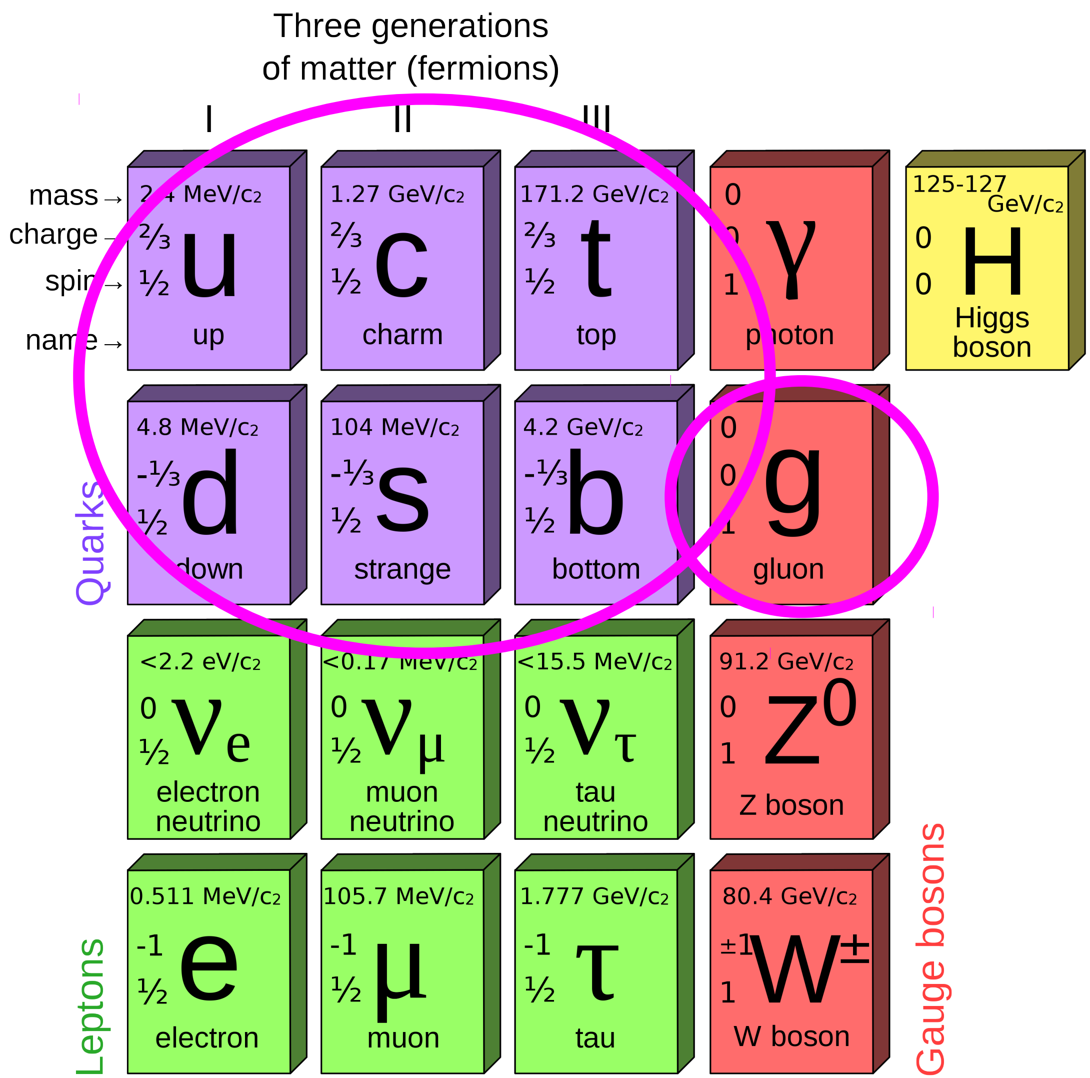
Quarks and Hadrons



Quantum Chromo Dynamics (QCD)

3 color charges (red, green, blue)

<u>Not real colors</u> but e.g. qx, qy, qz that can be +qx for quarks (red) and -qx for anti-quarks (anti-red)

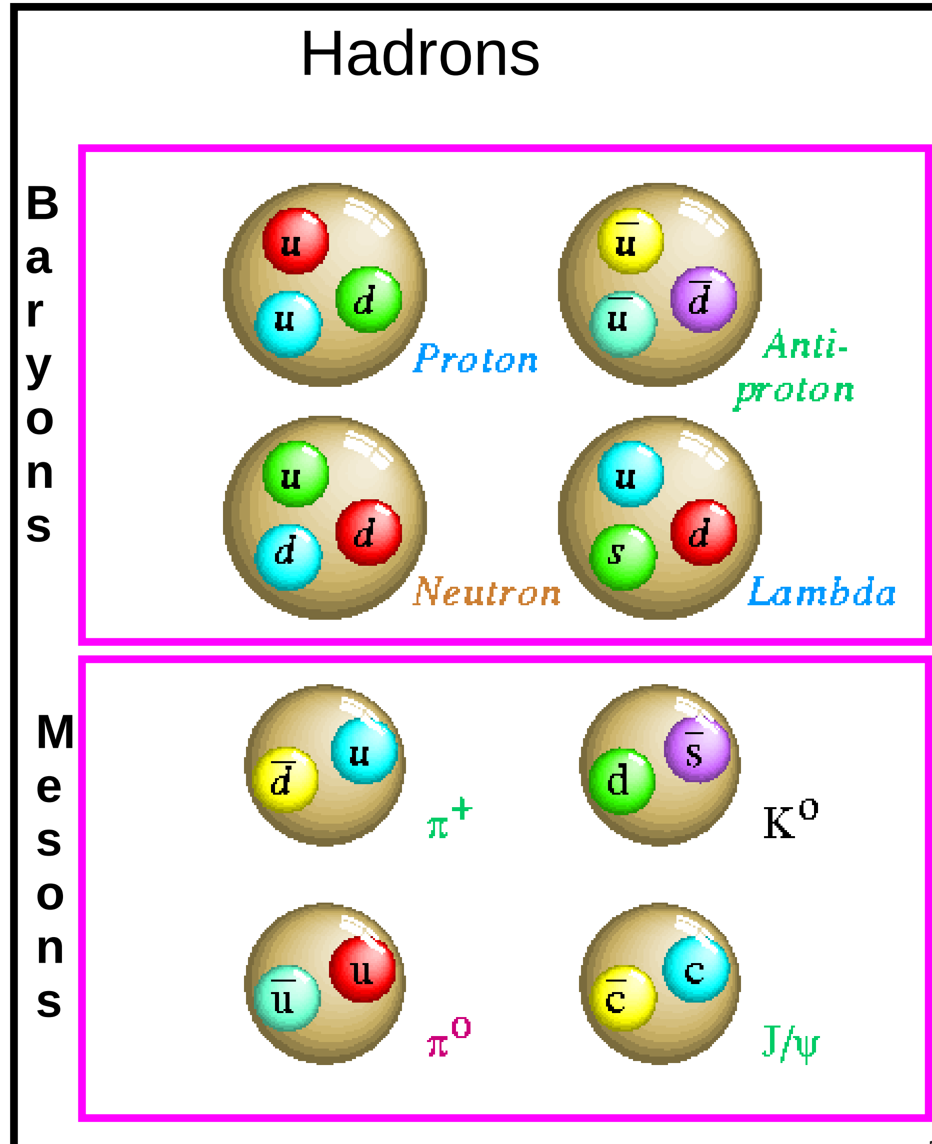
Hadrons have to be colorless

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	2 IIA 2A	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 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.0079																	2 He Helium 4.00260
3 Li Lithium 6.941	4 Be Beryllium 9.01218											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.998403	10 Ne Neon 20.1797
11 Na Sodium 22.989768	12 Mg Magnesium 24.305											13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9072	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium [208.9824]	85 At Astatine 209.9871	86 Rn Radon 222.0176
87 Fr Francium 223.0197	88 Ra Radium 226.0254	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Uuq Ununquadium [289]	115 Uup Ununpentium unknown	116 Uuh Ununhexium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.9055	58 Ce Cerium 140.115	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.9655	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.0278	90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium 237.0482	94 Pu Plutonium 244.0642	95 Am Americium 243.0614	96 Cm Curium 247.0703	97 Bk Berkelium 247.0703	98 Cf Californium 251.0796	99 Es Einsteinium [254]	100 Fm Fermium 257.0951	101 Md Mendelevium 258.1	102 No Nobelium 259.1009	103 Lr Lawrencium [262]

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetals	Nonmetals	Halogens	Noble Gas	Lanthanides	Actinides

Today: the periodic table of the hadrons:-)

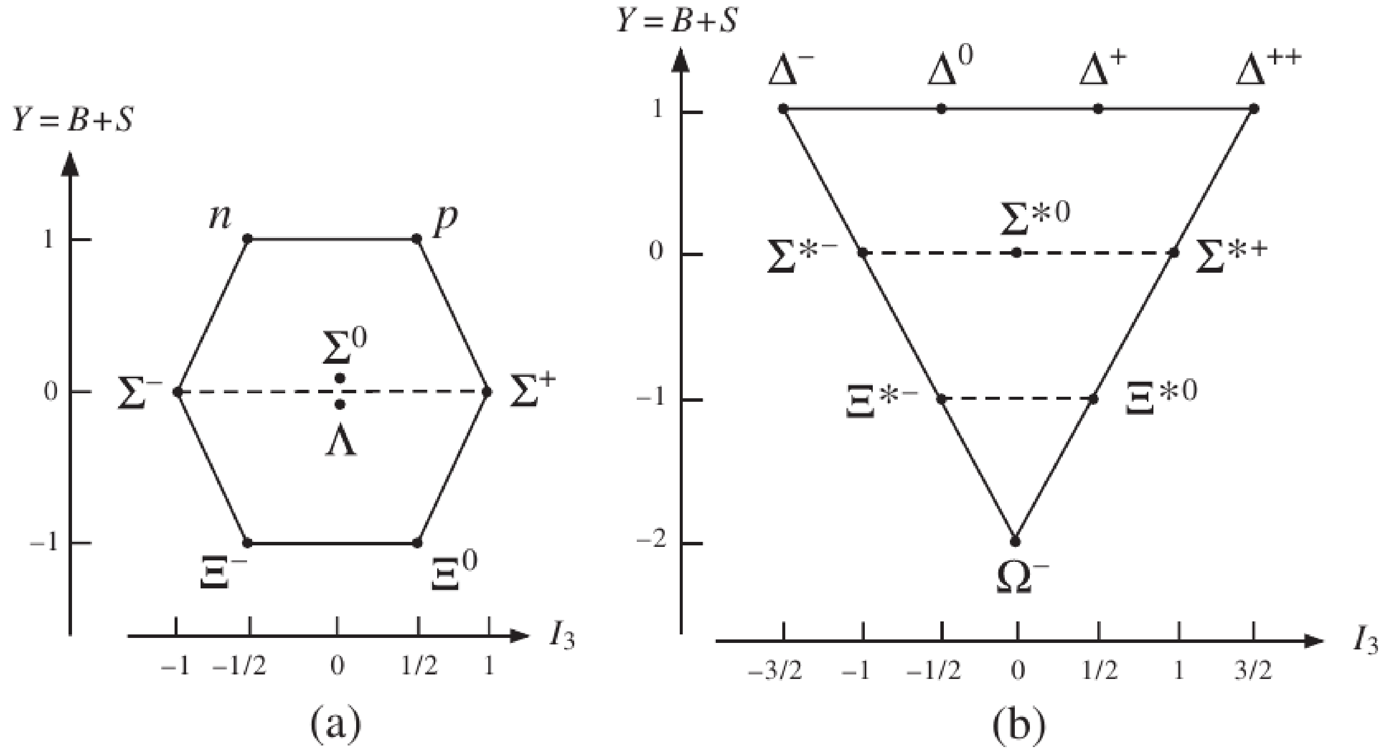


Figure 6.2 Weight diagrams for (a) the $J^P = \frac{1}{2}^+$ octet of light baryons and (b) the $J^P = \frac{3}{2}^+$ baryon decuplet.

Example of mesonic "energy levels": the $s\bar{u}$ system

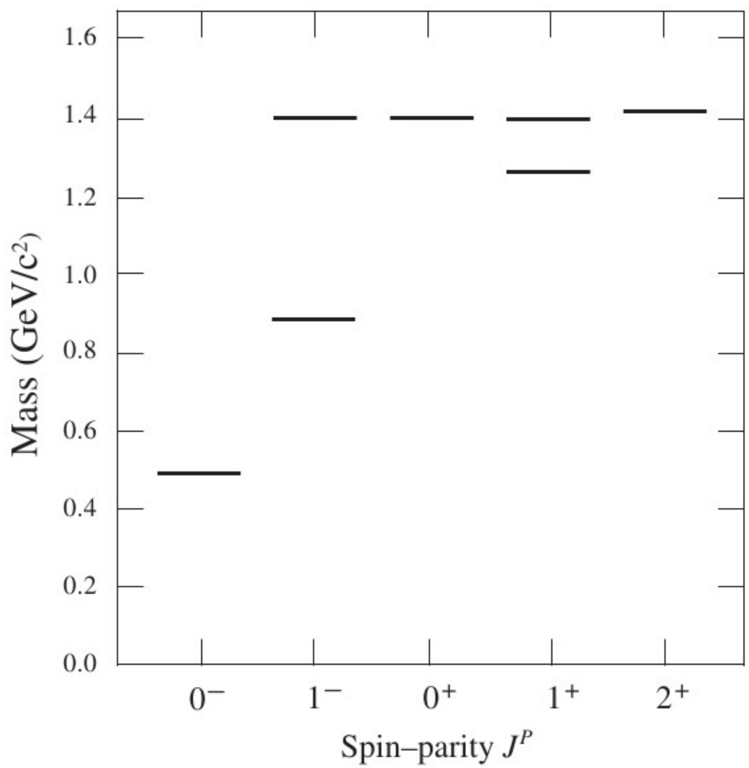


Figure 3.12 Observed bound states of the $s\bar{u}$ system with masses below 1.5 GeV/c^2, together with values of their spin-parities[9] J^P. The ground state is the $K^-(494)$ and the others can be interpreted as its excited states.

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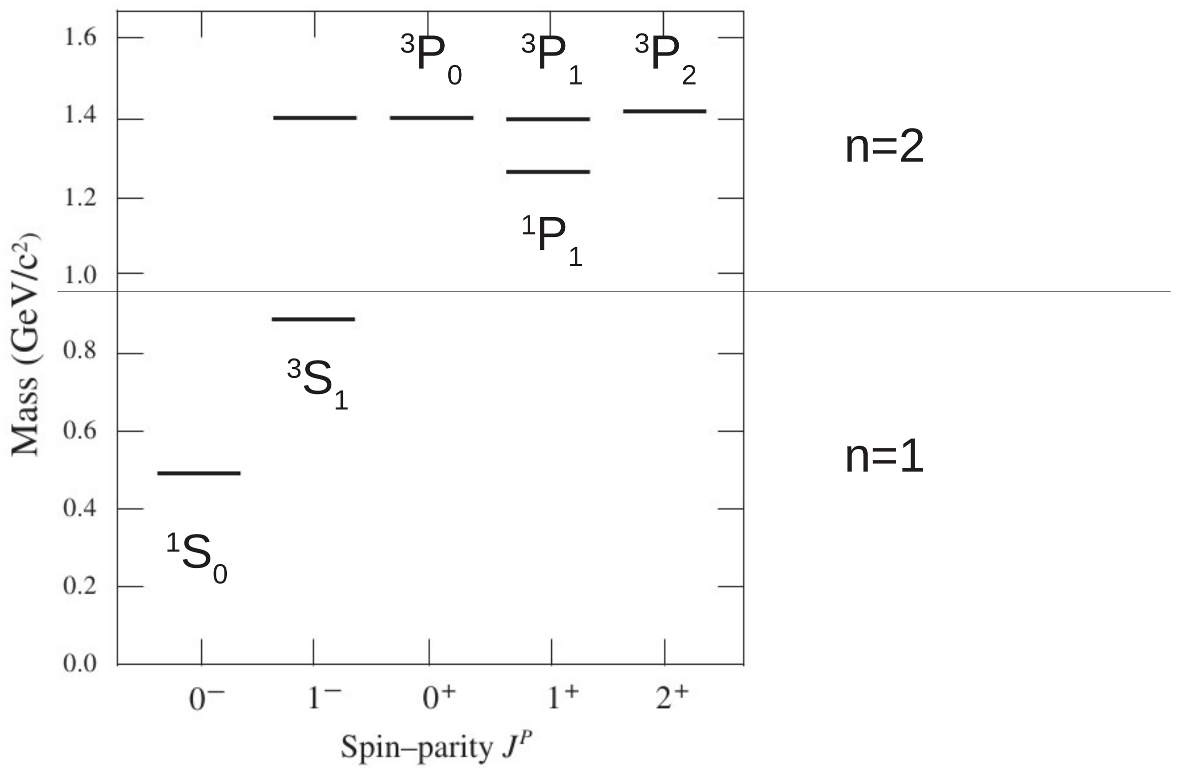

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L=0 and n = 1 mesonic uds states

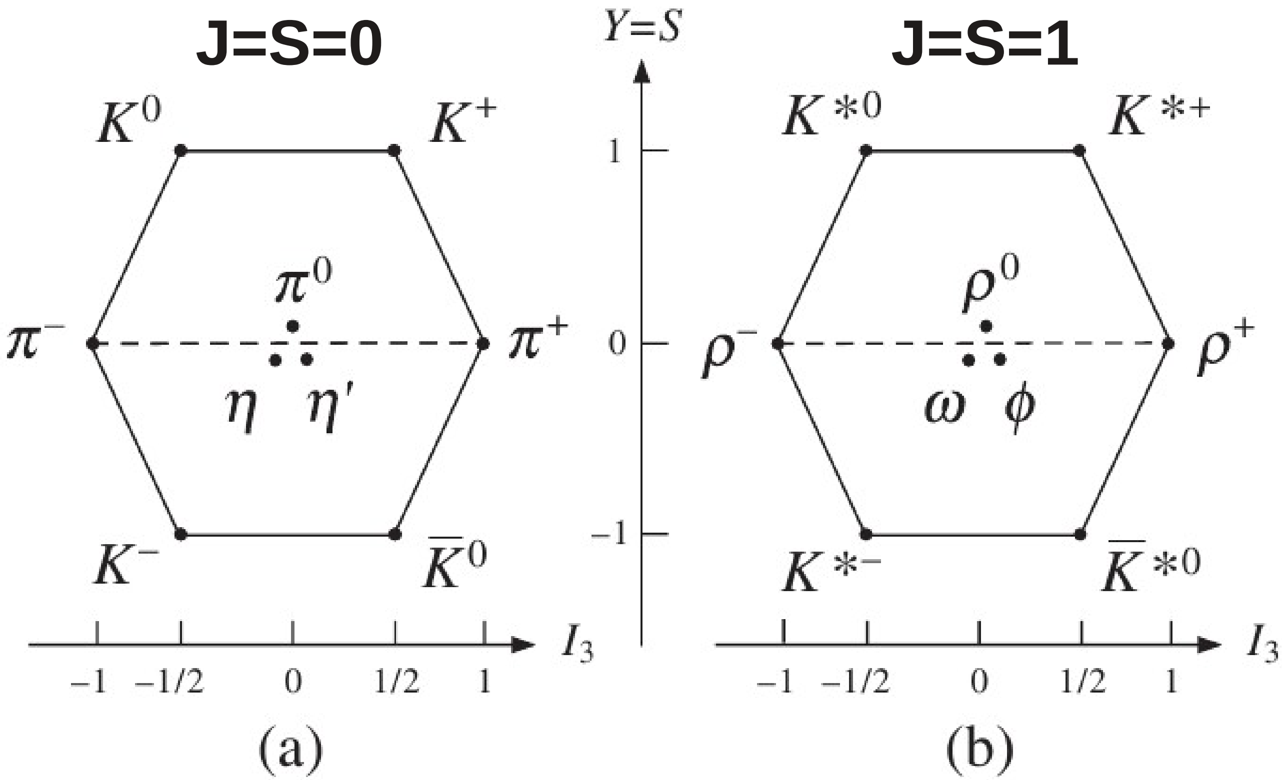
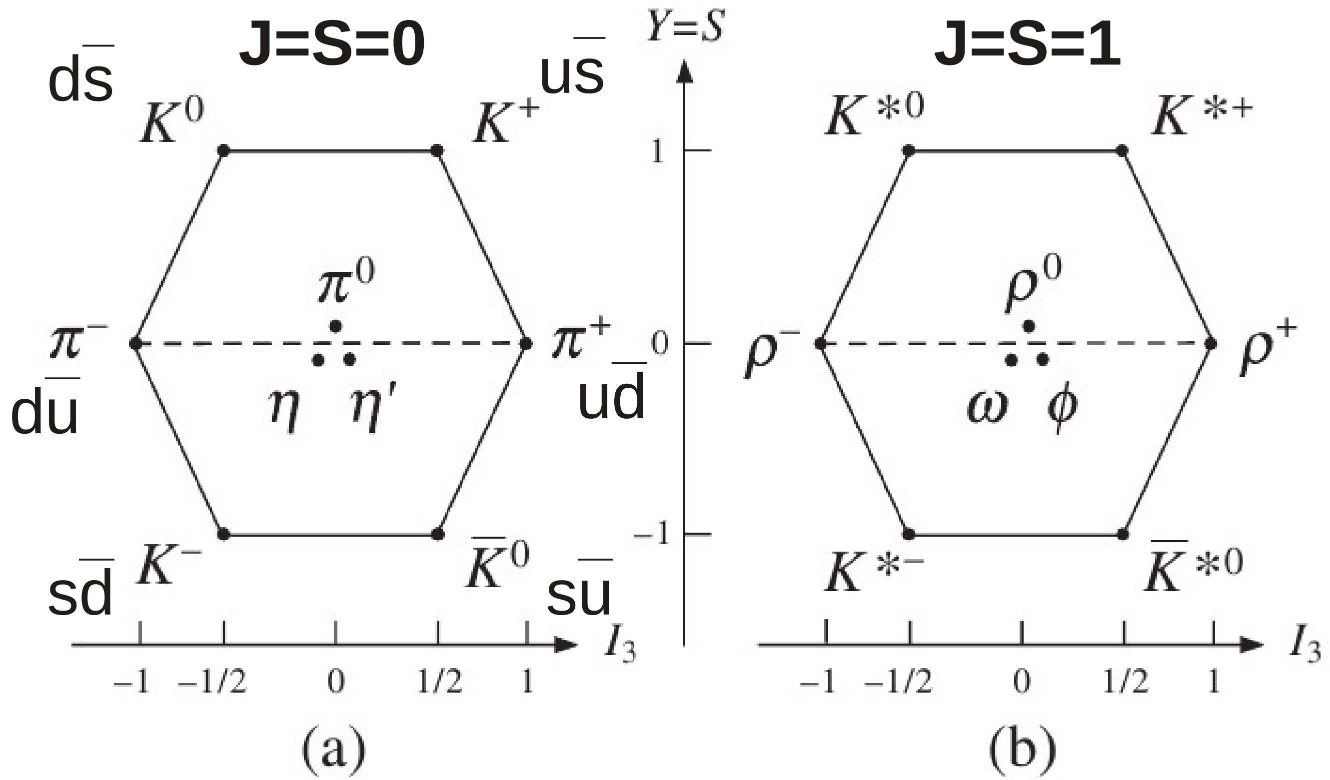


Figure 6.1 Weight diagrams for (a) the 0^- meson nonet and (b) the 1^- meson nonet.

L=0 and n = 1 mesonic uds states



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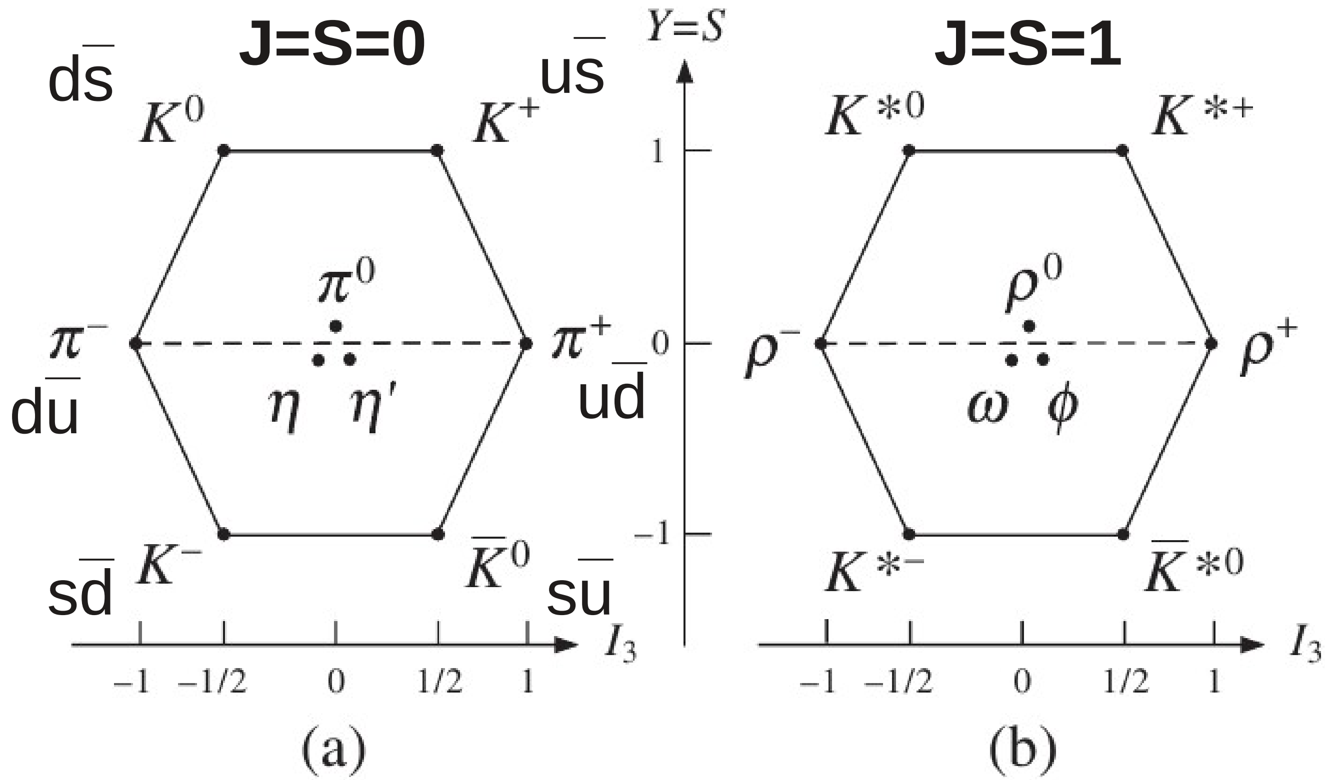


Figure 6.1 Weight diagrams for (a) the 0^- meson nonet and (b) the 1^- meson nonet.

π^0, ρ^0

$$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \quad (I=1, I_3=0), \qquad (6.23)$$

Mixture: $\eta, \eta', \omega, \Phi$

$$\begin{cases} \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \quad (I=0, I_3=0) & (6.24a) \\ s\bar{s} \quad (I=0, I_3=0), & (6.24b) \end{cases}$$

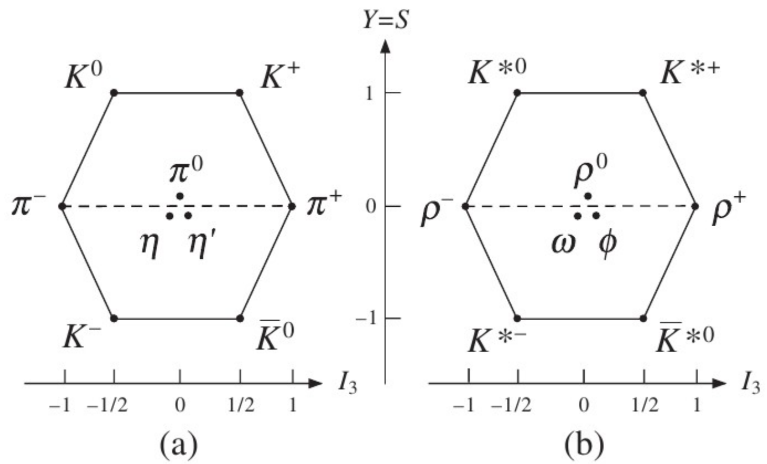


Figure 6.1 Weight diagrams for (a) the 0^- meson nonet and (b) the 1^- meson nonet.

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
$u\bar{d}$	$\pi^+(140)$	$\rho^+(768)^\#$	1	1	0
$\frac{(u\bar{u} - d\bar{d})}{\sqrt{2}}$	$\pi^0(135)$	$\rho^0(768)^\#$	0	1	0
$d\bar{u}$	$\pi^-(140)$	$\rho^-(768)^\#$	−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

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

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 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.

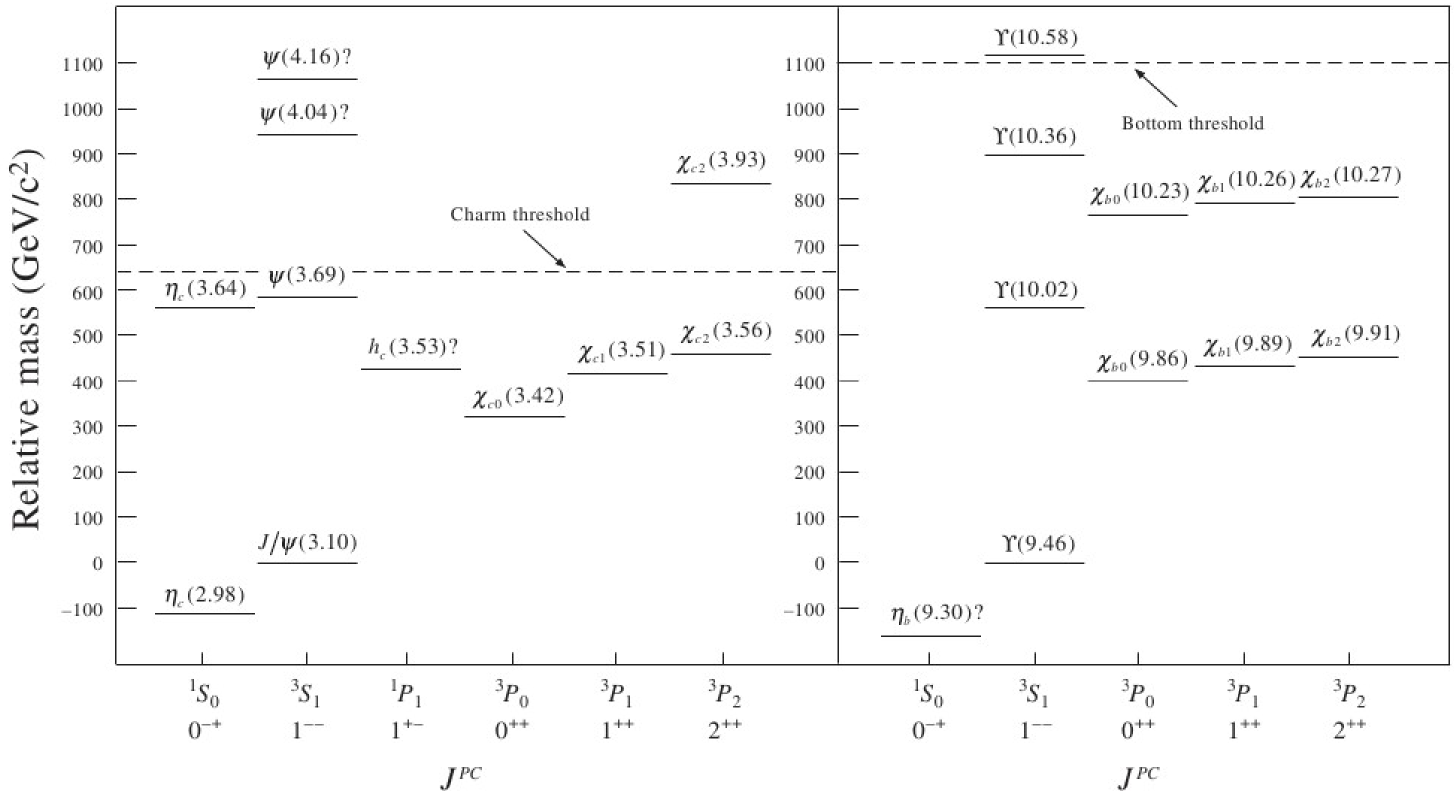
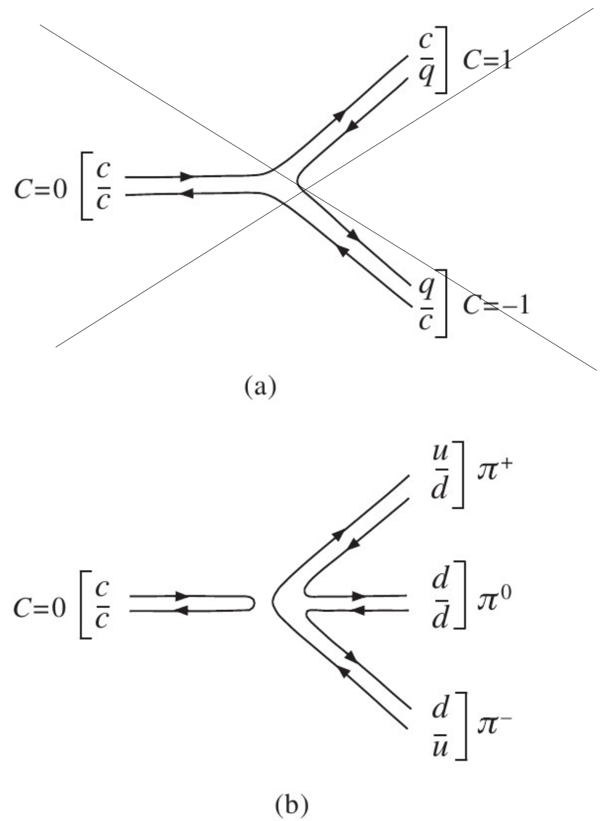


Figure 6.6 The observed states of the charmonium ($c\bar{c}$) and bottomium ($b\bar{b}$) for $L \leq 1$. The masses are given in units of GeV/c^2 and are plotted relative to that of the $^3S_1$ ground state.

Why is the J/ψ (1^-) famous? (the η_c (0^-)is lighter!)

Mass J/ψ : 3.10 GeV

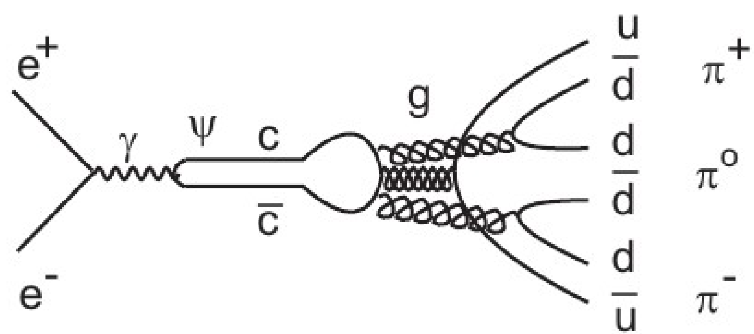
Mass D (lightest c meson) : 1.86 GeV



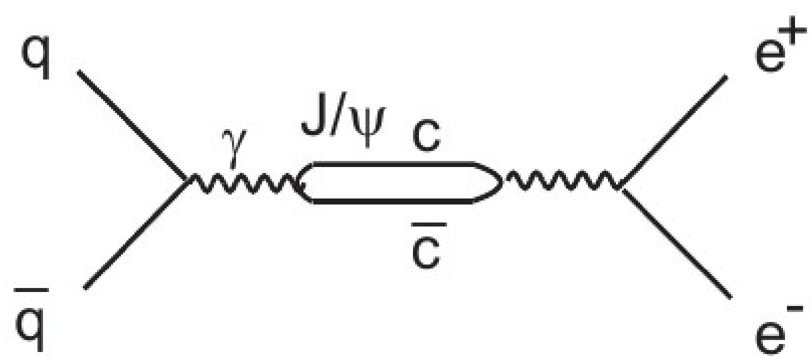
This decay is OZI suppressed
Decays are OZI suppressed when there are time regions where there are only internal gluon lines

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^-) has quantum number of virtual photon!

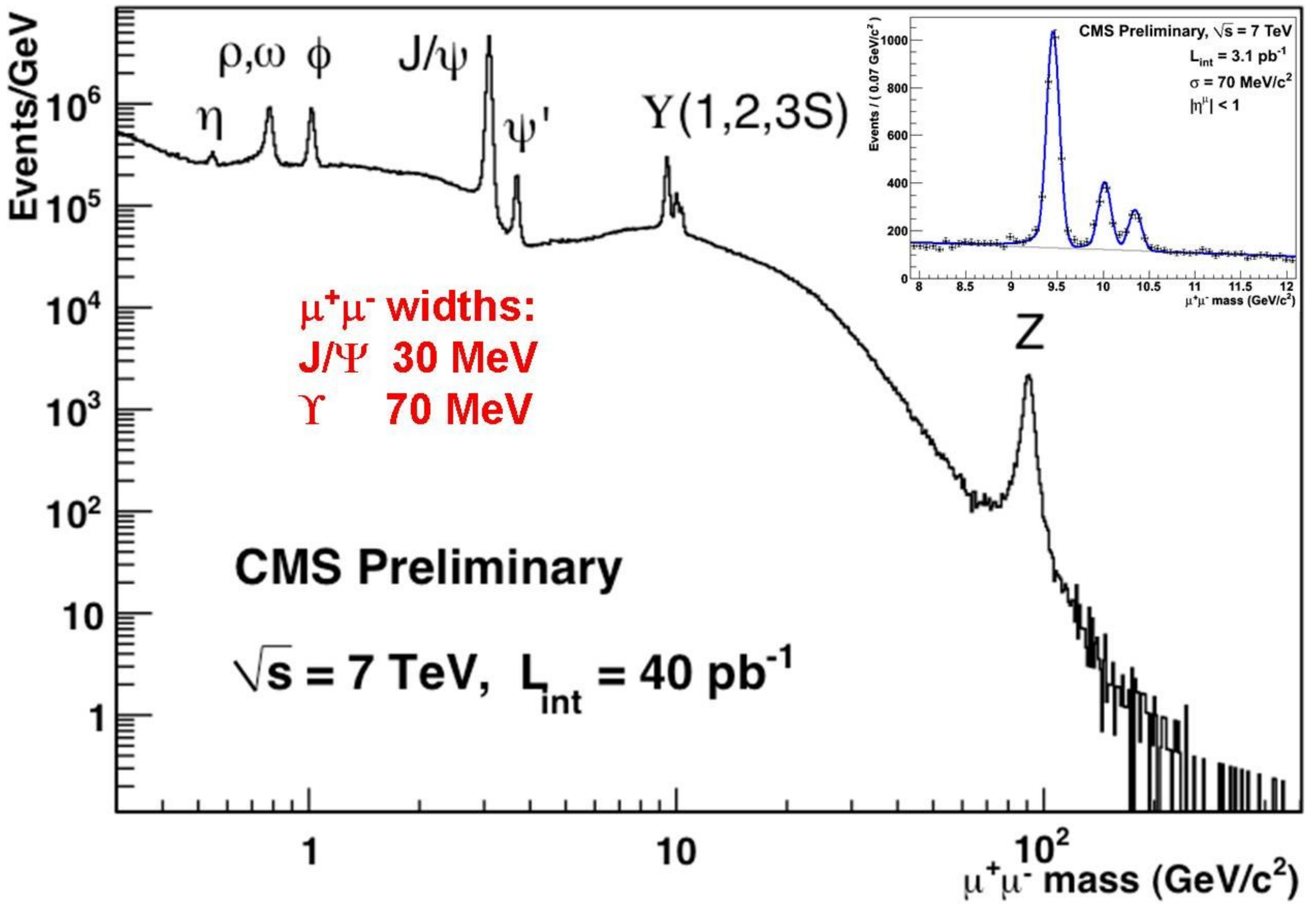


OZI suppressed!



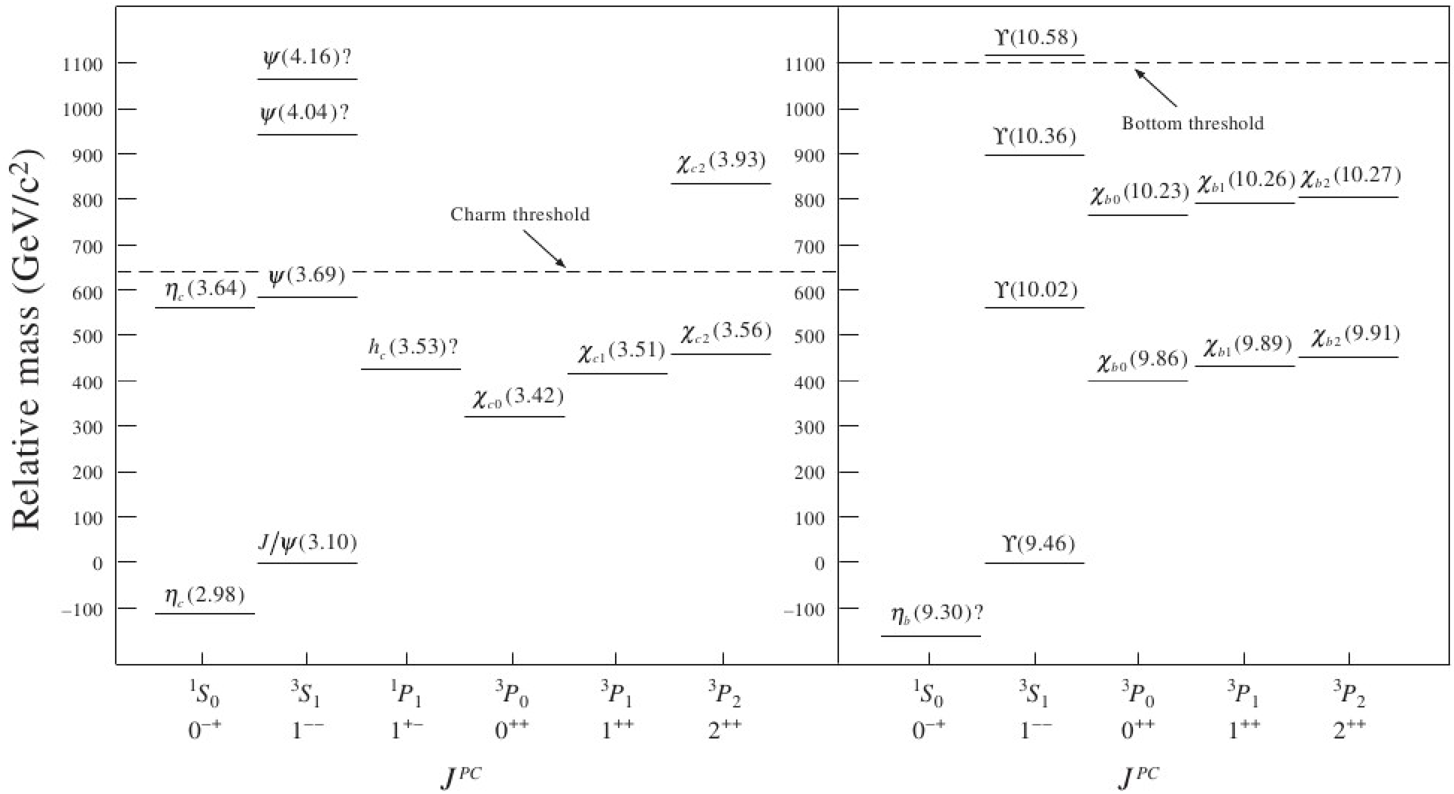
5% of decays
(and 5% to muons)

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



Note that except for η these are all 1^- states!

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



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A way to experimentally measure the strong potential

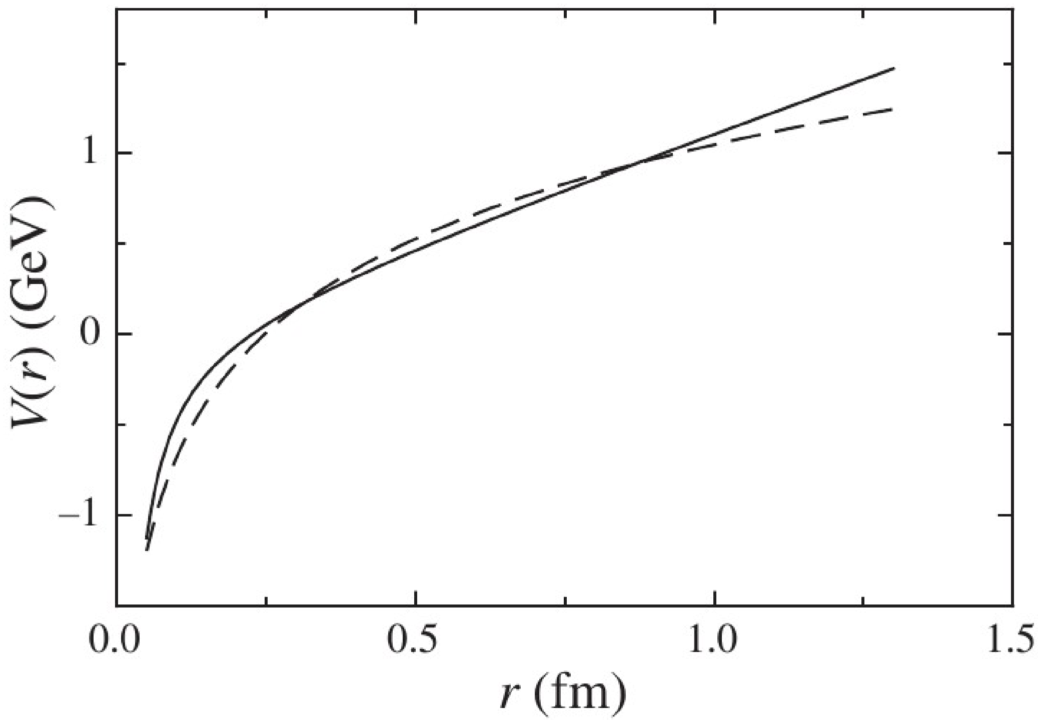
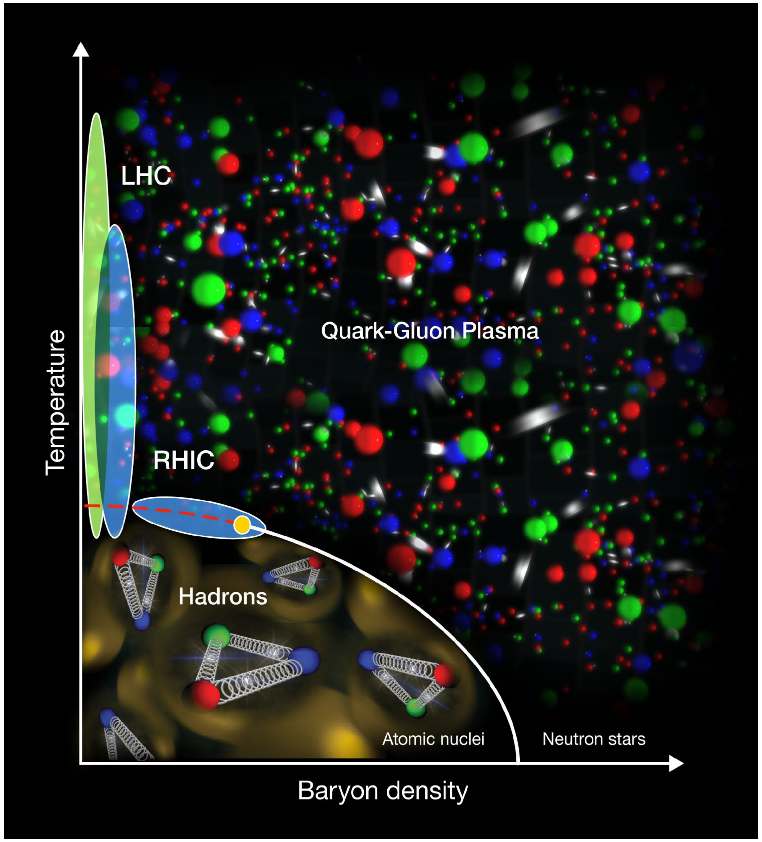


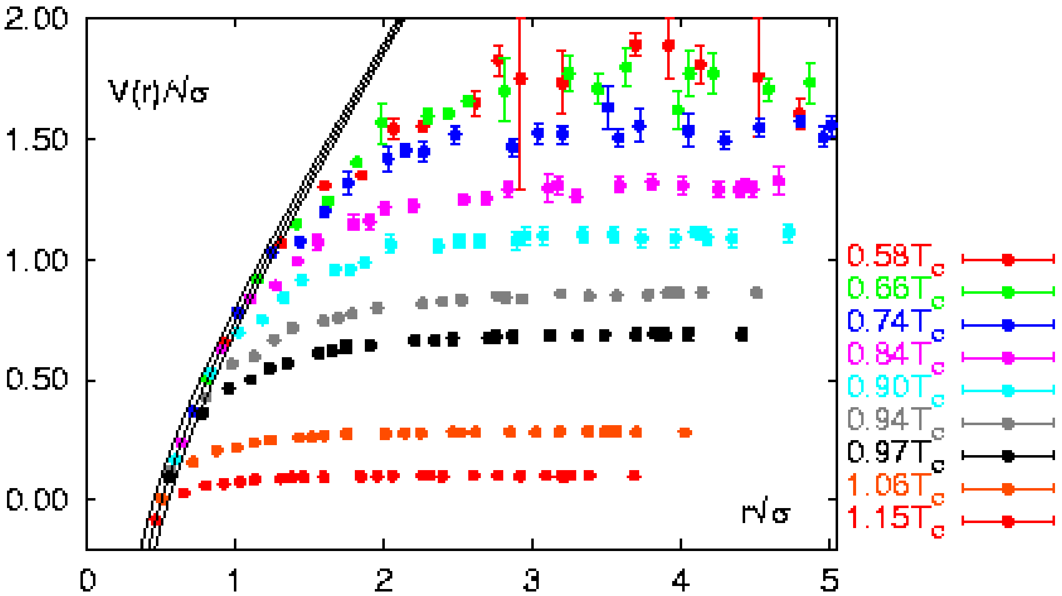
Figure 6.8 Heavy quark–antiquark potentials obtained from fitting the energy levels of charmonium and bottomium. The solid and dashed lines show the results obtained from the forms (6.57) and (6.58), respectively.

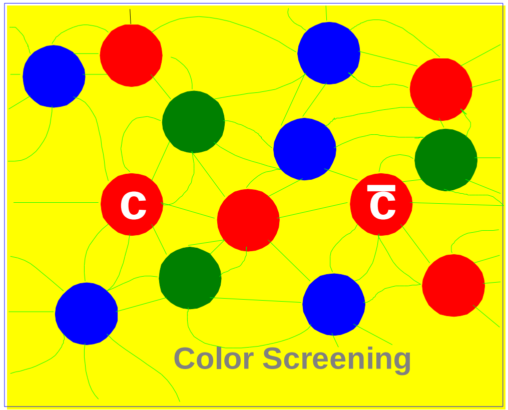
A small excursion

Lattice QCD results (Numerical non-perturbative)



Heavy quark potential



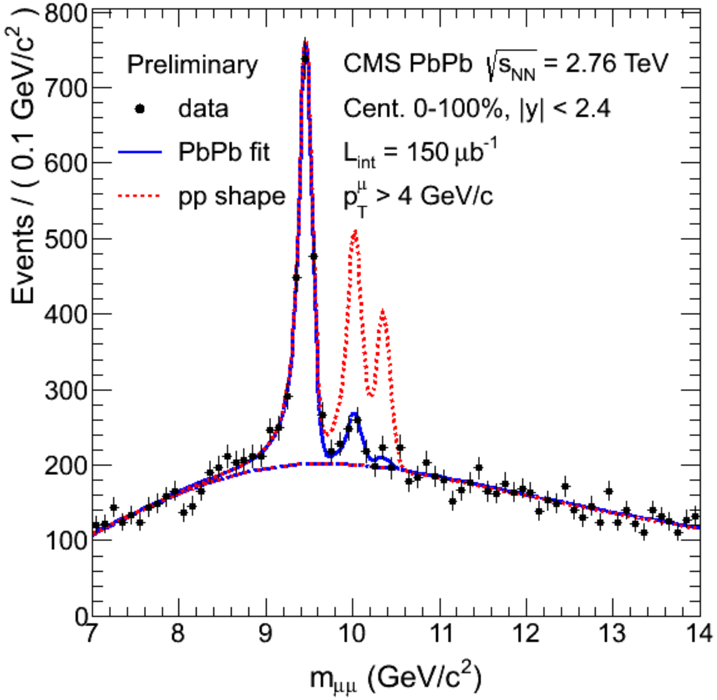


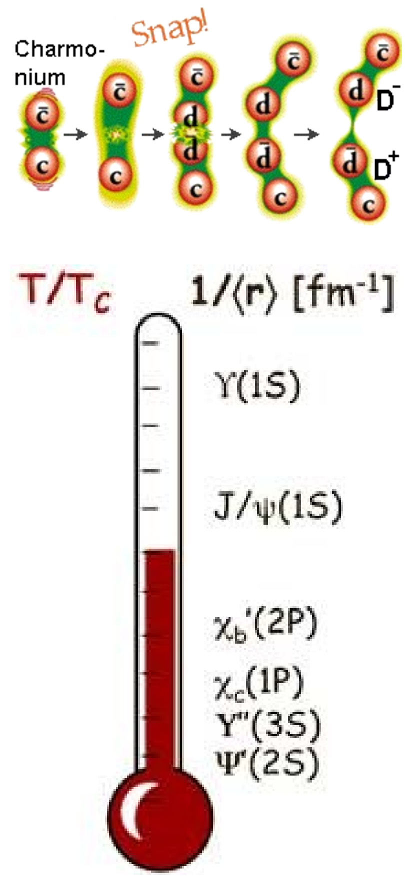
At T~Tc the strong potential is screened so e.g. c+c-bar states can disassociate.

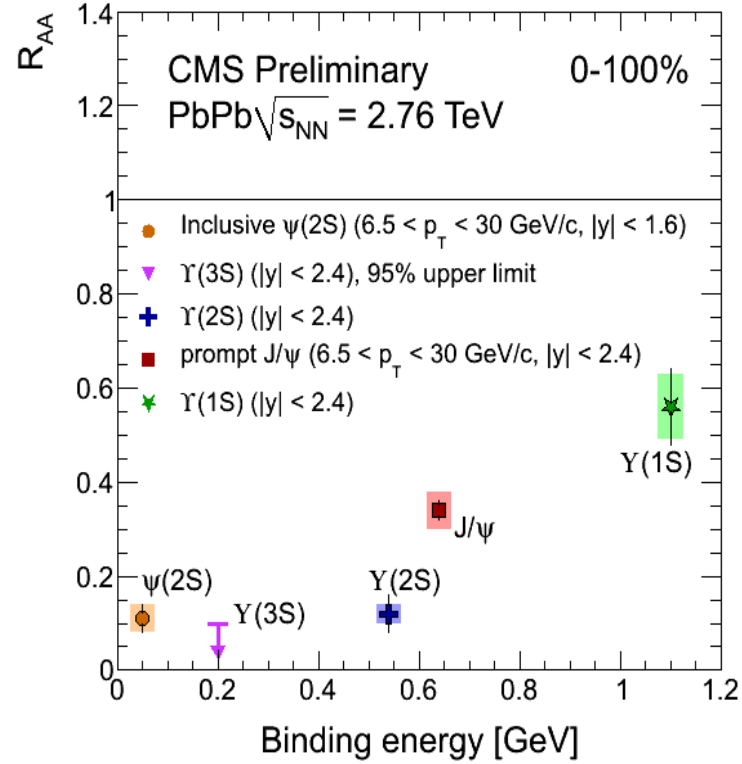
$^3S_1$ / 1^-

n=1, 2, 3

Note: 6.5<pT<30 GeV for J/ψ and ψ(2s)







Observation of sequential suppression of Y (b+b-bar) family

Expected in terms of binding energy

Unfortunately heavy quark results are more complex when systematically studied!

Next: let us understand the baryons!

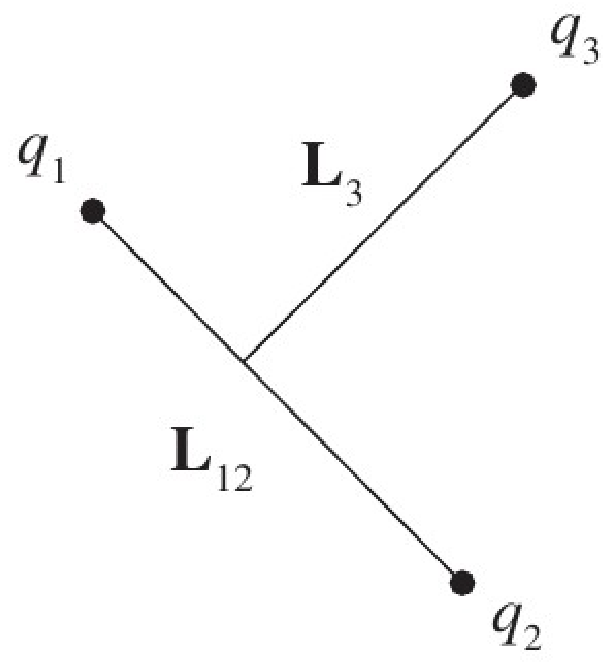
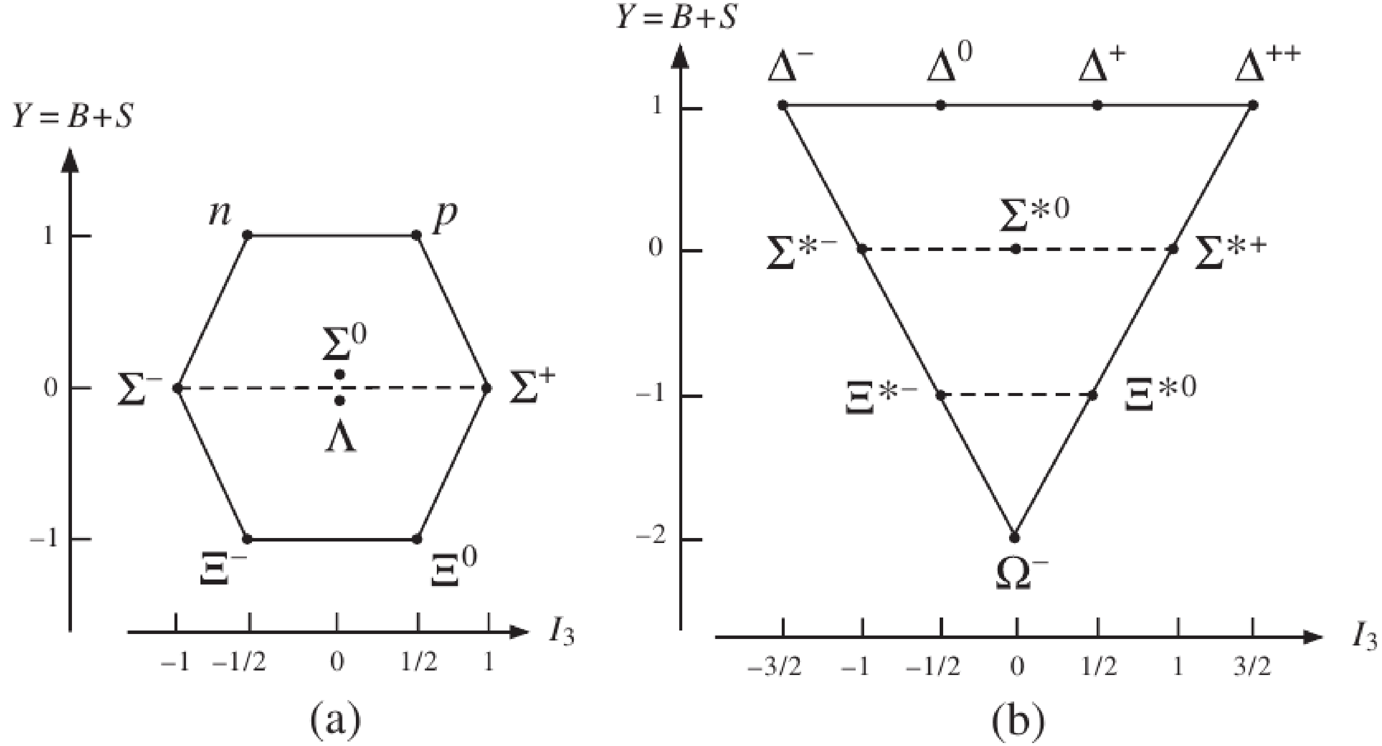


Figure 5.1 Internal orbital angular momenta of a three-quark state.

Only consider L = 0!

The baryonic systems with L=0 and n = 0



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Color is needed to make the Δ^{++} wavefunction antisymmetric!

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

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