Experiments at e^+-e^- flavour factories and LHCb

Part 1: Belle and BaBar I

Peter Križan

University of Ljubljana and J. Stefan Institute

University of Ljubljana

"Jožef Stefan" Institute

Contents of this course

- Lecture 1: Belle/BaBar: Introduction, B factories, detectors, measurements of angles of the unitarity triangle
- Lecture 2: Belle/BaBar: measurements of sides of the unitarity triangle, rare decays of B and D mesons, mixing
- Lecture 3: LHCb
- Lecture 4: Super flavour factories

http://www-f9.ijs.si/~krizan/sola/flavianet-karlsruhe09/flavianet-karlsruhe09.html

- Slides
- Literature

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 $K_L \to \mu^+\mu^-$ 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 ($\sin 2\phi_1 = \sin 2\beta$)

Tools to find/constrain 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: not easy to understand what is going on at the quark level (light quark bound system, large dimensions).

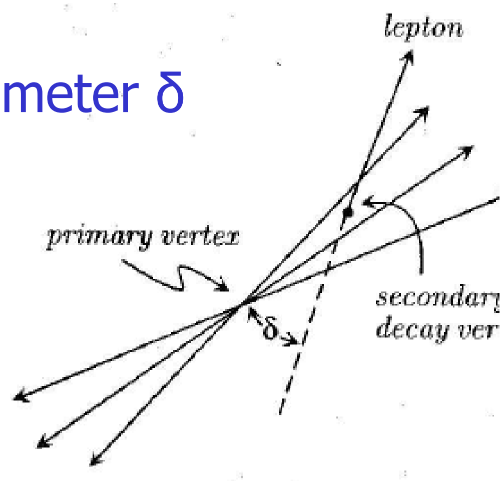
B has a heavy quark, a smaller system, and is easier for interpreting the experimental results.

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

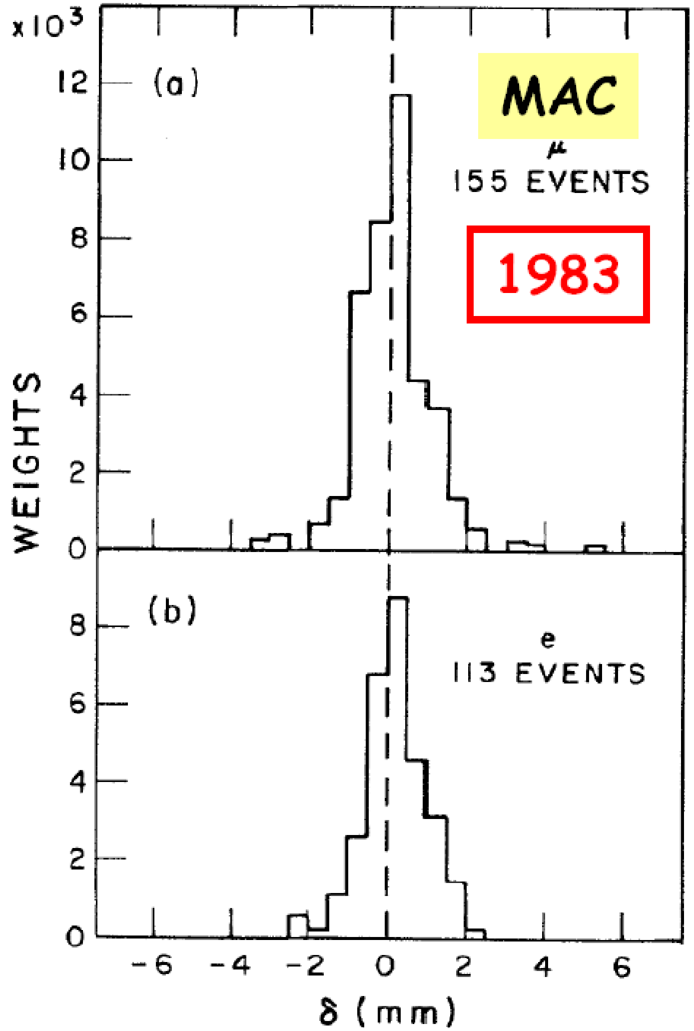


Lifetime implies: V_{cb} small

MAC: (1.8±0.6±0.4)ps

Mark II: (1.2±0.4±0.3)ps

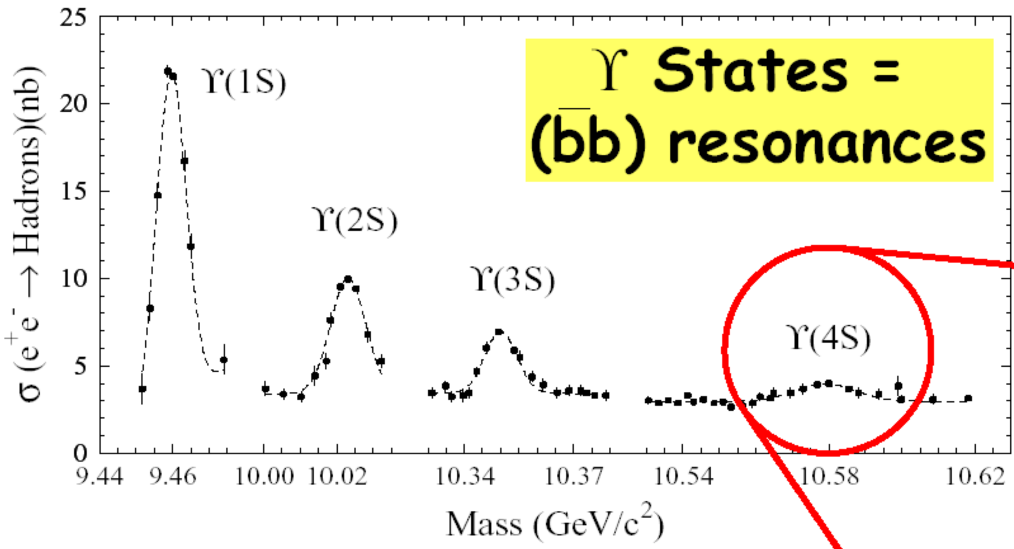
Integrated luminosity at 29 GeV: 109 (92) pb^{-1}~3,500 bb pairs

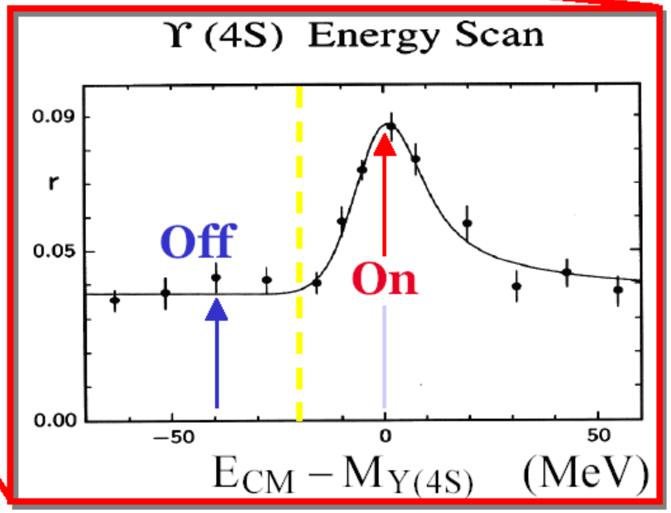


MAC, PRL **51**, 1022 (1983)

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)

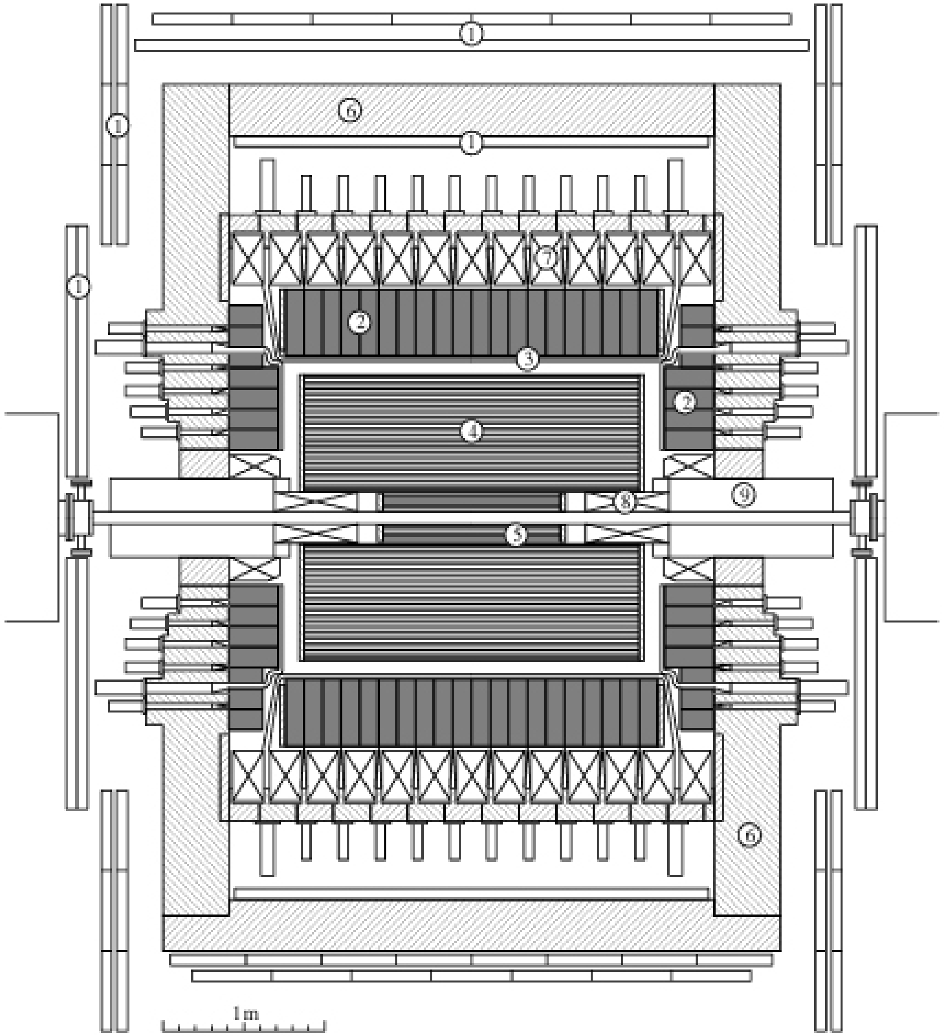
80s-90s: two very successful experiments:

•ARGUS at DORIS (DESY)

•CLEO at CESR (Cornell)

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

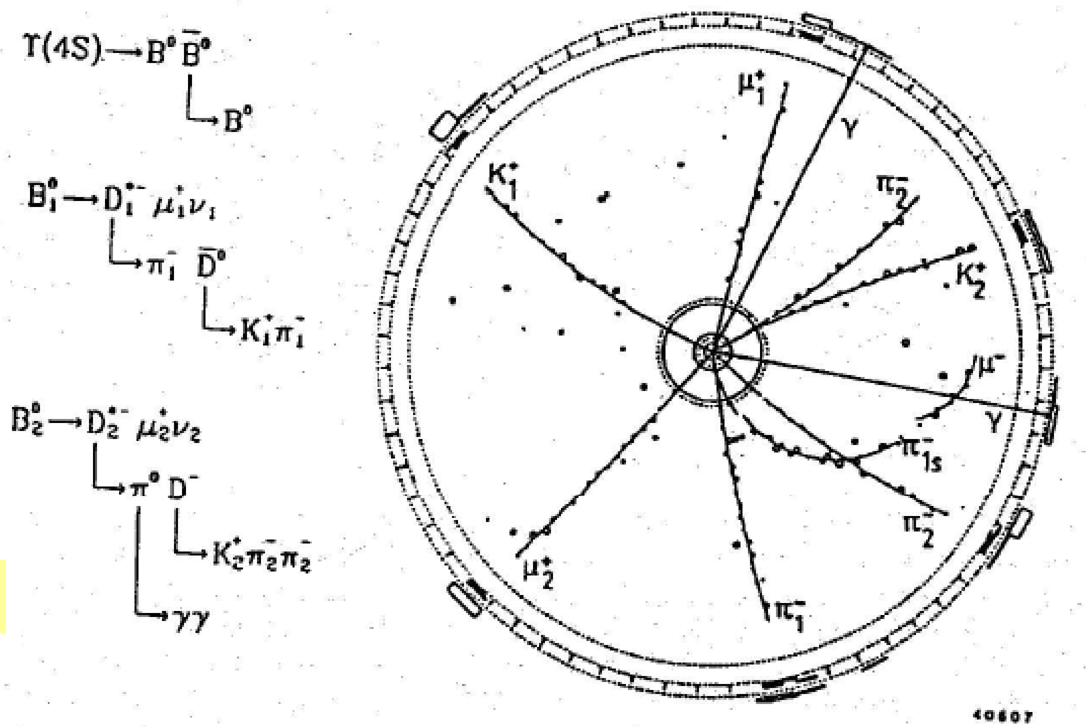
Large solid angle, excellent tracking and good particle identification (TOF, dE/dx, EM calorimeter, muon chambers).



Mixing in the B^0 system

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

Reconstructed event



$$\chi_d = 0.17 \pm 0.05$$

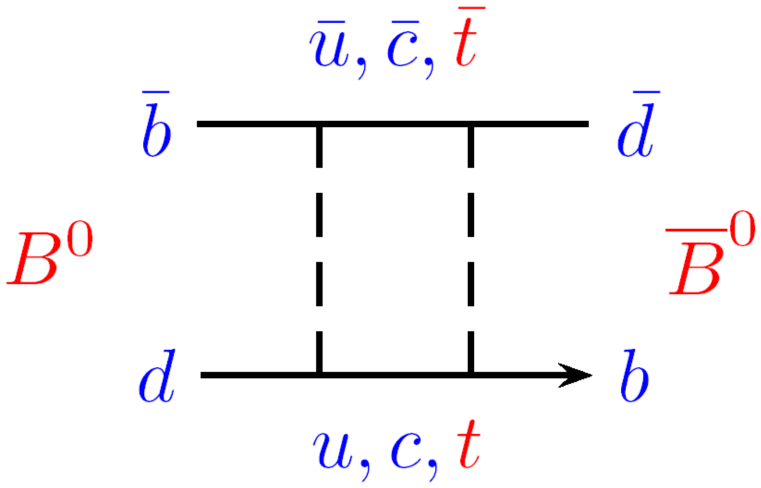
ARGUS, PL B **192**, 245 (1987)

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 $\Upsilon(4s)$

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

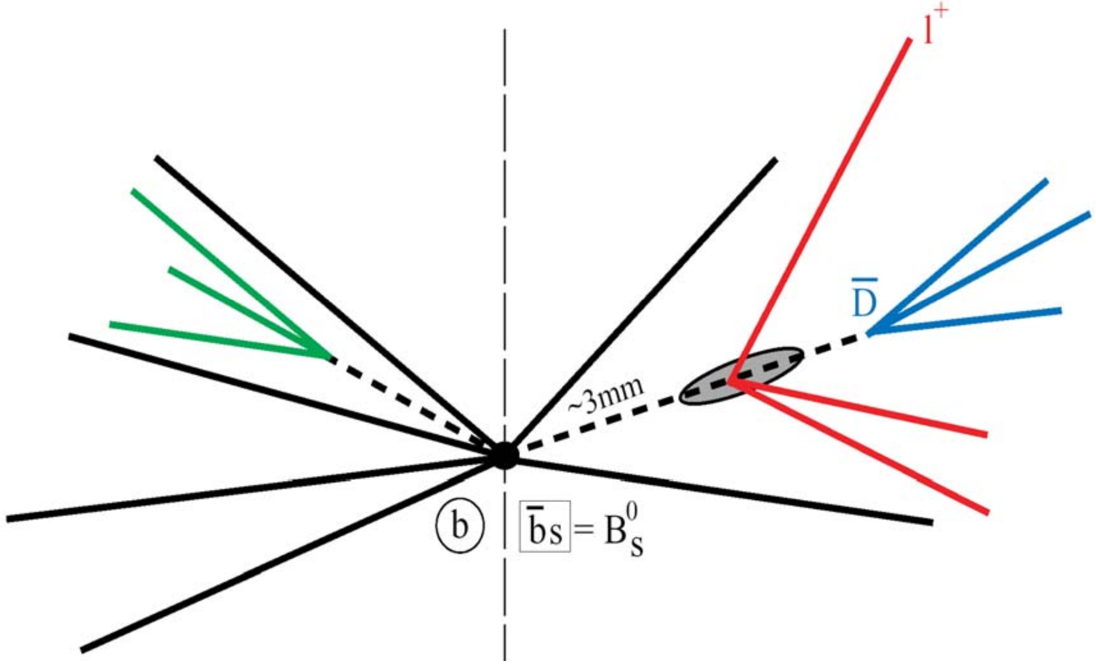
- B mesons
- D mesons
- τ^- lepton
- and even a measurement of ν_τ mass.

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).

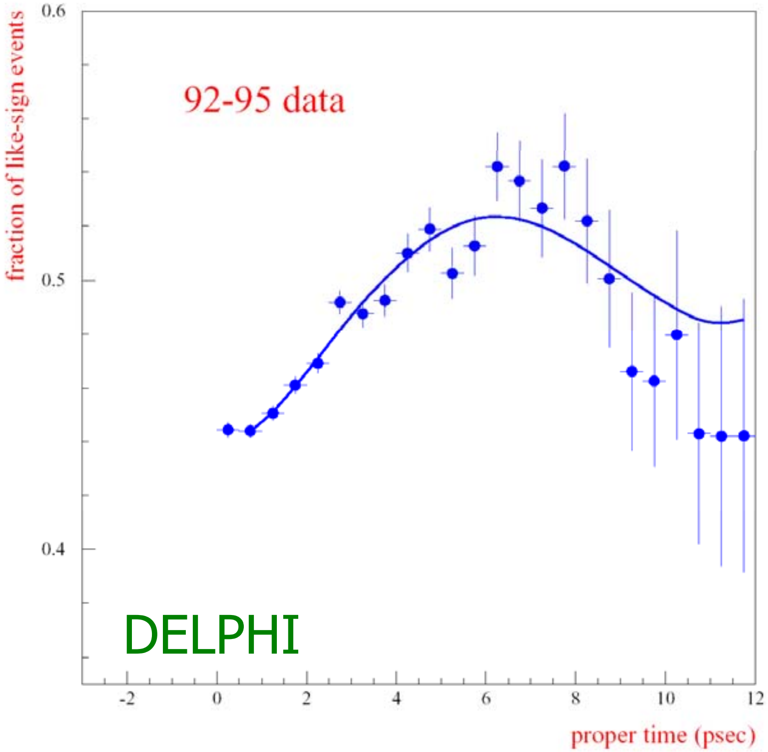
Studies of B mesons at LEP

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...)

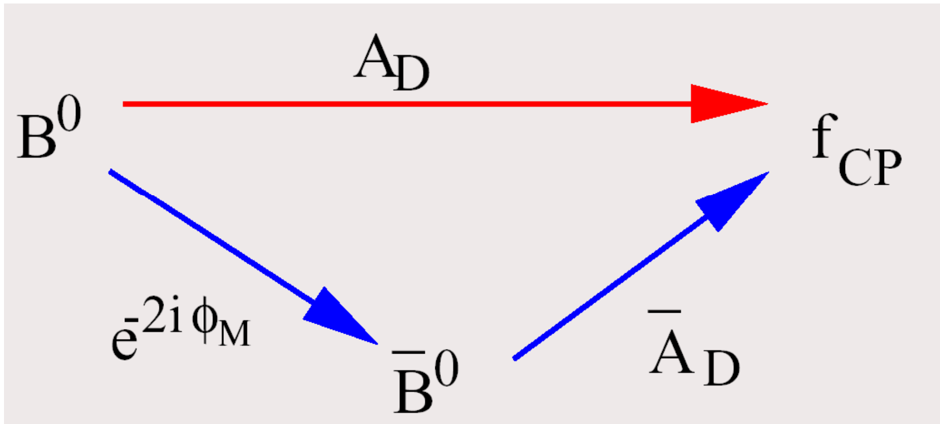
Large number of B mesons (but by far not enough to do the CP violation measurements...)

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 → J/ψ K_S

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

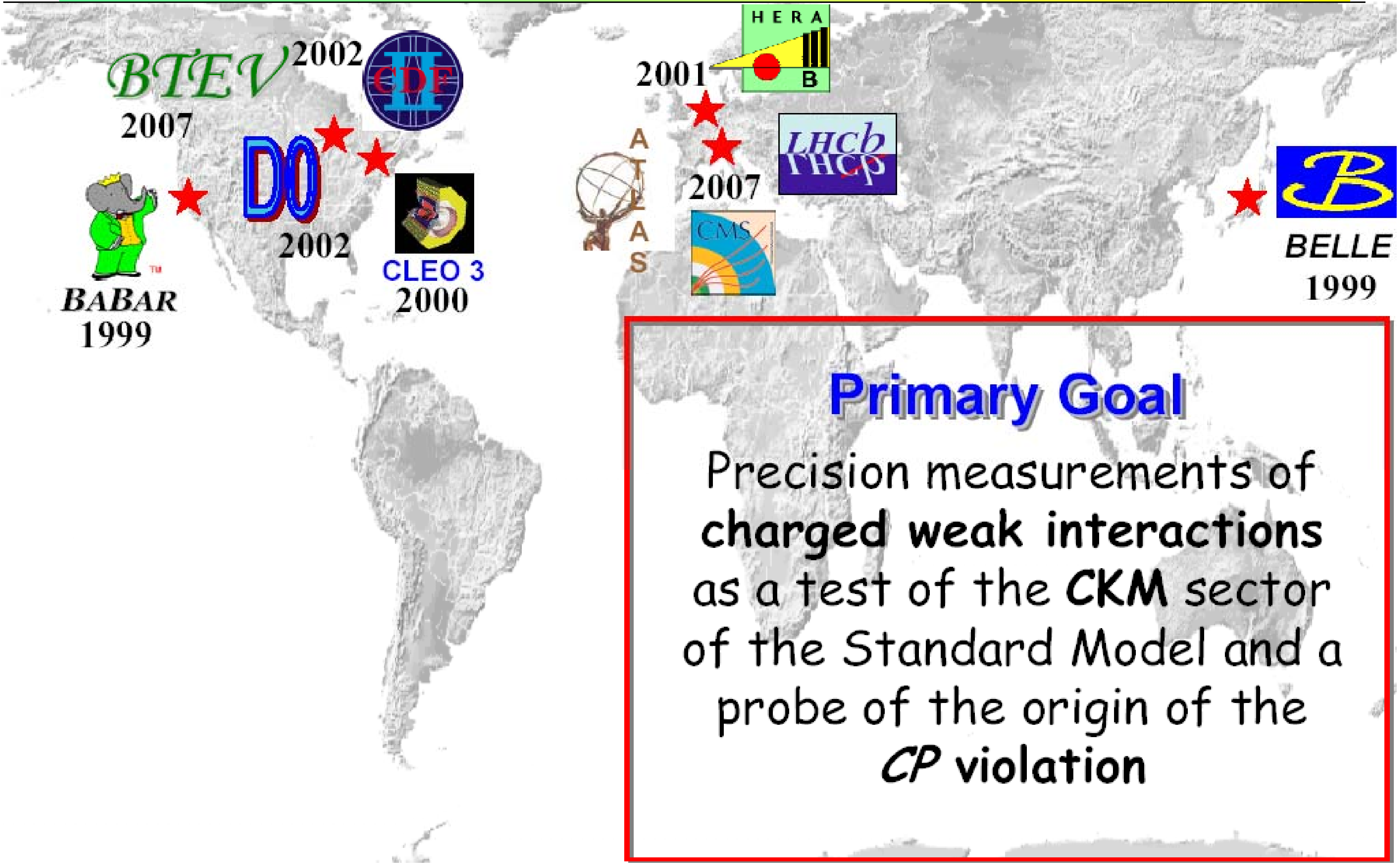
Theoretically clean way to one of the parameters ($\sin 2\phi_1$)

Use boosted BBbar system to measure the time evolution (P. Oddone)

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

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

- → A lot of physicists were after this holy grail



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 →$H_{11}=H_{22}$

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

diagonalize →

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

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

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

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

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

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

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 $\Delta\Gamma_B << \Delta m_B$

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

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

and

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

= a phase factor

or to the next order

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

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

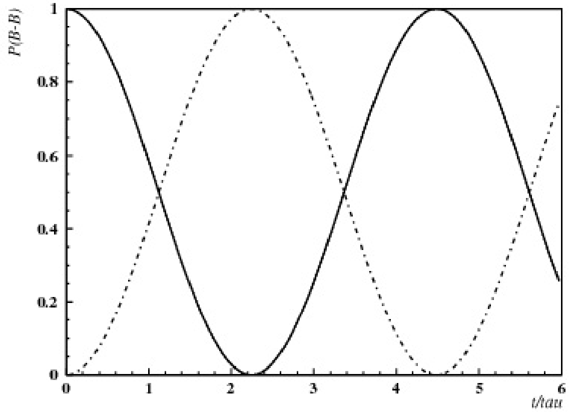
$$g_+(t) = e^{-iMt} e^{-\Gamma t/2} \cos(\Delta m t/2)$$
$$g_-(t) = e^{-iMt} e^{-\Gamma t/2} i \sin(\Delta m t/2)$$

$M = (M_H + M_L)/2$

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**

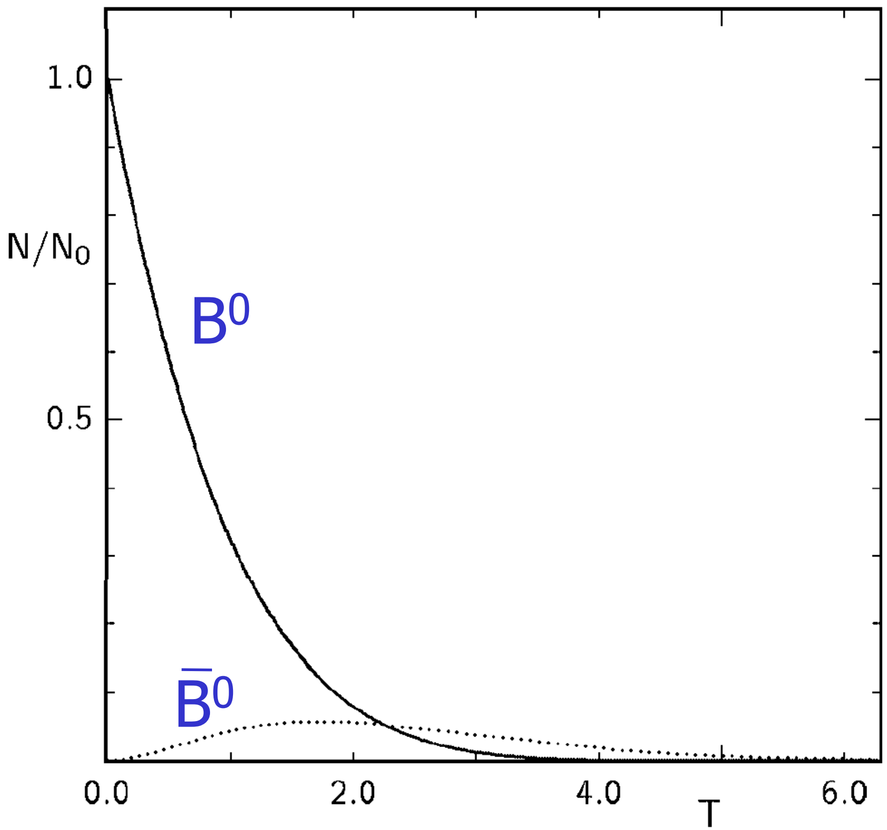
$$\left|\left\langle \overline{B}^0 \middle| B^0_{phys}(t)\right\rangle\right|^2 = |q/p|^2 |g_-(t)|^2 = |q/p|^2 \sin^2(\Delta m t/2)$$

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

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

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

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

Decay amplitude as a function of time:

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

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

... and similarly for the anti-B

CP violation: three types

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

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

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

Define a parameter λ

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

Three types of CP violation (CPV):

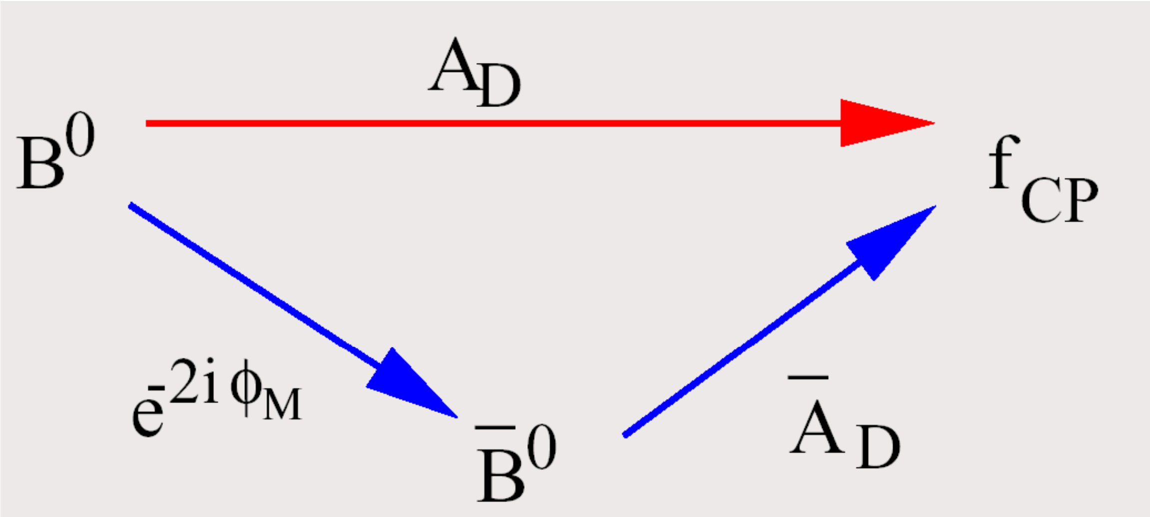
$$\left.\begin{array}{l} \not{CP} \text{ in decay: } |\bar{A}/A| \neq 1 \\ \\ \not{CP} \text{ in mixing: } |q/p| \neq 1 \end{array}\right\} |\lambda| \neq 1$$

$\not{CP}$ 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 $\pi^+ \pi^-$



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

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:

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

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

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

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

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

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

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

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

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

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

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

Detailed derivation → backup slides

CP violation in the interference between decays with and without mixing

One more form for λ:

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

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

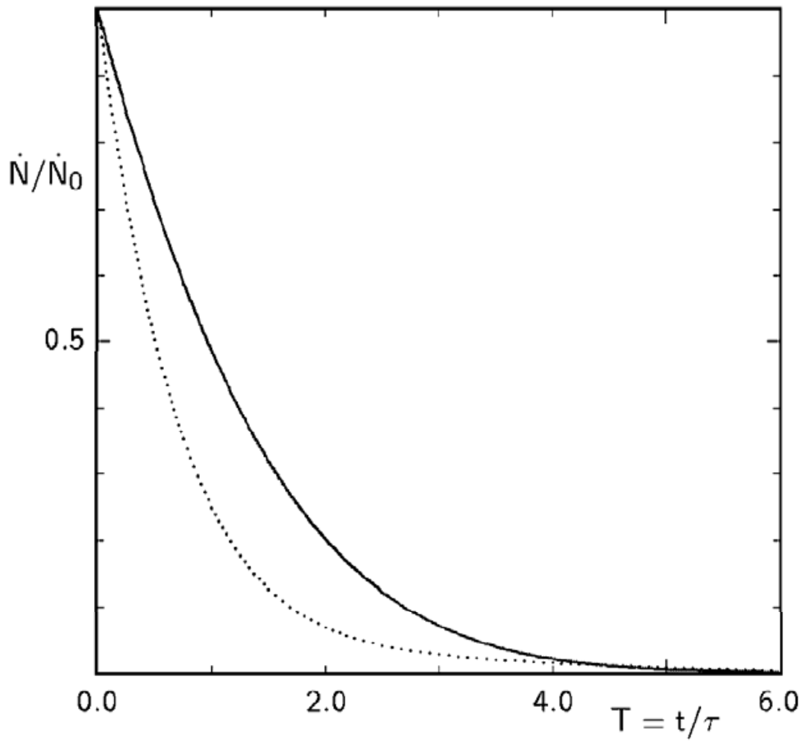
•one decays to a CP eigenstate f_{CP} (e.g. $\pi\pi$ or $J/\psi K_S$) at time t_{fCP} and

•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. $B^0 \to D^0\pi$, $D^0 \to K^-\pi^+$)

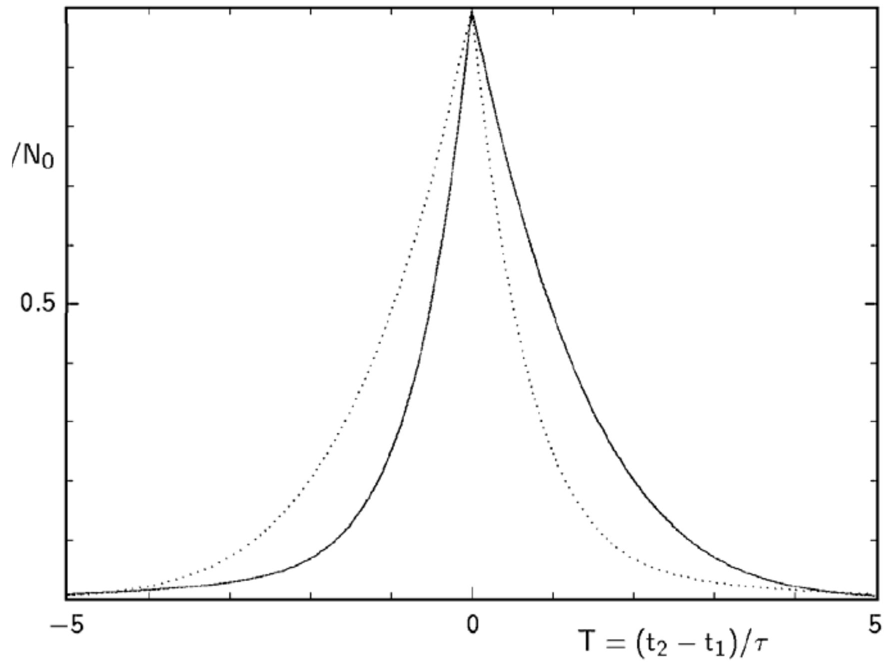
also known as 'tag' because it tags the flavour of the B meson it comes from

Decay rate to f_{CP}

Incoherent production
(e.g. hadron collider)



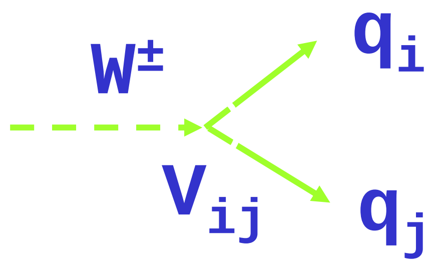
coherent production
at Y(4s)



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

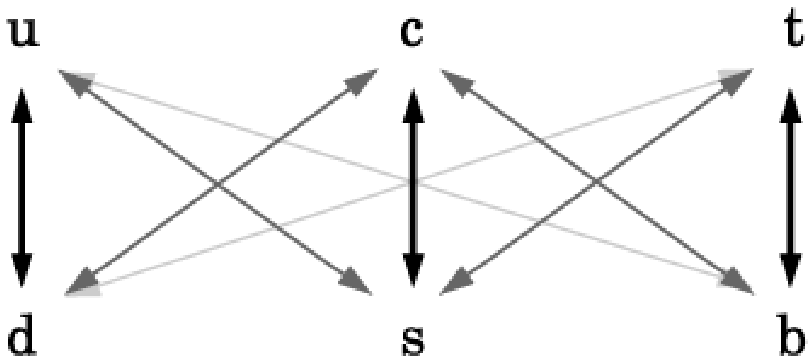
CP violation in SM

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



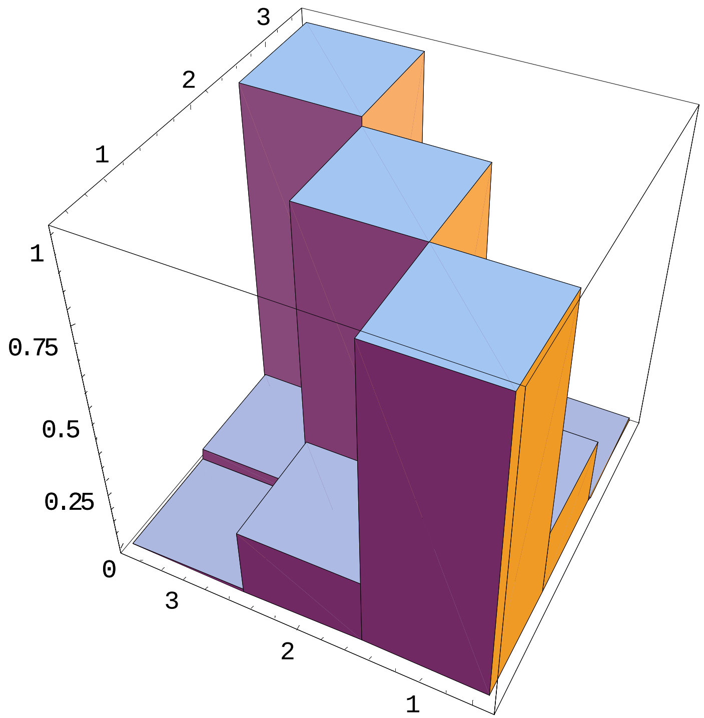
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM matrix

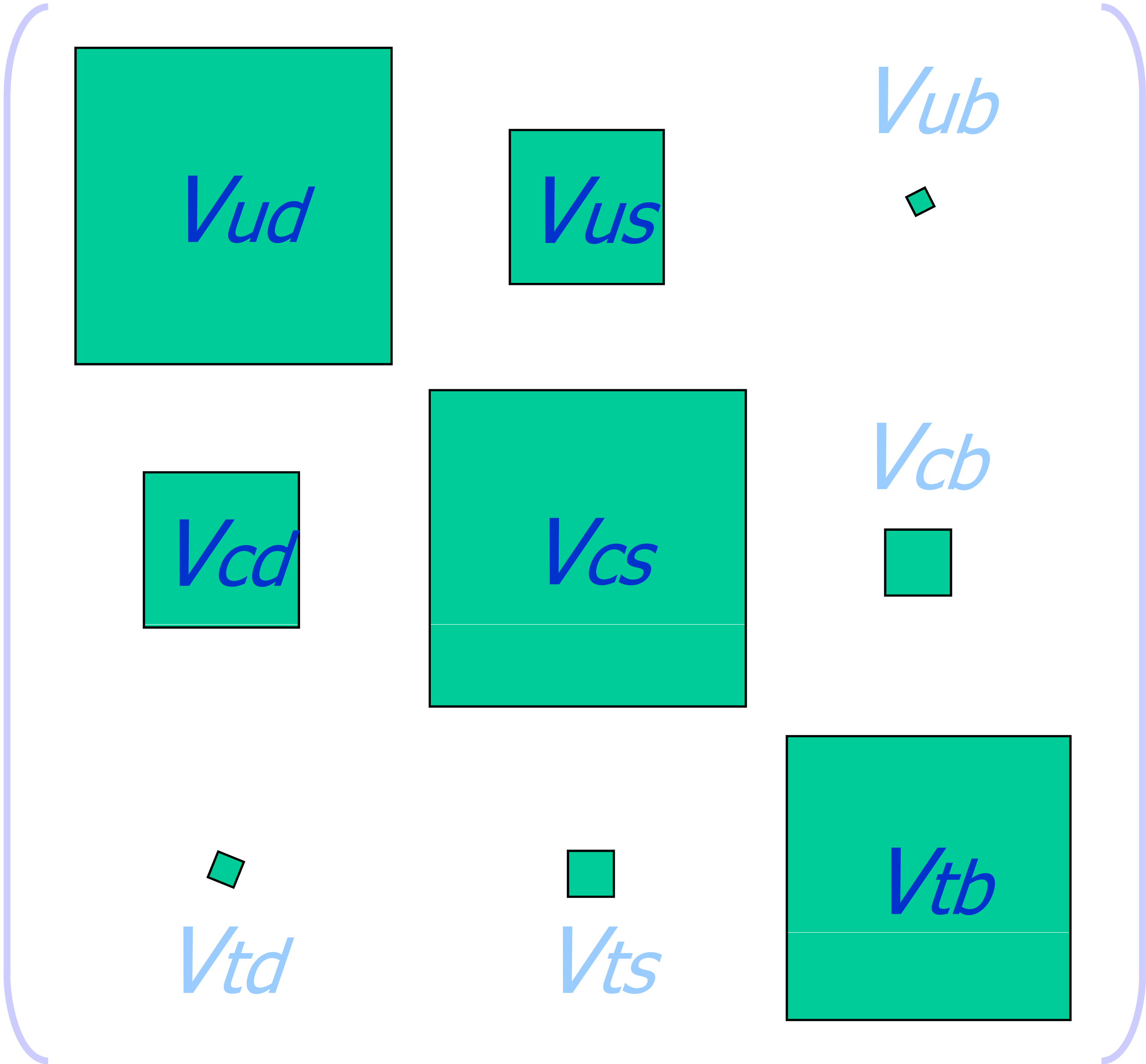


Transitions between members of the same family more probable (=thicker lines) than others

→CKM: almost a diagonal matrix, but not completely →



→CKM: almost real, but not completely!



CKM matrix

Almost a real 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: $1^{st}+2^{nd}$, $2^{nd}+3^{rd}$, $1^{st}+3^{rd}$ columns

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

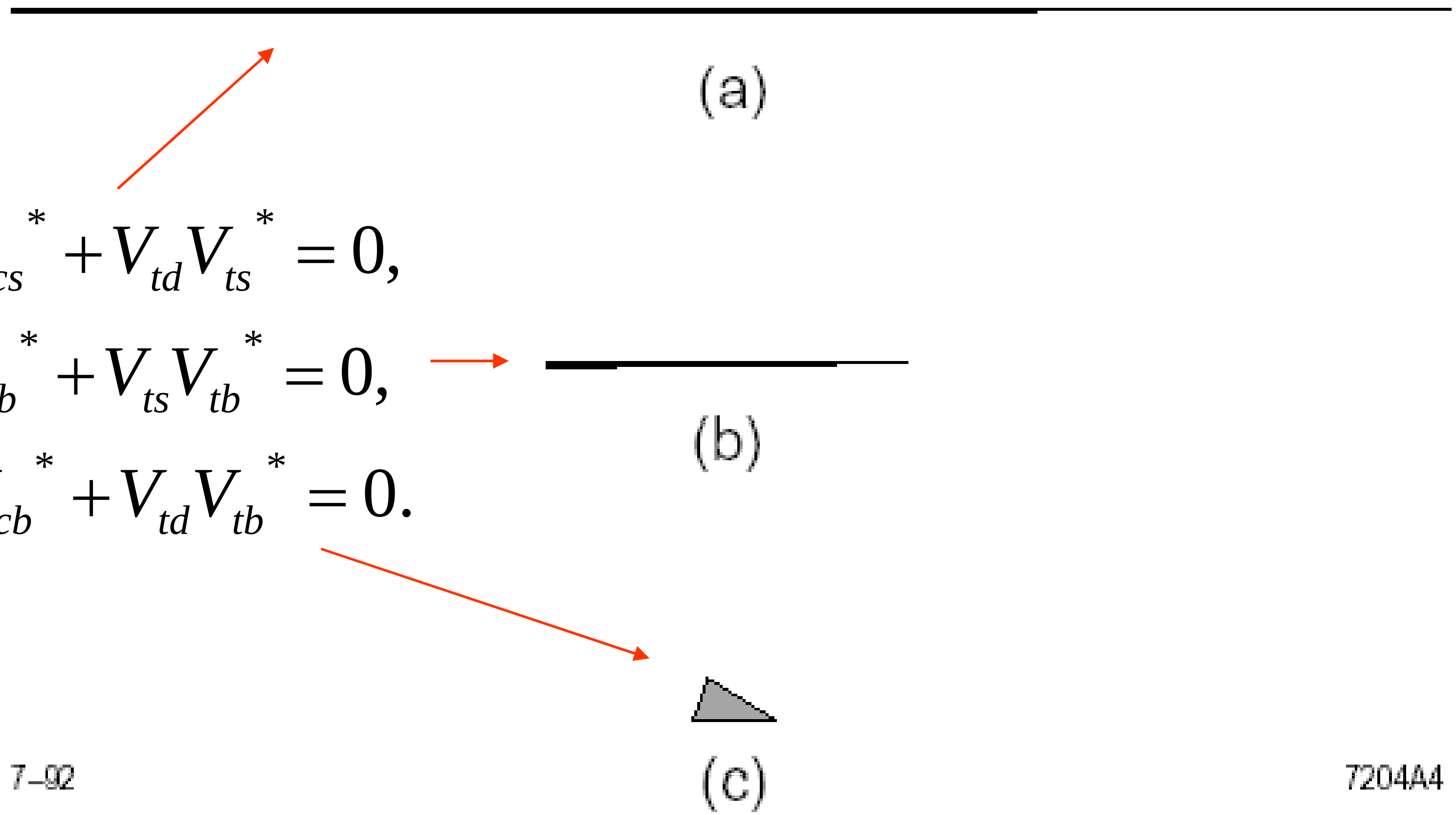
Geometrical representation: triangles in the complex plane.

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})

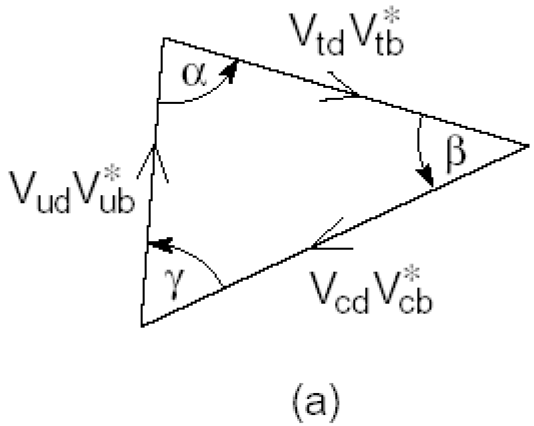
$$J=c_{12}c_{23}c_{13}^{2}s_{12}s_{23}s_{13}\sin\delta$$

Jarlskog invariant

Unitarity triangle

THE unitarity triangle:

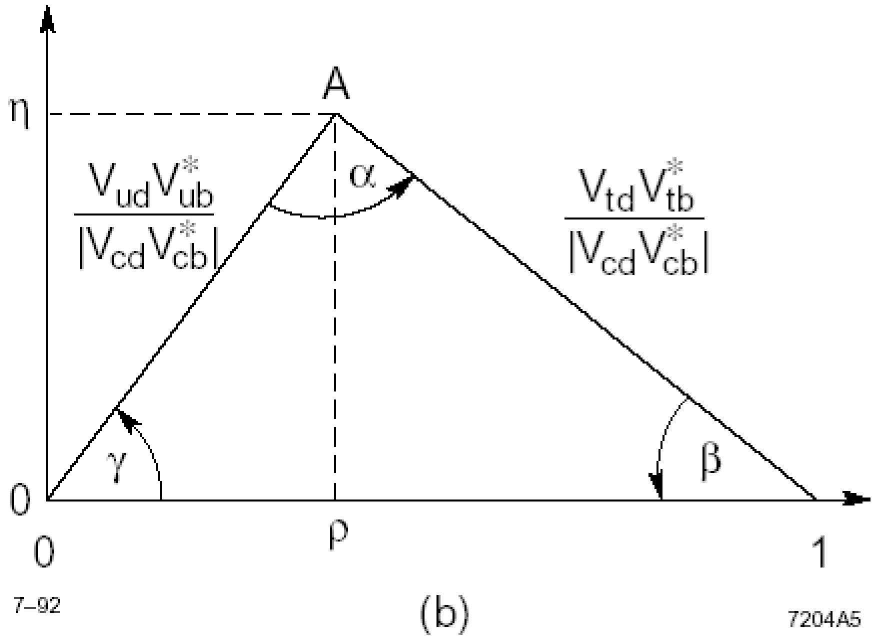
$$V_{ud}V_{ub}^{\;*} + V_{cd}V_{cb}^{\;*} + V_{td}V_{tb}^{\;*} = 0$$



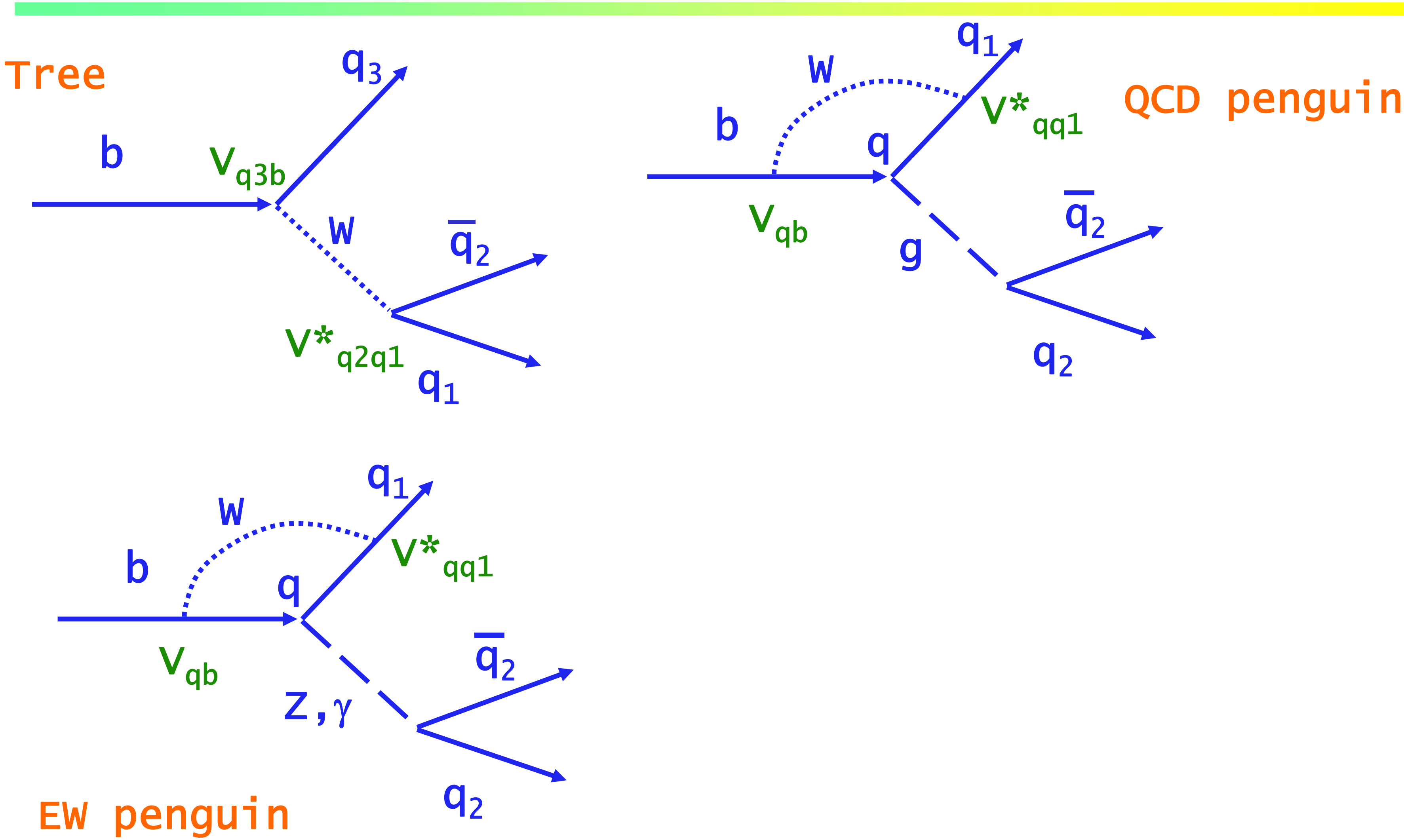
$$\alpha \equiv \phi_2 \equiv \arg\left(\frac{V_{td}V_{tb}^{\;*}}{V_{ud}V_{ub}^{\;*}}\right)$$

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

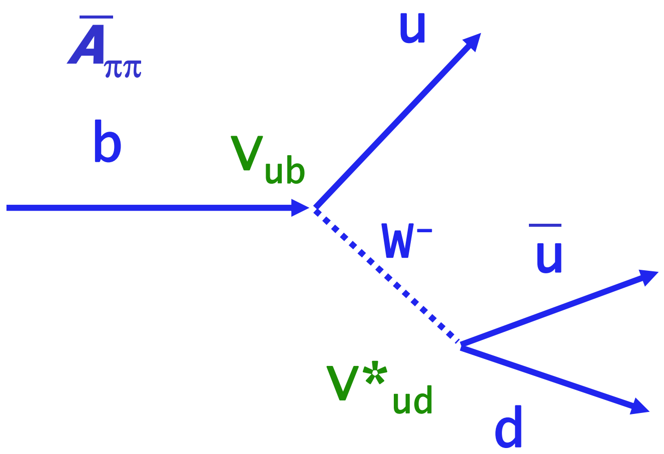
$$\gamma \equiv \phi_3 \equiv \arg\left(\frac{V_{ud}V_{ub}^{\;*}}{V_{cd}V_{cb}^{\;*}}\right) \equiv \pi - \alpha - \beta$$

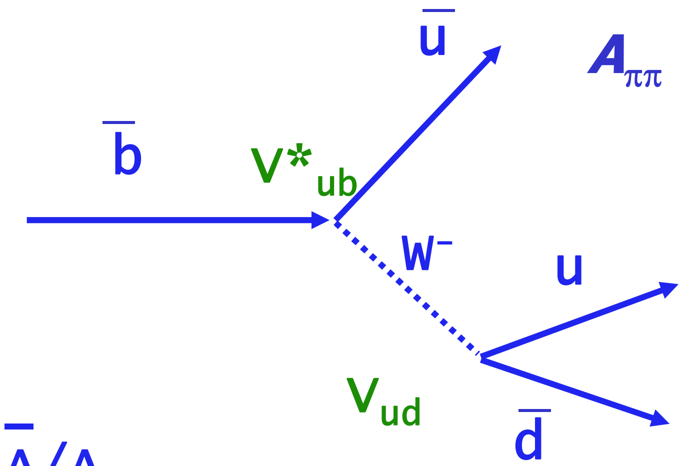


b decays


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

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





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

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

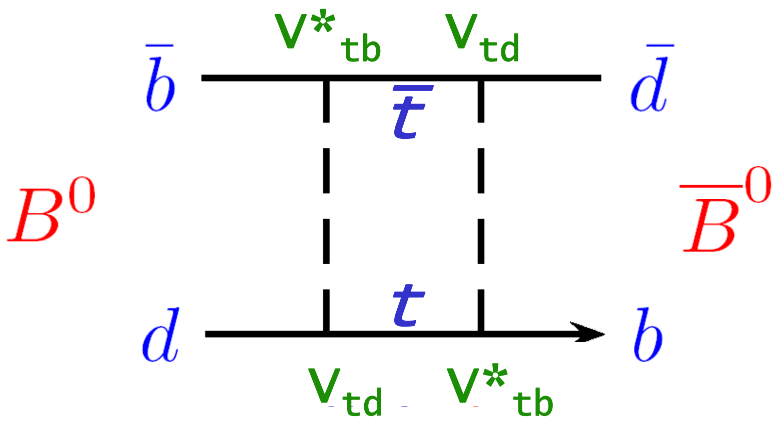
$$\alpha \equiv \phi_2 \equiv \arg\left(\frac{V_{td} V_{tb}{}^*}{V_{ud} V_{ub}{}^*}\right)$$

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

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

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

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

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

$b \to c$ 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)

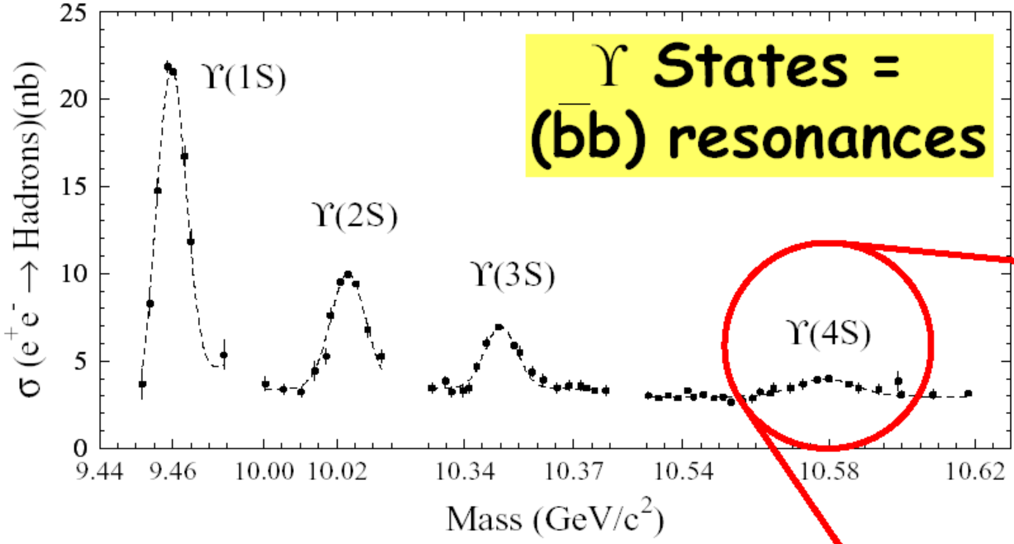
•Measure time difference between this decay and the decay of the associated B (f_{tag}) (from the flight path difference)

•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)



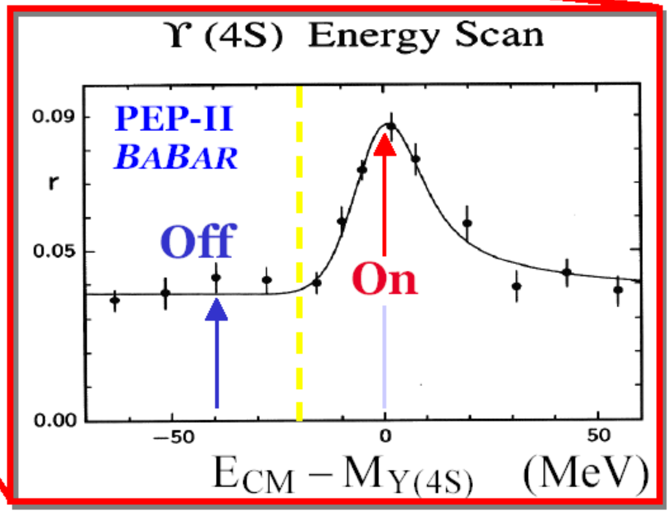
Cross Sections at Υ(4S):

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

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

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

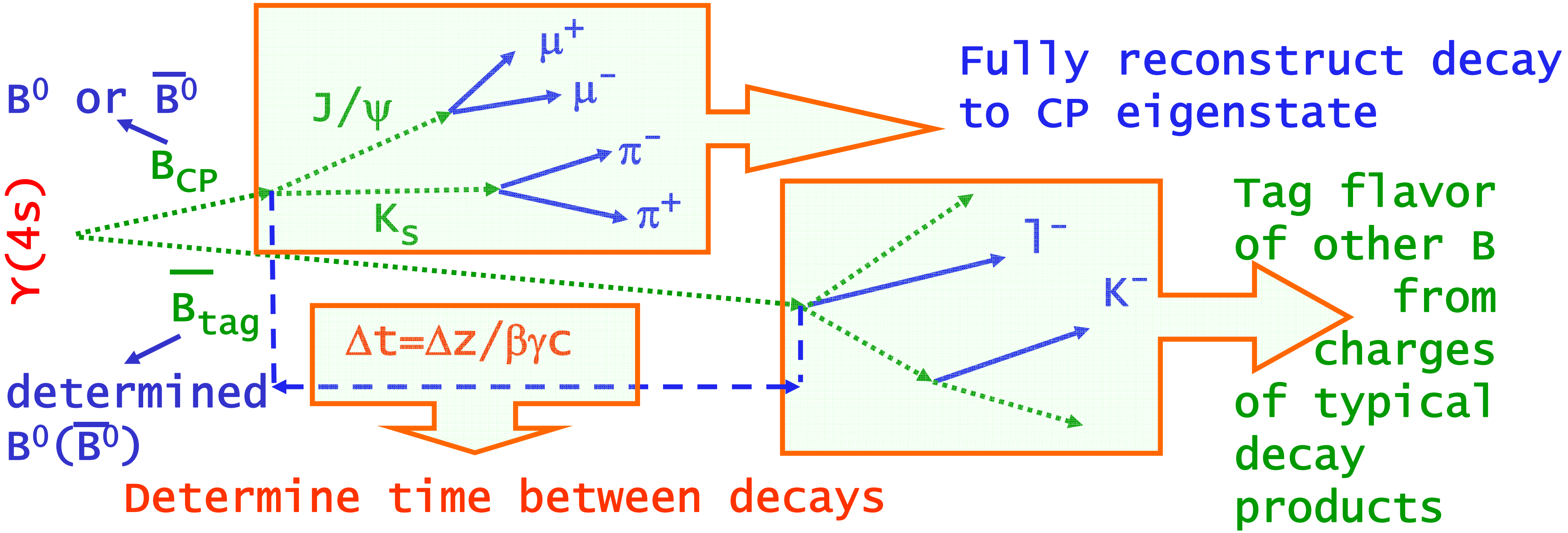
$u\bar{u} \sim 1.4$ nb



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

$L = 1$ state

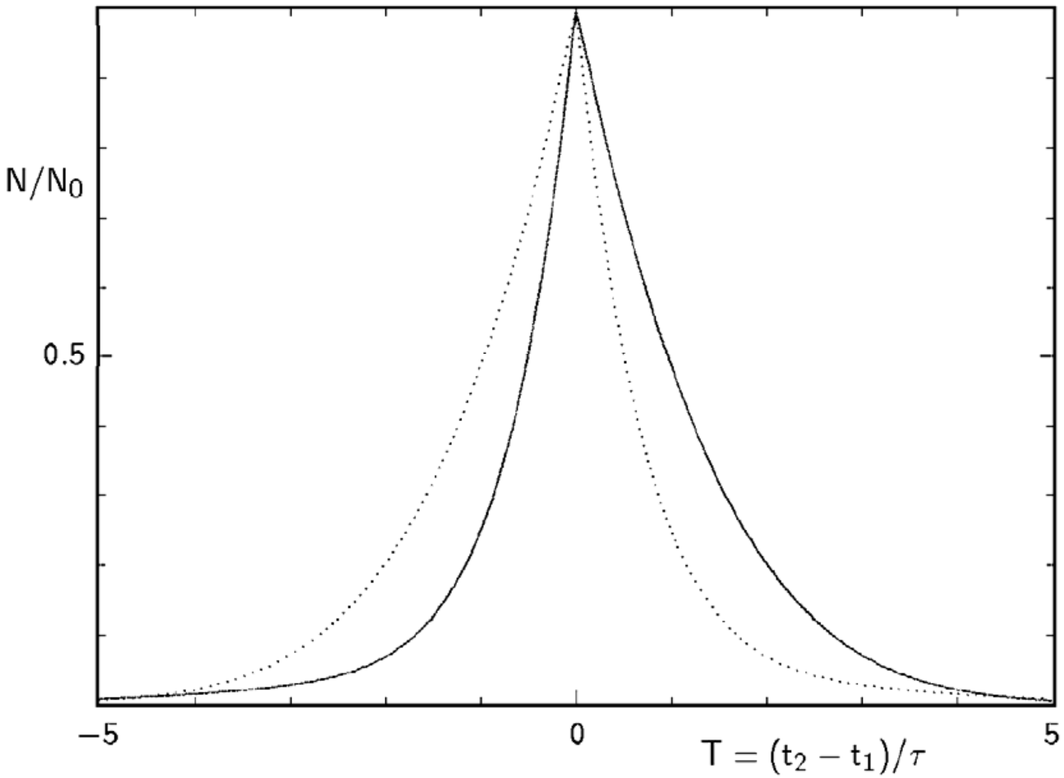
Principle of measurement



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).

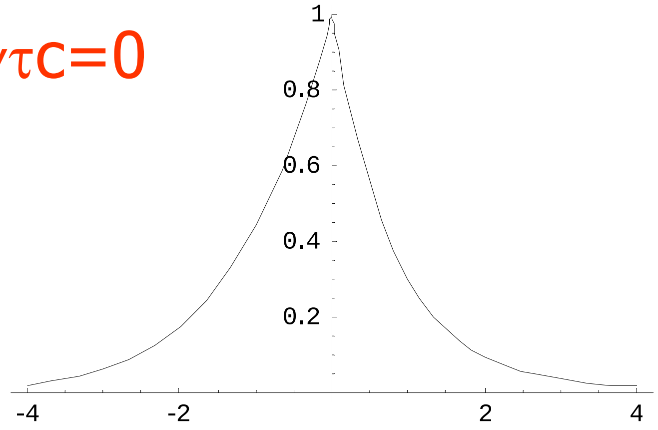
-> the two curves should not be smeared too much

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

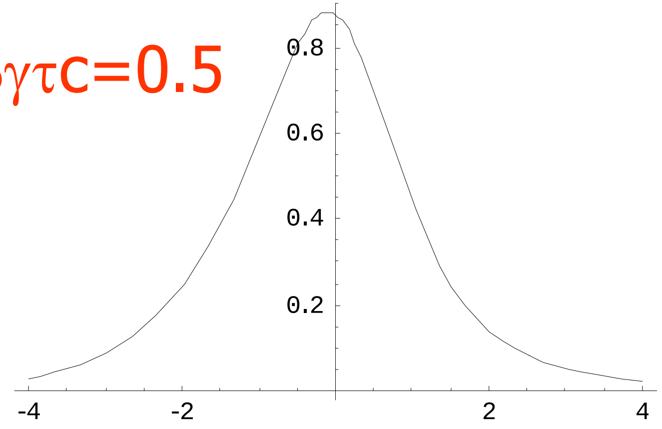
Experimental considerations

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

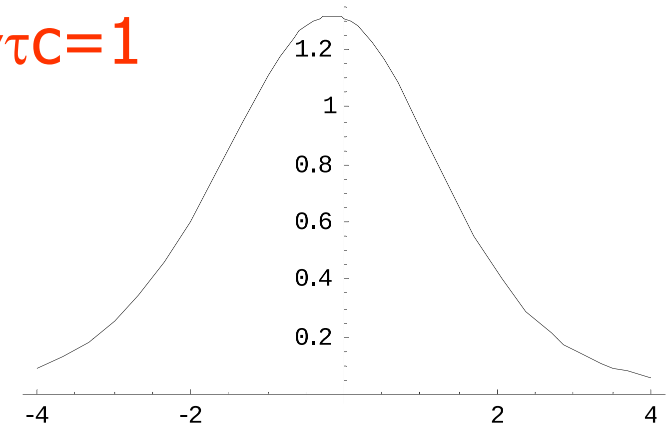
$\sigma(z)/\beta\gamma\tau c=0$



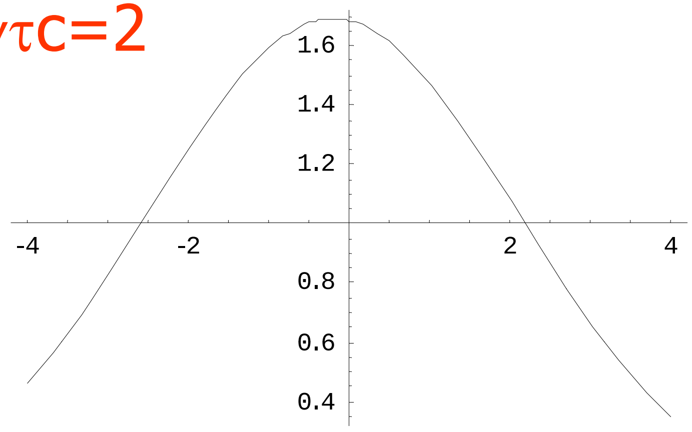
$\sigma(z)/\beta\gamma\tau c=0.5$



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



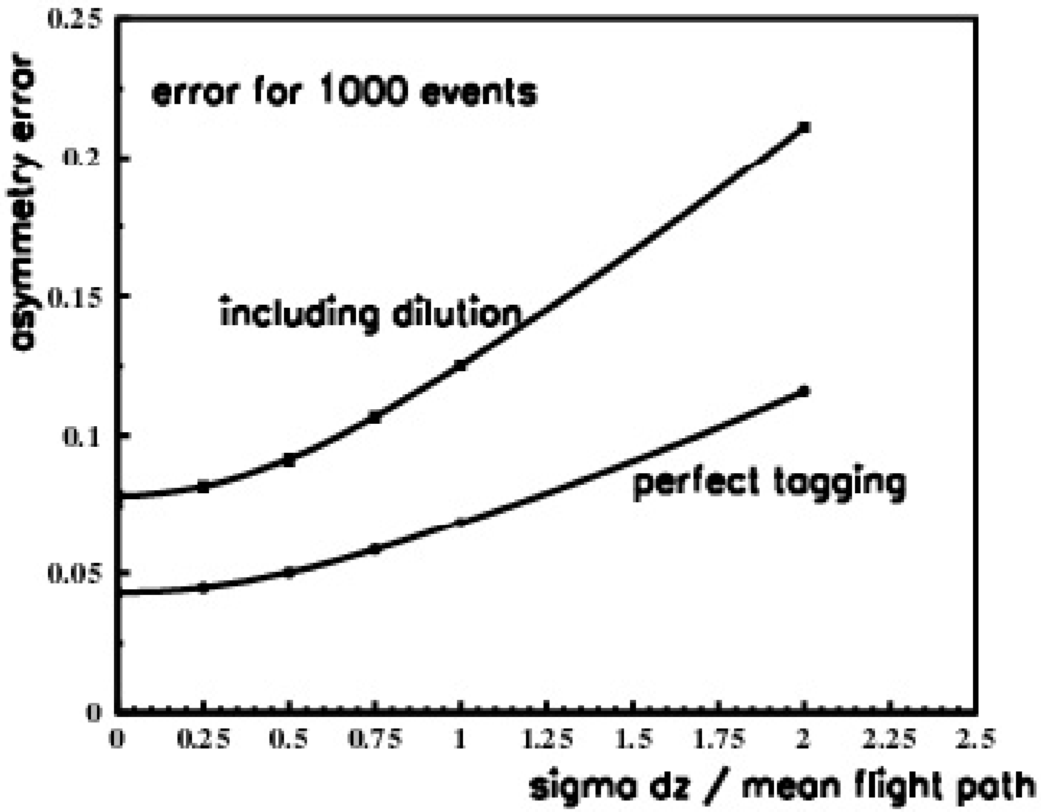
$\sigma(z)/\beta\gamma\tau c=2$



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 1000 events



Experimental considerations

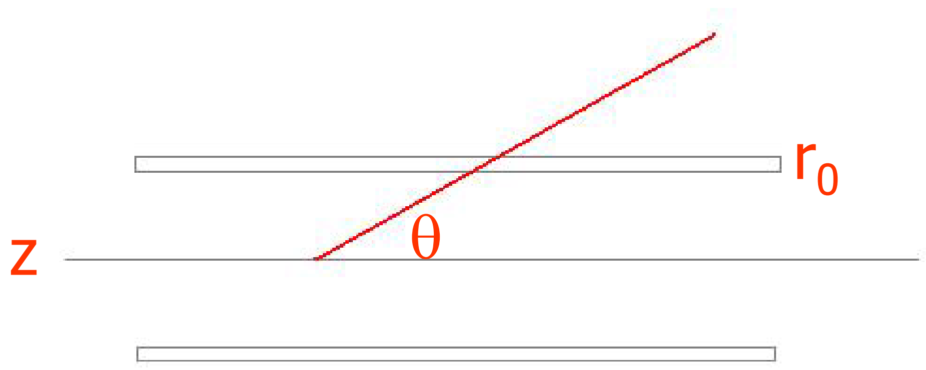
Choice of boost $\beta\gamma$:

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 $\theta(\beta\gamma)=\text{atan}(1/\beta\gamma)$ in the lab

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



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

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

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

Experimental considerations

Choice of boost $\beta\gamma$:

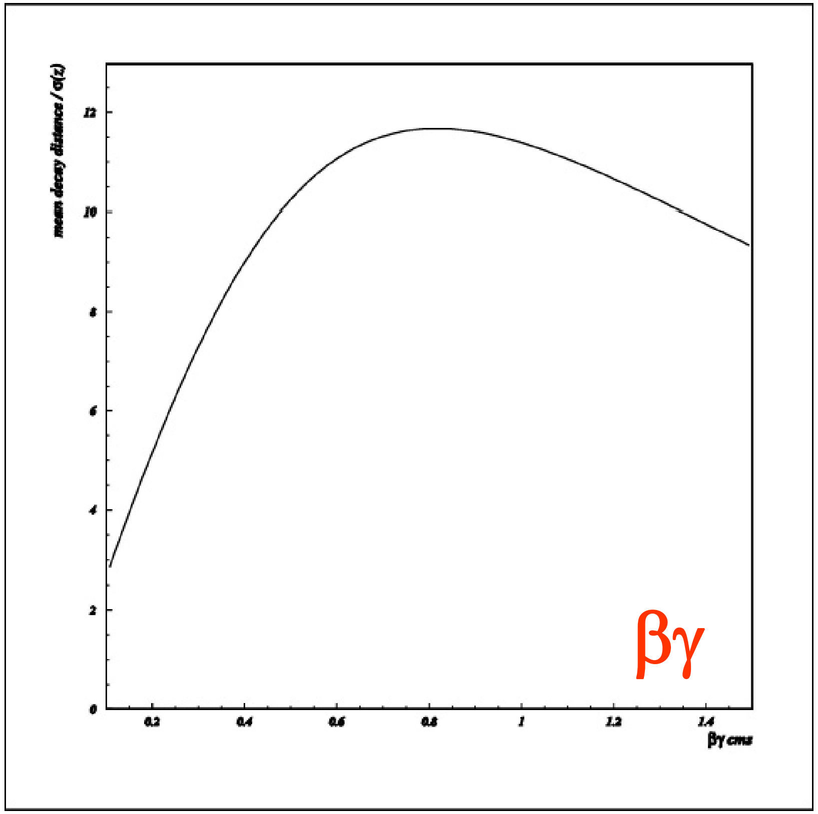
Optimize ration of typical B flight length to the vertex resolution

$\beta\gamma\tau c/\sigma(z)$ α $\beta\gamma \sin^{5/2}\theta(\beta\gamma)$

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

However....

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



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)

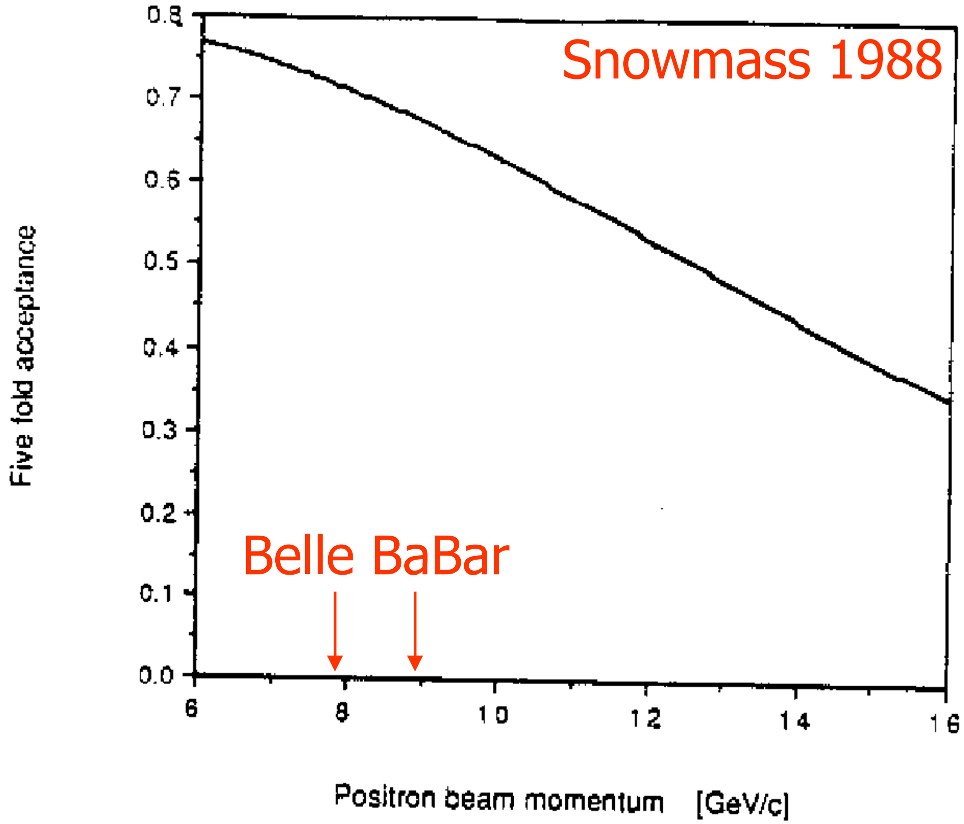
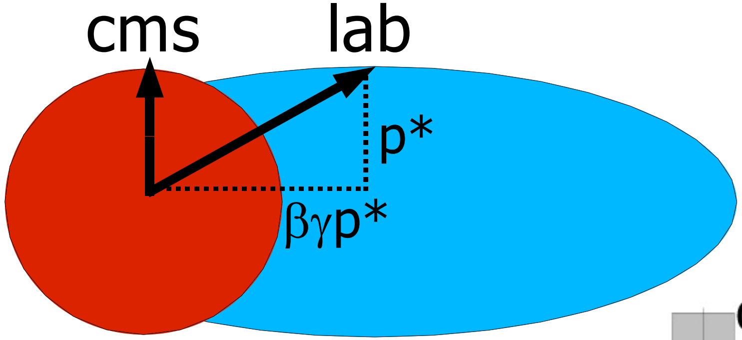


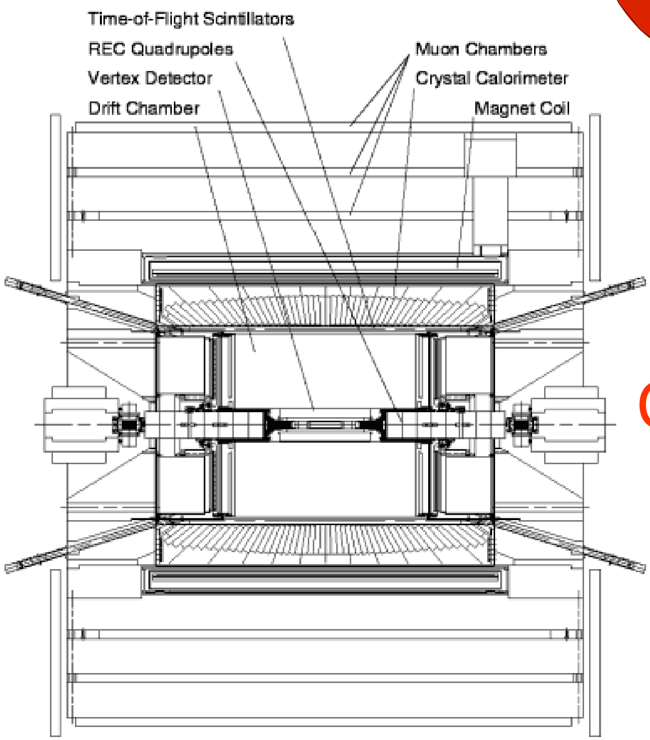
Figure 4. The acceptance of a detector covering $|\cos\theta_{lab}| < 0.95$ for five uncorrelated particles as a function of the energy of the more energetic beam in an asymmetric collider at the $\Upsilon(4S)$.

Experimental considerations

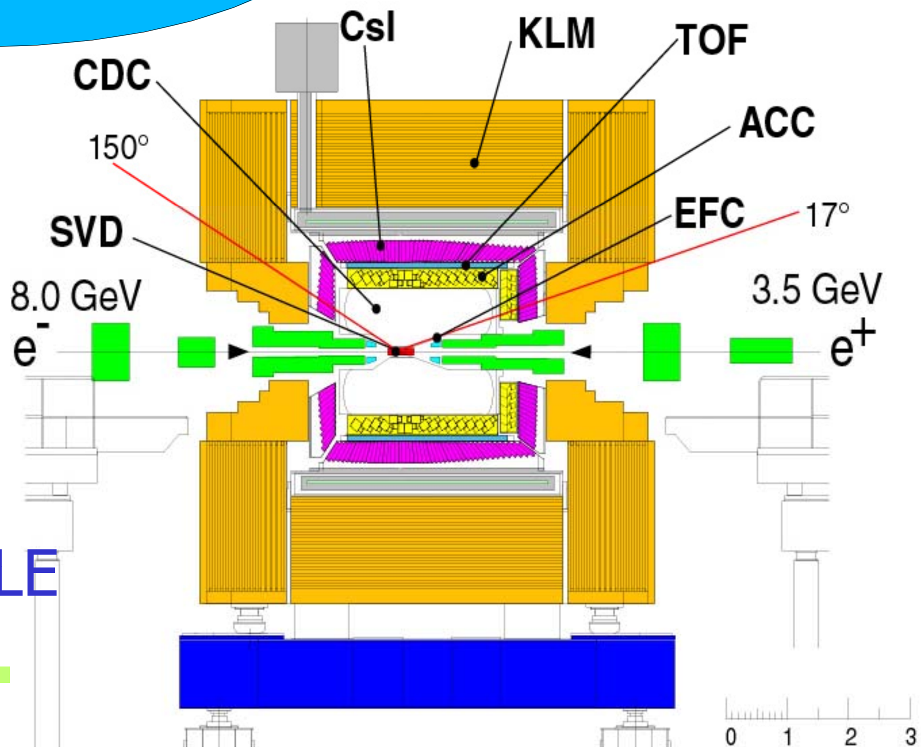
Detector form: symmetric for symmetric energy beams; slightly extended in the boost direction for an asymmetric collider.



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 * 2 * 8.4 10^{-4} * 0.118 * ½ * 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

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

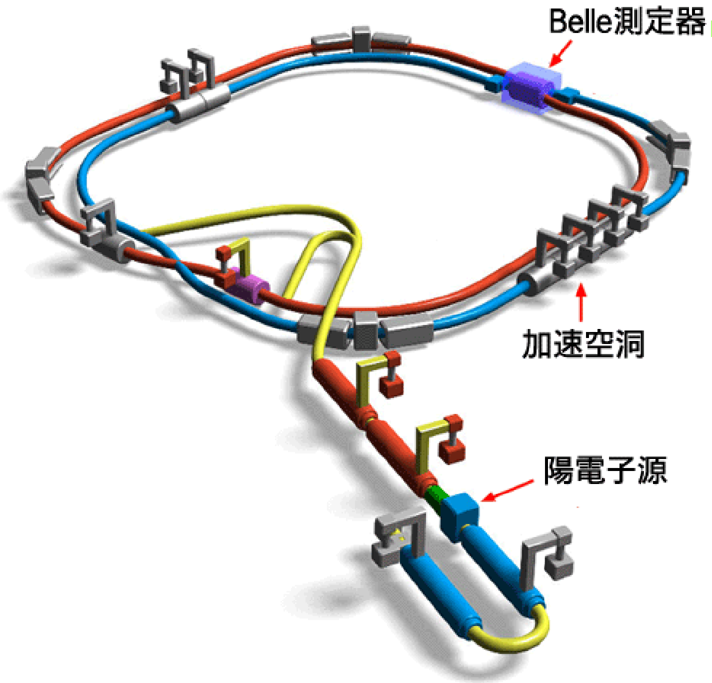
Cross section for Y(4s) production: 1.1 nb = 1.1 10^{-33} cm^2

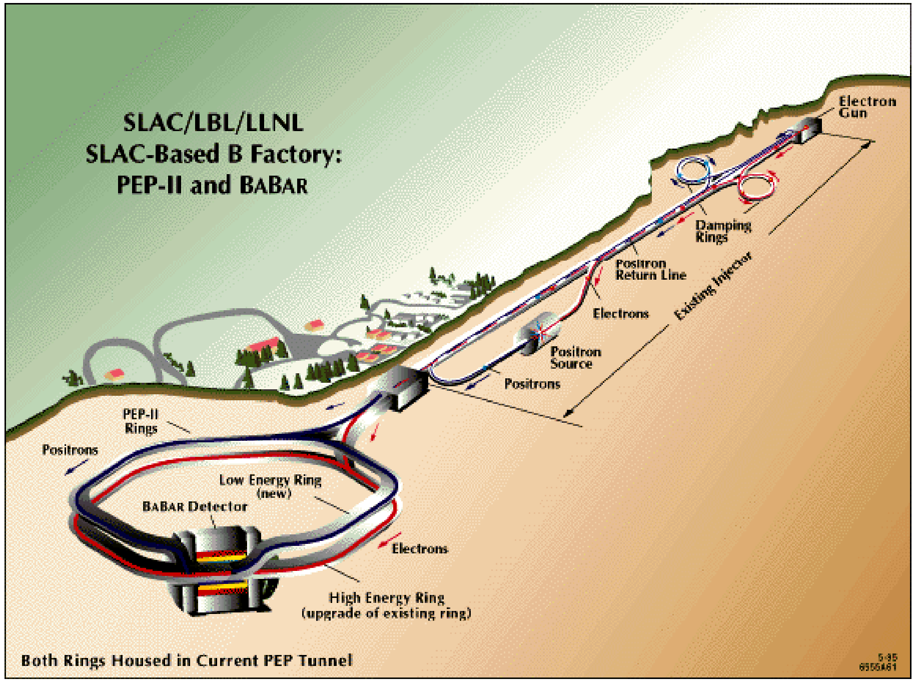
→ Accelerator figure of merit - luminosity - has to be

***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

$e^+ \rightarrow \Upsilon(4s) \leftarrow e^-$

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

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

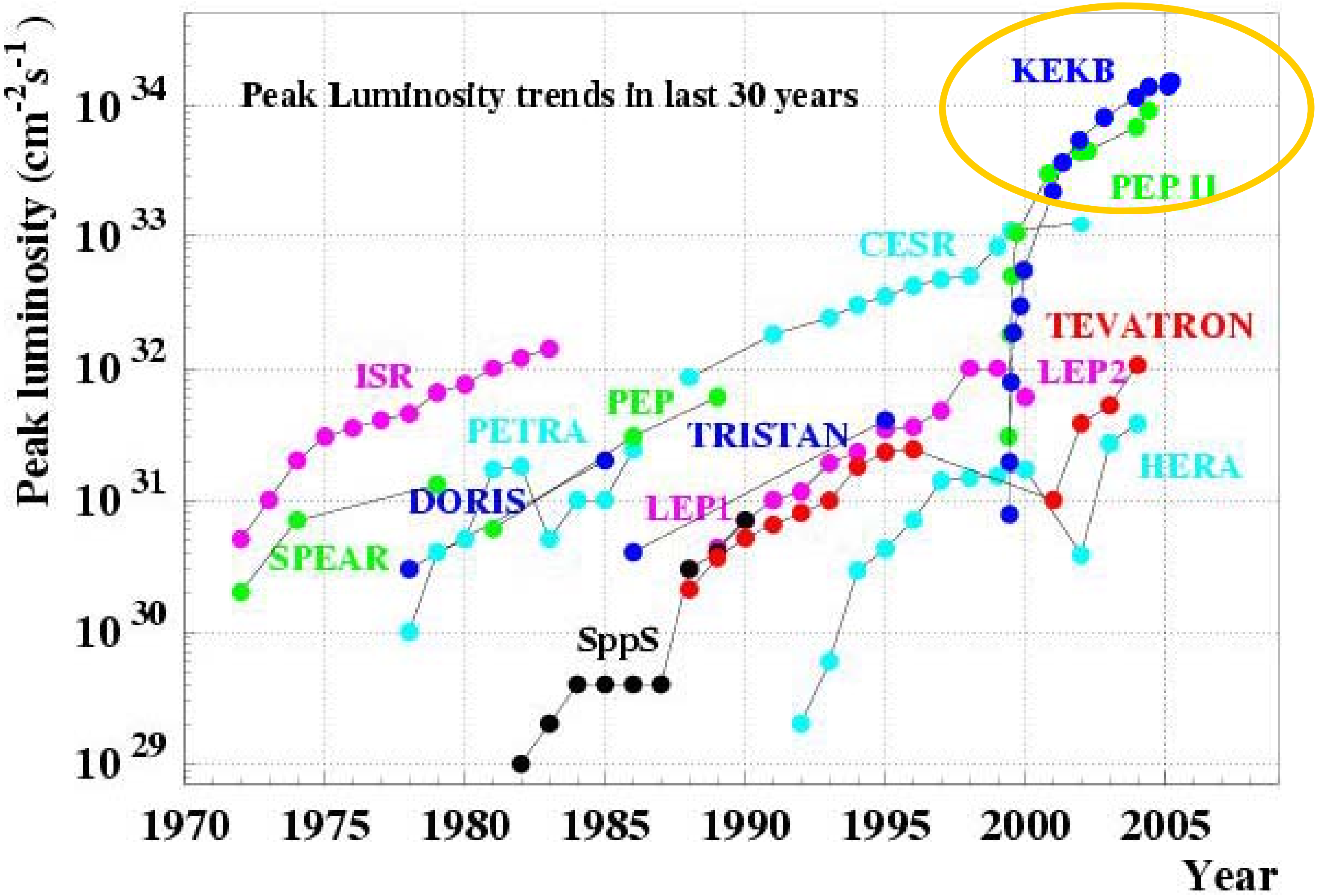
BaBar $p(e^-)=9$ GeV $p(e^+)=3.1$ GeV $\beta\gamma=0.56$

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

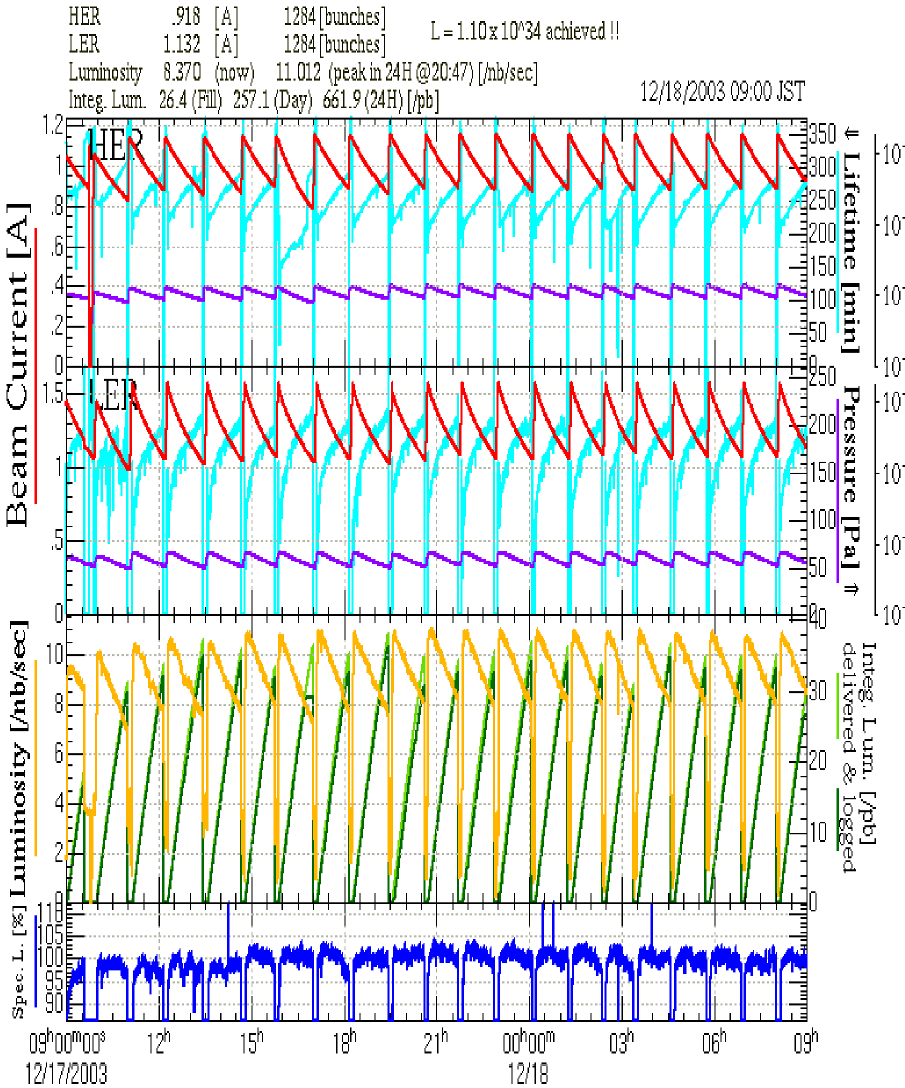
KEKB records: L_{peak} = 17/nb/sec (=1.7×10^{34} $s^{-1}cm^{-2}$)

L_{int}= 852/fb → ~900 M BB pairs

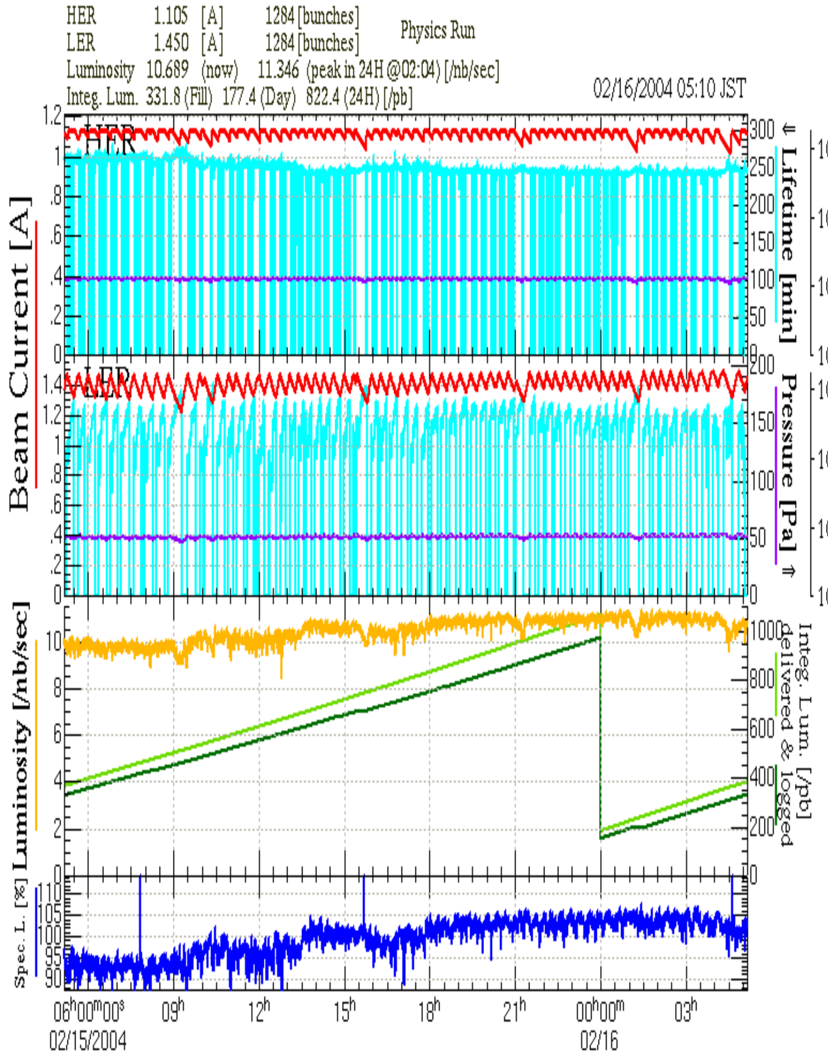
Accelerator performance



Normal injection *Continuous injection*



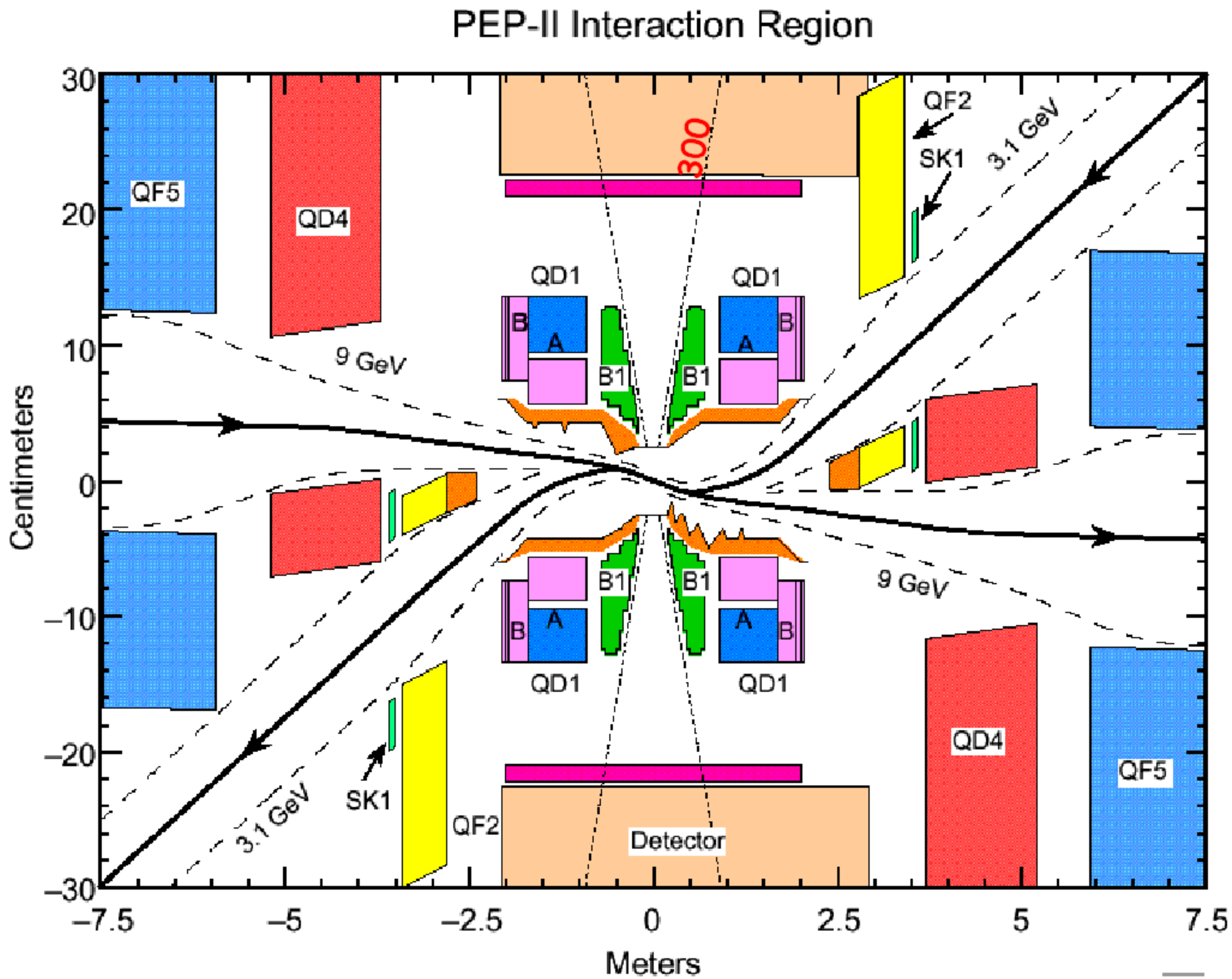
661/pb/day



→1182/pb/day

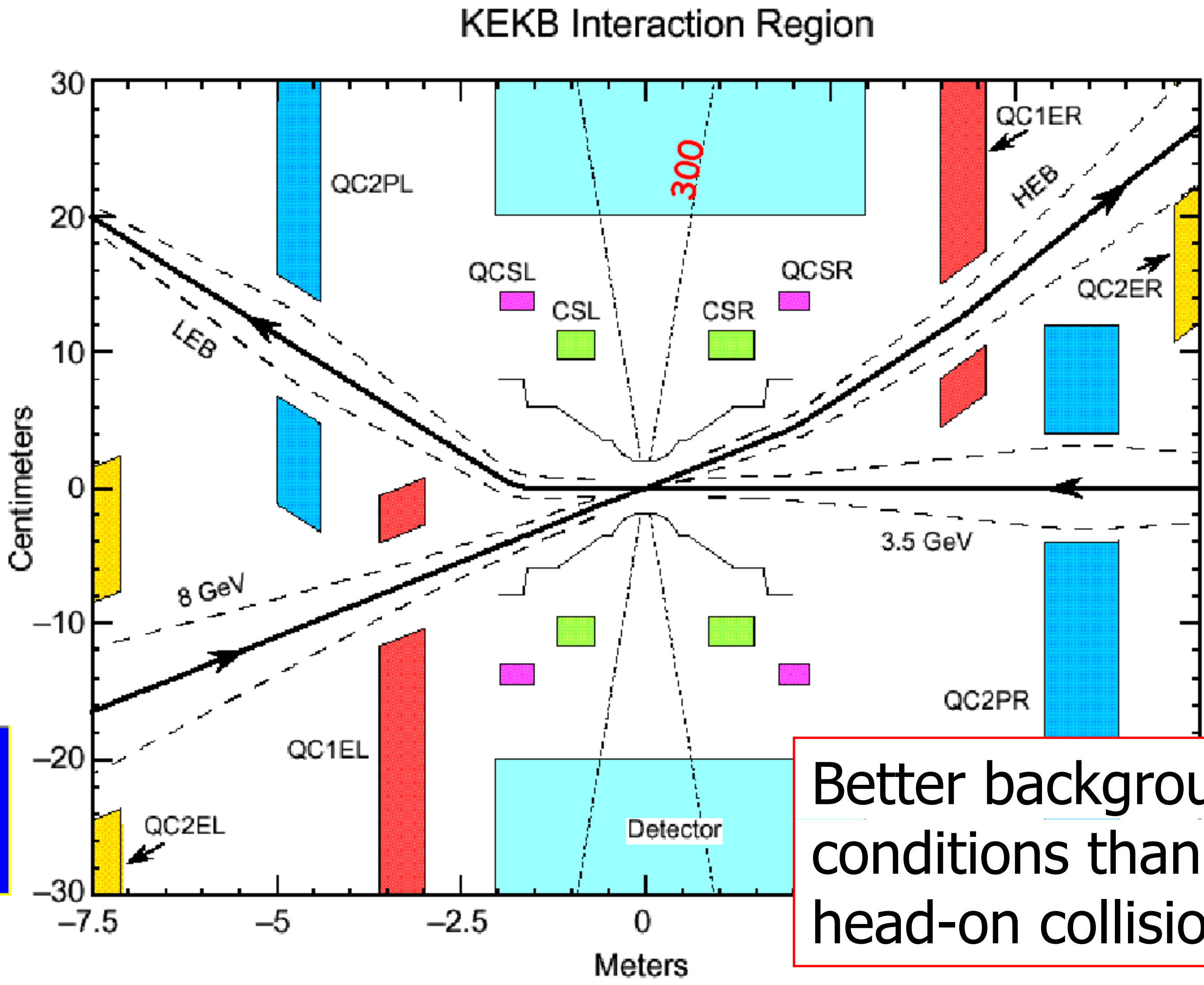
Interaction region: BaBar

Head-on collisions



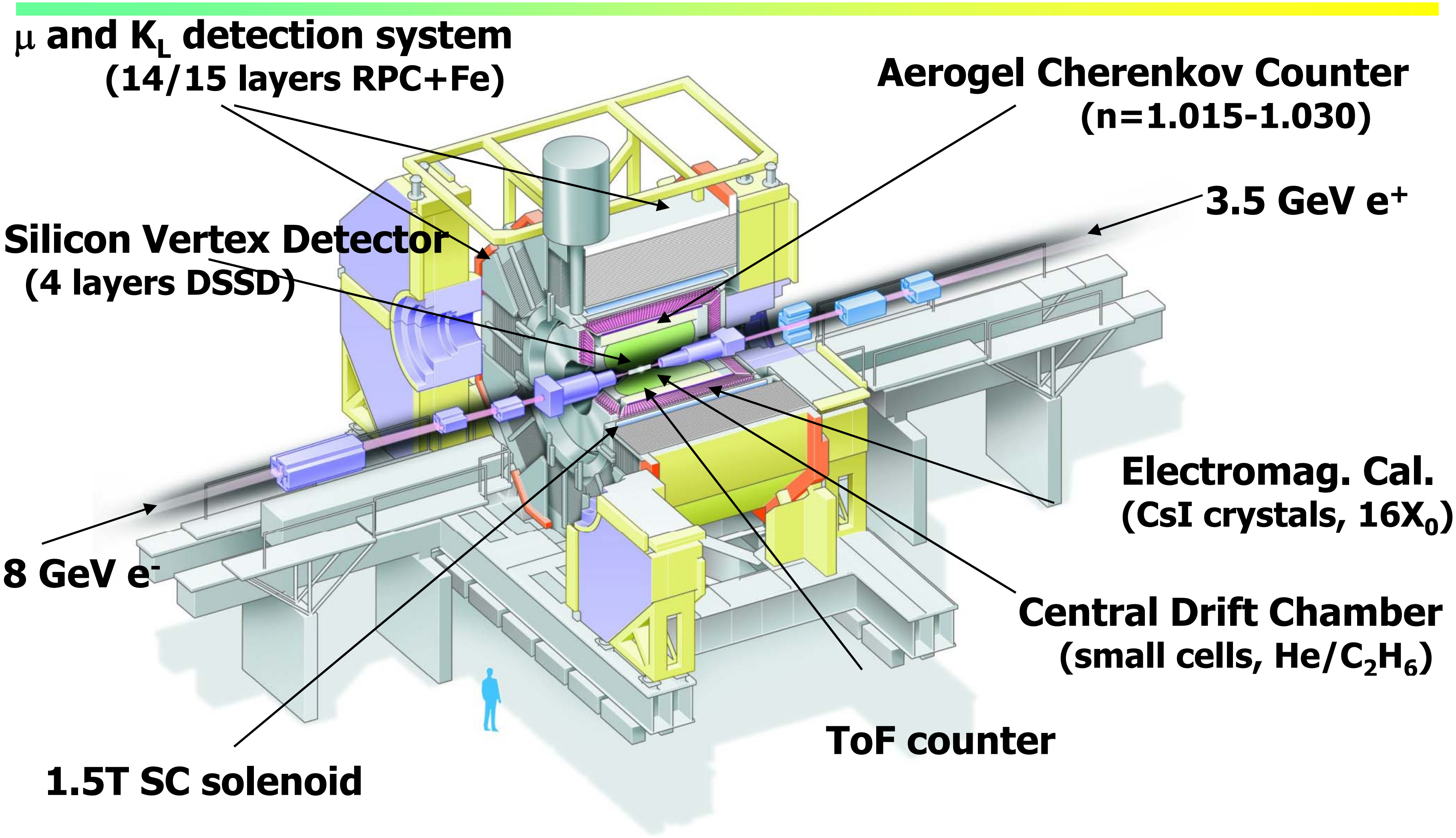
Interaction region: Belle

Collisions at a finite angle +-11mrad

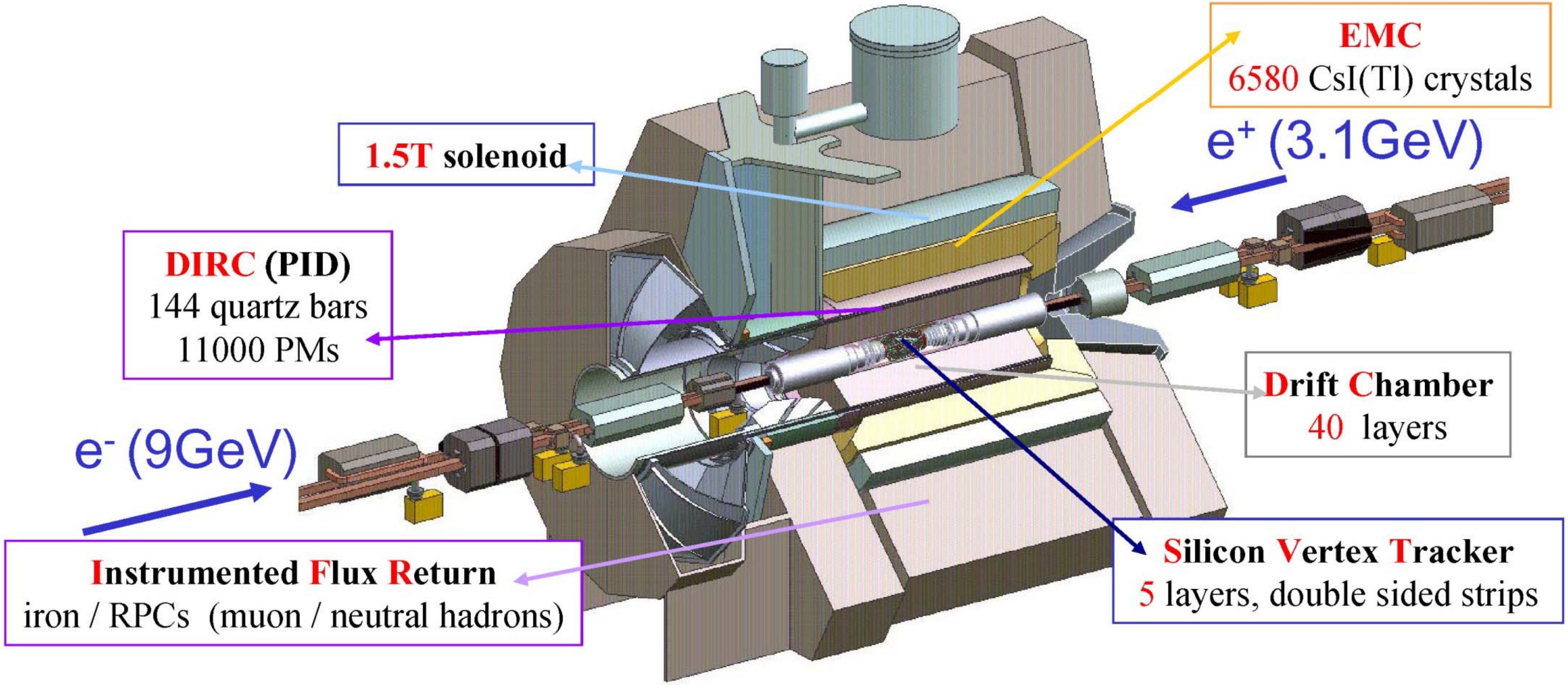


Better background conditions than in head-on collisions!

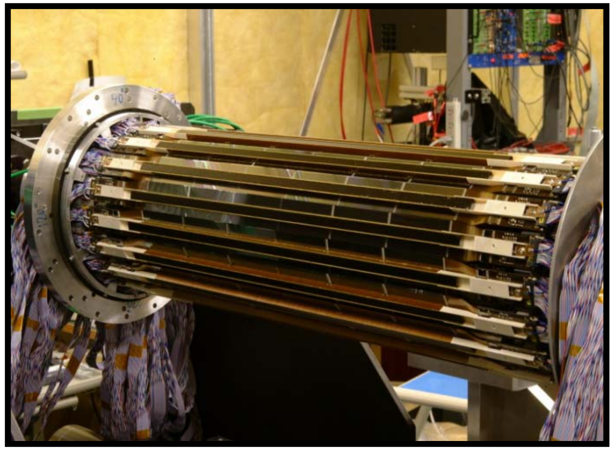
Belle spectrometer at KEK-B

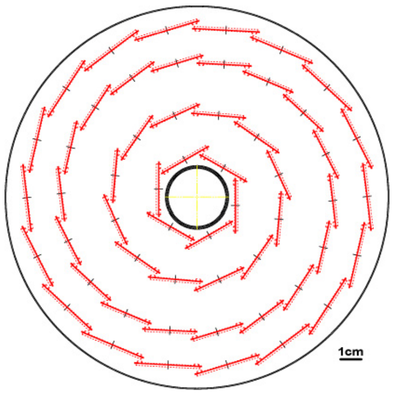


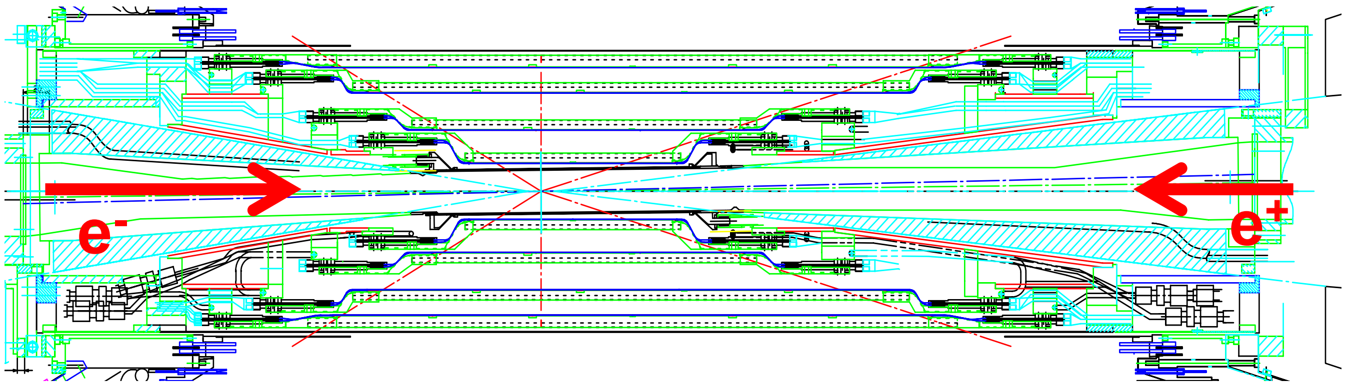
BaBar spectrometer at PEP-II



Silicon vertex detector (SVD)







4 layers

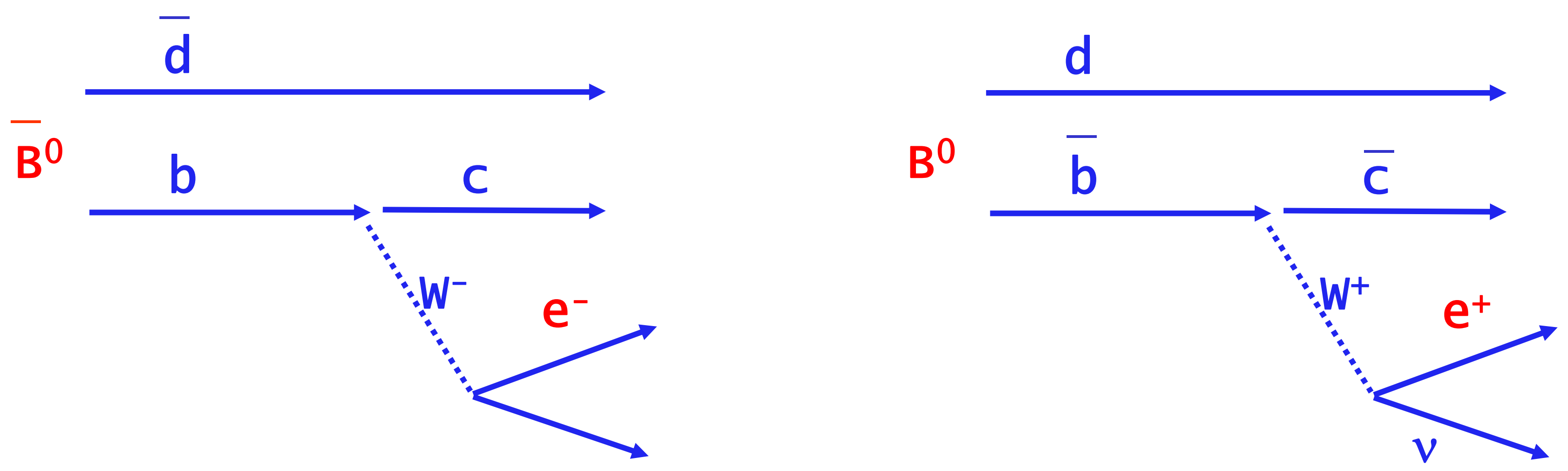
covering polar angle from 17 to 150 degrees

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)
- .....

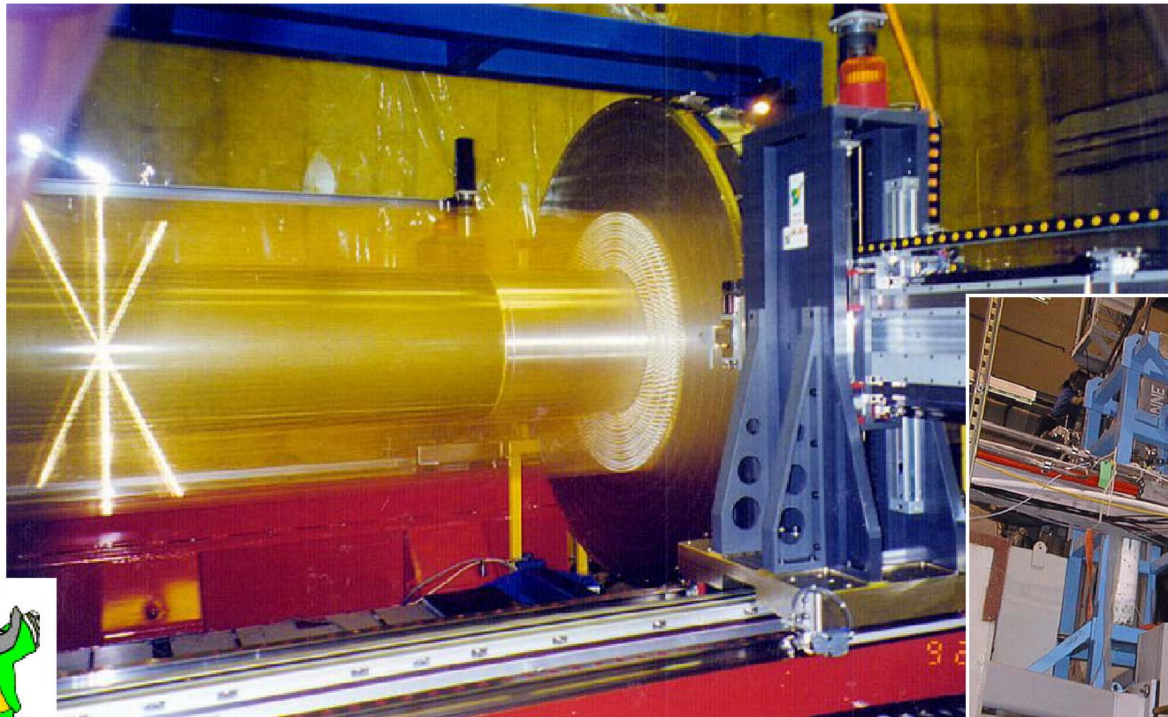
Charge measured from curvature in magnetic field,
→ need reliable particle identification

Tracking: BaBar drift chamber

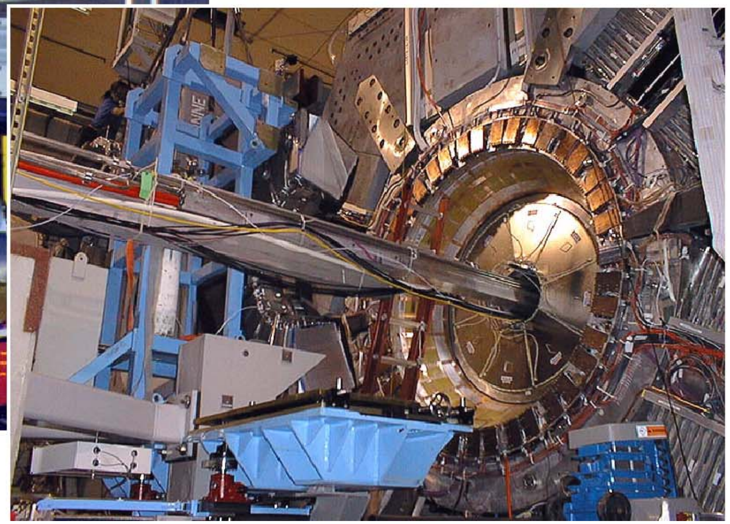
40 layers of wires (7104 cells) in 1.5 Tesla magnetic field

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):

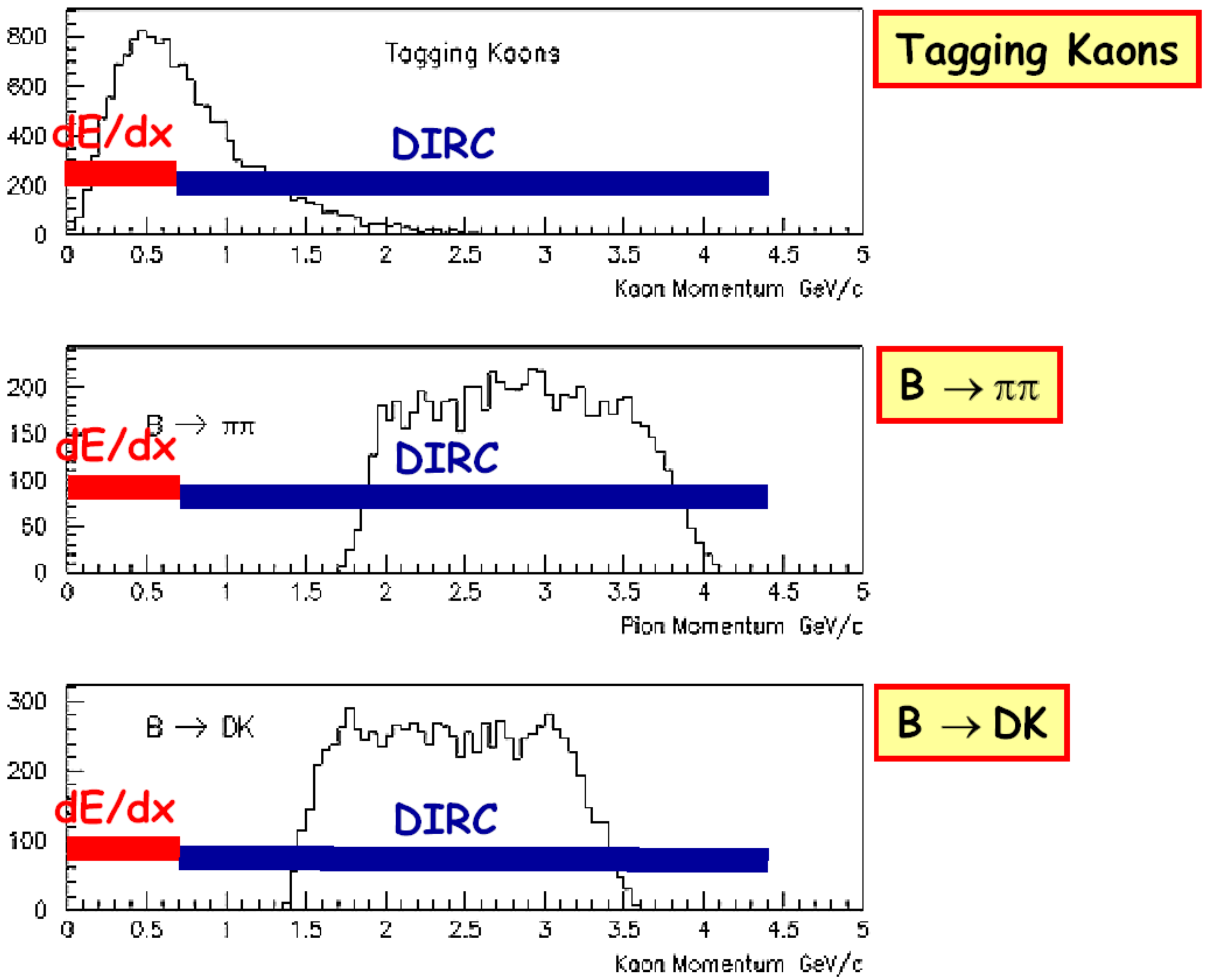
- Time-of-flight (TOF)
- dE/dx in a large drift chamber
- Cherenkov counters

K_L: chambers in the instrumented magnet yoke

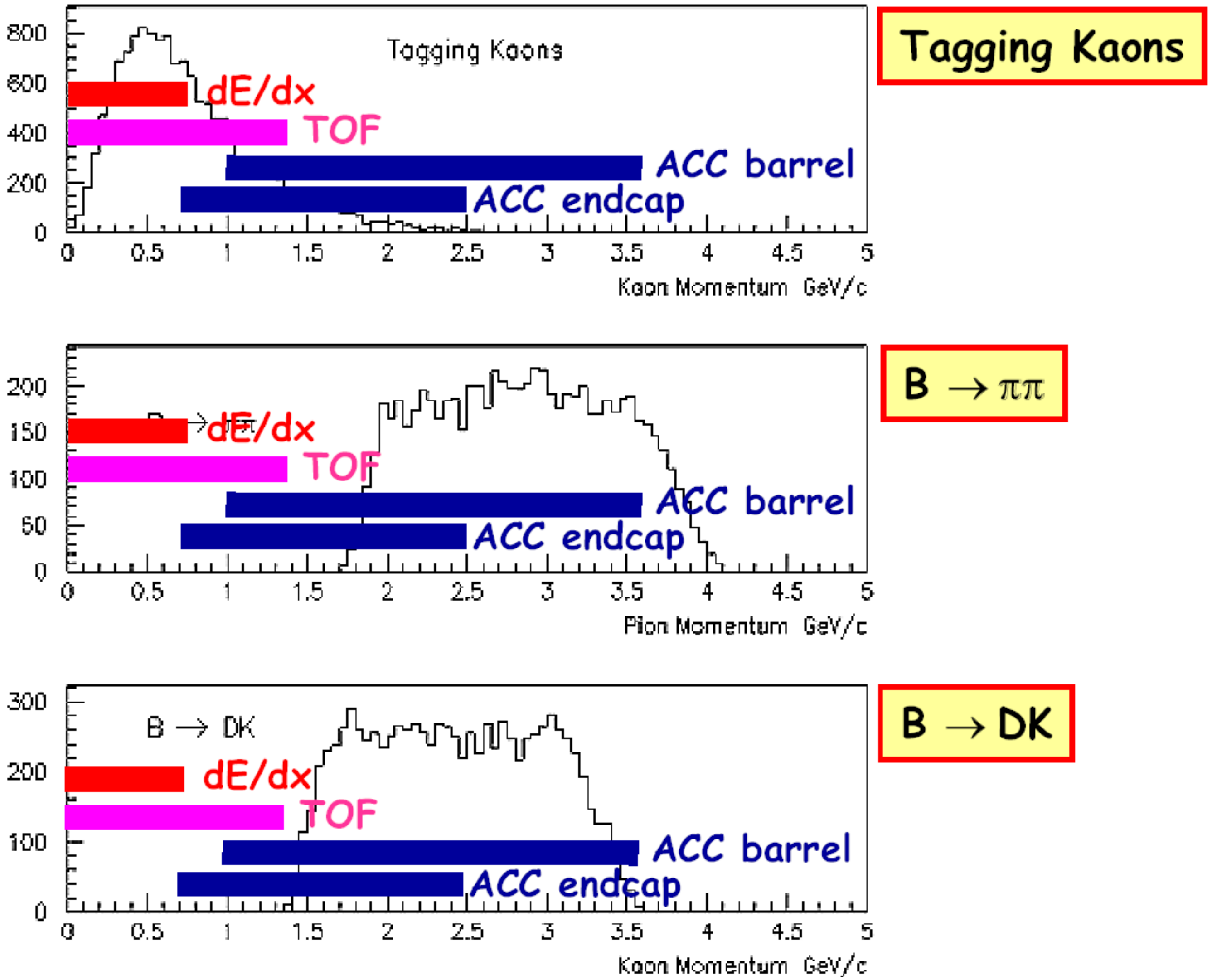
Electrons: electromagnetic calorimeter

Muon: chambers in the instrumented magnet yoke

PID coverage of kaon/pion spectra



PID coverage of kaon/pion spectra



Cherenkov counters

Essential part of particle identification systems.

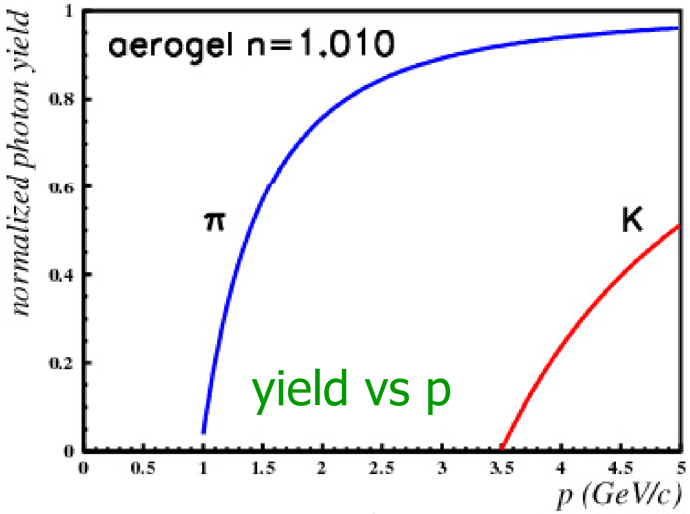
Cherenkov relation: $\cos\theta = c/nv = 1/\beta n$

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

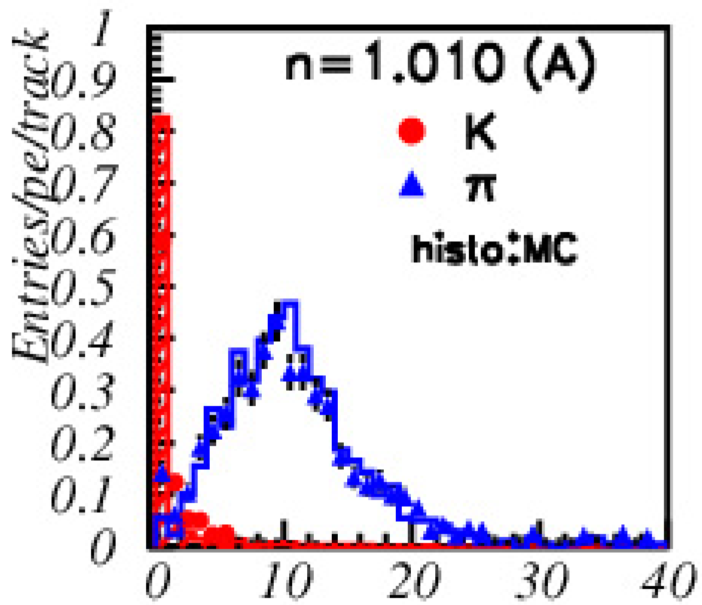
Ring Imaging (RICH) counter → measure Čerenkov angle and count photons

Belle ACC (aerogel Cherenkov counter): threshold Čerenkov counter

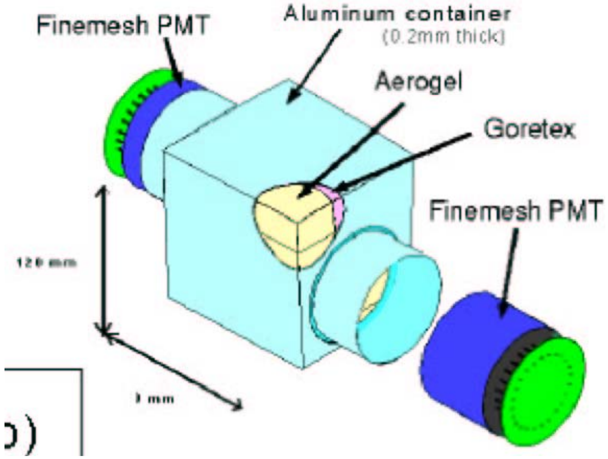
K (below thr.) vs. π (above thr.): adjust n



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

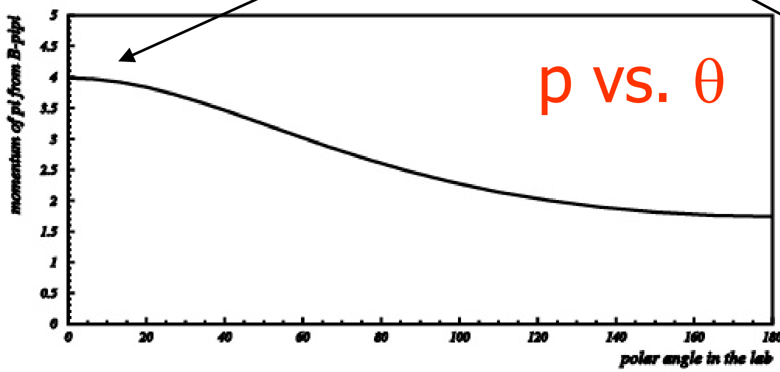


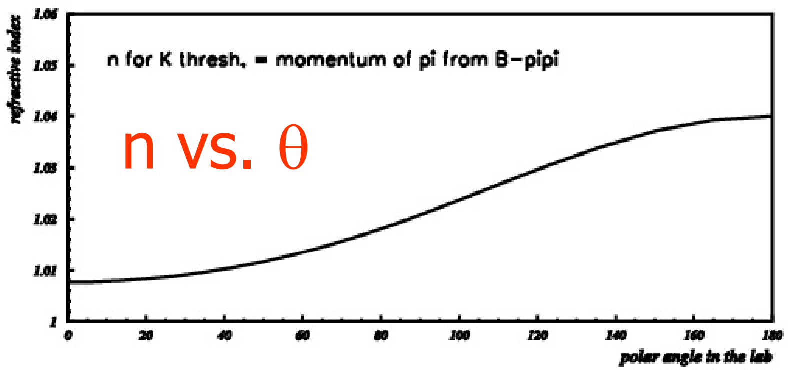
Detector unit: a block of aerogel and two fine-mesh PMTs

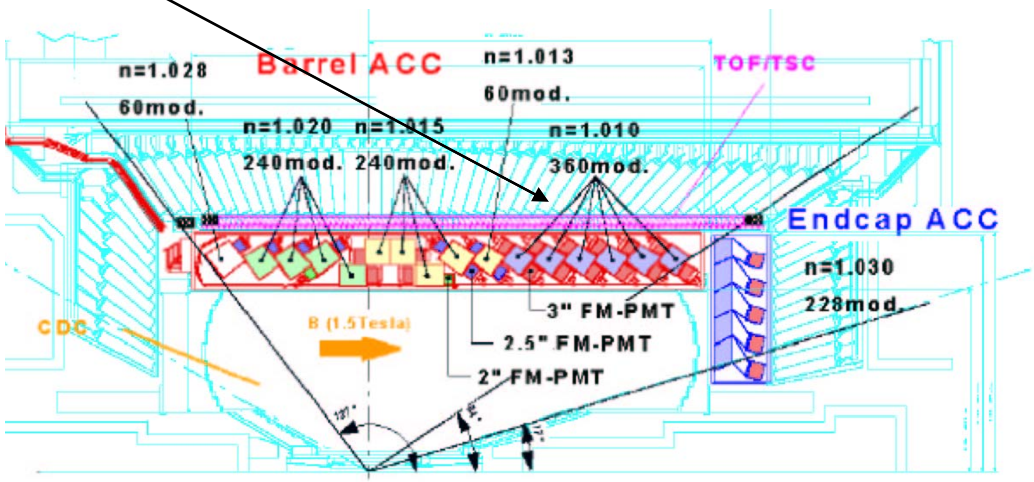


Belle ACC (aerogel Cherenkov counter): threshold Cherenkov counter

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



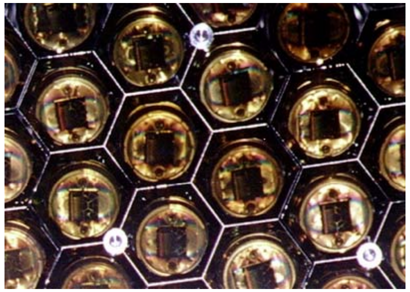


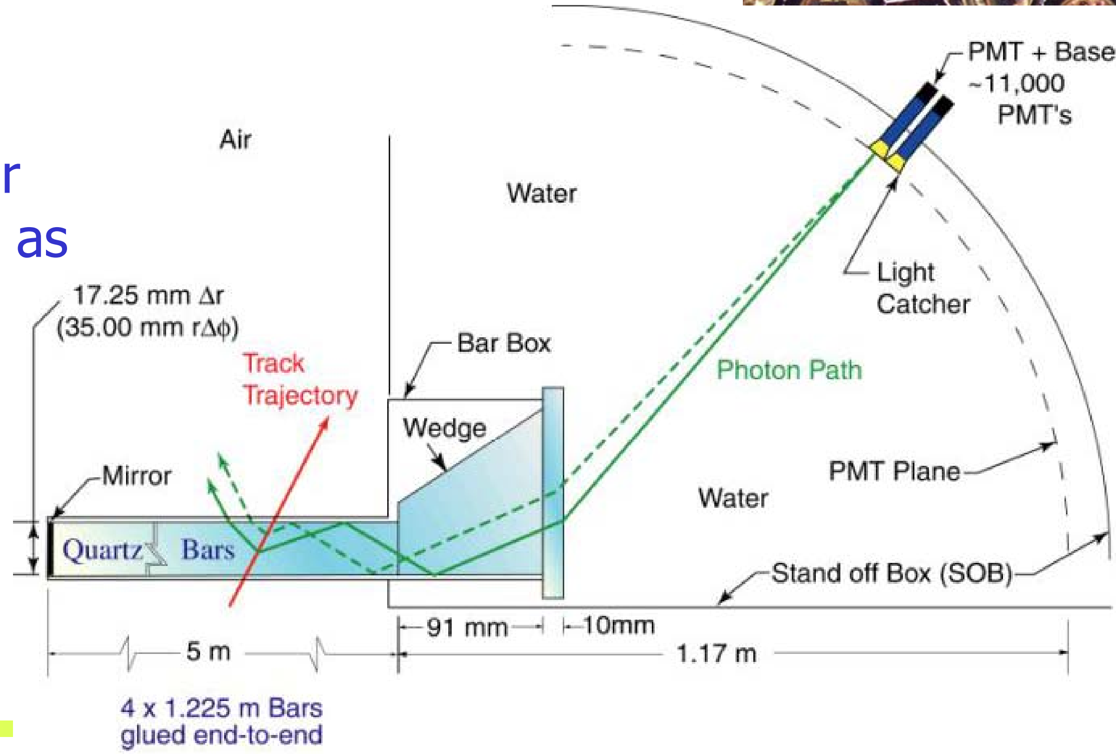


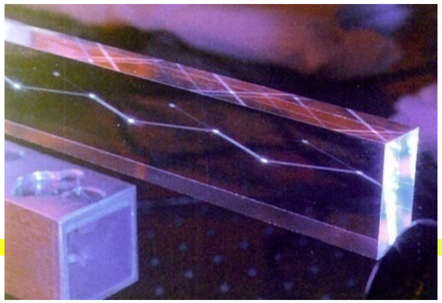
DIRC: Detector of Internally Reflected Cherekov photons

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.

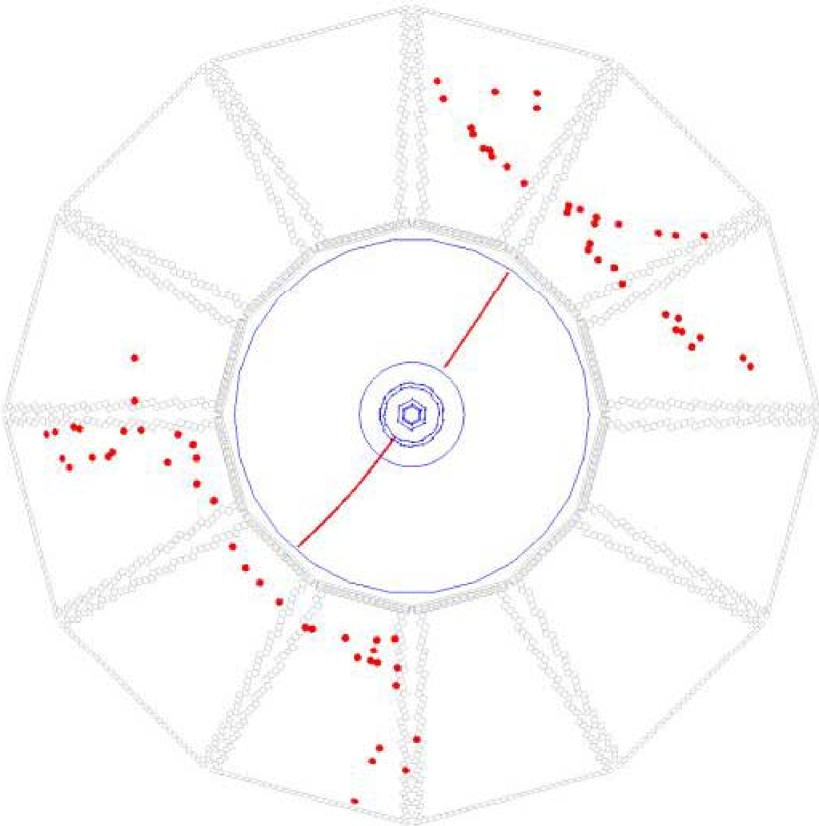




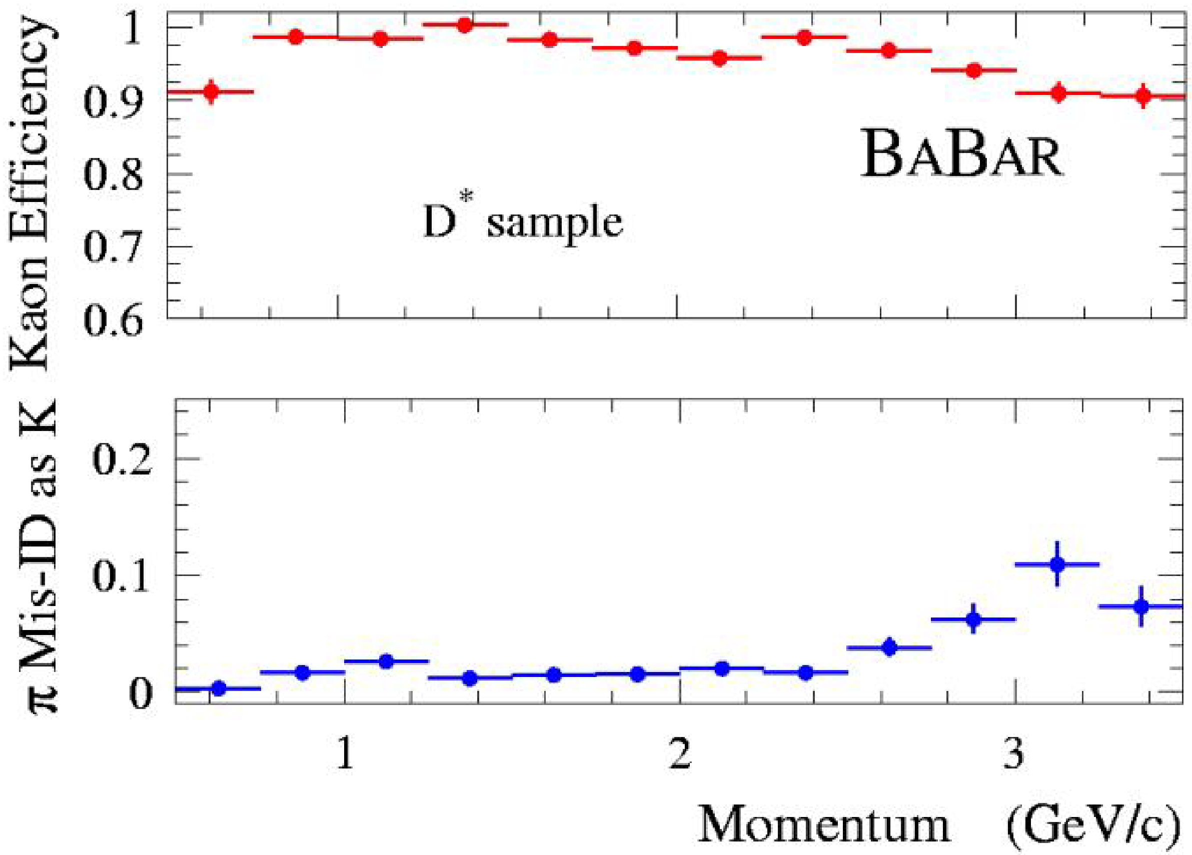


DIRC event

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



DIRC performance



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

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

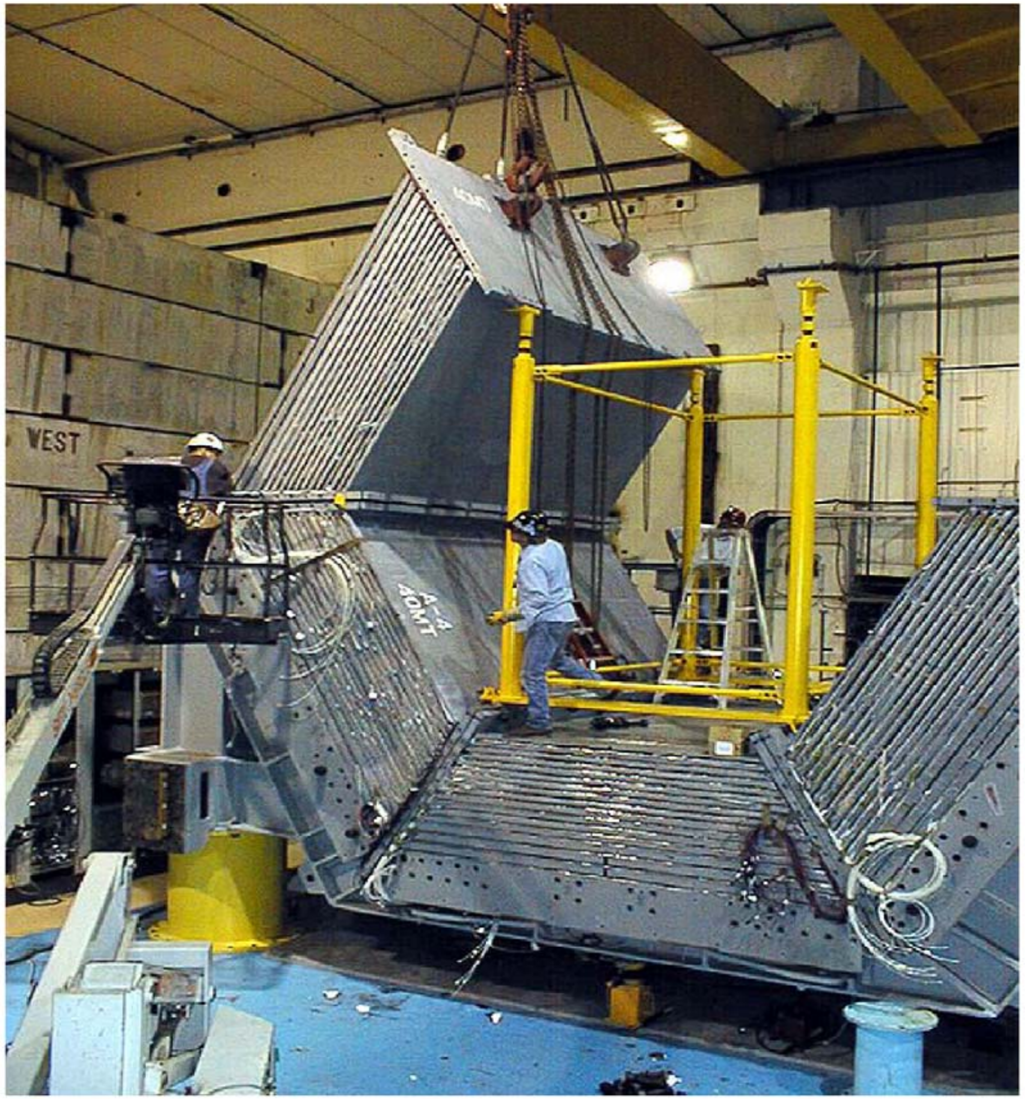
Muon and K_L detector

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

Bakelite RPCs at BABAR

(problems with aging)

Glass RPCs at Belle



Muon and K_L detector

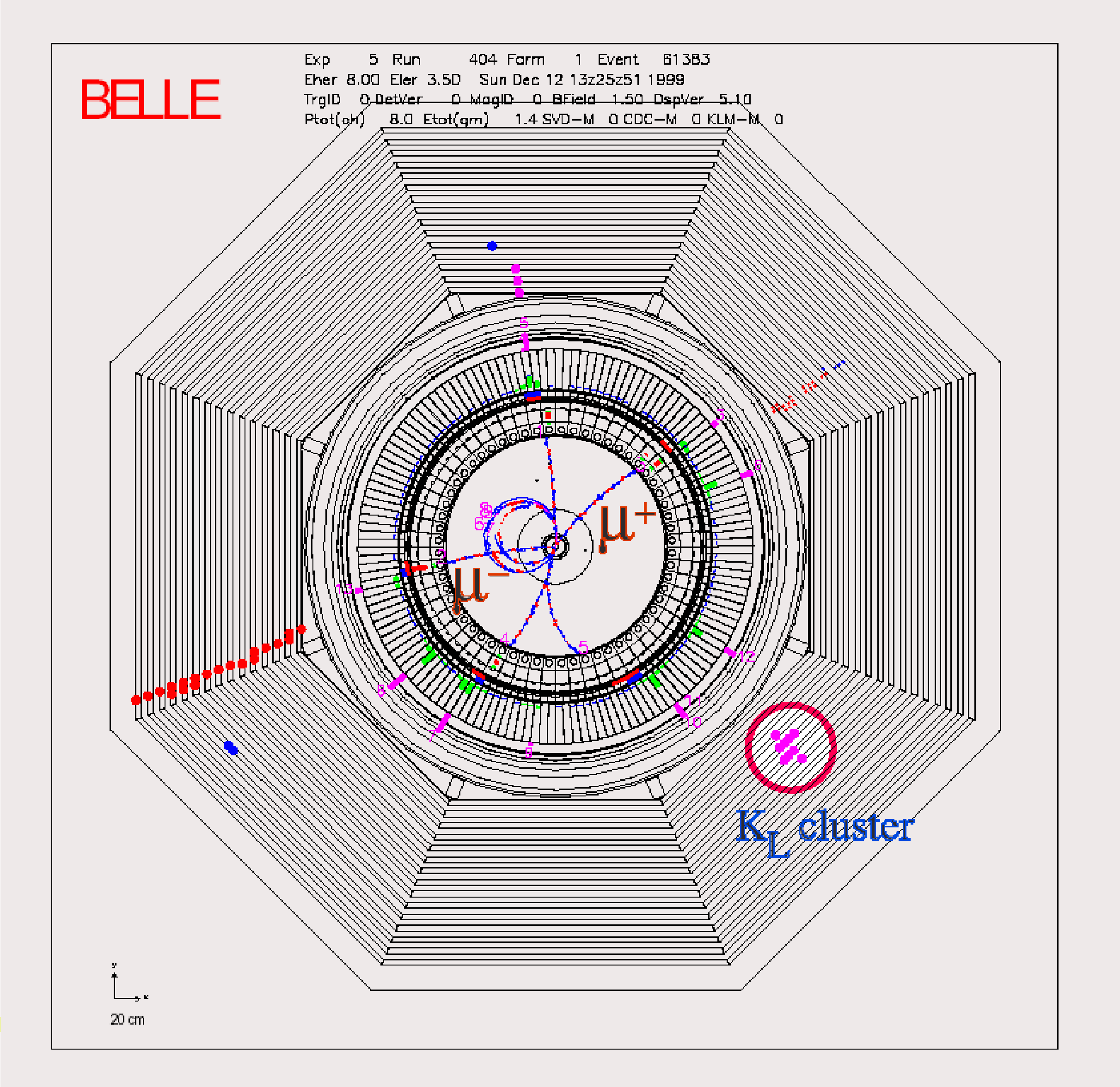
Example:

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

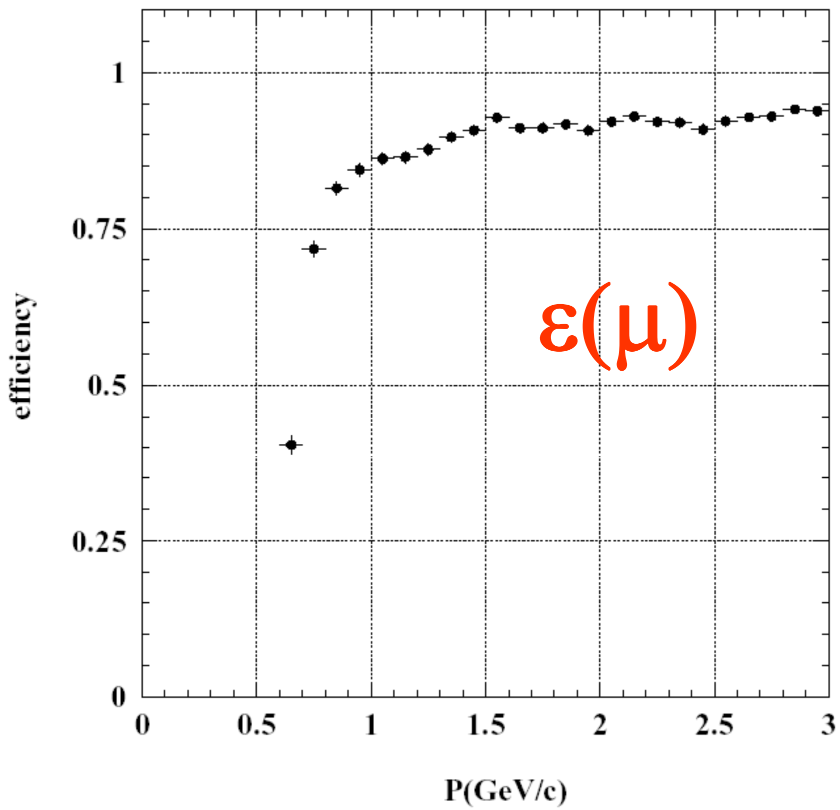


Fig. 109. Muon detection efficiency vs. momentum in KLM.

fake probability

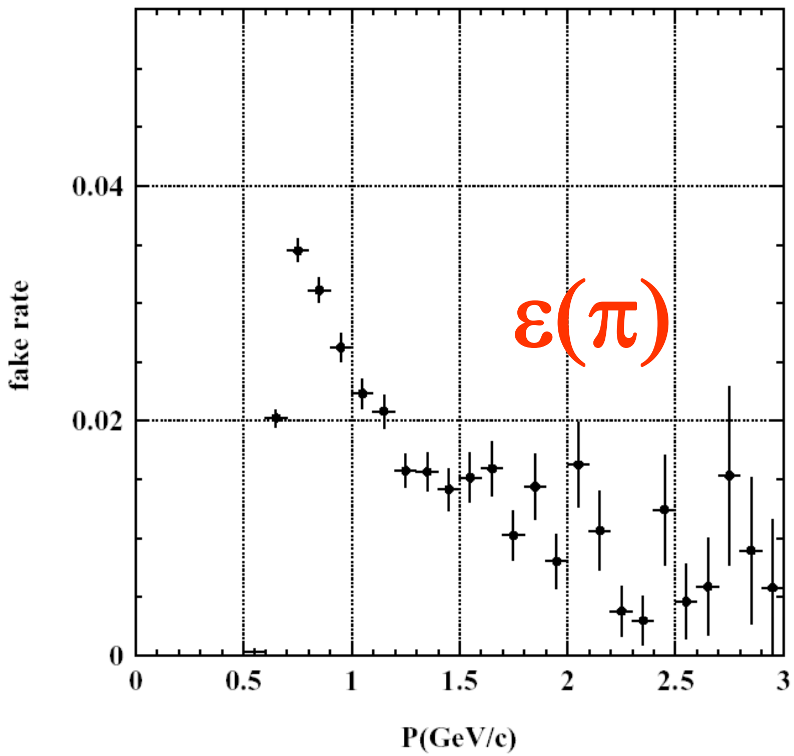


Fig. 110. Fake rate vs. momentum in KLM.

Muon and K_L detector performance

K_L detection: resolution in direction →

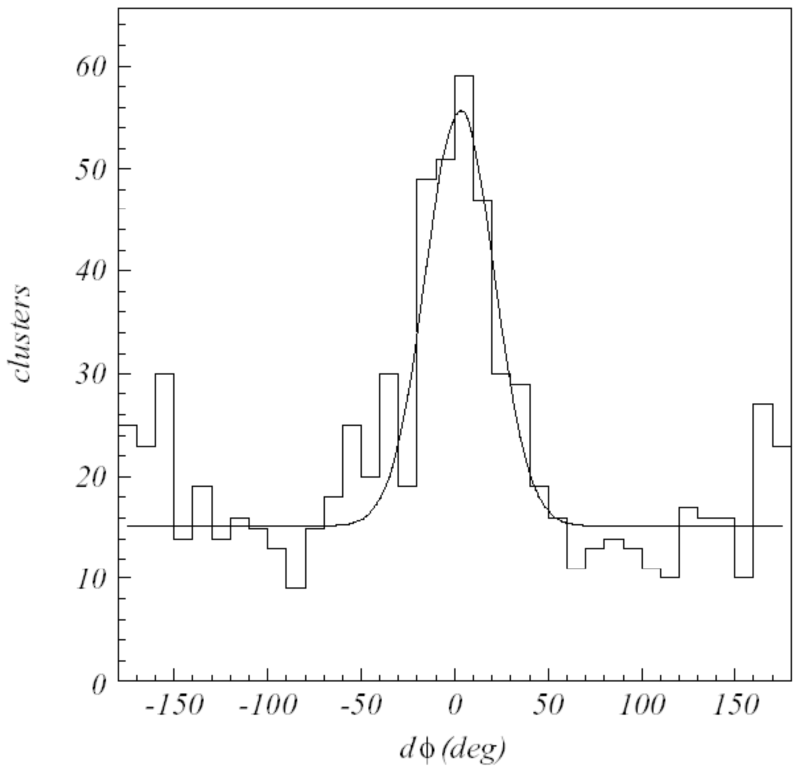
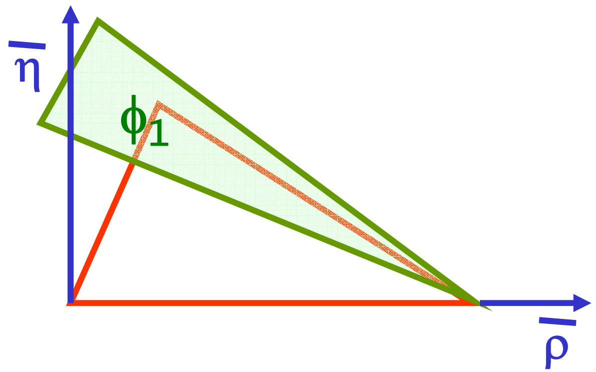


Fig. 107. Difference between the neutral cluster and the direction of missing momentum in KLM.

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

How to measure sin2ϕ_1?



To measure sin2ϕ_1, we have to measure the time dependent CP asymmetry in $B^0 \rightarrow J/\Psi\ K_s$ decays

$$a_{f_{CP}} = -\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t) = \boxed{\sin 2\phi_1}\sin(\Delta m t)$$

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

In addition to $B^0 \rightarrow J/\Psi\ K_s$ decays we can also use decays with any other charmonium state instead of J/Ψ. Instead of K_s we can use channels with K_L (opposite CP parity).

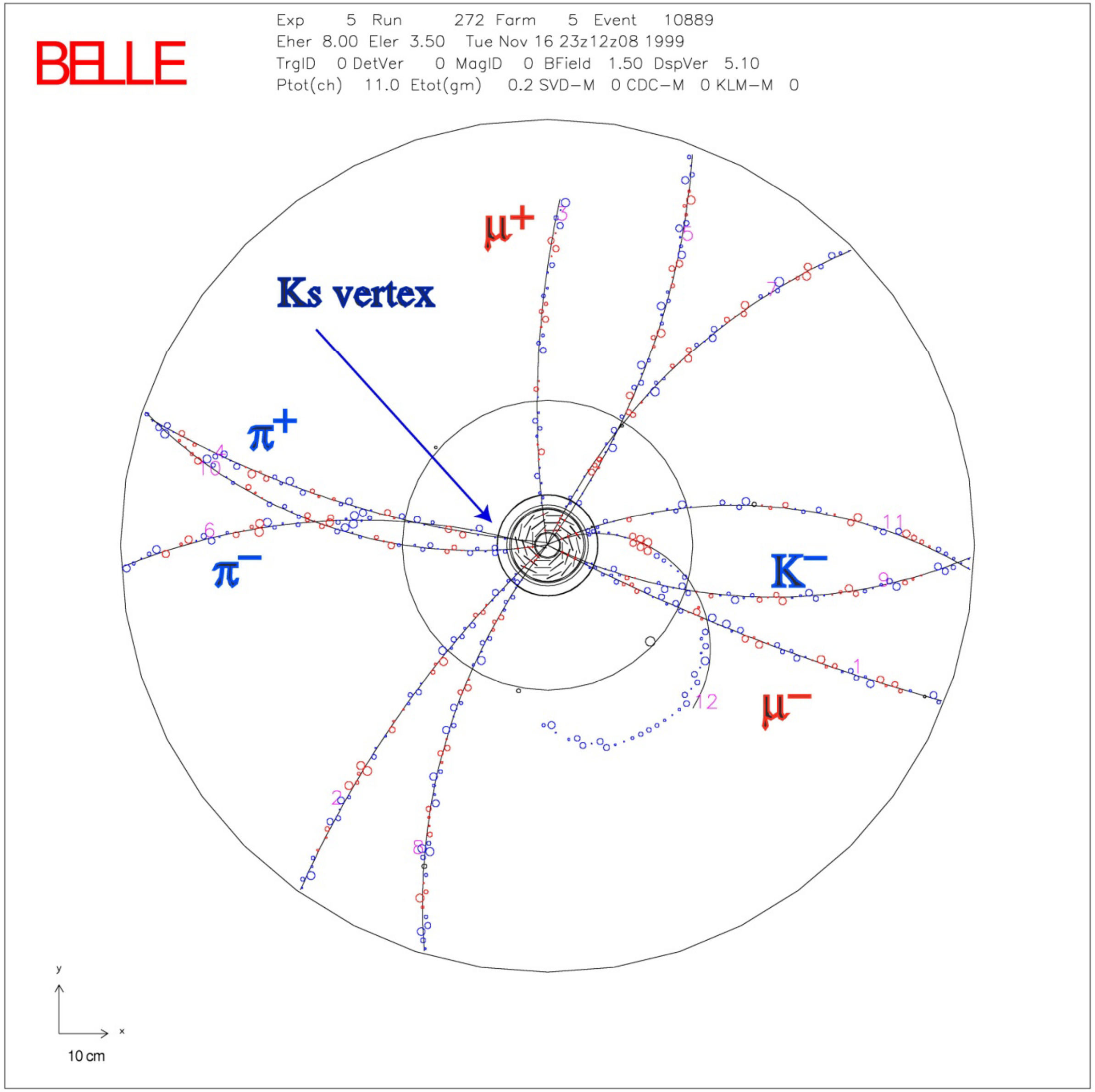
Reconstructing chamonium states

Reconstructing final states X which decayed to several particles (x,y,z):
From the measured tracks calculate the invariant mass of the system (i=x,y,z):

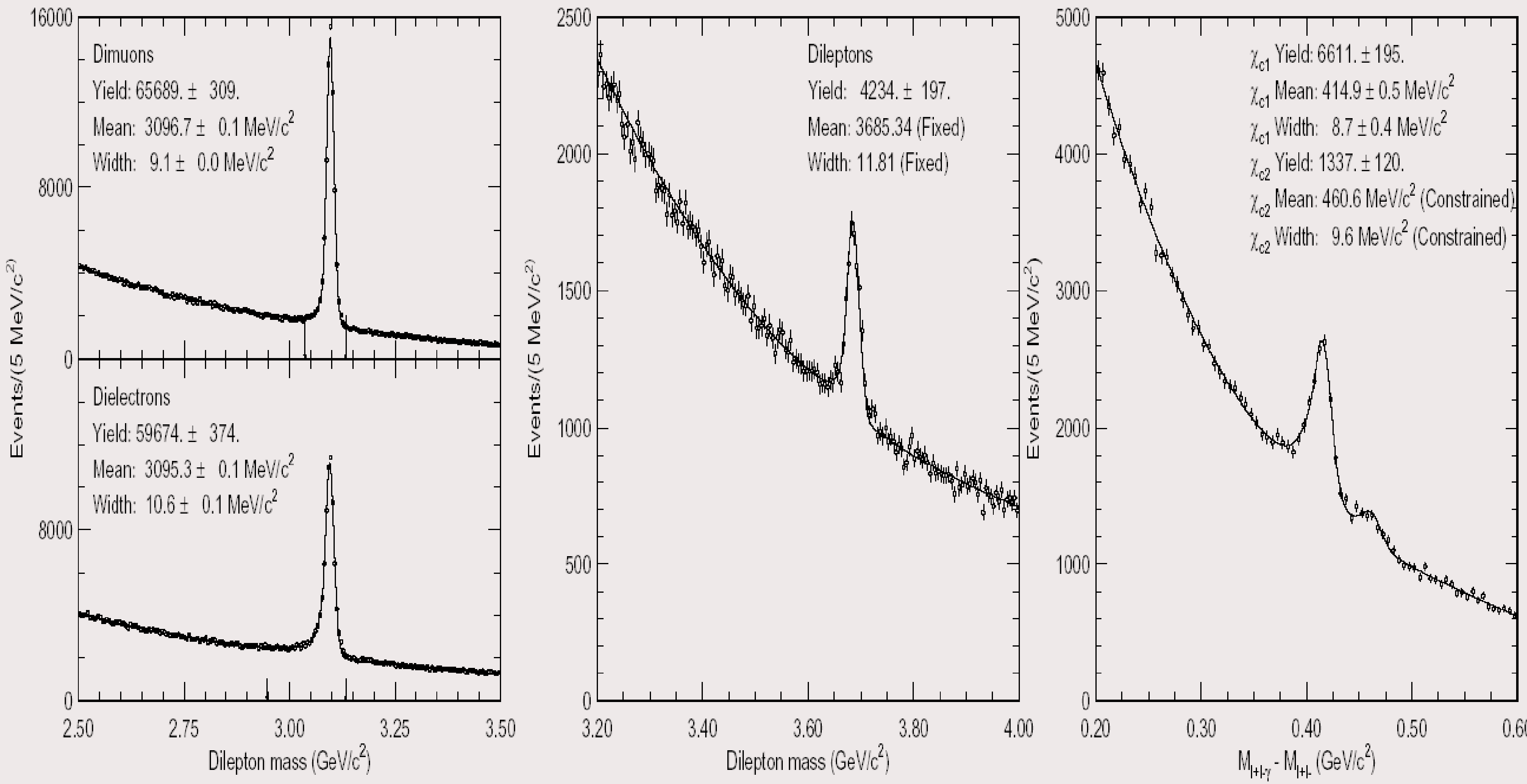
$$M = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2}$$

The candidates for the X->xyz decay show up as a peak in the distribution on (mostly combinatorial) background.
The name of the game: have as little background under the peak as possible without loosing the events in the peak (=reduce background and have a small peak width).

A golden channel event



Reconstructing chamonium states



$J/\psi \to \mu^+\mu^-, e^+e^-$

$\sigma_M = 9.6(10.7)\mathrm{GeV}/c^2$

$\psi(2s) \to \mu^+\mu^-, e^+e^-$

$\sigma_M = 12.1\mathrm{GeV}/c^2$

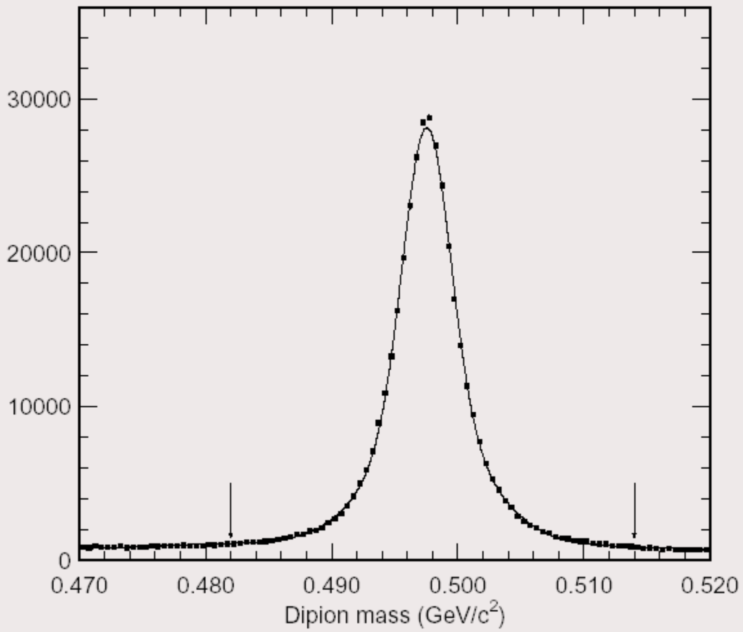
$\chi_{c1}, \chi_{c2} \to J/\psi\gamma$

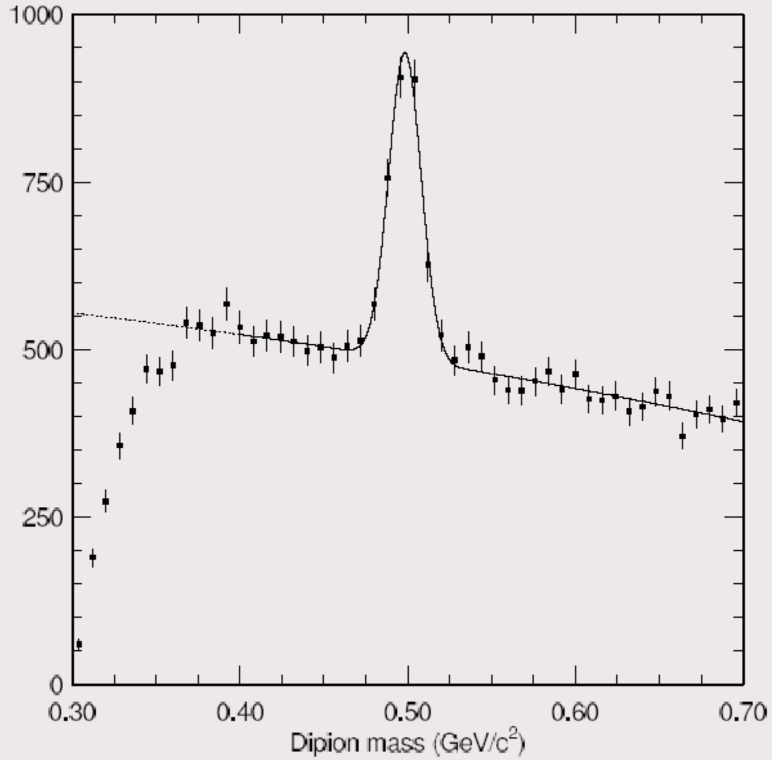
$\sigma_{\Delta M} = 7.0\mathrm{GeV}/c^2$

Reconstructing K^0_S

$K_S \to \pi^+\pi^-$

$\sigma_M = 4.1 \mathrm{GeV}/c^2$

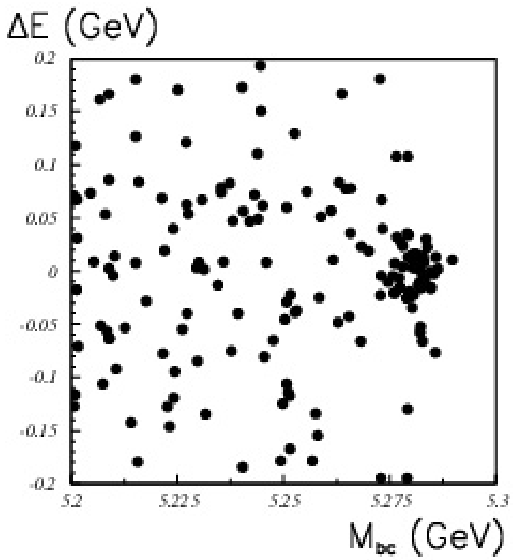


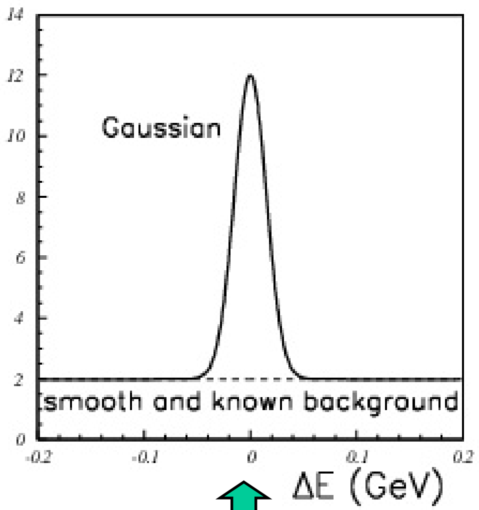


$K_S \to \pi^0\pi^0$

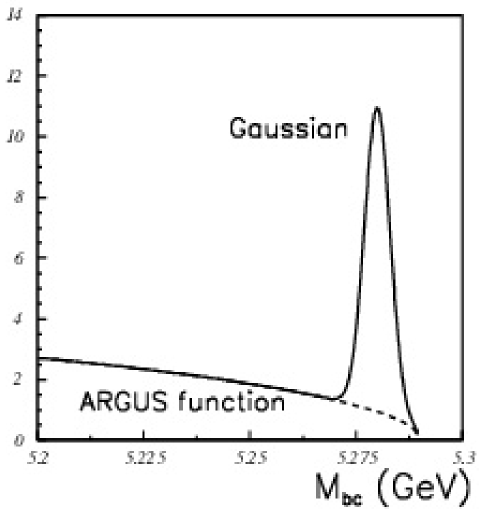
$\sigma_M = 9.3 \mathrm{GeV}/c^2$

Reconstruction of rare B meson decays





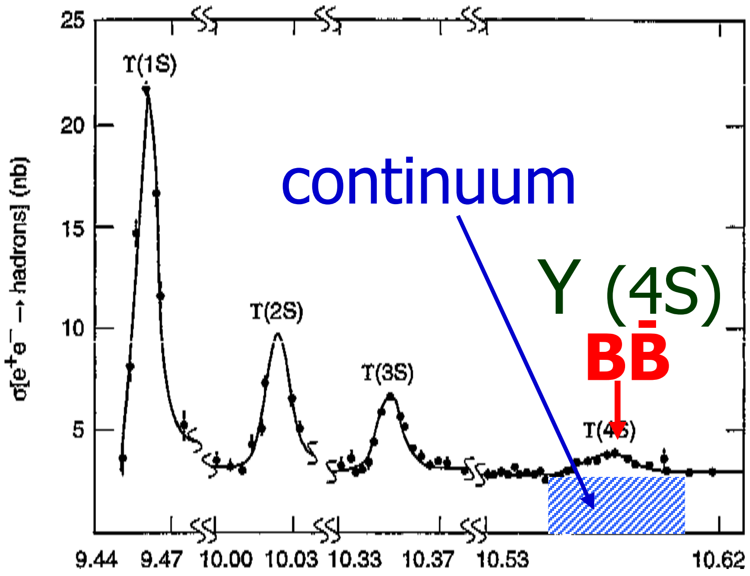
Reconstructing rare B meson decays at Υ(4s): use two variables,
beam constrained mass M_{bc}
and
energy diference DE



$$\Delta E \equiv \sum E_i - E_{CM}/2$$

$$M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum \vec{p}_i)^2}$$

Continuum suppression



$e^+e^- \rightarrow$ *qq* "continuum" (~3x BB)

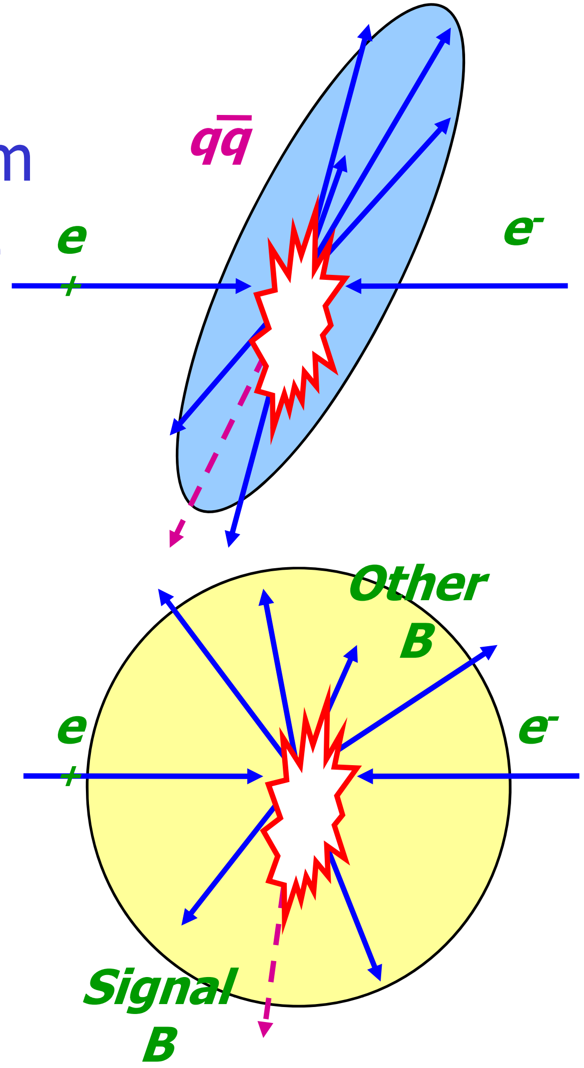
To suppress: use event shape variables

Continuum

Jet-like

BB

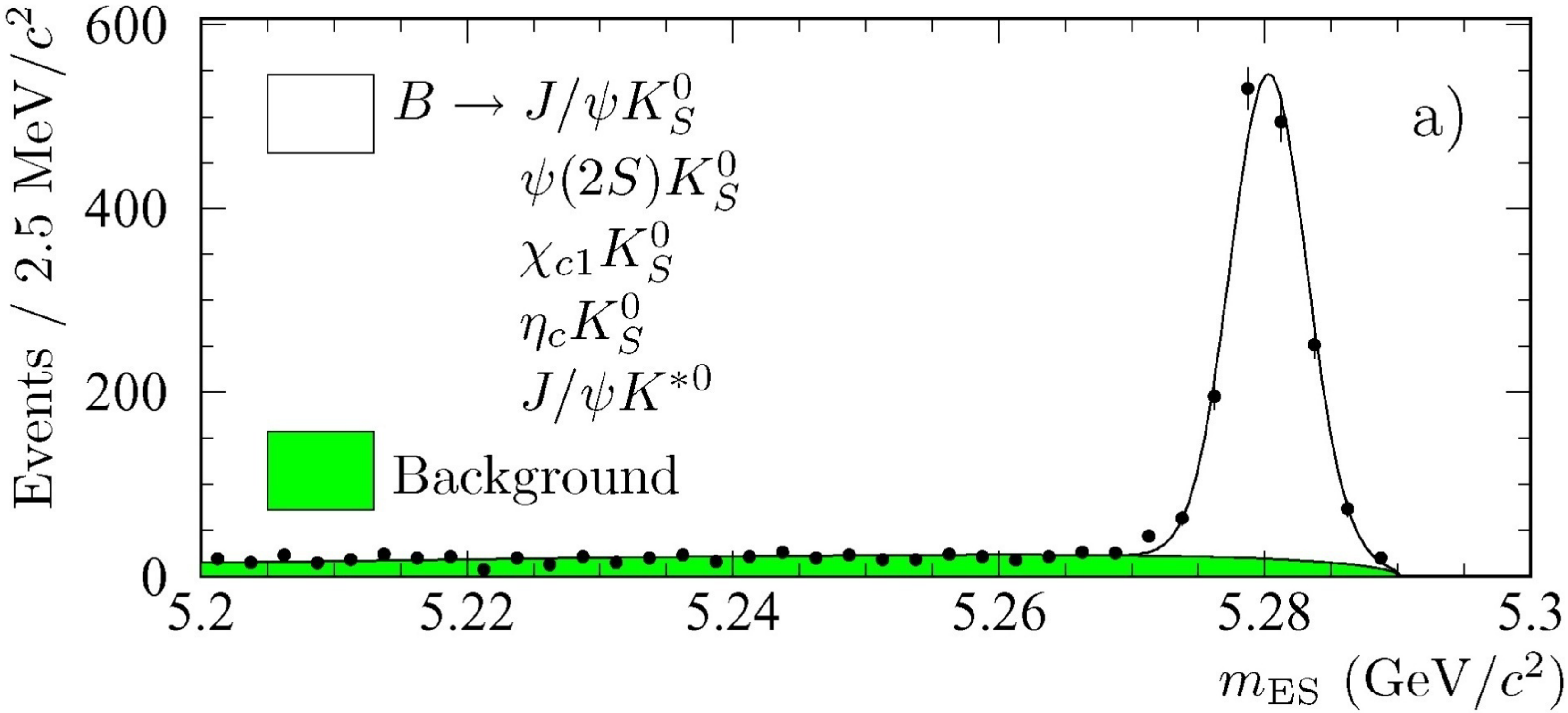
spherical



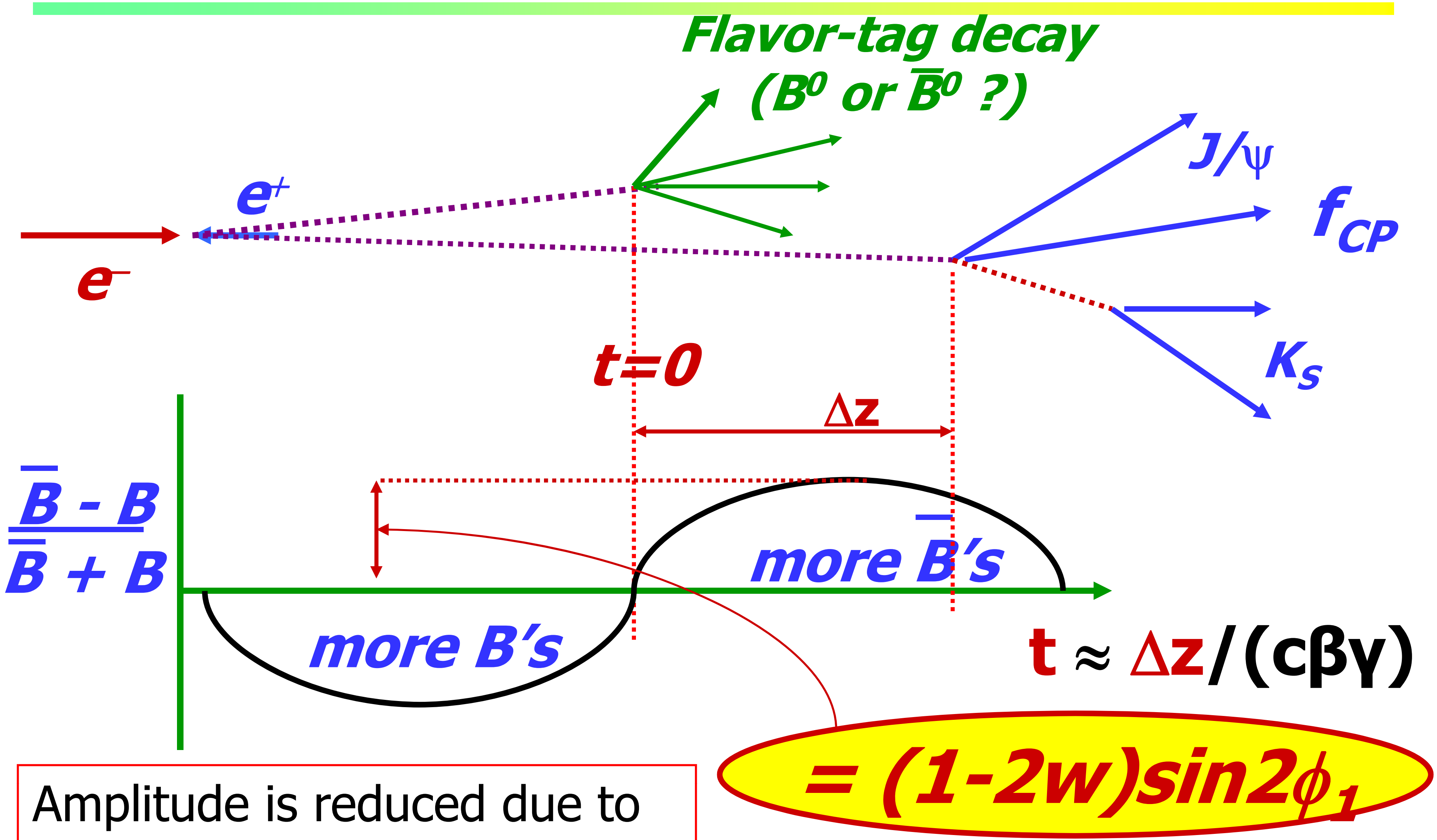
Reconstruction of b-> c anti-c s CP=-1 eigenstates

$J/\Psi(\Psi,\chi_{c1},\eta_c)$ $K_s(K^{*0})$ sample $(\eta_f=-1)$
from $88(85)\times10^6$ $B\bar{B}$

BaBar 2002 result

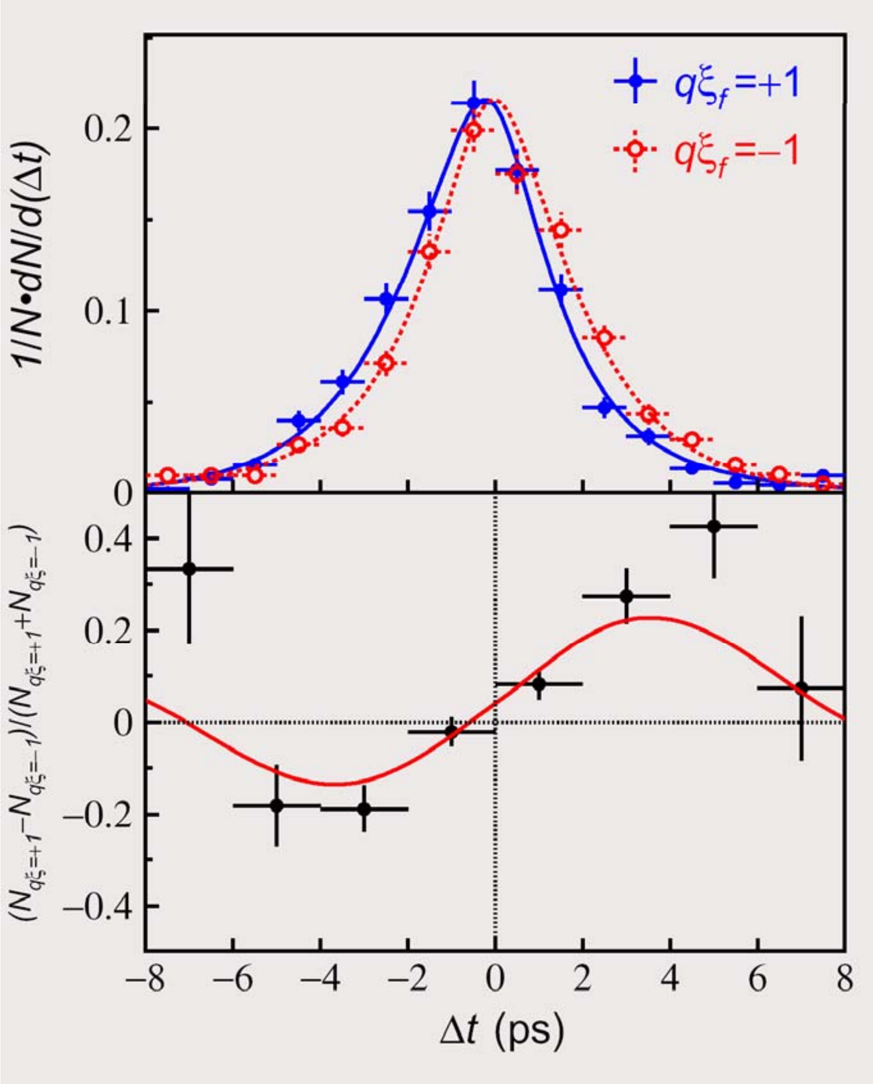


Principle of CPV Measurement



Amplitude is reduced due to imperfect tagging

Final result



CP is violated! Red points differ from blue.

Red points: anti-B^0 -> f_{CP} with CP=-1 (or B^0 -> f_{CP} with CP=+1)

Blue points: B^0 -> f_{CP} with CP=-1 (or anti-B^0 -> f_{CP} with CP=+1)

Belle, 2002 statistics
(78/fb, 85M B B pairs)

Fitting the asymmetry

Fitting function:

$$P_{sig}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left\{1 + q(1-2w_l)\,\mathrm{Im}\,\lambda \sin \Delta m t\right\} \otimes R(t)$$

Miss-tagging probability

Resolution function:
from self-tagged events
B→D*lν, Dπ, ...

q=+1 or =-1 (B or anti-B on the tag side)

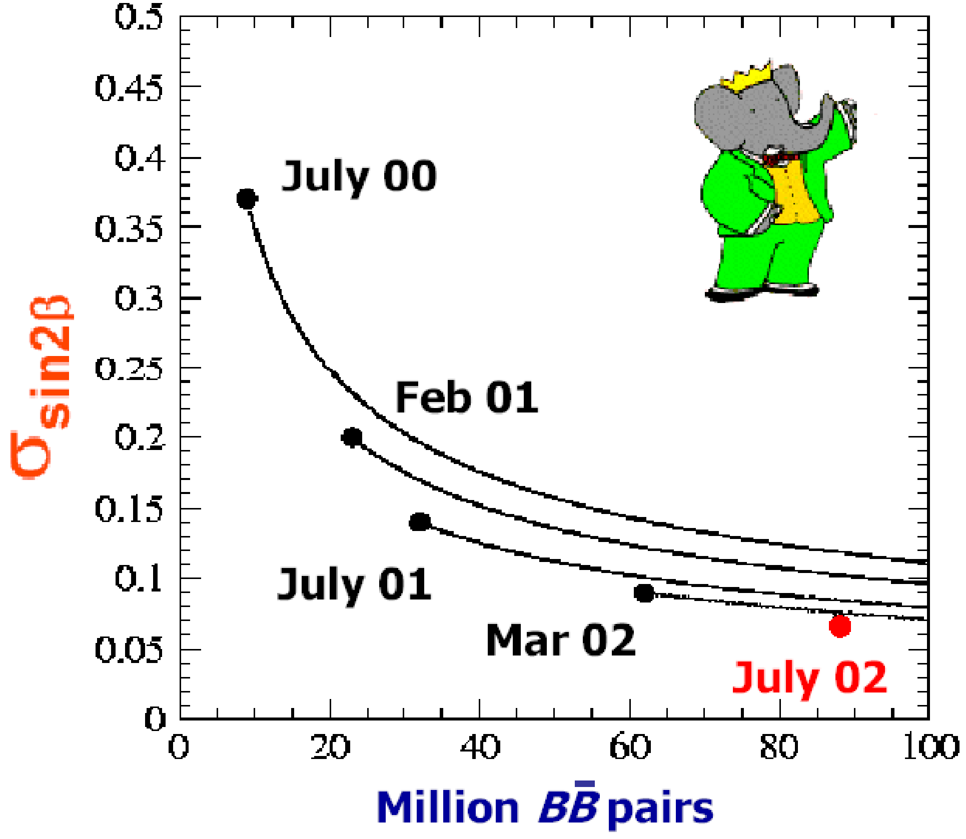
Fitting: unbinned maximum likelihood fit event-by-event

Fitted parameter: Im(λ)

More data....

Larger sample →
- smaller statistical error (1/√N)
- better understanding of the detector, calibration etc

→ error improves by better than with 1/√N



$b \to c$ 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/ψ K_S $(\pi^+ \pi^-)$: CP=-1

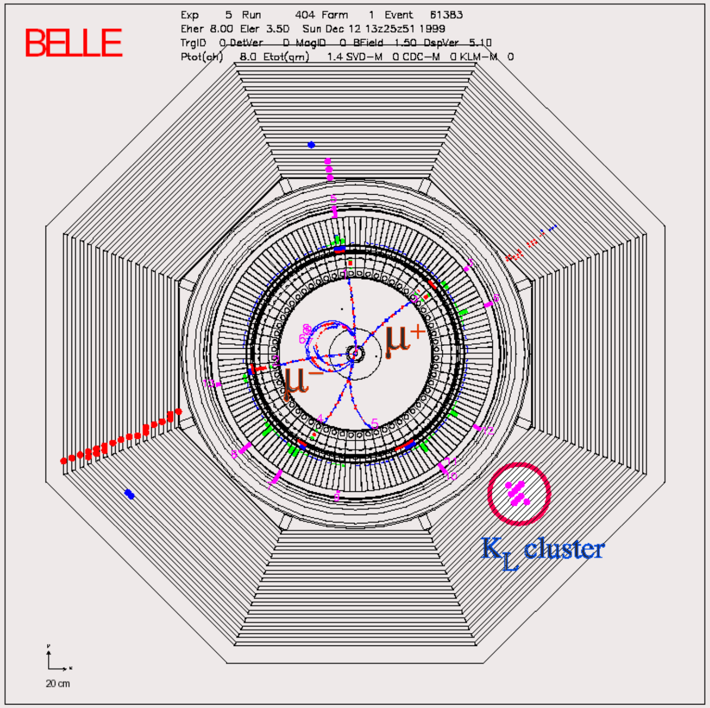
- J/ψ: P=-1, C=-1 (vector particle $J^{PC}=1^{--}$): CP=+1
- K_S (->$\pi^+ \pi^-$): CP=+1, orbital ang. momentum of pions=0 -> P $(\pi^+ \pi^-)=(\pi^- \pi^+)$, C$(\pi^- \pi^+)$ $=(\pi^+ \pi^-)$
- orbital ang. momentum between J/ψ and K_S l=1, P=$(-1)^1$=-1

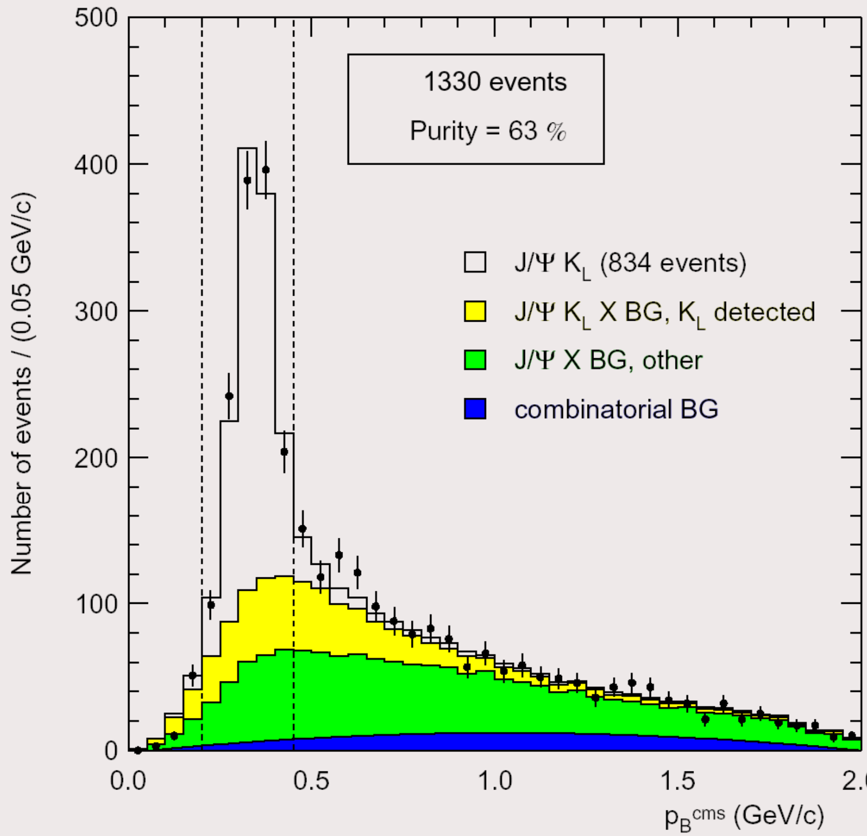
J/ψ $K_L(3\pi)$: CP=+1

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

Reproduction of b-> c anti-c s CP=+1 eigenstates

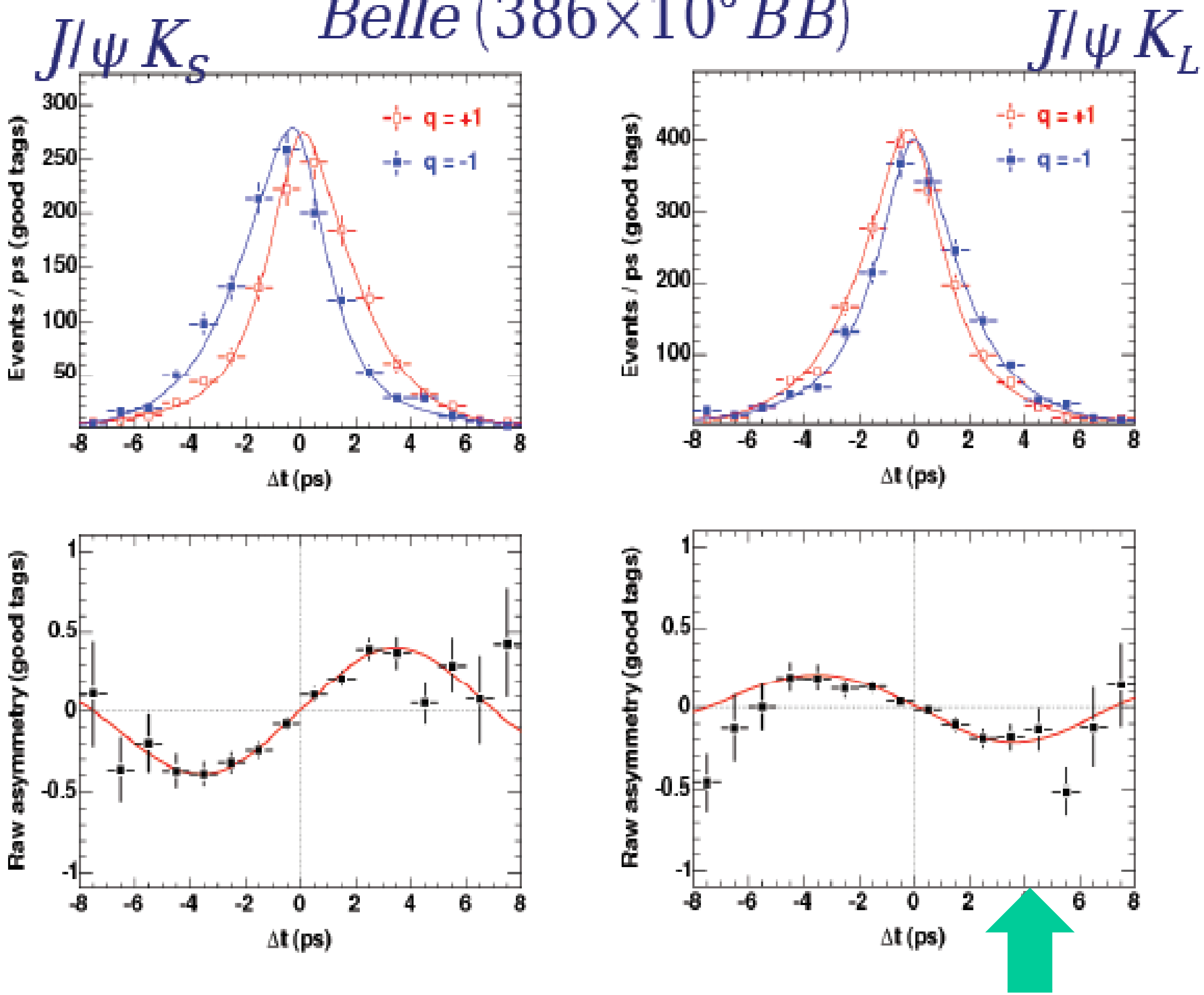
- detection of K_L in KLM and ECL
- K_L direction, no energy





- $p^* \approx 0.35$ GeV/c for signal events
- background shape is determined from MC, and its size from the fit to the data

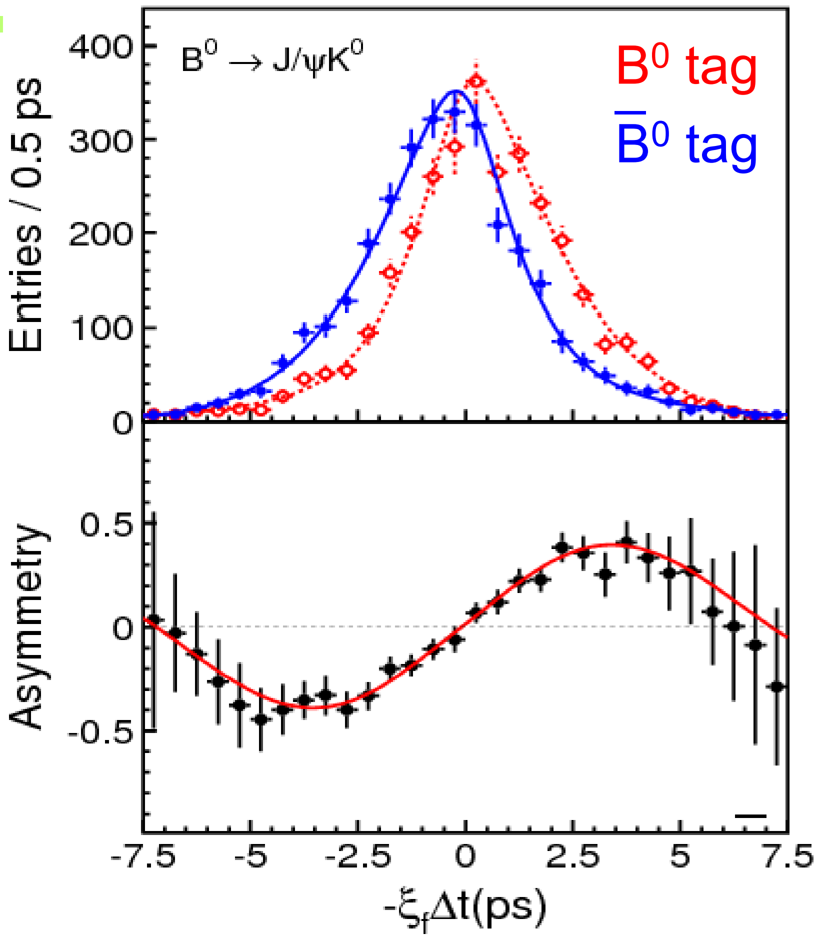
$Belle\,(386\times10^6\,B\bar{B})$



Different CP → sine wave with a flipped sign

CP violation in the B system

CP violation in B system: from the discovery in $B^0 \rightarrow J/\Psi\ K_s$ decays (2001) to a precision measurement (2006)

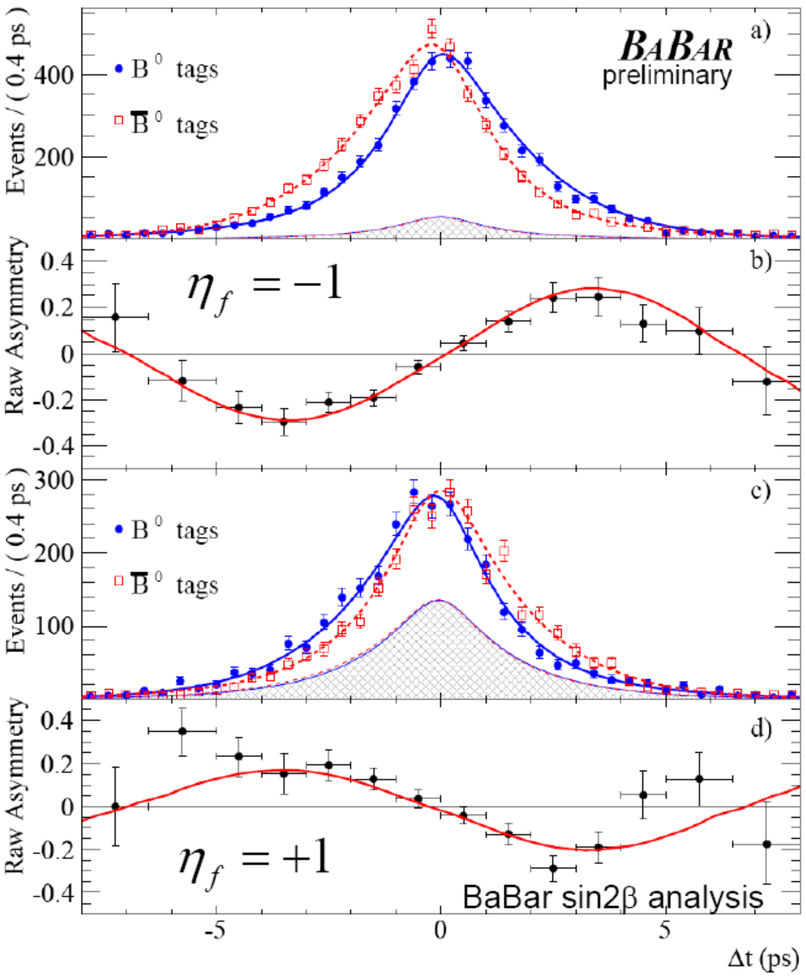


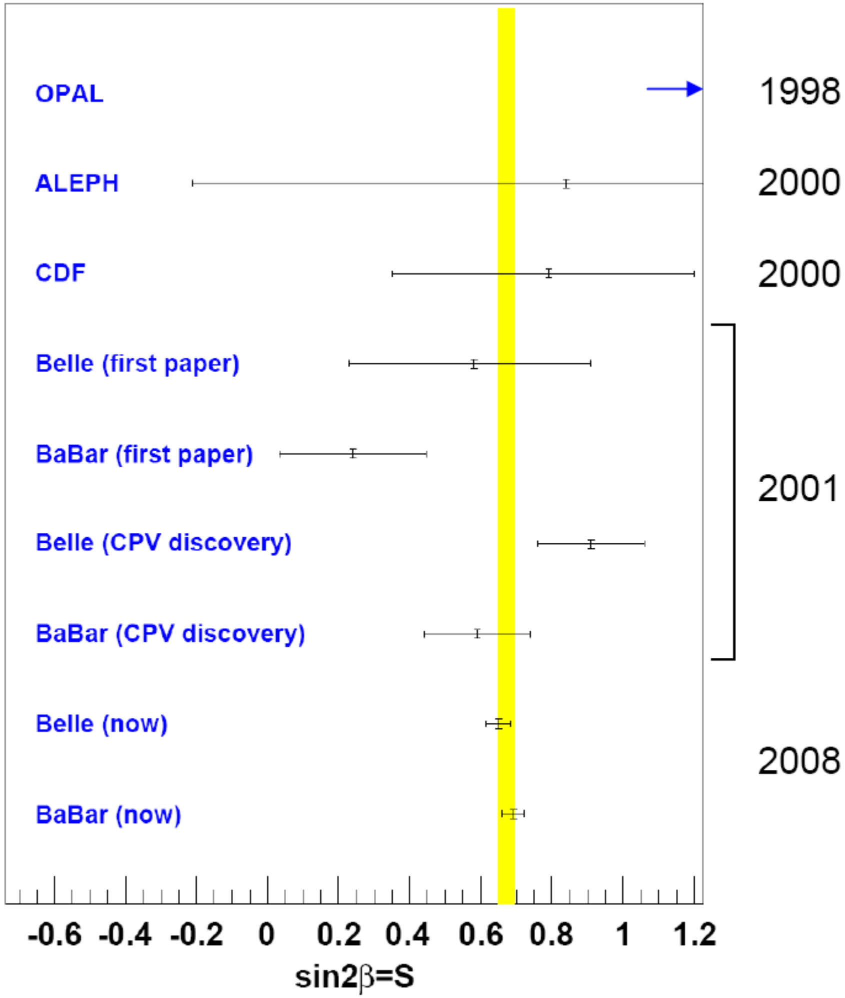
$\sin 2\phi_1 = \sin 2\beta$ from $b \rightarrow ccs$

535 M $B\overline{B}$ pairs

$\sin 2\phi_1 = 0.642 \pm 0.031$ (stat) ± 0.017 (syst)

CP violation in the B system - history

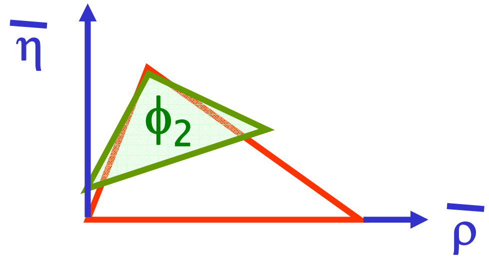




Belle Collaboration, **98**, 031802 (2007)
Belle Collaboration, Phys. Rev. Lett. D **77**, 091103 (2008)
BaBar Collaboration, SLAC-PUB-13317, PRL 99, 171803 (2007)

How to measure $\phi_2\,(\alpha)$?

To measure $\sin 2\phi_2$, we measure the time dependent CP asymmetry in $B^0 \to \pi\pi$ decays



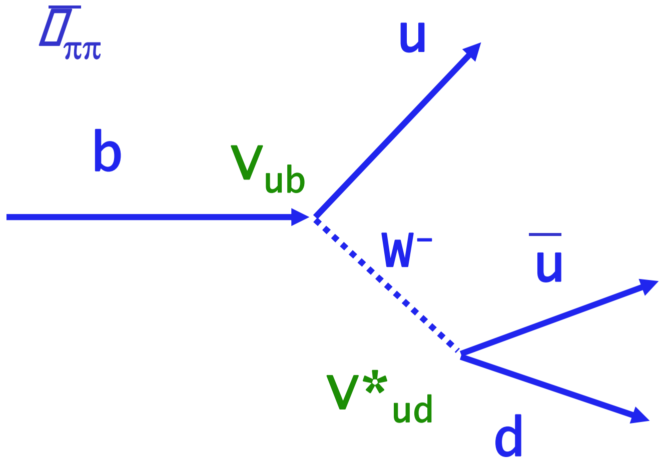
$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP}, t) - P(B^0 \to f_{CP}, t)}{P(\overline{B}^0 \to f_{CP}, t) + P(B^0 \to f_{CP}, t)} =$$

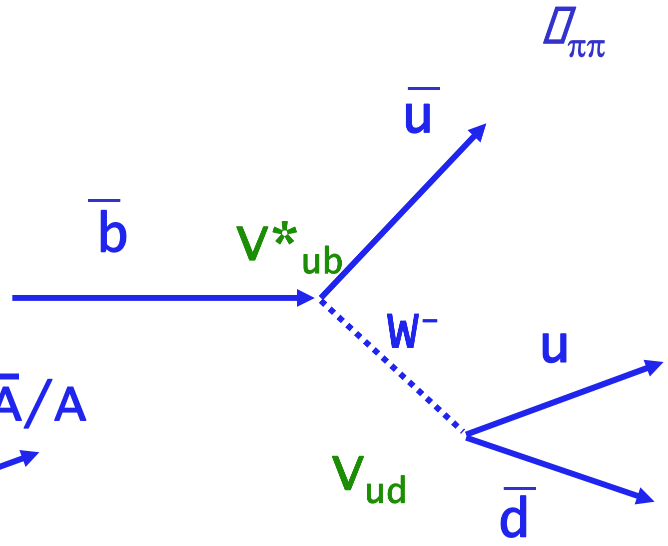
$$= \frac{(1 - |\lambda_{f_{CP}}|^2)\cos(\Delta m t) - 2\,\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)}{1 + |\lambda_{f_{CP}}|^2}$$

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

In this case $\lambda \neq 1 \to$ much harder to extract ϕ_2 from the CP violation measurement

Decay asymmetry calculation for B→π⁺ π⁻ - tree diagram only



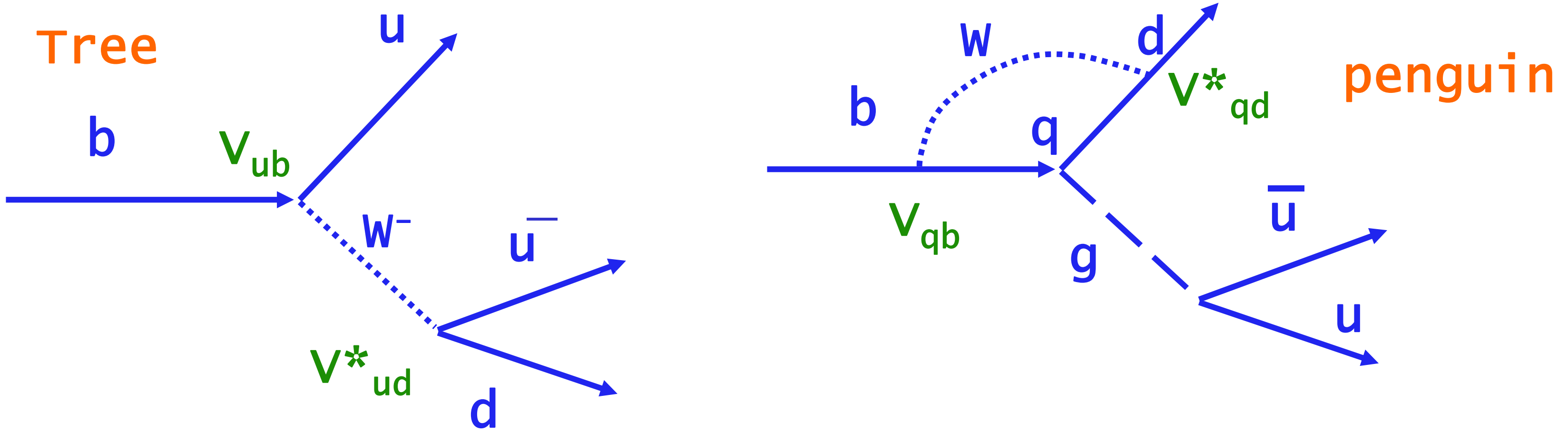


$$\lambda_{\pi\pi} = \eta_{\pi\pi} \underbrace{\boxed{\left(\frac{V_{tb}^{\;*}V_{td}}{V_{tb}V_{td}^{\;*}}\right)}}_{(q/p)} \underbrace{\boxed{\left(\frac{V_{ud}^{\;*}V_{ub}}{V_{ud}V_{ub}^{\;*}}\right)}}_{\bar{A}/A}$$

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

Neglected possible penguin amplitudes ->

$\pi^+ \pi^-$ - tree vs penguin

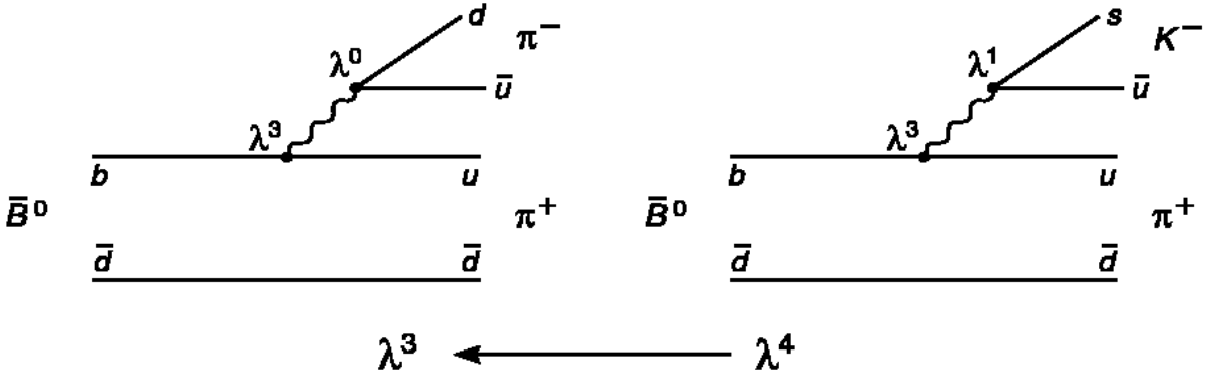


$V_{ub}V_{ud}^* = A\lambda^3(\rho - i\eta)$
$V_{tb}V_{td}^* = A\lambda^3(1 - \rho + i\eta)$

How much does the penguin contribute?

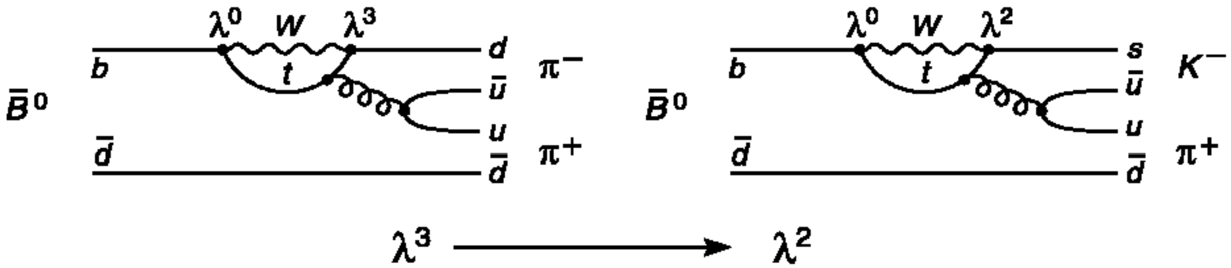
Compare $B \to K^+\pi^-$ and $B \to \pi^+\pi^-$ →

Diagrams for B→ ππ, Kπ decays



ππ

□π

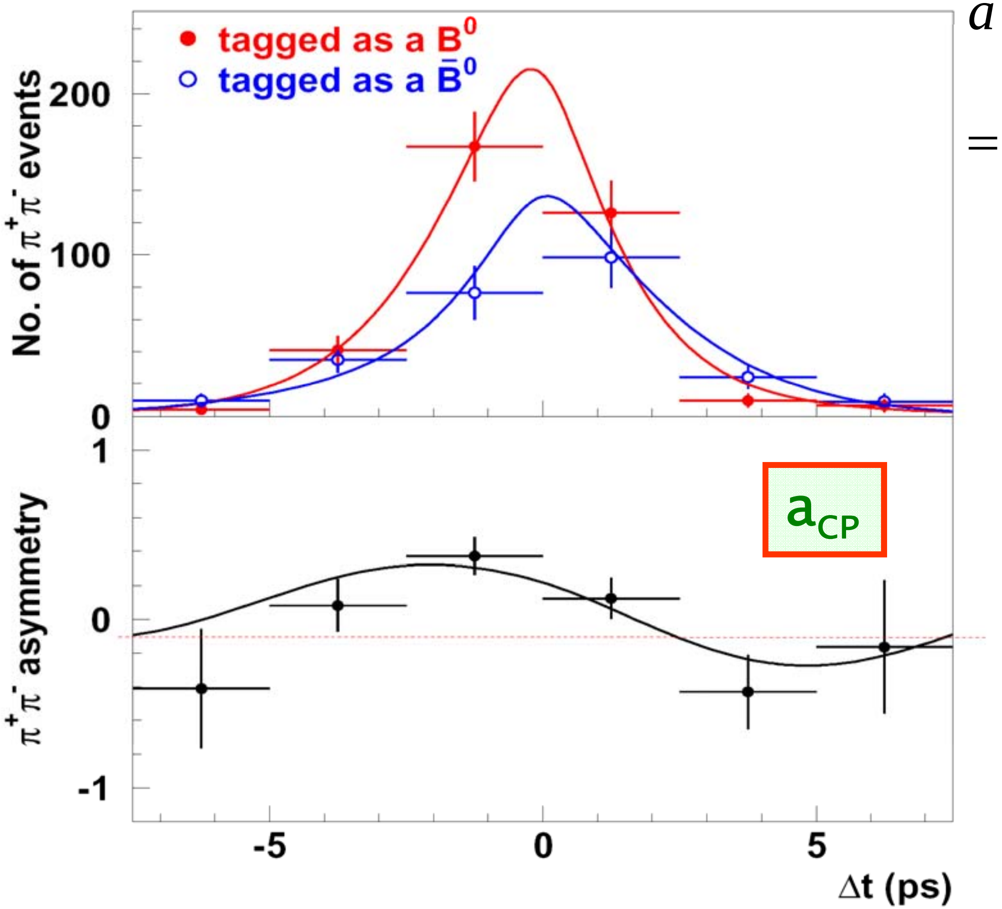


•Penguin amplitudes (without CKM factors) expected to be equal in both.

•BR(ππ) ~ 1/4 BR(Kπ)

•Kπ: penguin dominant → penguin in ππ must be important

B→$\pi^+ \pi^-$: results of the fit, plotted with background subtracted



Belle 2005 sample

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

$$= S_{f_{CP}} \sin(\Delta m t) - A_{f_{CP}} \cos(\Delta m t)$$

$\mathcal{S}_{\pi\pi}$ = -0.67±0.16±0.06

$\mathcal{A}_{\pi\pi}$ = 0.56±0.12±0.06

→ direct CP violation!

Evident on this plot: Number of anti-B events < Number of B events

CP asymmetry in time integrated rates

$$a_f = \frac{\Gamma(B \to f) - \Gamma(\overline{B} \to \overline{f})}{\Gamma(B \to f) + \Gamma(\overline{B} \to \overline{f})} = \frac{1 - |\overline{A}/A|^2}{1 + |\overline{A}/A|^2}$$

Need $|\overline{A}/A| \neq 1$: how do we get there?

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

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

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

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

→ Need at least two interfering amplitudes with different weak and strong phases.

B->$\pi^+ \pi^-$: interpretation

Interpretation:

tree +

tree level

strong phase
diff. P-T

$$\lambda_{\pi\pi} = e^{2i\phi_2} \quad \rightarrow \quad \lambda_{\pi\pi} = e^{2i\phi_2} \frac{1+|P/T|\, e^{i\delta+i\phi_3}}{1+|P/T|\, e^{i\delta-i\phi_3}} \equiv |\lambda_{\pi\pi}|\, e^{2i\phi_{2eff}}$$

weak phase
(changes sign)

$$A_{\pi\pi} = 0 \quad \rightarrow \quad A_{\pi\pi} \propto \sin\delta$$

$$S_{\pi\pi} = \sin(2\phi_2) \rightarrow \quad S_{\pi\pi} = \sqrt{1-A^2_{\pi\pi}}\, \sin(2\phi_{2eff})$$

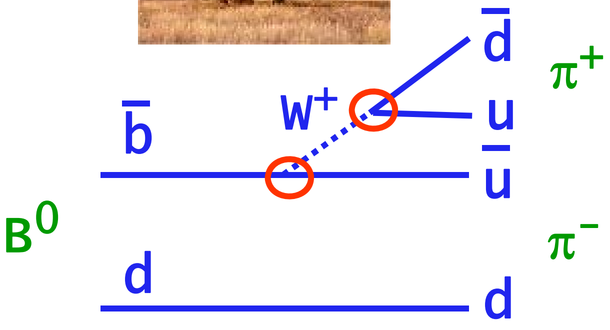
ϕ_{2eff} depends on δ, ϕ_3, ϕ_2 and |P/T|

$\pi = \phi_1 + \phi_2 + \phi_3 \rightarrow \phi_{2eff}$ depends on δ, ϕ_1, ϕ_2 and |P/T|

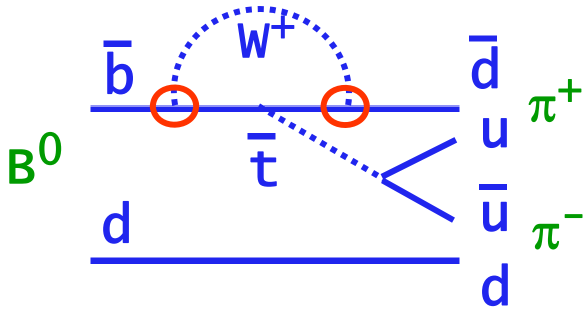
ϕ_1: well measured

Extracting ϕ_2: isospin relations

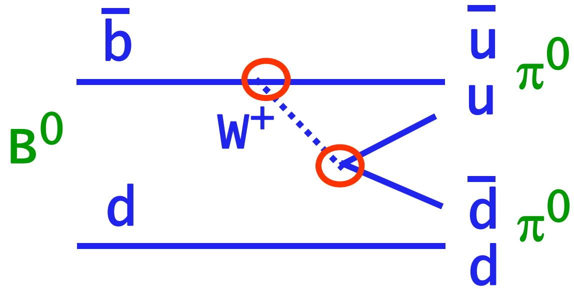
$B^0 \rightarrow \pi^+\pi^-, \pi^0\pi^0$



$T \sim V_{ub}{}^*V_{ud} \sim \lambda^3$



$P \sim V_{tb}{}^*V_{td} \sim \lambda^3$



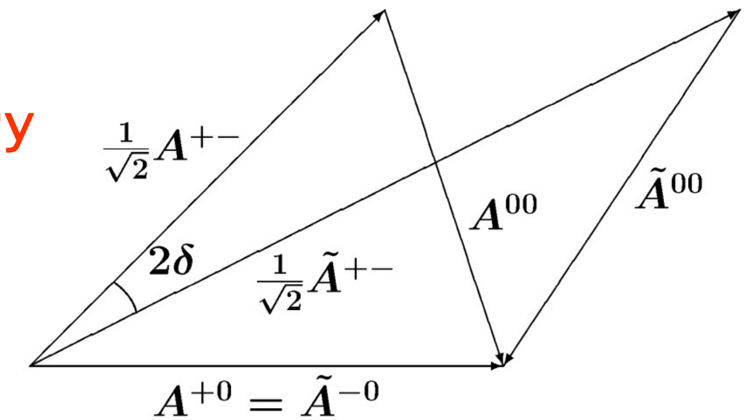
$T_c \sim V_{ub}{}^*V_{ud}$

No pengiun!

Constraint: relation of decay amplitudes in the SU(2) symmetry

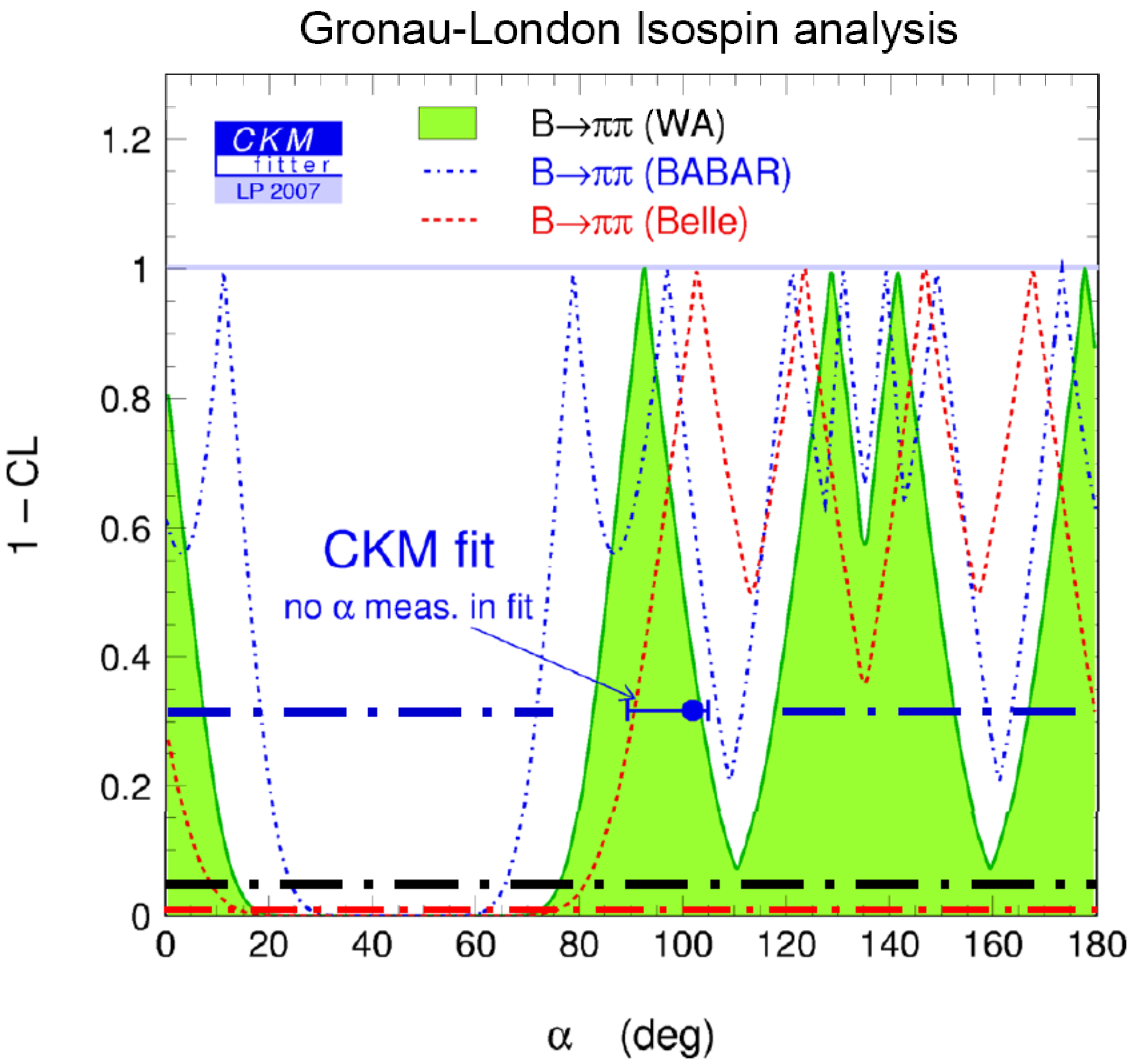
$\bar{A}^{+0} = 1/\sqrt{2}\ \bar{A}^{+-} + \bar{A}^{00}$

$A^{-0} = 1/\sqrt{2}\ A^{+-} + A^{00}$



- Inputs from:

$$B^0 \to \pi^+\pi^-$$
$$B^+ \to \pi^+\pi^0$$
$$B^0 \to \pi^0\pi^0$$



How do I read plots like this?

- 1-CL = 1: central value reported from measurements, before considering uncertainties.
- 1-CL = 0: Region excluded by experiment.
- If we think in terms of Gaussian errors, then 1-CL = 0.317, 0.046, 0.003 correspond to regions allowed at 1σ, 2σ and 3σ.

From: Adrian Bevan, slides at Helmholz International Summer School, Dubna, Russia, August 11-21, 2008

How do I read plots like this?

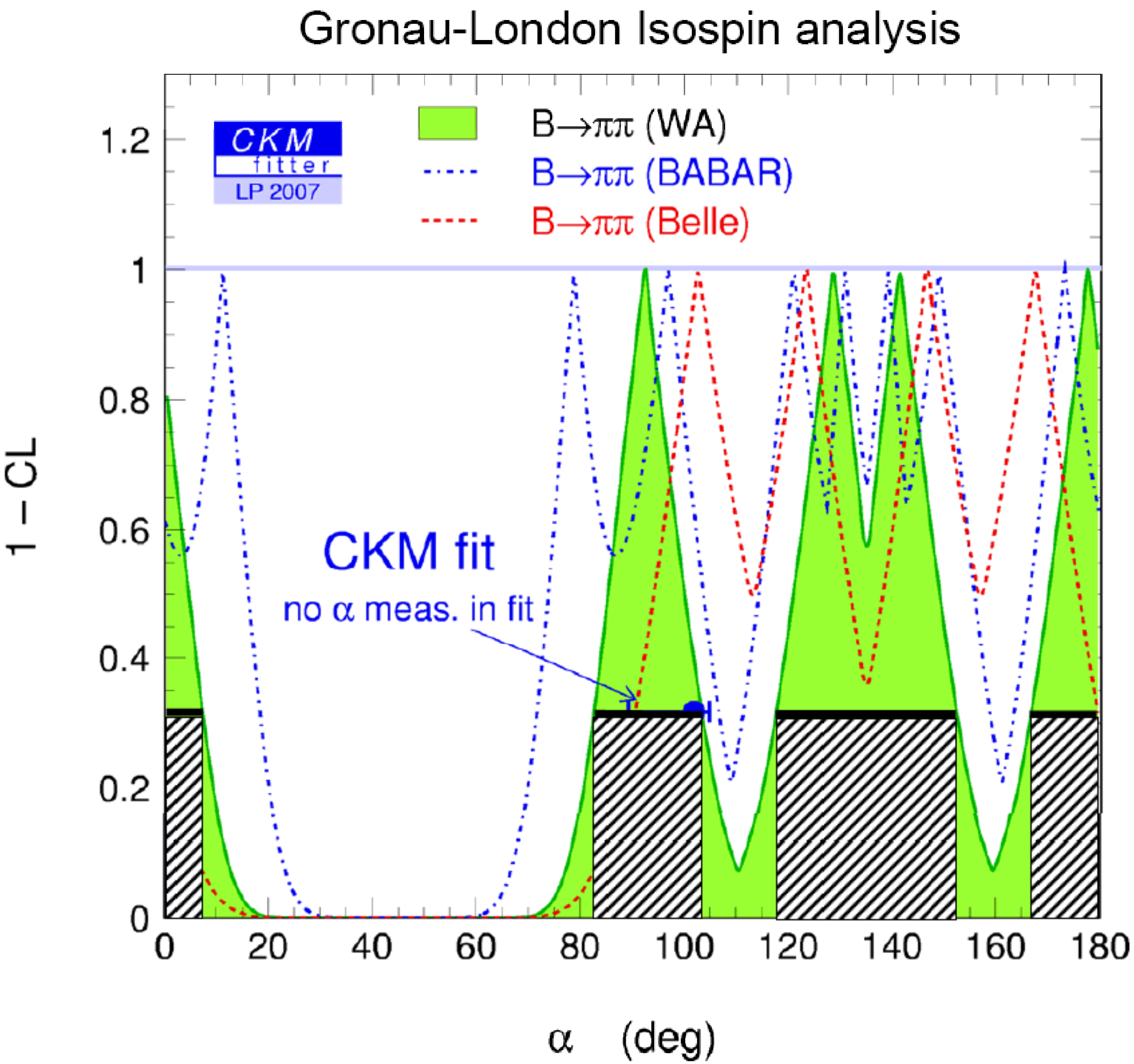
- At 68.3% CL = 1σ for Gaussian errors we have the following allowed regions for α:

$$\alpha < 7.5^\circ$$

$$82.5 < \alpha < 103.1^\circ$$

$$118.0 < \alpha < 152.4^\circ$$

$$\alpha > 166.7^\circ$$



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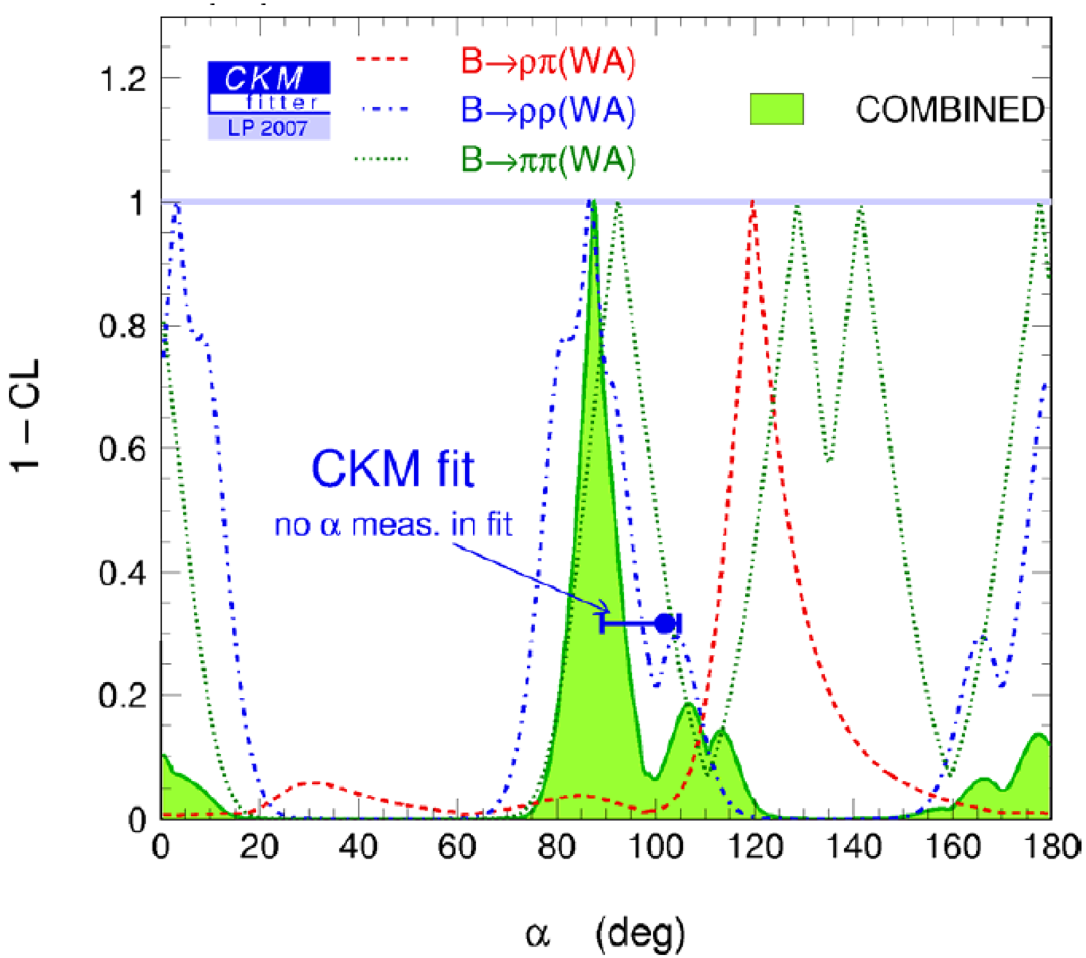
Extraction of ϕ_2

Use measured BRs and asymmetries in all three $B \to \pi\pi$ decays $\longrightarrow$ extract ϕ_2

Similar analysis also for $B \to \rho\rho$ (ϕ_2^{eff} closer to ϕ_2)

... and for $B \to \rho\pi$



By using SU(2)

$$\phi_2 = 97.5^o \pm {}^{6.2^o}_{5.3^o}$$

By using SU(3)

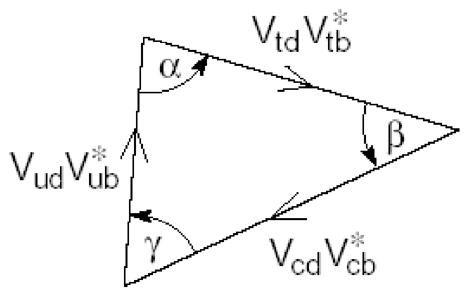
$$\phi_2 = 89.8^o \pm {}^{7.00^o}_{6.4^o}$$

How to measure ϕ_3?

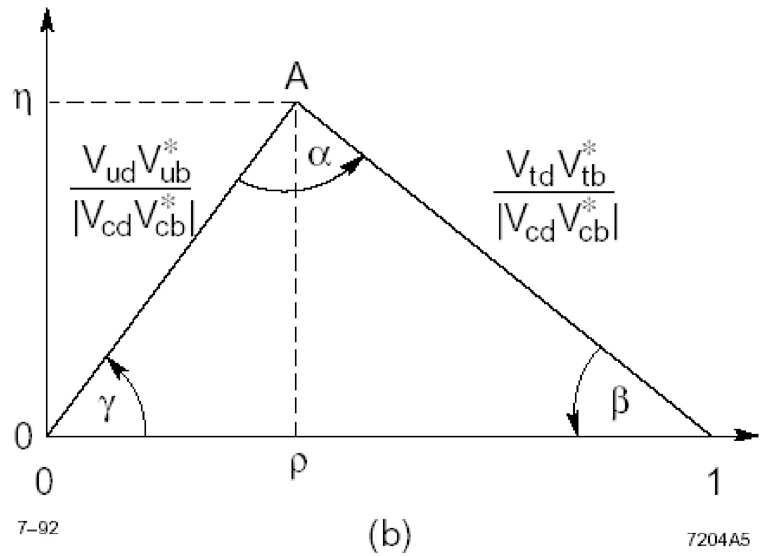
No easy (=tree dominated) channel
to measure ϕ_3 through CP
violation.

Any other idea? Yes.

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



(a)



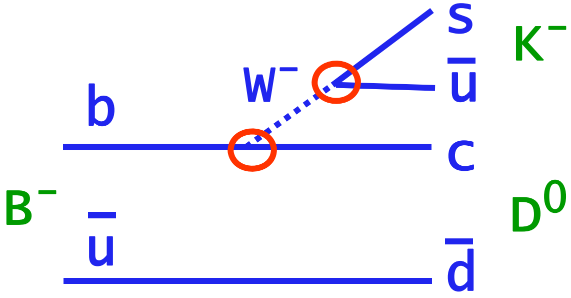
(b)

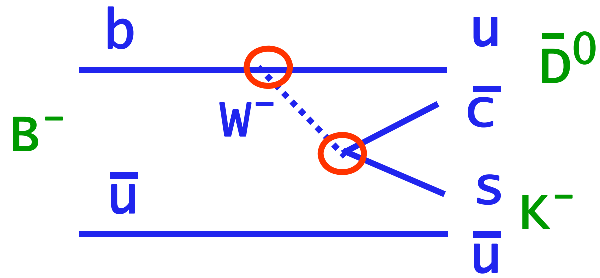
ϕ_3 from interference of a direct and colour suppressed decays

Basic idea: use $B^- \to K^- D^0$ and $B^- \to K^- \bar{D}^0$ with $D^0, \bar{D}^0 \to f$

interference $\leftrightarrow$ ϕ_3

f: any final state, common to decays of both D^0 and $\bar{D}^0$





$T \sim V_{cb}{}^* V_{us} \sim A\lambda^3$

$T_c \sim V_{ub}{}^* V_{cs} \sim A\lambda^3 (\rho + i\eta)$

$$(\rho + i\eta) \sim e^{i\phi_3}$$

ϕ_3 from interference of a direct and colour suppressed decays

Gronau,London,Wyler (GLW) 1991: $B^- \to K^- D^0_{CP}$
Atwood,Dunietz,Soni (ADS) 2001: $B^- \to K^- D^{0(*)}[K^+\pi^-]$
Belle;Giri,Zupan et al. (GGSZ), 2003: $B^- \to K^- D^{0(*)}[K_s\pi^+\pi^-]$
Dalitz plot

Density of the Dalitz plot depends on ϕ_3

Matrix element:

$$M_+ = f(m_+^2, m_-^2) + re^{i\phi_3 + i\delta} f(m_-^2, m_+^2),$$

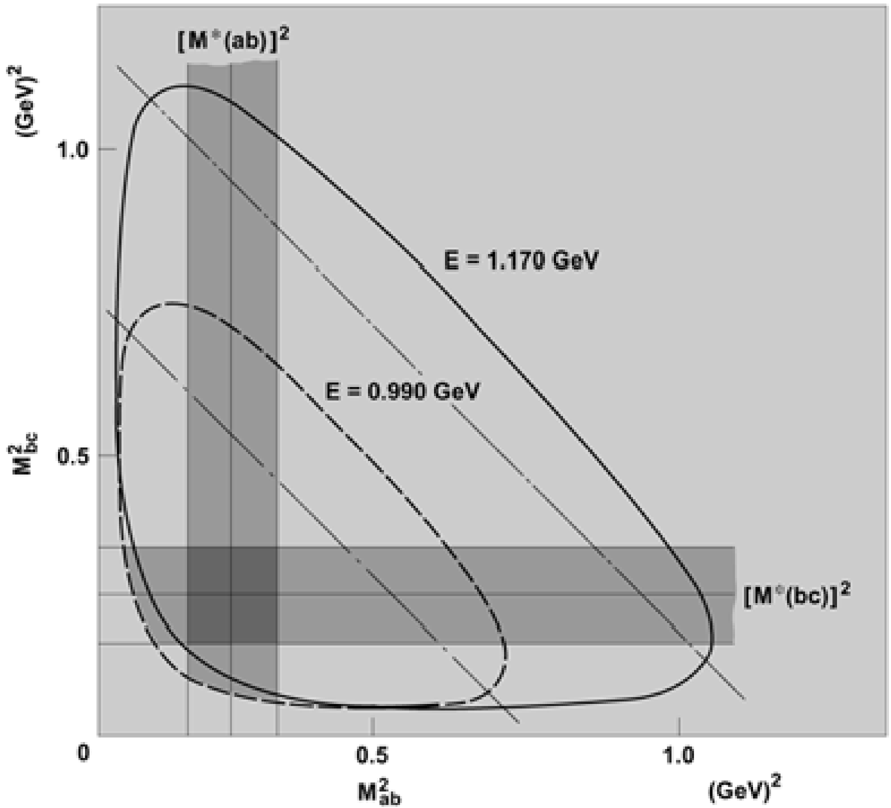
Sensitivity depends on

$$\boxed{r = \sqrt{\frac{Br(B^- \to \overline{D}^{(*)0} K^-)}{Br(B^- \to D^{(*)0} K^-)}} \approx 0.1 - 0.3}$$

or any other common 3-body decay

What is a Dalitz plot?

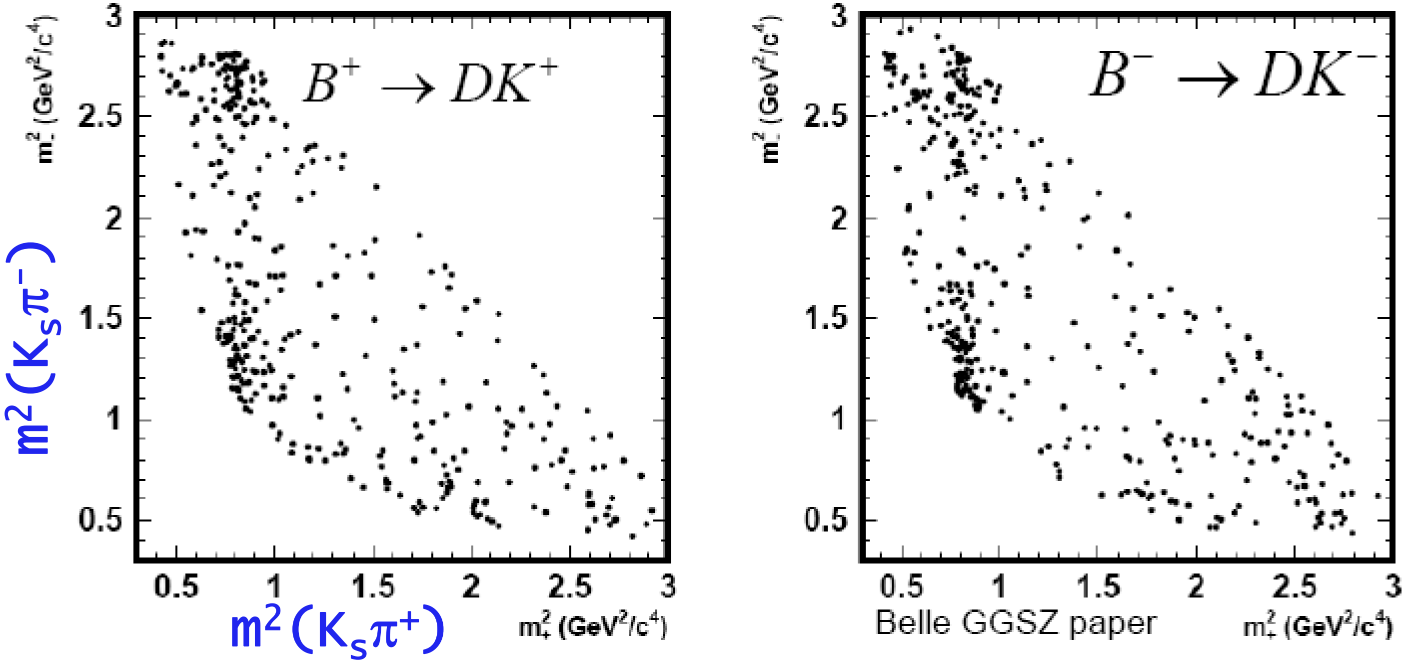
Example: three body decay X->abc. M_{ij} denotes the invariant mass of the two-particle system (*ij*) in a three body decay. Kinematic boundaries: drawn for equal masses $m_a = m_b = m_c = 0.14$ GeV and for two values of total energy E of the three-pion system. Resonance bands: drawn for states (*ab*) and (*bc*) corresponding to a (fictitious) resonance with M=0.5 GeV and G=0.2 GeV; dot-dash lines show the locations a (*ca*) resonance band would have for this mass of 0.5 GeV, for the two values of the total energy *E*.



The pattern becomes much more complicated, if the resonances interfere.

Richard H. Dalitz, "Dalitz plot", in AccessScience@McGraw-Hill, http://www.accessscience.com.

ϕ_3 from interference of a direct and colour suppressed decay



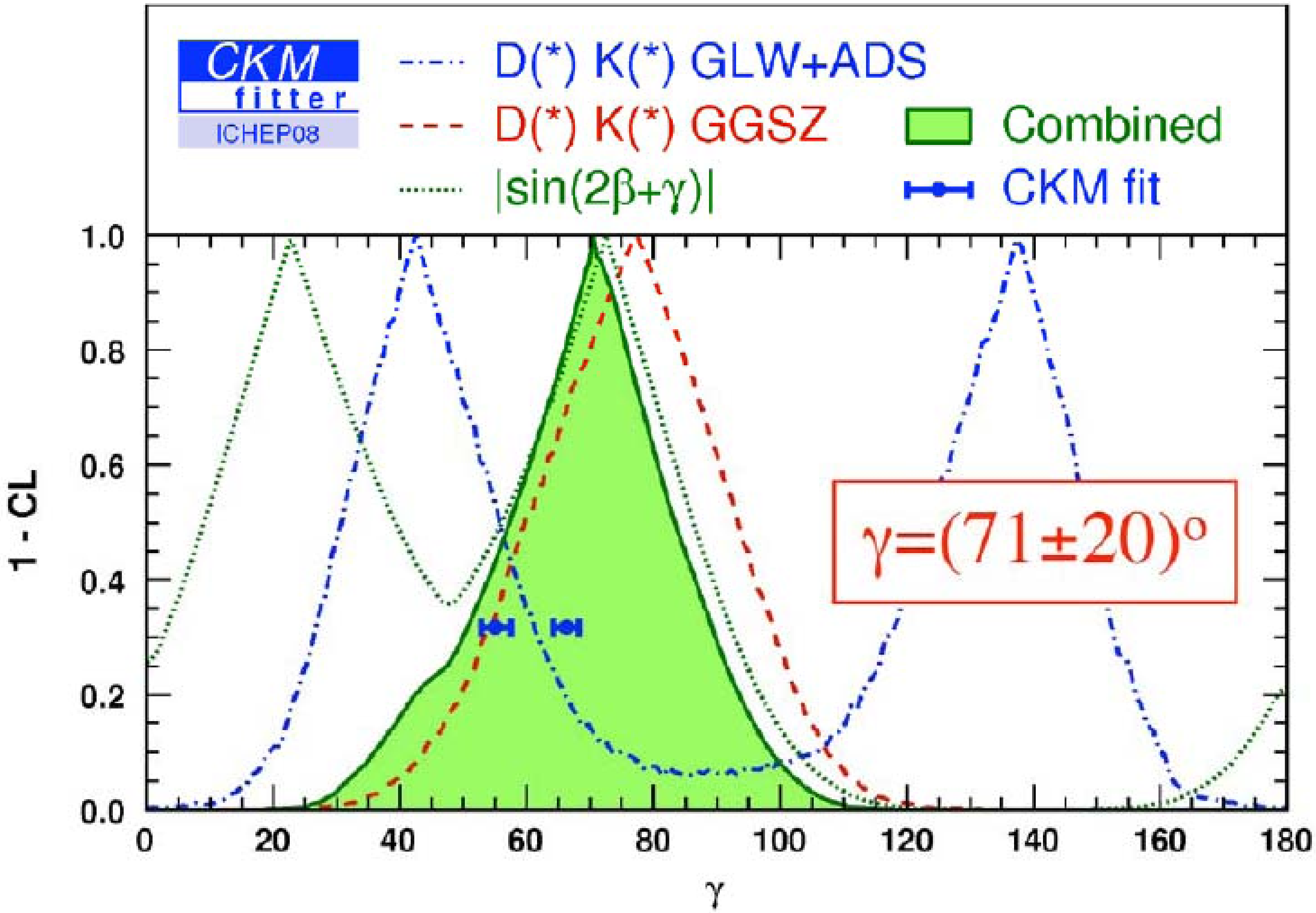
⇒ visible asymmetry

$$\gamma_{Belle} = \left(76^{+12}_{-13}\,_{stat} \pm 4_{syst} \pm 9_{model}\right)^\circ$$

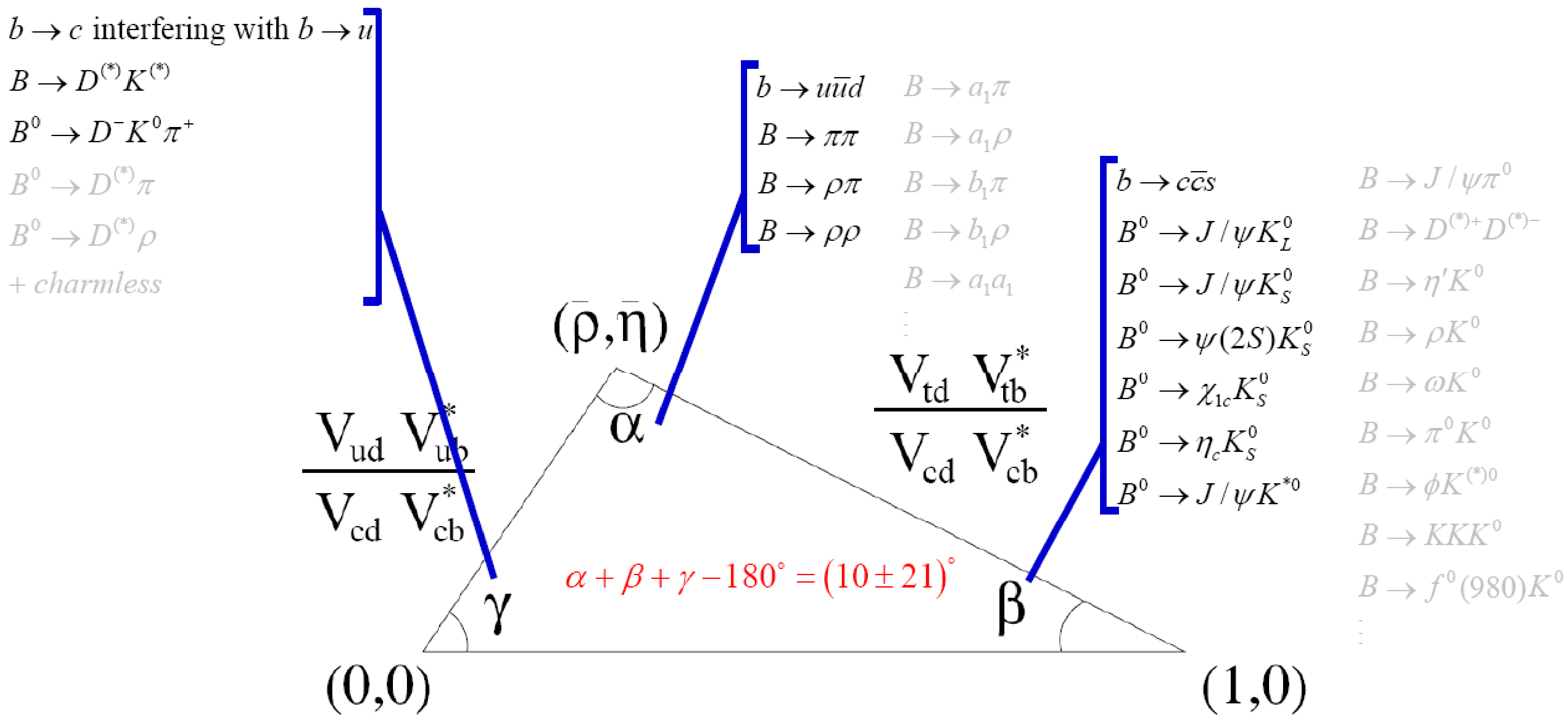
$$\gamma_{BaBar} = \left(76^{+23}_{-24}\,_{stat} \pm 5_{syst} \pm 5_{model}\right)^\circ$$

r_B = 0.16 (Belle), 0.09 (BaBar)

ϕ_3 summary, all methods



Unitarity triangle: angles, summary



From: Adrian Bevan, slides at Helmholz International Summer School, Dubna, Russia, August 11-21, 2008

Back-up slides

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?

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

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

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 ->

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

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

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

CP violation in mixing

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

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

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

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

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

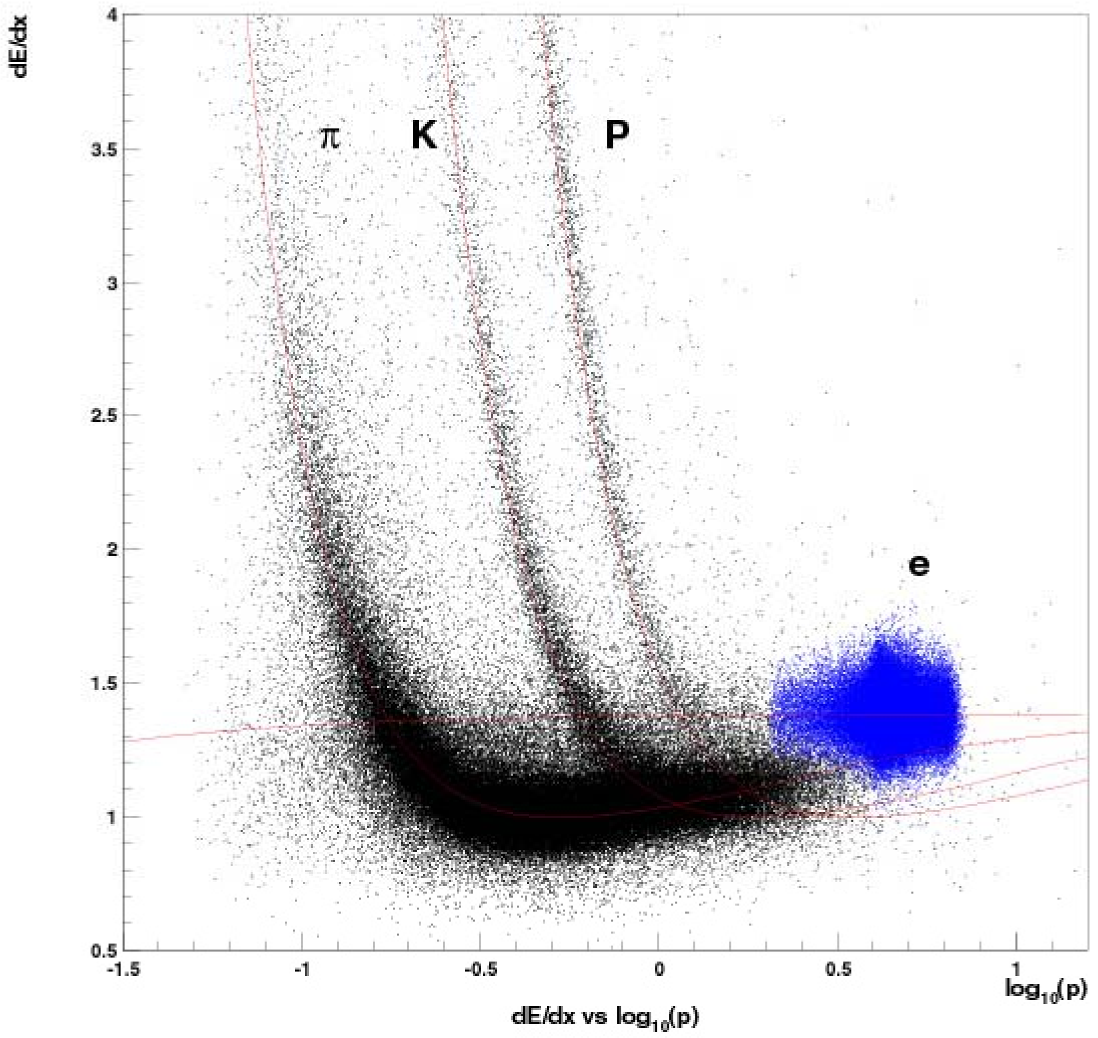
with $\lambda_{f_{CP}}=\frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$

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

Identification with dE/dx measurement

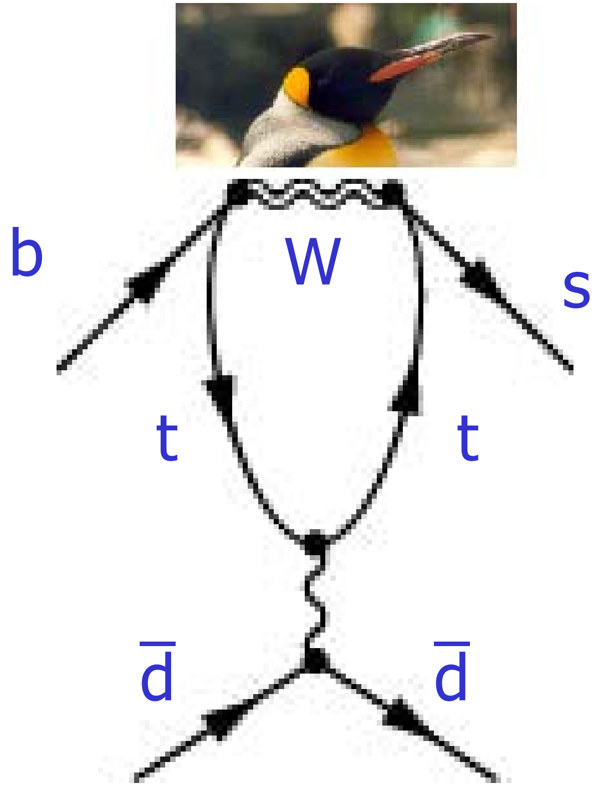
dE/dx performance in a large drift chamber.

Essential for hadron identification at low momenta.



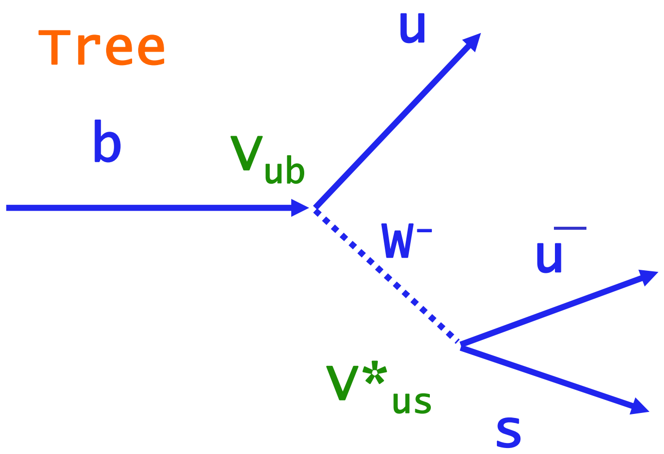
Why penguin?

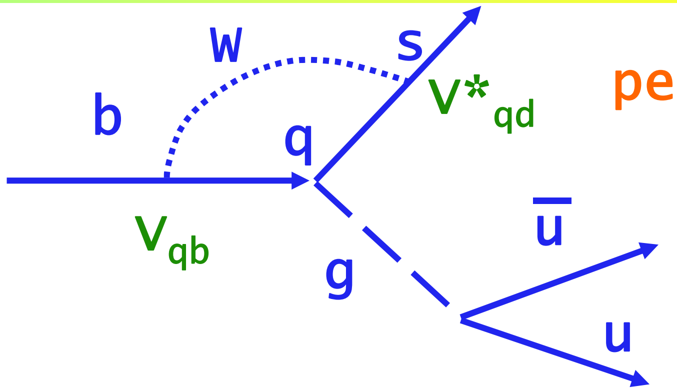
Example: b→s transition



$K^- \pi^+$ - tree vs penguin

Tree





penguin

$V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$
$V_{cb}V_{cs}^* = A\lambda^2$

Penguin amplitudes for $B \to K^+\pi^-$ and $B \to \pi^+\pi^-$ are expected to be equal. Contribution to A(uus) in $K^+\pi^-$ enhanced by λ **in comparison to** $\pi^+\pi^-$

$B \to K^+\pi^-$ tree contribution suppressed by λ^2 vs $\pi^+\pi^-$.

Experiment: $Br(B \to K^+\pi^-) = 1.85\ 10^{-5}$, $Br(B \to \pi^+\pi^-) = 0.48\ 10^{-5}$

$\to Br(B \to \pi^+\pi^-) \sim 1/4\ Br(B \to K^+\pi^-) \to$ penguin contribution must be sizeable

B->π$^+$ π$^-$: interpretation

Interpretation:

tree level

tree + 

$$\lambda_{\pi\pi} = e^{2i\phi_2} \quad \rightarrow \quad \lambda_{\pi\pi} = e^{2i\phi_2} \frac{1+|P/T|\,e^{i\delta+i\phi_3}}{1+|P/T|\,e^{i\delta-i\phi_3}} \equiv |\lambda_{\pi\pi}|\,e^{2i\phi_{2eff}}$$

strong phase diff. P-T

weak phase (changes sign)

$$A_{\pi\pi} = 0 \quad \rightarrow \quad A_{\pi\pi} \propto \sin\delta$$

$$S_{\pi\pi} = \sin(2\phi_2) \quad \rightarrow \quad S_{\pi\pi} = \sqrt{1-A^2{}_{\pi\pi}}\,\sin(2\phi_{2eff})$$

direct $\not{C}P$

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

$$= V_{ub}V_{ud}{}^* T_{u\bar{u}d}\left[1 + (P_d^u - P_d^t) + (V_{cb}V_{cd}{}^*/V_{ub}V_{ud}{}^*)(P_d^c - P_d^t)\right]$$

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

How to extract ϕ_2, δ and |P/T|?

ϕ_{2eff} depends on δ, ϕ_3, ϕ_2 and |P/T|

$\pi = \phi_1 + \phi_2 + \phi_3 \rightarrow \phi_{2eff}$ depends on δ, ϕ_1, ϕ_2 and |P/T|

ϕ_1: well measured

penguin amplitudes $B \rightarrow K^+\pi^-$ and $B \rightarrow \pi^+\pi^-$ are equal
$\rightarrow$ limits on |P/T| (~0.3);
considering the full interval of δ values one can obtain interval of ϕ_2 values;

isospin relations can be used to constrain δ
(or better to say $\phi_2 - \phi_{2eff}$);

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.