ITEP International Winter School of Physics

Heavy Flavors I

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- Flavor physics: introduction, with a little bit of history
- Flavor physics at B factories: CP violation
- Flavor physics at B factories: rare decays and searches for NP effects
- Super B factory
- Flavor physics at hadron machines: history, LHCb and LHCb upgrade

Contents, this lecture

- **Flavor physics: introduction, with a little bit of history**
- **Flavor physics at B factories: CP violation**
- Flavor physics at B factories: rare decays and searches for NP effects
- Super B factory
- Flavor physics at hadron machines: history, LHCb and LHCb upgrade

Flavour physics

Flavour physics

... is about
- quarks

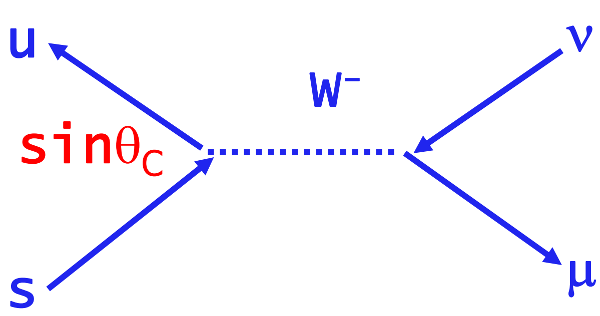
and
- their weak transitions and mixing
- CP violation

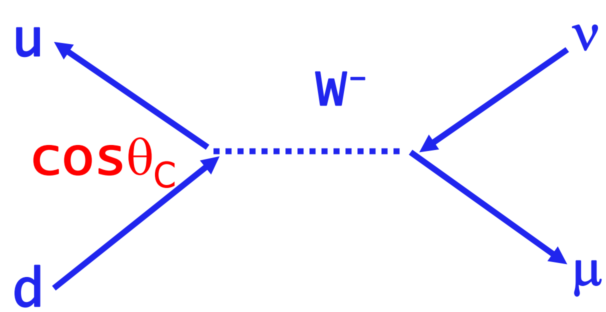
Flavour physics - origins

Discovery of strange particles K and Λ (readily produced in pairs just like pions and protons – strong interaction, slow decay – weak interaction)

Difference in $K^- \to \mu^- \nu$ and $\pi^- \to \mu^- \nu$ decay rates:

→ u quark couples to d $\cos\theta_C$ + s $\sin\theta_C$ (N. Cabbibo, 1963)





$\sin\theta_C = 0.22$

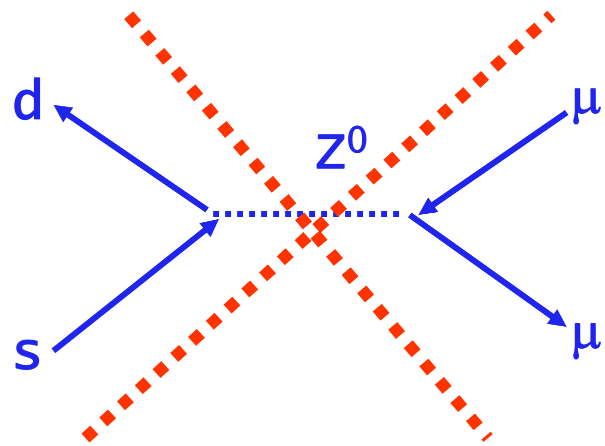
Flavour physics - origins

The smallness of $K_L \to \mu^+\mu^-$ (neutral current transition s→d) vs. $K^- \to \mu^- \nu$ (charged current s→u) by many orders of magnitude: can be solved if there is one more quark (c) – c quark couples to $-d \sin\theta_C + s \cos\theta_C$

Glashow-Iliopoulos-Maiani (GIM) mechanism forbids flavor changing neutral current (FCNC) transitions at tree level

From a measurement of the K^0 – anti-K^0 mixing frequency $\Delta m_K = m(K_L) - m(K_S)$ we can estimate the charm quark mass

forbidden



→c quark discovered in 1974!

u and c

couple in weak interactions to

rotated d and s

$\sin\theta_C = 0.22$

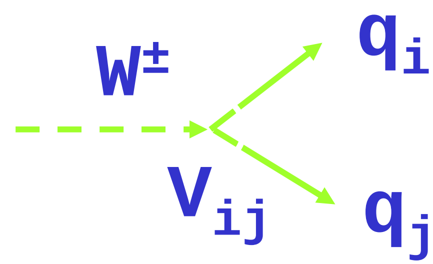
$$\begin{pmatrix} \cos\theta_C & \sin\theta_C \\ \sin\theta_C & \cos\theta_C \end{pmatrix}$$

Flavour physics and CP violaton

Discovery of CP violation in $K_L \to \pi^+ \pi^-$ decays (Fitch, Cronin, 1964)

Kobayashi and Maskawa (1973): to accommodate CP violation into the Standard Model, need three quark generations, six quarks

Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix



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

Flavour physics and CP violaton

Kobayashi and Maskawa (1973): to accommodate CP violation into the Standard Model, need three quark generations, six quarks (at the time when only u, d, and s were known!)

The missing quarks were found, one by one, in 1974, in 1977, and in 1994.

How to test the CP violation part of their theory?

Nature was kind, made sure there is enough mixing in the B meson system

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
- Discovery of a large 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.

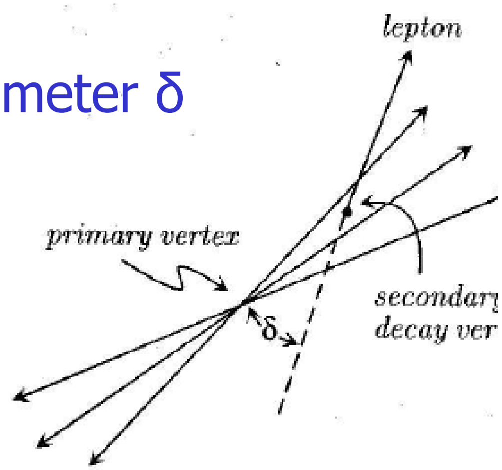
First B meson studies were carried out in 70s at e^+e^- colliders with c.m.s. energies ~20GeV, considerably above threshold (~2x5.3GeV)

B meson decays: mainly through a $b \rightarrow c$ transition, with a relative strength of V_{cb}

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

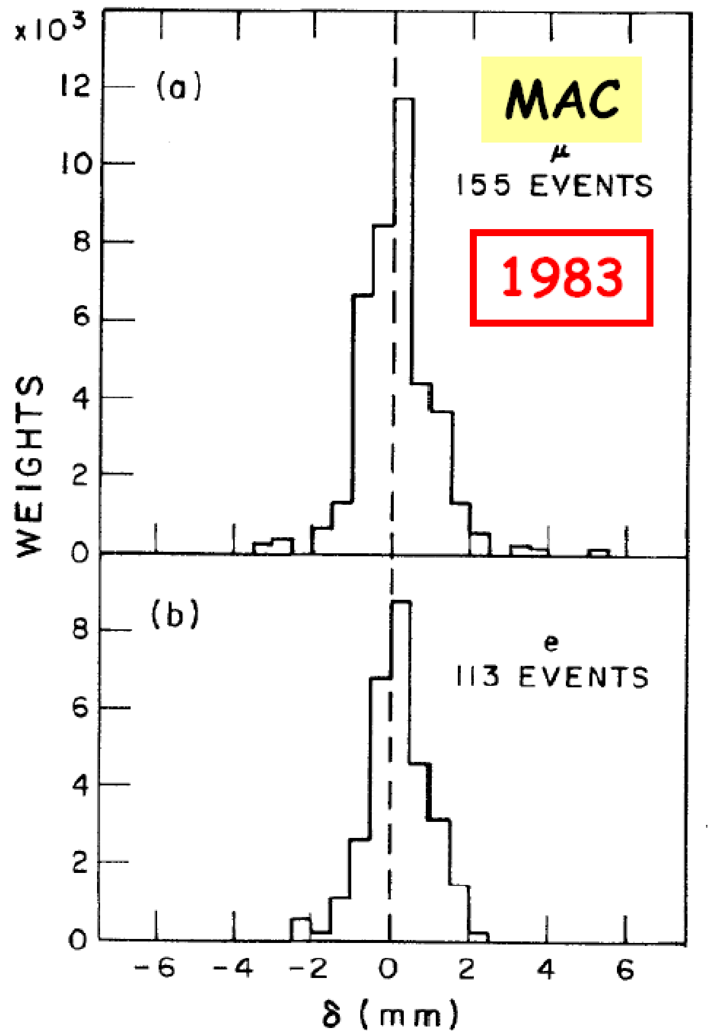


Lifetime implies: V_{cb} small

MAC: (1.8±0.6±0.4)ps

Mark II: (1.2±0.4±0.3)ps

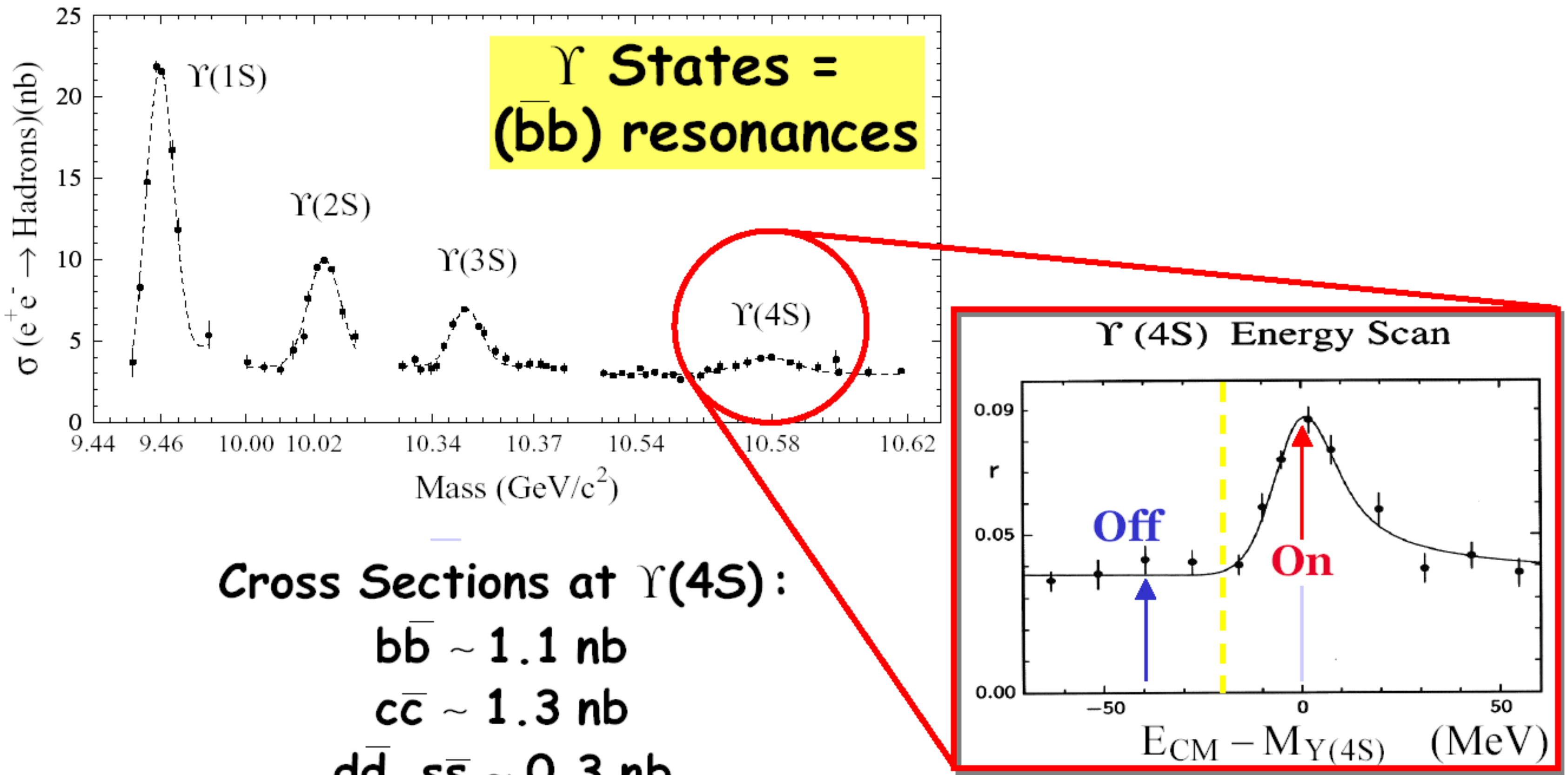
Integrated luminosity at 29 GeV: 109 (92) pb^{-1}~3,500 bb pairs



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

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

Systematic studies of B mesons: at 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

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

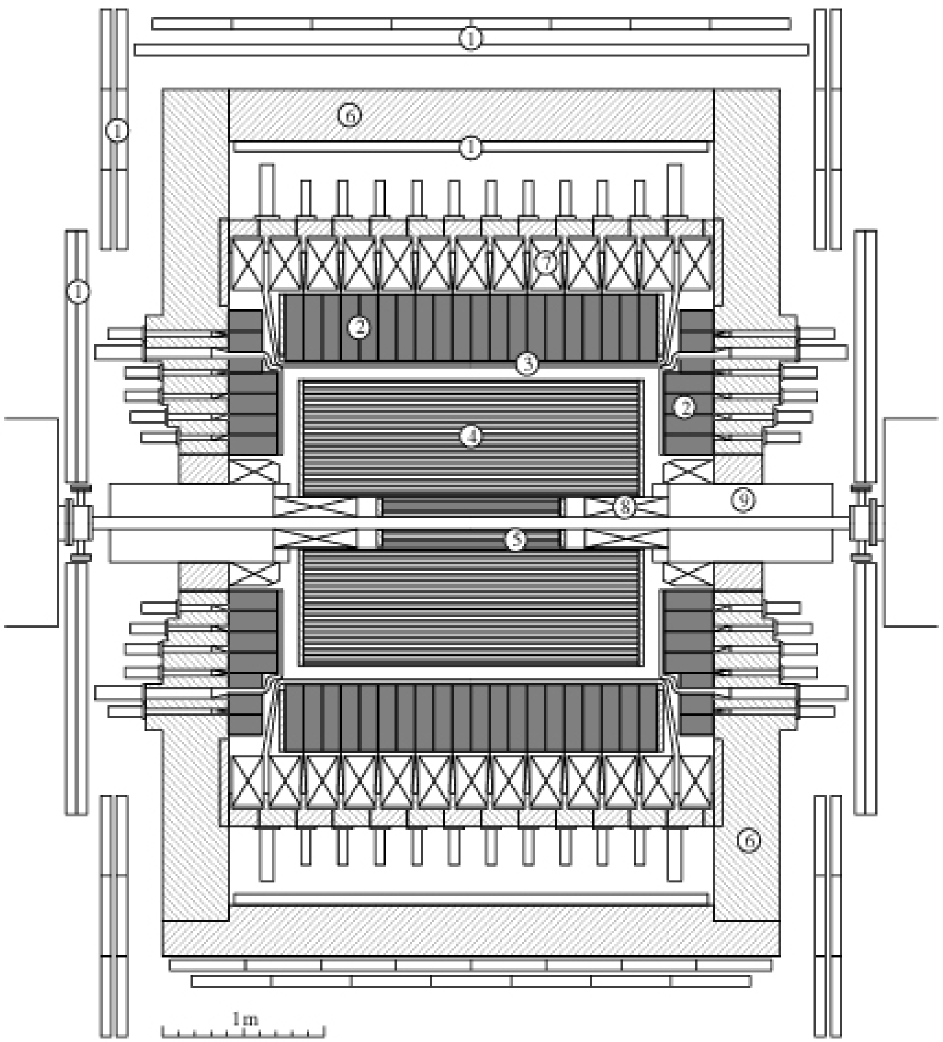
80s-90s: two very successful experiments:

•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).



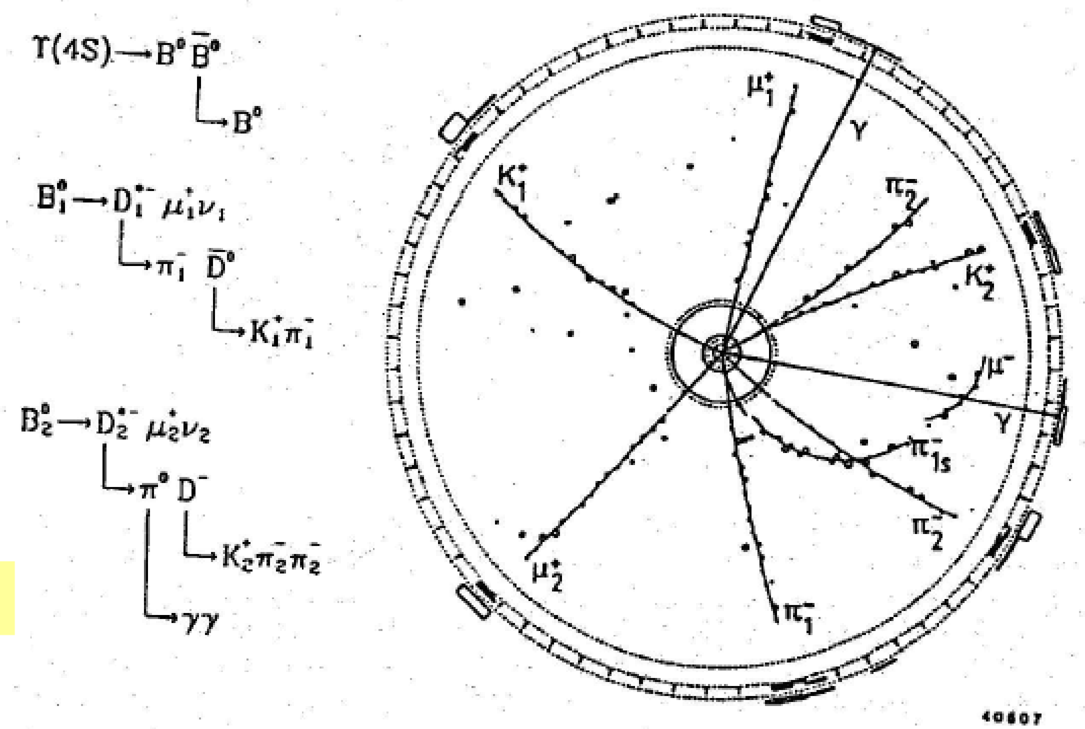
Argus: part of the group in 1988(?)

... and 20 years later

Mixing in the B^0 system

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

Reconstructed event



$$\chi_d = 0.17 \pm 0.05$$

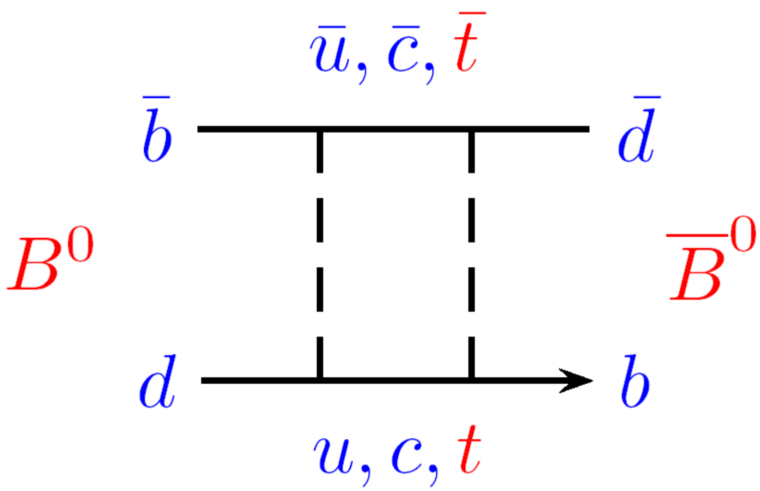
ARGUS, PL B **192**, 245 (1987)

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 Υ(4s)

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

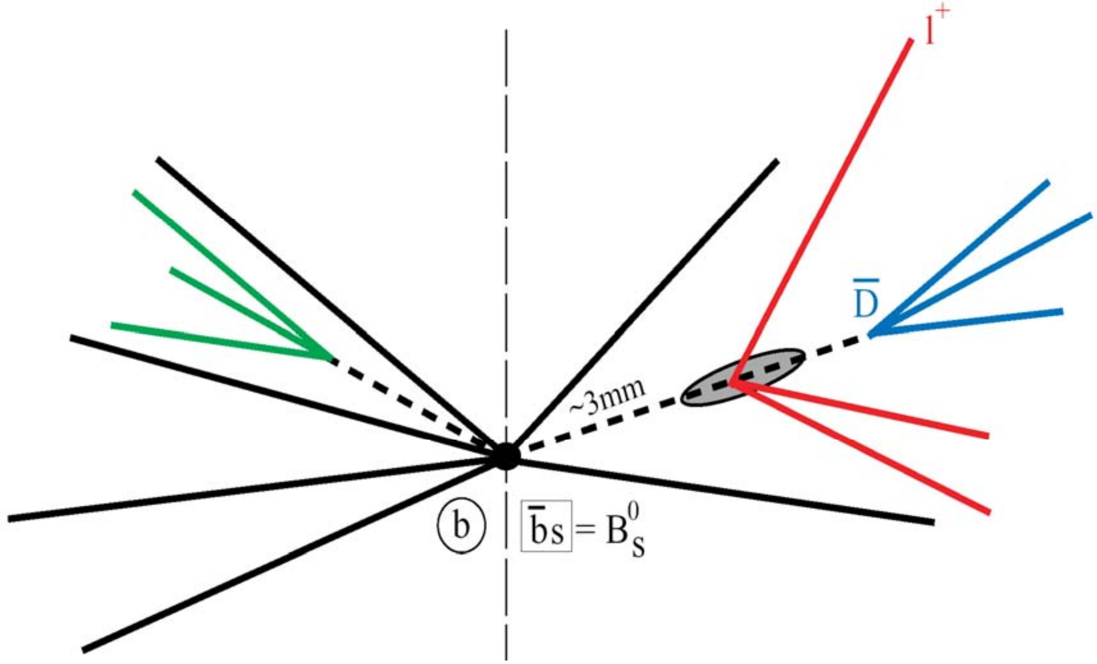
- B mesons
- D mesons
- τ^- lepton
- and even a measurement of ν_τ mass.

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).

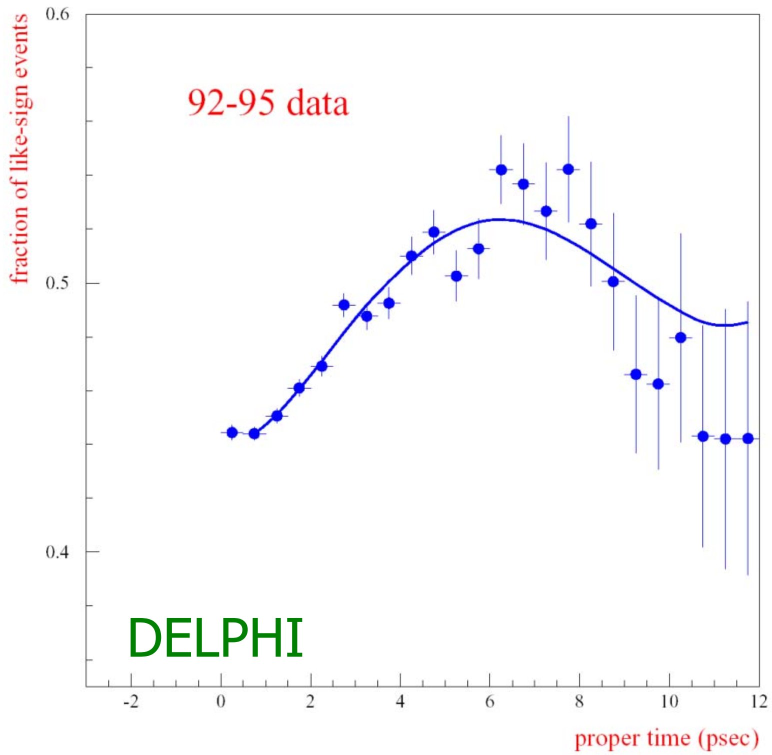
Studies of B mesons at LEP

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

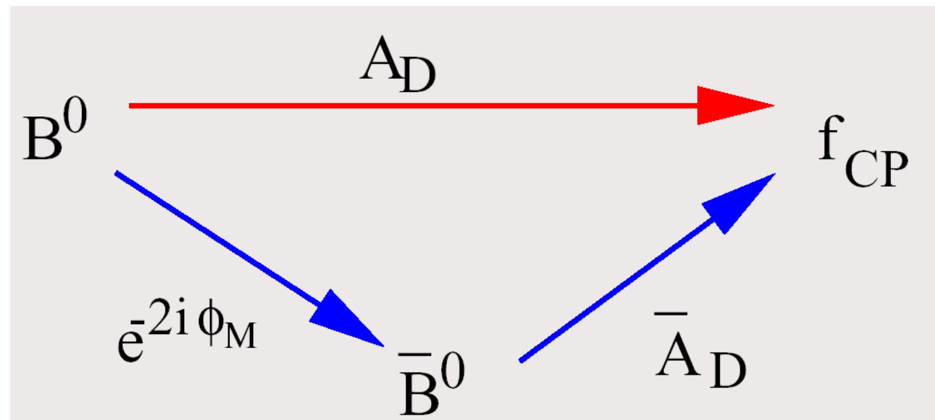
Almost measured mixing in the B_s system (bad luck...)

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

CP violation in the B System

Large B mixing → expect sizeable CP violation (CPV) in the B system

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)

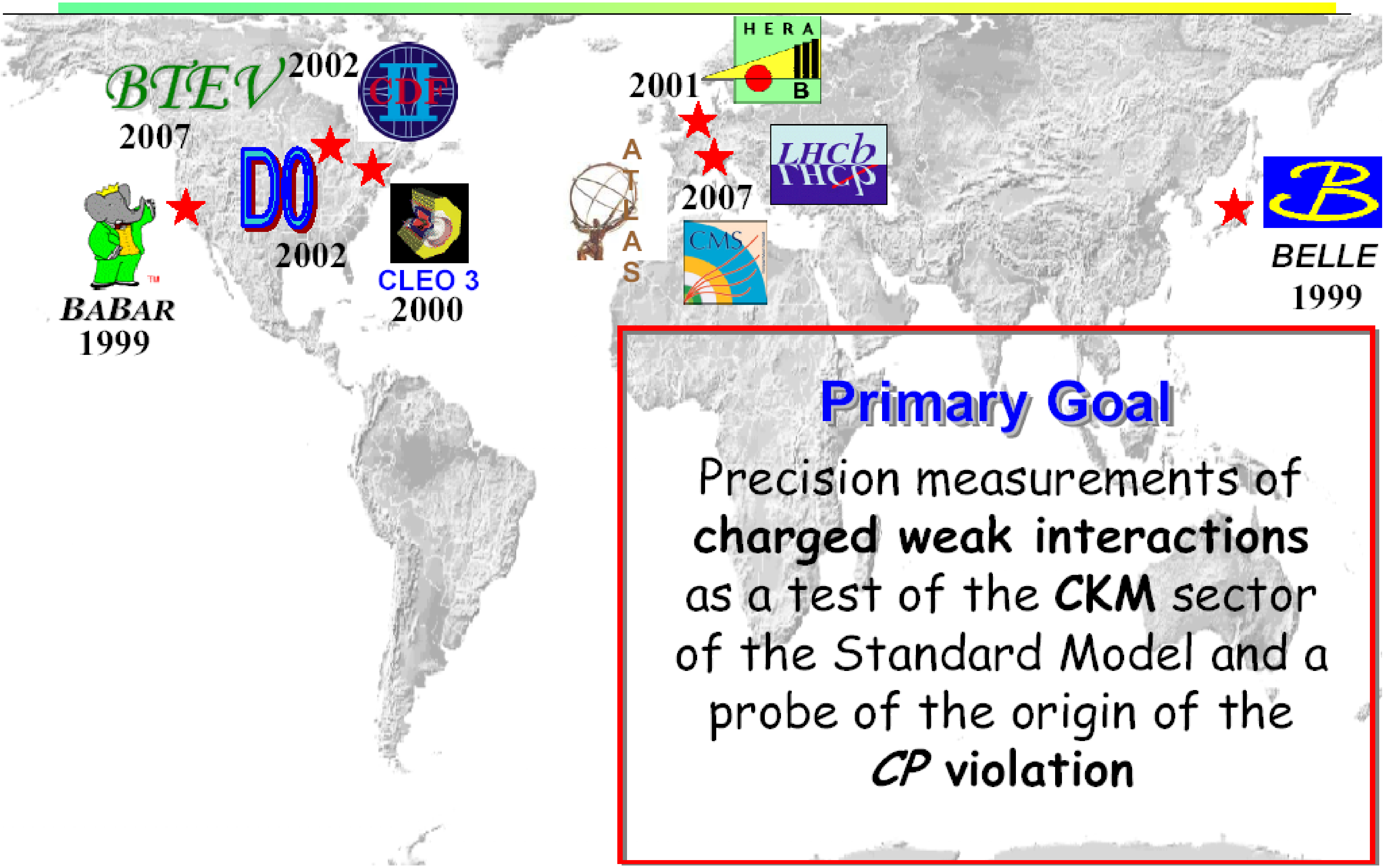
Theoretically clean way to one of the parameters ($\sin 2\phi_1$)

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

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



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

→ mass eigenstates B_L (light) and B_H (heavy) 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 by 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 $\Delta\Gamma_B << \Delta m_B$

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

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

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 $\exp(-iM_i t)$

→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 $\bar{B}^0$ 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

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

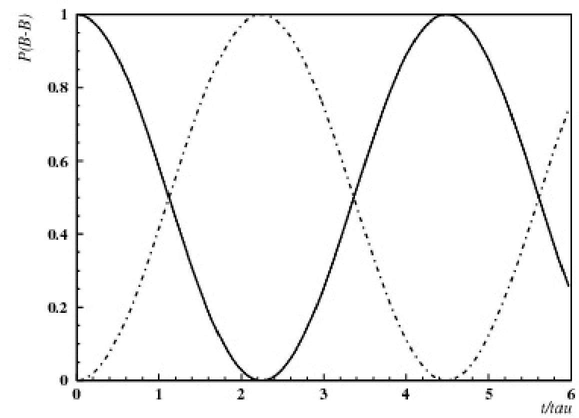
$$g_-(t) = e^{-iMt} e^{-\Gamma t/2} i \sin(\Delta m t/2)$$

$$M = (M_H + M_L)/2$$

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

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

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



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

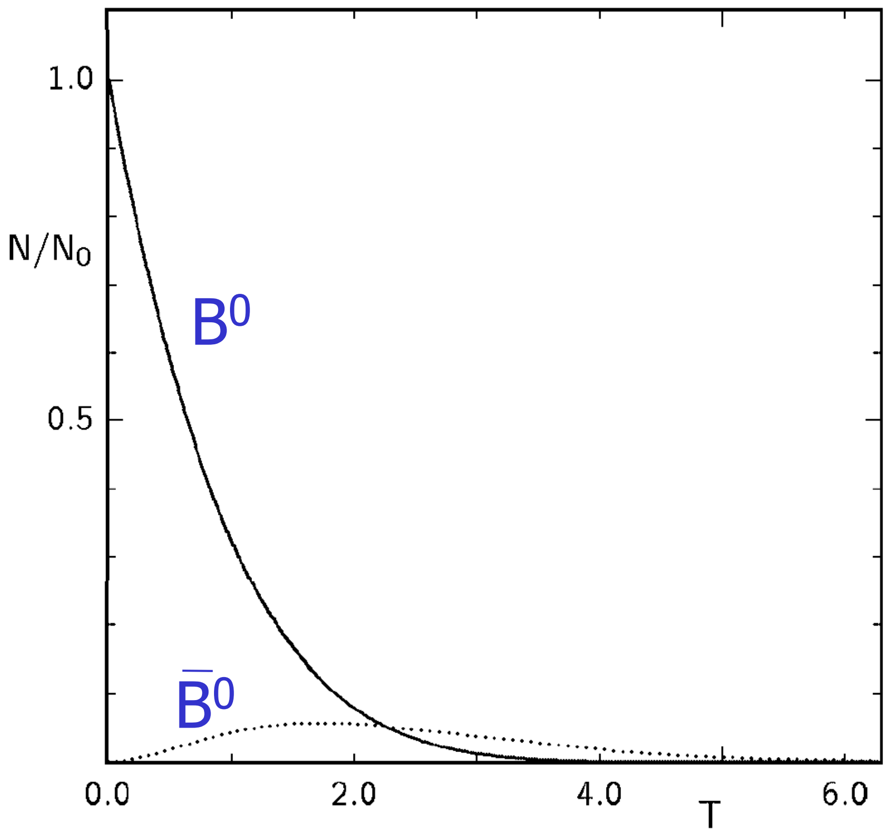
$$\left|\left\langle \overline{B}^0 \middle| B^0_{phys}(t)\right\rangle\right|^2 = |q/p|^2 |g_-(t)|^2 = |q/p|^2 \sin^2(\Delta m t/2)$$

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

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

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

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

Decay amplitude as a function of time:

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

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

... 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):

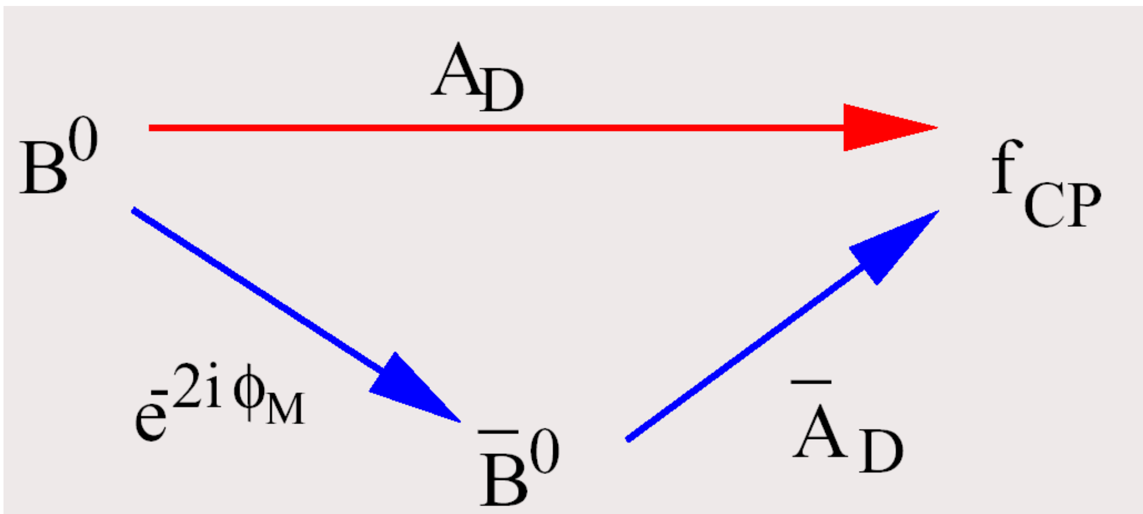
$$\left.\begin{array}{l} \cancel{CP} \text{ in decay: } |\bar{A}/A| \neq 1 \\ \\ \cancel{CP} \text{ in mixing: } |q/p| \neq 1 \end{array}\right\} |\lambda| \neq 1$$

$\cancel{CP}$ 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 $\pi^+ \pi^-$



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

We can get CP violation if $\mathrm{Im}(\lambda) \neq 0$, even if $|\lambda| = 1$

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 $\Upsilon(4s)$

B and anti-B from the $\Upsilon(4s)$ 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

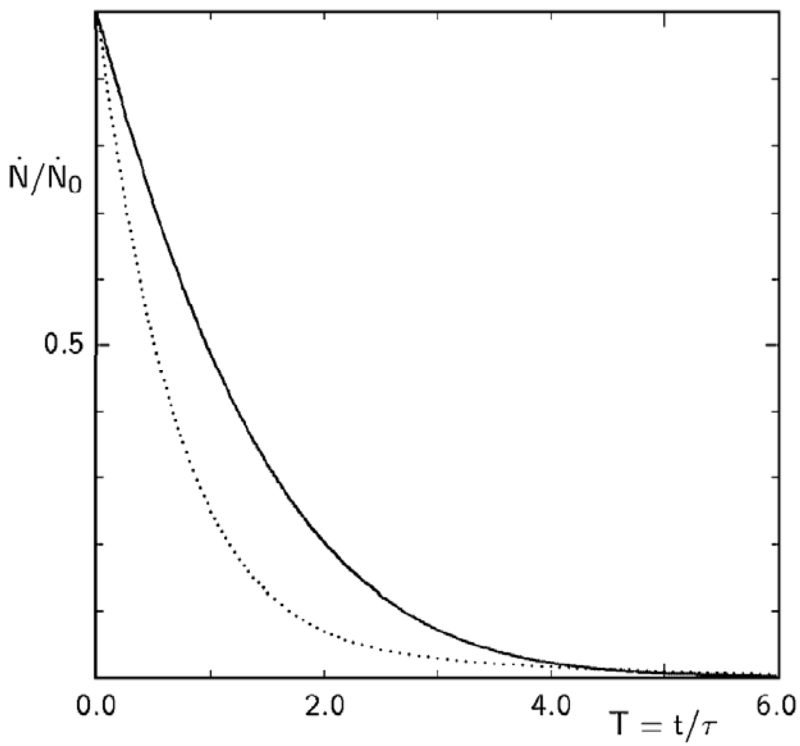
•the other at t_{ftag} to a flavor-specific state f_{tag} (=state only accessible to a B^0 and not to a anti-B^0 (or vice versa), e.g. $B^0 \to D^0\pi$, $D^0 \to K^-\pi^+$)

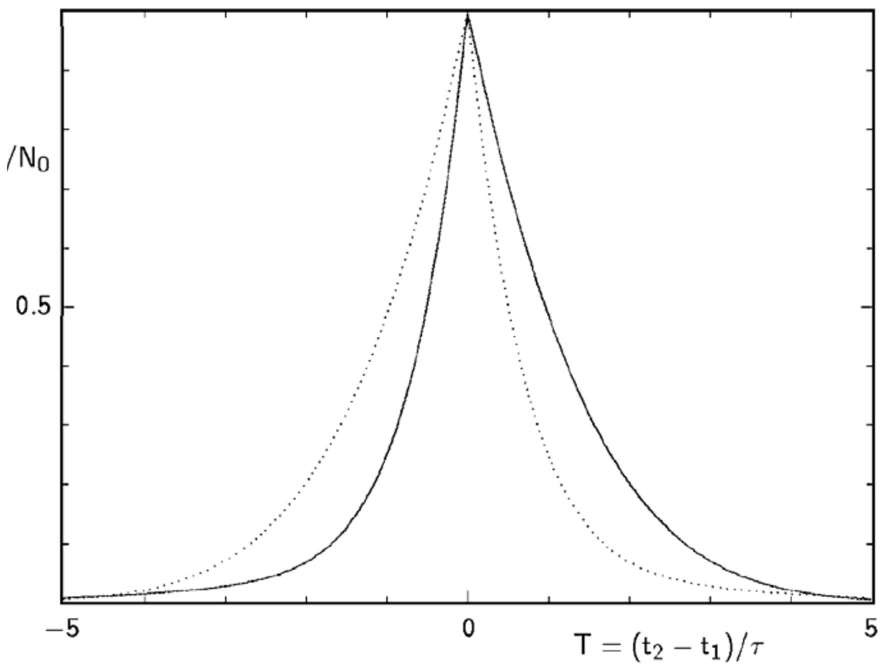
also known as 'tag' because it tags the flavour of the B meson it comes from

Decay rate to f_{CP}

Incoherent production
(e.g. hadron collider)

coherent production
at Υ(4s)

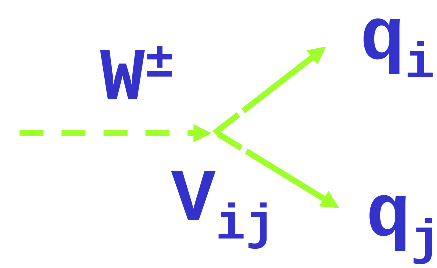




At Υ(4s): Time integrated asymmetry = 0

CP violation in SM

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



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

CP violation is possible in this scheme if V_{CKM} is not a real matrix (i.e. has a non-trivial complex phase)

CP violation in SM

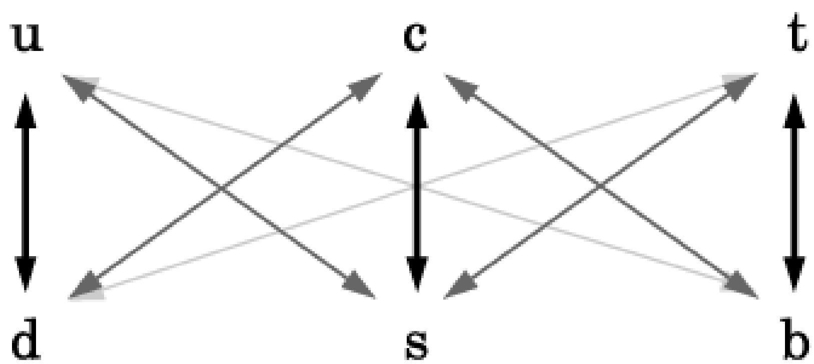
$$\mathcal{L} = V_{ij}\overline{U}_i\gamma^\mu(1-\gamma_5)D_jW_\mu + V_{ij}^*\overline{D}_i\gamma^\mu(1-\gamma_5)U_jW_\mu$$

$$\Updownarrow CP$$

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

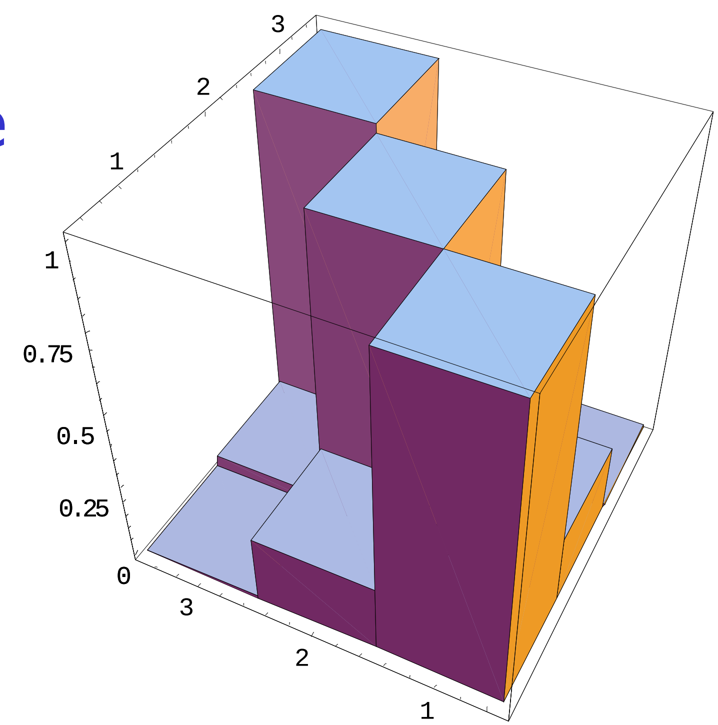
If $V_{ij}=V_{ij}^*$ ▶ $\mathcal{L}=\mathcal{L}_{CP}$ ▶ CP is conserved

CKM matrix

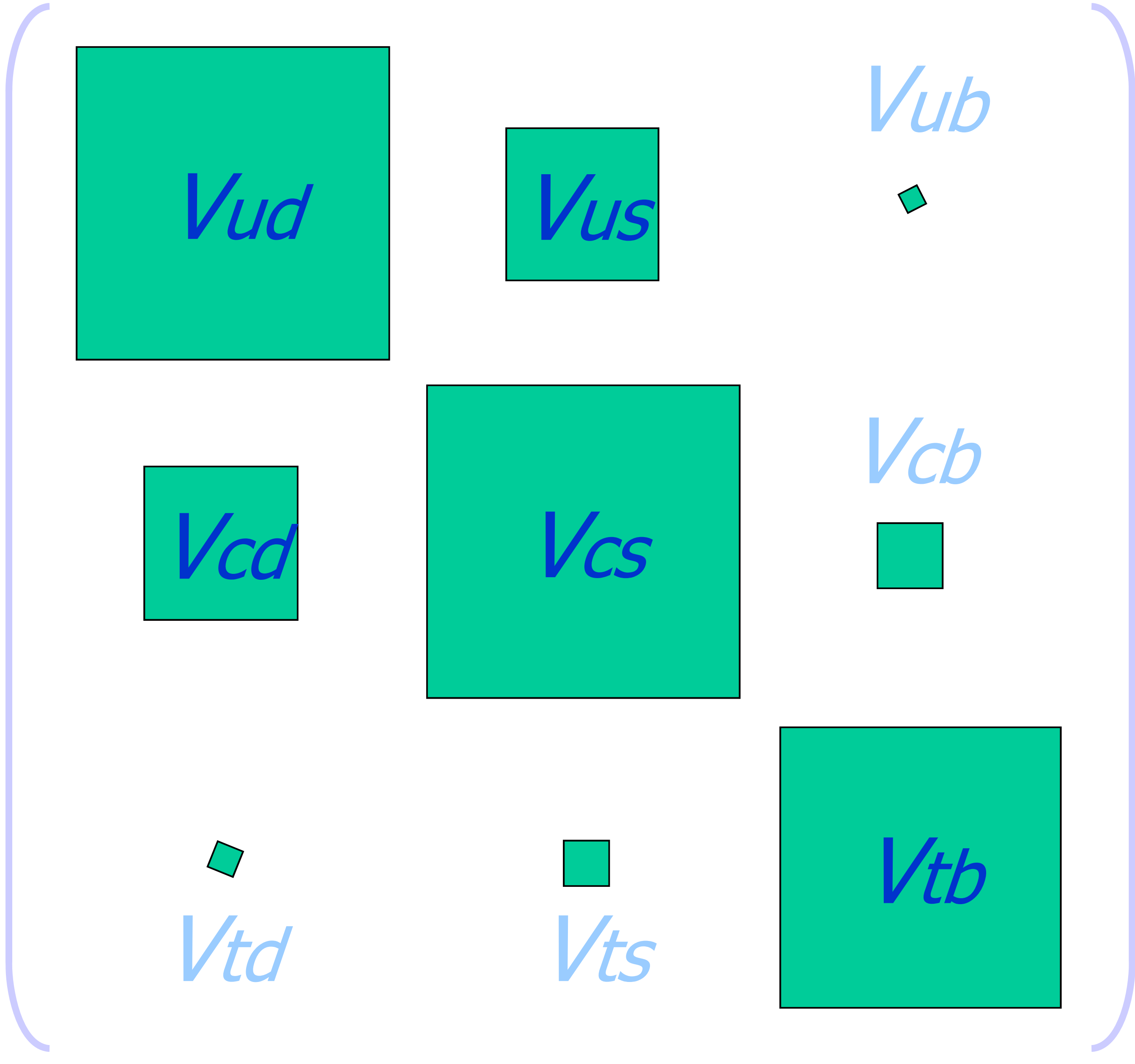


Transitions between members of the same family more probable (=thicker lines) than others

→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 (=sinθ_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

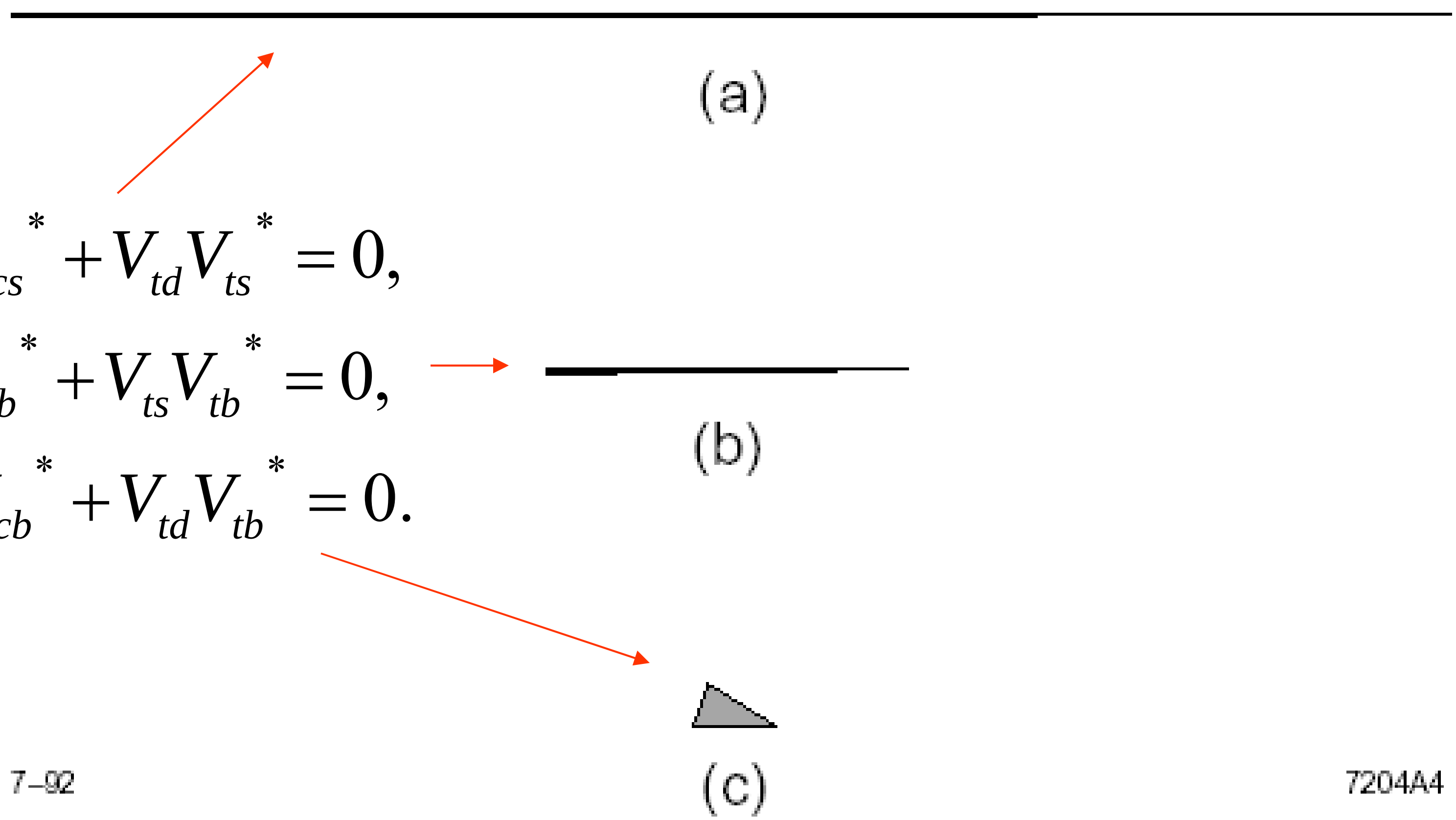
Rows and columns of the V matrix are orthogonal

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})

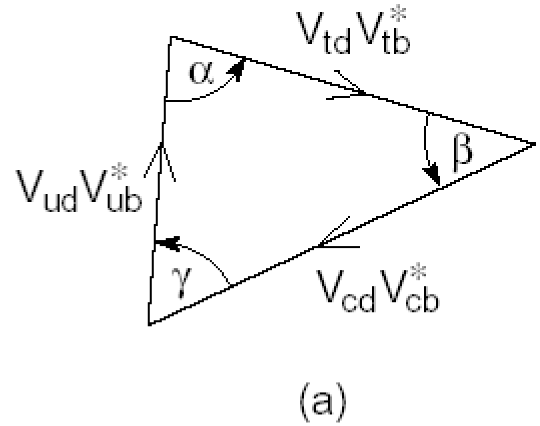
$$J=c_{12}c_{23}c_{13}^{2}s_{12}s_{23}s_{13}\sin\delta$$

Jarlskog invariant

Unitarity triangle

THE unitarity triangle:

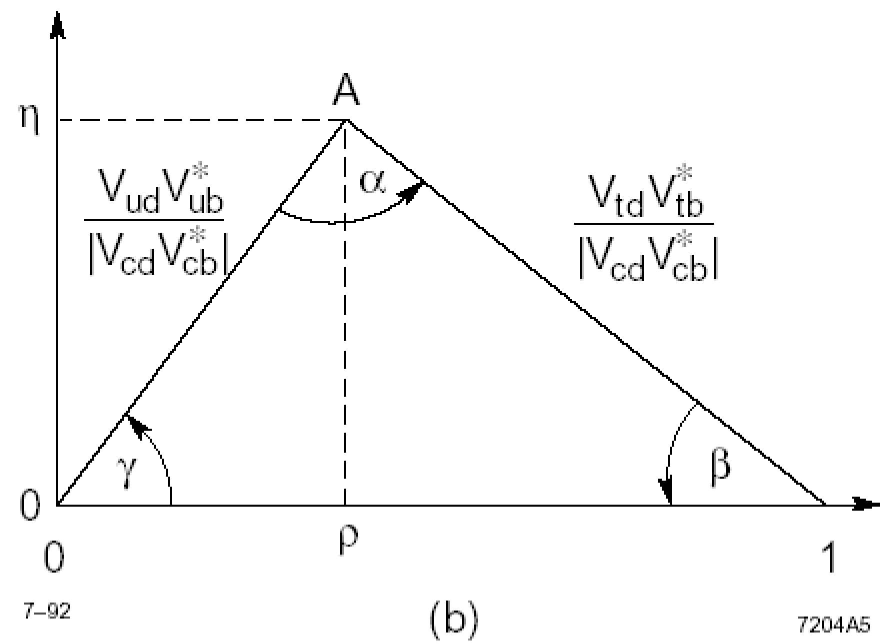
$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$$



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

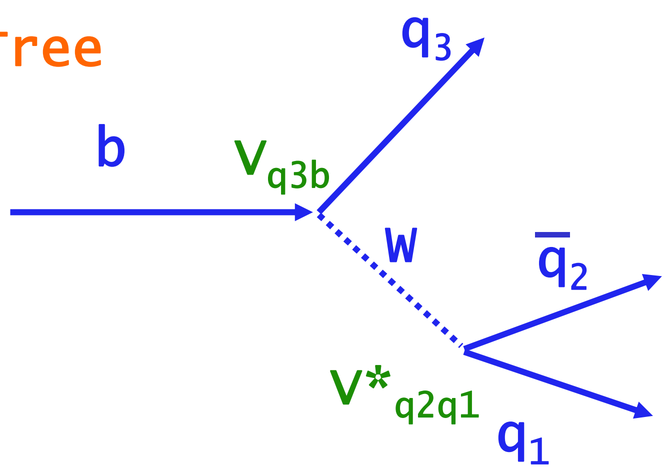
$$\beta \equiv \phi_1 \equiv \arg\left(\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right)$$

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

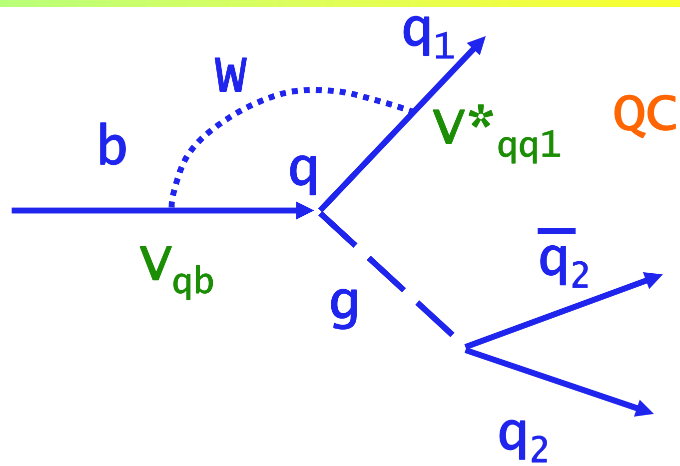


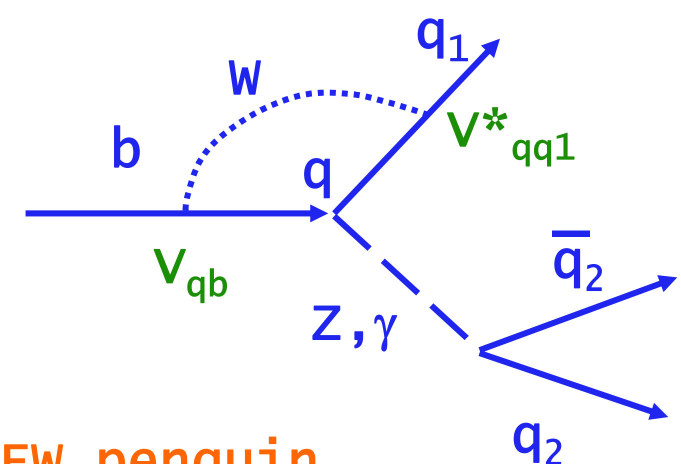
b decays

Tree



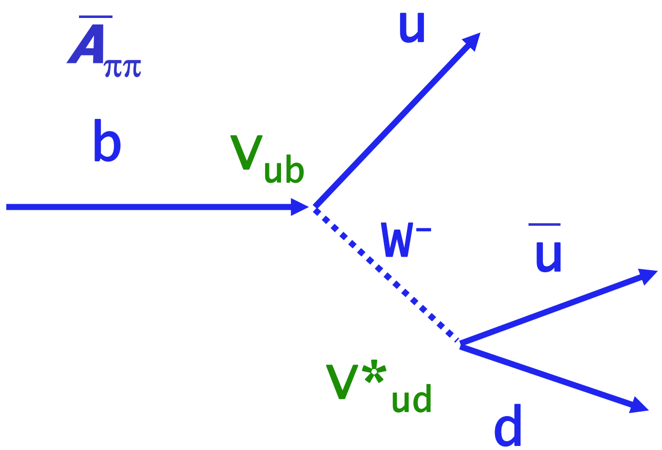
QCD penguin

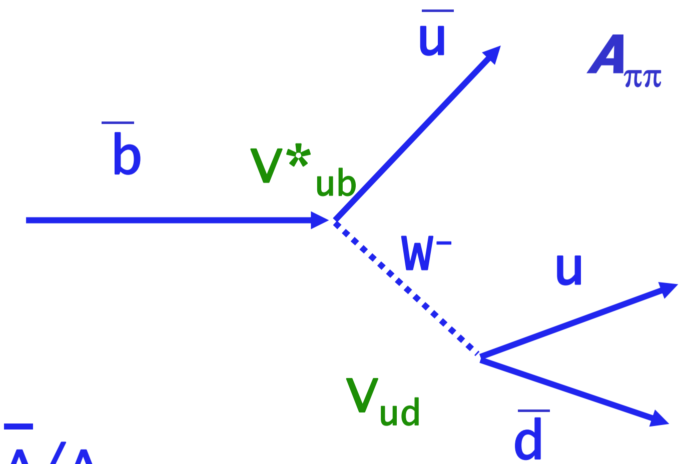




EW penguin

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





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

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

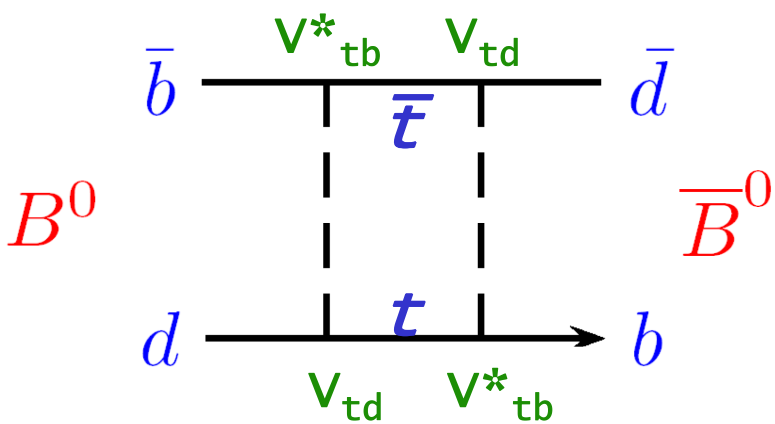
$$\alpha \equiv \phi_2 \equiv \arg\left(\frac{V_{td} V_{tb}{}^*}{V_{ud} V_{ub}{}^*}\right)$$

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

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

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

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

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

$b \rightarrow c$ 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}, $\eta_{f_{cp}}=+-1$

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

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

- J/ψ: P=-1, C=-1 (vector particle $J^{PC}=1^{--}$): CP=+1
- K_S ($\rightarrow \pi^+ \pi^-$): 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 CP 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
- 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 $B \rightarrow f_{CP}$ - CP eigenstate)

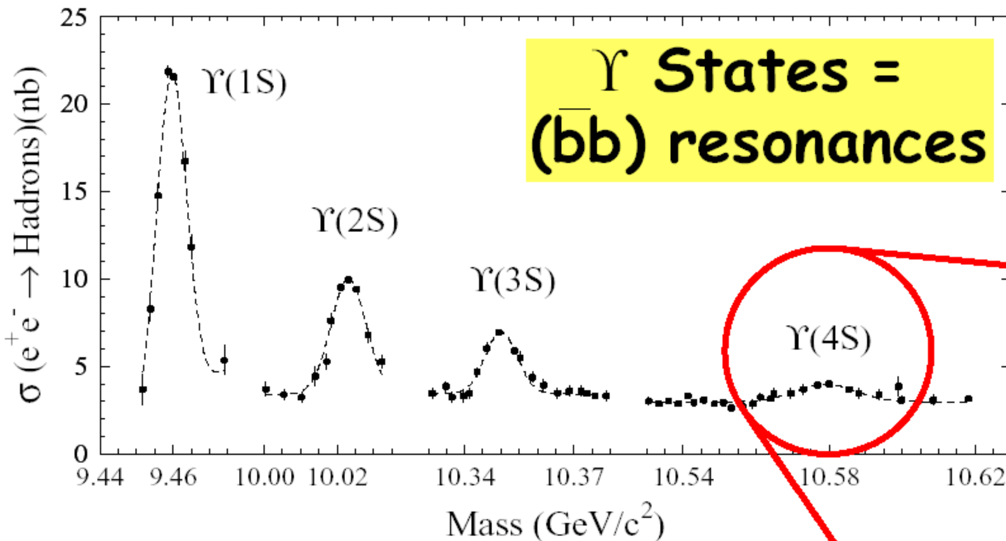
•Measure time difference between this decay and the decay of the associated B (f_{tag}) (from the flight path difference)

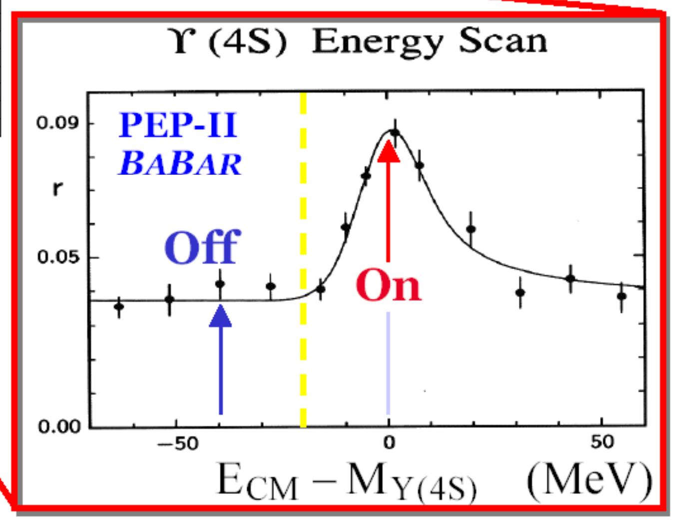
•Determine the flavour of the associated B (B or anti-B)

•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

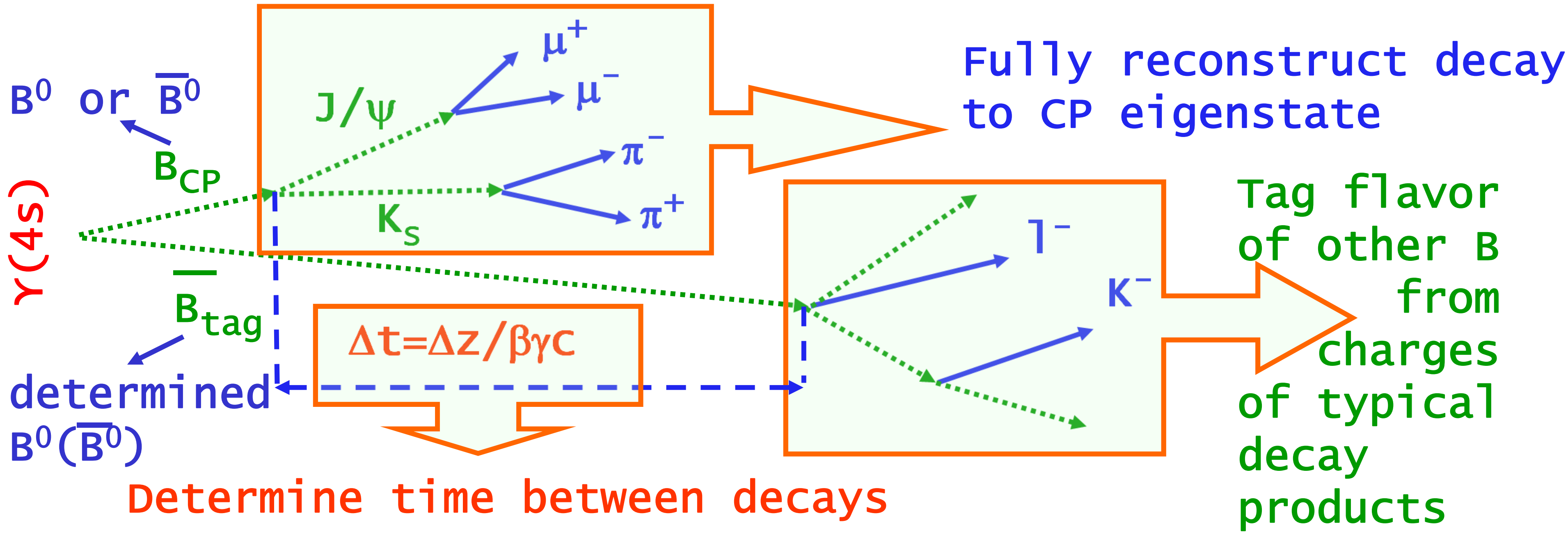
$d\bar{d}$, $s\bar{s} \sim 0.3$ nb

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

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

$L = 1$ state

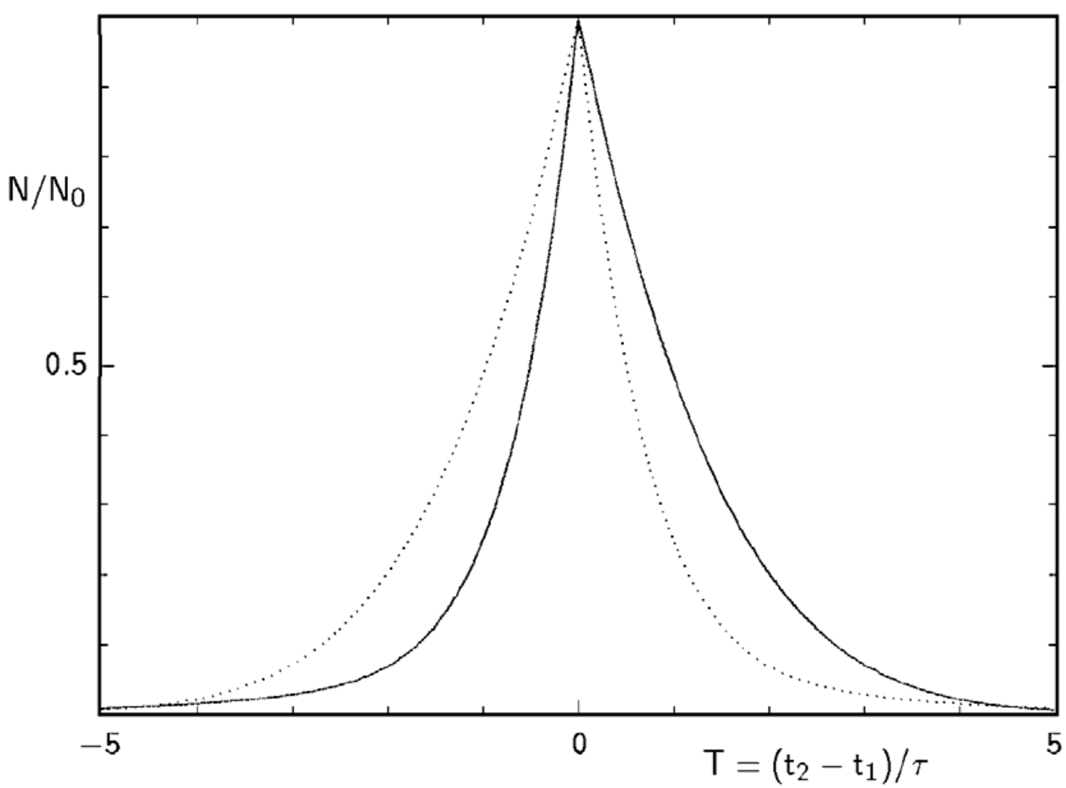
Principle of measurement



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).

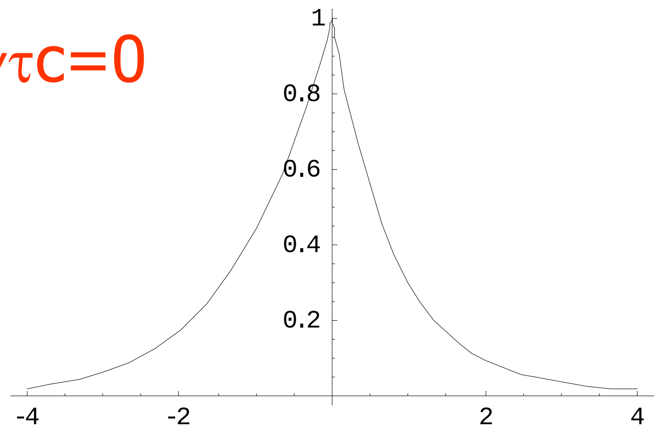
-> the two curves should not be smeared too much

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

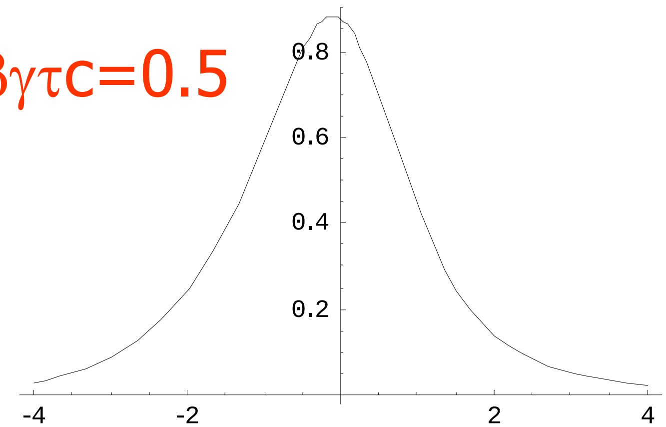
Experimental considerations

B decay rate vs t for different vertex resolutions σ(z) in units of typical B flight length βγτc

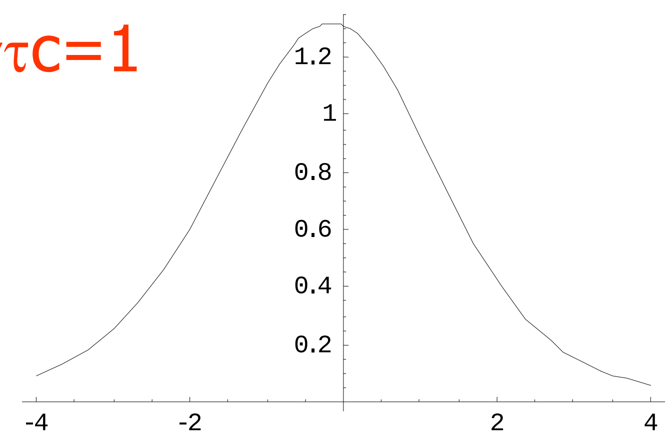
σ(z)/βγτc=0



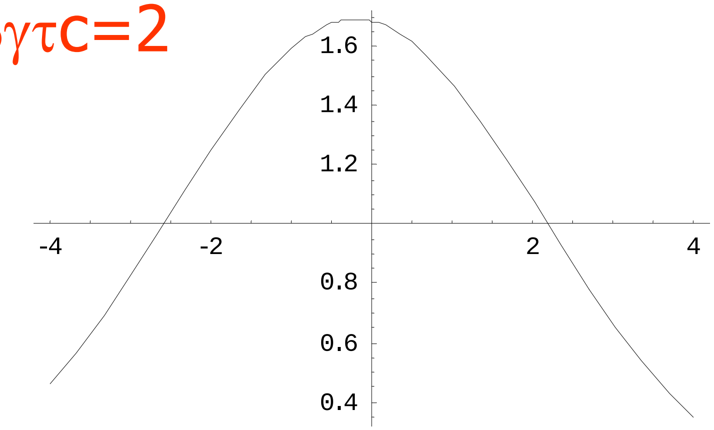
σ(z)/βγτc=0.5



σ(z)/βγτc=1



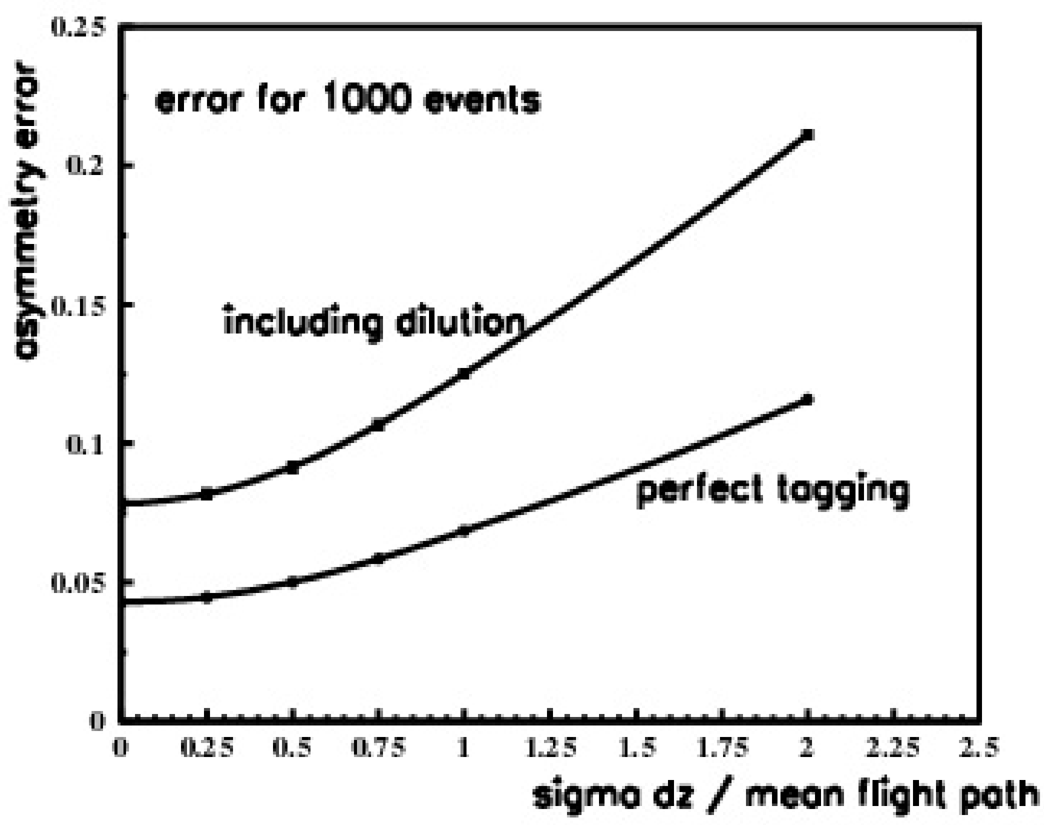
σ(z)/βγτc=2



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

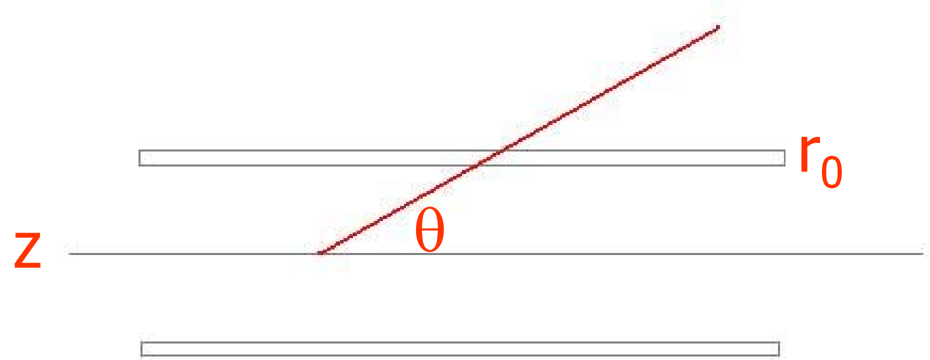
Choice of boost $\beta\gamma$:

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

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



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

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

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

Experimental considerations

Choice of boost $\beta\gamma$:

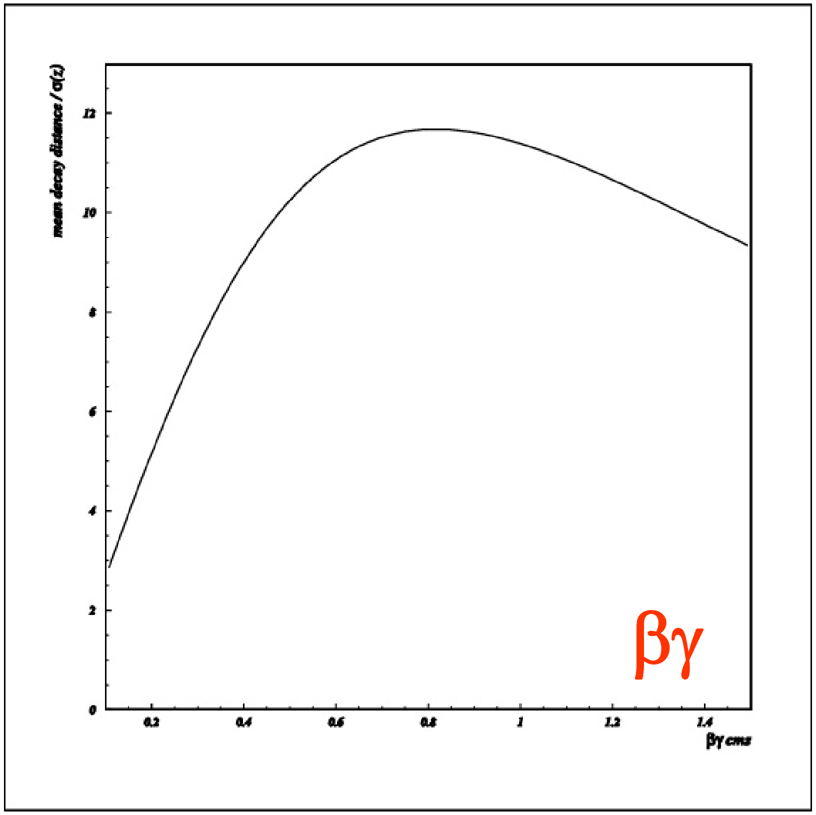
Optimize ratio of typical B flight length to the vertex resolution

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

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)

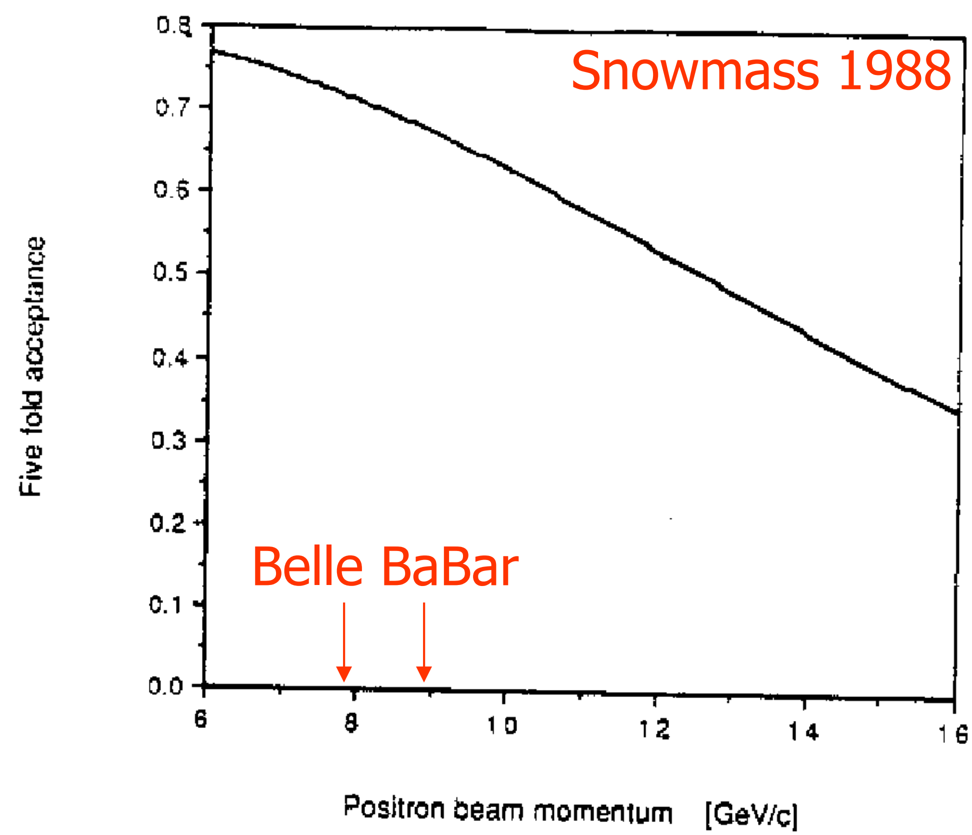
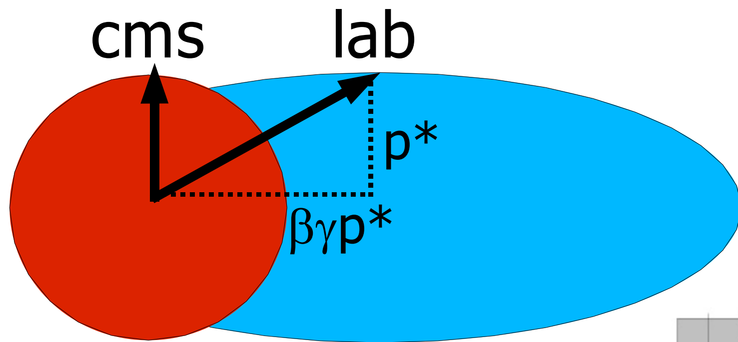


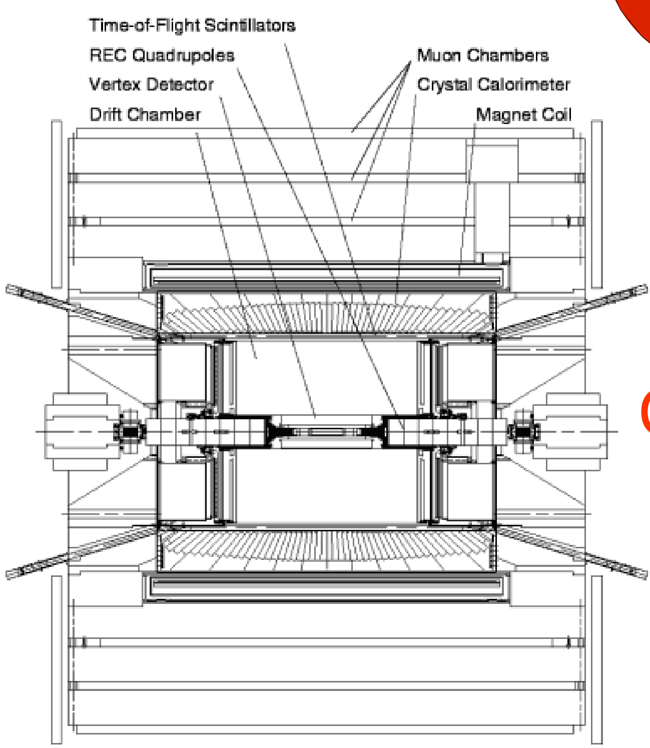
Figure 4. The acceptance of a detector covering $|\cos\theta_{lab}| < 0.95$ for five uncorrelated particles as a function of the energy of the more energetic beam in an asymmetric collider at the $\Upsilon(4S)$.

Experimental considerations

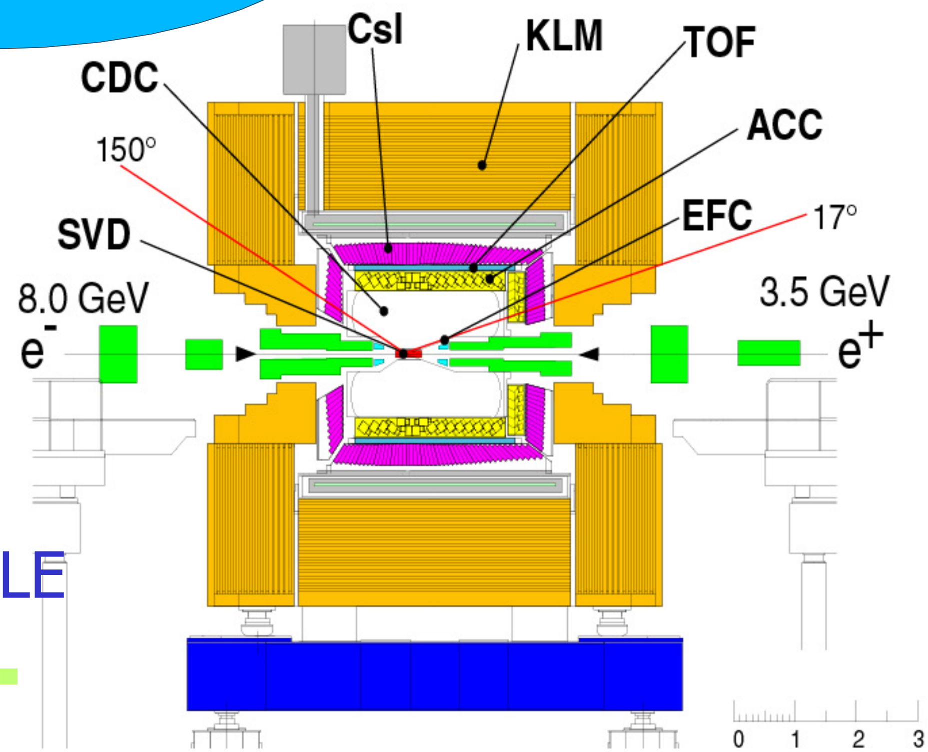
Detector form: symmetric for symmetric energy beams; slightly extended in the boost direction for an asymmetric collider.



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



CLEO



BELLE

How many events?

Rough estimate:

Need ~1000 reconstructed B-> $J/\psi\ K_S$ 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-> $J/\psi\ K^0$)=$8.4\ 10^{-4}$

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

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

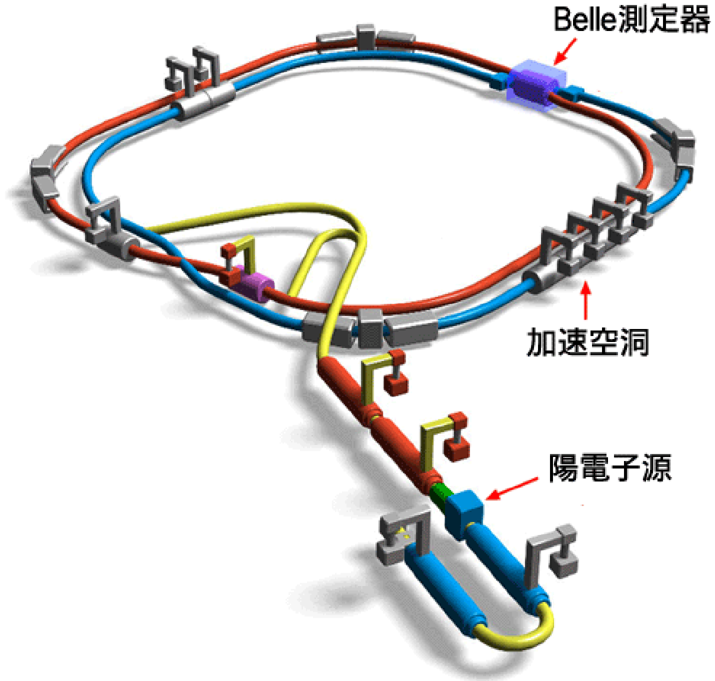
Cross section for Y(4s) production: 1.1 nb = 1.1 10^{-33} cm^2

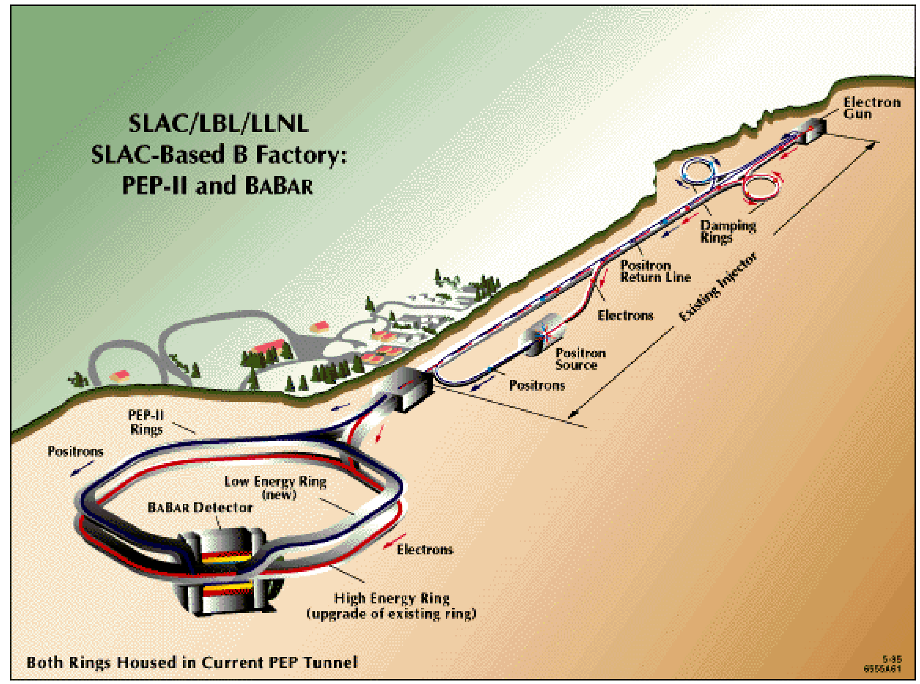
→ Accelerator figure of merit - luminosity - has to be

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

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

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

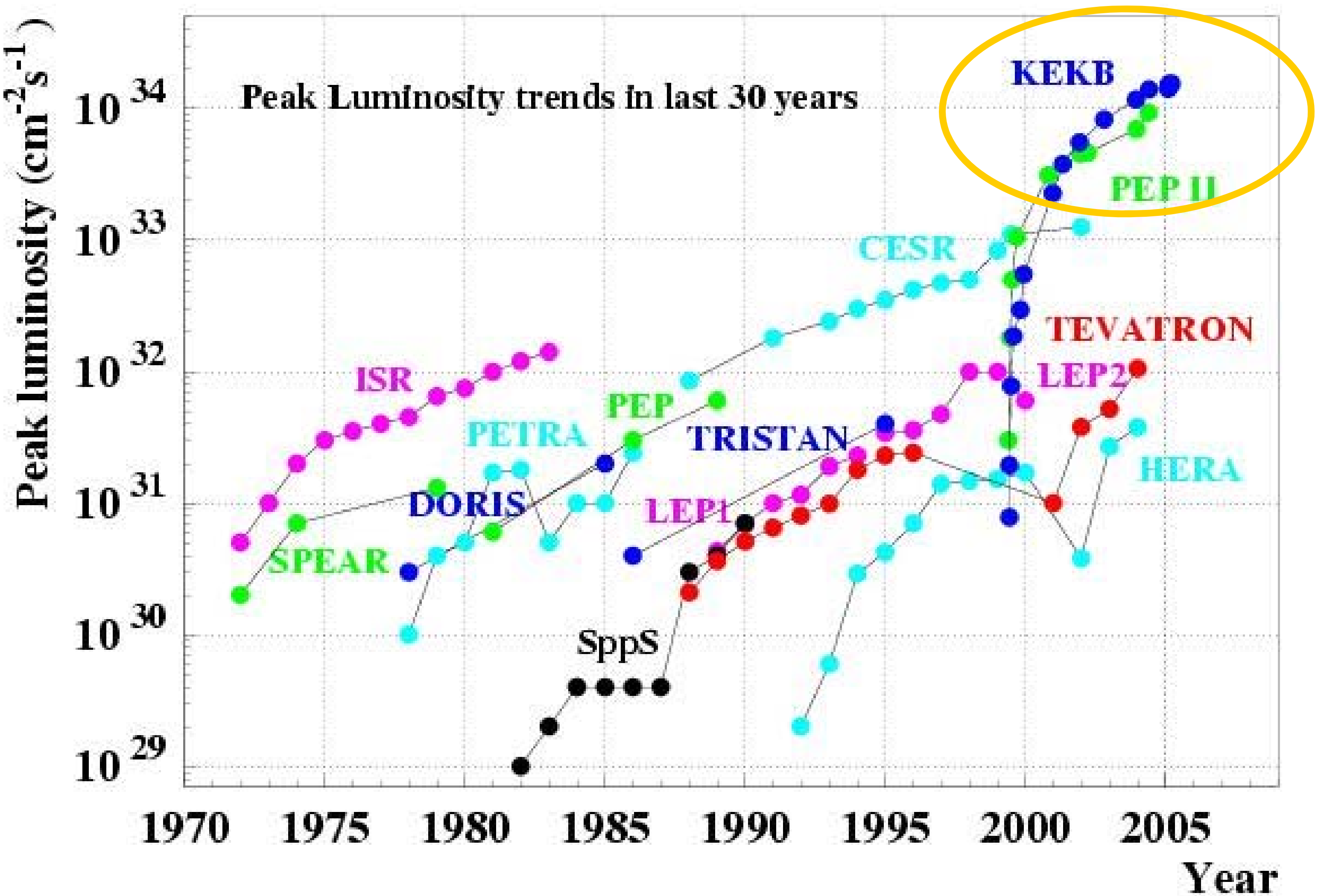
$\Delta z \sim c\beta\gamma\tau_B \sim 200\mu m$

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

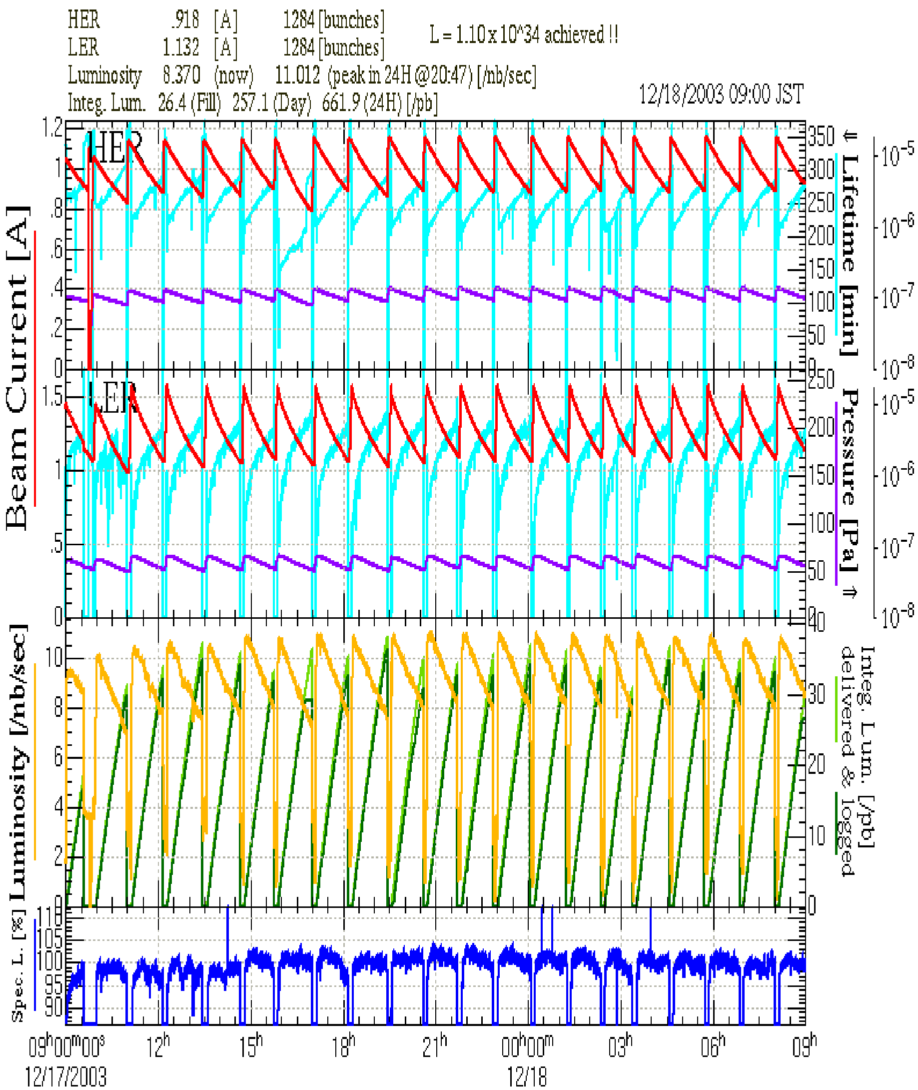
Belle $p(e^-)$=8 GeV $p(e^+)$=3.5 GeV $\beta\gamma$=0.42

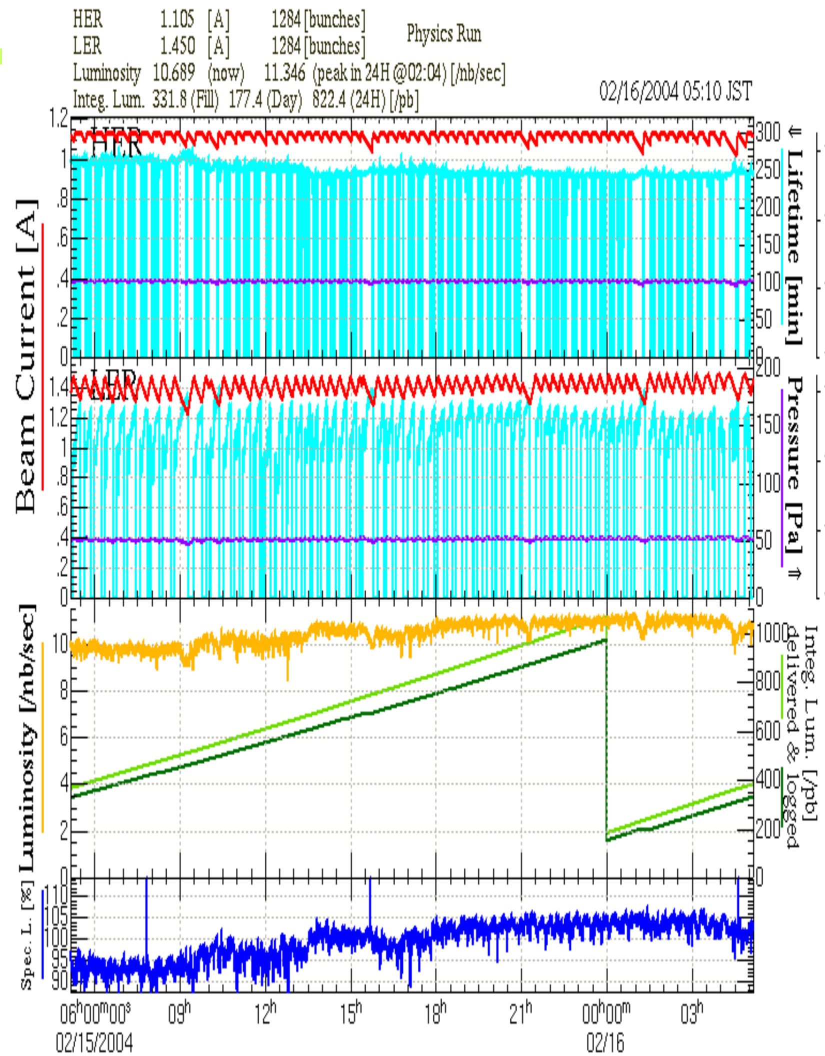

KEKB records: L_{peak} = 17/nb/sec (=1.7×10^{34} $s^{-1}cm^{-2}$)
L_{int}= 852/fb → ~900 M BB pairs
BELLE

Accelerator performance



Normal injection *Continuous injection*

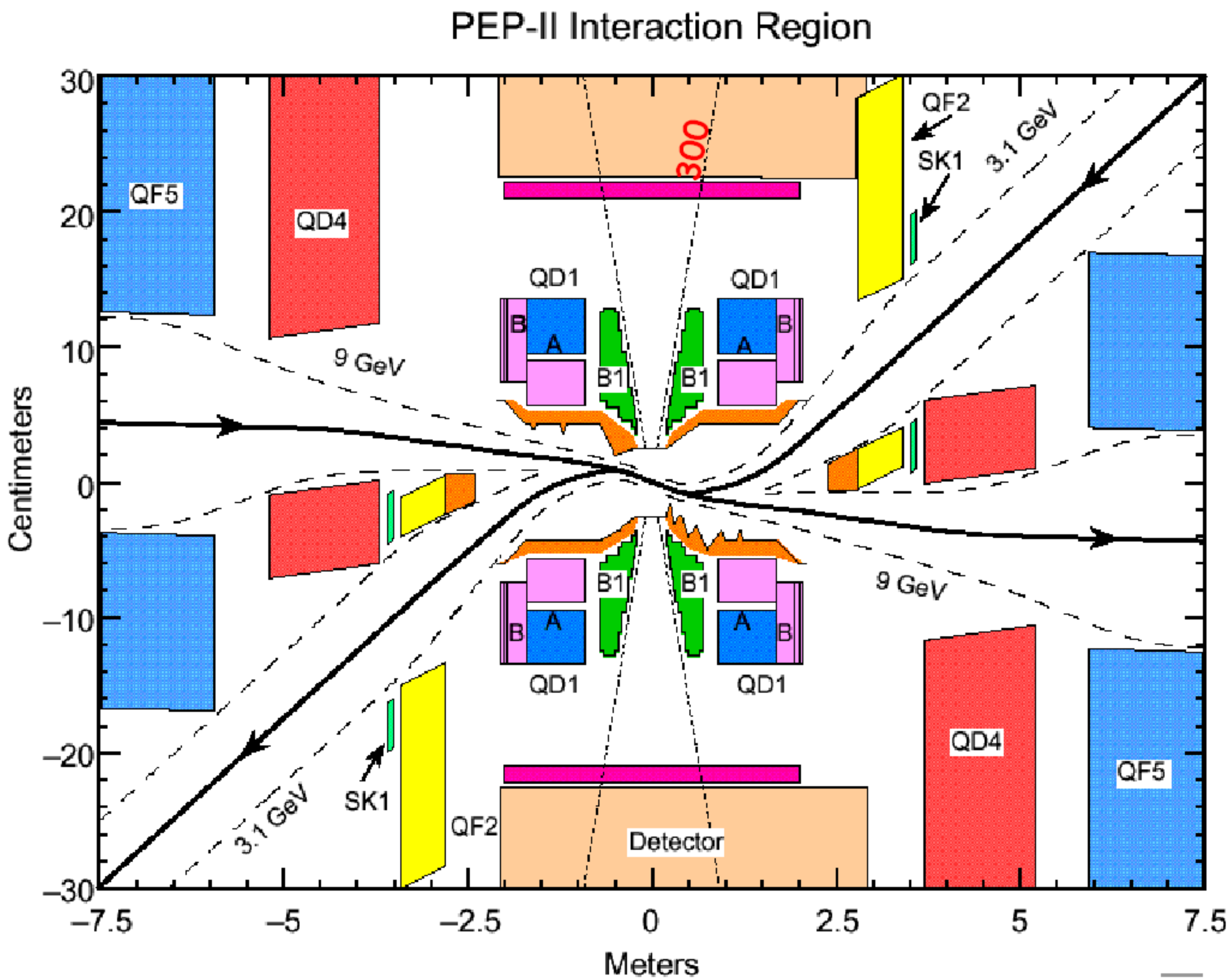




661/pb/day **→1182/pb/day**

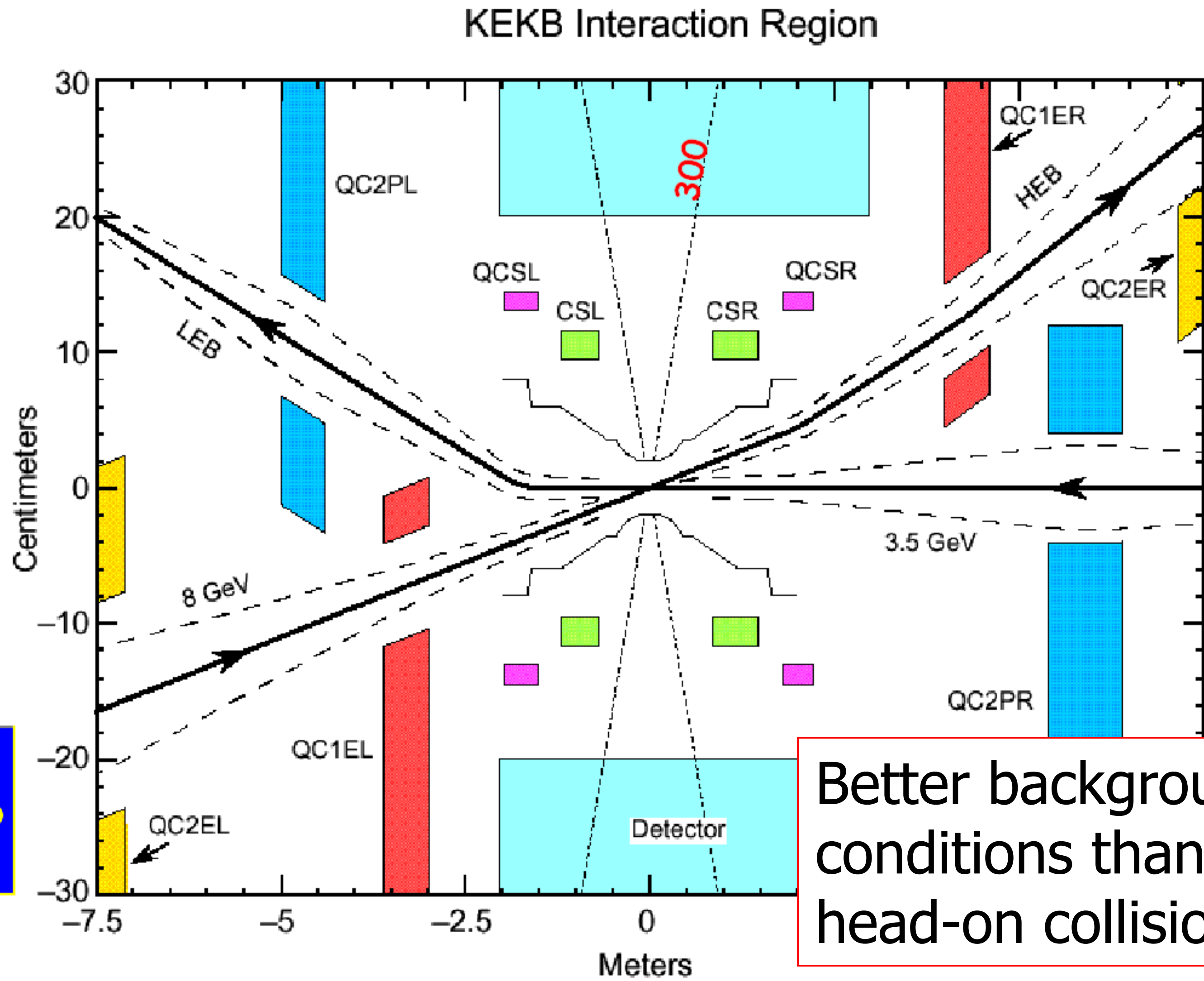
Interaction region: BaBar

Head-on collisions



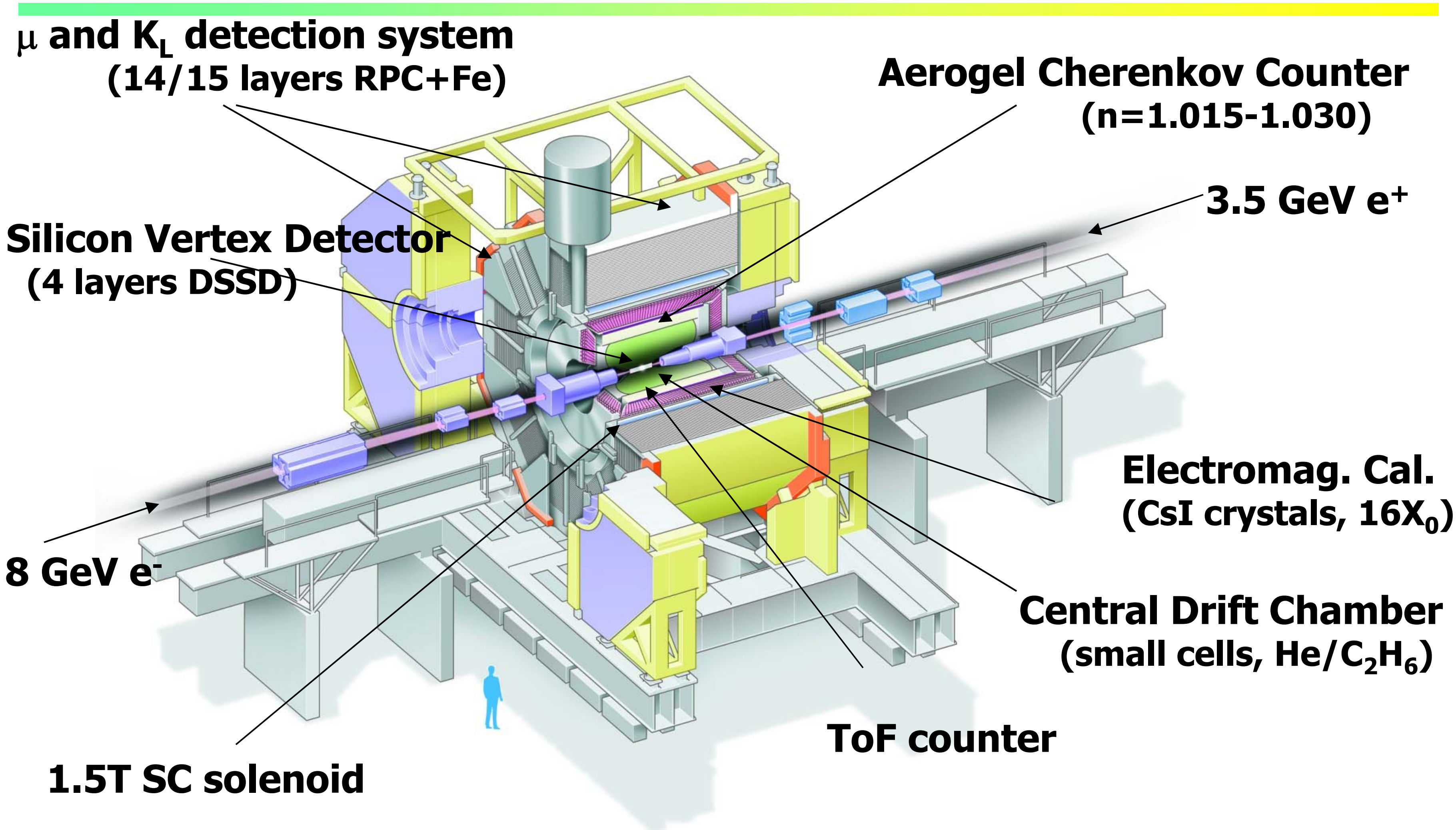
Interaction region: Belle

Collisions at a finite angle +-11mrad

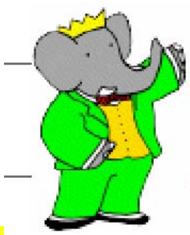


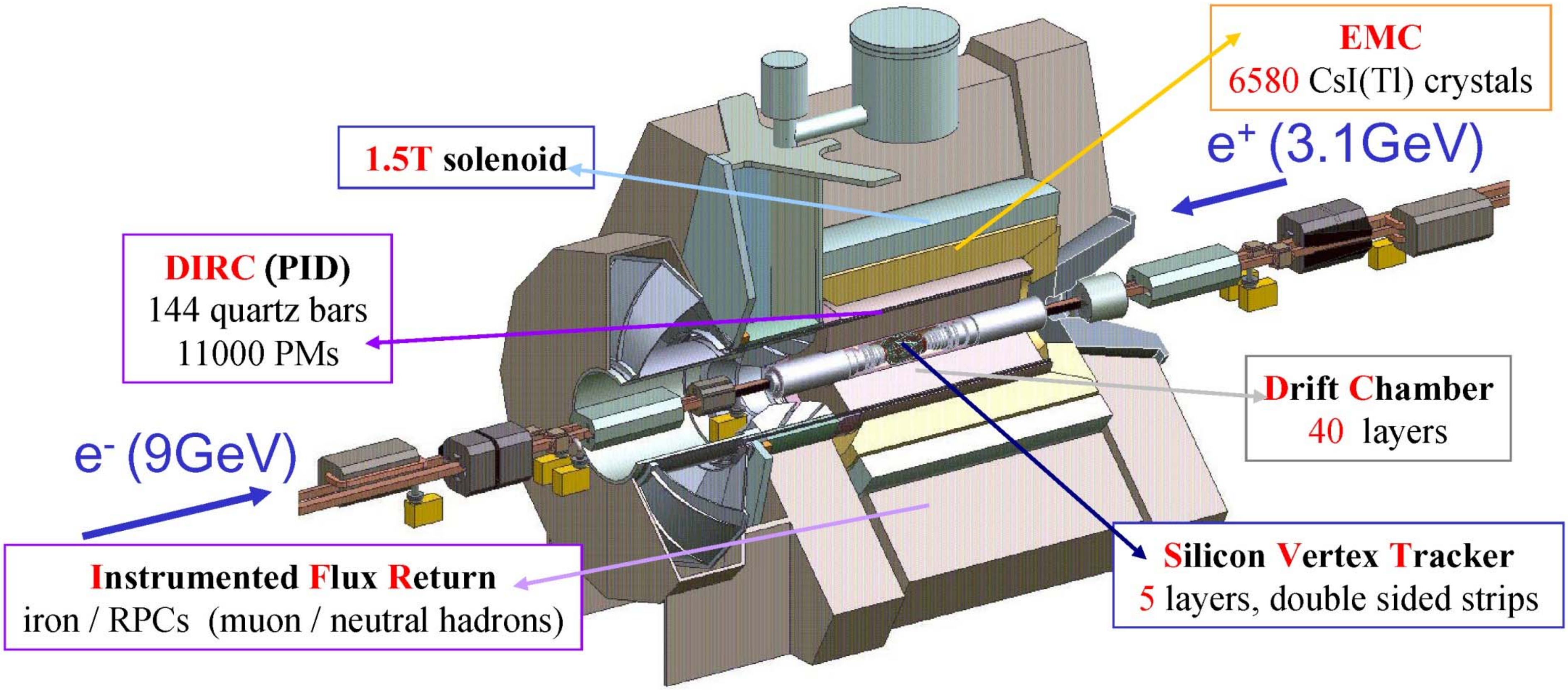
Better background conditions than in head-on collisions!

Belle spectrometer at KEK-B

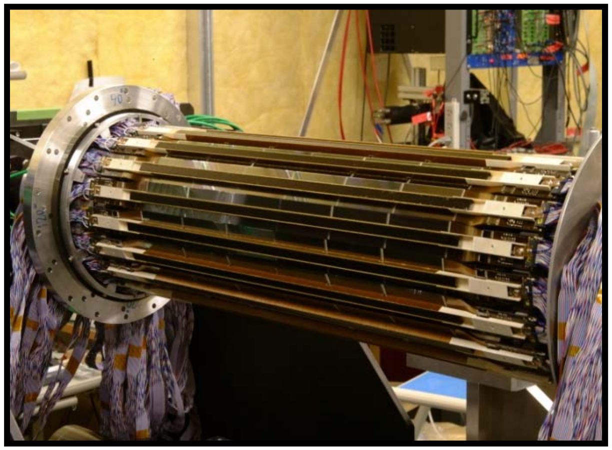


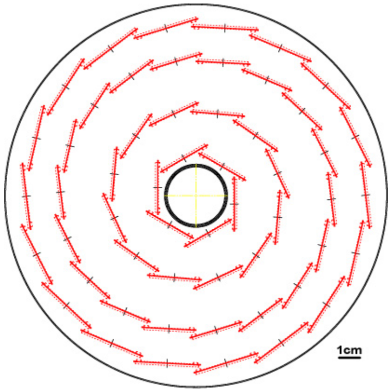
BaBar spectrometer at PEP-II

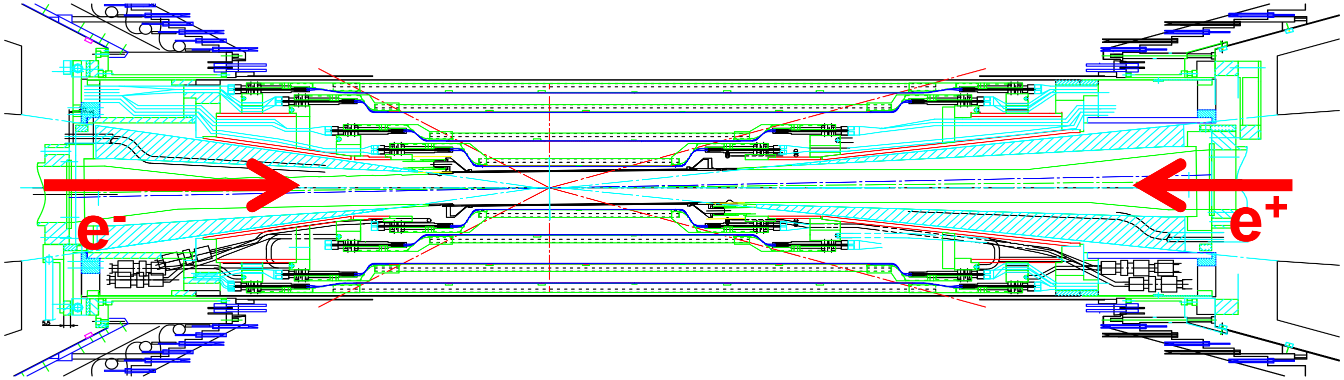




Silicon vertex detector (SVD)







4 layers

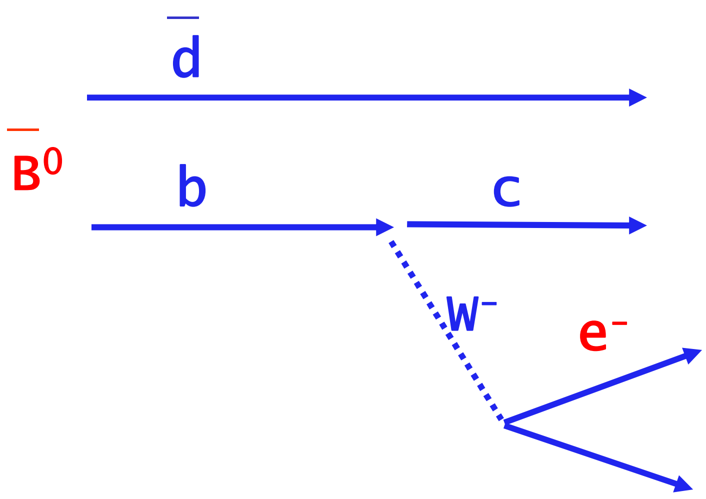
covering polar angle from 17 to 150 degrees

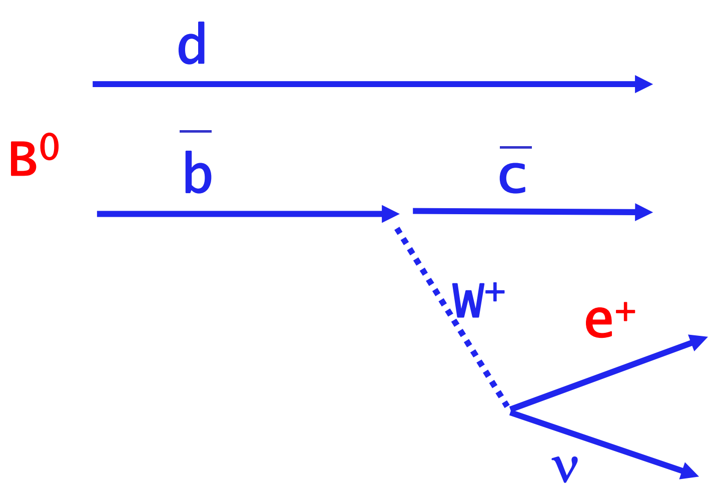
Flavour tagging

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,

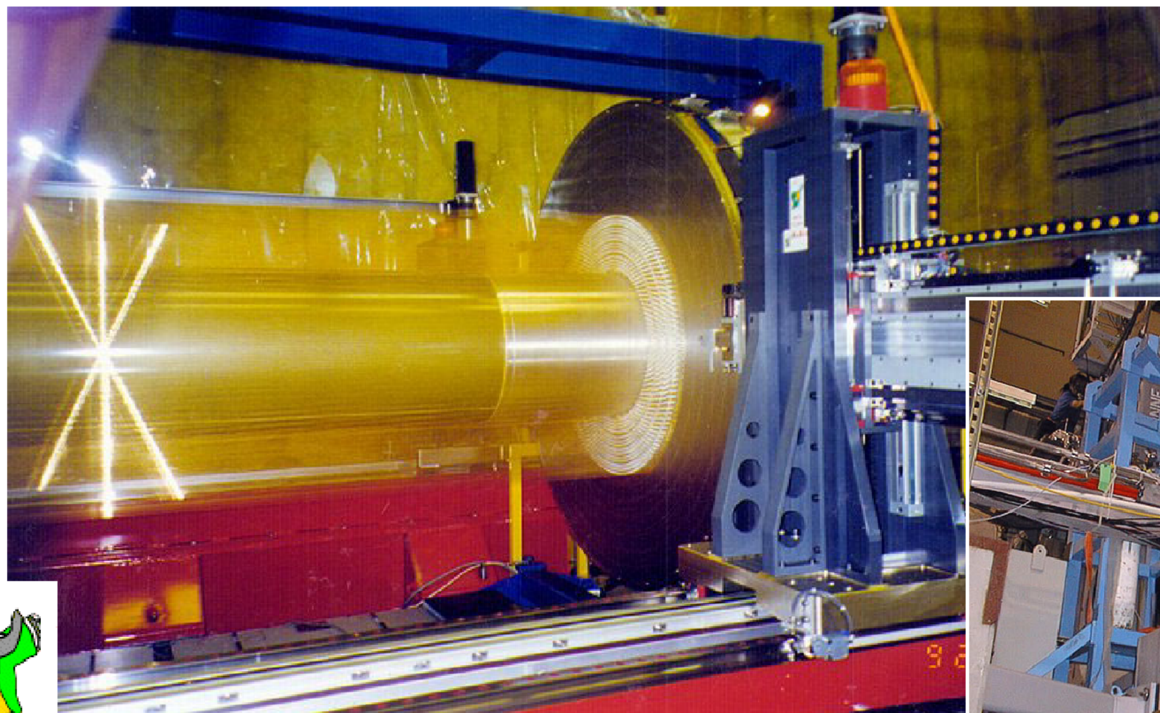
→ need reliable particle identification

Tracking: BaBar drift chamber

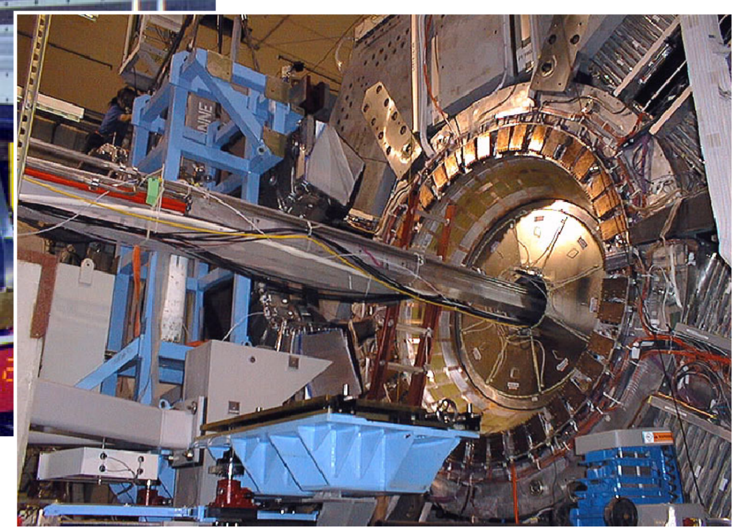
40 layers of wires (7104 cells) in 1.5 Tesla magnetic field

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):

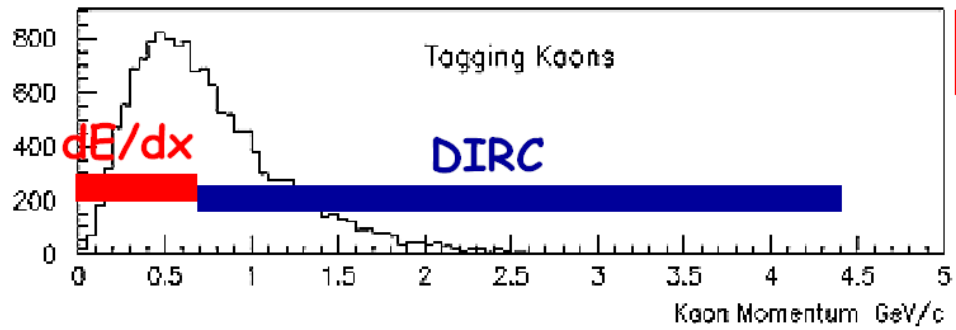
- Time-of-flight (TOF)
- dE/dx in a large drift chamber
- Cherenkov counters

K_L: instrumented magnet yoke

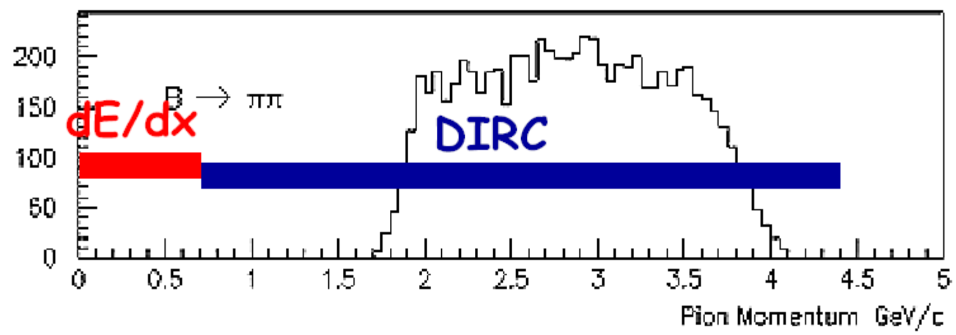
Electrons: electromagnetic calorimeter

Muon: instrumented magnet yoke

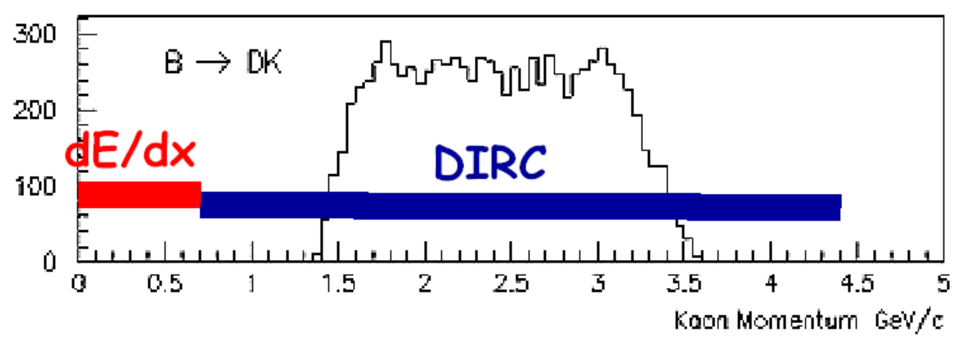
PID coverage of kaon/pion spectra



Tagging Kaons

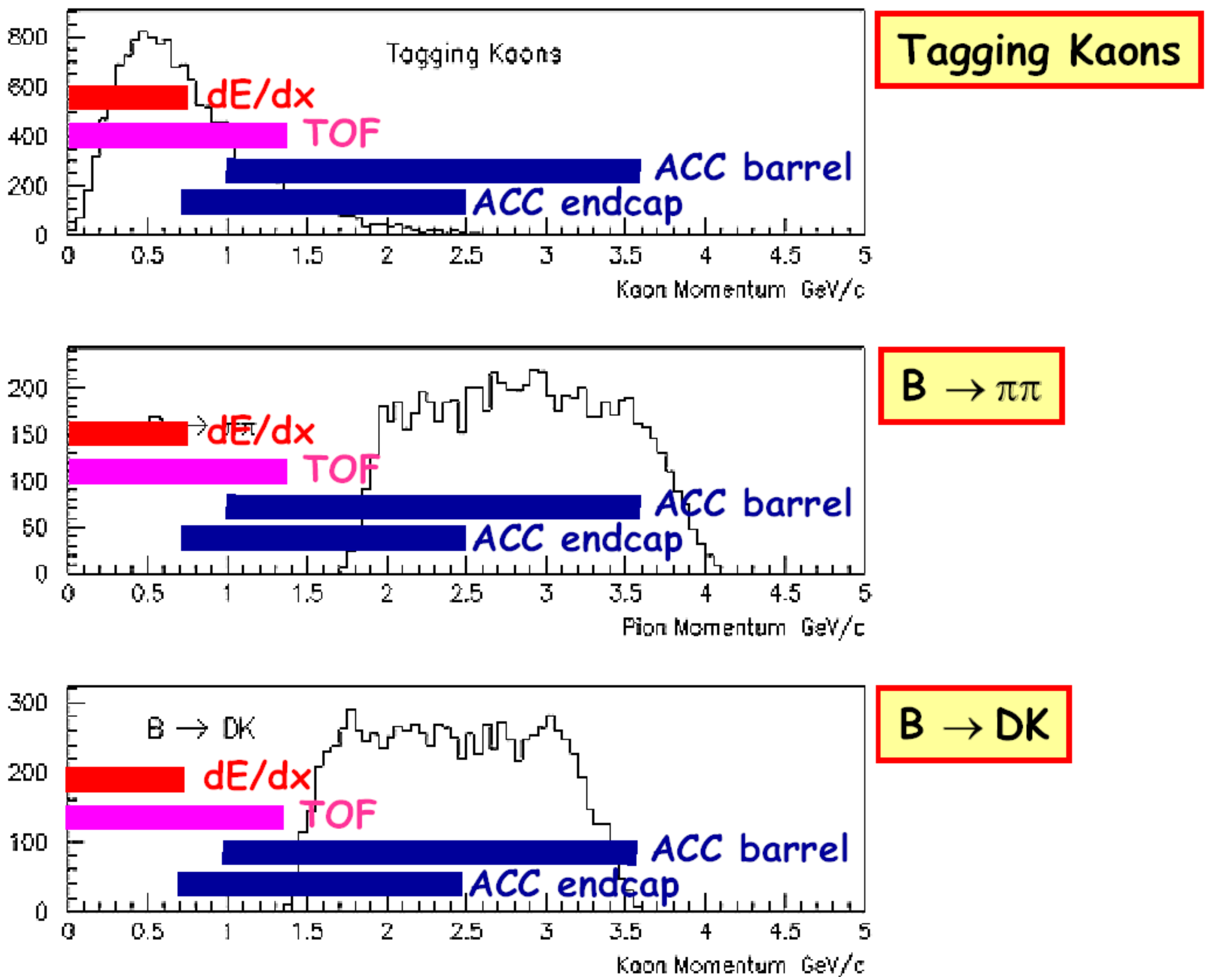


$B \rightarrow \pi\pi$



$B \rightarrow DK$

PID coverage of kaon/pion spectra



Cherenkov counters

Essential part of particle identification systems.

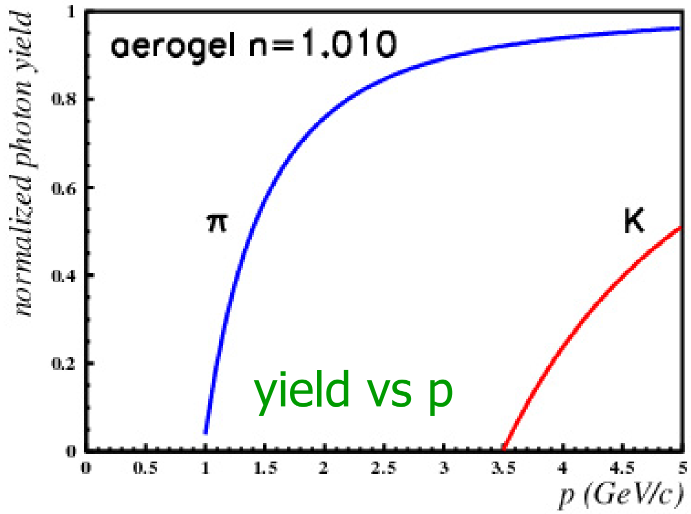
Cherenkov relation: $\cos\theta = c/nv = 1/\beta n$

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

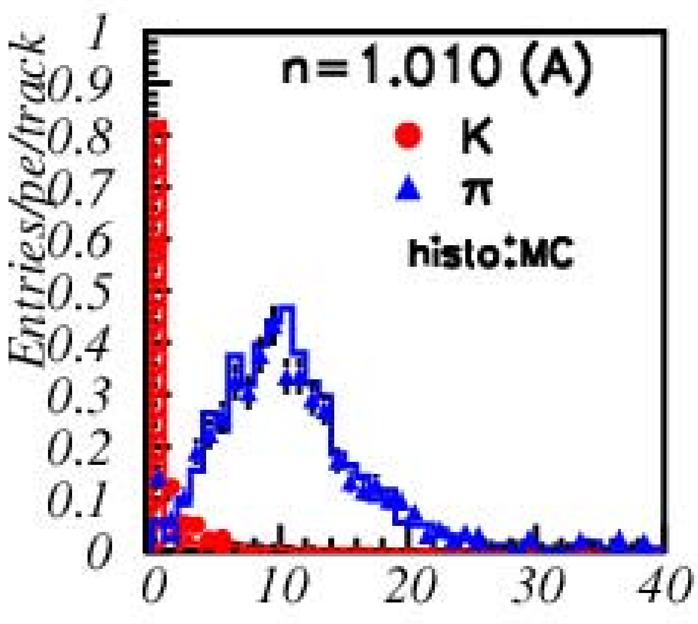
Ring Imaging (RICH) counter → measure Čerenkov angle and count photons

Belle ACC (aerogel Cherenkov counter): threshold Čerenkov counter

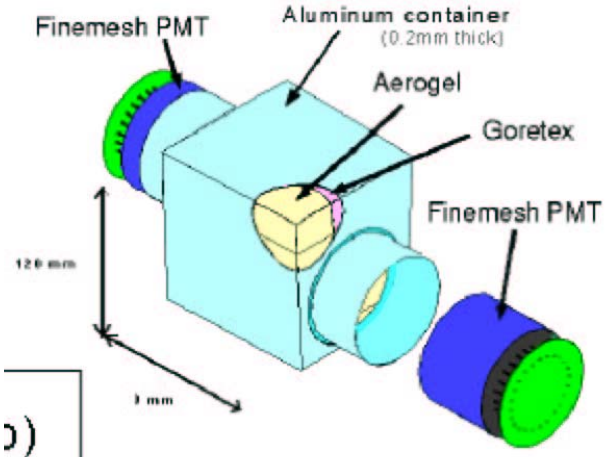
K (below thr.) vs. π (above thr.): adjust n



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

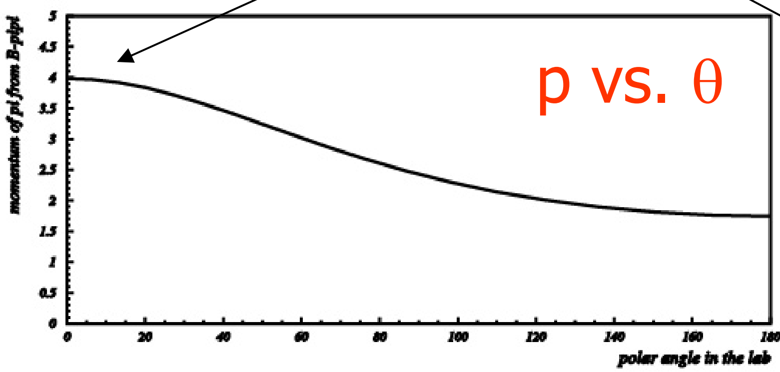


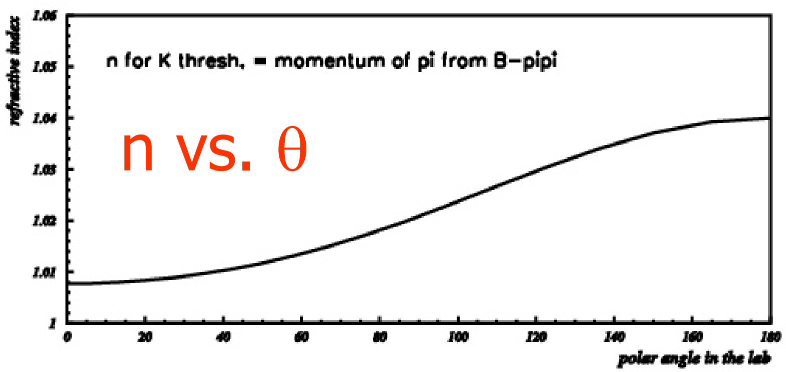
Detector unit: a block of aerogel
and two fine-mesh PMTs

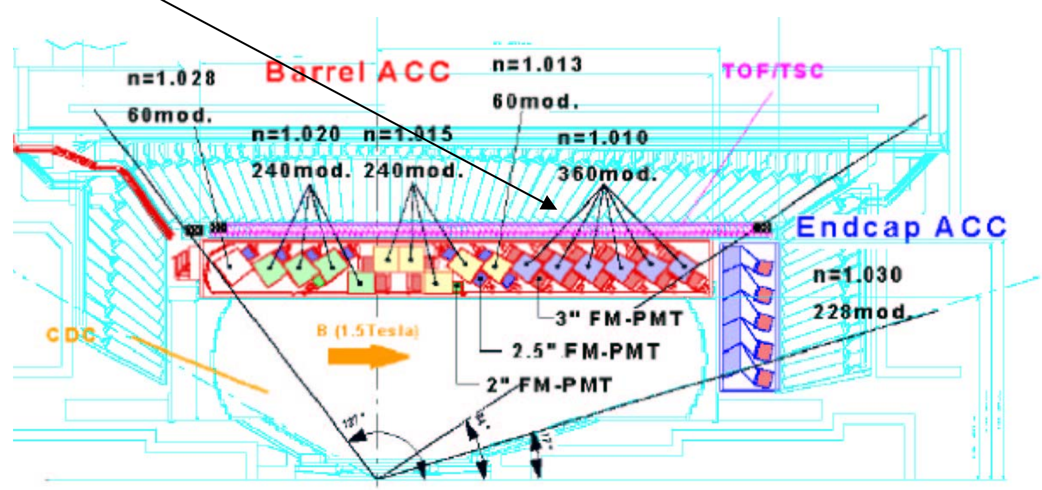


Belle ACC (aerogel Cherenkov counter): threshold Cherenkov counter

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

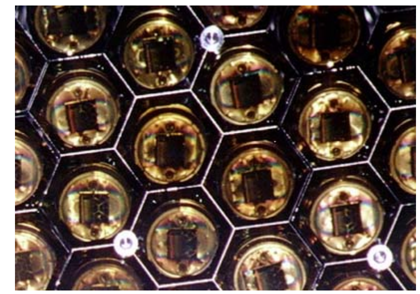




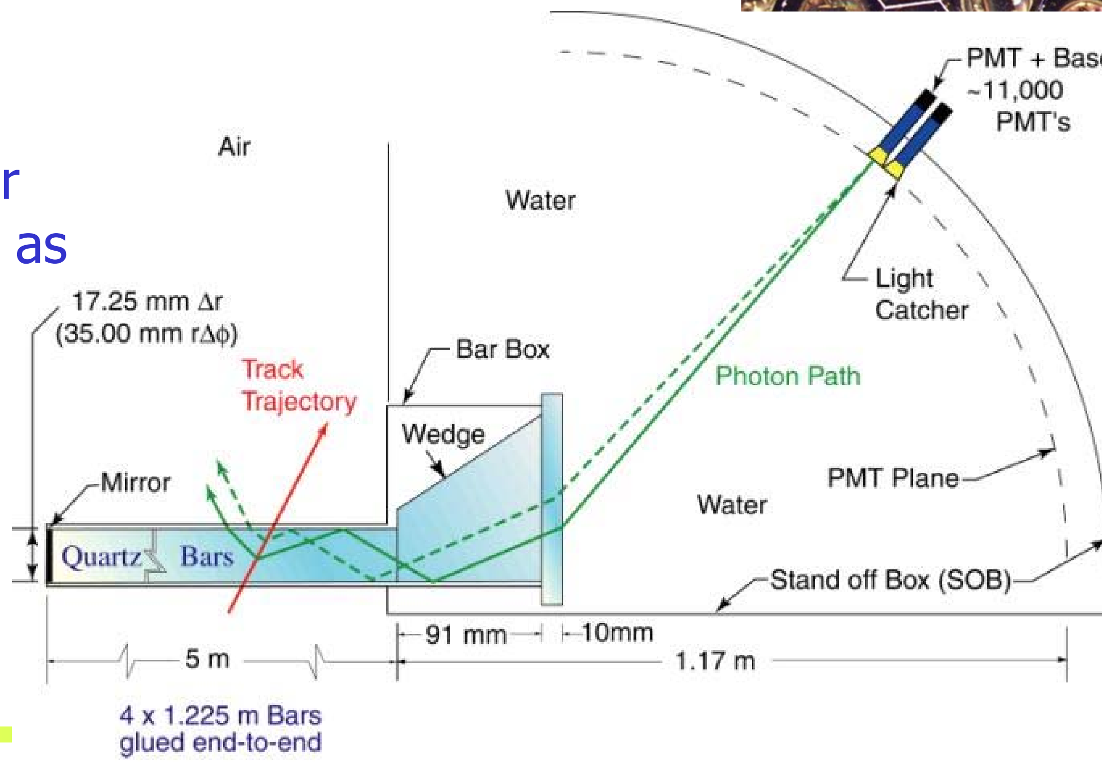


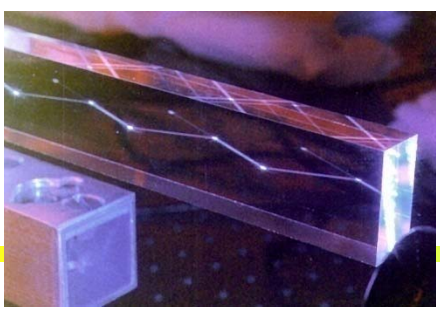
DIRC: Detector of Internally Reflected Cherekov photons

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



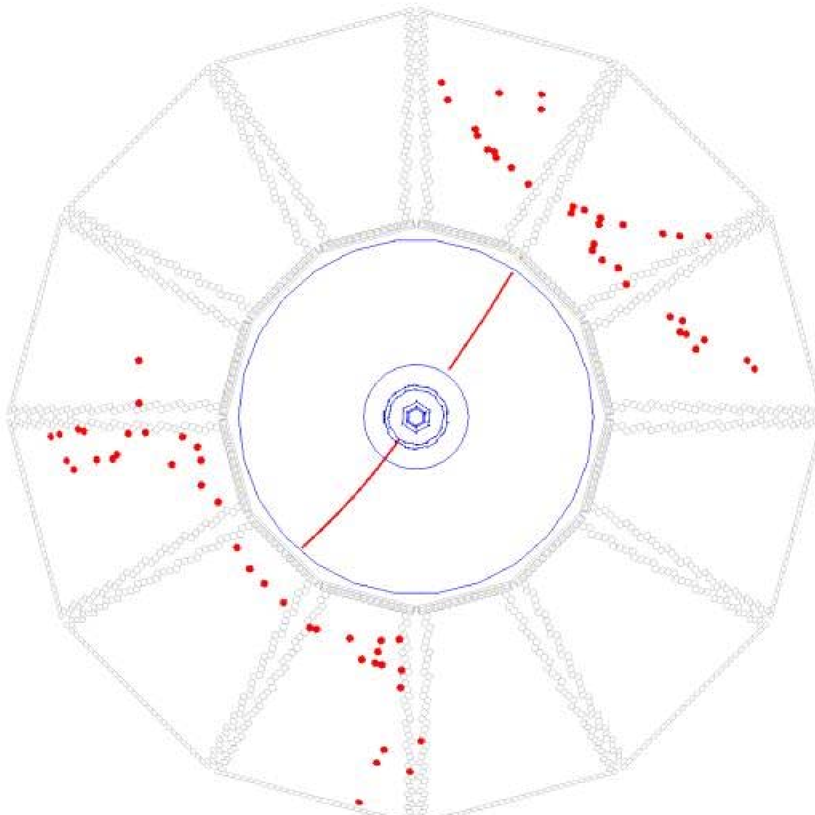
DIRC: a special kind of RICH (Ring Imaging Cherenkov counter) where Čerenkov photons trapped in a solid radiator (e.q. quartz) are propagated along the radiator bar to the side, and detected as they exit and traverse a gap.



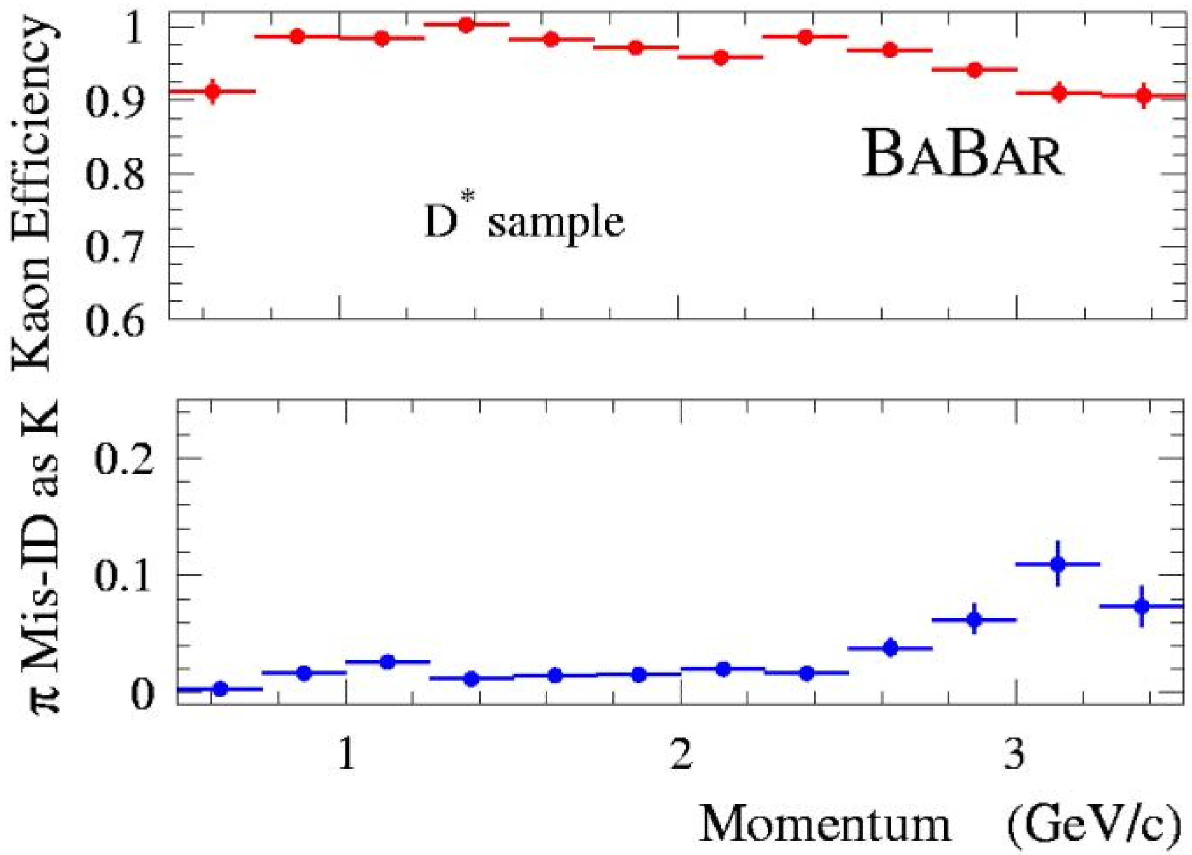


DIRC event

Babar DIRC: a Bhabha event $e^+ e^- \text{-->} e^+ e^-$



DIRC performance



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

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.

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

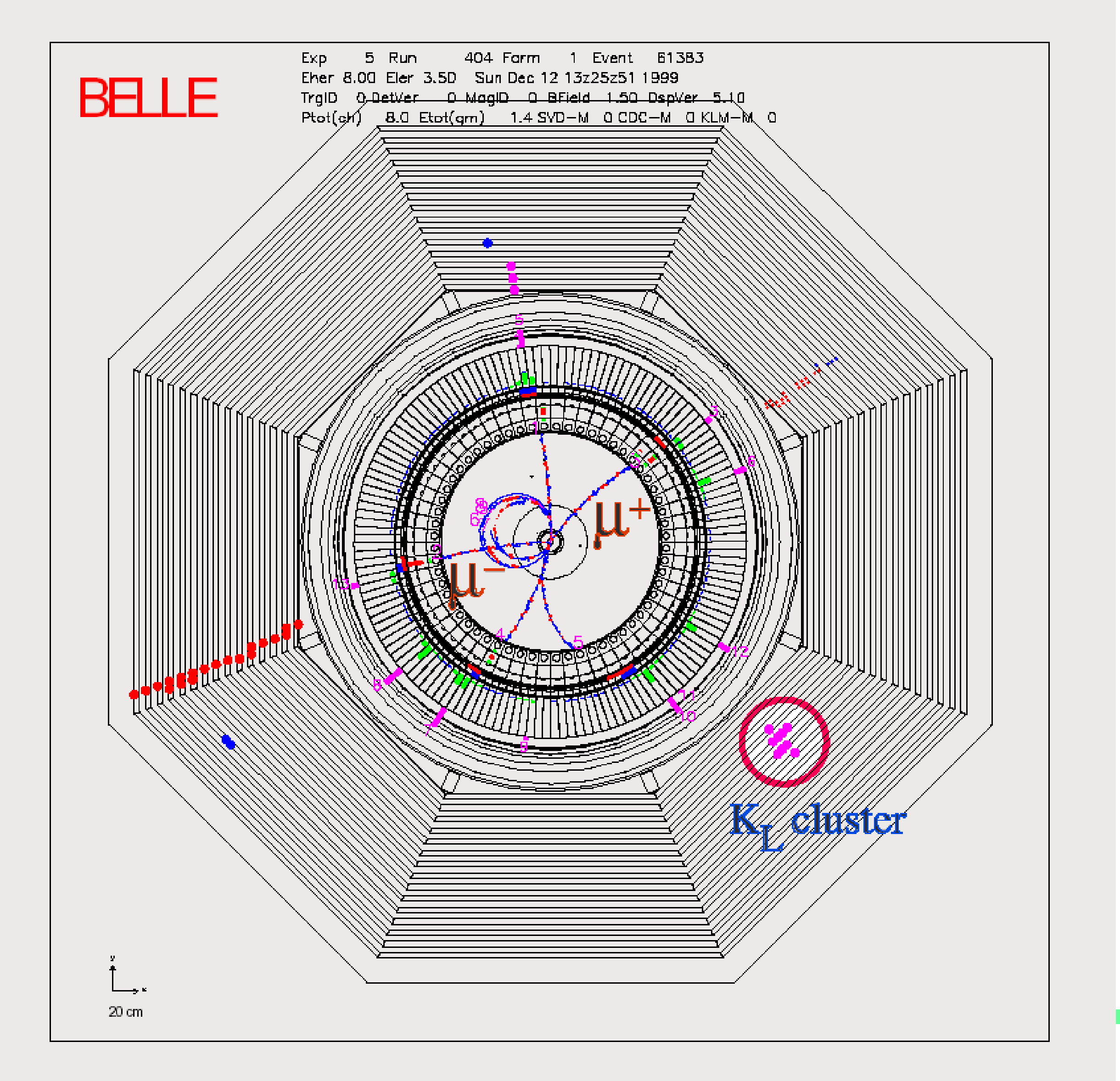
Example:

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

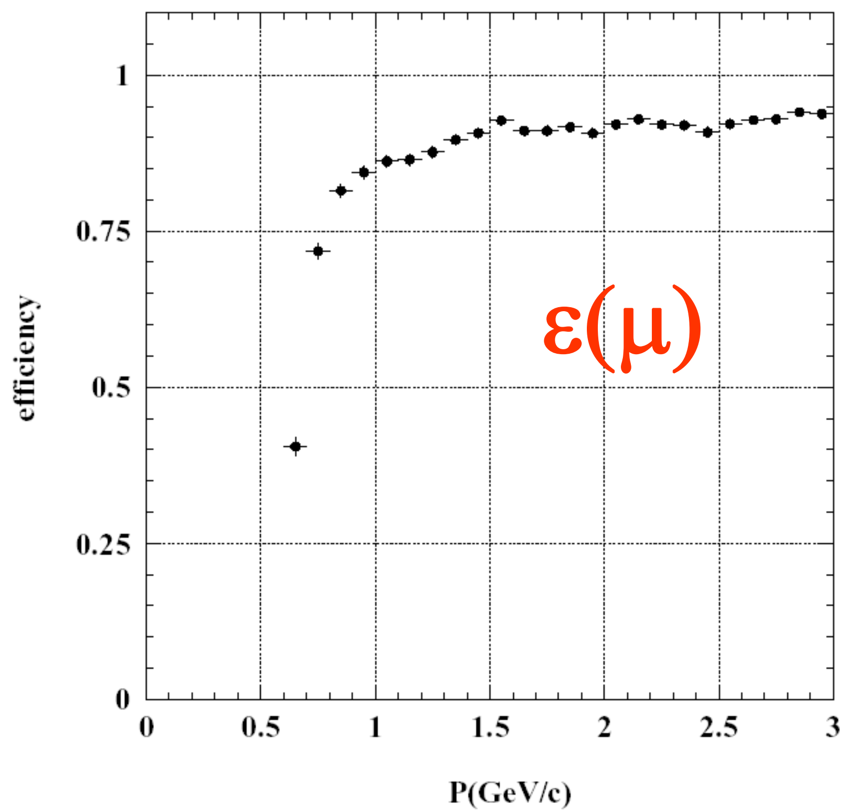


Fig. 109. Muon detection efficiency vs. momentum in KLM.

fake probability

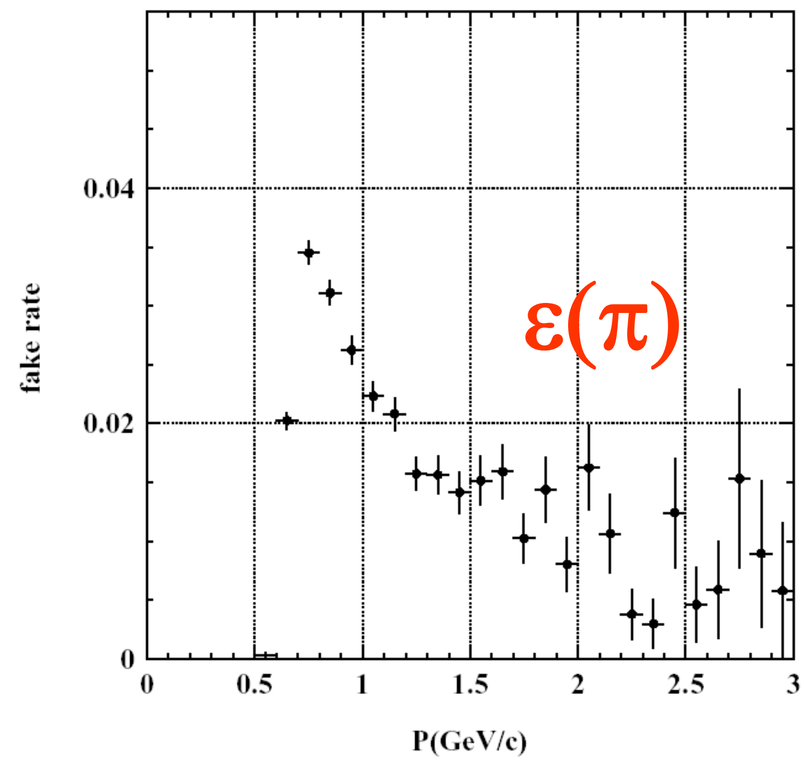


Fig. 110. Fake rate vs. momentum in KLM.

Muon and K_L detector performance

K_L detection: resolution in direction →

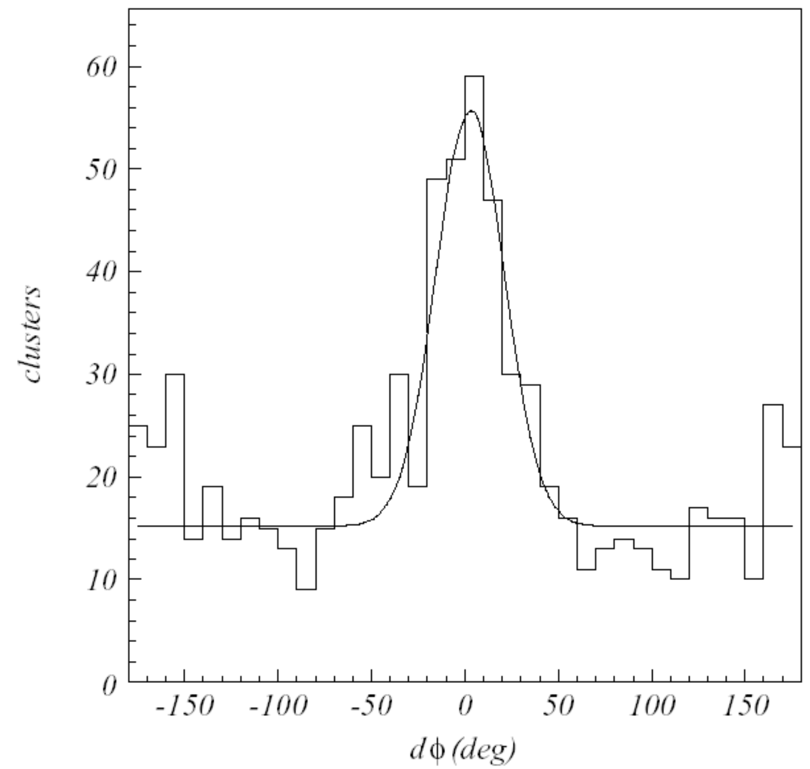
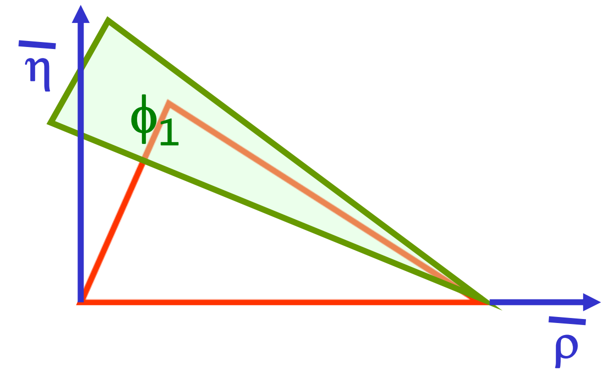


Fig. 107. Difference between the neutral cluster and the direction of missing momentum in KLM.

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 $B^0 \to J/\Psi\ K_s$ 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 $B^0 \to J/\Psi\ K_s$ 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).

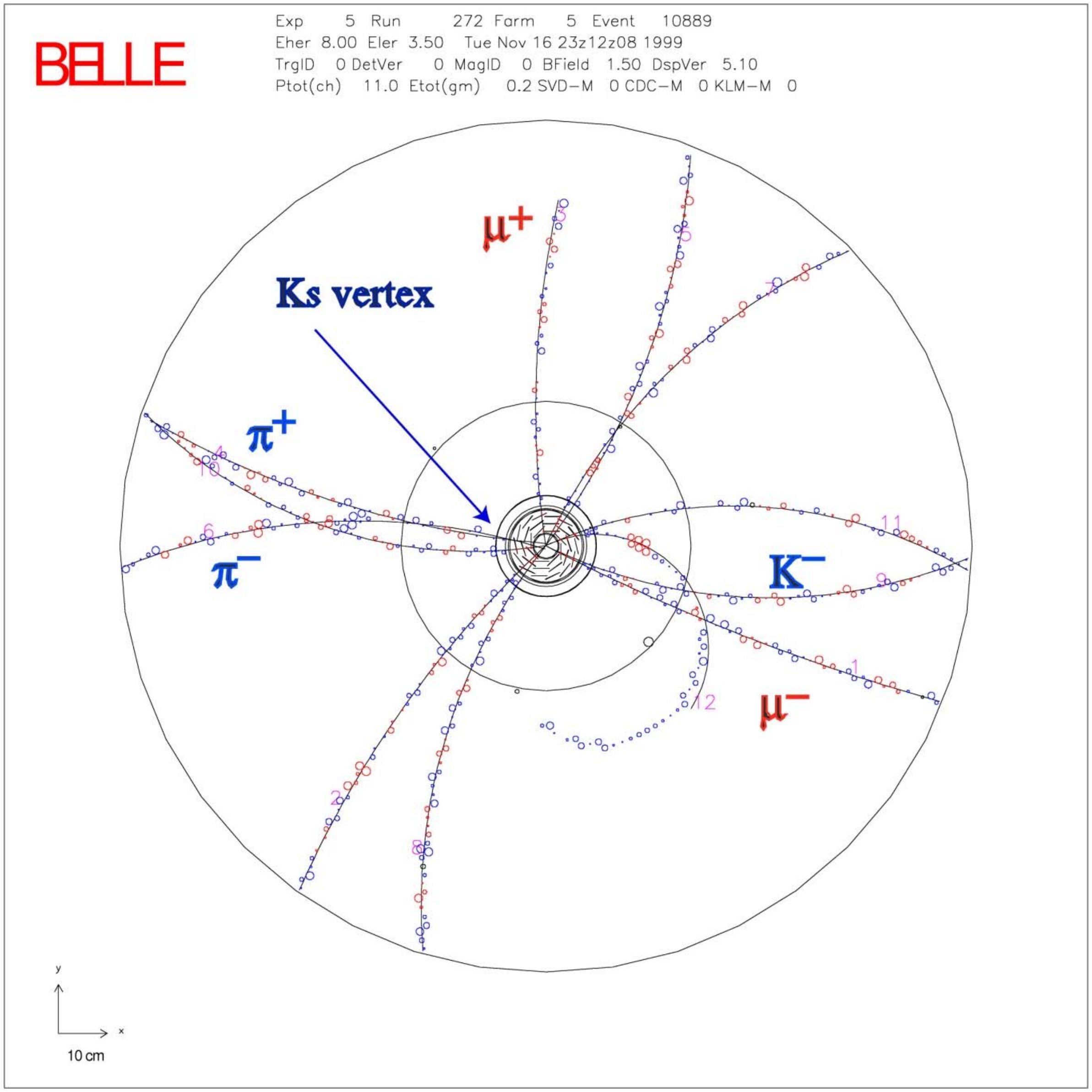
Reconstructing chamonium states

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

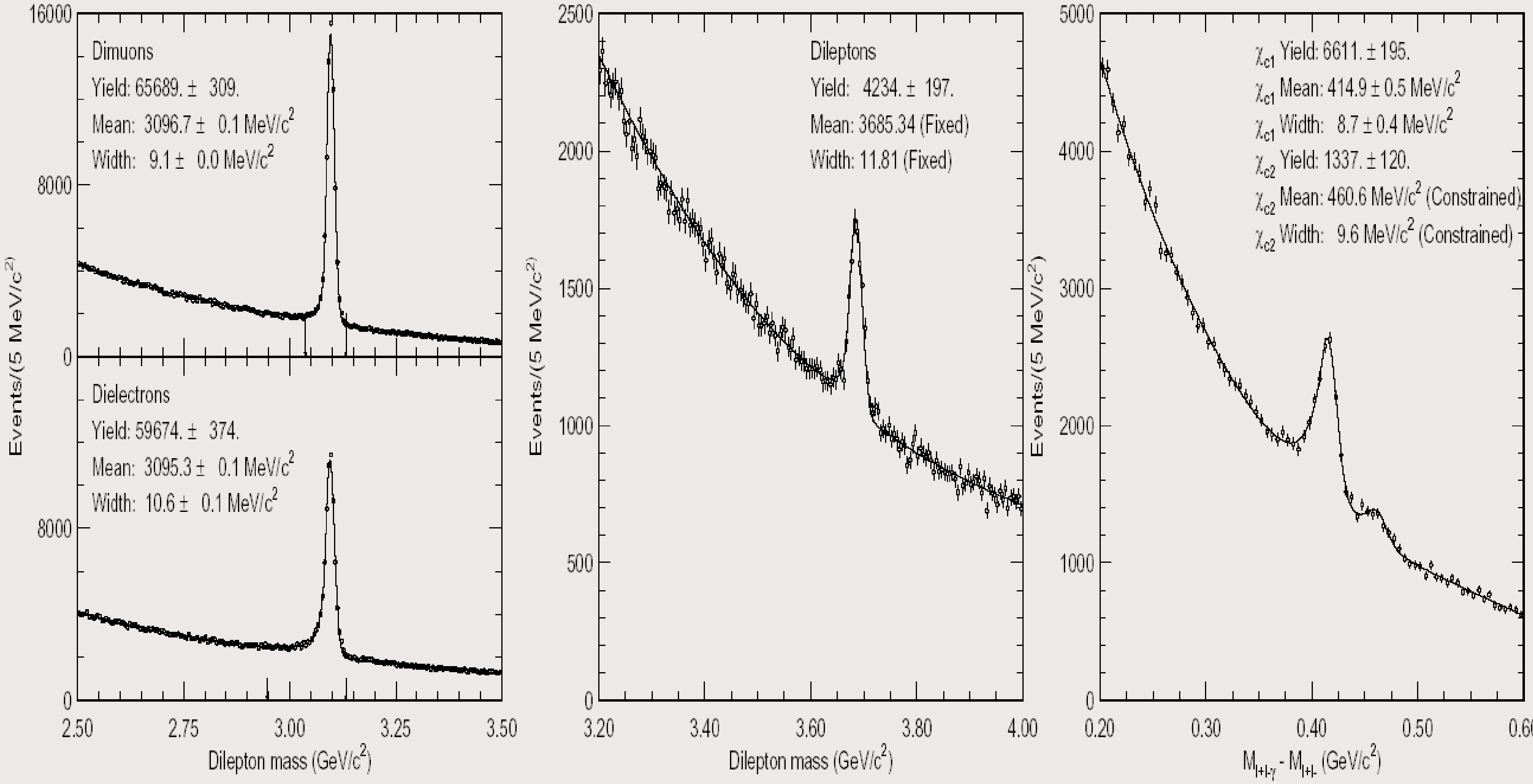
$$M = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2}$$

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



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

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

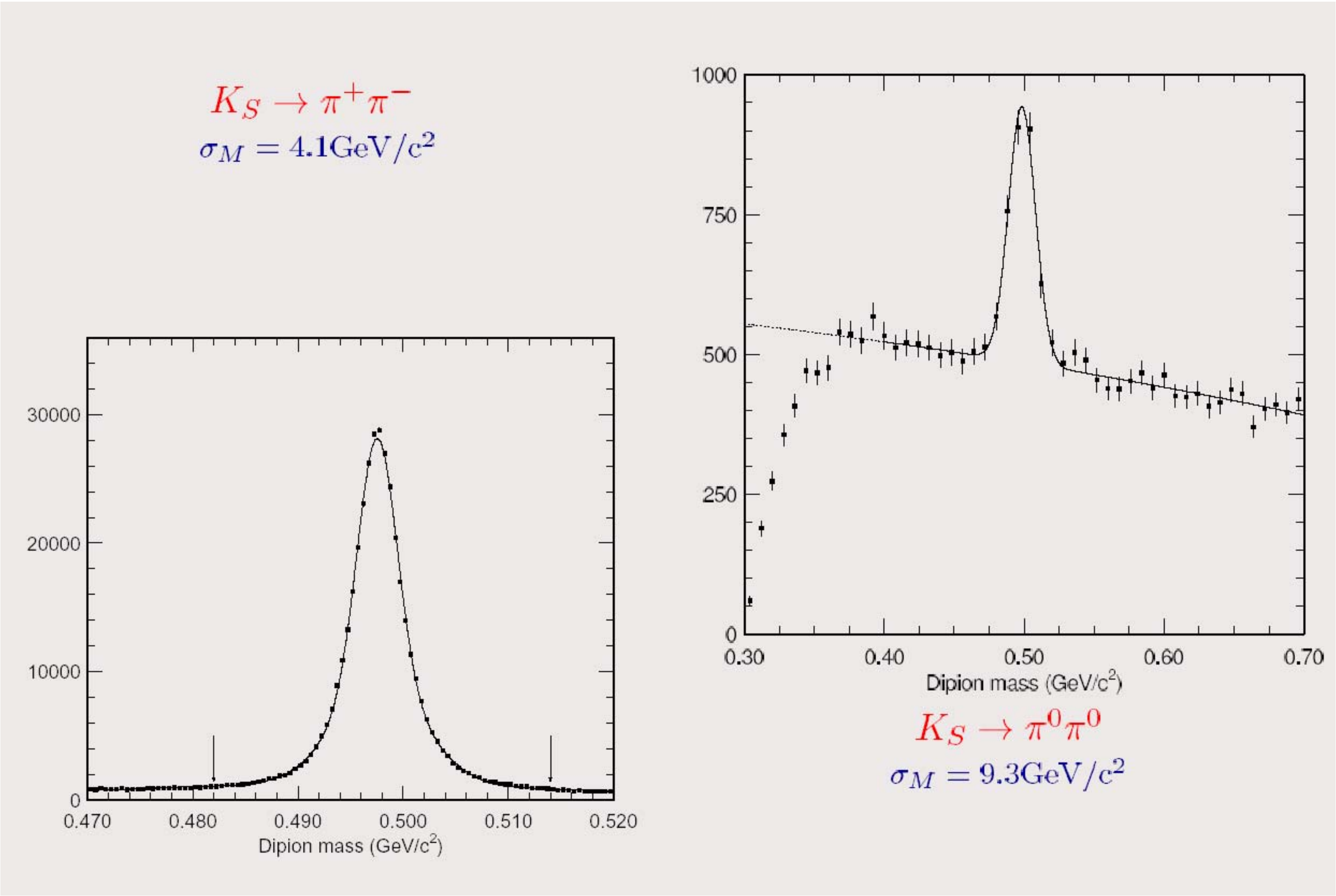
$\psi(2s) \to \mu^+\mu^-, e^+e^-$

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

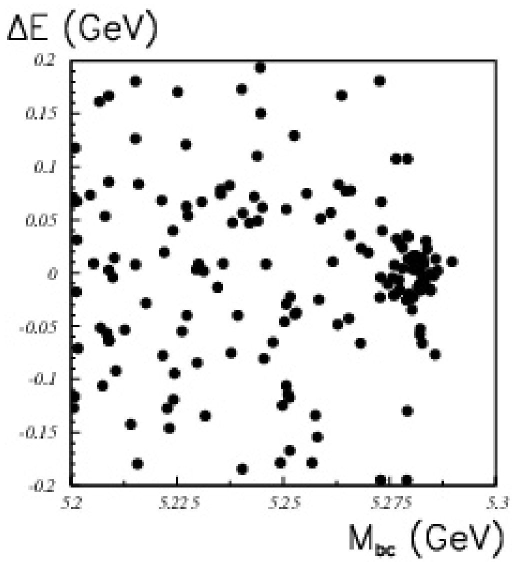
$\chi_{c1}, \chi_{c2} \to J/\psi\gamma$

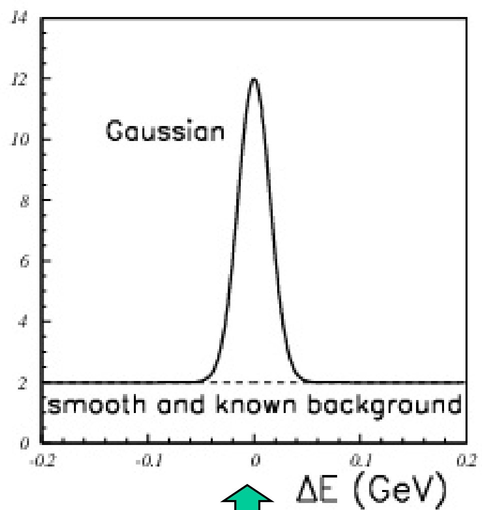
$\sigma_{\Delta M} = 7.0\mathrm{GeV}/c^2$

Reconstructing K^0_S



Reconstruction of rare B meson decays





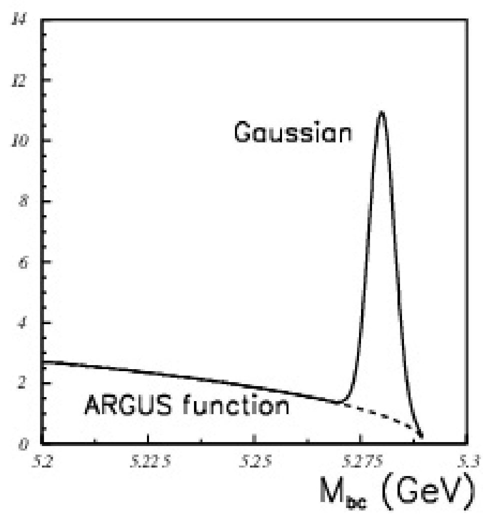
Reconstructing rare B meson decays at Y(4s): use two variables,

beam constrained mass M_{bc}

and

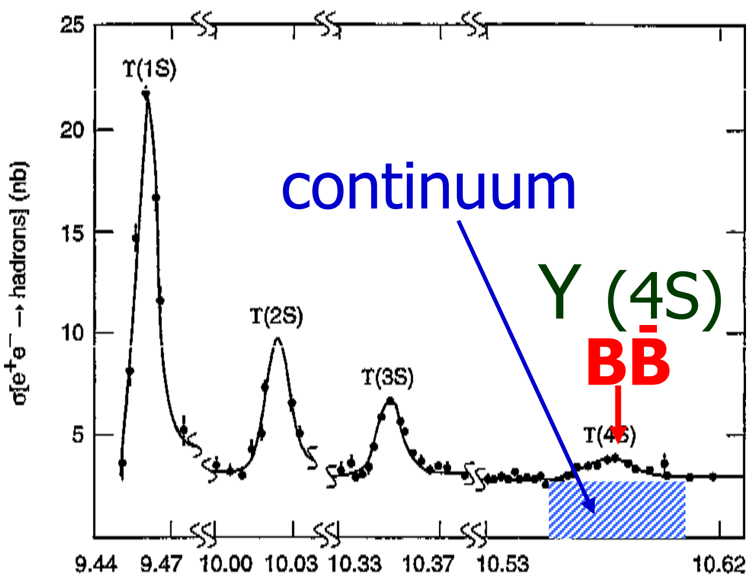
energy diference DE

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



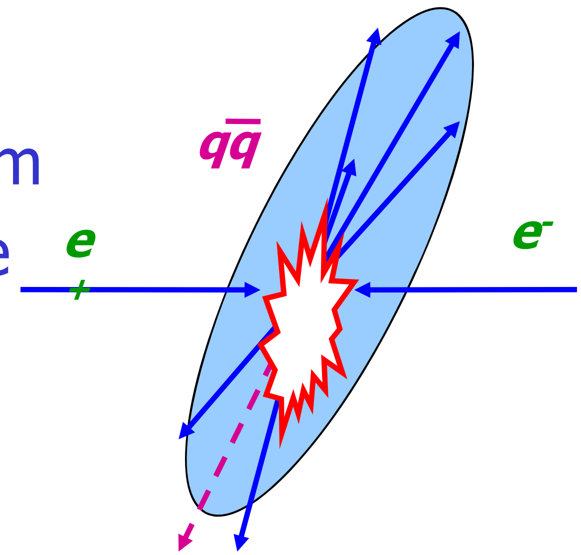
$$M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum \vec{p}_i)^2}$$

Continuum suppression



Continuum

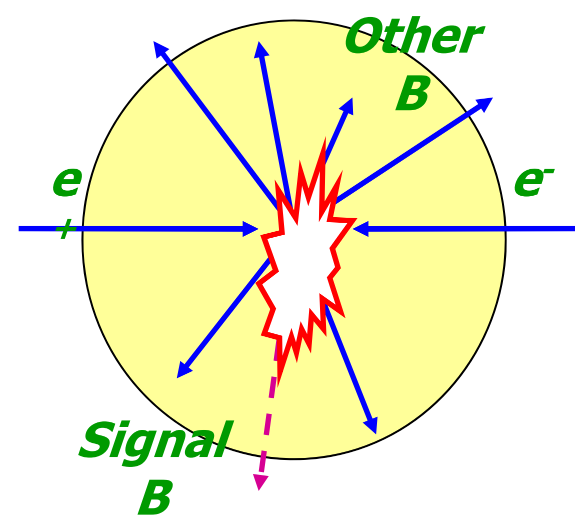
Jet-like



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

BB

spherical

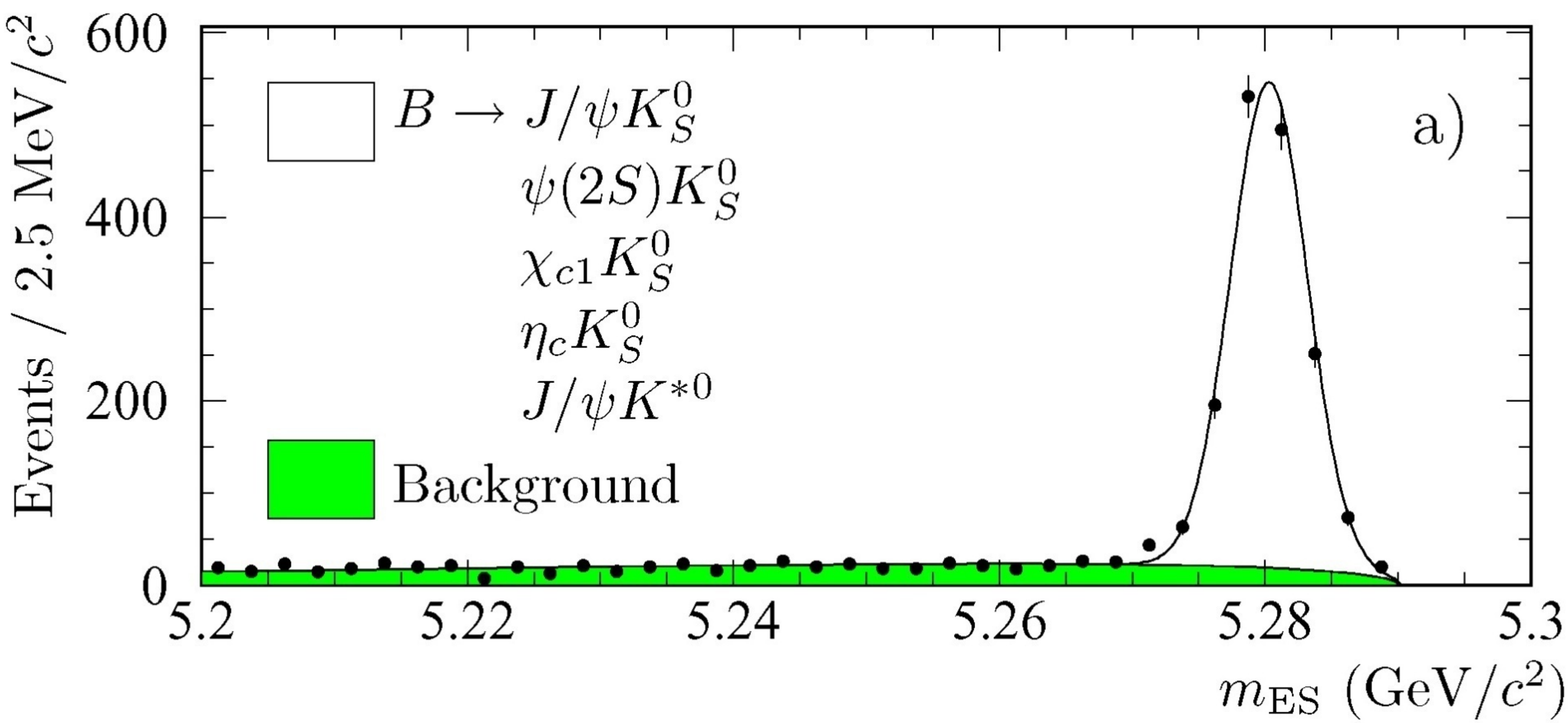


To suppress: use event shape variables

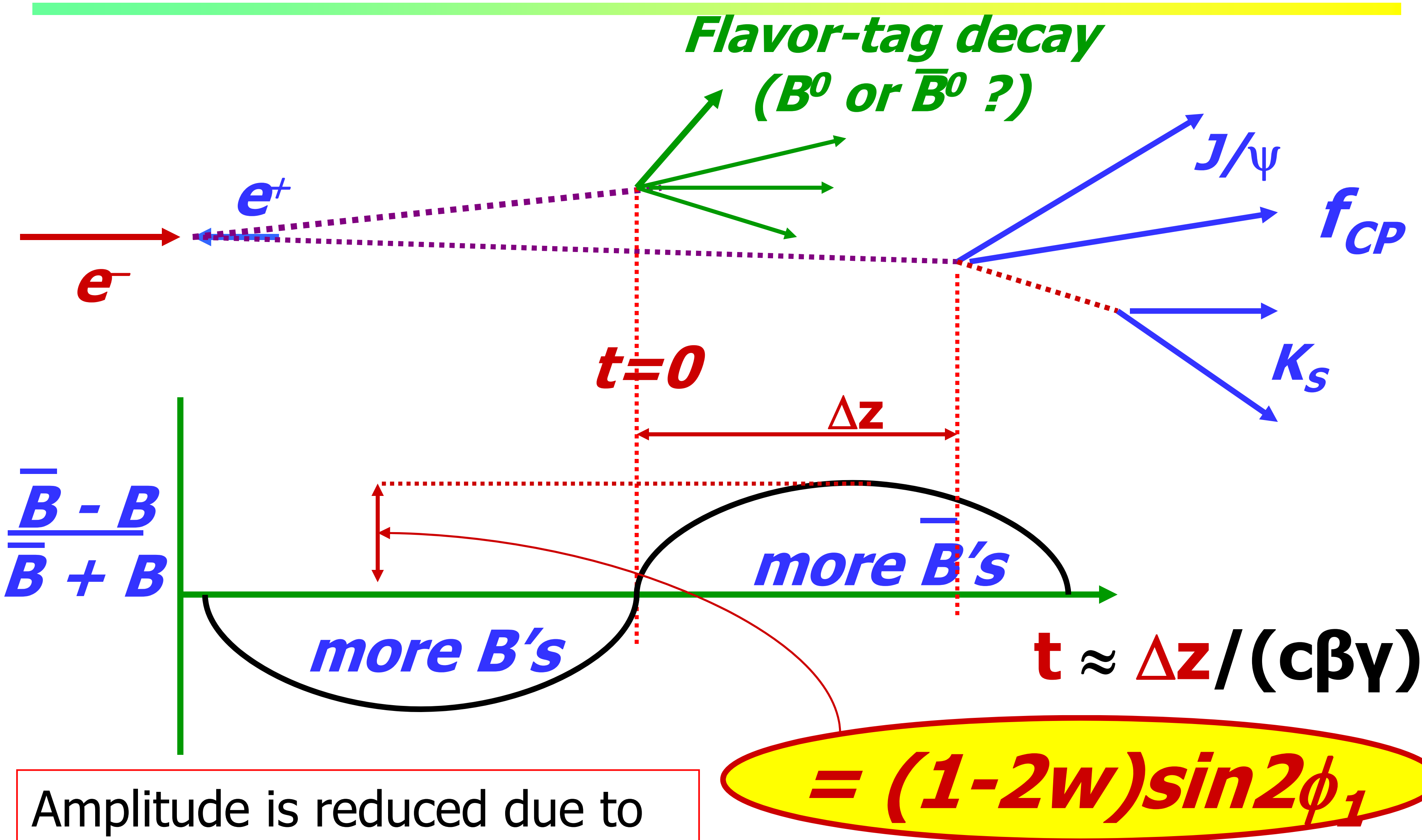
Reconstruction of b-> c anti-c s
CP=-1 eigenstates

$J/\Psi(\Psi,\chi_{c1},\eta_c)$ $K_s(K^{*0})$ sample $(\eta_f=-1)$
from 88(85)x10^6 $B\overline{B}$

BaBar 2002 result

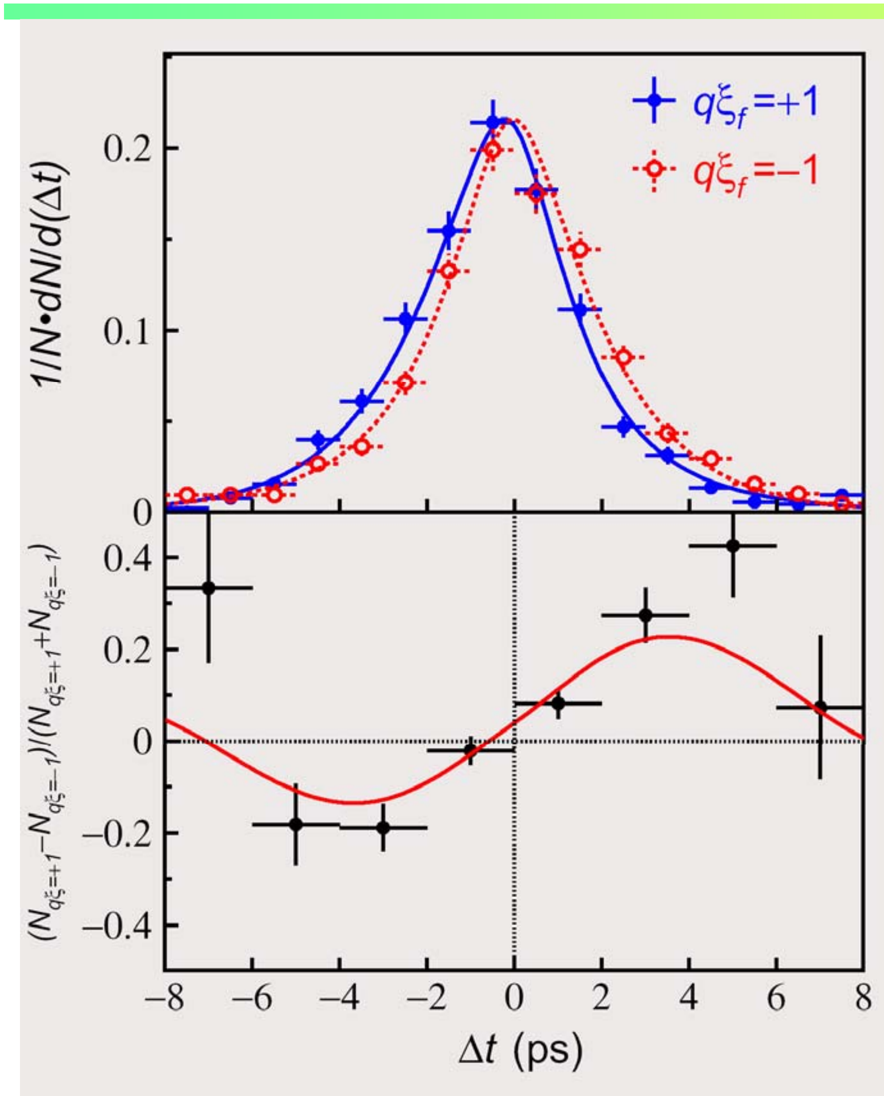


Principle of CPV Measurement



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)

$b \rightarrow c$ 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}, $\eta_{\mathbf{fcp}}$=+-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

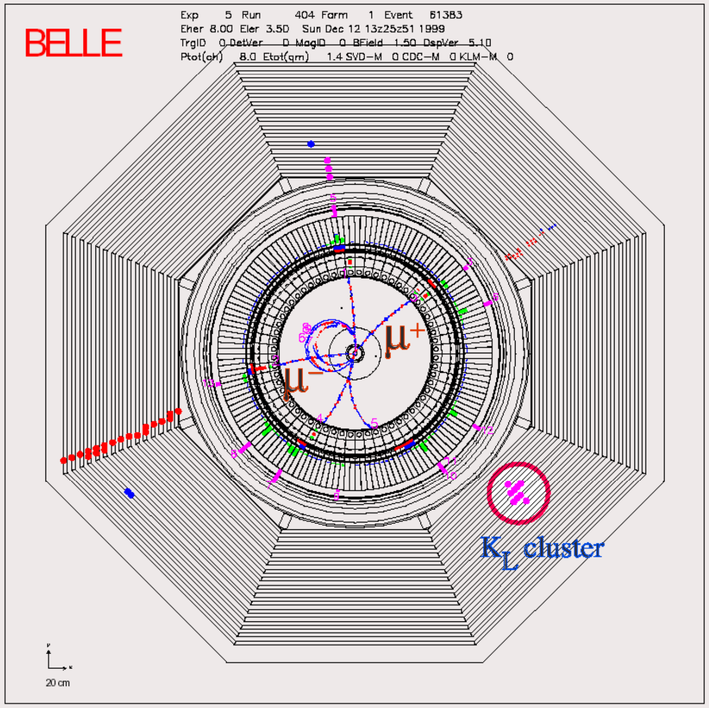
- J/ψ: P=-1, C=-1 (vector particle $J^{PC}=1^{--}$): CP=+1
- K_S (->$\pi^+ \pi^-$): CP=+1, orbital ang. momentum of pions=0 ->
  P $(\pi^+ \pi^-)=(\pi^- \pi^+)$, C$(\pi^- \pi^+)$ =$(\pi^+ \pi^-)$
- orbital ang. momentum between J/ψ and K_S l=1, P=$(-1)^1$=-1

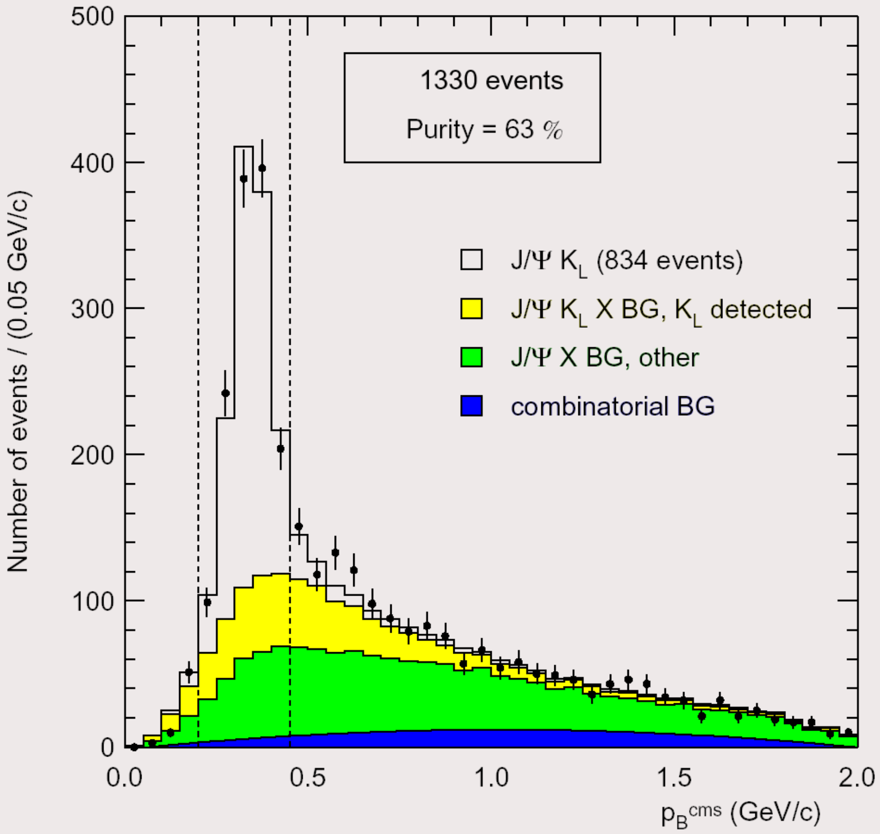
$J/\psi\ K_L(3\pi)$: CP=+1

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

Reconstruction of b→ c anti-c s
CP=+1 eigenstates

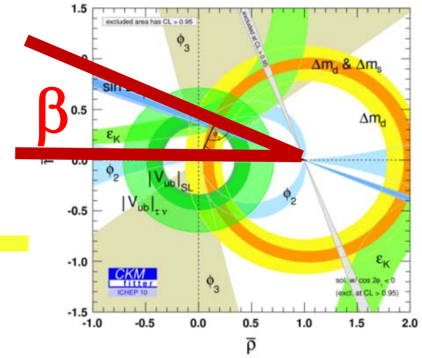
- detection of K_L in KLM and ECL
- K_L direction, no energy





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

Final measurement of $\sin 2\phi_1$ ($=\sin 2\beta$)

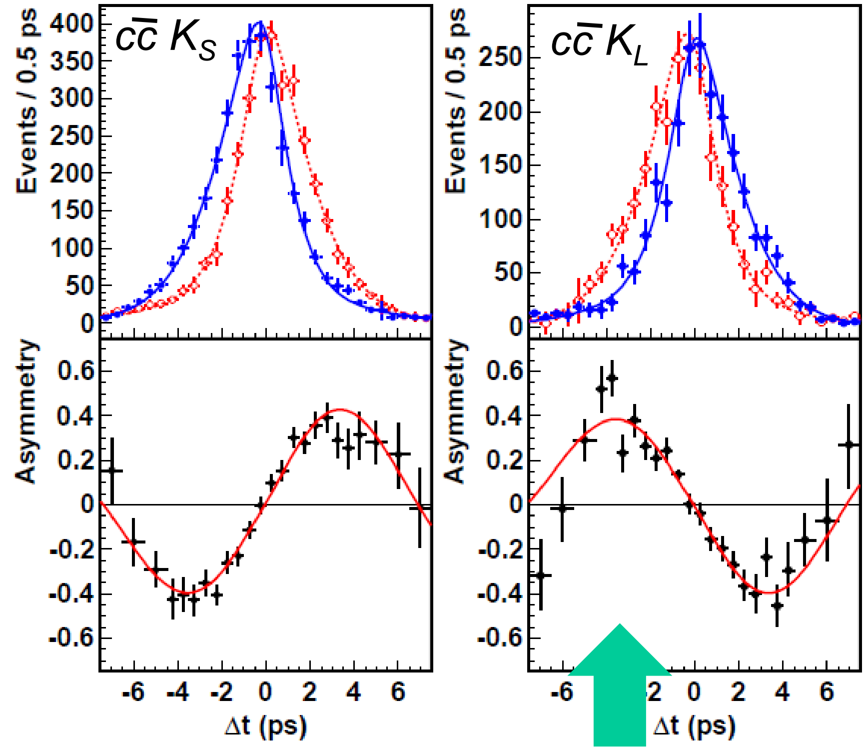


ϕ_1 from CP violation measurements in $B^0 \to c\bar{c}\, K^0$

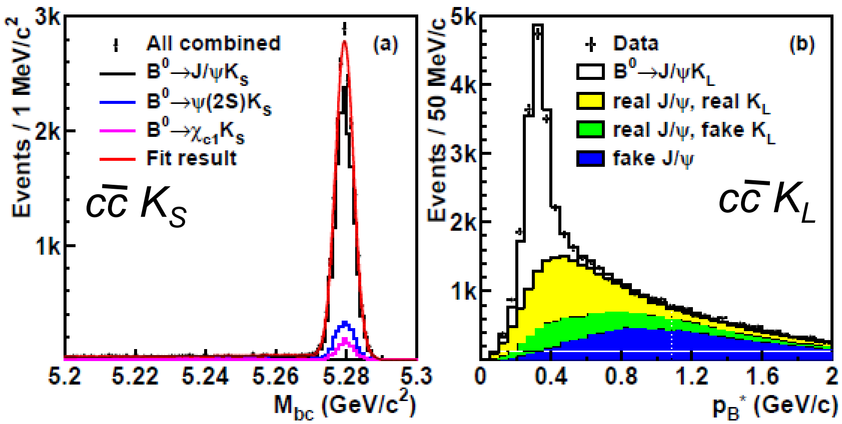
Final measurement: with improved tracking, more data, improved systematics (and more statistics

$cc = J/\psi,\ \psi(2S),\ \chi_{c1}$ → 25k events

Detector effects: wrong tagging, finite Δt resolution → determined using control data samples

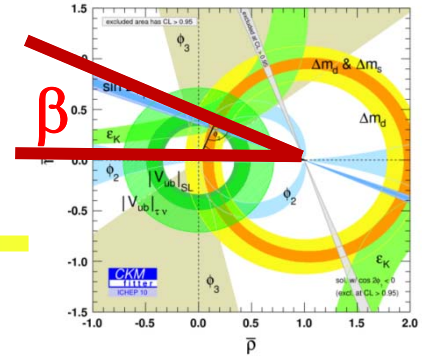


Opposite CP → sine wave with a flipped sign



Belle, final, 710 fb^{-1}, PRL 108, 171802 (2012)

Final measurements of $\sin 2\phi_1$ ($=\sin 2\beta$)



ϕ_1 from $B^0 \to c\bar{c}\, K^0$

Final results for $\sin 2\phi_1$

Belle, PRL 108, 171802 (2012)

BaBar, PRD 79, 072009 (2009)

Belle:	0.668 ± 0.023 ± 0.012
BaBar:	0.687 ± 0.028 ± 0.012

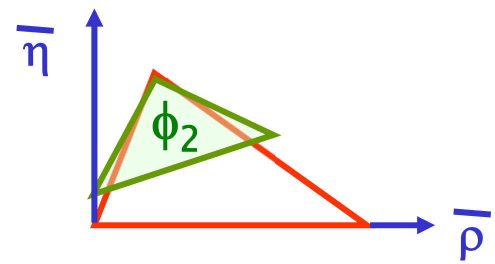
with a single experiment precision of ~4%!

Comparison with LHCb:

- The power of tagging at B factories: 33% vs ~2-3% at LHCb
- LHCb: with 8k tagged $B_d \to J/\psi K_S$ events from 1/fb measured
  $\sin 2\beta = 0.73 \pm 0.07(\text{stat.}) \pm 0.04(\text{syst.})$
- Uncertainties at B factories - e.g., Belle final result
  $\sin 2\beta = 0.668 \pm 0.023(\text{stat.}) \pm 0.012(\text{syst.})$ - are 3x smaller than at LHCb

How to measure ϕ_2 (α)?

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



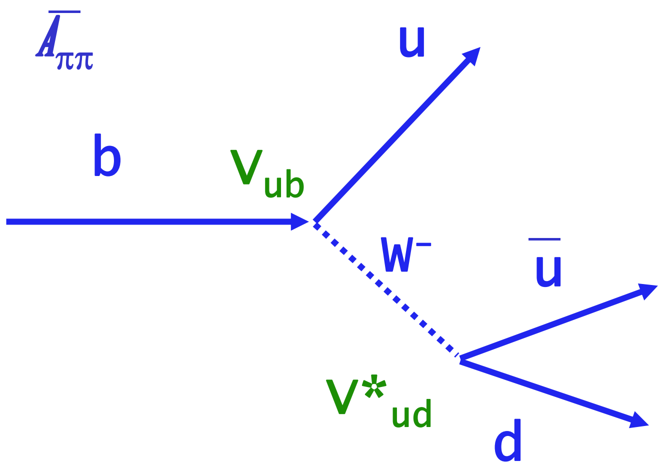
$$a_{f_{CP}} = \frac{P(\overline{B}^0 \rightarrow f_{CP}, t) - P(B^0 \rightarrow f_{CP}, t)}{P(\overline{B}^0 \rightarrow f_{CP}, t) + P(B^0 \rightarrow f_{CP}, t)} =$$

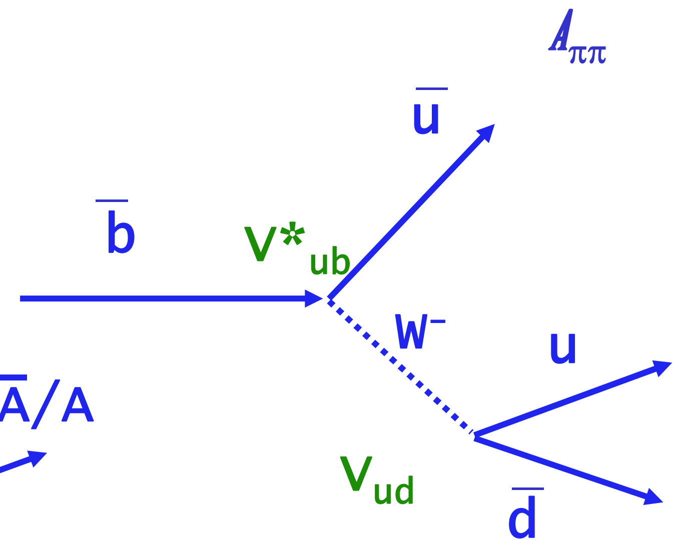
$$= \frac{(1 - |\lambda_{f_{CP}}|^2)\cos(\Delta m t) - 2\,\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)}{1 + |\lambda_{f_{CP}}|^2}$$

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

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

Decay asymmetry calculation for B→$\pi^+ \pi^-$ - tree diagram only



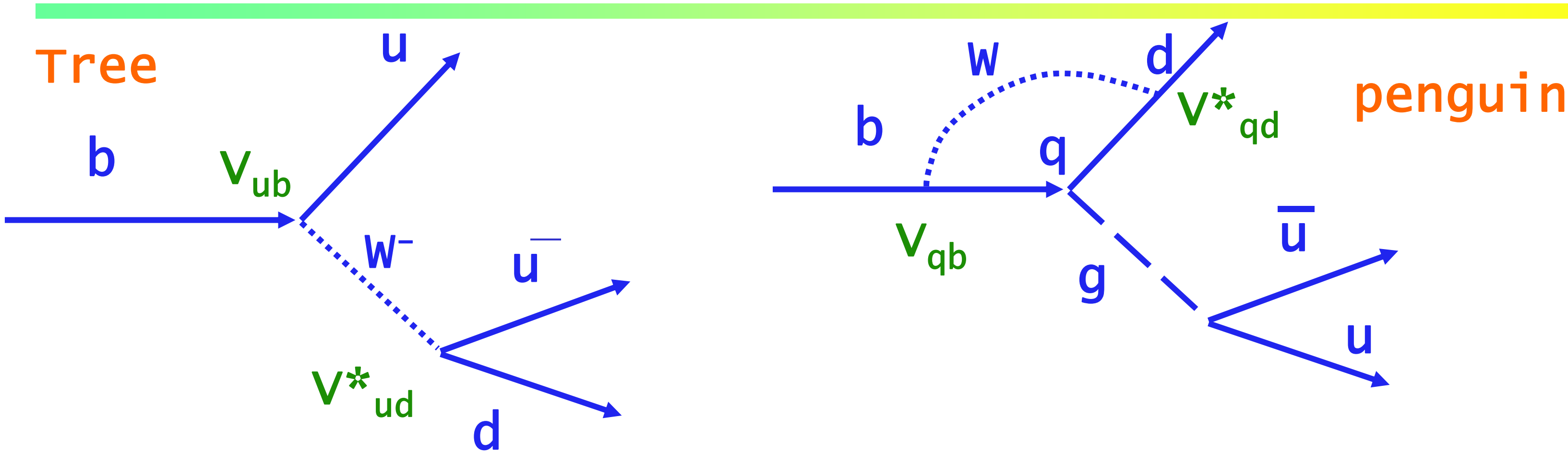


$$\lambda_{\pi\pi} = \eta_{\pi\pi} \overbrace{\boxed{\left(\frac{V_{tb}{}^* V_{td}}{V_{tb} V_{td}{}^*}\right)}}^{(q/p)} \overbrace{\boxed{\left(\frac{V_{ud}{}^* V_{ub}}{V_{ud} V_{ub}{}^*}\right)}}^{\bar{A}/A}$$

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

Neglected possible penguin amplitudes ->

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

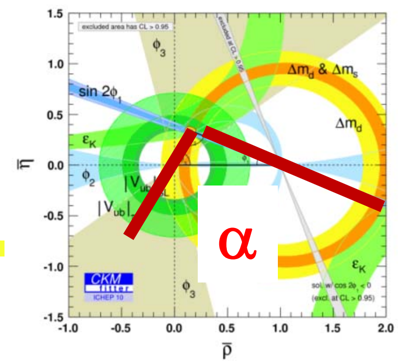


$V_{ub}V_{ud}^* = A\lambda^3(\rho - i\eta)$
$V_{tb}V_{td}^* = A\lambda^3(1-\rho + i\eta)$

A sizable penguin contribution!

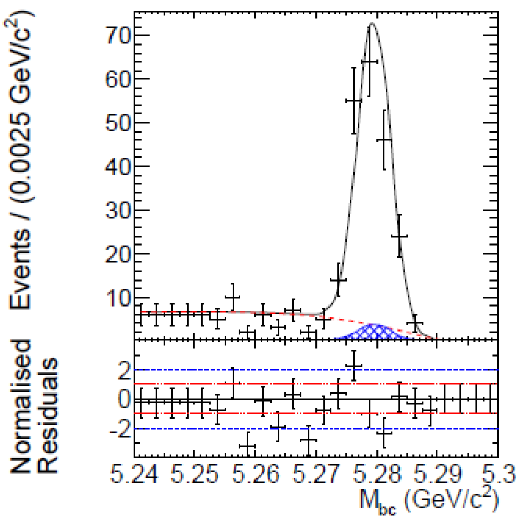
→ Disentangle ambiguities due to penguin polution by using related $\pi\pi$, $\rho\rho$, $\rho\pi$ decays

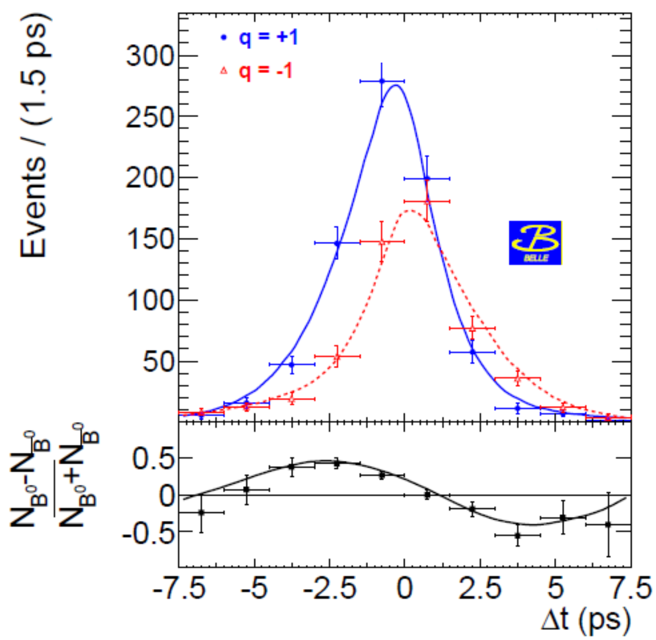
Final measurement of ϕ_2 (α) in $B \to \pi^+\pi^-$ decays



ϕ_2 from CP violation measurements in $B^0 \to \pi^+\pi^-$

Belle, 710 fb^{-1}
PRD **88**, 092003 (2013)





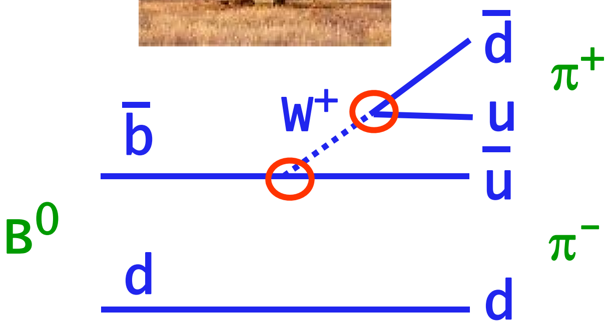
$$a_{f_{CP}} = $$
$$= C\cos(\Delta m t) + S\sin(\Delta m t)$$

Belle:
$S = -0.64 \pm 0.08 \pm 0.03$
$C = -0.33 \pm 0.06 \pm 0.03$

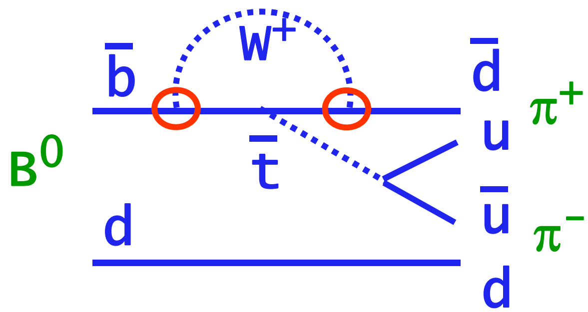
BaBar:
$S = -0.68 \pm 0.10 \pm 0.03$
$C = -0.25 \pm 0.08 \pm 0.02$

Extracting ϕ_2: isospin relations

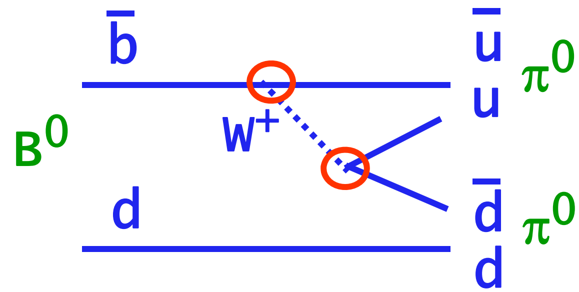
$B^0 \to \pi^+\pi^-, \pi^0\pi^0$



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



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



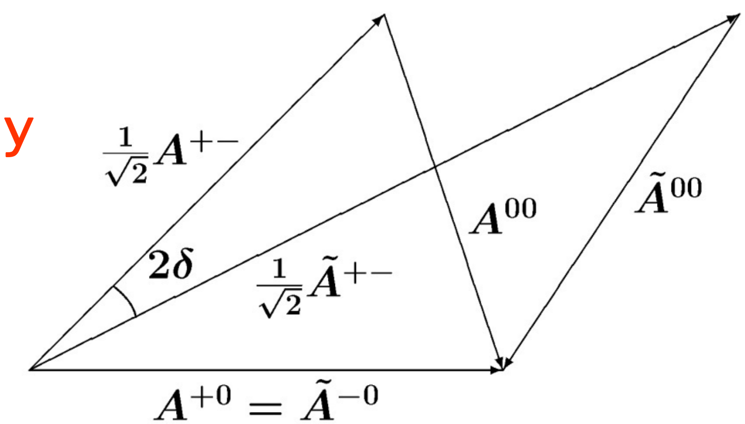
$T_c \sim V_{ub}{}^*V_{ud}$

No pengiun!

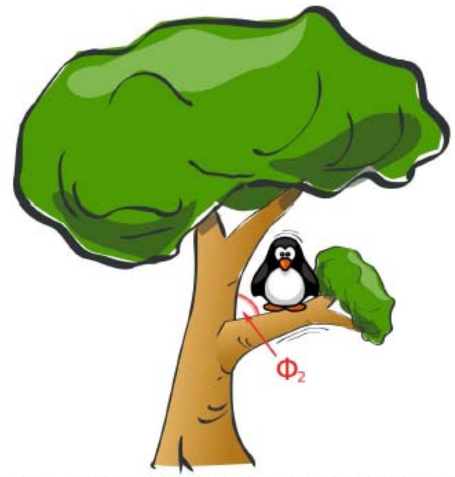
Constraint: relation of decay amplitudes in the SU(2) symmetry

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

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



Measurement of B → $\pi^0\pi^0$ decays



Pit Vanhoefer, CKM2014

ϕ_2 from CP violation measurements in $B^0 \to \pi^+\pi^-$
Extraction not easy because of the penguin contribution

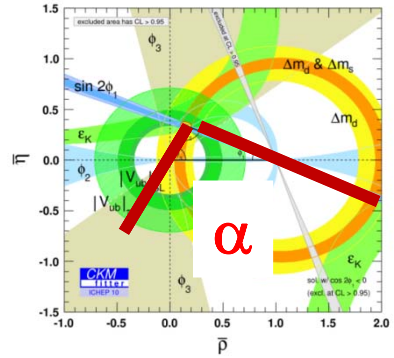
BR for the $B \to \pi^0\pi^0$ decay important to resolve this issue.

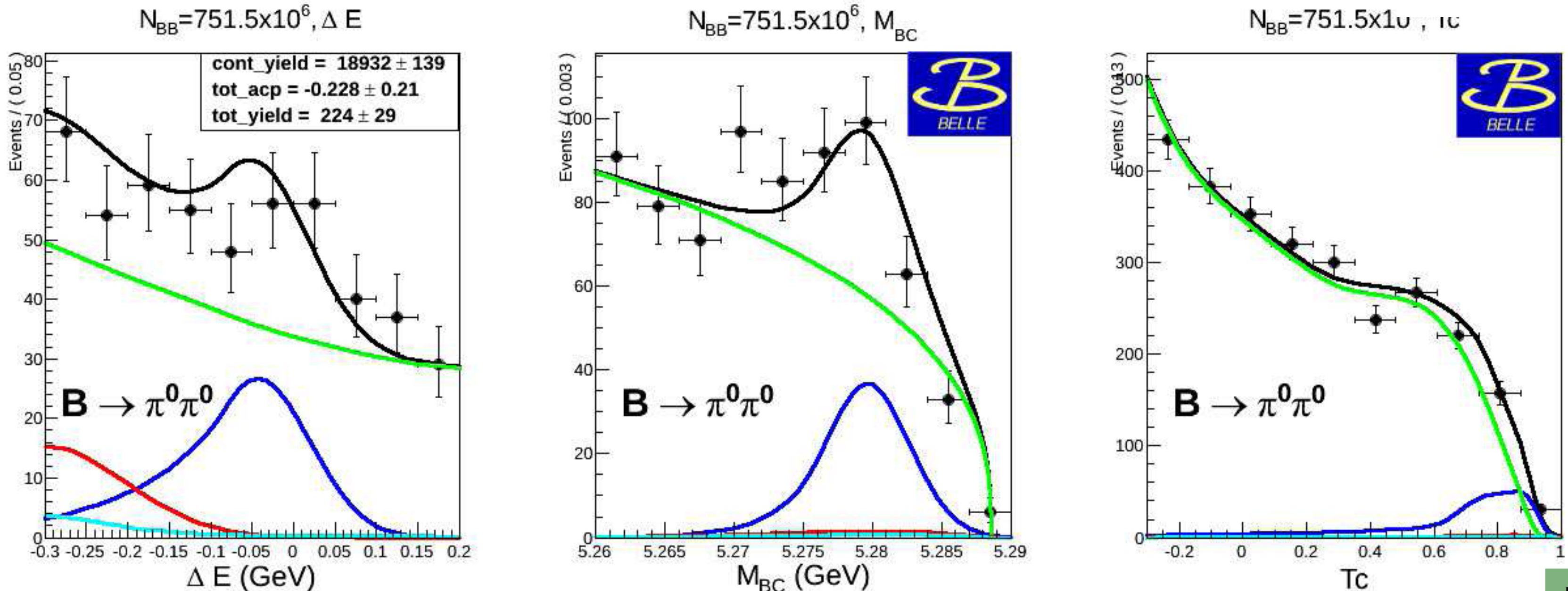
Hard channel to measure: four gammas, continuum (ee→qq) background

- Theory: BR<1x10-6 (Phys.Rev.D83:034023,2011)
- Belle, 1/3 of data PRL 94, 181803(2005) = (2.32 +0.4-0.5 +0.2-0.3) 10^{-6}
- BaBar PR D87 052009 (1.83 ± 0.21 ± 0.13) 10^{-6}

Belle new result with full data set: Improved rejection of out-of-time electromagnetic calorimeter hits (some of which contribute to a peaking background).

Measurement of $B \to \pi^0\pi^0$ decays





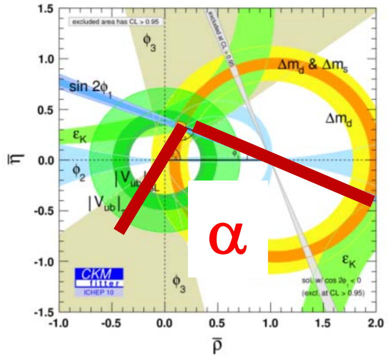
Preliminary

$Br(B \to \pi^0\pi^0) = (0.90 \pm 0.20\ (\mathrm{stat}) \pm 0.15(\mathrm{syst}))\cdot 10^{-6}$

(6.7σ significance)

A_{CP} under preparation → stay tuned

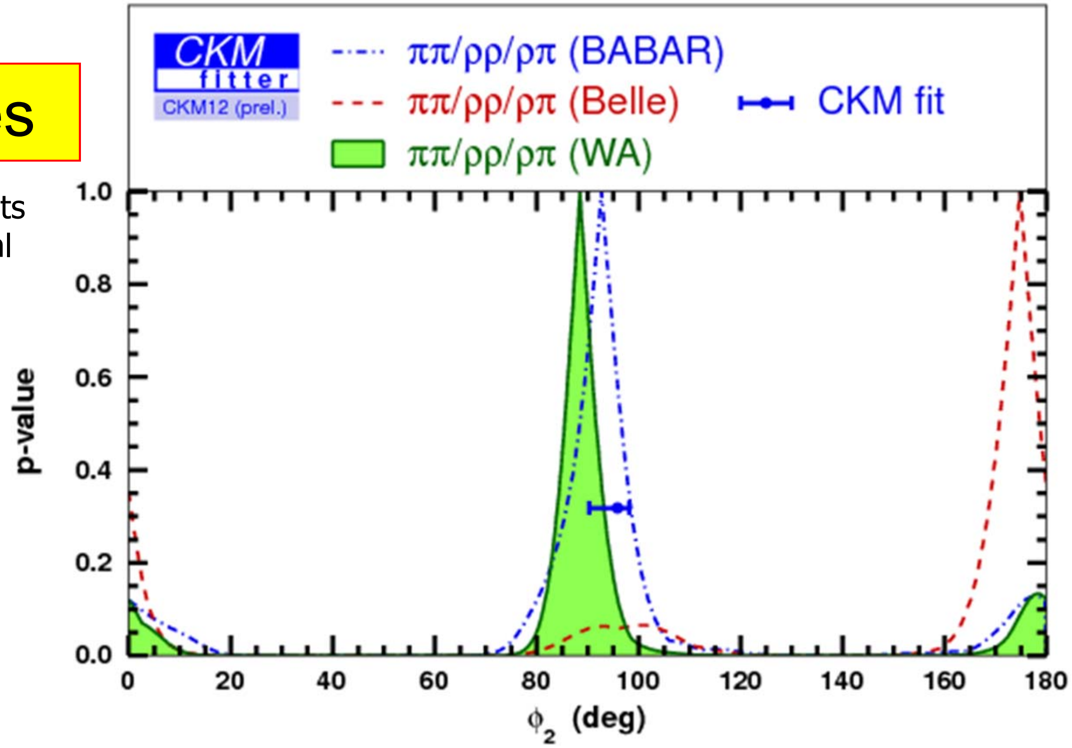
Improved measurement of ϕ_2 (α) in $B \to \pi\pi, \rho\rho, \rho\pi$ decays



ϕ_2 (α) from CP violation and branching fraction measurements in $B \to \pi\pi, \rho\rho, \rho\pi$

$\phi_2 = \alpha = (85.4^{+4.0}_{-3.8})$ degrees

http://ckmfitter.in2p3.fr/www/results/plots_fpcp13/ckm_res_fpcp13.html



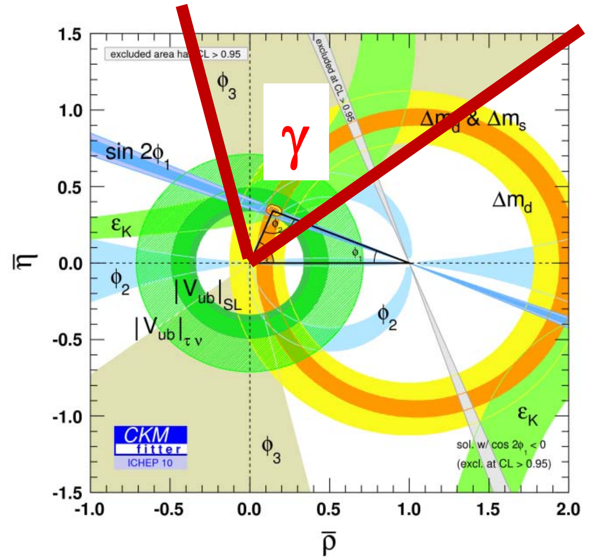
p-value (1-CL) = 1: central value
p-value (1-CL) = 0.317 limits the one-sigma region.

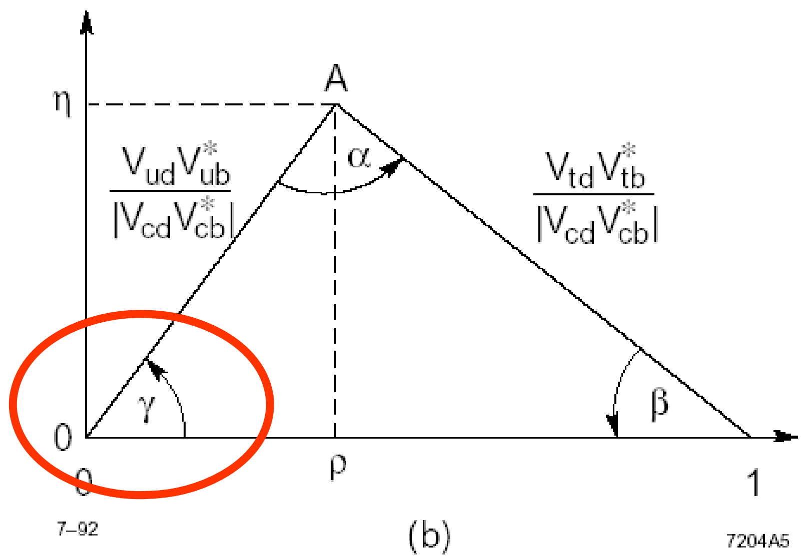
Still to be updated for the final version!

How to measure ϕ_3?

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

Any other idea? Yes.



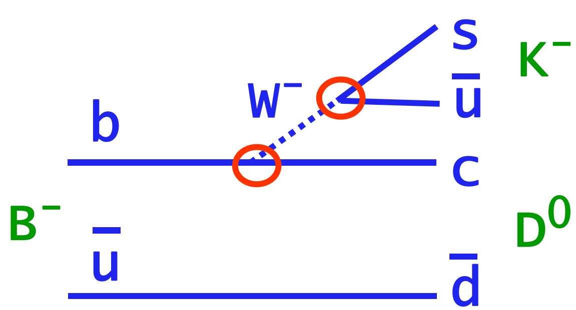


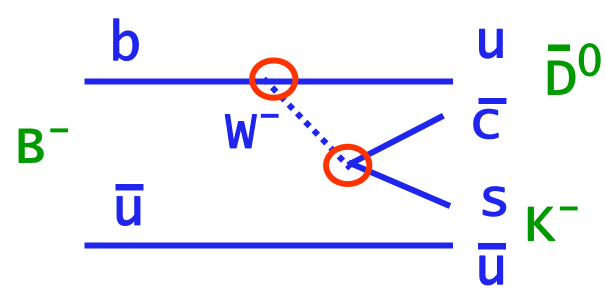
$$\gamma \equiv \phi_3 \equiv \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

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 ↔ ϕ_3

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





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

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

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 (Bondar et al), 2002;
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

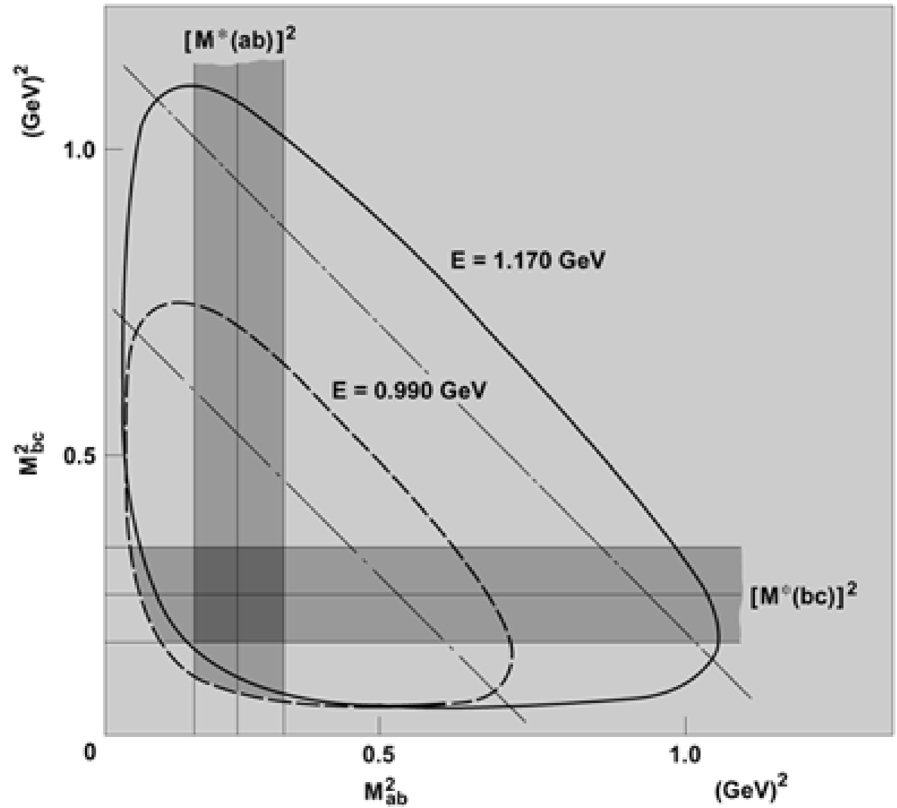
What is a Dalitz plot?

Example: three body decay X→abc.
Assume $m_a = m_b = m_c = 0.14$ GeV

M_{ij} : invariant mass of the two-particle system (*ij*) in a three body decay.

Kinematic boundaries: drawn for two values of total energy *E* of the three-pion system.

Resonance bands: shown for states (*ab*) and (*bc*) corresponding to a (fictitious) resonance with M=0.5 GeV and Γ=0.2 GeV; dot-dash lines show the locations a (*ca*) resonance band would have a mass of 0.5 GeV, for the two values of the total energy *E*.



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

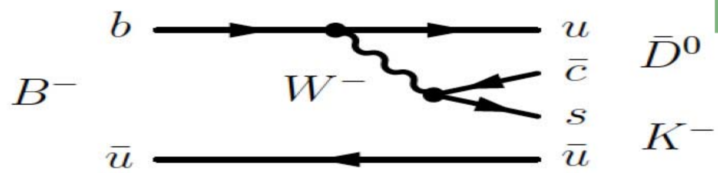
Richard H. Dalitz, "Dalitz plot", in AccessScience@McGraw-Hill, http://www.accessscience.com.

ϕ_3 (=γ) with Dalitz analysis

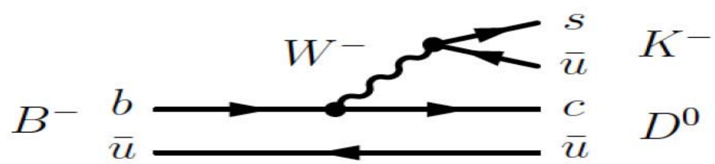
A. Giri et al., PRD68, 054018 (2003)
A. Bondar et al (Belle), Proc. BINP Meeting on Dalitz Analyses, 2002

GGSZ method:

The best way to measure ϕ_3



Color+CKM suppressed

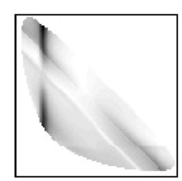
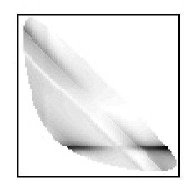


Favored

$\overset{(-)}{D^0} \to K_S\pi^+\pi^-$

3-body $D^0 \to K_S\pi^+\pi^-$ Dalitz amplitude

$$|M_\pm(m_+^2, m_-^2)|^2 = |f_D(m_+^2, m_-^2) + re^{i\delta_B \pm i\phi_3} f_D(m_-^2, m_+^2)|^2$$

$= \Big|$  $+ re^{i\delta_B \pm i\phi_3}$  $\Big|^2$

Model dependent description of f_D using continuum D* data $\Rightarrow$ systematic uncertainty

ϕ_3=(78 ± 12 ± 4 ± 9)°

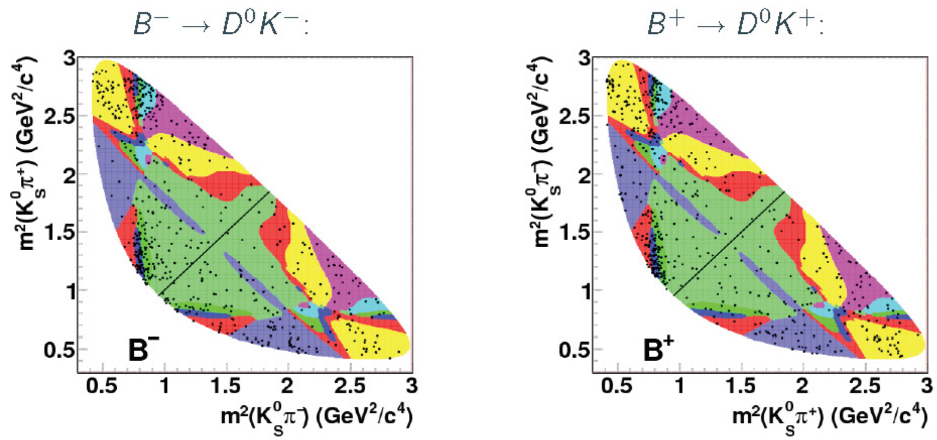
Belle, PRD81, 112002, (2010), 605 fb^{-1}

ϕ_3=(68 ± 14 ± 4 ± 3)°

BaBar, PRL 105, 121801, (2010)

ϕ_3 (=γ) from model-independent/binned Dalitz method

GGSZ method: How to avoid the model dependence?
→ Suitably subdivide the Dalitz space into bins



$$M_i^{\pm} = h\{K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_{\pm} c_i + y_{\pm} s_i)\}$$

$$x_{\pm} = r_B \cos(\delta_B \pm \phi_3) \quad y_{\pm} = r_B \sin(\delta_B \pm \phi_3)$$

M_i: # B decays in bins of D Dalitz plane, K_i: # D^0 ($\overline{D^0}$) decays in bins of D Dalitz plane ($D^* \to D\pi$), c_i, s_i: strong ph. difference between symm. Dalitz points ← Cleo, PRD82, 112006 (2010)

BELLE

Use only DK
N_{sig} = 1176 ± 43

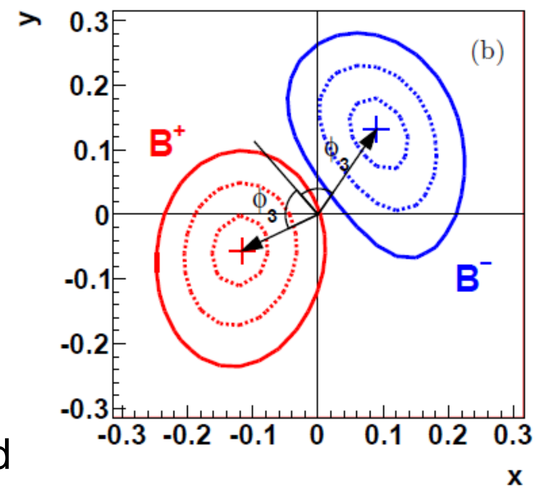
Belle, 710 fb^{-1}, Phys. Rev. D85 (2012) 112014

4-dim fit for signal yield (ΔE, M_{bc}, $\cos\theta_{thrust}$, $\mathcal{F}$);

ϕ_3=(77.3 ± 15 ± 4.1 ± 4.3)°

from c_i, s_i (statist.!)

to be reduced with BESIII data



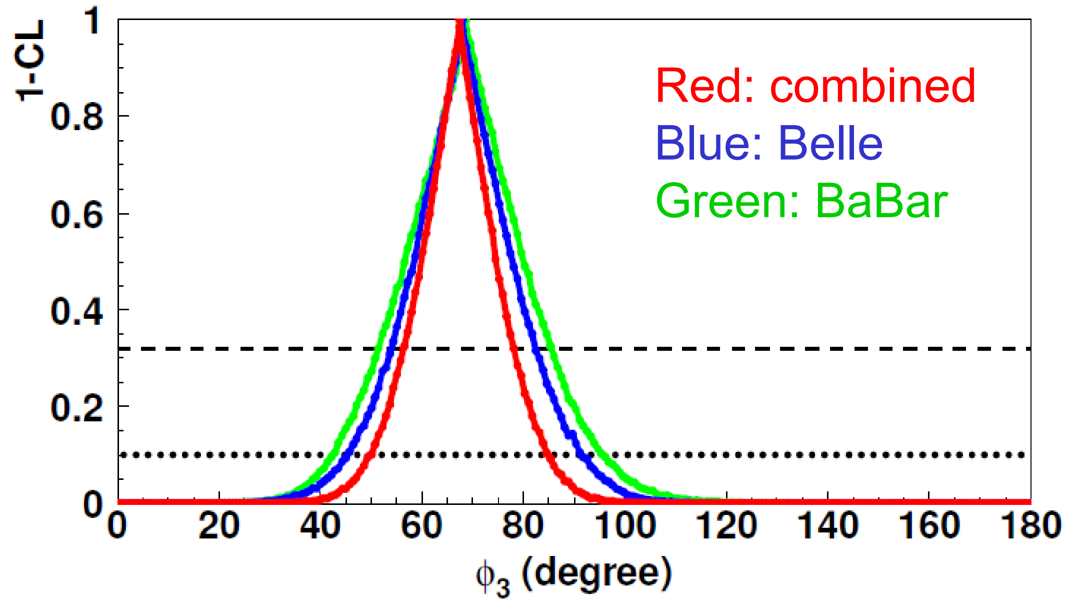
New method pioneered by Belle, very important for large event samples at LHCb and super B factory

ϕ_3 measurement

Combined ϕ_3 value:

$\boxed{\phi_3 = (67 \pm 11) \text{ degrees}}$

Note that at B factories the measurement of ϕ_3 finally turned out to be much better than expected!

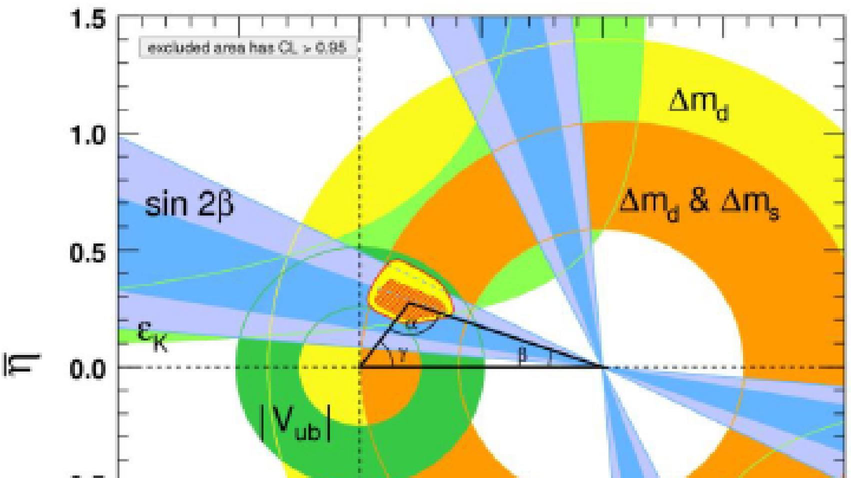


This is not the last word from B factories, analyses still to be finalized...

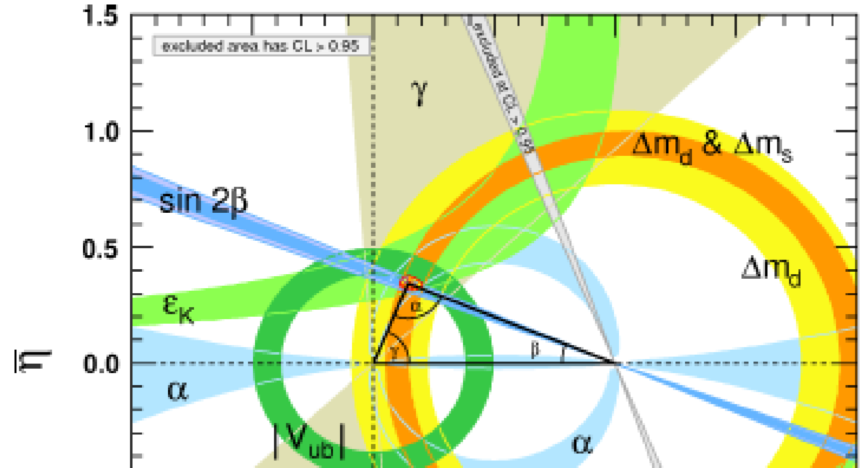
Summary: CP violation in the B system

B factories: CP violation in the B system: from the discovery (2001) to a precision measurement (2011) → remarkable agreement with KM

EPS 2001



EPS 2011



Tomorrow:

- Flavor physics: introduction, with a little bit of history
- Flavor physics at B factories: CP violation
- **Flavor physics at B factories: rare decays and searches for NP effects**
- **Super B factory**
- Flavor physics at hadron machines: history, LHCb and LHCb upgrade

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| ≠ 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

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

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

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

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

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

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

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

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

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

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

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

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

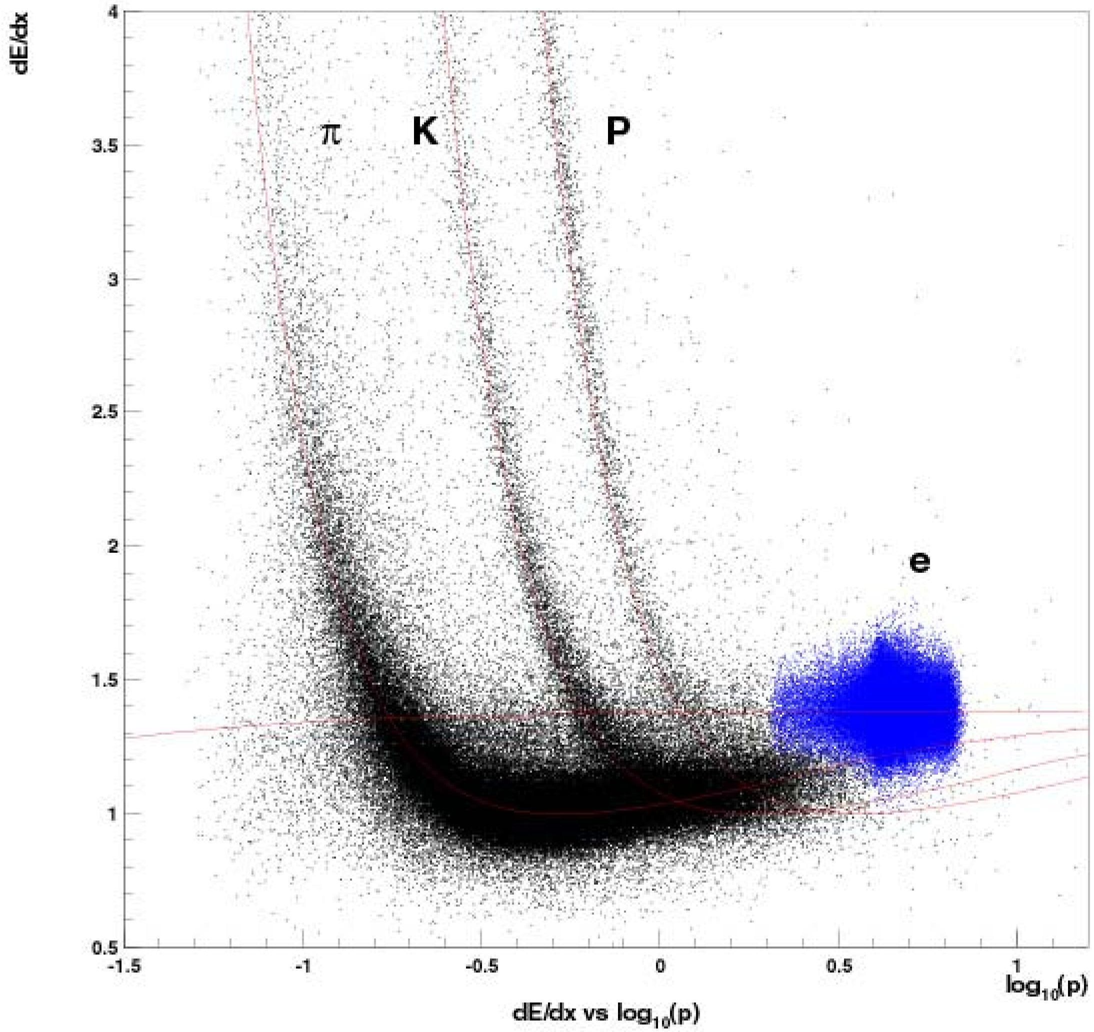
with $\lambda_{f_{CP}} = \dfrac{q}{p}\dfrac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$

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

Identification with dE/dx measurement

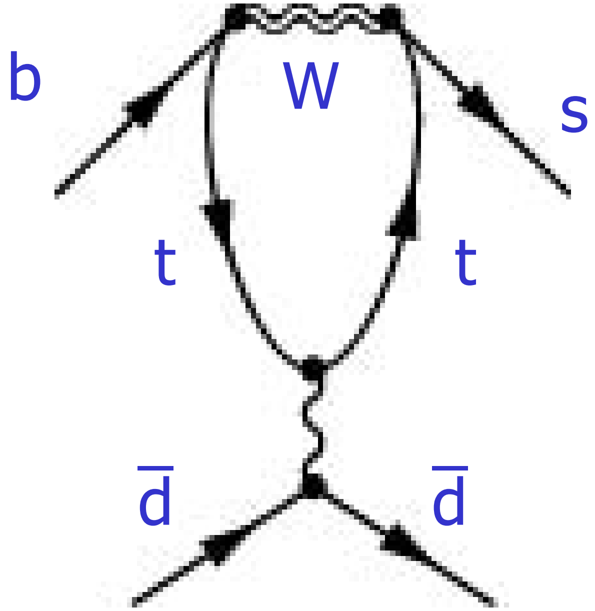
dE/dx performance in a large drift chamber.

Essential for hadron identification at low momenta.

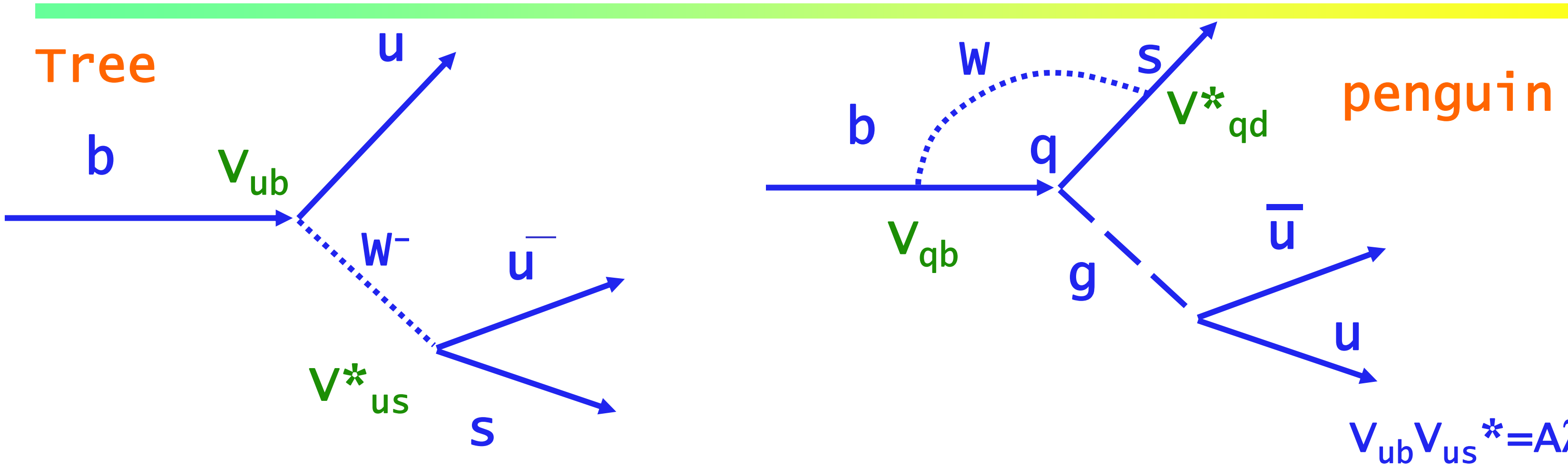


Why penguin?

Example: b→s transition



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



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

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->$\pi^+ \pi^-$: 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 $\cancel{C}P$

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

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

How to extract ϕ_2, δ and |P/T|?

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

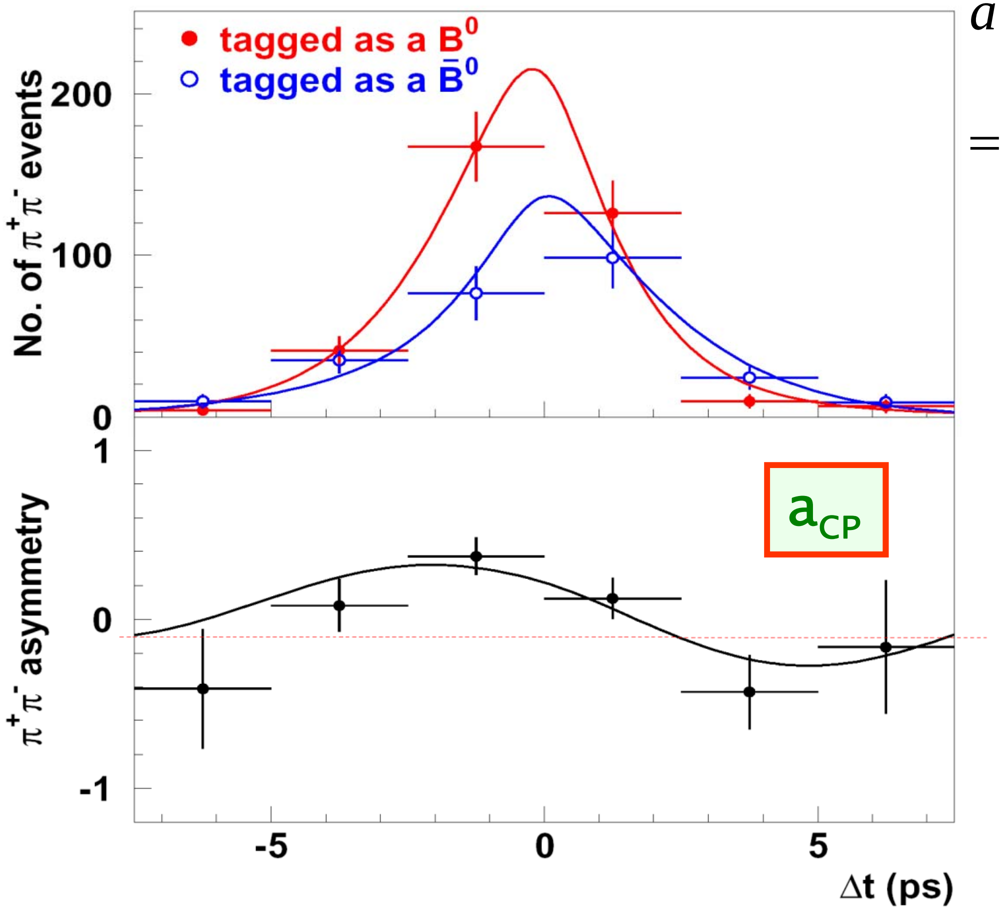
$\pi = \phi_1 + \phi_2 + \phi_3$ → ϕ_{2eff} depends on δ, ϕ_1, ϕ_2 and |P/T|

ϕ_1: well measured

penguin amplitudes $B \to K^+\pi^-$ and $B \to \pi^+\pi^-$ are equal
→ 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 $\phi_2 - \phi_{2eff}$);

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



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

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

$\mathcal{S}_{\pi\pi}$ = -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

Belle 2005 sample

CP asymmetry in time integrated rates ('direct CP', also for charged B)

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

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

strong phase diff. P-T

Interpretation:

tree +

tree level

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

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|

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

ϕ_1: well measured

- Inputs from:

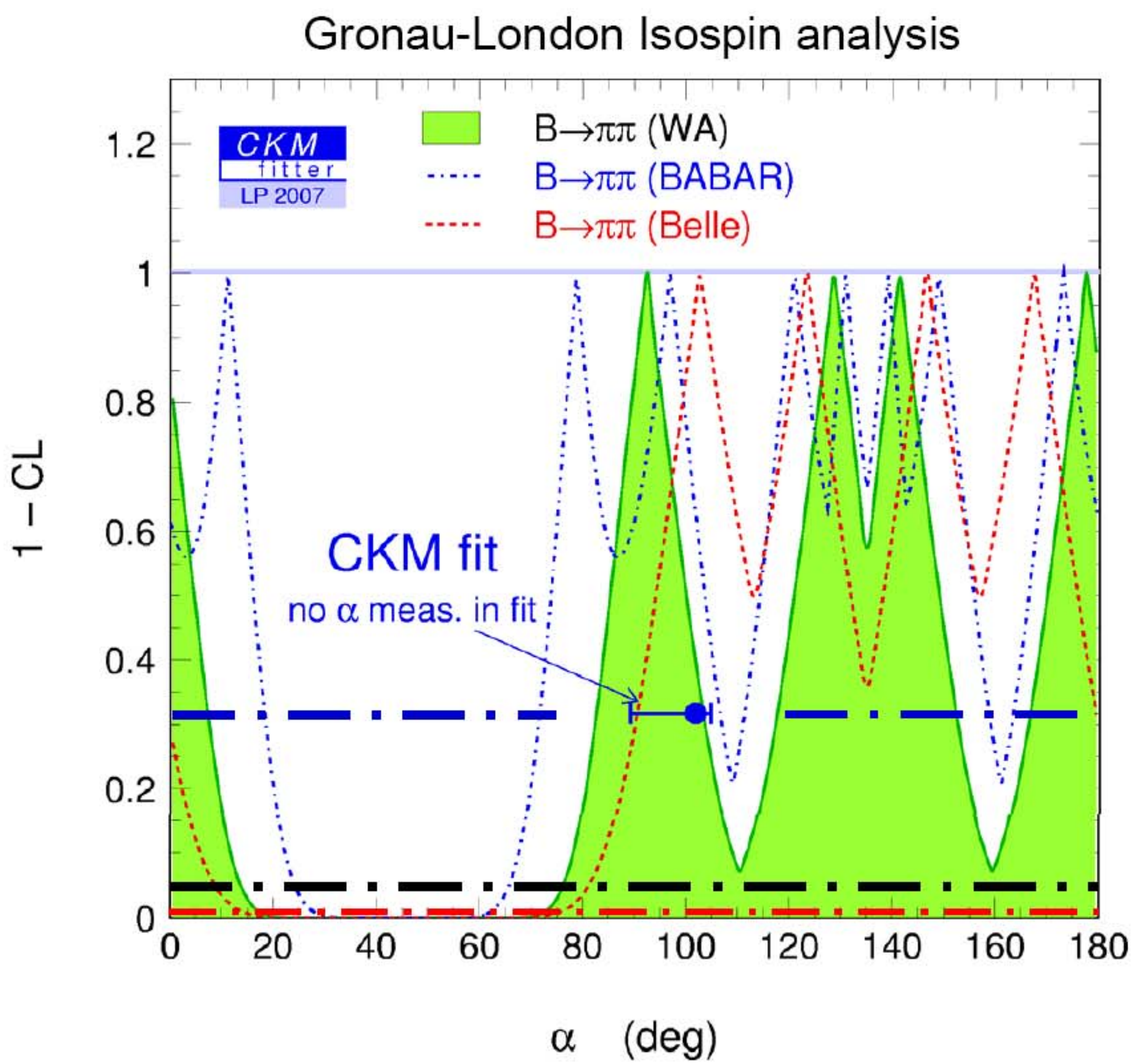
$$B^0 \to \pi^+\pi^-$$

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

$$B^0 \to \pi^0\pi^0$$

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?

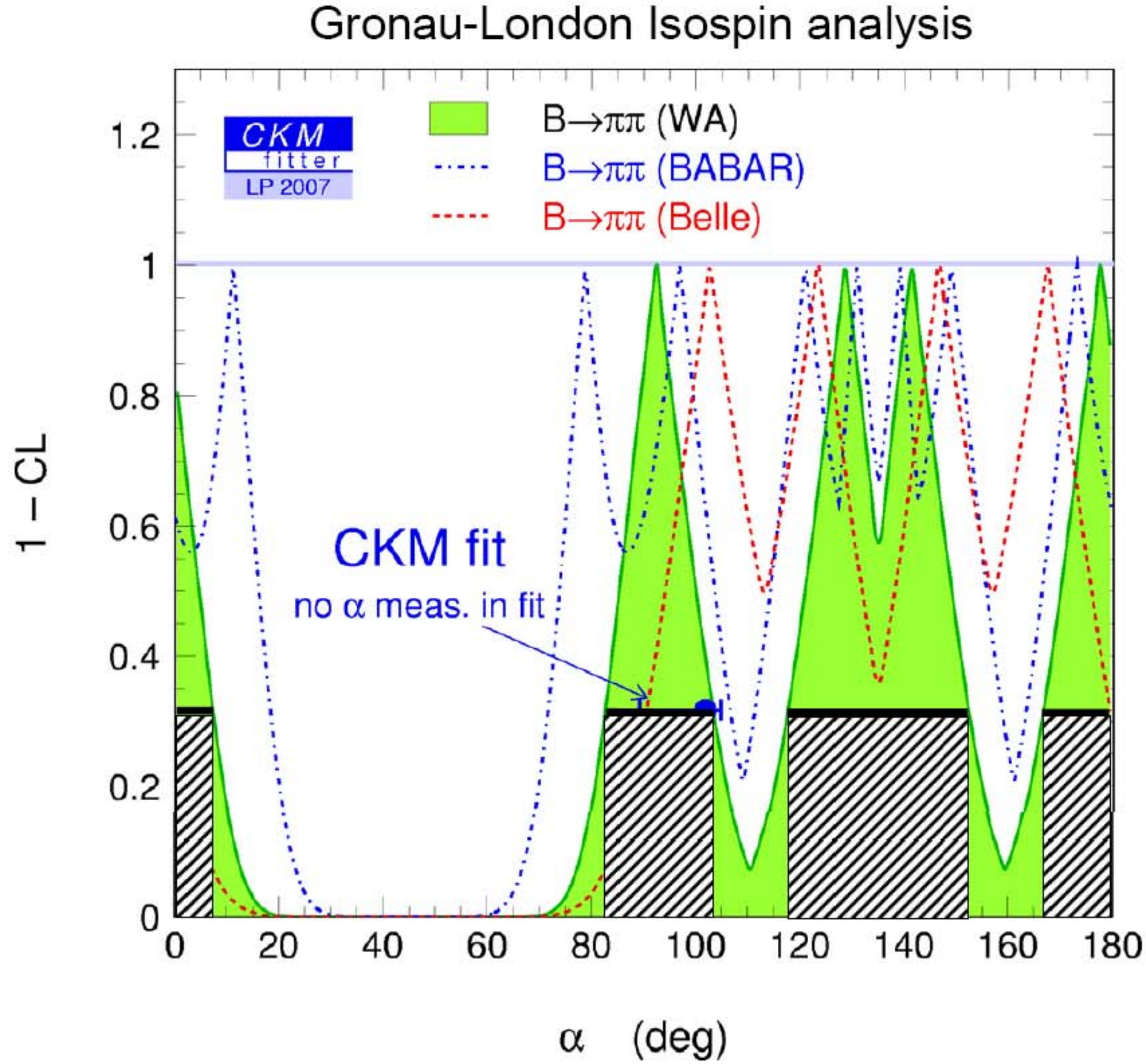
- At 68.3% CL = 1σ for Gaussian errors we have the following allowed regions for α:

$$\alpha < 7.5^{\circ}$$

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

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

$$\alpha > 166.7^{\circ}$$



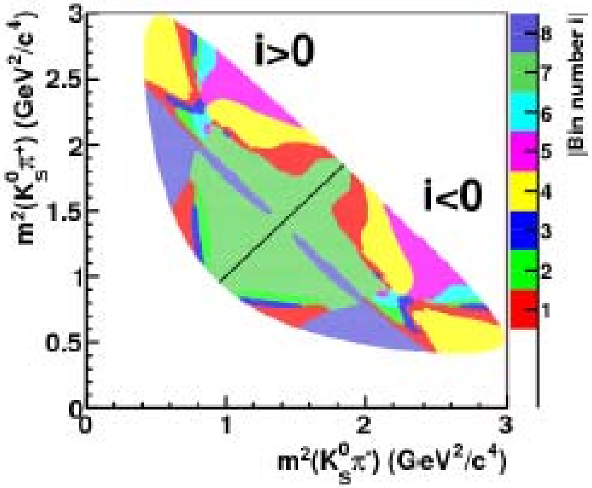
From: Adrian Bevan, slides at Helmholz International Summer School, Dubna, Russia, August 11-21, 2008

ϕ_3: Binned Dalitz plot analysis

Solution: use binned Dalitz plot and deal with numbers of events in bins.

[A. Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD **68**, 054018 (2003)]

[A. Bondar, A. P. EPJ C **47**, 347 (2006); EPJ C **55**, 51 (2008)]



$$M_i^{\pm} = h\{K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_{\pm}c_i + y_{\pm}s_i)\}$$

$$x_{\pm} = r_B\cos(\delta_B \pm \phi_3) \quad y_{\pm} = r_B\sin(\delta_B \pm \phi_3)$$

$M_i^{\pm}$: numbers of events in $D \to K^0_S\pi^+\pi^-$ bins from $B^{\pm} \to DK^{\pm}$

K_i: numbers of events in bins of flavor $\overline{D}^0 \to K^0_S\pi^+\pi^-$ from $D^* \to D\pi$.

c_i, s_i contain information about strong phase difference between symmetric Dalitz plot points $(m^2_{K^0_S\pi^+}, m^2_{K^0_S\pi^-})$ and $(m^2_{K^0_S\pi^-}, m^2_{K^0_S\pi^+})$:

$$c_i = \langle\cos\Delta\delta_D\rangle, \quad s_i = \langle\sin\Delta\delta_D\rangle$$

ϕ_3: Obtaining c_i, s_i

Coefficients c_i, s_i can be obtained in $\psi(3770) \to D^0\overline{D}^0$ decays.
Use quantum correlations between D^0 and $\overline{D}^0$.

- If both D decay to $K^0_S\pi^+\pi^-$, the number of events in i-th bin of $D_1 \to K^0_S\pi^+\pi^-$ and j-th bin of $D_2 \to K^0_S\pi^+\pi^-$ is

$$M_{ij} = K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-i}K_jK_{-j}}(c_ic_j + s_is_j).$$

  $\Rightarrow$ constrain c_i and s_i.

- If one D decays to a CP eigenstate, the number of events in i-th bin of another $D \to K^0_S\pi^+\pi^-$ is

$$M_i = K_i + K_{-i} \pm 2\sqrt{K_iK_{-i}}c_i.$$

  $\Rightarrow$ constrain c_i.

c_i, s_i measurement has been done by CLEO and can be done in future at BES-III.

CKM matrix

3x3 ortogonal matrix: 3 parameters - angles

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

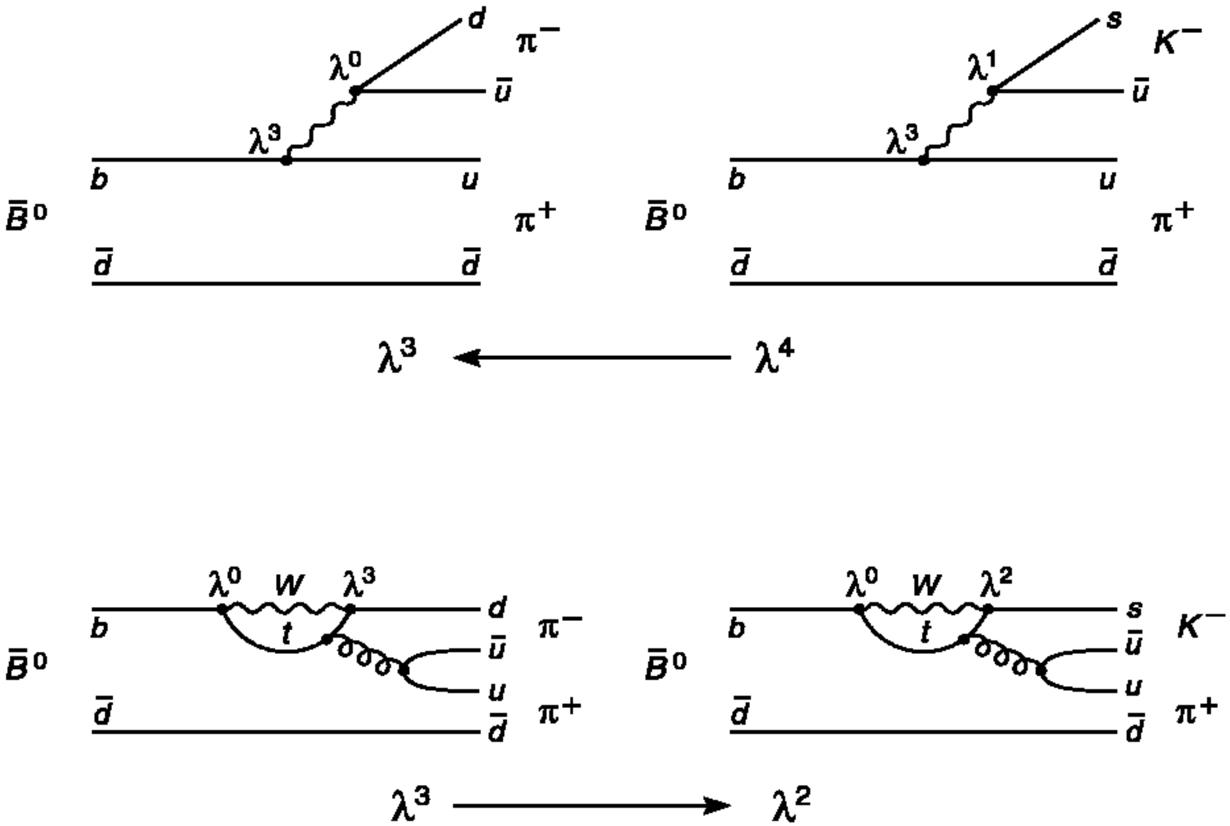
6 quarks: 5 relative phases can be transformed away (by redefinig the quark fields)

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.

Diagrams for B→ ππ, Kπ decays



ππ

Kπ

•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