Exotic hadrons in s-wave chiral dynamics

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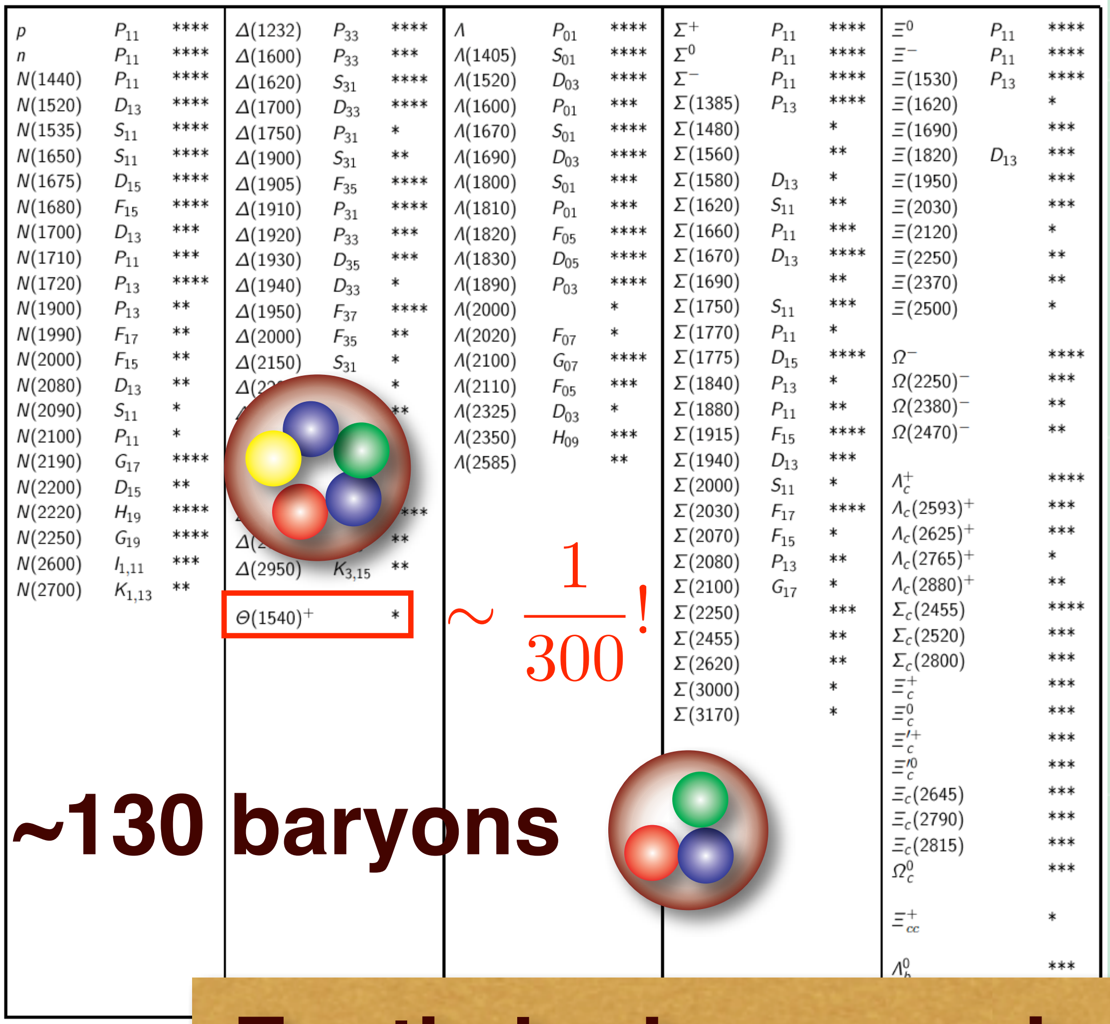
Exotic hadrons

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}	****
$N(2600)$	$I_{1,11}$	***
$N(2700)$	$K_{1,13}$	**

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

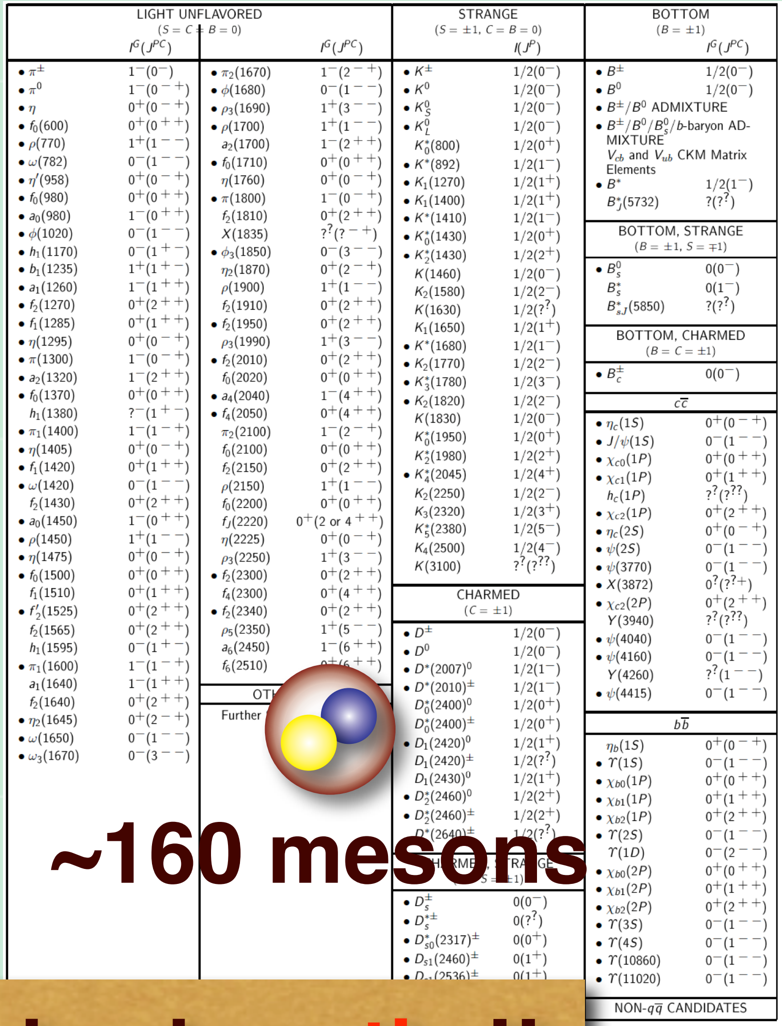
Λ	P_{01}	****
$\Lambda(1405)$	S_{01}	****
$\Lambda(1520)$	D_{03}	****
$\Lambda(1600)$	P_{01}	***
$\Lambda(1670)$	S_{01}	****
$\Lambda(1690)$	D_{03}	****
$\Lambda(1800)$	S_{01}	***
$\Lambda(1810)$	P_{01}	***
$\Lambda(1820)$	F_{05}	****
$\Lambda(1830)$	D_{05}	****
$\Lambda(1890)$	P_{03}	****
$\Lambda(2000)$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

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

Ξ^0	P_{11}	****
Ξ^-	P_{11}	****
$\Xi(1530)$	P_{13}	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	D_{13}	***
$\Xi(1950)$		***
$\Xi(2030)$		***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
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		***
$\Xi_c^{\prime+}$		***
$\Xi_c^{\prime0}$		***
$\Xi_c(2645)$		***
$\Xi_c(2790)$		***
$\Xi_c(2815)$		***
Ω_c^0		***
Ξ_{cc}^+		*
Λ_b^0		***

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

~130 baryons



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

	$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$
• π^0	$1^-(0^{-+})$
• η	$0^+(0^{-+})$
• $f_0(600)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$
• $\omega(782)$	$0^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$
• $\phi(1020)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$
• $b_1(1235)$	$1^+(1^{+-})$
• $a_1(1260)$	$1^-(1^{++})$
• $f_2(1270)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$
• $\eta(1295)$	$0^+(0^{-+})$
• $\pi(1300)$	$1^-(0^{-+})$
• $a_2(1320)$	$1^-(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$
• $\pi_1(1400)$	$1^-(1^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$
• $f_1(1420)$	$0^+(1^{++})$
• $\omega(1420)$	$0^-(1^{--})$
$f_2(1430)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$
• $f_0(1500)$	$0^+(0^{++})$
$f_1(1510)$	$0^+(1^{++})$
• $f_2'(1525)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$
$h_1(1595)$	$0^-(1^{+-})$
• $\pi_1(1600)$	$1^-(1^{-+})$
$a_1(1640)$	$1^-(1^{++})$
$f_2(1640)$	$0^+(2^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$
• $\omega(1650)$	$0^-(1^{--})$
• $\omega_3(1670)$	$0^-(3^{--})$

	$I^G(J^{PC})$
• $\pi_2(1670)$	$1^-(2^{-+})$
• $\phi(1680)$	$0^-(1^{--})$
• $\rho_3(1690)$	$1^+(3^{--})$
• $\rho(1700)$	$1^+(1^{--})$
$a_2(1700)$	$1^-(2^{++})$
• $f_0(1710)$	$0^+(0^{++})$
$\eta(1760)$	$0^+(0^{-+})$
• $\pi(1800)$	$1^-(0^{-+})$
$f_2(1810)$	$0^+(2^{++})$
$X(1835)$	$?^?(?^{-+})$
• $\phi_3(1850)$	$0^-(3^{--})$
$\eta_2(1870)$	$0^+(2^{-+})$
$\rho(1900)$	$1^+(1^{--})$
$f_2(1910)$	$0^+(2^{++})$
• $f_2(1950)$	$0^+(2^{++})$
$\rho_3(1990)$	$1^+(3^{--})$
• $f_2(2010)$	$0^+(2^{++})$
$f_0(2020)$	$0^+(0^{++})$
• $a_4(2040)$	$1^-(4^{++})$
• $f_4(2050)$	$0^+(4^{++})$
$\pi_2(2100)$	$1^-(2^{-+})$
$f_0(2100)$	$0^+(0^{++})$
$f_2(2150)$	$0^+(2^{++})$
$\rho(2150)$	$1^+(1^{--})$
$f_0(2200)$	$0^+(0^{++})$
$f_J(2220)$	$0^+(2 \text{ or } 4^{++})$
$\eta(2225)$	$0^+(0^{-+})$
$\rho_3(2250)$	$1^+(3^{--})$
• $f_2(2300)$	$0^+(2^{++})$
$f_4(2300)$	$0^+(4^{++})$
• $f_2(2340)$	$0^+(2^{++})$
$\rho_5(2350)$	$1^+(5^{--})$
$a_6(2450)$	$1^-(6^{++})$
$f_6(2510)$	$0^+(6^{++})$

OTH[illegible]

Further [illegible]

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
($C = S = \pm1$)

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

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
($B = C = \pm1$)

• $B_c^\pm$	$0(0^-)$

$c\overline{c}$

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

$b\overline{b}$

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

NON-$q\overline{q}$ CANDIDATES

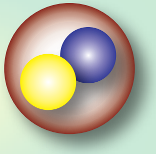
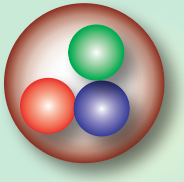
~160 mesons

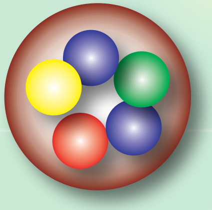
Exotic hadrons are indeed exotic !!

Motivation 1 : Exotic hadrons

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

Experimentally, they are exotic.

~160 mesons  **~130 baryons** 

1 pentaquark  **with ***

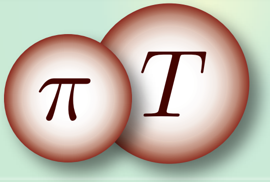
Theoretically, are they exotic?

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

Why aren't the exotics observed??

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)

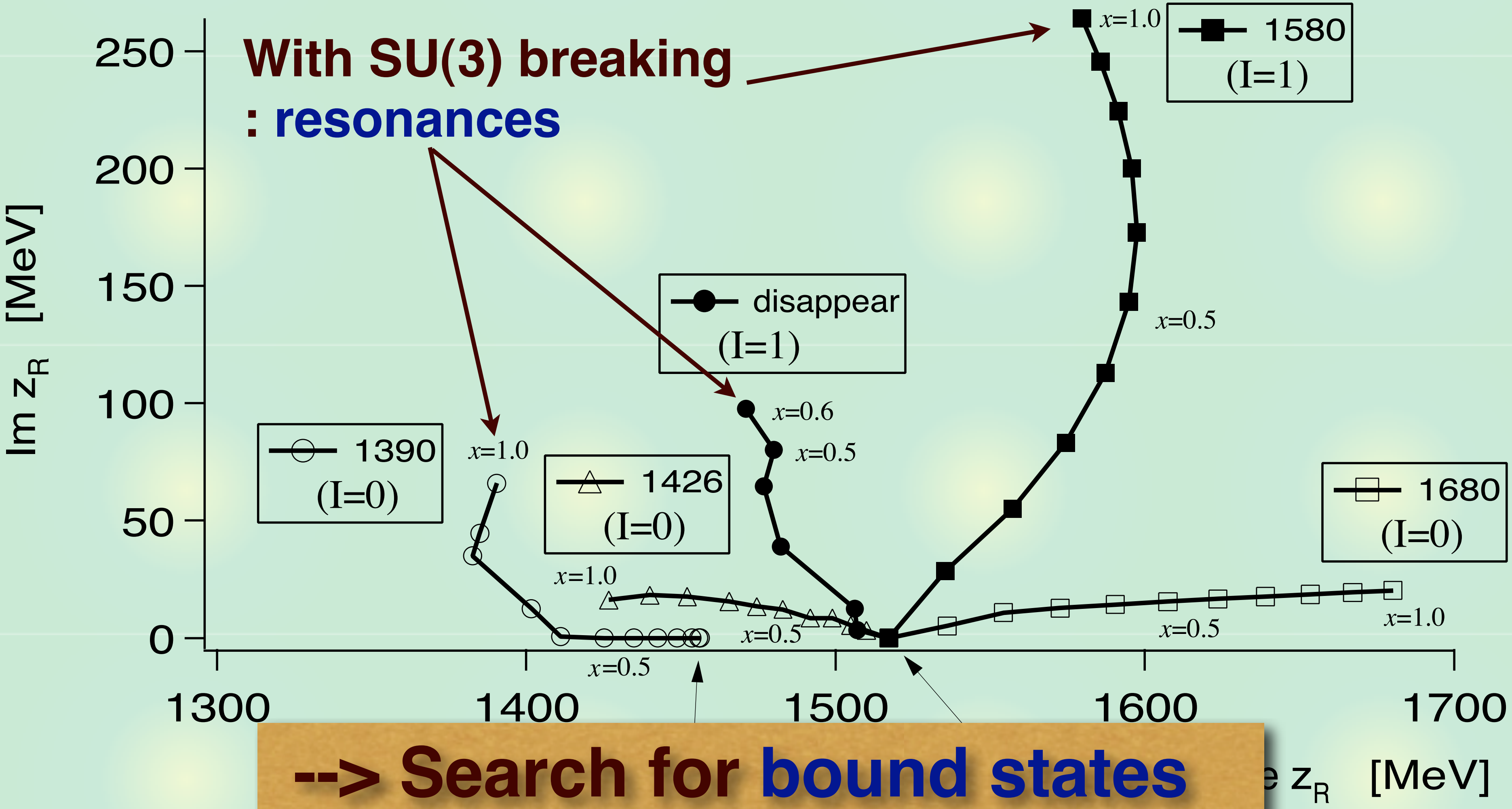
Many hadron resonances (Λ(1405), N(1535), Λ(1520), D_s(2317),...) are well described.

What about exotic hadrons?

Origin of the resonances

Trajectory of poles

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

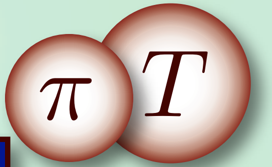


With SU(3) breaking
: resonances

--> 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

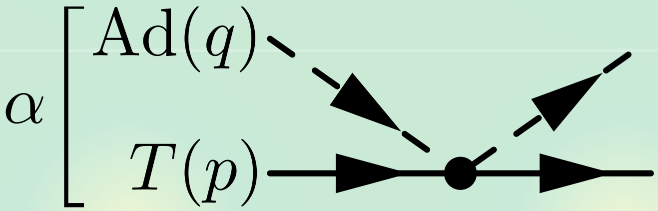
$$C_{\text{crit}} = \frac{2f^2}{m[-G(M_T + m)]}$$

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)



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

s-wave : Weinberg-Tomozawa term

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

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

Coupling : pion decay constant

model-independent interaction at low energy

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

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**

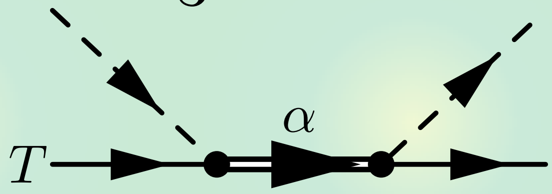
- ○ **Strength should be integer.**
- ○ **Sign is determined for most cases.**

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!**

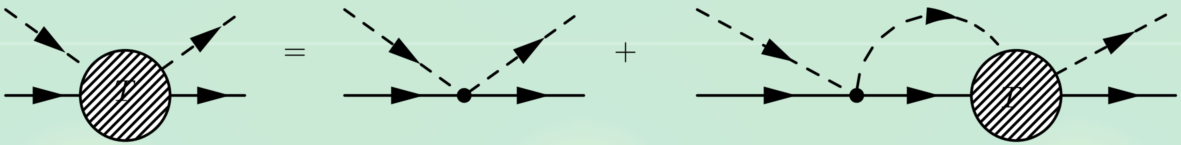
Universal attraction for more “exotic” channel

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

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)

Matching with the u-channel amplitude : OK

Bound state:

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

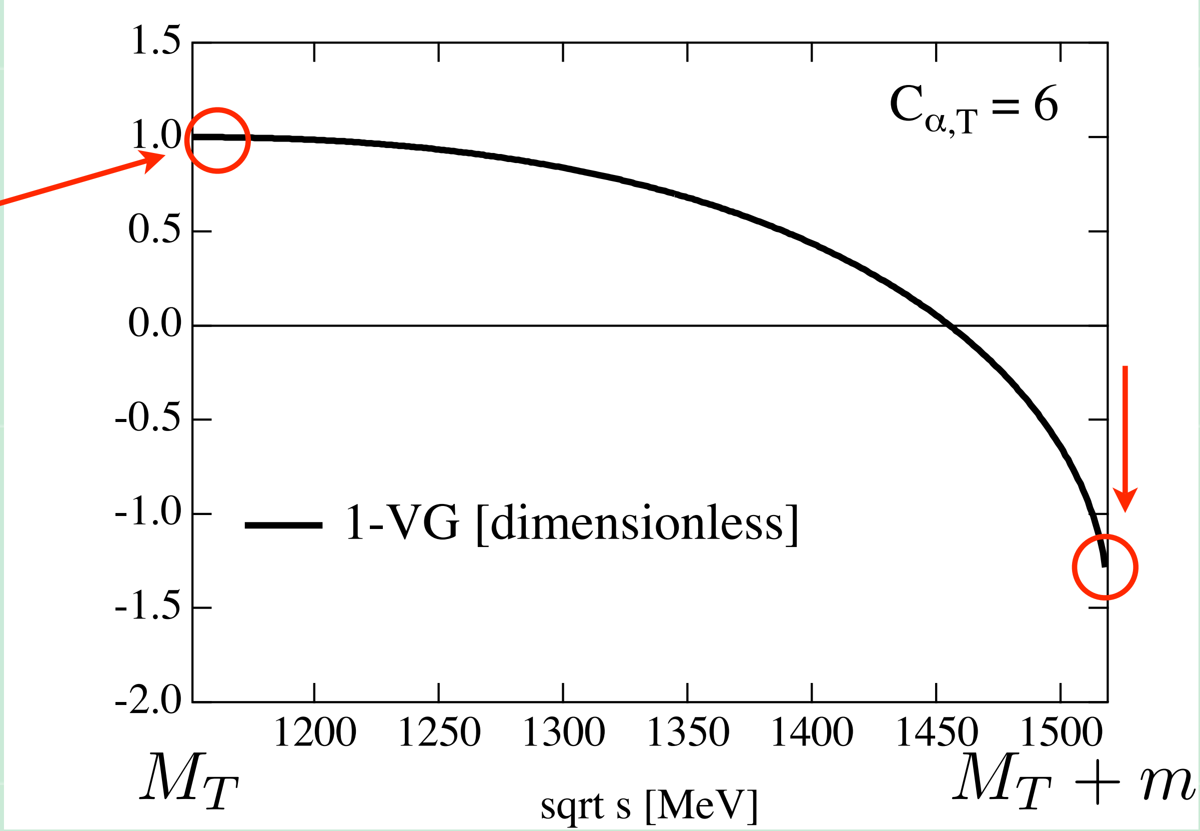
Critical attraction

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

Fixed

$G(M_T) = 0$

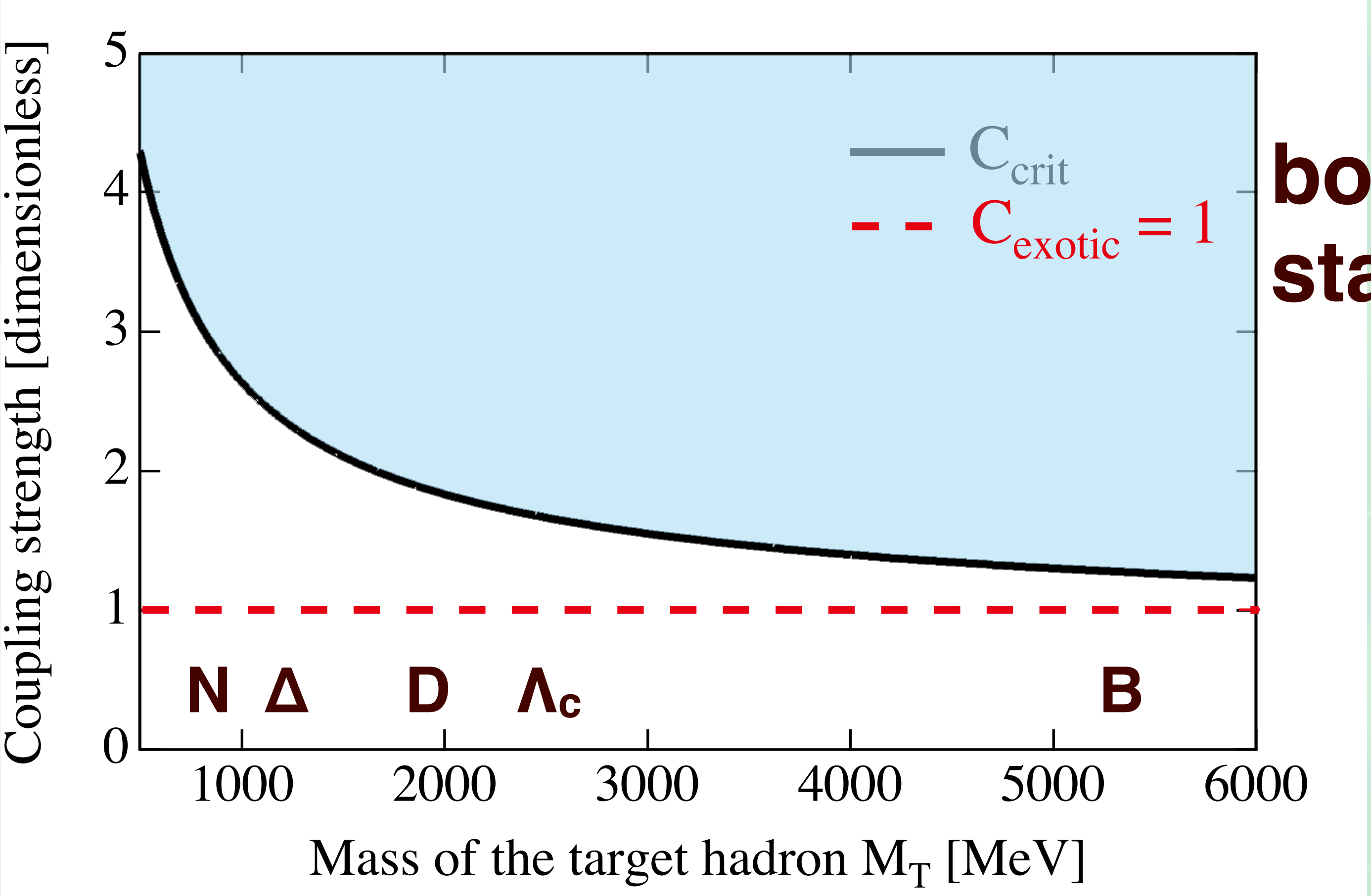
$1 - VG = 1$



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

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

Critical attraction and exotic channel



bound state

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

→ **Strength is not enough.**

Large Nc limit : introduction

1/Nc : a possible expansion parameter

G. ‘t Hooft, Nucl. Phys. B72, 461 (1974)
E. Witten, Nucl. Phys. B160, 57 (1979)

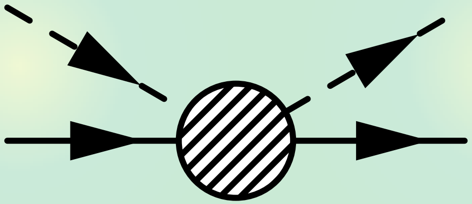
Scaling of the physical quantities <- Nc^2 gluons and Nc quarks.

Meson mass : $m \sim \mathcal{O}(1)$

Baryon mass : $M \sim \mathcal{O}(N_c)$

Decay constant : $f \sim \mathcal{O}(\sqrt{N_c})$

MB scattering :



$\sim \mathcal{O}(1)$

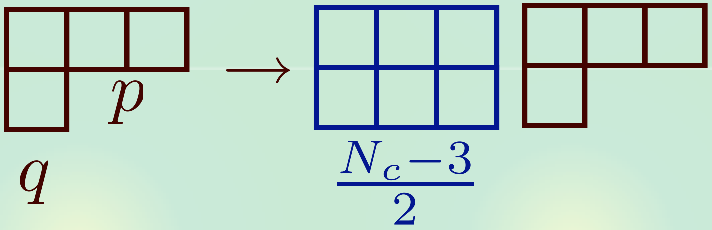
Coupling strengths in large Nc limit

WT interaction in large Nc limit

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

Flavor representation of baryons

$$[p,q] \to \text{``}[p,q]\text{''} = \left[p, q + \tfrac{N_c - 3}{2}\right]$$



Coupling strength has linear Nc dependence

$$\underline{C_{\text{``}\alpha\text{''},\text{``}T\text{''}}(N_c)} = C_2(\text{``}T\text{''}) - C_2(\text{``}\alpha\text{''}) + 3$$

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

Coupling strengths for the general target

For arbitrary Nc, $V \propto -\frac{C}{f^2} \sim -\frac{C(N_c)}{N_c}$

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

○ **No attraction in exotic channels.**

Coupling strengths : Examples

Coupling strengths with arbitrary Nc

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

α	“1”	“8”	“10”	“$\overline{10}$”	“27”	“35”
$T =$ “8”	$\frac{9+N_c}{2}$	3	0	$\frac{3-N_c}{2}$	$\frac{-2-N_c}{2}$	
$T =$ “10”		6	3		$\frac{5-N_c}{2}$	$\frac{-3-N_c}{2}$

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

- ○ **Exotic attraction -> repulsive**
- ○ **Two poles of Λ(1405)?**

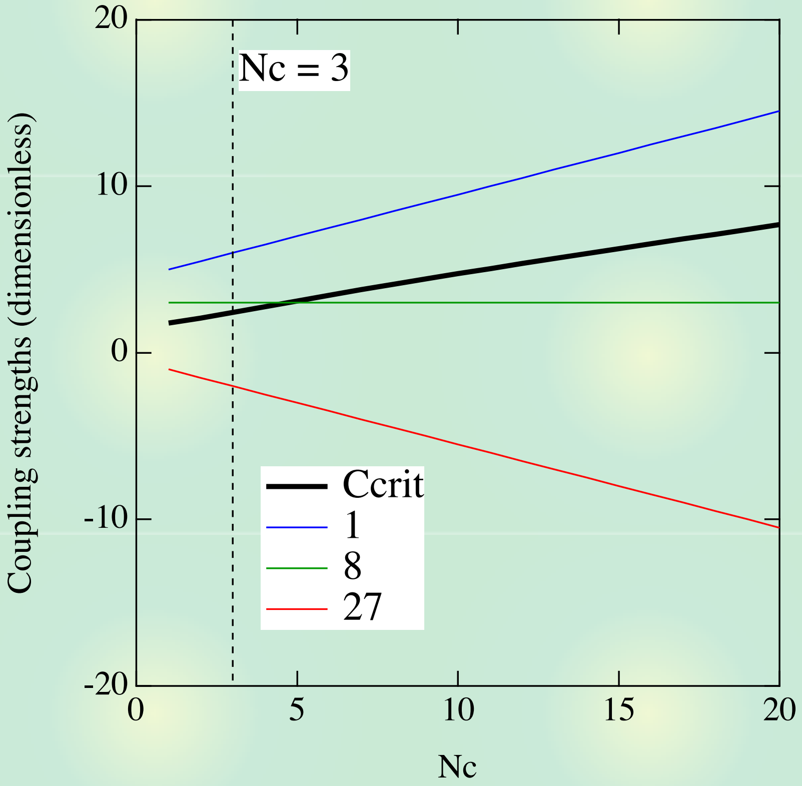
S = -1 I = 0 channel in SU(3) basis

α	"1"	"8_s"	"8_a"	"27"
$T =$ "8"	$\frac{9+N_c}{2}$	3	3	$\frac{-2-N_c}{2}$

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

$$M_T(N_c) = M_0 \times \frac{N_c}{3}$$

$$f(N_c) = f_0 \times \sqrt{\frac{N_c}{3}}$$



○ **Bound state in "1" in the large Nc limit.**

S = -1 I = 0 channel in Isospin basis

Basis transformation via CG Coef. with Nc

T.D. Cohen, and R.F. Lebed, Phys. Rev. D 70, 096015 (2004)

$$\begin{array}{cc}
 & \begin{array}{cccc} \bar{K}N & \pi\Sigma & \eta\Lambda & K\Xi \end{array} \\
C_{ij}(N_c) = & \begin{pmatrix}
\frac{1}{2}(3+N_c) & -\frac{\sqrt{3}}{2}\sqrt{-1+N_c} & \frac{\sqrt{3}}{2}\sqrt{3+N_c} & 0 \\
-\frac{\sqrt{3}}{2}\sqrt{-1+N_c} & 4 & 0 & \frac{\sqrt{3+N_c}}{2} \\
\frac{\sqrt{3}}{2}\sqrt{3+N_c} & 0 & 0 & -\frac{\sqrt{3}}{2}\sqrt{-1+N_c} \\
0 & \frac{\sqrt{3+N_c}}{2} & -\frac{\sqrt{3}}{2}\sqrt{-1+N_c} & \frac{1}{2}(9-N_c)
\end{pmatrix}
\end{array}$$

Combining with the 1/Nc factor of $1/f^2$,

- $\bar{K}N$ -> $\bar{K}N$: attractive at large Nc
- $\bar{K}N$ -> $\pi\Sigma$: $\mathcal{O}(1/\sqrt{N_c})$
- $\pi\Sigma$ -> $\pi\Sigma$: $\mathcal{O}(1/N_c)$

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 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 dynamics.

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