2010/05/28

CP Violation and B-factory Experiments

KEK and JSPS
M. Kobayashi

Discovery of Antiparticle

Special Relativity (1905)
Quantum Mechanics (1925)

1928 Dirac Dirac equation

→ Antiparticle

1932 Anderson Discovery of Positron

Relativistic Quantum Field Theory

Every particle has its corresponding antiparticle

- same mass
- opposite charge

Discovery of Parity Violation

1956 Lee, Yang

1957 Wu

$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

→ V-A Theory

- P and C are violated
- Still CP is conserved

1964 Cronin, Fitch et al

~0.2% of K_L decay into

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

$$CP\left|K_L\right\rangle = -\left|K_L\right\rangle \quad \Leftrightarrow \quad CP\left|\pi^+\pi^-\right\rangle = \left|\pi^+\pi^-\right\rangle$$

$$\eta_{+-} = \frac{A\left(K_L \rightarrow \pi^+\pi^-\right)}{A\left(K_S \rightarrow \pi^+\pi^-\right)} = \varepsilon + \varepsilon'$$

$$\eta_{00} = \frac{A\left(K_L \rightarrow \pi^0\pi^0\right)}{A\left(K_S \rightarrow \pi^0\pi^0\right)} = \varepsilon - 2\varepsilon'$$

$$\left|\varepsilon\right| = 2.23\times10^{-3}$$

$$\mathrm{Re}\,\varepsilon'/\varepsilon = 1.65\times10^{-3}$$

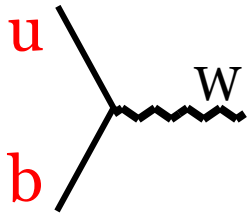
1973 Kobayashi, Maskawa

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



Why do complex coupling constants violate CP?

- Coupling Constants

particle	antiparticle
ϕ	ϕ^*
g	g^*

- Schrodinger Equation

$$i\hbar \frac{\partial}{\partial t}\psi(x) = H\psi(x)$$

$\longrightarrow$ $e^{-iEt/\hbar}$

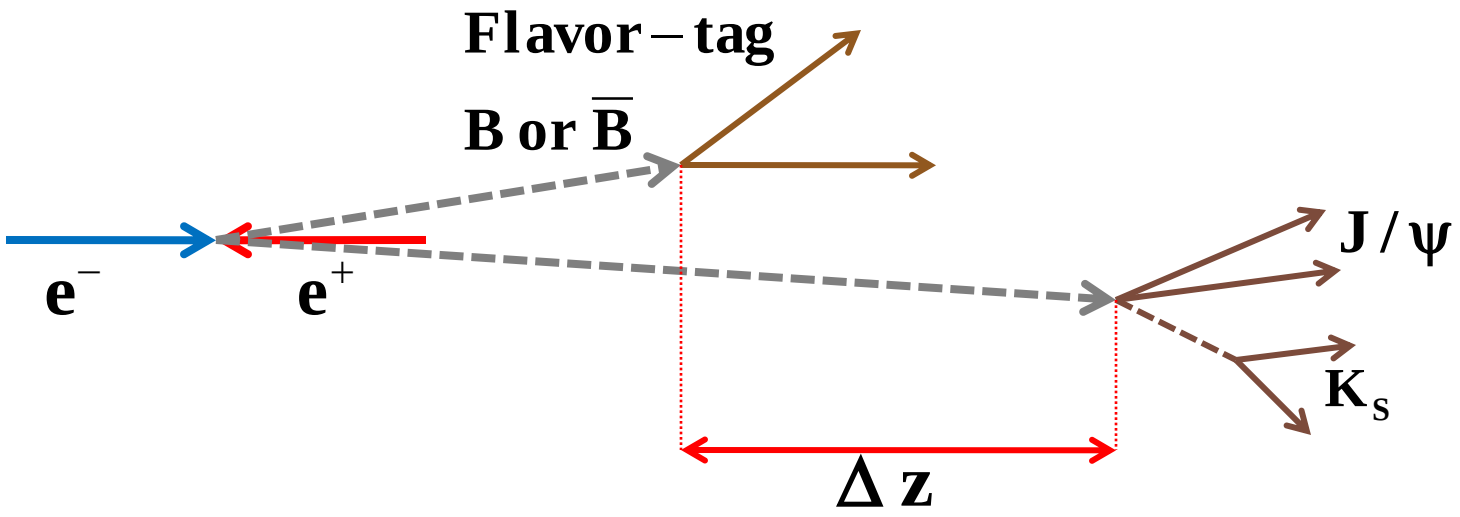
- 1974 discovery of J/ψ ⟶ c-quark
- 1975 discovery of τ-lepton
- 1977 discovery of Y ⟶ b-quark
- 1995 discovery of t-quark

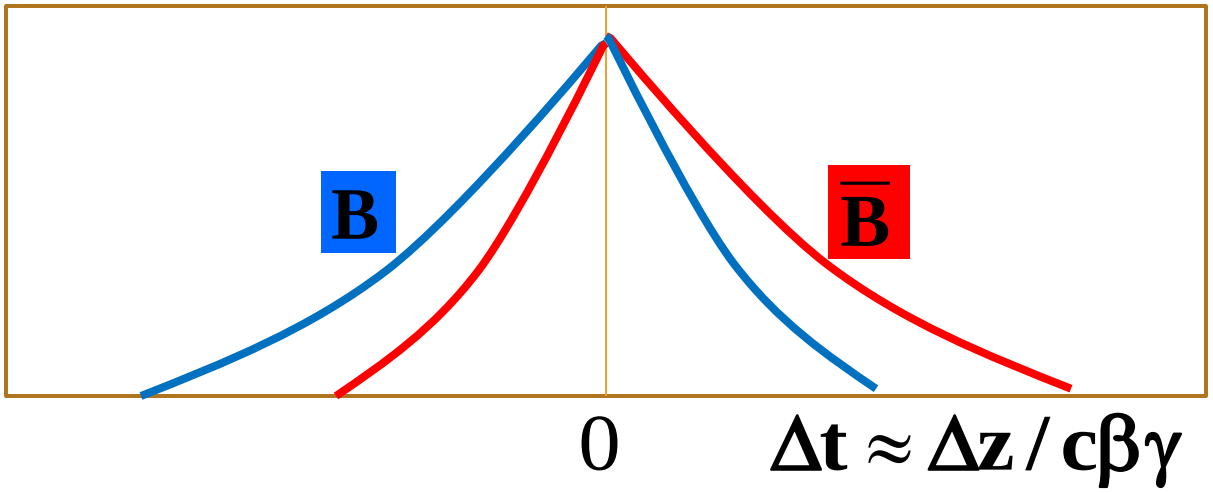
Large CP asymmetry in the B-meson system

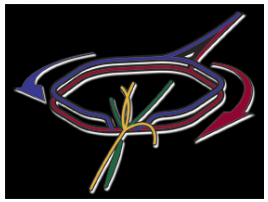
$$B_d \to J/\psi + K_S \quad \longleftrightarrow \quad \overline{B}_d \to J/\psi + K_S$$

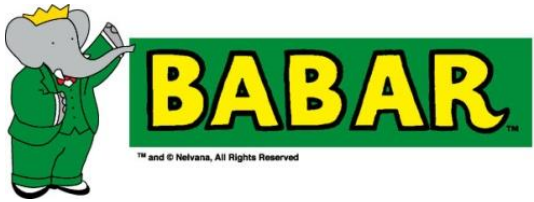
Asymmetry in decay time distribution

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





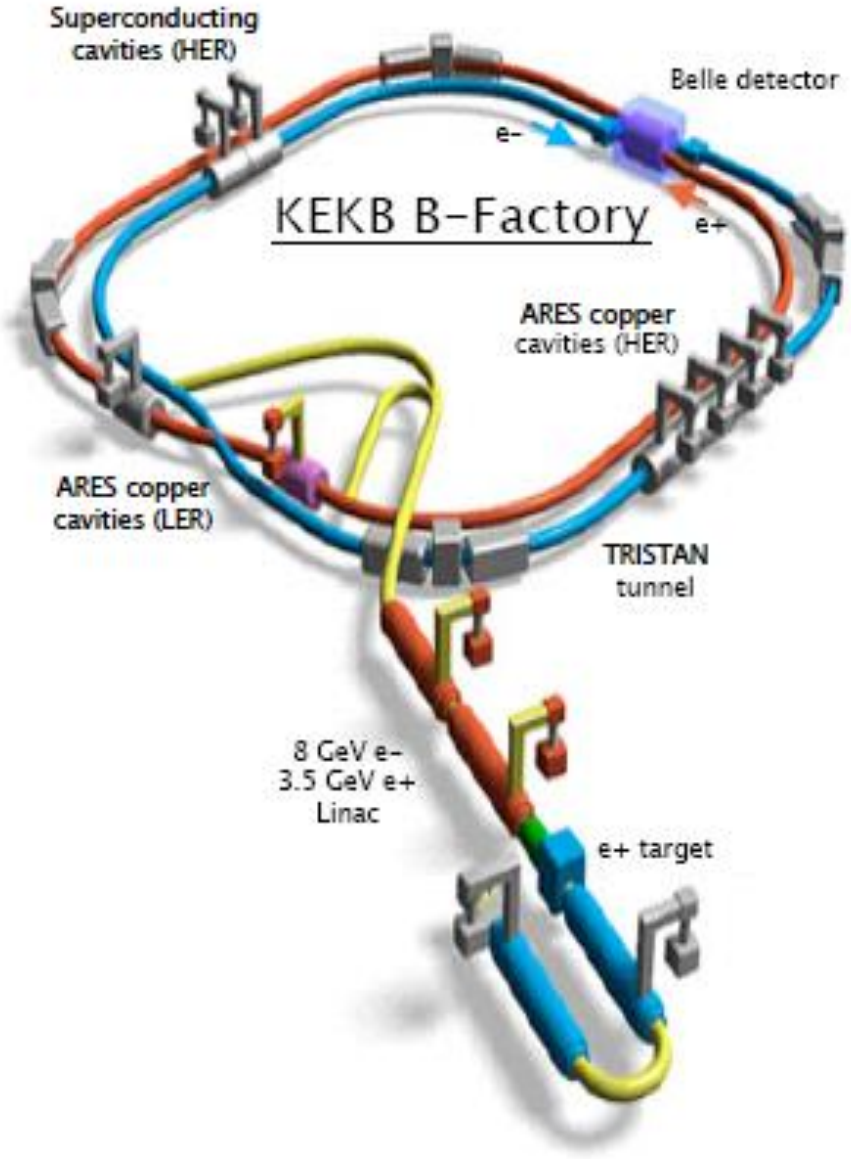


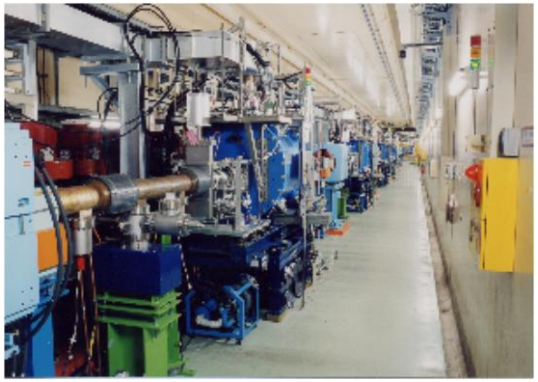


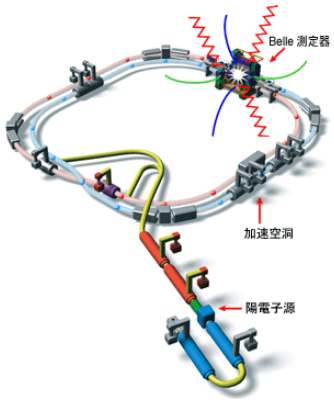
KEKB/Belle (Japan)

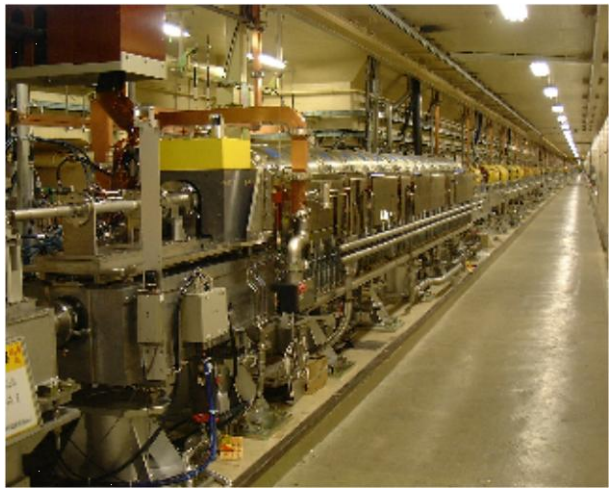
PEP-II/BaBar (US)

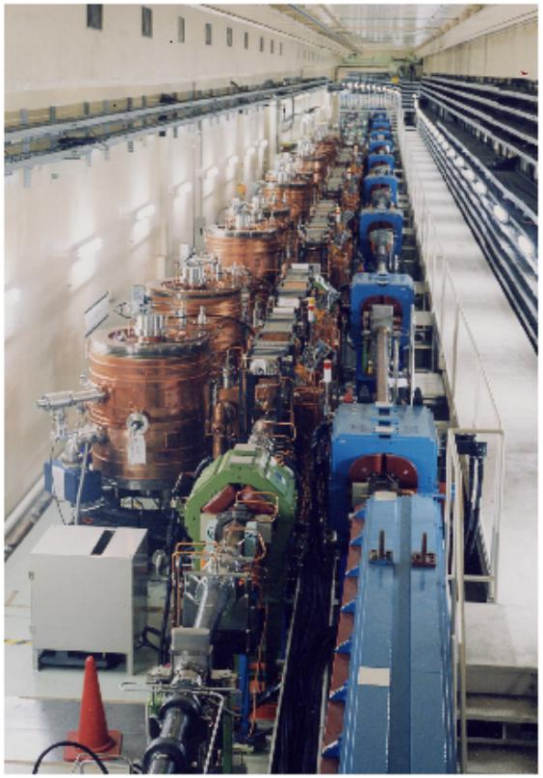
KEKB/Belle (Japan)	Feature	PEP-II/BaBar (US)
$E(e^-)$=8GeV, $E(e^+)$=3.5GeV Finite angle beam crossing		$E(e^-)$=9GeV, $E(e^+)$=3.1GeV Zero angle beam crossing
1994	Governmental Approval	1993
May 1999 – still running	Experiment	May 1999 – Apr. 2008

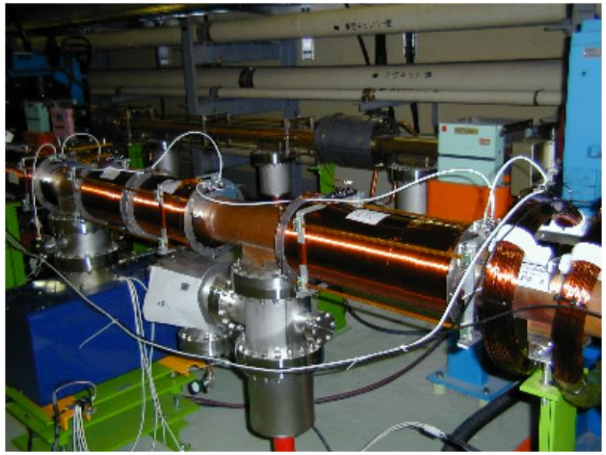

Superconducting
cavities (HER)
Belle detector
e–
KEKB B–Factory
e+
ARES copper
cavities (HER)
ARES copper
cavities (LER)
TRISTAN
tunnel
8 GeV e–
3.5 GeV e+
Linac
e+ target

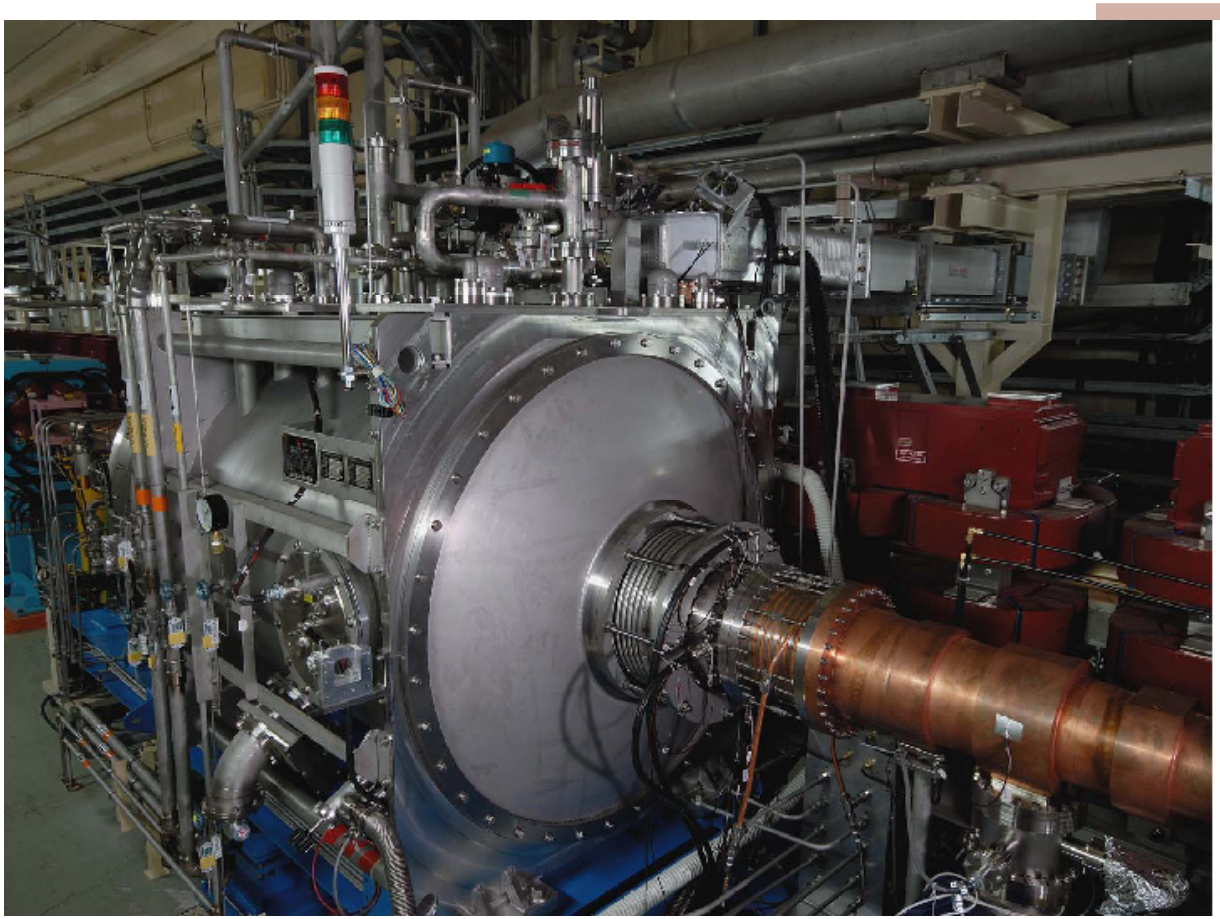


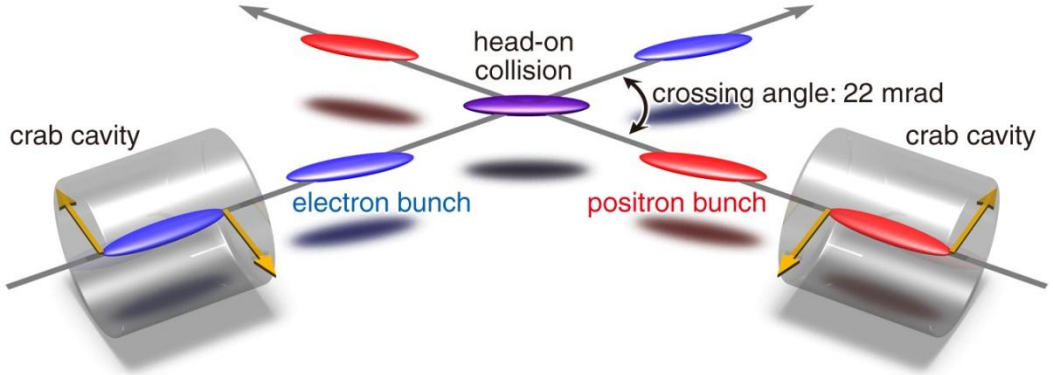

Belle 測定器
加速空洞
陽電子源

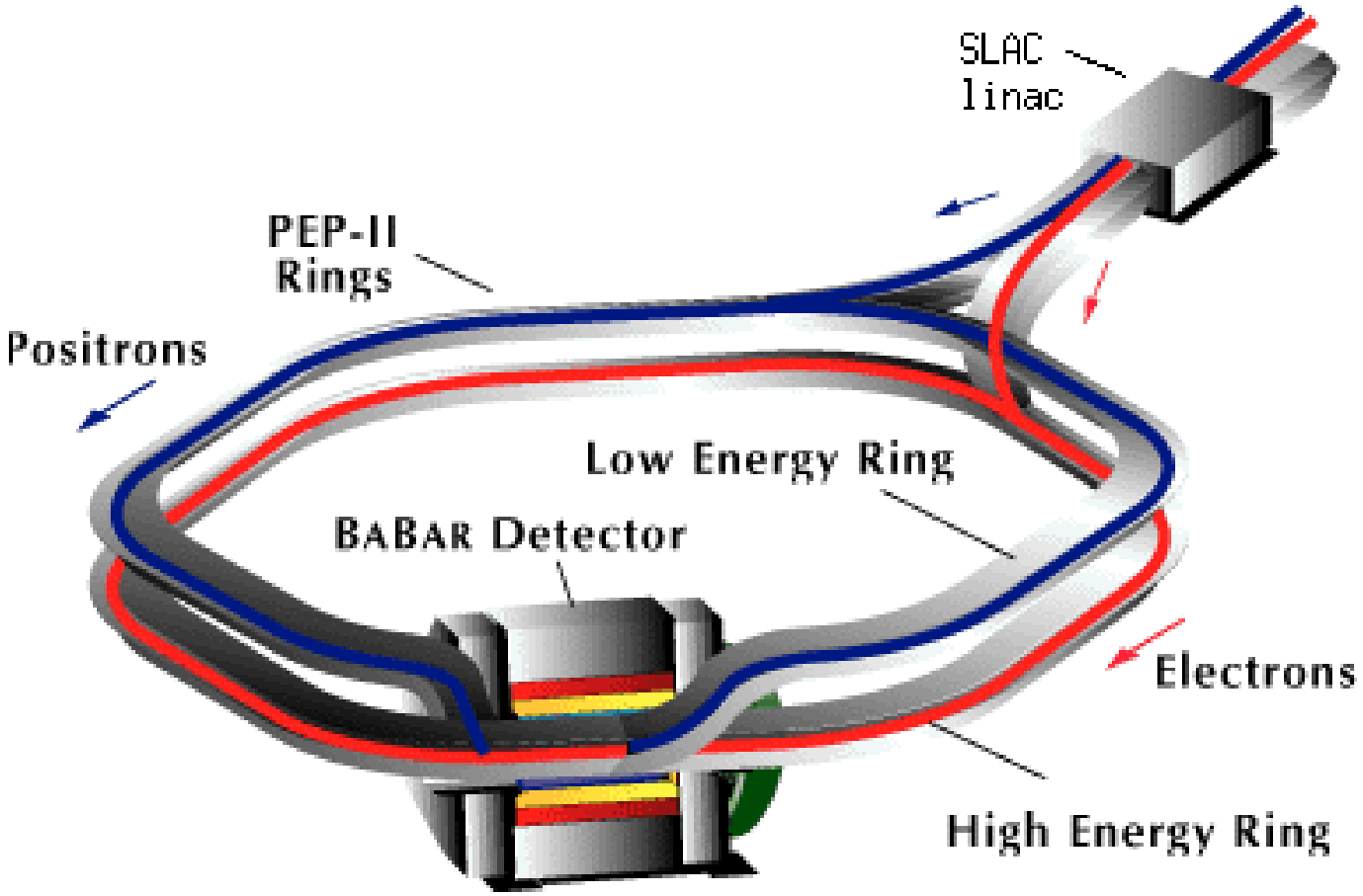






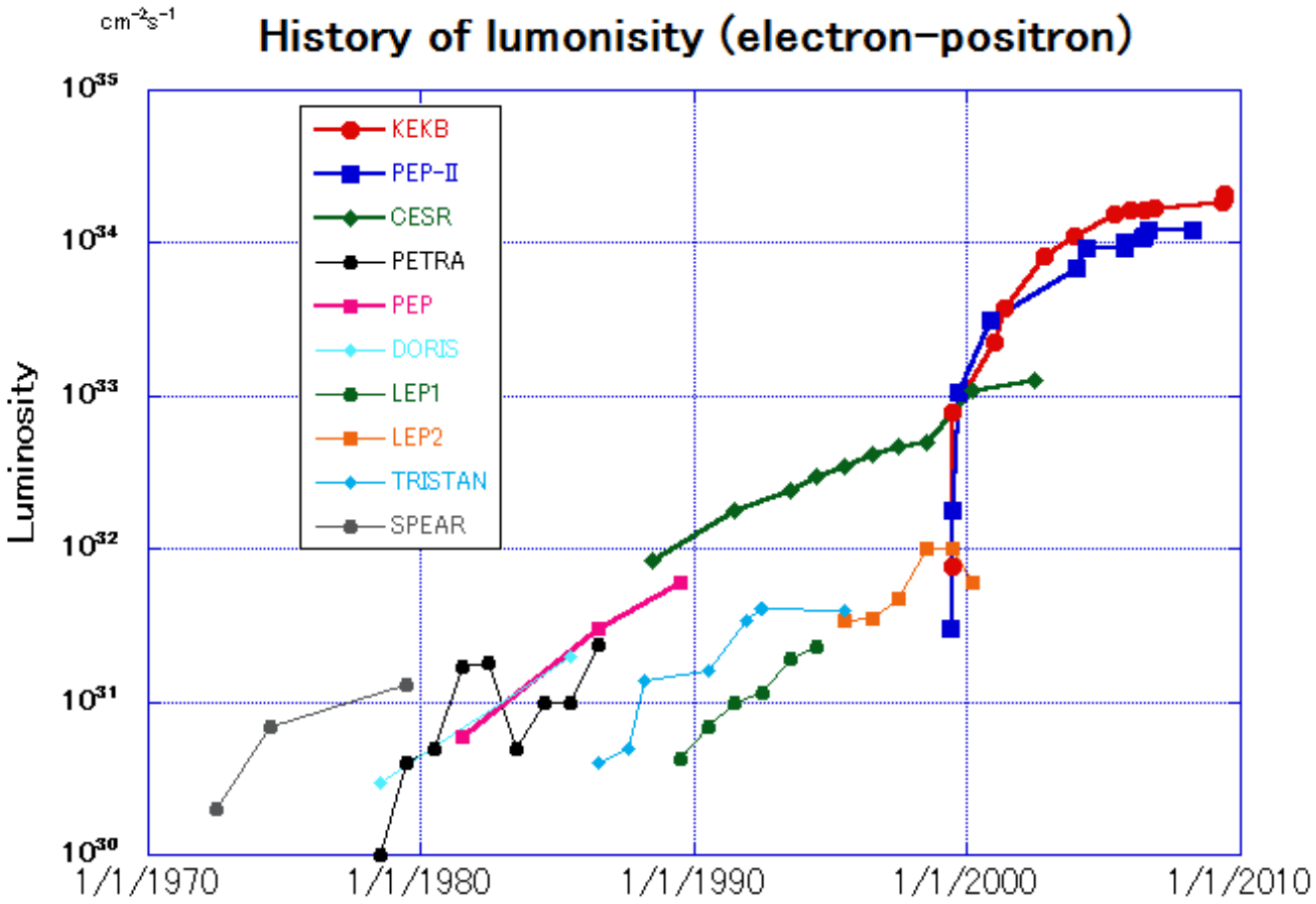


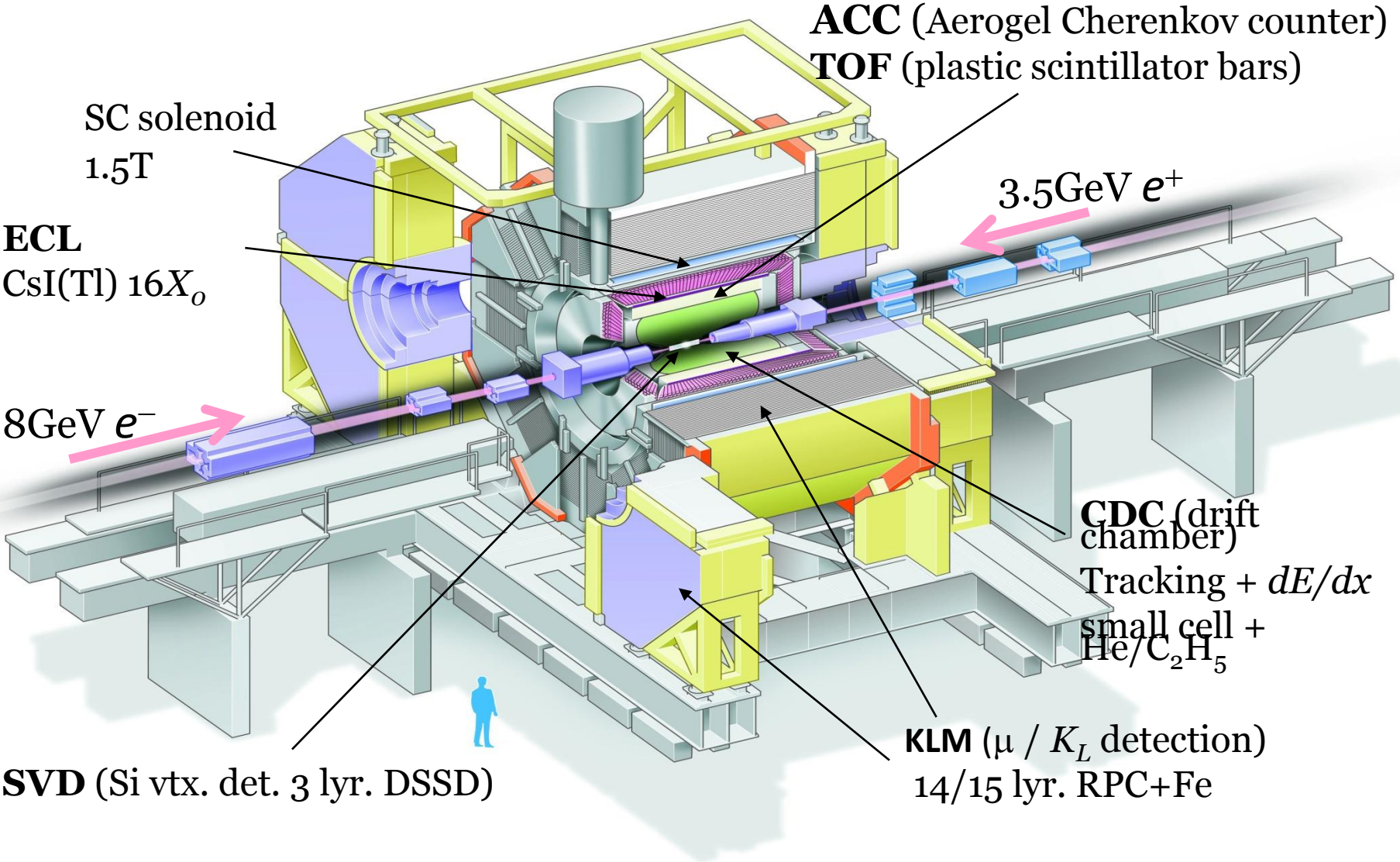

head-on
collision
crossing angle: 22 mrad
crab cavity
crab cavity
electron bunch
positron bunch

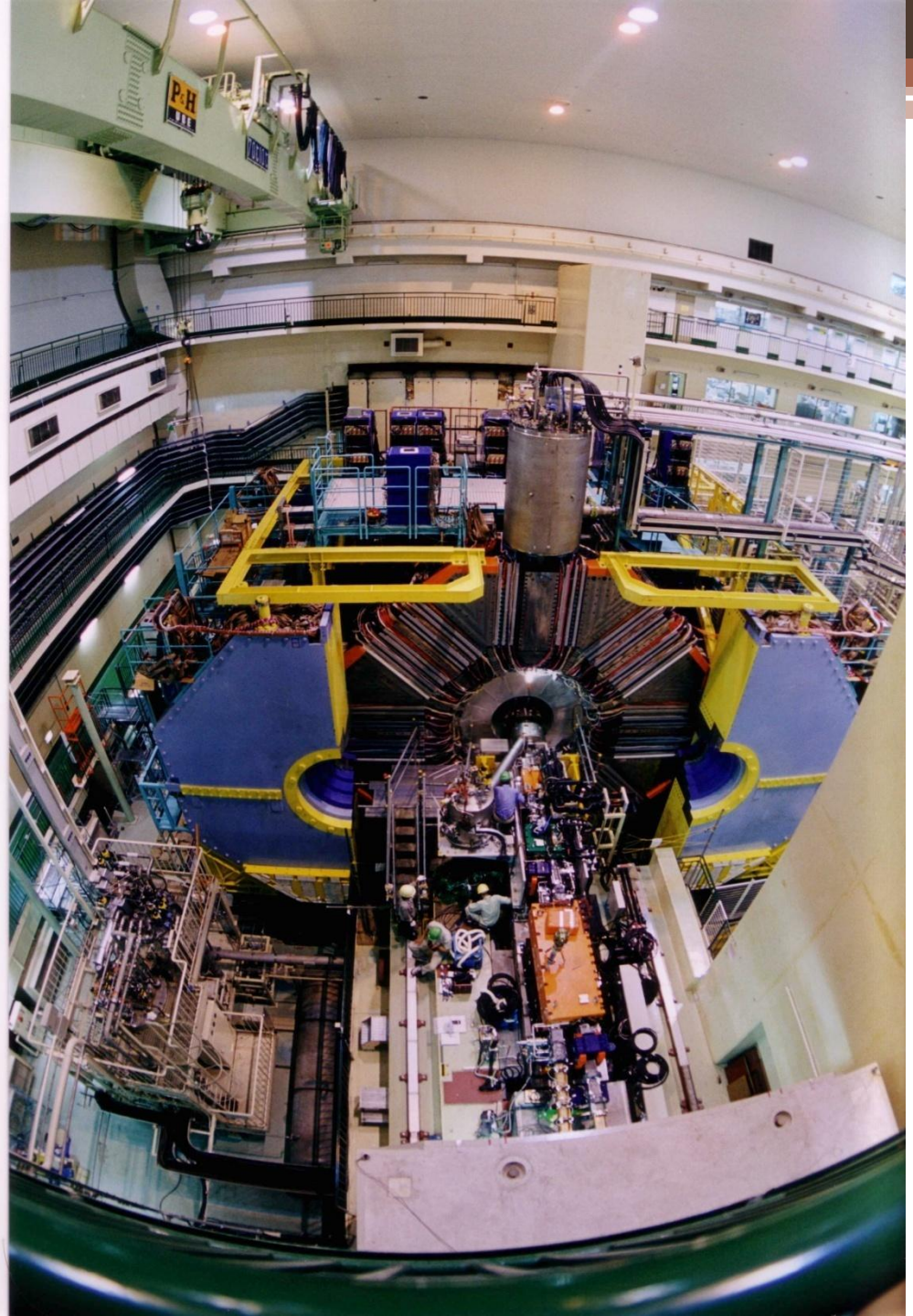

SLAC
linac
PEP-II
Rings
Positrons
Low Energy Ring
BABAR Detector
Electrons
High Energy Ring

KEKB $L = 2.1 \times 10^{34} cm^{-2} \sec^{-1}$

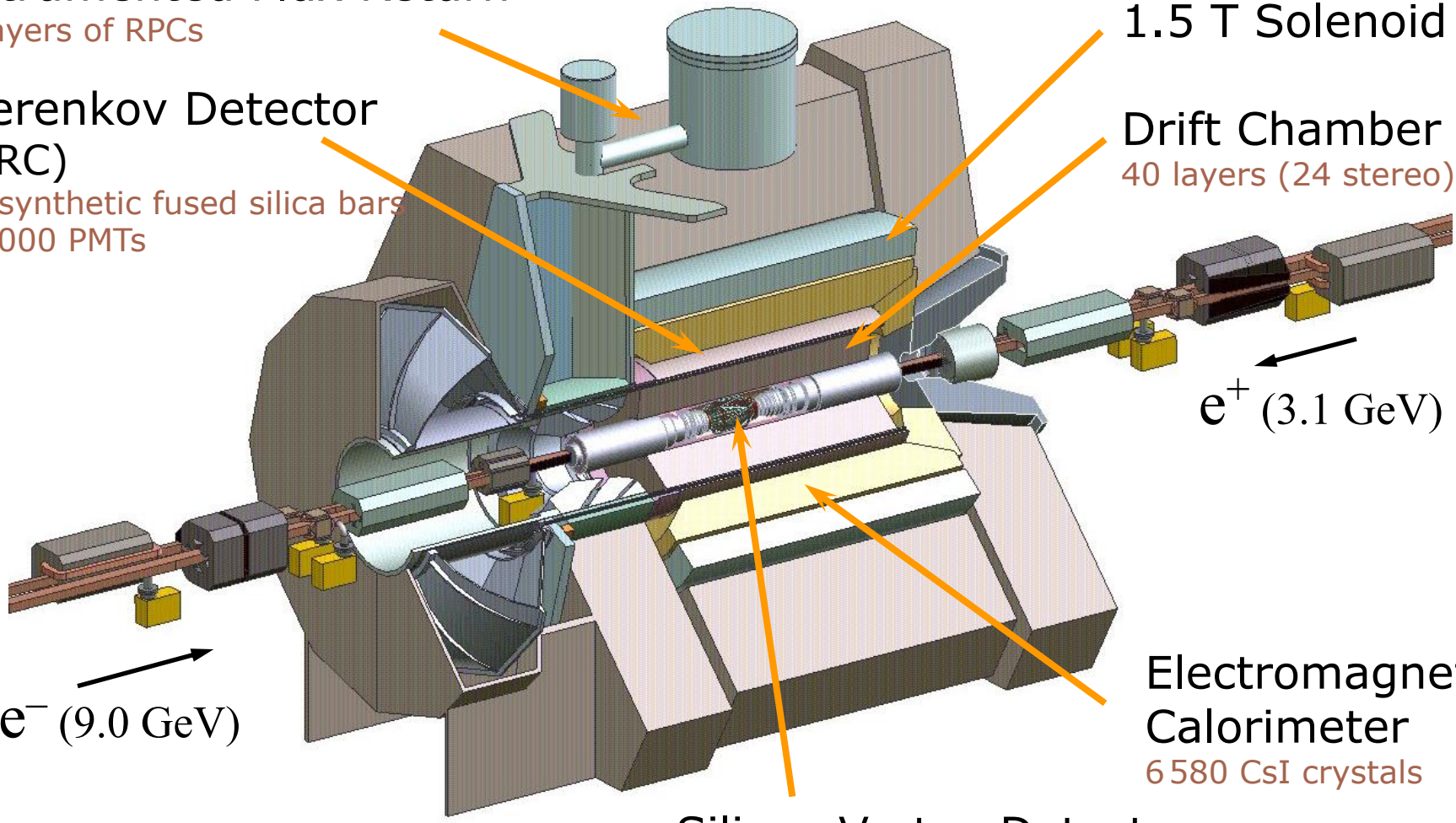
PEP-II $L = 1.2 \times 10^{34} cm^{-2} \sec^{-1}$

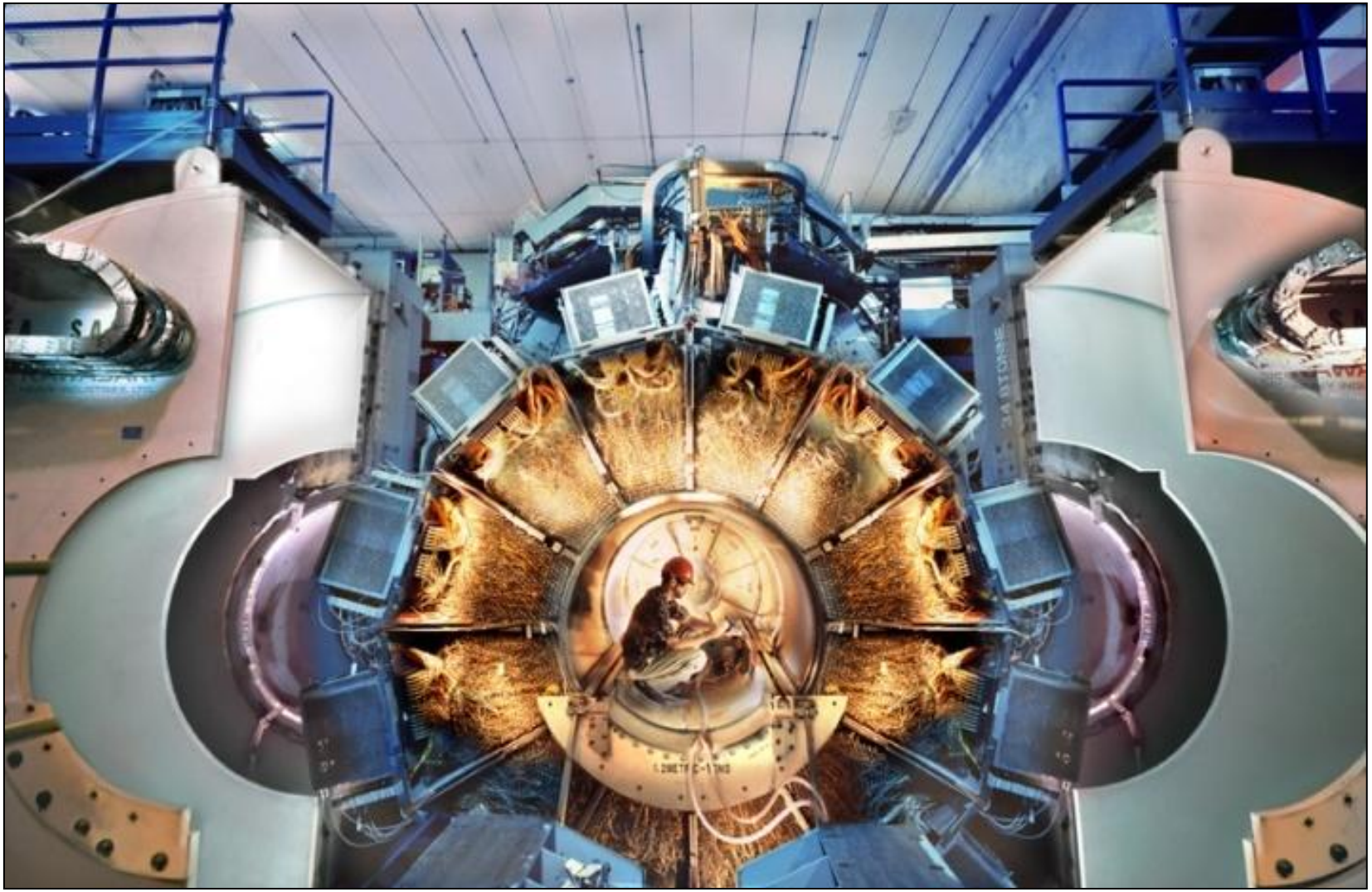


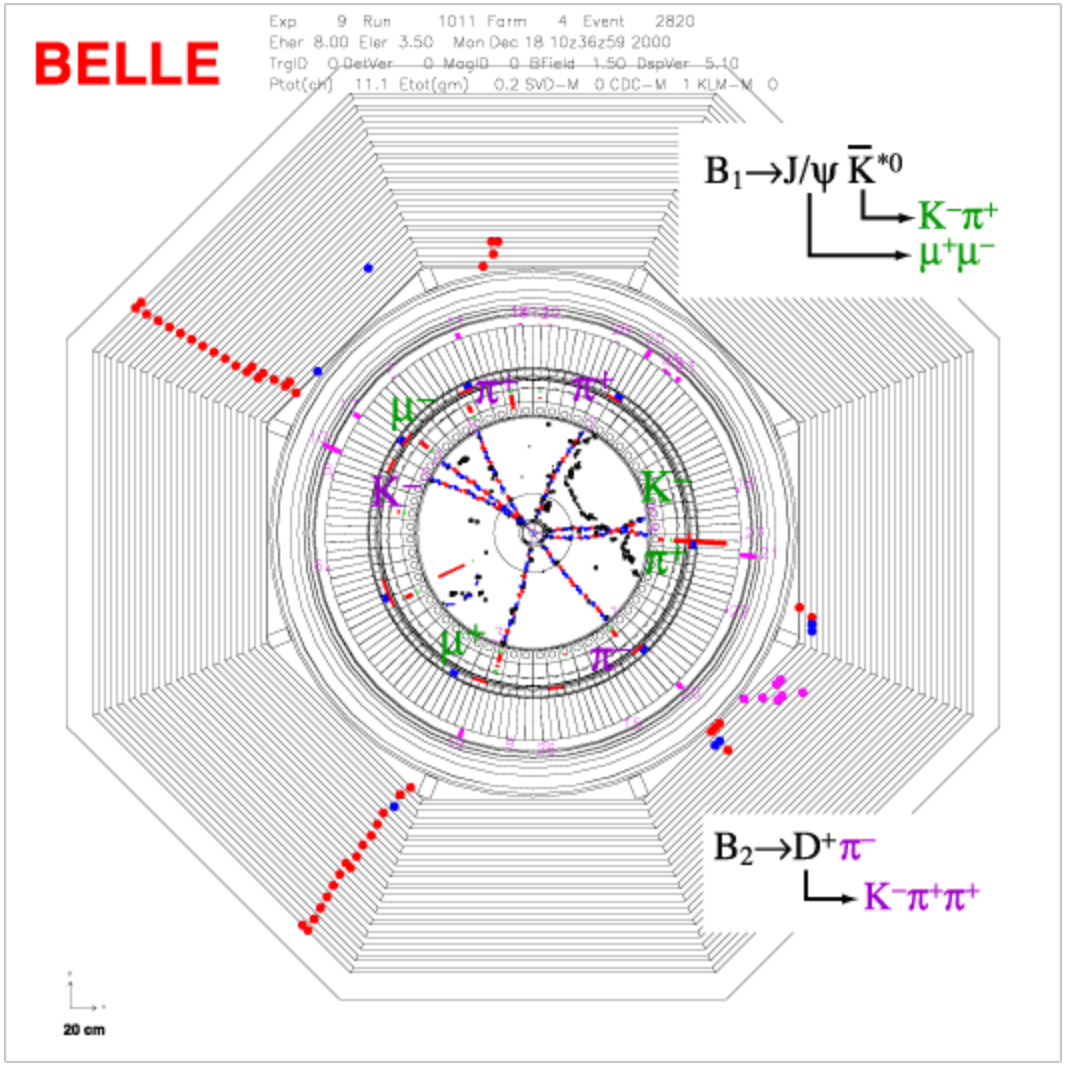

ACC (Aerogel Cherenkov counter)
TOF (plastic scintillator bars)
SC solenoid
1.5T
3.5GeV e^+
ECL
CsI(Tl) $16X_o$
8GeV e^-
CDC (drift chamber)
Tracking + dE/dx
small cell +
He/C_2H_5
KLM (μ / K_L detection)
14/15 lyr. RPC+Fe
SVD (Si vtx. det. 3 lyr. DSSD)

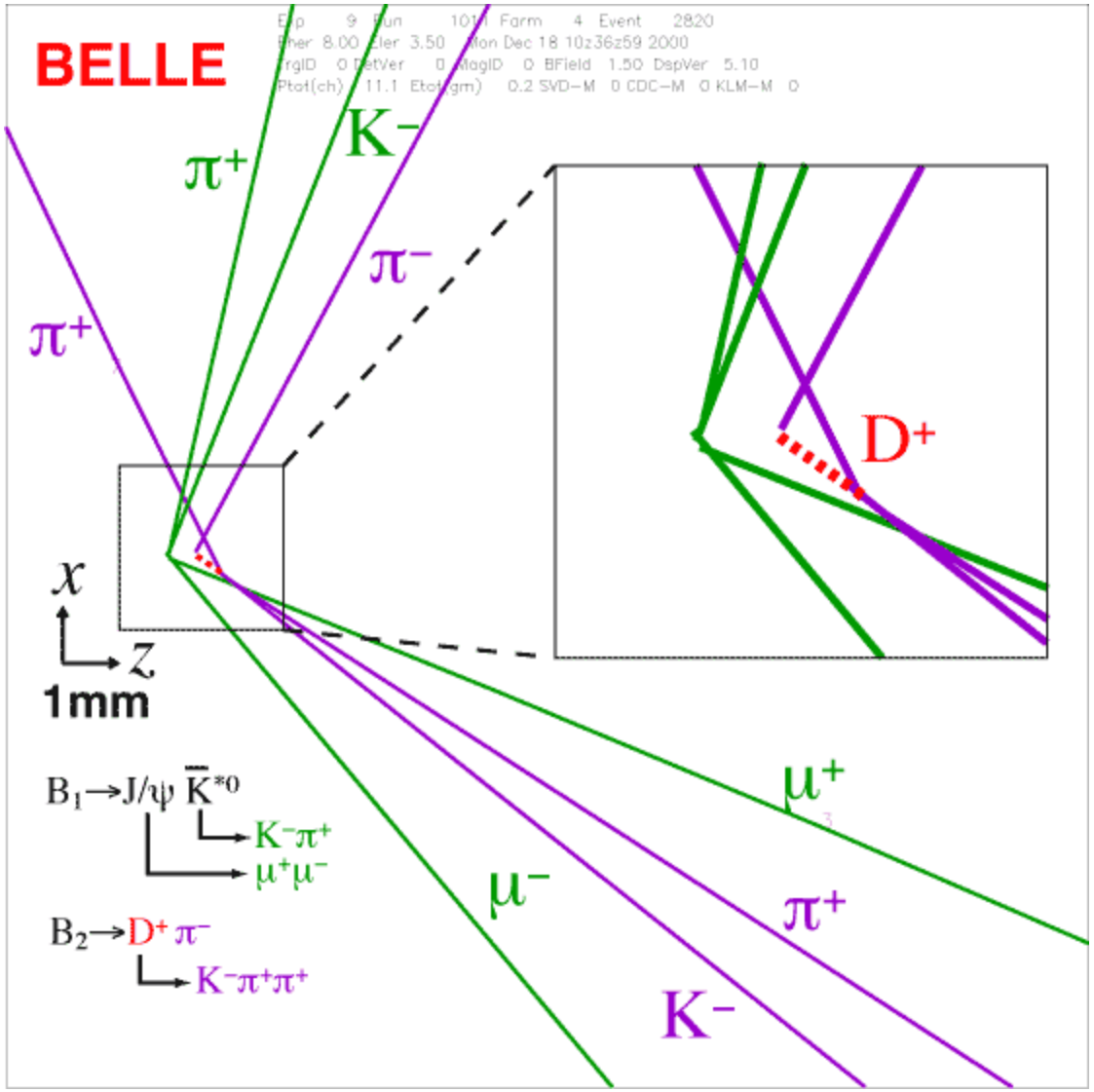


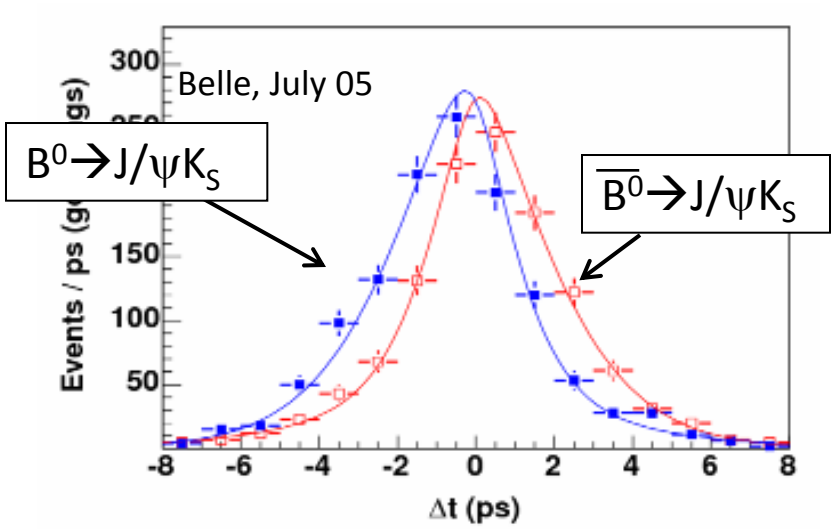
The BaBar detector

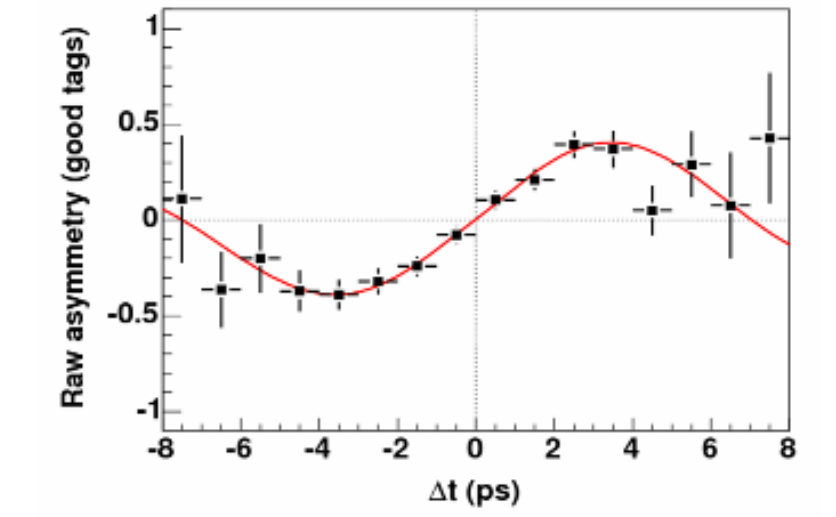


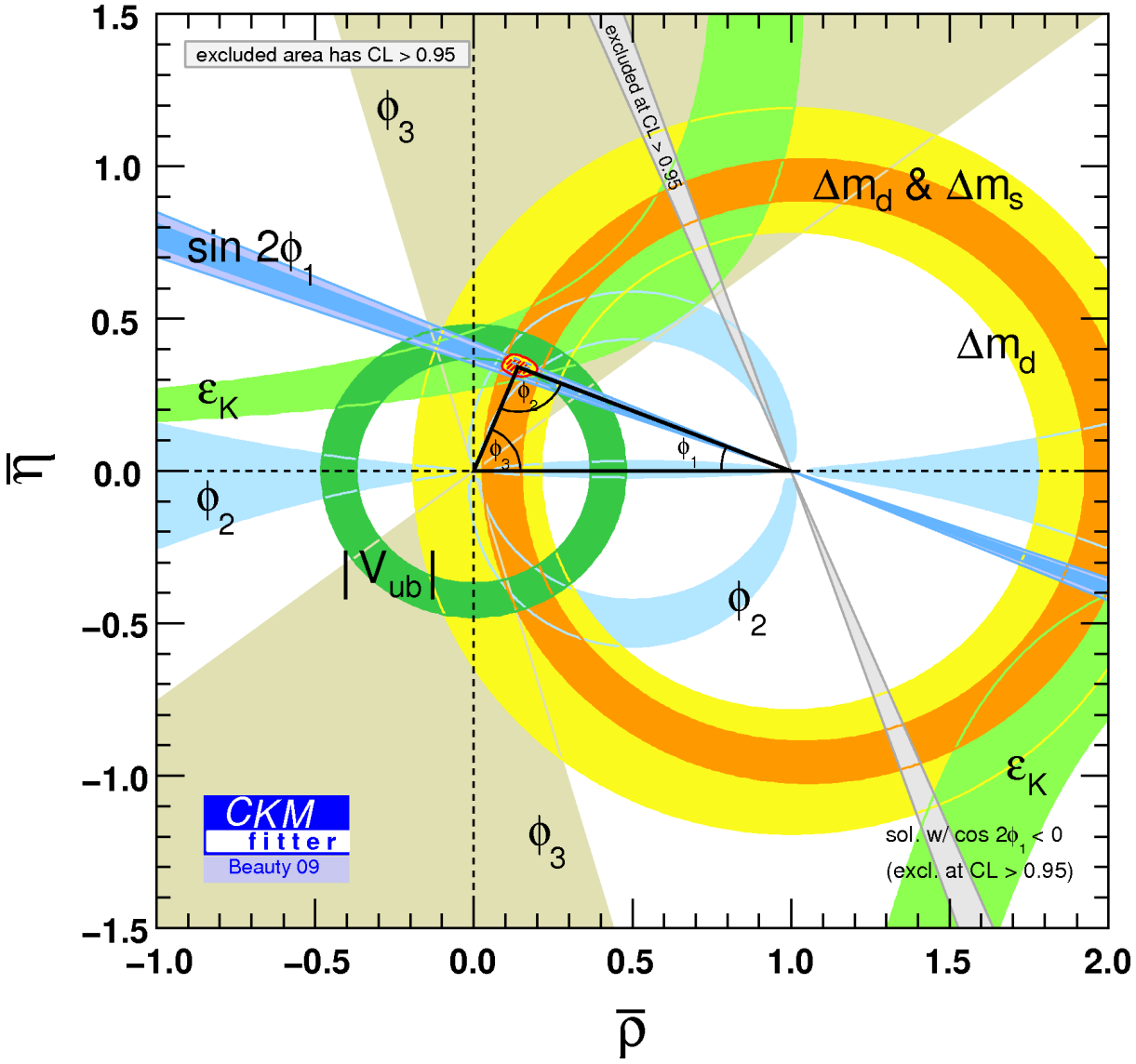



BELLE
Exp 9 Run 1011 Farm 4 Event 2820
Ebeam 8.00 Elec 3.50 Mon Dec 18 10:36:59 2000
TrgID 0 DetVer 0 MagID 0 BField 1.50 DspVer 5.10
Ptot(ch) 11.1 Etot(gm) 0.2 SVD-M 0 CDC-M 1 KLM-M 0
B1→J/ψ K̄*0
K⁻π⁺
μ⁺μ⁻
B2→D⁺π⁻
K⁻π⁺π⁺
μ⁻
π⁻
π⁺
K⁻
K⁻
π⁺
μ⁺
π⁻
20 cm


BELLE
Exp 9 Run 1011 Farm 4 Event 2820
Pher 8.00 Eler 3.50 Mon Dec 18 10:36:59 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 0 KLM-M 0
π+
K−
π−
π+
D+
x
z
1mm
B1→J/ψ K̄*0
K−π+
μ+μ−
B2→D+ π−
K−π+π+
μ+
μ−
π+
K−


Belle, July 05
$B^0 \to J/\psi K_S$
$\overline{B}^0 \to J/\psi K_S$
Events / ps
300
150
100
50
-8
-6
-4
-2
0
2
4
6
8
Δt (ps)


Raw asymmetry (good tags)
1
0.5
0
-0.5
-1
-8
-6
-4
-2
0
2
4
6
8
Δt (ps)



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

Present status of CP violation

- The Standard Model explains the dominant part of 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.

- Hints of slight deviation from the Standard Model are observed in the B-factory experiments.

Congratulations for

- the great accomplishment of SLAC and KEK in construction and operation of the B-factories with the luminosity of the record high,

- the success of BaBar and Belle in verifying the CP violation mechanism of the Standard Model.