PHY492: Nuclear & Particle Physics

Lecture 16

CP Violation

Weak Boson

K^0 & $\bar{K}^0$ mixing

- Parity violation in K^+ decay
  - 2 pions, P = +
  - 3 pions, P = -
  - T.D. Lee, C.N. Yang (1956)

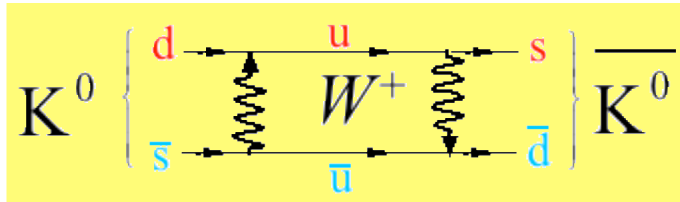
$$K^+ \to \pi^+\pi^0 \text{ or } \pi^+\pi^+\pi^- \quad (\tau = 1.2\times 10^{-8}\text{s})$$

$(\tau^+,\ \theta^+ \text{ puzzle})$

- Prediction for K^0 decays
  - M. Gell-Mann & A. Pais (1955)
  - Two decay constants
  - CP eigenstates are the key
  - Weak Interaction (2nd order) can cause particle ---> antiparticle for neutral particles

$$K^0 \to \pi^+\pi^- \quad (\tau = 0.9\times 10^{-10}\text{s}) \quad \text{fast}$$

$$K^0 \to \pi^+\pi^-\pi^0 \quad (\tau = 0.5\times 10^{-7}\text{s}) \quad \text{slow}$$



- K^0 is not an eigenstate of C or P.
- linear combinations are eigenstates of CP

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right) \qquad CP|K_1\rangle = +|K_1\rangle$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right) \qquad CP|K_2\rangle = -|K_2\rangle$$

K^0 & $\overline{K^0}$ oscillations

- Neutral K decays
  - $\pi^+\pi^-$, P = +1, C = +1, CP = +1
  - $\pi^+\pi^-\pi^0$, P = −1, C = +1, CP = −1

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right) \quad \text{fast decay}$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right) \quad \text{slow decay}$$

Invert

$$|K^0\rangle = \frac{1}{\sqrt{2}}\left(|K_1\rangle + |K_2\rangle\right)$$

$$|\bar{K}^0\rangle = -\frac{1}{\sqrt{2}}\left(|K_1\rangle - |K_2\rangle\right)$$

- K^0 & $\bar{K}^0$ created by strong interactions.
  - weak interactions select K_1 & K_2 and have slightly different masses ($\Delta m = m_2 - m_1$)
  - Mix of K_1 and K_2 will change as particle propagates
  - time dependence almost straight from QM text book.

$$|K_1(t)\rangle = K_1(0)\left[e^{im_1c^2t/\hbar}e^{-\Gamma_1 t/2\hbar}\right]$$

$$|K_2(t)\rangle = K_2(0)\left[e^{im_2c^2t/\hbar}e^{-\Gamma_2 t/2\hbar}\right]$$

- Starting with pure K^0, the $\bar{K}^0$ intensity grows then oscillates

$$I(\bar{K}^0) = \tfrac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - 2e^{-[(\Gamma_1+\Gamma_2)/2]t}\cos\left(\Delta mc^2 t/\hbar\right)\right]$$

$$\tau = 2\pi\hbar / \Delta mc^2 = 1.2\times 10^{-9}\,\text{s}$$

$$\Delta mc^2 = 3.52\times 10^{-6}\ \text{eV}$$

CP violation in K decays

- 1964 Christenson, Cronin, Fitch, & Turlay discover ~3x10^{-3} of K_2 beam decays to $\pi^+ + \pi^-$ or $\pi^0 + \pi^0$

K^0 and K^0-bar are not pure mixtures of CP eigenstates, K_1 & K_2

- Short lived version is called K_S^0 and long lived called K_L^0

  K_L^0 = mostly K_2 with a little K_1, so causes "indirect" CP violation

$$\left|K_L^0\right\rangle = \frac{1}{\sqrt{1+\left|\varepsilon\right|^2}}\left(\left|\mathrm{K}_2\right\rangle + \varepsilon\left|\mathrm{K}_1\right\rangle\right)$$

- Also H_{weak} has a very small direct CP violating term

  - Parity violation in weak interactions is maximal.

    No right handed neutrinos have ever been found.

    Relativistic quantum mechanics can handle this well.

  - CP violation is a whole other story, that continues to dominate about 1/2 of all HEP to this day.

What's all the fuss about CP violation?

- Semi-leptonic decays of K_L^0 :

$$|K_L\rangle \rightarrow \pi^+ + e^- + \bar{\nu}_e$$
$$|K_L\rangle \rightarrow \pi^- + e^+ + \nu_e$$

- If CP were a good symmetry decays should be identical (decay fraction, etc.)

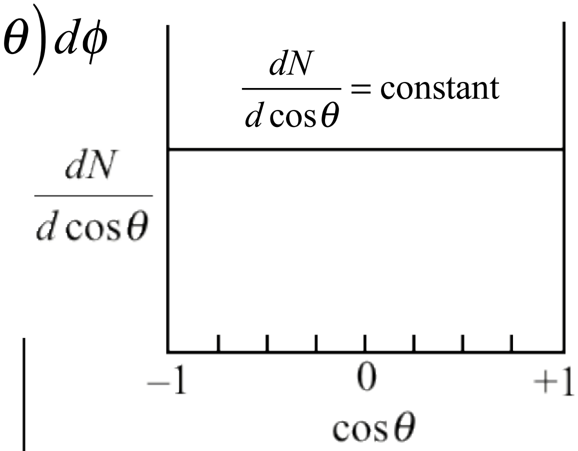
- Experiments show the e^+ decay greater than e^- decay by 3.3 parts in 1000, -> CP violation.

<u>Consequences of CP violation</u>

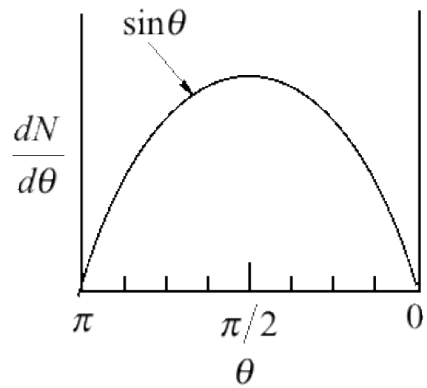
1. Makes absolute distinction of matter (e^-) from anti-matter (e^+).
2. Provides unambiguous definition of "positive" charge.
3. Since CPT is good symmetry, CP violation implies Time reversal symmetry (T) is also broken - though never seen.
4. May be responsible for matter-antimatter asymmetry in nature.

How to present angular data

- Differential solid angle: $d\Omega = \sin\theta d\theta d\phi = d(\cos\theta)d\phi$
- Isotropic distribution yields equal intensity in each solid angle element.



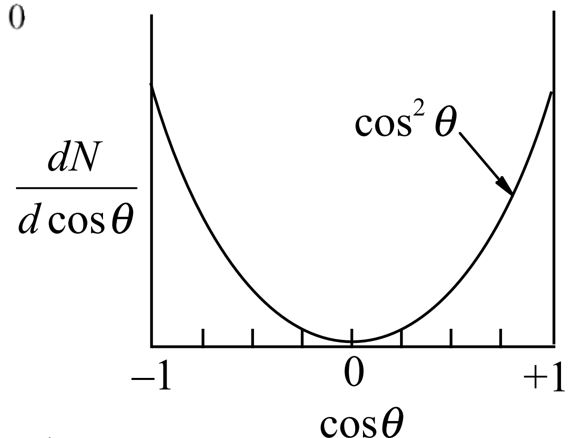
- Plotting a isotropic distribution vs θ does not yield a constant:



- *Rho* meson decay to 2 *pions*

$$\rho^0(J=1, J_z=0) \to \pi^+\pi^- \ \text{(both } J=0\text{)}$$

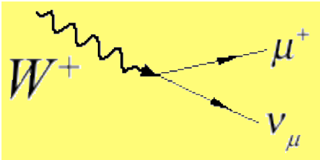
- Angular distribution: $\frac{d\sigma}{d\cos\theta} \sim |Y_{10}|^2 \sim \cos^2\theta$

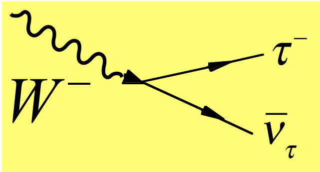


Actual data has some contributions from L=0,2 distorting the distribution

Weak interactions and W boson

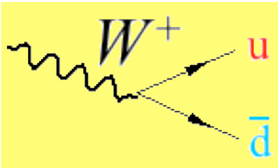
- Leptonic weak decays
  - quark color unchanged, W colorless
  - quark flavor change: e.g., d --> u
  - W^+ & W^- mediate flavor change
  - electron and antineutrino originate in W boson "decay"
- Given enough energy W can "decay" to
  - leptons heavier than an electron

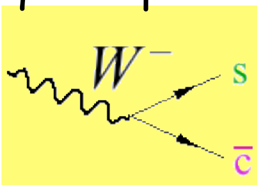




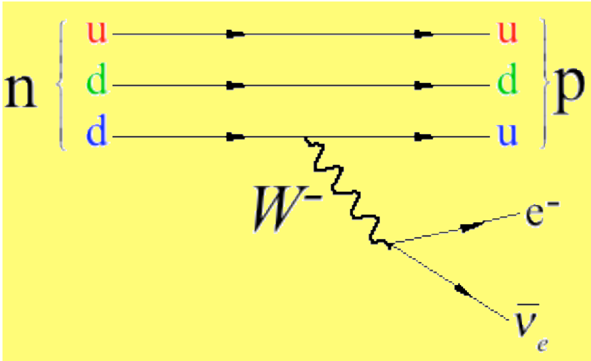
  - Hadrons, via colorless q q-bar pairs

Σ (quark charges)
= W charge



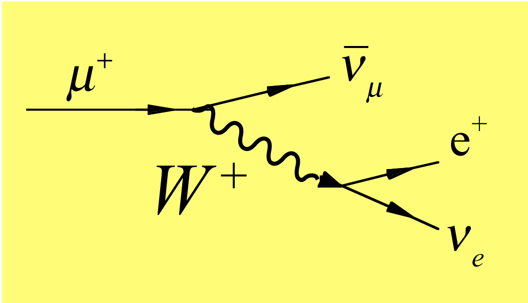


- Neutron β decay



$$n \rightarrow p + e^- + \bar{\nu}_e$$

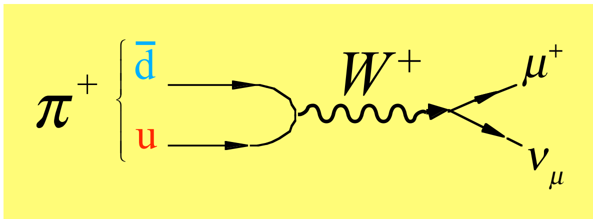
- Positive muon decay



$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

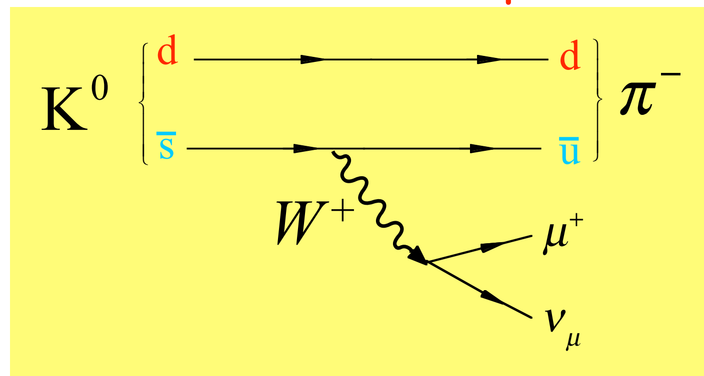
K^0 decays and the W boson

- π^+ meson leptonic decay



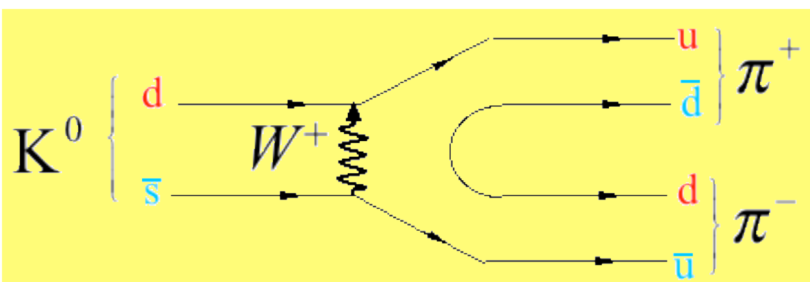
$$u \rightarrow d\left[W^+ \rightarrow \mu^+ + \nu_\mu\right]$$

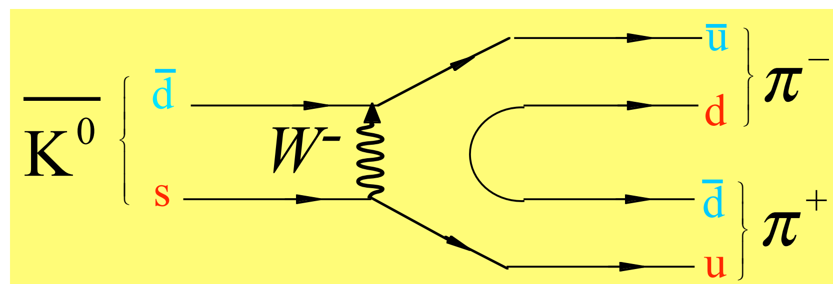
- K^0 meson semi-leptonic decay



$$\bar{s} \rightarrow \bar{u}\left[W^+ \rightarrow e^+ + \nu_e\right]$$

K^0 & $\overline{K^0}$ have hadronic decays to the same state $\pi^+ + \pi^-$

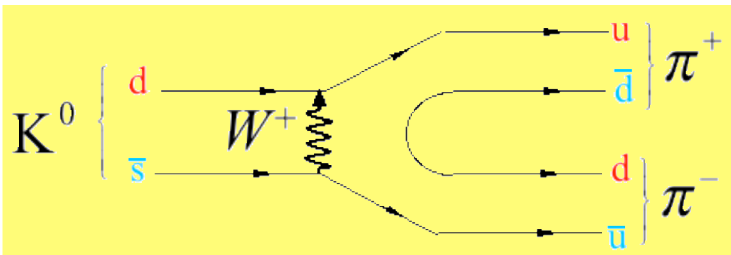


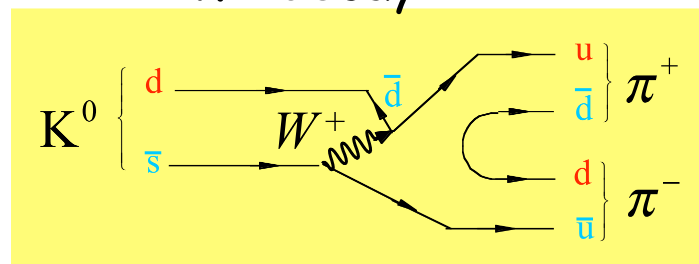


Why don't these diagrams look like the leptonic decay of W?

Feynman diagram wizardry

- W changes both quark flavors
- One quark flavor change + W "decay"





$K^0 \to \pi^+\pi^-$

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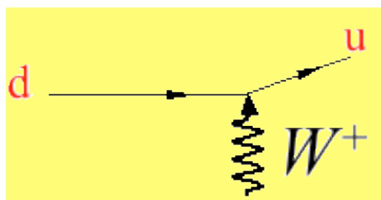
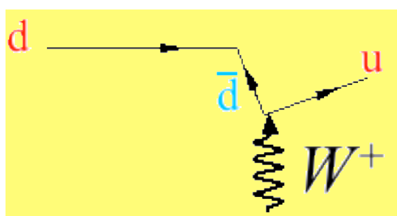
$d + W^+ \to u$



Quark "absorbs" a W and changes flavor

$W^+ \to \bar{d} + u$

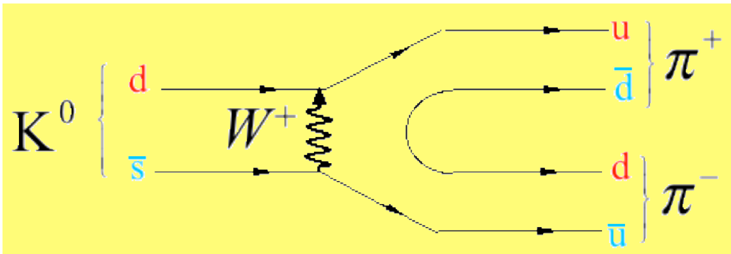


W "decay" with quark + anti-quark annihilation

Equivalent

- Changing direction of a quark line turns it into an anti-quark line

Weak interaction Feynman diagrams



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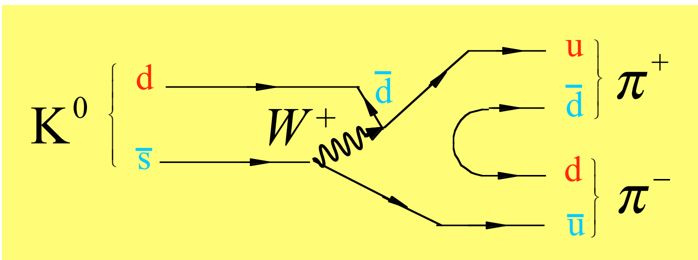

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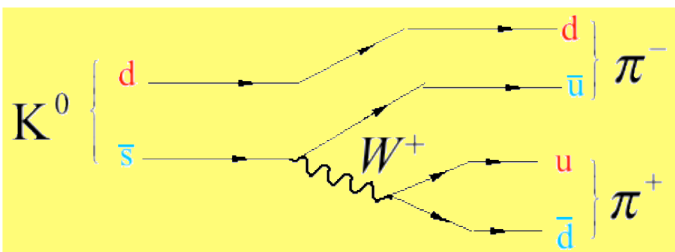

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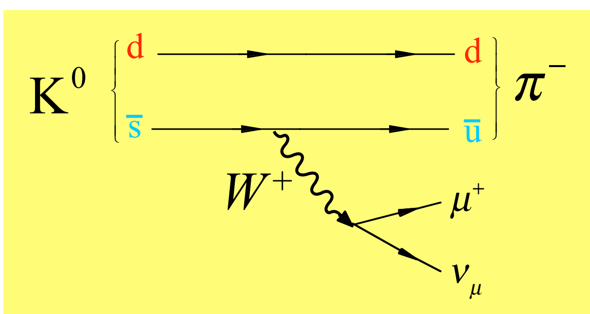

- One quark flavor change
  + W leptonic decay

K^0 & $\overline{K^0}$ mixing (review)

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$(\tau^+,\ \theta^+$ puzzle)

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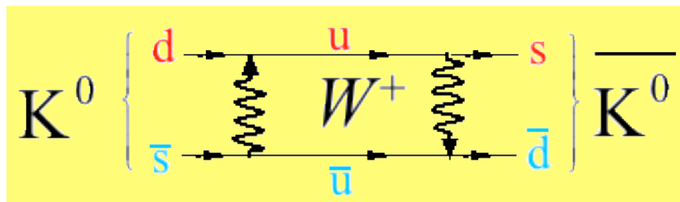

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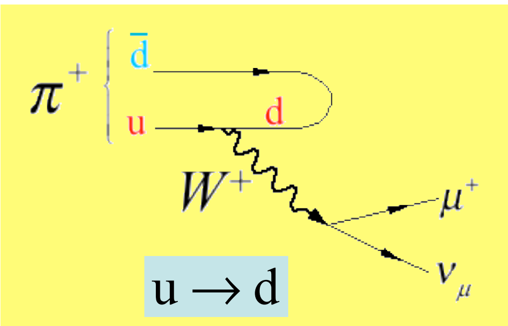
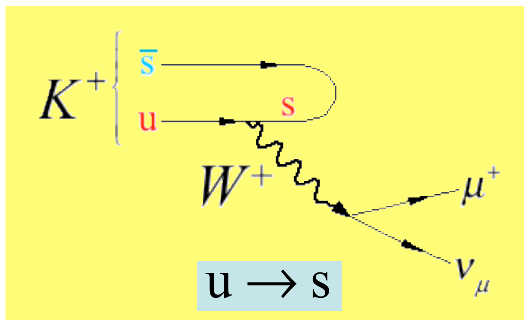
Mixing of quark generations

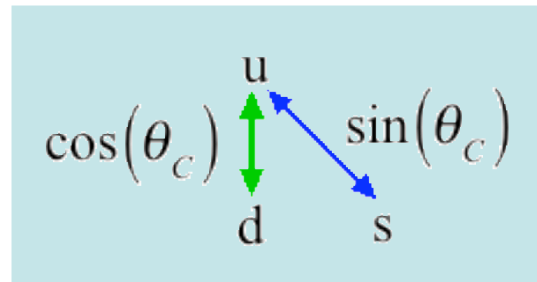
- Leptons don't cross generations (e, μ, τ)
- Cabibbo realizes an angle describes quark decays across generations
  - Cabibbo angle θ_C ~13° gives relative probability of u <--> d and u <--> s decays
  - Many decay rates explained by this angle. Example: meson leptonic decay.

	Generation		
Charge	1	2	3
+2/3	**u**	**c**	**t**
–1/3	**d**	**s**	**b**

Decays within a generation are favored over across generations







- π decay rate is proportional to $\cos^2(\theta_C)$
- K decay rate is proportional to $\sin^2(\theta_C)$
- Ratio of the rates: $\frac{\Gamma(K \to \mu\nu)}{\Gamma(\pi \to \mu\nu)} \sim \tan^2(\theta_c)$

with mass effect corrections, agreement is excellent

s/d quark mixing

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} \\ s \end{pmatrix} \to \begin{pmatrix} u \\ d \cdot \cos\theta_C + s \cdot \sin\theta_C \end{pmatrix}$$

strong interaction — weak interaction