Strange surprises

Why strange?

- Back in 1947, the need for the pion was obvious (Yukawa's theory of the strong force predicted it)
- The more massive "strange" particles that decayed slowly (weakly) to protons or pions didn't solve any existing problems; they created new ones
- For example, the famous τ-θ puzzle
- And then parity violation
- And then strangeness oscillations
- And then the quark model
- And then CP violation

Early discoveries

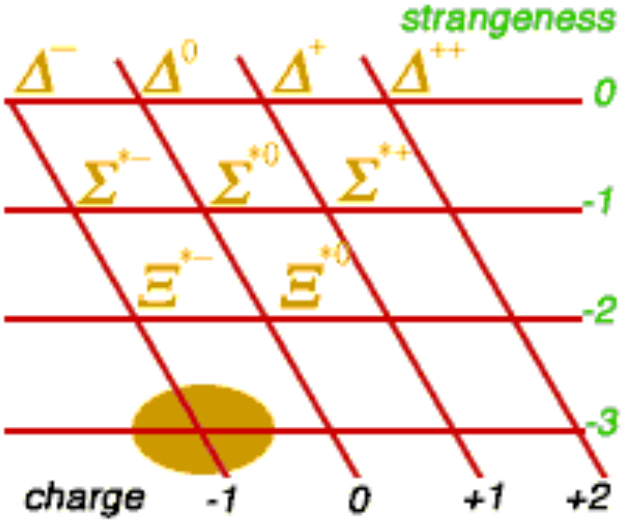
- Neutral and charged particles seen in cosmic rays
- Measurable decay lengths → meta-stable, decay weakly
- Weakly decaying baryon also seen ($\Lambda \rightarrow p\pi$)
- Two particles with same mass but opposite parity seen: $\theta \rightarrow \pi\pi$ (even parity) and $\tau \rightarrow \pi\pi\pi$ (odd parity)

- This led Lee and Yang to see if there was evidence for parity conservation in weak interactions…
- There wasn't, as we now know (the Wu Co^{60} experiment was proposed by Lee and Yang)

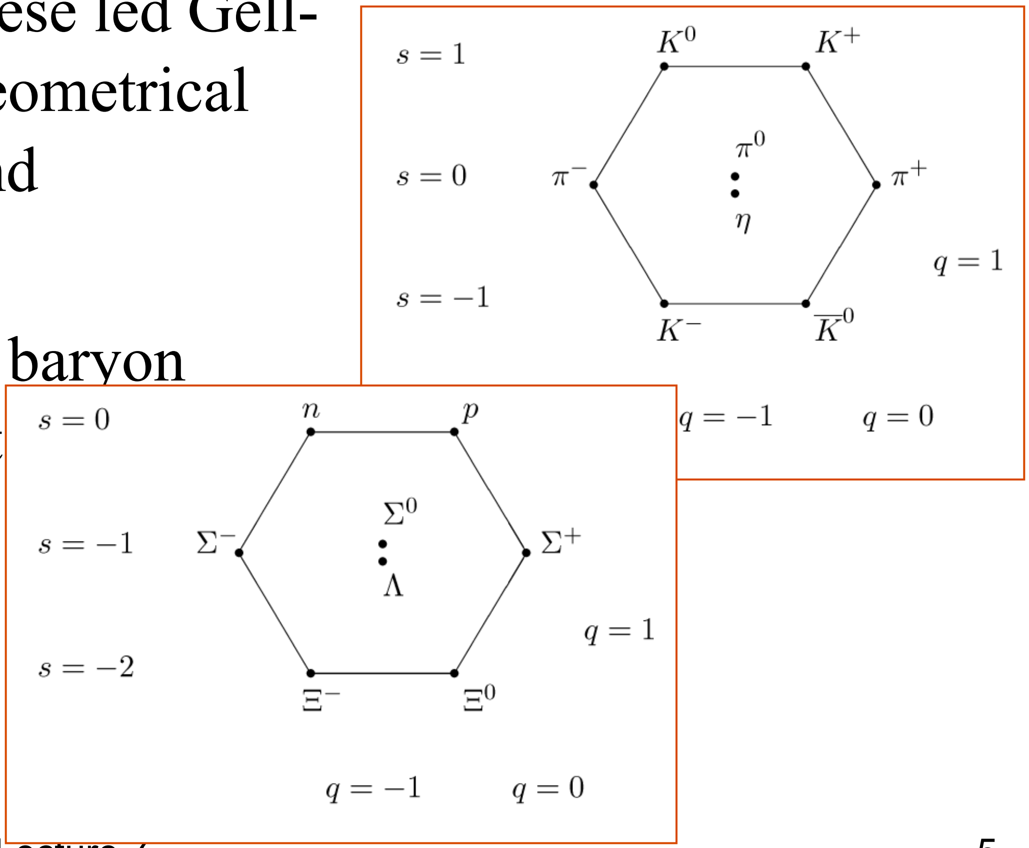
Weak interactions and parity

- In fact, parity is violated “maximally” by the weak interaction, which consists of a “V-A” current, namely a vector minus axial vector combination that corresponds to a left-handed current
- We now know this is because the W bosons transmitting the weak force are left-handed
- There are no right-handed W bosons, at least not with masses below 500 GeV or so
- Is this surprising? All DNA has the same chirality, as do many other biological molecules. (I’m not suggesting that the chirality of DNA is related to weak interactions, but selection of a single chirality state happens in other places in nature)

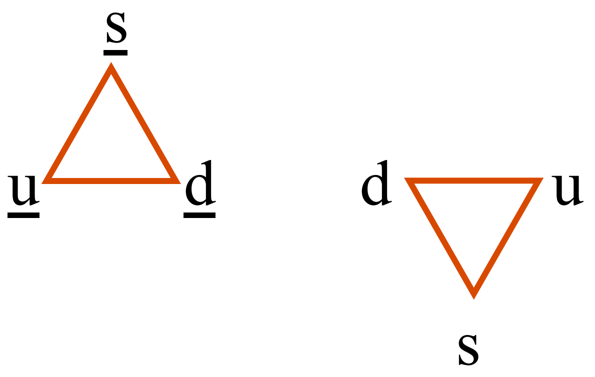
Particle zoo

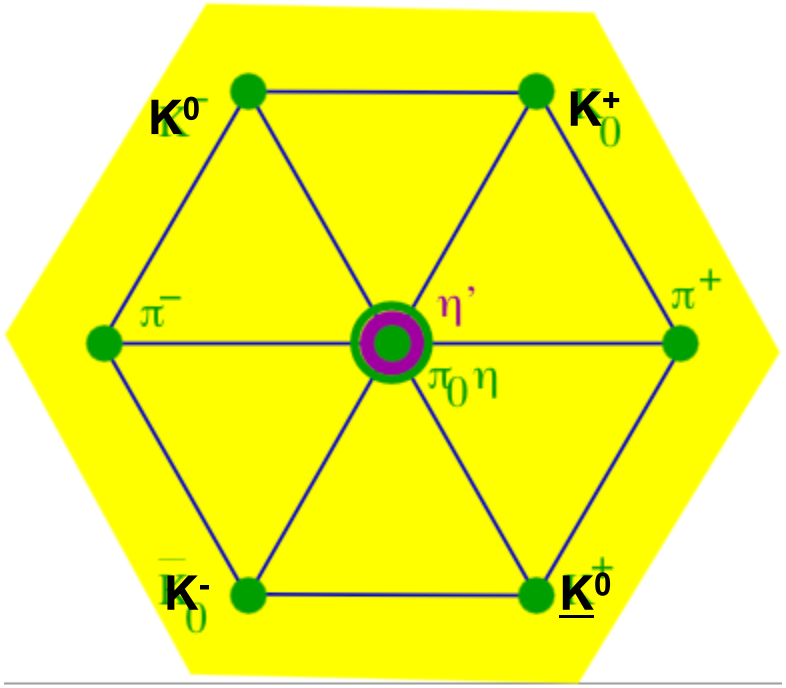


- With the advent of accelerators, many more hadrons were discovered (a couple dozen by 1961)
- Searching for patterns in these led Gell-Mann to arrange them in geometrical patterns based on charge and strangeness
- There was a meson octet, a baryon octet and a baryon decuplet
- Missing particle (Ω^-, triply strange) was found in 1964



Quark model - 1964

- This led Gell-Mann and Zweig to propose 3 quarks: u, d, s
- 



- Meson "octet" became a "nonet"; the additional particle (η') had already been discovered
- Three states at center have Q=S=0; since they are flavorless combinations $u\underline{u}$, $d\underline{d}$ and $s\underline{s}$ with no preserved quantum numbers they can mix to form the 3 physical states

K^0-$\underline{K}^0$ oscillations

- K^0 mesons are produced in strong or EM interactions in states of definite *strangeness*
- 2nd order $\Delta s=2$ transition takes $K^0 \rightarrow \underline{K}^0$ making decay eigenstates distinct from flavour eigenstates
- Neutral K mesons can be viewed as a 2-state system:

$$\left|K^0\right\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad \left|\overline{K}^0\right\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

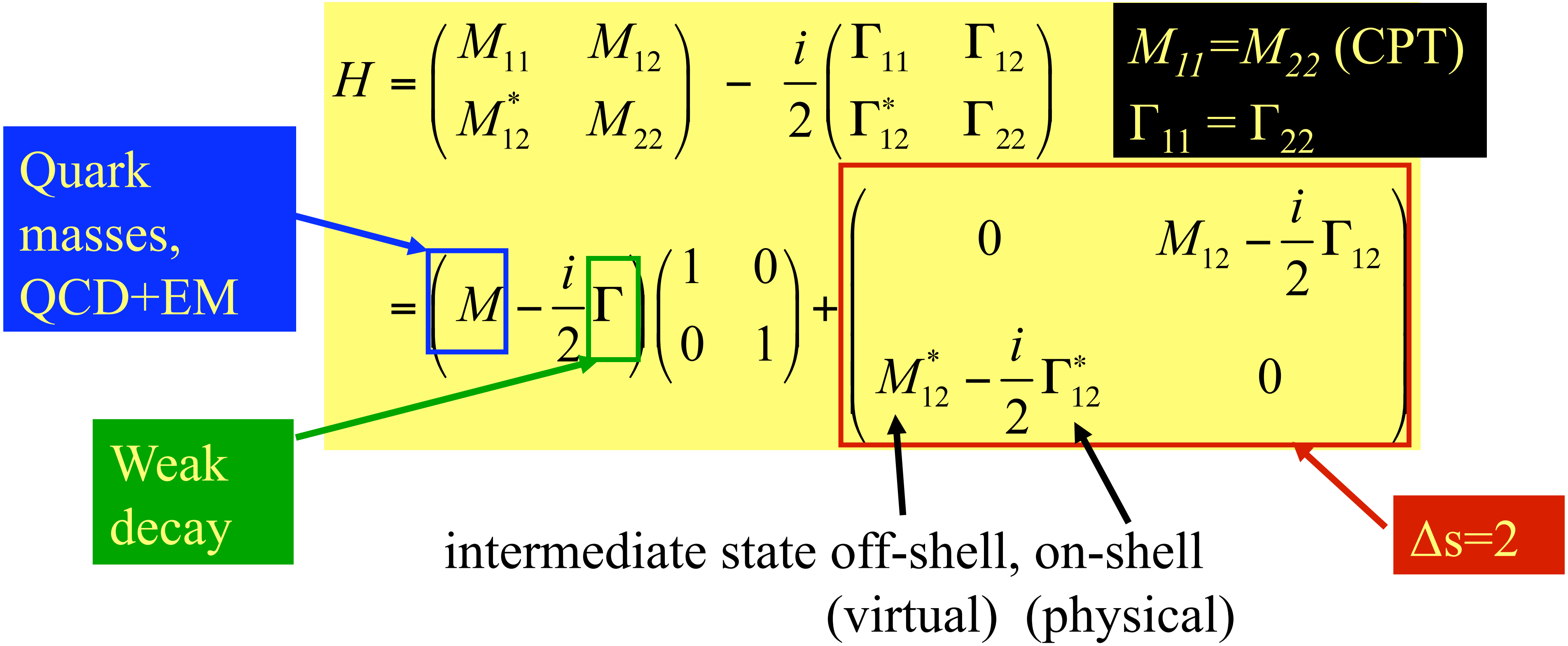
- Mass eigenstates diagonalize effective Hamiltonian

$$H\left|K_{L,S}\right\rangle = m_{K_L,K_S}\left|K_{L,S}\right\rangle$$

to produce the physically observable eigenstates

Effective Hamiltonian for mixing

- Two Hermitian matrices **M** and **Γ** describe physics



$$H = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}$$

$M_{11}=M_{22}$ (CPT)

$\Gamma_{11} = \Gamma_{22}$

$$= \left(\boxed{M} - \frac{i}{2}\boxed{\Gamma}\right)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \boxed{\begin{pmatrix} 0 & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & 0 \end{pmatrix}}$$

Quark masses, QCD+EM

Weak decay

Δs=2

intermediate state off-shell, on-shell
(virtual) (physical)

Time evolution

- The time evolution of the $K^0\underline{K}^0$ system satisfies

$$I(K^0) = \tfrac{1}{4}\left[e^{-\Gamma_L t} + e^{-\Gamma_S t} + 2e^{-[(\Gamma_L+\Gamma_S)/2]t}\cos\Delta mt\right]$$

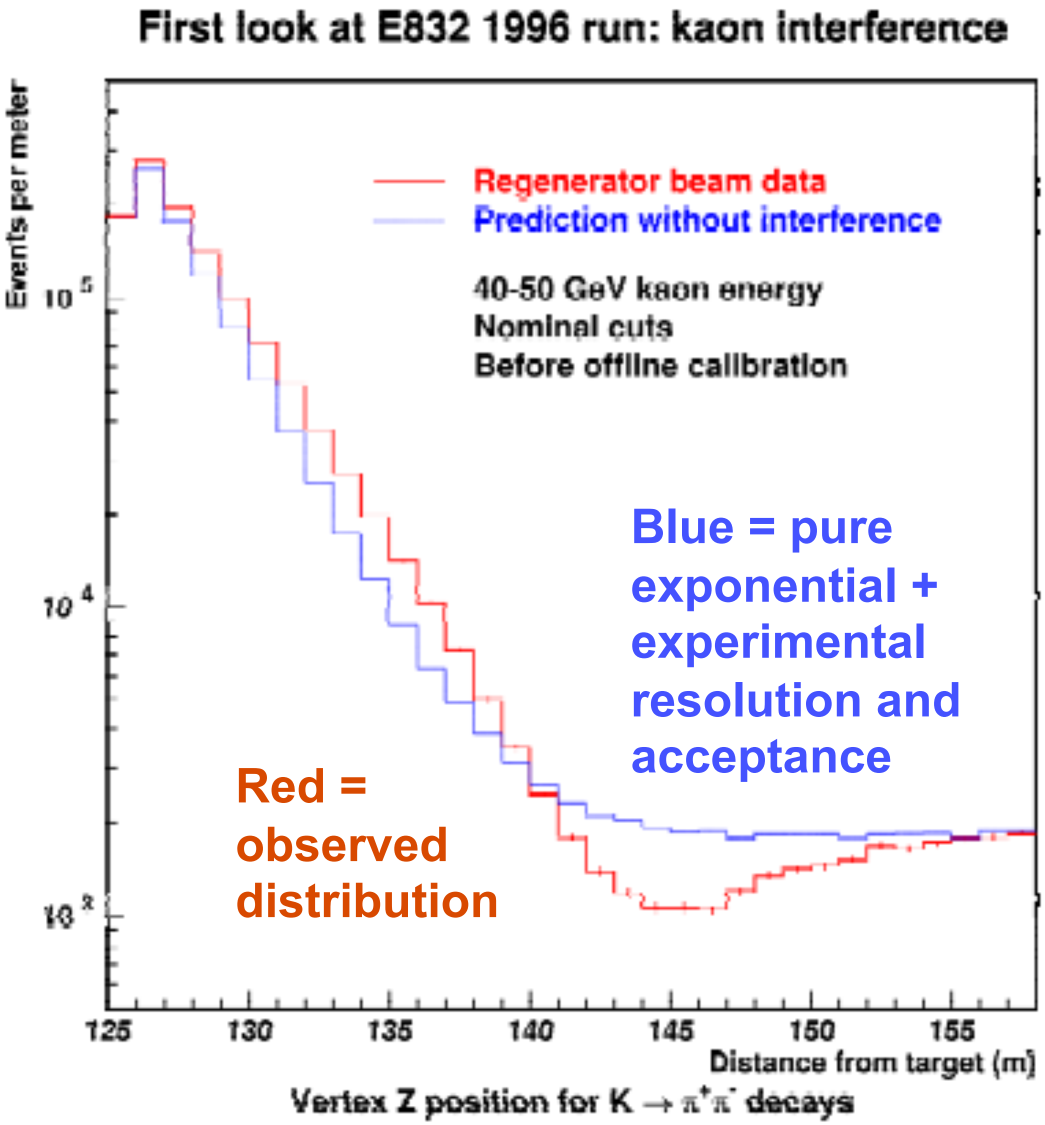
$$I(\overline{K}^0) = \tfrac{1}{4}\left[e^{-\Gamma_L t} + e^{-\Gamma_S t} - 2e^{-[(\Gamma_L+\Gamma_S)/2]t}\cos\Delta mt\right]$$

  where *I* is the intensity versus time of a particle initially produced as a K^0 (or $\underline{K}^0$), Γ_L and Γ_S are the total widths of the decay eigenstates (inverse of the lifetimes), and Δm is the mass difference between the decay eigenstates. t is proper time

- The strangeness of the state oscillates with frequency Δm
- Since $\Gamma_L << \Gamma_S$ the interference terms dies away more rapidly than the Γ_L exponential decay

Data on oscillations

- 40-50 GeV kaon energy → $\gamma \sim 100$
- $c\tau$ for $K_S \sim 2.7$ cm, so $L_{Ks} \sim 2.7$ m
- $L_{KL} \sim 1550$ m
- $\Delta m \sim .53\ 10^{10}\ s^{-1}$
  $\Delta m / \langle \Gamma \rangle \sim 0.9$



Blue = pure exponential + experimental resolution and acceptance

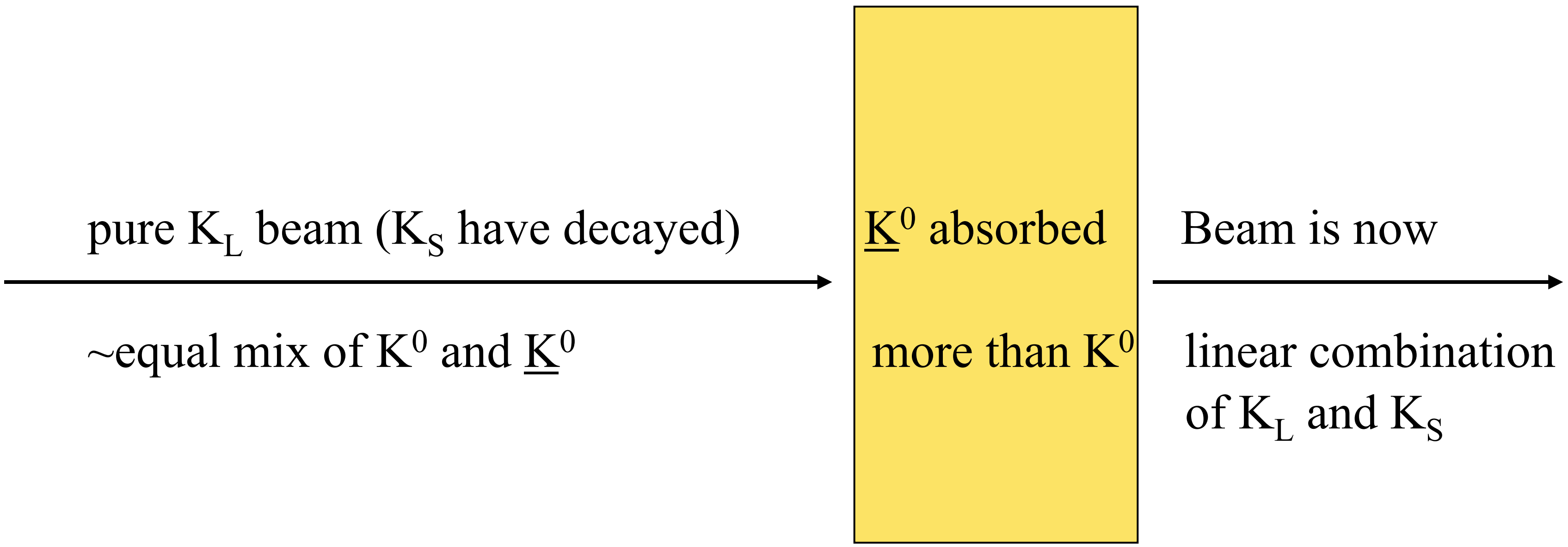
Red = observed distribution

Regeneration

- When traveling in vacuum the strangeness oscillates as shown previously
- When traveling through a slab of matter (not anti-matter!) the strong interactions differentiate between K^0 and K^0, with $\underline{K}^0$ being absorbed more rapidly
- The amplitudes of K^0 and $\underline{K}^0$ emerging from the slab will no longer be equal; the resultant beam will then include both K^0_L and K^0_S components; this is known as "regeneration"
- Predicted by Pais and Piccioni in 1955 and has been exploited extensively in experimental studies of neutral kaons

Regeneration

- Interferometry with kaons



pure K_L beam (K_S have decayed)

~equal mix of K^0 and $\underline{K}^0$

$\underline{K}^0$ absorbed

more than K^0

Beam is now

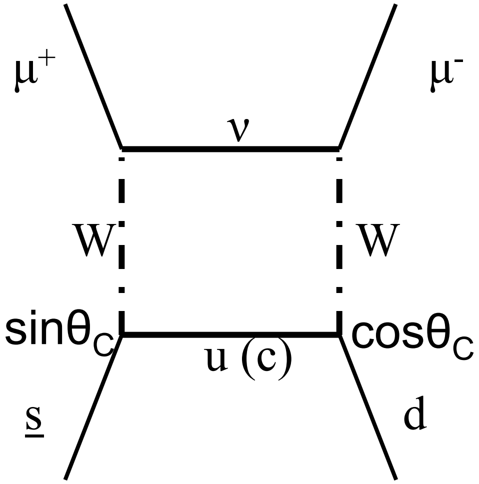
linear combination of K_L and K_S

Cabibbo angle

- Strange particles cannot decay via the strong or EM interactions, which conserve quark flavor
- The charge-changing weak interaction (W boson) can do so, but the coupling strength between quarks is governed by a set of (apparently) arbitrary parameters
- The strange quark coupling to the up quark has a strength given by $\sin\theta_C \sim 0.22$, where θ_C is the Cabibbo angle
- The down-up coupling strength is given by $\cos\theta_C \sim 0.98$
- The picture with 3 quarks is

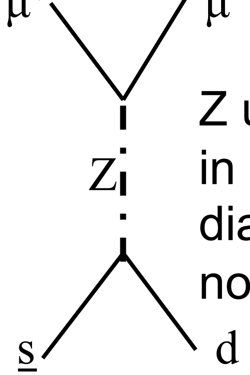
GIM mechanism

- As of 1970 all weak interactions known were charge changing; there was no evidence for weak neutral currents
- Glashow, Iliopoulos and Maiani noted that the absence of neutral currents (e.g. the decay $K^0 \rightarrow \mu^+\mu^-$) suggested the need for another charge +2/3 quark (a partner to s) to cancel the diagram at right; call it charm, c



- Charm was discovered 3 years later
- Mixing matrix relating weak and mass eigenstates; weak doublets are (u,d'), (c,s')

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$



Z unknown in 1970; this diagram is not in SM