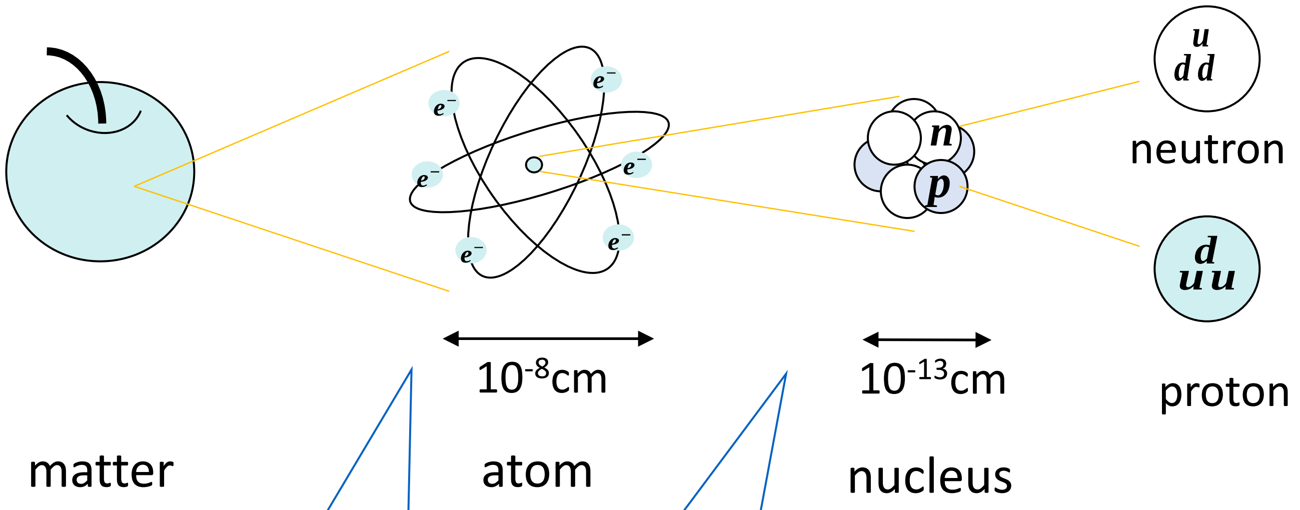
2015/10/08
Seoul Univ.

Matter and Antimatter

KEK and JSPS
M. Kobayashi

Structure of matter



Electromagnetic Interaction

Strong Interaction

$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^{-} + \bar{\boldsymbol{\nu}}$$

β–decay

Weak Interaction

Discovery of Antiparticle

Special Relativity (1905)
Quantum Mechanics (1925)

Schrodinger equation

$$\mathbf{i}\hbar \frac{\partial}{\partial \mathbf{t}} \psi(\mathbf{x}) = -\frac{\hbar^2}{2\mathbf{m}} \frac{\partial^2}{\partial \mathbf{x}^2} \psi(\mathbf{x})$$

⟸

$$E = \frac{p^2}{2m}$$

⇕

Dirac equation (Dirac 1928)

$$\mathbf{i}\hbar \frac{\partial}{\partial \mathbf{t}} \psi(\mathbf{x}) = \left(\frac{\hbar \mathbf{c}}{\mathbf{i}} \vec{\alpha} \cdot \frac{\partial}{\partial \vec{\mathbf{x}}} + \beta\, \mathbf{m}\mathbf{c}^2 \right) \psi(\mathbf{x})$$

$$\vec{\alpha}, \beta : 4 \times 4 \mathrm{matrix}$$

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

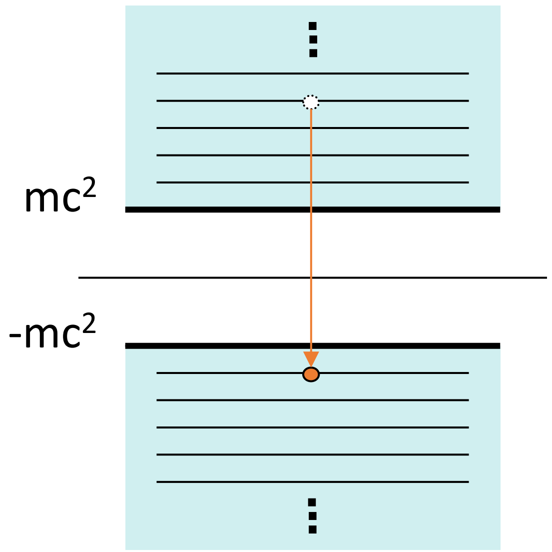
Solutions of the Dirac equation

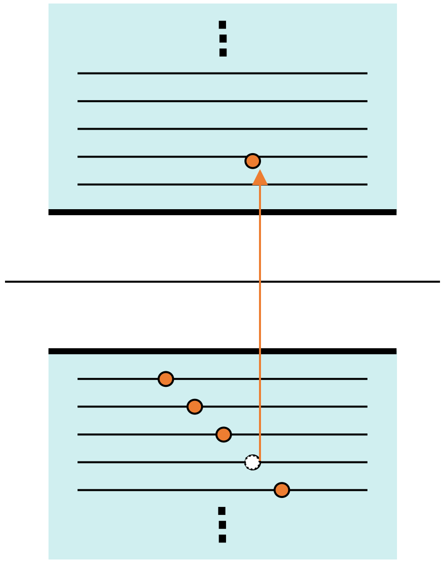
Positive energy

$$\mathbf{E} = \sqrt{\mathbf{p}^2\mathbf{c}^2 + \mathbf{m}^2\mathbf{c}^4} \geq \mathbf{mc}^2$$

Negative energy

$$\mathbf{E} = -\sqrt{\mathbf{p}^2\mathbf{c}^2 + \mathbf{m}^2\mathbf{c}^4} \leq -\mathbf{mc}^2$$





Dirac Sea

All negative energy states are occupied

Hole in the Dirac Sea

➡ Positively charged particle

1932 Anderson Discovery of Positron

Dirac's arguments : only for fermions

How about bosons ?

↓

Relativistic Quantum Field Theory

Every particle has its corresponding antiparticle

- same mass
- opposite charge

Note

- Self conjugate particle: a particle and an antiparticle are identical
  Example: Photon
- Neutral particles are not necessarily self conjugate
  Example: Neutron

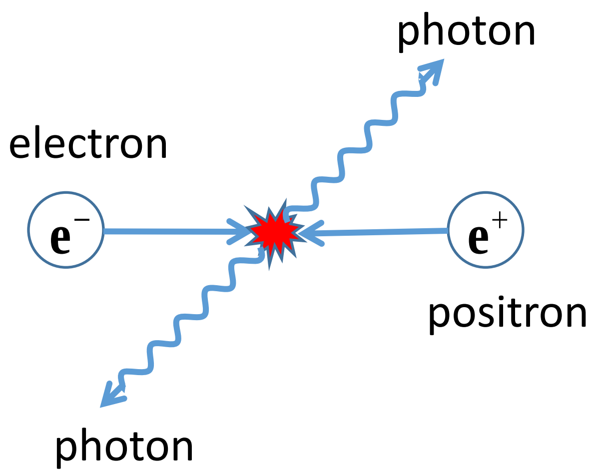
electron e^- ⇔ positron e^+

proton p ⇔ antiproton $\overline{p}$

neutron n ⇔ antineutron $\overline{n}$

Pair annihilation

$$e^- + e^+ \rightarrow \gamma + \gamma$$



Pair annihilation

$$\mathbf{e}^- + \mathbf{e}^+ \rightarrow \gamma + \gamma$$

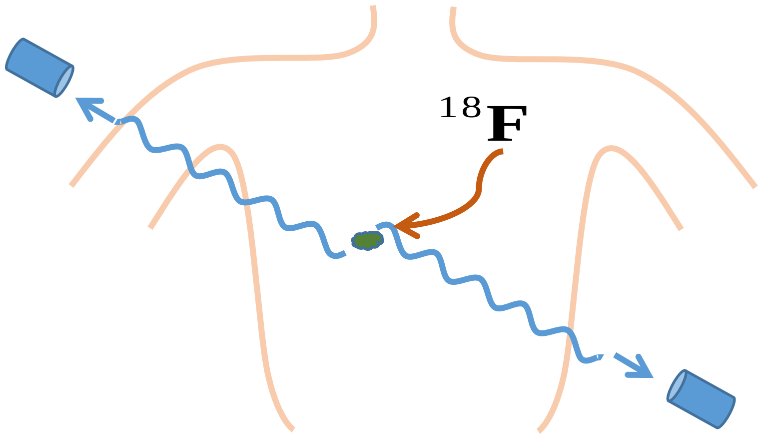
$$p + \bar{p} \rightarrow \pi + \pi + \cdots$$

Pair creation

$$\gamma + \gamma \rightarrow e^+ + e^-$$

$$p + p \rightarrow p + p + p + \bar{p}$$

PET



$$^{18}\mathbf{F} \rightarrow {}^{18}\mathbf{O} + \mathbf{e}^+ + \nu$$

CP symmetry

Invariance of the laws of nature under the exchange of particle and antiparticle

C (charge conjugation) : simple exchange of particle and antiparticle

P (parity) : space inversion

CP : combined operation of C and P

P violation was found in 1956.

→ C is also violated, but CP looked to hold true

Discovery of CP violation

1964 Cronin, Fitch et al

~0.2% of K_L decay into

$$\mathbf{K_L \rightarrow \pi^+ + \pi^-}$$

$$|\mathbf{K_L}\rangle = \mathbf{p}\,|\mathbf{K^0}\rangle + \mathbf{q}\,|\overline{\mathbf{K}}^0\rangle$$

$$|\mathbf{p}| \neq |\mathbf{q}| \quad \Rightarrow \ \textbf{CP violation}$$

Hadron : strongly interaction particles

proton p neutron n

pion $\pi^+ \ \pi^- \ \pi^0$

kaon $K^+ \ K^- \ K^0 \ \overline{K}^0$ lambda Λ sigma $\Sigma^+ \ \Sigma^- \ \Sigma^0$

1956 Sakata **Sakata Model**

All the hadrons are composite states of

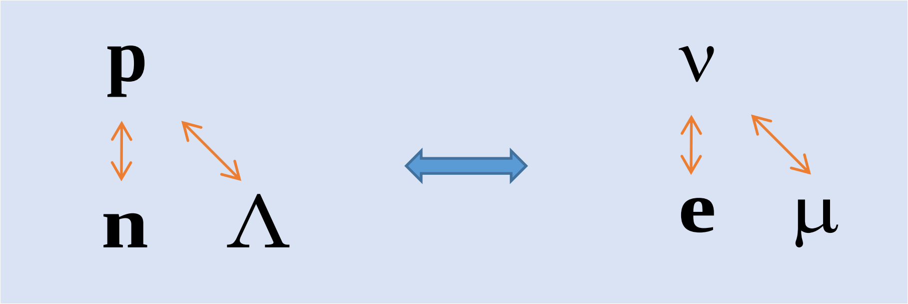
$p, \quad n, \quad \Lambda$: Fundamental Triplet

$p\bar{n}$	$p\bar{\Lambda}$	$\Lambda p\bar{n}$	$\Lambda\Lambda\bar{n}$
π^+	K^+	Σ^+	Ξ^0

Courtesy of Sakata Memorial Archival Library

Shoichi Sakata
1911-1970

Weak Interaction in the Sakata Model



1959 Gamba, Marshak, Okubo

B-L Symmetry

1960 Maki, Nakagawa, Ohnuki, Sakata

Nagoya Model : $\mathbf{p} = \langle \mathbf{B}^{+}\nu \rangle, \mathbf{n} = \langle \mathbf{B}^{+}\mathbf{e} \rangle, \Lambda = \langle \mathbf{B}^{+}\mu \rangle$

B^{+} : B - matter

Discovery of Two Neutrinos

1962 Danby et al. PRL 9, 36 (1962)

$\nu_e \updownarrow e \qquad \nu_\mu \updownarrow \mu$

Modification of Nagoya Model

1962 Katayama, Matumoto, Tanaka and Yamada
Progr. Theor. Phys. 28, 675 (1962)

1962 Maki, Nakagawa and Sakata
Progr. Theor. Phys. 28, 870 (1962)

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

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

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

Neutrino Mixing: Maki, Nakagawa, Sakata (MNS)

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

$$\boldsymbol{\nu}_1 = \cos\delta\ \boldsymbol{\nu}_e + \sin\delta\ \boldsymbol{\nu}_\mu$$

$$\boldsymbol{\nu}_2 = -\sin\delta\ \boldsymbol{\nu}_e + \cos\delta\ \boldsymbol{\nu}_\mu$$

$\nu_e \leftrightarrow e \qquad \nu_\mu \leftrightarrow \mu$

Identify ν_1, ν_2 as the mass eigenstates

They formulated lepton flavor mixing precisely.

Bare field: $\psi_0 = \begin{pmatrix} \mu_0 \\ \mathbf{e}_0 \end{pmatrix}, \quad \varphi_0 = \begin{pmatrix} \nu_{\mu 0} \\ \nu_{\mathbf{e}0} \end{pmatrix}$

$$\mathbf{L}_{int} = [(\overline{\psi}_0 \Lambda \psi_0) + (\overline{\varphi}_0 \Lambda' \varphi_0)]\, \mathbf{X}^* \mathbf{X}$$

Λ, Λ': 2x2 mass matrices

Difference of mass diagonalization

→ Mixing angle

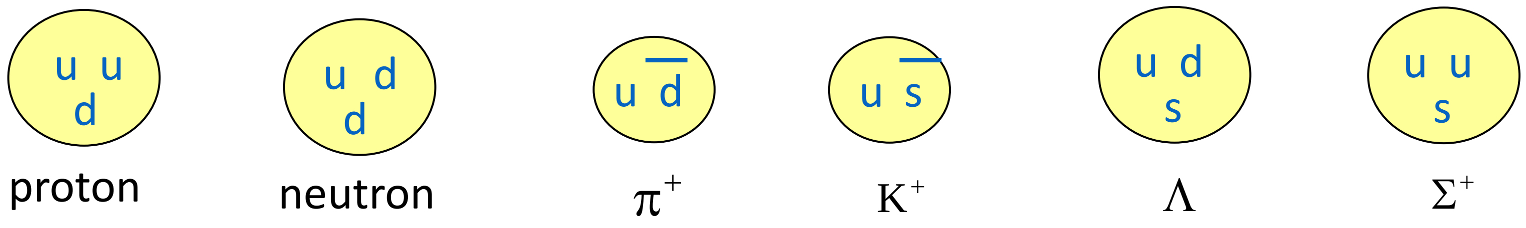
Courtesy of Sakata Memorial Archival Library

S. Sakata Z. Maki M. Nakagawa

Quark Model

1964 Gell-Mann

quark	u	d	s
	$2/3e$	$-1/3e$	$-1/3e$



1963 Cabibbo

Cabibbo angle θ_C

$$u \leftrightarrow d' = \cos\theta_C \; d + \sin\theta_C \; s$$

Status at the end of 1960's

Fundamental particles

quarks	u	
	d	s
leptons	ν_e	ν_μ
	e	μ

Fundamental interactions

Electromagnetic — Renormalization theory, Tomonaga-Schwinger-Feynman

Weak
Strong
} No satisfactory theory

1971 ‘t Hooft : Renormalization of Non-Abelian gauge theory

→
- Weinberg-Salam-Glashow theory for Electro-Weak Int.
- QCD for Strong Int.

1973 Kobayashi, Maskawa

How to accommodate CP violation

What we found
- Not possible with three or four quarks
- Existence of unknown particles
- A possible candidate is six-quark model

u	c	t
d	s	b

Flavor Mixing of 4-Quark Model

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

Redefinition of quark fields

$$u \to e^{i\delta_u} u, \quad d \to e^{i\delta_d} d, \cdots$$

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

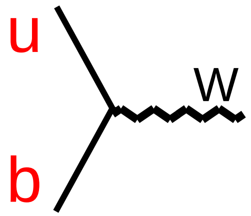
→ No CP Violation

6-Quark Model for CP Violation

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix} \qquad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

→ Complex Coupling Constant



Development of Experiments

- 1974 Discovery of J/ψ particle — c-quark
- 1975 Discovery of τ-lepton → ν_e ν_μ ν_τ / e μ τ
- 1977 Discovery of Υ particle — b-quark
- 1995 Discovery of t-quark

Theory of Strong Interactions

- 1973 QCD Asymptotic freedom

→ Quark confinement

→ **Standard Model**

Status at the end of 1960's

The Standard Model

Fundamental particles

quarks	u	c	t
	d	s	b
leptons	ν_e	ν_μ	ν_τ
	e	μ	τ

Fundamental interactions

Electromagnetic — Renormalization theory, Tomonaga-Schwinger-Feynman

Electromagnetic + Weak — Weinberg-Salam-Glashow Theory

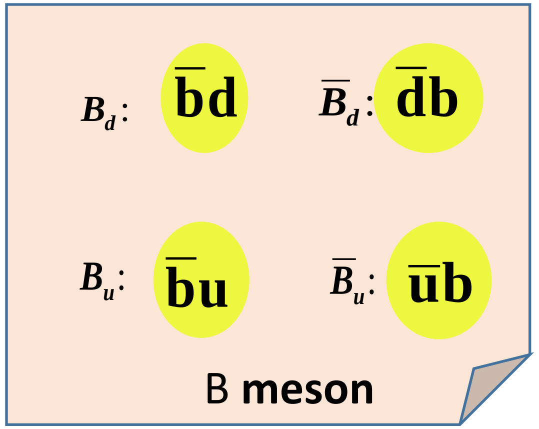
Weak, Strong — No satisfactory theory

Strong — QCD

CP violation experiments at B-factories

B-factories at KEK and SLAC

- e^+e^- collider
- optimized for B-meson production
- asymmetric energy



KEKB/Belle (Japan)

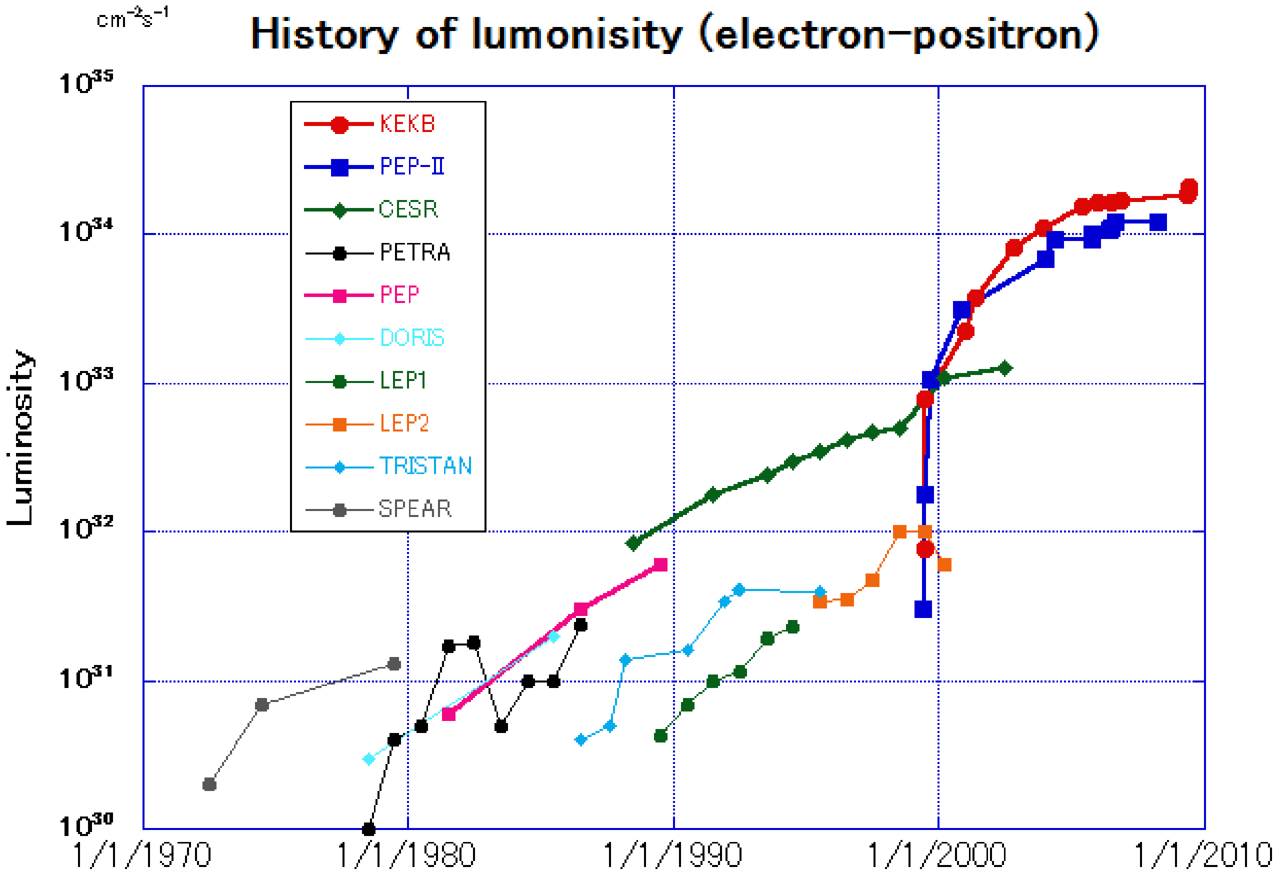
PEP-II/BaBar (US)

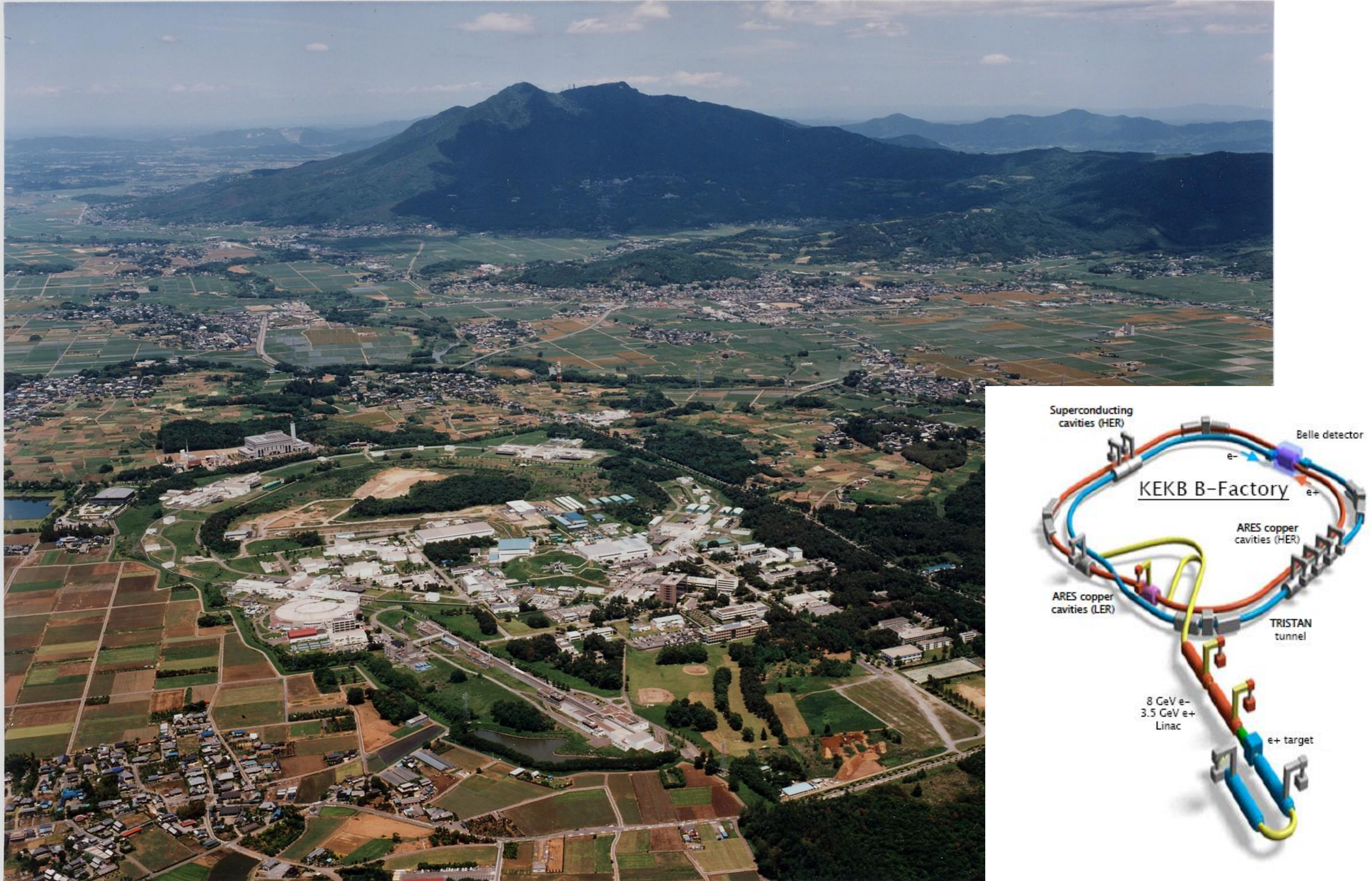
KEKB/Belle (Japan)		PEP-II/BaBar (US)
$E(e^-)$=8GeV, $E(e^+)$=3.5GeV Finite angle beam crossing	Feature	$E(e^-)$=9GeV, $E(e^+)$=3.1GeV Zero angle beam crossing
1994	Governmental Approval	1993
May 1999 – Jun. 2010	Experiment	May 1999 – Apr. 2008

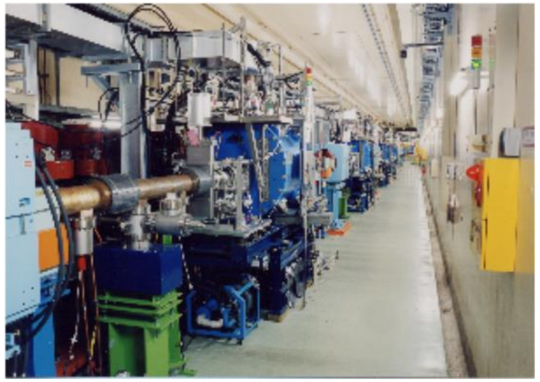
→ **Super KEKB**

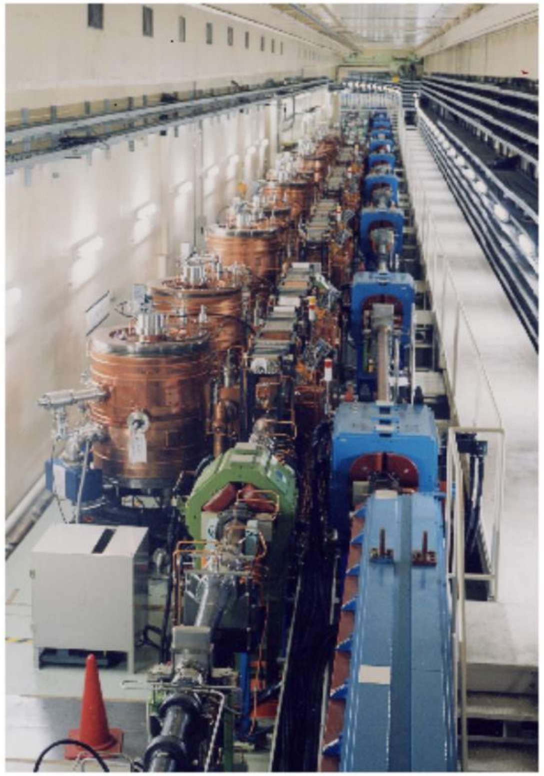
$$\text{KEKB}\ \ L = 2.1\times10^{34} cm^{-2} \sec^{-1}$$

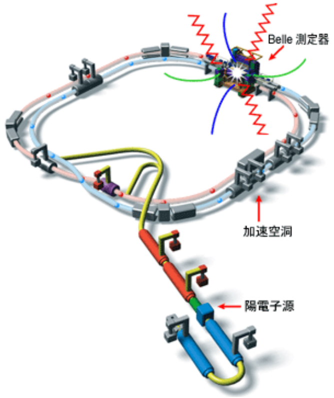
$$\text{PEP-II}\ \ L = 1.2\times10^{34} cm^{-2} \sec^{-1}$$

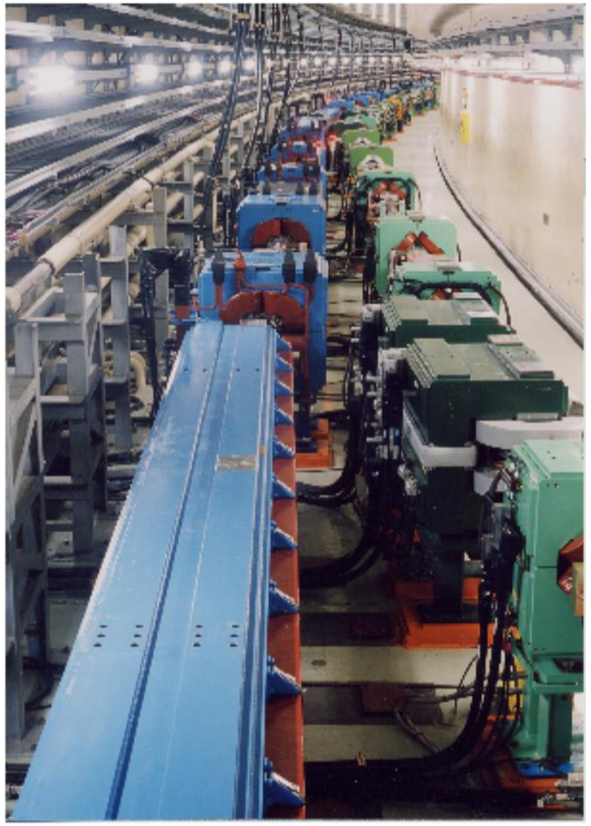


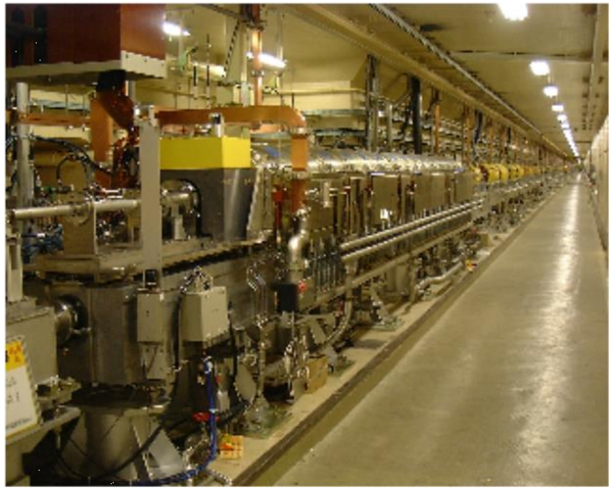

Superconducting cavities (HER)
Belle detector
e-
e+
KEKB B-Factory
ARES copper cavities (HER)
ARES copper cavities (LER)
TRISTAN tunnel
8 GeV e-
3.5 GeV e+
Linac
e+ target

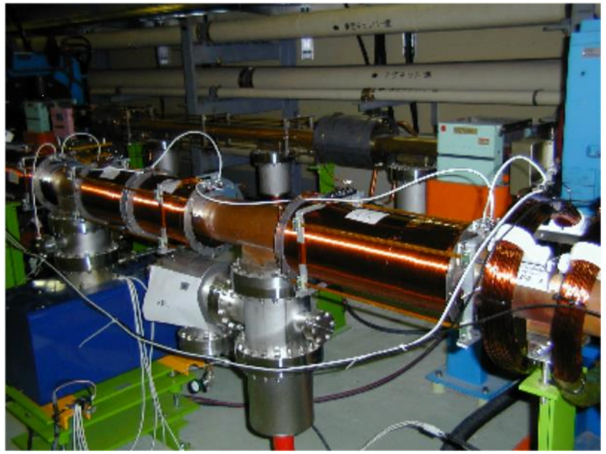





Belle 測定器
加速空洞
陽電子源

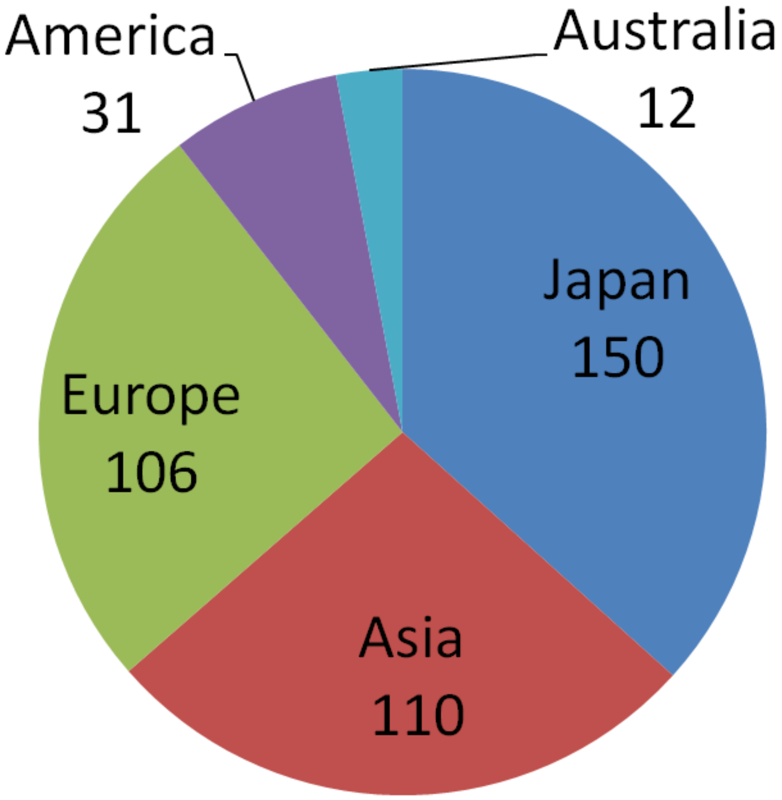


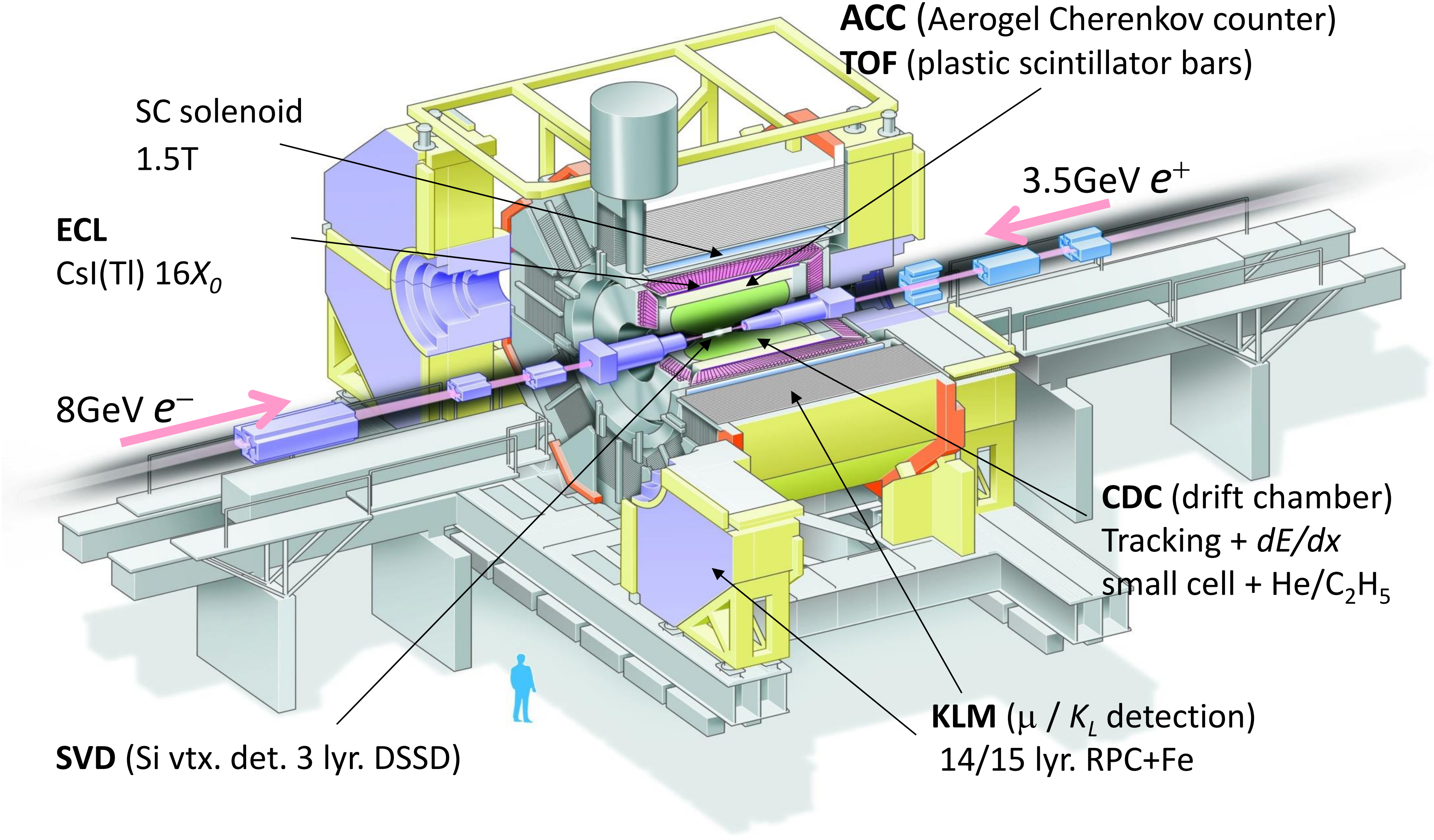




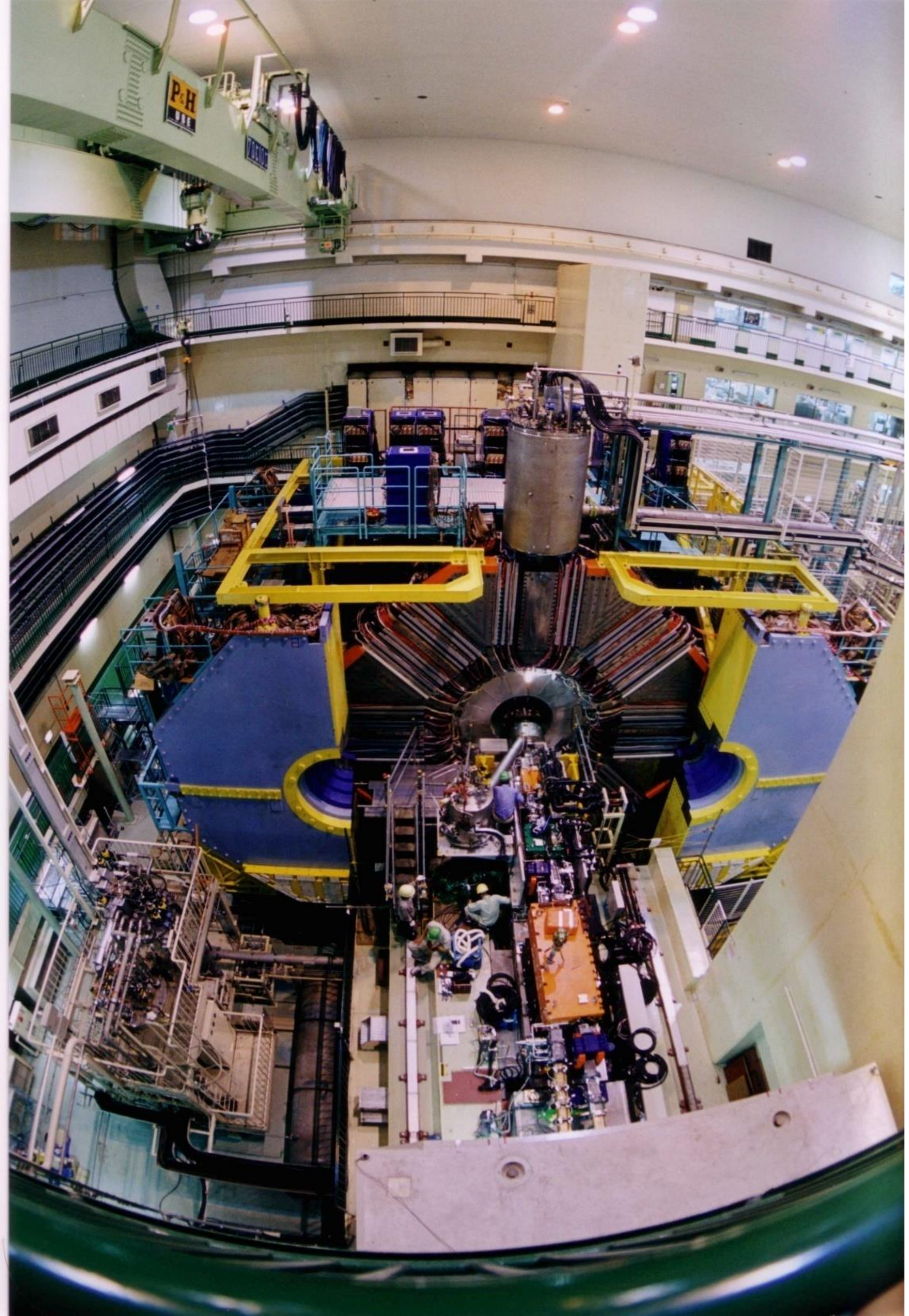
Belle Members

15 Countries and Regions
62 Institution
409 Members

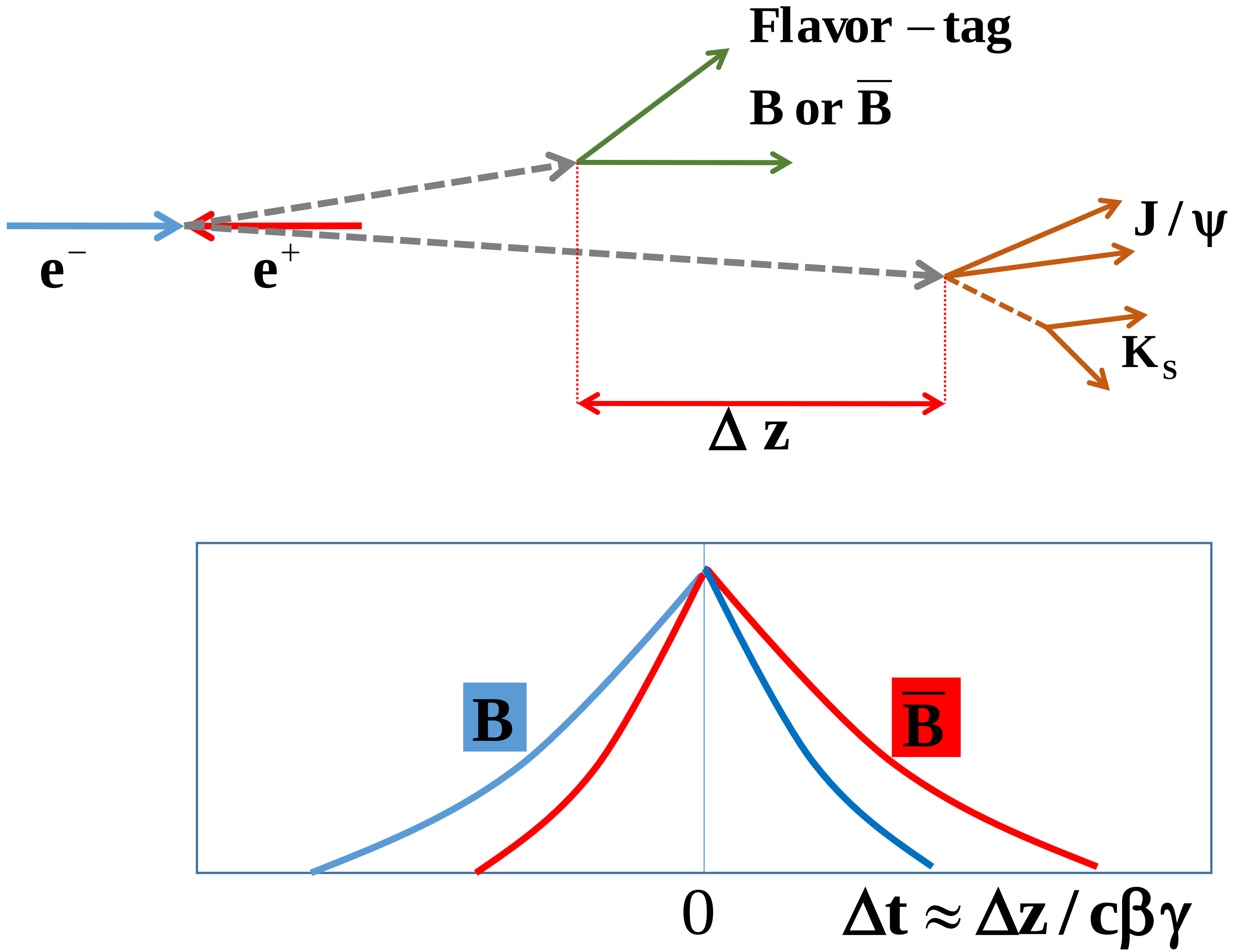


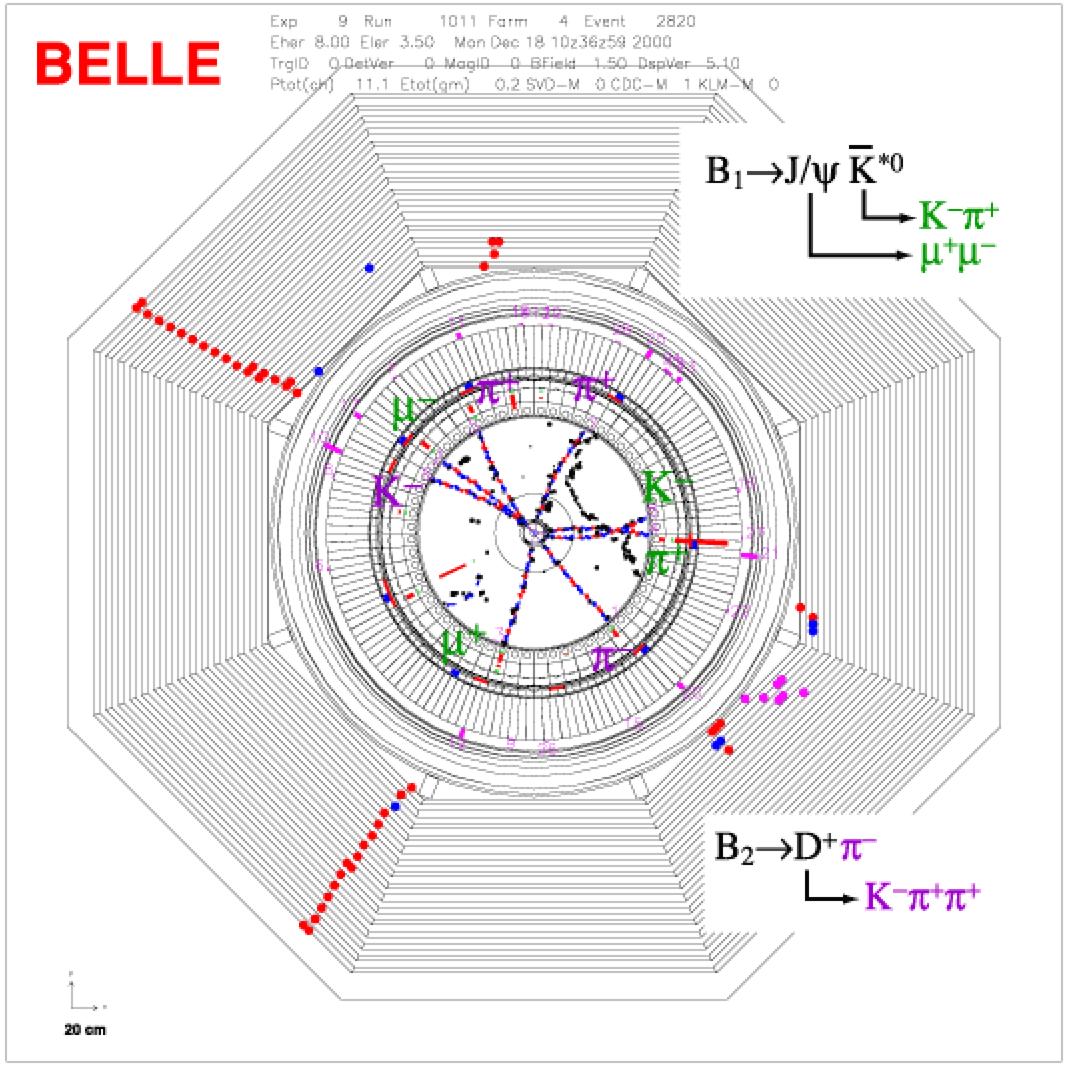


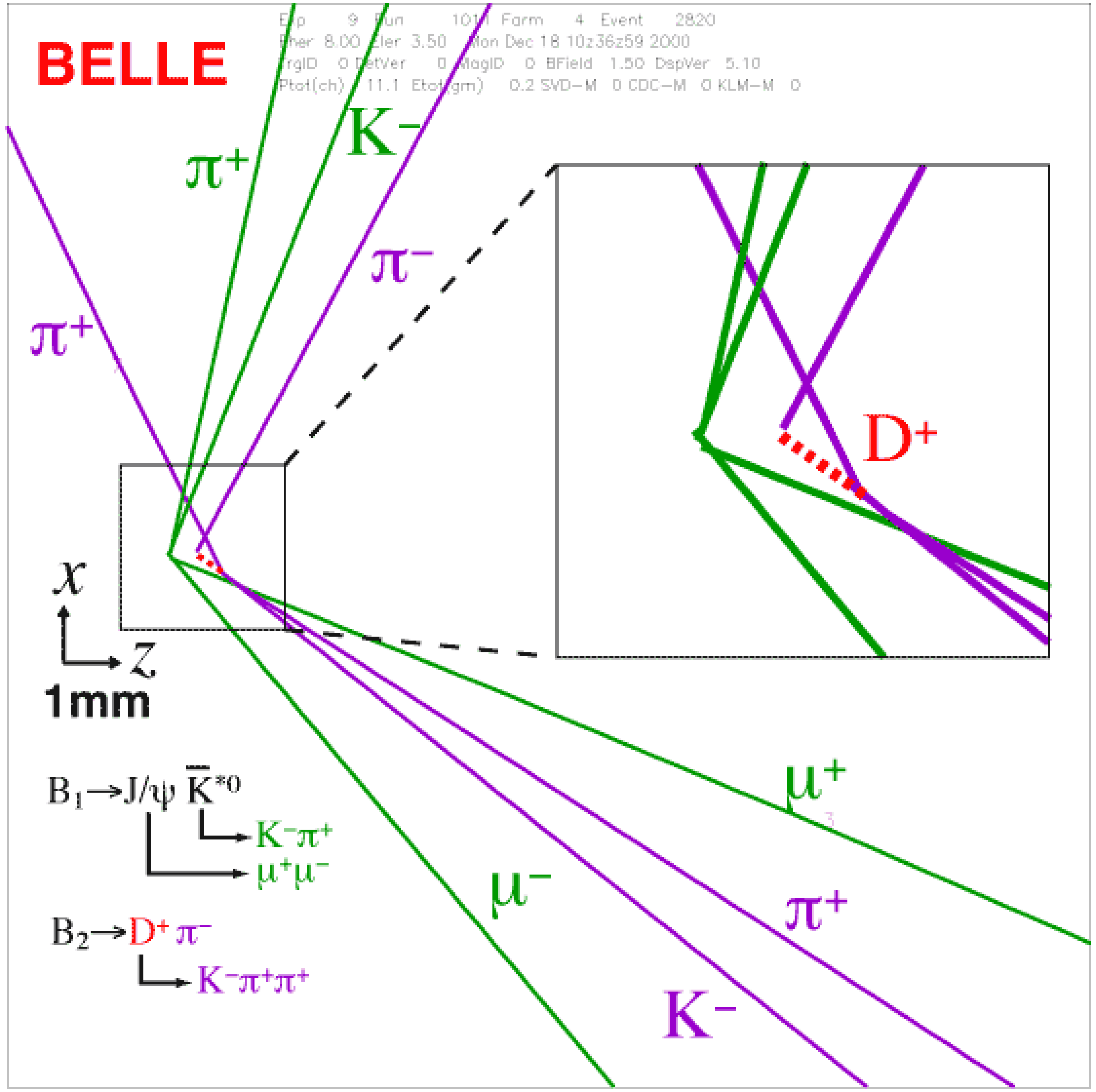
ACC (Aerogel Cherenkov counter)
TOF (plastic scintillator bars)
SC solenoid
1.5T
ECL
CsI(Tl) $16X_0$
3.5GeV e^+
8GeV e^-
CDC (drift chamber)
Tracking + dE/dx
small cell + He/C_2H_5
KLM (μ / K_L detection)
14/15 lyr. RPC+Fe
SVD (Si vtx. det. 3 lyr. DSSD)


P&H

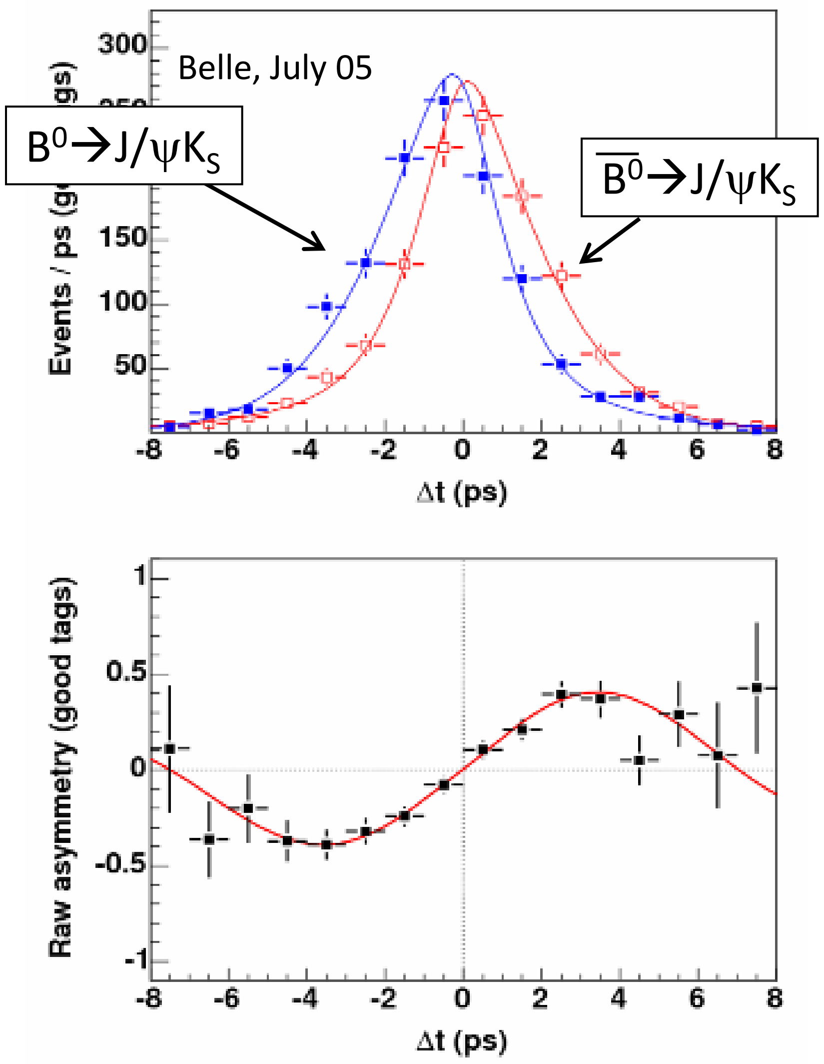
$$e^+ + e^- \rightarrow B_d + \overline{B}_d$$



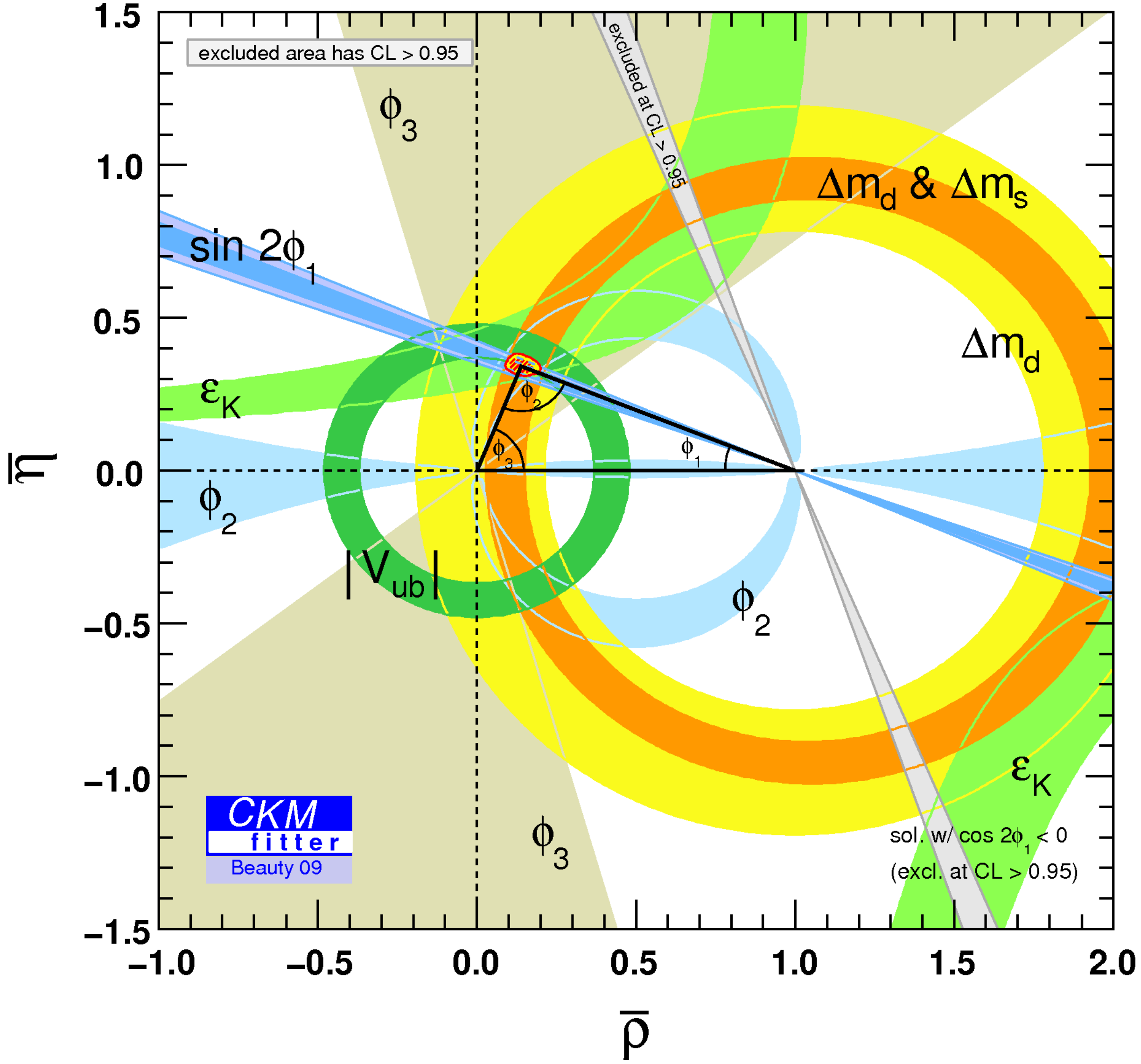

BELLE
Exp 9 Run 1011 Farm 4 Event 2820
Eher 8.00 Eler 3.50 Mon Dec 18 10z36z59 2000
TrgID 0 DetVer 0 MagID 0 BField 1.50 DspVer 5.10
Ptot(ch) 11.1 Etot(gm) 0.2 SVD-M 0 CDC-M 1 KLM-M 0
B1→J/ψ K̄*0
K−π+
μ+μ−
μ−
π+
π+
K−
K−
π+
μ+
π−
B2→D+π−
K−π+π+
20 cm



BELLE
9 Farm 4 Event 2820
8.00 3.50 Dec 18 10z36z59 2000
0 0 0 BField 1.50 DspVer 5.10
Ptot(ch) 11.1 0.2 SVD−M 0 CDC−M 0 KLM−M 0
π+
K−
π−
π+
D+
x
z
1mm
μ+
μ−
π+
K−
B1→J/ψ K̄*0
└→K−π+
└→μ+μ−
B2→D+ π−
└→K−π+π+



Belleグループ提供

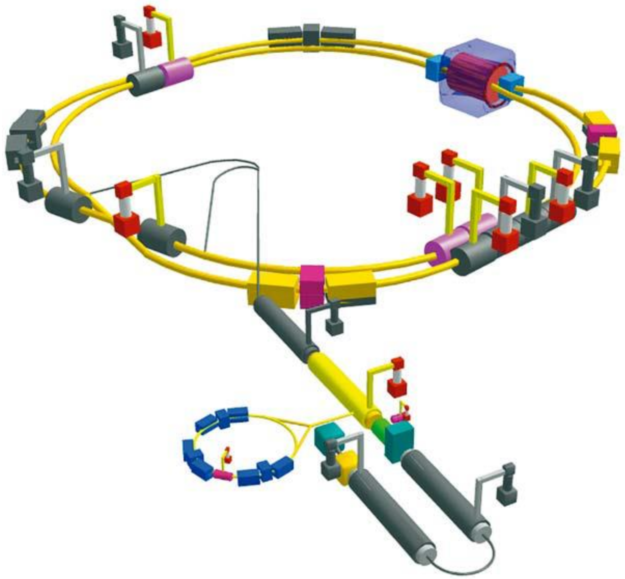


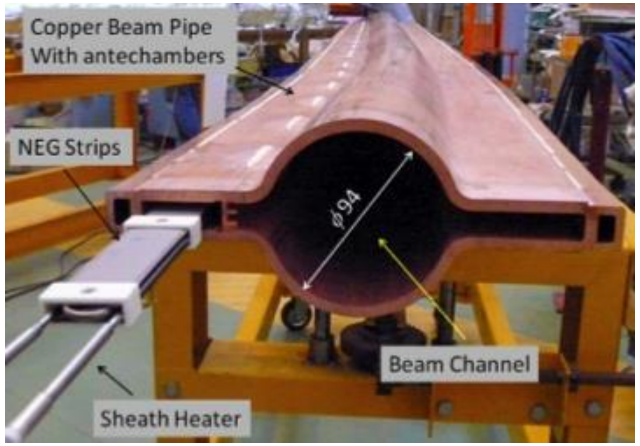
CKMfitter Group (J. Charles *et al.*),
Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184],
updated results and plots available at: http://ckmfitter.in2p3.fr

Super KEKB

40 times higher luminositiy

Commissioning starts in January 2016



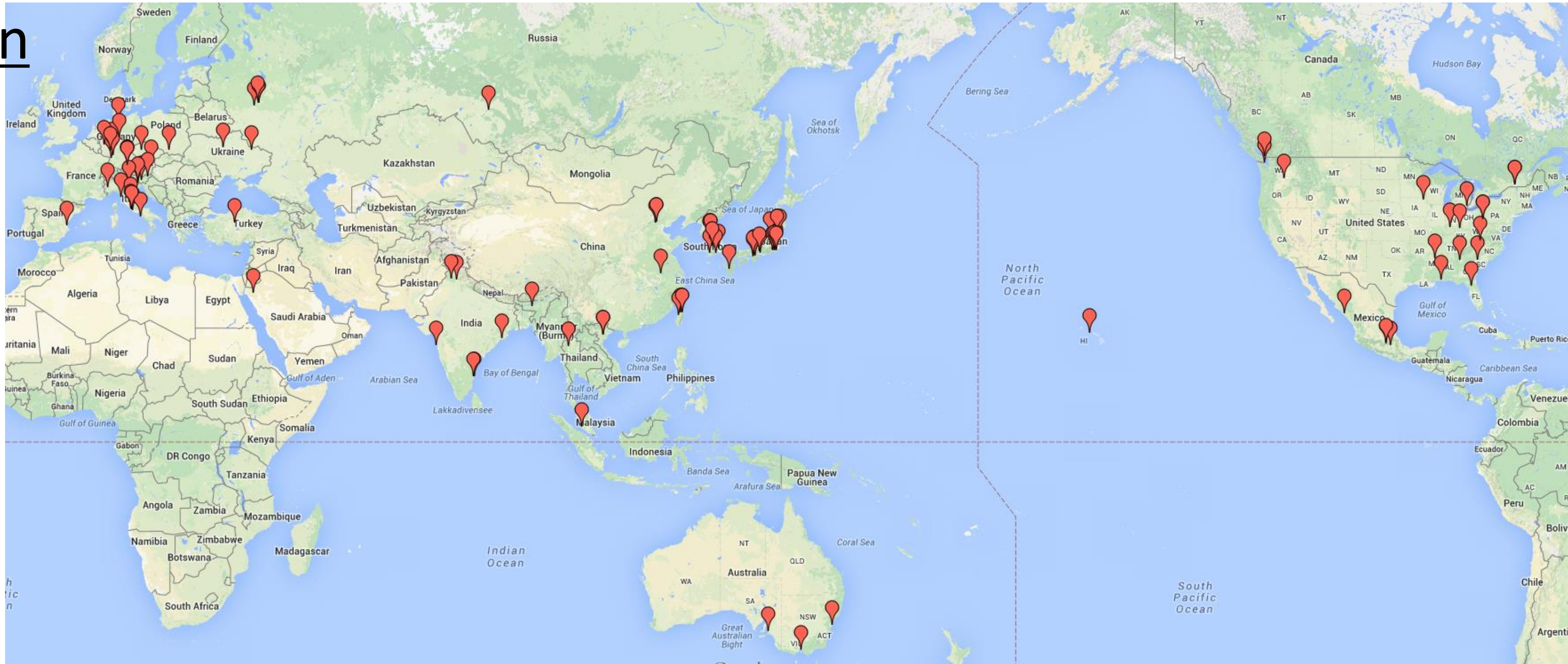


Belle-II Collaboration

23 countries/regions

99 institutions

>600 scientists



Big-Bang

The Universe was in a high-temperature high-density state

Particles and antiparticles coexisted

↓

Pair annihilation

↓

Matter was composed from remnant particles

$$\langle \mathbf{kT} \rangle >> \mathbf{mc}^2$$

$$\gamma + \gamma \rightarrow \mathbf{e}^- + \mathbf{e}^+$$

$$\gamma + \gamma \leftarrow \mathbf{e}^- + \mathbf{e}^+$$

How did number difference occur?

Sakharov's three conditions

- Baryon number non-conservation
- C and CP violation
- Imequilibrium

Present status of CP violation

- The standard model explains CP violation in both K-mesons and B-mesons

- The standard model, however, cannot explain the matter dominance of the Universe. There will be yet unknown particles and unknown CP violating interactions.