Exotic hadrons in s-wave chiral dynamics

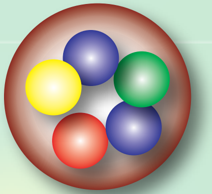
Tetsuo Hyodo[a]

YITP, Kyoto[a]

2007, Feb. 9th

Pentaquark Θ^+

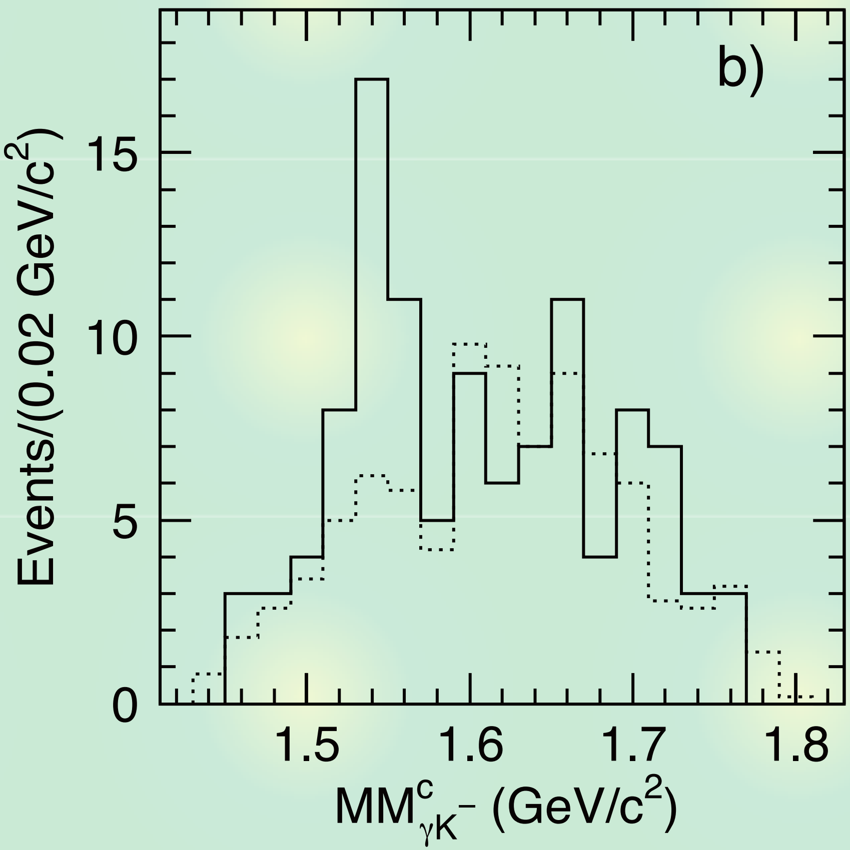
Θ^+ : uudd$\bar{s}$ state



S = +1

Candidate for a manifestly exotic hadron

$$\gamma n \to K^- K^+ n \quad \text{in } C$$

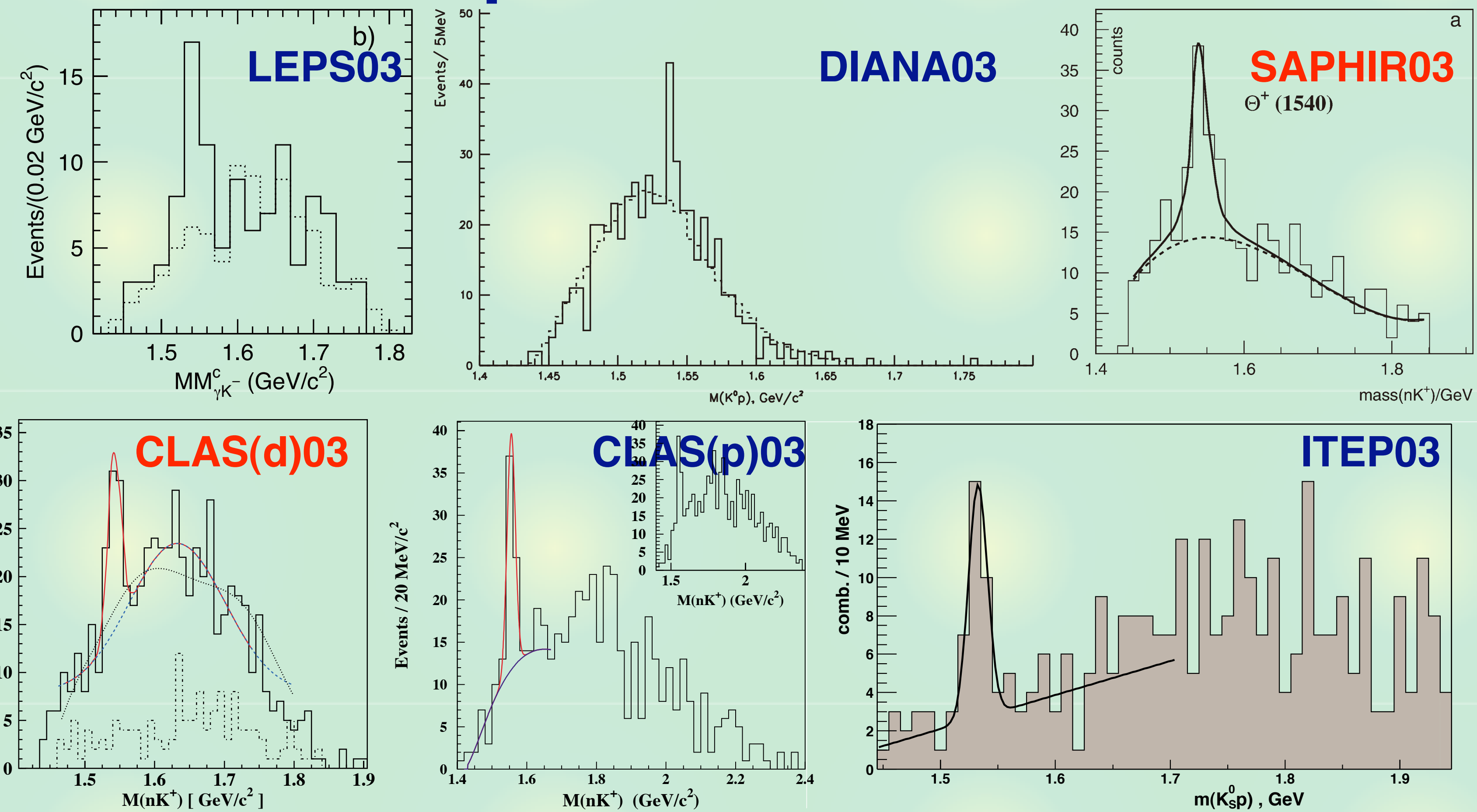


LEPS2003

Let us take a look at experiments

Status of pentaquark Θ⁺

2003 ~ 2004 : 6 positive results

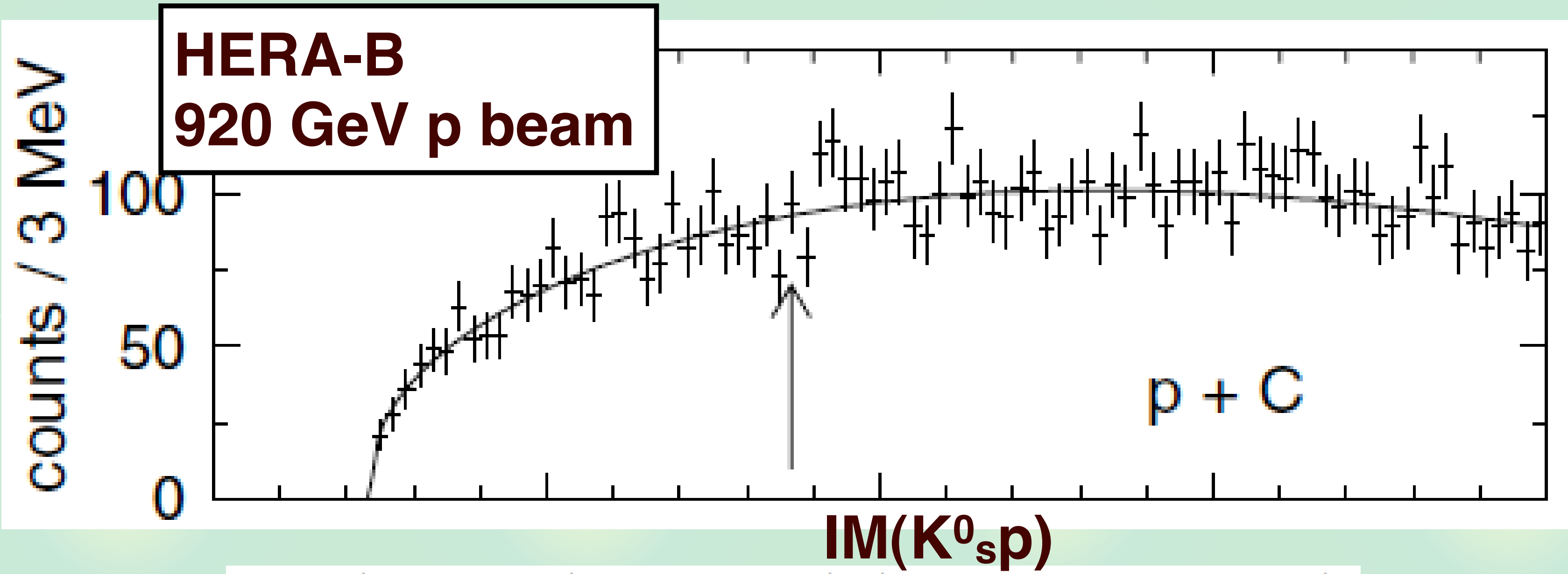


Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

$\Theta(1540)^+$ $\qquad$ $I(J^P) = 0(?^?)$ $\quad$ Status: ∗∗∗

Status of pentaquark Θ^+

~ 2005 : 12 positive results,
7 negative (high-energy inclusive).



elman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) and 2005 partial update for edition 2006 (UR

$\Theta(1540)^+$ $I(J^P) = 0(?^?)$ Status: $**$

*** limited number of resonances are observed in high energy exp.**

Status of pentaquark Θ^+

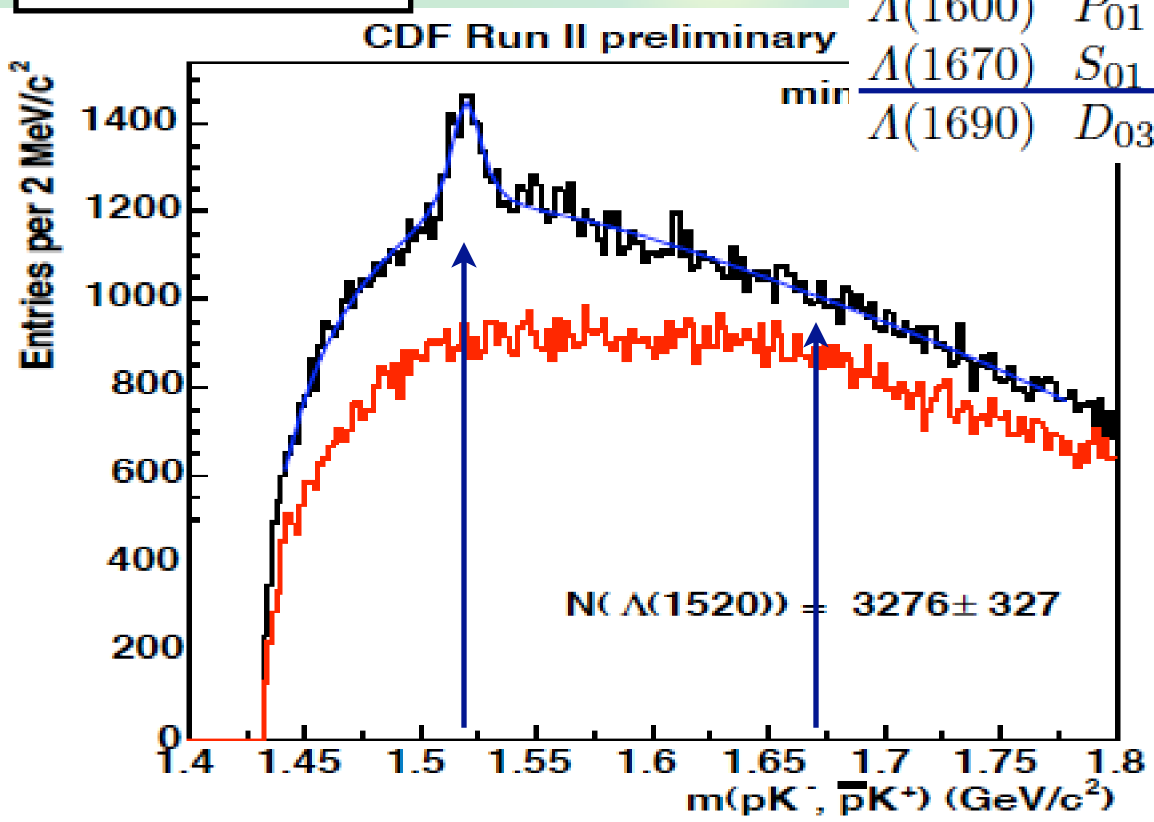
What about Λ(1670)?

Particle	$L_{I \cdot 2J}$	Overall status	$N\overline{K}$
$\Lambda(1116)$	P_{01}	****	
$\Lambda(1405)$	S_{01}	****	****
$\Lambda(1520)$	D_{03}	****	****
$\Lambda(1600)$	P_{01}	***	***
$\Lambda(1670)$	S_{01}	****	****
$\Lambda(1690)$	D_{03}	****	****

Γ = 15 MeV

Γ = 35 MeV

CDF
1.96 TeV $p\bar{p}$



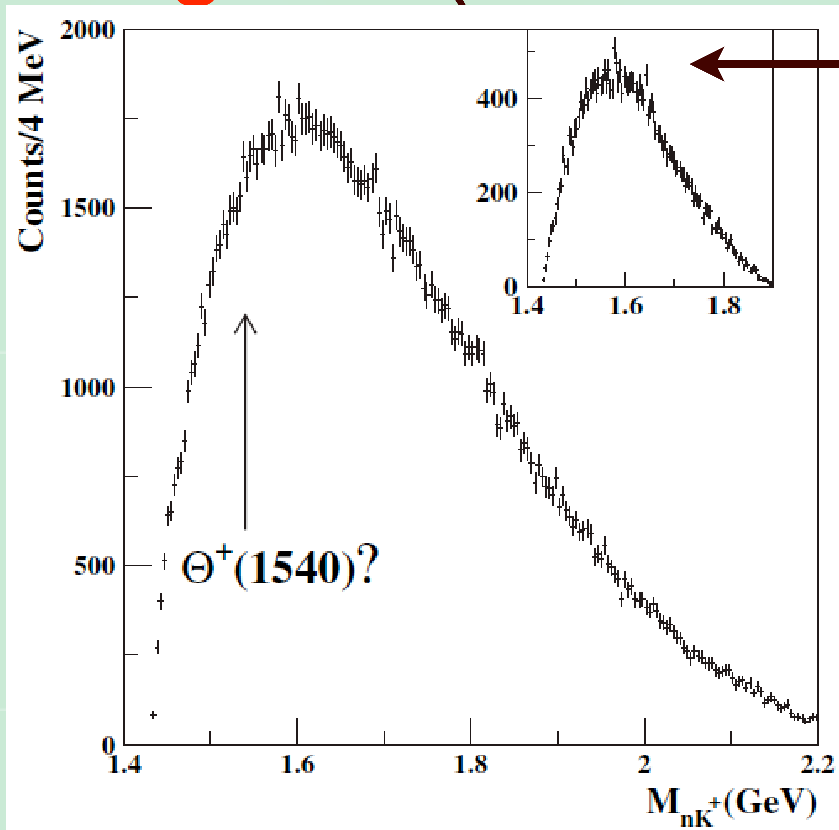
Same argument:
Σ(1670) in K^0p?
Γ = 60 MeV

Status of pentaquark Θ⁺

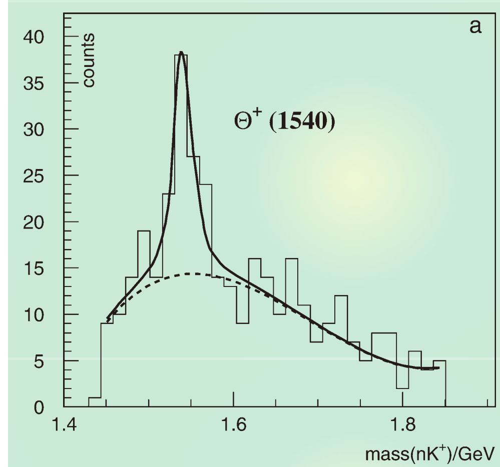
~ present : 14 positive results, 13 negative (also in low energy)

CLAS06

$$\gamma p \to \bar{K}^0 K^+ n$$



Same kinematical cuts with SAPHIR03



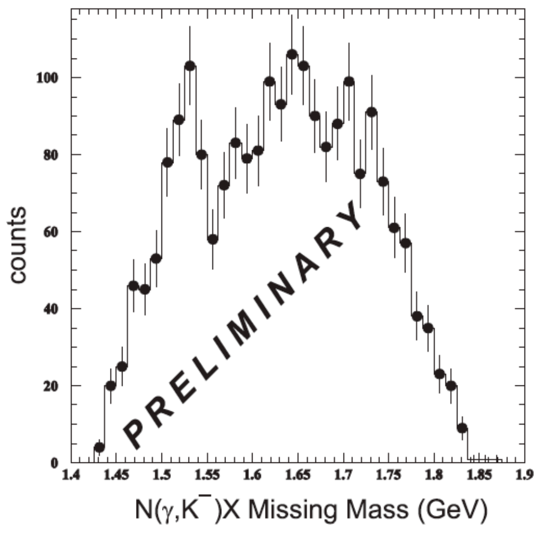
Citation: W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006) (URL: http://pdg.lbl.gov)

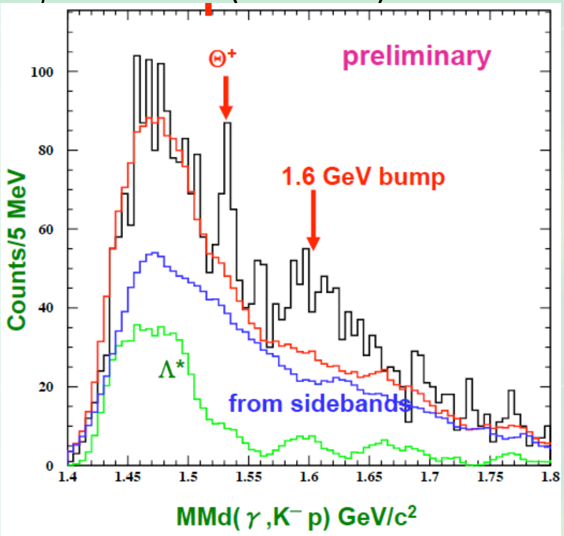
$\Theta(1540)^+$ $I(J^P) = 0(?^?)$ Status: *

Status of pentaquark Θ^+

New positive(?) results:

LEPS $\gamma n \to K^- K^+ n \quad \text{in } d$ $\qquad \gamma d \to \Lambda(1520) K N$

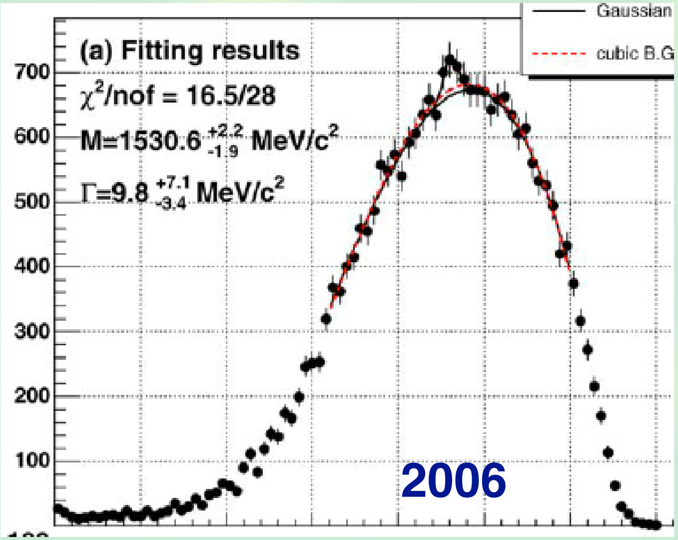




See Titov et al, PRC2006

KEK

$\pi^- p \to K^- X$

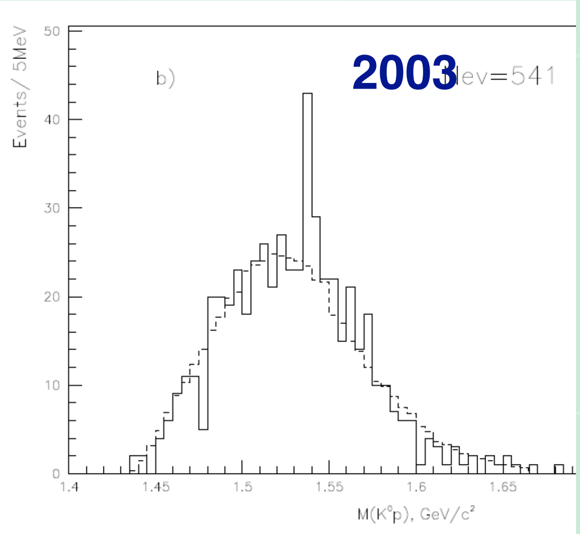


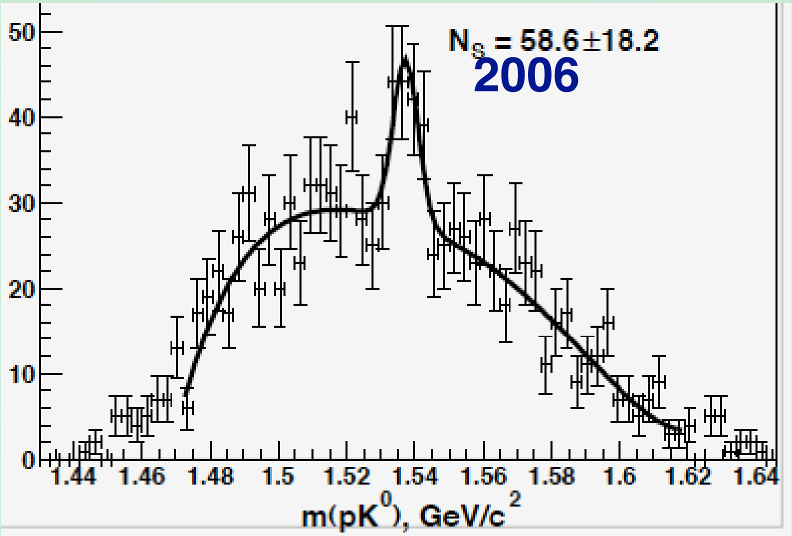
Status of pentaquark Θ⁺

Updated positive results:

DIANA

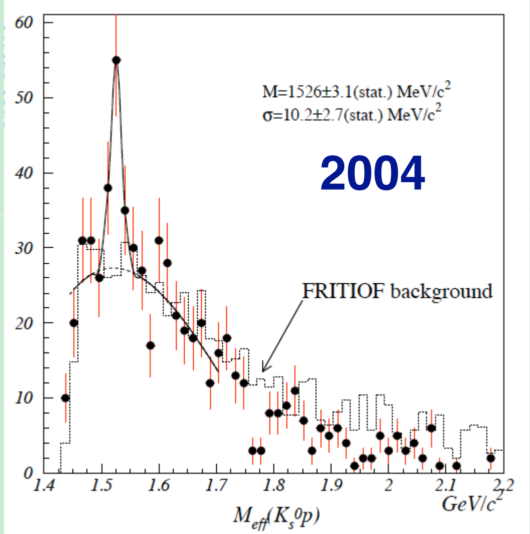
$K^+ n \to K^0 p \quad \text{in } Xe$

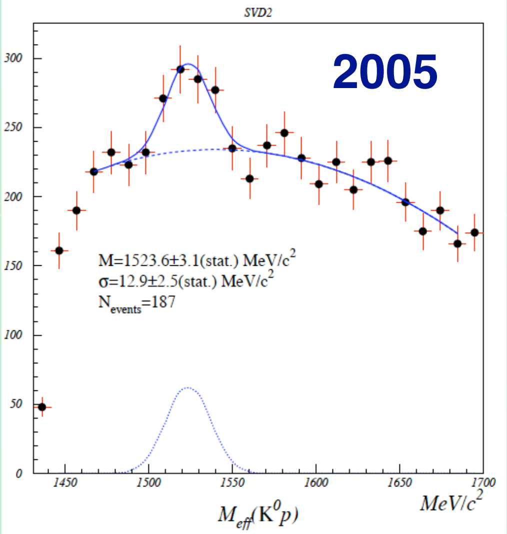




SVD

$pA \to pK^0_s + X$



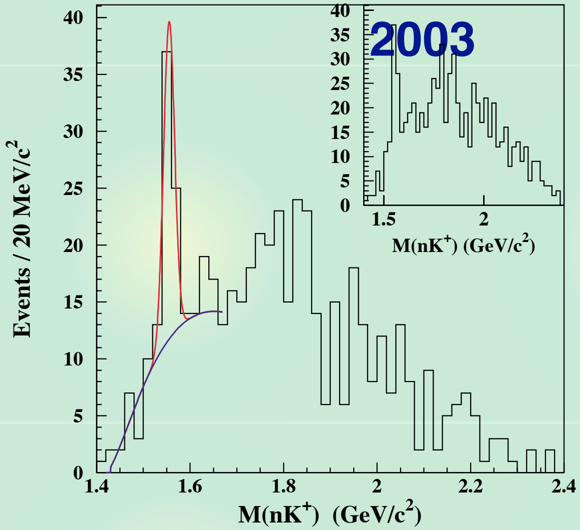


Status of pentaquark Θ+

Remaining (not yet denied) positive results:

CLAS(p)

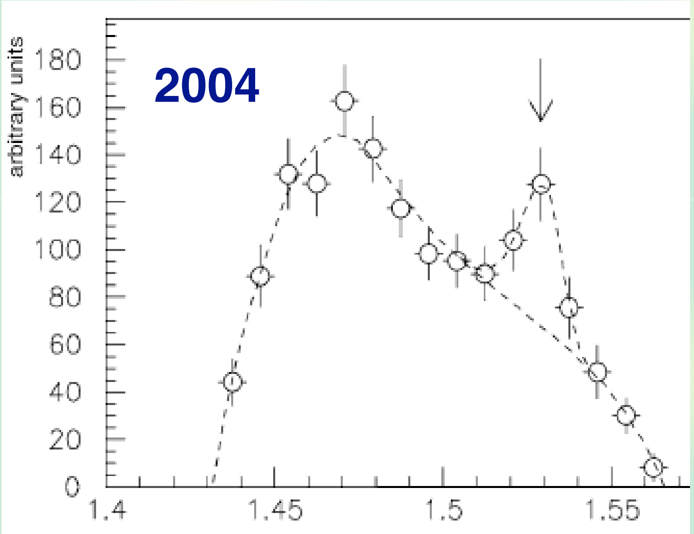
$\gamma p \to \pi^+ K^- K^+ n$



7 sigma!!
The experiment will be run in 2007

COSY-TOF

$pp \to p K^0 \Sigma^+$



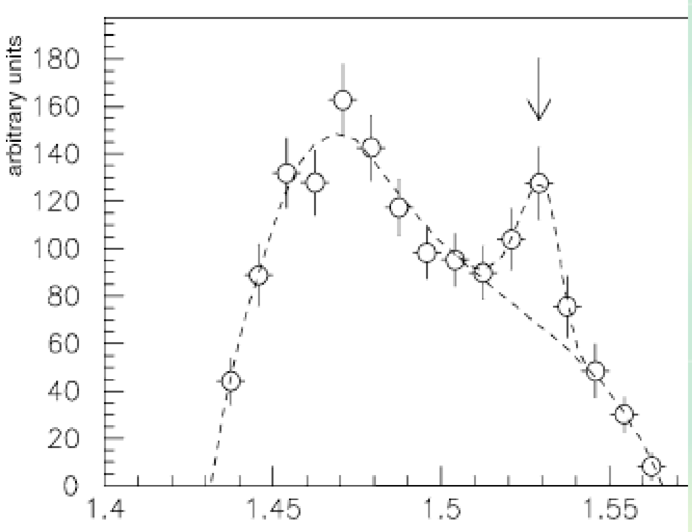
4-6 sigma
Large no. of events!!

last year new data came up...

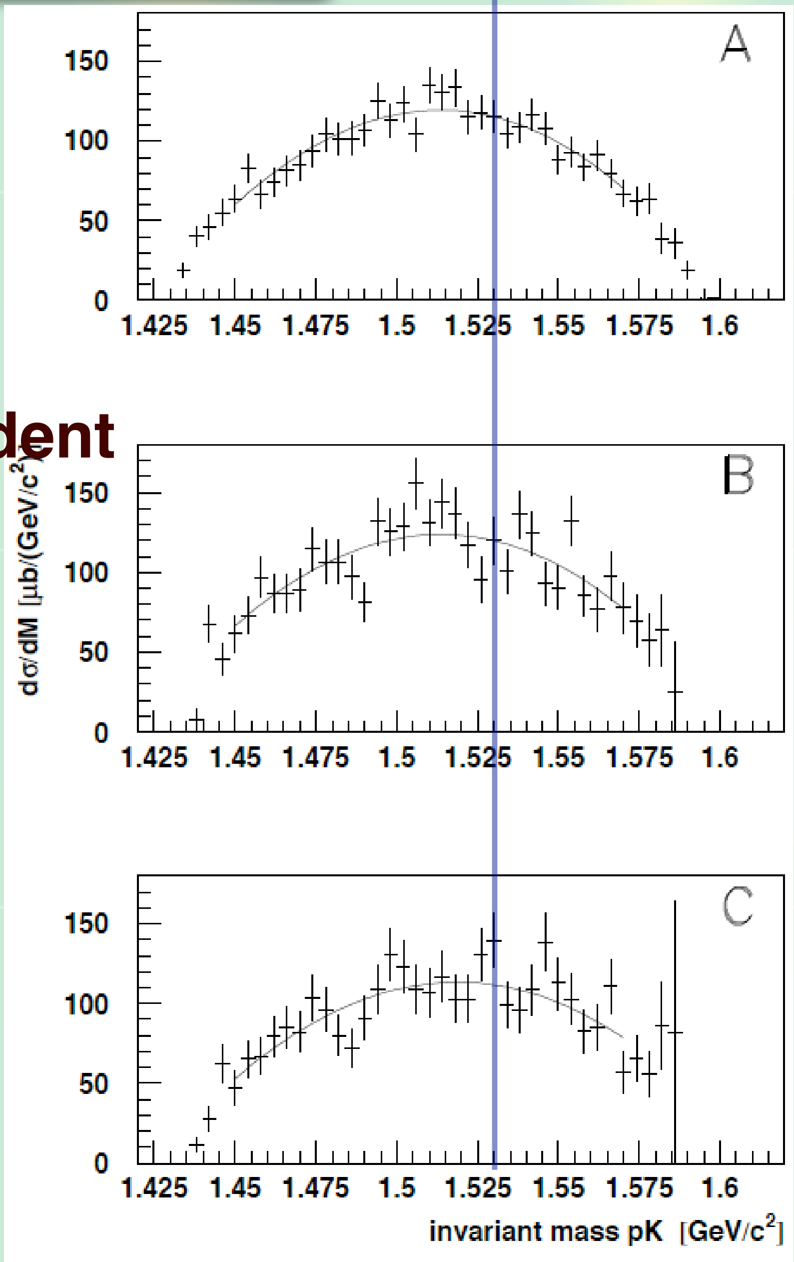
Status of pentaquark Θ⁺

COSY new (hep-ex/0612048)

$$pp \rightarrow pK^0\Sigma^+$$



new data
3 independent analysis



"Analysis does not confirm Θ."
cross section σ < 0.3 μb

Beam energy slightly different
"A" does not tag Σ⁺ decay
previous σ = 0.4 ± 0.1 ± 0.1 μb

Exotic hadrons

Observed hadrons in experiments (PDG06) :

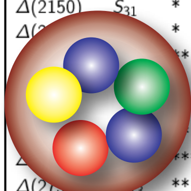
p	P_{11}	****
n	P_{11}	****
$N(1440)$	P_{11}	****
$N(1520)$	D_{13}	****
$N(1535)$	S_{11}	****
$N(1650)$	S_{11}	****
$N(1675)$	D_{15}	****
$N(1680)$	F_{15}	****
$N(1700)$	D_{13}	***
$N(1710)$	P_{11}	***
$N(1720)$	P_{13}	****
$N(1900)$	P_{13}	**
$N(1990)$	F_{17}	**
$N(2000)$	F_{15}	**
$N(2080)$	D_{13}	**
$N(2090)$	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}	*
$\Delta(2$ [illegible]	[illegible]	*
[illegible]	[illegible]	**
[illegible]	[illegible]	****
$\Delta(27$ [illegible]	[illegible]$_{,13}$	**
$\Delta(2950)$	$K_{3,15}$	**
$\Theta(1540)^+$		*

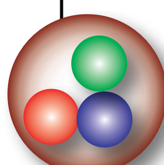
Λ	P_{01}	****
$\Lambda(1405)$	S_{01}	****
$\Lambda(1520)$	D_{03}	****
$\Lambda(1600)$	P_{01}	***
$\Lambda(1670)$	S_{01}	****
$\Lambda(1690)$	D_{03}	****
$\Lambda(1800)$	S_{01}	***
$\Lambda(1810)$	P_{01}	***
$\Lambda(1820)$	F_{05}	****
$\Lambda(1830)$	D_{05}	****
$\Lambda(1890)$	P_{03}	****
$\Lambda(2000)$		*
$\Lambda(2020)$	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		***
$\Xi_c'^+$		***
$\Xi_c'^0$		***
$\Xi_c(2645)$		***
$\Xi_c(2790)$		***
$\Xi_c(2815)$		***
Ω_c^0		***
Ξ_{cc}^+		*
Λ_b^0		***



1 / 286 !

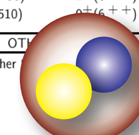


127 baryons

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[illegible]	
$f_2(1640)$	$0^+(2^{++})$	Further [illegible]	
• $\eta_2(1645)$	$0^+(2^{-+})$		
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

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

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	



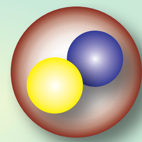
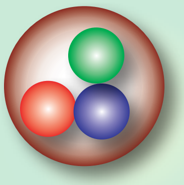
159 mesons

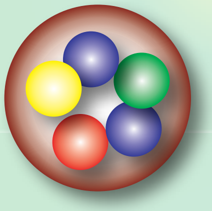
Exotic hadrons are indeed exotic !!

Motivation 1 : Exotic hadrons

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

Experimentally, they are **exotic**.

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 ~ π T

- ○ 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)

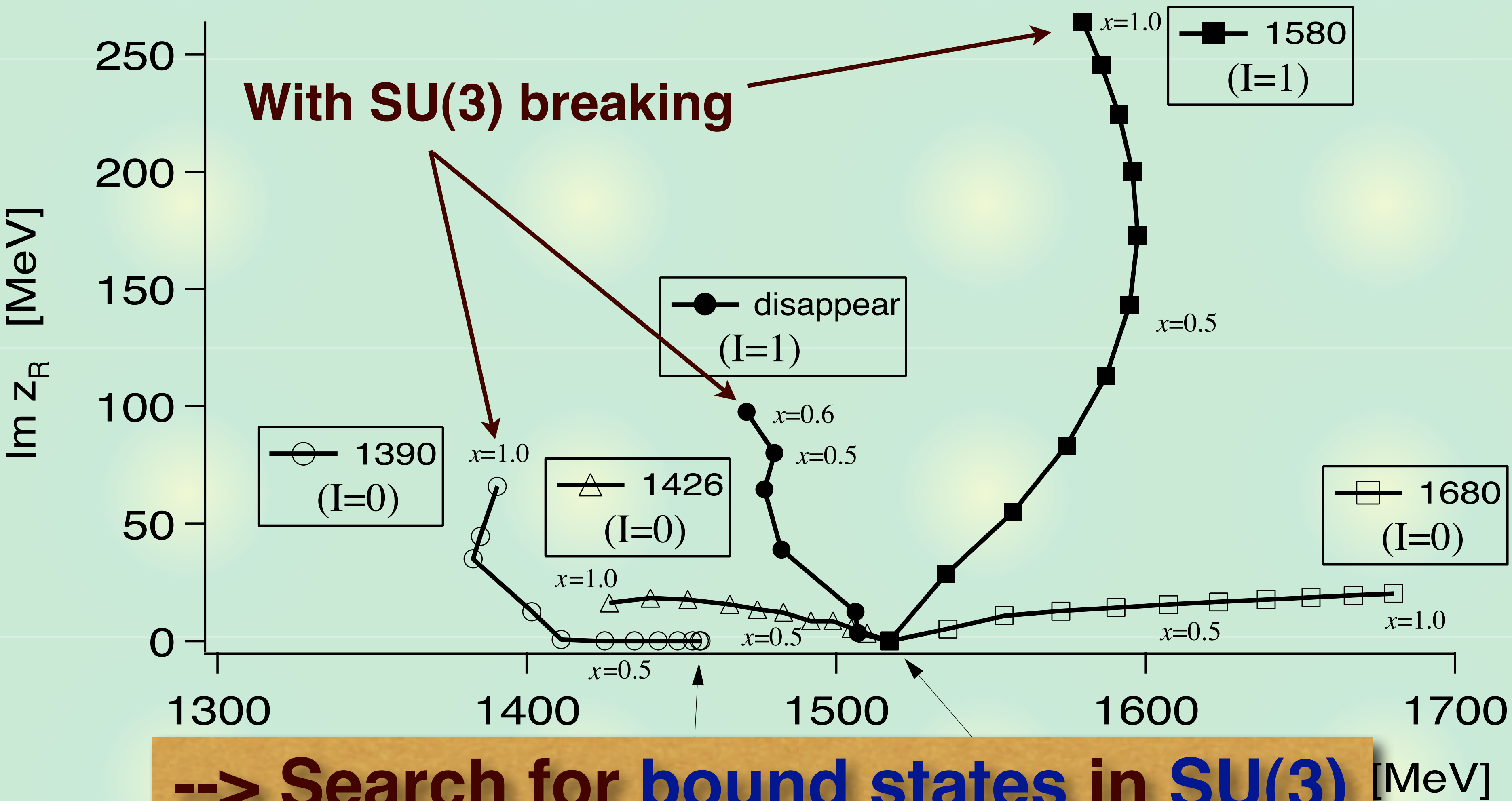
Many hadron resonances (Λ(1405), N(1535), Λ(1520), D_s(2317),...) are well described.

What about exotic hadrons?

Origin of the resonances

Pole positions :

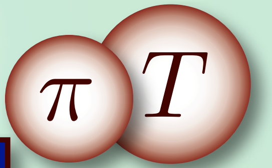
D. Jido, *et al.*, Nucl. Phys. A 723, 205 (2003)



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

Outline

Hadron-NG boson bound state



Chiral Symmetry

s-wave low energy interaction

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

Scattering theory

Critical strength for a bound state

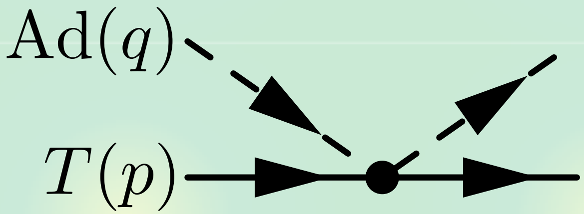
$$C_{\mathrm{crit}} = \frac{2f^2}{m\left(-G(M_T + m)\right)}$$

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

→ **No exotic state exists.**

Low energy s-wave interaction

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

$\alpha \Big[$ 

$\Big]$

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

s-wave : Weinberg-Tomozawa term

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

proportional to pion energy

Coupling : pion decay constant

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

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

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

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

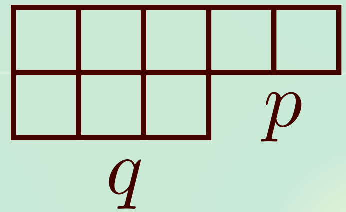
α	$C_{\alpha,T}$	sign
$[p+1, q+1]$	$-p-q$	repulsive
$[p+2, q-1]$	$1-p$	
$[p-1, q+2]$	$1-q$	
$[p, q]$	3	attractive
$[p, q]$	3	attractive
$[p+1, q-2]$	$3+q$	attractive
$[p-2, q+1]$	$3+p$	attractive
$[p-1, q-1]$	$4+p+q$	attractive

- **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,



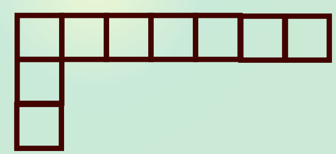
$$E = \epsilon\theta(\epsilon) + \nu\theta(\nu)$$

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

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

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

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



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

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

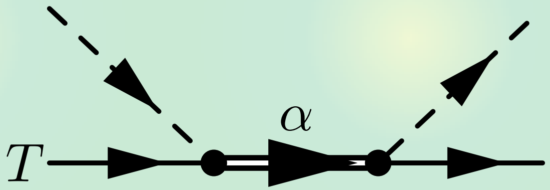
Exotic channels

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!**

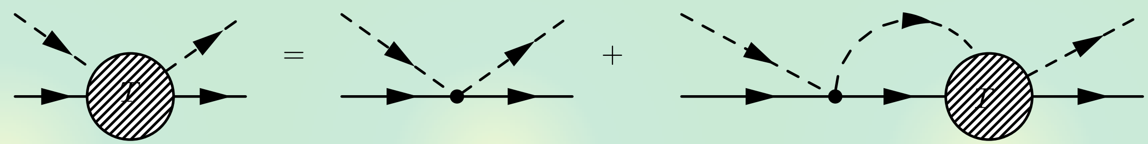
Universal attraction for more "exotic" channel

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

Renormalization and bound states

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

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



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)

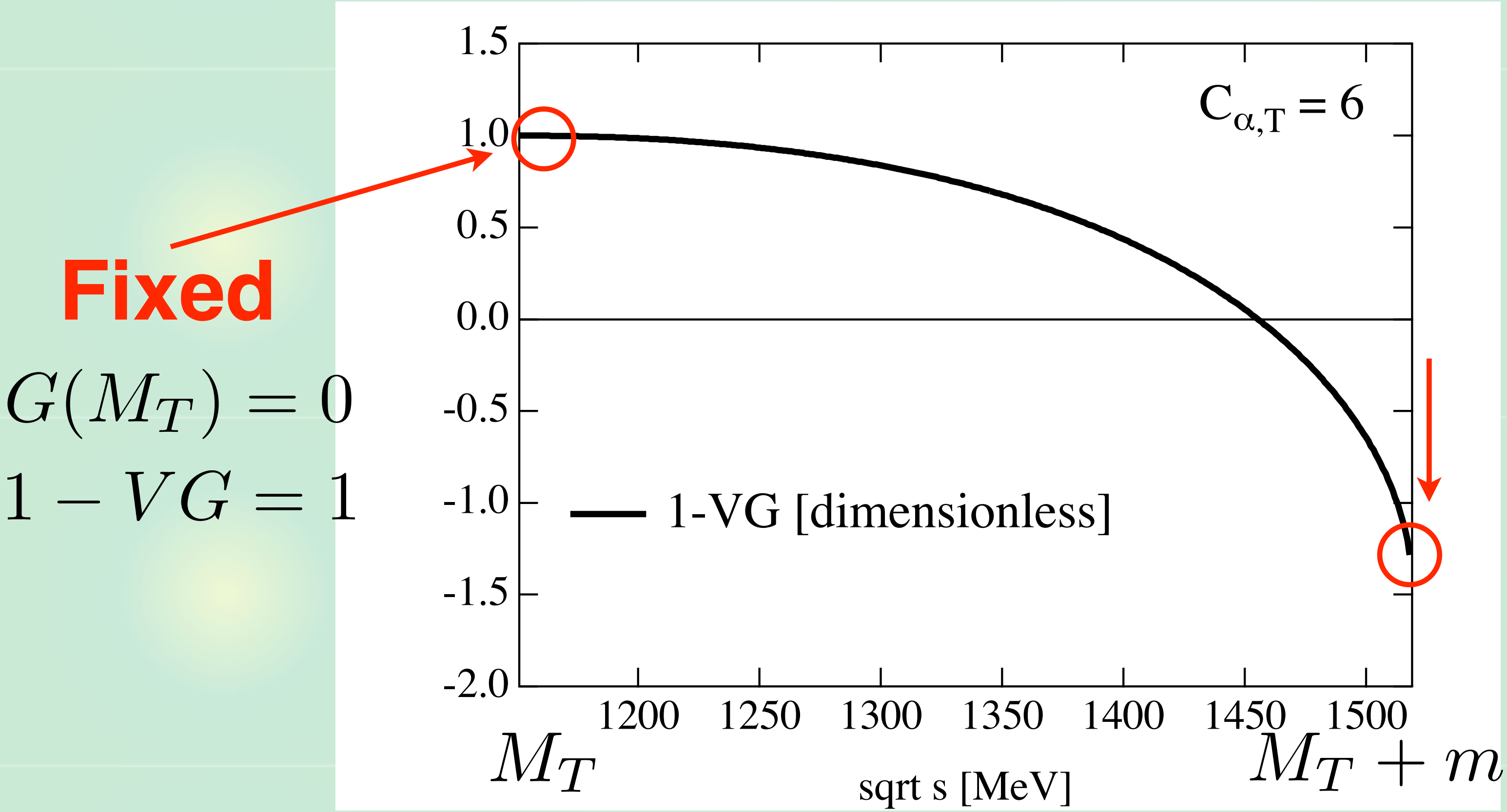
Matching with the u-channel amplitude : OK

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.**

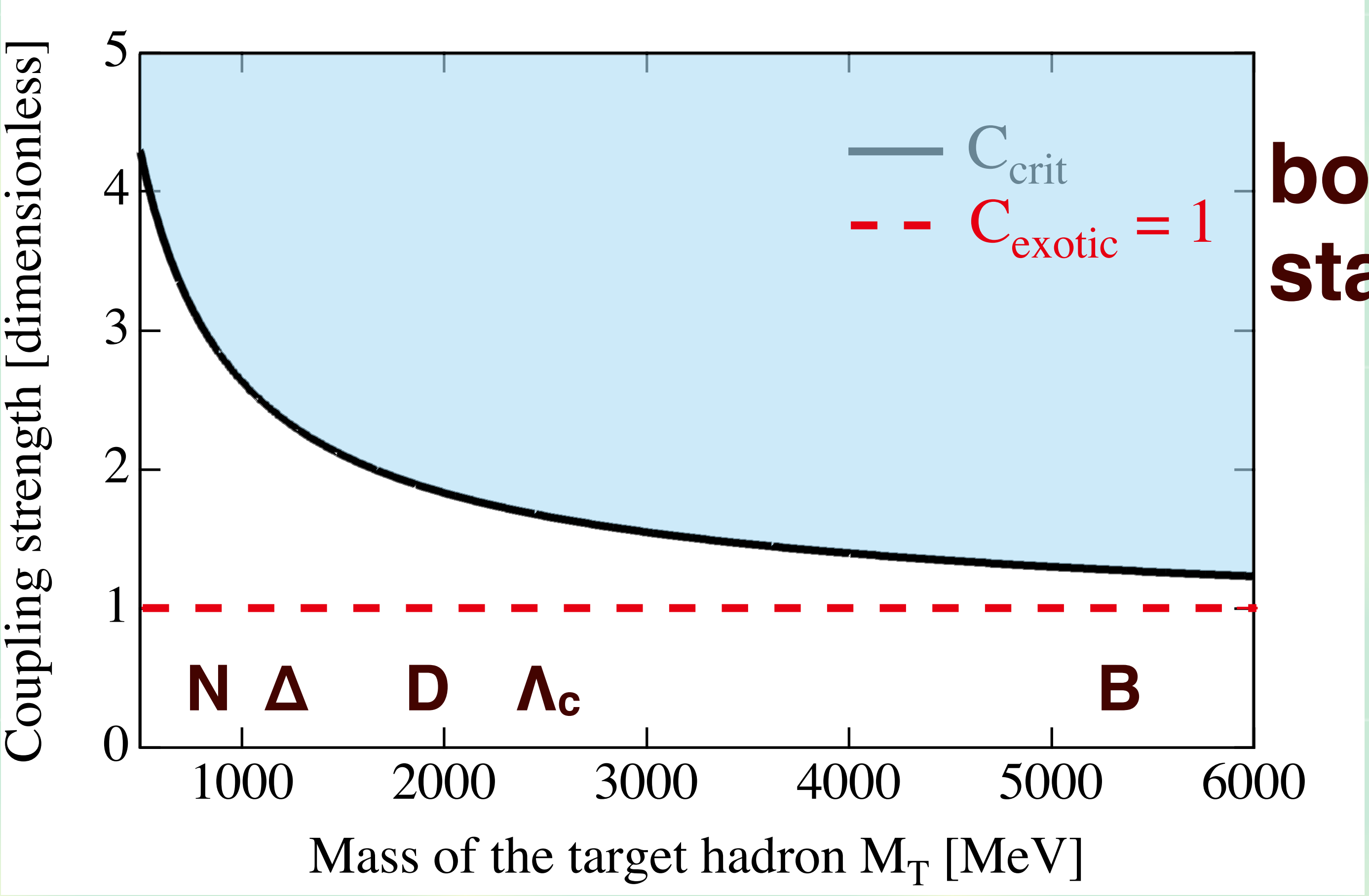


Critical attraction : $1 - VG = 0$ at $\sqrt{s} = M_T + m$

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

Critical attraction and exotic channel

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



bound state

➡ **Strength is not enough.**

Large Nc limit : introduction

1/Nc : a possible expansion parameter

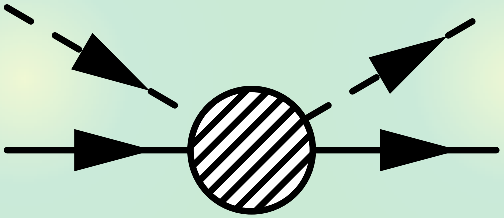
G. 't Hooft, Nucl. Phys. B72, 461 (1974)
E. Witten, Nucl. Phys. B160, 57 (1979)

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

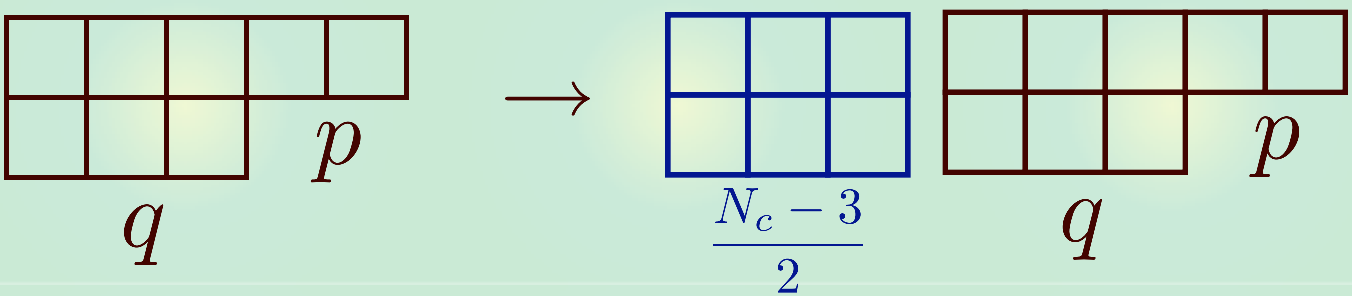
WT interaction in large Nc limit

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

Flavor representation

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

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



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

Non-trivial Nc dependence

Coupling strengths for the general target

For arbitrary Nc,

$$V \propto -\frac{1}{f^2} C \sim \frac{1}{N_c} C(N_c)$$

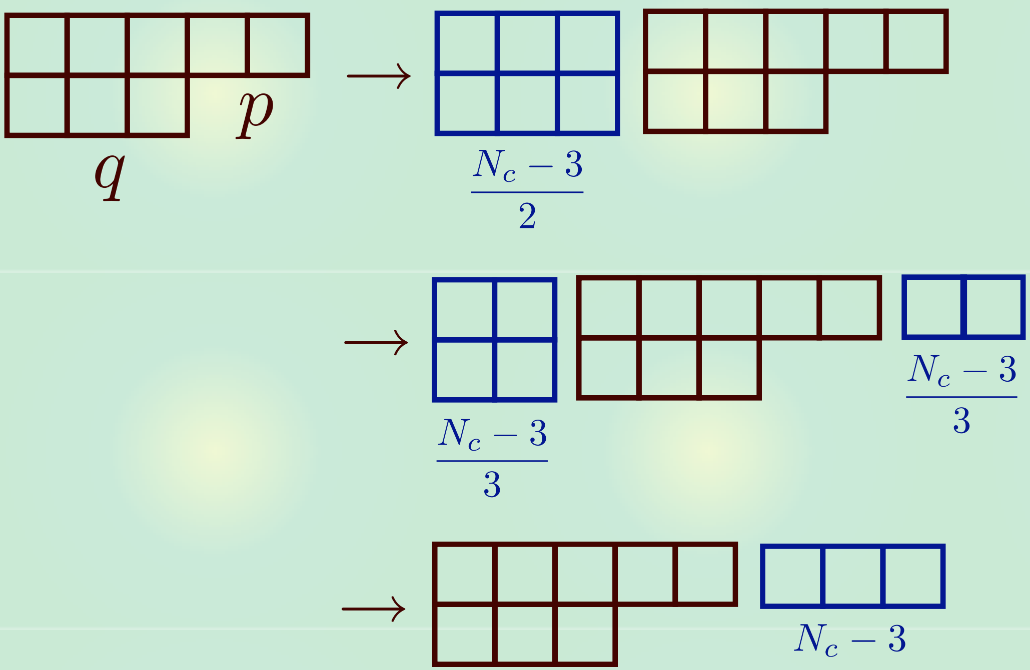
α	$C_{\text{``}\alpha\text{''},\text{``}T\text{''}}(N_c)$	$V(N_c \to \infty)$	ΔE
$[p+1, q+1]$	$(3-N_c)/2 - p - q$	repulsive	1 or 0
$[p+2, q-1]$	$1-p$	0	1 or 0
$[p-1, q+2]$	$(5-N_c)/2 - q$	repulsive	1 or 0
$[p, q]$	3	0	0
$[p, q]$	3	0	0
$[p+1, q-2]$	$(3+N_c)/2 + q$	attractive	0 or -1
$[p-2, q+1]$	$3+p$	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.

Different large Nc extensions

There are different ways for Nc extension :

Dulinski, Acta Phys. Polon. B19, 891 (1988)
Praszalowicz, Talk at YKIS2006



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

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

$$[p,q] \to [p + N_c - 3, q]$$

- **No attraction exists in exotic channels for all extensions.**

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

Attraction -> repulsion

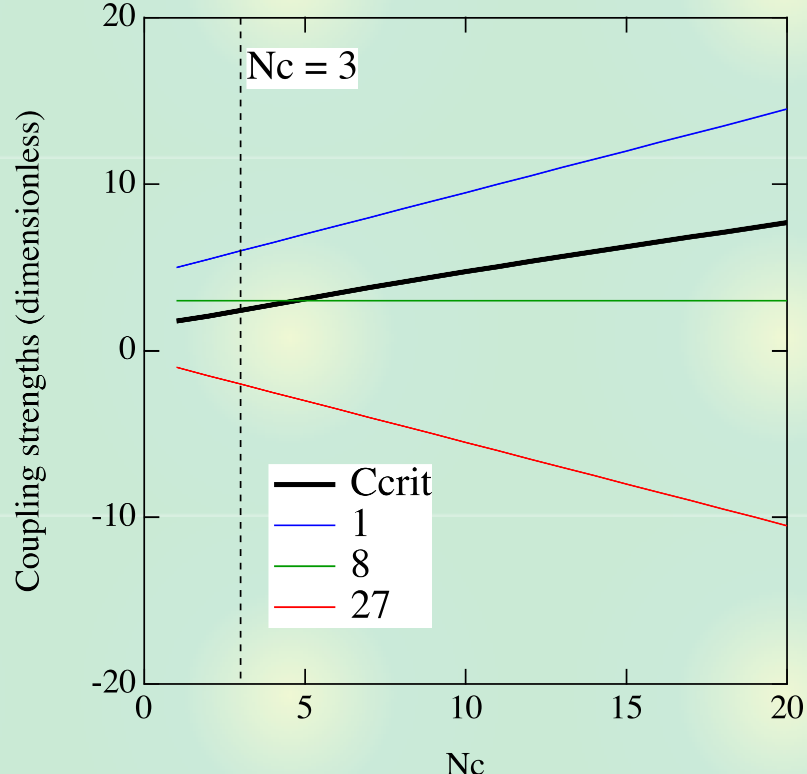
S = -1 I = 0 channel in SU(3) basis

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

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

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

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



○ **Attraction in "1" is strong enough.**

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)

$$\begin{array}{cccc} \bar{K}N & \pi\Sigma & \eta\Lambda & K\Xi \end{array}$$

$$C_{ij}(N_c) = \begin{pmatrix} \frac{1}{2}(3+N_c) & -\frac{\sqrt{3}}{2}\sqrt{-1+N_c} & \frac{\sqrt{3}}{2}\sqrt{3+N_c} & 0 \\ -\frac{\sqrt{3}}{2}\sqrt{-1+N_c} & 4 & 0 & \frac{\sqrt{3+N_c}}{2} \\ \frac{\sqrt{3}}{2}\sqrt{3+N_c} & 0 & 0 & -\frac{\sqrt{3}}{2}\sqrt{-1+N_c} \\ 0 & \frac{\sqrt{3+N_c}}{2} & -\frac{\sqrt{3}}{2}\sqrt{-1+N_c} & \frac{1}{2}(9-N_c) \end{pmatrix}$$

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

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

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 : $C_{\text{exotic}} < C_{\text{crit}}$
- **No attractive interaction exists** in exotic channels in the large Nc limit.

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