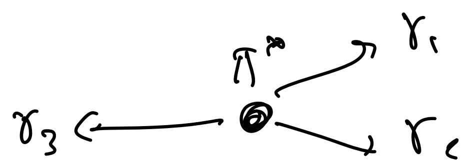
$\mathbb{C}$ parity   internal discrete sym.   Inversion.

particle	$\longleftrightarrow$	anti particle.	
q		$-q$	
B		$-B$	Baryon #
L		$-L$	Lepton #
Strangeness S		$-S$	Strangeness.
$\vec{x}$		$\vec{x}$	
$\vec{p}$		$\vec{p}$	
$\vec{S}$		$\vec{S}$	spin.

$\pi^0 \longrightarrow \gamma\gamma \Rightarrow C_{\pi^0} = +1.$ EM $C_\gamma = -1$

π^0 eigenstate of $\mathbb{C}$ parity.

$\pi^0 \to \gamma\gamma\gamma$?



$\pi^0 \to \gamma$

Particle Data Group

pdg.lbl.gov

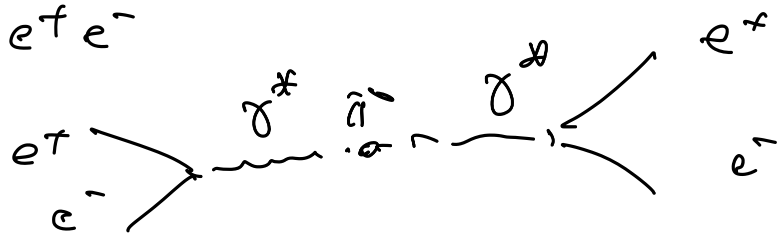
π^0 DECAY MODES

For decay limits to particles which are not established, see the appropriate Search sections (A^0 (axion) and Other Light Boson (X^0) Searches, etc.).

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	2γ		(98.823 ± 0.034) %	S=1.5
Γ_2	$e^+ e^- \gamma$		(1.174 ± 0.035) %	S=1.5
Γ_3	γ positronium		$(1.82 \pm 0.29) \times 10^{-9}$	
Γ_4	$e^+ e^+ e^- e^-$		$(3.34 \pm 0.16) \times 10^{-5}$	
Γ_5	$e^+ e^-$		$(6.46 \pm 0.33) \times 10^{-8}$	
Γ_6	4γ		$< 2 \times 10^{-8}$	CL=90%
Γ_7	$\nu\overline{\nu}$		[a] $< 2.7 \times 10^{-7}$	CL=90%
Γ_8	$\nu_e \overline{\nu}_e$		$< 1.7 \times 10^{-6}$	CL=90%
Γ_9	$\nu_\mu \overline{\nu}_\mu$		$< 1.6 \times 10^{-6}$	CL=90%
Γ_{10}	$\nu_\tau \overline{\nu}_\tau$		$< 2.1 \times 10^{-6}$	CL=90%
Γ_{11}	$\gamma\nu\overline{\nu}$		$< 6 \times 10^{-4}$	CL=90%
	Charge conjugation (*C*) or Lepton Family number (*LF*) violating modes			
Γ_{12}	3γ	*C*	$< 3.1 \times 10^{-8}$	CL=90%
Γ_{13}	$\mu^+ e^-$	*LF*	$< 3.8 \times 10^{-10}$	CL=90%
Γ_{14}	$\mu^- e^+$	*LF*	$< 3.4 \times 10^{-9}$	CL=90%
Γ_{15}	$\mu^+ e^- + \mu^- e^+$	*LF*	$< 3.6 \times 10^{-10}$	CL=90%

$\pi^0 \to \gamma^* + \gamma$

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



$\pi^0 \to e^+ \mu^- \quad e^- \mu^+$

$m_{\pi^0} > m_e + m_\mu$

Parity and C parity of composite states.

$P_1 P_2$

$\pi^+ \pi^-$

$\pi^+ \pi^+$

$q \bar{q}$

$q_1 \bar{q}_2$

$q_1 q_2 q_3$

fermions bosons

final state of interest $P \bar{P}$ $\quad F\bar{F} \quad B\bar{B}$

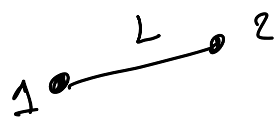
$\psi(P_1 P_2) = \psi_{space} \psi_{spin}$.

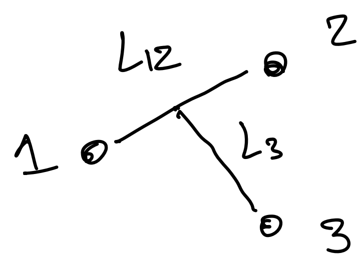
$\mathbb{P} \psi = P_1 P_2 \, \mathbb{P} \psi_{space} \psi_{spin}$.

$F\bar{F} \quad P_1 P_2 = -1$.

$B\bar{B} \quad P_1 P_2 = +1$

$\mathbb{P} \psi_{space} = (-1)^l \psi_{space}$





$P = P_1 P_2 P_3 (-1)^{L_{12} + L_3}$

$\pi^+ = |u\bar{d}\rangle \qquad S = 0 \qquad L = 0.$

$$P_\pi = (+1)(-1)(-1)^0 = -1.$$

P	vector / polar vector	$\vec{x}$, $\vec{p}$	$\longrightarrow$	$-\vec{x}$, $-\vec{p}$
pseudo vector / axial vector		$\vec{L} = \vec{x} \times \vec{p}$		$\vec{L}$
	scalar	S		S
pseudo scalar		A		$-A$

$\boxed{\text{C parity of particle pairs}}$

$|\psi\rangle = |p_1 p_2\rangle$

bosons $B\bar{B}$ $\quad C_{intrinsic} = +1$

fermions $F\bar{F}$ $\quad C_{intrinsic} = -1$

$$C\,\psi(p_1 p_2) = C[\psi_{space}\,\psi_{spin}\,\psi_{intrinsic}]$$

Example $\pi^+\pi^-$ $\qquad$ Rest frame of $\pi^+\pi^-$

spinless bosons.

$$\pi^- \longleftarrow \cdot \longrightarrow \pi^+$$
$$\Downarrow C$$
$$\pi^+ \longleftarrow \cdot \longrightarrow \pi^-$$

$\pi^- \longleftarrow \quad \longrightarrow \pi^+$

$\Downarrow \; \mathbb{P}$

$\pi^+ \longleftarrow \quad \longrightarrow \pi^- \qquad P = (-1)^\ell$

$$\mathbb{C}\,\psi_{\pi^+\pi^-} = \mathbb{P}\,\psi_{\pi^+\pi^-} = (-1)^\ell\,\psi_{\pi^+\pi^-}$$

$$\mathbb{C}_{\pi^+\pi^-} = (-1)^\ell\, C_{\pi^+} C_{\pi^-}$$

Example: e^+e^- $\quad s = \frac{1}{2}$

$e^+ \overset{\Rightarrow}{\longleftarrow} \quad \overset{\Leftarrow}{\longrightarrow} e^- \quad \xrightarrow{\mathbb{C}} \quad e^- \overset{\Rightarrow}{\longleftarrow} \quad \overset{\Leftarrow}{\longrightarrow} e^+$

$e^+ \overset{\Rightarrow}{\longleftarrow} \quad \overset{\Leftarrow}{\longrightarrow} e^- \quad \xrightarrow{\mathbb{P}} \quad e^- \overset{\Leftarrow}{\longleftarrow} \quad \overset{\Rightarrow}{\longrightarrow} e^+$

$e^+ \overset{\Rightarrow}{\longleftarrow} \quad \overset{\Leftarrow}{\longrightarrow} e^- \quad \xrightarrow[\text{spin exchange}]{\mathbb{P} +} \quad e^- \overset{\Rightarrow}{\longleftarrow} \quad \overset{\Leftarrow}{\longrightarrow} e^+$

$\mathbb{C} = \mathbb{P}$ + spin exchange.

$$\mathbb{C}_{e^+e^-} = (-1)^\ell\,(-1)^{S+1}\,\underset{F\bar{F}}{(-1)}$$

$$\mathbb{C}\,\psi_{p\bar{p}} = \mathbb{C}\,\psi_{space}\,\psi_{spin}\,\psi_{intrinsic}$$

$F\bar{F} \qquad (-1)^\ell \quad (-1)^{S+1} \quad (-1)$

$B\bar{B} \qquad (-1)^\ell \quad (-1)^{S} \quad (+1)$

$$\mathbb{C}_{p\bar{p}} = (-1)^{\ell+S}$$

Isospin

n $\quad m_N \simeq 940$ MeV. $\qquad \frac{\Delta m}{m} = \frac{1}{1000}$

p $\quad \Delta M \simeq 1$ MeV

$$\text{nucleon} = \begin{pmatrix} p \\ n \end{pmatrix} \qquad I = \frac{1}{2} \qquad I_3 = \pm 1/2$$

$$\pi^{\pm}, \pi^0 \qquad \frac{\Delta m}{m} \simeq \frac{3 \text{ MeV}}{140 \text{ MeV}} \qquad I = 1, \; I_3 = \pm 1, 0$$

pp

pn $\quad$ nucleus of deuterium. $\qquad Z = 1 \quad A = 2$

nn $\qquad p = |\tfrac{1}{2}, +\tfrac{1}{2}\rangle \qquad n = |1/2, -1/2\rangle$.

$p \otimes n$ $\qquad I \;\; I_3 \qquad \frac{1}{2} \otimes \frac{1}{2} = 1 \oplus \frac{3}{}$

singlet $\quad pn. \quad |0, 0\rangle \longrightarrow \frac{1}{\sqrt{2}}\left(|1/2, 1/2\rangle - |1/2, -1/2\rangle\right)$

triplet $\quad pp$

$\quad pn \quad \frac{1}{\sqrt{2}}\left(|1/2, 1/2\rangle + |\tfrac{1}{2}, -1/2\rangle\right) = |1, 0\rangle$

$\quad nn. \quad |1, -1\rangle$

Hypothesis: $|pn\rangle = |0, 0\rangle$

$\qquad\quad \parallel$

$\qquad |d\rangle$

$\lvert I, I_3\rangle$	I_3				I_3	$\lvert I, I_3\rangle$
		$p + p \longrightarrow$	$d + \pi^+$			$\lvert 1, 1\rangle$
$\lvert 1, 1\rangle$	$+1$	$+\frac{1}{2} \quad +\frac{1}{2}$	$0 \quad +1$		$+1$	
		$p + n \longrightarrow$	$d + \pi^0$			$\lvert 1, 0\rangle$
$\frac{1}{\sqrt{2}}(\lvert 1,0\rangle + \lvert 0,0\rangle)$	$\emptyset$	$+\frac{1}{2} \quad -\frac{1}{2}$	$0 \quad 0$			
		$n + n \longrightarrow$	$d + \pi^-$			$\lvert 1, -1\rangle$
$\lvert 1, -1\rangle$	-1	$-\frac{1}{2} \quad -\frac{1}{2}$	$0 \quad -1$			

$N_{events}(p+p \to d+\pi^+) \propto \sigma(p+p \to d+\pi^+)$

$\sigma \propto |M_{fi}|^2 \, \rho(E_f)$

$$R = \frac{\sigma(p+p \to d+\pi^+)}{\sigma(p+n \to d+\pi^0)} = \frac{|M_{fi}(pp)|^2}{|M_{fi}(pn)|^2} \frac{\rho(pp)}{\rho(pn)}$$

$\simeq 1$

$M_{fi}(pp) = \langle 1,1 | H_I | 1,1 \rangle$

$M_{fi}(pn) = \frac{1}{\sqrt{2}} \left(\langle 1,0 | H_I | 1,0 \rangle \right) + \frac{1}{\sqrt{2}} \left(\cancel{\langle 0,0 | H_I | 1,0 \rangle} \right)$

if I conserved in strong. inter.

$H_I |1,0\rangle = \alpha(\ldots) |1,0\rangle$

$\langle 0,0 | H_I | 1,0 \rangle = \alpha(\ldots) \underbrace{\langle 0,0 | 1,0 \rangle}_{=0}$

$$R = \frac{1}{\left|\frac{1}{\sqrt{2}}\right|^2} \underbrace{\frac{|M|^2}{|M|^2}}_{\simeq 1} \simeq 2$$

$$\Rightarrow \frac{\#(p+p \to d+\pi^+)}{\#(p+n \to d+\pi^0)} \simeq 2$$

beam of π^+/π^-

$\pi^+ + p \to \pi^+ + p.$

$\pi^+ + n \to \pi^+ + n.$

$\to \pi^0 + p$

$$\frac{\sigma(\pi^+ + p)}{\sigma(\pi^- + p)} \simeq 3.$$

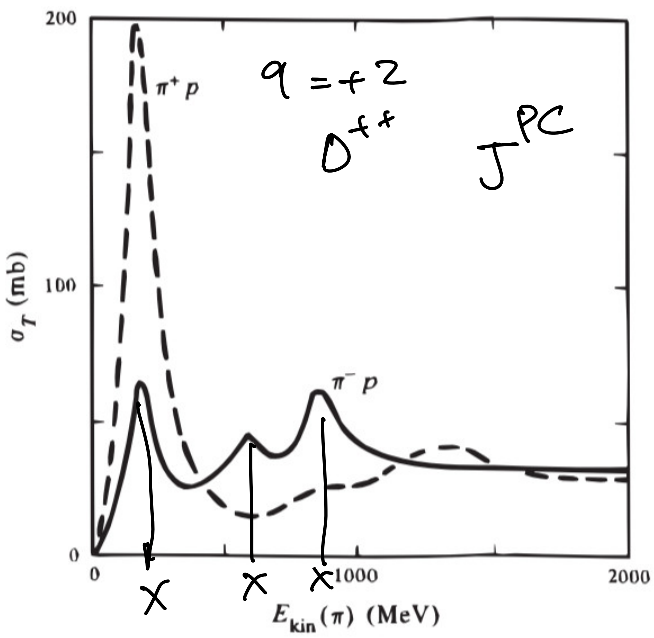


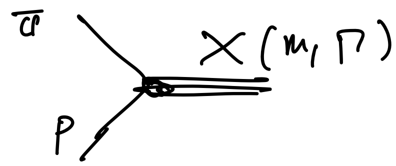
Figure 5.35: Total cross section as a function of pion kinetic energy for the scattering of positive and negative pions from protons. (1 mb = 1 millibarn = 10^{-27} cm^2.)

$(E_\pi, \vec{p}_p)$ $\qquad$ $P = (m_p, 0)$

π

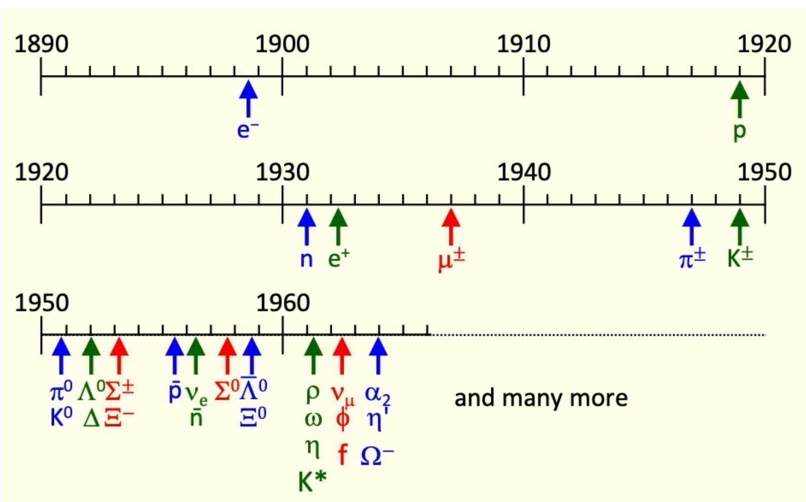
$K_\pi = E_\pi - M_\pi$

Compute m_X



$$\pi^+ p \to (\;\;) \to \pi^+ + p.$$

$q_1 \bar{q}_2$ $\qquad$ $+\frac{2}{3} + \frac{1}{3}$ $\qquad$ $\begin{pmatrix} +\frac{2}{3} \\ -\frac{1}{3} \end{pmatrix}$ $\qquad$ uuu $\quad$ $q = \cancel{3} \times \frac{2}{\cancel{3}}$



strong decay.

$\tau \simeq 10^{-23}$ sec.

strange particles.
produced with strong interaction

$p + p \to K^+$

$$p + p \longrightarrow K^+ + p + p + K^-$$

	$p+p$	K^+	$p+p$	K^-
B	+1 +1	0	+1 +1	
L	0		0	
S	0	+1	0 0	−1
Q	+2	+1	+1 +1	−1

τ strange particles.

$\simeq 10^{-10} - 10^{-8}$ s.

$$\pi^- + p \longrightarrow p + X$$

nucleus: A, Z

$$Q = Z \qquad I_3 = +\frac{1}{2} Z + \left(-\frac{1}{2}\right)(A - Z)$$

$$\Rightarrow I_3 = Z\left(\frac{1}{2} + \frac{1}{2}\right) - \frac{1}{2} A. =$$

$$\Rightarrow I_3 = Q - \frac{B}{2}$$

$$\Rightarrow Q = I_3 + \frac{B}{2}$$

Gell-Mann.
Nishijima.

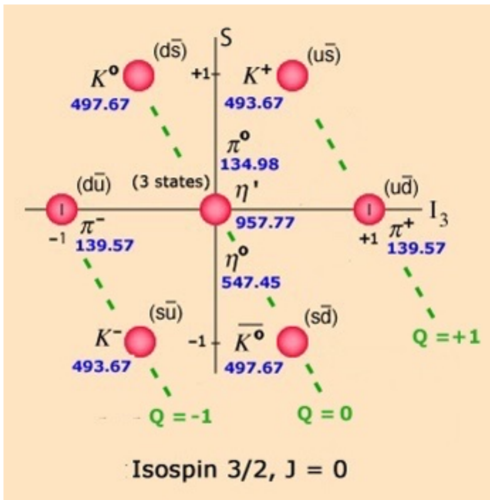
$$\pi^+: \quad Q = +1 + \frac{0}{2}$$

strange particles: $K^+, K^-, K^0, \bar{K}^0$

$$Q = I_3 + \frac{B + S}{2}$$

Name	$\pi^{\pm}$	π^0	$K^{\pm}$	K^0	η	p	n	Λ	$\Sigma^{\pm,0}$	Δ
Mass (MeV)	140	135	494	498	548	938	940	1116	1190	1232
Charge	±1	0	±1	0	0	1	0	0	±1,0	2,±1,0
Parity	–	–	–	–	–	+	+	+	+	+
Baryon n.	0	0	0	0	0	1	1	1	1	1
Spin	0	0	0	0	0	½	½	½	½	$^3/_2$

Eightfold way. 1961– 1964.



Meson = $q_1 \bar{q}_2$

$\frac{1}{2} \otimes \frac{1}{2}$

$S = 0, 1$ mesons.

Gell-Mann, Zweig 1964

Hypoth: 3 quarks. $\begin{pmatrix} u \\ d \\ s \end{pmatrix}$ SU(3) Flavor

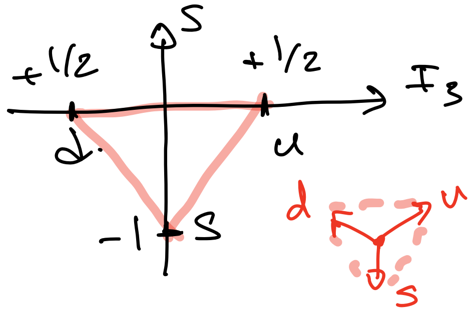
Mesons: $3 \otimes \bar{3} = 8 \oplus 1$

$I_3 = \begin{pmatrix} u \\ d \end{pmatrix} \begin{matrix} +\frac{1}{2} \\ -\frac{1}{2} \end{matrix}$

s : $I_3 = 0$.

$S = \pm 1$

S $S_u = S_d = 0$.

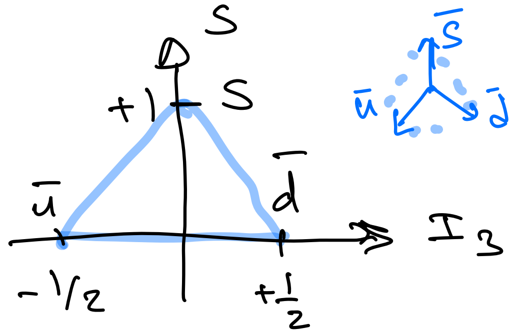


$u: I_3 = +\frac{1}{2}$ $S=0.$

$d: I_3 = -1/2$ $S=0.$

$s: I_3=0$ $S=-1$

strageness



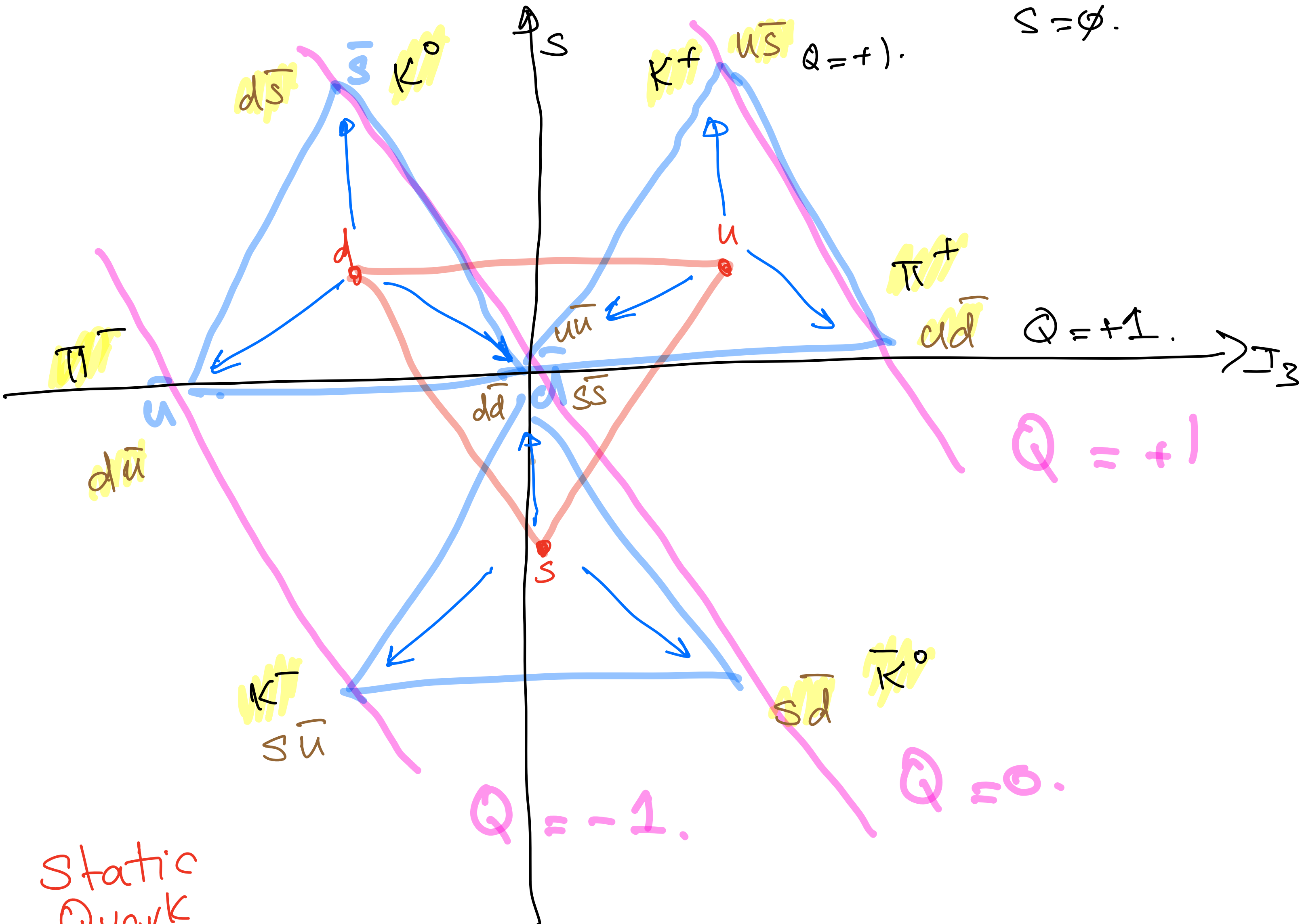
$\bar{u}: I_3 = -1/2$ $S=0.$

$\bar{d}: I_3 = +1/2$ $S=0.$

$\bar{s}: I_3 = 0$ $S=+1.$

Spin: ⇑ ⇓.

$S = \emptyset.$



Static Quark Model

what about $u\bar{u}$, $d\bar{d}$, $s\bar{s}$?