Physics at B-factories

Part 1: Introduction, CP violation primer, detectors

Peter Križan

University of Ljubljana and J. Stefan Institute

University of Ljubljana

“Jožef Stefan” Institute

Contents of this course

•Lecture 1: Introduction, CP violation primer, detectors

•Lecture 2: Measurements of angles and sides of the unitarity triangle

•Lecture 3: Searches for physics beyond SM, outlook, summary

http://www-f9.ijs.si/~krizan/sola/bad-liebenzell/bad-liebenzell.html

•Slides

•Literature

•Program, timetable

Standard Model: content

Particles:

- leptons (e,ν_e), (μ,ν_μ), (τ,ν_τ)
- quarks (u,d), (c,s), (t,b)

Interactions:

- Electromagnetic (γ)
- Weak (W^+, W^-, Z^0)
- Strong (g)

Higgs field

Flavour physics

B factories main topic: flavour physics

... is about

- quarks

and

- their mixing
- CP violation

Flavour physics and CP violaton

Moments of glory in flavour physics are very much related to CP violation:

Discovery of CP violation (1964)

The smallness of $K_L \rightarrow \mu^+\mu^-$ predicts charm quark

GIM mechanism forbids FCNC at tree level

KM theory describing CP violation predicts third quark generation

$\Delta m_K = m(K_L) - m(K_S)$ predicts charm quark mass range

Frequency of $B^0\overline{B^0}$ mixing predicts a heavy top quark

Proof of Kobayashi-Maskawa theory ($\sin 2\phi_1$)

Tools to find physics beyond SM: search for new sources of flavour/CP-violating terms

CP Violation

Fundamental quantity: distinguishes matter from anti-matter.

A bit of history:

- First seen in K decays in 1964
- Kobayashi and Maskawa propose in 1973 a mechanism to fit it into the Standard Model → had to be checked in at least one more system, needed 3 more quarks
- Discovery of B anti-B mixing at ARGUS in 1987 indicated that the effect could be large in B decays (I.Bigi and T.Sanda)
- Many experiments were proposed to measure CP violation in B decays, some general purpose experiments tried to do it
- Measured in the B system in 2001 by the two dedicated spectrometers Belle and BaBar at asymmetric e^+e^- colliders - B factories

What happens in the B meson system?

Why is it interesting? Need at least one more system to understand the mechanism of CP violation.

Kaon system: hard to understand what is going on at the quark level (light quark bound system, large dimensions).

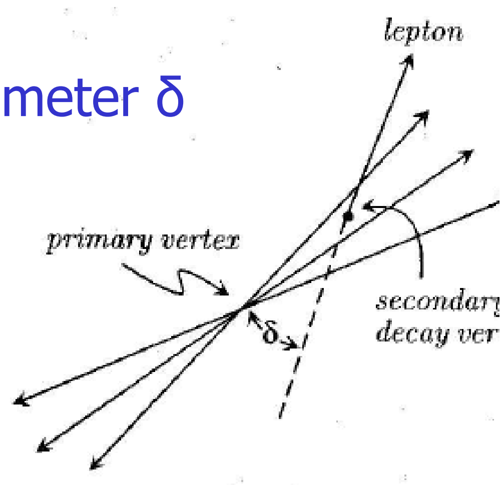
B has a heavy quark, a smaller system, and is easier for interpreting the experimental results.

First B meson studies were carried out in 70s at e^+e^- colliders with cms energies ~20GeV, considerably above threshold (~2x5.3GeV)

B mesons: long lifetime

Isolate samples of high-p_T leptons (155 muons, 113 electrons) wrt thrust axis

Measure impact parameter δ wrt interaction point

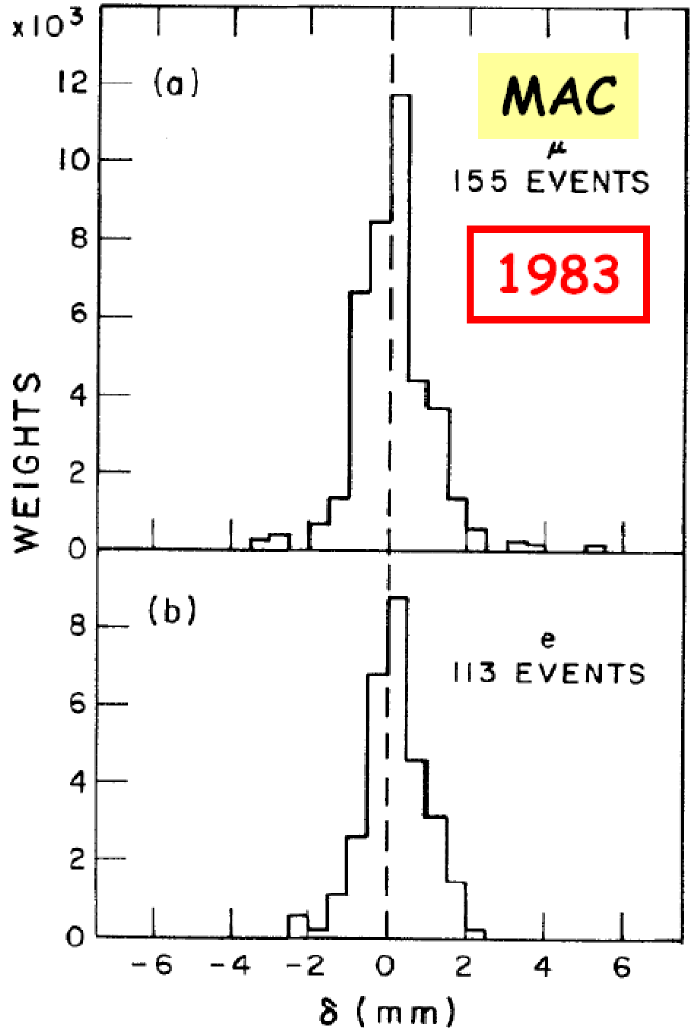


Lifetime implies V_{cb} small

MAC: (1.8±0.6±0.4)ps

Mark II: (1.2±0.4±0.3)ps

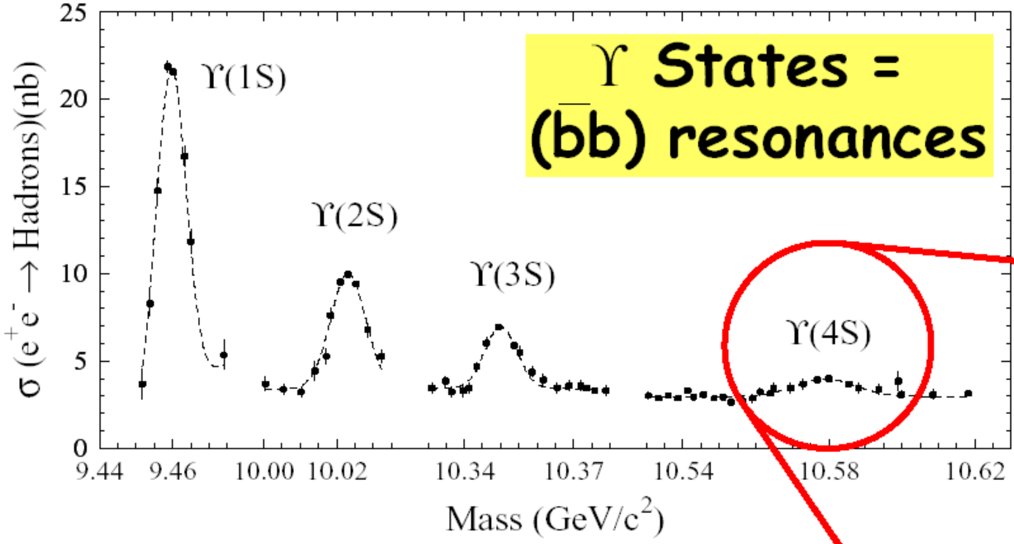
Integrated luminosity at 29 GeV: 109 (92) pb^{-1}~3,500 bb pairs



MAC, PRL **51**, 1022 (1983)

MARK II, PRL **51**, 1316 (1983)

Systematic studies of B mesons: at $\Upsilon(4s)$



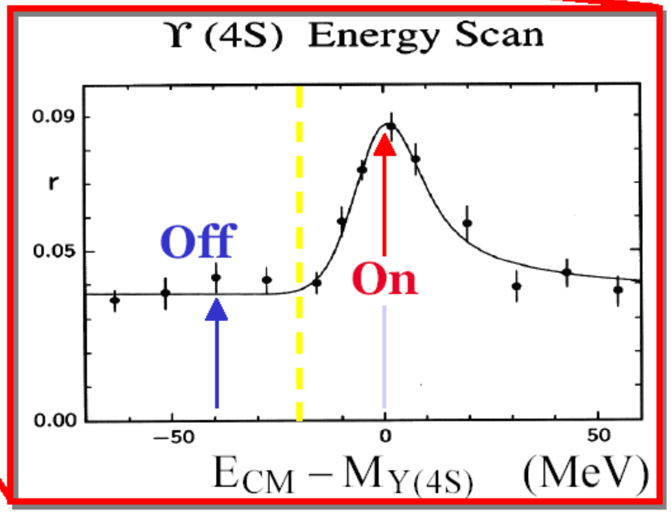
Cross Sections at $\Upsilon(4S)$:

$b\bar{b} \sim 1.1$ nb

$c\bar{c} \sim 1.3$ nb

$d\bar{d}$, $s\bar{s} \sim 0.3$ nb

$u\bar{u} \sim 1.4$ nb



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

$L = 1$ state

Systematic studies of B mesons at Υ(4s)

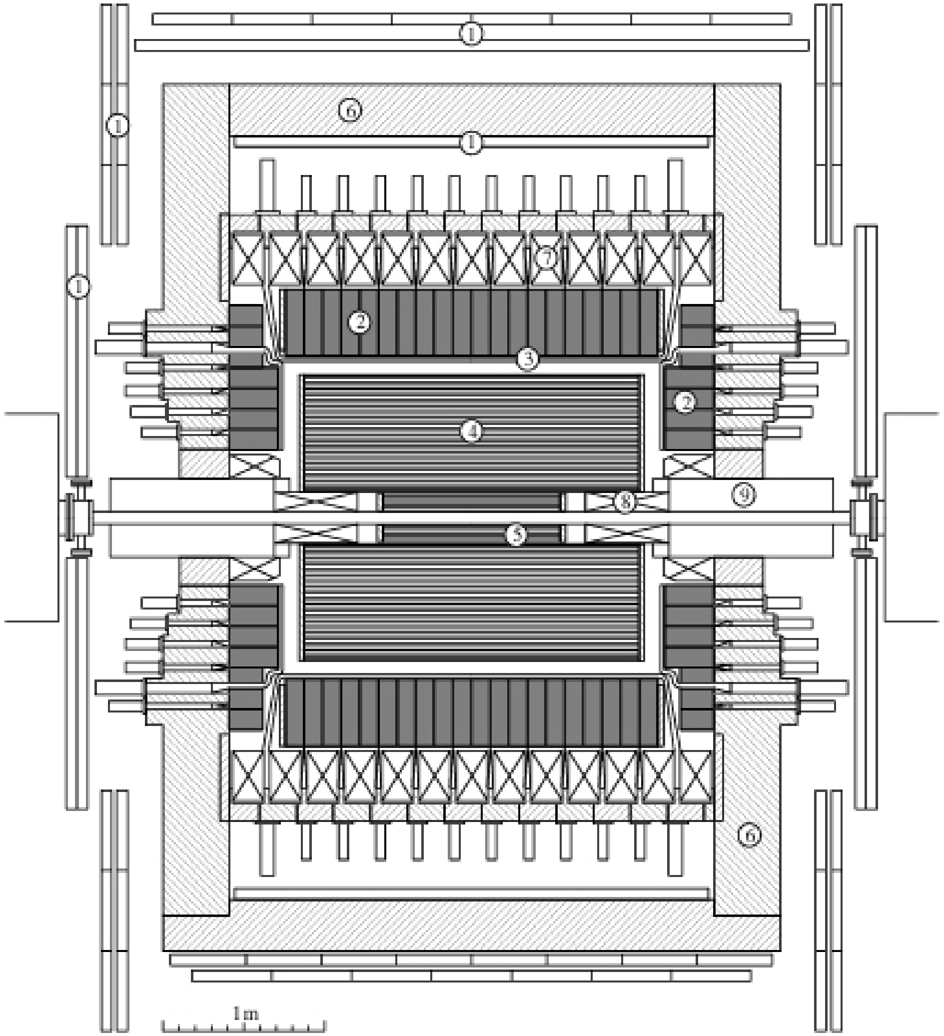
80s-90s: two very successful experiments:

•ARGUS at DORIS (DESY)

•CLEO at CESR (Cornell)

Magnetic spectrometers at e^+e^- colliders (5.3GeV+5.3GeV beams)

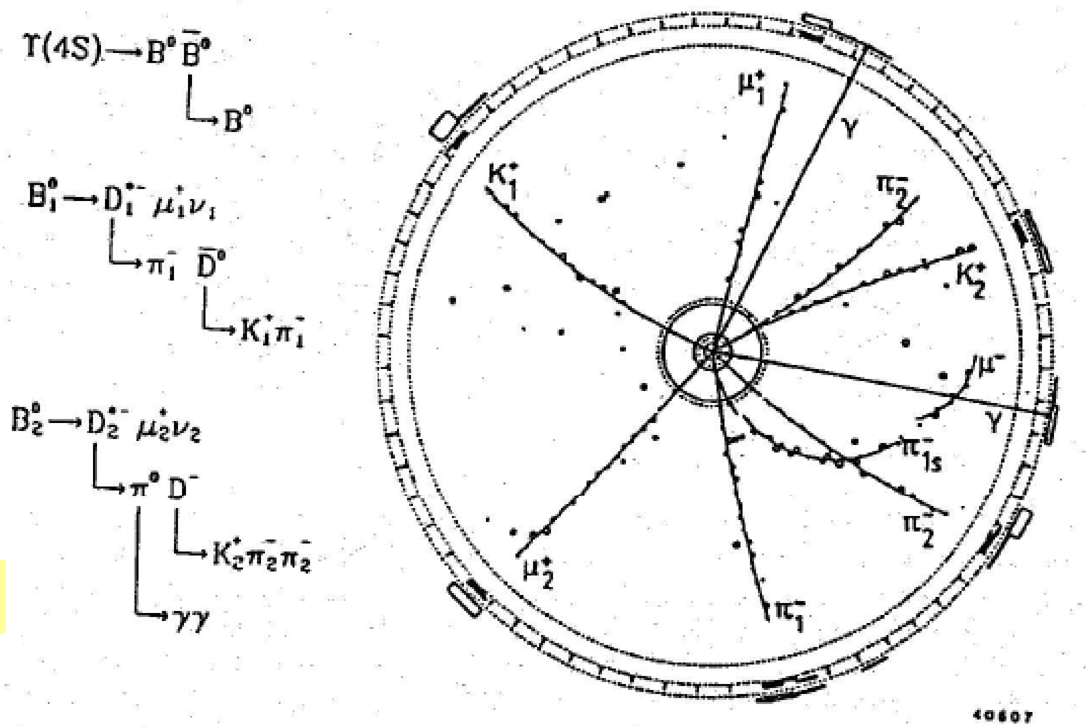
Large solid angle, excellent tracking and good particle identification (TOF, dE/dx, EM calorimeter, muon chambers).



Mixing in the B^0 system

1987: ARGUS discovers BB mixing: B^0 turns into anti-B^0

Reconstructed event



$$\chi_d = 0.17 \pm 0.05$$

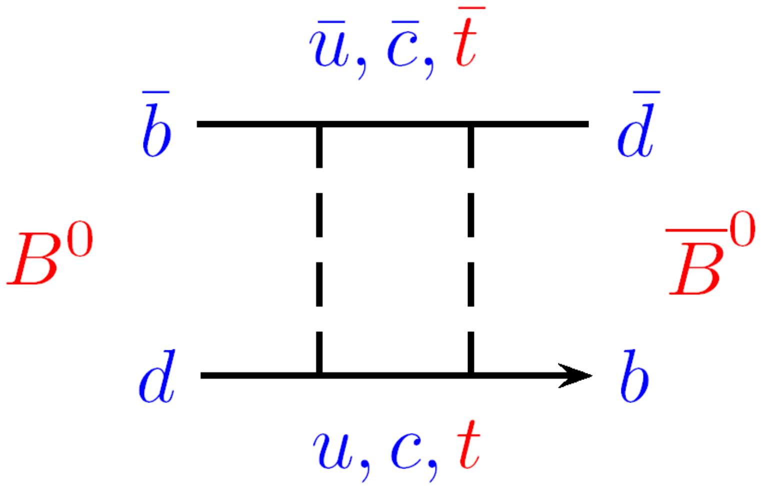
ARGUS, PL B **192**, 245 (1987)

cited >1000 times.

Time-integrated mixing rate: 25 like sign, 270 opposite sign dilepton events

Integrated Y(4S) luminosity 1983-87: 103 pb^{-1} ~110,000 B pairs

Mixing in the B^0 system



$$\Delta m \propto$$

$$|V_{tb}^* \, V_{td}|^2 m_t^2 \;\propto\; \lambda^6 m_t^2$$

$$|V_{cb}^* \, V_{cd}|^2 m_c^2 \;\propto\; \lambda^6 m_c^2$$

Large mixing rate → high top mass (in the Standard Model)

The top quark has only been discovered seven years later!

Systematic studies of B mesons at Y(4s)

ARGUS and CLEO: In addition to mixing many important discoveries or properties of

- B mesons
- D mesons
- τ^- lepton
- and even a measurement of ν_τ mass.

After ARGUS stopped data taking, and CESR considerably improved the operation, CLEO dominated the field in late 90s (and managed to compete successfully even for some time after the B factories were built).

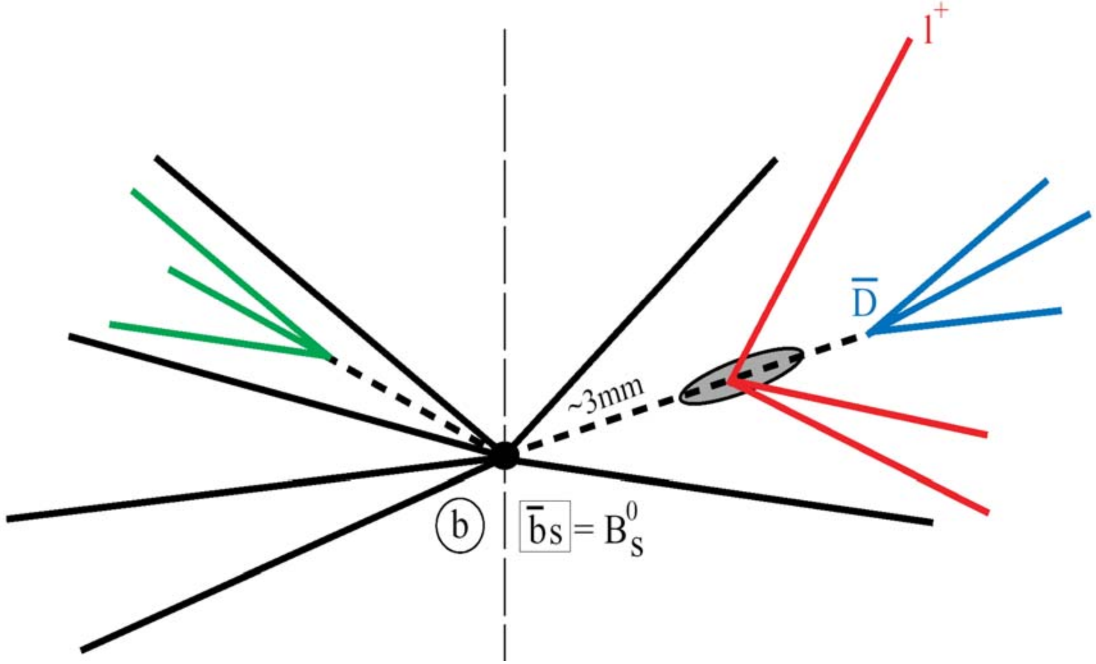
Studies of B mesons at LEP

90s: study B meson properties at the Z^0 mass by exploiting

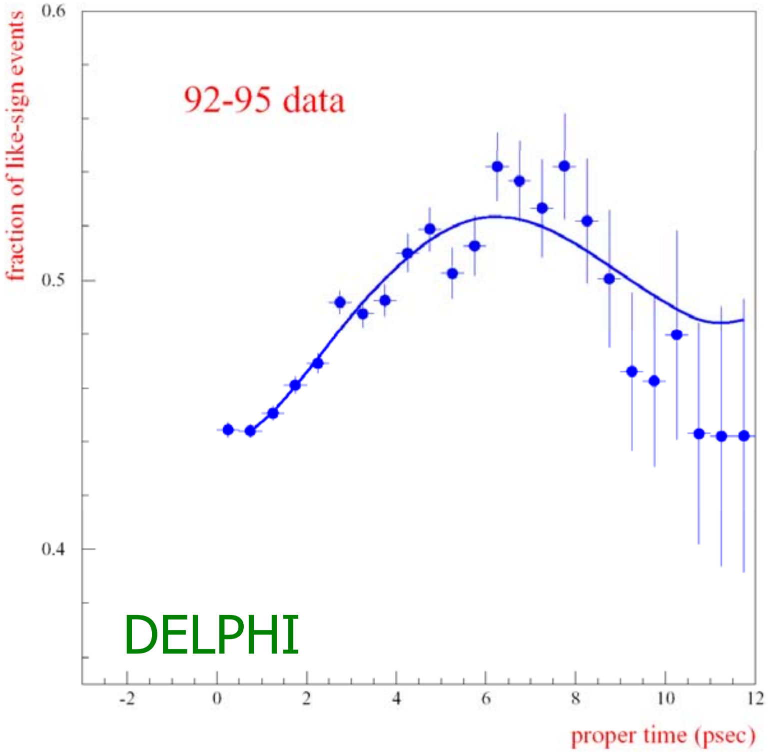
•Large solid angle, excellent tracking, vertexing, particle identification

•Boost of B mesons → time evolution (lifetimes, mixing)

•Separation of one B from the other → inclusive rare b→u



Studies of B mesons at LEP and SLC



$B^0 \rightarrow$ anti-B^0 mixing, time evolution

Fraction of events with like sign lepton pairs

Almost measured mixing in the B_s system (bad luck...)

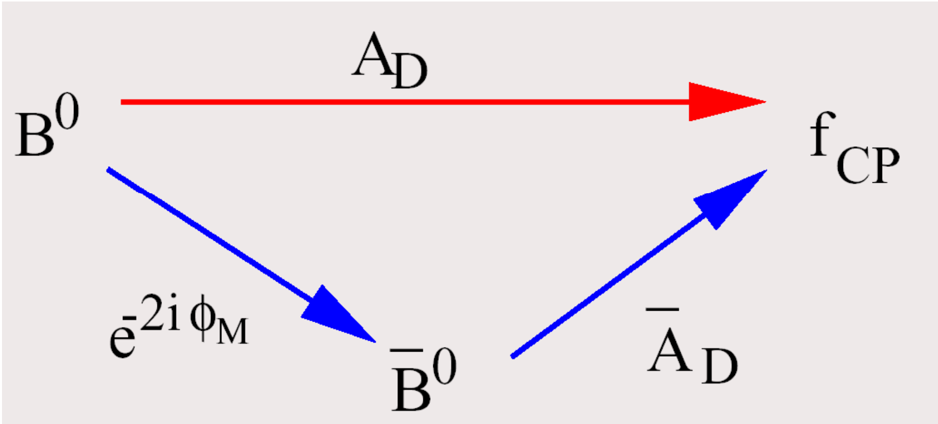
Large number of B mesons (but by far not enough to do the CP violation measurements...)

Mixing → expect sizeable CP Violation (CPV) in the B System

CPV through interference of decay amplitudes

CPV through interference of mixing diagram

CPV through interference between mixing and decay amplitudes



Directly related to CKM parameters in case of a single amplitude

Golden Channel: $B \rightarrow J/\psi\, K_S$

Soon recognized as the best way to study CP violation in the B meson system (I. Bigi and T. Sanda 1987)

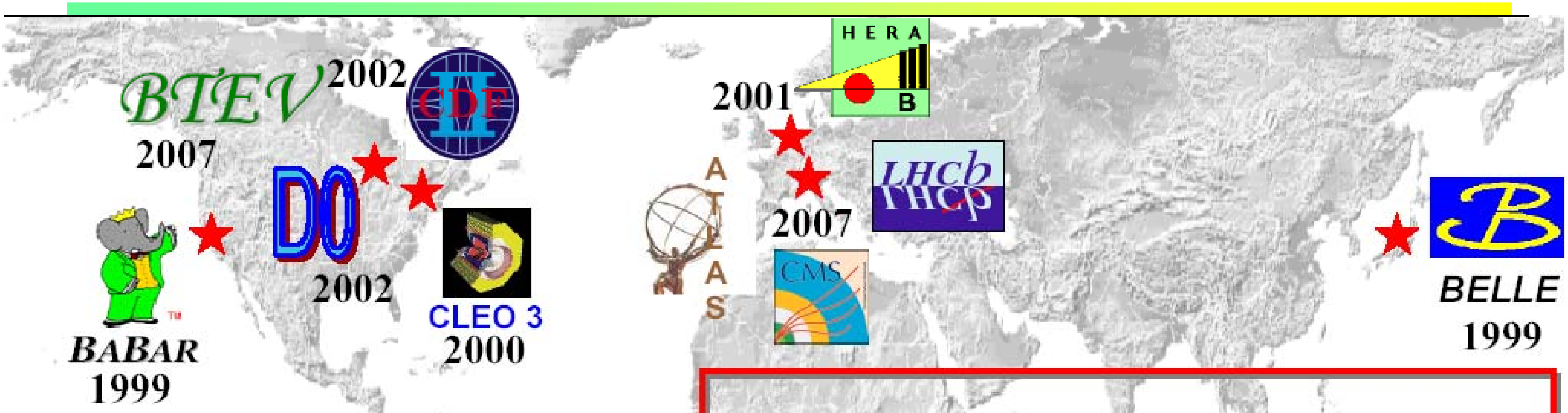
Theoretically clean way to one of the parameters ($\sin 2\phi_1$)

Clear experimental signatures ($J/\psi \rightarrow \mu^+\mu^-$, e^+e^-, $K_S \rightarrow \pi^+\pi^-$)

Relatively large branching fractions for b->ccs ($\sim 10^{-3}$)

→ A lot of physicists were after this holy grail

Genesis of Worldwide Effort



Primary Goal

Precision measurements of **charged weak interactions** as a test of the **CKM** sector of the Standard Model and a probe of the origin of the ***CP* violation**

Time evolution in the B system

An arbitrary linear combination of the neutral B-meson flavor eigenstates

$$a\left|B^0\right\rangle + b\left|\overline{B}^0\right\rangle$$

is governed by a time-dependent Schroedinger equation

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = H\begin{pmatrix} a \\ b \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} a \\ b \end{pmatrix}$$

M and Γ are 2x2 Hermitian matrices. CPT invariance $\rightarrow H_{11}=H_{22}$

$$M = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}, \Gamma = \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

diagonalize $\rightarrow$

Time evolution in the B system

The light B_L and heavy B_H mass eigenstates with eigenvalues $m_H, \Gamma_H, m_L, \Gamma_L$ are given by

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$

$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

With the eigenvalue differences

$$\Delta m_B = m_H - m_L, \Delta\Gamma_B = \Gamma_H - \Gamma_L$$

They are determined from the M and Γ matrix elements

$$(\Delta m_B)^2 - \frac{1}{4}(\Delta\Gamma_B)^2 = 4(|M_{12}|^2 - \frac{1}{4}|\Gamma_{12}|^2)$$

$$\Delta m_B \Delta\Gamma_B = 4\,\mathrm{Re}(M_{12}\Gamma_{12}^{\ *})$$

The ratio p/q is

$$\frac{q}{p} = -\frac{\Delta m_B - \frac{i}{2}\Delta\Gamma_B}{2(M_{12} - \frac{i}{2}\Gamma_{12})} = -\frac{2(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)}{\Delta m_B - \frac{i}{2}\Delta\Gamma_B}$$

What do we know about Δm_B and $\Delta\Gamma_B$?

Δm_B=(0.502+-0.007) ps^{-1} well measured

→ $\Delta m_B/\Gamma_B = x_d$ =0.771+-0.012

$\Delta\Gamma_B/\Gamma_B$ not measured, expected O(0.01), due to decays common to B and anti-B - O(0.001).

→ **$\Delta\Gamma_B << \Delta m_B$**

Since $\Delta\Gamma_B << \Delta m_B$

$$\Delta m_B = 2|M_{12}|$$

$$\Delta\Gamma_B = 2\,\mathrm{Re}(M_{12}\Gamma_{12}^{\ *})/|M_{12}|$$

and

$$\frac{q}{p} = -\frac{|M_{12}|}{M_{12}}$$

= a phase factor

or to the next order

$$\frac{q}{p} = -\frac{|M_{12}|}{M_{12}}\left[1 - \frac{1}{2}\mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)\right]$$

B^0 and $\overline{B}^0$ can be written as an admixture of the states B_H and B_L

$$\left|B^0\right\rangle = \frac{1}{2p}\left(\left|B_L\right\rangle + \left|B_H\right\rangle\right)$$

$$\left|\overline{B}^0\right\rangle = \frac{1}{2q}\left(\left|B_L\right\rangle - \left|B_H\right\rangle\right)$$

Time evolution

Any B state can then be written as an admixture of the states B_H and B_L, and the amplitudes of this admixture evolve in time

$$a_H(t) = a_H(0) e^{-iM_H t} e^{-\Gamma_H t/2}$$

$$a_L(t) = a_L(0) e^{-iM_L t} e^{-\Gamma_L t/2}$$

A B^0 state created at t=0 (denoted by B^0_{phys}) has

$a_H(0) = a_L(0) = 1/(2p)$;

an anti-B at t=0 (anti-B^0_{phys}) has

$a_H(0) = -a_L(0) = 1/(2q)$

At a later time t, the two coefficients are not equal any more because of the difference in phase factors exp(-iMt)

→initial B^0 becomes a linear combination of B and anti-B

→mixing

Time evolution of B's

Time evolution can also be written in the B^0 in $\overline{B}^0$ basis:

$$\left|B^0_{phys}(t)\right\rangle = g_+(t)\left|B^0\right\rangle + (q/p)g_-(t)\left|\overline{B}^0\right\rangle$$

$$\left|\overline{B}^0_{phys}(t)\right\rangle = (p/q)g_-(t)\left|B^0\right\rangle + g_+(t)\left|\overline{B}^0\right\rangle$$

with

$$g_+(t) = e^{-iMt}e^{-\Gamma t/2}\cos(\Delta m t/2)$$

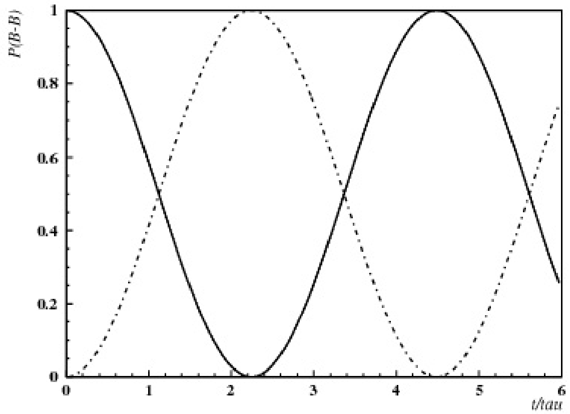
$$g_-(t) = e^{-iMt}e^{-\Gamma t/2} i\sin(\Delta m t/2)$$

$M = (M_H+M_L)/2$

If B mesons were stable ($\Gamma=0$), the time evolution would look like:

$$g_+(t) = e^{-iMt}\cos(\Delta m t/2)$$

$$g_-(t) = e^{-iMt}\, i\sin(\Delta m t/2)$$



→Probability that a B turns into its anti-particle **→beat**

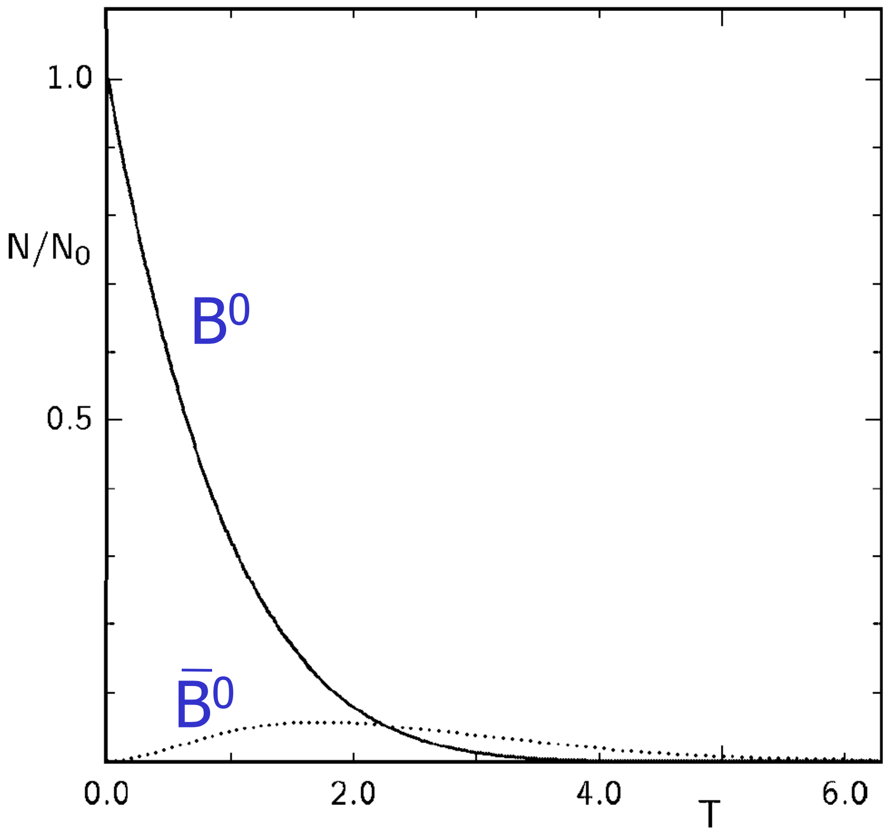
$$\left|\left\langle \overline{B}^0 \middle| B^0_{phys}(t)\right\rangle\right|^2 = |q/p|^2 |g_-(t)|^2 = |q/p|^2 \sin^2(\Delta m t/2)$$

→Probability that a B remains a B

$$\left|\left\langle B^0 \middle| B^0_{phys}(t)\right\rangle\right|^2 = |g_+(t)|^2 = \cos^2(\Delta m t/2)$$

→Expressions familiar from quantum mechanics of a two level system

B mesons of course do decay →



B^0 at t=0

Evolution in time

- Full line: B^0
- dotted: B^0

T: in units of $\tau=1/\Gamma$

Decay probability

Decay probability $P(B^0 \to f, t) \propto \left| \langle f | H | B^0_{phys}(t) \rangle \right|^2$

Decay amplitudes of B and anti-B to the same final state ***f***

$$A_f = \langle f | H | B^0 \rangle$$

$$\overline{A}_f = \langle f | H | \overline{B}^0 \rangle$$

Decay amplitude as a function of time:

$$\langle f | H | B^0_{phys}(t) \rangle = g_+(t) \langle f | H | B^0 \rangle + (q/p) g_-(t) \langle f | H | \overline{B}^0 \rangle$$

$$= g_+(t) A_f + (q/p) g_-(t) \overline{A}_f$$

... and similarly for the anti-B

CP violation: three types

Decay amplitudes of B and anti-B to the same final state ***f***

$$A_f = \langle f | H | B^0 \rangle$$

$$\overline{A}_f = \langle f | H | \overline{B}^0 \rangle$$

Define a parameter λ

$$\lambda = \frac{q}{p} \frac{\overline{A}_f}{A_f}$$

Three types of CP violation (CPV):

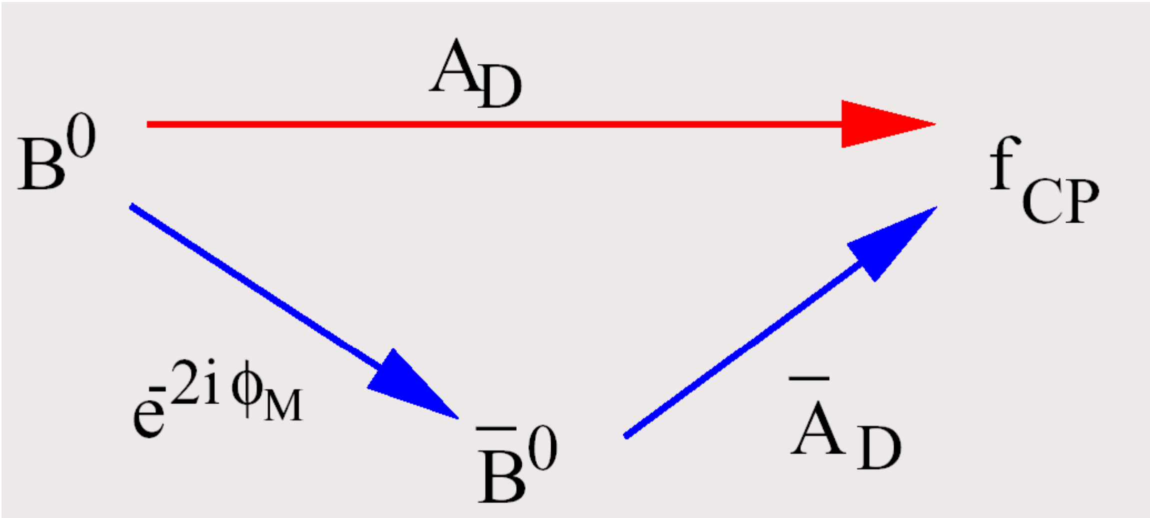
$$\left.\begin{array}{l} \cancel{CP} \text{ in decay: } |\overline{A}/A| \neq 1 \\ \\ \cancel{CP} \text{ in mixing: } |q/p| \neq 1 \end{array}\right\} \; |\lambda| \neq 1$$

$\cancel{CP}$ in interference between mixing and decay: even if $|\lambda| = 1$ if only $\mathrm{Im}(\lambda) \neq 0$

CP violation in the interference between decays with and without mixing

CP violation in the interference between mixing and decay to a state accessible in both B^0 and anti-B^0 decays

For example: a CP eigenstate f_{CP} like $\pi^+ \pi^-$



$$\lambda = \frac{q}{p} \frac{\overline{A}_f}{A_f}$$

We can get CP violation if Im(λ) ≠ 0, even if |λ| = 1

CP violation in the interference between decays with and without mixing

Decay rate asymmetry:

$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP}, t) - P(B^0 \to f_{CP}, t)}{P(\overline{B}^0 \to f_{CP}, t) + P(B^0 \to f_{CP}, t)}$$

Decay rate:

$$P(B^0 \to f_{CP}, t) \propto \left| \left\langle f_{CP} \middle| H \middle| B^0_{phys}(t) \right\rangle \right|^2$$

Decay amplitudes vs time:

$$\left\langle f_{CP} \middle| H \middle| B^0_{phys}(t) \right\rangle = g_+(t) \left\langle f_{CP} \middle| H \middle| B^0 \right\rangle + (q/p) g_-(t) \left\langle f_{CP} \middle| H \middle| \overline{B}^0 \right\rangle$$

$$= g_+(t) A_{f_{CP}} + (q/p) g_-(t) \overline{A}_{f_{CP}}$$

$$\left\langle f_{CP} \middle| H \middle| \overline{B}^0_{phys}(t) \right\rangle = (p/q) g_-(t) \left\langle f_{CP} \middle| H \middle| B^0 \right\rangle + g_+(t) \left\langle f_{CP} \middle| H \middle| \overline{B}^0 \right\rangle$$

$$= (p/q) g_-(t) A_{f_{CP}} + g_+(t) \overline{A}_{f_{CP}}$$

$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP}, t) - P(B^0 \to f_{CP}, t)}{P(\overline{B}^0 \to f_{CP}, t) + P(B^0 \to f_{CP}, t)} =$$

$$= \frac{\left|(p/q)g_-(t)A_{f_{CP}} + g_+(t)\overline{A}_{f_{CP}}\right|^2 - \left|g_+(t)A_{f_{CP}} + (q/p)g_-(t)\overline{A}_{f_{CP}}\right|^2}{\left|(p/q)g_-(t)A_{f_{CP}} + g_+(t)\overline{A}_{f_{CP}}\right|^2 + \left|g_+(t)A_{f_{CP}} + (q/p)g_-(t)\overline{A}_{f_{CP}}\right|^2} =$$

$$= \frac{(1-|\lambda_{f_{CP}}|^2)\cos(\Delta m t) - 2\,\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)}{1+|\lambda_{f_{CP}}|^2}$$

$$= C\cos(\Delta m t) + S\sin(\Delta m t)$$

$$\lambda = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

Non-zero effect if Im(λ) ≠ 0,
even if |λ| = 1

If |λ| = 1 → $\boxed{a_{f_{CP}} = -\mathrm{Im}(\lambda)\sin(\Delta m t)}$

Detailed derivation → backup slides

CP violation in the interference between decays with and without mixing

One more form for λ:

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = \eta_{f_{CP}} \frac{q}{p}\frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}$$

η_{fcp}=+-1 CP parity of f_{CP}

→ we get one more (–1) sign when comparing asymmetries in two states with opposite CP parity

$$a_{f_{CP}} = -\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)$$

B and anti-B from the Υ(4s)

B and anti-B from the Υ(4s) decay are in a L=1 state.

They cannot mix independently (either BB or anti-B anti-B states are forbidden with L=1 due to Bose symmetry).

After one of them decays, the other evolves independently ->

-> only time differences between one and the other decay matter (for mixing).

Assume

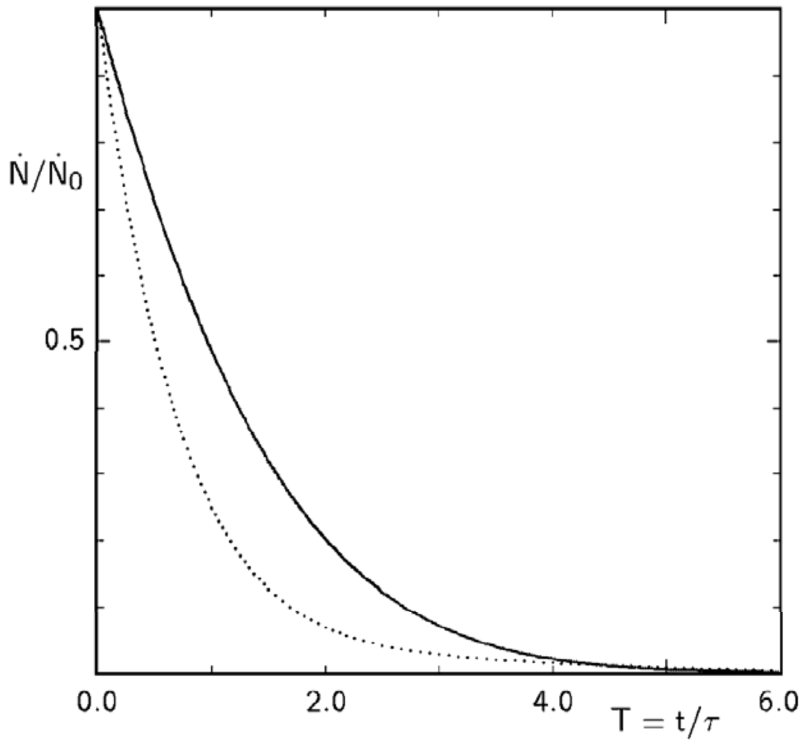
•one decays to a CP eigenstate f_{CP} (e.g. $\pi\pi$ or $J/\psi K_S$) at time t_{fCP} and

•the other at t_{ftag} to a flavor-specific state f_{tag} (=state only accessible to a B^0 and not to a anti-B^0 (or vice versa), e.g. $B^0 \to D^0\pi$, $D^0 \to K^-\pi^+$)

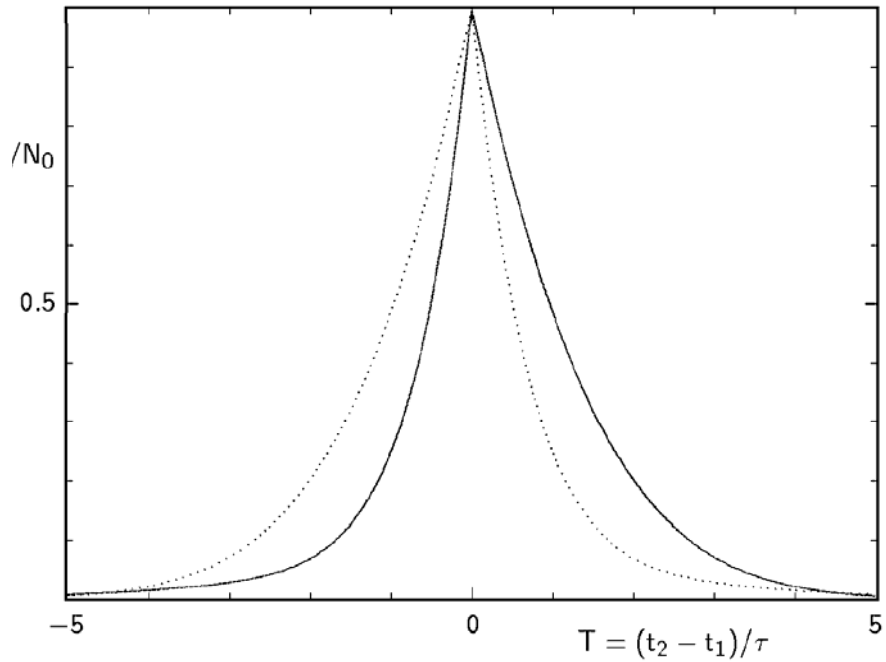
also known as 'tag' because it tags the flavour of the B meson it comes from

Decay rate to f_{CP}

Incoherent production
(e.g. hadron collider)



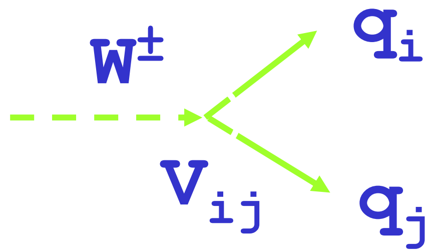
coherent production
at Y(4s)



At Y(4s): Time integrated asymmetry = 0

CP violation in SM

CP violation: consequence of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix



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

CKM matrix

3x3 ortogonal matrix: 3 parameters - angles

3x3 unitary matrix: 18 parameters, 9 conditions = 9 free parameters, 3 angles and 6 phases

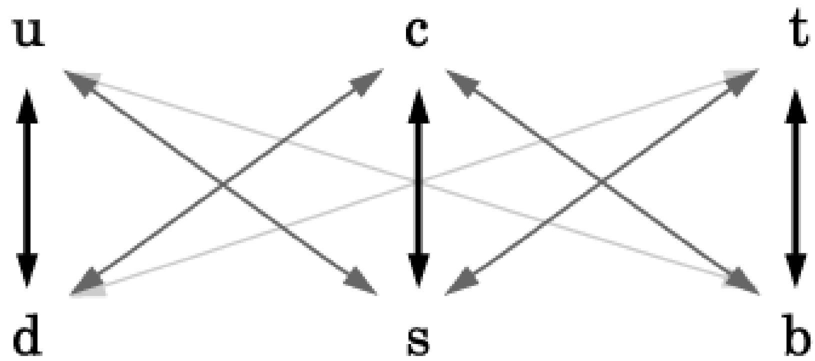
6 quarks: 5 relative phases can be transformed away (by redefinig the quark fields)

1 phase left -> the matrix is in general complex

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{13} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

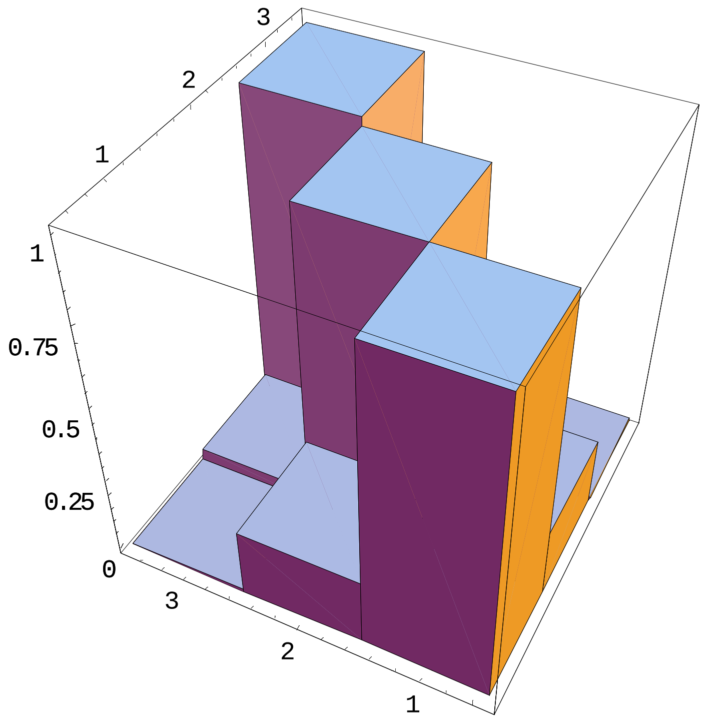
$s_{12}=\sin\theta_{12}$, $c_{12}=\cos\theta_{12}$ etc.

CKM matrix



Transitions between members of the same family more probable (=thicker lines) than others

-> CKM: almost a diagonal matrix, but not completely ->



CKM matrix

Almost a diagonal matrix, but not completely ->

Wolfenstein parametrisation: expand in the parameter
λ (=$\sin\theta_c$=0.22)

A, ρ and η: all of order one

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Unitary relations

Rows and columns of the V matrix are orthogonal

Three examples: 1st+2nd, 2nd+3rd, 1st+3rd columns

$$V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} = 0,$$
$$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0,$$
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0.$$

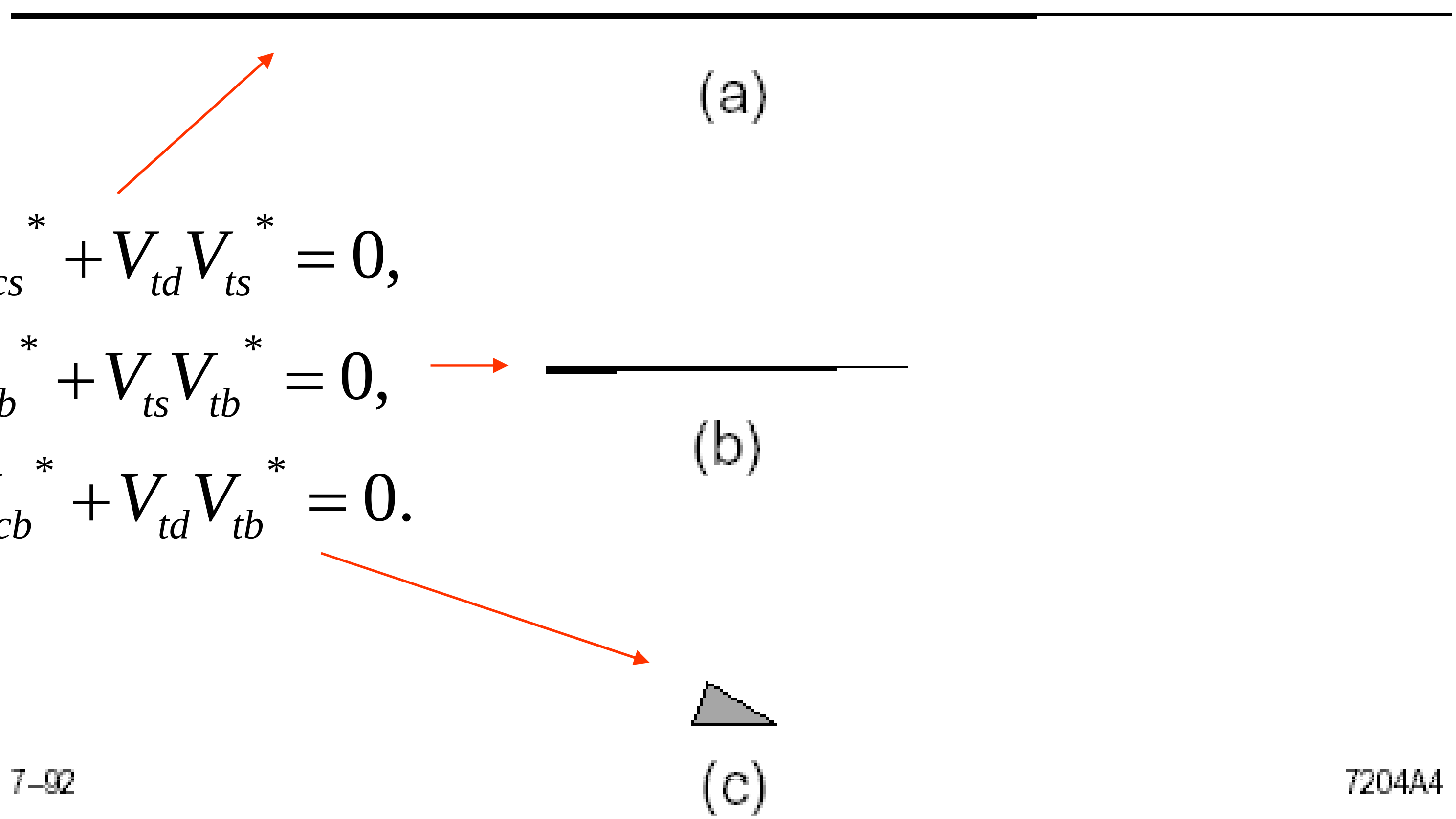
Geometrical representation: triangles in the complex plane.

Unitary triangles

$$V_{ud}V_{us}^{*}+V_{cd}V_{cs}^{*}+V_{td}V_{ts}^{*}=0,$$

$$V_{us}V_{ub}^{*}+V_{cs}V_{cb}^{*}+V_{ts}V_{tb}^{*}=0,$$

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



All triangles have the same area J/2 (about 4×10^{-5})

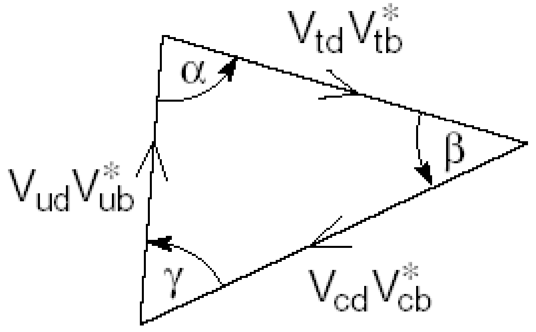
$$J = c_{12}c_{23}c_{13}^{2}s_{12}s_{23}s_{13}\sin\delta$$

Jarlskog invariant

Unitarity triangle

THE unitarity triangle:

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



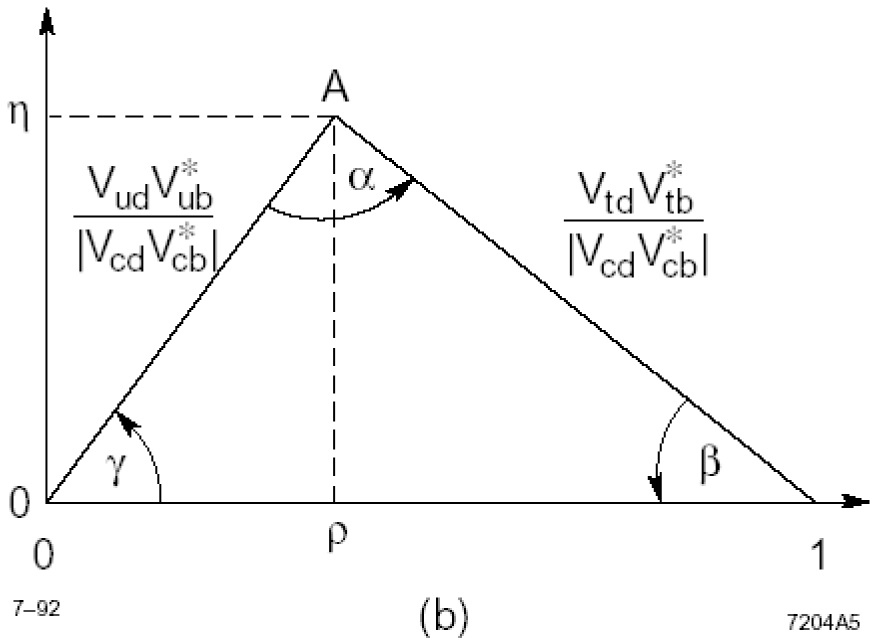
(a)

Two notations:

$\phi_1=\beta$

$\phi_2=\alpha$

$\phi_3=\gamma$



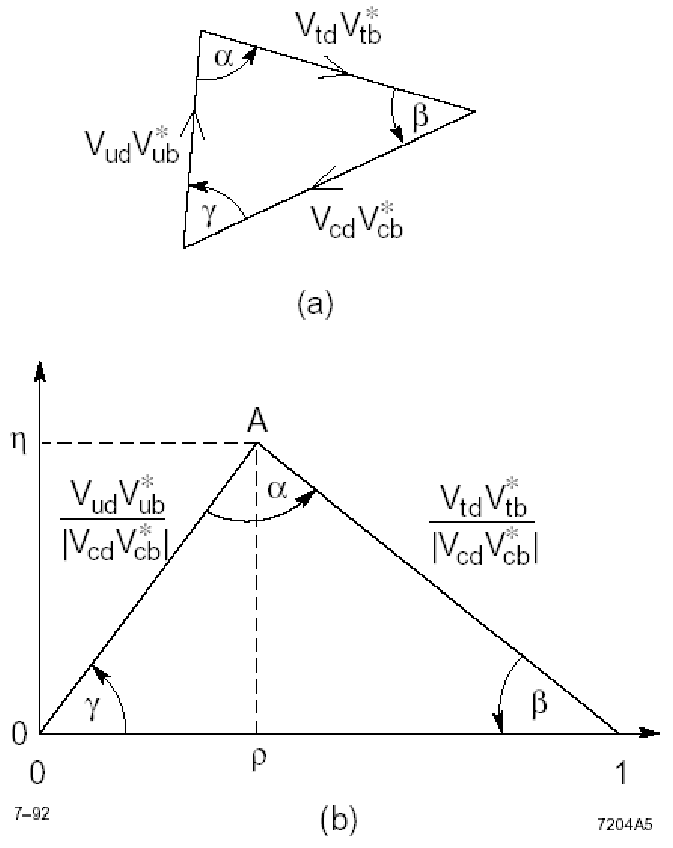
(b)

Angles of the unitarity triangle

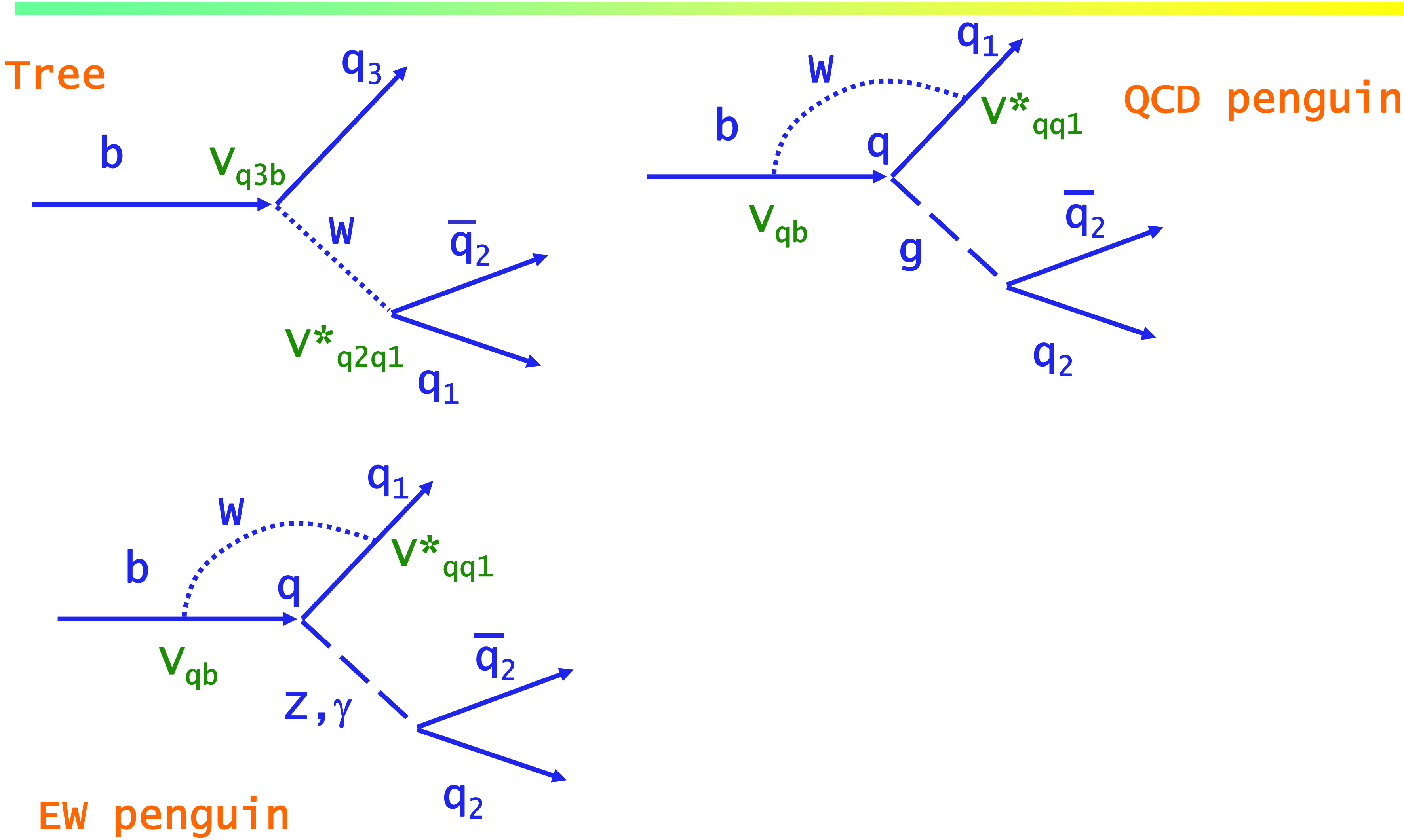
$$\alpha \equiv \phi_2 \equiv \arg\left(\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta \equiv \phi_1 \equiv \arg\left(\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\gamma \equiv \phi_3 \equiv \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \equiv \pi - \alpha - \beta$$



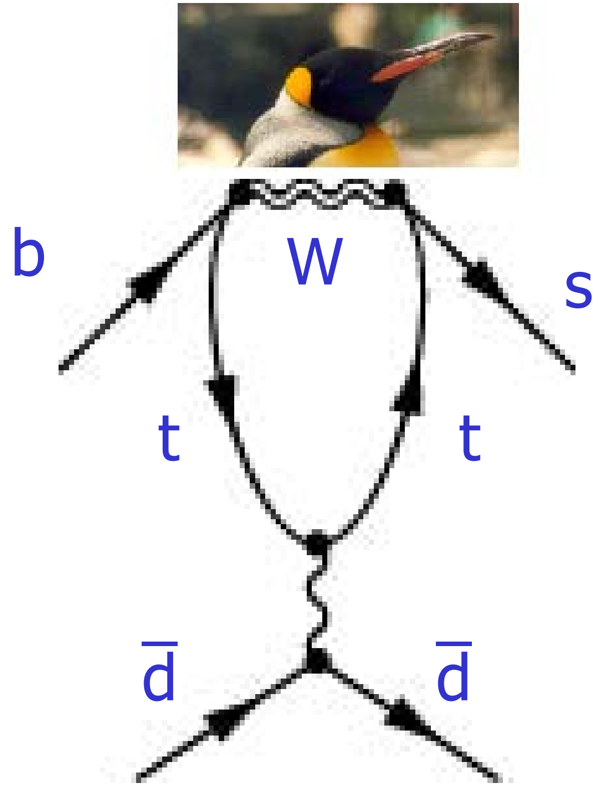
b decays



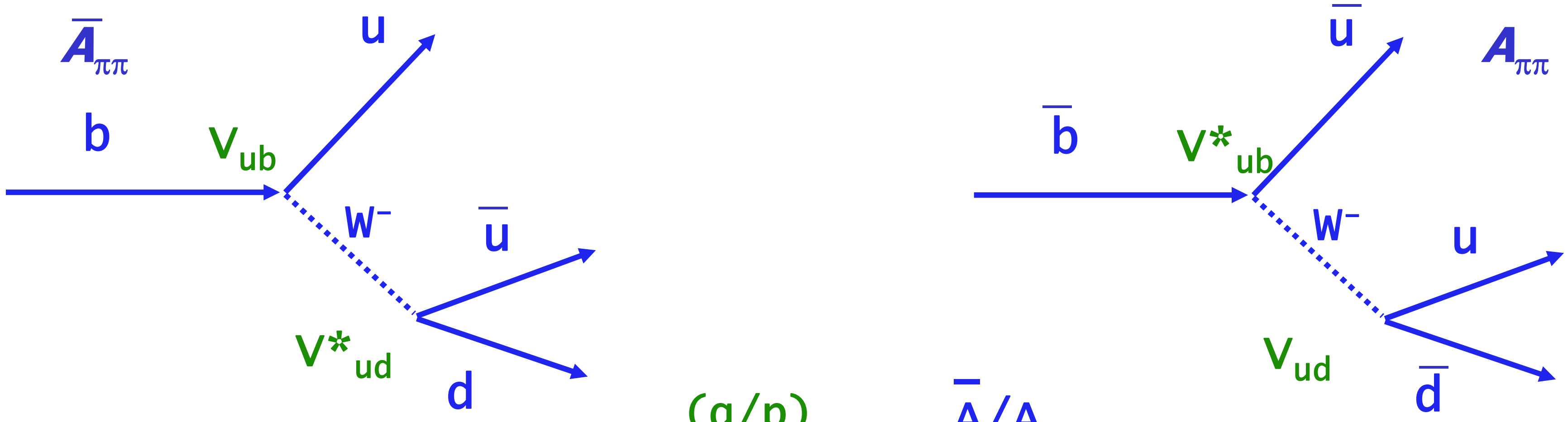
Tree
b
V_{q3b}
q_3
W
$\bar{q}_2$
V^*_{q2q1}
q_1
QCD penguin
b
W
q_1
V^*_{qq1}
q
V_{qb}
g
$\bar{q}_2$
q_2
EW penguin
b
W
q_1
V^*_{qq1}
q
V_{qb}
Z,γ
$\bar{q}_2$
q_2

Why penguin?

Example: b→s transition



Decay asymmetry predictions – example $\pi^+ \pi^-$



$$\lambda_{\pi\pi} = \eta_{\pi\pi} \underbrace{\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \right)}_{(q/p)} \underbrace{\left(\frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*} \right)}_{\bar{A}/A}$$

$$\mathrm{Im}(\lambda_{\pi\pi}) = \sin 2\phi_2$$

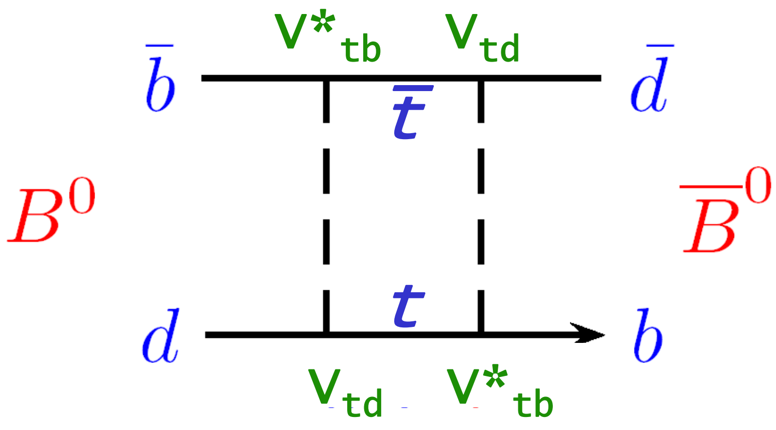
$$\alpha \equiv \phi_2 \equiv \arg \left(\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} \right)$$

N.B.: for simplicity we have neglected possible penguin amplitudes (which is wrong as we shall see later, when we will do it properly).

A reminder:

$$\frac{q}{p} = -\frac{|M_{12}|}{M_{12}}$$

$$\Delta m_B = 2|M_{12}|$$



$$\Delta m \propto$$

$$|V_{tb}^* \; V_{td}|^2 m_t^2 \;\; \propto \;\; \lambda^6 m_t^2$$

$$|V_{cb}^* \; V_{cd}|^2 m_c^2 \;\; \propto \;\; \lambda^6 m_c^2$$

Decay asymmetry predictions – example J/ψK_S

$b \to c\bar{c}s$: Take into account that we measure the $\pi^+\pi^-$ component of K_S – also need the $(q/p)_K$ for the K system

$$\lambda_{\psi Ks} = \eta_{\psi Ks} \underbrace{\boxed{\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)}}_{(q/p)_B} \underbrace{\boxed{\left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right)}}_{\bar{A}/A} \underbrace{\boxed{\left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right)}}_{(q/p)_K} =$$

$$= \eta_{\psi Ks} \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cb}}{V_{cb}^*} \frac{V_{cd}^*}{V_{cd}}\right)$$

$$\mathrm{Im}(\lambda_{\psi Ks}) = \sin 2\phi_1$$

$$\beta \equiv \phi_1 \equiv \arg\left(\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*}\right)$$

$b \to c$ anti-c s
CP=+1 and CP=-1 eigenstates

$$a_{f_{CP}} = -\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)$$

Asymmetry sign depends on the CP parity of the final state f_{CP}, η_{fcp}=+-1

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

$J/\psi\, K_S\, (\pi^+ \pi^-)$: CP=-1

- J/ψ: P=-1, C=-1 (vector particle $J^{PC}=1^{--}$): CP=+1
- K_S (->$\pi^+ \pi^-$): CP=+1, orbital ang. momentum of pions=0 ->
  $P(\pi^+ \pi^-)=(\pi^- \pi^+)$, $C(\pi^- \pi^+) = (\pi^+ \pi^-)$
- orbital ang. momentum between J/ψ and K_S L=1, $P=(-1)^1=-1$

$J/\psi\, K_L(3\pi)$: CP=+1

Opposite parity to $J/\psi\, K_S\, (\pi^+ \pi^-)$, because $K_L(3\pi)$ has CP=-1

How to measure CP violation?

Principle of measurement

Experimental considerations

Choice of boost

Spectrometer design

Babar and Belle spectrometers

Principle of measurement

Principle of measurement:

•Produce pairs of B mesons, moving in the lab system

•Find events with B meson decay of a certain type (usually B -> f_{CP} - CP eigenstate)

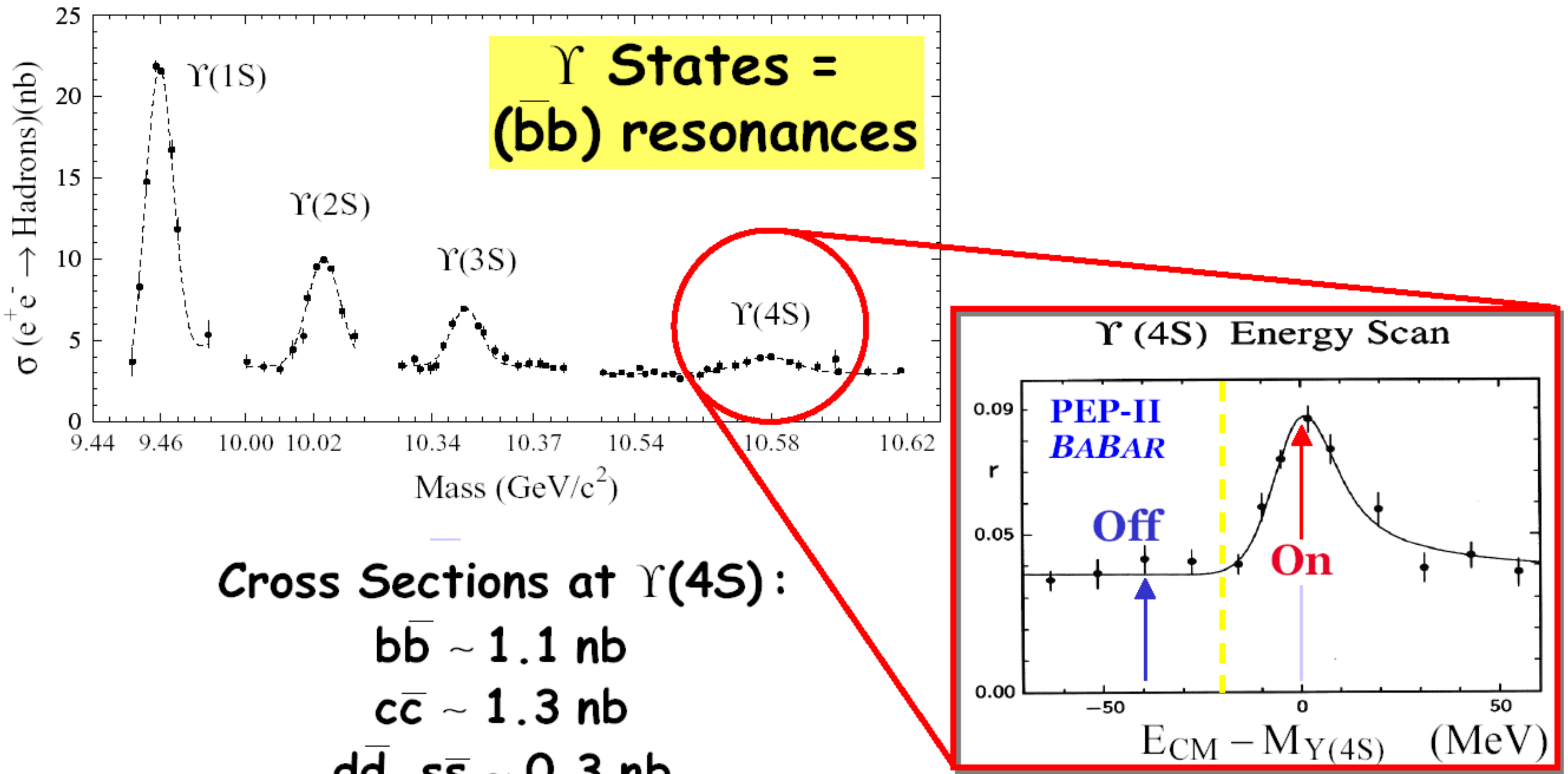
•Measure time difference between this decay and the decay of the associated B (f_{tag}) (from the flight path difference)

•Determine the flavour of the associated B (B or anti-B)

•Measure the asymmetry in time evolution for B and anti-B

Restrict for the time being to B meson production at Y(4s)

B meson production at Υ(4s)



Cross Sections at Υ(4S):

$b\bar{b} \sim 1.1$ nb

$c\bar{c} \sim 1.3$ nb

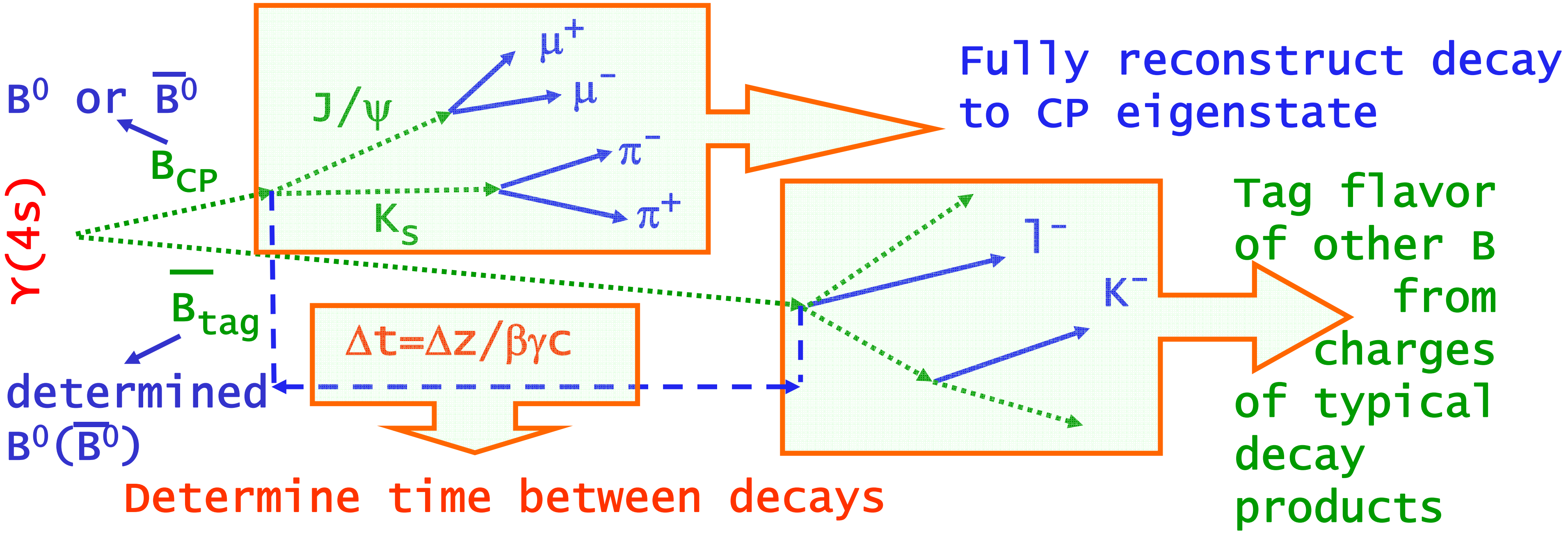
$d\bar{d}$, $s\bar{s} \sim 0.3$ nb

$u\bar{u} \sim 1.4$ nb

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

$L = 1$ state

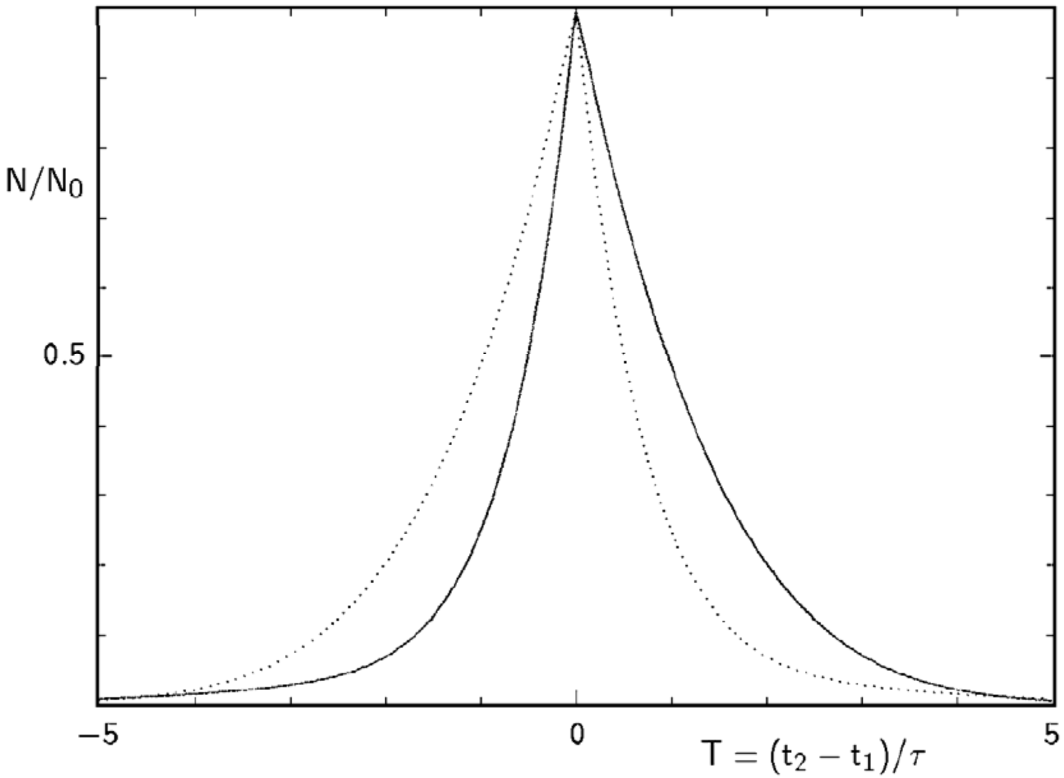
Principle of measurement



Experimental considerations

What kind of vertex resolution do we need to measure the asymmetry?

$$P(B^0(\overline{B}^0) \to f_{CP}, t) = e^{-\Gamma t}\left(1 \mp \sin(2\phi_1)\sin(\Delta m t)\right)$$



Want to distinguish the decay rate of B (dotted) from the decay rate of anti-B (full).

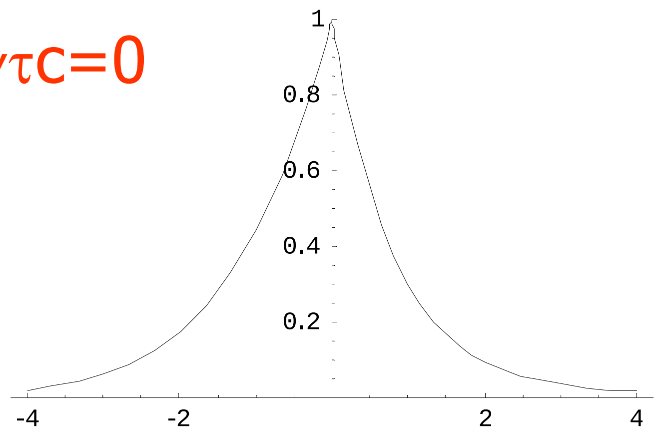
-> the two curves should not be smeared too much

Integrals are equal, time information mandatory! (true at Y(4s), but not for incoherent production)

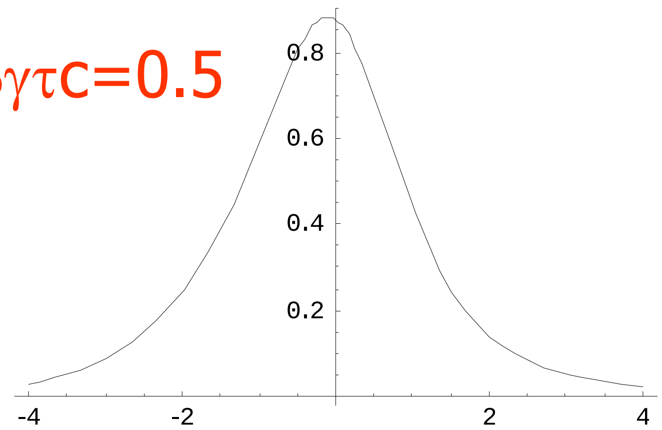
Experimental considerations

B decay rate vs t for different vertex resolutions in units of typical B flight length $\sigma(z)/\beta\gamma\tau c$

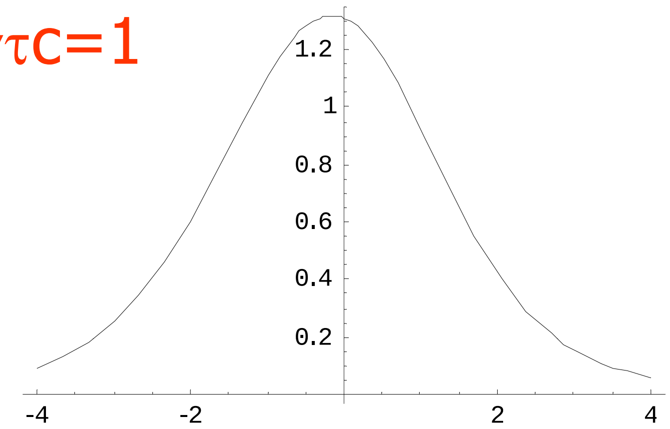
$\sigma(z)/\beta\gamma\tau c=0$



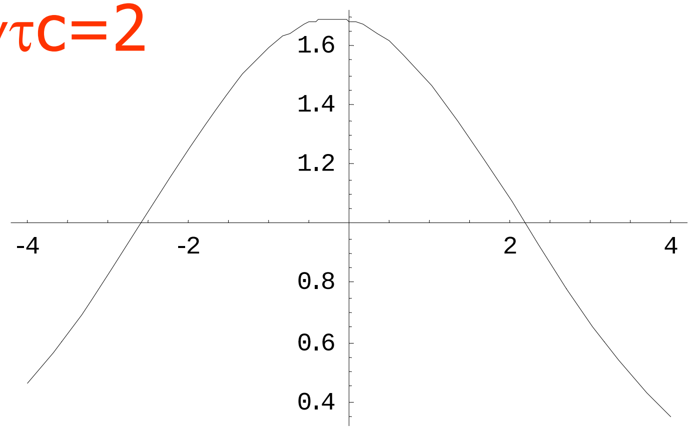
$\sigma(z)/\beta\gamma\tau c=0.5$



$\sigma(z)/\beta\gamma\tau c=1$



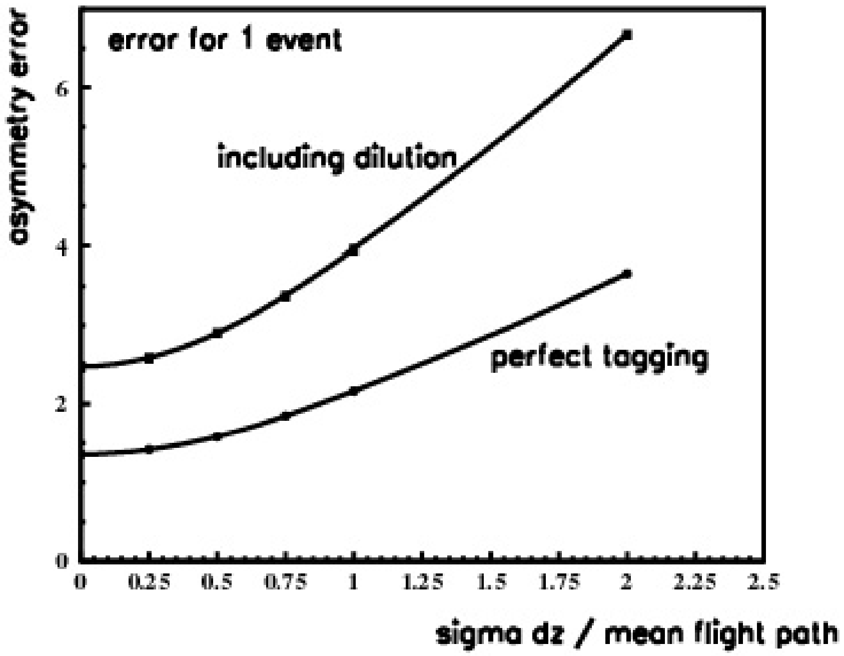
$\sigma(z)/\beta\gamma\tau c=2$



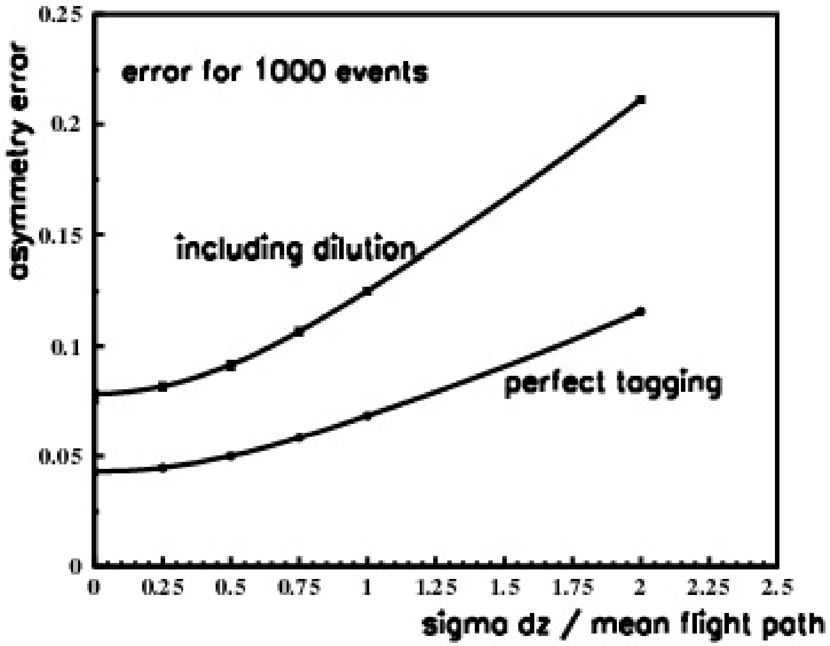
Experimental considerations

Error on $\sin 2\phi_1 = \sin 2\beta$ as function of vertex resolution in units of typical B flight length $\sigma(z)/\beta\gamma\tau c$

For 1 event



for 1000 events



Experimental considerations

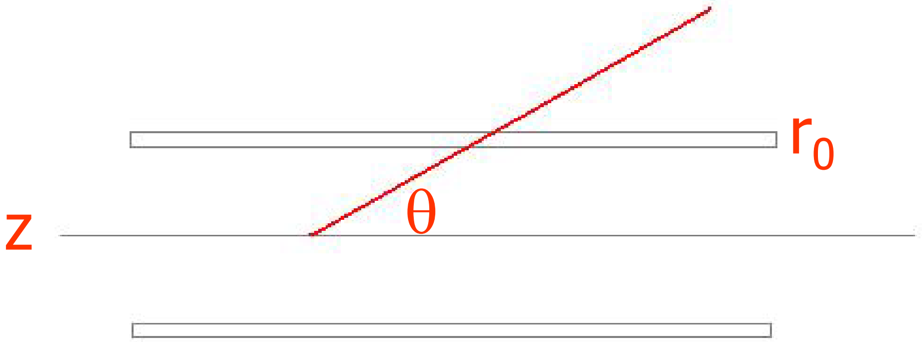
Choice of boost $\beta\gamma$:

Vertex resolution vs. path length

Typical B flight length: $z_B=\beta\gamma\tau c$

Typical two-body topology: decay products at 90^o in cms; at $\theta=\mathrm{atan}(1/\beta\gamma)$ in the lab

Assume: vertex resolution determined by multiple scattering in the first detector layer and beam pipe wall at r_0



$$\sigma_\theta = 15\ \mathrm{MeV}/p\ \sqrt{(d/\sin\theta X_0)}$$

$$\sigma(z) = r_0\, \sigma_\theta / \sin^2\theta$$

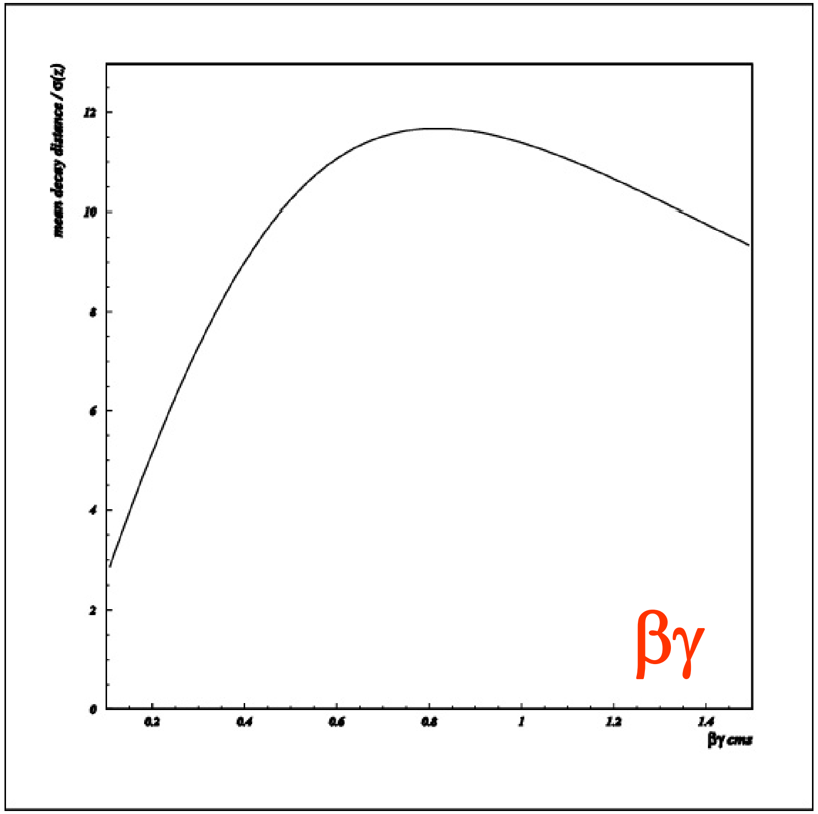
$$\Rightarrow \quad \sigma(z)\ \alpha\ r_0/\sin^{5/2}\theta$$

Experimental considerations

Choice of boost $\beta\gamma$:

Vertex resolution in units of typical B flight length

$\beta\gamma\tau c/\sigma(z)$



Boost around $\beta\gamma=0.8$ seems optimal

However....

Experimental considerations

Which boost...

Arguments for a smaller boost:

- Larger boost -> smaller acceptance ->
- Larger boost -> it becomes hard to damp the betatron oscillations of the low energy beam: less synchrotron radiation at fixed ring radius (same as the high energy beam)

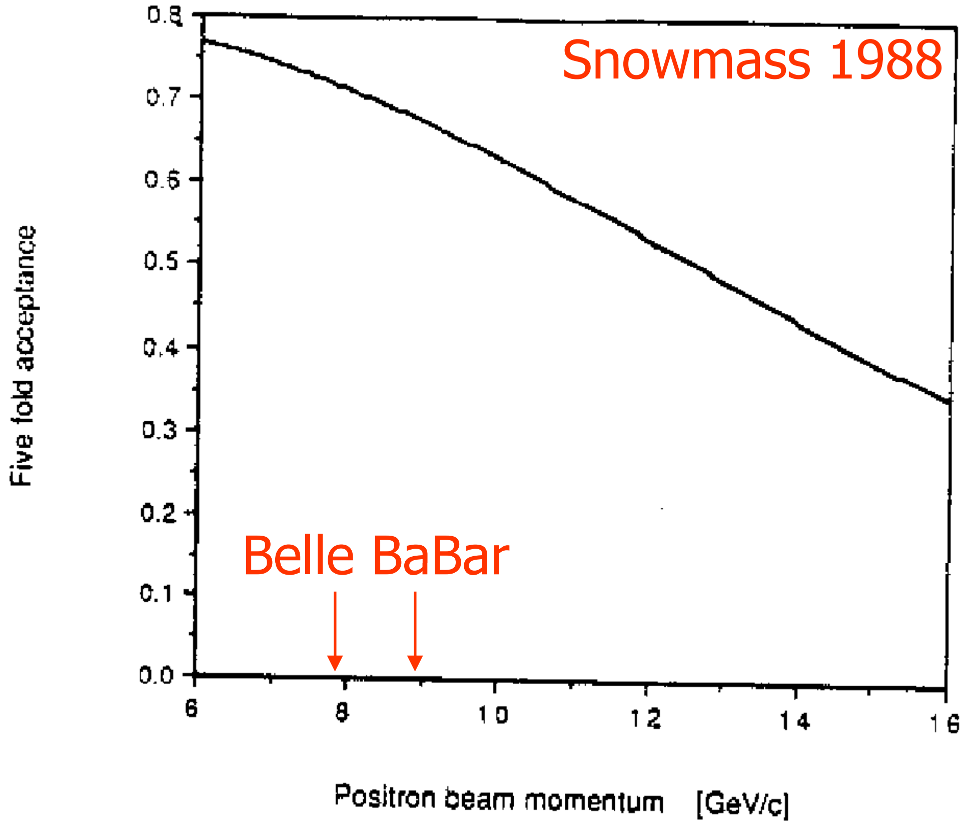
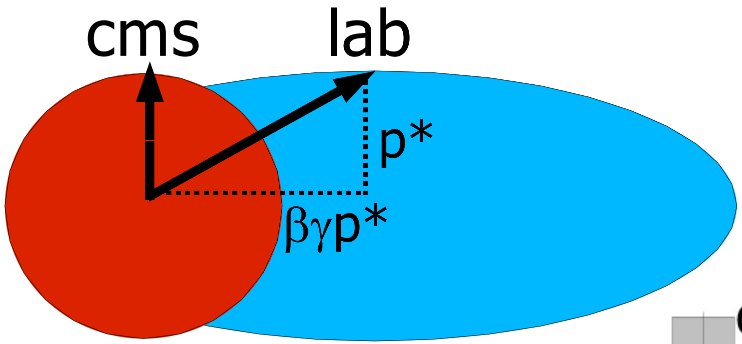


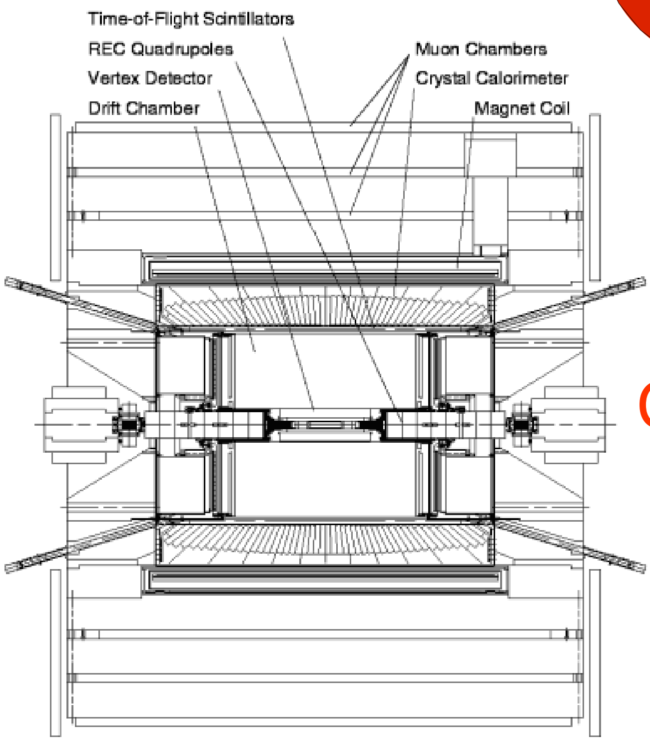
Figure 4. The acceptance of a detector covering $|\cos\theta_{lab}| < 0.95$ for five uncorrelated particles as a function of the energy of the more energetic beam in an asymmetric collider at the $\Upsilon(4S)$.

Experimental considerations

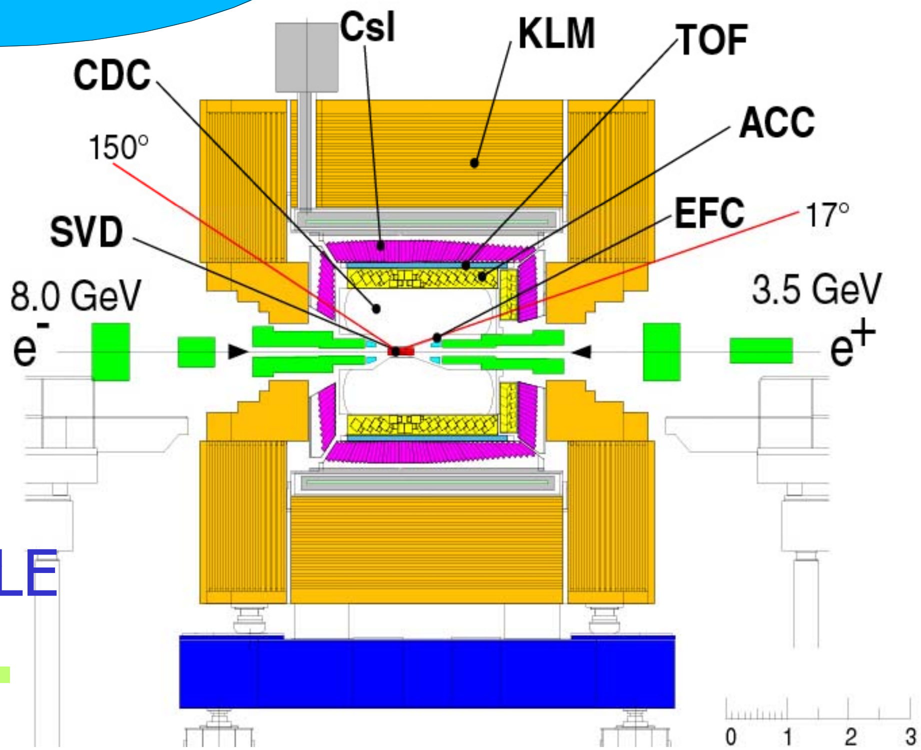
Detector form: symmetric for symmetric energy beams; slightly extended in the boost direction for an asymmetric collider.



Exaggerated plot: in reality $\beta\gamma=0.5$



CLEO



BELLE

How many events?

Rough estimate:

Need ~1000 reconstructed B-> J/ψ K_S decays with J/ψ -> ee or $\mu\mu$, and K_S-> $\pi^+ \pi^-$

½ of Y(4s) decays are B^0 anti-B^0 (but 2 per decay)

BR(B-> J/ψ K^0)=8.4 10^{-4}

BR(J/ψ -> ee or $\mu\mu$)=11.8%

½ of K^0 are K_S, BR(K_S-> $\pi^+ \pi^-$)=69%

Reconstruction effiency ~ 0.2 (signal side: 4 tracks, vertex, tag side pid and vertex)

N(Y(4s)) = 1000 / (½ * ½ * 2 * 8.4 10^{-4} * 0.118 * 0.69 * 0.2) =
= 140 M

How to produce 140 M BB pairs?

Want to produce 140 M pairs in two years

Assume effective time available for running is 10^7 s per year.

→ need a rate of 140 10^6 / (2 10^7 s) = 7 Hz

Observed rate of events = Cross section x Luminosity

$$\frac{dN}{dt} = L\sigma$$

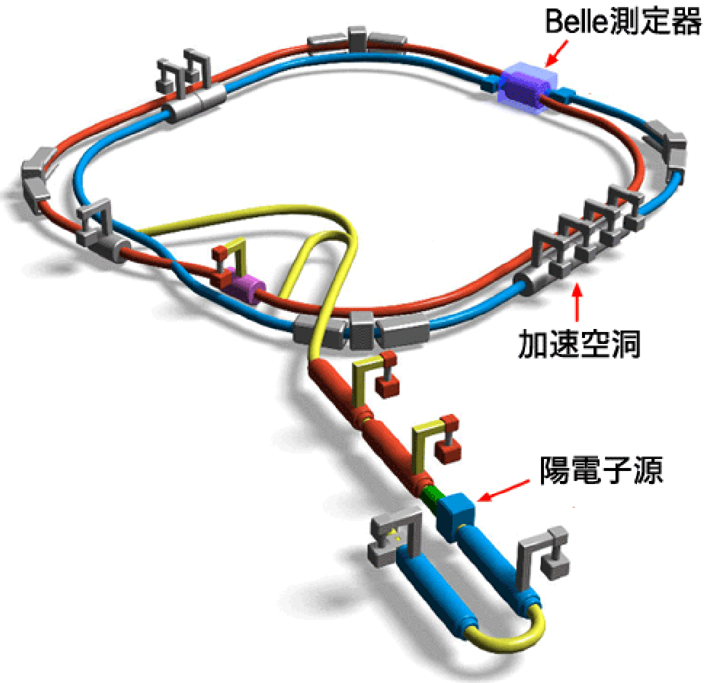
Cross section for Y(4s) production: 1.1 nb = 1.1 10^{-33} cm^2

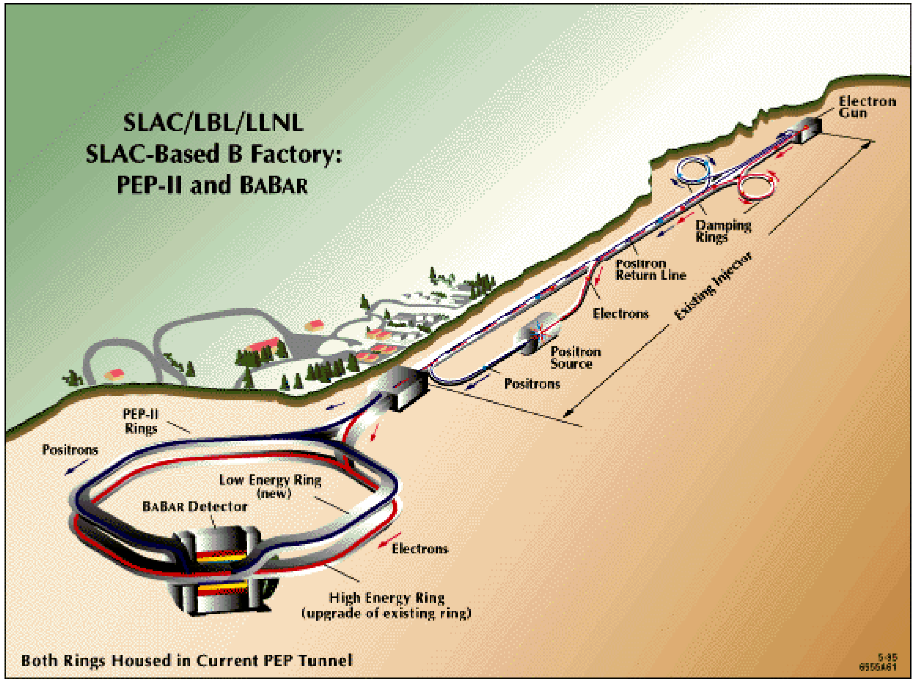
→ Accelerator figure of merit - luminosity - has to be

$\mathcal{L}$ = 6.5 /nb/s = 6.5 10^{33} cm^{-2} s^{-1}

This is much more than any other accelerator achieved before!

Colliders: asymmetric B factories





$\sqrt{s}=10.58$ GeV

$e^+ \longrightarrow \Upsilon(4s) \longleftarrow e^-$

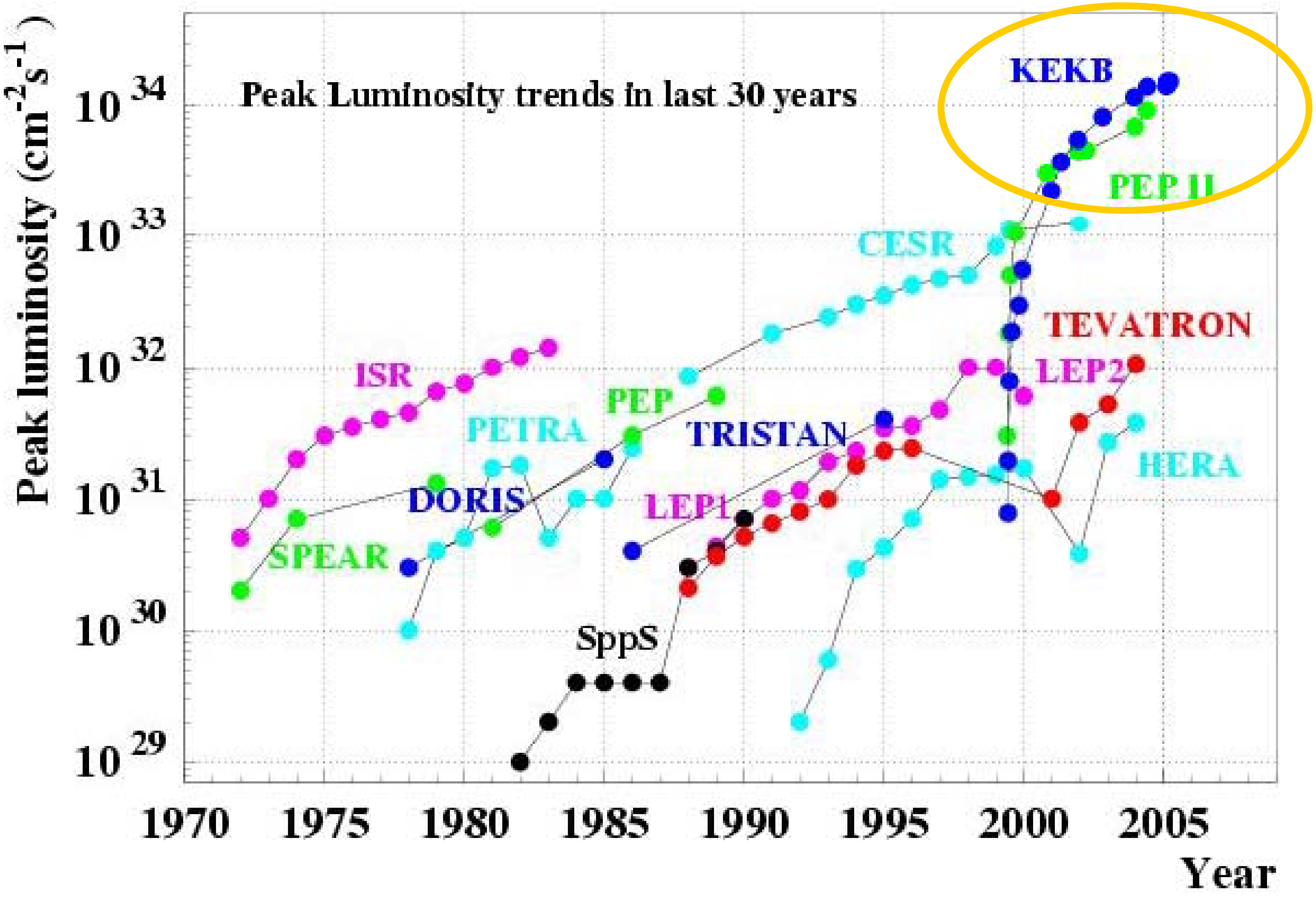
$\Upsilon(4s) \rightarrow B\,\bar{B}$

$\Delta z \sim c\beta\gamma\tau_B \sim 200\mu m$

BaBar	$p(e^-)=9$ GeV	$p(e^+)=3.1$ GeV	$\beta\gamma=0.56$
Belle	$p(e^-)=8$ GeV	$p(e^+)=3.5$ GeV	$\beta\gamma=0.42$

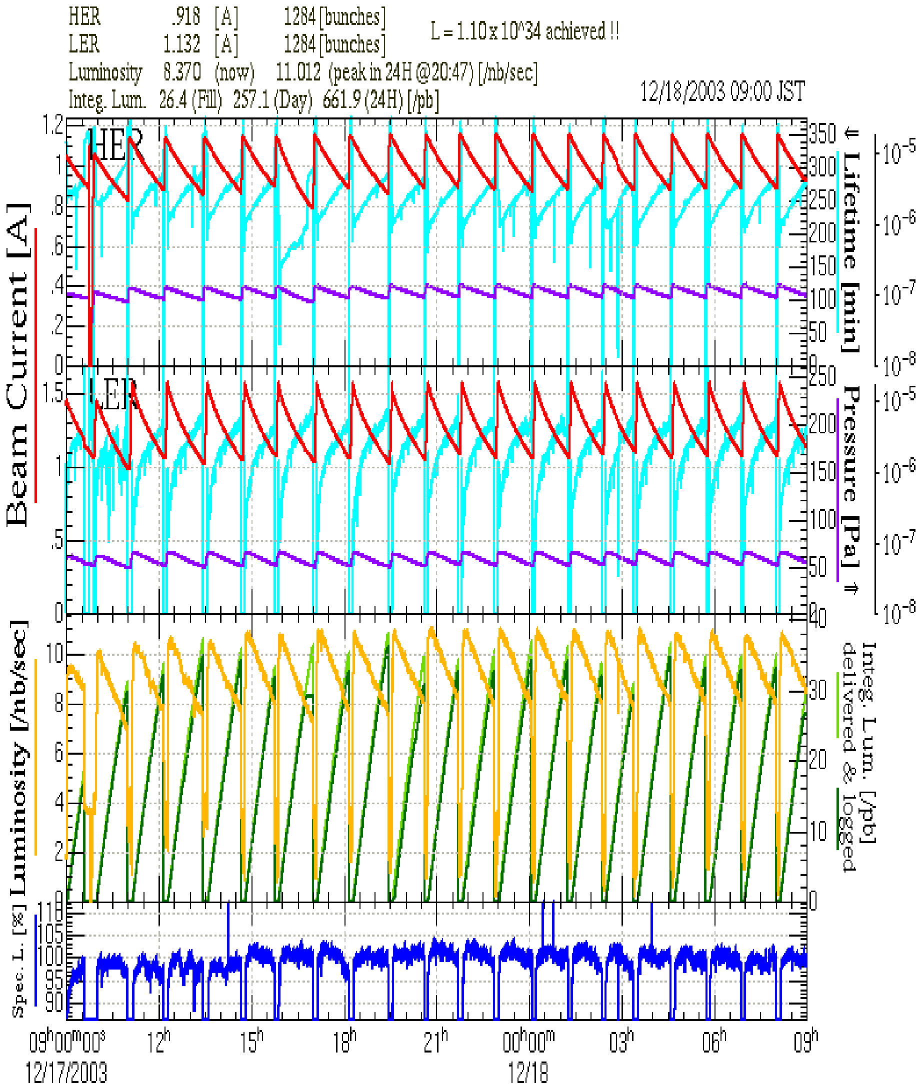

KEKB records: L_{peak} = 17/nb/sec (=1.7×10^{34} $s^{-1}cm^{-2}$)
L_{int}= 852/fb → ~900 M BB pairs
BELLE

Accelerator performance

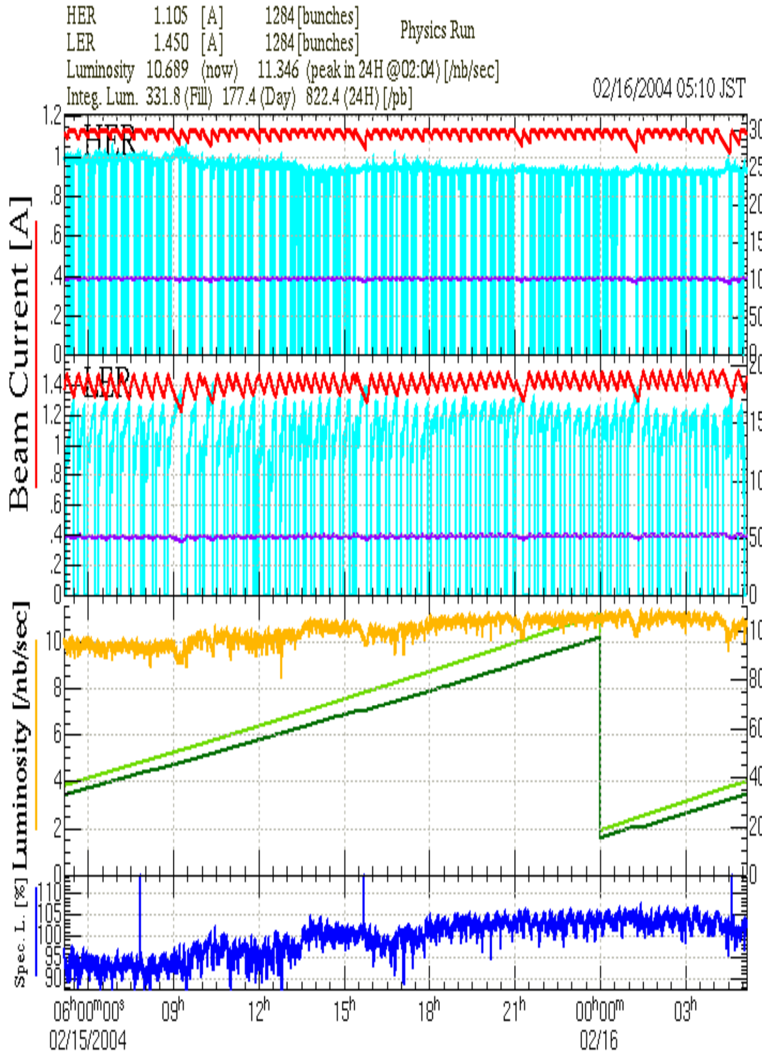


Normal injection

Continuous injection



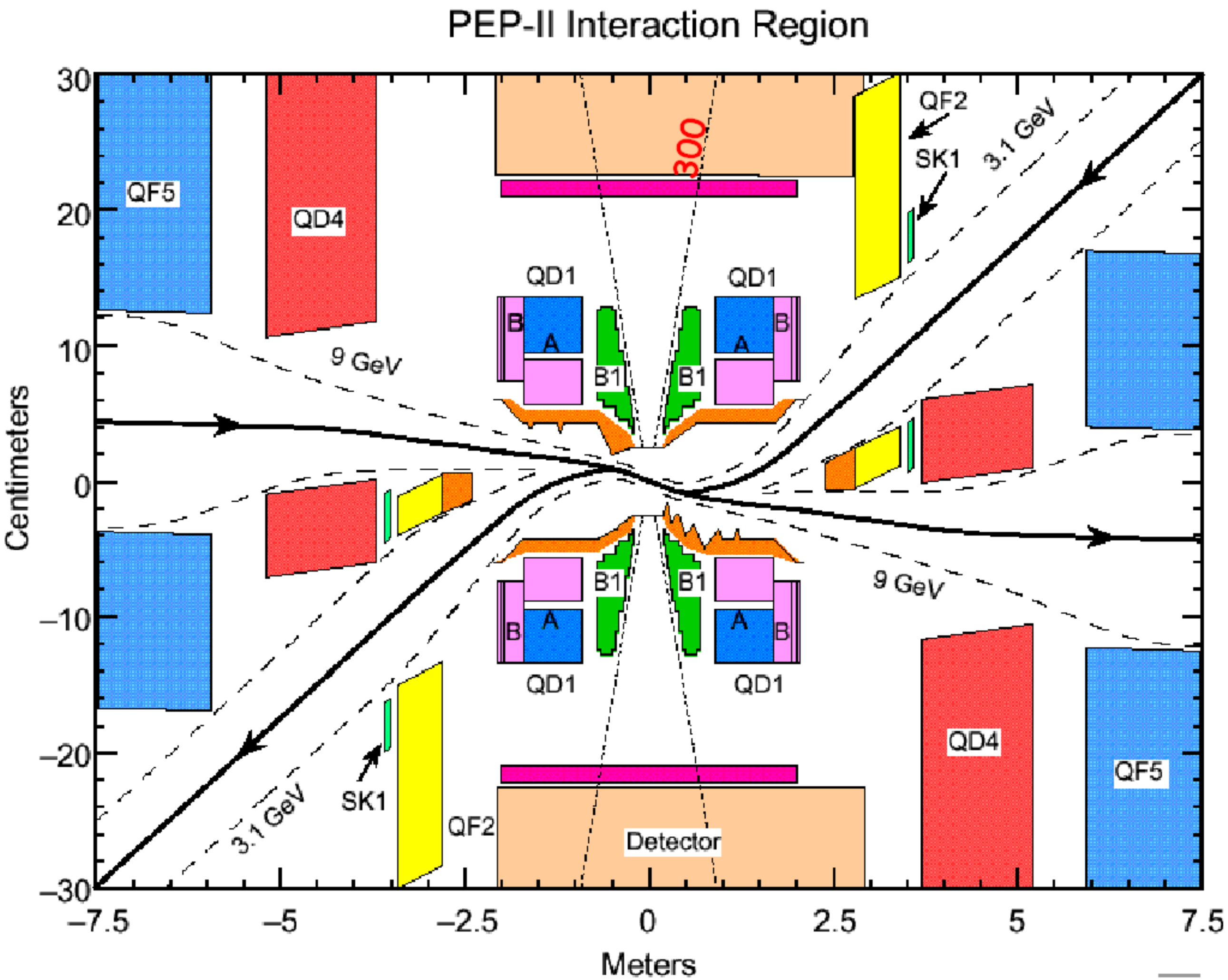
661/pb/day



→1182/pb/day

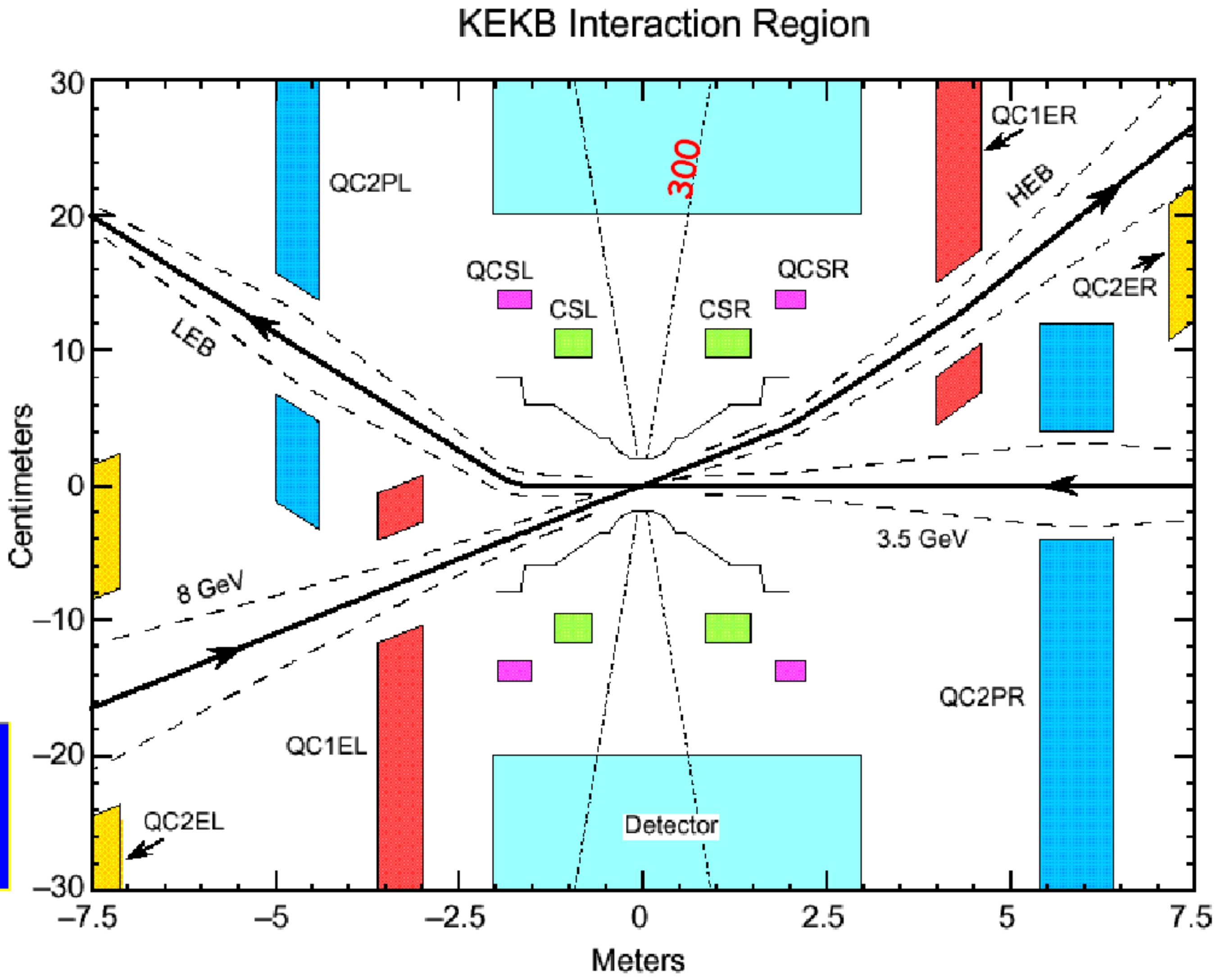
Interaction region: BaBar

Head-on collisions

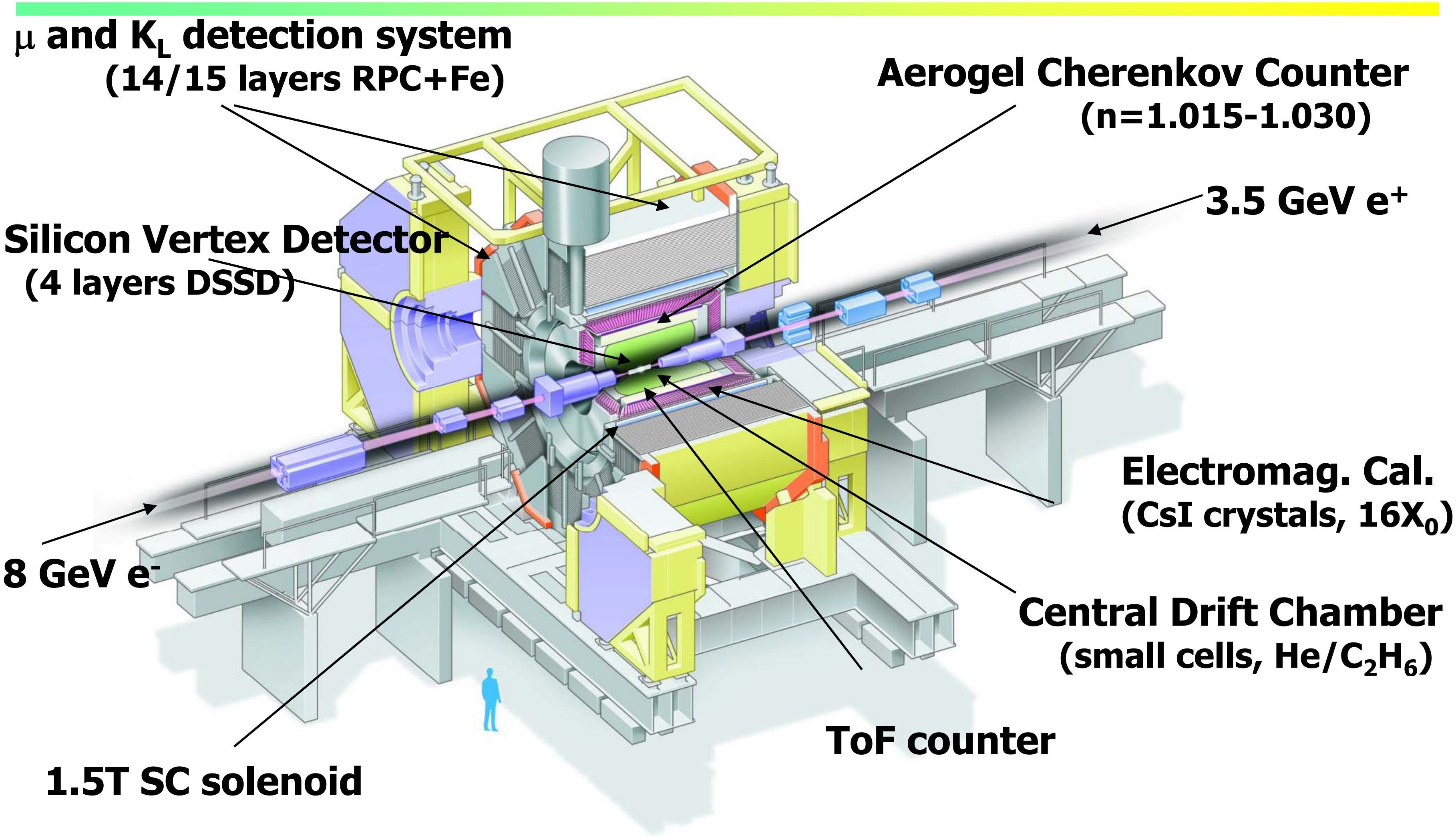


Interaction region: Belle

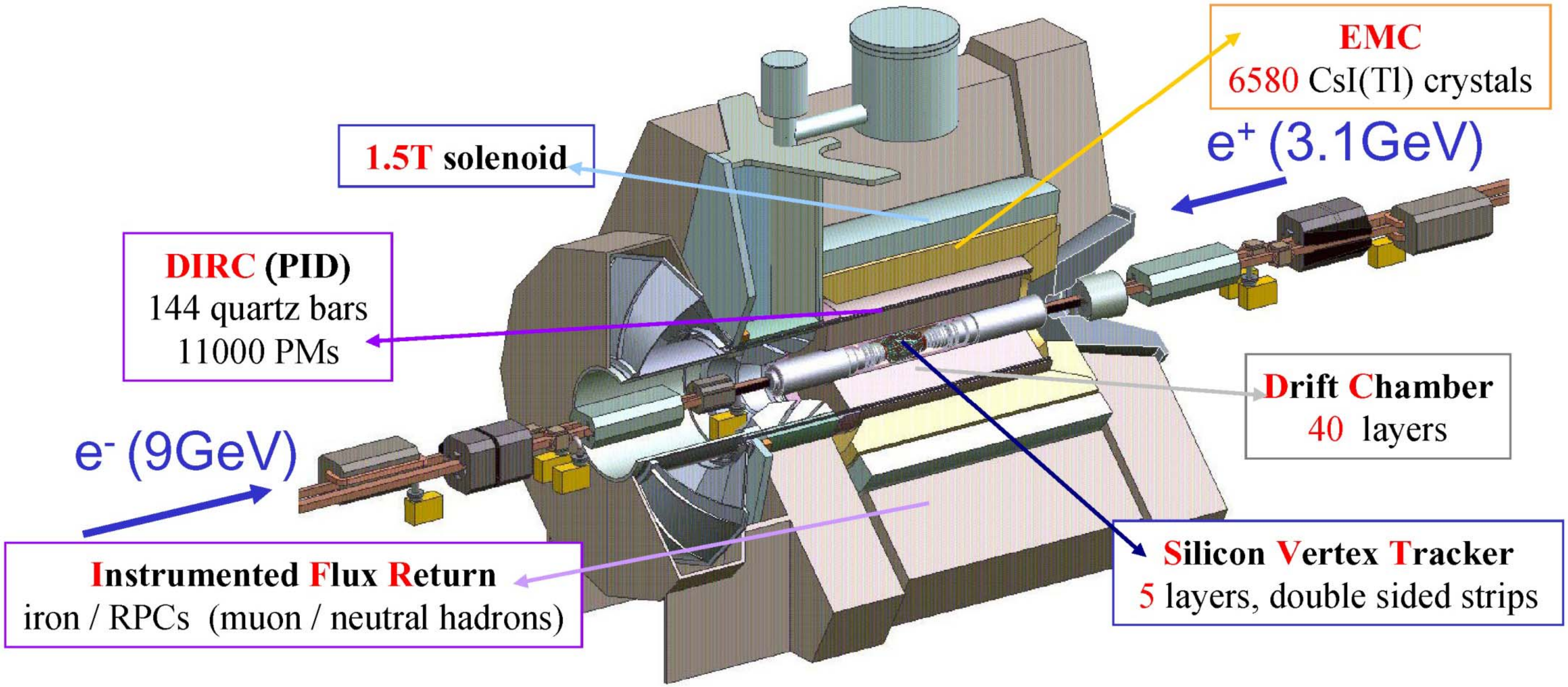
Collisions at a finite angle +-11mrad



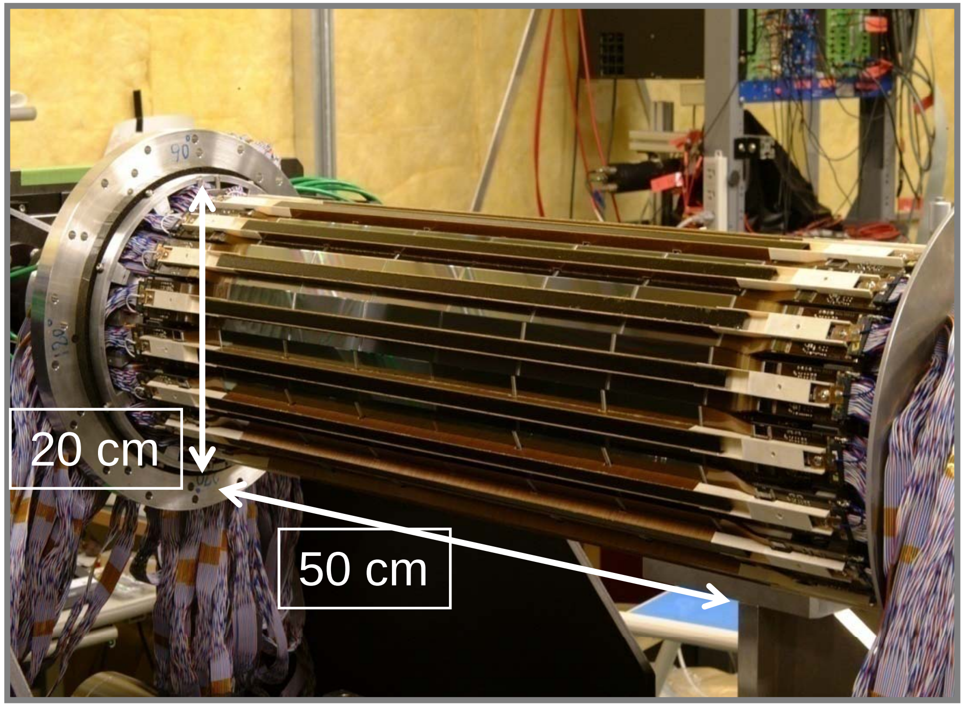
Belle spectrometer at KEK-B

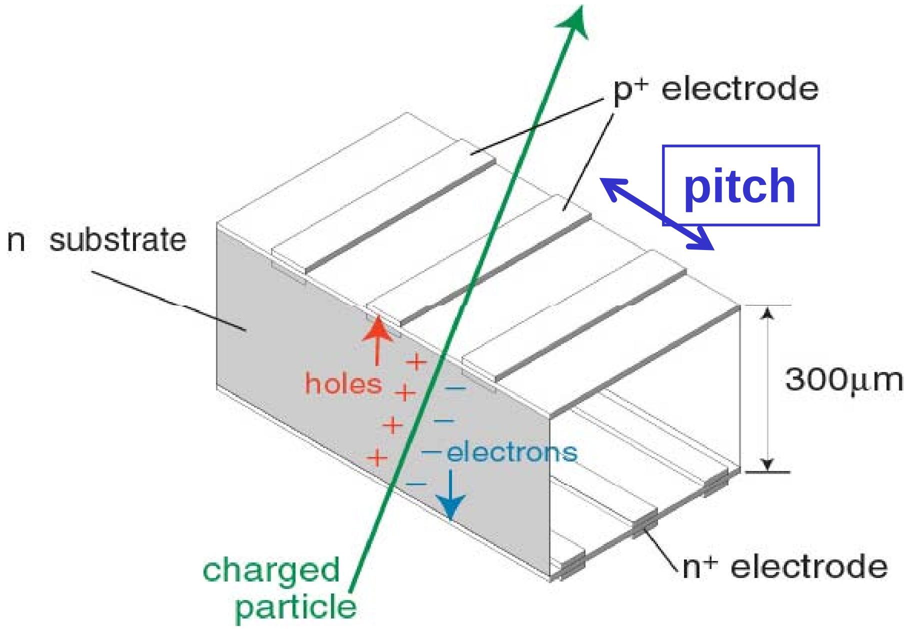


BaBar spectrometer at PEP-II



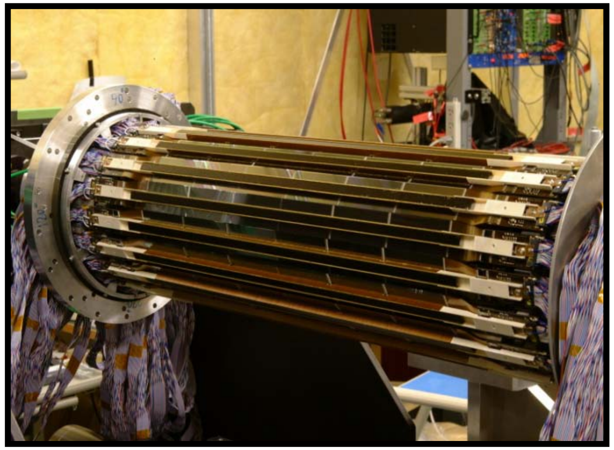
Silicon vertex detector (SVD)

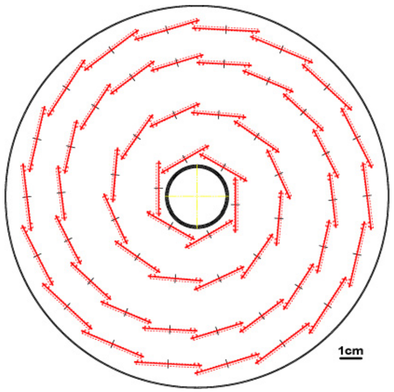


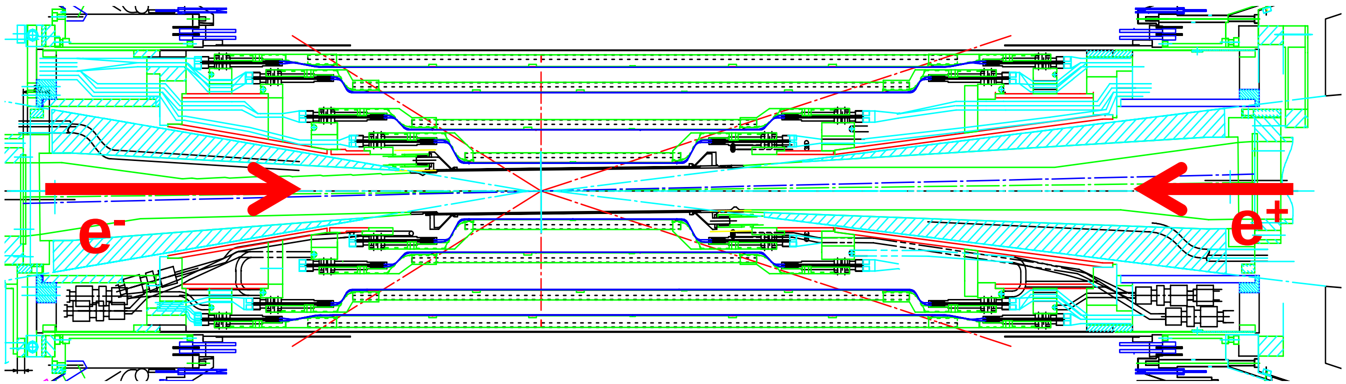


Two coordinates measured at the same time; strip pitch: 50 μm (75 μm); resolution about 15 μm (20 μm).

Silicon vertex detector (SVD)







4 layers

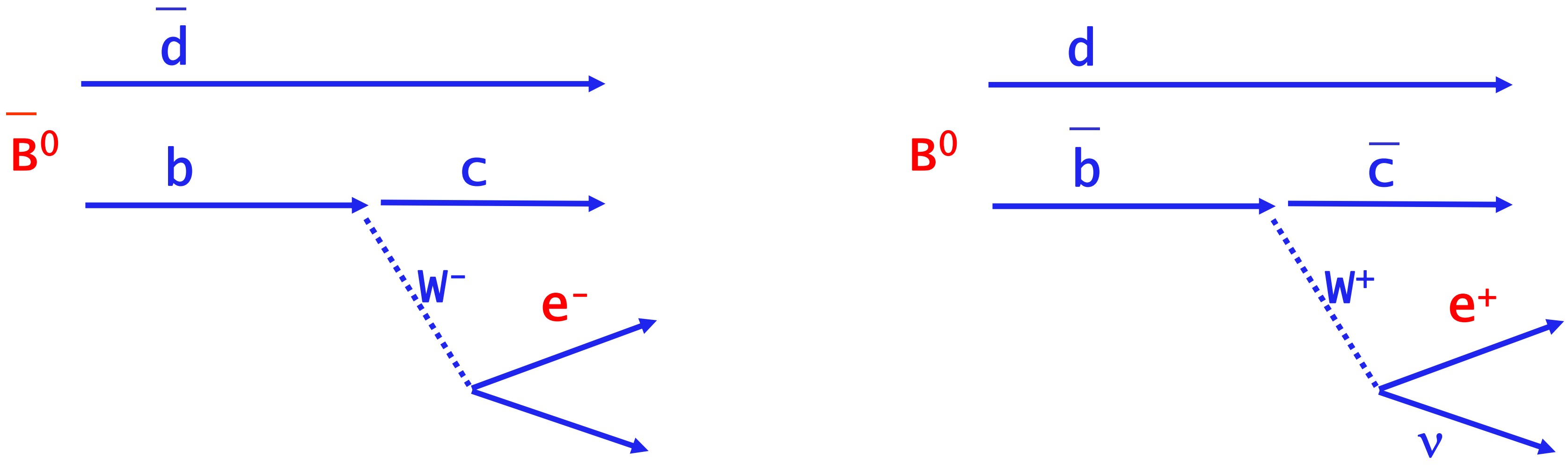
covering polar angle from 17 to 150 degrees

Flavour tagging

Was it a B or an anti-B that decayed to the CP eigenstate?

Look at the decay products of the associated B

- Charge of high momentum lepton



Flavour tagging

Was it a B or anti-B that decayed to the CP eigenstate?

Look at the decay products of the associated B

- Charge of high momentum lepton
- Charge of kaon
- Charge of 'slow pion' (from $D^{*+} \rightarrow D^0 \pi^+$ and $D^{*-} \rightarrow D^0 \pi^-$ decays)
- .....

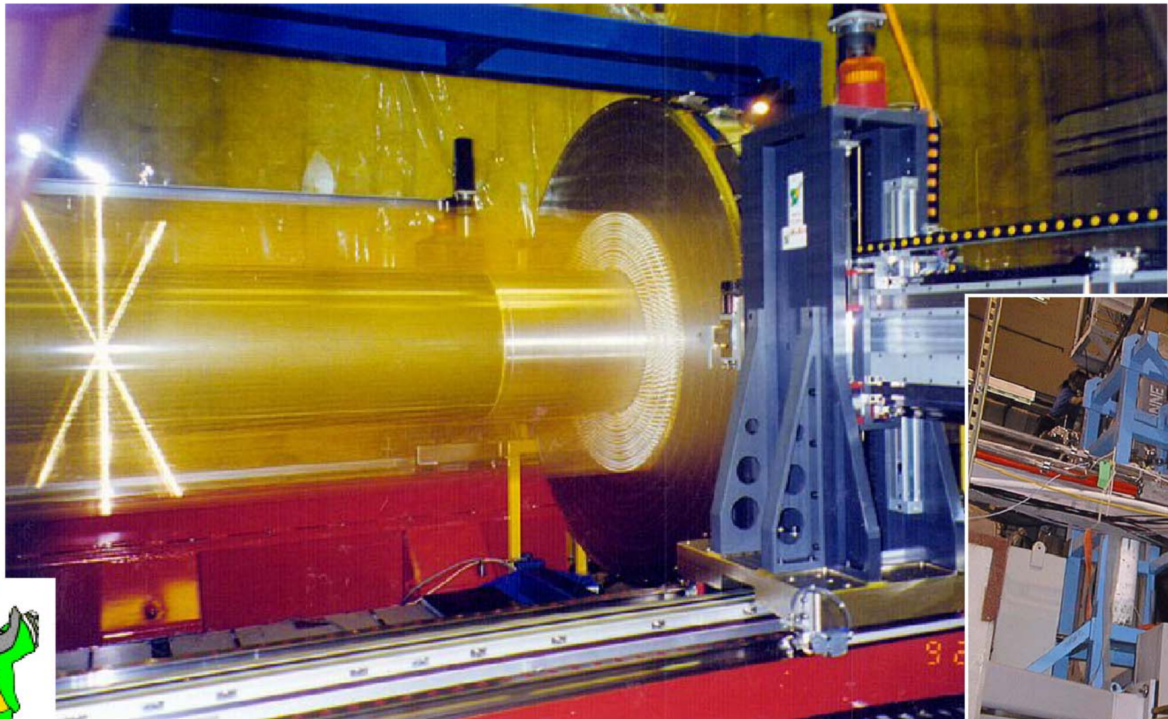
Charge measured from curvature in magnetic field,
→ need reliable particle identification

Tracking: BaBar drift chamber

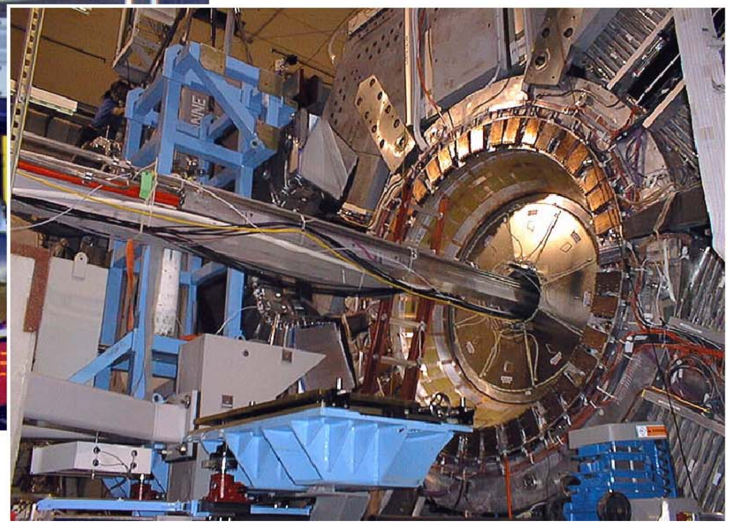
40 layers of wires (7104 cells) in 1.5 Tesla magnetic field

Helium:Isobutane 80:20 gas, Al field wires, Beryllium inner wall, and all readout electronics mounted on rear endplate

Particle identification from ionization loss (7% resolution)



$$\frac{\sigma(p_T)}{p_T} = 0.13\% \times p_T + 0.45\%$$



16 axial, 24 stereo layers

Identification

Hadrons (π, K, p):

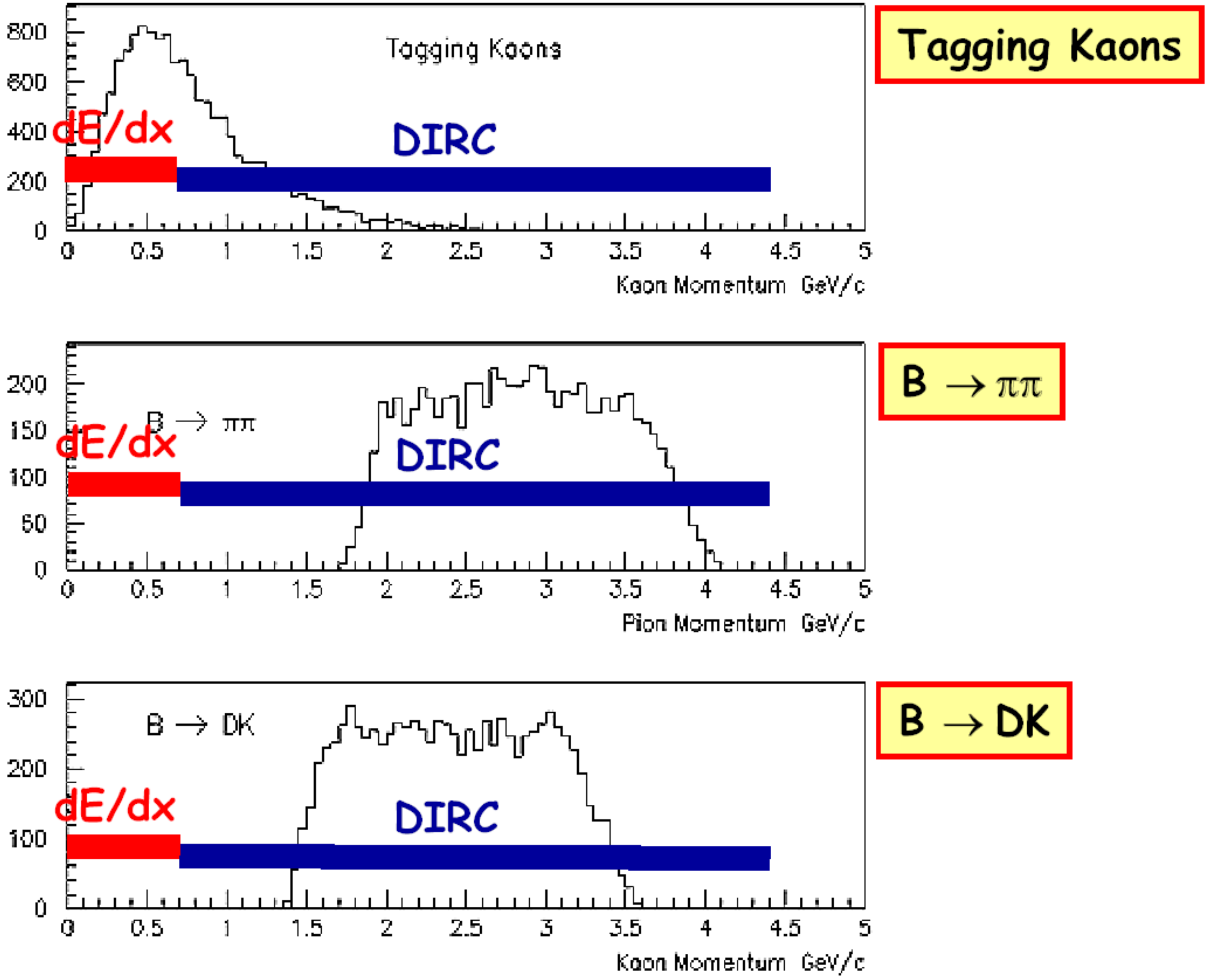
- Time-of-flight (TOF)
- dE/dx in a large drift chamber
- Cherenkov counters

K_L: chambers in the instrumented magnet yoke

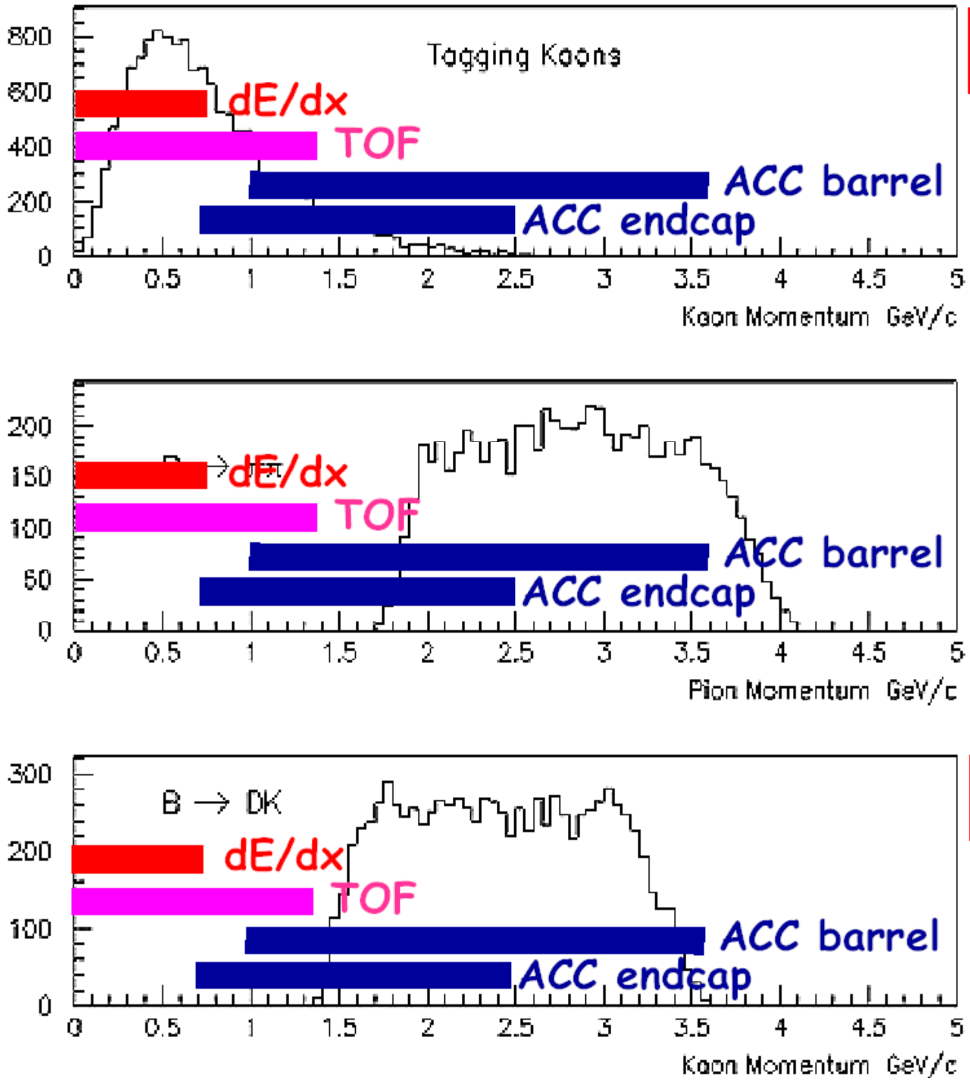
Electrons: electromagnetic calorimeter

Muon: chambers in the instrumented magnet yoke

PID coverage of kaon/pion spectra



PID coverage of kaon/pion spectra



Tagging Kaons

$B \to \pi\pi$

$B \to DK$

Cherenkov counters

Essential part of particle identification systems.

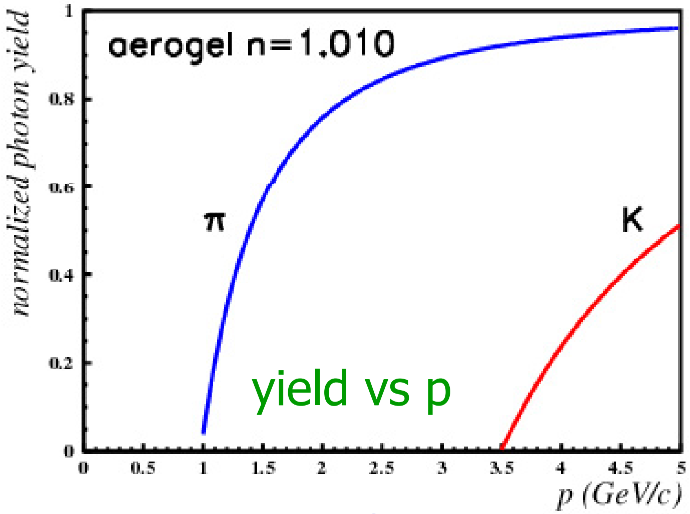
Cherenkov relation: $\cos\theta = c/nv = 1/\beta n$

Threshold counters → count photons to separate particles below and above threshold; for $\beta < \beta_t = 1/n$ (below threshold) no Čerenkov light is emitted

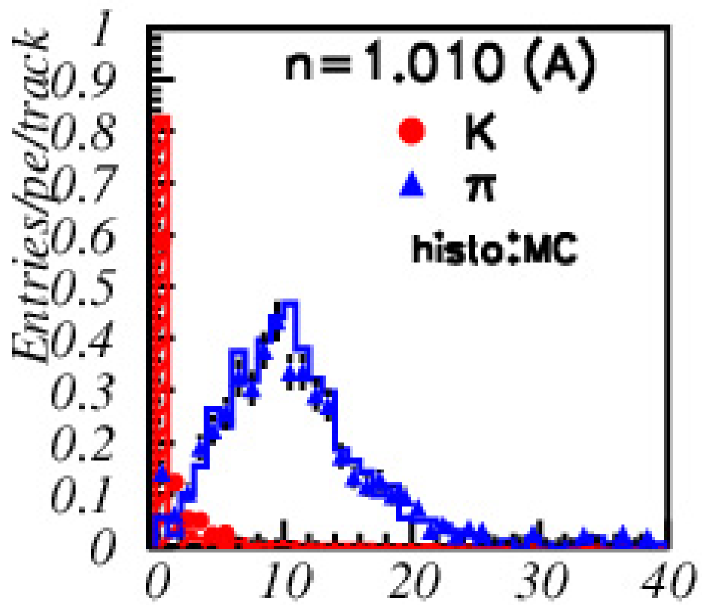
Ring Imaging (RICH) counter → measure Čerenkov angle and count photons

Belle ACC (aerogel Cherenkov counter): threshold Čerenkov counter

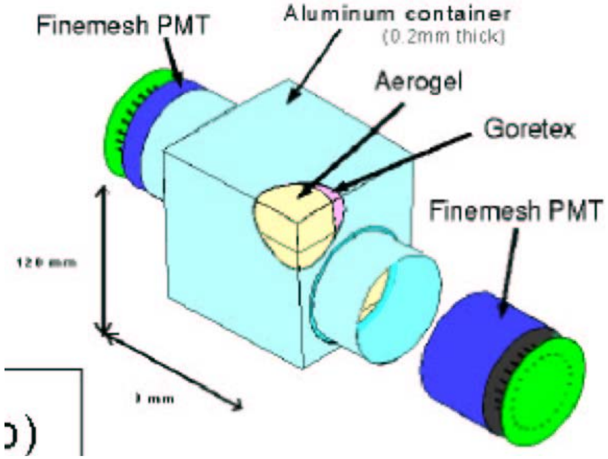
K (below thr.) vs. π (above thr.): adjust n



measured for 2 GeV < p < 3.5 GeV
expected, measured ph. yield

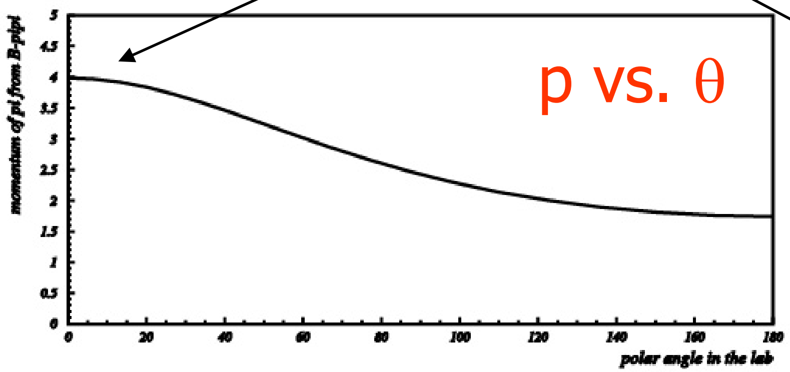


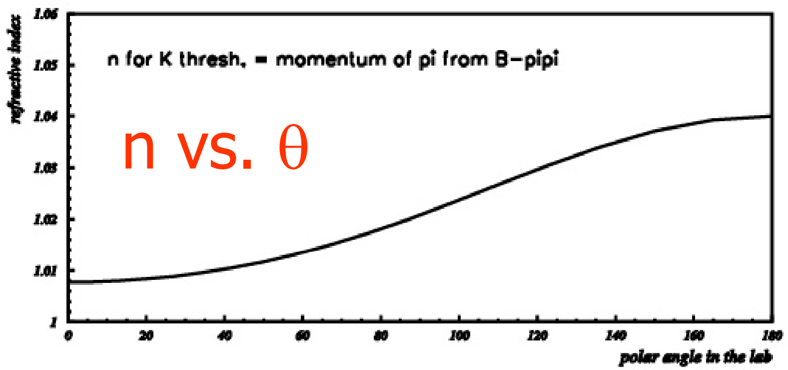
Detector unit: a block of aerogel and two fine-mesh PMTs

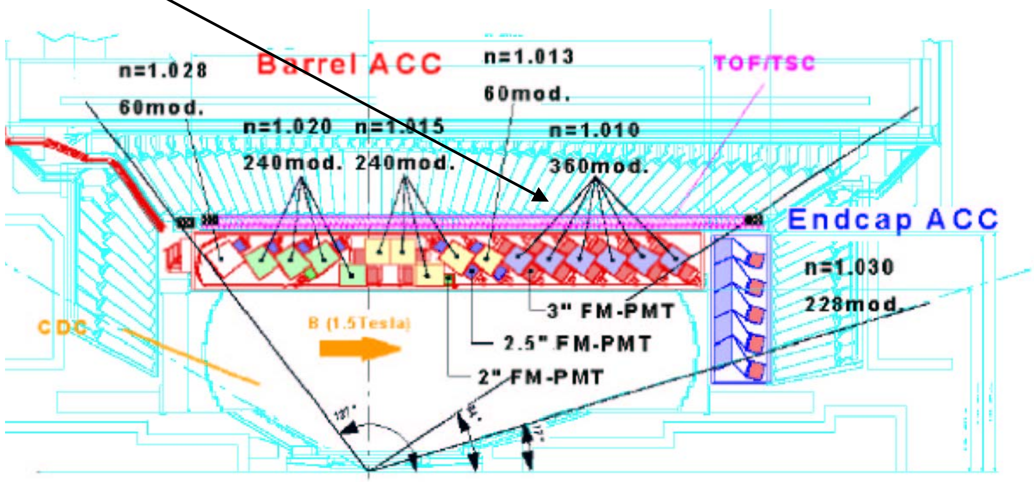


Belle ACC (aerogel Cherenkov counter): threshold Cherenkov counter

K (below thr.) vs. π (above thr.): adjust n for a given angle kinematic region (more energetic particles fly in the 'forward region')



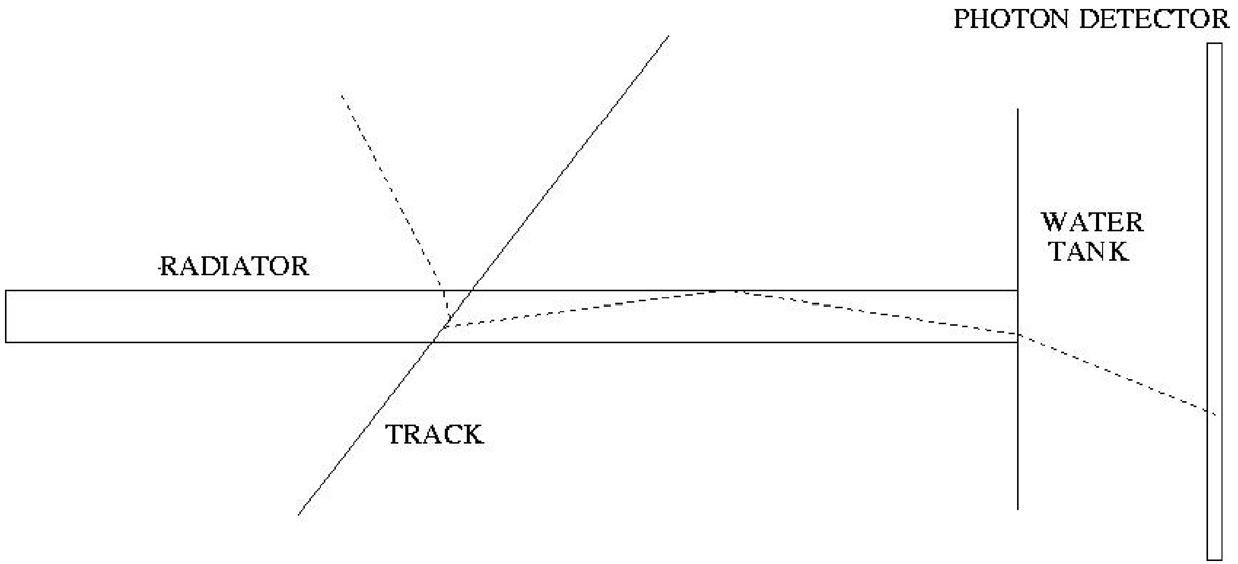




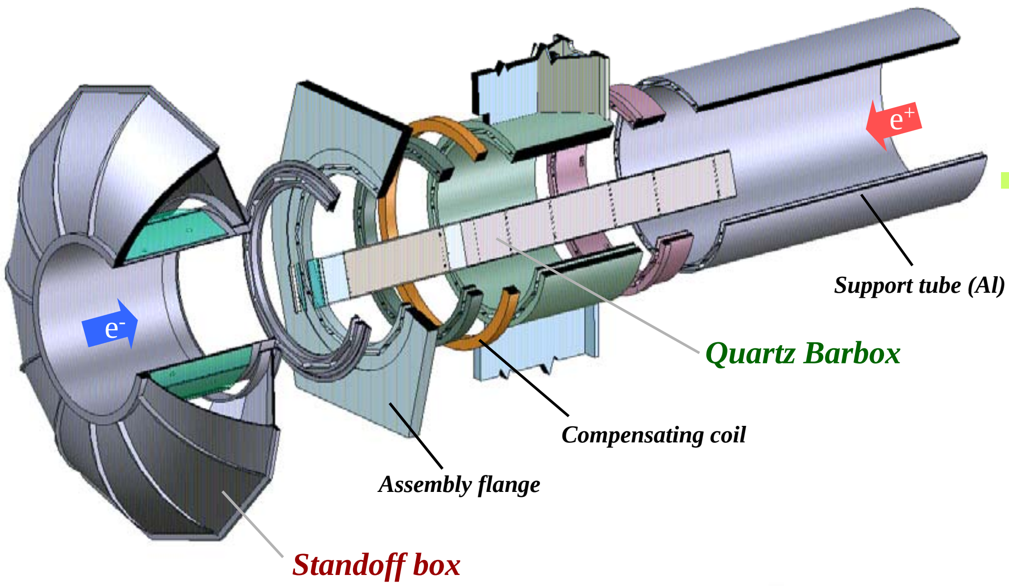
DIRC: Detector of Internally Reflected Cherekov photons

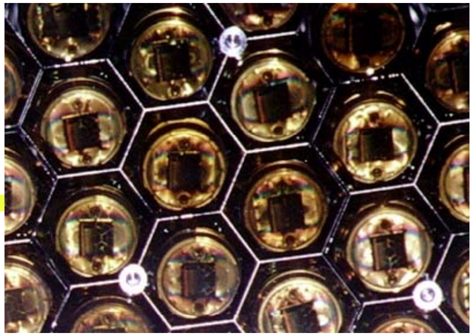
Use Cherenkov relation $\cos\theta = c/nv = 1/\beta n$ to determine velocity from angle of emission

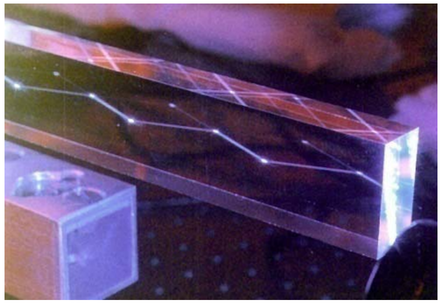
DIRC: a special kind of RICH (Ring Imaging Cherenkov counter) where Čerenkov photons trapped in a solid radiator (e.q. quartz) are propagated along the radiator bar to the side, and detected as they exit and traverse a gap.

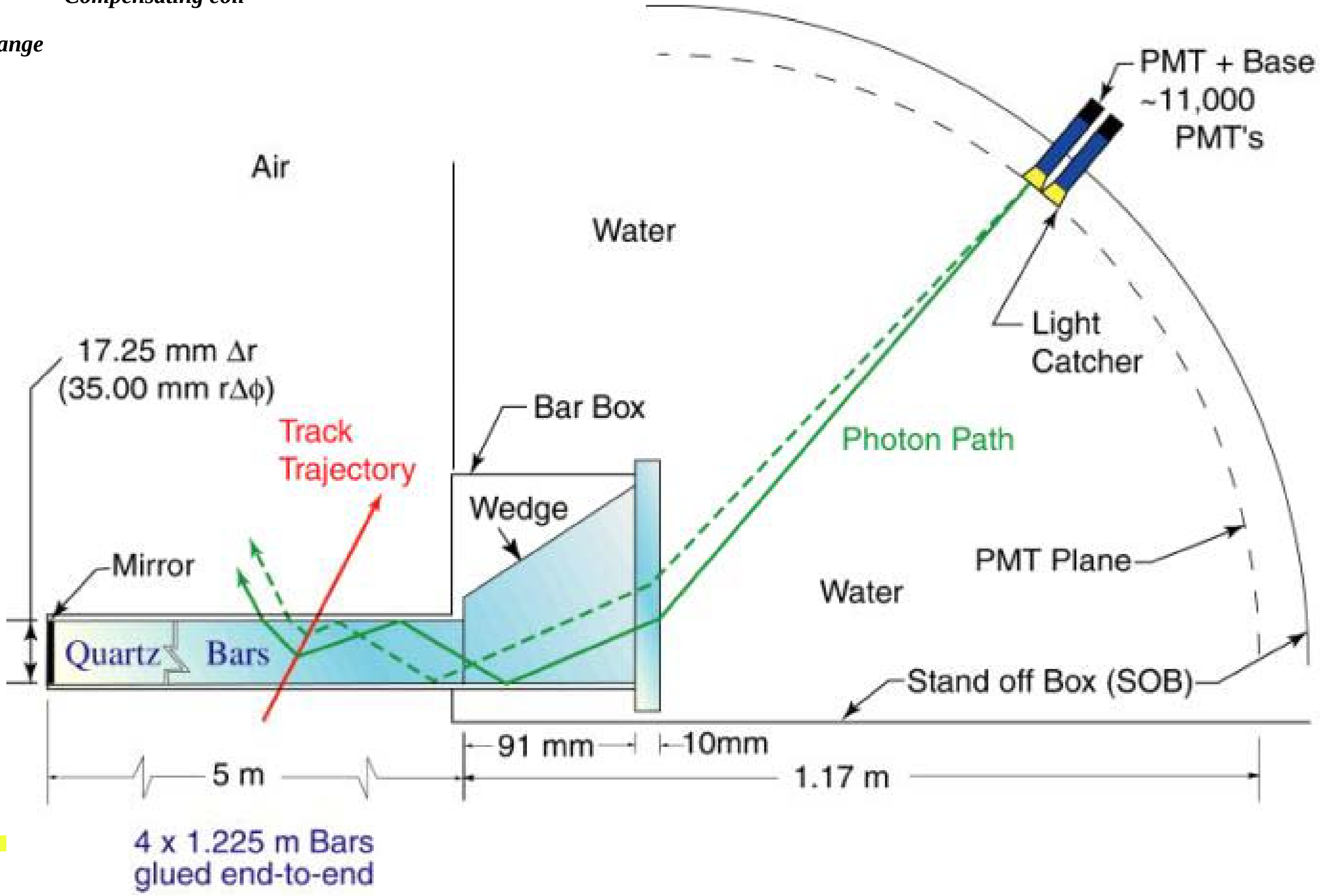


DIRC


e-
e+
Support tube (Al)
Quartz Barbox
Compensating coil
Assembly flange
Standoff box

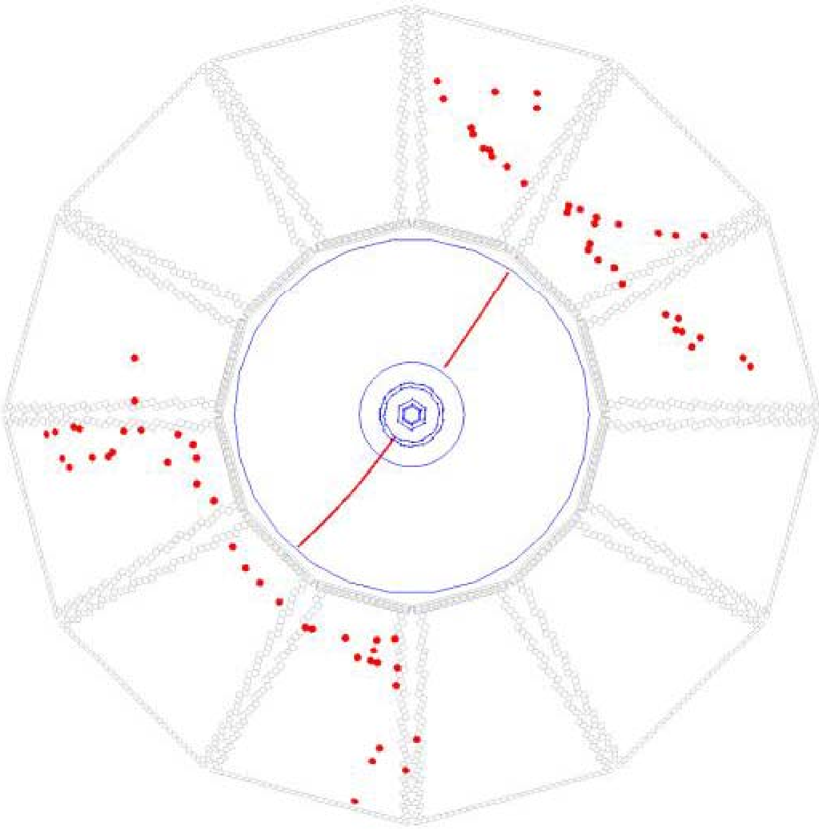




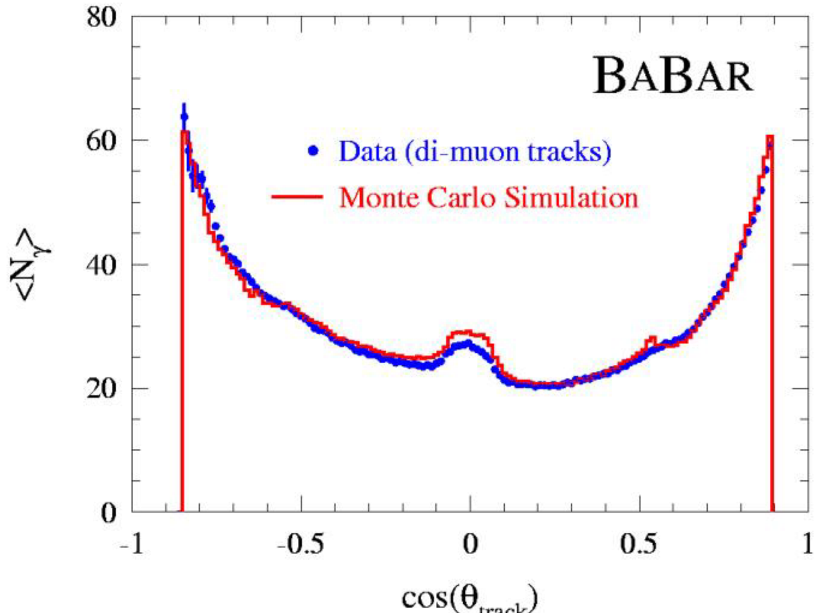

PMT + Base
~11,000
PMT's
Air
Water
Light
Catcher
17.25 mm Δr
(35.00 mm rΔϕ)
Track
Trajectory
Bar Box
Photon Path
Wedge
Mirror
PMT Plane
Water
Quartz
Bars
Stand off Box (SOB)
91 mm
10mm
5 m
1.17 m
4 x 1.225 m Bars
glued end-to-end

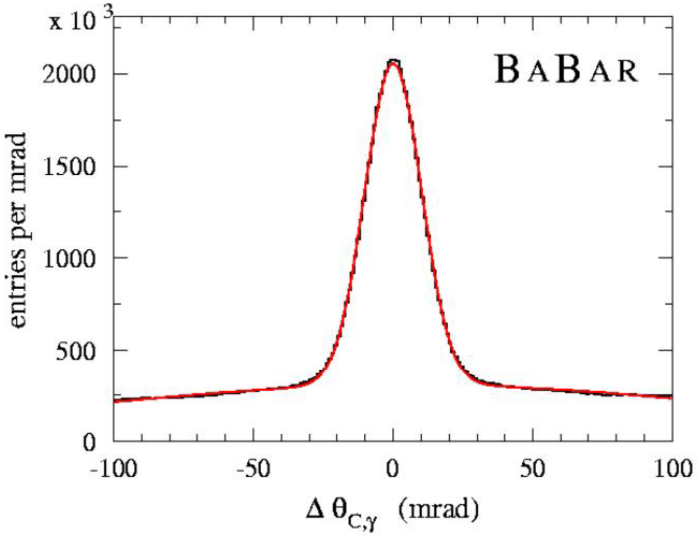
DIRC event

Babar DIRC: a Bhabha event $e^+ e^- \to e^+ e^-$

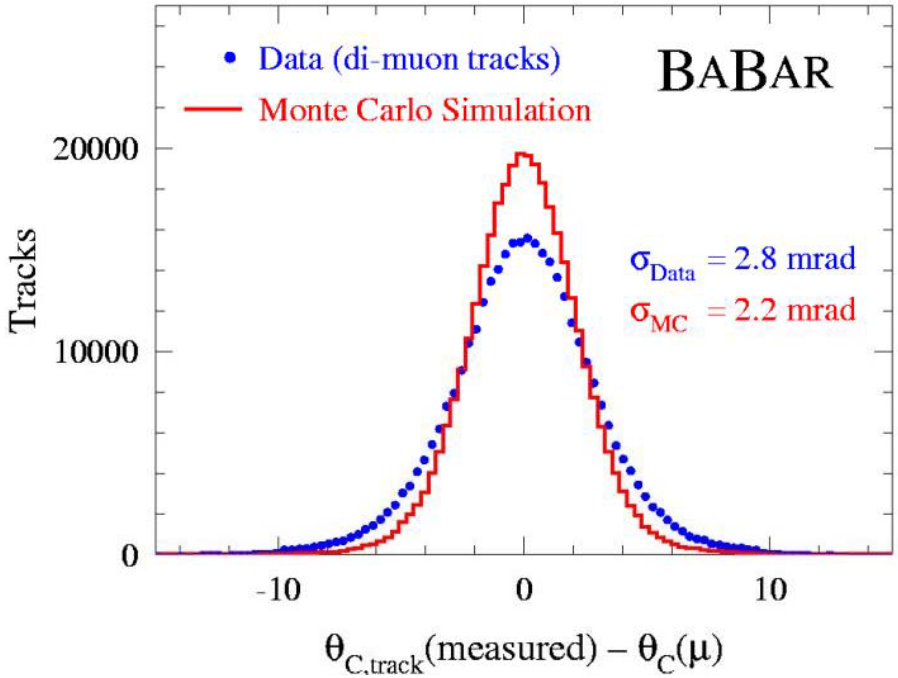


DIRC performance

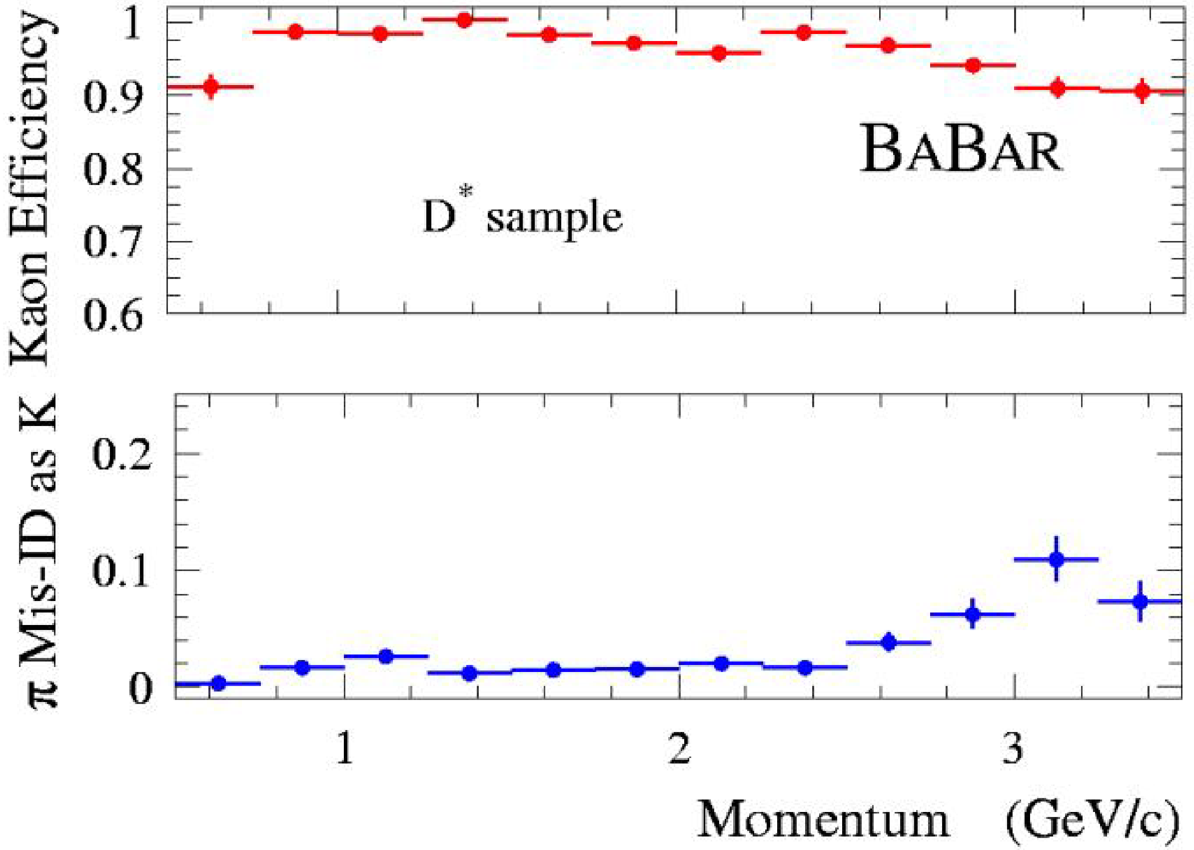




Performance



DIRC performance



To check the performance, use kinematically selected decays:
$D^{*+} \rightarrow \pi^+ D^0$, $D^0 \to K^- \pi^+$

Calorimetry Design

Requirements

•Best possible energy and position resolution: 11 photons per Υ(4S) event; 50% below 200 MeV in energy

•Acceptance down to lowest possible energies and over large solid angle

•Electron identification down to low momentum

Constraints

•Cost of raw materials and growth of crystals

•Operation inside magnetic field

•Background sensitivity

Implementation

Thallium-doped Cesium-Iodide crystals with 2 photodiodes per crystal

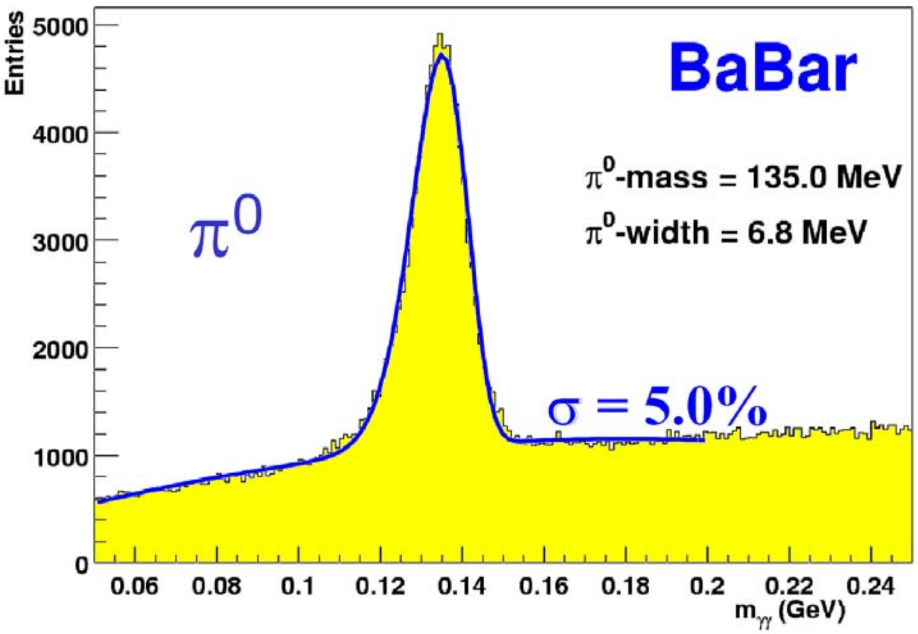
Thin structural cage to minimize material between and in front of crystals

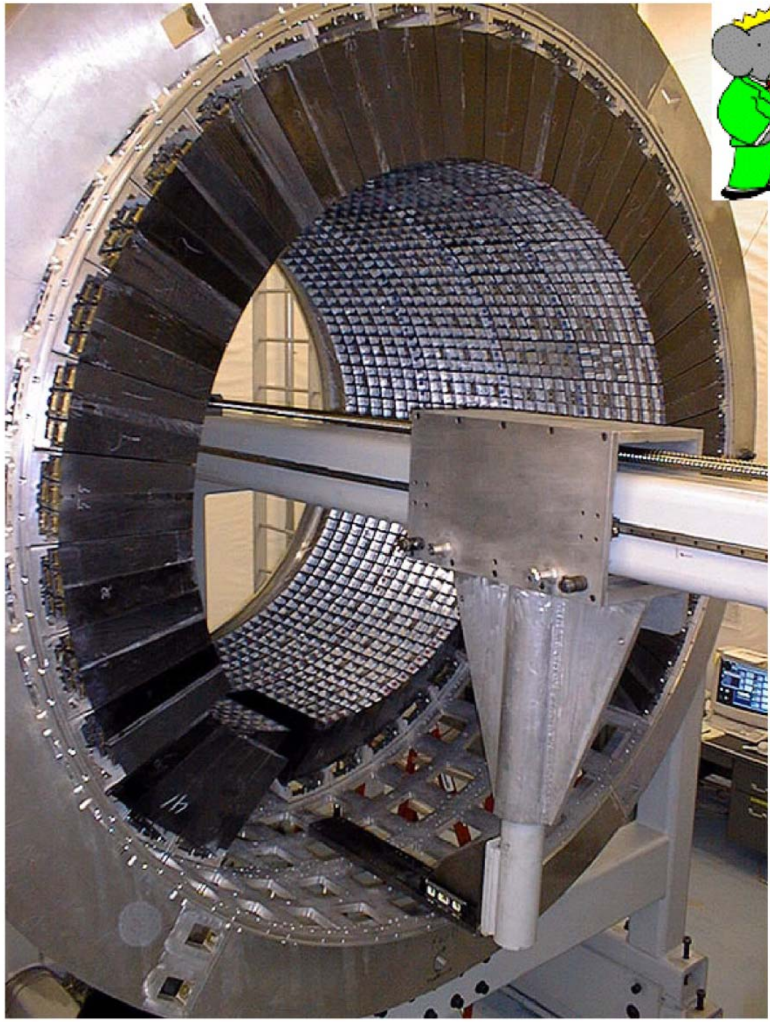
Calorimetry: BaBar

6580 CsI(Tl) crystals with photodiode readout

About 18 X_0, inside solenoid

$$\frac{\sigma(E)}{E} = \frac{(2.32 \pm 0.03 \pm 0.3)\%}{\sqrt[4]{E}} \oplus (1.85 \pm 0.07 \pm 0.1)\%$$





Muon and K_L detector

Separate muons from hadrons (pions and kaons): exploit the fact that muons interact only e.m., while hadrons interact strongly → need a few interaction lengths (about 10x radiation length in iron, 20x in CsI)

Detect K_L interaction (cluster): again need a few interaction lengths.

Some numbers: 3.9 interaction lengths (iron) + 0.8 interaction length (CsI)

Interaction length: iron 132 g/cm^2, CsI 167 g/cm^2

$(dE/dx)_{min}$: iron 1.45 MeV/(g/cm^2), CsI 1.24 MeV/(g/cm^2)

→ ΔE_{min} = (0.36+0.11) GeV = 0.47 GeV → reliable identification of muon above ~600 MeV

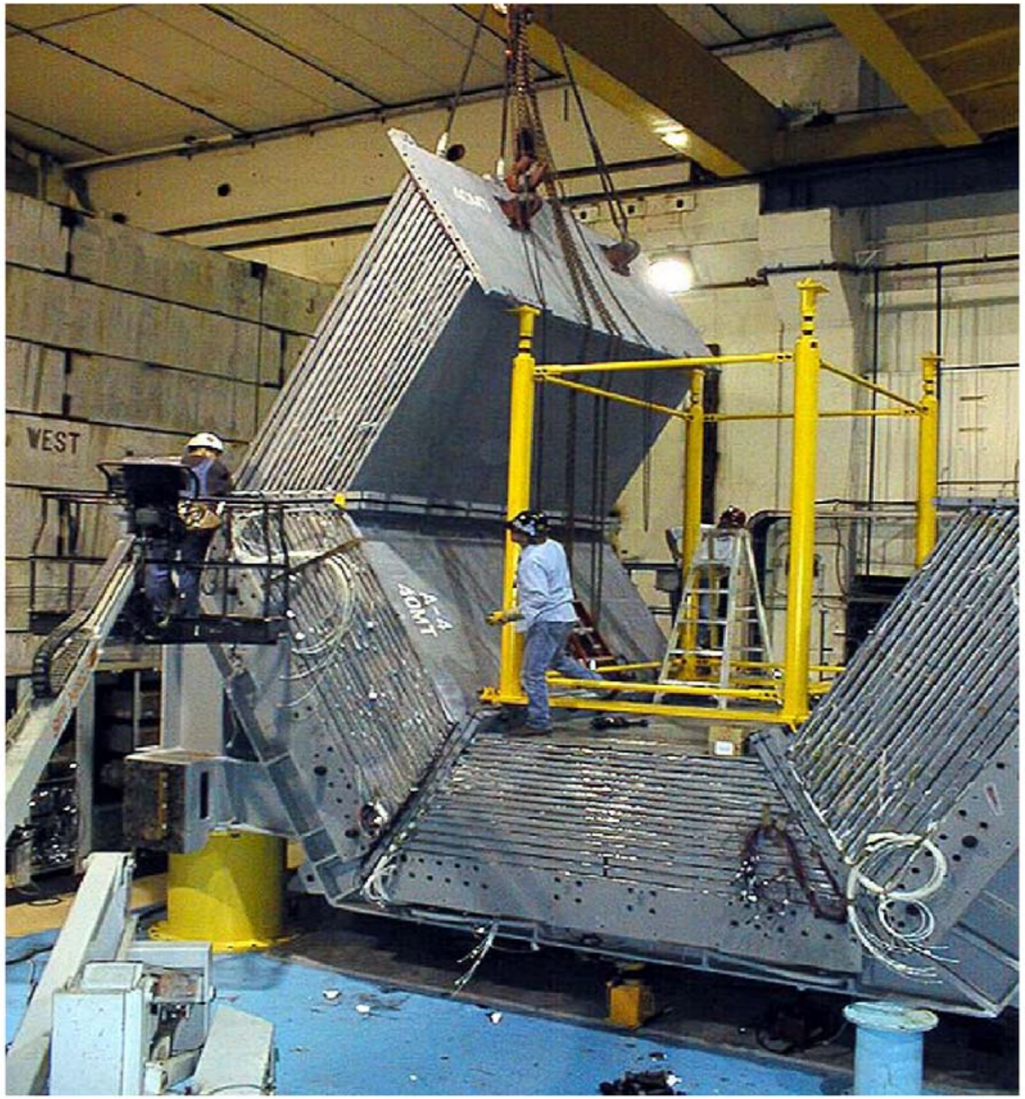
Muon and K_L detector

Up to 21 layers of resistive-plate chambers (RPCs) between iron plates of flux return

Bakelite RPCs at BABAR

Glass RPCs at Belle

(better choice)



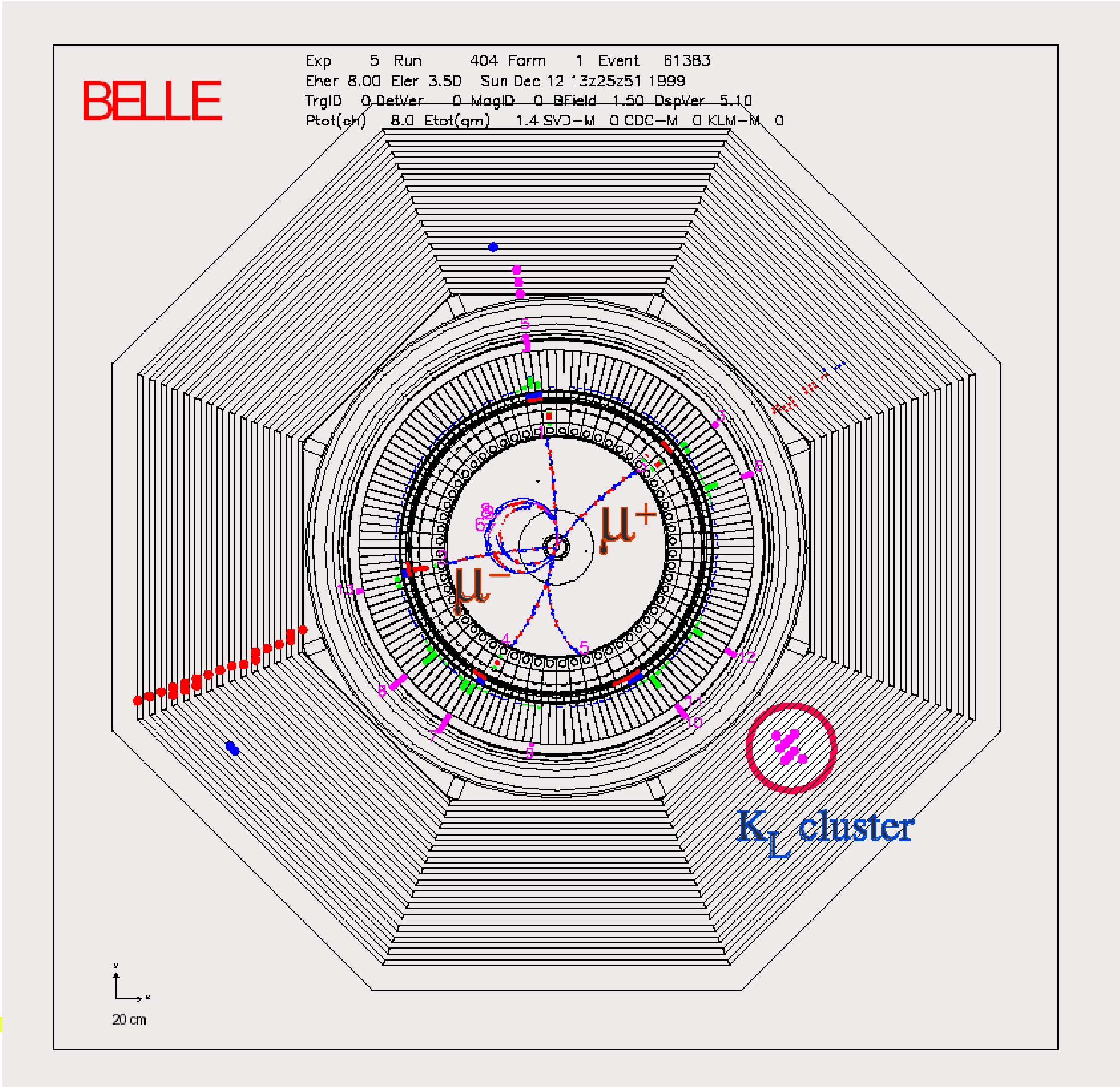
Muon and K_L detector

Example:

event with

- two muons and a
- K_L

and a pion that partly penetrated into the muon chamber system



Muon and K_L detector performance

Muon identification >800 MeV/c

efficiency

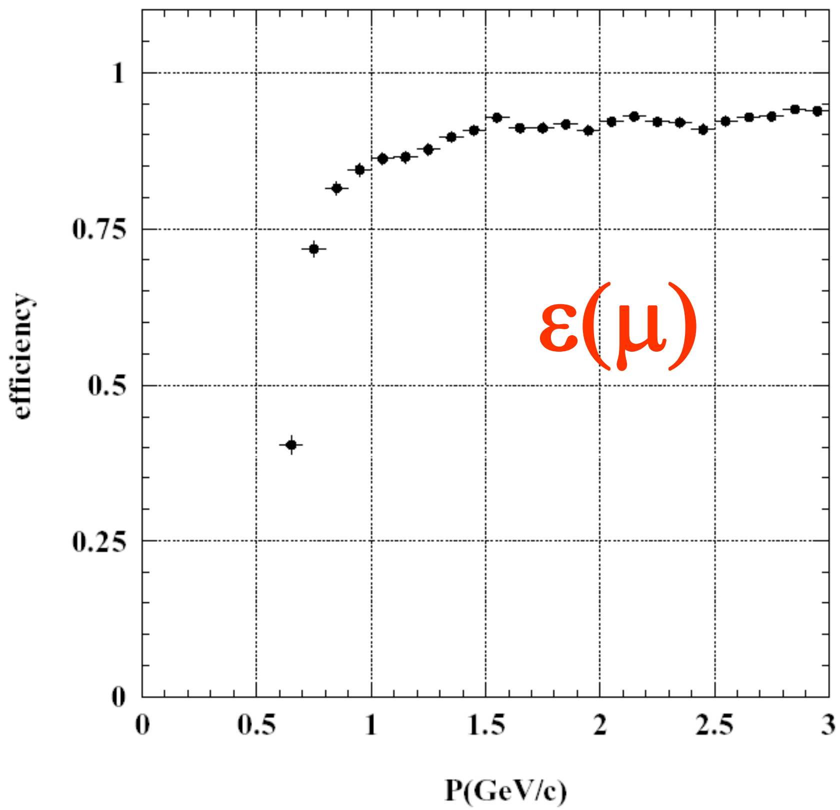


Fig. 109. Muon detection efficiency vs. momentum in KLM.

fake probability

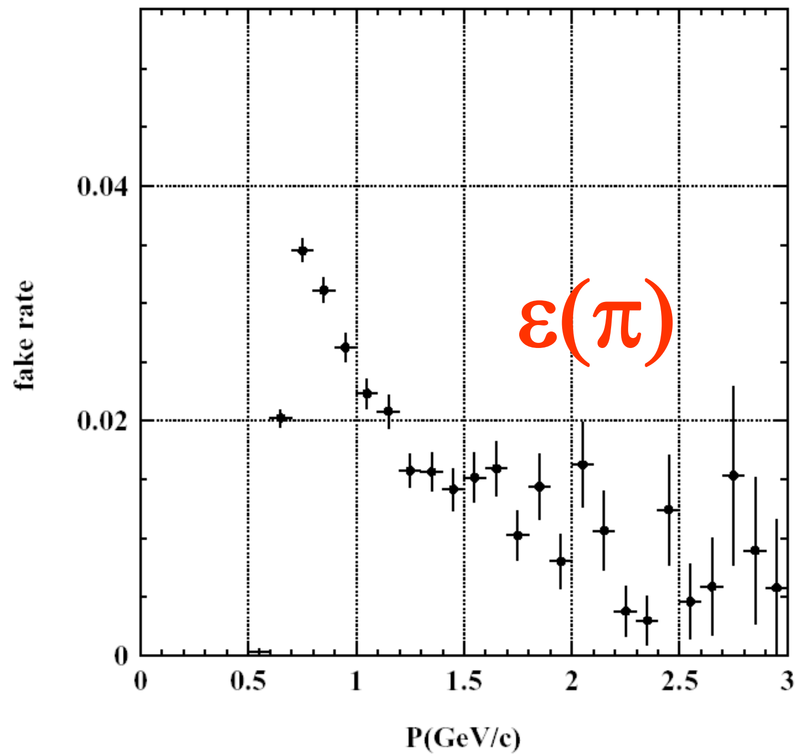


Fig. 110. Fake rate vs. momentum in KLM.

Muon and K_L detector performance

K_L detection: resolution in direction →

K_L detection: also with possible with electromagnetic calorimeter (0.8 interactin lengths)

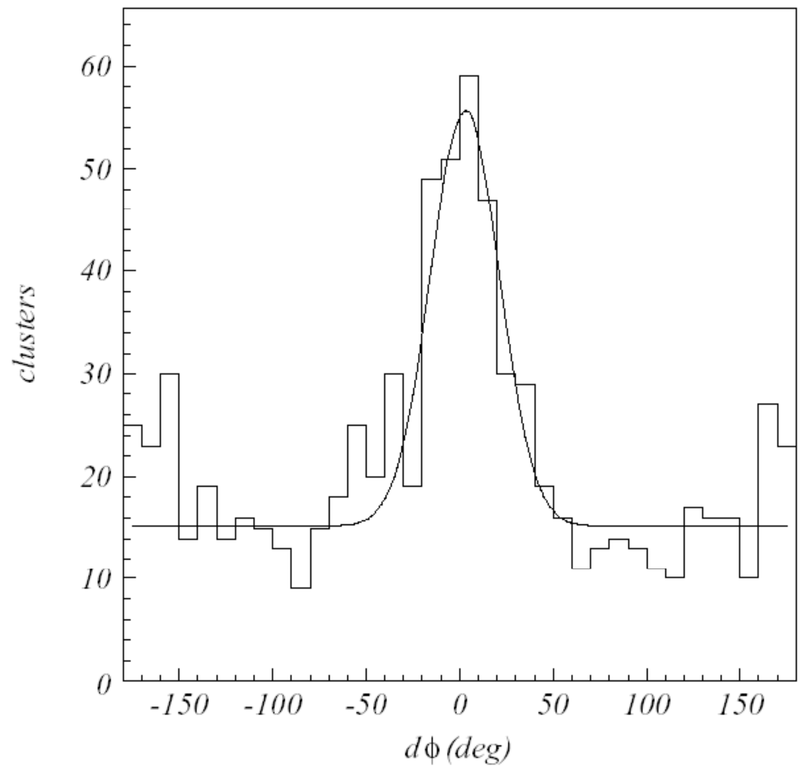


Fig. 107. Difference between the neutral cluster and the direction of missing momentum in KLM.

Back-up slides

Introduction to CP

Initial condition of the universe $N_B - N_{\bar{B}} = 0$

Today our vicinity (at least up to ~ 10 Mpc) is made of matter and not of anti-matter

nb. baryons (matter)

$$\frac{N_B - N_{\bar{B}}}{N_\gamma} = 10^{-10} - 10^{-9}$$

Nb of photons (microvawe backg)

In the early universe $B + \bar{B} \rightarrow \gamma \leftrightarrow N_\gamma = N_B + N_{\bar{B}}$

How did we get from

$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 0 \quad \text{to} \quad \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 10^{-10} - 10^{-9} \ ?$$

(one out of 10^{10} baryons did not anihillate)

Introduction to CP

Three conditions (A.Saharov, 1967):

- baryon number violation
- violation of CP and C symmetries
- non-equillibrium state

$X \to f_a$ (N_B^a, r) $X \to f_b$ $(N_B^b, 1-r)$ baryon number f_b

$\bar{X} \to \bar{f}_a$ $(-N_B^a, \bar{r})$ $\bar{X} \to \bar{f}_b$ $(-N_B^b, 1-\bar{r})$ decay probability

Change in baryon number in the decay of X:

$$\Delta B = rN_B^a + (1-r)N_B^b + \bar{r}(-N_B^a) + (1-\bar{r})(-N_B^b) =$$

$$= (r-\bar{r})(N_B^a - N_B^b)$$

Introduction to CP

$$N_B - N_{\bar{B}} = \Delta B n_X =$$
$$= (r - \bar{r})(N_B^a - N_B^b) n_X$$

X decays to states with $N_B^a \neq N_B^b$
-> baryon number violation

$r \neq \bar{r}$ ->
violation of CP in C

In the thermal equilibrium reverse processes would cause ΔB=0 -> need an out-of-equilibrium state

For example: X lives long enough -> Universe cools down -> no X production possible

Introduction to CP

C: charge conjugation $C|B^0\rangle = |\overline{B}^0\rangle$

P: space inversion $P|B^0\rangle = -|B^0\rangle$

CP: combined operation $CP|B^0\rangle = -|\overline{B}^0\rangle$

Introduction to CP

Example: weak decay $\tau^- \to \pi^- \nu_\tau$

$\pi^- \longleftarrow \tau^- \longrightarrow \nu_\tau$	P $\leftrightarrow$	$\nu_\tau \longleftarrow \tau^- \longrightarrow \pi^-$
		forbidden
$\updownarrow$ C		$\updownarrow$ C
$\pi^+ \longleftarrow \tau^+ \longrightarrow \bar{\nu}_\tau$	P $\leftrightarrow$	$\bar{\nu}_\tau \longleftarrow \tau^+ \longrightarrow \pi^+$
forbidden		

C or P transformed processes: forbidden.

CP transformed process: allowed

CP violation in decay

$\not{CP}$ in decay: $|\bar{A}/A| \neq 1$

(and of course also $|\lambda| \neq 1$)

$$a_f = \frac{\Gamma(B^+ \to f,t) - \Gamma(B^- \to \bar{f},t)}{\Gamma(B^+ \to f,t) + \Gamma(B^- \to \bar{f},t)} =$$

$$= \frac{1 - |\bar{A}/A|^2}{1 + |\bar{A}/A|^2}$$

Also possible for the neutral B.

CP violation in decay

CPV in decay: $|\bar{A}/A| \neq 1$: how do we get there?

In general, A is a sum of amplitudes with strong phases δ_i and weak phases ϕ_i. The amplitudes for anti-particles have same strong phases and opposite weak phases ->

$$A_f = \sum_i A_i e^{i(\delta_i + \varphi_i)}$$

$$\bar{A}_{\bar{f}} = \sum_i A_i e^{i(\delta_i - \varphi_i)}$$

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| = \left|\frac{\sum_i A_i e^{i(\delta_i - \varphi_i)}}{\sum_i A_i e^{i(\delta_i + \varphi_i)}}\right|$$

$$|A_f|^2 - |\bar{A}_{\bar{f}}|^2 = \sum_{i,j} A_i A_j \sin(\varphi_i - \varphi_j)\sin(\delta_i - \delta_j)$$

CPV in decay: need at least two interfering amplitudes with different weak and strong phases.

CP violation in mixing

$\cancel{CP}$ in mixing: |q/p| ≠ 1 (again |λ| ≠ 1)

In general: probability for a B to turn into an anti-B can differ from the probability for an anti-B to turn into a B.

$$\left|B^0_{phys}(t)\right\rangle = g_+(t)\left|B^0\right\rangle + (q/p)g_-(t)\left|\overline{B}^0\right\rangle$$

$$\left|\overline{B}^0_{phys}(t)\right\rangle = (p/q)g_-(t)\left|B^0\right\rangle + g_+(t)\left|\overline{B}^0\right\rangle$$

Example: semileptonic decays:

$$\left\langle l^-\nu X\right|H\left|B^0_{phys}(t)\right\rangle = (q/p)g_-(t)A^*$$

$$\left\langle l^+\nu X\right|H\left|\overline{B}^0_{phys}(t)\right\rangle = (p/q)g_-(t)A$$

CP violation in mixing

$$a_{sl} = \frac{\Gamma(\overline{B}^0_{phys}(t) \to l^+ \nu X) - \Gamma(B^0_{phys}(t) \to l^- \nu X)}{\Gamma(\overline{B}^0_{phys}(t) \to l^+ \nu X) + \Gamma(B^0_{phys}(t) \to l^- \nu X)} =$$

$$= \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

-> Small, since to first order **|q/p|~1.** Next order:

$$\frac{q}{p} = -\frac{|M_{12}|}{M_{12}} \left[1 - \frac{1}{2} \mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}} \right) \right]$$

Expect O(0.01) effect in semileptonic decays

CP violation in the interference between decays with and without mixing

$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP},t) - P(B^0 \to f_{CP},t)}{P(\overline{B}^0 \to f_{CP},t) + P(B^0 \to f_{CP},t)} =$$

$$\lambda = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

$$= \frac{\left|(p/q)g_-(t)A_{f_{CP}} + g_+(t)\overline{A}_{f_{CP}}\right|^2 - \left|g_+(t)A_{f_{CP}} + (q/p)g_-(t)\overline{A}_{f_{CP}}\right|^2}{\left|(p/q)g_-(t)A_{f_{CP}} + g_+(t)\overline{A}_{f_{CP}}\right|^2 + \left|g_+(t)A_{f_{CP}} + (q/p)g_-(t)\overline{A}_{f_{CP}}\right|^2} =$$

$$= \frac{\left|(p/q)i\sin(\Delta mt/2)A_{f_{CP}} + \cos(\Delta mt/2)\overline{A}_{f_{CP}}\right|^2 - \left|\cos(\Delta mt/2)A_{f_{CP}} + (q/p)i\sin(\Delta mt/2)\overline{A}_{f_{CP}}\right|^2}{\left|(p/q)i\sin(\Delta mt/2)A_{f_{CP}} + \cos(\Delta mt/2)\overline{A}_{f_{CP}}\right|^2 + \left|\cos(\Delta mt/2)A_{f_{CP}} + (q/p)i\sin(\Delta mt/2)\overline{A}_{f_{CP}}\right|^2} =$$

$$= \frac{\left|(p/q)^2\lambda_{f_{CP}} i\sin(\Delta mt/2) + \cos(\Delta mt/2)\right|^2 - \left|\cos(\Delta mt/2) + \lambda_{f_{CP}} i\sin(\Delta mt/2)\right|^2}{\left|(p/q)^2\lambda_{f_{CP}} i\sin(\Delta mt/2) + \cos(\Delta mt/2)\right|^2 + \left|\cos(\Delta mt/2) + \lambda_{f_{CP}} i\sin(\Delta mt/2)\right|^2} =$$

$$= \frac{(1-|\lambda_{f_{CP}}|^2)\cos(\Delta mt) - 2\,\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta mt)}{1+|\lambda_{f_{CP}}|^2}$$

$$= C\cos(\Delta mt) + S\sin(\Delta mt)$$

Time evolution for B and anti-B from the Y(4s)

The time evolution for the B anti-B pair from Y(4s) decay

$$R(t_{tag},t_{f_{CP}}) = e^{-\Gamma(t_{tag}+t_{f_{CP}})}\left|\overline{A}_{tag}\right|^2\left|A_{f_{CP}}\right|^2$$

$$[1+\left|\lambda_{f_{CP}}\right|^2 + \cos\left[\Delta m(t_{tag}-t_{f_{CP}})\right](1-\left|\lambda_{f_{CP}}\right|^2)$$

$$-2\sin\left(\Delta m(t_{tag}-t_{f_{CP}})\right)\mathrm{Im}(\lambda_{f_{CP}})]$$

with $$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

→ in asymmetry measurements at Y(4s) we have to use t_{ftag}-t_{fCP} instead of absolute time t.

CP violation in SM

$$\mathcal{L} = V_{ij}\overline{U}_i\gamma^\mu(1-\gamma_5)D_jW_\mu^+ + V_{ij}^*\overline{D}_i\gamma^\mu(1-\gamma_5)U_jW_\mu$$

$$\Updownarrow CP$$

$$\mathcal{L}_{CP} = V_{ij}\overline{D}_i\gamma^\mu(1-\gamma_5)U_jW_\mu + V_{ij}^*\overline{U}_i\gamma^\mu(1-\gamma_5)D_jW_\mu$$

If $V_{ij}=V_{ij}^*$ ▶ $\mathcal{L}=\mathcal{L}_{CP}$ ▶ CP is conserved

CKM matrix

define $$s_{12} \equiv \lambda, s_{23} \equiv A\lambda^2, s_{13}e^{-i\delta} \equiv A\lambda^3(\rho - i\eta)$$

Then to O(λ^6)

$$V_{us} = \lambda, V_{cb} = A\lambda^2,$$

$$V_{ub} = A\lambda^3(\bar{\rho} - i\bar{\eta}),$$

$$V_{td} = A\lambda^3(1 - \bar{\rho} - i\bar{\eta}),$$

$$\mathrm{Im}V_{cd} = -A\lambda^5\eta,$$

$$\mathrm{Im}V_{ts} = -A\lambda^4\eta,$$

$$\bar{\rho} = \rho(1 - \frac{\lambda^2}{2}), \bar{\eta} = \eta(1 - \frac{\lambda^2}{2})$$

Decay amplitude structure

Quark diagrams: classified in tree (T), penguin and electroweak penguin contributions (P).

Measure the angles: need a pair of quark and anti-quark $q\bar{q}$ in the final state.

Describe the weak-phase structure of B-decay amplitude for the trasition $b \rightarrow q\bar{q}q'$: sum of three terms with definite CKM coefficients:

$$A(q\bar{q}q') = V_{tb}V_{tq'}^{\ *}P_{q'}^{t} + V_{cb}V_{cq'}^{\ *}(T_{c\bar{c}q'}\delta_{qc} + P_{q'}^{c}) + V_{ub}V_{uq'}^{\ *}(T_{u\bar{u}q'}\delta_{qu} + P_{q'}^{u})$$

Decay amplitude structure: *qqs* and *qqd* decays

Use the unitarity condition to simplify the expressions for individual amplitudes:

$$A(c\bar{c}s) = V_{cb}V_{cs}^{\ *}(T_{c\bar{c}s} + P_s^c - P_s^t) + V_{ub}V_{us}^{\ *}(P_s^u - P_s^t),$$

$$A(u\bar{u}s) = V_{cb}V_{cs}^{\ *}(P_s^c - P_s^t) + V_{ub}V_{us}^{\ *}(T_{u\bar{u}s} + P_s^u - P_s^t),$$

$$A(s\bar{s}s) = V_{cb}V_{cs}^{\ *}(P_s^c - P_s^t) + V_{ub}V_{us}^{\ *}(P_s^u - P_s^t).$$

Nice feature: penguin amplitudes only come as differences.

$$A(c\bar{c}d) = V_{tb}V_{td}^{\ *}(P_d^t - P_d^u) + V_{cb}V_{cd}^{\ *}(T_{c\bar{c}d} + P_d^c - P_d^u),$$

$$A(u\bar{u}d) = V_{tb}V_{td}^{\ *}(P_d^t - P_d^c) + V_{ub}V_{ud}^{\ *}(T_{u\bar{u}d} + P_d^u - P_d^t),$$

$$A(s\bar{s}d) = V_{tb}V_{td}^{\ *}(P_d^t - P_d^u) + V_{cb}V_{cd}^{\ *}(P_d^c - P_d^u).$$

Decay asymmetry predictions - overview

Five classes of B decays.

Classes 1 and 2 are expected to have relatively small direct CP violations -> particularly interesting for extracting CKM parameters from interference of decays with and without mixing.

In the remaining three classes, direct CP violations could be significant, decay asymmetries cannot be cleanly interpreted in terms of CKM phases.

1. Decays dominated by a single term: b->ccs and b-> sss. SM cleanly predicts zero (or very small) direct CP violations because the second term is Cabibbo suppressed. Any observation of large direct CP-violating effects in these cases would be a clue to beyond Standard Model physics. The modes $B^+ \to J/\psi K^+$ and $B^+ \to \phi K^+$ are examples of this class. The corresponding neutral modes have cleanly predicted relationships between CKM parameters and the measured asymmetry from interference between decays with and without mixing.

Decay asymmetry predictions - overview

2. Decays with a small second term: b->ccd and b->uud. The expectation that penguin-only contributions are suppressed compared to tree contributions suggests that these modes will have small direct CP violation effects, and an approximate prediction for the relationship between measured asymmetries in neutral decays and CKM phases can be made.

3. Decays with a suppressed tree contribution: b->uus. The tree amplitude is suppressed by small mixing angles, $V_{ub}V_{us}$. The no-tree term may be comparable or even dominate and give large interference effects. An example is B->ρK.

Decay asymmetry predictions - overview

4. Decays with no tree contribution: b->ssd. Here the interference comes from penguin contributions with different charge 2/3 quarks in the loop. An example is B->KK.

5. Radiative decays: b->sγ . The mechanism here is the same as in case 4 except that the leading contributions come from electromagnetic penguins. An example is B->$K^*\gamma$.

Decay asymmetry predictions – overview
b->qqs

$B \to q\bar{q}s$ Decay Modes

Quark Process	Leading Term	Secondary Term	Sample B_d Modes	B_d Angle	Sample B_s Modes	B_s Angle
$b \to c\bar{c}s$	$V_{cb}V_{cs}^* = A\lambda^2$ tree + penguin $(c-t)$	$V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$ penguin only $(u-t)$	$J/\psi\ K_S$	β	$\psi\eta'$ $D_s\overline{D}_s$	β_S
$b \to s\bar{s}s$	$V_{cb}V_{cs}^* = A\lambda^2$ penguin only $(c-t)$	$V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$ penguin only $(u-t)$	ϕK_S	β	$\phi\eta'$	0
$b \to u\bar{u}s$ $b \to d\bar{d}s$	$V_{cb}V_{cs}^* = A\lambda^2$ penguin only $(c-t)$	$V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$ tree + penguin $(u-t)$	$\pi^0\ K_S$ ρK_S	competing terms	$\phi\pi^0$ $K_S K_S$	competing terms
$b \to c\bar{u}s$ $b \to u\bar{c}s$	$V_{cb}V_{us}^* = A\lambda^3$ $V_{ub}V_{cs}^* = A\lambda^3(\rho - i\eta)$	0	$D^0K \searrow$ common $\overline{D}^0K \nearrow$ modes	γ	$D^0\phi \searrow$ common $\overline{D}^0\phi \nearrow$ modes	γ

Decay asymmetry predictions – overview
b->qqd

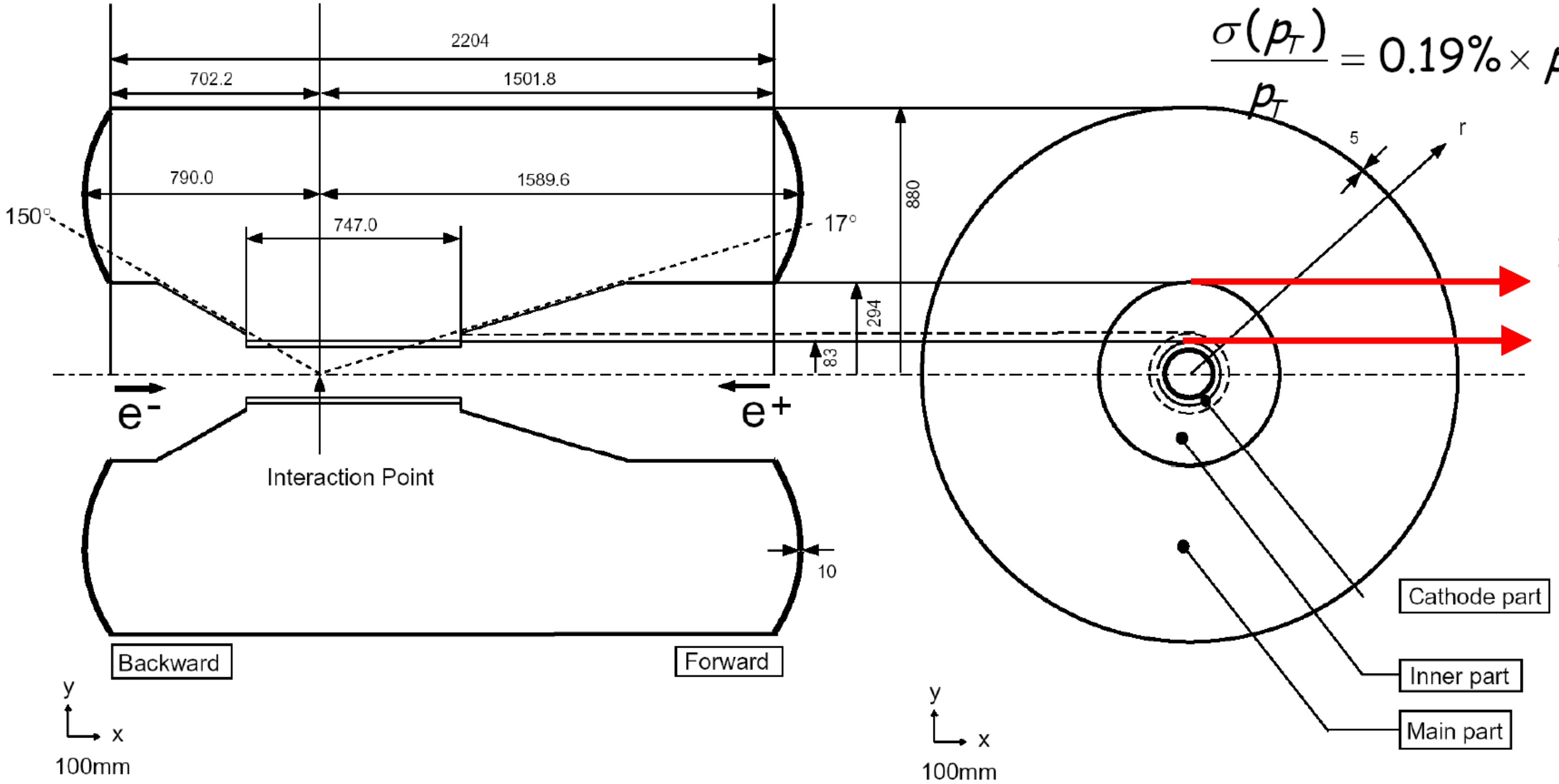
$b \to q\bar{q}d$ Decay Modes

Quark Process	Leading Term	Secondary Term	Sample B_d Modes	B_d Angle * (leading terms only)	Sample B_s Modes	B_s Angle * (leading term)
$b \to c\bar{c}d$	$V_{cb}V_{cd}^* = -A\lambda^3$ tree + penguin $(c-u)$	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only $(t-u)$	D^+D^-	$^*\beta$	ψK_S	β_S
$b \to s\bar{s}d$	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only $(t-u)$	$V_{cb}V_{cd}^* = A\lambda^3$ penguin only $(c-u)$	$\phi\pi$ $K_S\overline{K}_S$	competing terms	ϕK_S	competing terms
$b \to u\bar{u}d$ $b \to d\bar{d}d$	$V_{ub}V_{ud}^* = A\lambda^3(\rho-i\eta)$ tree + penguin (uc)	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only $(t-c)$	$\pi\pi$; $\pi\rho$ $\pi\, a_1$	$^*\alpha$	$\pi^0 K_S$ $\rho^0 K_S$	competing terms
$b \to c\bar{u}d$ $b \to u\bar{c}d$	$V_{cb}V_{ud}^* = A\lambda^2$ $V_{ub}V_{cd}^* = -A\lambda^4(\rho-i\eta)$	0	$D^0\pi^0 \searrow$ common $\overline{D}^0\pi^0 \nearrow$ modes	γ	$D^0K_S \searrow$ common $\overline{D}^0K_S \nearrow$ modes	γ

Tracking: Belle central drift chamber

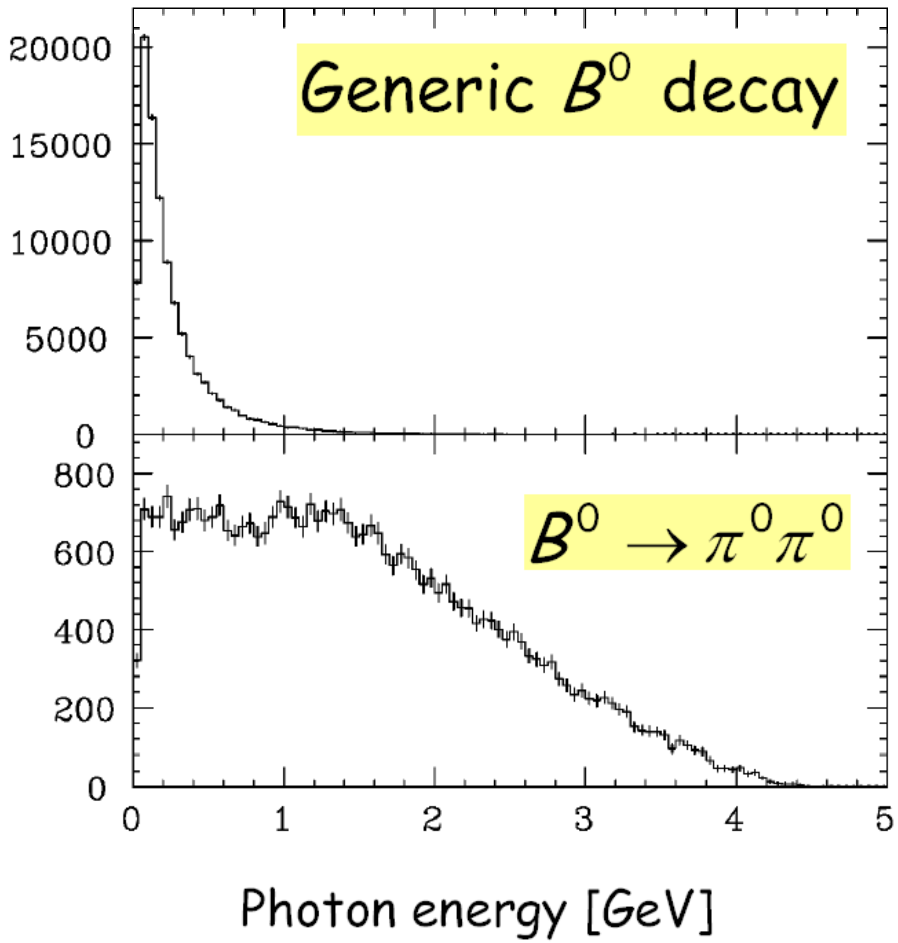
- 50 layers of wires (8400 cells) in 1.5 Tesla magnetic field
- Helium:Ethane 50:50 gas, Al field wires, CF inner wall with cathodes, and preamp only on endplates
- Particle identification from ionization loss (5.6-7% resolution)

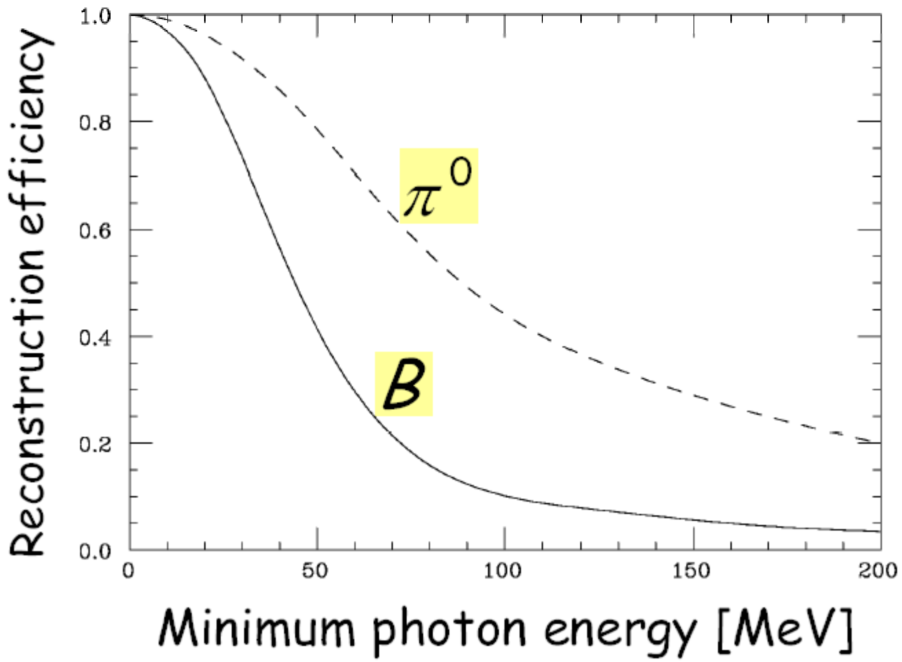
$$\frac{\sigma(p_T)}{p_T} = 0.19\% \times p_T \oplus \frac{0.30\%}{\beta}$$



15 layers: 8.8-22.4 cm radius

Requirements: Photons





Identification with dE/dx measurement

dE/dx performance in a large drift chamber.

Essential for hadron identification at low momenta.