

CP Violation and Flavor Mixing

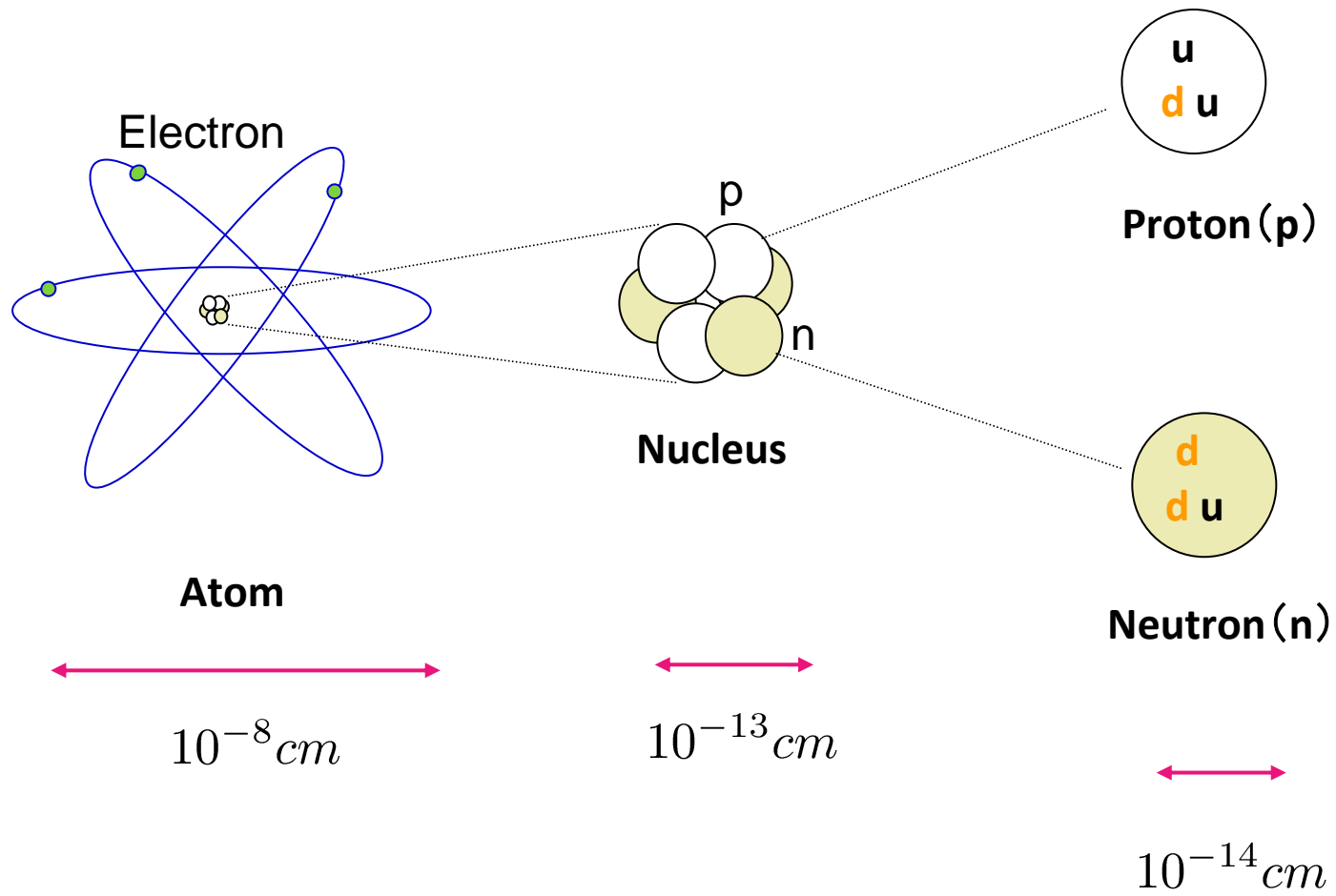
Makoto Kobayashi

KEK and JSPS

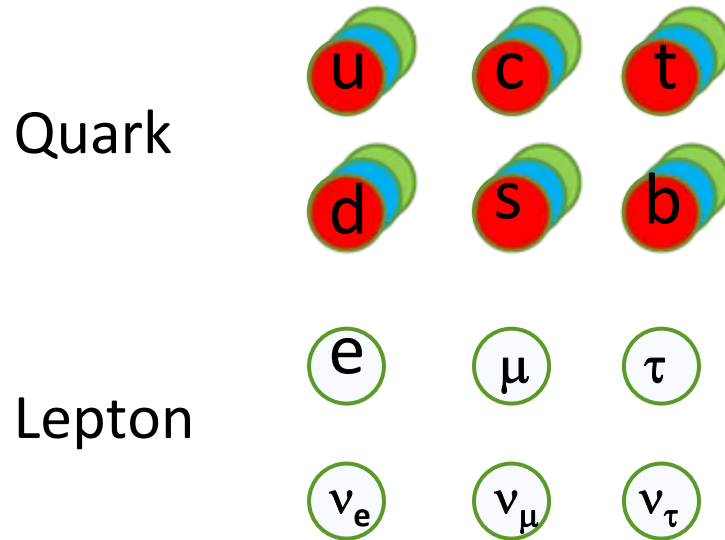
Plan

- 1. Introduction to the Standard Model**
- 2. Sakata and His Group**
- 3. The CP Paper with Maskawa**
- 4. Experimental Verification at B-factories**
- 5. Lepton Flavor Mixing**

Introduction to the Standard Model



Fundamental Particles



Fundamental Interactions

- Strong Interaction
- Electro-Magnetic Interaction
- Weak Interaction

QCD

Weinberg-Salam-Glashow Theory

Established in 1970's

- Development of gauge theory 1971 't Hooft

Electro-Magnetic Interaction

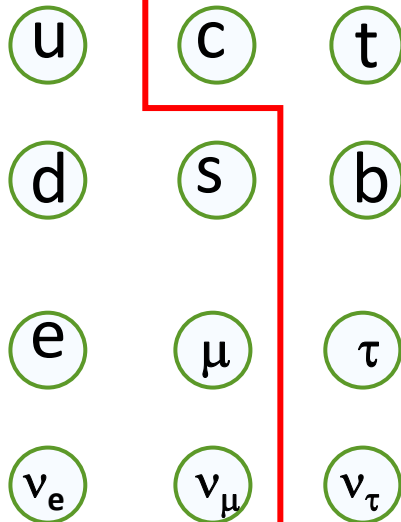
Strong Interaction

Weak Interaction

- Discoveries of new flavors

1964 Gell-Mann
quark model

u, d, s



After 1970

1973

Kobayashi Maskawa
Six-Quark Model

1947~ Discovery of Strange Particles

Hadron : strongly interacting particle

p n $\pi^{\pm 0}$ Λ

Λ $\Sigma^{\pm 0}$ Ξ K^{\pm} K^0 Λ

Strange Particles



Courtesy of Sakata Memorial Archival Library

Shoichi Sakata
1911-1970

1956 Sakata Sakata Model

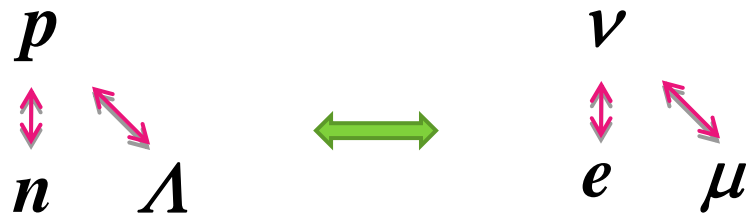
All the hadrons are composite states of

p, n, Λ : Fundamental Triplet

Weak Interaction in the Sakata Model

$$\beta\text{-decay} \quad n \rightarrow p + e^{-} + \bar{\nu}$$

$$\text{strange particle} \quad \Lambda \rightarrow p + e^{-} + \bar{\nu}$$



1959 Gamba, Marshak, Okubo
B-L Symmetry

1960 Maki, Nakagawa, Ohnuki, Sakata

Nagoya Model :

$$p = \langle B^+ \nu \rangle, n = \langle B^+ e \rangle, \Lambda = \langle B^+ \mu \rangle$$

1962 Discovery of Two Neutrinos

$$\begin{array}{cc}
 \nu_e & \nu_\mu \\
 \updownarrow & \updownarrow \\
 e & \mu
 \end{array}$$

Lepton Flavor Mixing
MNS Matrix

1962 Maki, Nakagawa, Sakata

$$p = \langle B^+ \nu_1 \rangle, \quad n = \langle B^+ e \rangle, \quad \Lambda = \langle B^+ \mu \rangle, \quad p' = \langle B^+ \nu_2 \rangle$$

$$\nu_1 = \cos \theta \nu_e + \sin \theta \nu_\mu$$

$$\nu_2 = -\sin \theta \nu_e + \cos \theta \nu_\mu$$

→ Neutrino Oscillation

→ 4th Fundamental Particle (GIM scheme)

1962 Katayama, Matumoto, Tanaka, Yamada

Cosmic Ray Events

1971 Niu et al.

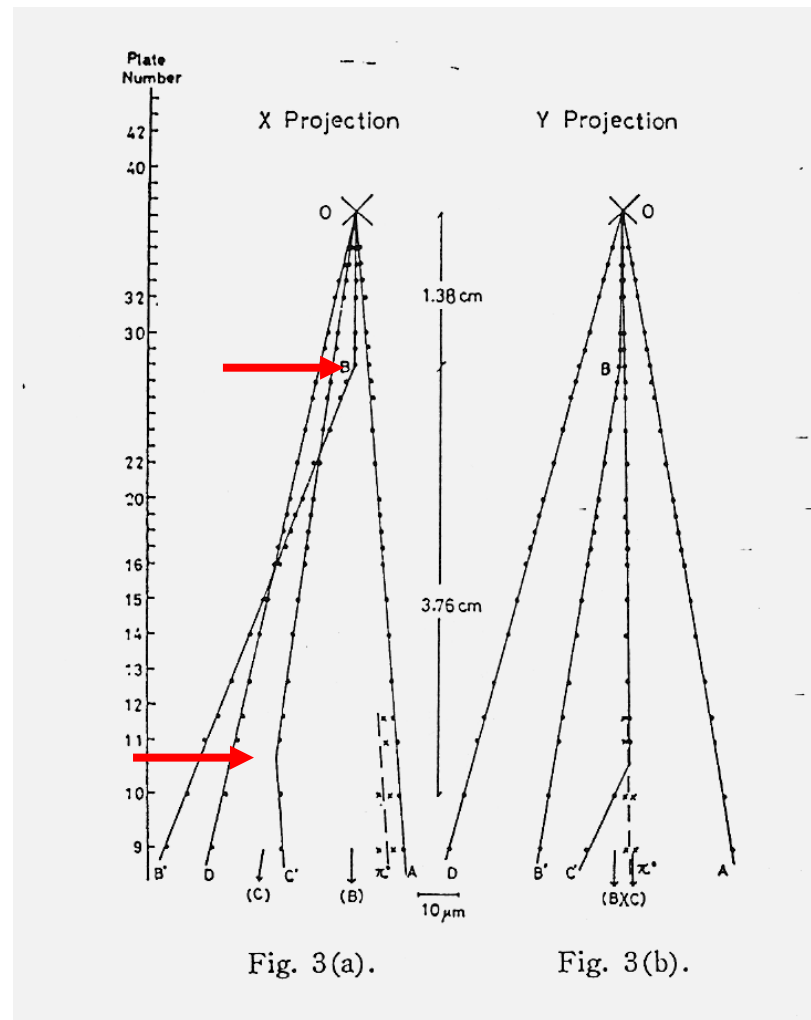
Evidence for the 4th element?



Some Japanese groups began to investigate the four-quark model

Emulsion Technique

- Applied to accelerator exp.
- Life time measurement of the new flavors



1971 't Hooft : Renormalization of Non-Abelian gauge theory

→ Renormalizable Electro-Weak Theory

(Weinberg-Salam-Glashow)

1973 Kobayashi, Maskawa

How to accommodate CP violation

CP Violation

1964 Cronin et al.

$$K_L \rightarrow \pi\pi$$

Essential difference
between particles
and anti-particles

What we found

- Not possible in four-quark models
- Existence of unknown particles
- A possible candidate is six-quark model

Flavor Mixing

Mismatch between gauge symmetry and particle spectra

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

CP Violation

Complex elements not removable by the phase convention

$$\begin{pmatrix} e^{-i\delta_u} & 0 \\ 0 & e^{-i\delta_c} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} e^{i\delta_d} & 0 \\ 0 & e^{i\delta_s} \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}$$

6-Quark Model

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

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

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

- An imaginary number parameter violates CP

- 1974 Discovery of J/ψ \longrightarrow c-quark
- 1975 Discovery of τ -lepton

1975 S. Pakvasa, H. Sugawara

1976 J.R Ellis, M-K Gaillard, D. Nanopoulos

- 1977 Discovery of Y \longrightarrow b-quark
- 1995 Discovery of t-quark

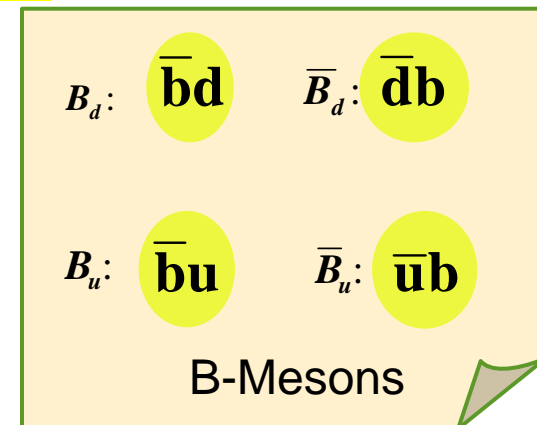
Large CP violation in the B-meson system

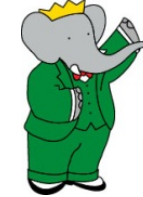
1980 Carter, Sanda

1981 Bigi, Sanda



B-Factory





KEKB/Belle (Japan)

PEP-II/BaBar (US)

$E(e^-)=8\text{GeV}$,
 $E(e^+)=3.5\text{GeV}$
Finite angle beam crossing

Feature

$E(e^-)=9\text{GeV}$,
 $E(e^+)=3.1\text{GeV}$
Zero angle beam crossing

1994

Governmental Approval

1993

May 1999 –
still running

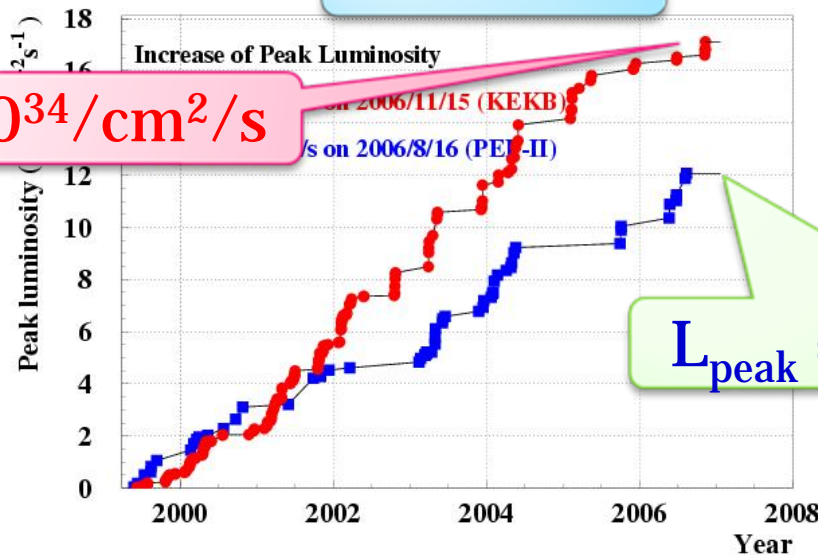
Experiment

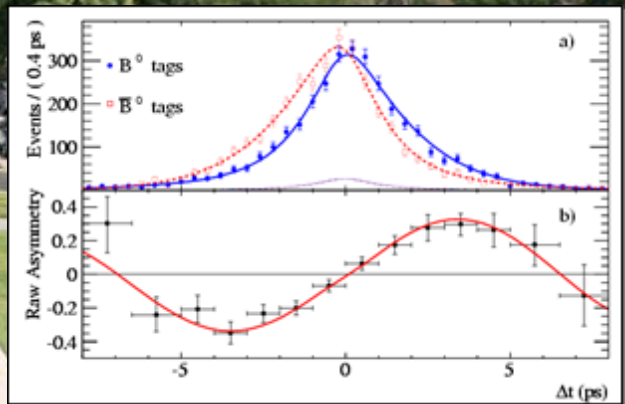
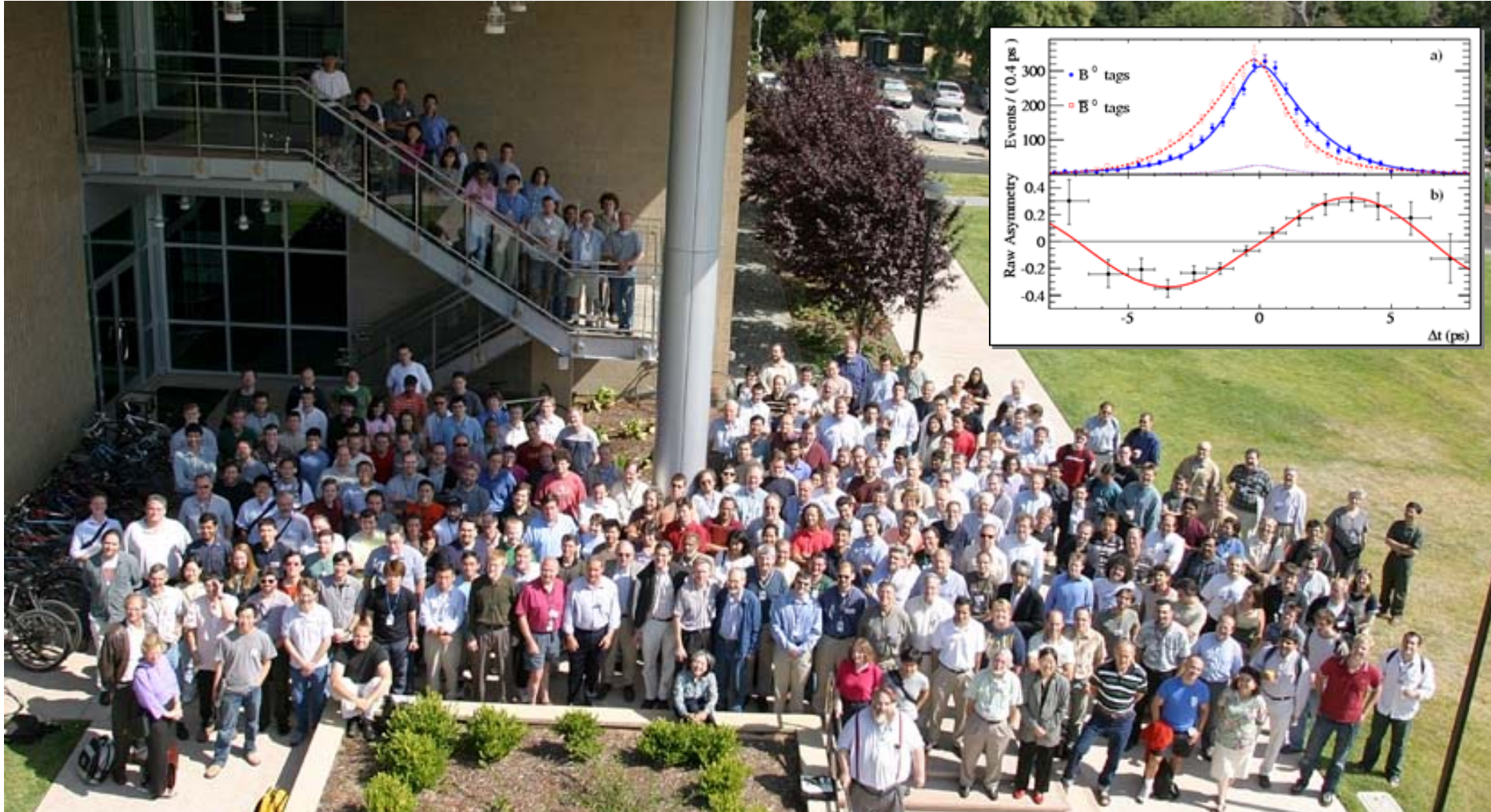
May 1999 –
Apr. 2008

$L_{\text{peak}} = 1.7 \times 10^{34} / \text{cm}^2 / \text{s}$

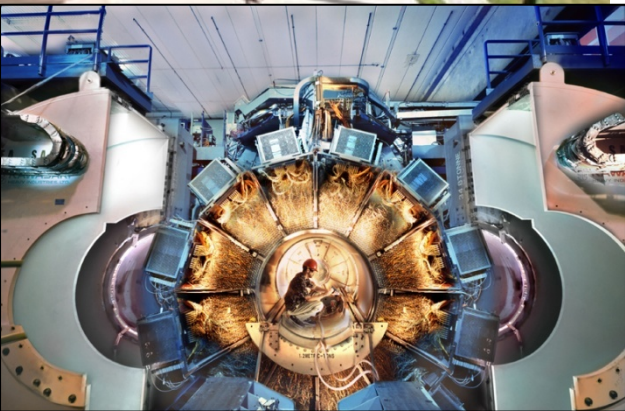
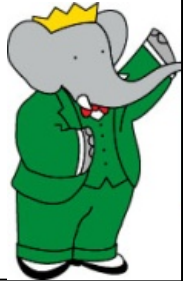
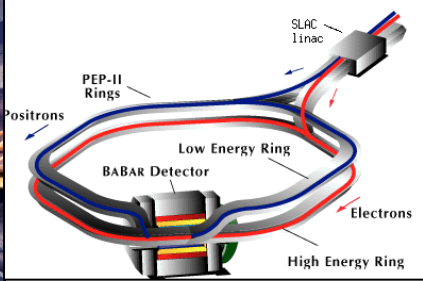
Friendly competition of two experiments over a decade

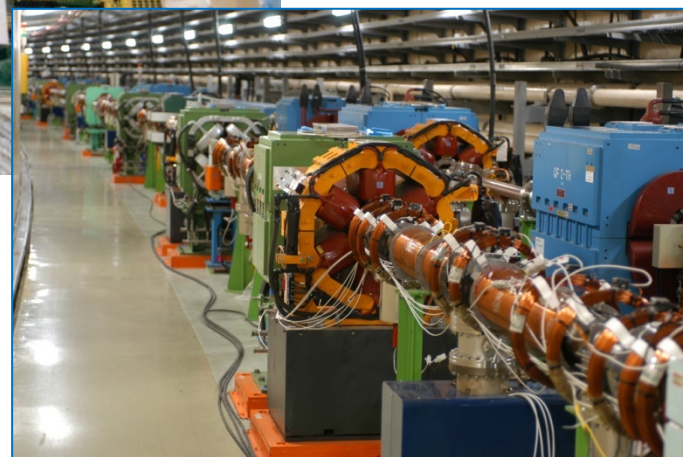
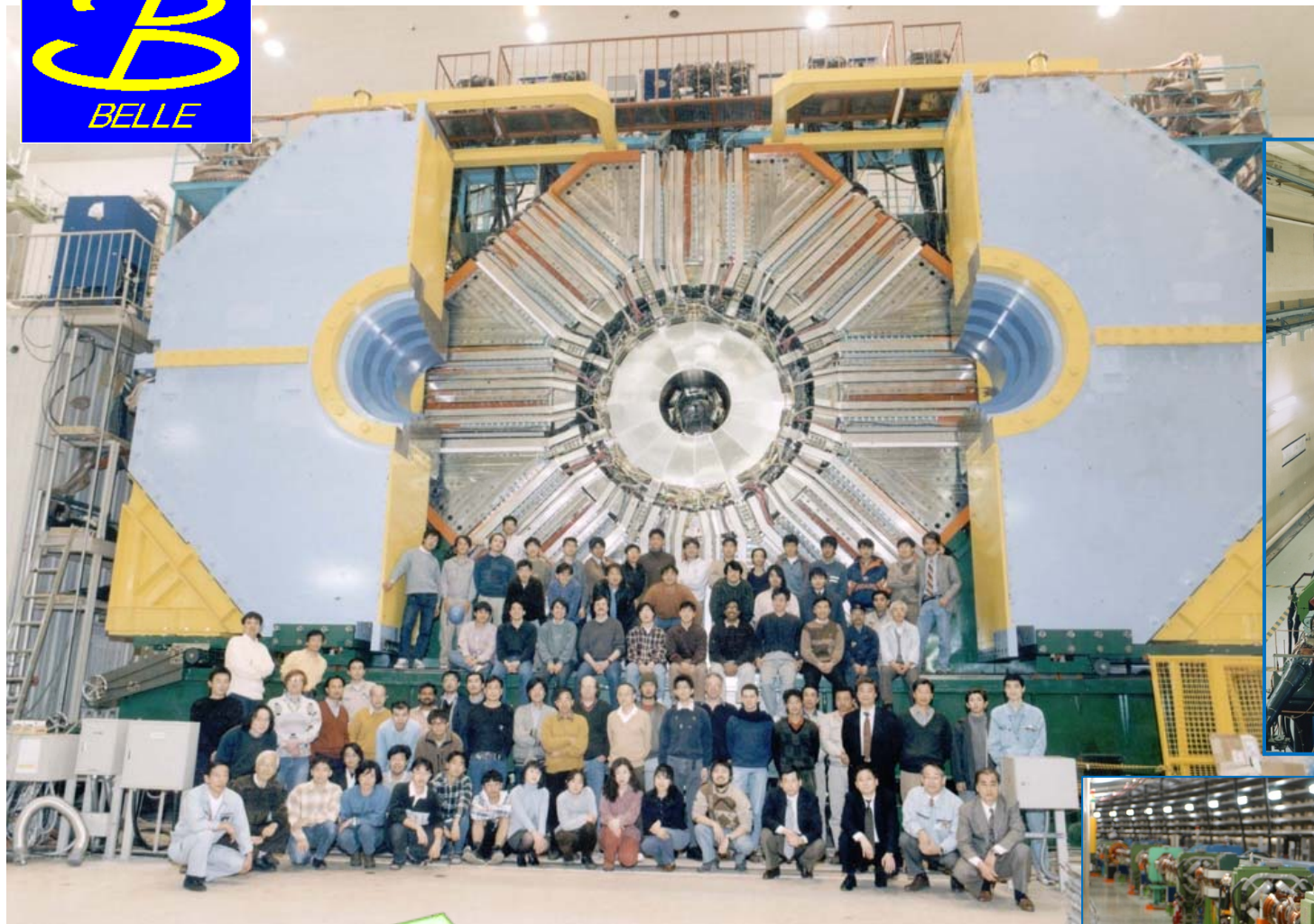
$L_{\text{peak}} = 1.2 \times 10^{34} / \text{cm}^2 / \text{s}$





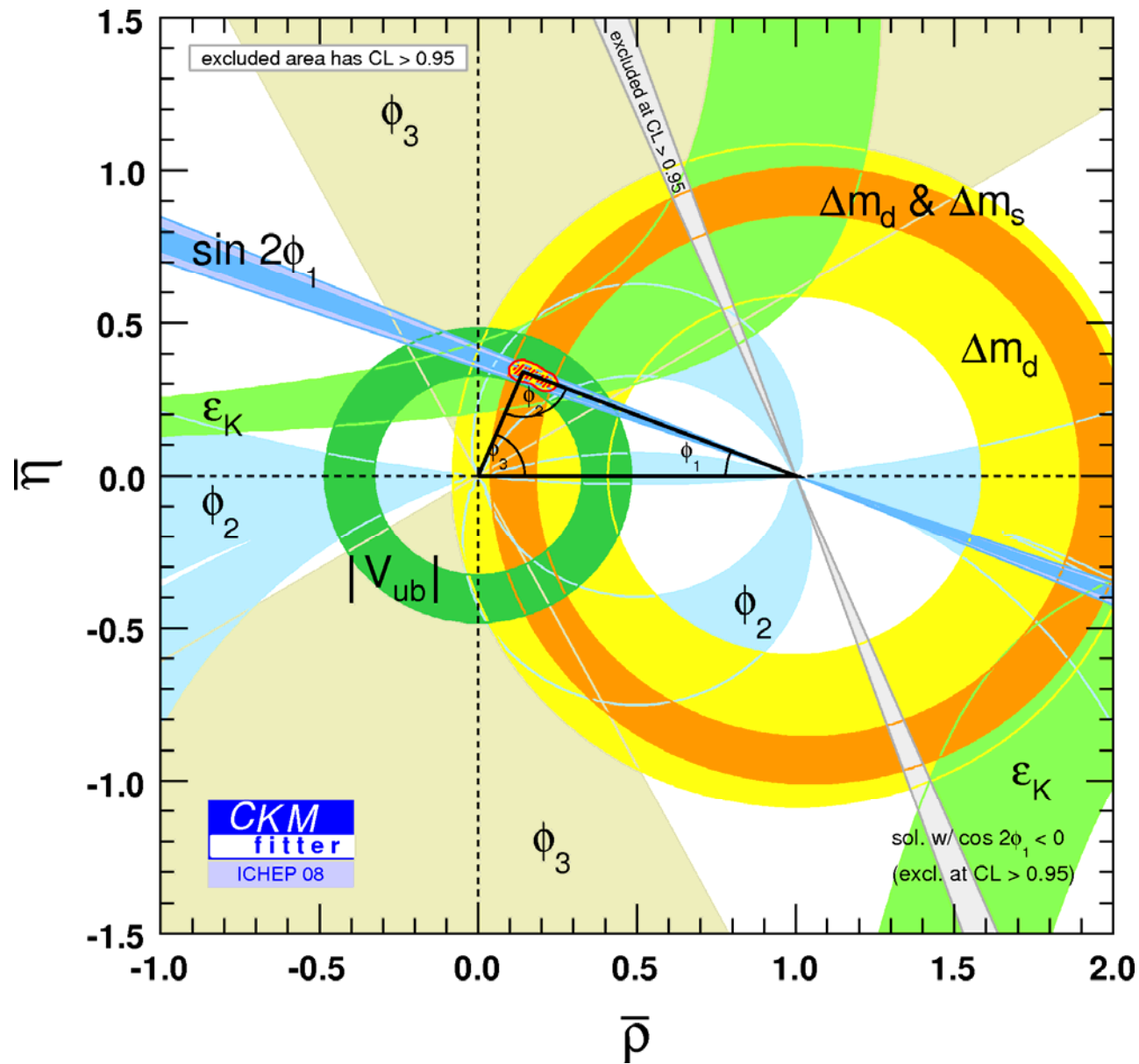
PeP-II





Belle:
14 countries, 59 institutes,
about 400 researchers

Experimental Verification at B-Factories



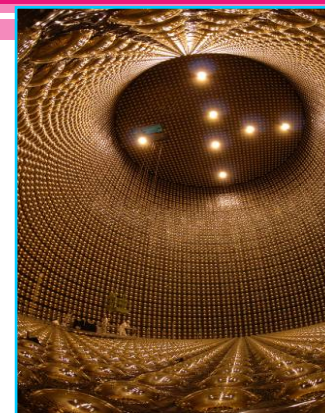
Present Status of CP Violation

B-factory results show that quark mixing is the dominant source of CP violation

B-factory results allow room for additional source from new physics

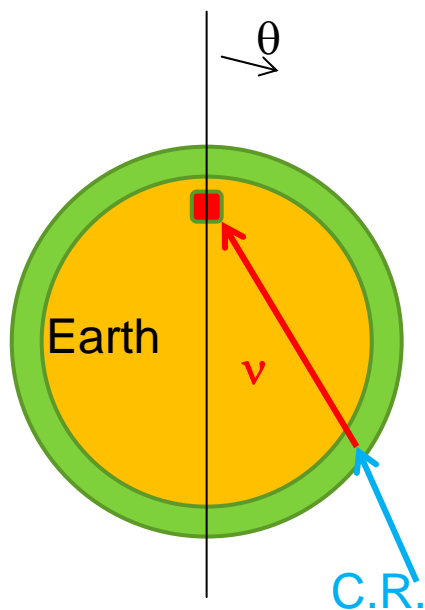
Matter dominance of the Universe seems requiring new source of CP violation

Discovery of neutrino oscillation at Super-Kamiokande using atmospheric neutrinos



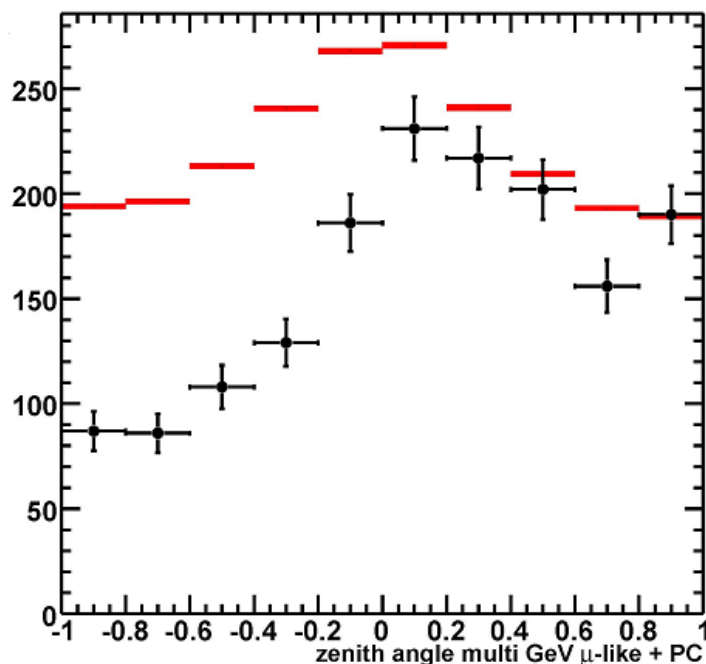
Super-K 1996~

Atmospheric Neutrino



Multi-GeV μ -like + PC

Super Kamiokande I Preliminary 1489.2 days



J.Raaf, Talk at Neutrino 2008



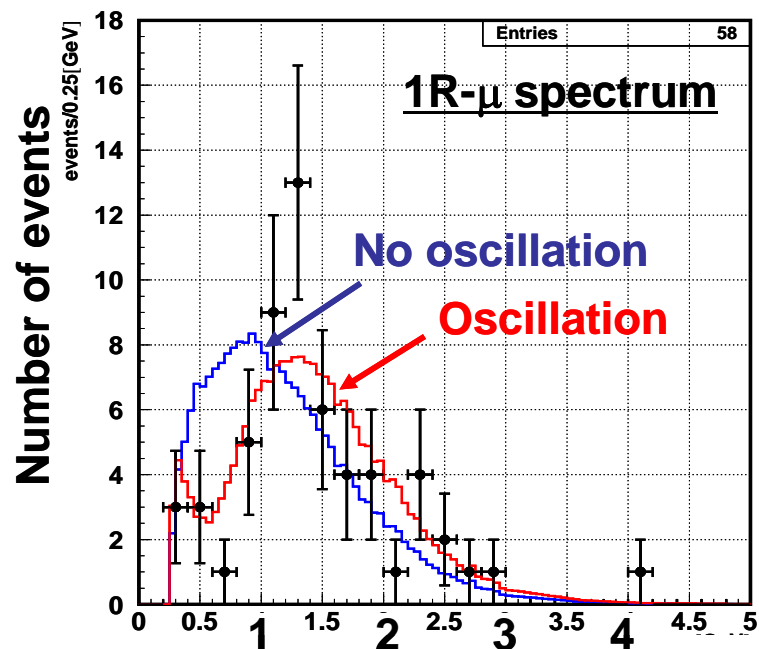
Courtesy of KEK

Yoichi Totsuka
1942-2008

K2K experiment

ν_μ : KEK-PS

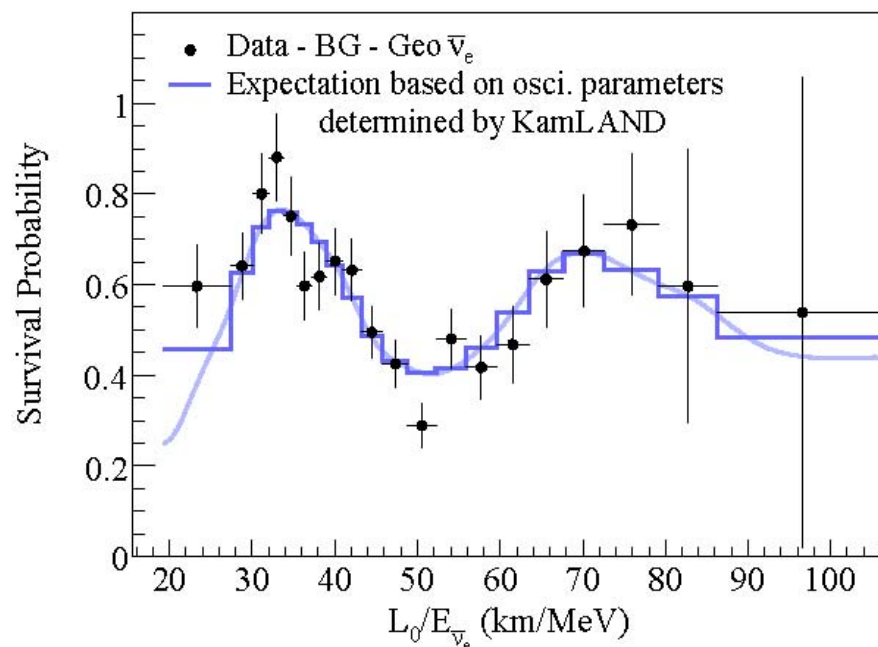
fit_out.0x03.cmb.free.1.shape



ν_μ disappearance

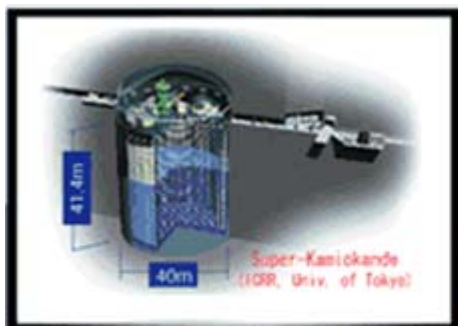
KamLAND experiment

$\bar{\nu}_e$: reactor

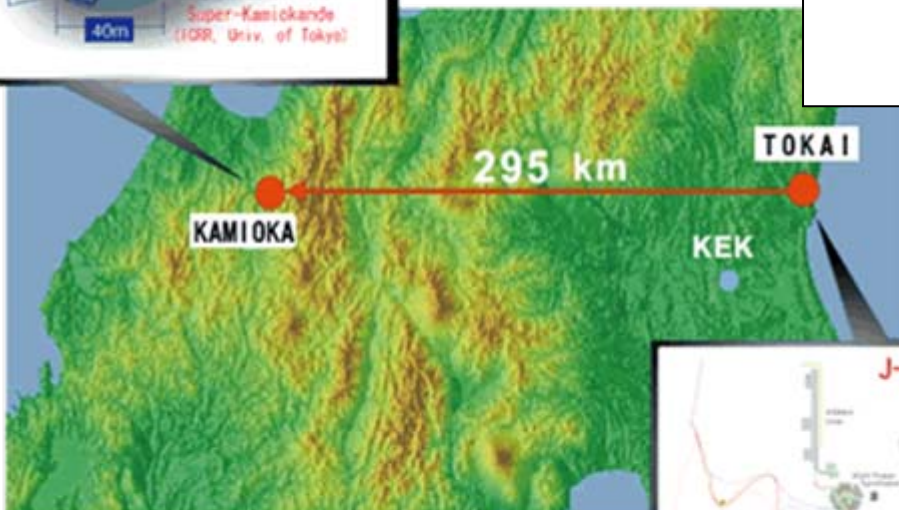


$\bar{\nu}_e$ disappearance

T2K experiment



ν_{μ} created at JPARC
→ Super-K



Aiming to discover
 ν_e appearance