



# Quantum Chromo Dynamics (QCD)

3 color charges (red, green, blue)

**Not real colors** but e.g.  $q_x, q_y, q_z$  that can be  $+q_x$  for quarks (red) and  $-q_x$  for anti-quarks (anti-red)

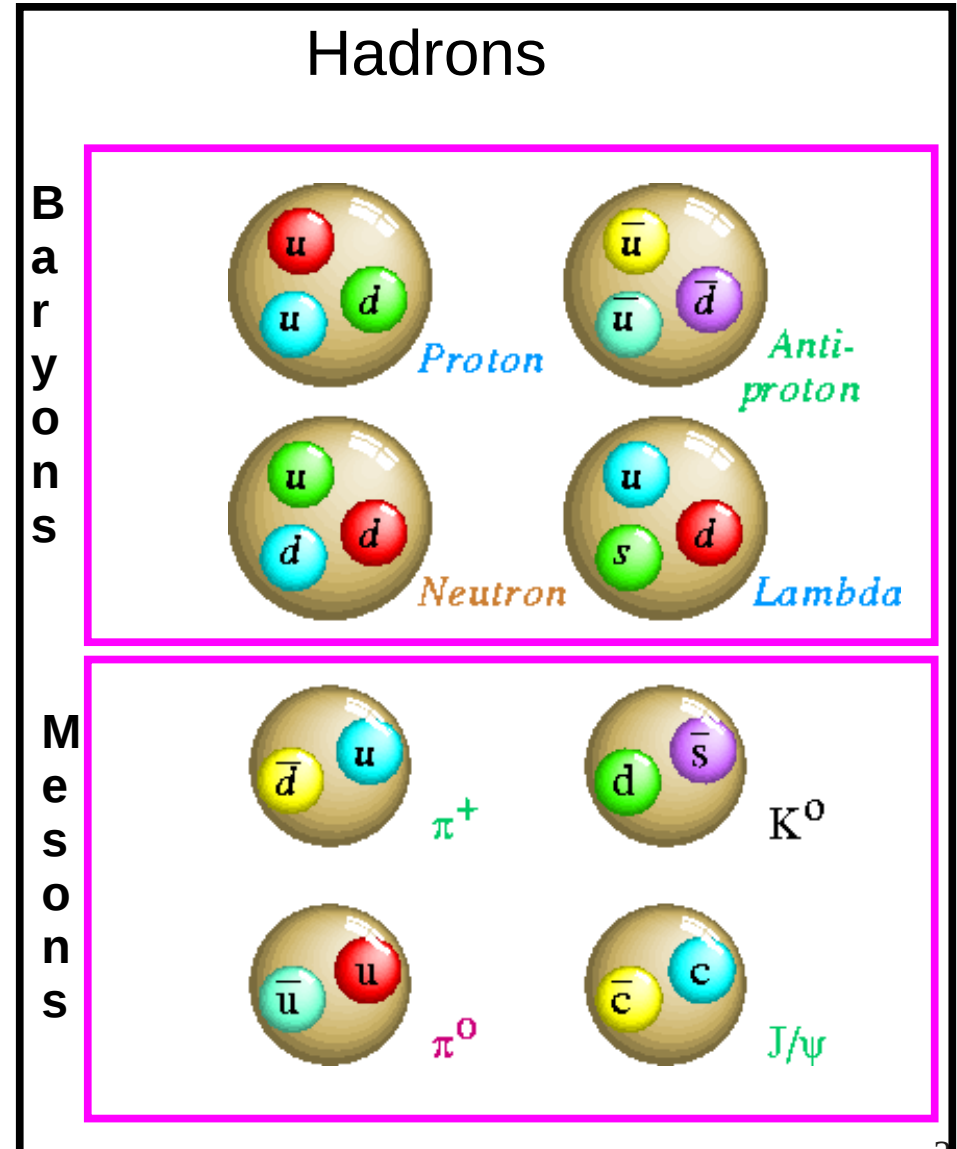
Hadrons have to be colorless

Baryons have all 3 colors

Mesons has a color and an anti-color

A single quark cannot be observed because it has color!

The quarks are confined inside the hadrons!



# Periodic Table of the Elements

1 1IA 11A																	18 VIIIA 8A
1 <b>H</b> Hydrogen 1.0079	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 <b>He</b> Helium 4.00260
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.01218											5 <b>B</b> Boron 10.811	6 <b>C</b> Carbon 12.011	7 <b>N</b> Nitrogen 14.00674	8 <b>O</b> Oxygen 15.9994	9 <b>F</b> Fluorine 18.998403	10 <b>Ne</b> Neon 20.1797
11 <b>Na</b> Sodium 22.989768	12 <b>Mg</b> Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 <b>Al</b> Aluminum 26.981539	14 <b>Si</b> Silicon 28.0855	15 <b>P</b> Phosphorus 30.973762	16 <b>S</b> Sulfur 32.066	17 <b>Cl</b> Chlorine 35.4527	18 <b>Ar</b> Argon 39.948
19 <b>K</b> Potassium 39.0983	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.95591	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.9415	24 <b>Cr</b> Chromium 51.9961	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.847	27 <b>Co</b> Cobalt 58.9332	28 <b>Ni</b> Nickel 58.6934	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.64	33 <b>As</b> Arsenic 74.92159	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.80
37 <b>Rb</b> Rubidium 85.4678	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.90585	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.90638	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium 98.9072	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.9055	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.5	53 <b>I</b> Iodine 126.90447	54 <b>Xe</b> Xenon 131.29
55 <b>Cs</b> Cesium 132.90543	56 <b>Ba</b> Barium 137.327	57-71	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.9479	74 <b>W</b> Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.22	78 <b>Pt</b> Platinum 195.08	79 <b>Au</b> Gold 196.9665	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.3833	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98037	84 <b>Po</b> Polonium [208.9824]	85 <b>At</b> Astatine 209.9871	86 <b>Rn</b> Radon 222.0176
87 <b>Fr</b> Francium 223.0197	88 <b>Ra</b> Radium 226.0254	89-103	104 <b>Rf</b> Rutherfordium [261]	105 <b>Db</b> Dubnium [262]	106 <b>Sg</b> Seaborgium [266]	107 <b>Bh</b> Bohrium [264]	108 <b>Hs</b> Hassium [269]	109 <b>Mt</b> Meitnerium [268]	110 <b>Ds</b> Darmstadtium [269]	111 <b>Rg</b> Roentgenium [272]	112 <b>Cn</b> Copernicium [277]	113 <b>Uut</b> Ununtrium unknown	114 <b>Uuq</b> Ununquadium [289]	115 <b>Uup</b> Ununpentium unknown	116 <b>Uuh</b> Ununhexium [288]	117 <b>Uus</b> Ununseptium unknown	118 <b>Uuo</b> Ununoctium unknown
Lanthanide Series		57 <b>La</b> Lanthanum 138.9055	58 <b>Ce</b> Cerium 140.115	59 <b>Pr</b> Praseodymium 140.90765	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium 144.9127	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.9655	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.92534	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93032	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.93421	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967	
Actinide Series		89 <b>Ac</b> Actinium 227.0278	90 <b>Th</b> Thorium 232.0381	91 <b>Pa</b> Protactinium 231.03588	92 <b>U</b> Uranium 238.0289	93 <b>Np</b> Neptunium 237.0482	94 <b>Pu</b> Plutonium 244.0642	95 <b>Am</b> Americium 243.0614	96 <b>Cm</b> Curium 247.0703	97 <b>Bk</b> Berkelium 247.0703	98 <b>Cf</b> Californium 251.0796	99 <b>Es</b> Einsteinium [254]	100 <b>Fm</b> Fermium 257.0851	101 <b>Md</b> Mendelevium 258.1	102 <b>No</b> Nobelium 259.1009	103 <b>Lr</b> Lawrencium [262]	
Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetals	Nonmetals	Halogens	Noble Gas	Lanthanides	Actinides								

# Today: the periodic table of the hadrons:-)

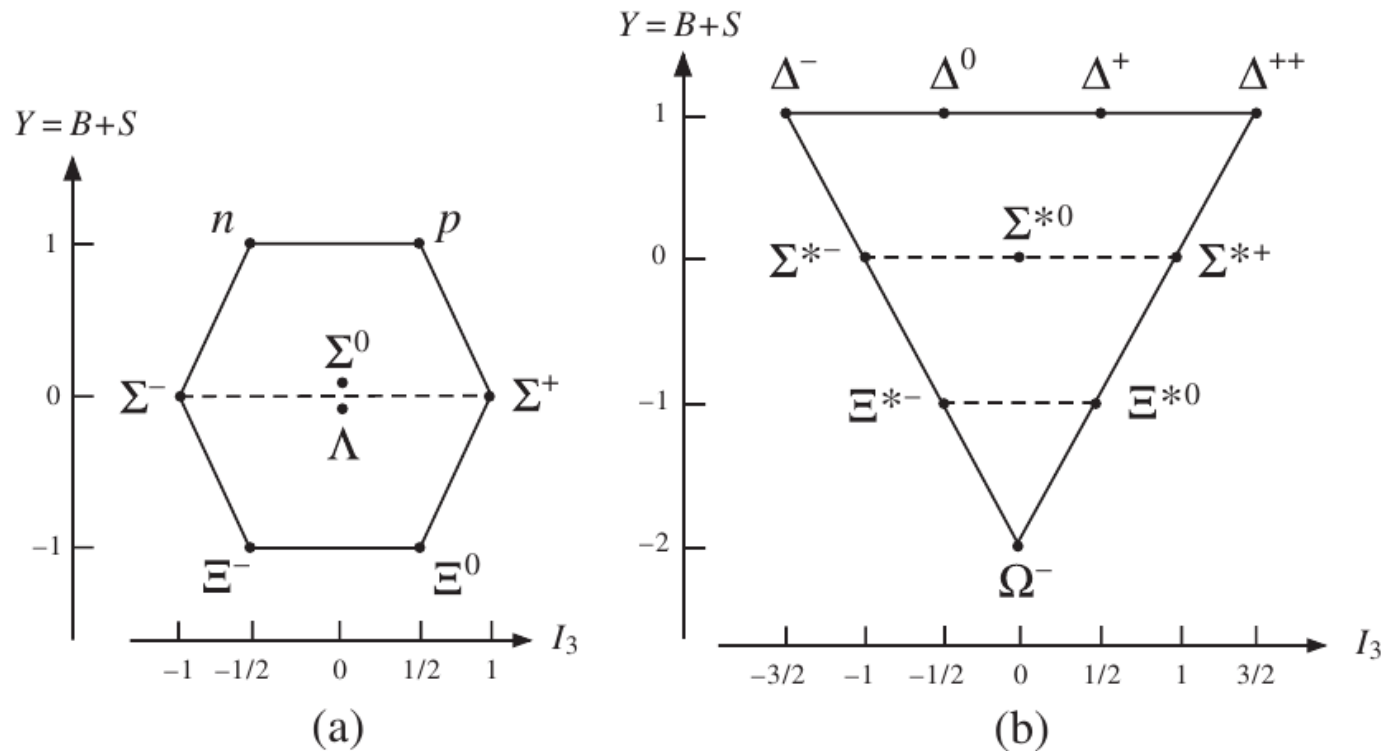


Figure 6.2 Weight diagrams for (a) the  $J^P = \frac{1}{2}^+$  octet of light baryons and (b) the  $J^P = \frac{3}{2}^+$  baryon decuplet.

# Example of mesonic “energy levels”: the $s\bar{u}$ system

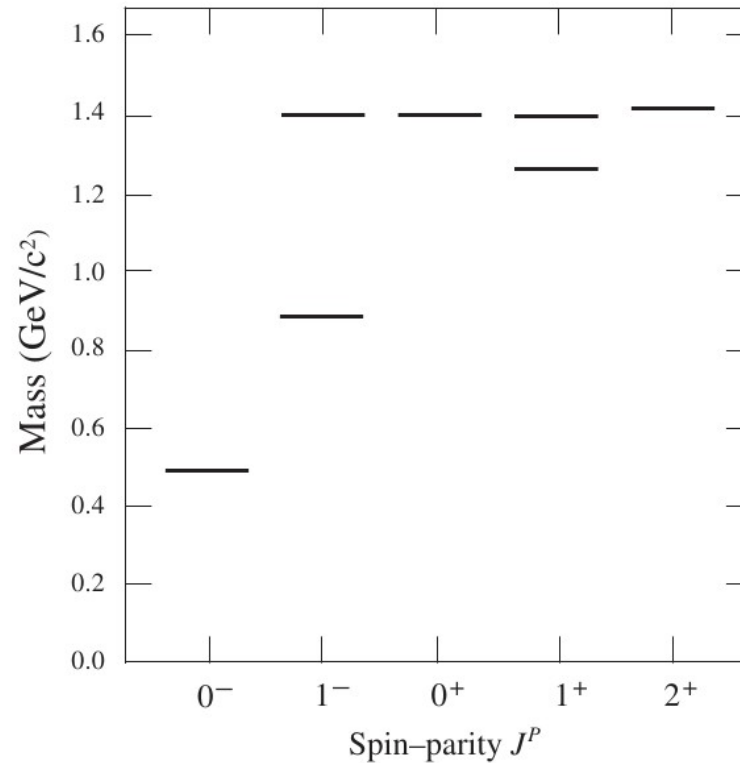


Figure 3.12 Observed bound states of the  $s\bar{u}$  system with masses below  $1.5 \text{ GeV}/c^2$ , together with values of their spin-parities<sup>9</sup>  $J^P$ . The ground state is the  $K^-$  (494) and the others can be interpreted as its excited states.

# Example of mesonic “energy levels”: the $s\bar{u}$ system

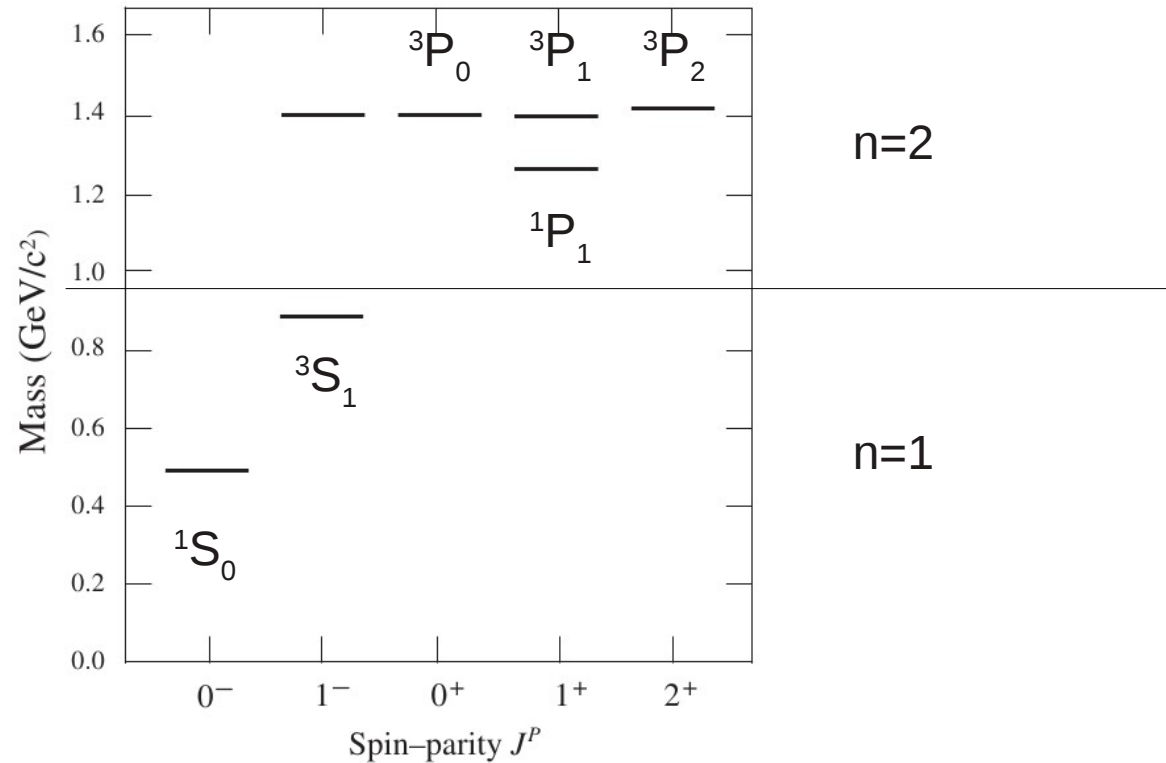


Figure 3.12 Observed bound states of the  $s\bar{u}$  system with masses below  $1.5 \text{ GeV}/c^2$ , together with values of their spin-parities<sup>9</sup>  $J^P$ . The ground state is the  $K^-$  (494) and the others can be interpreted as its excited states.

# L=0 and n = 0 mesonic uds states

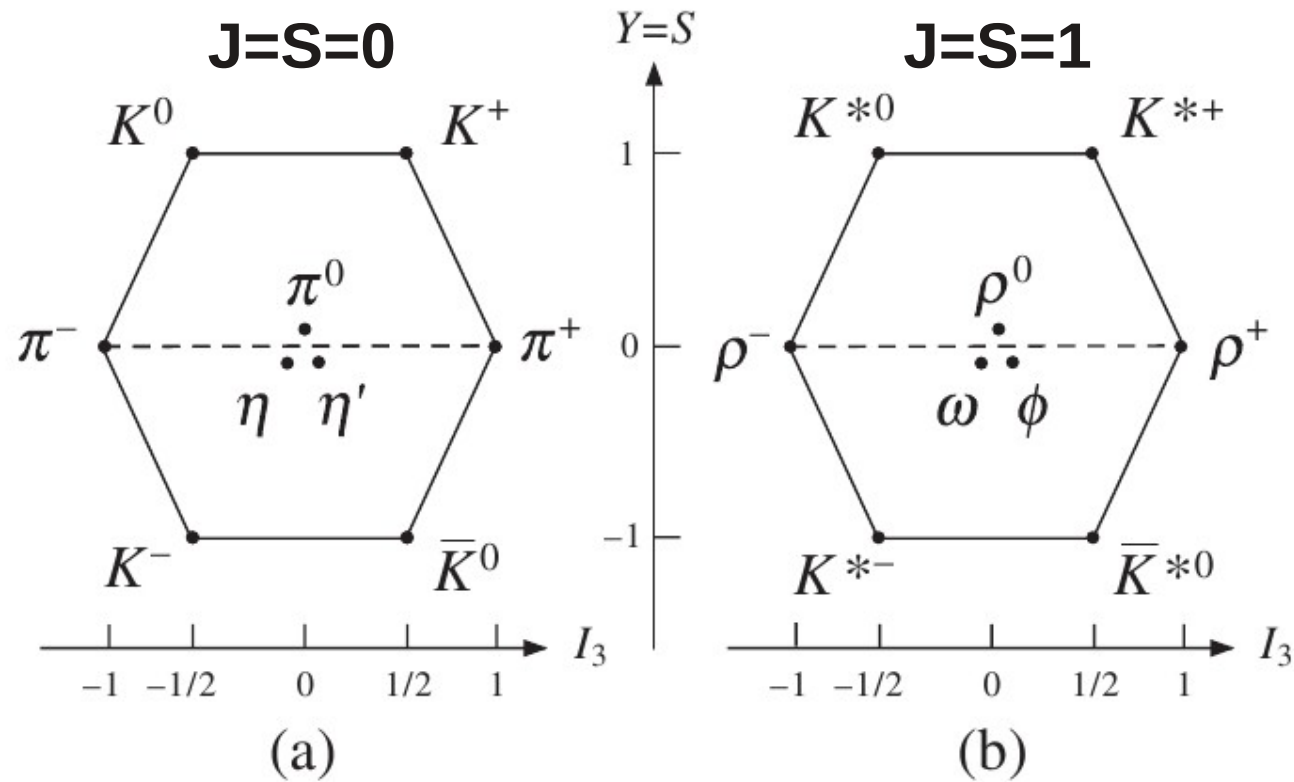


Figure 6.1 Weight diagrams for (a) the  $0^-$  meson nonet and (b) the  $1^-$  meson nonet.

$$\pi^0, \rho^0 \quad \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \quad (I = 0, I_3 = 0) \quad (6.24a)$$

$$\text{Mixture: } \left\{ \begin{array}{l} \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \quad (I = 0, I_3 = 0) \quad (6.24a) \\ s\bar{s} \quad (I = 0, I_3 = 0), \quad (6.24b) \end{array} \right. \eta, \eta', \omega, \phi$$

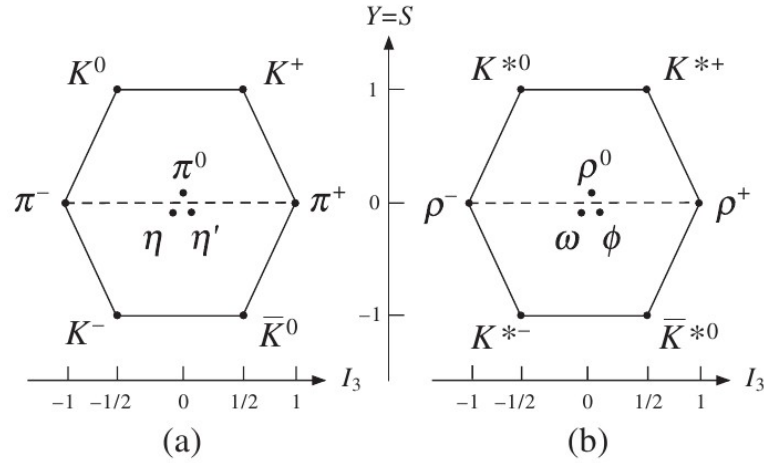


Figure 6.1 Weight diagrams for (a) the  $0^-$  meson nonet and (b) the  $1^-$  meson nonet.

TABLE 6.4 The states of the light  $L = 0$  meson nonets.

Quark content	$0^-$ state	$1^-$ state	$I_3$	$I$	$Y = S$
$u\bar{s}$	$K^+$ (494)	$K^{*+}$ (892)	1/2	1/2	1
$d\bar{s}$	$K^0$ (498)	$K^{*0}$ (896)	-1/2	1/2	1
-----					
$u\bar{d}$	$\pi^+$ (140)	$\rho^+$ (768) <sup>#</sup>	1	1	0
$\frac{(u\bar{u} - d\bar{d})}{\sqrt{2}}$	$\pi^0$ (135)	$\rho^0$ (768) <sup>#</sup>	0	1	0
$d\bar{u}$	$\pi^-$ (140)	$\rho^-$ (768) <sup>#</sup>	-1	1	0
-----					
$s\bar{d}$	$\bar{K}^0$ (498)	$\bar{K}^{*0}$ (896)	1/2	1/2	-1
$s\bar{u}$	$K^-$ (494)	$K^{*-}$ (892)	-1/2	1/2	-1
-----					
See text	$\eta$ (549)	$\omega$ (782)	0	0	0
See text	$\eta'$ (958)	$\phi$ (1019)	0	0	0

<sup>#</sup> The measured mass difference between the neutral and charged  $\rho$  mesons is  $m(\rho^0) - m(\rho^+) = 0.3 \pm 2.2 \text{ MeV}/c^2$ .



TABLE 6.9 Predicted  $c\bar{c}$  and  $b\bar{b}$  states with principal quantum numbers  $n = 1$  and 2 and radial quantum number  $n_r = n - L$ , compared with experimentally observed states. Masses are given in  $\text{MeV}/c^2$ .

$^{2S+1}L_J$	$n$	$n_r$	$J^{PC}$	$c\bar{c}$ state	$b\bar{b}$ state
$^1S_0$	1	1	$0^{-+}$	$\eta_c(2980)$	$\eta_b(9300)\#$
$^3S_1$	1	1	$1^{--}$	$J/\psi(3097)$	$\Upsilon(9460)$
$^3P_0$	2	1	$0^{++}$	$\chi_{c0}(3415)$	$\chi_{b0}(9859)$
$^3P_1$	2	1	$1^{++}$	$\chi_{c1}(3511)$	$\chi_{b1}(9893)$
$^3P_2$	2	1	$2^{++}$	$\chi_{c2}(3556)$	$\chi_{b2}(9913)$
$^1P_1$	2	1	$1^{+-}$	$h_c(3526)\#$	
$^1S_0$	2	2	$0^{-+}$	$\eta_c(3638)$	
$^3S_1$	2	2	$1^{--}$	$\psi(3686)$	$\Upsilon(10023)$

# State is not well established and its quantum number assignments are unknown.

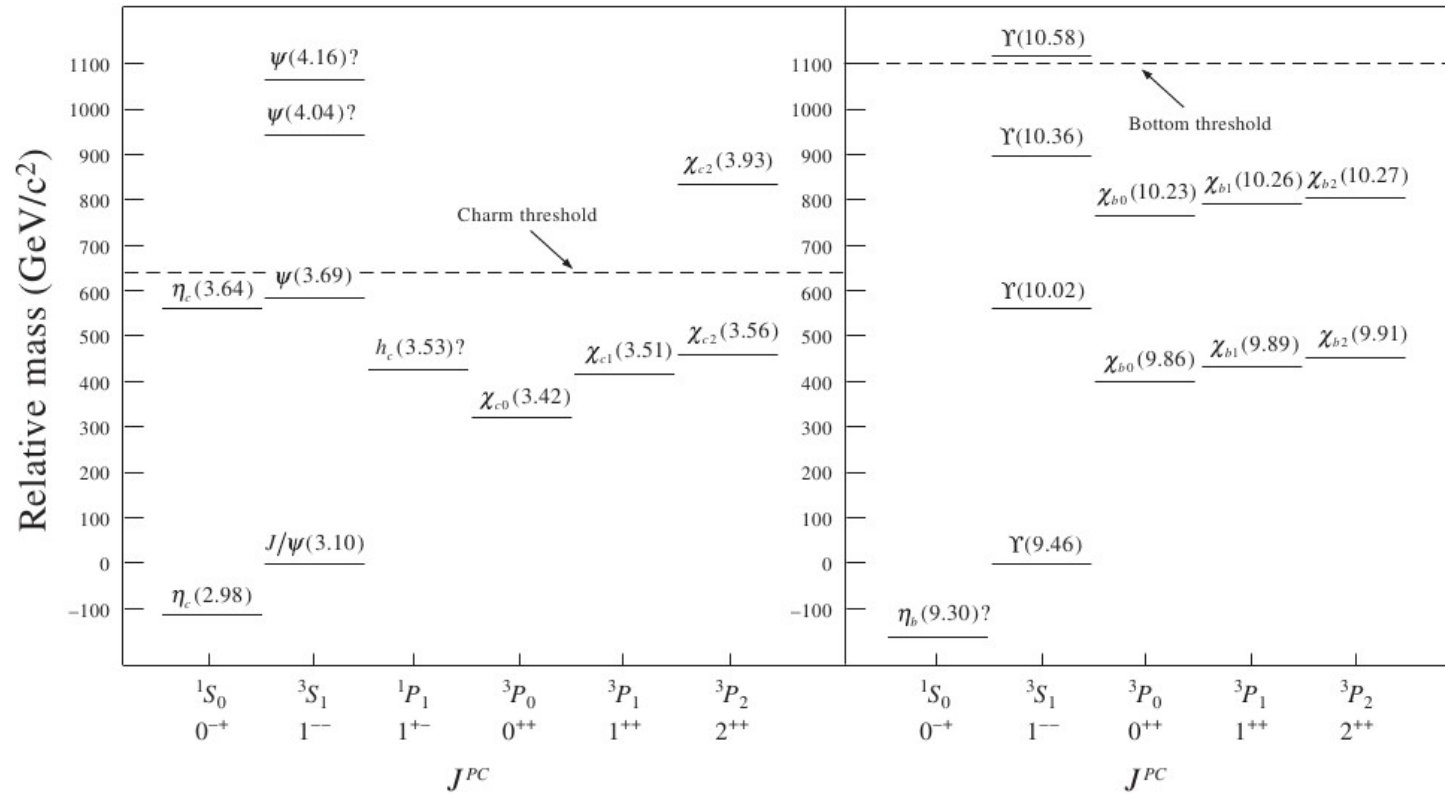
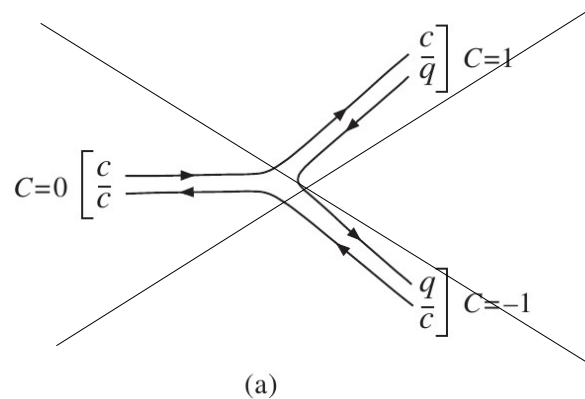


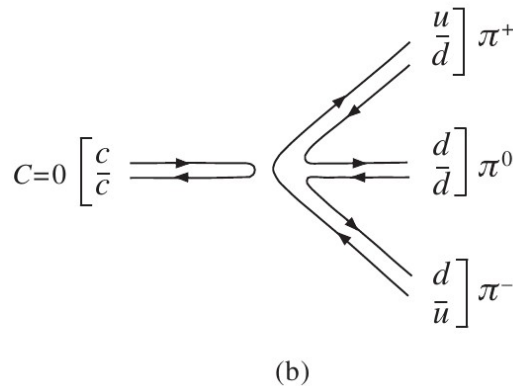
Figure 6.6 The observed states of the charmonium ( $c\bar{c}$ ) and bottomium ( $b\bar{b}$ ) for  $L \leq 1$ . The masses are given in units of  $\text{GeV}/c^2$  and are plotted relative to that of the  $^3S_1$  ground state.

# Why is the $J/\psi$ ( $1^-$ ) famous? (the $\eta_c$ ( $0^-$ ) is lighter!)

Mass  $J/\psi$  :  
3.10 GeV



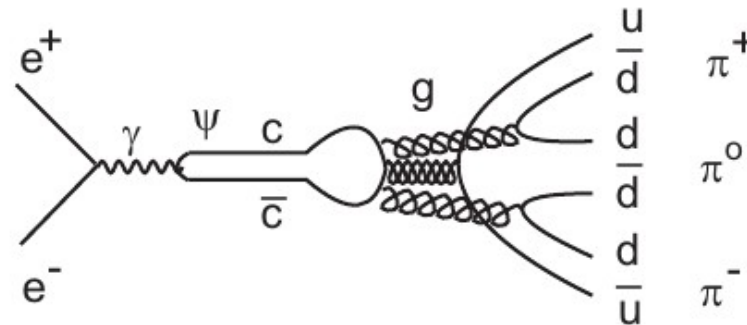
Mass D (lightest c meson) :  
1.86 GeV



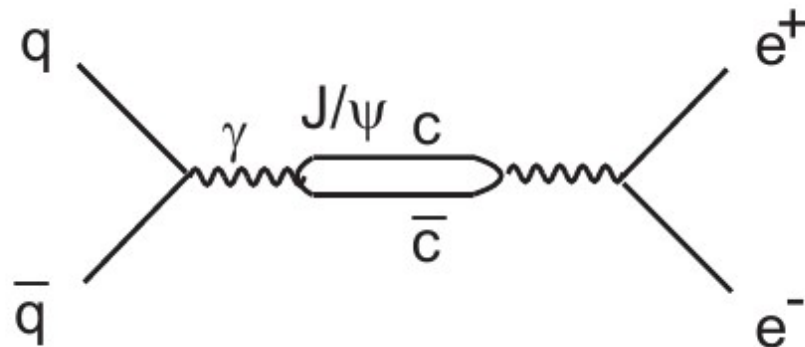
This decay is OZI suppressed  
Decays are OZI suppressed  
when there are time regions  
where there are only internal  
gluon lines

Figure 6.5 Quark diagrams for (a) the decay of a charmonium state to a pair of charmed mesons and (b) an example of a decay to noncharmed mesons.

# J/ψ (1<sup>-</sup>) has quantum number of virtual photon!

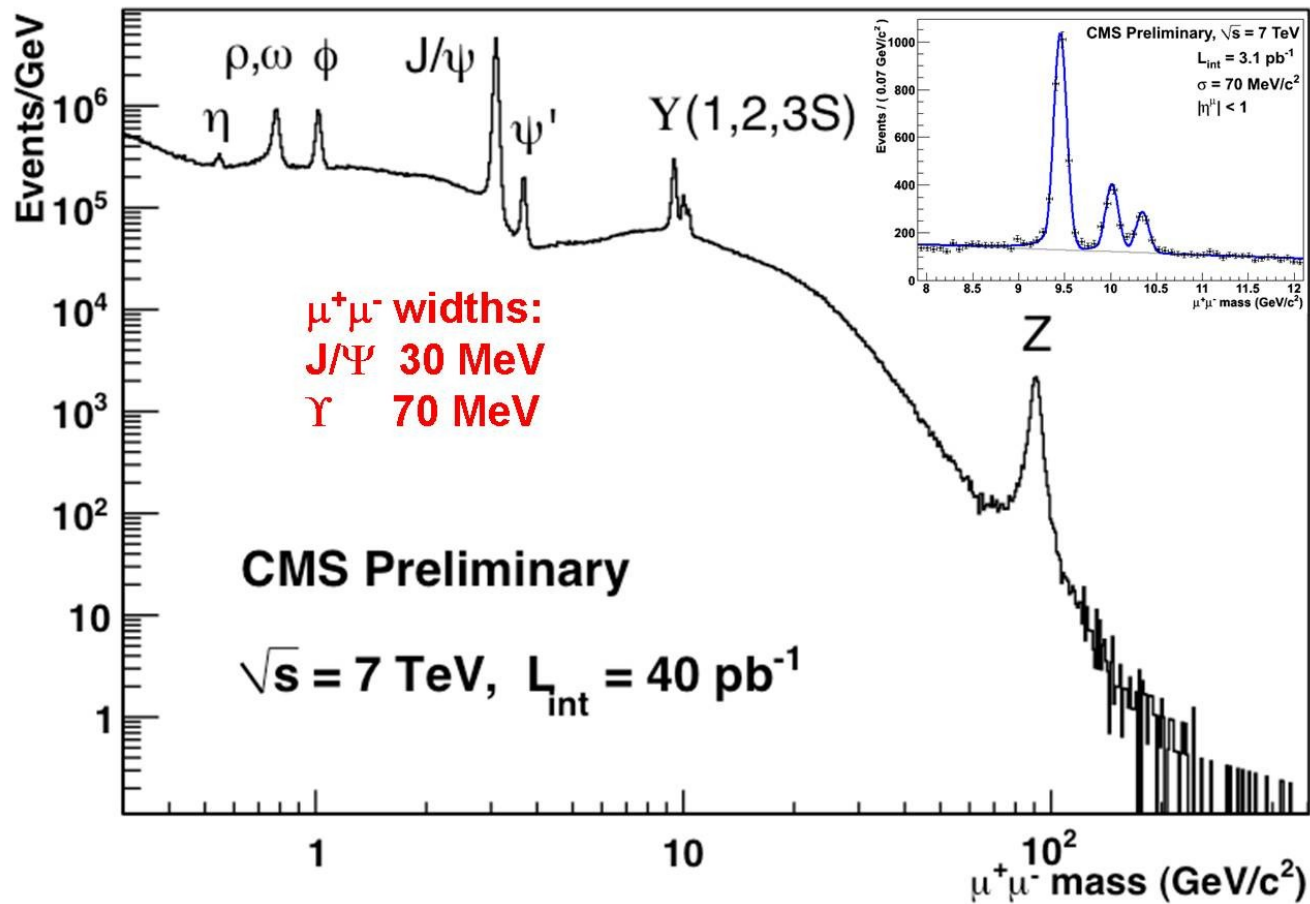


OZI suppressed!



5% of decays  
(and 5% to muons)

# Very easy identification! (if you have a good detector:-)



Note that except for  $\eta$  these are all  $1^-$  states!

# What can we more do with energy levels: model them!

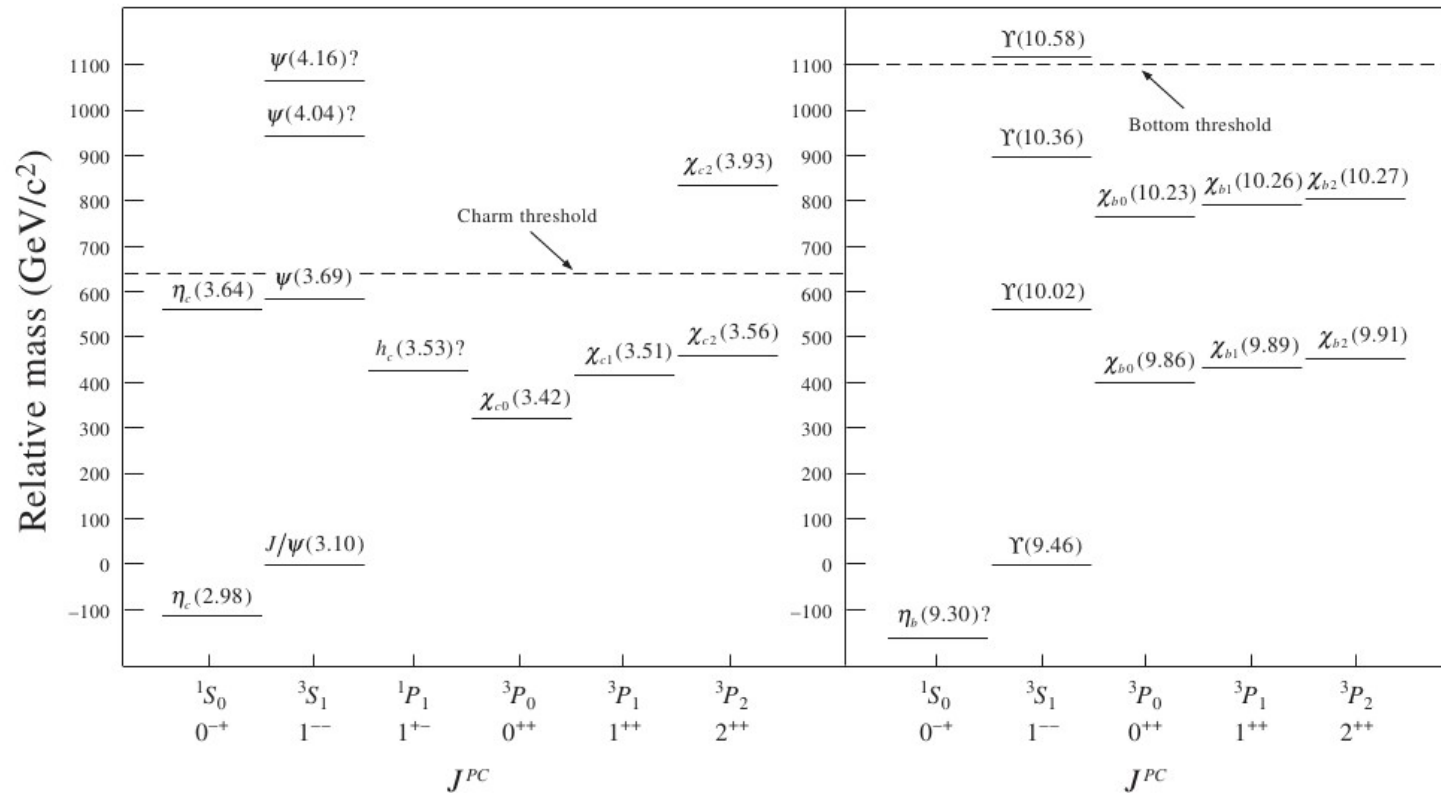


Figure 6.6 The observed states of the charmonium ( $c\bar{c}$ ) and bottomium ( $b\bar{b}$ ) for  $L \leq 1$ . The masses are given in units of  $\text{GeV}/c^2$  and are plotted relative to that of the  $^3S_1$  ground state.

# A way to experimentally measure the strong potential

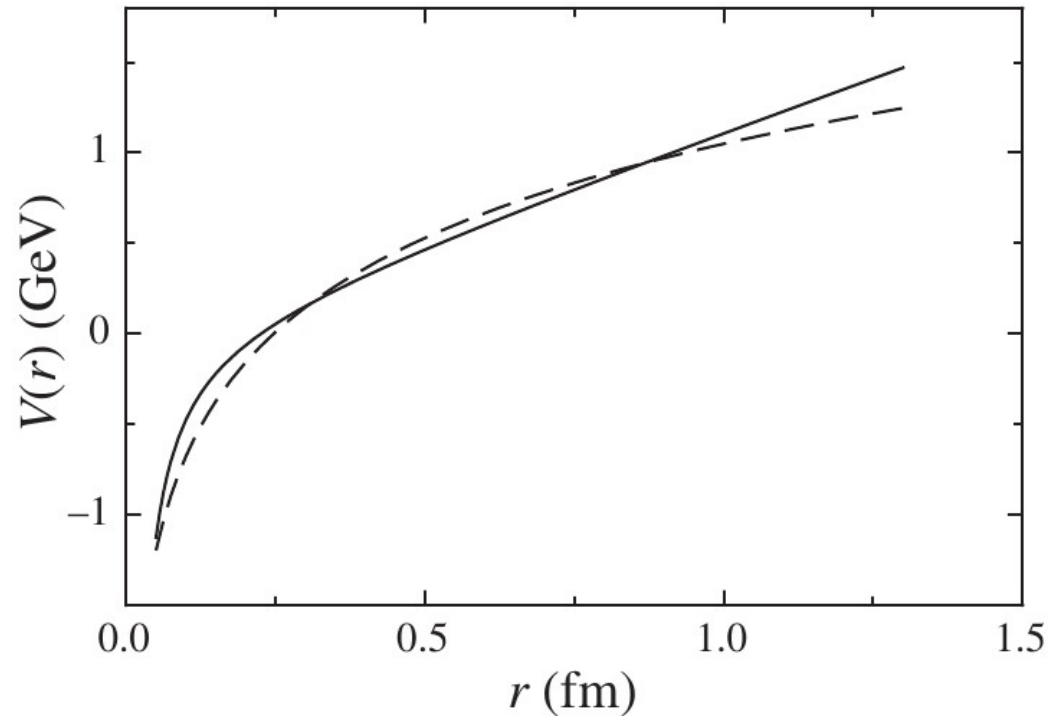


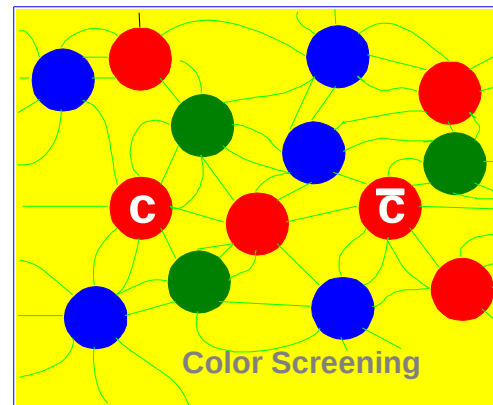
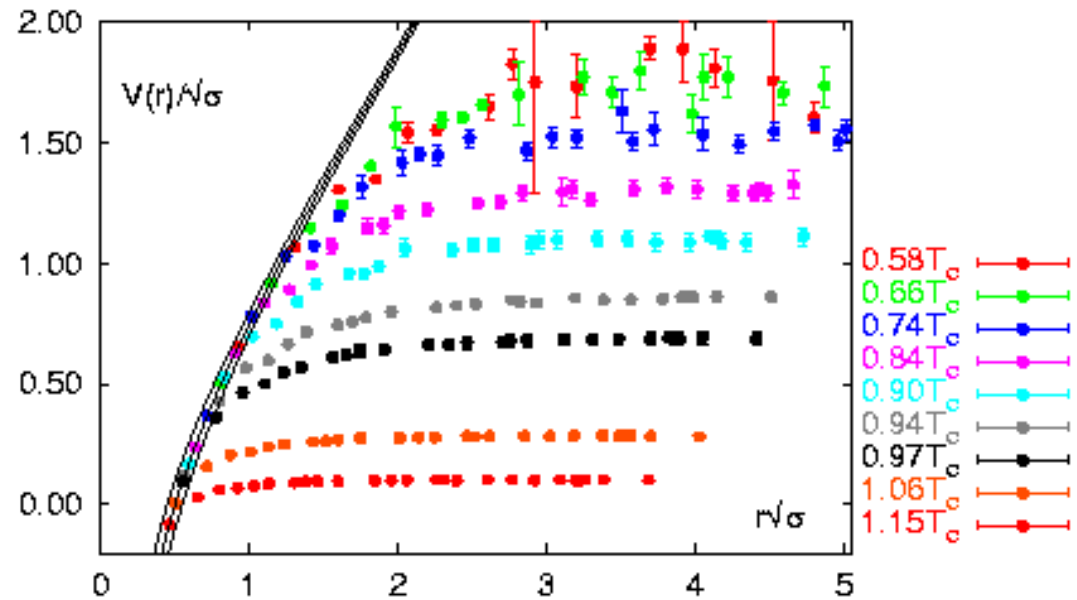
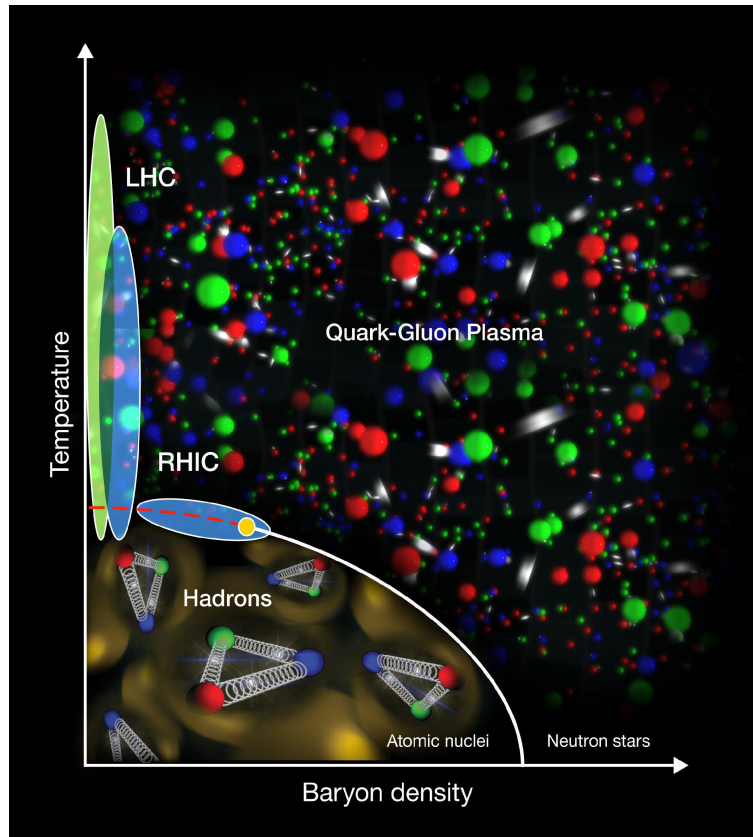
Figure 6.8 Heavy quark–antiquark potentials obtained from fitting the energy levels of charmonium and bottomium. The solid and dashed lines show the results obtained from the forms (6.57) and (6.58), respectively.

# A small excursion



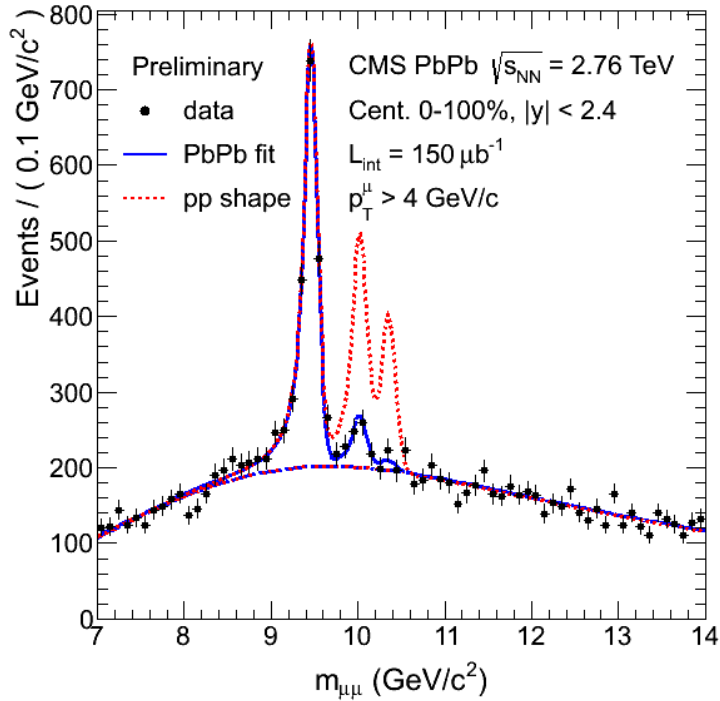
# Lattice QCD results (Numerical non-perturbative)

## Heavy quark potential

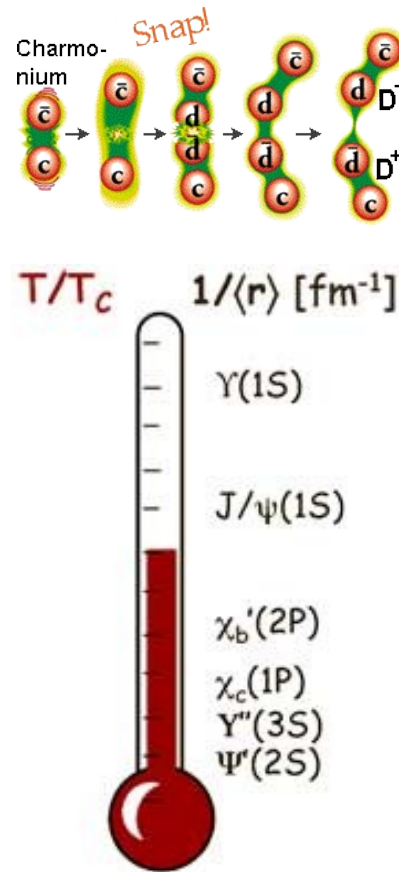


At  $T \sim T_c$  the strong potential is screened so e.g.  $c+c\text{-bar}$  states can disassociate.

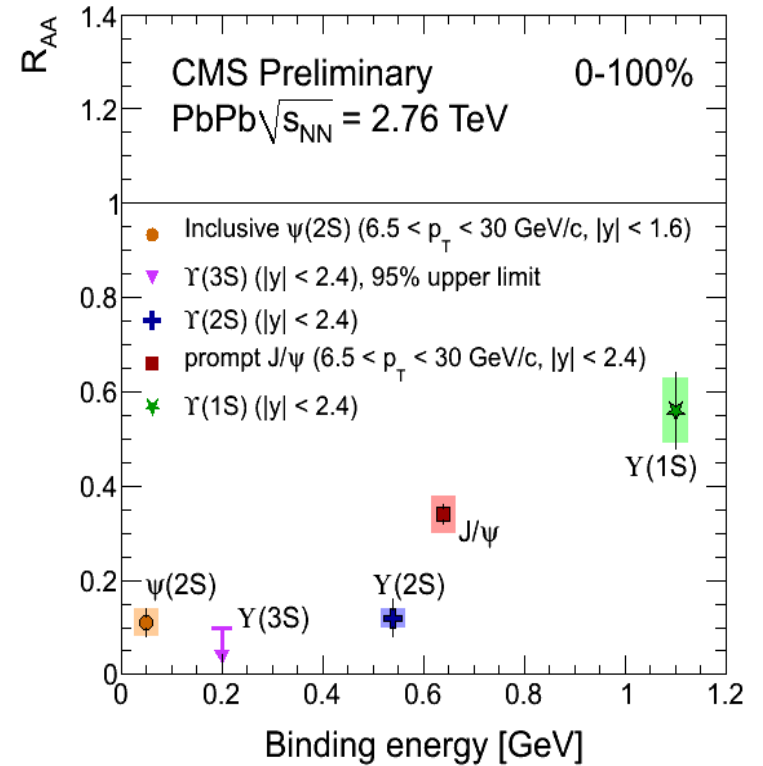
${}^3S_1 / 1^-$   
 $n=1, 2, 3$



Observation of sequential  
suppression of  $Y$  ( $b+b\text{-bar}$ )  
family



Note:  $6.5 < p_T < 30$  GeV for  $J/\psi$  and  $\psi(2s)$



Expected in terms of  
binding energy

Unfortunately heavy quark results are more complex when systematically studied!

# Next: let us understand the baryons!

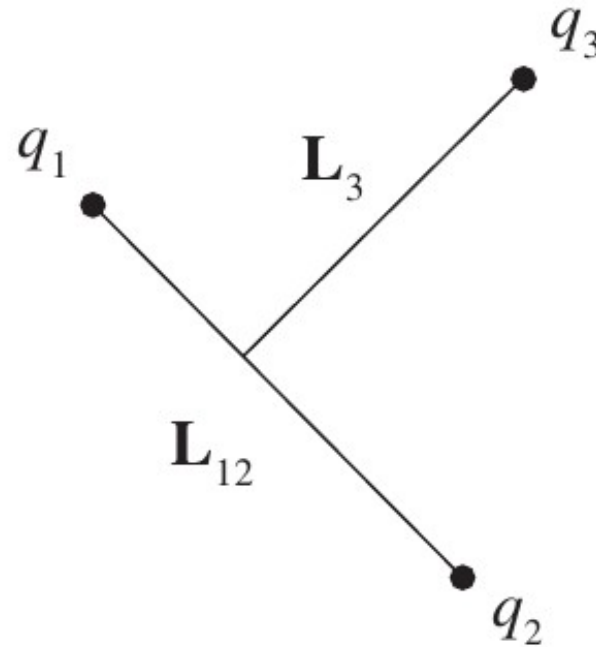


Figure 5.1 Internal orbital angular momenta of a three-quark state.

Only consider  $L = 0$ !

# The baryonic systems with $L=0$ and $n = 0$

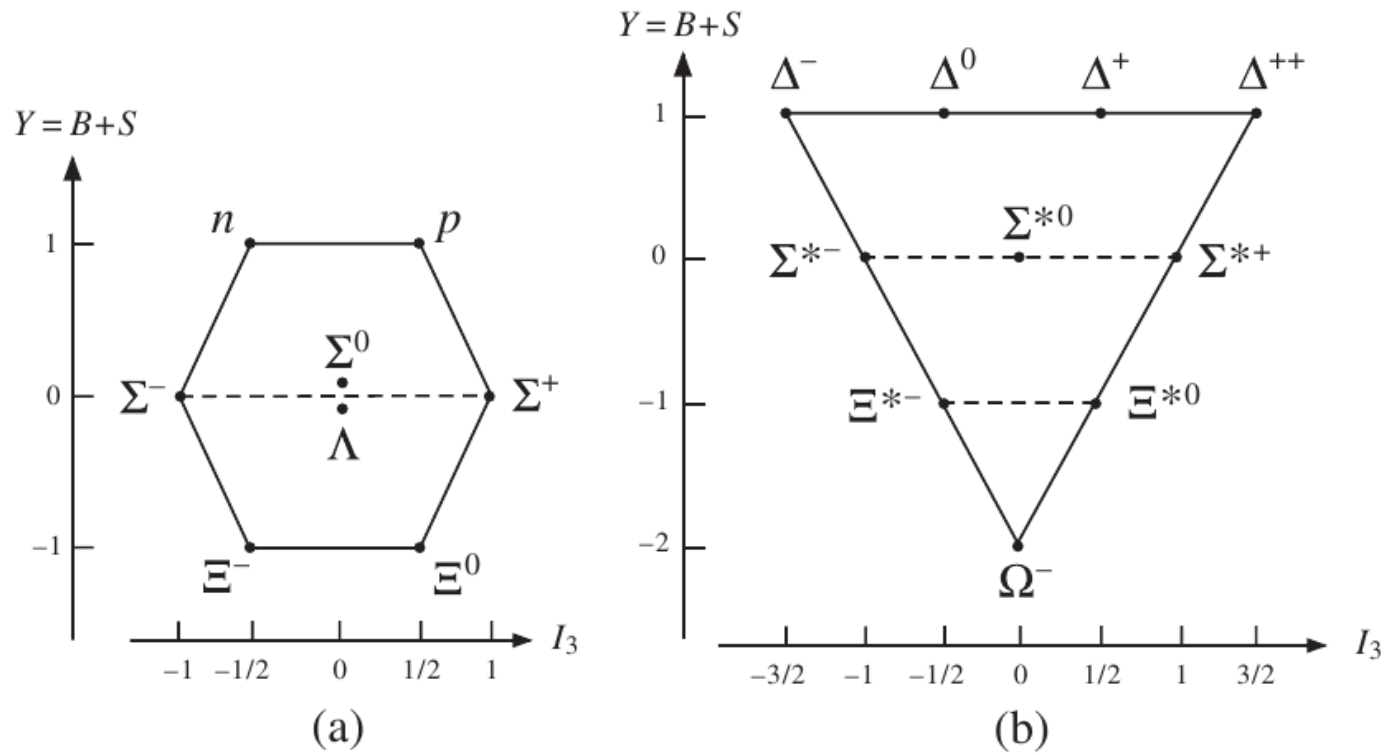


Figure 6.2 Weight diagrams for (a) the  $J^P = \frac{1}{2}^+$  octet of light baryons and (b) the  $J^P = \frac{3}{2}^+$  baryon decuplet.

Color is needed to make the  $\Delta^{++}$  wavefunction antisymmetric!

$$\chi_B^C = \frac{1}{\sqrt{6}}(r_1 g_2 b_3 - g_1 r_2 b_3 + b_1 r_2 g_3 - b_1 g_2 r_3 + g_1 b_2 r_3 - r_1 b_2 g_3), \quad (6.36)$$

- Show that this is anti-symmetric when you exchange  $1 \leftrightarrow 2$ ,  $2 \leftrightarrow 3$ , and  $1 \leftrightarrow 3$
- This means that the rest of the wavefunction (spin, flavor, L) symmetric!