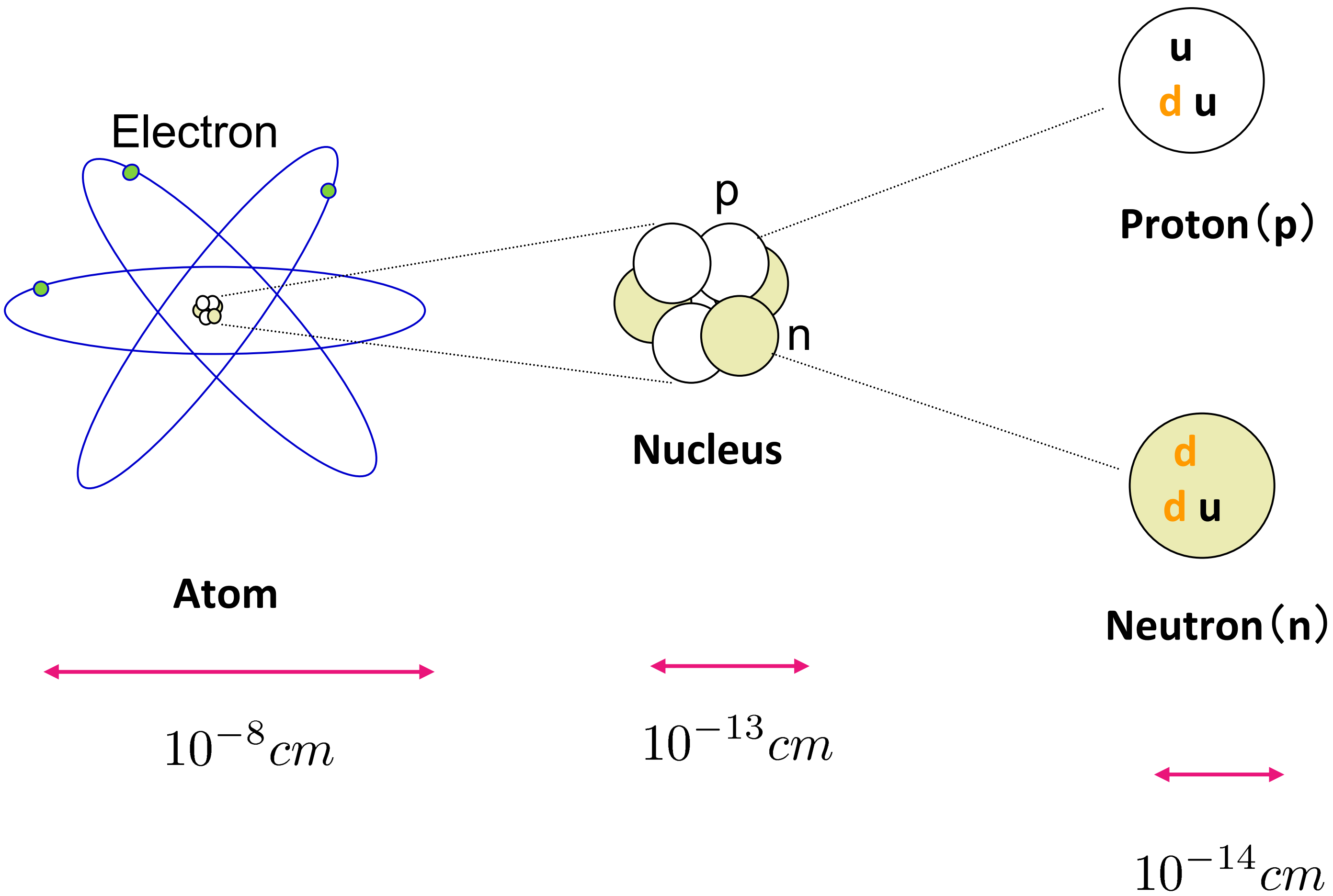
CP Violation and Flavor Mixing

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

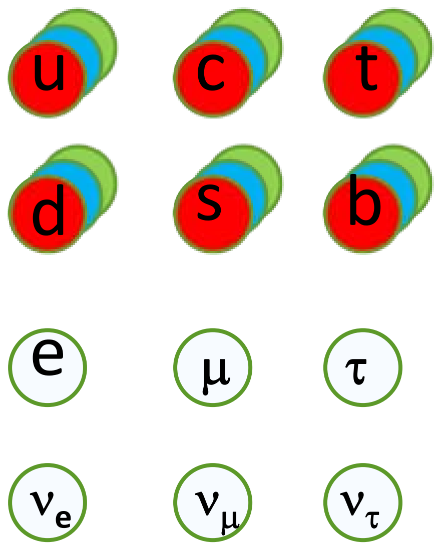

Electron
p
n
u
d u
Proton (p)
Nucleus
d
d u
Atom
Neutron (n)
$10^{-8} cm$
$10^{-13} cm$
$10^{-14} cm$

Introduction to the Standard Model

Fundamental Particles

Quark

Lepton



Fundamental Interactions

- Strong Interaction — QCD
- Electro-Magnetic Interaction
- Weak Interaction

Electro-Magnetic Interaction and Weak Interaction: 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

u	c	t
d	s	b
e	μ	τ
ν_e	ν_μ	ν_τ

After 1970

1973
Kobayashi Maskawa
Six-Quark Model

Sakata and His Group

1947~ Discovery of Strange Particles

Hadron : strongly interacting particle

$p \quad n \quad \pi^{\pm 0} \quad \Lambda$

$\Lambda \quad \Sigma^{\pm 0} \quad \Xi \quad K^{\pm} \quad K^{0} \quad \Lambda$

Strange Particles

Courtesy of Sakata Memorial Archival Library

Shoichi Sakata
1911-1970

1956 Sakata Sakata Model

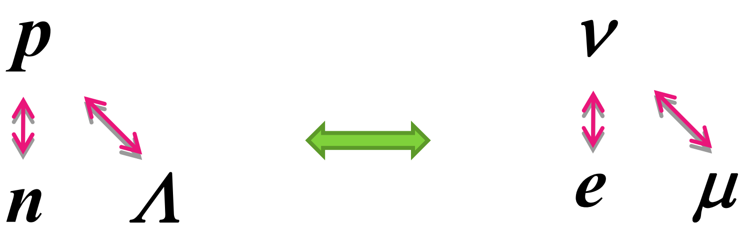
All the hadrons are composite states of

$p, \quad n, \quad \Lambda$: Fundamental Triplet

Sakata and His Group

Weak Interaction in the Sakata Model

β-decay	$n \rightarrow p + e^{-} + \overline{\nu}$
strange paticle	$\Lambda \rightarrow p + e^{-} + \overline{\nu}$



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

$$\nu_e \quad \nu_\mu$$
$$\Updownarrow \quad \Updownarrow$$
$$e \quad \mu$$

Lepton Flavor Mixing

MNS Matrix

1962 Maki, Nakagawa, Sakata

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

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

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

⇨ Neutrino Oscillation

⇨ 4th Fundametal 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

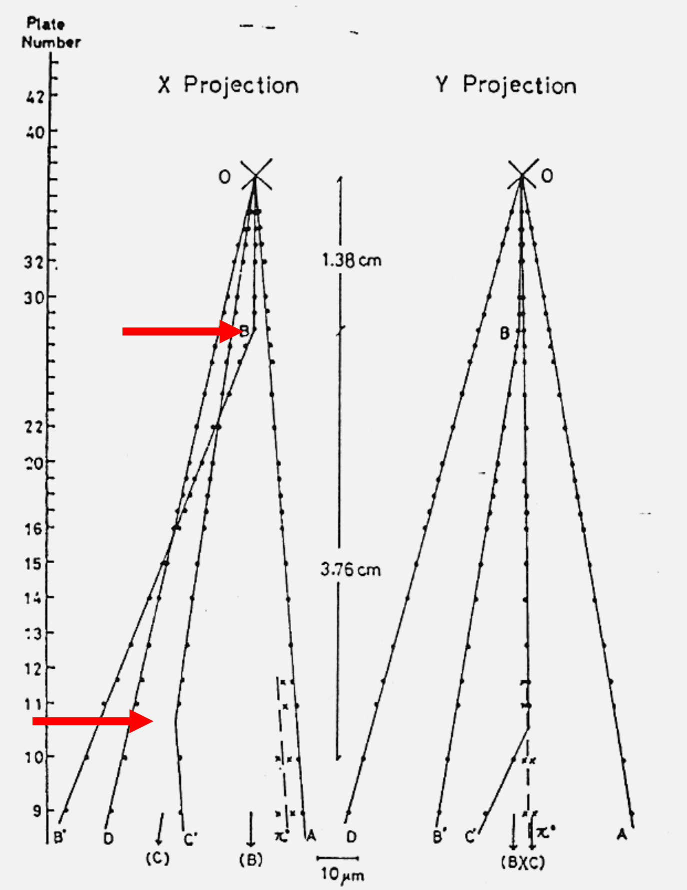


Fig. 3(a). Fig. 3(b).

Emulsion Technique

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

CP Paper with Maskawa

1971 'tHooft : Renormalization of Non-Abelian gauge theory

⟶ Renormalizable Electro-Weak Theory

(Weinberg-Salam-Glashow)

CP Violation

1964 Cronin et al.

$K_L \to \pi\pi$

Essential difference between particles and anti-particles

1973 Kobayashi, Maskawa

How to accommodate CP violation

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

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix}$$

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

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

CP Paper with Maskawa

- 1974 Discovery of J/ψ → **c-quark**
- 1975 Discovery of τ -lepton

1975 S. Pakvasa, H. Sugawara
1976 J.R Ellis, M-K Gaillard, D. Nanopoulos

- 1977 Discovery of Υ → **b-quark**
- 1995 Discovery of t-quark

Large CP violation in the B-meson system

1980 Carter, Sanda
1981 Bigi, Sanda

→ **B-Factory**

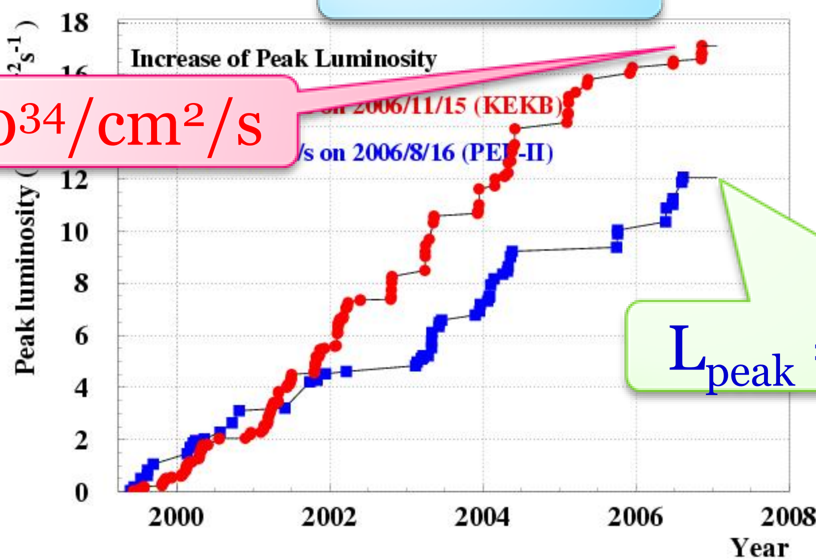
B_d: $\bar{b}d$	$\bar{B}_d$: $\bar{d}b$
B_u: $\bar{b}u$	$\bar{B}_u$: $\bar{u}b$

B-Mesons

KEKB/Belle (Japan) | PEP-II/BaBar (US)

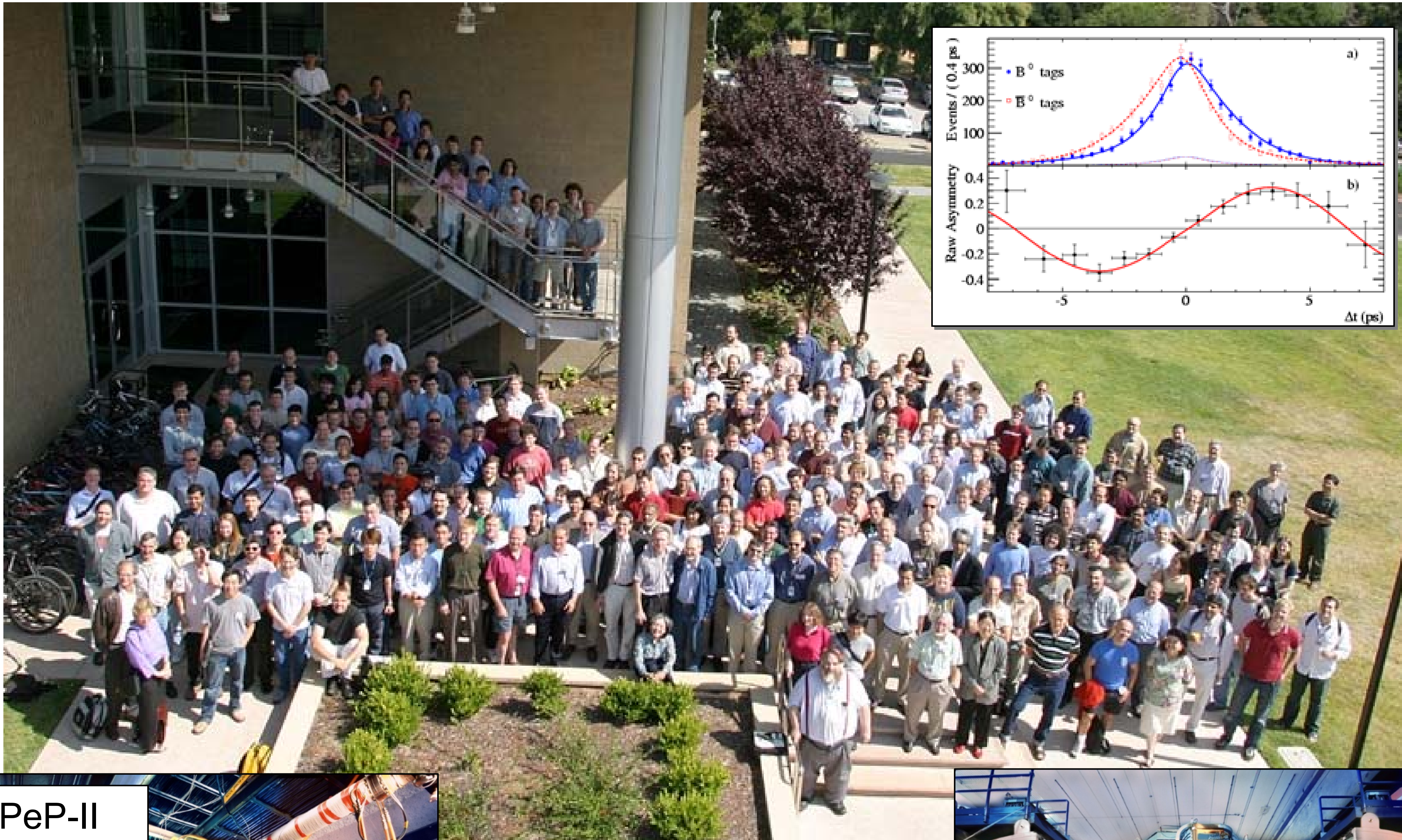
KEKB/Belle (Japan)		PEP-II/BaBar (US)
$E(e^-)$=8GeV, $E(e^+)$=3.5GeV, Finite angle beam crossing	Feature	$E(e^-)$=9GeV, $E(e^+)$=3.1GeV, Zero angle beam crossing
1994	Governmental Approval	1993
May 1999 – still running	Experiment	May 1999 – Apr. 2008

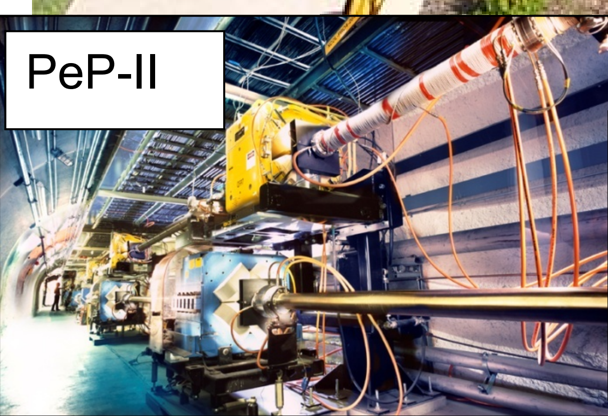
$L_{peak} = 1.7 \times 10^{34}/cm^2/s$

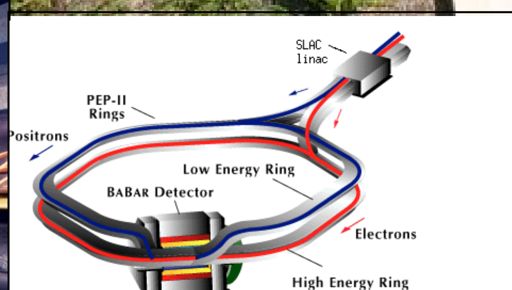


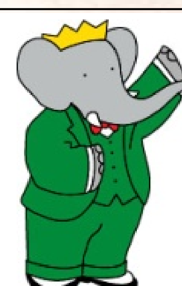
Friendly competition of two experiments over a decade

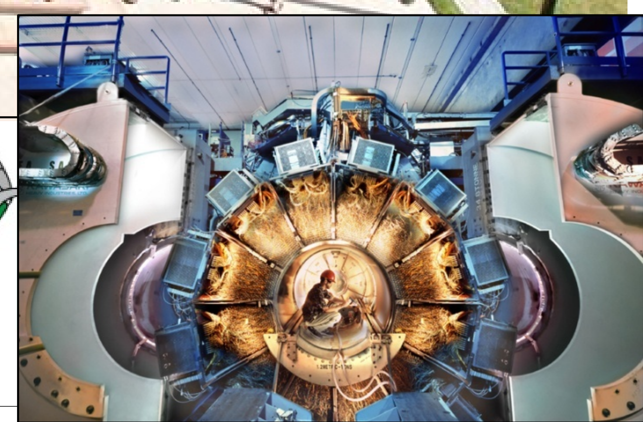
$L_{peak} = 1.2 \times 10^{34}/cm^2/s$

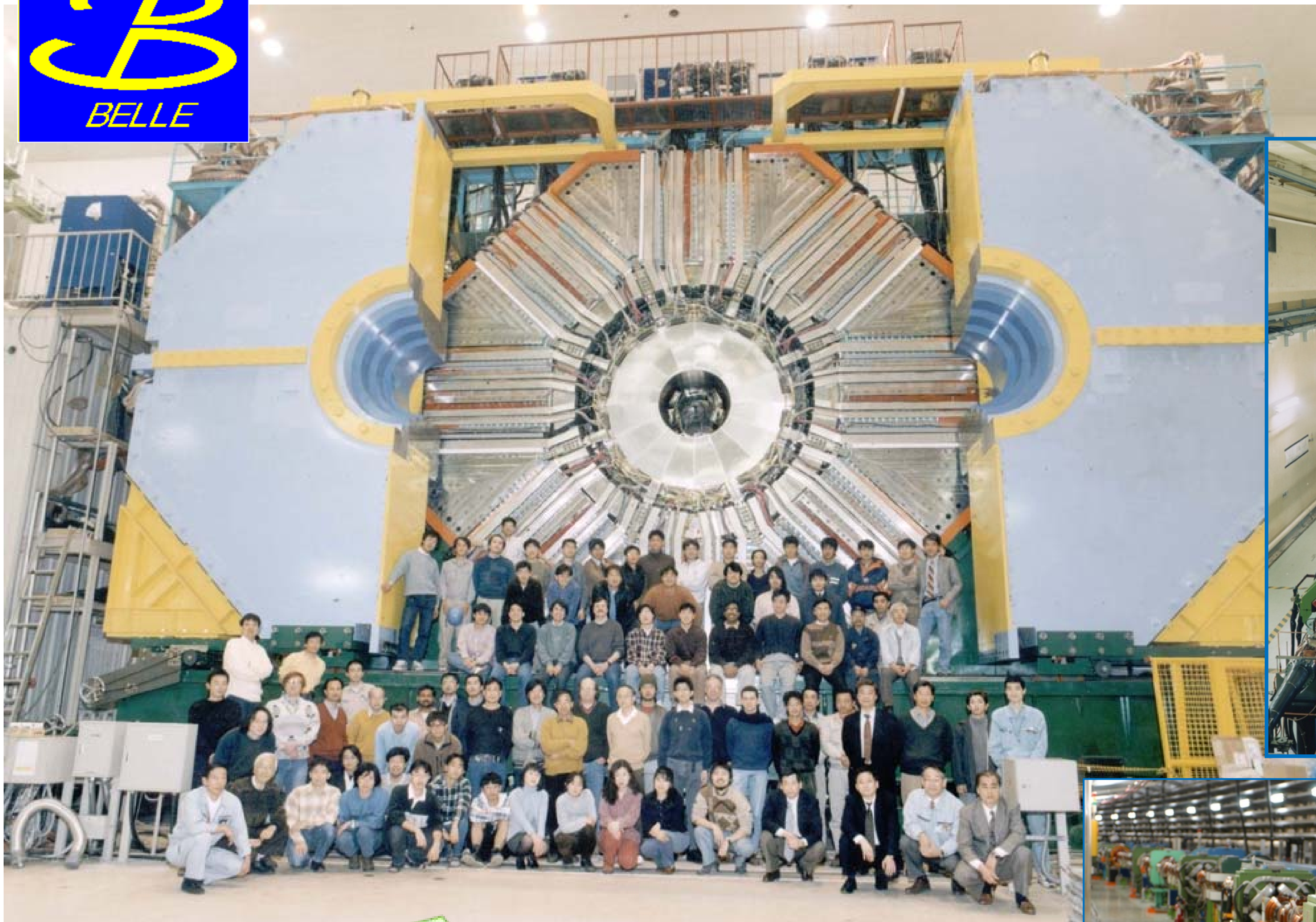

a)
Events / (0.4 ps)
300
200
100
B⁰ tags
$\overline{B}^0$ tags
b)
Raw Asymmetry
0.4
0.2
0
-0.2
-0.4
-5
0
5
Δt (ps)


PeP-II


SLAC linac
PEP-II Rings
Positrons
Low Energy Ring
BABAR Detector
Electrons
High Energy Ring

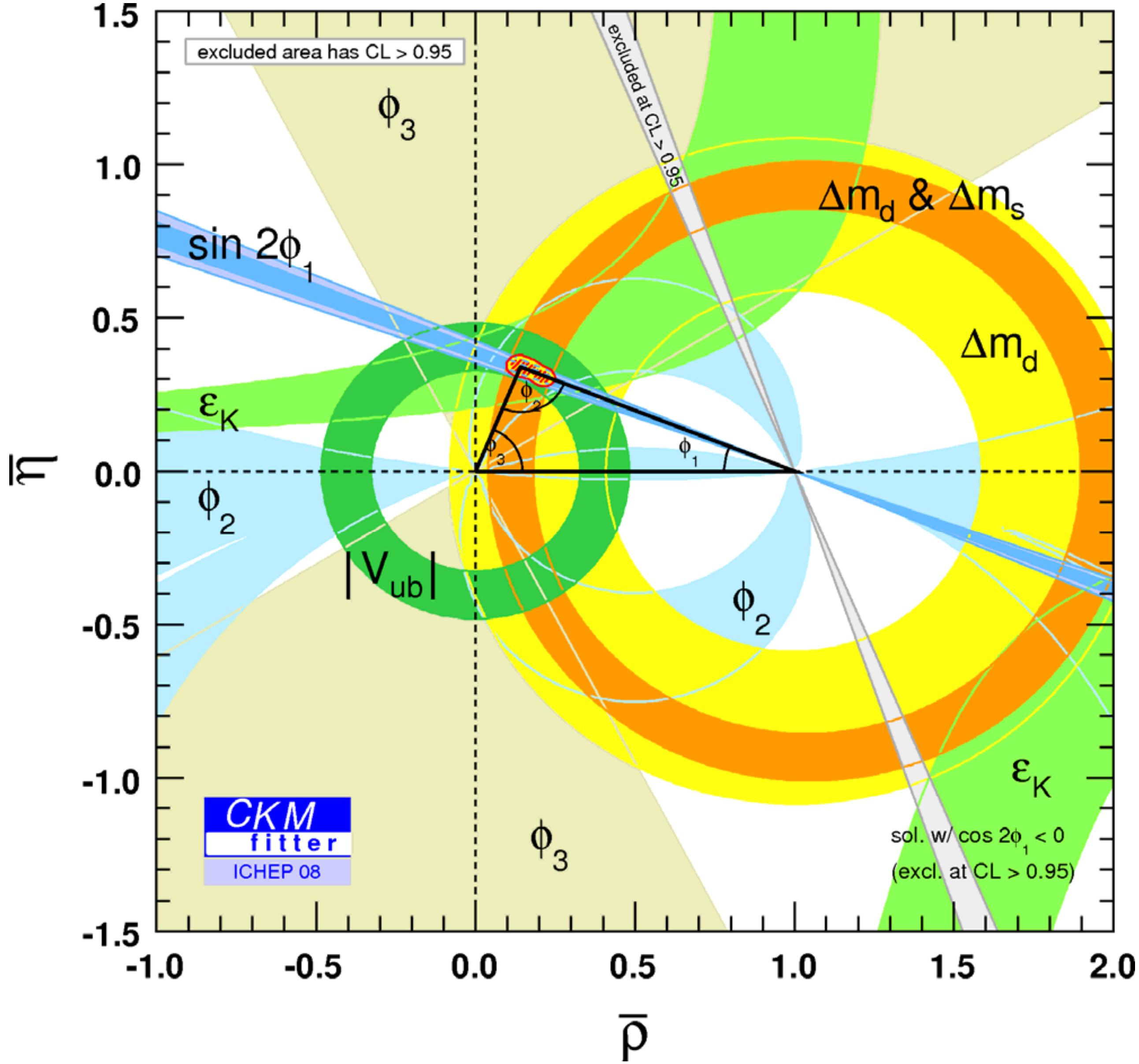






Belle:
14 countries, 59 institutes,
about 400 researchers

Experimental Verification at B-Factories



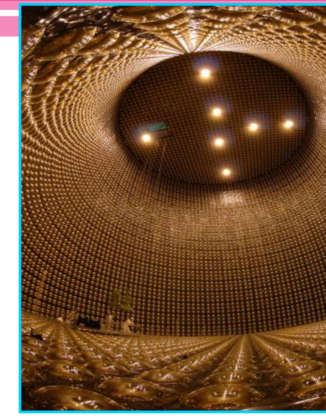
Present Status of CP Violation

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

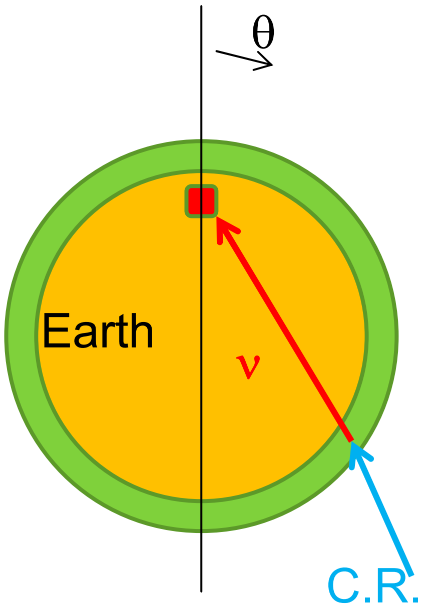
Matter dominance of the Universe seems requiring new source of CP violation

Discovery of neutrino oscillation at Super-Kamiokande using atmospheric neutrinos

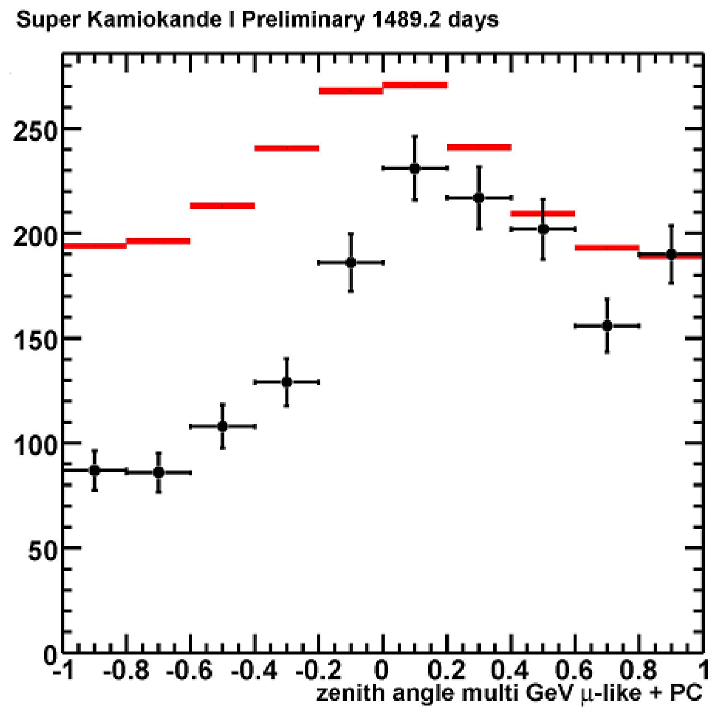


Super-K 1996〜

Atmospheric Neutrino



Multi-GeV μ-like + PC



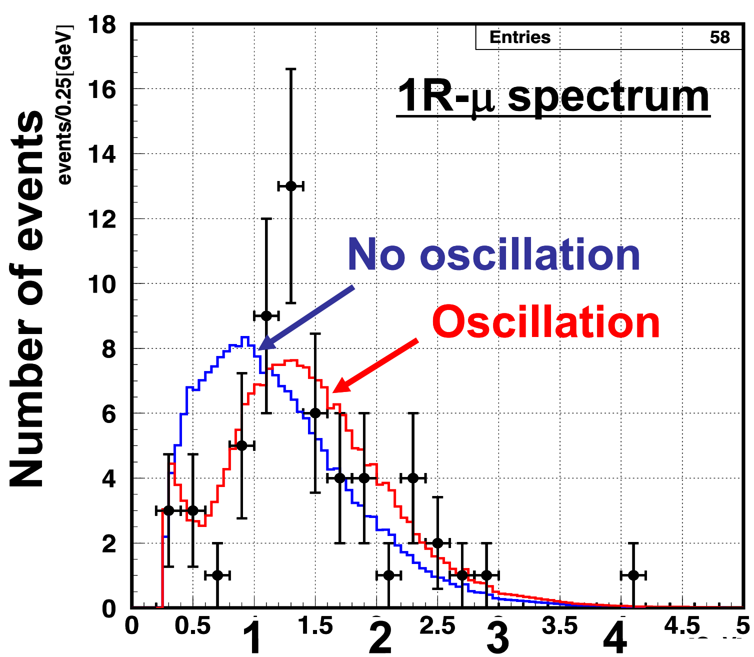
J.Raaf, Talk at Neutrino 2008

Courtesy of KEK

Yoji Totsuka
1942-2008

K2K experiment

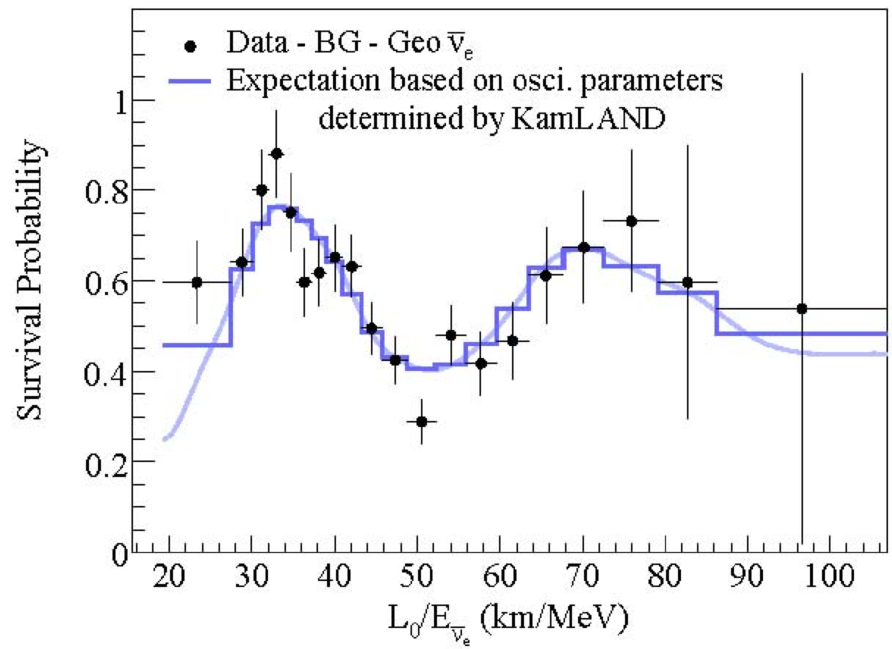
ν_μ : KEK-PS



ν_μ disapearance

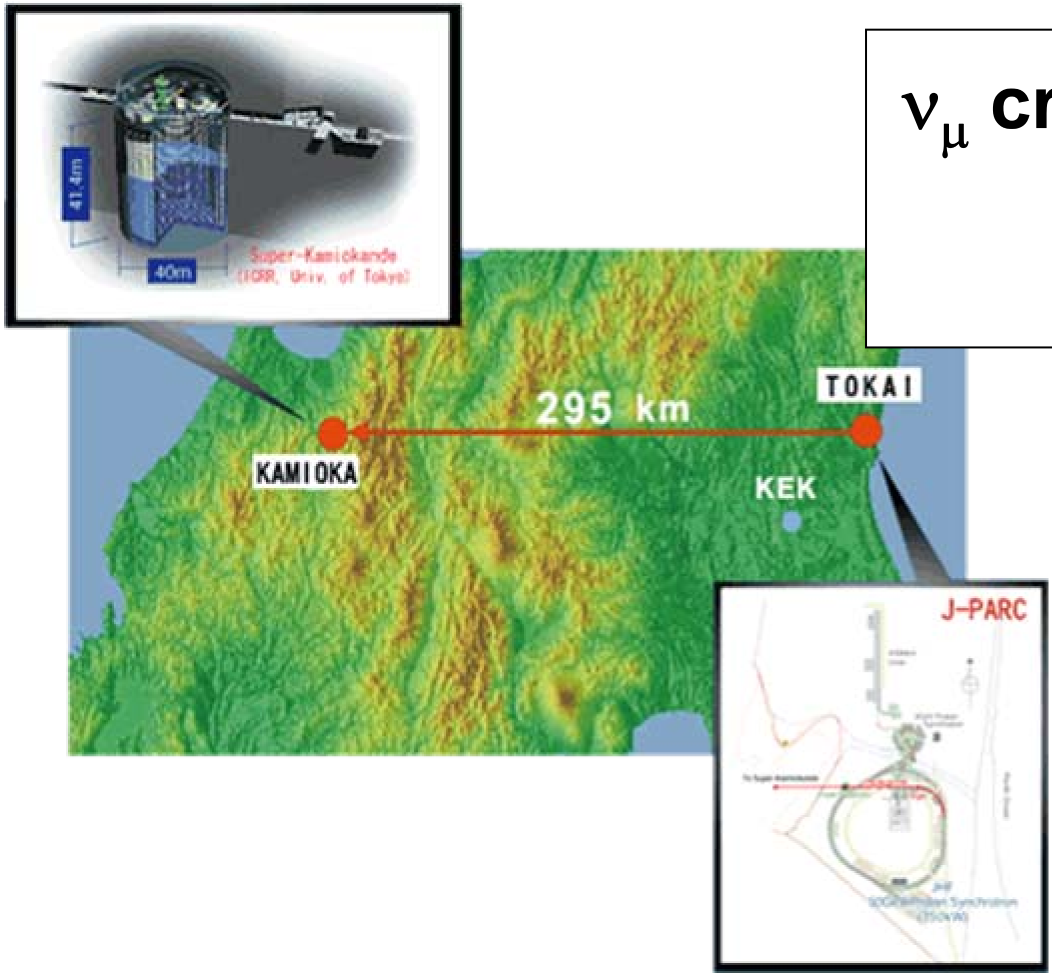
KamLAND experiment

$\bar{\nu}_e$: reactor



ν_e disapearance

T2K experiment



ν_μ created at JPARC

⟶ Super-K

Aiming to discover

ν_e appearance