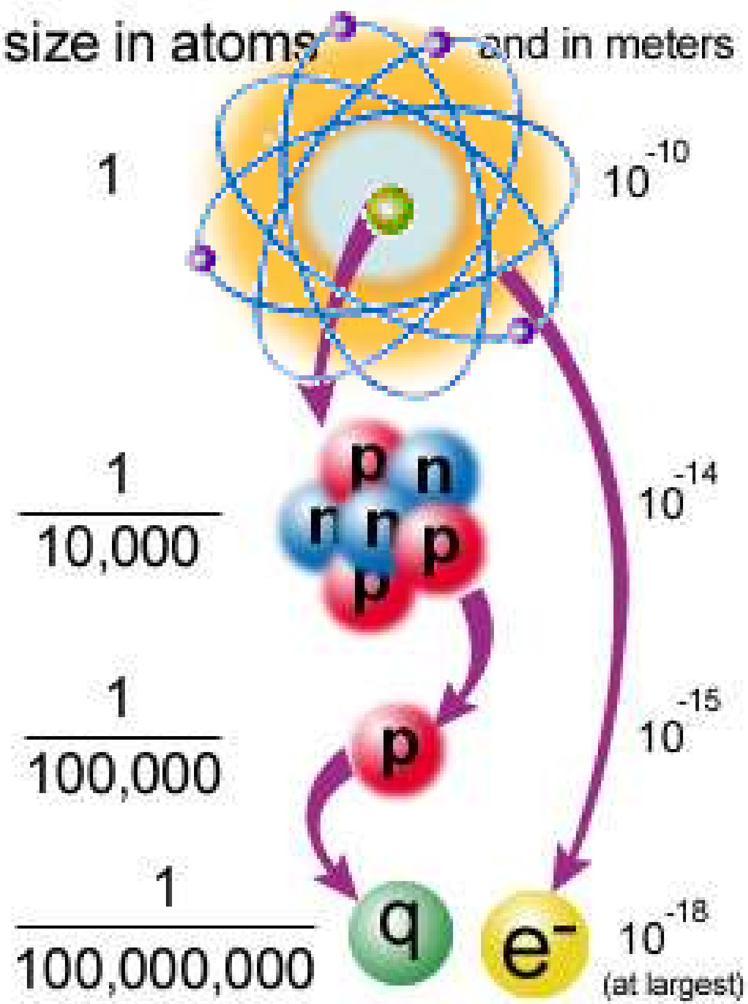
Quarks, hadrons, and structure

some selected literature

- *"Introduction to Elementary Particles"* D. Griffiths
- *"Quarks & Leptons"* F. Halzen & A. Martin
- *"The Experimental Foundations of Particle Physics"* R. Cahn & G. Goldhaber
- *"Gauge Theories in Particle Physics"* I.J.R. Aitchison & A.J.G. Hey
- *"Introduction to High Energy Phyics"* D.H. Perkins
- *"Facts and Mysteries in Elementary Particle Physics"* (M. Veltman)
- *"Review of Particle Properties"* http://pdg.lbl.gov

Typical scales

1 fm = 10^{-15} m



FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

Classification of quarks

Quark	q	Spin	Q	I	I3	S	N
Up	u	½	+2/3	½	+½	0	1/3
Down	d	½	-1/3	½	-½	0	1/3
Strange	s	½	-1/3	0	0	1	1/3

Q = charge, I = isospin, S = strangeness, N = baryon number

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

The spin ½ baryon octet

Particle	Mass	Stable	Q	Spin	I	I3	L	B	S	Y
p	938.2	Yes	+1	½	½	½	0	1	0	1
n	939.6	No	0	½	½	-½	0	1	0	1
Λ^0	1115.6	No	0	½	0	0	0	1	-1	0
Σ^+	1189.4	No	+1	½	1	1	0	1	-1	0
Σ^0	1192.5	No	0	½	1	0	0	1	-1	0
Σ^-	1197.4	No	-1	½	1	-1	0	1	-1	0
Ξ^0	1314.9	No	0	½	½	½	0	1	-2	-1
Ξ^-	1321.3	No	-1	½	½	-½	0	1	-2	-1

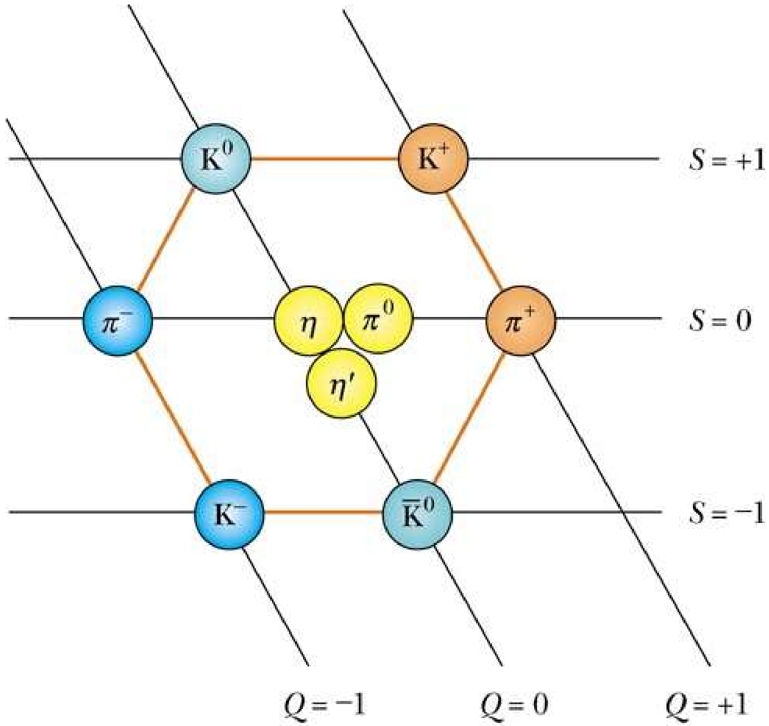
The spin 3/2 baryon decuplet

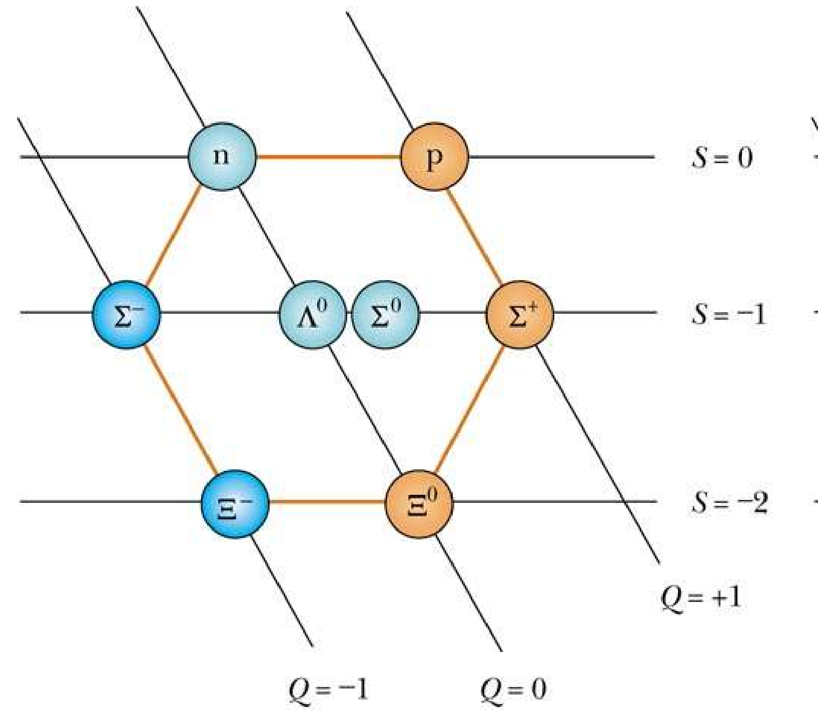
Particle	Mass	Stable	Q	Spin	I	I3	L	B	S	Y
Δ^-	~1230	No	-1	3/2	3/2	-3/2	0	1	0	1
Δ^0	~1230	No	0	3/2	3/2	-½	0	1	0	1
Δ^+	~1230	No	+1	3/2	3/2	+½	0	1	0	1
Δ^{++}	~1230	No	+2	3/2	3/2	+3/2	0	1	0	1
Σ^{*-}	1383	No	-1	3/2	1	-1	0	1	-1	0
Σ^{*0}	1384	No	0	3/2	1	0	0	1	-1	0
Σ^{*+}	1387	No	1	3/2	1	1	0	1	-1	0
Ξ^{*-}	1532	No	-1	3/2	½	-½	0	1	-2	-1
Ξ^{*-}	1535	No	0	3/2	½	½	0	1	-2	-1
Ω^-	1672	No	-1	3/2	0	0	0	1	-3	-2

The eightfold way

mesons

baryons

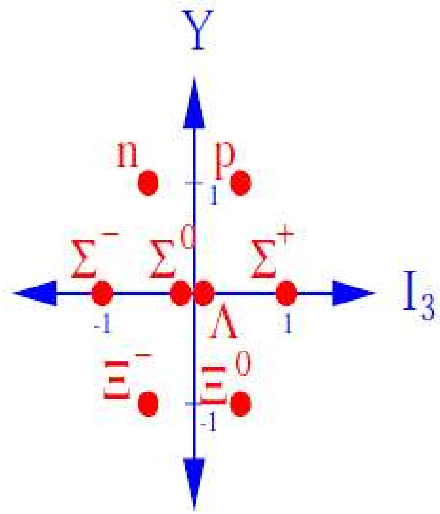




EXAMPLES OF MULTIPLETS

Baryon Octet

$J^P = \frac{1}{2}^+$

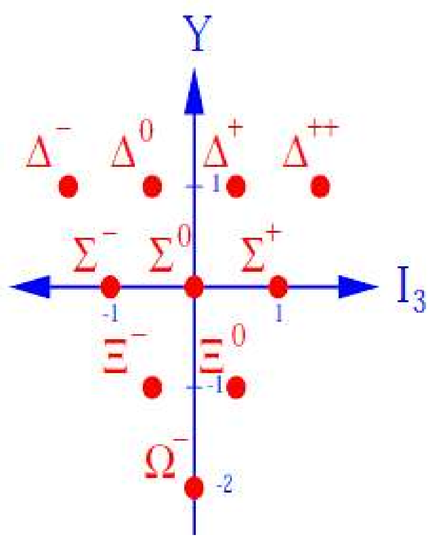


N(939)	I=1/2
Σ(1193)	I=1
Λ(1116)	I=0
Ξ(1318)	I=1/2

$$\frac{Q}{e} = I_3 + \frac{1}{2}(N+S)$$
$$= I_3 + \frac{1}{2}Y$$

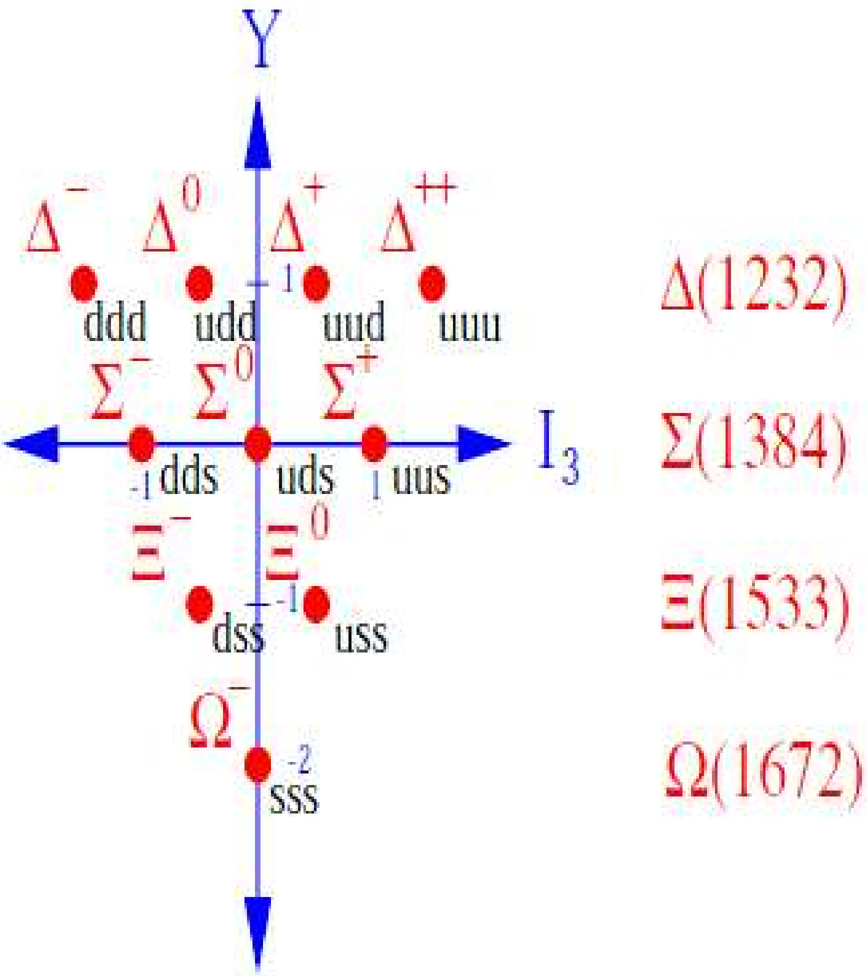
Baryon Decuplet

$J^P = \frac{3}{2}^+$



Δ(1232)	I=3/2
Σ(1384)	I=1
Ξ(1533)	I=1/2
Ω(1672)	I=0

We can identify the 10 symmetric states with the baryon $J^P = \frac{3}{2}^+$ decuplet.



We now have a $J^P = \frac{3}{2}^+$ decuplet and a $J^P = \frac{1}{2}^+$ octet of baryons. (18 out of the 27 states used).

It turns out that the remaining 8 mixed symmetry flavour states form a $J^P = \frac{3}{2}^-$ octet of baryon resonances of higher mass.

$N(1520)$	$I = \frac{1}{2}$	
$\Lambda(1520)$	$I = 0$	SPINS
$\Xi(1820)$	$I = \frac{1}{2}$	$\uparrow\uparrow\uparrow$
$\Sigma(1670)$	$I = 1$	

The antisymmetric flavour state forms a $J^P = \frac{1}{2}^-$ singlet baryon resonance, the $\Lambda(1405)$.

	S	Δm
$\Delta(1232)$	0	
		152 MeV
$\Sigma(1384)$	-1	
		149 MeV
$\Xi(1533)$	-2	
		139 MeV
$\Omega(1672)$	-3	

Proton flavor wave function with spin up

$$|\psi_{p\uparrow}> = \frac{1}{\sqrt{18}} \left[\begin{array}{l} 2u\uparrow d\downarrow u\uparrow + 2d\downarrow u\uparrow u\uparrow + 2u\uparrow u\uparrow d\downarrow \\ -u\downarrow d\uparrow u\uparrow - d\uparrow u\downarrow u\downarrow - u\uparrow u\downarrow d\uparrow \\ -u\uparrow d\uparrow u\downarrow - d\uparrow u\uparrow u\downarrow - u\downarrow u\uparrow d\uparrow \end{array} \right]$$

note: this must be symmetric because color is antisymmetric, remember uuu is symmetric.

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

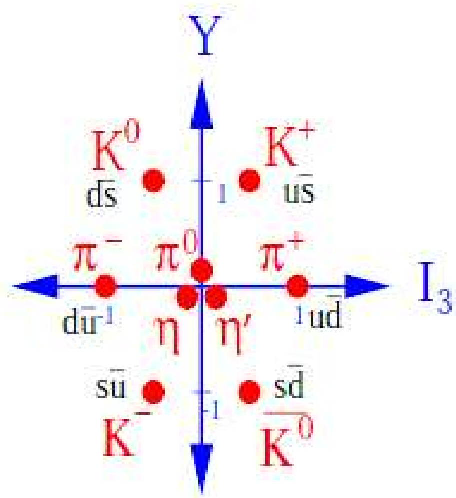
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Particle	Mass	Stable	Q	Spin	I	I3	L	B	S
e	0.51	Yes	-1	½			1	0	0
ν	~0	Yes	0	½			1	0	0
$\pi^{\pm}$	139.6	No	± 1	0	1	± 1	0	0	0
π^0	134.9	No	0	0	1	0	0	0	0
η	548.8	No	0	0	0	0	0	0	0
K^+	493.6	No	+1	0	½	+½	0	0	+1
K^-	493.6	No	-1	0	½	-½	0	0	-1
K^0	497.7	No	0	0	½	-½	0	0	+1
K^0	497.7	No	0	0	½	+½	0	0	-1
p	938.2	Yes	+1	½	½	½	0	1	0
n	939.6	No	0	½	½	-½	0	1	0

Under the quark hypothesis the mesons are $q\bar{q}$ states.
With 3 flavours, u, d, s we have 9 combinations $q\bar{q}$.

- The pseudoscalar nonet $J^P = 0^-$ are 9 states with spins ↑↓ (L=0)
- The vector nonet $J^P = 1^-$ are 9 states with spins ↑↑ (L=0)

<u>Pseudoscalar Mesons</u>



$m(K^0)$, $m(\bar{K}^0)$ } 497.7 MeV
$m(K^+)$, $m(K^-)$ } 493.7 MeV
$m(\pi^+)$, $m(\pi^-)$ } 139.6 MeV
$m(\pi^0)$ 135.0 MeV
$m(\eta)$ 547.5 MeV
$m(\eta')$ 957.8 MeV

The $I_3 = 0$, $Y = 0$ states π^0, η, η' will be linear combinations of the states $u\bar{u}$, $d\bar{d}$, $s\bar{s}$.

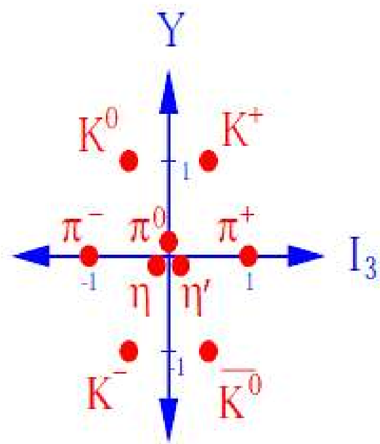
Since the π^0 forms an isospin triplet with π^+ ($u\bar{d}$) and π^- ($d\bar{u}$) it is reasonable to expect the wavefunction will involve u, d only. In fact it is

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u})$$

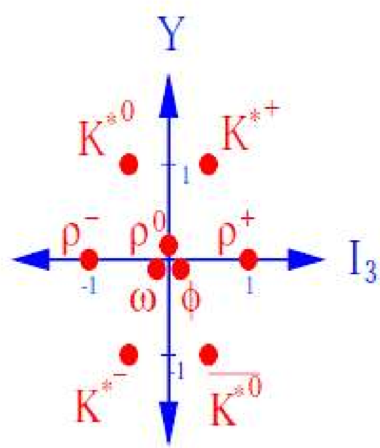
MESON MULTIPLETS

The observed lowest mass meson states form the following multiplets, which are nonets.

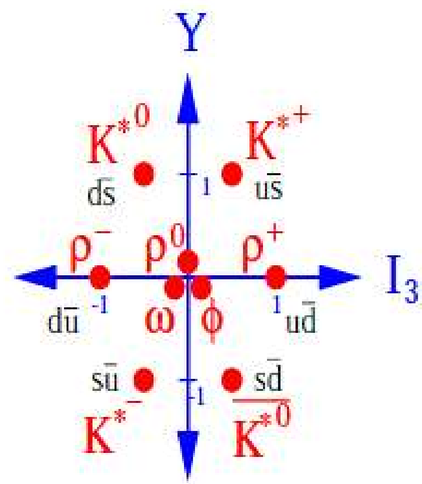
Pseudoscalar Mesons $J^P = 0^-$



Vector Mesons $J^P = 1^-$



Vector Mesons



$m(K^{*0})$, $m(\overline{K^{*0}})$ } 896.1 MeV

$m(K^{*+})$, $m(K^{*-})$ } 891.6 MeV

$m(\rho^+)$, $m(\rho^-)$, $m(\rho^0)$ } 768.5 MeV

$m(\omega)$ 781.9 MeV

$m(\phi)$ 1019.4 MeV

Again, the 3 central states ρ^0, ω, ϕ are linear combinations of the states $u\overline{u}$, $d\overline{d}$, $s\overline{s}$

$$
\begin{aligned}
|\rho^0\rangle &= \frac{1}{\sqrt{2}}(d\overline{d} - u\overline{u}) \\
|\phi_1\rangle &= \frac{1}{\sqrt{3}}(u\overline{u} + d\overline{d} + s\overline{s}) \\
|\phi_8\rangle &= \frac{1}{\sqrt{6}}(2s\overline{s} - u\overline{u} - d\overline{d})
\end{aligned}
$$

The physical states ω and ϕ turn out to be linear combinations (mixtures) of the ϕ_1 and ϕ_8 states

$$
\begin{pmatrix} |\phi\rangle \\ |\omega\rangle \end{pmatrix} = \begin{pmatrix} cos\theta_V & sin\theta_V \\ -sin\theta_V & cos\theta_V \end{pmatrix} \begin{pmatrix} |\phi_8\rangle \\ |\phi_1\rangle \end{pmatrix}
$$

where $\theta_V \approx +35^o$.

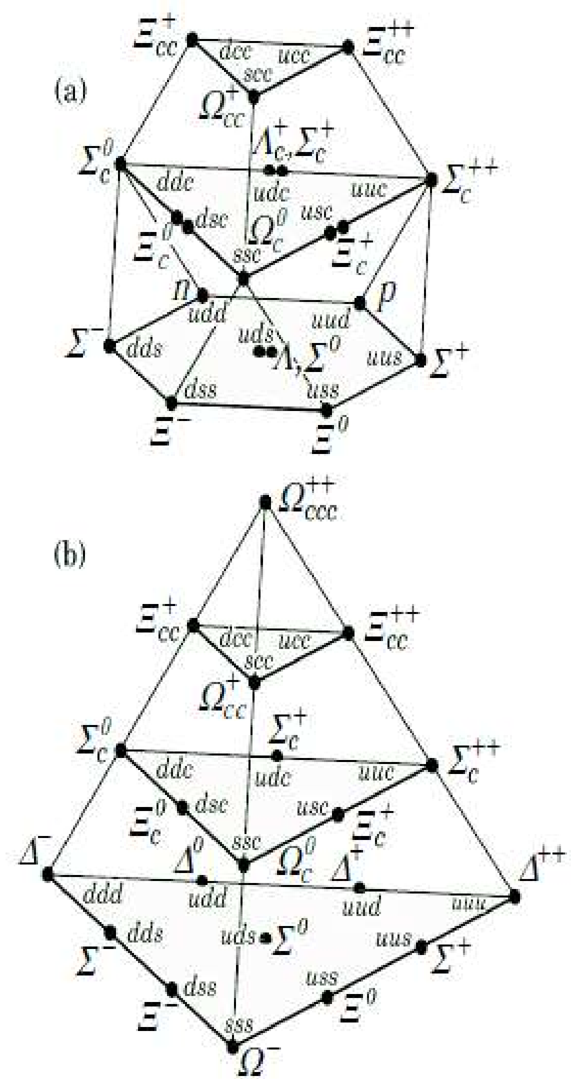
constructing the phi and omega mesons

$$
\begin{aligned}
|\phi\rangle &= \frac{\sqrt{2}}{\sqrt{3}}|\phi_8\rangle + \frac{1}{\sqrt{3}}|\phi_1\rangle \\
&= \frac{\sqrt{2}}{\sqrt{3}}\frac{1}{\sqrt{6}}(2s\bar{s} - u\bar{u} - d\bar{d}) + \frac{1}{\sqrt{3}}\frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s}) \\
&= \frac{1}{3}(2s\bar{s} - u\bar{u} - d\bar{d}) + \frac{1}{3}(u\bar{u} + d\bar{d} + s\bar{s}) \\
&= s\bar{s}
\end{aligned}
$$

$sin\theta_V = 1/\sqrt{3}$

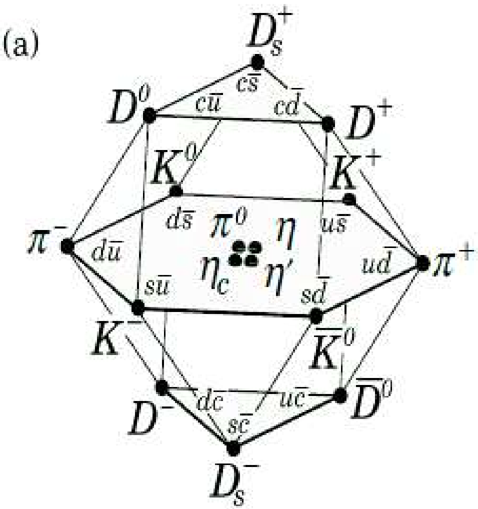
$$
\begin{aligned}
|\omega\rangle &= -\frac{1}{\sqrt{3}}|\phi_8\rangle + \frac{\sqrt{2}}{\sqrt{3}}|\phi_1\rangle \\
&= -\frac{1}{\sqrt{3}}\frac{1}{\sqrt{6}}(2s\bar{s} - u\bar{u} - d\bar{d}) + \frac{\sqrt{2}}{\sqrt{3}}\frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s}) \\
&= -\frac{1}{\sqrt{18}}(2s\bar{s} - u\bar{u} - d\bar{d}) + \frac{2}{\sqrt{18}}(u\bar{u} + d\bar{d} + s\bar{s}) \\
&= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})
\end{aligned}
$$

BARYON MULTIPLETS WITH 4 QUARKS

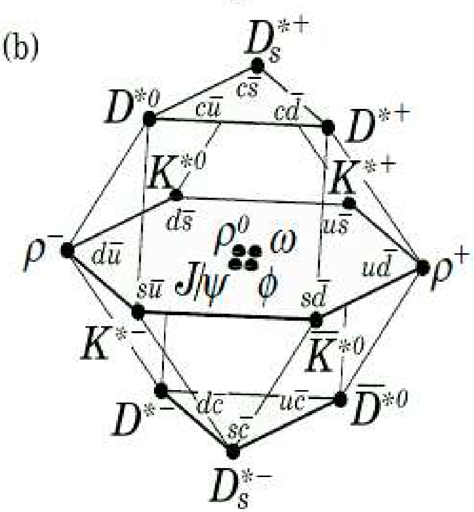


MESON MULTIPLETS WITH 4 QUARKS

(a)



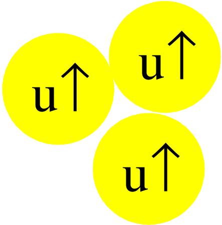
(b)



(QCD)

The theory of quarks and gluons

color charge
based on a local SU(3) gauge symmetry
field quanta: eight gluons g

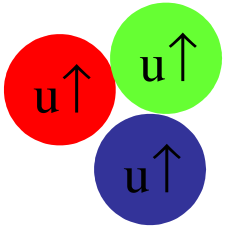


Quark structure: p = uud , n = udd , Δ^{++}=uuu

Problem: the Δ^{++} consists of three identical quarks and is thereby symmetric under u↔u permutations; its $|JJ_z\rangle = |\frac{3}{2}\frac{3}{2}\rangle$ state has a symmetric intrinsic spin wave function (J=3/2). Hence violates Pauli principle!

Δ^{++}

Solution: Invent new (hidden) internal degree of freedom: color charge



All bound states of quarks are colorless i.e. white

<u>baryons</u>: multiply with:

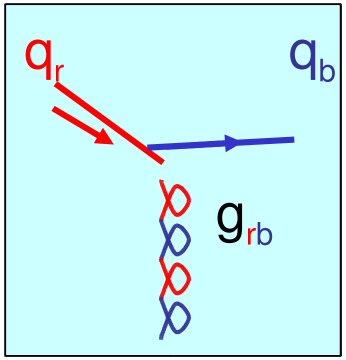
$(RGB-RBG-GRB-BGR+BRG+GBR)/\sqrt{6}$ (anti-symmetric in color)

<u>mesons</u>: multiply with:

$(R\bar{R}+B\bar{B}+G\bar{G})/\sqrt{3}$ (symmetric in color)

QCD: color interaction

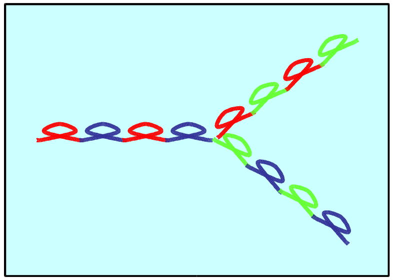
Fundamental interaction vertex:



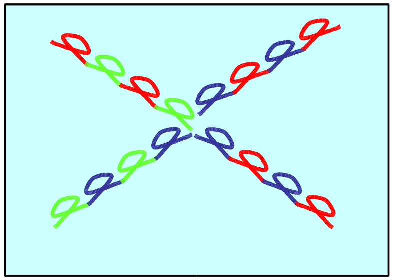
Quarks carry color; anti-quarks carry anti-color

Gluons carry a color and anti-color charge; eight (not nine!) possible combinations

Gluons (as opposed to photons) carry "charge" and hence can couple to themselves!

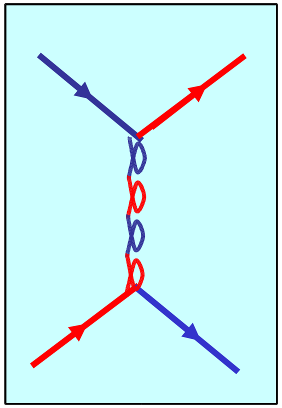


$g \rightarrow gg$



$gg \rightarrow gg$

By combination of vertices more complicated (and realistic!) processes can be described:



$qq \rightarrow qq$

QCD confinement and jets

Within a proton the quarks behave as almost free particles because at such distances the strong coupling constant α_s is small.
This we call asymptotic freedom.

Once the distances between individual quarks becomes large; the coupling constant gets large and in the region in between the quarks new particle/anti-particle pairs can be created.
This we call confinement.

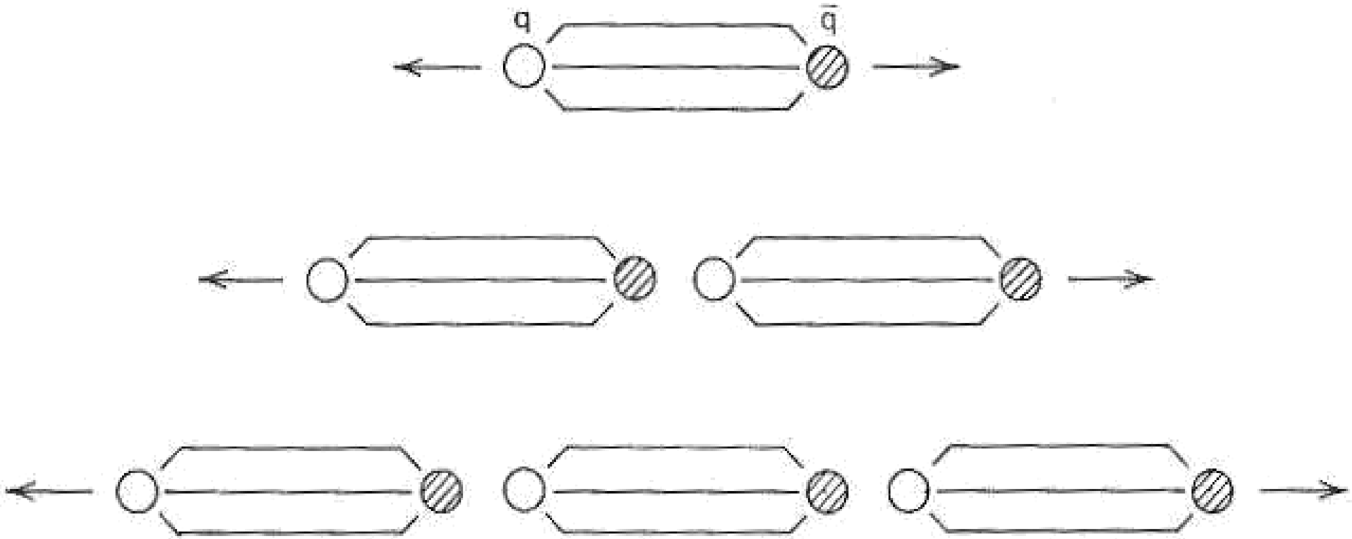
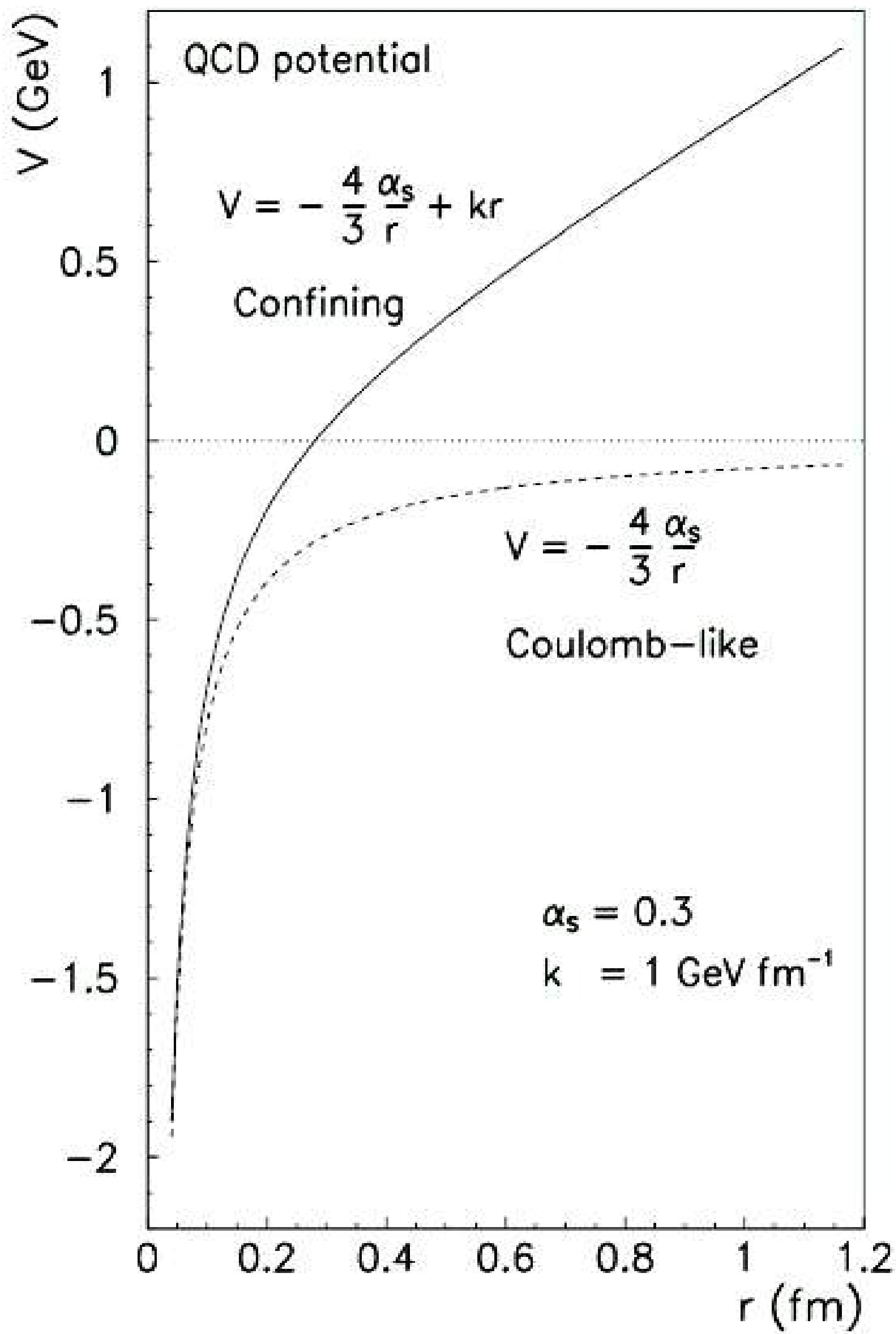
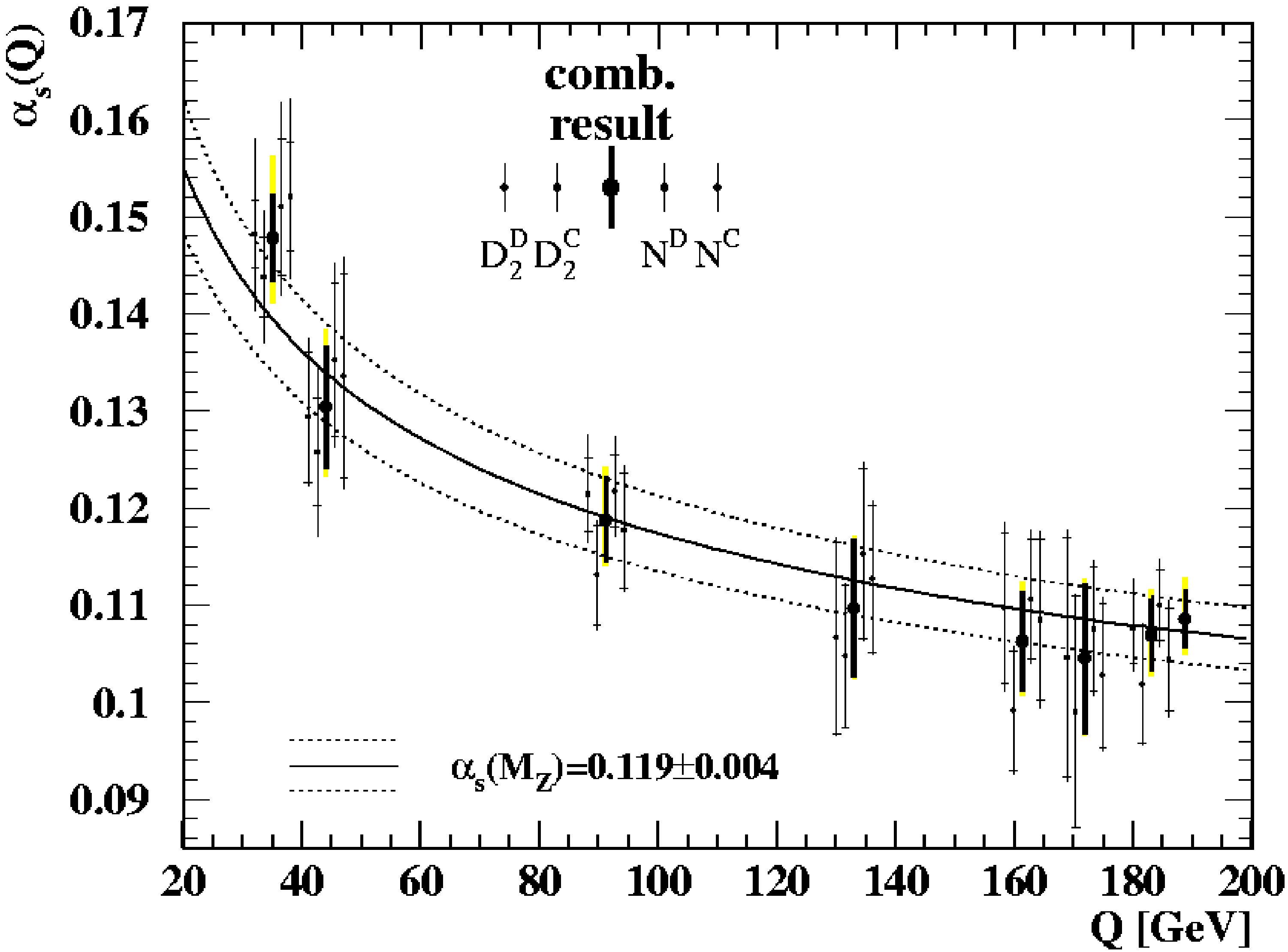


Fig. 1.14 Jet formation when a quark and antiquark separate.



QCD potential
$V = -\frac{4}{3}\frac{\alpha_s}{r} + kr$
Confining
$V = -\frac{4}{3}\frac{\alpha_s}{r}$
Coulomb−like
$\alpha_s = 0.3$
$k = 1$ GeV fm^{-1}
V (GeV)
r (fm)
1
0.5
0
−0.5
−1
−1.5
−2
0
0.2
0.4
0.6
0.8
1
1.2

α_s



$\alpha_S(M_Z) = 0.119 \pm 0.004$