PHYSICS 489/1489

LECTURE 15: WEAK INTERACTION OF HADRONS

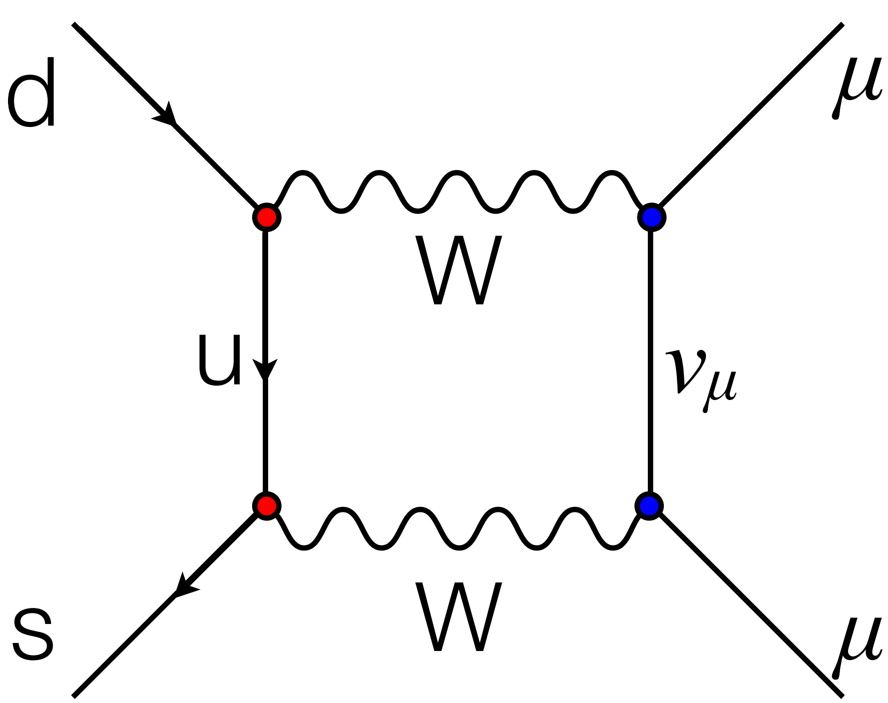
LAST TIME

- Weird stuff about weak interactions
  - Massive gauge bosons (W, Z)
  - Helicity suppression
  - GIM suppression
  - CKM factors/suppression

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

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

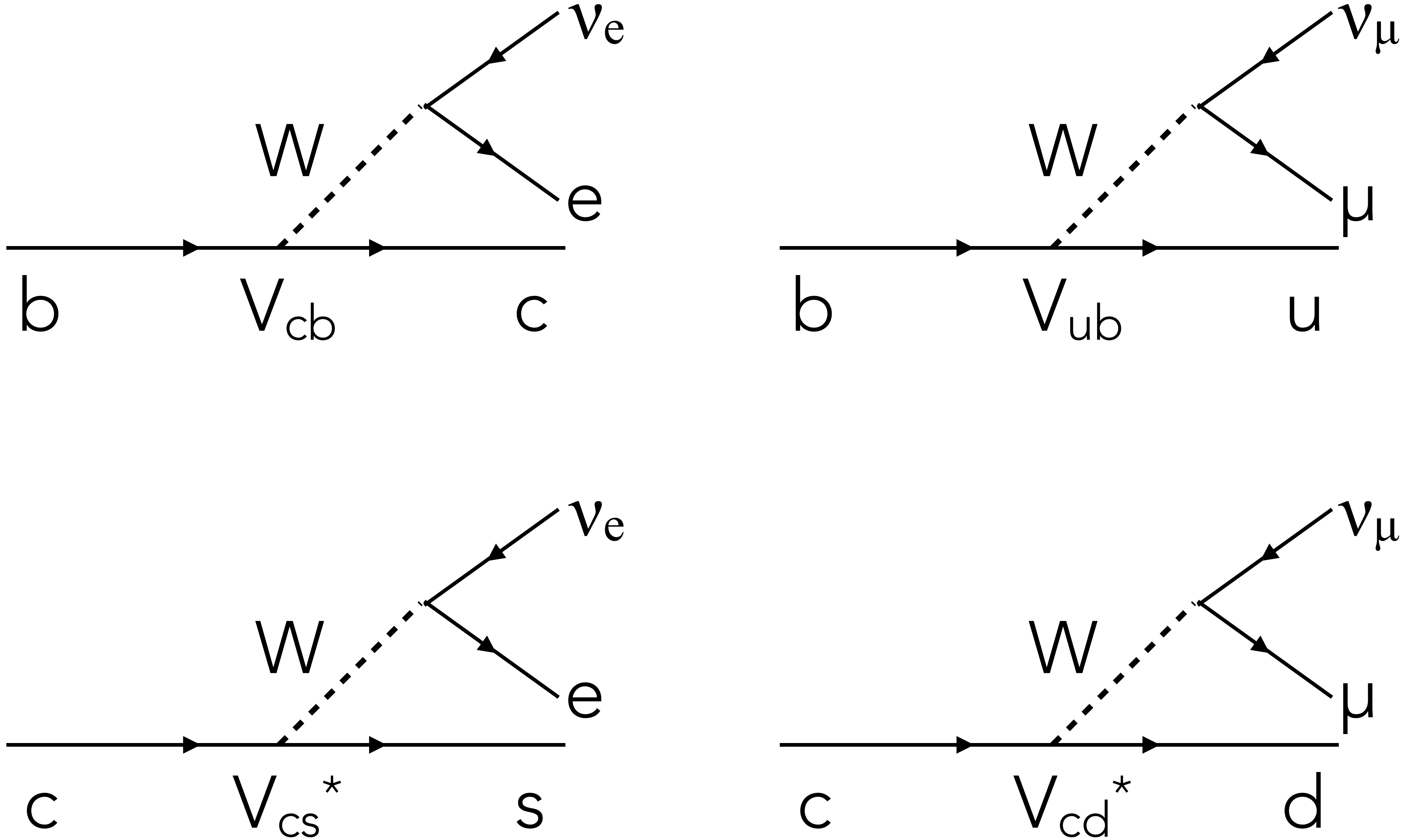
- Apply
  - factor of V_{ab}^* for a→b transition
  - factor of V_{ab} for b→a transition
    - note that antiquark transitions are complex conjugated relative to quark transitions
    - "just follow the arrows"

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

CKM MATRIX ELEMENTS

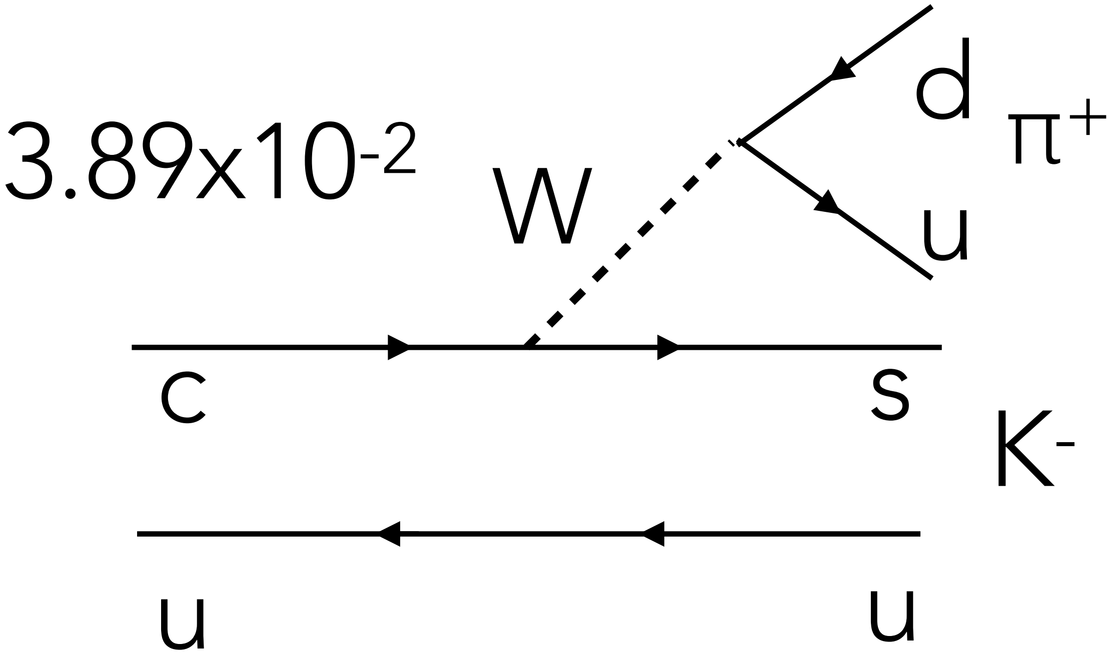
- V_{CKM} matrix elements are completely arbitrary apart from unitarity of the matrix
  - they are universal (one factor for each quark transition)
  - they need to be measured experimentally
  - why should the matrix be unitary?
- How do we measure CKM matrix elements?

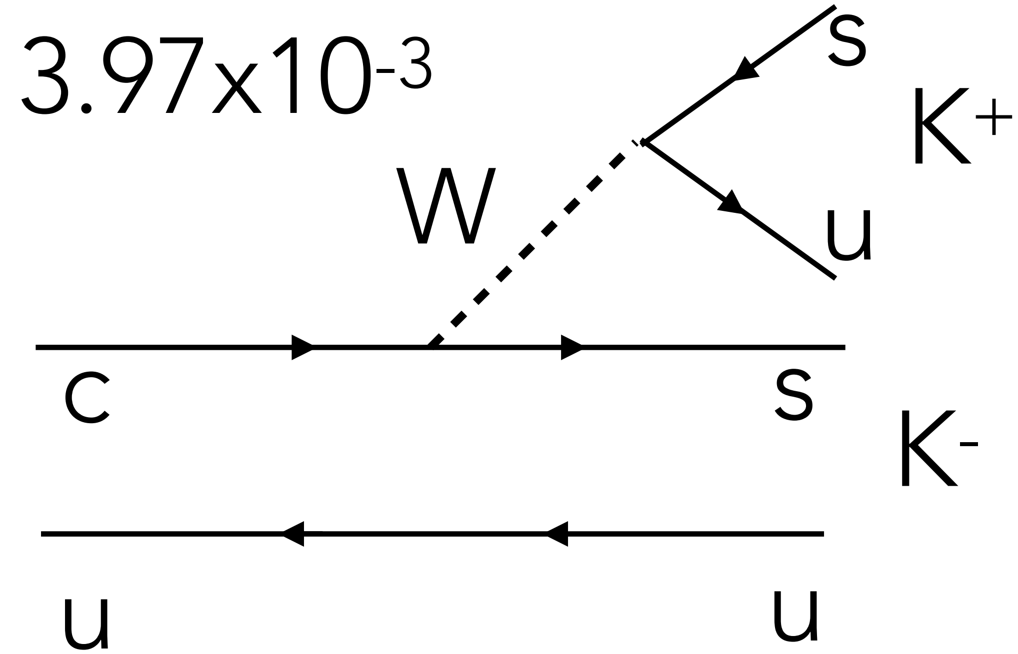
SEMI-LEPTONIC DECAYS

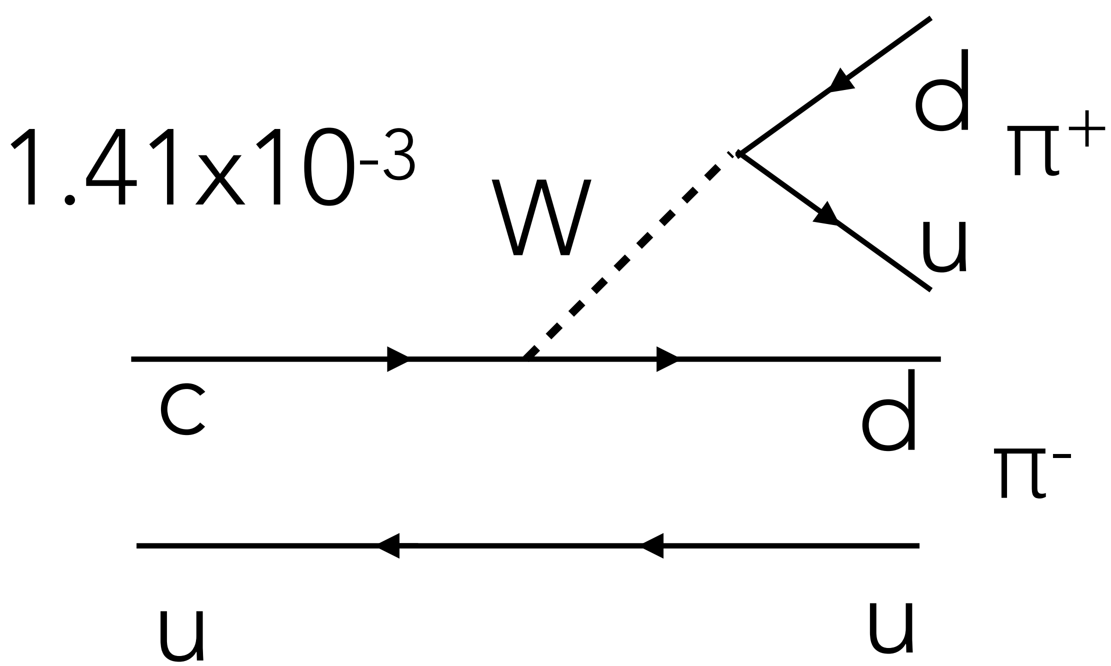


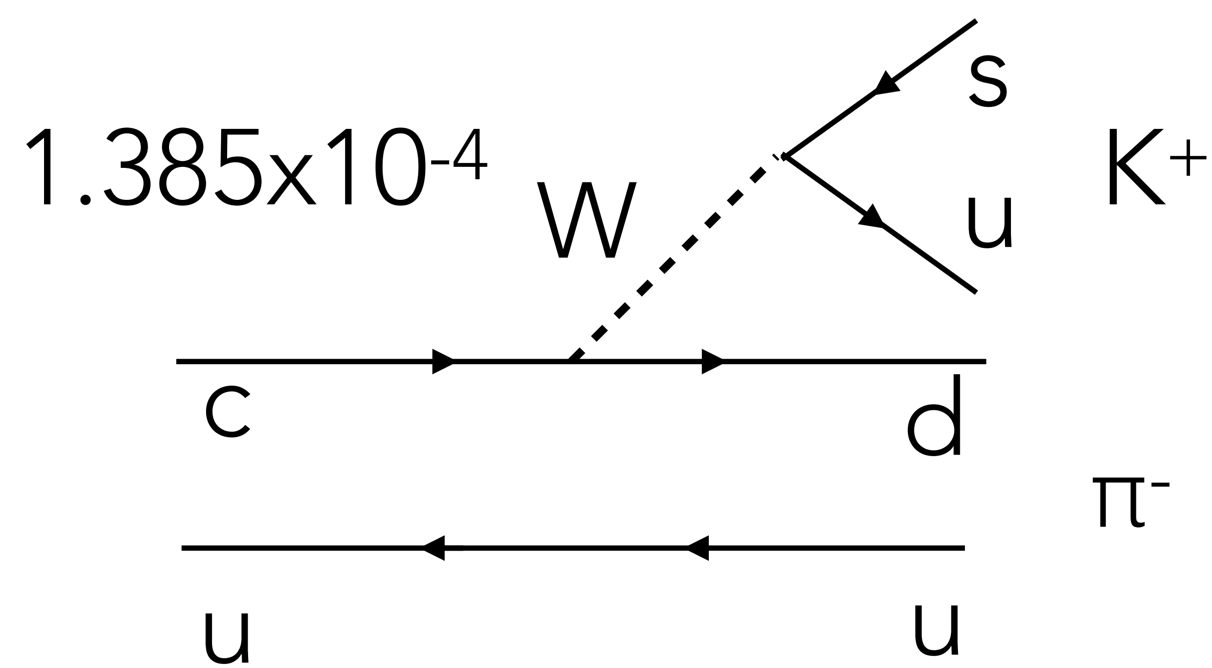
- Note that the initial and final quark states must take the form of a "hadron": a meson or a baryon

CABIBBO/CKM FAVORED/SUPPRESSED



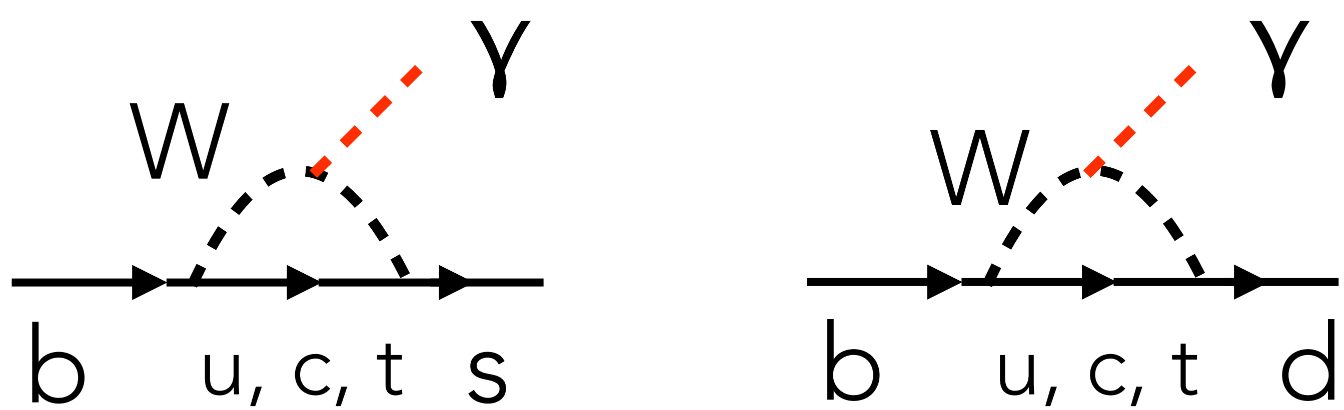






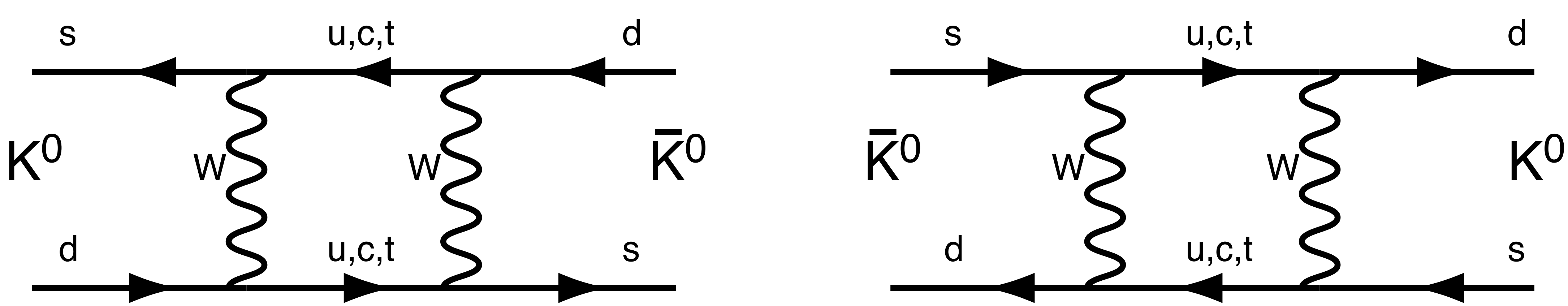
"PENGUINS" AND "BOXES"

- Penguin diagrams:



  - effective "flavor changing neutral currents"

- Box diagrams:
  - allows meson ↔ anti-meson transitions

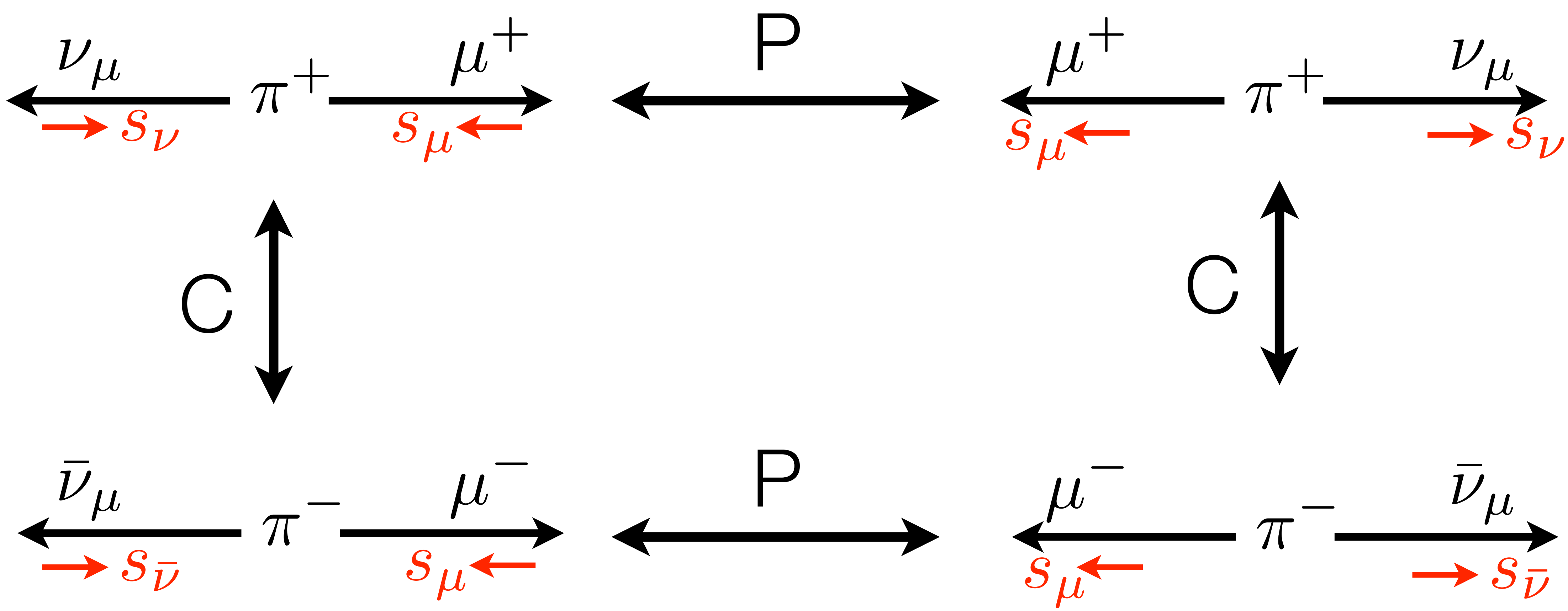


C SYMMETRY

- 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 state 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 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

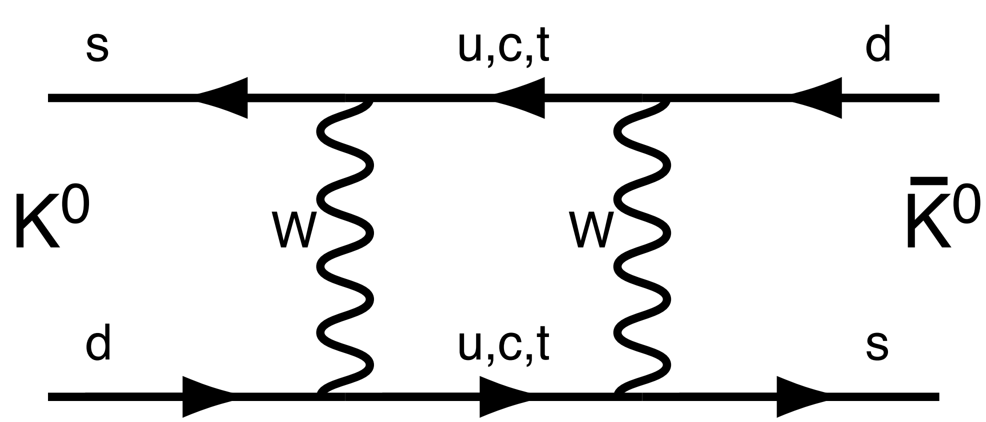
- Two types of neutral kaons product in strong interactions

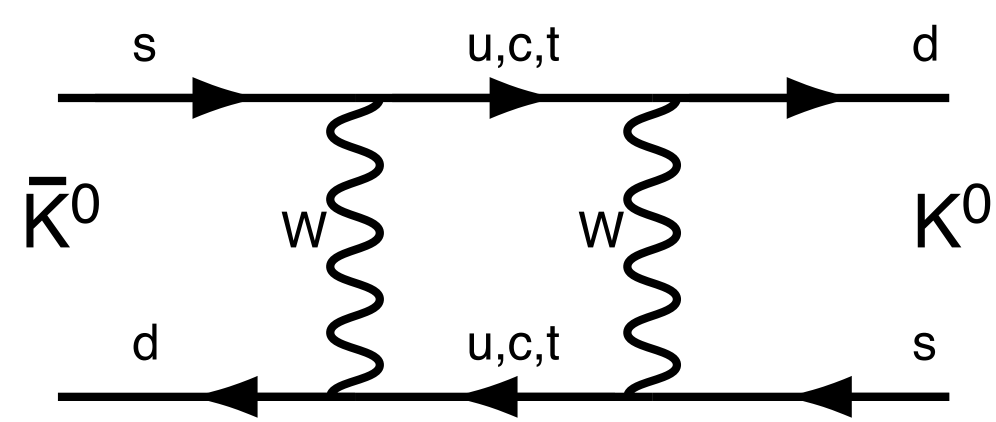
$$|K^0\rangle \rightarrow |\bar{s}d\rangle \qquad |\bar{K^0}\rangle \rightarrow |s\bar{d}\rangle$$

- As flavour states, we can produce them as follows

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

- 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:

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

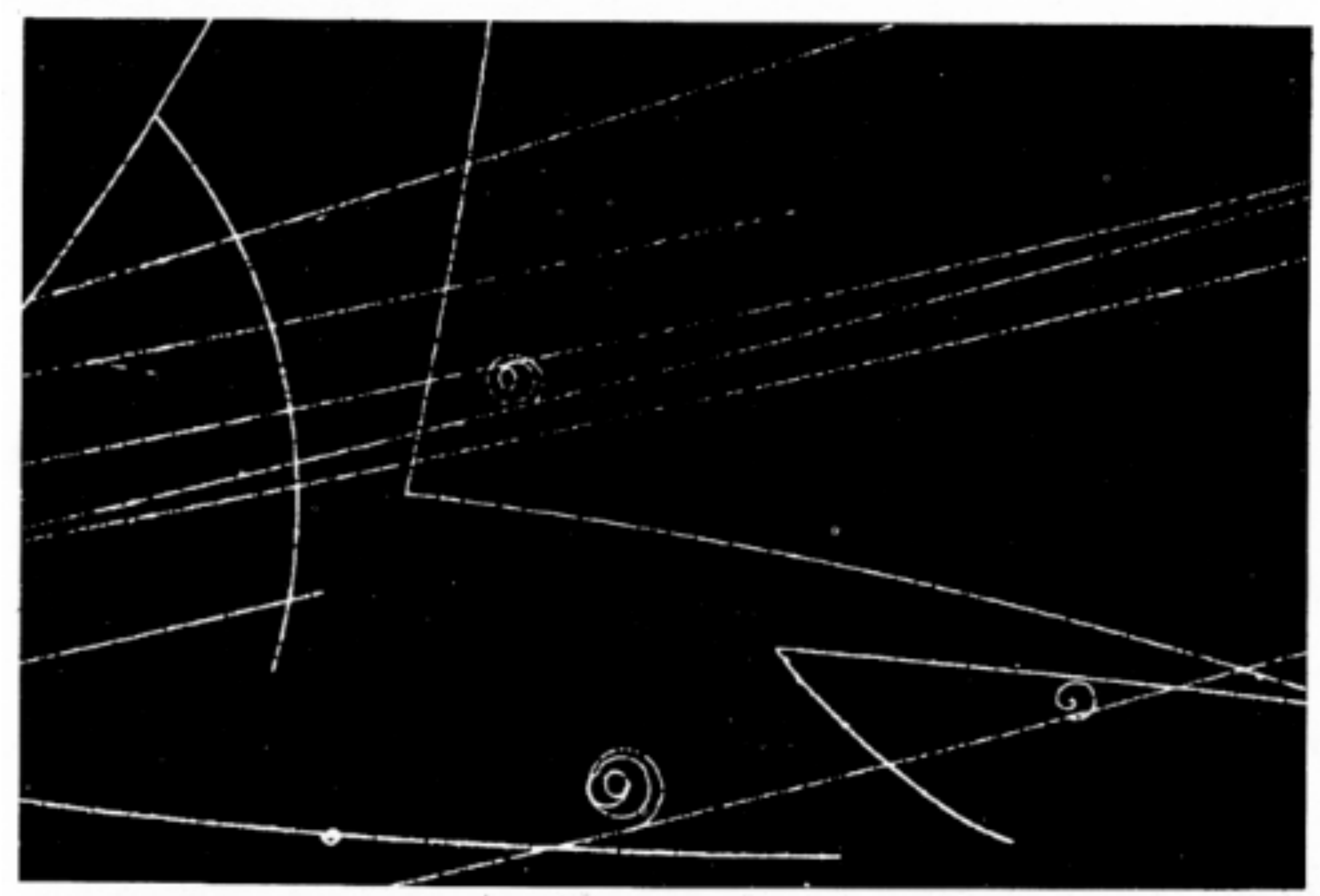
$$|K_2\rangle = \frac{1}{\sqrt{2}}\left[|K_0\rangle - \bar{K}_0\rangle\right] \quad CP|K_2\rangle = \frac{1}{\sqrt{2}}\left[|\bar{K}_0\rangle - K_0\rangle\right] = -|K_2\rangle$$

DECAY MODES

- Consider final states of two or three pions:

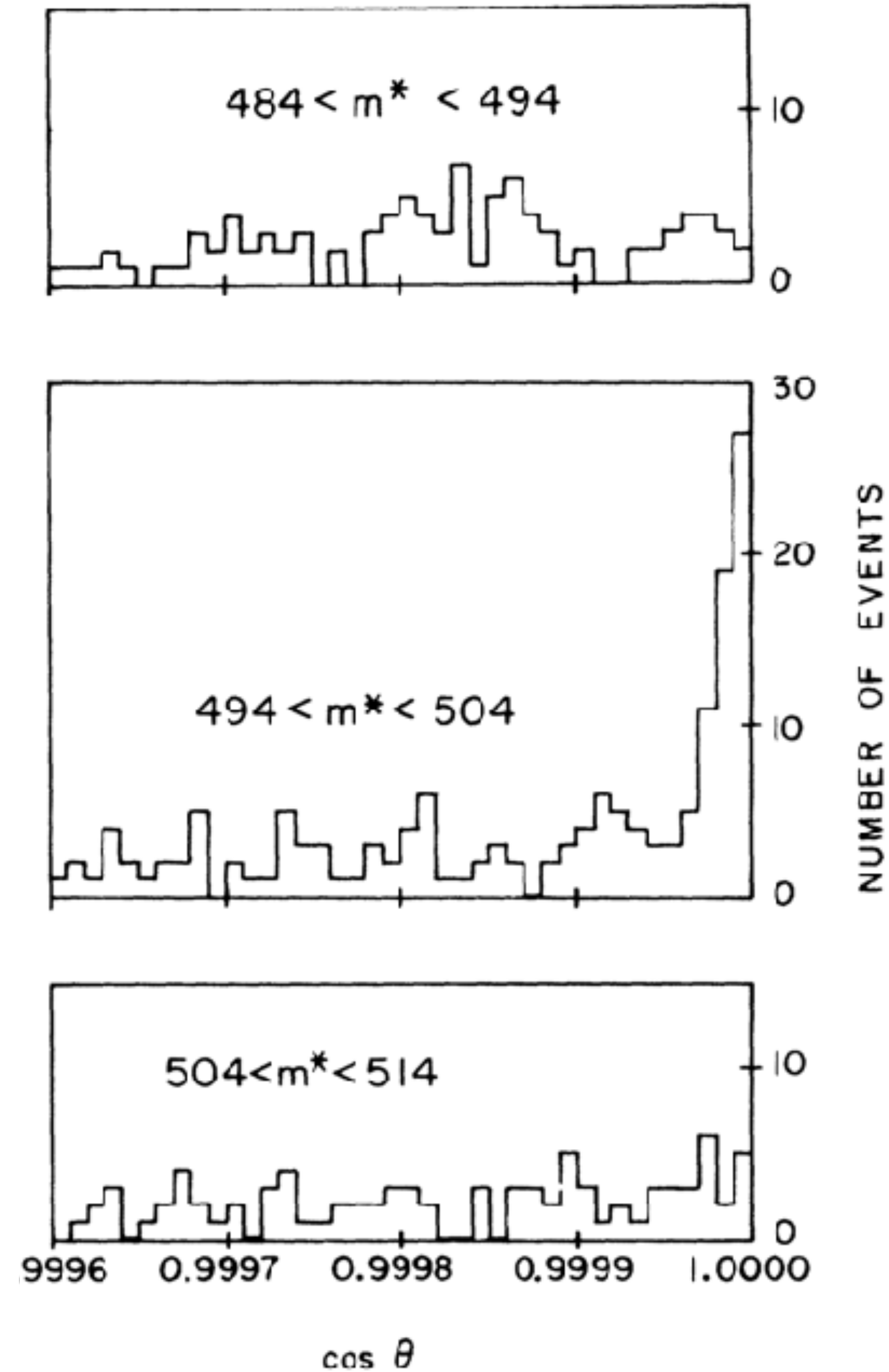
$$K \to \pi\pi \quad C: 1^2 \quad P: (-1)^2 \quad CP: +1 \times +1 = +1$$
$$K \to \pi\pi\pi \quad C: 1^3 \quad P: (-1)^3 \quad CP: +1 \times -1 = -1$$

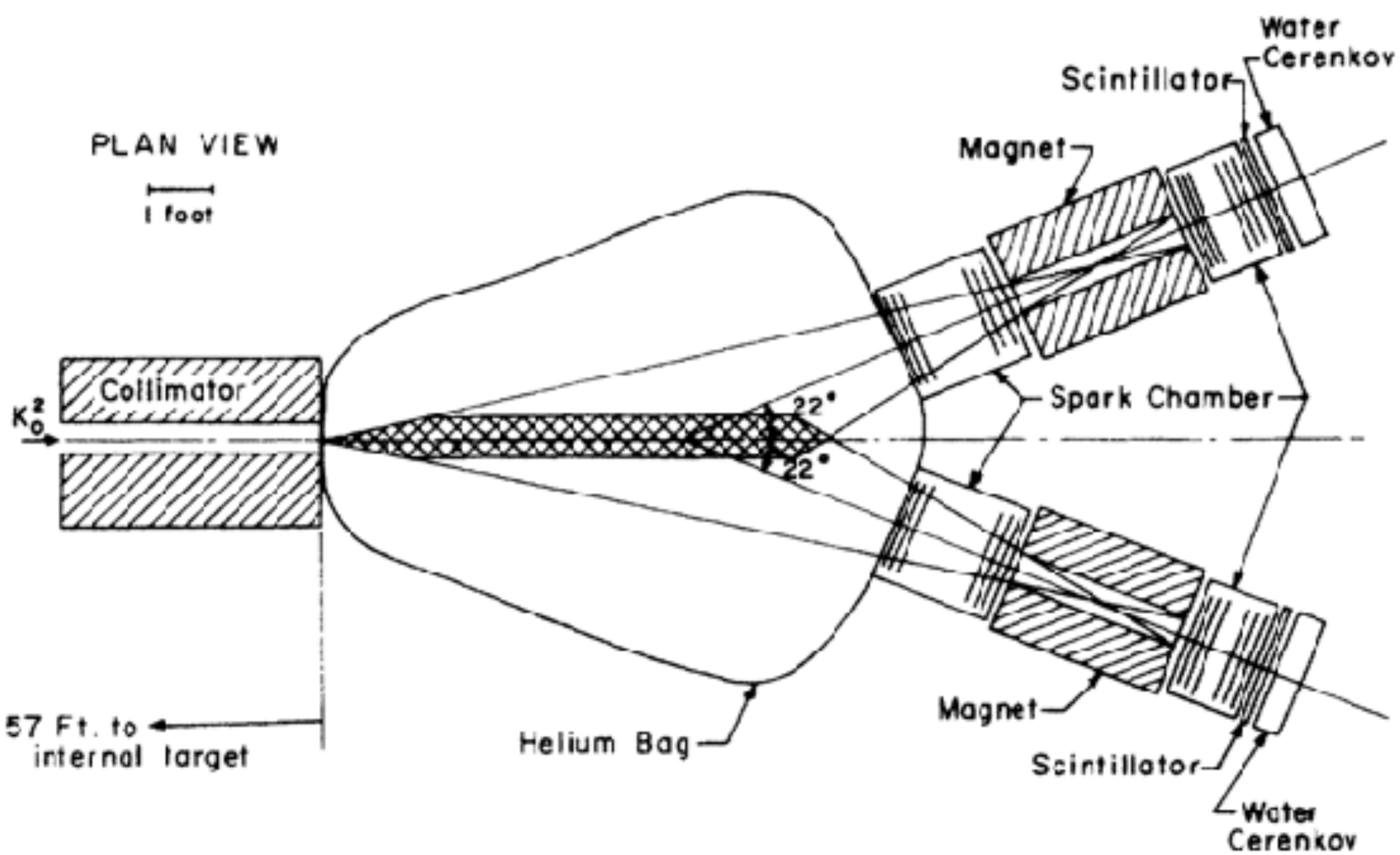
- CP symmetry means
  - K_1 can decay to ππ but not πππ
  - K_2 can decay to πππ but not ππ
- This means that K_2 has a longer lifetime than K_1
- Experimentally:
  - $t_1 = 8.95 \times 10^{-11}$ s
  - $t_2 = 5.11 \times 10^{-8}$ s



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 $K \to \pi\pi$ decay?

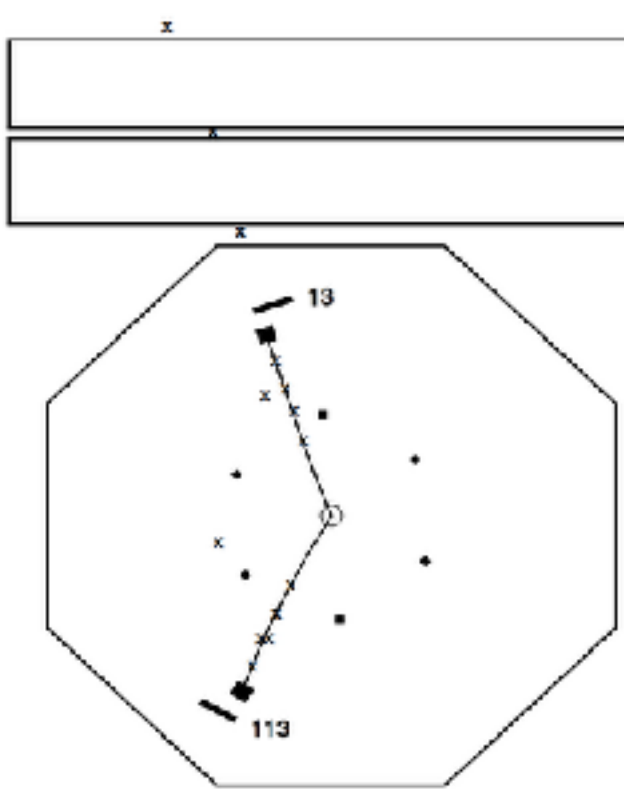




THE THIRD GENERATION

ν_e	ν_μ	ν_τ
e	μ	τ

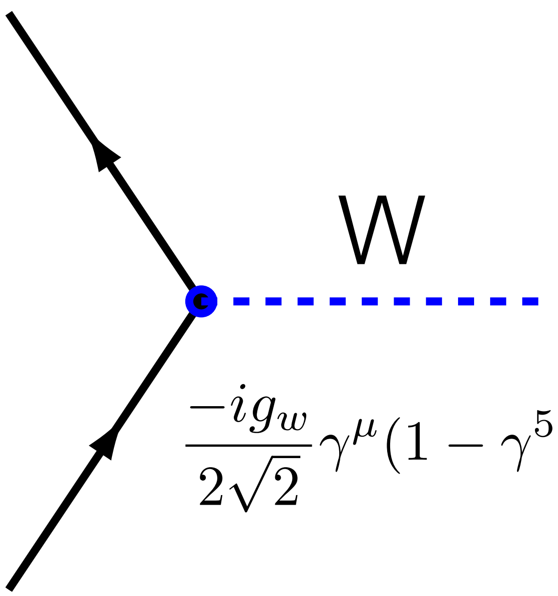
u	c	t
d	s	b



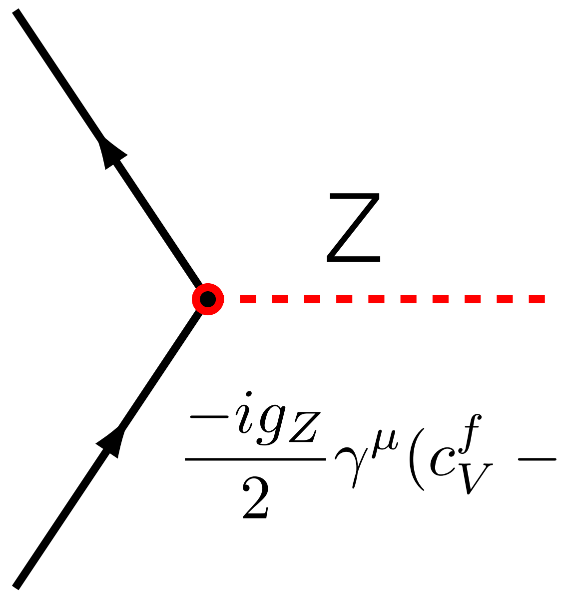
- Kobayashi and Maskawa contemplated that CP violation comes from mixing
  - phase in the mixing will switch sign when considering quark vs antiquark transitions
  - Impossible to generate phase in mixing with only two generations
  - at least three are needed
- First indication came from the discovery 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

MISSION IMPOSSIBLE

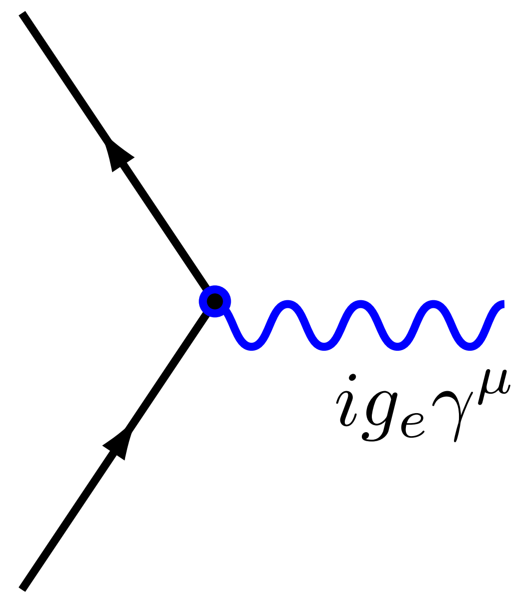
- There are hints that EM and weak interactions have a common origin
  - similar gauge structure, universal coupling constant, etc.
- But there are obvious and dramatic differences:
  - Structure of the vertex is different . . ….



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



$$\frac{-ig_Z}{2}\gamma^\mu(c_V^f - c_A^f\gamma^5)$$



$$ig_e\gamma^\mu$$

- masses of the intermediaries . . . . .

$$\frac{-i(g_{\mu\nu}-q_\mu q_\nu/M_W^2c^2)}{q^2-M_W^2c^2} \qquad \frac{-i(g_{\mu\nu}-q_\mu q_\nu/M_Z^2c^2)}{q^2-M_Z^2c^2} \qquad \frac{-ig_{\mu\nu}}{q^2}$$

- How to achieve "electroweak unification" . . next time

SUMMARY

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

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- No class next week
- Please read 15.1-15.3