CP Violation and Flavor Mixing

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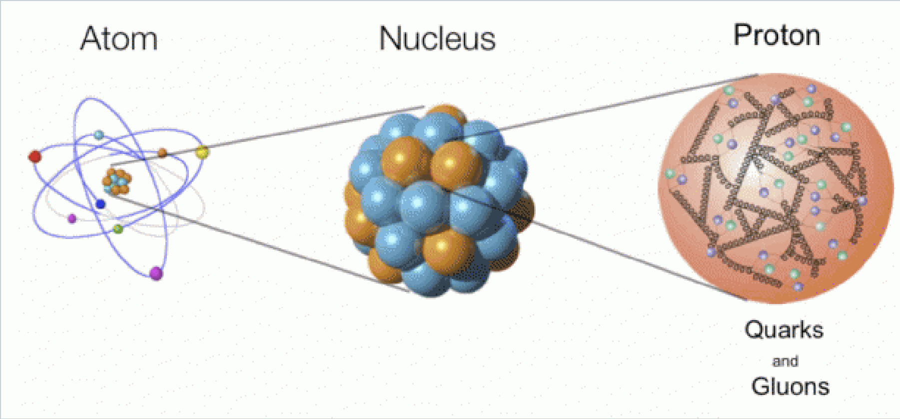
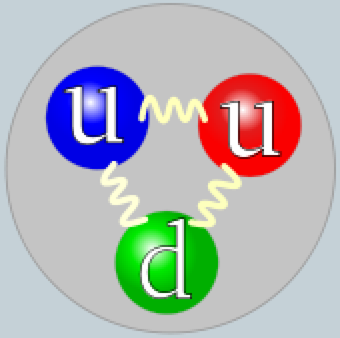
Outline

- 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



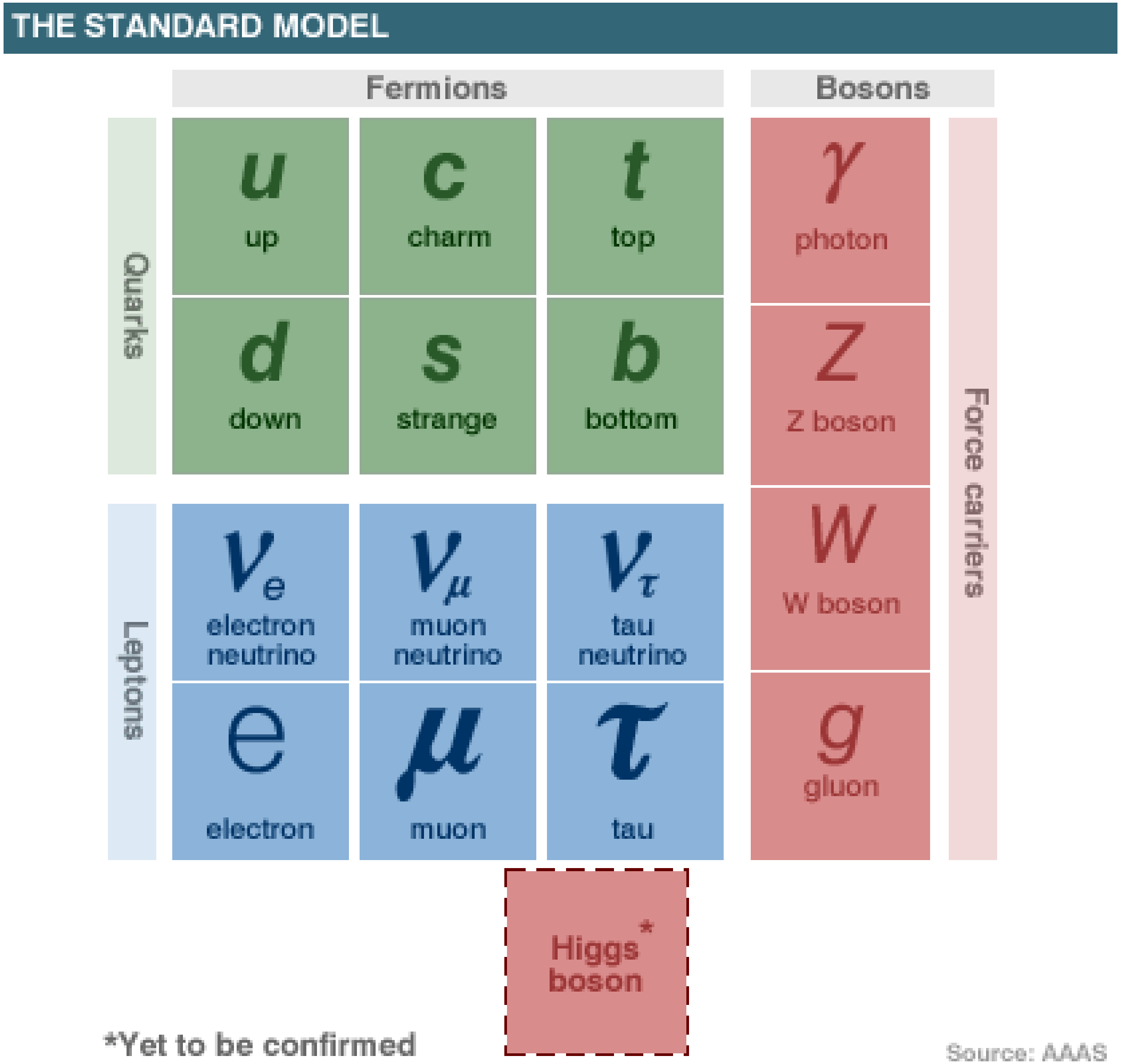


Standard Model

-Established in the 1970's

- Describes how particles interact via the strong and electroweak forces

- Does not incorporate general relativity and dark matter

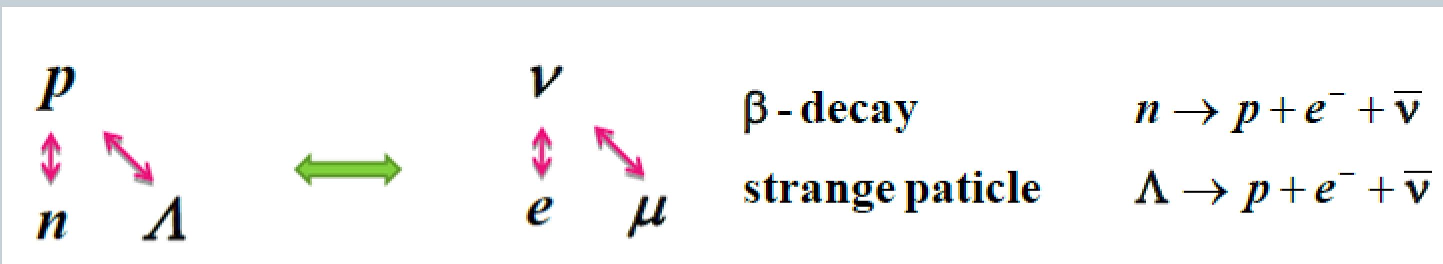


History

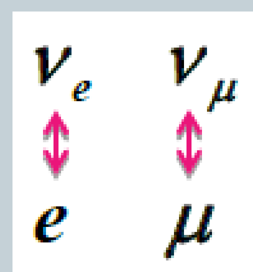
- Studied under Professor Shiochi Sakata and the Particle Physics group at Nagoya University
  - All 3 Nobel laureates from 2008 studied under Sakata
- Work of Sakata
  - Sakata Model- precursor to Quark model

Developments

- 1950's- many new and strange particles discovered
  - "explosion" of particles
- 1956- Sakata Model
  - Hadrons are composite particles of triplets of p, n, Λ

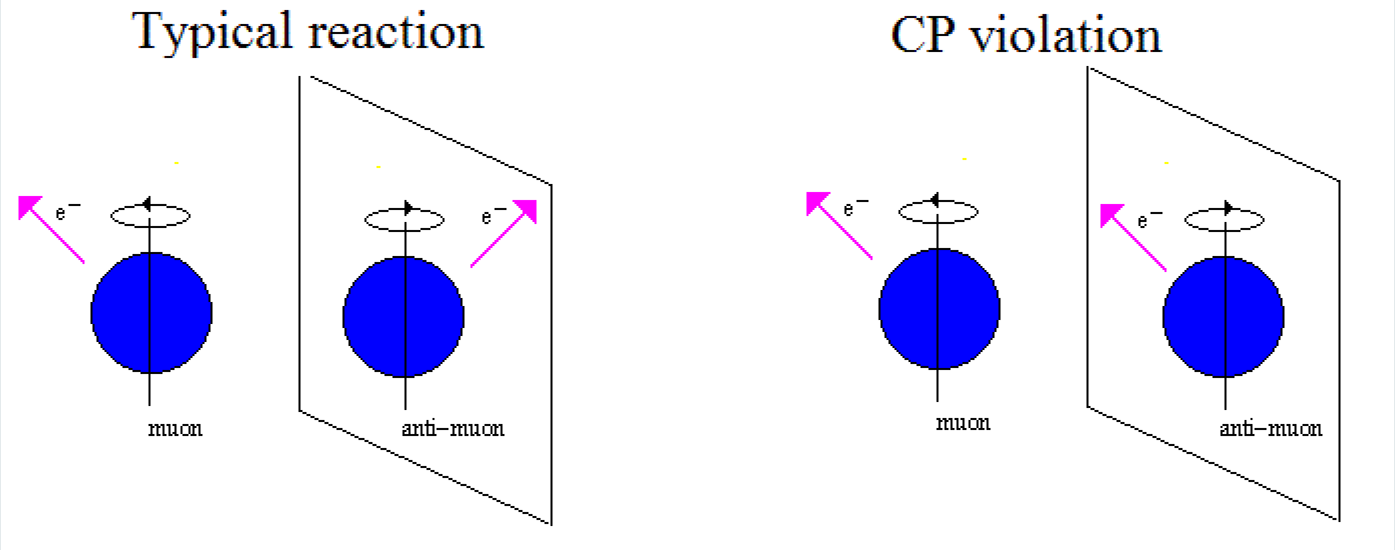


- 1962- discovered 2nd neutrino
  - Sakata presented MNS matrix
  - 1st quantitative theory of neutrino oscillation



Six Quark Model

- CP violation discovered in 1964 in decay of K^o 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

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

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

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

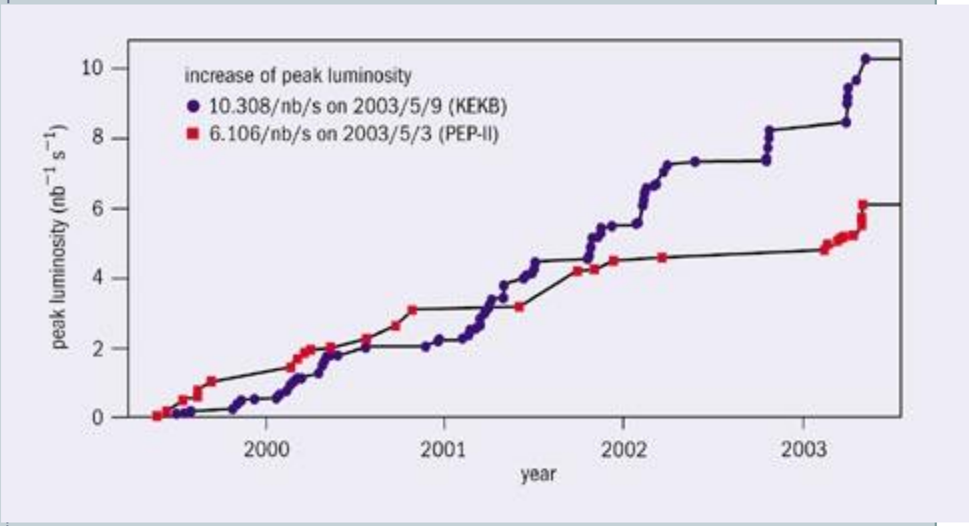
  - At the time, other proposed models had this same property

Six Quark Model

- 1974- J/ψ discovered
  - Bound state of the c, anti-c quarks
- 1975- τ 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



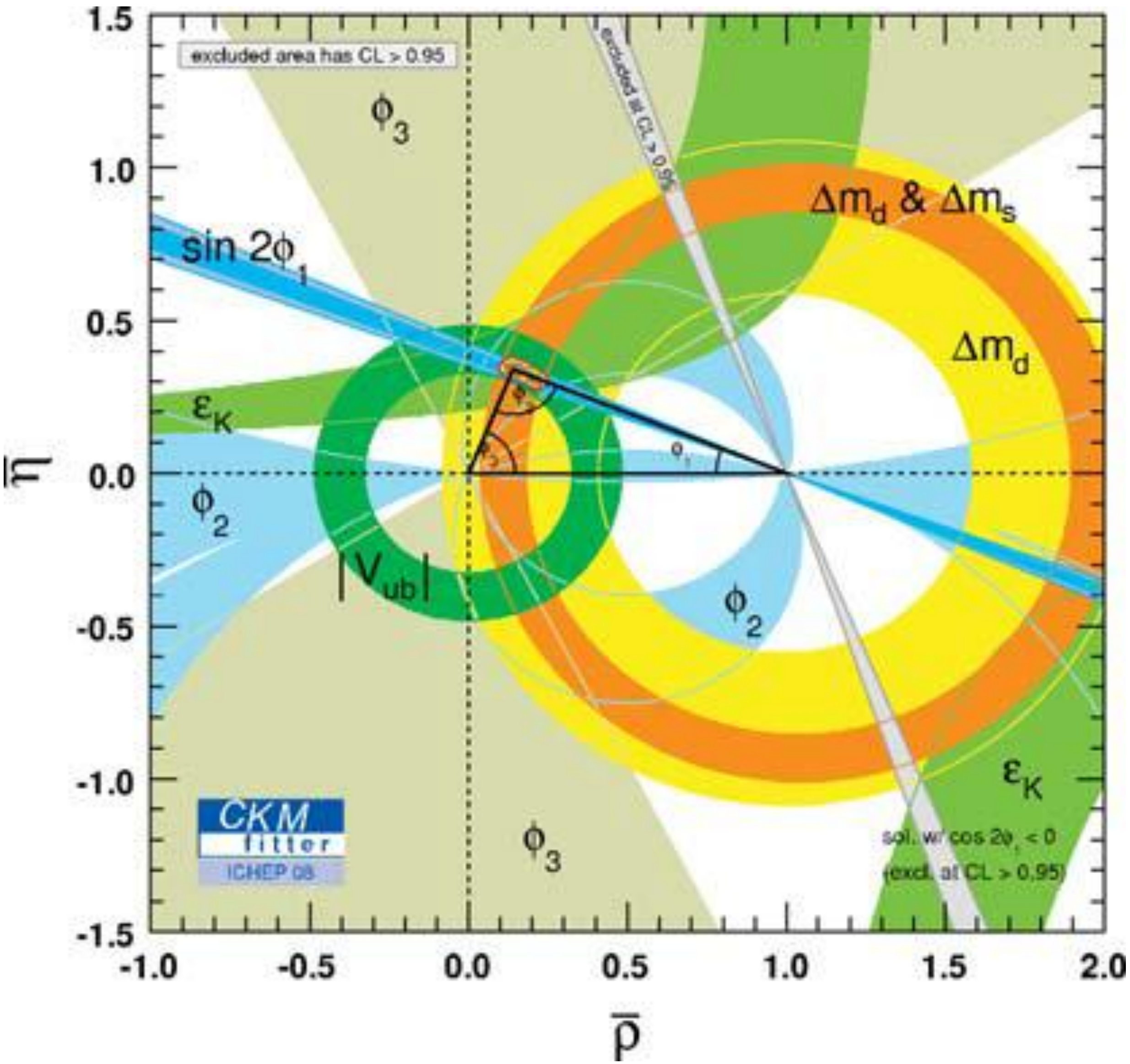
Experimental Results

-Colored circle show experimental constraints

-All overlap in one small region, colored red

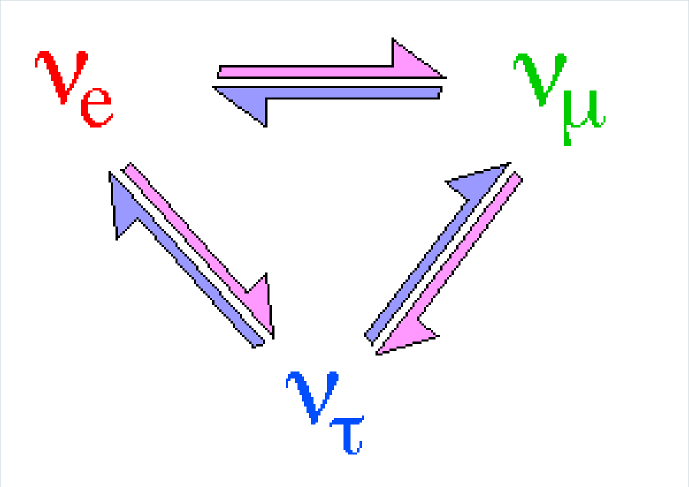
-Can choose parameters in this region only

-6 quark model explains all the results for parameters in this region



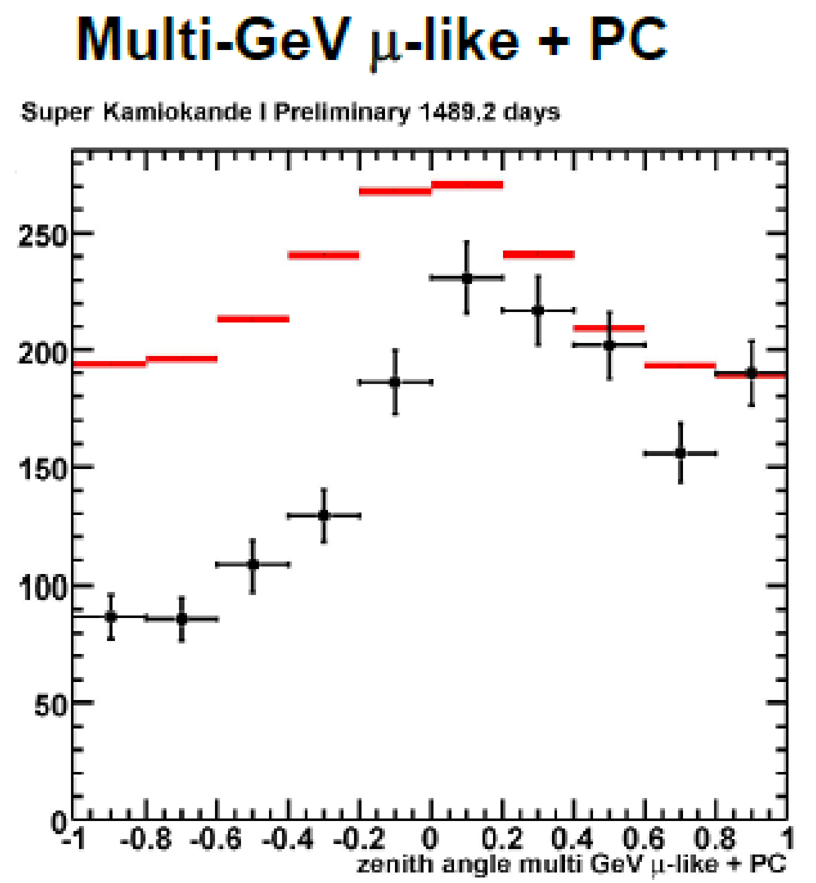
Results

- 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

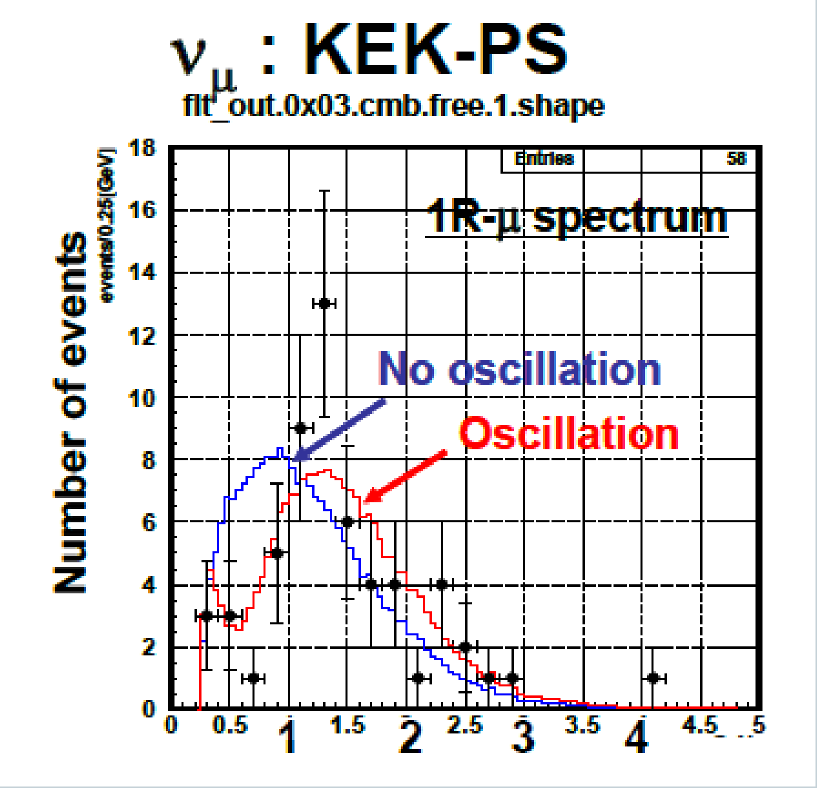
- Super Kamiokande
  - Consistent with neutrino oscillation predictions
- KAMLand
  - Same observations
- Future experiments
  - T2K- similar to K2K but with higher intensities
  - $\nu_\mu \longrightarrow \nu_e$ oscillations
- Crucial for estimating size of CP violation from leptons



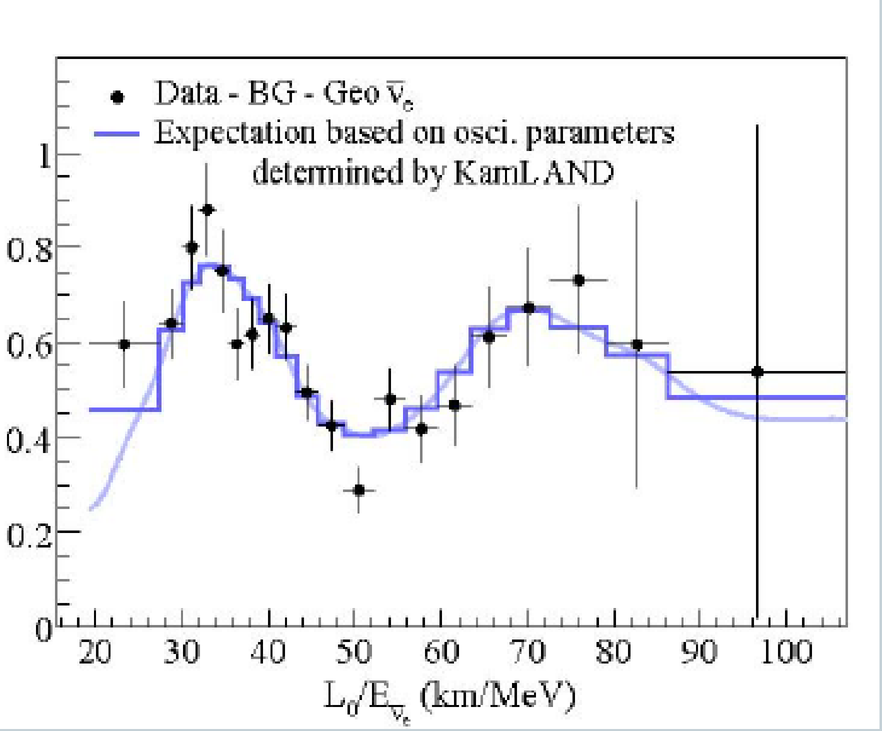
J.Raaf, Talk at Neutrino 2008

Experimental Results

K2K Data (ν_μ)



KAMLand Data (ν_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

- "Makoto Kobayashi - Nobel Lecture". Nobelprize.org. 8 Sep 2011 http://www.nobelprize.org/nobel_prizes/physics/laureates/2008/kobayashi-lecture.html
- Kobayashi, Makoto, and Toshihide Maskawa, "CP-Violation in the Renormalizable Theory of Weak Interaction." *Progress of Theoretical Physics,* Vol. 49, No. 2, February 1973. 652-57.