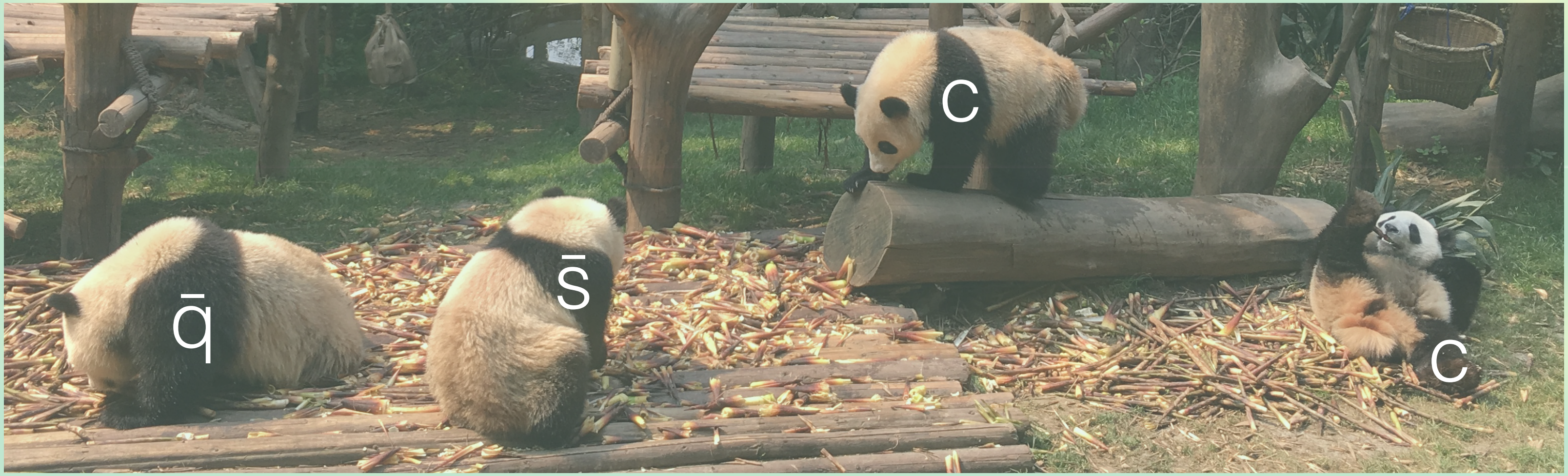
Exotic hadrons and emergent long range correlation in QCD



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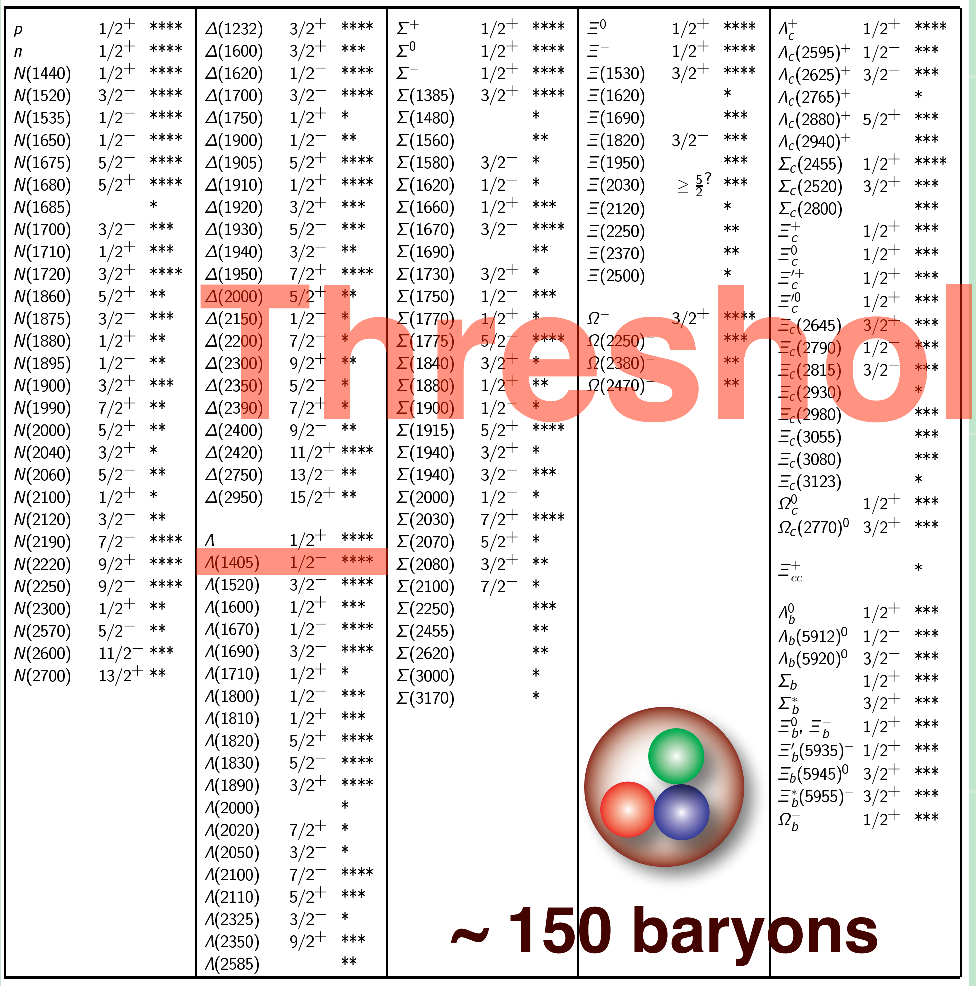
Classification of hadrons

Observed hadrons

PDG2018 : http://pdg.lbl.gov/



p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	**
$N(1895)$	$1/2^-$	**
$N(1900)$	$3/2^+$	***
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$		*
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2050)$	$3/2^-$	*
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

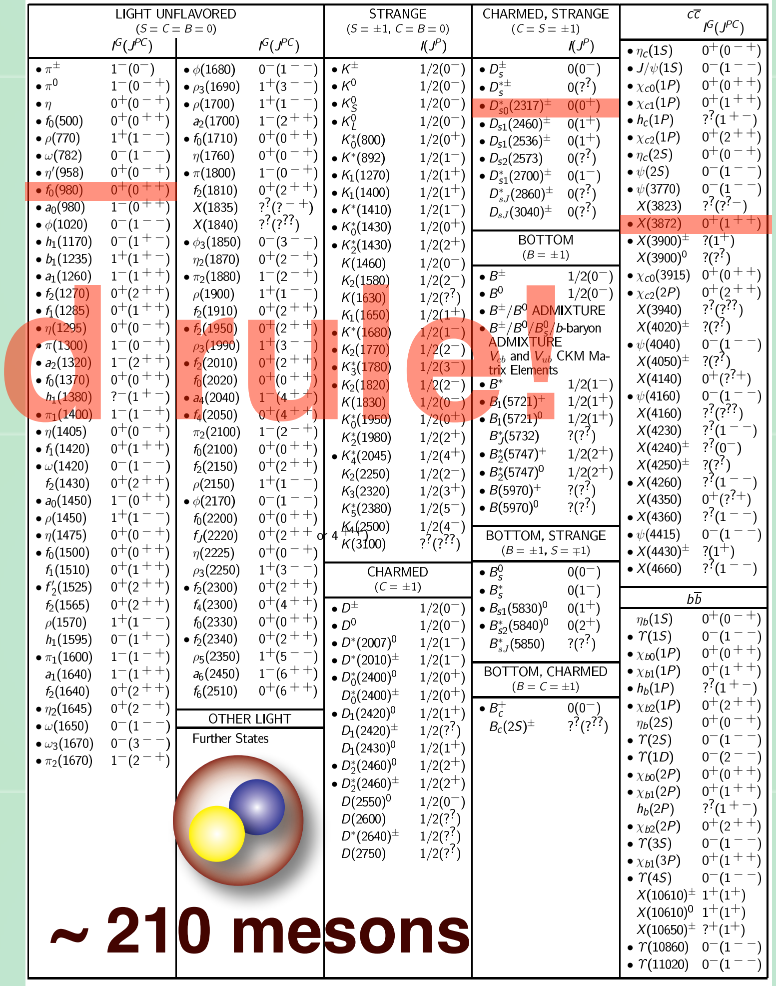
Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$		**
$\Sigma(1730)$	$3/2^+$	*
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1770)$	$1/2^+$	*
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1840)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1900)$	$1/2^-$	*
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^+$	*
$\Sigma(1940)$	$3/2^-$	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*
Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
$\Xi_b'(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b^*(5955)^-$	$3/2^+$	***
Ω_b^-	$1/2^+$	***

~ 150 baryons

Threshold rule!



LIGHT UNFLAVORED ($S = C = B = 0$)	$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$
• π^0	$1^-(0^{-+})$
• η	$0^+(0^{-+})$
• $f_0(500)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$
• $\omega(782)$	$0^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$
• $\phi(1020)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$
• $b_1(1235)$	$1^+(1^{+-})$
• $a_1(1260)$	$1^-(1^{++})$
• $f_2(1270)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$
• $\eta(1295)$	$0^+(0^{-+})$
• $\pi(1300)$	$1^-(0^{-+})$
• $a_2(1320)$	$1^-(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$
• $\pi_1(1400)$	$1^-(1^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$
• $f_1(1420)$	$0^+(1^{++})$
• $\omega(1420)$	$0^-(1^{--})$
$f_2(1430)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$
• $f_0(1500)$	$0^+(0^{++})$
$f_1(1510)$	$0^+(1^{++})$
• $f_2'(1525)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$
$h_1(1595)$	$0^-(1^{+-})$
• $\pi_1(1600)$	$1^-(1^{-+})$
$a_1(1640)$	$1^-(1^{++})$
$f_2(1640)$	$0^+(2^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$
• $\omega(1650)$	$0^-(1^{--})$
• $\omega_3(1670)$	$0^-(3^{--})$
• $\pi_2(1670)$	$1^-(2^{-+})$

	$I^G(J^{PC})$
• $\phi(1680)$	$0^-(1^{--})$
• $\rho_3(1690)$	$1^+(3^{--})$
• $\rho(1700)$	$1^+(1^{--})$
$a_2(1700)$	$1^-(2^{++})$
• $f_0(1710)$	$0^+(0^{++})$
$\eta(1760)$	$0^+(0^{-+})$
• $\pi(1800)$	$1^-(0^{-+})$
$f_2(1810)$	$0^+(2^{++})$
$X(1835)$	$?^?(?^{-+})$
$X(1840)$	$?^?(?^{??})$
• $\phi_3(1850)$	$0^-(3^{--})$
$\eta_2(1870)$	$0^+(2^{-+})$
• $\pi_2(1880)$	$1^-(2^{-+})$
$\rho(1900)$	$1^+(1^{--})$
$f_2(1910)$	$0^+(2^{++})$
• $f_2(1950)$	$0^+(2^{++})$
$\rho_3(1990)$	$1^+(3^{--})$
• $f_2(2010)$	$0^+(2^{++})$
$f_0(2020)$	$0^+(0^{++})$
• $a_4(2040)$	$1^-(4^{++})$
• $f_4(2050)$	$0^+(4^{++})$
$\pi_2(2100)$	$1^-(2^{-+})$
$f_0(2100)$	$0^+(0^{++})$
$f_2(2150)$	$0^+(2^{++})$
$\rho(2150)$	$1^+(1^{--})$
• $\phi(2170)$	$0^-(1^{--})$
$f_0(2200)$	$0^+(0^{++})$
$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$\eta(2225)$	$0^+(0^{-+})$
$\rho_3(2250)$	$1^+(3^{--})$
• $f_2(2300)$	$0^+(2^{++})$
$f_4(2300)$	$0^+(4^{++})$
$f_0(2330)$	$0^+(0^{++})$
• $f_2(2340)$	$0^+(2^{++})$
$\rho_5(2350)$	$1^+(5^{--})$
$a_6(2450)$	$1^-(6^{++})$
$f_6(2510)$	$0^+(6^{++})$

OTHER LIGHT

Further States

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	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(0^-)$
$D(2600)$	$1/2(?^?)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2750)$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)$	$0(?^?)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{sJ}^*(2860)^\pm$	$0(?^?)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)	
• $B^\pm$	$1/2(0^-)$
• 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^*	$1/2(1^-)$
• $B_1(5721)^+$	$1/2(1^+)$
• $B_1(5721)^0$	$1/2(1^+)$
$B_J^*(5732)$	$?(?^?)$
• $B_2^*(5747)^+$	$1/2(2^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$
• $B(5970)^+$	$?(?^?)$
• $B(5970)^0$	$?(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)	
• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)	
• B_c^+	$0(0^-)$
$B_c(2S)^\pm$	$?^?(?^{??})$

$c\overline{c}$	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
$X(3823)$	$?^?(?^{?-})$
• $X(3872)$	$0^+(1^{++})$
• $X(3900)^\pm$	$?(1^+)$
$X(3900)^0$	$?(?^?)$
• $\chi_{c0}(3915)$	$0^+(0^{++})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
$X(4020)^\pm$	$?(?^?)$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4230)$	$?^?(1^{--})$
$X(4240)^\pm$	$?^?(0^-)$
$X(4250)^\pm$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
• $X(4430)^\pm$	$?(1^+)$
• $X(4660)$	$?^?(1^{--})$

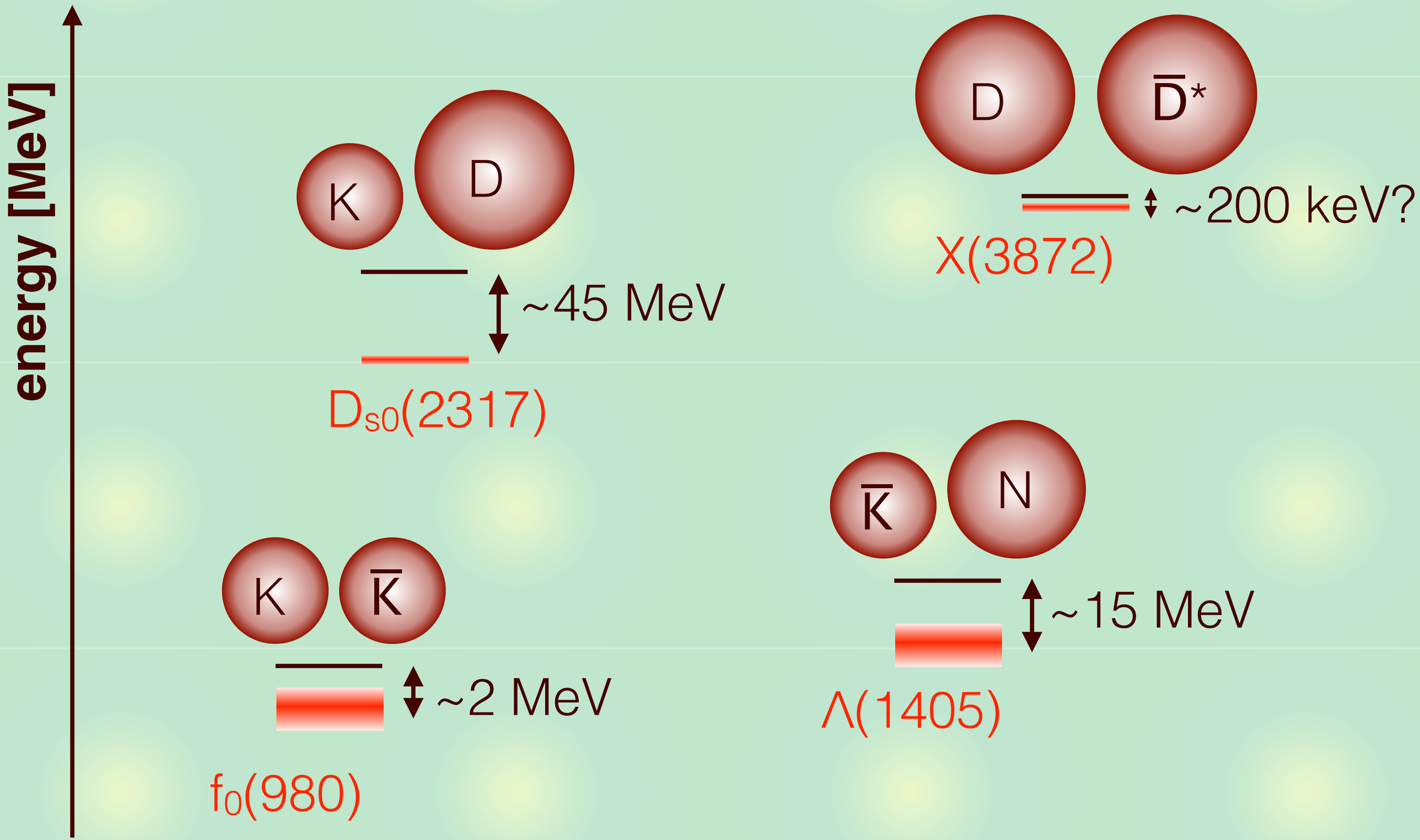
$b\overline{b}$	
$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$?^?(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$?^?(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_{b1}(3P)$	$0^+(1^{++})$
• $\Upsilon(4S)$	$0^-(1^{--})$
$X(10610)^\pm$	$1^+(1^+)$
$X(10610)^0$	$1^+(1^+)$
$X(10650)^\pm$	$?^+(1^+)$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

~ 210 mesons

All ~ 360 hadrons emerge from single QCD Lagrangian.

Threshold rules in hadron spectroscopy

Hadrons near an s-wave two-body threshold



“hadronic molecule” (various flavors, baryon numbers, …)

Two-body universal physics

Near-threshold s-wave state: universal physics

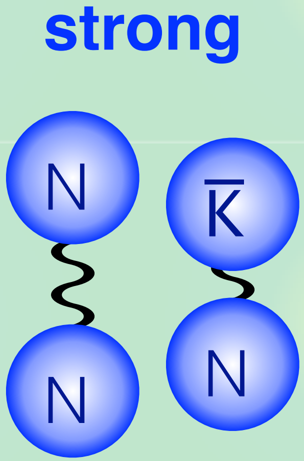
E. Braaten, H.-W. Hammer, Phys. Rept. 428, 259 (2006);
P. Naidon, S. Endo, Rept. Prog. Phys. 80, 056001 (2017)

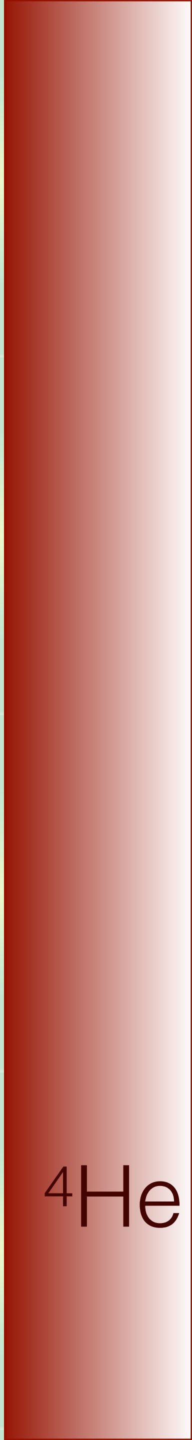
- **scattering length** |a| ≫ **interaction range** r_e
- **size of (quasi-)bound state** ~ |a| **: loosely bound**
- **relation with eigenenergy** E

$$a(E) \sim \frac{i}{k} = \frac{i}{\sqrt{2\mu E}}$$

Examples: d, Λ(1405), ^{4}He **dimer**

	NN [fm]	$\bar{K}$N [fm]	^{4}He [a_0]
a(E)	**4.3**	**1.2-0.8i**	**178**
a_{emp}	**5.1**	**1.4-0.9i**	**189**
r_e	**1.4**	**0.4**	**10**

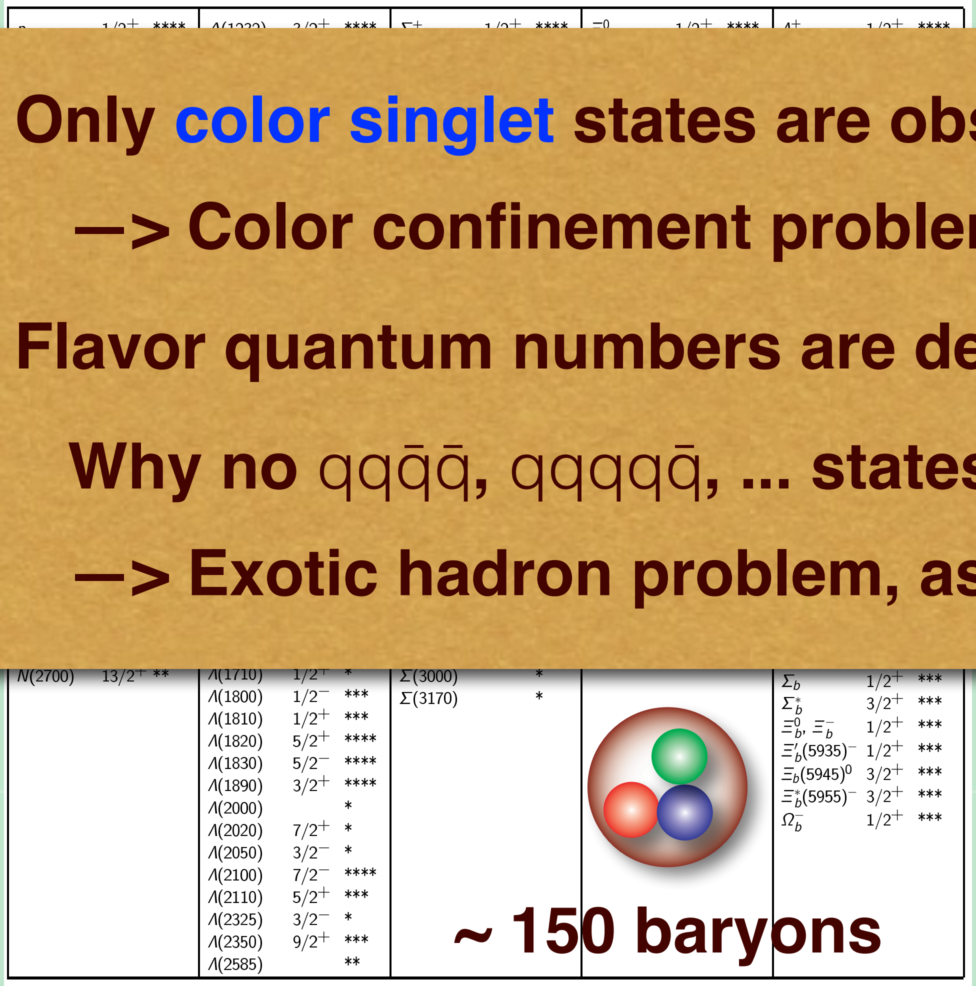




Classification of hadrons

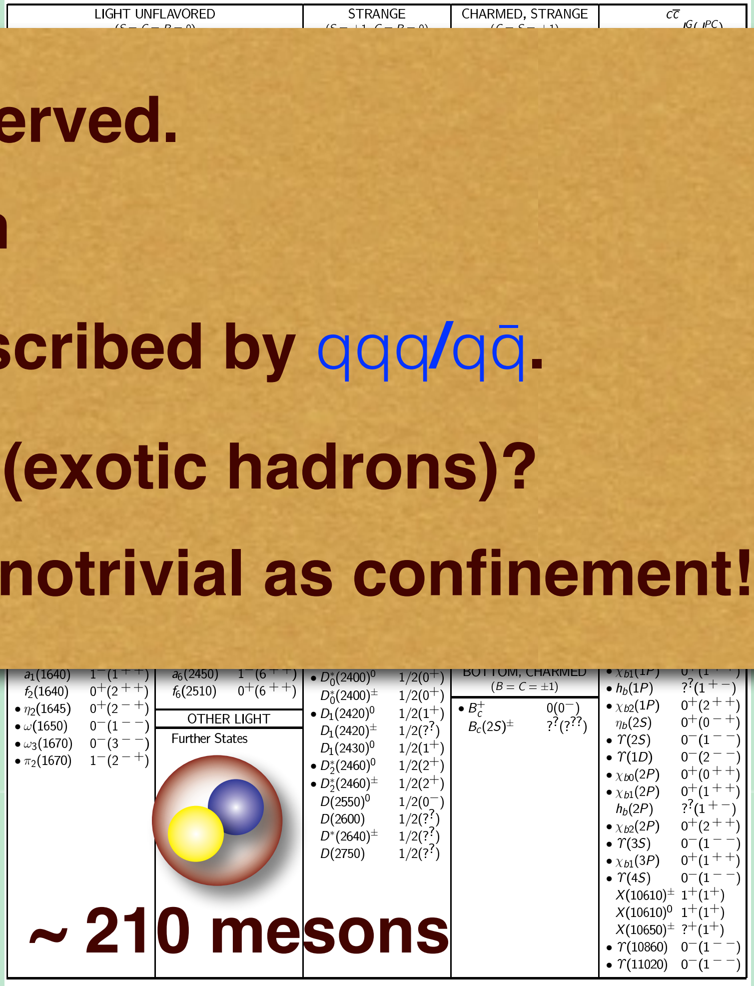
Observed hadrons

PDG2018 : http://pdg.lbl.gov/



$N(2700)$ $13/2^+$ **	$\Lambda(1710)$ $1/2^+$ *	$\Sigma(3000)$ *		Σ_b $1/2^+$ ***
	$\Lambda(1800)$ $1/2^-$ ***	$\Sigma(3170)$ *		Σ_b^* $3/2^+$ ***
	$\Lambda(1810)$ $1/2^+$ ***			Ξ_b^0, Ξ_b^- $1/2^+$ ***
	$\Lambda(1820)$ $5/2^+$ ****			$\Xi_b'(5935)^-$ $1/2^+$ ***
	$\Lambda(1830)$ $5/2^-$ ****			$\Xi_b(5945)^0$ $3/2^+$ ***
	$\Lambda(1890)$ $3/2^+$ ****			$\Xi_b^*(5955)^-$ $3/2^+$ ***
	$\Lambda(2000)$ *			Ω_b^- $1/2^+$ ***
	$\Lambda(2020)$ $7/2^+$ *			
	$\Lambda(2050)$ $3/2^-$ *			
	$\Lambda(2100)$ $7/2^-$ ****			
	$\Lambda(2110)$ $5/2^+$ ***			
	$\Lambda(2325)$ $3/2^-$ *			
	$\Lambda(2350)$ $9/2^+$ ***			
	$\Lambda(2585)$ **			

~ 150 baryons



LIGHT UNFLAVORED		STRANGE	CHARMED, STRANGE	$c\bar{c}$
$a_1(1640)$ $1^-(1^{++})$	$a_6(2450)$ $1^-(6^{++})$	• $D_0^*(2400)^0$ $1/2(0^+)$	BOTTOM, CHARMED $(B = C = \pm1)$	• $\chi_{b1}(1P)$ $0^+(1^{++})$
$f_2(1640)$ $0^+(2^{++})$	$f_6(2510)$ $0^+(6^{++})$	$D_0^*(2400)^\pm$ $1/2(0^+)$		• $h_b(1P)$ $?^?(1^{+-})$
• $\eta_2(1645)$ $0^+(2^{-+})$		• $D_1(2420)^0$ $1/2(1^+)$	• B_c^+ $0(0^-)$	• $\chi_{b2}(1P)$ $0^+(2^{++})$
• $\omega(1650)$ $0^-(1^{--})$	OTHER LIGHT	$D_1(2420)^\pm$ $1/2(?^?)$	$B_c(2S)^\pm$ $?^?(?^{??})$	$\eta_b(2S)$ $0^+(0^{-+})$
• $\omega_3(1670)$ $0^-(3^{--})$	Further States	$D_1(2430)^0$ $1/2(1^+)$		• $\Upsilon(2S)$ $0^-(1^{--})$
• $\pi_2(1670)$ $1^-(2^{-+})$		• $D_2^*(2460)^0$ $1/2(2^+)$		• $\Upsilon(1D)$ $0^-(2^{--})$
		• $D_2^*(2460)^\pm$ $1/2(2^+)$		• $\chi_{b0}(2P)$ $0^+(0^{++})$
		$D(2550)^0$ $1/2(0^-)$		• $\chi_{b1}(2P)$ $0^+(1^{++})$
		$D(2600)$ $1/2(?^?)$		$h_b(2P)$ $?^?(1^{+-})$
		$D^*(2640)^\pm$ $1/2(?^?)$		• $\chi_{b2}(2P)$ $0^+(2^{++})$
		$D(2750)$ $1/2(?^?)$		• $\Upsilon(3S)$ $0^-(1^{--})$
				• $\chi_{b1}(3P)$ $0^+(1^{++})$
				• $\Upsilon(4S)$ $0^-(1^{--})$
				$X(10610)^\pm$ $1^+(1^+)$
				$X(10610)^0$ $1^+(1^+)$
				$X(10650)^\pm$ $?^+(1^+)$
				• $\Upsilon(10860)$ $0^-(1^{--})$
				• $\Upsilon(11020)$ $0^-(1^{--})$

~ 210 mesons

Only color singlet states are observed.

—> Color confinement problem

Flavor quantum numbers are described by $qqq/q\bar{q}$.

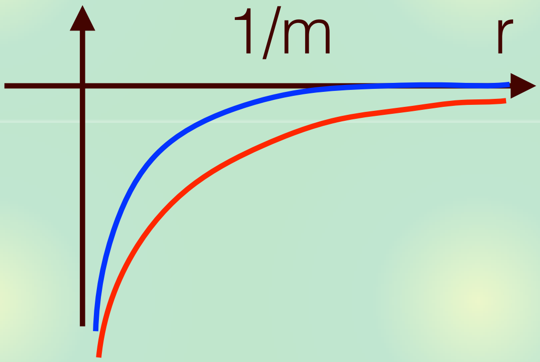
Why no $qq\bar{q}\bar{q}$, $qqqq\bar{q}$, ... states (exotic hadrons)?

—> Exotic hadron problem, as notrivial as confinement!

All ~ 360 hadrons emerge from single QCD Lagrangian.

Long range correlation in QCD?

Two-body potential



$V(r) \propto \frac{1}{r}$: long (infinite) range

$V(r) \propto \frac{e^{-mr}}{r}$: finite (~1/m) range

Hadron-hadron interaction is considered to be finite range.

- **Longest interaction range**
  <— exchange of lightest particle (π) ~ 1 fm

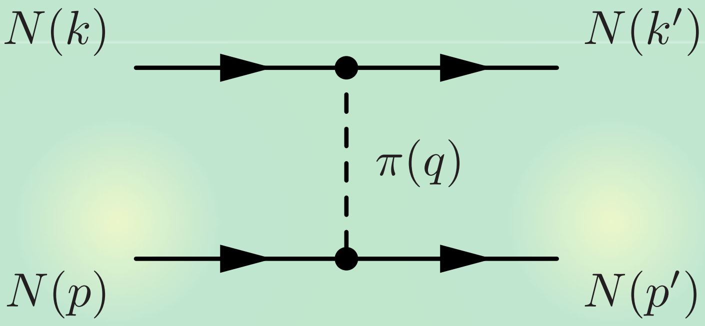
- **Absence of the long range force is the basis for the (standard) scattering theory, Lüscher/HAL method, etc.**

There can be (quasi) long range force beyond 1 fm.

M. Sanchez Sanchez, L.S. Geng, J. Lu, T. Hyodo, M.P. Valderrama, PRD98, 054001 (2018

NN **potential**

Low energy NN **interaction :** π **exchange**



- **Static approx.** $p^\mu = (M_N, \boldsymbol{p}), \quad p'^\mu = (M_N, \boldsymbol{p}'), \quad q^\mu = p'^\mu - p^\mu = (0, \boldsymbol{q})$
- **Coupling** $g\bar{N} i\gamma_5 \pi N \sim g\chi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{q}\chi$ **(isospin ignored)**

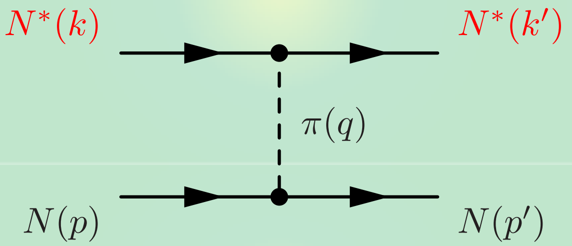
Potential

$$\frac{1}{(q^0)^2 - \boldsymbol{q}^2 - m_\pi^2}$$

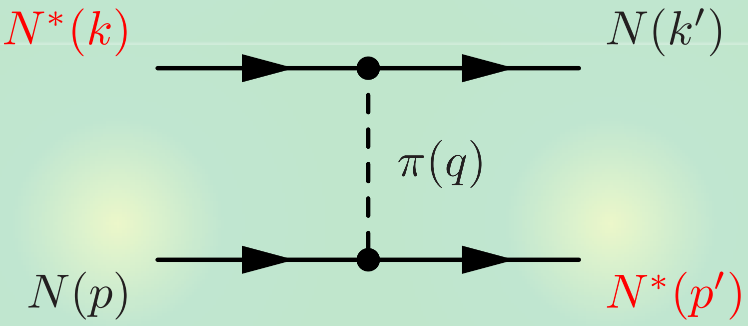
$$V(\boldsymbol{r}) \sim \text{F.T.}\left\{ g^2 \underline{(\boldsymbol{\sigma}_1\cdot\boldsymbol{q})(\boldsymbol{\sigma}_2\cdot\boldsymbol{q})} \underline{\frac{-1}{\boldsymbol{q}^2 + m_\pi^2}} \right\}$$

Tensor op. **Yukawa** $\frac{e^{-m_\pi r}}{r}$

NN* potential (exchange)



NN*(J^P=1/2-) interaction



Mass difference
= energy transfer

$$\Delta = M_{N^*} - M_N$$

- **Static approx.** $p^\mu = (M_N, \boldsymbol{p}), \quad p'^\mu = (M_{N^*}, \boldsymbol{p}'), \quad q^\mu = (\Delta, \boldsymbol{q})$
- **Coupling** $\tilde{g}\, \bar{N}^* \pi N + \mathrm{h.c.} \sim \tilde{g}\, \chi^\dagger \mathbf{1} \chi$

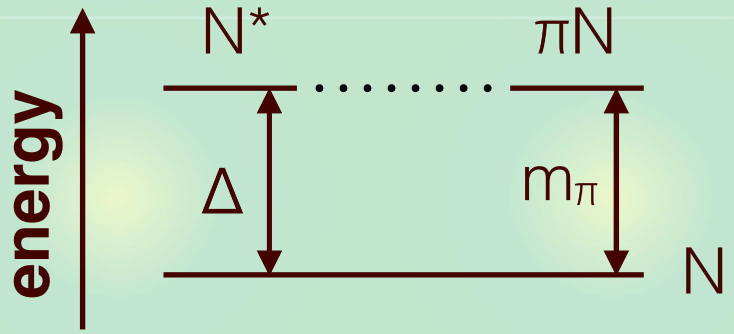
Potential (P$_\sigma$: spin exchange factor) $\mu = \sqrt{m_\pi^2 - \Delta^2}$

$$V(r) \sim \mathrm{F.T.} \left\{ \tilde{g}^2 \frac{1}{\Delta^2 - \boldsymbol{q}^2 - m_\pi^2} \right\} P_\sigma = \mathrm{F.T.} \left\{ \tilde{g}^2 \frac{-1}{\boldsymbol{q}^2 + \mu^2} \right\} P_\sigma \sim \tilde{g}^2 P_\sigma \frac{e^{-\mu r}}{r}$$

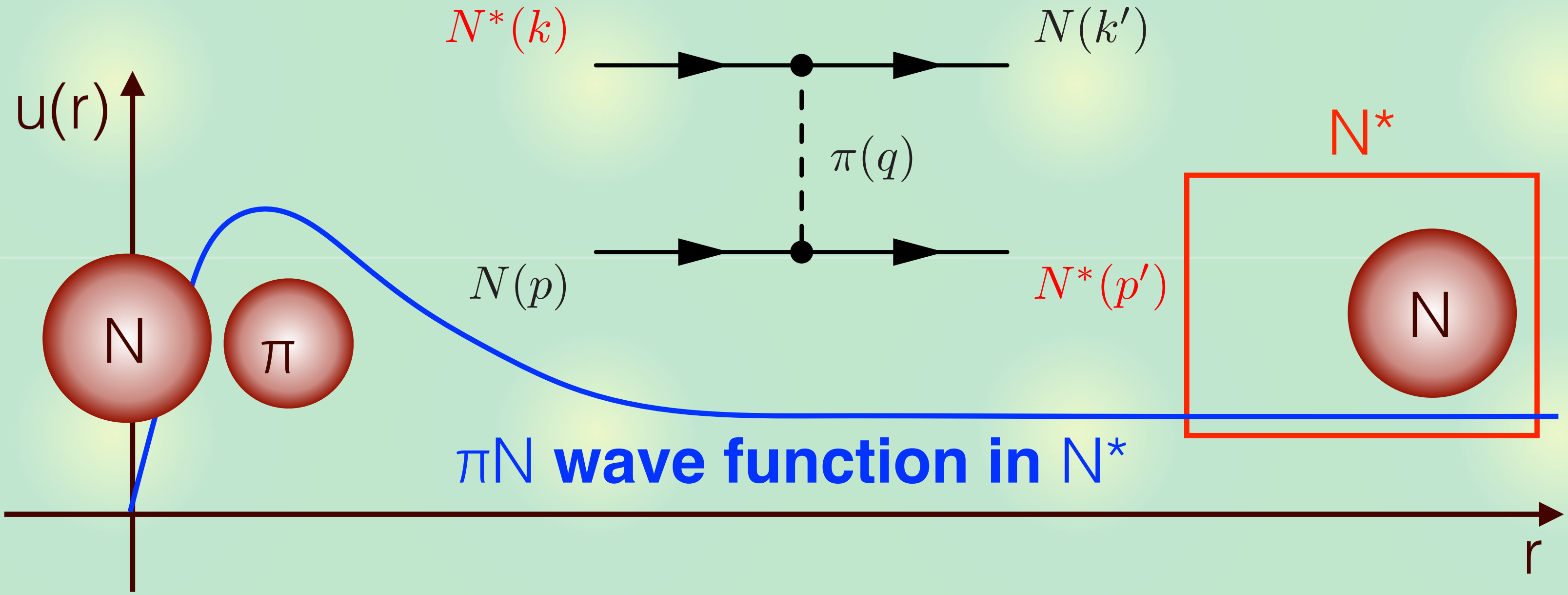
- **Sign of** V(r) **is fixed and attractive (c.f.** σ **exchange in** NN**)**
- **Effective mass** μ=0 **—> long range force (Coulomb like)**

Unitary limit and zero-energy resonance

What does $\mu = (m_\pi^2 - \Delta^2)^{1/2} = 0 \Leftrightarrow \Delta = m_\pi$ **mean?**



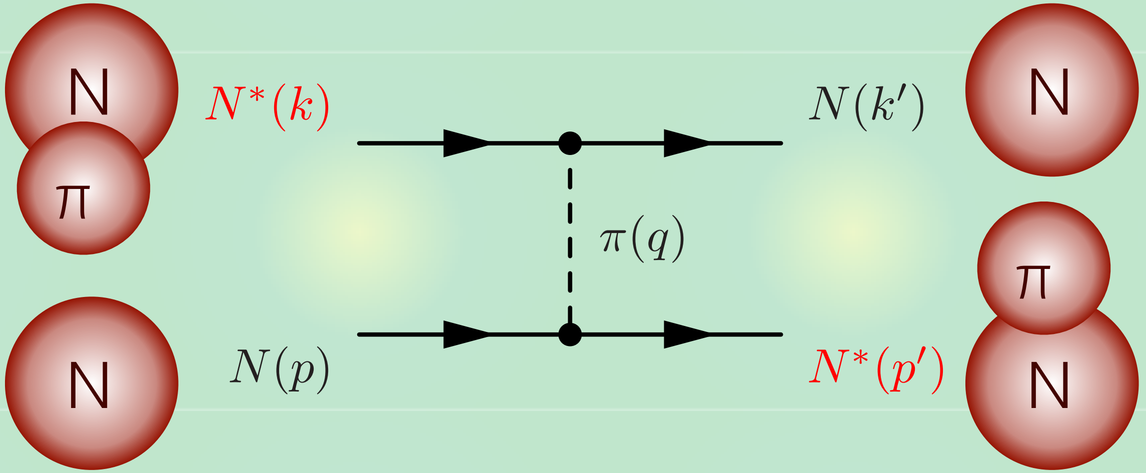
- $\Delta = m_\pi$ **: N* lies on top of the πN threshold —>** $a_{\pi N} = \infty$



πN **wave function in** N*

Remarks and toward physical realization

N*N ~ πNN : **effective description of three-body system**



Similarity with the Efimov effect

- spatially large three-body system via unitary two-body int.

Realization in physical hadron systems

- No system with exact $\mu=0$ (N***:** $\Delta\sim595$ MeV / $m_\pi\sim140$ MeV)

- Is there any system with small μ**?**

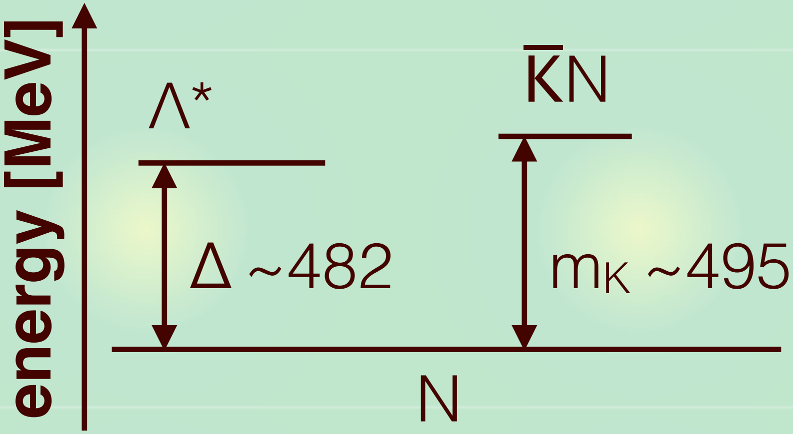
Strange dibaryon

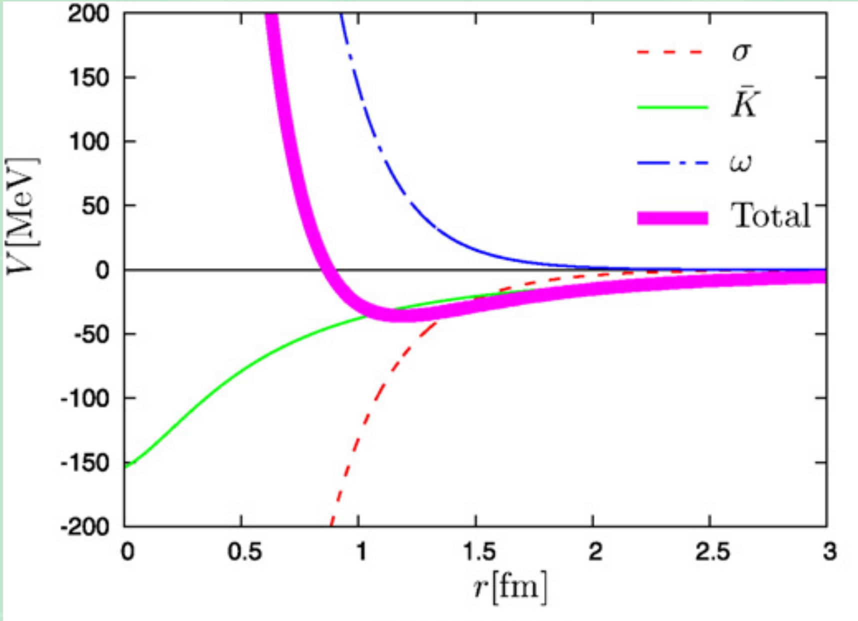
$\Lambda(1405)=\Lambda^*$: **$\bar{K}N$ quasibound state near the threshold**

T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)

- **$\bar{K}$ exchange between Λ^* and N**

Λ^* **(at 1420 MeV), $\bar{K}N$ threshold**





(a) $\Lambda_1^* N, {}^1S_0$

- $\mu \sim 91$ **MeV: $\bar{K}$ exchange has longer tail than expected**
- **attractive in spin singlet channel —> $\bar{K}NN$ as Λ^*N system**

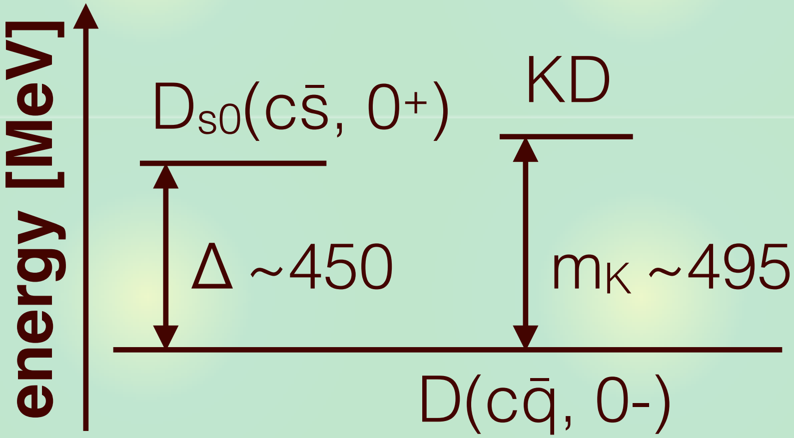
T. Uchino, T. Hyodo, M. Oka, Nucl. Phys. A, 868-869, 53 (2011)

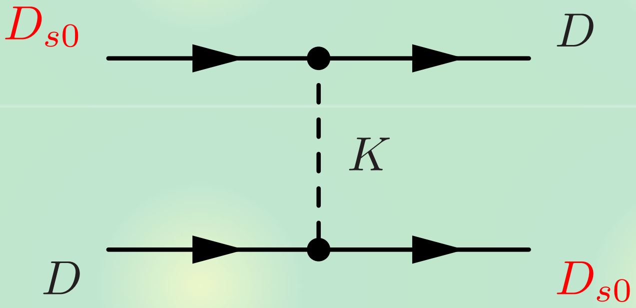
Doubly charmed exotic meson

We consider $D_{s0}(c\bar{s}, 0^+)D(c\bar{q}, 0^-)$ **system via** K **exchange**

- **Charm** C=2**: manifestly** **exotic** **(**$cc\bar{q}\bar{s}$**)**

$D_{s0}(2317)$**,** KD **threshold**





- K **exchange gives** **quasi-long range** **(**$\mu \sim 200$ **MeV) attraction**

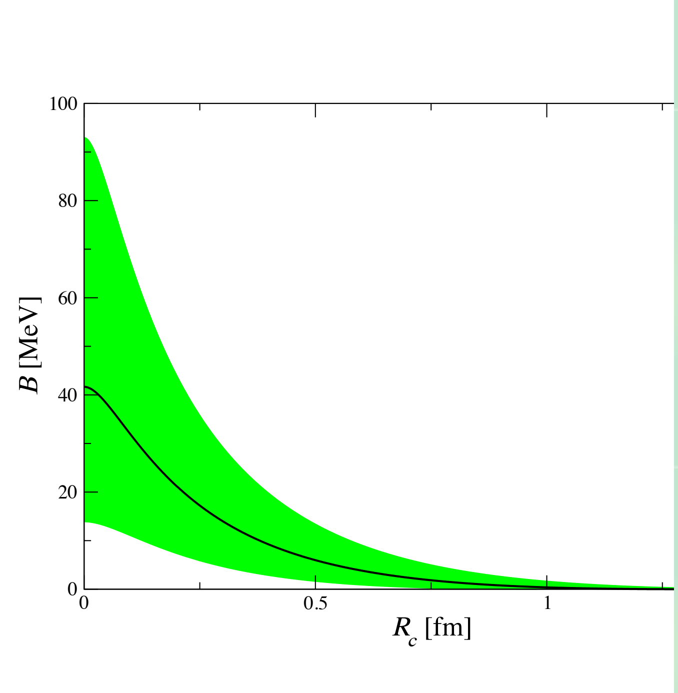
Can the attraction generate a bound state?

Prediction of binding energy

Effective Lagrangian for $D_{s0}DK$ **(and HQ partners) coupling**

$$\mathcal{L} = \frac{h}{2}\mathrm{Tr}[\bar{H}_a S_b \not{A}_{ab}\gamma_5] + \mathrm{C.C.}$$

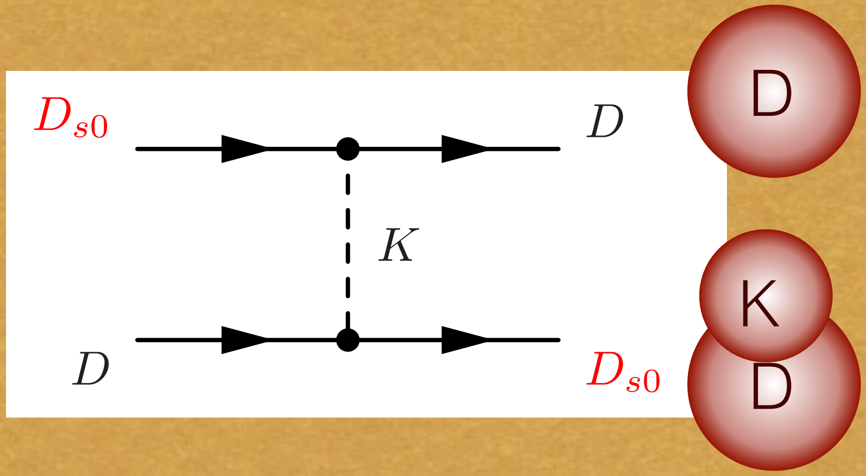
- **coupling constant** h **:** D_0 —>Dπ **decay + SU(3) symmetry**
- **Short range cutoff** R_c **<— hadron size**



- R_c ~ 0.5 **fm —>** ~ 6 **MeV binding**

Summary

- **Long range correlation among hadrons emerges when the mass difference Δ matches with the mass of the exchange particle** m**.**



$$V(r) \sim \frac{e^{-\mu r}}{r}, \quad \mu = \sqrt{m^2 - \Delta^2}$$

- K **exchange in** $D_{s0}(0^+)D(0^-)$ **system:** μ~200 **MeV**
—> prediction of exotic charmed tetraquark

M. Sanchez Sanchez, L.S. Geng, J. Lu, T. Hyodo, M.P. Valderrama,
Phys. Rev. D98, 054001 (2018)