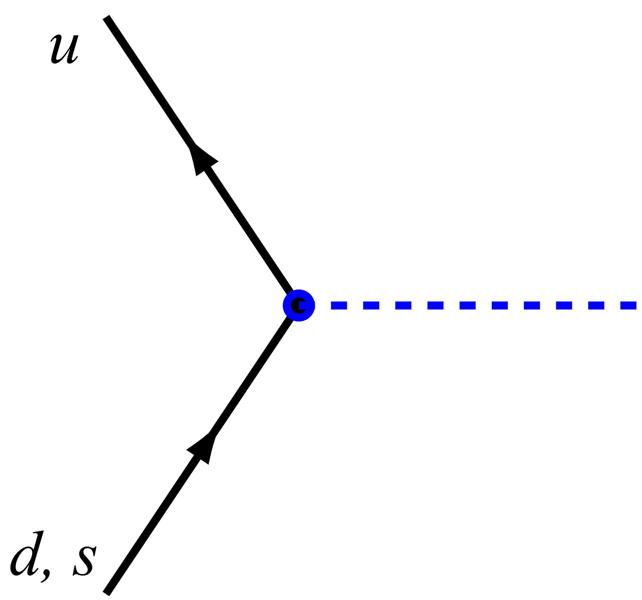
PHYSICS 489/1489

LECTURE 16: WEAK INTERACTION OF HADRONS

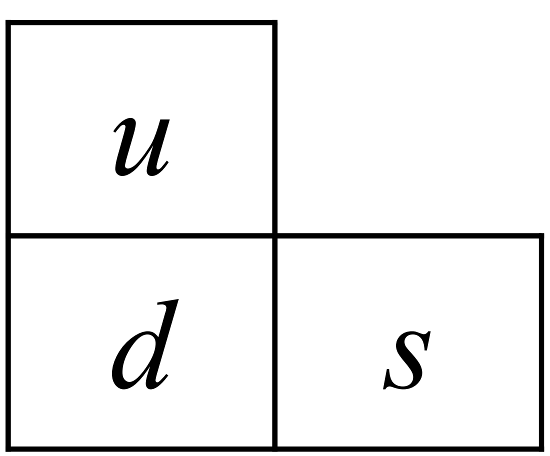
ANNOUNCEMENTS

- Problem Set 3 due on Friday 1700
- No class next Tuesday
- No office hours Monday, Tuesday
  - Sorry!
    - Please feel free to send me email about questions, etc. or to set up an appointment at another time.
- Midterm grade proposal
  - replace midterm grade with final grade if final grade is higher
  - i.e. final is worth 60% of total grade if final > midterm
  - otherwise final is worth 40% and midterm 20%

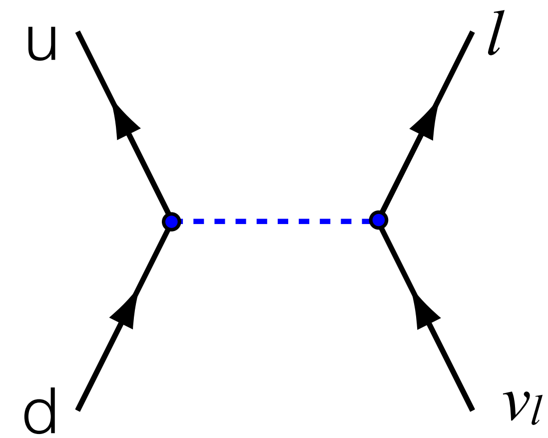
WEAK INTERACTION OF QUARKS

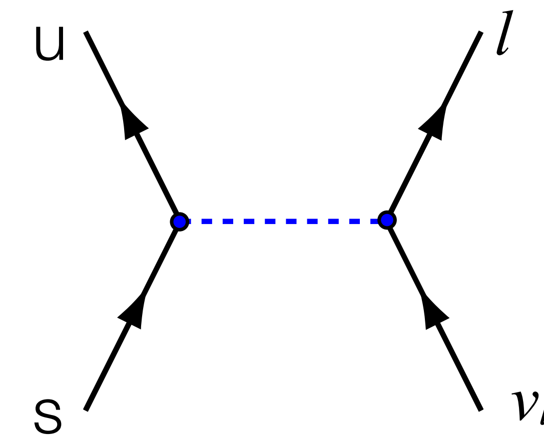


$$\frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$



- Step back to 1960s when we “knew” of three quarks
- Noticed that decays of “strange’ particles was much slower than expected
- We can compare pion/kaon decays





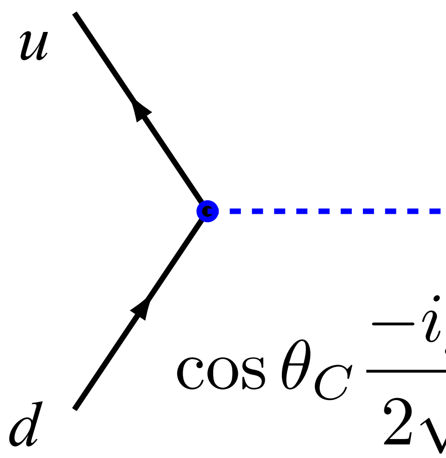
m_π = 139.57 MeV

m_K = 493.68 MeV

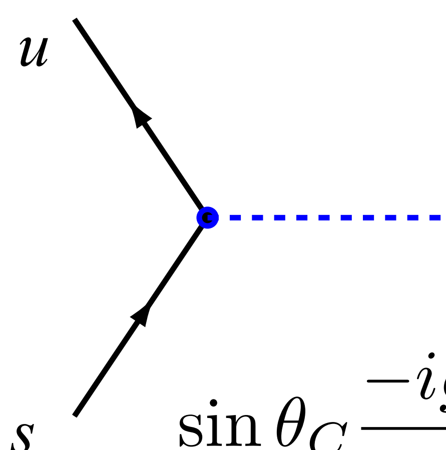
$$\Gamma = \frac{f_\pi^2}{\pi\hbar m_\pi^3}\left(\frac{g_w}{4M_W}\right)^4 m_l^2(m_\pi^2 - m_l^2)^2$$

$$\frac{\Gamma(K^- \to \mu^- + \nu_\mu)}{\Gamma(\pi^- \to \mu^- + \nu_\mu)} = \left(\frac{m_\pi}{m_K}\right)^3\left(\frac{m_K^2 - m_\mu^2}{m_\pi^2 - m_\mu^2}\right)^2 \sim 18$$

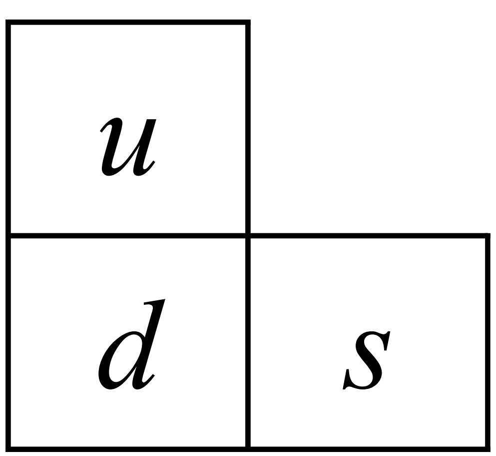
CABIBBO ANGLE



$$\cos\theta_C \frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$

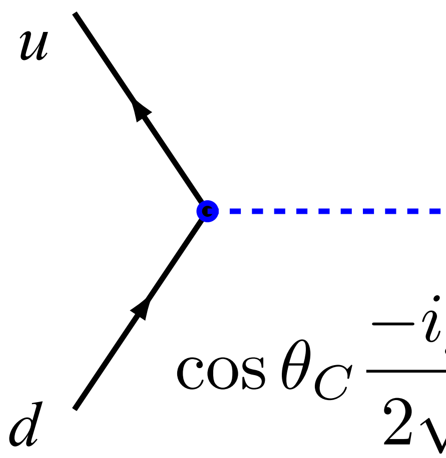


$$\sin\theta_C \frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$

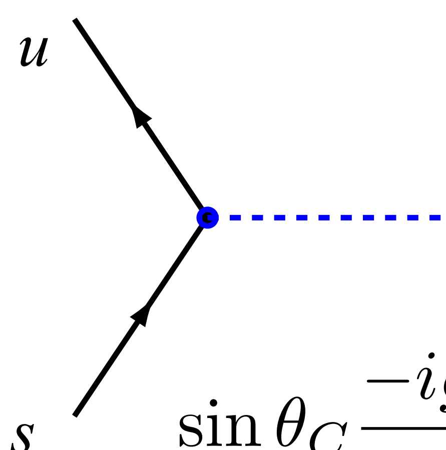


- Experiments find that this ratio is more like 1.3, indicating that something is wrong with our picture
- Cabbibo postulated that:
  - d ↔ u transitions scaled by factor of cos θ_c
  - d ↔ c transitions scaled by factor of sin θ_c
  - experimentally $\theta_c \sim 13°$
- Cabibbo was able to relate a host of decay rates for strange and non-strafe particles with a single parameter
  - "Cabibbo favored": decays with cos θ_c factor
  - "Cabibbo suppressed": decays with sin θ_c factor

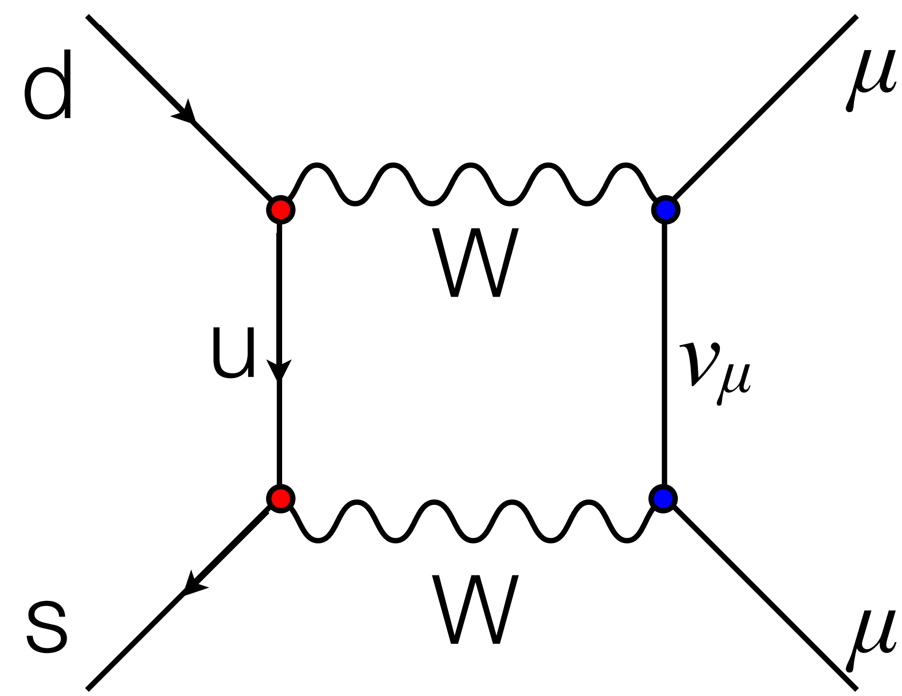
STILL A PROBLEM

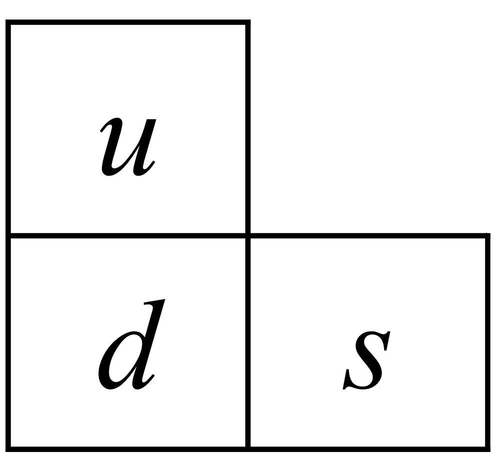


$$\cos\theta_C \frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$



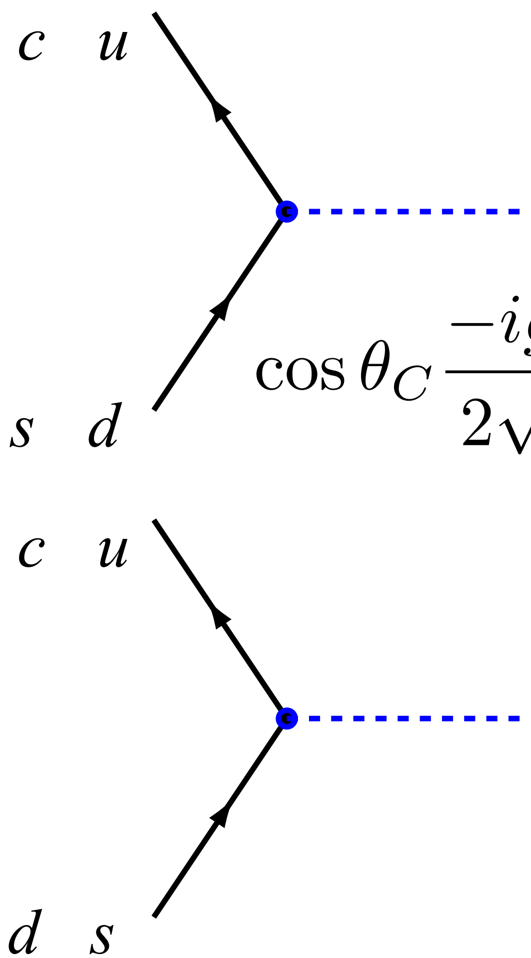
$$\sin\theta_C \frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$



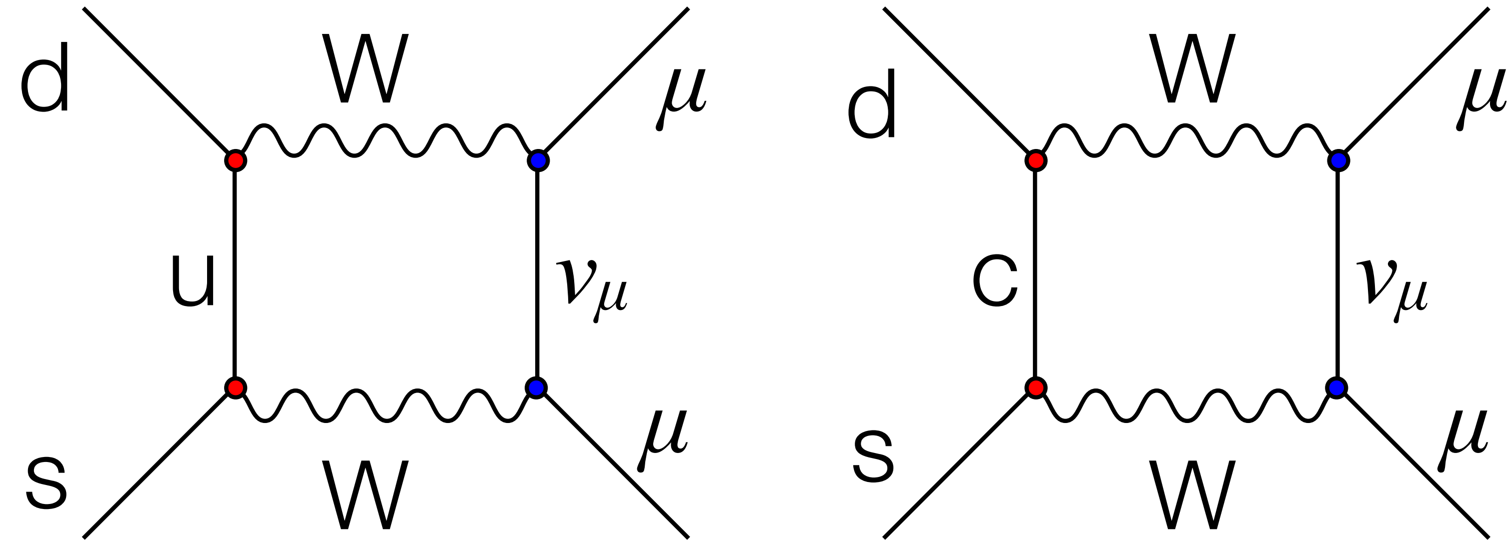


- Above process should happen as $K^0 \rightarrow \mu^+ + \mu^-$
  - but its rate as much lower than expected, even after considering Cabibbo factors

GIM MECHANISM



$$\cos\theta_C \frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$



$$A_1 \sim \sin\theta_C \cos\theta_C \qquad A_2 \sim -\sin\theta_C \cos\theta_C$$

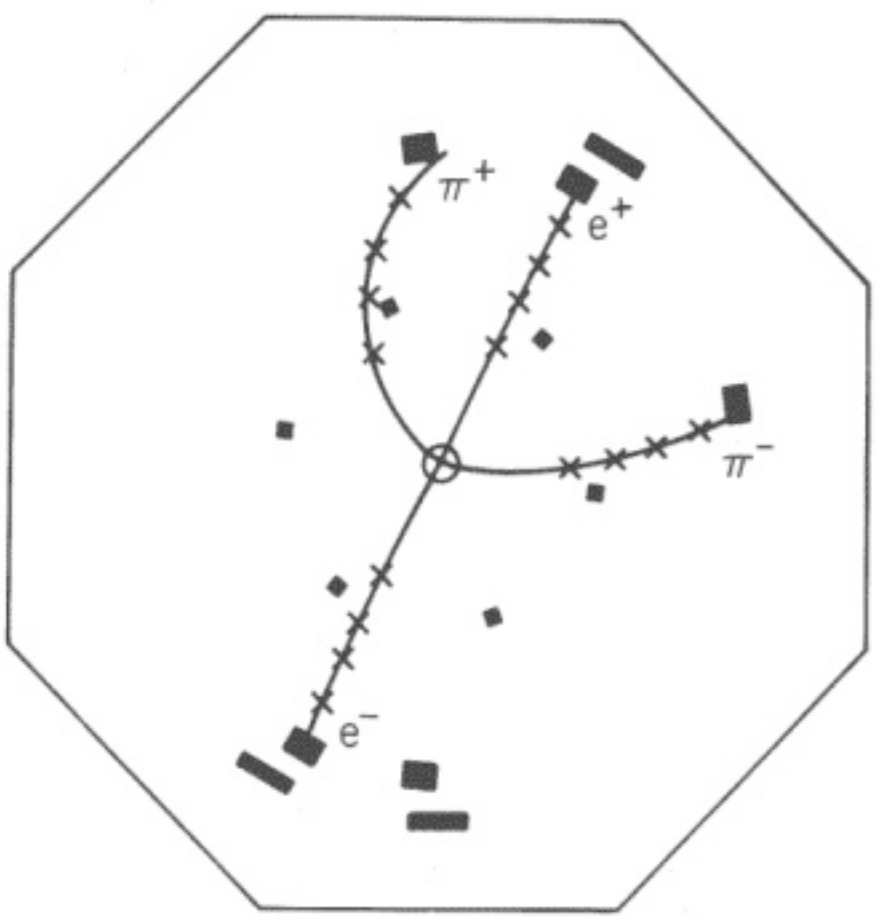
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

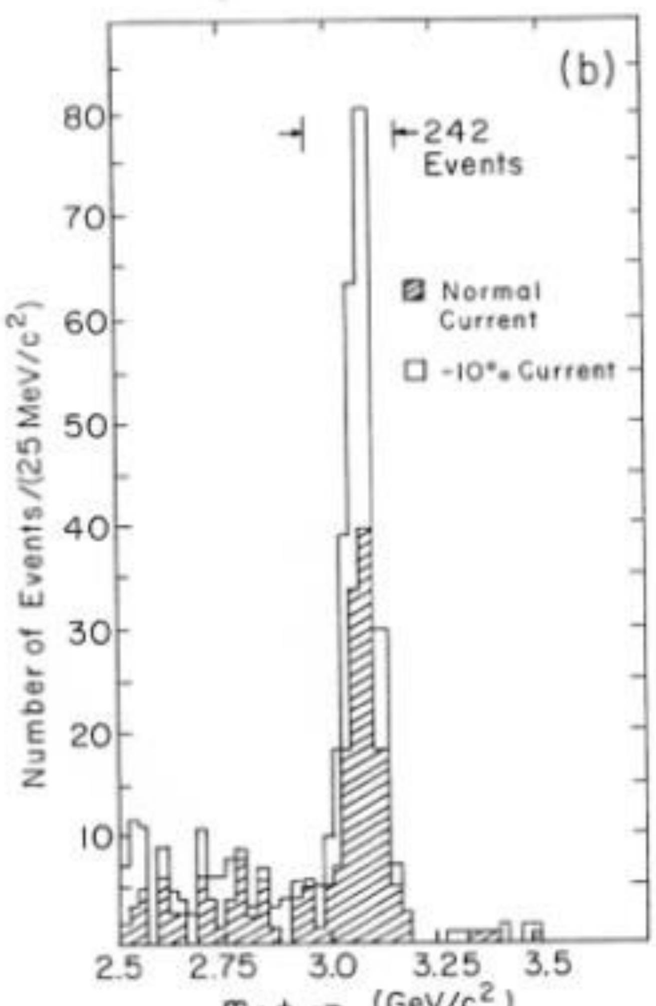
u	c
d	s

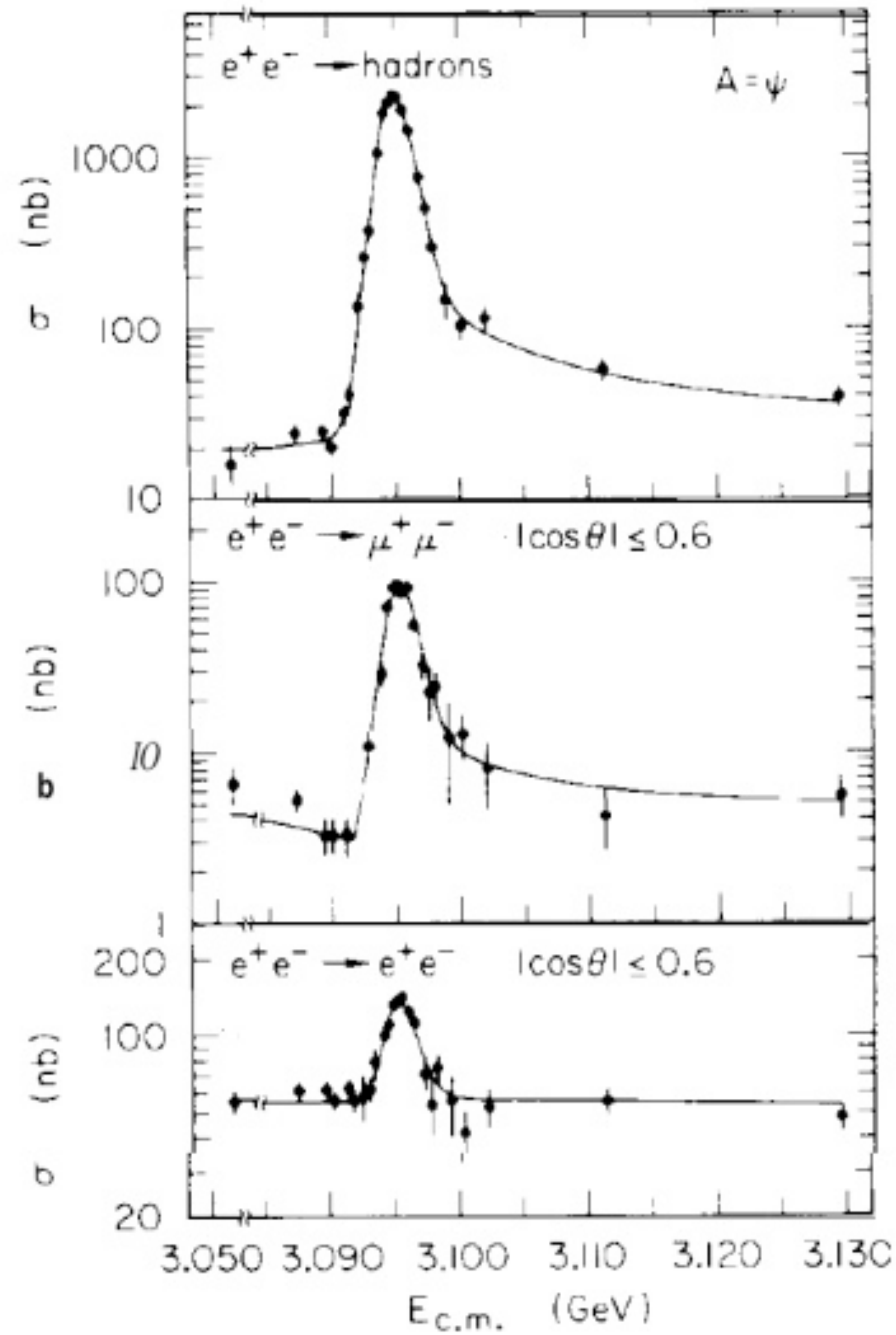
- Introduce a fourth quark
  - "charm" that cancels contribution from u quark
- "Mixing"
  - mass eigenstates (conventional name for quarks) are linear combination of "flavor eigenstates" as indicated above
  - d' is defined as state that couples to u via the W boson
  - s' is defined as state that couples to c via W boson

THE NOVEMBER REVOLUTION

- 1974: Discovery of the J/ψ particle
  - evidence of a bound state with a heavy quark
  - Brought together many elements of what we call the standard model
    - quarks, gauge theory, etc



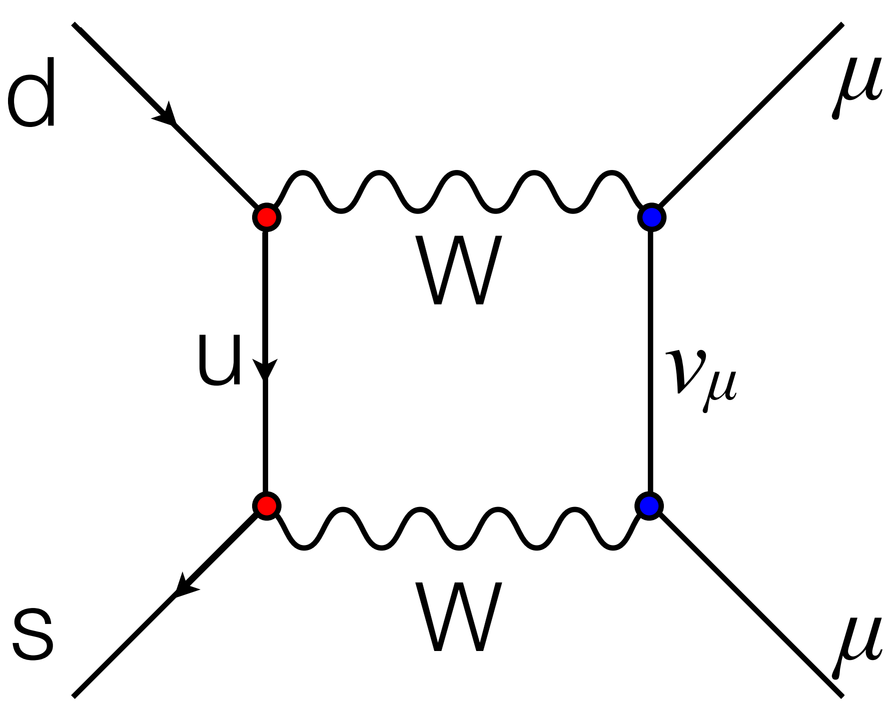




TOWARDS THREE GENERATIONS

ν_e	ν_μ	ν_τ
e	μ	τ

u	c	t
d	s	b



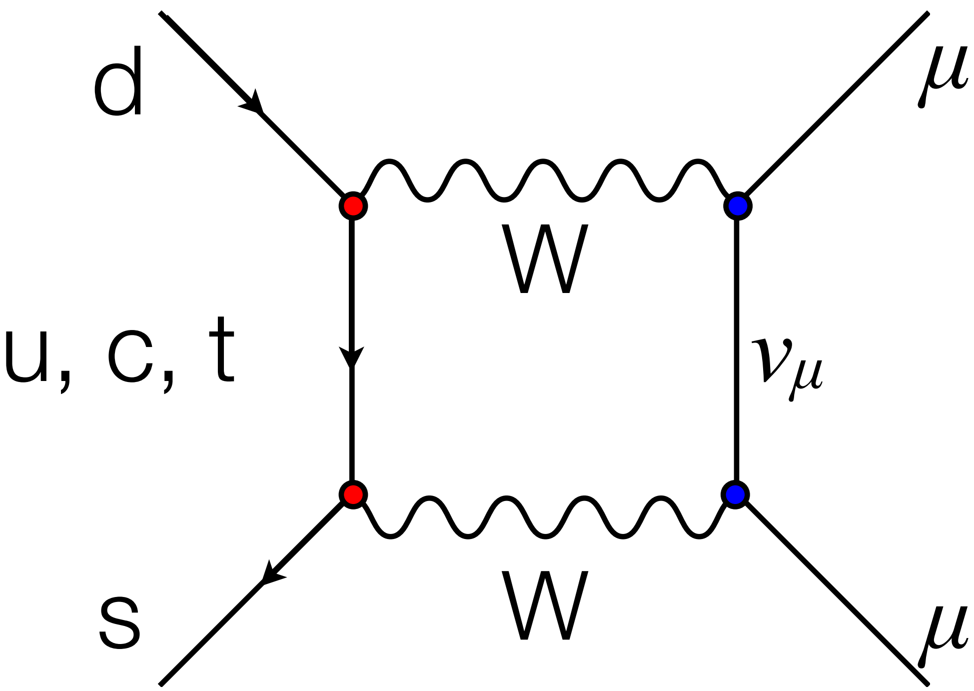
- Prior to the discovery of the Charm quark, Kobayashi and Maskawa contemplated the possibility of six quarks (three generations) in 1964
- Generalize Cabibbo angle to 3x3 matrix relating mass/flavor states

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Apply
  - factor of V_{ab}^* for a→b transition
  - factor of V_{ab} for b→a transition
    - note that antiquark transitions are complex conjugated relative to quark transitions
    - “just follow the arrows”

$$V_{ud}\frac{-ig_W}{2\sqrt{2}}\gamma^\mu(1-\gamma^5) \qquad V_{us}^*\frac{-ig_W}{2\sqrt{2}}\gamma^\nu(1-\gamma^5)$$

GIM MECHANISM in CKM



$$V_{ud}\frac{-ig_W}{2\sqrt{2}}\gamma^\mu(1-\gamma^5) \qquad V_{us}^*\frac{-ig_W}{2\sqrt{2}}\gamma^\nu(1-\gamma^5)$$

$$V_{cd}\frac{-ig_W}{2\sqrt{2}}\gamma^\mu(1-\gamma^5) \qquad V_{cs}^*\frac{-ig_W}{2\sqrt{2}}\gamma^\nu(1-\gamma^5)$$

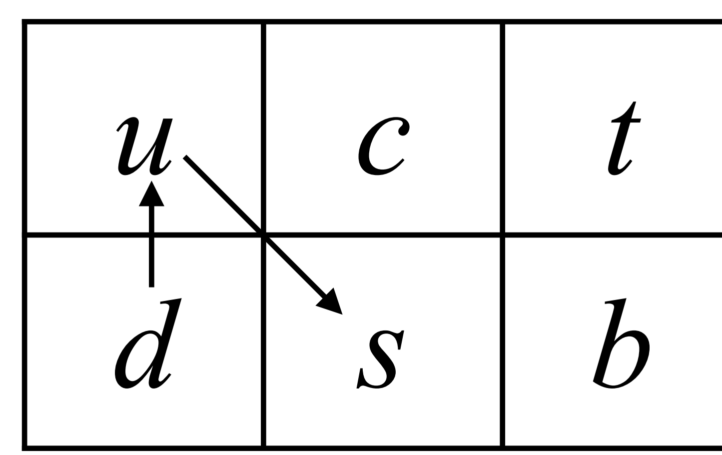
$$V_{td}\frac{-ig_W}{2\sqrt{2}}\gamma^\mu(1-\gamma^5) \qquad V_{ts}^*\frac{-ig_W}{2\sqrt{2}}\gamma^\nu(1-\gamma^5)$$

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^*$$

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- In general, “flavor changing neutral currents” that proceed via a loop and two CC transitions will have this suppression
- “Nature abhors flavour changing neutral currents”

$$|U_{CKM}| \sim \begin{pmatrix} 0.9738 & 0.2272 & 0.0040 \\ 0.2271 & 0.9730 & 0.0422 \\ 0.0081 & 0.0416 & 0.9991 \end{pmatrix}$$

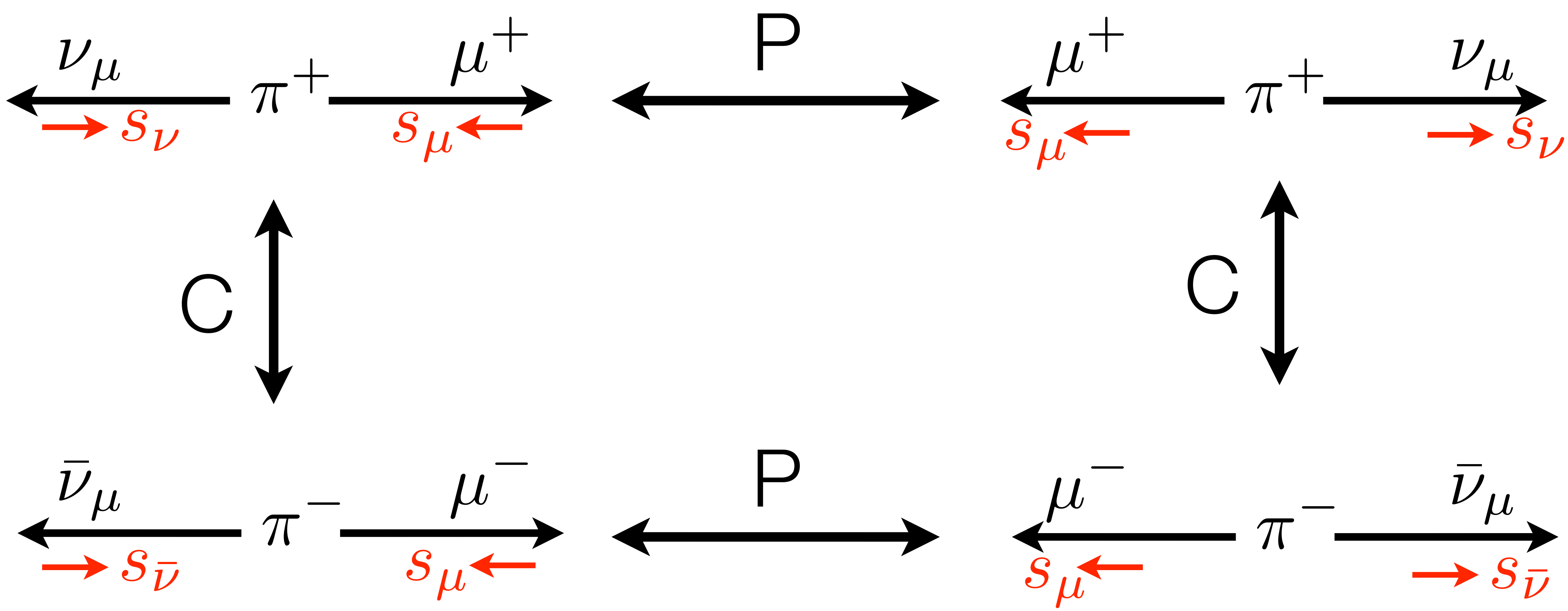


C SYMMETRY

- Charge conjugation: flips all internal quantum numbers
  - charge, color, lepton number, etc.
  - particle turns into anti-particle
  - e.g. electron->positron, proton->antiproton, photon->photon
  - since charge conjugating twice gives us the same particle the eigenvalue must be ±1
- Convention:
  - $C|\gamma\rangle = -|\gamma\rangle$
  - since we have the decay $\pi^0 \rightarrow \gamma + \gamma$, the means that $C|\pi^0\rangle = +|\pi^0\rangle$
  - Consequence:
  - $\pi^0 \rightarrow \gamma + \gamma + \gamma$ should not happen if C is a symmetry

CP SYMMETRY

- In studying pion decay we found that P is violated due to the V-A coupling:



- Historically, people wanted to save some sort of space inversion symmetry so that considered "CP" symmetry
  - mirror symmetry accompanied by charge conjugation restores symmetry

THE NEUTRAL KAONS

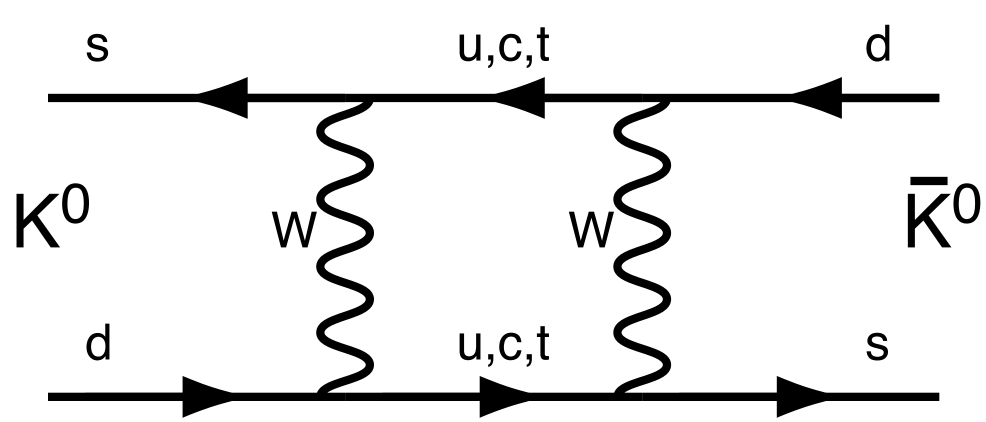
- Two types of neutral kaons product in strong interactions

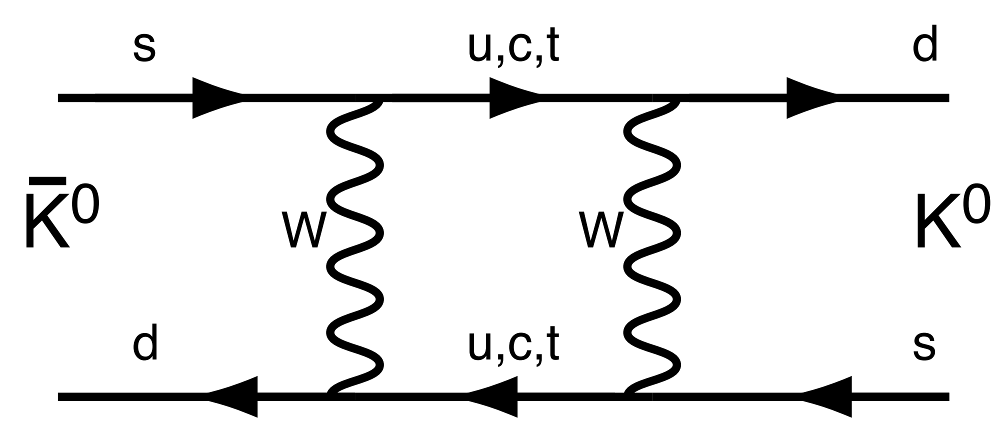
$$|K^0\rangle \to |\bar{s}d\rangle \qquad |\bar{K^0}\rangle \to |s\bar{d}\rangle$$

- As flavour states, we can produce them as follows

$$\begin{aligned}\pi^- + p &\to \Lambda + K^0\\ \pi^- + p &\to n + n + \bar{\Lambda} + \bar{K^0}\\ \pi^+ + p &\to p + K^+ + \bar{K^0}\end{aligned}$$

- After production, they live long enough that the following "mixing" processes occur





MIXING

- Mixing means kaon produced initially as a flavour state (i.e. K^0 or $\overline{K^0}$) is no long a state of definite flavour
  - it is a linear combination of K^0 and $\overline{K^0}$
- Consider the C and P properties of these states:

Thomson's convention

$$C|K^0\rangle = -|\bar{K}^0\rangle \qquad P|K^0\rangle = -|K^0\rangle$$

$$C|\bar{K}^0\rangle = -|K^0\rangle \qquad P|\bar{K}^0\rangle = -|\bar{K}^0\rangle$$

- Then we can construct CP eigenstates:

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left[|K_0\rangle + \bar{K}_0\rangle\right] \quad CP|K_1\rangle = \frac{1}{\sqrt{2}}\left[|\bar{K}_0\rangle + K_0\rangle\right] = +|K_1\rangle$$

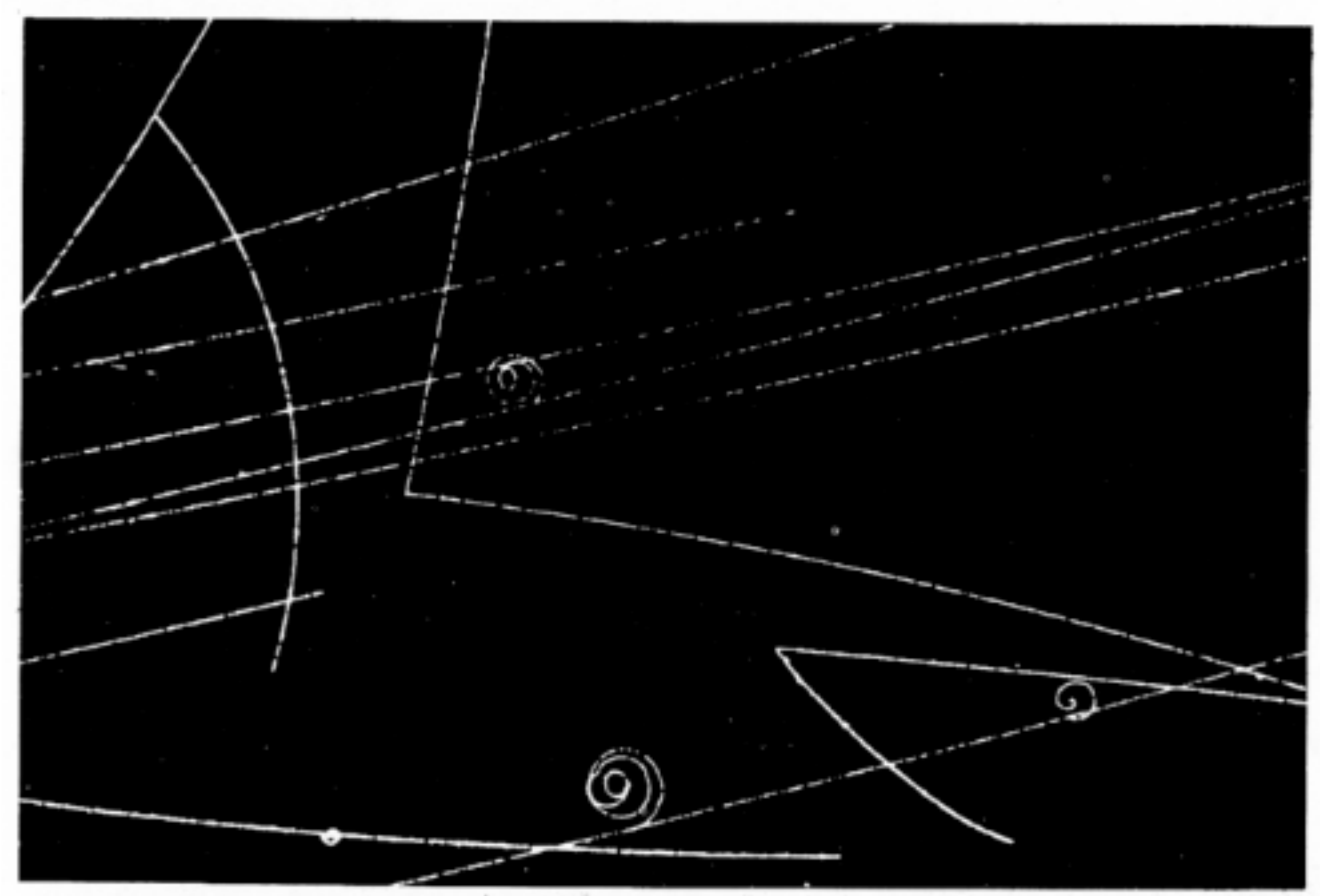
$$|K_2\rangle = \frac{1}{\sqrt{2}}\left[|K_0\rangle - \bar{K}_0\rangle\right] \quad CP|K_2\rangle = \frac{1}{\sqrt{2}}\left[|\bar{K}_0\rangle - K_0\rangle\right] = -|K_2\rangle$$

DECAY MODES

- Consider final states of two or three pions:

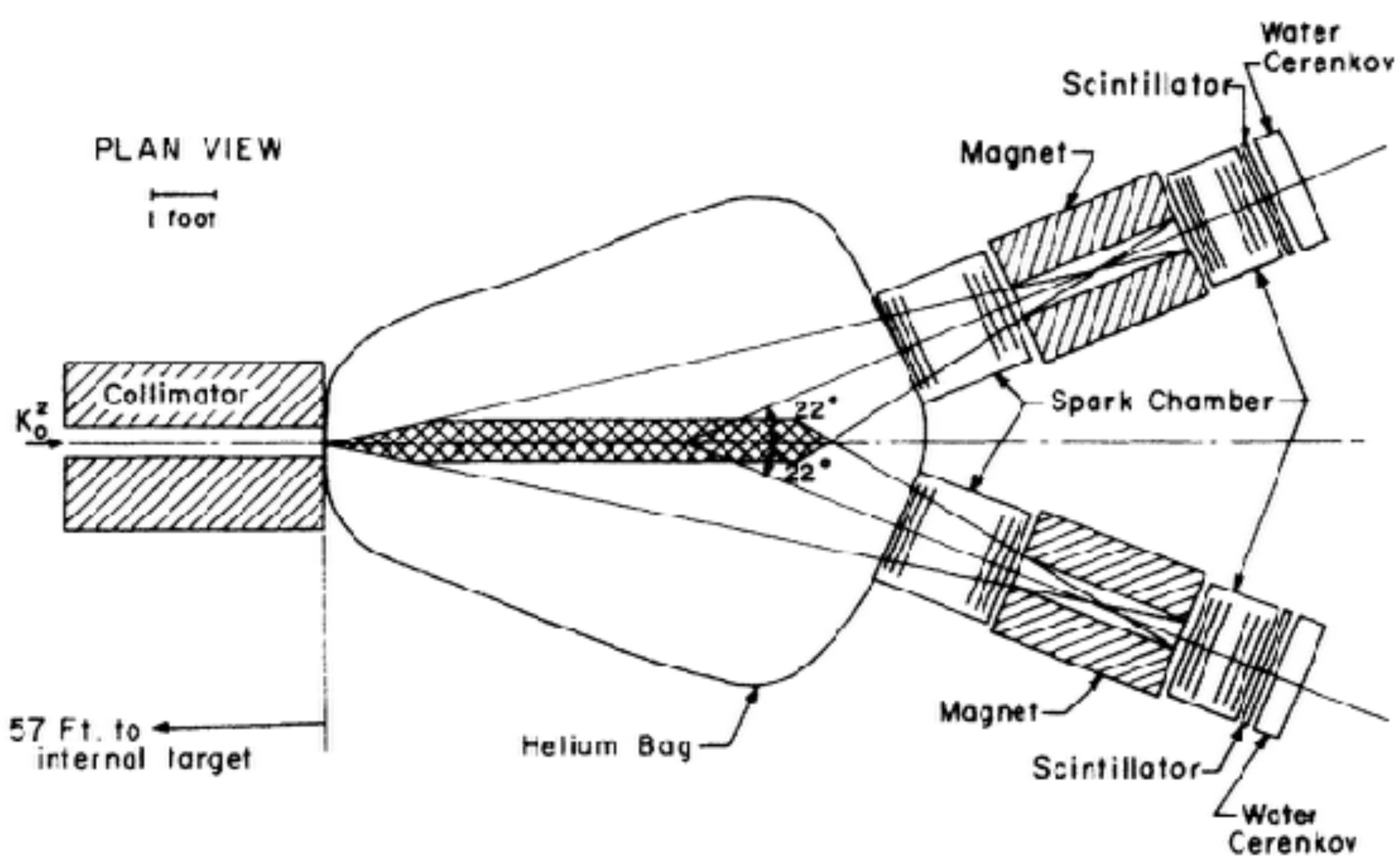
$$K \to \pi\pi \quad C: 1^2 \quad P: (-1)^2 \quad CP: +1 \times +1 = +1$$
$$K \to \pi\pi\pi \quad C: 1^3 \quad P: (-1)^3 \quad CP: +1 \times -1 = -1$$

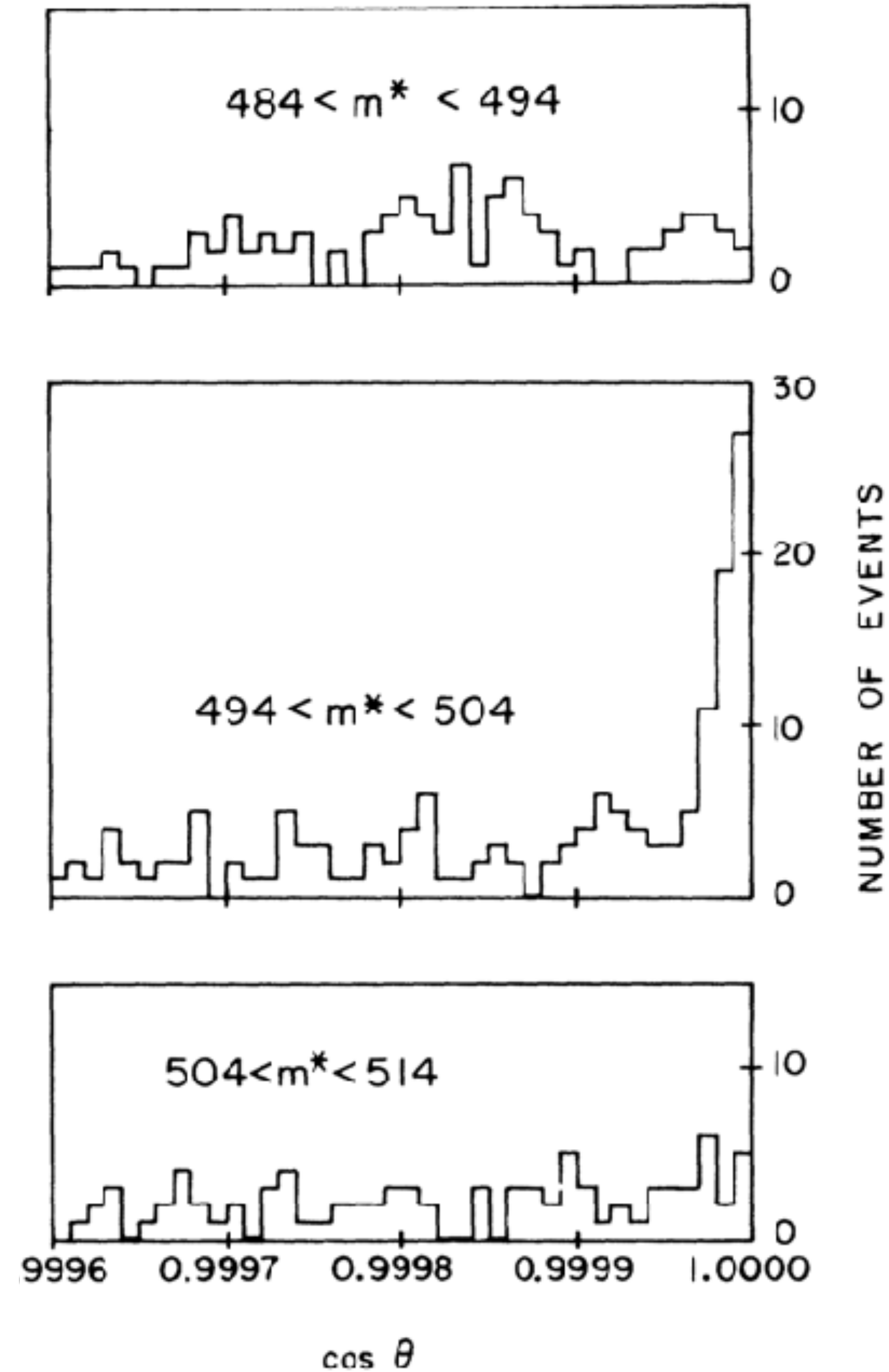
- CP symmetry means
  - K_1 can decay to ππ but not πππ
  - K_2 can decay to πππ but not ππ
- This means that K_2 has a longer lifetime than K_1
- Experimentally:
  - $t_1 = 8.95 \times 10^{-11}$ s
  - $t_2 = 5.11 \times 10^{-8}$ s



CP VIOLATION IN KAON DECAY

- Produce a beam of K^0
  - propagate ~20 meters to decay K_1
  - all that is left is K_2
  - Do we see any $K \rightarrow \pi\pi$ decay?

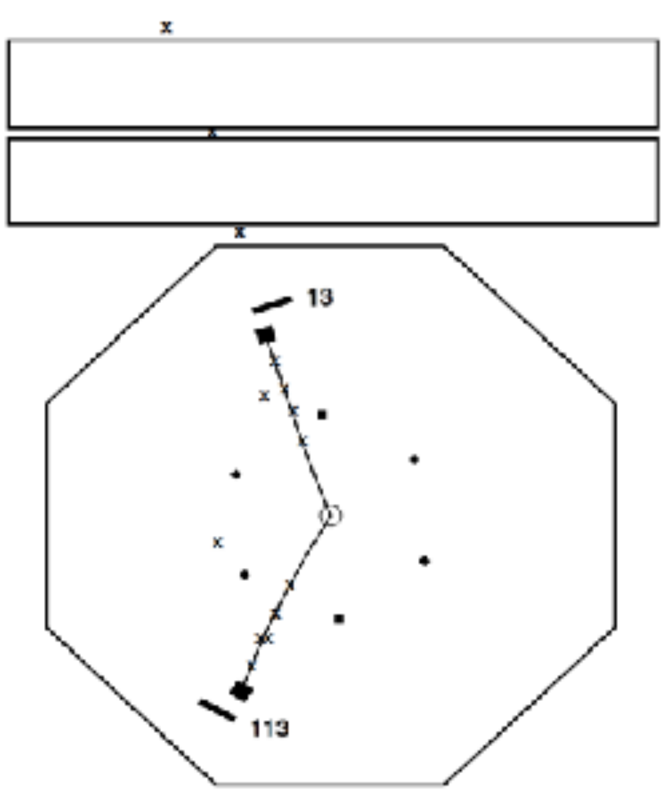




THE THIRD GENERATION

ν_e	ν_μ	ν_τ
e	μ	τ

u	c	t
d	s	b



- Kobayashi and Maskawa contemplated that CP violation comes from mixing
  - phase in the mixing will switch sign when considering quark vs antiquark transitions
  - Impossible to generate phase in mixing with only two generations
  - at least three are needed
- First indication came from the discovery of the τ in 1975 at SLAC
  - bottom quark discovered in 1977
  - top quark in 1994
  - ν_τ in 2000
- Experiments (kaon, B-factories, etc.) confirm Kobayashi and Maskawa's explanation for CP violation in quarks

SUMMARY

- Three forms of weak decay suppression
  - overall at low energies (long lifetimes, small cross sections)
  - helicity suppression
  - Cabibbo suppression
  - GIM suppression
- Symmetry violations
  - Parity is maximally violated for weak CC interactions
  - CP is also violated

REMINDER

- No class next Tuesday
- No office hours Monday, Tuesday
  - Sorry!
    - Please feel free to send me email about questions, etc. or to set up an appointment at another time.
- Please read Chapter 15