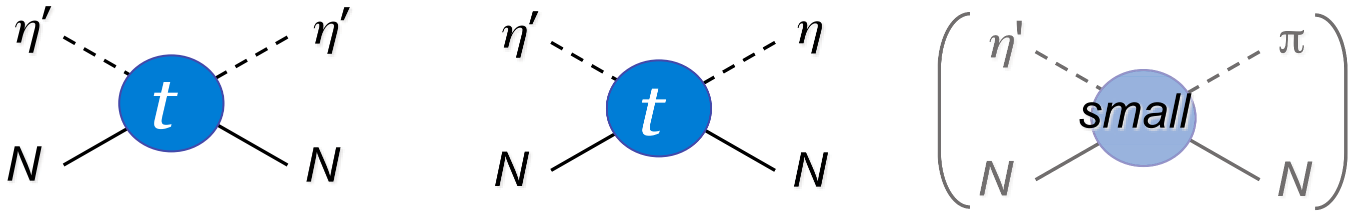
η' mainly contibutes to elastic channel,
not to inelastic channel

~ the anomaly effect [D.Jido, H.Nagahiro, S.Hirenzaki, PRC85(12)]

α Only free parameter in this model.

Inputs for V_{opt}

[Oset-Ramos:PLB704(11)]



$\lvert a_{\eta' N} \rvert$ [fm]	α	$t_{\eta' N \to \eta' N}$	$t_{\eta' N \to \eta N}$
0.1	–0.193	**–1.26 – 0.25*i***	–0.015 + 0.67*i*
0.3	–0.834	**–3.85 – 0.31*i***	–0.2 + 0.7*i*
0.5	–1.79	**–6.43 – 0.43*i***	–0.39+ 0.72*i*
1.0	–9.67	**–12.9 – 1.01*i***	–0.85+ 0.77*i*

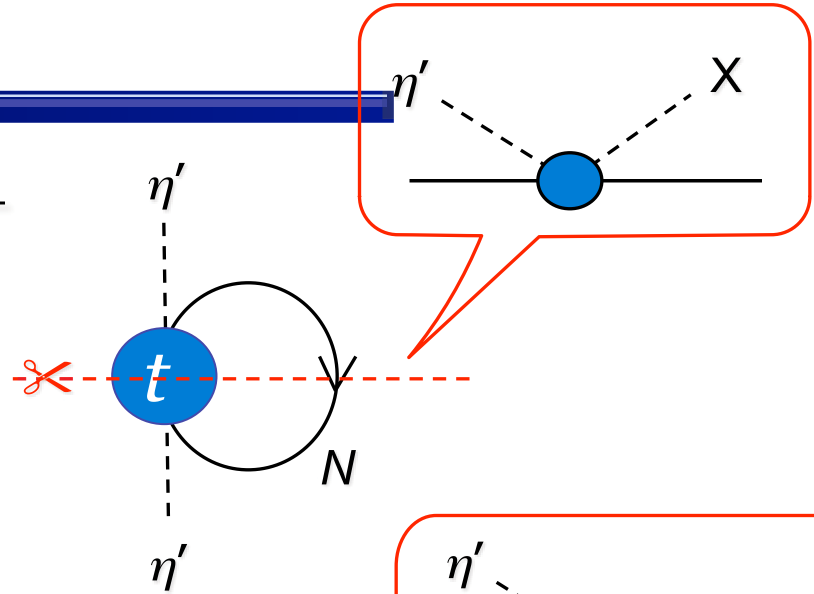
[10^{-2} MeV^{-1}]
@ threshold

Attractive sign is assumed. (No exp. Info. on sign)

Our calculation for $V^{opt}_{\eta' N}$

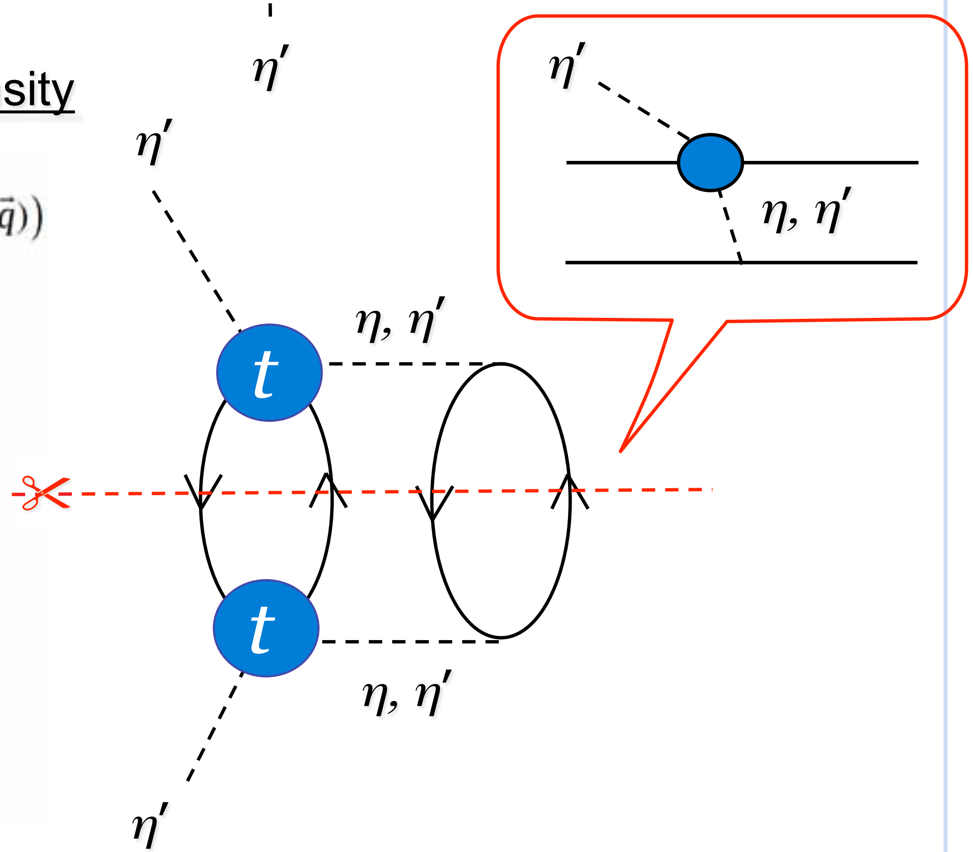
<u>optical potential V_{opt} : Lowest order in desnity</u>

$$V^{1st}_{opt} = \frac{\Pi^{1st}}{2\omega_{\eta'}} = \frac{t\rho}{2\omega_{\eta'}}$$



<u>optical potential V_{opt} : Second oder in density</u>

$$\begin{aligned}
-i\Pi^{2nd}(p_{\eta'}) = &- \sum_{x,x'=\eta,\eta'} \int \frac{d^4q}{(2\pi)^4} \rho^2 \left(\frac{M}{E(\vec{q})}\right)^2 (1-n(\vec{q})) \\
&\times t_{\eta' N \to xN} t_{x'N \to \eta' N} V_x V_{x'} q^2 \\
&\times \frac{1}{p^0_{\eta'} - q^0 + E_F - E(\vec{q}) + i\epsilon} \\
&\times \left[\frac{1}{q^0 + E_F - E(\vec{q}) + i\epsilon} + \frac{1}{-q^0 + E_F - E(\vec{q}) + i\epsilon}\right] \\
&\times \frac{1}{q^2 - m_x^2 + i\epsilon} \frac{1}{q^2 - m_{x'}^2 + i\epsilon},
\end{aligned}$$



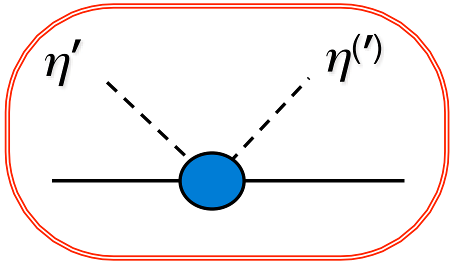
Numerical result : potential depth

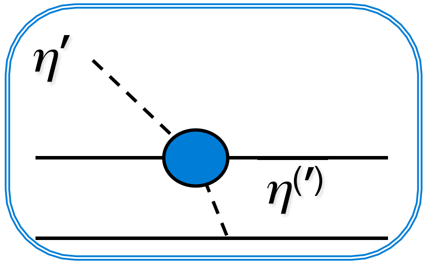
in unit of MeV

$\lvert a_{\eta' N} \rvert$ [fm]	Potential depth at $\rho = \rho_0$		
	$V_{\mathrm{opt}}^{\mathrm{1st}}$ +	$V_{\mathrm{opt}}^{\mathrm{2nd}}$ =	$V_{\mathrm{opt}}^{\mathrm{total}}$
0.1	(□8.6□1.7*i*)	(□0.1□0.1*i*)	(□8.7□1.8*i*)
0.3	(□2	9*i*)	(□26.8□3.0*i*)
0.5	(□43.8□3.0*i*)	(□1.3□2.5*i*)	(□44.1□5.5*i*)
1	(□87.7□6.9*i*)	(□4.1□10.4*i*)	(□91.8□17.2*i*)

~ COSY

$\mathrm{Re}V \gg \mathrm{Im}V$





Γ ~ 15-25 MeV
~ TAPS transparency ratio

- η'(958) mesic nuclei formation

- (p,d) reaction

（γ induced reaction:

H.Nagahiro, S.Hirenzaki, Phys.Rev.Lett.94 (2005)232503)

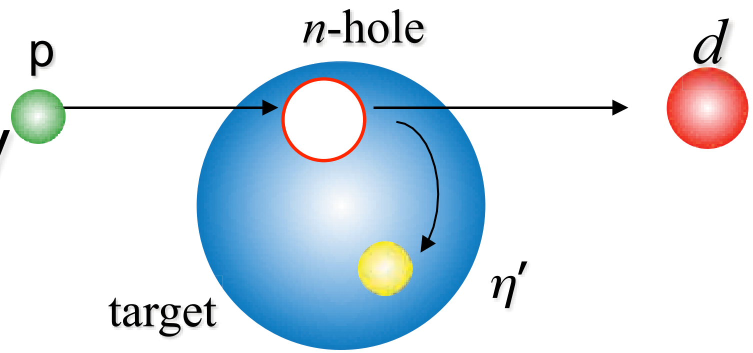
$\eta'(958)$ mesic nuclei formation by (p,d) reaction

K. Itahashi et al., Prog. Theor. Phys. 128 (2012) 601-613.
H. Nagahiro, et al., Phys. Rev. C 87, 045201 (2013).

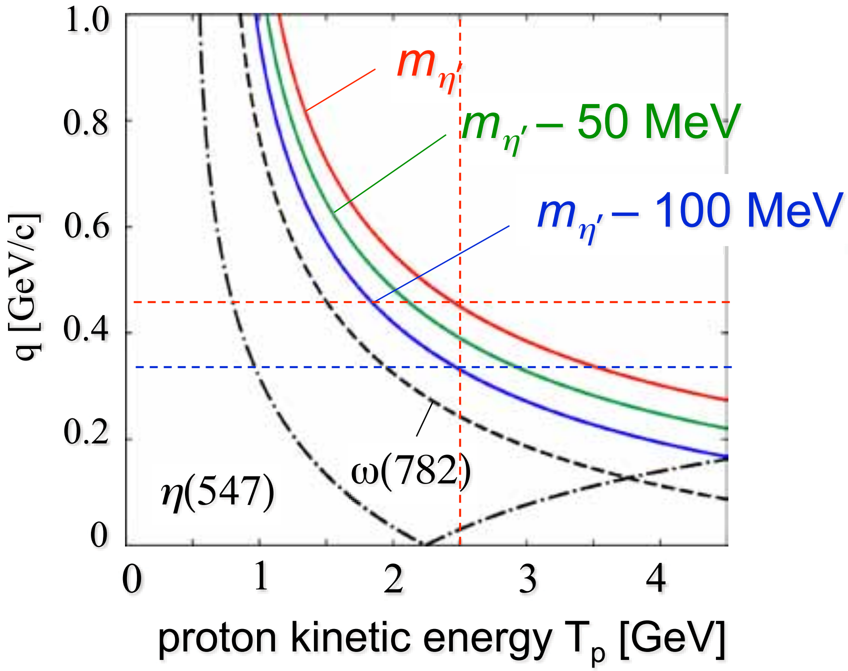
proton kinetic energy T_p=2.5GeV

target : ^{12}C

forward reaction : θ_d = 0 deg.



momentum transfer



elementary cross section pn →$d\eta'$

no experimental information

$\sigma_{pp\to pp\eta'}$ ~ 0.2μb @ T_p = 2.5 GeV

J.Klaja *et al.*, PRC81(10)035209 (COSY)

Assumption1 : Same ratio as η production

$$\frac{\sigma(pn\to d\eta')}{\sigma(pp\to pp\eta')} \sim \frac{\sigma(pn\to d\eta)}{\sigma(pp\to pp\eta)} \sim 10$$

CELSIUS/WASA, PRL70(97)2642

Assumption2 : Flat distribution in CM

$$\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{Lab.}}_{pn\to d\eta'} \sim 30\ \mu\mathrm{b/sr}$$

η'(958) mesic nuclei formation by (p,d) reaction

optical potentials

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

Various combination within the range of
V_0 = 0 ~ –150 MeV, W_0= –5 ~ –20 MeV

Γ	W_0 \ V_0	–150	–100	–50	0
10	–5	✓	✓	✓	
20	–10	✓	✓	✓	
30	–15	✓	✓	✓	
40	–20	✓	✓	✓	✓

in unit of MeV

cf.) coupled-channel
$|a_{\eta' N}|$=0.5-1.0 fm
case

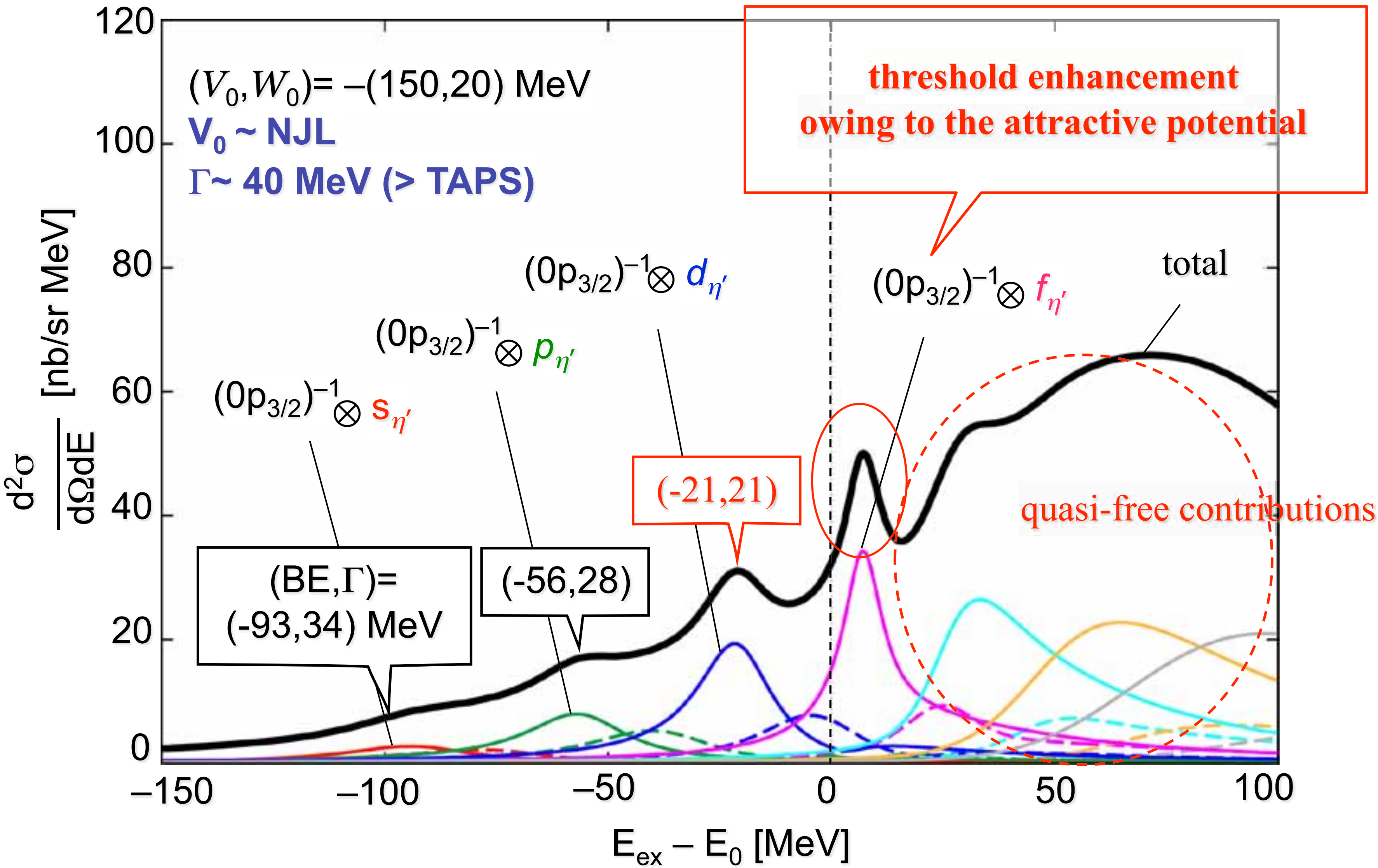
cf.)
$\Gamma_{\eta'}$ ~ 15-25 MeV @ ρ_0
CBELSA/TAPS
M. Nanova *et al.*, PLB

cf.) NJL with KMT

$\Delta m_{\eta'}$ ~ –150 MeV @ ρ_0

Numerical results : –(150, 20) MeV : $^{12}C(p,d)^{11}C_{\eta'}$

Green's function method [Morimatsu-Yazaki, NPA435(85)727]



Summary

Clear origin of mass shift is very important.

- η'(958) seems Special.
  - » Clear Origin of Mass Reduction by $\langle \bar{q}q \rangle$ change with help of $U_A(1)$
  - » Re V ~ Δm >> ImV, thanks to $U_A(1)$
- Narrow Peak expected for η' Mesic Nuclei Formation, Missing mass spectra.
- Consistency with the scattering length data ?

Vector mesons

Naruki, M., *et al.* (KEK-PS E325 Collaboration), 2006, Phys. Rev. Lett. 96, 092301.

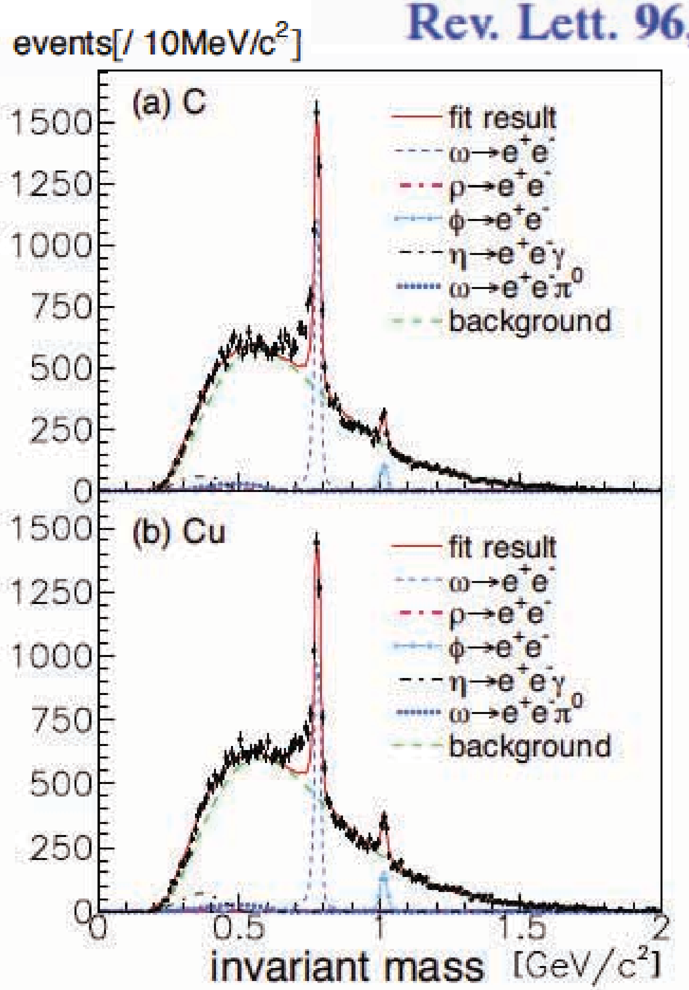


FIG. 53. (Color online) Invariant-mass spectra of e^+e^- for the (a) C and (b) Cu targets. The solid lines are the best-fit results, which is the sum of the known hadronic decays, $\omega \to e^+e^-$ (dashed line), $\phi \to e^+e^-$ (thick dash-dotted line), $\eta \to e^+e^-\gamma$ (dash-dotted line), and $\omega \to e^+e^-\pi^0$ (dotted line) together with the combinatorial background (long-dashed line). $\rho \to e^+e^-$ is not visible (Naruki *et al.*, 2006).

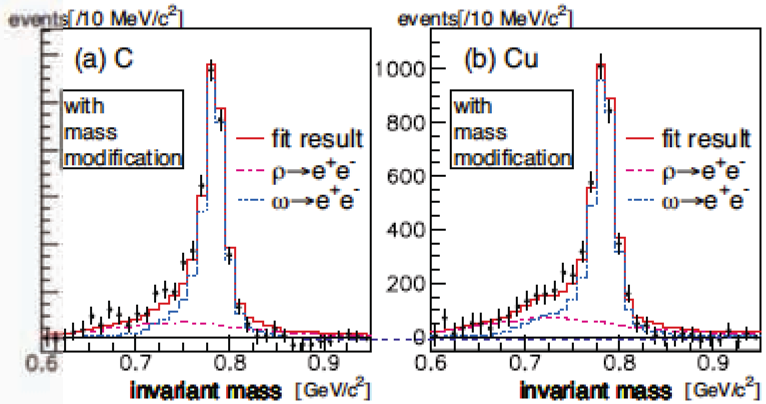
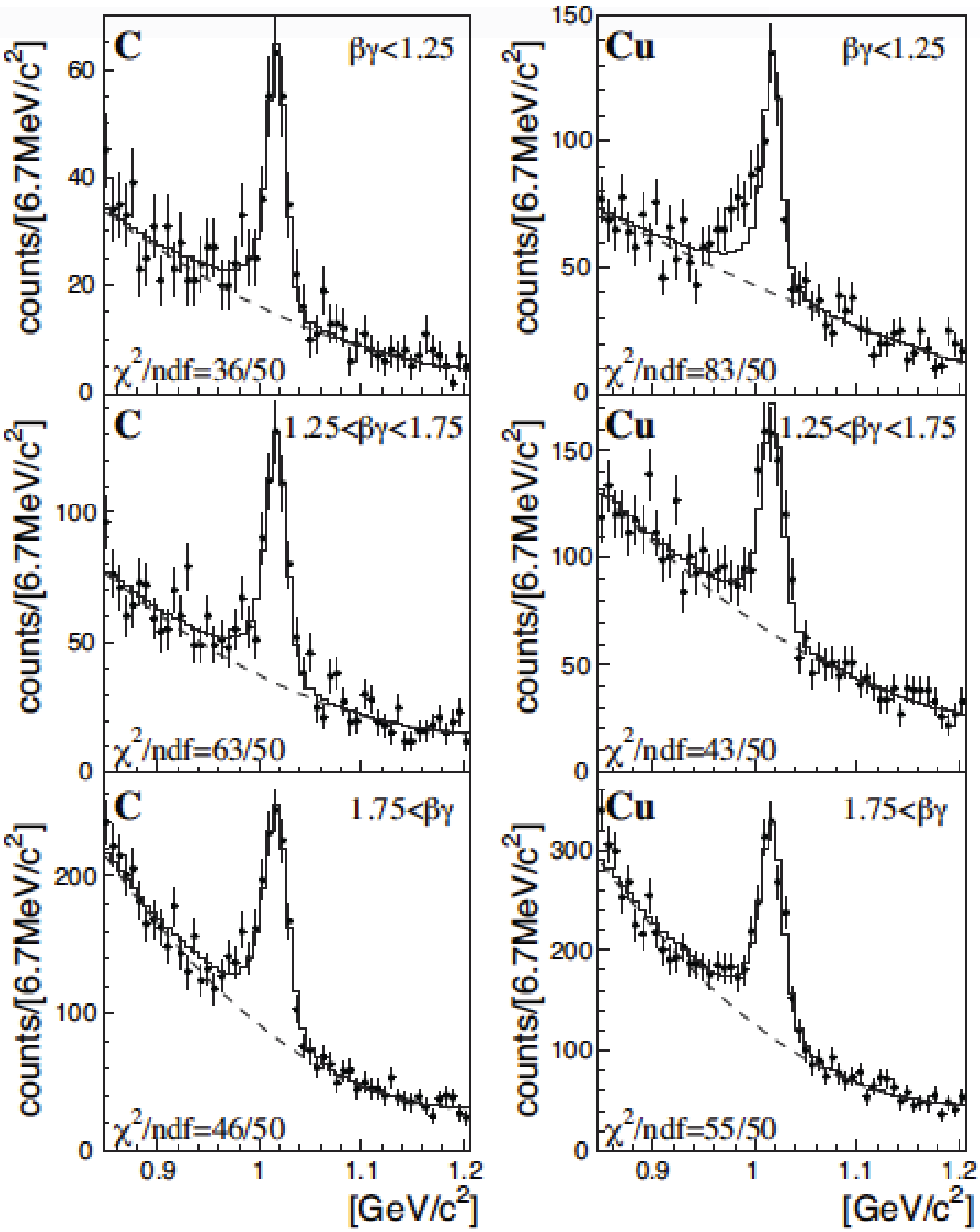


FIG. 54. (Color online) Invariant-mass spectra of e^+e^-. The combinatorial background and the shapes of $\eta \to e^+e^-\gamma$ and $\omega \to e^+e^-\pi^0$ were subtracted. The result of the model calculation considering the in-medium modification for the (a) C and (b) Cu targets. The solid lines show the best-fit results. In (a) and (b), the shapes of $\omega \to e^+e^-$ (dotted line) and $\omega \to e^+e^-$ (dash-dotted line) were modified according to the model using the formula $m_V(\rho)/m_V(0) = 1 - k(\rho/\rho_0)$ with $k = 0.092$ (Naruki *et al.*, 2006).

ρ、ω の interfer は悩ましそう

Muto, R., *et al.* (KEK-PS E325 Collaboration), 2007, Phys. Rev. Lett. 98, 042501.



Φ は isolate したpeak として見える。これはいい点。

ただし寿命が長過ぎ。ほとんど外に出てしまう。遅いの (low p)だけを選択すれば Systematic な情報にならないか。。

FIG. 55. Obtained e^+e^- distributions with the fit results. The target and $\beta\gamma$ region are shown in each panel. The points with error bars represent the data. The solid lines represent the fit results with an expected $\phi \rightarrow e^+e^-$ shape and a quadratic background. The dashed lines represent the background (Muto *et al.*, 2007).

Vector Meson Mass Shift by Invariant mass

Ryugo S. Hayano and Tetsuo Hatsuda: Hadron properties in the nuclear medium

TABLE IV. Compilation of experimental results on the in-medium mass and width of the ρ, ω, and ϕ mesons produced with elementary reactions, measured in different experiments. This is based on updating the table prepared by Metag (2008a).

	Invariant mass			Attenuation	
	E325 @ KEK	CLAS-g7 @ JLab	CBELSA/TAPS		LEPS @ SPring-8
Reaction	pA 12 GeV	γA 0.6–3.8 GeV	γA 0.7–2.5 GeV		γA 1.5–2.5 GeV
Momentum	$p>0.5$ GeV/c	$p>0.8$ GeVc	$p<0.5$ GeV/c	$0.4<p<1.7$ GeV/c	$1.1<p<2.2$ GeV/c
ρ	↑ $\Delta m(\rho_0)/m=-9\%$	$\Delta m\approx 0$ Some broadening			
ω	↓ No broadening		$\Delta m(\rho_0)/m=-14\%$[a]	$\Gamma_\omega(\rho_0)=130$–$150$ MeV/c^2 $\rightarrow\sigma_{\omega N}\approx 70$ mb	
ϕ	$\Delta m(\rho_0)/m=-3.4\%$ $\Gamma_\phi(\rho_0)\approx 15$ MeV/c^2				$\sigma_{\phi N}=35$ mb $\rightarrow\Gamma_\phi(\rho_0)\approx 80$ MeV/c^2

[a]This may change as a result of the ongoing reanalysis (Metag, 2008b).

明らかに、Data は収束していない。この表だけみると酷い印象。

- 先ほどのTable のような状況ではなかなか難しい。でもTable から初めに素人（私）が受けた印象程ひどいわけではない。
- まずは高精度高統計の実験でデータとしての決定版をJPARC で出してもらうのは必須（Background のさっ引きも）
- ρ, ω の正確な分離は可能か。。。？
- E16 で期待される様な Φ の Momentum dependence の観測も重要 (Systematic info. として)

さて何が面白そうか？

- Φの山が分離して『2山』になる➔mass shift の観測・決着
- Mass shift が小さかったら『1山』➔面白く無いのか？

- 核内Φを利用して
  『<N|sbar s|N>を実験的に決め』てほしい。
  (KEK東海での議論、Philipp 君、etc)

- 実験的にはΦのmass shift が小さかった時には『1山観測』で、
  どこまで<N|sbar s|N>の上限に制限を与えられるか要検討。

(『2山』みえた場合よりも解析は難しいでしょう。
➔JAM 等のシミュレーション手法で断面積を得る事が必要？)

- 幅の決定 (<=>LEPS) 精度。

<N|sbar s|N>重要性

（慈道さん、永廣さん）

- 核子の strange component がどれくらいか？

  ➔ハドロン物理にとって重要

- 核子に対する s quark の影響、本当に小さいのか？（核子の構造、sea quark）

- <N|qbar q|N> ： nuclear matter における基本的な量。種々の現象に関連するはず。（ex. KN sigma term => kaon condensation in neutron star）
- SU(2) <N|qbar q|N> の情報（ex. Pionic atom から ）と併せて、『flavor SU(3) の実験的情報が

  meson in medium から揃えられる』

  と言えないか？

- K. Griest 'Calculation of Rates for Direct Detection of Neutralino Dark Matter' PRL61, 666(1988). (Dark matter candidate のneutralino の観測の為の断面積計算）

Summary

- Lepton pair invariant mass による in-medium Vector meson property (KEK E325）
- 最新のQCD sum rule 解析紹介
- Φ の性質 (mass shift) からの <N|sbar s|N>の決定。
  期待。JPARC E16
- Secondary beam を利用した、Meson-Nucleus Spectroscopy（永廣、慈道、JPARC E26）