Exotic hadrons in s-wave chiral dynamics

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Introduction : QCD at low energy

Quantum chromodynamics (QCD)

--> strong interaction of quarks and gluons

At low energies: confinement, chiral symmetry breaking

Chiral perturbation theory (ChPT)

--> Effective Field Theory of mesons and baryons

current algebra (low energy theorem) : OK

systematic low energy expansion

Ex.) πN scattering length is well reproduced

What happens if the low energy interaction is strong?

Ex.) $\bar{K}N$ scattering

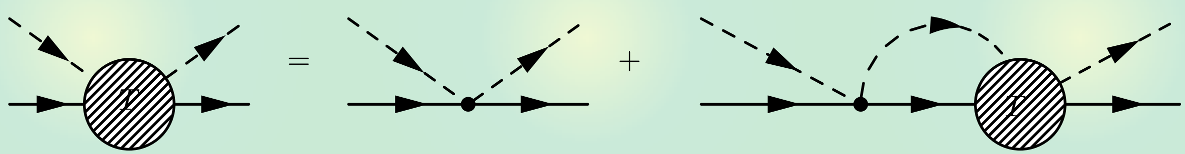
Λ(1405)

➡ non-perturbative framework

Chiral dynamics for non-exotic hadrons

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

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

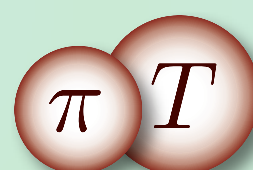


WT interaction model-independent

cutoff (subtraction constant)

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

(s-wave) hadron excited states ~



Chiral dynamics for non-exotic hadrons

(s-wave) hadron excited states ~ π T

Many hadron resonances are well described.

light baryon	$J^P = 1/2^-$	$\Lambda(1405)$ $\Lambda(1670)$ $\Sigma(1670)$
		$N(1535)$ $\Xi(1620)$ $\Xi(1690)$
	$J^P = 3/2^-$	$\Lambda(1520)$ $\Xi(1820)$ $\Sigma(1670)$
heavy		$\Lambda_c(2880)$ $\Lambda_c(2593)$ $D_s(2317)$
light meson	$J^P = 1^+$	$b_1(1235)$ $h_1(1170)$ $h_1(1380)$ $a_1(1260)$
		$f_1(1285)$ $K_1(1270)$ $K_1(1440)$
	$J^P = 0^+$	$\sigma(600)$ $\kappa(900)$ $f_0(980)$ $a_0(980)$

Chiral interaction is STRONG

Exotic hadrons in hadron spectrum

Observed hadrons in experiments (PDG06) :

p	P_{11}	****
n	P_{11}	****
N(1440)	P_{11}	****
N(1520)	D_{13}	****
N(1535)	S_{11}	****
N(1650)	S_{11}	****
N(1675)	D_{15}	****
N(1680)	F_{15}	****
N(1700)	D_{13}	***
N(1710)	P_{11}	***
N(1720)	P_{13}	****
N(1900)	P_{13}	**
N(1990)	F_{17}	**
N(2000)	F_{15}	**
N(2080)	D_{13}	**
N(2090)	S_{11}	*
N(2100)	P_{11}	*
N(2190)	G_{17}	****
N(2200)	D_{15}	**
N(2220)	H_{19}	****
N(2250)	G_{19}	****
N(2600)	$I_{1,11}$	***
N(2700)	$K_{1,13}$	**

Δ(1232)	P_{33}	****
Δ(1600)	P_{33}	***
Δ(1620)	S_{31}	****
Δ(1700)	D_{33}	****
Δ(1750)	P_{31}	*
Δ(1900)	S_{31}	**
Δ(1905)	F_{35}	****
Δ(1910)	P_{31}	****
Δ(1920)	P_{33}	***
Δ(1930)	D_{35}	***
Δ(1940)	D_{33}	*
Δ(1950)	F_{37}	****
Δ(2000)	F_{35}	**
Δ(2150)	S_{31}	*
[illegible]	[illegible]	*
[illegible]	[illegible]	**
[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	***
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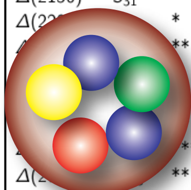
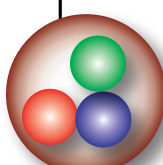
Δ(2950)	$K_{3,15}$	**
$\Theta(1540)^+$		*

Λ	P_{01}	****
Λ(1405)	S_{01}	****
Λ(1520)	D_{03}	****
Λ(1600)	P_{01}	***
Λ(1670)	S_{01}	****
Λ(1690)	D_{03}	****
Λ(1800)	S_{01}	***
Λ(1810)	P_{01}	***
Λ(1820)	F_{05}	****
Λ(1830)	D_{05}	****
Λ(1890)	P_{03}	****
Λ(2000)		*
Λ(2020)	F_{07}	*
Λ(2100)	G_{07}	****
Λ(2110)	F_{05}	***
Λ(2325)	D_{03}	*
Λ(2350)	H_{09}	***
Λ(2585)		**

Σ^+	P_{11}	****
Σ^0	P_{11}	****
Σ^-	P_{11}	****
Σ(1385)	P_{13}	****
Σ(1480)		*
Σ(1560)		**
Σ(1580)	D_{13}	*
Σ(1620)	S_{11}	**
Σ(1660)	P_{11}	***
Σ(1670)	D_{13}	****
Σ(1690)		**
Σ(1750)	S_{11}	***
Σ(1770)	P_{11}	*
Σ(1775)	D_{15}	****
Σ(1840)	P_{13}	*
Σ(1880)	P_{11}	**
Σ(1915)	F_{15}	****
Σ(1940)	D_{13}	***
Σ(2000)	S_{11}	*
Σ(2030)	F_{17}	****
Σ(2070)	F_{15}	*
Σ(2080)	P_{13}	**
Σ(2100)	G_{17}	*
Σ(2250)		***
Σ(2455)		**
Σ(2620)		**
Σ(3000)		*
Σ(3170)		*

Ξ^0	P_{11}	****
Ξ^-	P_{11}	****
Ξ(1530)	P_{13}	****
Ξ(1620)		*
Ξ(1690)		***
Ξ(1820)	D_{13}	***
Ξ(1950)		***
Ξ(2030)		***
Ξ(2120)		*
Ξ(2250)		**
Ξ(2370)		**
Ξ(2500)		*
Ω^-		****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**
Λ_c^+		****
$\Lambda_c(2593)^+$		***
$\Lambda_c(2625)^+$		***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$		**
$\Sigma_c(2455)$		****
$\Sigma_c(2520)$		***
$\Sigma_c(2800)$		***
Ξ_c^+		***
Ξ_c^0		***
$\Xi_c'^+$		***
$\Xi_c'^0$		***
$\Xi_c(2645)$		***
$\Xi_c(2790)$		***
$\Xi_c(2815)$		***
Ω_c^0		***
Ξ_{cc}^+		*
Λ_b^0		***



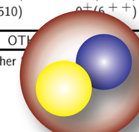


$\sim \frac{1}{300}$!

~130 baryons

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_2(1270)$	$0^+(2^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$	• $f_2(1950)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $\pi(1300)$	$1^-(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $a_2(1320)$	$1^-(2^{++})$	$f_0(2020)$	$0^+(0^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $a_4(2040)$	$1^-(4^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $f_4(2050)$	$0^+(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$	$f_0(2100)$	$0^+(0^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$f_2(2150)$	$0^+(2^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$\rho(2150)$	$1^+(1^{--})$
$f_2(1430)$	$0^+(2^{++})$	$f_0(2200)$	$0^+(0^{++})$
• $a_0(1450)$	$1^-(0^{++})$	$f_J(2220)$	$0^+(2 \text{ or } 4^{++})$
• $\rho(1450)$	$1^+(1^{--})$	$\eta(2225)$	$0^+(0^{-+})$
• $\eta(1475)$	$0^+(0^{-+})$	$\rho_3(2250)$	$1^+(3^{--})$
• $f_0(1500)$	$0^+(0^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_1(1510)$	$0^+(1^{++})$	$f_4(2300)$	$0^+(4^{++})$
• $f_2'(1525)$	$0^+(2^{++})$	• $f_2(2340)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$h_1(1595)$	$0^-(1^{+-})$	$a_6(2450)$	$1^-(6^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	$f_6(2510)$	$0^+(6^{++})$
$a_1(1640)$	$1^-(1^{++})$	OTH	
$f_2(1640)$	$0^+(2^{++})$	Further	
• $\eta_2(1645)$	$0^+(2^{-+})$		
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		



STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K_S^0	$1/2(0^-)$
• K_L^0	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
$D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D^*(2640)^\pm$	$1/2(?^?)$

CHARMED, STRANGE ($S = \pm1$)

• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$

BOTTOM ($B = \pm1$)

	$I^G(J^{PC})$
• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B_s^0	$0(0^-)$
B_s^*	$0(1^-)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

• $B_c^\pm$	$0(0^-)$

$c\bar{c}$

• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
$h_c(1P)$	$?^?(?^{??})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^?(?^{?+})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$Y(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
$Y(4260)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$

$b\bar{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
$\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

NON-$q\bar{q}$ CANDIDATES

~160 mesons

Exotic hadrons are indeed exotic !!

Exotic hadrons : experiment vs theory

Exotic hadrons : valence quark-antiquark(s)

non-exotic $uds, \quad u\bar{d}, \quad uds\, u\bar{u}, \quad u\bar{d}\, u\bar{u}, \ldots$

exotic $uudd\bar{s}, \quad ud\bar{s}\bar{s}, \ldots$

Experimentally, they are exotic ~ 1/300.

Theoretically, are they exotic?

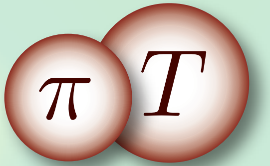
--> There is no simple way to forbid exotic states in QCD, effective models, ...

--> Evidences of multiquark components in non-exotic hadrons.

Why aren’t the exotics observed??

Outline

Possibility of exotic hadron as a bound state of a target hadron and the NG boson

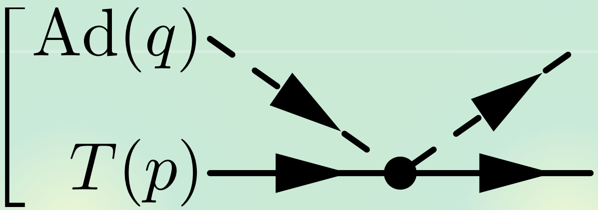


We need to check

- ○ s-wave low energy interaction?
- ○ Exotic channel?
- ○ Is the interaction strong?

Low energy s-wave interaction

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

α 

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

s-wave : Weinberg-Tomozawa term

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

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

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

model-independent interaction at low energy

Coupling strength has linear Nc dependence

T. Hyodo, D. Jido, L. Roca, 0712.3347 [hep-ph], Phys. Rev. D, in press.

Coupling strengths : Examples

Coupling strengths : (positive is attractive)

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

α	$\mathbf{1}$	$\mathbf{8}$	$\mathbf{10}$	$\overline{\mathbf{10}}$	$\mathbf{27}$	$\mathbf{35}$
$T = \mathbf{8}(N, \Lambda, \Sigma, \Xi)$	6	3	0	0	-2	
$T = \mathbf{10}(\Delta, \Sigma^*, \Xi^*, \Omega)$		6	3		1	-3

α	$\overline{\mathbf{3}}$	$\mathbf{6}$	$\overline{\mathbf{15}}$	$\mathbf{24}$
$T = \overline{\mathbf{3}}(\Lambda_c, \Xi_c)$	3	1	-1	
$T = \mathbf{6}(\Sigma_c, \Xi_c^*, \Omega_c)$	5	3	1	-2

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

Coupling strengths : General expression

For a general target $T = [p, q]$

$\alpha \in [p, q] \otimes [1, 1]$	$C_{\alpha,T}$	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

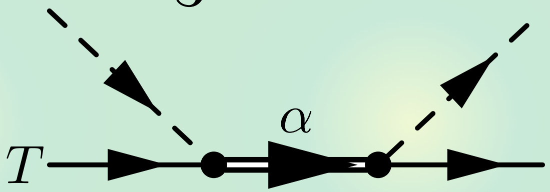
- Strength should be integer.
- Sign is determined for most cases.

Exotic channels

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

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

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



- ○ $\alpha = [p+1, q+1] : C_{\alpha,T} = -p-q$

  repulsive

- ○ $\alpha = [p+2, q-1] : C_{\alpha,T} = 1-p$

  attraction : $p = 0$ then $\nu_T \geq 0 \to B \geq -q/3$

  not considered here

- ○ $\alpha = [p-1, q+2] : C_{\alpha,T} = 1-q$

  attraction : $q = 0$ then $\nu_T \leq 0 \to B \geq p/3$ **OK!**

Universal attraction for more “exotic” channel

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

Unitarization : N/D method

Unitarity cut --> N, unphysical cut --> D

$$T(s) = N(s)/D(s)$$

$$\mathrm{Im} D(s) = \mathrm{Im}[T^{-1}(s)]N(s) = -\rho(s)N(s) \quad \text{for } s > s_+$$

$$\mathrm{Im} N(s) = \mathrm{Im}[T(s)]D(s) \quad \text{for } s < s_-$$

Neglect unphysical cut, set N=1

$$T^{-1}(s) = \left(a(s_0) + \frac{s - s_0}{2\pi} \int_{s^+}^{\infty} ds' \frac{\rho(s')}{(s' - s)(s' - s_0)} \right) + \mathcal{T}^{-1}(s)$$

loop function

$\to G(s)$

Interaction (tree level)

subtraction constant (regularization parameter of the loop)

Renormalization and bound states

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

$$T_\alpha(\sqrt{s}) = \frac{1}{1 - V_\alpha(\sqrt{s}) G(\sqrt{s})} V_\alpha(\sqrt{s})$$

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)

Exclude the genuine quark states in G

T. Hyodo, D. Jido and A. Hosaka, arXiv: 0803.2550 [nucl-th]

Bound state:

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

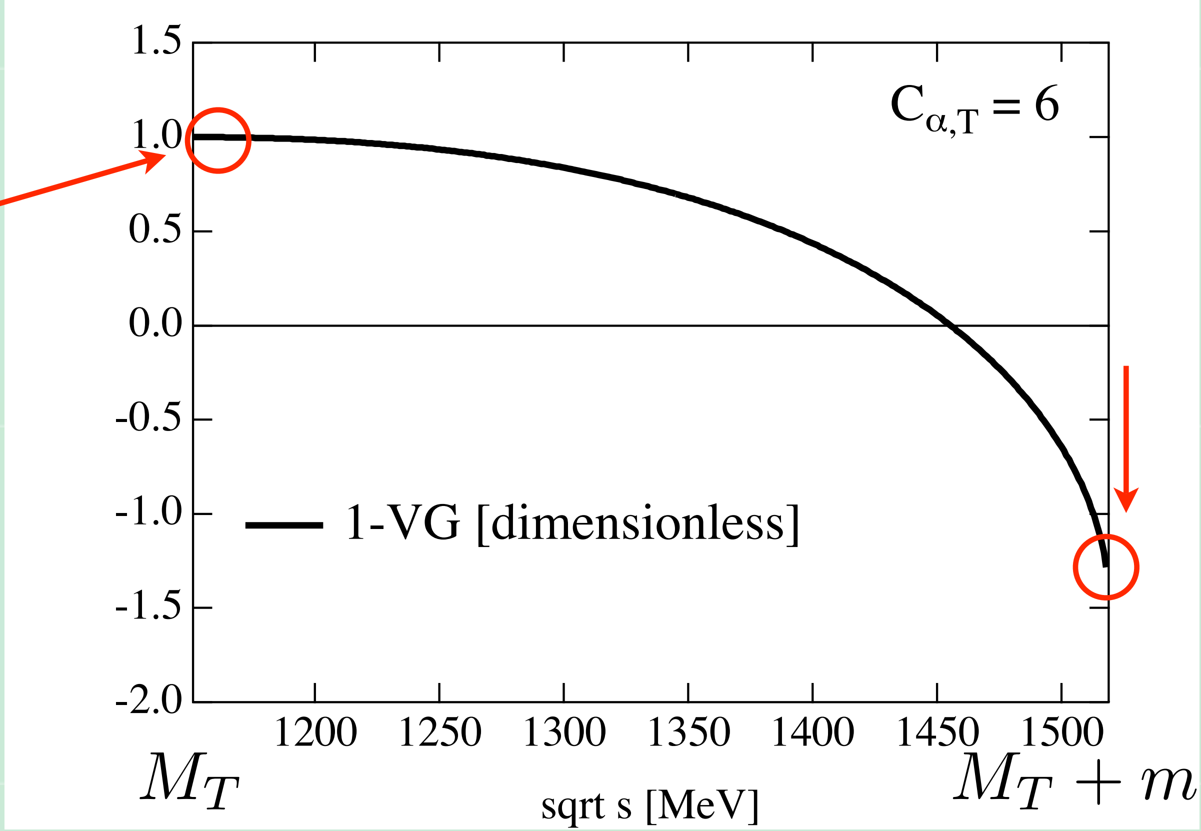
Critical attraction

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

Fixed

$G(M_T) = 0$

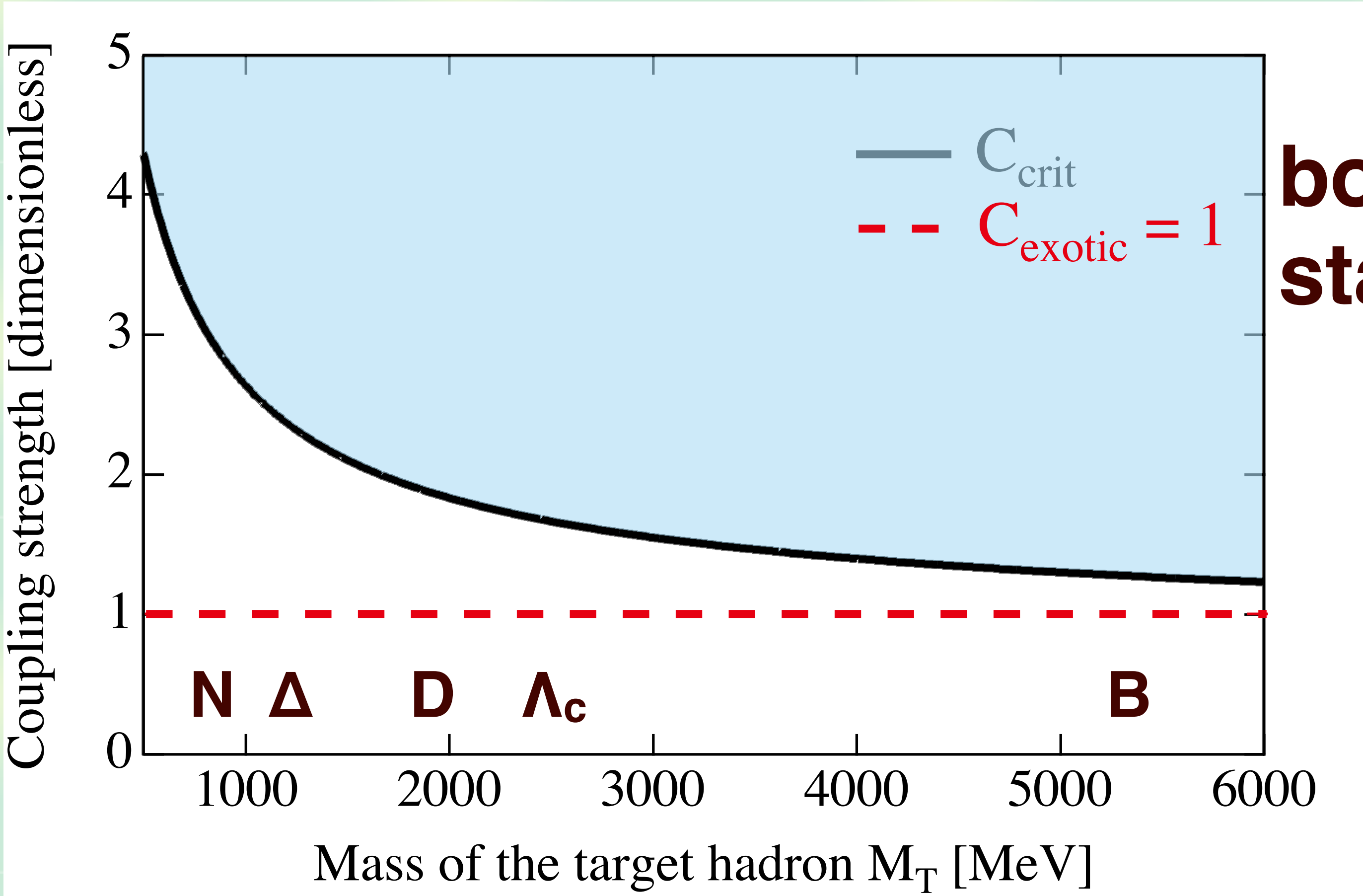
$1 - VG = 1$



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

$$\Rightarrow \quad C_{\rm crit} = \frac{2f^2}{m[-G(M_T+m)]}$$

Critical attraction and exotic channel



bound state

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

→ **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 interactions in exotic channels are in most cases repulsive.**
- **There are attractive interactions in exotic channels, with universal and the smallest strength :** $C_{\text{exotic}} = 1$
- **The strength is not enough to generate a bound state :** $C_{\text{exotic}} < C_{\text{crit}}$

The result is model independent as far as we respect chiral symmetry.

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,...

In Nature, it is difficult to generate exotic hadrons as in the same way with Λ(1405), Λ(1520),... based on chiral interaction.

T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. Lett. 97, 192002 (2006)
T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. D 75, 034002 (2007)