Exotic Hadrons in s-Wave Chiral Dynamics

Tetsuo Hyodo[a]

D. Jido[a], and A. Hosaka[b]

YITP, Kyoto[a] *RCNP, Osaka[b]*

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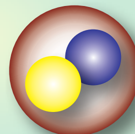
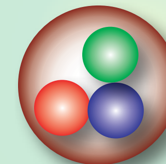
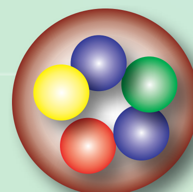
Motivation 1 : Exotic hadrons

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

Experimentally, they are exotic.

PDG(2006) :

159 mesons  **127 baryons** 

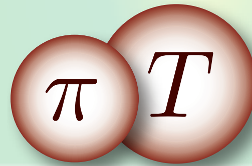
1 pentaquark  **with ***

Theoretically, are they exotic?

--> QCD does not forbid exotic states, effective models neither.

How exotic are they??

Motivation 2 : Chiral unitary approaches

Hadron excited states ~ 

- ○ **Interaction <-- chiral symmetry**
- ○ **Amplitude <-- unitarity**

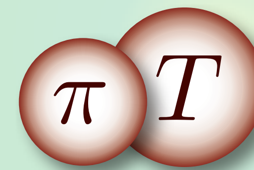
N. Kaiser, P. B. Siegel and W. Weise, Nucl. Phys. A594, 325 (1995)
E. Oset and A. Ramos, Nucl. Phys. A635, 99 (1998)
J. A. Oller and U. G. Meissner, Phys. Lett. B500, 263 (2001)
M.F.M. Lutz and E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002)

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

--> Examine exotic hadrons in flavor 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

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

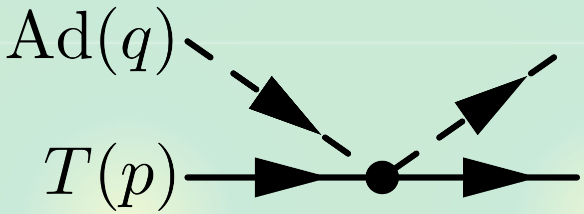
physical values : $C_{\text{exotic}} < C_{\text{crit}}$

→ **No exotic state exists.**

Low energy s-wave interaction

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

α [



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

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)

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

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)

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

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

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

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

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

Exotic channels

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

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 $\nu_T \geq 0 \rightarrow B \leq -q/3$ **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 $\nu_T \leq 0 \rightarrow B \geq p/3$ **OK!**

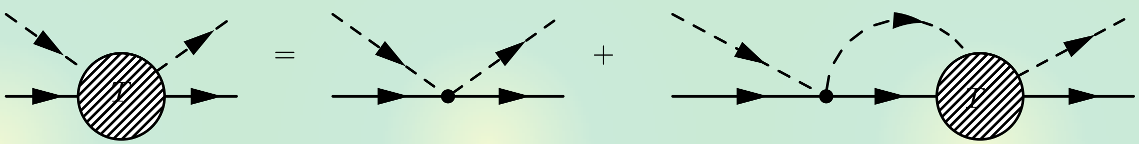
Universal attraction for more "exotic" channel

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

Renormalization and bound states

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

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



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)

Approximate crossing symmetry : OK

Bound state:

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

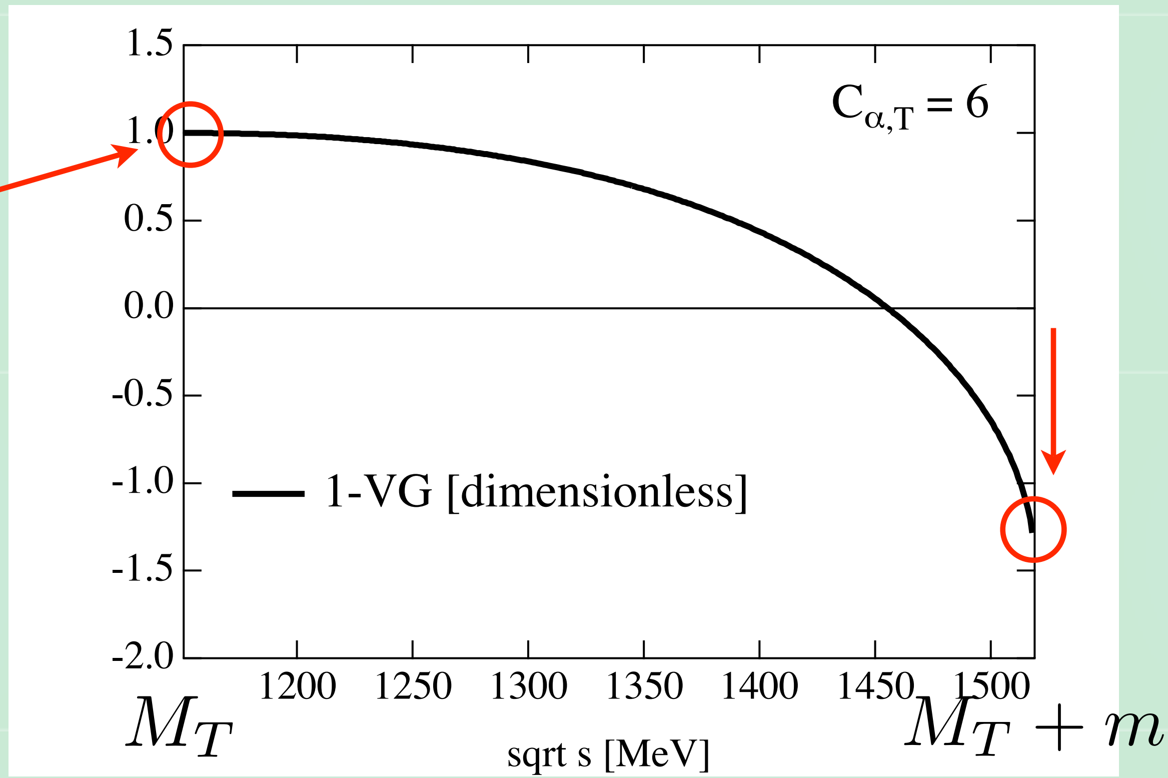
Critical attraction

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

Fixed

$G(M_T) = 0$

$1 - VG = 1$

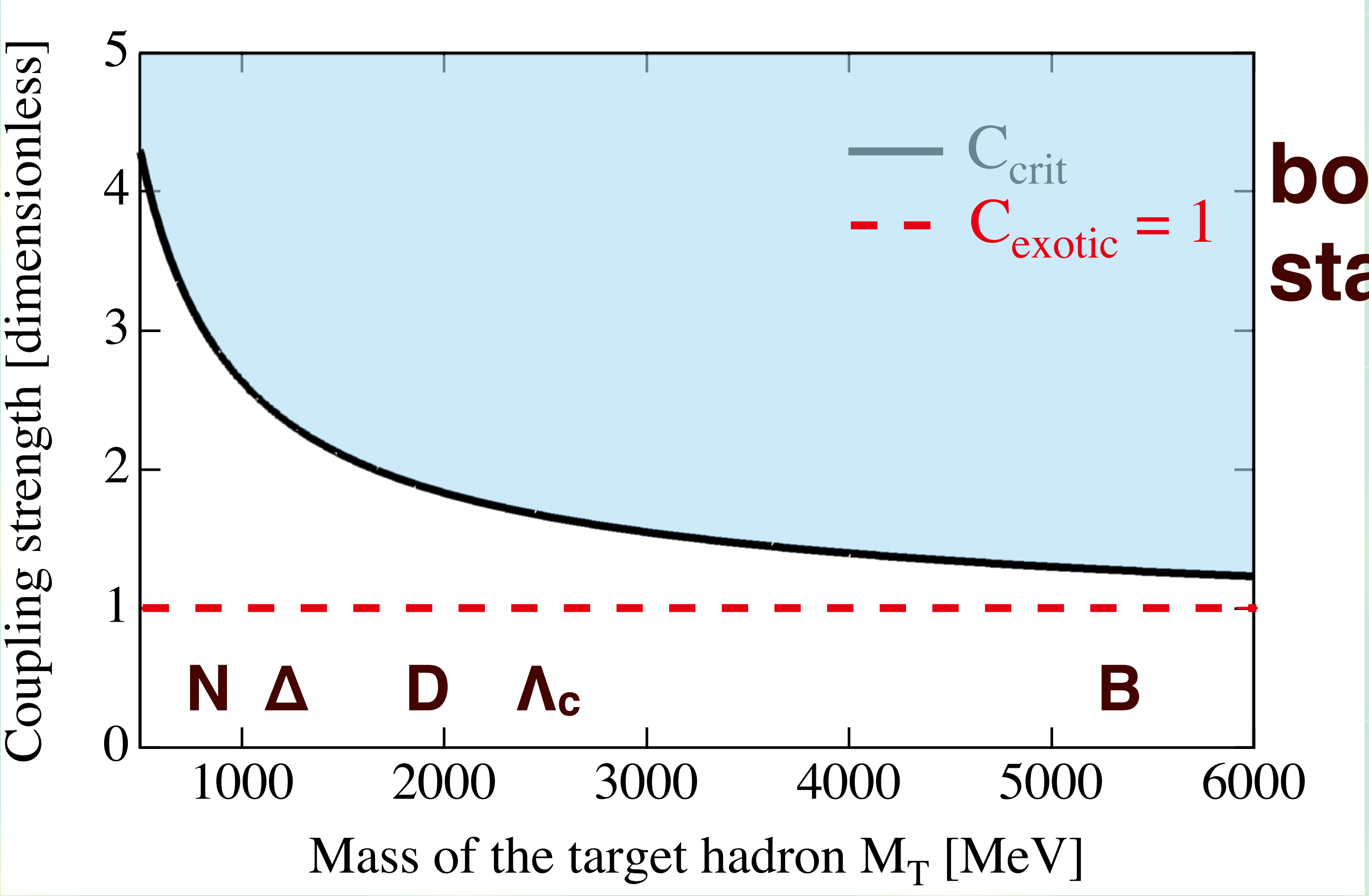


Critical attraction : $1 - VG = 0$ at $\sqrt{s} = M_T + m$

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

Critical attraction and exotic channel

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

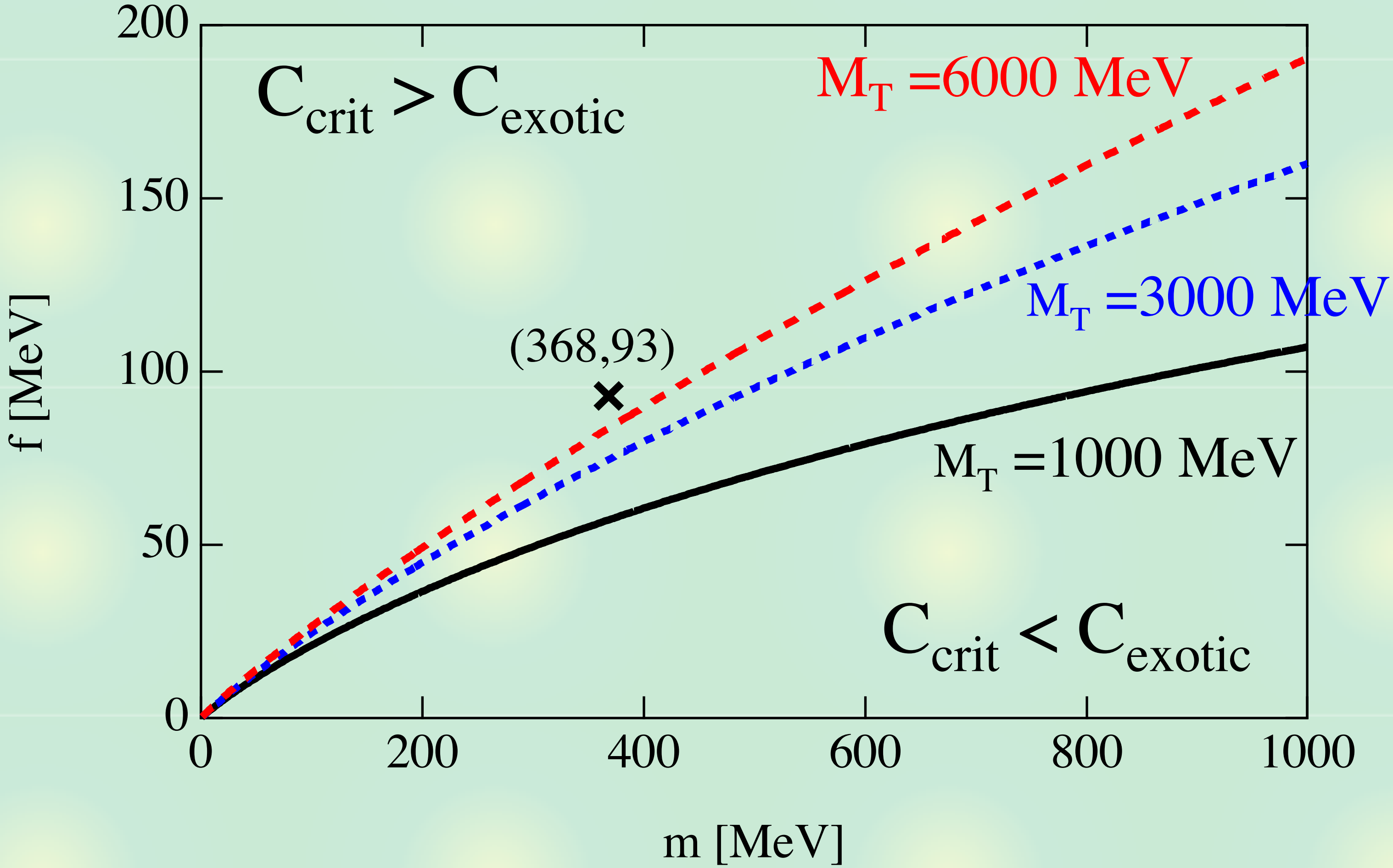


bound state

➡ **Strength is not enough.**

Discussion : Dependence on the parameters

Lines for C_{crit} = 1 in (m, f) plane



- ○ C_{crit} becomes smaller for M_T↗, m↗ and f↘.
- ○ difficult to generate a bound state.

Coupling strengths in large Nc limit

In large Nc limit

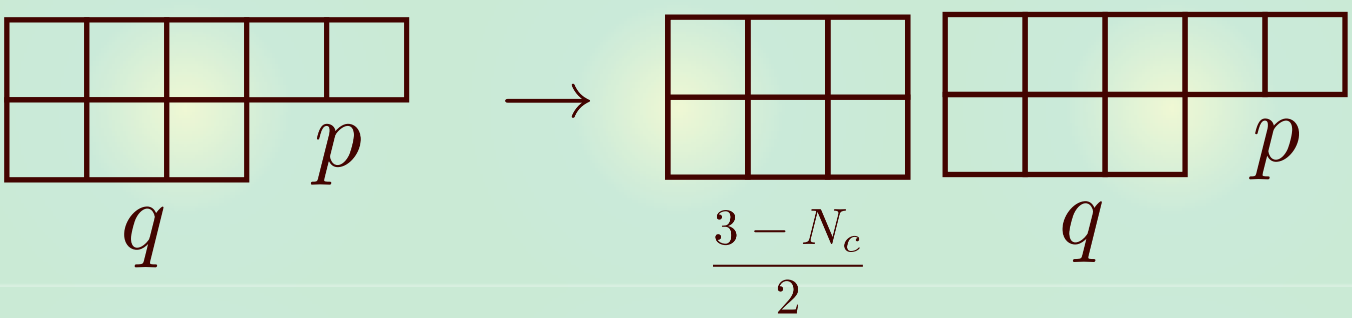
c.f. T.D. Cohen and R.F. Lebed
Phys. Rev. D74, 056006 (2006)

$$V_\alpha = -\frac{\omega}{2f^2} C_{\alpha,T} \sim \frac{1}{N_c} \times C_{\alpha,T}$$

Flavor representation

$$C_2(T) - C_2(\alpha) + 3$$

$$[p,q] \to [p, q + \frac{3-N_c}{2}]$$



$$C([p, q + \frac{3-N_c}{2}]) = \frac{1}{3}\left(-\frac{9}{4} + p^2 + \frac{3q}{2} + pq + q^2\right) + \frac{1}{3}\left(p + \frac{q}{2}\right) N_c + \frac{N_c^2}{12}$$

Non-trivial Nc dependence

Coupling strengths in large Nc limit

C_α with arbitrary Nc : (positive is attractive)

α	“1”	“8”	“10”	“$\overline{10}$”	“27”	“35”
T=“8”	$\frac{9}{2}+\frac{N_c}{2}$	3	0	$\frac{3}{2}-\frac{N_c}{2}$	$-\frac{1}{2}-\frac{N_c}{2}$	
T=“10”			3		$\frac{5}{2}-\frac{N_c}{2}$	$-\frac{1}{2}-\frac{N_c}{2}$

Λ(1405) two-pole?

α	“$\bar{3}$”	“6”	“$\overline{15}$”	“24”
T=“$\bar{3}$”	3	1	$-\frac{N_c}{3}$	
T=“6”	5	3	$\frac{5}{2}-\frac{N_c}{2}$	$\frac{1}{2}-\frac{5N_c}{6}$

Exotic attractions --> repulsions

Discussion 1 : large Nc behavior

For arbitrary Nc, $[p,q] \to \left[p, q+\frac{3-N_c}{2}\right]$ $V \propto -\frac{1}{f^2}C \sim \frac{1}{N_c}C(N_c)$

α	$C_{``\alpha", ``T"}(N_c)$	$V(N_c \to \infty)$	ΔE
$[p+1, q+1]$	$(3-N_c)/2-p-q$	repulsive	1 or 0
$[p+2, q-1]$	$1-p$	0	1 or 0
$[p-1, q+2]$	$(5-N_c)/2-q$	repulsive	1 or 0
$[p, q]$	3	0	0
$[p, q]$	3	0	0
$[p+1, q-2]$	$(3+N_c)/2+q$	attractive	0 or -1
$[p-2, q+1]$	$3+p$	0	0 or -1
$[p-1, q-1]$	$(5+N_c)/2+p+q$	attractive	0 or -1

- **Exotic attraction --> repulsion**
- **No attraction in exotic channels.**

Summary 1

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 : $C_{\text{exotic}} = 1$
- This is **not enough** to generate a bound state : $C_{\text{exotic}} < C_{\text{crit}}$
- **No attractive interaction exists** in exotic channels in the large Nc limit.

Summary 2

Caution! on the conclusions...

- 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...

We show that no exotic hadron exists as in the same way with Λ(1405), Λ(1520), D_s(2317),... based on group theory and chiral dynamics.

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