Physics 661

Particle Physics Phenomenology

November 25, 2003

Quarks in Hadrons

- Charm and beauty ✓
- Quarkonium ✓
- Baryon decuplet
- Quark spin and color
- Baryon octet
- Pseudoscalar mesons
- Vector mesons
- Other tests of the quark model
- Mass relations and hyperfine splitting
- EM mass differences and isospin symmetry
- Baryon magnetic moments
- Heavy quark mesons
- The top quarks

Quark Model

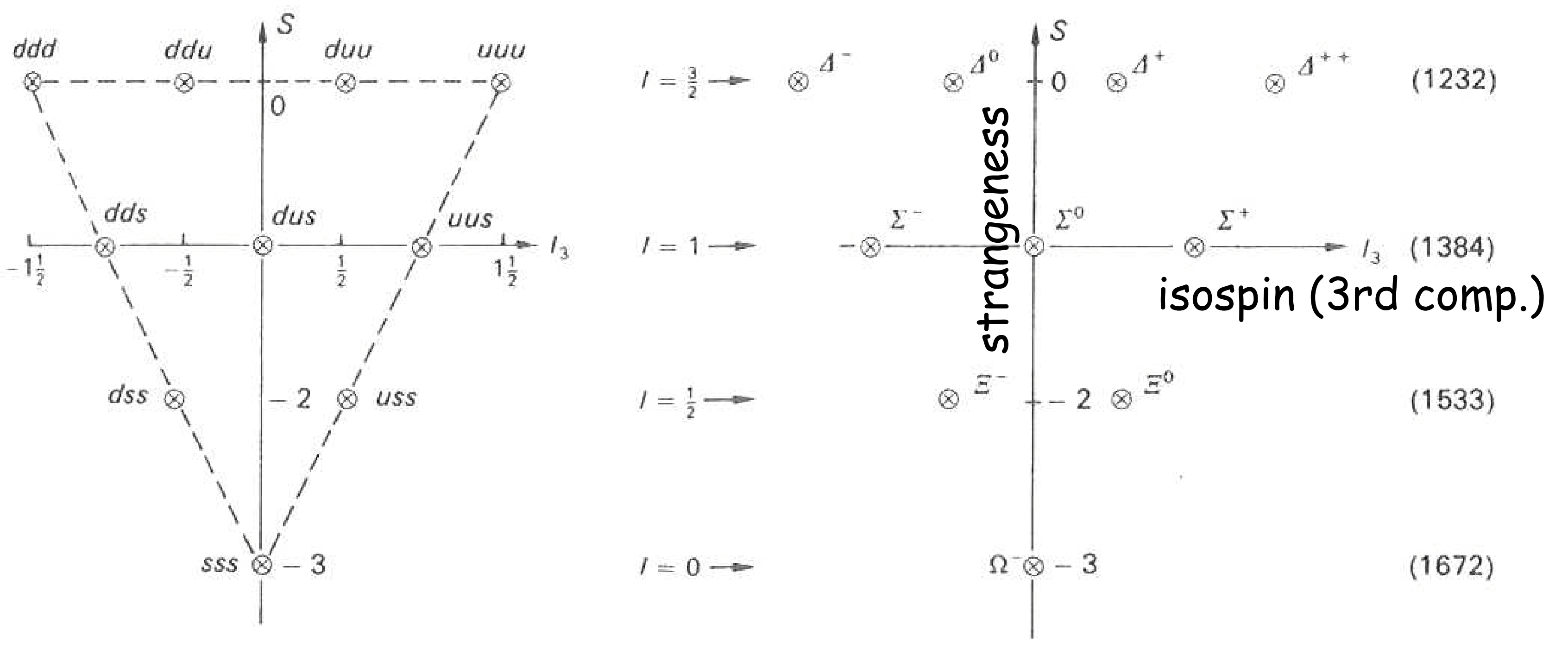
- Patterns of observed particles led to proposal in early 1960's that hadrons were composed of quarks
  - u, d, and s (at that time)

- Were quarks real?
  - exhaustive searches for free quarks were unsuccessful

- With the discovery of "confined" quarks in the 1970's it was realized that quarks truly exist, but cannot be freed

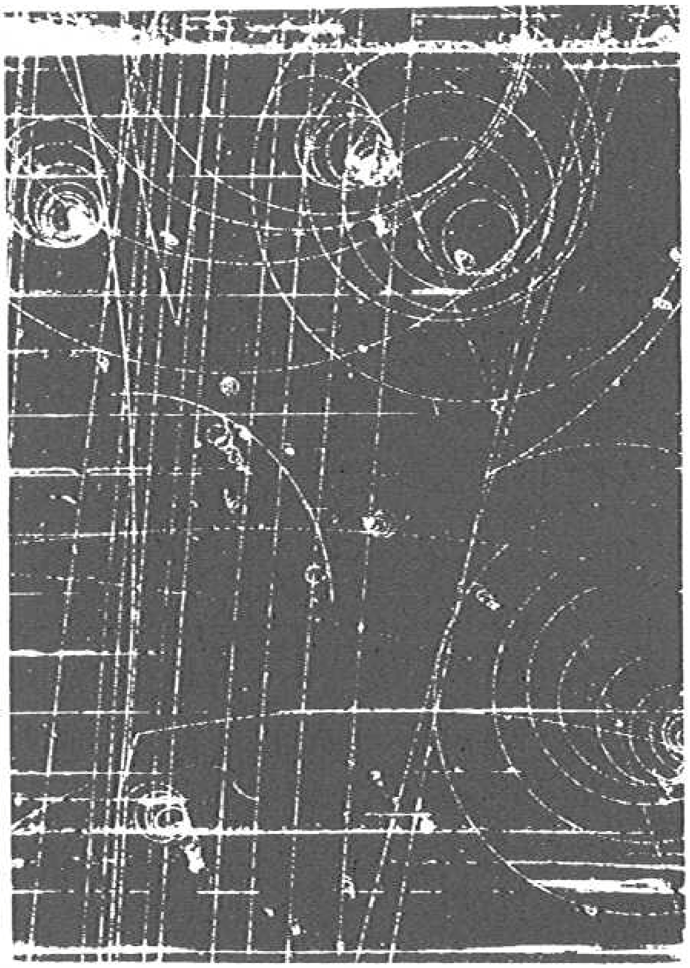
Baryon Decuplet

- Lightest spin 3/2 baryons



Before the Ω^- was discovered it (and its properties) were predicted by this pattern

Discovery of the Ω^-



$K^- + p \to \Omega^- + K^+ + K^0$

$\hookrightarrow \Xi^0 + \pi^-$ ($\Delta S = 1$ weak decay)

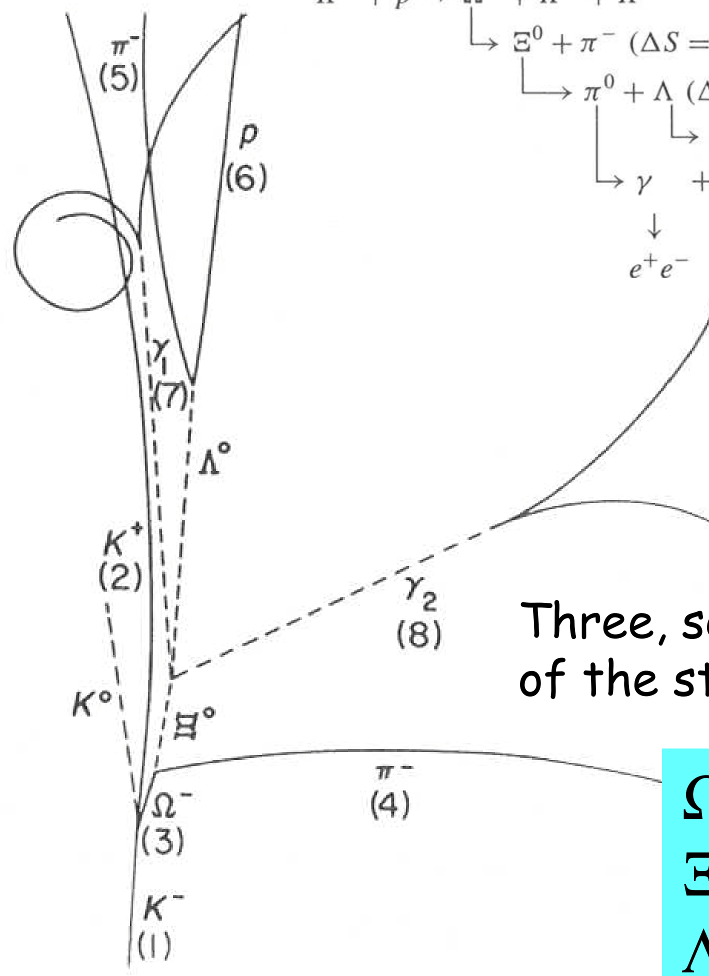
$\hookrightarrow \pi^0 + \Lambda$ ($\Delta S = 1$ weak decay)

$\hookrightarrow \pi^- + p$ ($\Delta S = 1$ weak decay)

$\hookrightarrow \gamma \quad + \quad \gamma$ (electromagnetic decay)

$\downarrow \qquad \downarrow$

$e^+e^- \quad e^+e^-$



Three, sequential decays of the strange quark

$\Omega^- = sss$

$\Xi^0 = ssu$

$\Lambda = sud$

Baryon Decuplet

- Notice the masses

  $M(\Delta) = 1232$

  $M(\Sigma) = 1384$

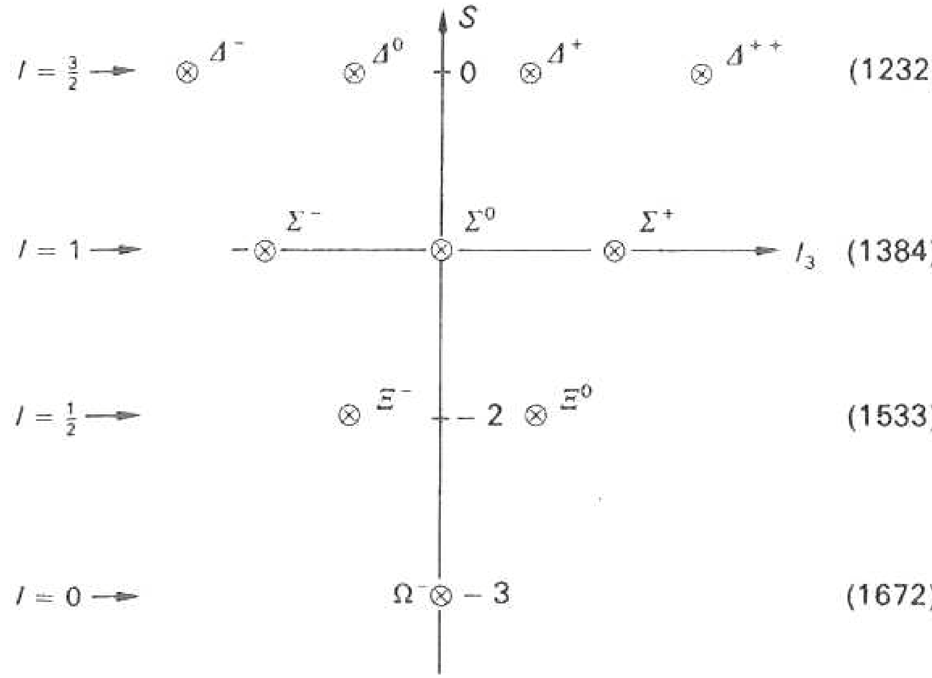
  $= M(\Delta) + 152$

  $M(\Xi) = 1533$

  $= M(\Sigma) + 149$

  $M(\Omega) = 1672$

  $= M(\Xi) + 139$



We see an orderly increase of mass with number of strange quarks

Group Theory

- Quarks are fundamental representations of the group SU(3)

$$3 \otimes 3 = 6 \oplus 3$$

$$3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$$

1 is anti-symmetric under interchange of two quarks
10 is symmetric under interchange of two quarks
8's are mixed under interchange of two quarks

Quark Spin and Color

- Consider the Δ^{++}
  - spin 3/2   (uuu)
  - therefore u↑u↑u↑
    - now, this appears to violate the Pauli principle
      - two or more identical fermions cannot exist in the same quantum state
    - resolution, another quantum number (color) and each of the u quarks have a different value:

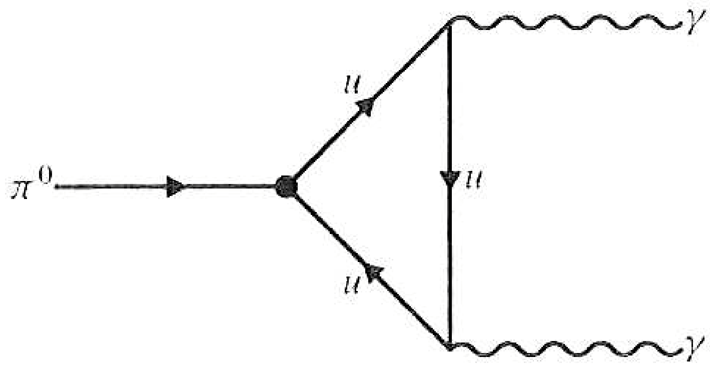
      u↑(red)u↑(green)u↑(blue)

      and we have to aniti-symmetrize the color

      u↑u↑u↑ (rgb-rbg+brg-bgr+gbr-grb)

Quark Spin and Color

- We also know from the rate of decay of the π^0 that there are three colors



$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 7.73 eV $(N_c/3)^2$
Γ(observed) = 7.76 $\pm$ 0.6 eV
N_c = 2.99 $\pm$ 0.12

- Also the rate of $e^+e^- \rightarrow$ hadrons tells us N_c = 3

Baryon Octet

- Multiplet including the neutron and proton
  - lightest spin 1/2 baryons
  - wavefunction symmetric under simultaneous interchange of flavor and spin
  - total wave-function must be anti-symmetric
    - (flavor)(spin)(color)(space)
    - color is anti-symmetric for all hadrons because they are color-neutral, singlet states
    - space is symmetric because L=0
    - $\therefore$ (flavor)(spin) is symmetric

Baryon Octet

- Consider the proton (uud)
  - two quarks in the spin singlet state
    - $(\uparrow\downarrow - \downarrow\uparrow)/\sqrt{2}$ (anti-symmetric)
  - these quarks must also be in an anti-symmetric flavor state for an overall symmetric flavor-spin wavefunction
    - $(ud-du)/\sqrt{2}$ (anti-symmetric)
  - Third Quark is spin up

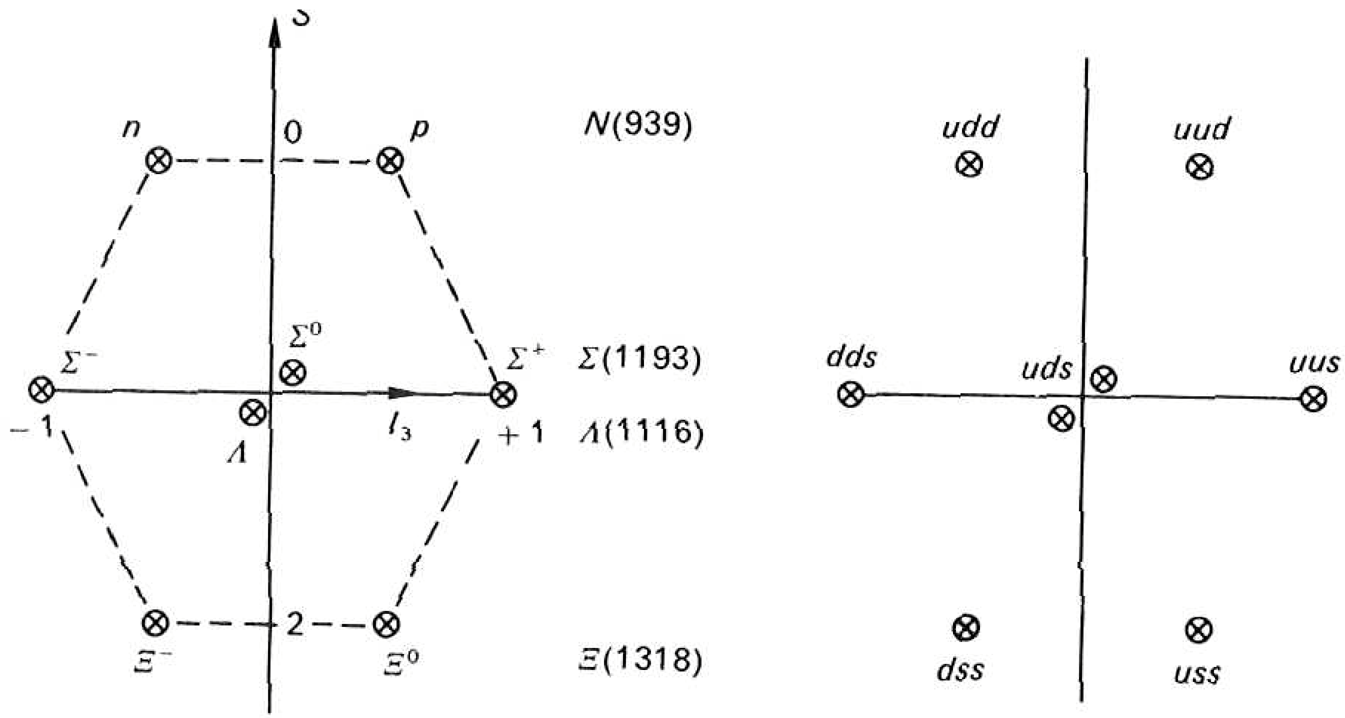
    $(u\uparrow d\downarrow - u\downarrow d\uparrow - d\uparrow u\downarrow + d\downarrow u\uparrow)\, u\uparrow$

Baryon Octet

- Now symmetrize by making cyclic permutation

$$(2u\uparrow u\uparrow d\downarrow + 2d\downarrow u\uparrow u\uparrow + 2u\uparrow d\downarrow u\uparrow$$
$$- u\downarrow d\uparrow u\uparrow - u\uparrow u\downarrow d\uparrow - u\downarrow u\uparrow d\uparrow$$
$$- d\uparrow u\downarrow u\uparrow - u\uparrow d\uparrow u\downarrow - d\uparrow u\uparrow u\downarrow) / \sqrt{18}$$

Baryon Octet



Baryon Octet

- Notice the masses

  $M(N) = 939$

  $M(\Sigma) = 1193$

  $= M(N) + 254$

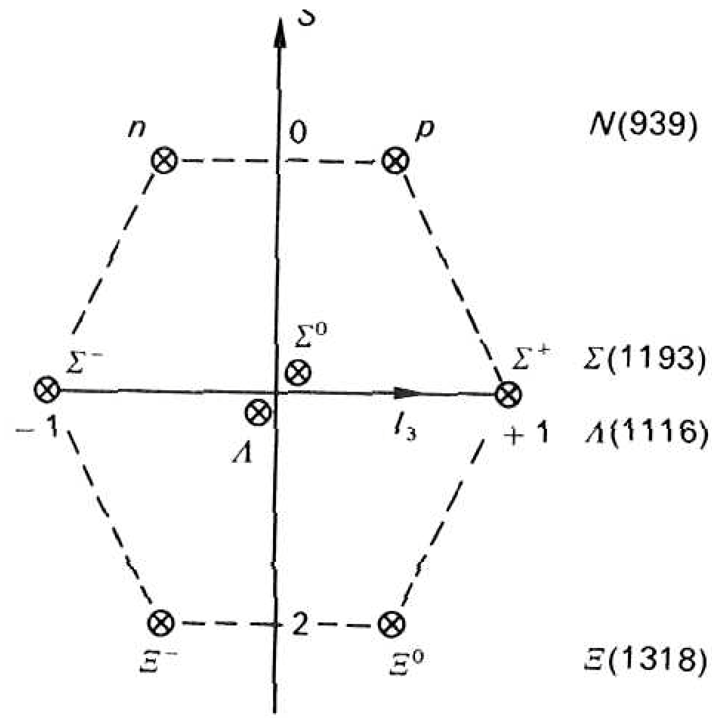
  $M(\Lambda) = 1116$

  $= M(N) + 177$

  $M(\Xi) = 1318$

  $= M(\Sigma) + 125$

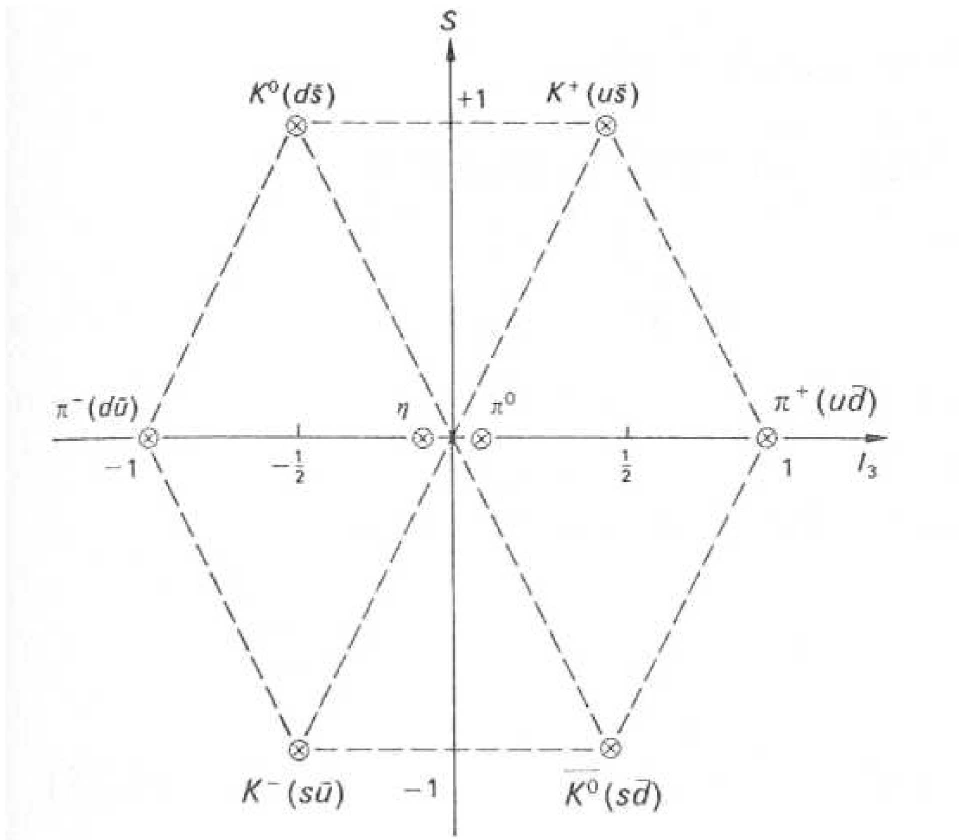
  $= M(\Lambda) + 202$



Pattern is more complicated than for decuplet

Light Pseudoscalar Mesons

- Combine a quark and an antiquark
  - $3 \otimes \overline{3} = 8 \oplus 1$



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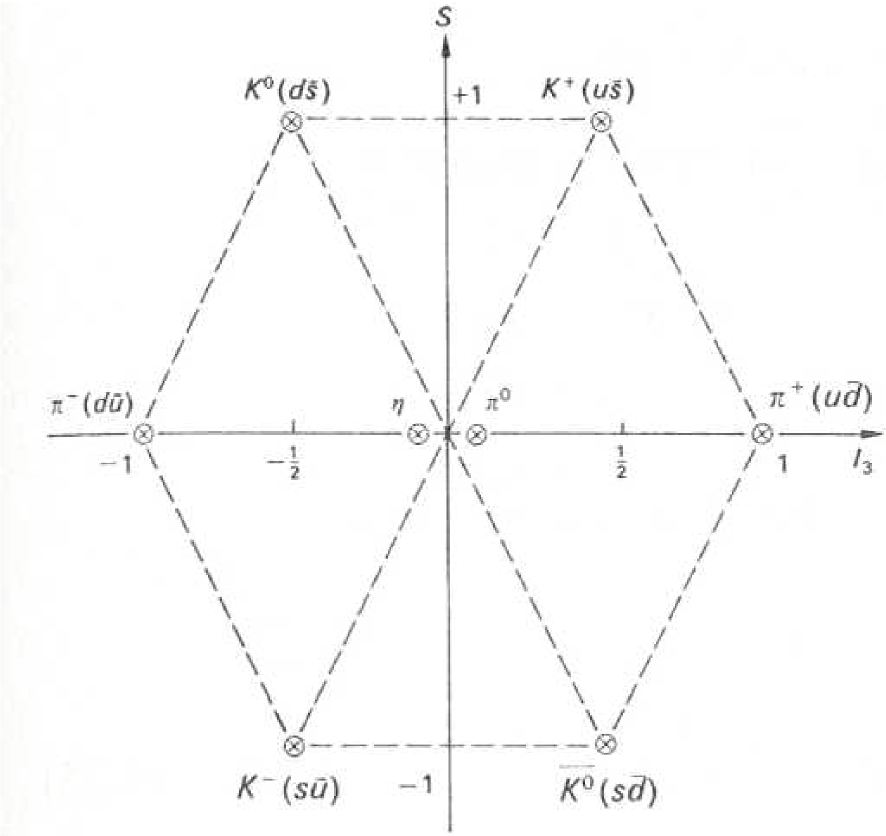


The strangeless mesons

I	I_3	Wavefunction	Q/e
1	1	$u\bar{d} = \pi^+$	+1
1	−1	$-\bar{u}d = \pi^-$	−1
1	0	$\frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u}) = \pi^0$	0
0	0	$\frac{1}{\sqrt{2}}(d\bar{d} + u\bar{u}) = \eta$	0

This table ignores the strange quarks

Light Pseudoscalar Mesons

- C operation on quarks
  - (Condon-Shortly convention)

	Nucleons		Quarks	
I_3	particle	antiparticle	particle	antiparticle
$+\frac{1}{2}$	p	$+\bar{n}$	u	$+\bar{d}$
$-\frac{1}{2}$	n	$-\bar{p}$	d	$-\bar{u}$

Light Pseudoscalar Mesons

	I	I_3	S	Meson	Quark combination	Decay	Mass, MeV
octet	1	1	0	π^+	$u\bar{d}$	$\pi^{\pm} \to \mu\nu$	140
	1	-1	0	π^-	$d\bar{u}$		
	1	0	0	π^0	$\frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u})$	$\pi^0 \to 2\gamma$	135
	$\frac{1}{2}$	$\frac{1}{2}$	$+1$	K^+	$u\bar{s}$	$K^+ \to \mu\nu$	494
	$\frac{1}{2}$	$-\frac{1}{2}$	$+1$	K^0	$d\bar{s}$	$K^0 \to \pi^+\pi^-$	498
	$\frac{1}{2}$	$-\frac{1}{2}$	-1	K^-	$\bar{u}s$	$K^- \to \mu\nu$	494
	$\frac{1}{2}$	$\frac{1}{2}$	-1	$\bar{K}^0$	$\bar{d}s$	$\bar{K}^0 \to \pi^+\pi^-$	498
	0	0	0	η_8	$\frac{1}{\sqrt{6}}(d\bar{d} + u\bar{u} - 2s\bar{s})$	$\eta \to 2\gamma$	549
singlet	0	0	0	η_0	$\frac{1}{\sqrt{3}}(d\bar{d} + u\bar{u} + s\bar{s})$	$\eta' \to \eta\pi\pi$ $\to 2\gamma$	958

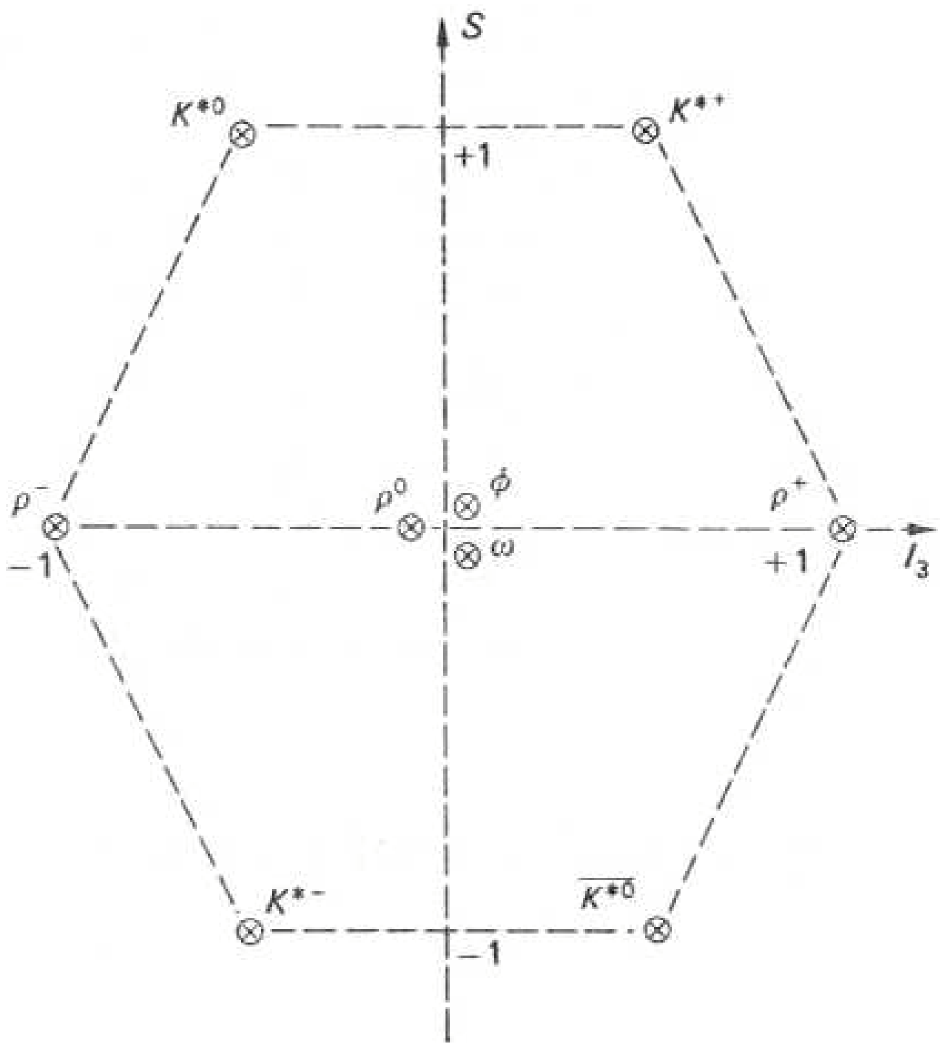
Light Pseudoscalar Mesons

Gell-Mann Okubo Mass Formula

$$4(M_K)^2 = M_\pi^2 + 3\ M_\eta^2$$

$$0.988\ \text{GeV}^2 = 0.924\ \text{GeV}^2$$

The light vector mesons



Mass, MeV	Dominant decay mode
776	$\rho \to 2\pi$
892	$K^* \to K\pi$
783	$\omega \to 3\pi$
1019	$\phi \to K\bar{K}$

The light vector mesons

$\phi(1020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	K^+K^-	(49.4 ± 0.7) %
Γ_2	$K_L^0 K_S^0$	(33.6 ± 0.6) %
Γ_3	$\rho\pi + \pi^+\pi^-\pi^0$	(15.5 ± 0.6) %
Γ_4	$\rho\pi$	
Γ_5	$\pi^+\pi^-\pi^0$	
Γ_6	$\eta\gamma$	(1.298 ± 0.029) %
Γ_7	$\pi^0\gamma$	$(1.24 \pm 0.10) \times 10^{-3}$
Γ_8	e^+e^-	$(2.96 \pm 0.05) \times 10^{-4}$
Γ_9	$\mu^+\mu^-$	$(2.9 \pm 0.4) \times 10^{-4}$
Γ_{10}	ηe^+e^-	$(1.3 {}^{+0.8}_{-0.6}) \times 10^{-4}$
Γ_{11}	$\pi^+\pi^-$	$(7.3 \pm 1.3) \times 10^{-5}$

$\omega(782)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-\pi^0$	(88.6 ± 0.7) %
Γ_2	$\pi^0\gamma$	(8.66 ± 0.35) %
Γ_3	$\pi^+\pi^-$	(2.23 ± 0.30) %
Γ_4	neutrals (excluding $\pi^0\gamma$)	$(4.8 {}^{+7.7}_{-3.1}) \times 10^{-3}$
Γ_5	$\eta\gamma$	$(6.5 \pm 1.0) \times 10^{-4}$
Γ_6	$\pi^0 e^+e^-$	$(5.9 \pm 1.9) \times 10^{-4}$
Γ_7	$\pi^0\mu^+\mu^-$	$(9.6 \pm 2.3) \times 10^{-5}$
Γ_8	e^+e^-	$(6.97 \pm 0.13) \times 10^{-5}$

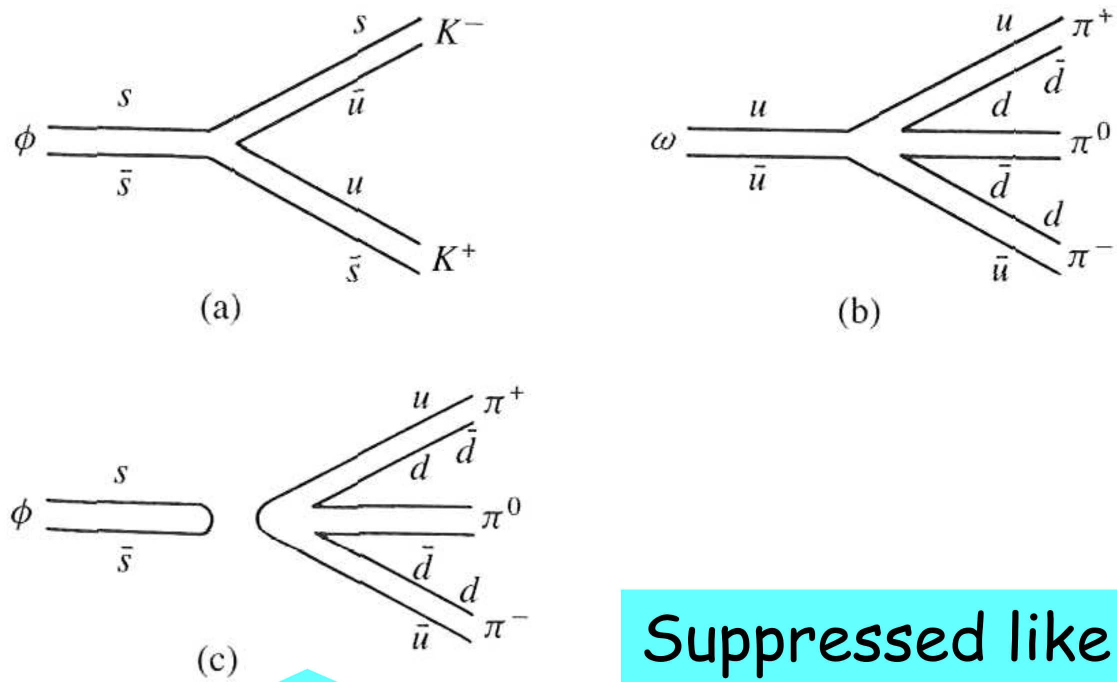
The light vector mesons

- "ideal mixing"

  $\phi = (\phi_0 - \sqrt{2}\,\phi_8) / \sqrt{3} = s\bar{s}$

  $\omega = (\phi_8 + \sqrt{2}\,\phi_0) / \sqrt{3} = (d\bar{d} + u\bar{u})$

The light vector mesons



Suppressed like J/ψ, because of unconnected quark lines (OZI rule)