Exotic Hadrons in s-Wave Chiral Dynamics

 

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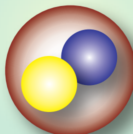
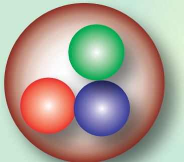
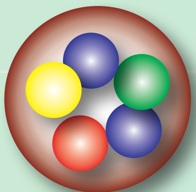
Motivation 1 : Exotic hadrons

Exotic hadrons : states other than $q\bar{q}$, qqq.

Experimentally, they are exotic.

PDG(2006) :

159 mesons  127 baryons 

1 pentaquark  with *

Theoretically, are they exotic?

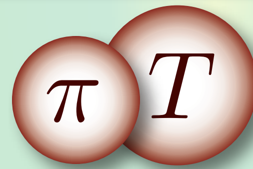
--> QCD does not forbid exotic states,

effective models neither.

We would like to study the existence of exotic hadrons

Motivation 2 : Chiral unitary approaches

Hadron excited states ~



- Interaction <-- chiral symmetry
- Amplitude <-- unitarity

R.H. Dalitz and S.F. Tuan, Ann. Phys. (N.Y.) 10, 307 (1960)
J.H.W. Wyld, Phys. Rev. 155, 1649 (1967)

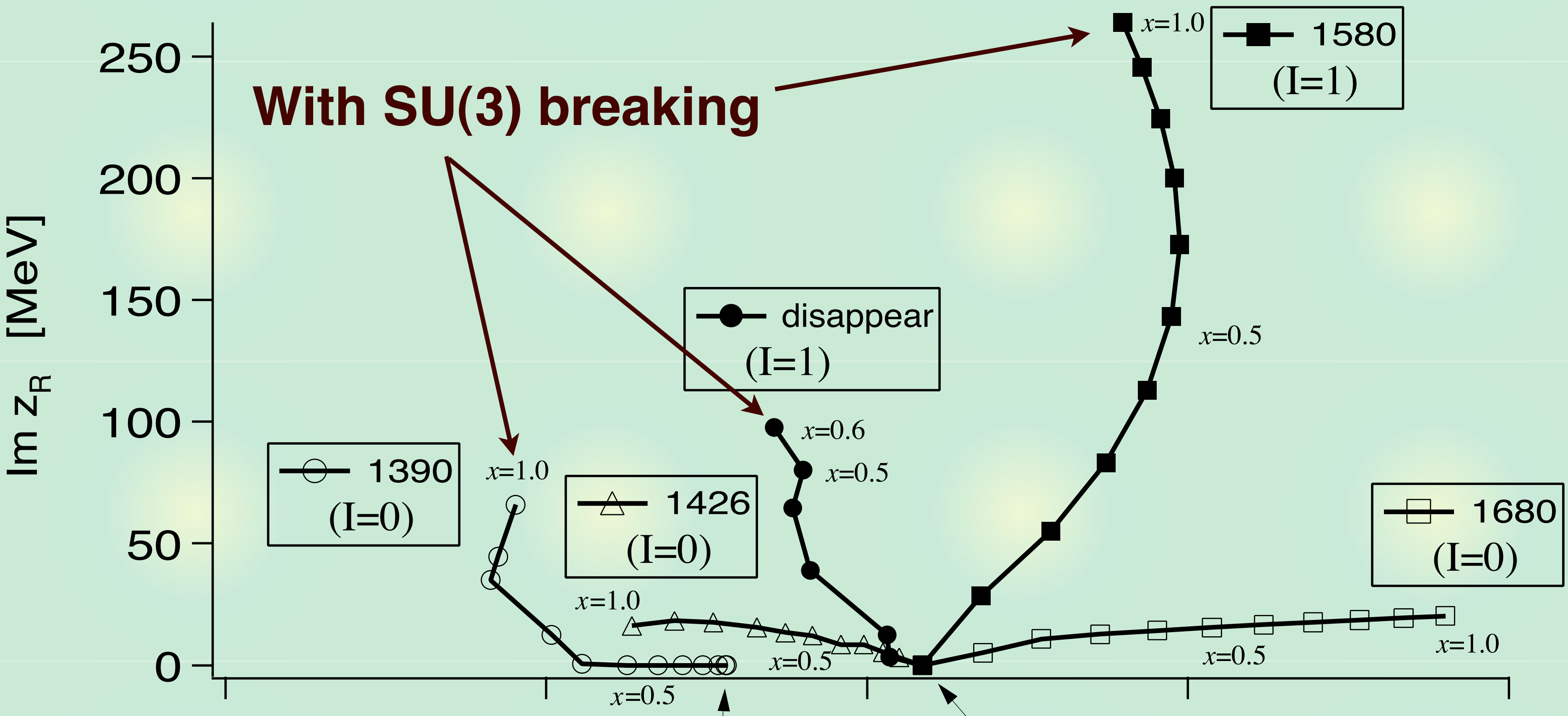
N. Kaiser, P. B. Siegel and W. Weise, Nucl. Phys. A594, 325 (1995)
E. Oset and A. Ramos, Nucl. Phys. A635, 99 (1998)
J. A. Oller and U. G. Meissner, Phys. Lett. B500, 263 (2001)
M.F.M. Lutz and E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002)

Many hadron resonances (Λ(1405), N(1535), Λ(1520), D_s(2317),...) are well described.

What about exotic hadrons?

Origin of the resonances

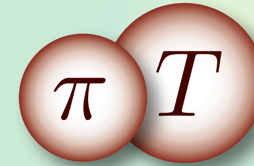
D. Jido, *et al.*, Nucl. Phys. A 723, 205 (2003)



--> Search for bound states in SU(3) symmetric limit.

Outline

Hadron-NG boson bound state



Chiral symmetry

s-wave low energy interaction

$$V_\alpha = -\frac{\omega}{2f^2} C_{\alpha,T} \qquad C_{\text{exotic}} = 1$$

Scattering theory

Critical strength for a bound state

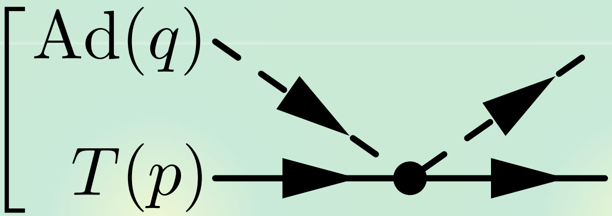
$$C_{\text{crit}} = \frac{2f^2}{m\big(-G(M_T+m)\big)}$$

physical values : $C_{\text{exotic}} < C_{\text{crit}}$

→ **No exotic state exists in SU(3) limit.**

Low energy s-wave interaction

Scattering of a target (T) with the pion (Ad)

α 

$$= \frac{1}{f^2}\frac{p\cdot q}{2M_T}\left\langle \boldsymbol{F}_T \cdot \boldsymbol{F}_{\mathrm{Ad}} \right\rangle_\alpha + \mathcal{O}\left((m/M_T)^2\right)$$

In s-wave,

$$V_\alpha = -\frac{\omega}{2f^2} C_{\alpha,T}$$

- ○ proportional to pion energy
- ○ pion decay constant (No LEC)

Y. Tomozawa, Nuovo Cim. 46A, 707 (1966)
S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

$$C_{\alpha,T} \equiv -\left\langle 2\boldsymbol{F}_T \cdot \boldsymbol{F}_{\mathrm{Ad}} \right\rangle_\alpha = C_2(T) - C_2(\alpha) + 3 \quad (\text{for } N_f = 3)$$

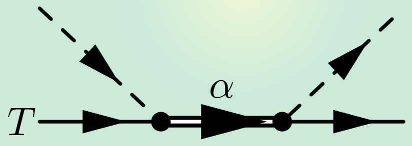
Coupling strengths : Examples

Examples of Cα : (positive is attractive)

$$C_{\alpha,T} = C_2(T) - C_2(\alpha) + 3$$

α	**1**	**8**	**10**	**$\overline{10}$**	**27**	**35**
T=8 (N,Λ,Σ,Ξ)	6	3	0	0	−2	
T=10(Δ,Σ*,Ξ*,Ω)		6	3		1	−3

α	**$\bar{3}$**	**6**	**$\overline{15}$**	**24**
T=$\bar{3}$ (Λ_c,Ξ_c)	3	1	−1	−2
T=6 (Σ_c,Ξ_c*,Ω_c)	5	3	1	



- **Exotic channels : mostly repulsive**
- **Attractive interaction : C = 1**

Coupling strengths : General expression

$$T = [p, q] \qquad \alpha \in [p, q] \otimes [1, 1]$$

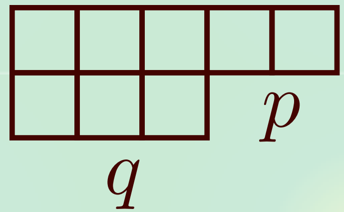
α	$C_{\alpha,T}$	sign
$[p+1, q+1]$	$-p-q$	repulsive
$[p+2, q-1]$	$1-p$	
$[p-1, q+2]$	$1-q$	
$[p, q]$	3	attractive
$[p, q]$	3	attractive
$[p+1, q-2]$	$3+q$	attractive
$[p-2, q+1]$	$3+p$	attractive
$[p-1, q-1]$	$4+p+q$	attractive

- ○ **C should be integer.**
- ○ **Sign is determined for most cases.**

Exoticness

Exoticness : minimal number of extra $\bar{q}q$.

For $[p,q]$ and baryon number B,



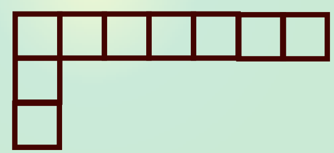
$$E = \epsilon\theta(\epsilon) + \nu\theta(\nu)$$

$$\epsilon \equiv \frac{p+2q}{3} - B, \qquad \nu \equiv \frac{p-q}{3} - B$$

V. Kopeliovich, Phys. Lett. B259, 234 (1991)
D. Diakonov and V. Petrov, Phys. Rev. D 69, 056002 (2004)

but... $[p,q] = [6,0] = \mathbf{28}, \quad B = 1$

$E = 2, \quad \epsilon = 1$

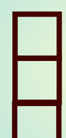


uuu u$\bar{\text{d}}$ u$\bar{\text{d}}$

E. Jenkins and A.V. Manohar, Phys. Rev. Lett. 93, 022001 (2004)

but... $[p,q] = [0,0] = \mathbf{1}, \quad B = 1$

$E = 0, \quad \epsilon = -1, \quad \nu = -1$



uds

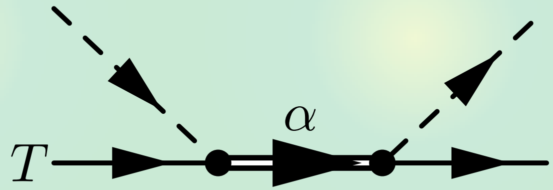
Exotic channels

Consider α is more "exotic" than T

For $[p, q]$ and baryon number B,

$$E = \epsilon\theta(\epsilon) + \nu\theta(\nu) \qquad \epsilon \equiv \frac{p+2q}{3} - B, \quad \nu \equiv \frac{p-q}{3} - B$$

$\Delta E = E_\alpha - E_T = +1$ is realized when



- $\Delta\epsilon = 1,\ \Delta\nu = 0,\ \epsilon_T \geq 0,$
  $\alpha = [p+1, q+1] : C_{\alpha,T} = -p-q$ **repulsive**
- $\Delta\epsilon = 0,\ \Delta\nu = 1,\ \nu_T \geq 0,$
  $\alpha = [p+2, q-1] : C_{\alpha,T} = 1-p$
  attraction : $p = 0$ then $\nu_T \geq 0 \to B \leq -q/3$ **not considered here**
- $\Delta\epsilon = 1,\ \Delta\nu = -1,\ \nu_T \leq 0,$
  $\alpha = [p-1, q+2] : C_{\alpha,T} = 1-q$
  attraction : $q = 0$ then $\nu_T \leq 0 \to B \geq p/3$ **OK!**

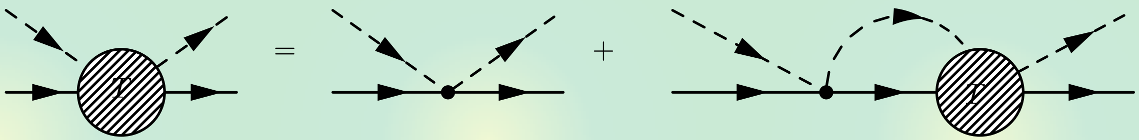
Universal attraction for more "exotic" channel

$$C_{\text{exotic}} = 1 \quad \text{for} \quad T = [p, 0], \quad \alpha = [p-1, 2]$$

Renormalization and bound states

Solve the scattering problem with $V_\alpha = -\frac{\omega}{2f^2} C_{\alpha,T}$

$$T = \frac{1}{1 - VG} V$$



Elastic unitarity : OK

Renormalization parameter : condition

$$G(\mu) = 0, \quad \Leftrightarrow \quad T(\mu) = V(\mu) \quad \text{at} \quad \mu = M_T$$

K. Igi and K. Hikasa, Phys. Rev. D59, 034005 (1999)

M.F.M. Lutz and E. Kolomeitsev, Nucl. Phys. A700, 193-308 (2002)

Matching with the u-channel amplitude : OK

Bound state:

$$1 - V(M_b)G(M_b) = 0 \qquad M_T < M_b < M_T + m$$

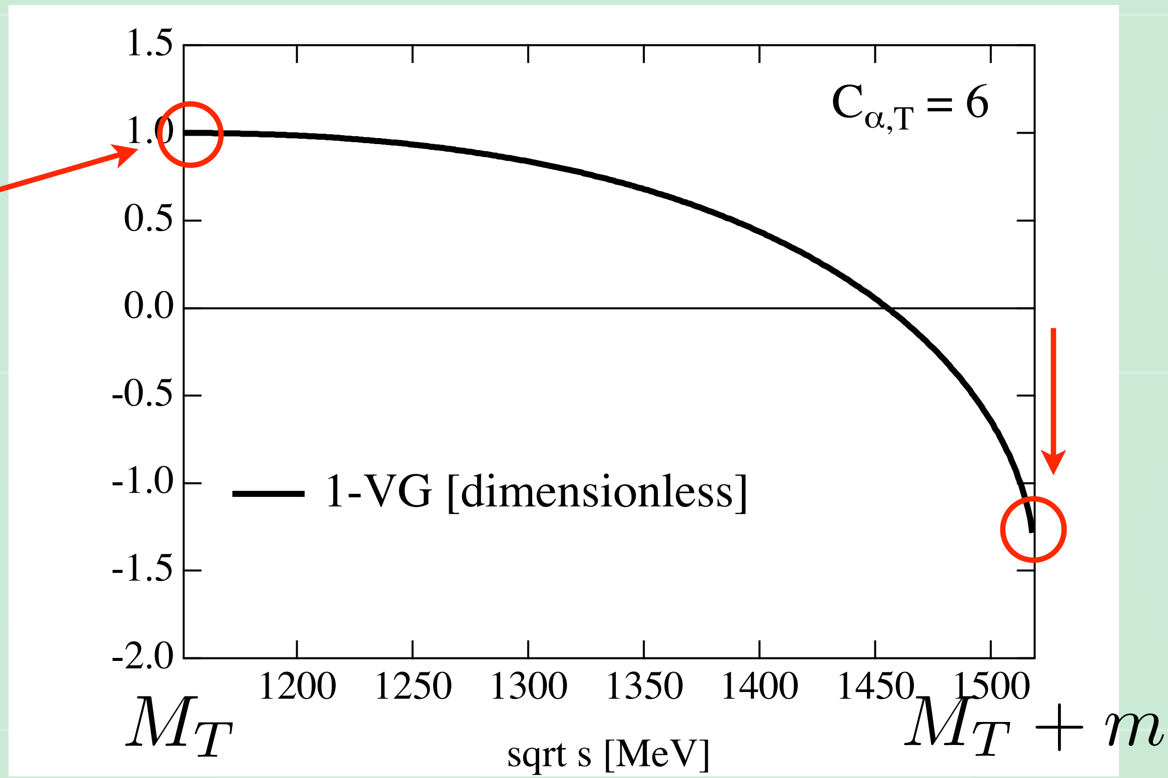
Critical attraction

$1 - V(\sqrt{s})G(\sqrt{s})$ **: monotonically decreasing.**

Fixed

$G(M_T) = 0$

$1 - VG = 1$

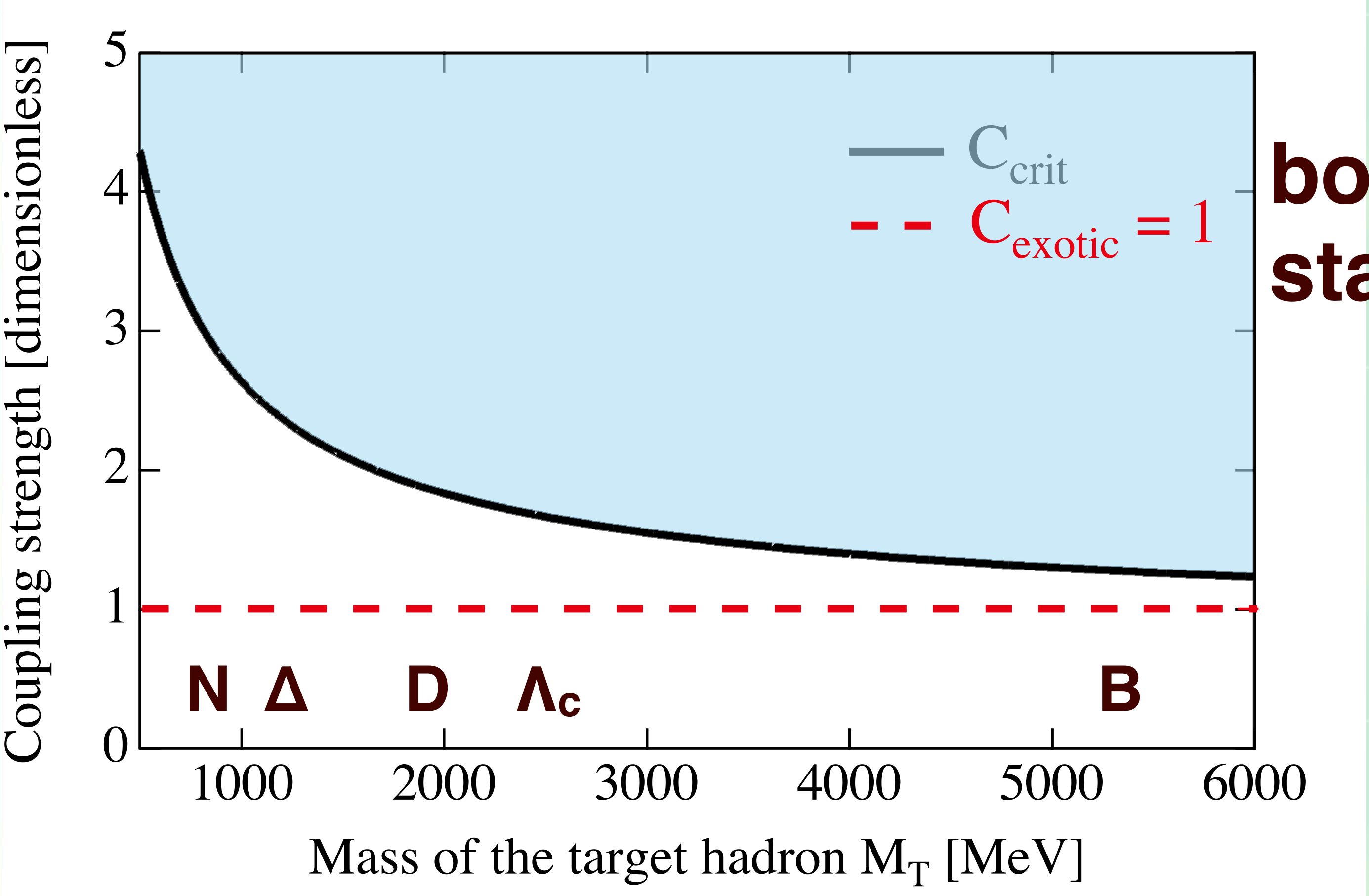


Critical attraction : $1 - VG = 0$ at $\sqrt{s} = M_T + m$

$$C_{\text{crit}} = \frac{2f^2}{m\left(-G(M_T + m)\right)}$$

Critical attraction and exotic channel

$$m = 368 \text{ MeV and } f = 93 \text{ MeV}$$



bound state

Strength is not enough.

Summary 1 : SU(3) limit

We study the exotic bound states in s-wave chiral dynamics in flavor SU(3) limit.

- The interaction in exotic channels are in most cases repulsive.

- There are attractions in exotic channels, with universal and the smallest strength :

$$C_{\rm exotic} = 1$$

- This is not enough to generate a bound state :

$$C_{\rm exotic} < C_{\rm crit}$$

Summary 2 : Physical world

Caution!

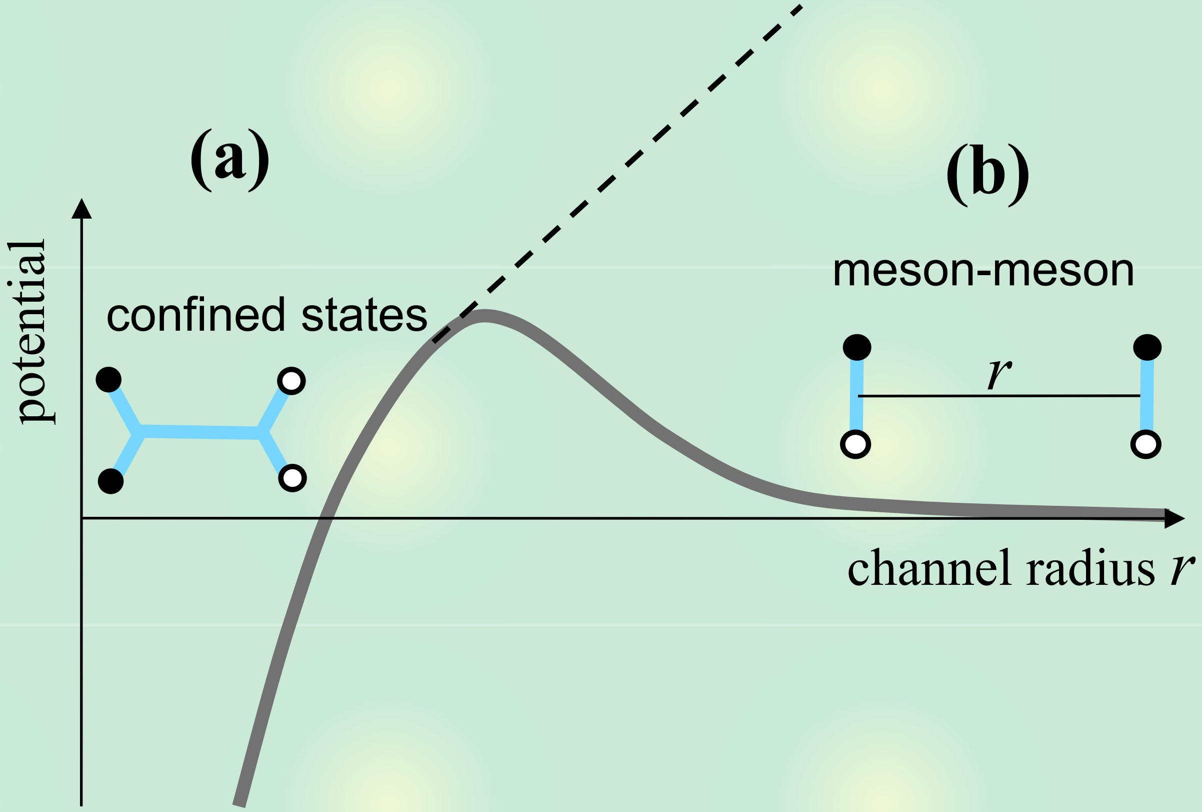
- The exotic hadrons here are the s-wave meson-hadron molecule states ($1/2^-$ for Θ^+).
- We do not exclude the exotics which have other origins (genuine quark state, soliton rotation,...)
- In practice, SU(3) breaking effect, higher order terms,...

It is difficult to generate exotic hadrons as in the same way with Λ(1405), Λ(1520),... based on chiral dynamics.

T. Hyodo, D. Jido and A. Hosaka, Phys. Rev. Lett. 97, 192002 (2006)
T. Hyodo, D. Jido and A. Hosaka, hep-ph/0611004, Accepted in Phys. Rev. D.

Possible exotic states 1 : Genuine quark state

$q^2\bar{q}^2$ Coupling of four-quark and meson-molecule



Y. Kanada-En'yo @ YKIS06

Possibility of exotic states 2

S. Sarkar, E. Oset and M.J. Vicente Vacas, Eur. Phys. J. A24, 287 (2005)

S = +1, I=1, KΔ resonance?

27 plet in SU(3) : $C_{\mathrm{exotic}} = 1$

Large dependence on the input parameter (subtraction constant)

C. Garcia-Recio, J. Nieves and L.L. Salcedo, Phys. Rev. D74, 034025 (2006)

S = +1, K*N bound state at 1.7-1.8 GeV

SU(6) extension of the WT term
<-- valid for chiral mesons?

Possibility of exotic states 3

S. Sarkar, E. Oset, M.J.Vicente Vacas, Nucl. Phys. A750, 294 (2005)

S = 0, I=3/2, Δ(1700)

Δπ, Δη, Σ*K : 10, 27, 35

M. Doering, E. Oset, M. Strottman, Phys. Lett. B639, 59 (2006)

Couplings of the generated resonance are very different from 10 assignment

--> dominated by 27 plet?

(Attractive) coupled channels in lower energy

--> resonance in exotic channel ??