B Factories

- search for the origin of CP violation -

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B-factory:
e^+e^- collider running on $\Upsilon 4S$

$\Upsilon 4S$ (made of $b\bar{b}$ quark pairs) $\to B^0\bar{B}^0$, B^+B^-

Main goal:
Study of CP violation.

$<e^+e^-$ **B-factory accelerators** $>$

$e^+e^- \to \Upsilon 4S(10.58GeV) \to B^0\bar{B}^0$ or B^+B^-

B pairs nearly at rest in $\Upsilon 4S$

Symmetric energies

(CESR at Cornell)

$$E_{e^-} = E_{e^+} = \frac{M_{\Upsilon 4S}}{2} = 5.29GeV$$

Asymmetric energies

(PEP-II at Stanford, KEK-B at Tsukuba)

$$\xrightarrow{\qquad\qquad E_{e^-} \qquad\qquad}\xleftarrow{\qquad E_{e^+} \qquad}$$

$\Upsilon 4S$ (and B's) is moving in the lab frame.
$\to$ B decay time measurements (Why? Later.)

$$E_{\mathrm{CM}} = 2\sqrt{E_{e^+}E_{e^-}} = M_{\Upsilon 4S}$$

$$\begin{cases} E_{\Upsilon 4S} = E_{e^-} + E_{e^+} \\ P_{\Upsilon 4S} = E_{e^-} - E_{e^+} \end{cases}$$

$$\to \qquad \beta_{\Upsilon 4S} = \frac{P_{\Upsilon 4S}}{E_{\Upsilon 4S}} = \frac{E_{e^-} - E_{e^+}}{E_{e^-} + E_{e^+}}$$

Beam separation

Charge in each beam bunch cannot be too large
$\rightarrow$ **many bunches**

Want collision to occur only at one location
$\rightarrow$ **beam separation**
(avoid parasitic crossings)

CESR: Pretzel orbit
Interweaving e^+e^- orbits within a single ring
Crossing angle $= \pm 2.3$ mrad

PEP-II: Separation by bending magnet

$$E_{e^+} \neq E_{e^-}$$

$\rightarrow e^+, e^-$ beams bend differently

Head-on collision

KEK-B: Finite-angle crossing
Crossing angle $= \pm 11$ mrad

Large crossing angle

$\rightarrow$ Beam instability
Luminosity reduction (geometrical)

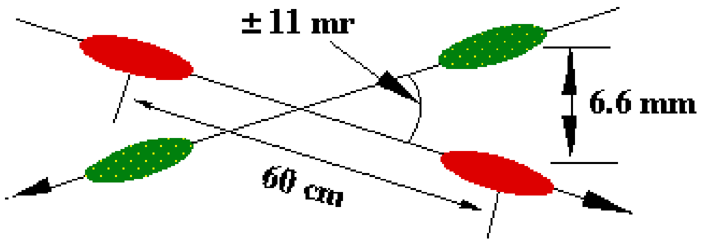
Looks OK for now.

Crab crossing

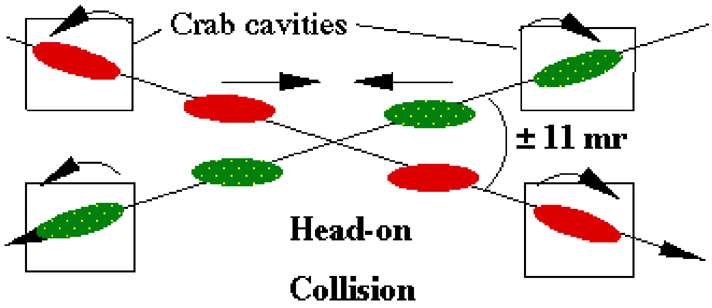
(KEK-B: installation in a few years)

In case finite-angle crossing causes problems

□ Without crab cavities

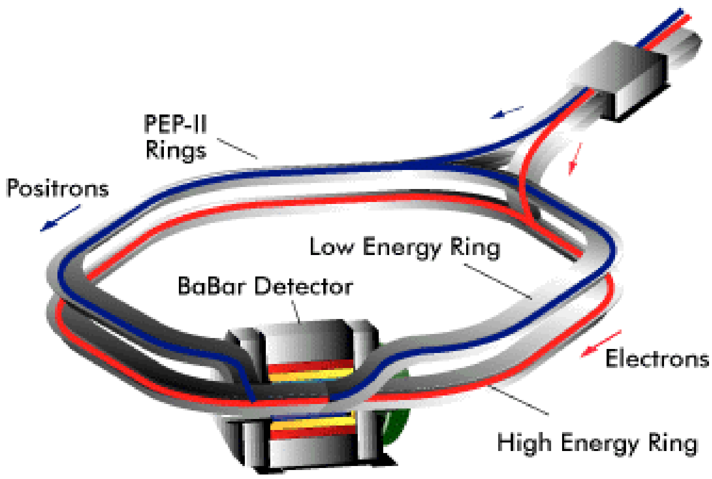


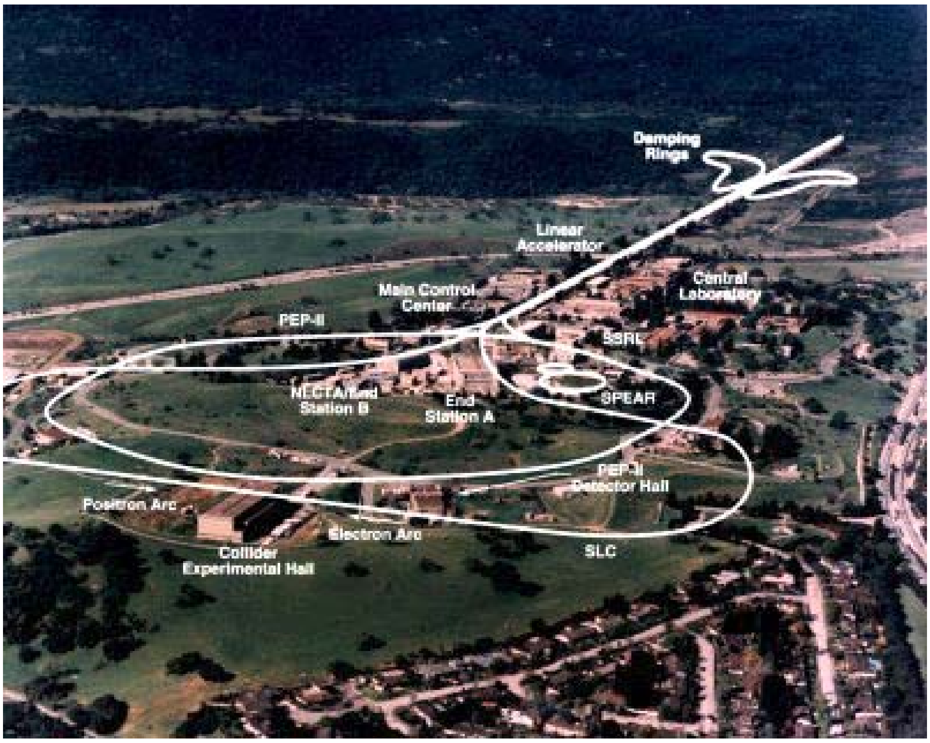
□ With crab cavities



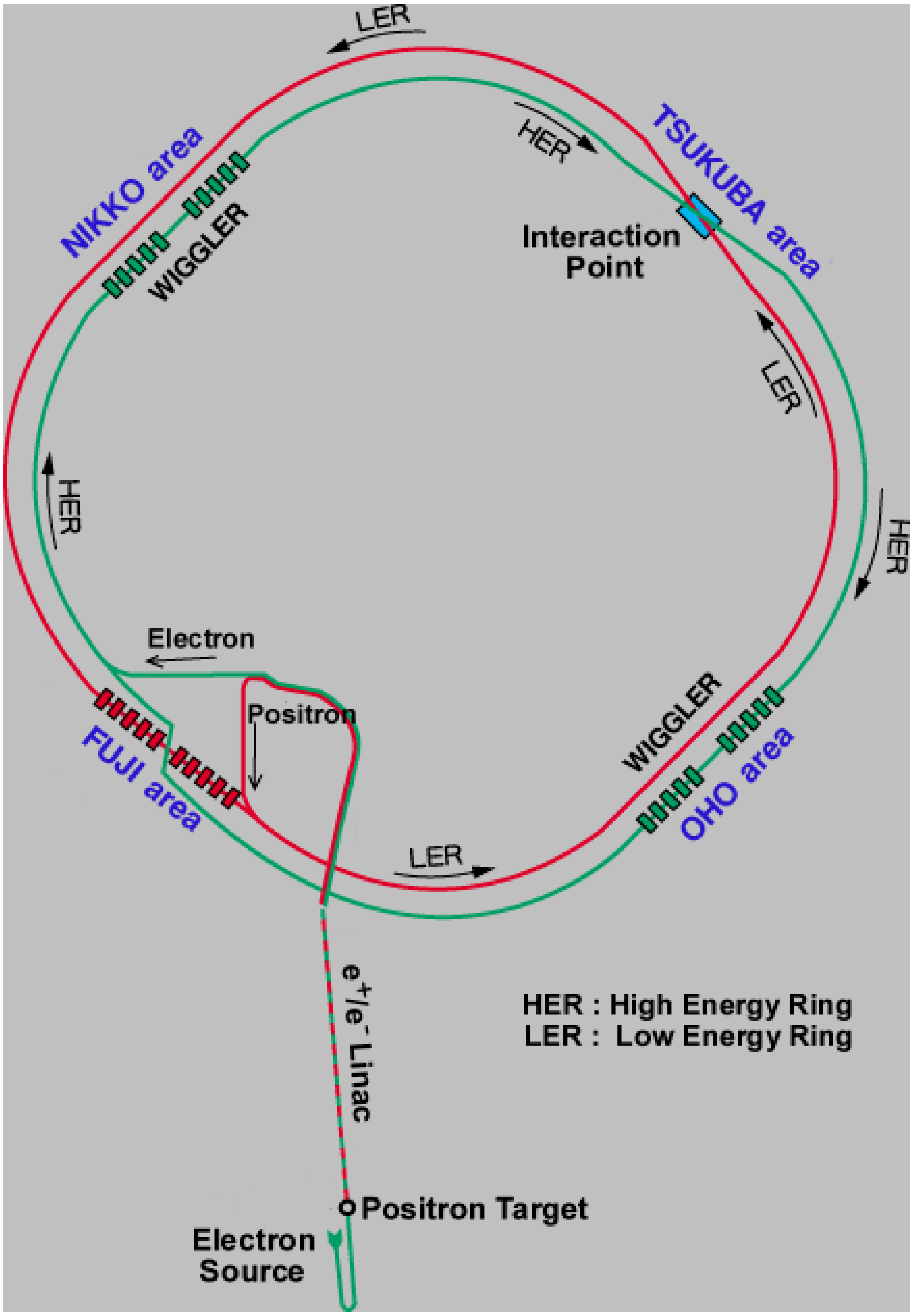
→ complete overlap of beams
(No geometrical luminosity loss.
Suppresses beam-beam instability)

PEP-II (SLAC)


PEP-II
Rings
Positrons
Low Energy Ring
BaBar Detector
Electrons
High Energy Ring


Damping
Rings
Linear
Accelerator
Central
Laboratory
Main Control
Center
PEP-II
SSRL
SPEAR
End
Station A
PEP-II
Detector Hall
Positron Arc
Electron Arc
SLC
Collider
Experimental Hall

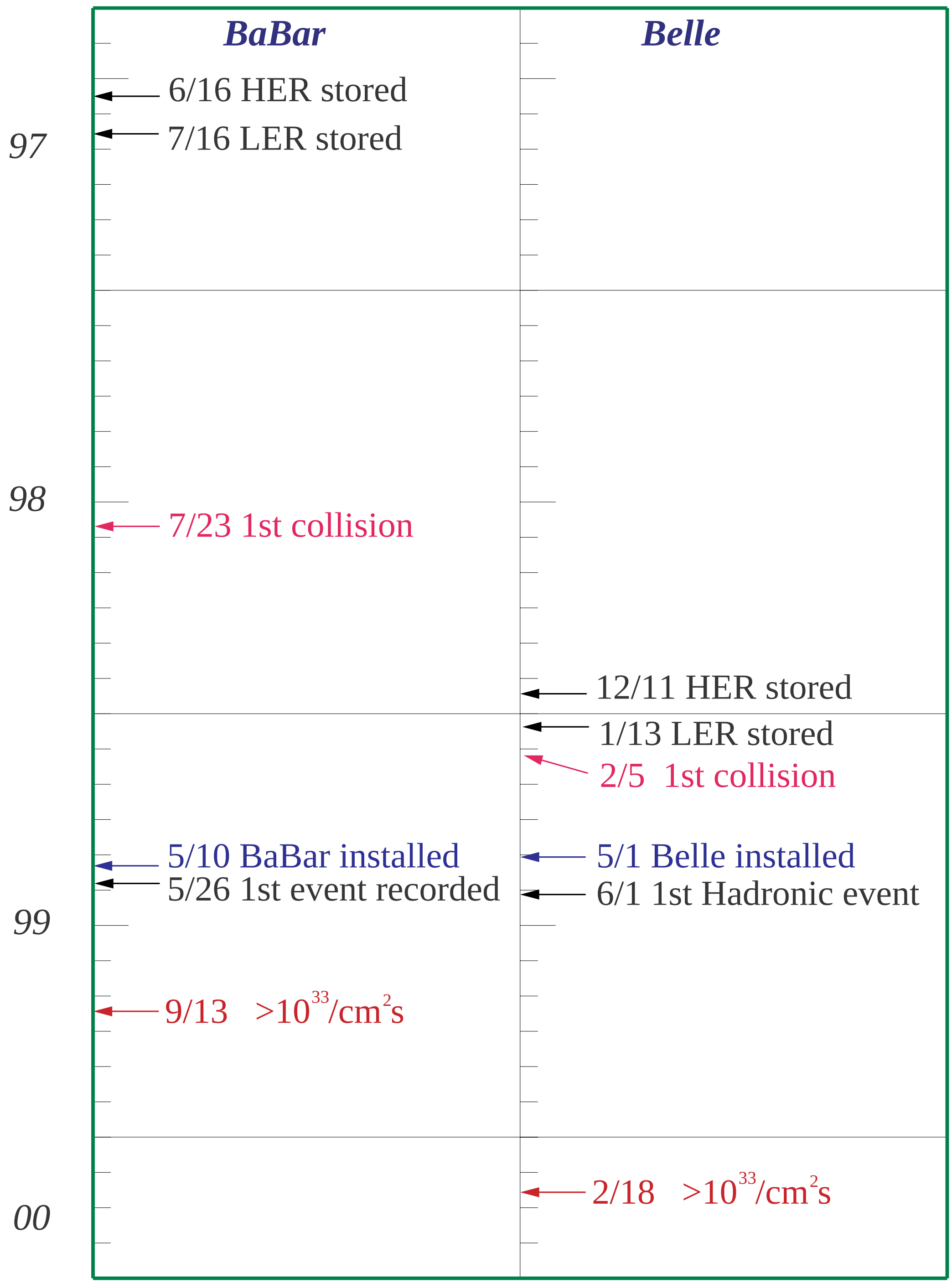
KEK-B (KEK, Japan)



machine	$CESR$	$PEP\text{-}II$	$KEK\text{-}B$
detector	$CLEO$	$BaBar$	$Belle$
circumference (km)	0.768	2.199	3.016
# of rings	1	2	2
E_{e^+}(GeV)	5.3	3.1	3.5
E_{e^-}(GeV)	5.3	9.0	8.0
$\beta_{\Upsilon 4S}$	~ 0	0.49	0.39
$\delta E/E$	6×10^{-4}	7×10^{-4}	7×10^{-4}
Δt_{bunch}	$14ns$	$4.2ns$	$2ns$
bunch size(w)	500μ	181μ	77μ
" (h)	10μ	5.4μ	1.9μ
" (l)	$1.8cm$	$1.0cm$	$0.4cm$
crossing angle(mrad)	± 2.3	0	± 11
Luminosity($cm^{-2}s^{-1}$)	1.5×10^{33}	3×10^{33}	10×10^{33}
$\#B\bar{B}/s$	1.5	3	10
achievements so far			
Lum(peak)	12×10^{32}	31×10^{32}	38×10^{32}
$\int Ldt$ (fb^{-1})	xxx	31.0	24.0

1 fb^{-1} $\sim 10^6$ $B\bar{B}$ pairs

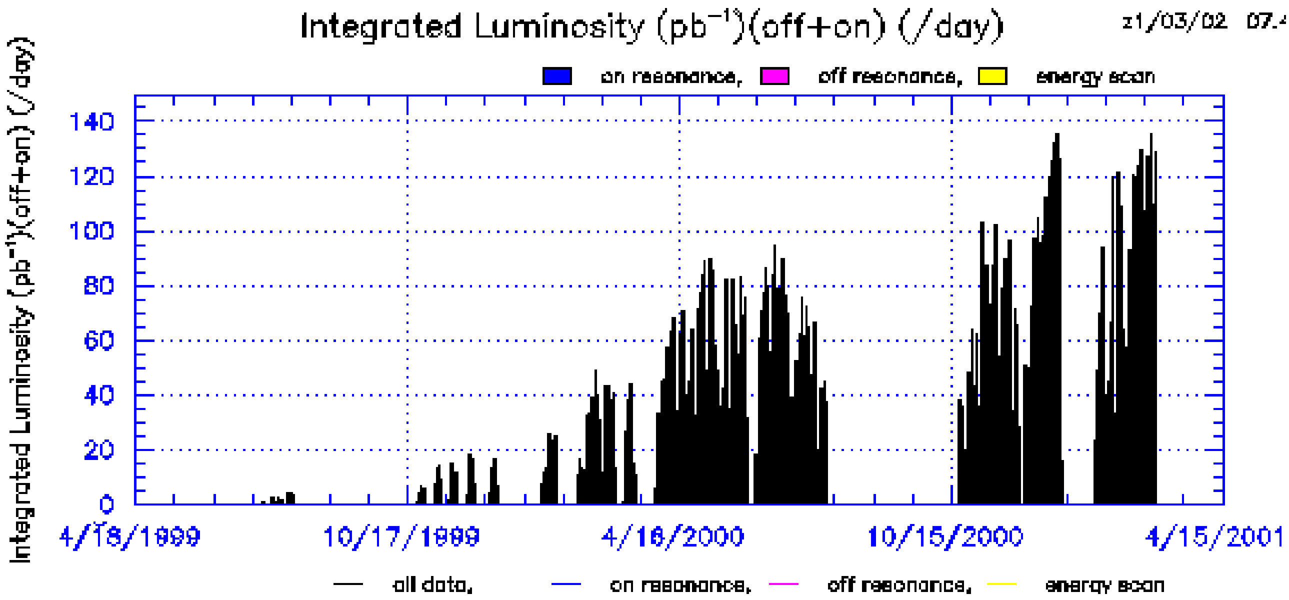
Benchmarks

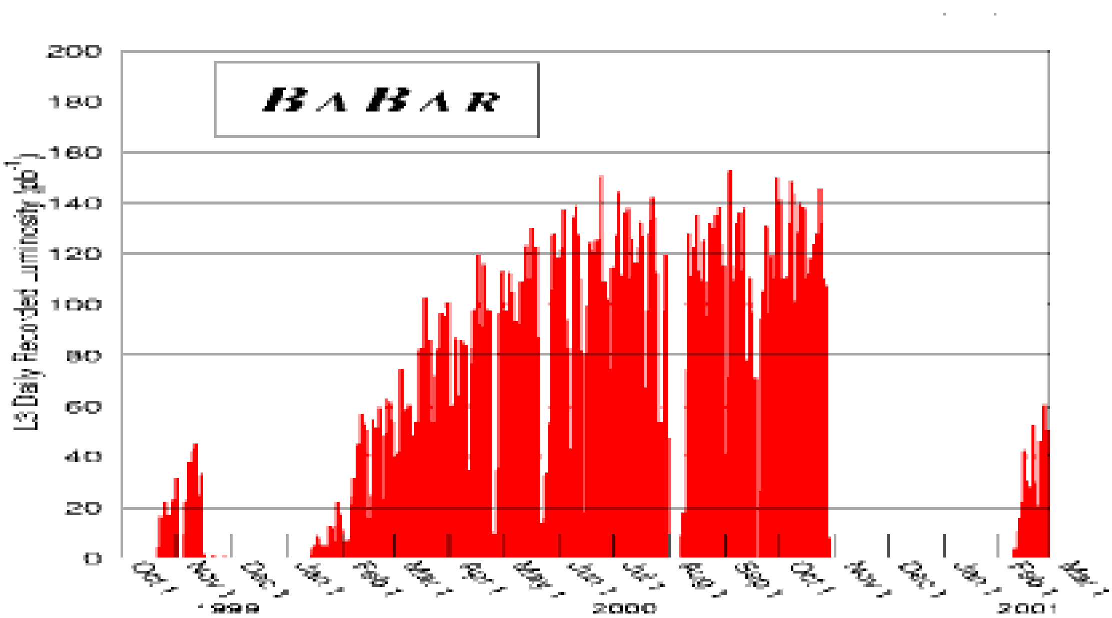


BaBar
Belle
97
98
99
00
6/16 HER stored
7/16 LER stored
7/23 1st collision
5/10 BaBar installed
5/26 1st event recorded
9/13 >10^33/cm^2s
12/11 HER stored
1/13 LER stored
2/5 1st collision
5/1 Belle installed
6/1 1st Hadronic event
2/18 >10^33/cm^2s

Luminosity

Belle

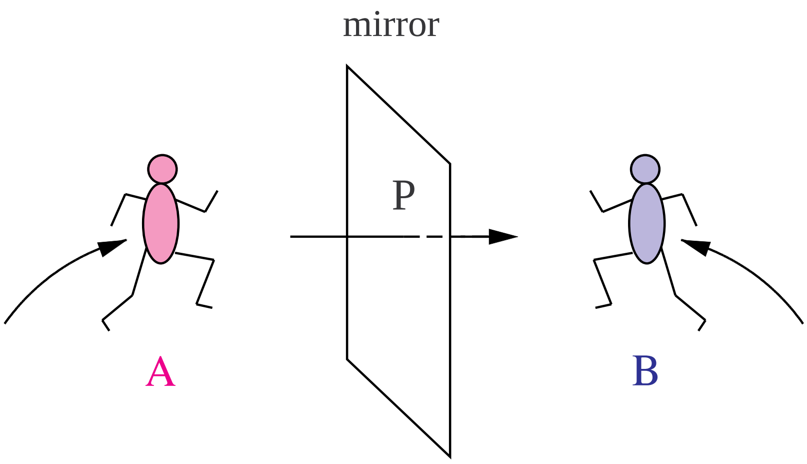




Introduction to CP violation

Symmetry in physical laws

- Parity (mirror inversion) as an example -



- Suppose motion A satisfies a law of physics.
- Reflect A in the mirror, and think that the motion in the mirror (B) is actually happening.
- **Does B satisfy the same law of physics?**

If YES, and so for all motions that satisfy the law, then the law of physics is **symmetric** under parity, or it **conserves** parity.

Symmetry $\leftrightarrow$ Conservation

(Naether's theorem)

Parity symmetry and conservation of parity

(Quantum mechanics)

Transition amplitude $S_{f,i}$ from state i to state f:

$$S_{f,i} = \langle f|S|i\rangle$$

Parity inverted states:

$$|Pi\rangle \equiv P|i\rangle\,, \quad |Pf\rangle \equiv P|f\rangle\,.$$

If S operator is invariant under (commute with) P

$$\boxed{PSP^\dagger = S}$$

$$\rightarrow \; S_{Pf,Pi} = \langle f|P^\dagger \underbrace{S}_{PSP^\dagger} P|i\rangle = \langle f|S|i\rangle = S_{f,i}$$

Namely, the parity-inverted process occurs at the same rate, and the physics is thus **symmetric under parity**.

If $PSP^\dagger = S$ and i and f are eigenstates of P:

$$P|i\rangle = \eta_i|i\rangle\,, \quad P|f\rangle = \eta_f|f\rangle\,, \quad (\eta_{i,f} = \pm 1)$$

$$S_{f,i} = \langle f| \underbrace{S}_{PSP^\dagger} |i\rangle = \eta_f\eta_i\langle f|S|i\rangle = \eta_f\eta_i S_{f,i}$$

Namely, $S_{f,i} = 0$ unless $\eta_i = \eta_f$:

$\rightarrow$ **parity quantum number is conserved**.

$$\boxed{P \text{ conservation} \overset{PSP^\dagger = S}{\longleftrightarrow} \text{Symmetry under } P}$$

CP symmetry: similarly formulated.

K^0-$\bar{K}^0$ system: the only place CPV (CP Violation) have been seen (before B^0 meson).

1964, K_L (as well as K_S) $\to \pi^+\pi^-(CP+)$

This is CPV because:

$Br(K_S \to \pi\pi) \sim 1 \Rightarrow$ natural to identify

$$K_S = K_1(CP+), \quad K_L = K_2(CP-)$$

- If $K_L = K_2$ really,

$$K_2(CP-) \;\to\; \pi^+\pi^-(CP+)$$

(CPV in decay- or - direct CPV)

- If $K_L \neq K_2$, $\to$ $CP+$ component in K_L

$$\begin{aligned} K_2(CP-) &= K_L - \epsilon_0 K_S \\ &\xrightarrow{t} c_1 K_L + c_2 K_S \ (CP \text{ mixture }) \end{aligned}$$

(CPV in mixing- or - indirect CPV)

Either case, both $K_L \& K_S \to \pi^+\pi^-$ is CPV

$$\left(\begin{array}{l}\text{A neutron is a physical state \underline{and} not a } CP \\ \text{eigenstate. But it does not mix (evolve) as} \\ \text{far as we know.} \\ \qquad\qquad\qquad \Rightarrow \ \text{not } CPV\end{array}\right)$$

All CPV effects so far are consistent with the hypothesis that

$$\boxed{\begin{array}{l}CPV \text{ in the } K^0\text{-}\bar{K}^0 \text{ system is purely indirect} \\ \text{(mixing) with} \\ \qquad\qquad \epsilon_0 = (2.26 \times 10^{-3})\ e^{i44^\circ}\end{array}}$$

Direct CPV in K found by:

$KTeV(Fermilab) \quad NA48(CERN)$

Hypothetical intereaction that causes indirect CPV: **'Superweak'** (Wolfenstein, 1964)

We now have a 'real' theoretical model of CPV: **the Standard Model**

Standard-Model quark-W Interaction

$$L_{\text{int}}(t) = \int d^3x \big(\mathcal{L}_{qW}(x) + \mathcal{L}^{\dagger}_{qW}(x)\big)$$

$$\mathcal{L}_{qW}(x) = \frac{g}{\sqrt{8}} \sum_{i,\,j=1,3} V_{i\,j}\, \bar{U}_i\, \gamma_\mu (1-\gamma_5) D_j\, W^\mu$$

$$U_i(x) \equiv \begin{pmatrix} u(x) \\ c(x) \\ t(x) \end{pmatrix}\ , \qquad D_j(x) \equiv \begin{pmatrix} d(x) \\ s(x) \\ b(x) \end{pmatrix}$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Masukawa (CKM) matrix
(Unitary)

Experimentally, V has a hierarchical structure.
Approximately,

$$|V_{i\,j}| \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\lambda \sim 0.22$$

Transformation of L_{int} under CP

CP: exchanges particle $(n) \leftrightarrow$ antiparticle $(\bar{n})$
flips momentum sign $(\vec{p} \leftrightarrow -\vec{p})$ (a)
keeps the spin z-component (σ) the same

Such CP operator in Hilbert space is not unique:

$$\mathcal{C}\mathcal{P} a^\dagger_{n,\vec{p},\sigma} \mathcal{P}^\dagger \mathcal{C}^\dagger = \eta_n a^\dagger_{\bar{n},-\vec{p},\sigma}$$

η_n: 'CP phase': arbitrary, depends on n
(for antiparticle: $\eta_{\bar{n}} = (-)^{2J} \eta_n^*$, J =spin)

The choice of η_n amounts to choosing a specific operator in Hilbert space among those satisfying (a).

Then, a pure algebra leads to

$$\begin{aligned}\mathcal{C}\mathcal{P}\ &\bar{u}(x)\gamma_\mu(1-\gamma_5)d(x)W^\mu(x)\ \mathcal{P}^\dagger\mathcal{C}^\dagger \\ &= \eta_u \eta_d^* \eta_W^* \left(\bar{u}(x')\gamma^\mu(1-\gamma_5)d(x')W_\mu(x')\right)^\dagger\end{aligned}$$

$$x' \equiv (t, -\vec{x})$$

$\mathcal{L}_{qW}$ transforms as (taking $\eta_W = 1$)

$$\mathcal{CP}\ \mathcal{L}_{qW}(x)\ \mathcal{P}^\dagger\mathcal{C}^\dagger = \frac{g}{\sqrt{8}} \sum_{i,\,j=1,3} \eta_{U_i}\eta^*_{D_j} V_{i\,j} \left(\bar{U}_i(x')\ \gamma^\mu(1-\gamma_5)D_j(x')W_\mu(x')\right)^\dagger$$

IF $\eta_{U_i}\eta^*_{D_j}$ can be chosen such that

$$\boxed{\eta_{U_i}\eta^*_{D_j} V_{i\,j} = V^*_{i\,j}\,,}$$

then, $\mathcal{CP}\ \mathcal{L}_{qW}(x)\ \mathcal{P}^\dagger\mathcal{C}^\dagger = \mathcal{L}^\dagger_{qW}(x')$

Namely,

$$\mathcal{L}_{qW} \overset{CP}{\leftrightarrow} \mathcal{L}^\dagger_{qW}$$

$\rightarrow$ $L_{\text{int}}(t)$ becomes invariant under CP:

$$\begin{aligned}\mathcal{CP}\ L_{\text{int}}(t)\ \mathcal{P}^\dagger\mathcal{C}^\dagger &= \int d^3x\ \mathcal{CP}\left[\mathcal{L}_{qW}(x) + \mathcal{L}^\dagger_{qW}(x)\right]\mathcal{P}^\dagger\mathcal{C}^\dagger \\ &= \int d^3x\ \left[\mathcal{L}^\dagger_{qW}(x') + \mathcal{L}_{qW}(x')\right] \\ &= L_{\text{int}}(t)\end{aligned}$$

$\rightarrow$ S matrix is invariant under CP

Condition for CP Invariance

The CP invariance condition (2) is equivalent to

$\boxed{\text{rotate the quark phases to make } V_{i,j} \text{ all real.}}$

Can the CKM matrix be made real
by rotating quark phases?

Count the degrees of freedom

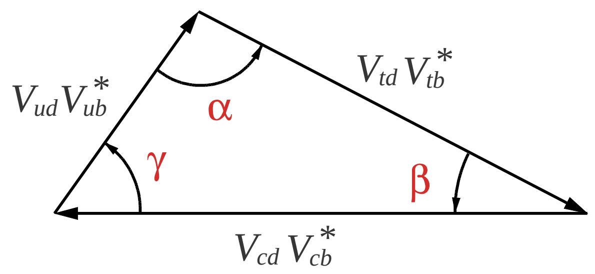
3×3 complex matrix	18
Unitarity condition $V^\dagger V = I$	-9
Quark relative phases	-5
Eular angles (real)	-3
Complex phase	1

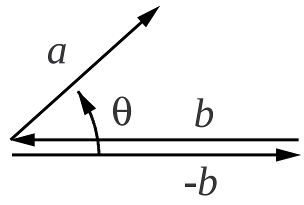
One irreducible complex phase $\rightarrow$ CP violation
(Kobayashi, Masukawa)

One complex phase $\rightarrow$ Unitarity Triangle

e.g: orthogonality of d-column and b-column:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$





$$\theta = \arg \frac{a}{-b}$$

$$\alpha \equiv \arg\left(\frac{V_{td}V_{tb}^*}{-V_{ud}V_{ub}^*}\right), \ \beta \equiv \arg\left(\frac{V_{cd}V_{cb}^*}{-V_{td}V_{tb}^*}\right), \ \gamma \equiv \arg\left(\frac{V_{ud}V_{ub}^*}{-V_{cd}V_{cb}^*}\right)$$

(Another notation: $\alpha \equiv \phi_2$, $\beta \equiv \phi_1$, $\gamma \equiv \phi_3$)

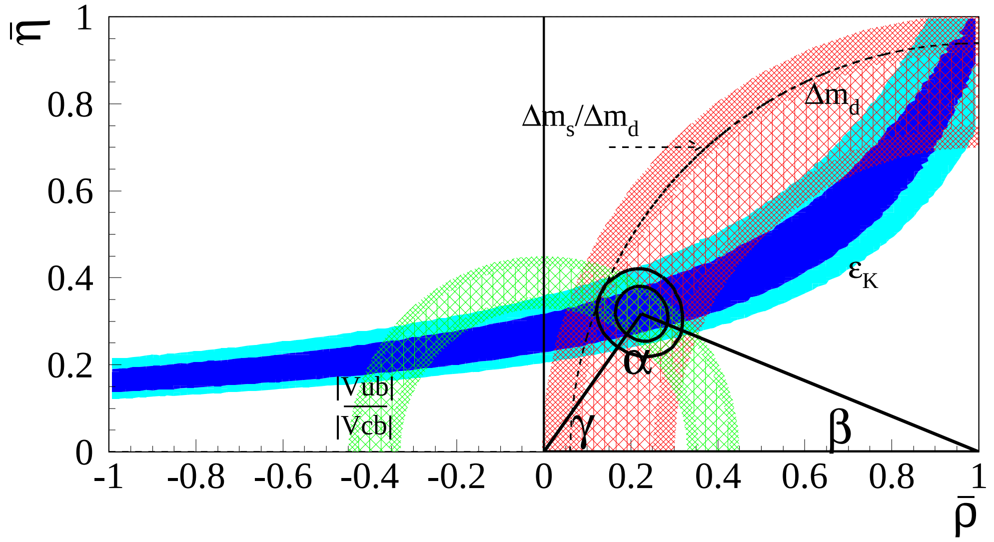
If the CKM matrix is real, the triangle is a line.

How does the CKM unitarity triangle look?

Experimental inputs:

1. $|V_{ub}/V_{cb}|$ (by $b \to ue\nu$)
2. B^0-$\bar{B}^0$ mixing $\to |V_{td}|$
3. ϵ_K **(from Kaon system)**

Many people have performed a fit.
One recent example: Ciuchini et.al.:



Normalized to the bottom length of the triangle.
(two bands for each are 68% and 95% c.l.)

Three bands cross at one point
$\to$ already a triumph of the standard model.

If the K-M model of CP violation is correct, $\rightarrow$ CP Violation (CPV) in B meson decays

1. CPV in mixing. (neutral B)
   Particle-antiparticle imbalance in physical neutral B states ($B_{a,b}$): $|\langle B^0|B_{a,b}\rangle|^2 \neq |\langle \bar{B}^0|B_{a,b}\rangle|^2$
   Expected to be small.

2. CPV in decay. (neutral and charged B)
   Partial decay rate asymmetries.

$$|Amp(B \rightarrow f)| \neq |Amp(\bar{B} \rightarrow \bar{f})|$$

   ($Amp(B^0 \rightarrow f)$: instantaneous decay amplitude.)
   Difficult to analyse $\rightarrow$ 2nd-round measurements.

3. CPV by mixing-decay interference. (neutral B)
   When both $B^0 \& \bar{B}^0$ can decay to the same final state f:

$$\begin{tikzcd} & \bar{B}^0 \arrow[dr] & \\ B^0 \arrow[ur] \arrow[rr] & & f \end{tikzcd} \qquad \begin{tikzcd} & B^0 \arrow[dr] & \\ \bar{B}^0 \arrow[ur] \arrow[rr] & & \bar{f} \end{tikzcd}$$

   the inteference results in

$$\Gamma_{B^0 \rightarrow f}(t) \neq \Gamma_{\bar{B}^0 \rightarrow \bar{f}}(t)\,.$$

   Most promissing.

Mixing-decay interference

Eigenstates of mass & decay rate (assume CPT):

$$(*) \quad \begin{cases} B_a = pB^0 + q\bar{B}^0 \\ B_b = pB^0 - q\bar{B}^0 \end{cases},$$

B_a (mass: m_a, decay rate: γ_a)
B_b (mass: m_b, decay rate: γ_b)

In good approximation, $\gamma_a = \gamma_b (\equiv \gamma)$
$\longrightarrow$ decay rate decuople from the arguments below.
(Also, p, q becomes pure phases)

Time evolution:

$$B_a \longrightarrow B_a e^{-im_a t}, \qquad B_b \longrightarrow B_b e^{-im_b t}.$$

Solving (*) for B^0 and $\bar{B}^0$,
the time evolutions of pure B^0 or $\bar{B}^0$ at $t = 0$ are

$$\begin{cases} B^0 \longrightarrow B^0 \cos \dfrac{\delta m}{2} t - \dfrac{q}{p} \bar{B}^0 i \sin \dfrac{\delta m}{2} t \\ \bar{B}^0 \longrightarrow \bar{B}^0 \cos \dfrac{\delta m}{2} t - \dfrac{p}{q} B^0 i \sin \dfrac{\delta m}{2} t \end{cases},$$

$$(\delta m \equiv m_a - m_b)$$

Amplitude for pure B^0 or $\bar{B}^0$ at $t = 0$
to decay to f at t:

$$\begin{cases} A_{B^0 \to f}(t) = A \cos \frac{\delta m}{2} t - \frac{q}{p} \bar{A} i \sin \frac{\delta m}{2} t \\ A_{\bar{B}^0 \to f}(t) = \bar{A} \cos \frac{\delta m}{2} t - \frac{p}{q} A i \sin \frac{\delta m}{2} t \end{cases},$$

$$A \equiv Amp(B^0 \to f)\,, \quad \bar{A} \equiv Amp(\bar{B}^0 \to f)\,.$$

The probability that a pure $B^0(\overline{B}^0)$ at $t = 0$ decays to a final state f at t: (for f: CP eigenstate):

$$\boxed{\Gamma_{B^0(\bar{B}^0) \to f}(t) = e^{-\gamma t} |pA|^2 \left[1 \pm \Im \left(\frac{q\overline{A}}{pA} \right) \sin \delta m \, t \right]}$$

$\longrightarrow CPV$ by def.

The Time-dependent asymmetry is

$$\boxed{A_{CP}(t) = \Im \left(\frac{q\overline{A}}{pA} \right) \sin \delta m \, t}$$

How to prepare ('tag') pure $B^0/\bar{B}^0$ on $\Upsilon 4S$?

Since $\bar{B}^0$ decays to $e^- + X$ but not $e^+ + X$ (X: something), look at the other side:

$$\Upsilon 4S \to \begin{cases} B^0 \to f \\ \bar{B}^0 \to e^- X \end{cases}$$

If the other side decays to e^-, then f came from B^0 - ?

In reality, $B^0\bar{B}^0$ pair is created in a coherent $L = 1$ state which is asymmetric. The time evolution in the $\Upsilon 4S$ system is (with a simple algebra)

$$\begin{aligned} \Upsilon 4S &\to (B^0\bar{B}^0 - \bar{B}^0 B^0) \\ &\to e^{-\gamma t}(B^0\bar{B}^0 - \bar{B}^0 B^0) \end{aligned}$$

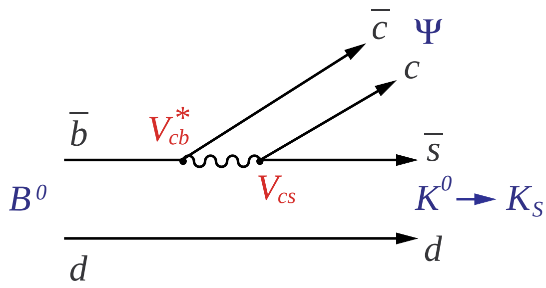
If one finds one side to be $\bar{B}^0$ at t, then the other side is pure B^0 **at the same time** t, then it will evolve as before.

$\to \Gamma_{B^0(\bar{B}^0)\to f}(t)$ applies to $\Upsilon 4S$ with

$$t \;\to\; \Delta t \equiv t(f) - t(\text{tag})\,,$$

$$(\text{and } e^{-\gamma t} \to e^{-\gamma|\Delta t|})$$

The gold-plated mode $f = \Psi K_S$

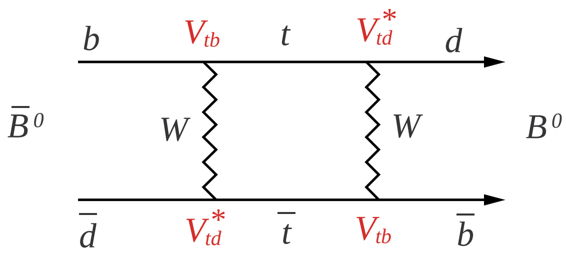


What is $\Im \frac{q\bar{A}}{pA}$ for this mode?

q/p is obtained by diagonzlizing

$$H_{\text{eff}} = \begin{pmatrix} \langle B^0|H|B^0\rangle & \langle B^0|H|\bar{B}^0\rangle \\ \langle \bar{B}^0|H|B^0\rangle & \langle \bar{B}^0|H|\bar{B}^0\rangle \end{pmatrix}$$

$\langle \bar{B}^0|H|B^0\rangle$:



$$\rightarrow \frac{q}{p} = \frac{\langle \bar{B}^0|H|B^0\rangle}{|\langle \bar{B}^0|H|B^0\rangle|} = -\frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}}$$

$$f = \Psi K_S$$

$$\frac{\bar{A}}{A} = \frac{\langle K_S|\bar{K}^0\rangle\langle\Psi\bar{K}^0|H|\bar{B}^0\rangle}{\langle K_S|K^0\rangle\langle\Psi K^0|H|B^0\rangle} = \frac{-q_K^*}{p_K^*}\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}$$

With a similar procedure to the B case,

$$\frac{q_K}{p_K} = -\frac{V_{cd}V_{cs}^*}{V_{cd}^*V_{cs}}.$$

Combinig all,

$$\frac{q\bar{A}}{pA} = \left(\frac{V_{cd}V_{cb}^*}{-V_{td}V_{tb}^*}\right)^* \Big/ \left(\frac{V_{cd}V_{cb}^*}{-V_{td}V_{tb}^*}\right)$$

With the definition of the angle β:

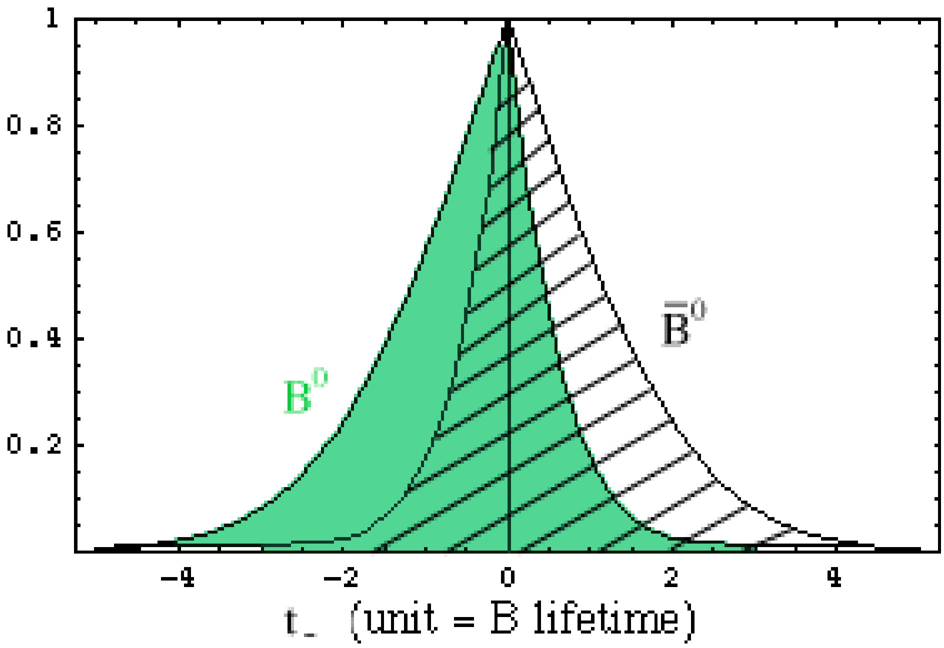
$$\beta = \arg\left(\frac{V_{cd}V_{cb}^*}{-V_{td}V_{tb}^*}\right)$$

$$\boxed{\to \Im\frac{q\bar{A}}{pA} = -\sin 2\beta \quad (\Psi K_S)}$$

$$\Upsilon 4S \to \begin{cases} B_1 \to \Psi K_S \ (t_1) \\ B_2 \to e^{\mp} X \ \ (t_2) \end{cases}$$

$$\Gamma_{e^{\mp},\Psi K_S}(\Delta t) = N(1 \mp \sin 2\beta \sin \delta m \Delta t)$$

$$(\Delta t \equiv t_1 - t_2)$$



$B^0 \equiv e^-$ tag, $\quad \bar{B}^0 \equiv e^+$ tag,

Total area is the same for $B^0/\bar{B}^0$

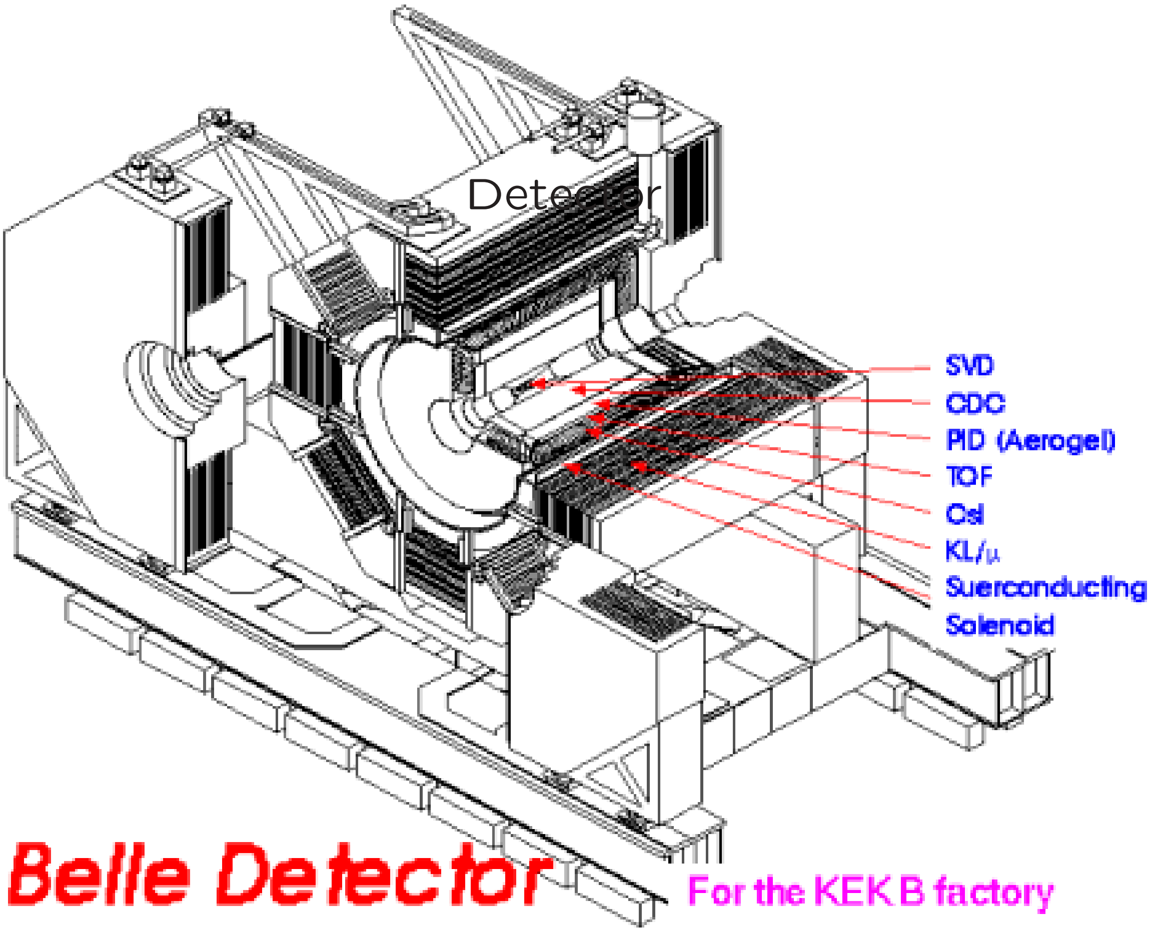
$\to$ need to measure Δt

$\Rightarrow$ **Asymmetric B-factory**

(moving B's $\to$ decay vertexes $\to$ Δt)

[At CLEO, $B^0\bar{B}^0$ are nearly at rest]

Detector



- SVD: Silicon vertex detector.
  resolution ~ 100 μm (B lifetime $= 200$ μm)
- CDC: charged particle tracking
- PID: π/K separation
- TOF: π/K separation
- Cal: electron/photon detection
- KL/μ: K_L/muon detection

$<$**Full reconstruction on** $\Upsilon 4S >$

$$B \to f_1 \cdots f_n$$

Energy and absolute momentum of B in the $\Upsilon 4S$ frame are known:

$$E_B = E_{\text{beam}} = 5.290 \text{ GeV}$$
$$|\vec{P}_B| = \sqrt{E_{\text{beam}}^2 - M_B^2} = 0.34 \text{ GeV/c}$$

$\rightarrow$**Move to the** $\Upsilon 4S$ **rest frame** and require that candidates satisfy

$$E_{\text{tot}} = E_{\text{beam}}\,, \quad |\vec{P}_{\text{tot}}| = |\vec{P}_B|$$

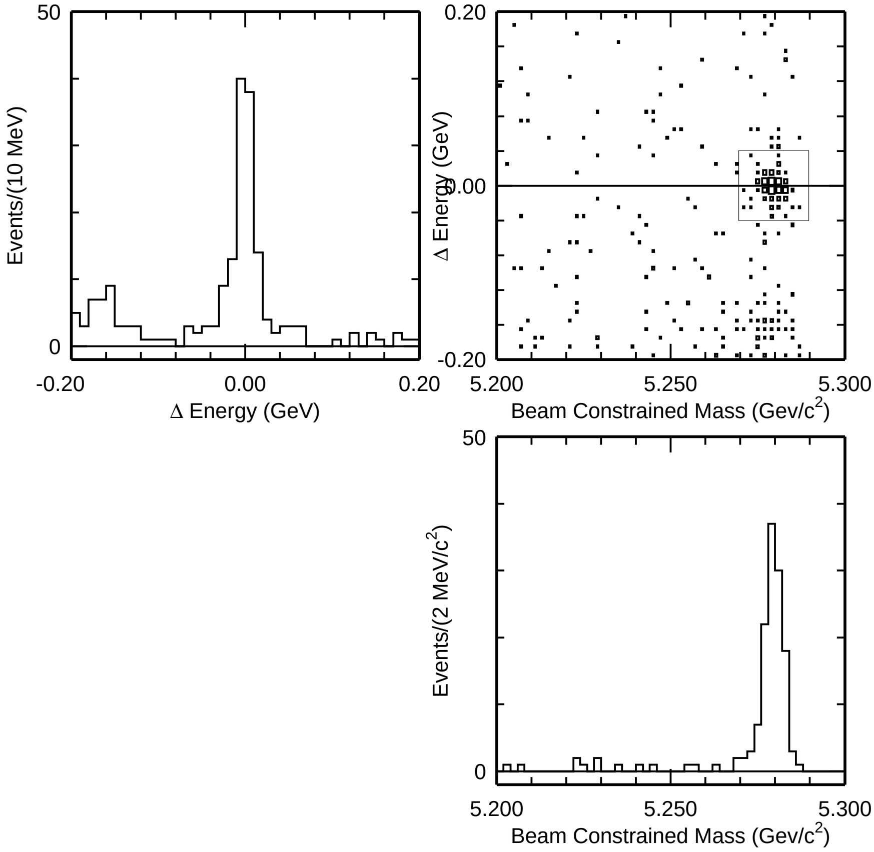
where

$$E_{\text{tot}} \equiv \sum_{i=1}^{n} E_i\,, \quad \vec{P}_{\text{tot}} \equiv \sum_{i=1}^{n} \vec{P}_i$$

Instead of E_{tot} and $|\vec{P}_{\text{tot}}|$, we often use

$$\Delta E \equiv E_{\text{tot}} - E_B \qquad \text{(energy difference)}$$
$$M_{\text{bc}} \equiv \sqrt{E_{\text{beam}}^2 - \vec{P}_{\text{tot}}^2} \qquad \text{(beam-constrained mass)}$$

$$\Psi \to e^+e^-, \mu^+\mu^- \;, \quad K_S \to \pi^+\pi^-$$

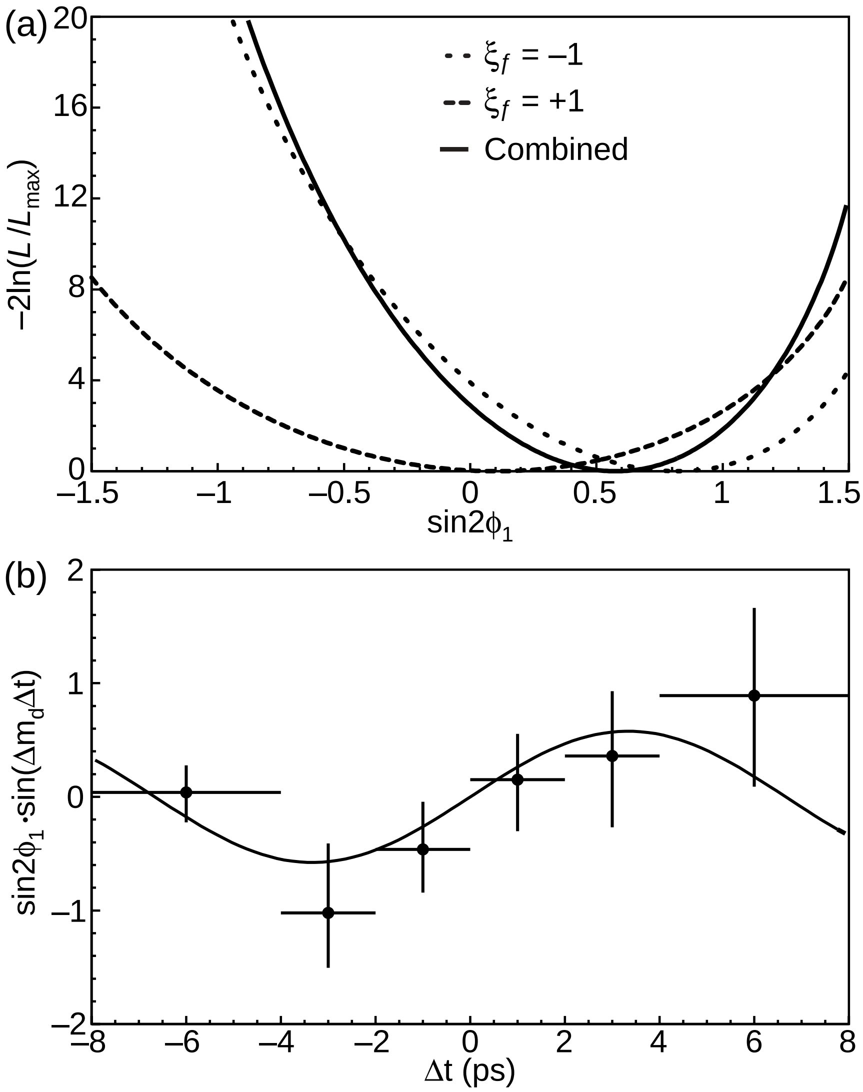


Also use

- $\Psi' K_S$, $\chi_{c1} K_S$, $\eta_c K_S$ $(\xi_f = -1)$
- $\Psi \pi^0$, ΨK_L $(\xi_f = +1)$
- Tagging by $\mu^\pm$, $K^\pm$, $\pi^\pm$

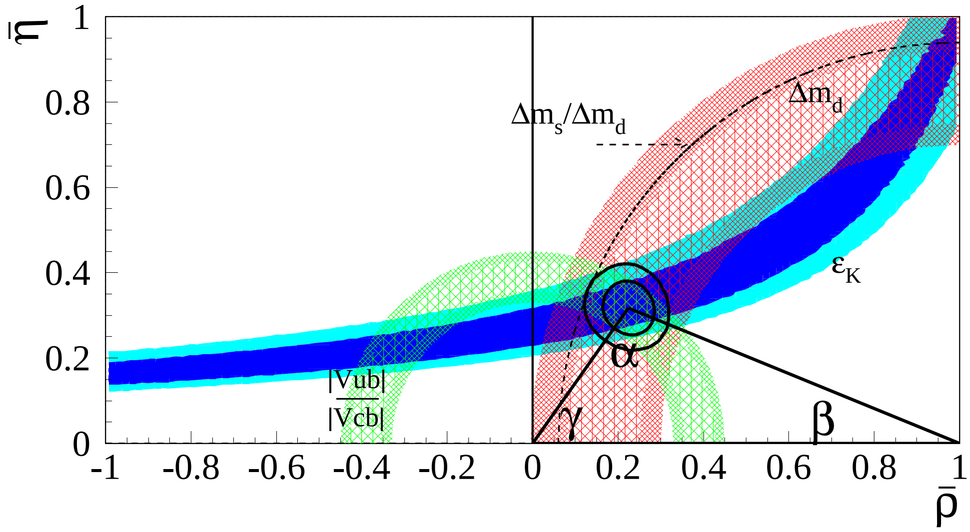
ξ_f: CP of the final state (sign in front of $\sin 2\beta$)

Result on $\sin 2\beta$ **(**$\equiv \sin 2\phi_1$**)**



$$\sin 2\beta = 0.58^{+0.32}_{-0.34}(stat)^{+0.09}_{-0.10}(sys)$$

In terms of the unitarity triangle)



The Belle result is consistent with the standard model.

Other experiments:

Experiment	year	$\sin 2\beta$
BaBar	2001	$0.34 \pm 0.22 \pm 0.05$
CDF ($p\bar{p}$)	2000	$0.79^{+0.41}_{-0.44}$
Aleph (Z^0)	2000	$0.93^{+0.64+0.36}_{-0.88-0.24}$

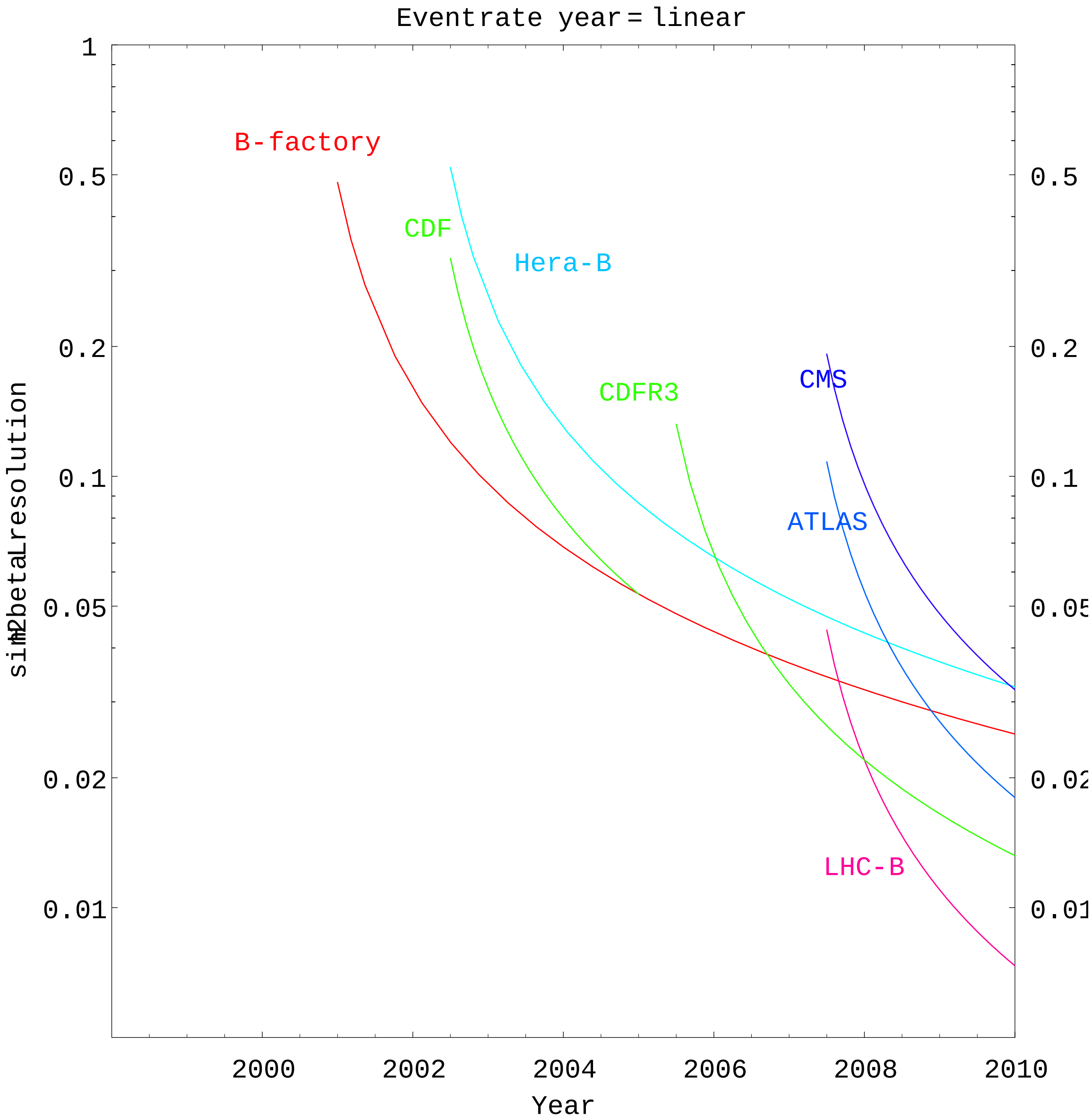
Prospects for Belle

- Reduce the beampipe size $\rightarrow \times 2$ improvement of vertex resolution (2002).
- Collect ~ 30 fb^{-1} per year for a few years.
- Installation of crab cavities, ante-chambers (2004?)
- Measure angles α/ϕ_2 and γ/ϕ_3.
  ($\pi^+\pi^-$, DK, $D^*\pi$ modes etc.)
- Measure the sizes of the unitarity triangle better.

General prospects in B-physics

- CDF/D0 (Fermilab $p\bar{p}$) will join the game in 2002.
- HERA-B may join the game soon.
- LHC detectors (LHC-b and ATLAS, CMS) will start in 2006.
- BTeV (Fermilab) will start in 2008

EXtrapolation of $\sin 2\beta$ sensitivities
(rough, irresponsible guesses)



Assumed linear increase of luminosity with time.