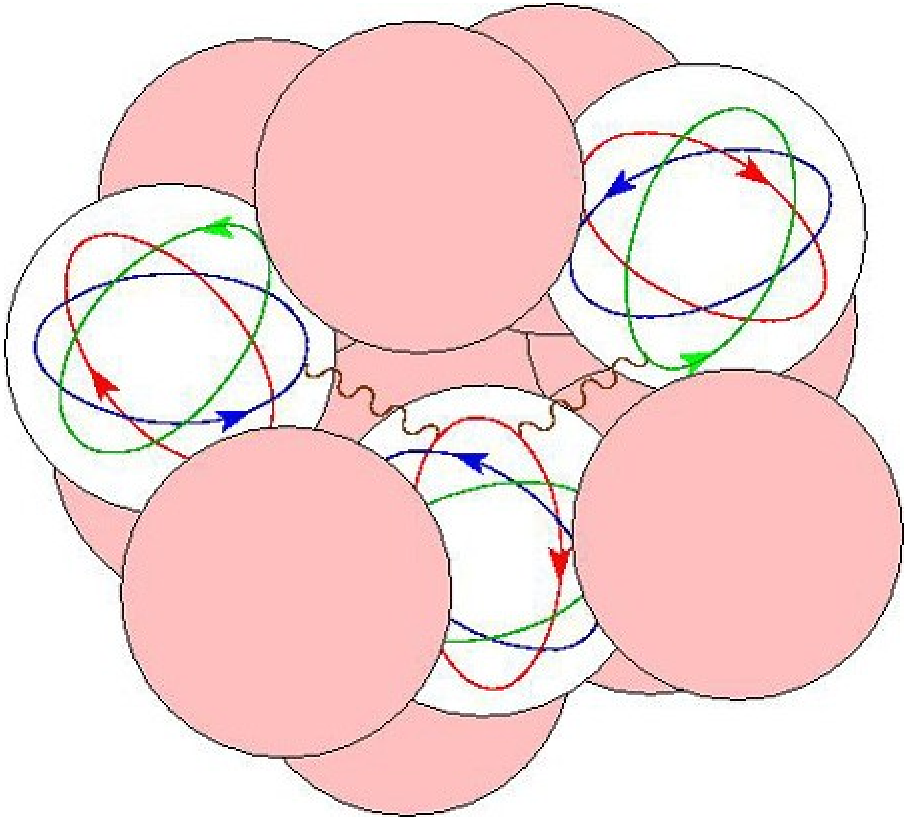
Quark Model

History and current status

Manon Bischoff

Heavy-Ion Seminar 2013



Outline

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Historical background

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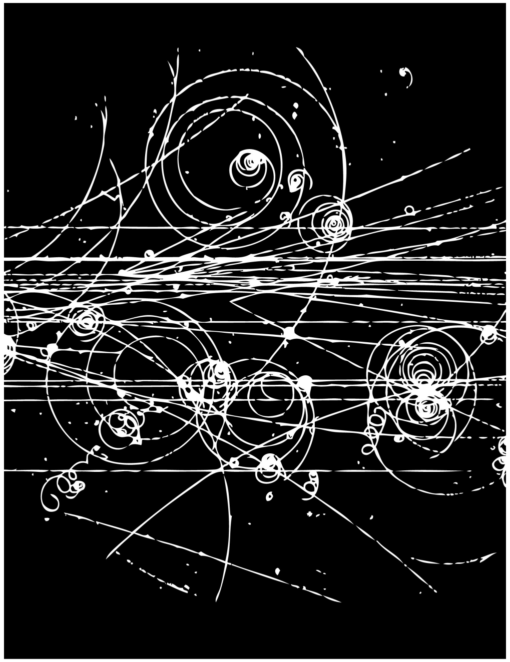
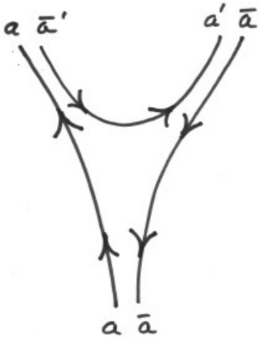


- Particle zoo (bubble chambers, ...)
- 1949: Fermi + Yang: Pion not elementary particle
- 1950's: Isospin SU(2) symmetry of strong int.
- 1953 Exp.: additional quantum number: strangeness
- 1956: Sakata proposes that pion consists of three particles (n,p,Λ)
- 1961: Gell-Mann: Eightfold way: SU(3) symmetry

Historical background

- 1962: Prediction of Ω^- particle (measured 1964)
- 1964: Gell-Mann, Zweig: Quark Model (u,d,s)
- 1964: Greenberg: Color as quantum number
- 1964: Zweig Rule
- 1967-73: Measurements confirm substructure of nucleons
- 1974: Discovery of charm Quark (Ψ/J)
- 1977: Discovery of bottom Quark
- 1978: Discovery of the Gluon
- 1995: Discovery of the Top Quark



Group Theory and the Quark Model

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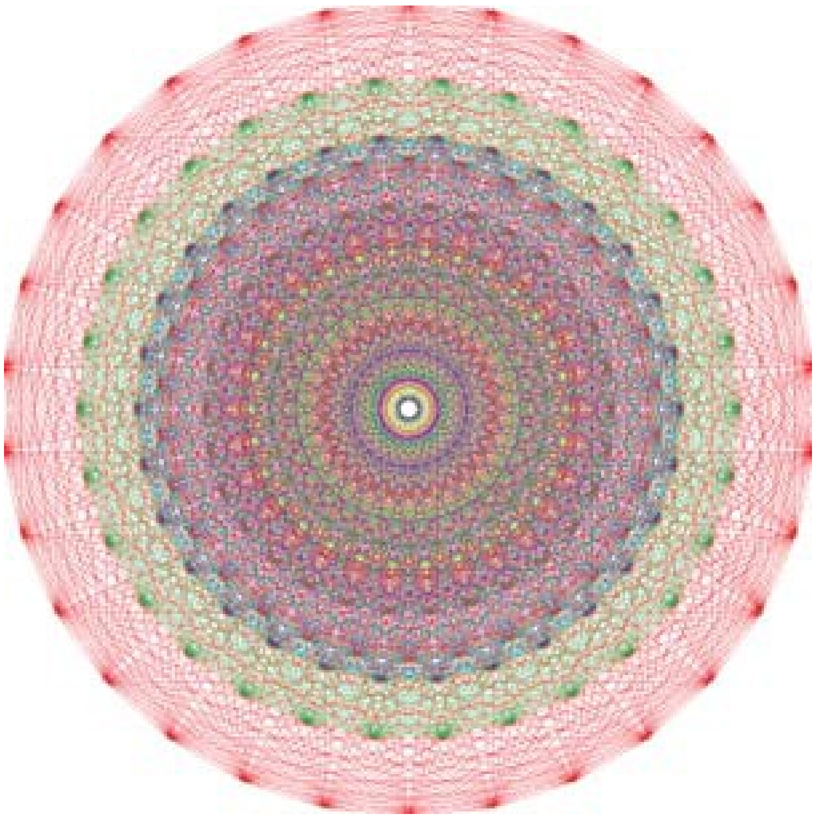

Group Theory: Basic definitions

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Definition: Group

Set with assignment, satisfying

(I) $f, g \in G \quad \Rightarrow \quad fg \in G$

(II) $f, g, h \in G \quad \Rightarrow \quad (fg)h = f(gh)$

(III) neutral element

(IV) inverse element

Definition: Representation

Mapping D that projects elements of G on linear operators GL(V), with following properties:

(I) $D(e) = 1$

(II) $D(g_1)D(g_2) = D(g_1 g_2)$

Definition: Invariant subspace

$D : G \longrightarrow GL(V)$. A subspace $U \subset V$ is called invariant, if

$D(g)U \subset U, \quad \forall g \in G$

Group Theory: Basic definitions

Definition: Reducible representation

A representation is reducible, if it has an invariant subspace.

It is then equiv. to:
$$\begin{pmatrix} D_1(g) & 0 & \dots \\ 0 & D_2(g) & \\ \dots & & D_3(g) \end{pmatrix}$$

$$D = D_1 \oplus D_2 \oplus D_3 \oplus \dots$$

SU(2)

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- Well known group (Quantum mechanics,...)
- Special Unitary group: fundamental representation in 2 dimensions:

$$M = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \qquad \det M \overset{!}{=} 1 \qquad MM^\dagger = M^\dagger M = 1$$

- Those matrices have following properties:
  - Can be written as: $M = e^{-\frac{i}{2}\vec{\sigma}\vec{\alpha}}$
  - Pauli matrices:

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

  - Commutation relation: $[\sigma_i, \sigma_j] = i\epsilon_{ijk}\sigma_k$
  - Define raising and lowering operators: $\sigma_\pm = \sigma_x \pm i\sigma_y$

$$\sigma_+ \begin{pmatrix} 0 \\ 1 \end{pmatrix} \propto \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \sigma_- \begin{pmatrix} 1 \\ 0 \end{pmatrix} \propto \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Group Theory: Lie Groups

Definition: Lie Group

g depends on continuous parameter α.

Natural representation:

$$D(\alpha) = e^{i\alpha_a X_a}$$

with the generators: $X_a = -i \frac{\partial}{\partial \alpha_a} D(\alpha)|_{\alpha=0}$

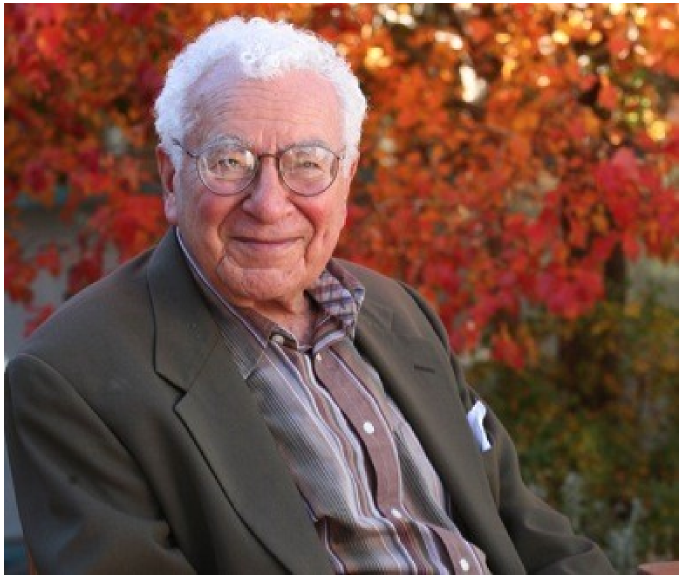
Lie Algebra: $[X_a, X_b] = i f_{abc} X_c$ Adjoint representation

Group Theory: SU(3)

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$



Gell-Mann matrices, analogous to Pauli matrices

Group Theory: SU(3)

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Define raising and lowering operators for the eigenvalues of the diagonal matrices:

$$e^1_\pm = \frac{1}{2}(\lambda_1 \pm i\lambda_2)$$

$$e^2_\pm = \frac{1}{2}(\lambda_6 \pm i\lambda_7)$$

$$e^3_\pm = \frac{1}{2}(\lambda_4 \pm i\lambda_5)$$

Eigenvalues of λ_3	Eigenvalues of λ_8
1	$1/\sqrt{3}$
-1	$1/\sqrt{3}$
0	$-2/\sqrt{3}$

$e^1_\pm$, $e^2_\pm$, $e^3_\pm$

Vector $(EV_{\lambda_3}, EV_{\lambda_8})$ is called weight

Group Theory: SU(3) representations

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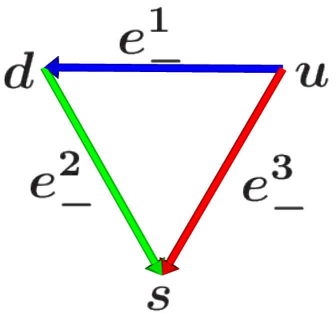
Examples for irreducible representations:

1) Fundamental representation: (3-dimensional)

states	weight
u=(1,0,0)	$(1, 1/\sqrt{3})$
d=(0,1,0)	$(-1, 1/\sqrt{3})$
s=(0,0,1)	$(0, -1/\sqrt{3})$



To construct weight diagram, apply highest weight procedure:

I) Determine highest weight: $e^i_+ |\psi\rangle = 0$

II) Apply lowering operators on it

This representation is called the **3**

Group Theory: SU(3) representations

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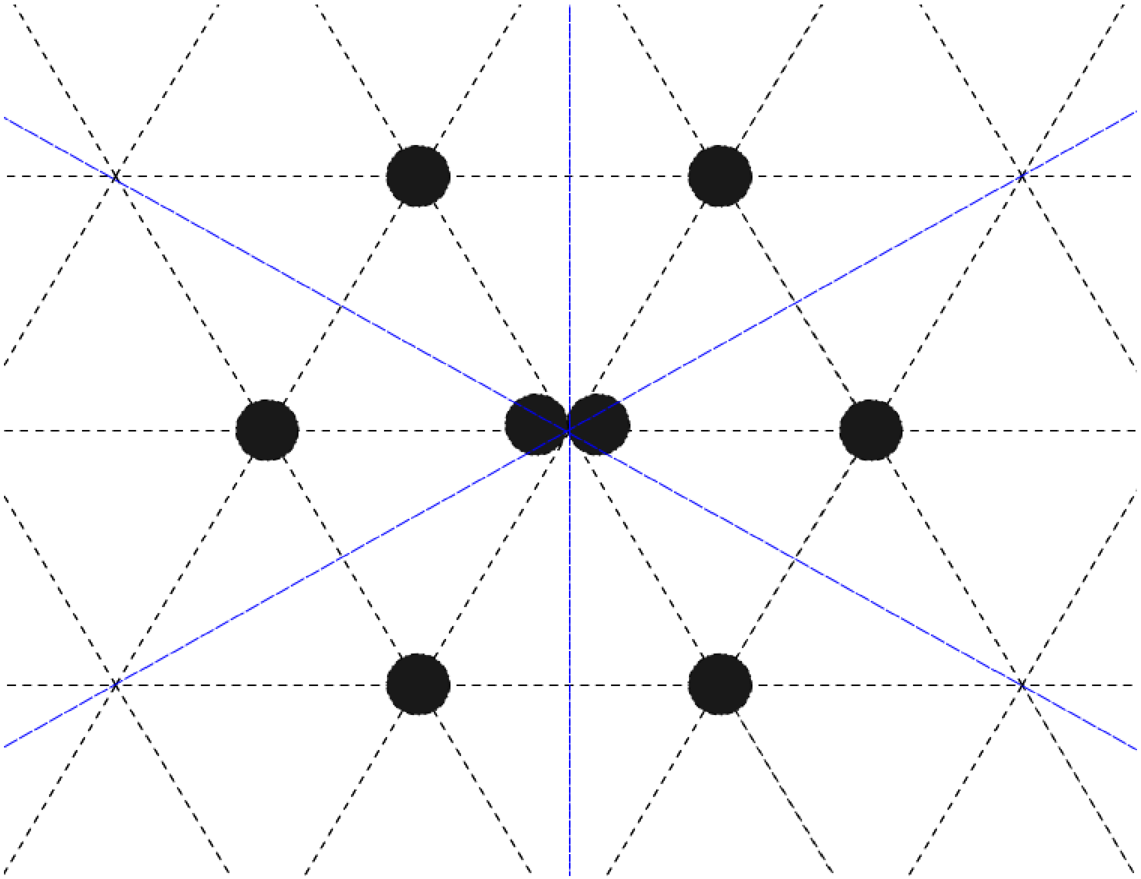
2) Adjoint representation: (8 dimensional)

$$ad_x(y) = [x, y]$$

v	$[\lambda_3, v]$	$[\lambda_8, v]$	weight
λ_3	0	0	$(0,0)$
λ_8	0	0	$(0,0)$
e^1_+	e^1_+	0	$(1,0)$
e^1_-	$-e^1_-$	0	$(-1,0)$
e^2_+	$-1/2e^2_+$	$\sqrt{3}/2e^2_+$	$(-1/2, \sqrt{3}/2)$
e^2_-	$1/2e^2_-$	$-\sqrt{3}/2e^2_-$	$(1/2, -\sqrt{3}/2)$
e^3_+	$1/2e^3_+$	$\sqrt{3}/2e^3_+$	$(1/2, \sqrt{3}/2)$ ← Highest weight
e^3_-	$-1/2e^3_-$	$-\sqrt{3}/2e^3_-$	$(-1/2, -\sqrt{3}/2)$

Group Theory: SU(3) representations

Weight diagram for adjoint representation:



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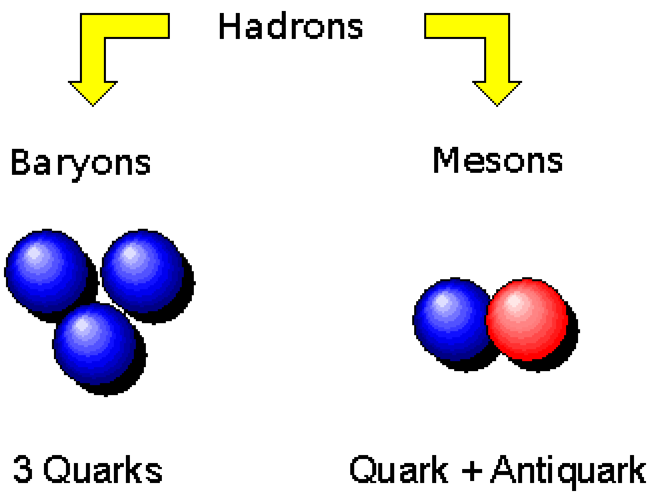
This representation is called the **8**

Group Theory and the Quark Model

- 1961 Gell-Mann identifies Falvor- SU(3) as symmetry group of strong interaction
- 1964 Gell-Mann and Zweig develop Quark Model
- Basis vectors of fundamental representations are Quark states
- Baryon: made of 3 Quarks
- Meson: made of 2 Quarks

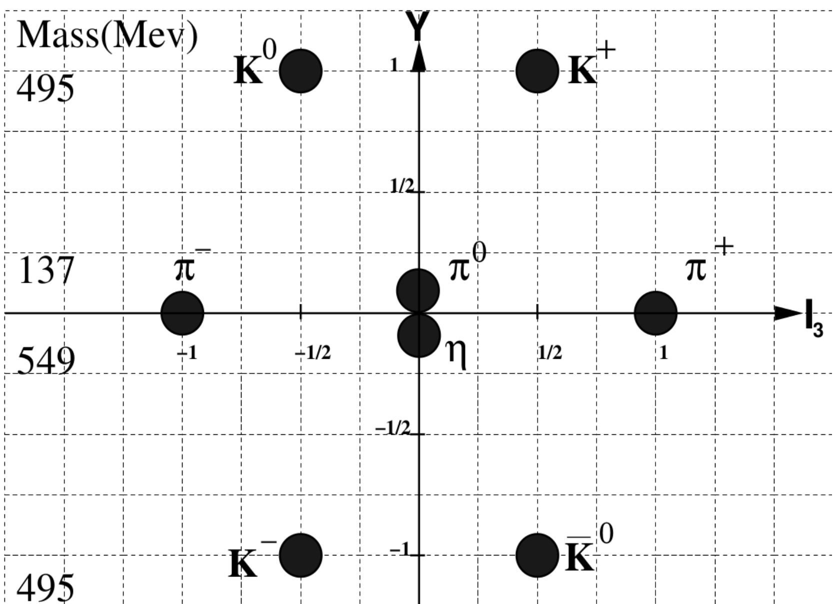


Group Theory and the Quark Model

- Classification of Mesons by plotting Hypercharge Y against Isospin I_z:

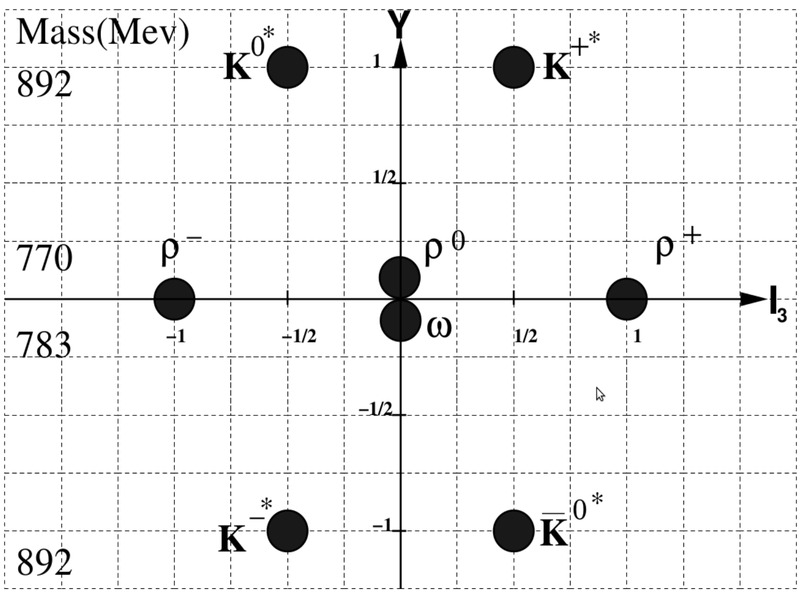
Pseudoscalar meson octet:

$B = 0 \quad J = 0$



Vector meson octet:

$B = 0 \quad J = 1$



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+ J=0 meson **singlet** η'

+ J=1 meson **singlet** ϕ

Group Theory and the Quark Model

- Mesons composed by 2 Quarks: $\mathbf{3} \otimes \mathbf{3}$
- Tensor product gives:

Quark content and weights for $\mathbf{3} \otimes \mathbf{3}$	
Quark Content	*Weight*
$u \otimes u$	$(1, \frac{1}{\sqrt{3}})$
$d \otimes d$	$(-1, \frac{1}{\sqrt{3}})$
$s \otimes s$	$(0, -\frac{2}{\sqrt{3}})$
$u \otimes d,\ d \otimes u$	$(0, \frac{1}{\sqrt{3}})$
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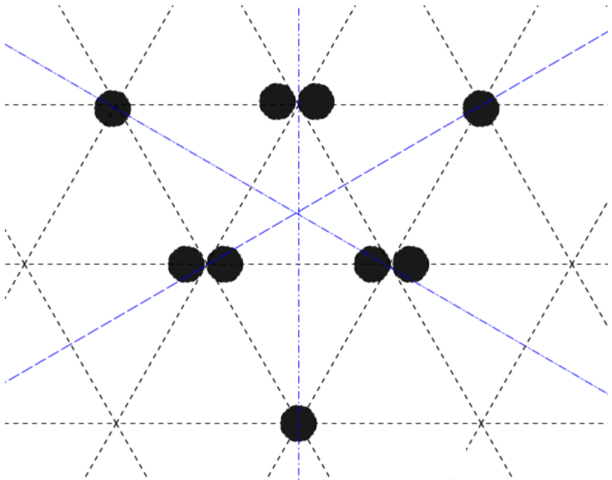

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Not an irreducible representation of SU(3)!

⇒ Split into sums of irred. Rep.:

1) Find highest weight
2) Apply lowering operators
3) Erase those points of the diagram

Group Theory and the Quark Model

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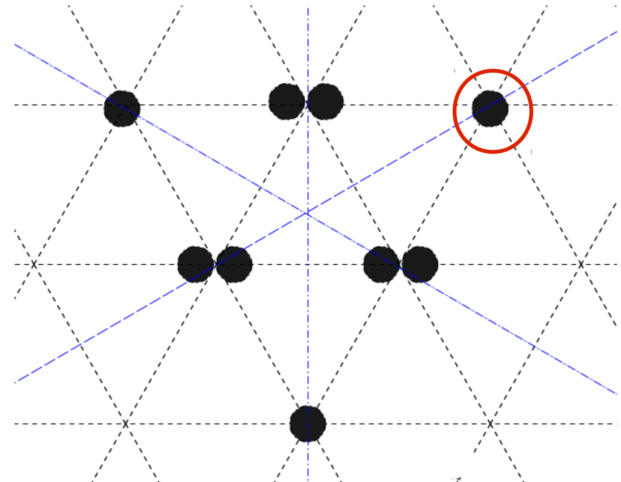

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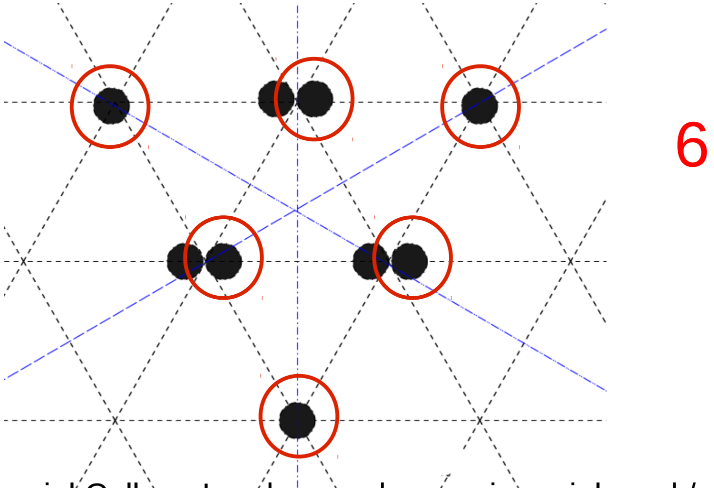

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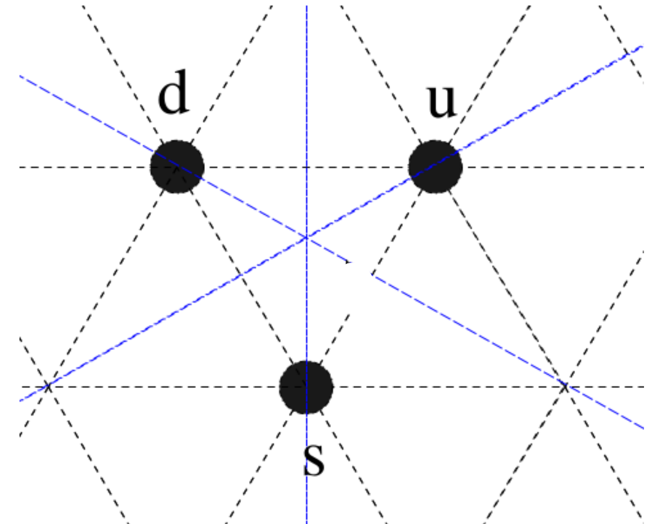

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Group Theory and the Quark Model

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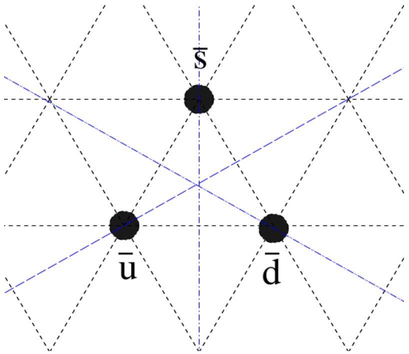
- Now we know that: $\mathbf{3} \otimes \mathbf{3} = \mathbf{6} \oplus \mathbf{3}$
- Obviously not describing mesons, which are categorized by octet states
- Solution: Quark + Antiquark: $\mathbf{3} \otimes \bar{\mathbf{3}}$

$\bar{\mathbf{3}}$ Representation:



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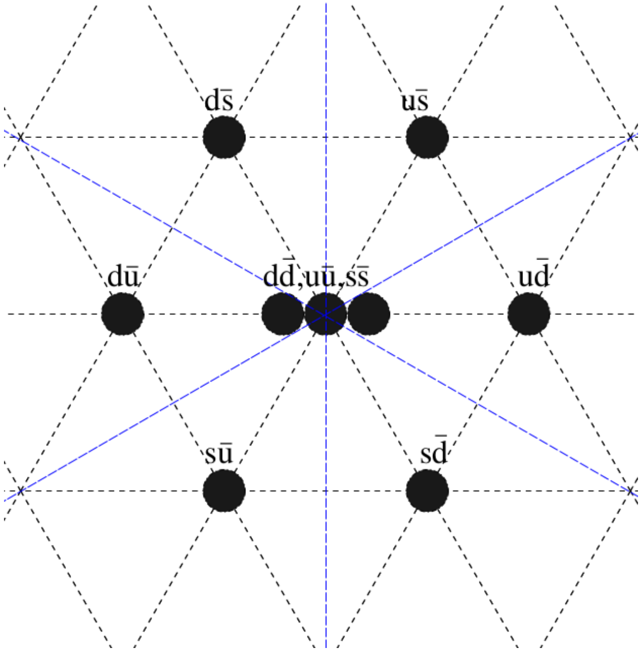

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Group Theory and the Quark Model

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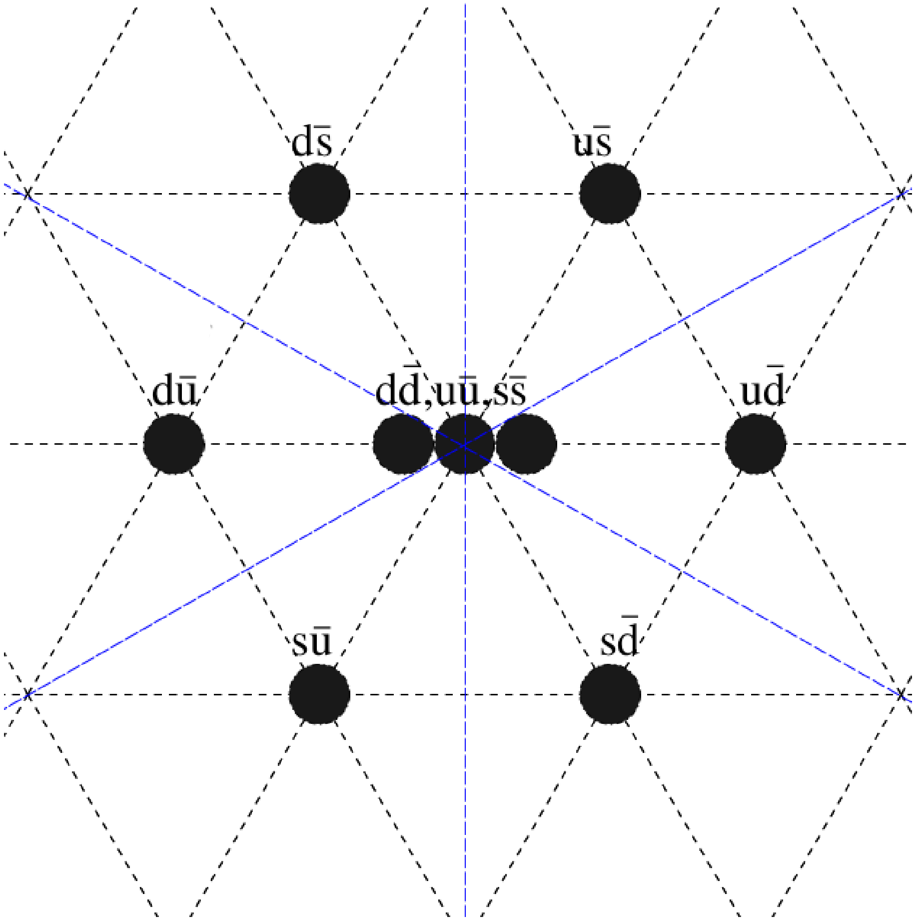

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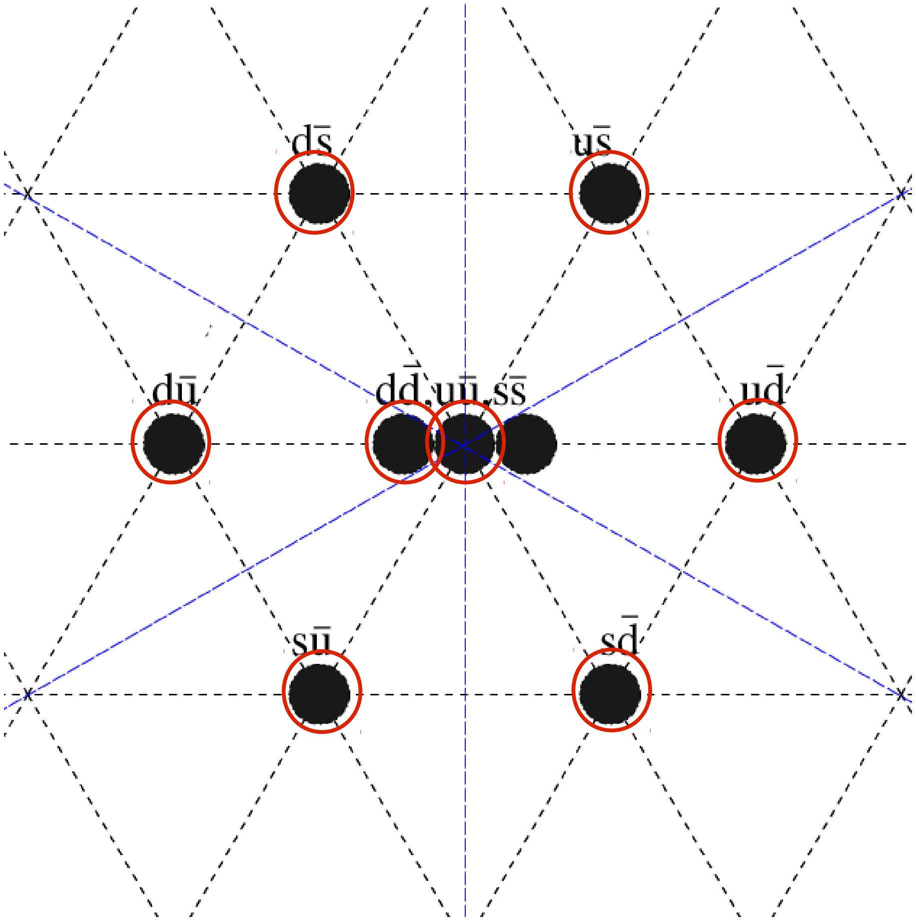

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Group Theory and the Quark Model

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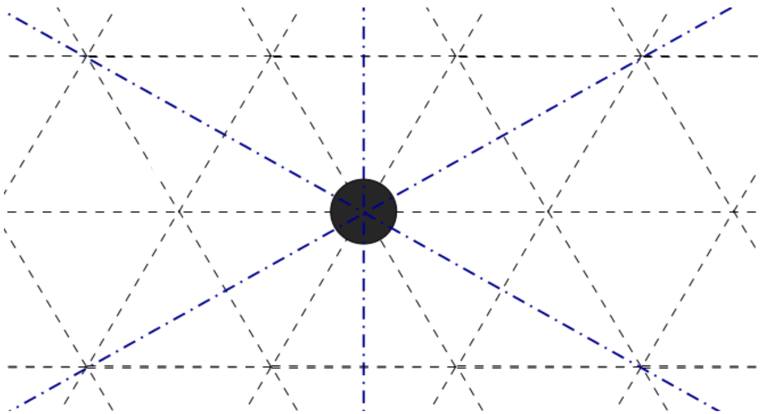

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So, that shows that:

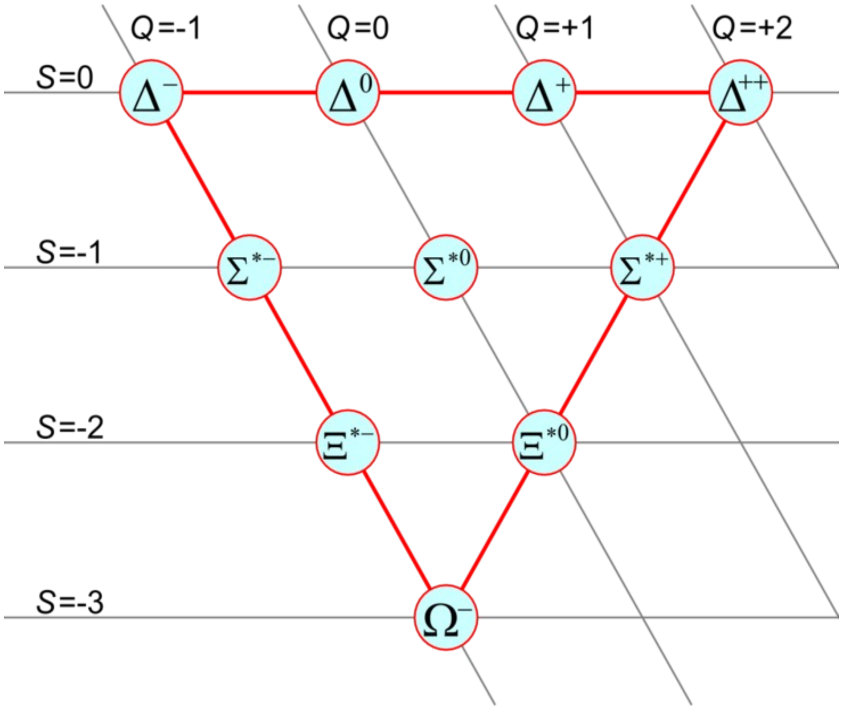
$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1}$$

Mesons are made of a Quark and Antiquark

Group Theory and the Quark Model

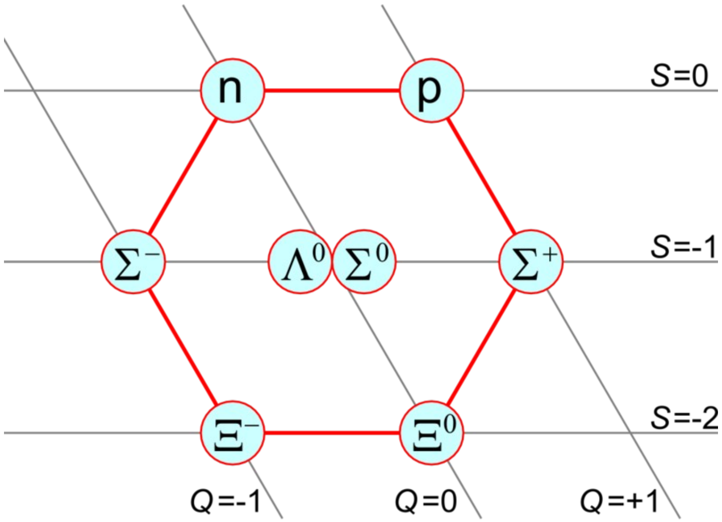
- Same procedure can be done for Baryons: $\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$
- The weight diagrams then look like:

Baryon decuplet: B=1, J=3/2



Particle data group pdg.lbl.gov/

Baryon octet: B=1 J=1/2



+ **Baryon singlet**: B=1, J=1/2 $\Lambda^{0\star}$

Gell-Mann-Okubo Mass formula

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- Calculate masses of nucleons
- Assumptions:
  - Binding energy independent of Flavor
  - Quark mass difference is responsible for mass difference in SU(3) representations
  - Exact SU(2): $m_u = m_d$
- Quark content of the pseudoscalar mesons:

$$\pi^+ \sim \bar{d}u, \quad \pi^0 \sim \frac{1}{\sqrt{2}}(\bar{u}u - \bar{d}d), \quad \pi^- \sim \bar{u}d$$

$$K^+ \sim \bar{s}u, \quad K^0 \sim \bar{s}d, \quad \bar{K}^0 \sim \bar{d}s, \quad K^- \sim \bar{u}ds$$

$$\eta^0 \sim \frac{1}{\sqrt{6}}(\bar{u}u + \bar{d}d - 2\bar{s}s)$$

$$m_\pi^2 = B(m_0 + 2m_u)$$

$$m_K^2 = B(m_0 + m_u + m_s)$$

$$m_\eta^2 = B(m_0 + \frac{2}{3}(m_u + 2m_s))$$

$$B, m_0 = \text{const.}$$

Mass formula:

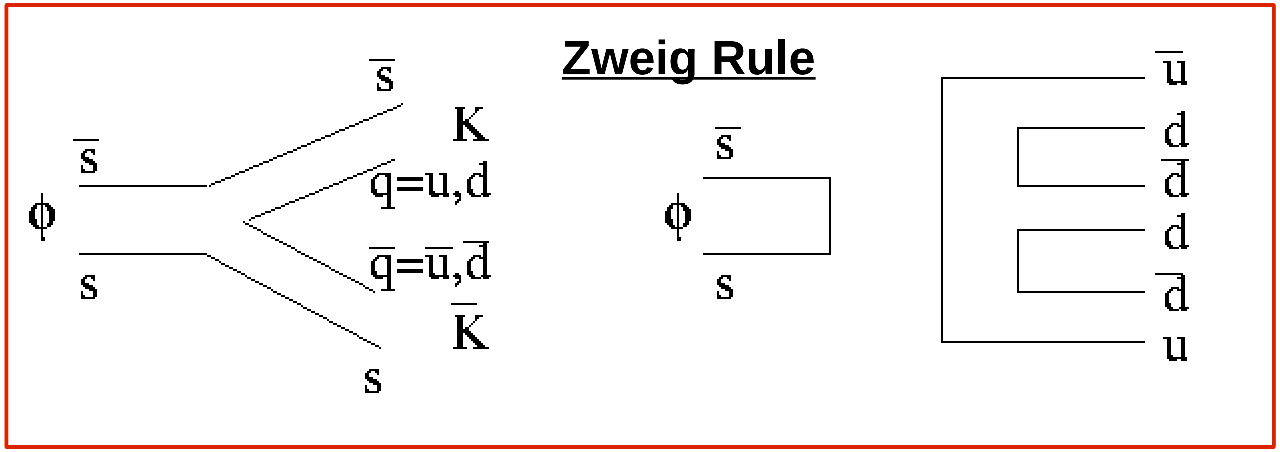
$$4m_K^2 = m_\pi^2 + 3m_\eta^2$$

Gell-Mann-Okubo Mass formula

- For vector mesons: problems with experimental data
- Quark content the same as before $(\pi, K, \eta) \leftrightarrow (\rho, K^*, \omega)$
- Problem: ω mixes with singlet state ϕ
- Almost ideal mixing: $\omega = \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d)$

  $\phi = \bar{s}s$
- Decay: $\omega \longrightarrow 3\pi$

  $\phi \longrightarrow \bar{K}K$



Are Quarks physical entities?

- Quark model describes and predicts particles correctly
- Properties of Quarks:

  Point-like particles
  Spin ½
  Fractional charges: u=2/3, d=-1/3, s=-1/3
  Strange Quark: S=-1

- Do they exist?

Pro Quark	Contra Quark
Why no mesons with S=2	Fractional charge
Anomalous magnetic moments of baryons	Can't measure 1 Quark
Mass split	Violate Pauli principle

→ $\Delta^{++} = (u, u, u)$

Quark Model

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- Solution to that problem:

  additional quantum number: Color
- Need at least 3 Colors: $|\boldsymbol{r}\rangle, |\boldsymbol{g}\rangle, |\boldsymbol{b}\rangle$
- Explains why mesons are only built of 1 Quark and 1 Antiquark
- Quantum numbers of Quarks:

	d	u	s
Q − electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$
I − isospin	$\frac{1}{2}$	$\frac{1}{2}$	0
I_z − isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0
S − strangeness	0	0	-1

Quark Model

- Solution to that problem:

  additional quantum number: Color
- Need at least 3 Colors: $|r\rangle, |g\rangle, |b\rangle$ → QCD
- Explains why mesons are only built of 1 Quark and 1 Antiquark
- Quantum numbers of Quarks:

	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	$+1$	0	0
B – bottomness	0	0	0	0	-1	0
T – topness	0	0	0	0	0	$+1$

Excited states and exotic hadrons

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- Categorization of (excited) mesons: J^{PC}

$|l - s| \leq J \leq l + s$

$P = (-1)^{l+1} \quad C = (-1)^{l+s}$,for non-flavoured mesons

- Allowed states and forbidden states:

0--	0+-	0-+	0++
1--	1+-	1-+	1++
2--	2+-	2-+	2--
3--	3+-	3-+	3++

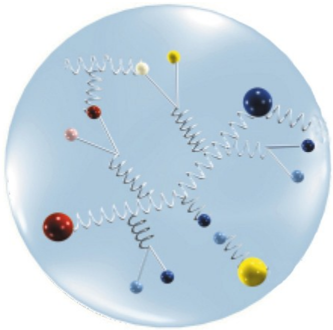
- Forbidden states called exotic states, could exist!

$\pi_1(1400)$ $\pi_1(1600)$

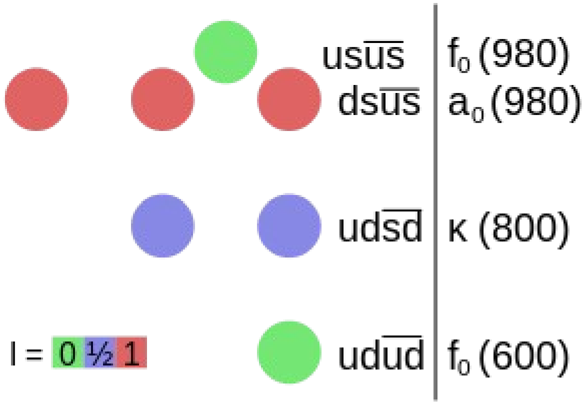
From the Quark Model to QCD

- Discovery of Color: Color SU(3) (Gauge degree of freedom)
- **Flavor SU(3) not fundamental**
- Color SU(3) implies gauge bosons: Gluons
- Quantum field theory of strong interactions: QCD
- Quarks not free in Hadrons
- Parton model, Gluons, See-Quarks, ...
- Exotic states could exist: Hybrids, Glueballs, etc.

  (Lattice QCD)



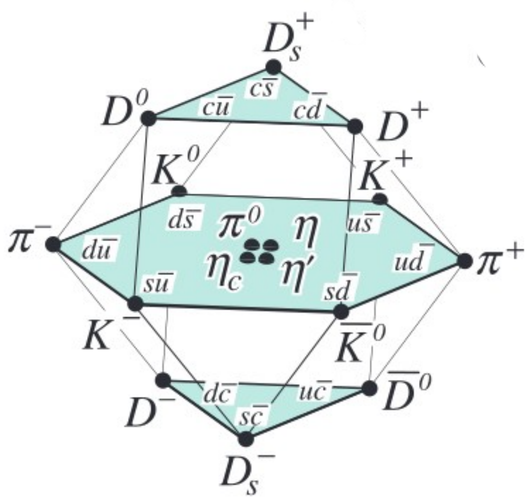
Candidates for tetraquarks:

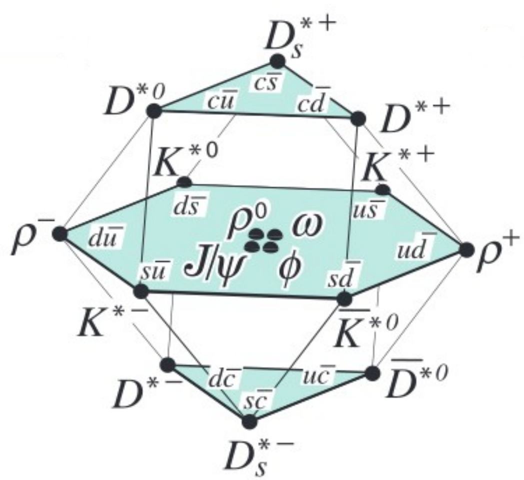


Wikipedia

Heavy Quarks in the Quark Model

- Include **charm quark** in the Quark Model:
- Not a SU(4) symmetry, due to mass difference!





Particle data group pdg.lbl.gov/

Pseudoscalar mesons

Vector mesons

(analogous for bottom Quark)

Light Quark, heavy Antiquark:

$$\mathbf{3} \otimes \mathbf{1} = \mathbf{3}$$

Light Antiquark, heavy Quark:

$$\bar{\mathbf{3}} \otimes \mathbf{1} = \bar{\mathbf{3}}$$

Heavy Antiquark, heavy Quark:

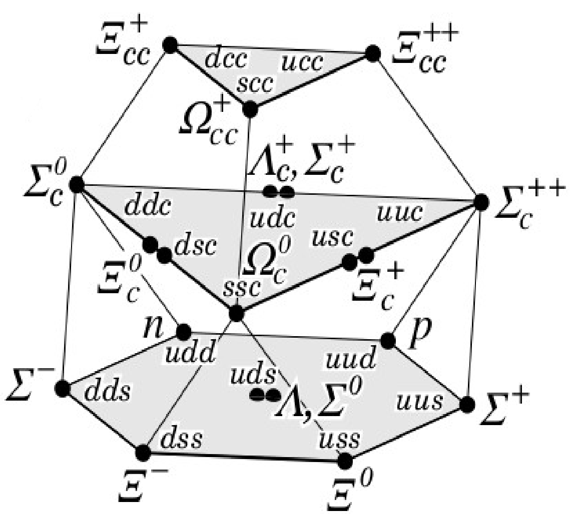
$$\bar{\mathbf{1}} \otimes \mathbf{1} = \mathbf{1}$$

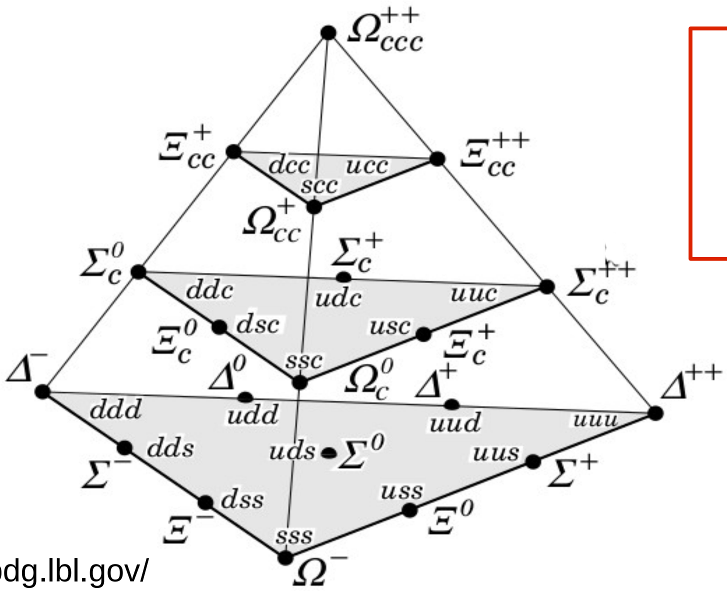
Heavy Quarks in the Quark Model

- Include charm quark in the Quark Model:
- Not a SU(4) symmetry, due to mass difference!

2 Light Quarks, heavy Quark:

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{1} = \bar{\mathbf{3}} \oplus \mathbf{6}$$





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J=1/2 baryons

J=3/2 baryons

(analogous for bottom Quark)

Heavy Quarks in the Quark Model

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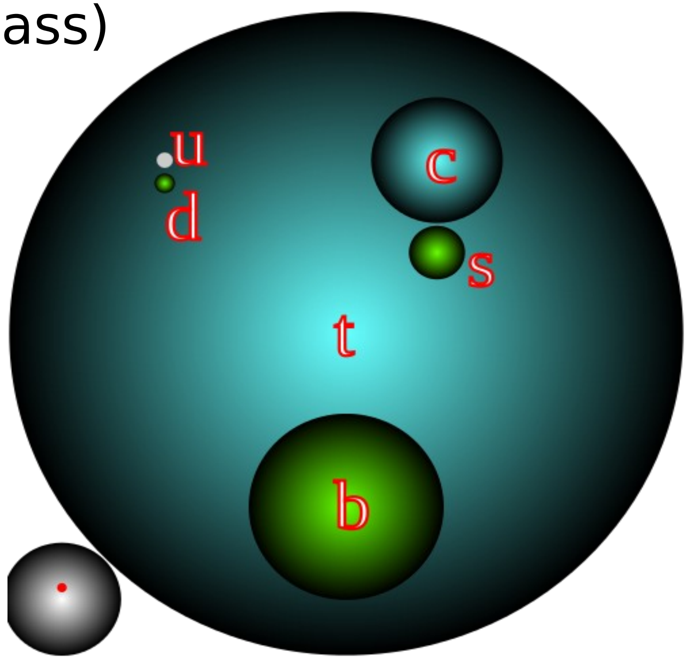
- Six Quarks don't form SU(6) Flavor symmetry (mass)
- Top Quark doesn't form Hadrons (lifetime)

Quark	Mass in MeV
Up	1.7 - 3.1
Down	4.1 - 5.7
Strange	80 - 130
Charm	1120 - 1340
Bottom	4130 - 4370
Top	172 000 – 174 000



Wikipedia

Actual status

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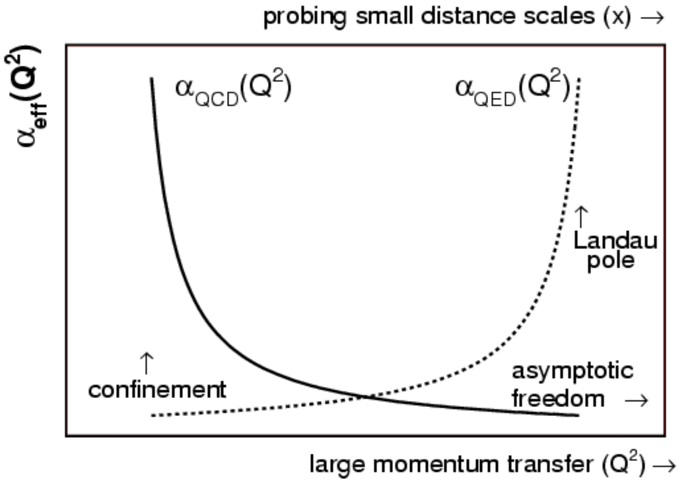
- Ground states of Hadrons well known
- Quark model for excited states is investigated
  - Introduce dynamics for Quarks
  - Relativistic / Nonrelativistic Potentials
- Heavy Quark expansion (effective field theory)
- QCD:
  - Confinement problem
  - Asymptotic freedom of QCD
  - Nonperturbative QCD: Lattice QCD, DSE, ...



Collider detector Fermilab: cdf.fnal.gov/

Thanks for your attention!!!

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