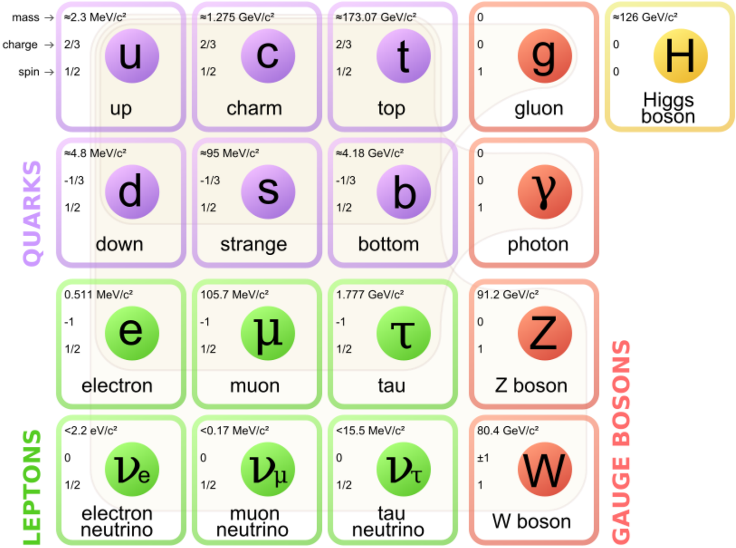
- SiLab Lecture Series -
Physics is Tops

Caleb Fangmeier

University of Nebraska - Lincoln

December 3, 2016

The Standard Model Today



The Standard Model Circa 1973

- Only discovered quarks were up, down, and strange
- Parity and charge have been discovered to be independently violated in

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

- So CP was proposed as the "real" mirror symmetry
- CP violation led to the proposal of a third generation of quarks

The Standard Model Circa 1973

- Only discovered quarks were up, down, and strange
- Parity and charge have been discovered to be independently violated in

$$\pi^+ \to \mu^+ + \nu_\mu$$

- So CP was proposed as the "real" mirror symmetry
- CP violation led to the proposal of a third generation of quarks

The Standard Model Circa 1973

- Only discovered quarks were up, down, and strange
- Parity and charge have been discovered to be independently violated in

$$\pi^+ \to \mu^+ + \nu_\mu$$

- So CP was proposed as the "real" mirror symmetry
- CP violation led to the proposal of a third generation of quarks

The Standard Model Circa 1973

- Only discovered quarks were up, down, and strange
- Parity and charge have been discovered to be independently violated in

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

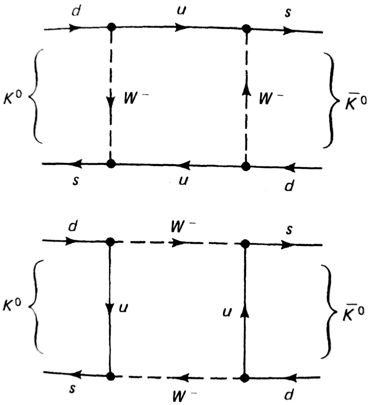
- So CP was proposed as the "real" mirror symmetry
- CP violation led to the proposal of a third generation of quarks

The Neutral Kaon

- K^0 are produced via strong iteractions with definite quark flavour content.
- However, certain diagrams allow for $K^0 \rightleftharpoons \overline{K}^0$ mixing
- The result is that Kaons evolve into superpositions of K^0 and $\overline{K}^0$

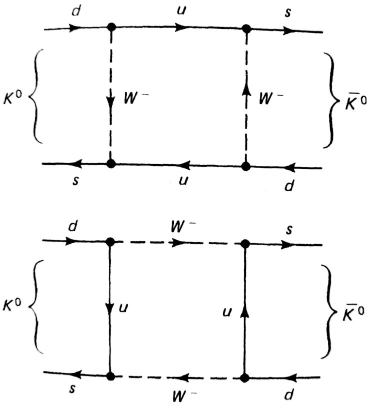
The Neutral Kaon

- K^0 are produced via strong iteractions with definite quark flavour content.
- However, certain diagrams allow for $K^0 \rightleftharpoons \overline{K^0}$ mixing
- The result is that Kaons evolve into superpositions of K^0 and $\overline{K^0}$



The Neutral Kaon

- K^0 are produced via strong iteractions with definite quark flavour content.
- However, certain diagrams allow for $K^0 \rightleftharpoons \overline{K}^0$ mixing
- The result is that Kaons evolve into superpositions of K^0 and $\overline{K}^0$



The Neutral Kaon - CP Eigenstates

- If CP is a symmetry of nature, we can form eigenstates of CP in the $|K^0\rangle, |\overline{K^0}\rangle$ system.
- The action of C,P, and CP on these states is:

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

- Two eigenstates of CP can be formed.

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

The Neutral Kaon - CP Eigenstates

- If CP is a symmetry of nature, we can form eigenstates of CP in the $|K^0\rangle, |\overline{K}^0\rangle$ system.
- The action of C,P, and CP on these states is:

$$
\begin{aligned}
C\,|K^0\rangle &= |\overline{K}^0\rangle & C\,|\overline{K}^0\rangle &= |K^0\rangle \\
P\,|K^0\rangle &= -\,|K^0\rangle & P\,|\overline{K}^0\rangle &= -\,|\overline{K}^0\rangle \\
CP\,|K^0\rangle &= -\,|\overline{K}^0\rangle & CP\,|\overline{K}^0\rangle &= -\,|K^0\rangle
\end{aligned}
$$

- Two eigenstates of CP can be formed.

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

The Neutral Kaon - CP Eigenstates

- If CP is a symmetry of nature, we can form eigenstates of CP in the $|K^0\rangle, |\bar{K^0}\rangle$ system.
- The action of C,P, and CP on these states is:

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

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

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

- Two eigenstates of CP can be formed.

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

The Neutral Kaon - CP Eigenstates

- If CP is a symmetry of nature, we can form eigenstates of CP in the $|K^0\rangle, |\bar{K^0}\rangle$ system.
- The action of C,P, and CP on these states is:

$$
\begin{aligned}
C|K^0\rangle &= |\bar{K^0}\rangle & C|\bar{K^0}\rangle &= |K^0\rangle \\
P|K^0\rangle &= -|K^0\rangle & P|\bar{K^0}\rangle &= -|\bar{K^0}\rangle \\
CP|K^0\rangle &= -|\bar{K^0}\rangle & CP|\bar{K^0}\rangle &= -|K^0\rangle
\end{aligned}
$$

- Two eigenstates of CP can be formed.

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

The Neutral Kaon - CP Eigenstates

- If CP is a symmetry of nature, we can form eigenstates of CP in the $|K^0\rangle, |\bar{K^0}\rangle$ system.
- The action of C,P, and CP on these states is:

$$
\begin{aligned}
C|K^0\rangle &= |\bar{K^0}\rangle & C|\bar{K^0}\rangle &= |K^0\rangle \\
P|K^0\rangle &= -|K^0\rangle & P|\bar{K^0}\rangle &= -|\bar{K^0}\rangle \\
CP|K^0\rangle &= -|\bar{K^0}\rangle & CP|\bar{K^0}\rangle &= -|K^0\rangle
\end{aligned}
$$

- Two eigenstates of CP can be formed.

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

The Neutral Kaon - Allowed Decays

- If the weak interaction conserves CP, then $|K_1\rangle$ can only decay into states with $CP = 1$ and $|K_2\rangle$ only to states with $CP = -1$.
- For example,

$$K_1 \rightarrow 2\pi \qquad K_2 \rightarrow 3\pi \qquad \text{Allowed}$$

$$K_1 \rightarrow 3\pi \qquad K_2 \rightarrow 2\pi \qquad \text{Forbidden}$$

The Neutral Kaon - Allowed Decays

- If the weak interaction conserves CP, then $|K_1\rangle$ can only decay into states with $CP = 1$ and $|K_2\rangle$ only to states with $CP = -1$.
- For example,

$$K_1 \rightarrow 2\pi$$
$$K_2 \rightarrow 3\pi$$

Allowed

$$K_1 \rightarrow 3\pi$$
$$K_2 \rightarrow 2\pi$$

Forbidden

The Neutral Kaon - CP Violation

- Furthermore, since the $K_1 \to 2\pi$ process happens much more quickly, the K_1 component of the superposition

$$|\Psi\rangle = \alpha\,|K_1\rangle + \beta\,|K_2\rangle$$

quickly disappears, leaving only

$$|\Psi\rangle = |K_2\rangle$$

- So a beam of neutral kaons consists of only a tiny fraction of K_1 after a few meters.
- If the "forbidden" process $K_2 \to 2\pi$ is observed down the beamline, it means that CP is not a true symmetry.

The Neutral Kaon - CP Violation

- Furthermore, since the $K_1 \to 2\pi$ process happens much more quickly, the K_1 component of the superposition

$$|\Psi\rangle = \alpha\,|K_1\rangle + \beta\,|K_2\rangle$$

quickly disappears, leaving only

$$|\Psi\rangle = |K_2\rangle$$

- So a beam of neutral kaons consists of only a tiny fraction of K_1 after a few meters.
- If the "forbidden" process $K_2 \to 2\pi$ is observed down the beamline, it means that CP is not a true symmetry.

The Neutral Kaon - CP Violation

- Furthermore, since the $K_1 \to 2\pi$ process happens much more quickly, the K_1 component of the superposition

$$|\Psi\rangle = \alpha\,|K_1\rangle + \beta\,|K_2\rangle$$

quickly disappears, leaving only

$$|\Psi\rangle = |K_2\rangle$$

- So a beam of neutral kaons consists of only a tiny fraction of K_1 after a few meters.
- If the "forbidden" process $K_2 \to 2\pi$ is observed down the beamline, it means that CP is not a true symmetry.

CP Violation

- CP Violation posed a theoretical problem with only two quark generations.
- The weak eigenstates of the down type quarkes are related to the flavor eigenstates via the Cabibbo angle θ_C.
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$
- But because the matrix elements are strictly real, CP is still conserved.

CP Violation

- However, with three quark generations there is instead this relation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Notice that the presence of δ means that some elements are necessarily complex, allowing for CP violation.
- This motivated the prediction of a third quark generation. (Note that this was even before the discovery of the charm)

- However, with three quark generations there is instead this relation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Notice that the presence of δ means that some elements are necessarily complex, allowing for CP violation.
- This motivated the prediction of a third quark generation. (Note that this was even before the discovery of the charm)

CP Violation

- However, with three quark generations there is instead this relation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Notice that the presence of δ means that some elements are necessarily complex, allowing for CP violation.
- This motivated the prediction of a third quark generation. (Note that this was even before the discovery of the charm)

References