Outline

- Introduction to the Standard Model
- Brief history of Particle Physics
- Work of Kobayashi
- Experimental Confirmation
- Lepton Flavor Mixing
Introduction

- Matter
  - $e^-, p^+, n$
- Standard Model
  - 6 quarks, six leptons, fundamental interactions
- Comprehensive model for the elementary interactions of particle physics
Standard Model

- Established in the 1970's
- Describes how particles interact via the strong and electroweak forces
- Does not incorporate general relativity and dark matter
History

- Studied under Professor Shiochi Sakata and the Particle Physics group at Nagoya University
  - All 3 Nobel laureates from 2008 studied under Sakata
- Work of Sakata
  - Sakata Model - precursor to Quark model
Developments

- **1950’s**- many new and strange particles discovered
  - “explosion” of particles
- **1956**- Sakata Model
  - Hadrons are composite particles of triplets of $p$, $n$, $\Lambda$
- **1962**- discovered 2$^{nd}$ neutrino
  - Sakata presented MNS matrix
  - 1$^{st}$ quantitative theory of neutrino oscillation
Six Quark Model

- CP violation discovered in 1964 in decay of $K^0$ meson
- CP violation - violation of conservation laws associated with charge and parity
  - Violation of symmetry between particles and their anti-particles
  - No realistic explanation for CP violation with 3 or 4 quarks
Six Quark Model

- Models with 3 or 4 quarks don’t work!!
- Kobayashi proposed the 6 quark model
  - One possible solution to the problem
  - Predicted the existence of unknown particles
- Gauge Theory allows for flavor mixing
  - Have properties in which different configurations of an unobservable field result in identical quantities
    - Ex: can’t measure EM field but can measure charge, energy, etc.
  - Flavor mixing is a superposition of states
Six Quark Model

- Particles are lumped into groups and can sometimes be a superposition of states
  - Irreducible complex #’s represent flavor mixing
    - \[
    \begin{pmatrix}
    u \\
    d'
    \end{pmatrix} \begin{pmatrix}
    c \\
    s'
    \end{pmatrix} \begin{pmatrix}
    t \\
    b'
    \end{pmatrix} \approx \begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
    \end{pmatrix} \begin{pmatrix}
    d' \\
    s' \\
    b'
    \end{pmatrix} = \begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
    \end{pmatrix} \begin{pmatrix}
    d \\
    s \\
    b
    \end{pmatrix}
    \]
  - At the time, other proposed models had this same property
Six Quark Model

- 1974- $J/\psi$ discovered
  - Bound state of the $c$, anti-$c$ quarks
- 1975- $\tau$ lepton discovered
  - Suggested there should be a third family of quarks
- 1977- Upsilon particle discovered
  - Bound state of 5$^{th}$ quark, the b and anti-b
- 1995- t quark discovered
  - 6$^{th}$ and final quark
Experimental Confirmation

- **B-factories**
  - Accelerator that produces B-mesons
    - Pairs of quarks with either a b or anti-b quark
- **Prediction of large asymmetry between b and anti-b**
  - Find decay time by measuring its position by using a vertex detector
- **KEKB in Japan and PEPII at SLAC**
  - Great luminosities
  - Friendly competition
Experimental Results

- Colored circle show experimental constraints
- All overlap in one small region, colored red
- Can choose parameters in this region only
- 6 quark model explains all the results for parameters in this region
Results

- Quark mixing primary source of CP violation!!
  - Found an asymmetry between b and anti-b decays
- Room for new physics beyond standard model
- Need additional source of CP violation
  - Not enough to account for matter anti-matter asymmetry
- Lepton Flavor mixing
Lepton Flavor Mixing

- Super Kamiokande
  - Consistent with neutrino oscillation predictions
- KAMLand
  - Same observations
- Future experiments
  - T2K - similar to K2K but with higher intensities
  - $\nu_\mu \rightarrow \nu_e$ oscillations
- Crucial for estimating size of CP violation from leptons
Experimental Results

K2K Data ($\nu_\mu$)  KAMLand Data ($\nu_e$)
Conclusions

- 3 and 4 quark models did not allow for CP violation
- 6 quark model proposed by Kobayashi accounted for this
  - Experimental evidence to back it up
  - Particles that were discovered and from B-factories
- Need another source of CP violation
  - Lepton flavor mixing
- Hints of this from experiments already but more work is needed to be done
References