Experiments in Particle Physics

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Contents of this course

- Lecture 1: Introduction, experimental methods, detectors, data analysis
- Lecture 2: Selection of particle physics experiments: flavour physics
- LHC experiments: see T. Kondo's lecture

http://www-f9.ijs.si/~krizan/sola/nagoya-ise/

- Slides
- Literature

Standard Model: content

Particles:

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

Interactions:

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

Higgs field

Flavour physics

... 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 ($\sin 2\phi_1$)

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

Distiguished in 2008 by the Nobel prize to Kobayashi and Maskawa

CP Violation

Fundamental quantity: distinguishes matter from anti-matter.

A bit of history:

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

What happens in the B meson system?

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

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

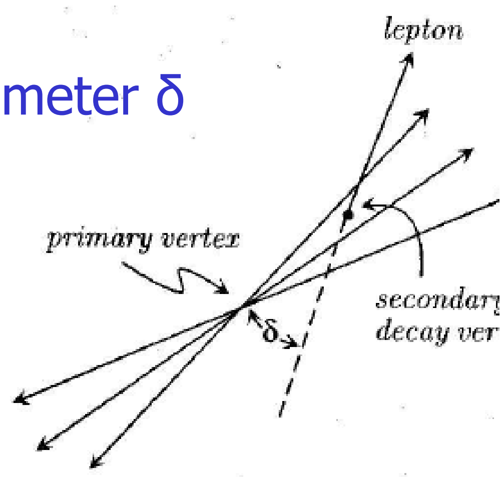
B has a heavy quark, a smaller system, and is easier for interpreting the experimental results.

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

B mesons: long lifetime

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

Measure impact parameter δ wrt interaction point

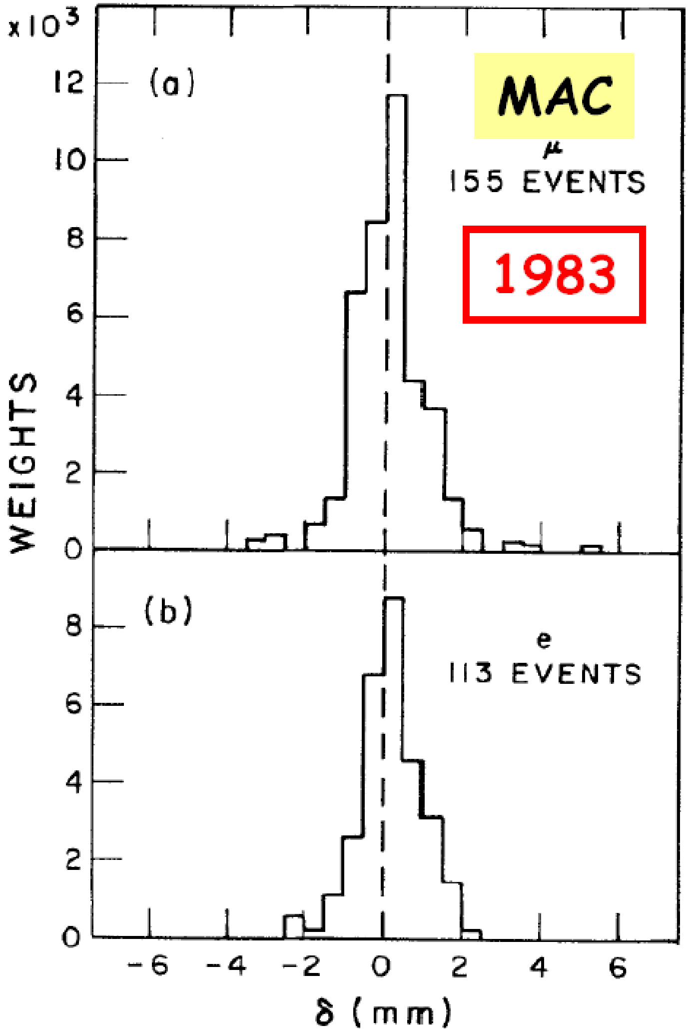


Lifetime implies V_{cb} small

MAC: (1.8±0.6±0.4)ps

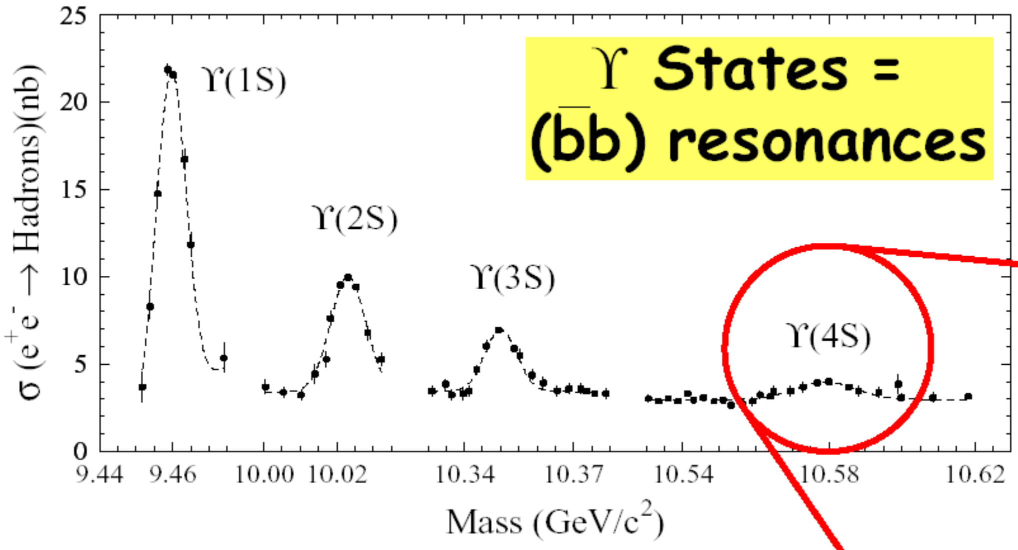
Mark II: (1.2±0.4±0.3)ps

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

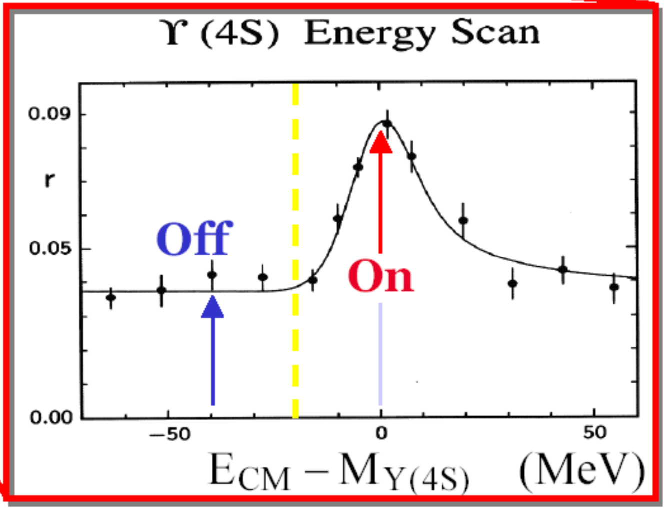


MAC, PRL **51**, 1022 (1983)
MARK II, PRL **51**, 1316 (1983)

Systematic studies of B mesons: at Υ(4s)



Υ States = $(b\bar b)$ resonances



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

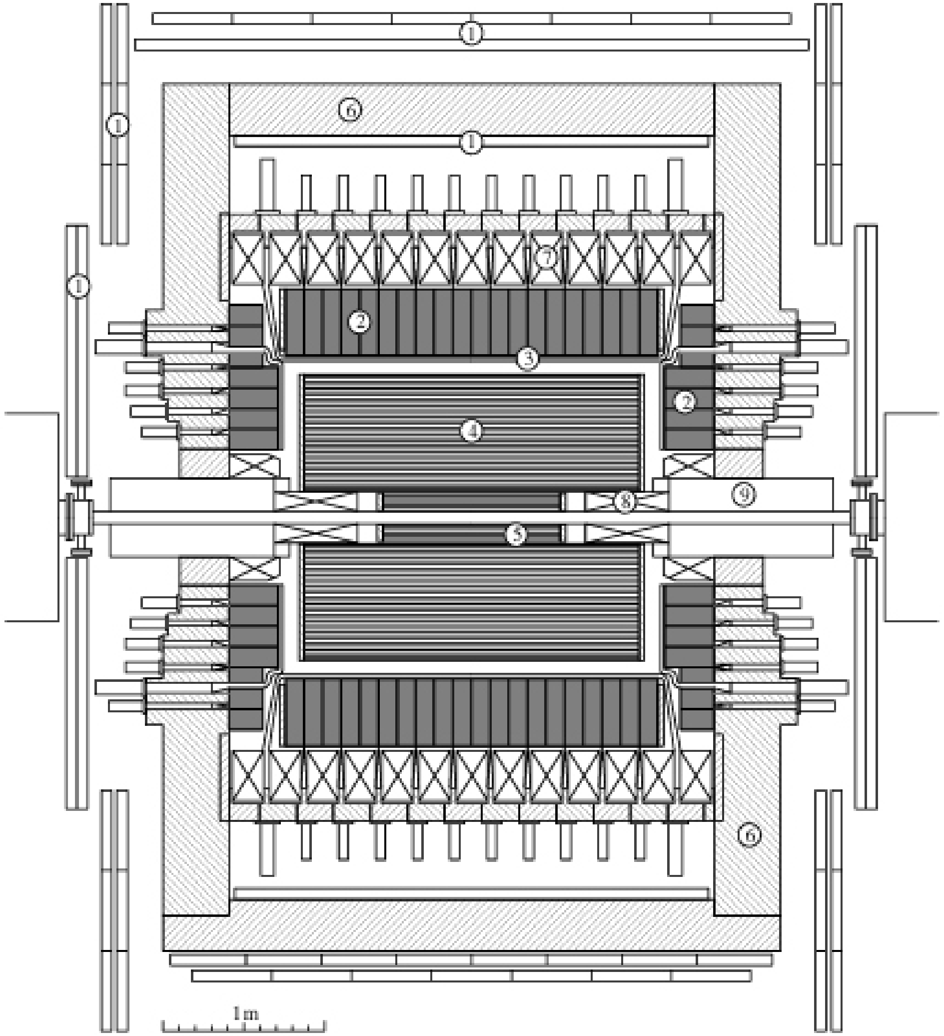
Systematic studies of B mesons at $\Upsilon(4s)$

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)

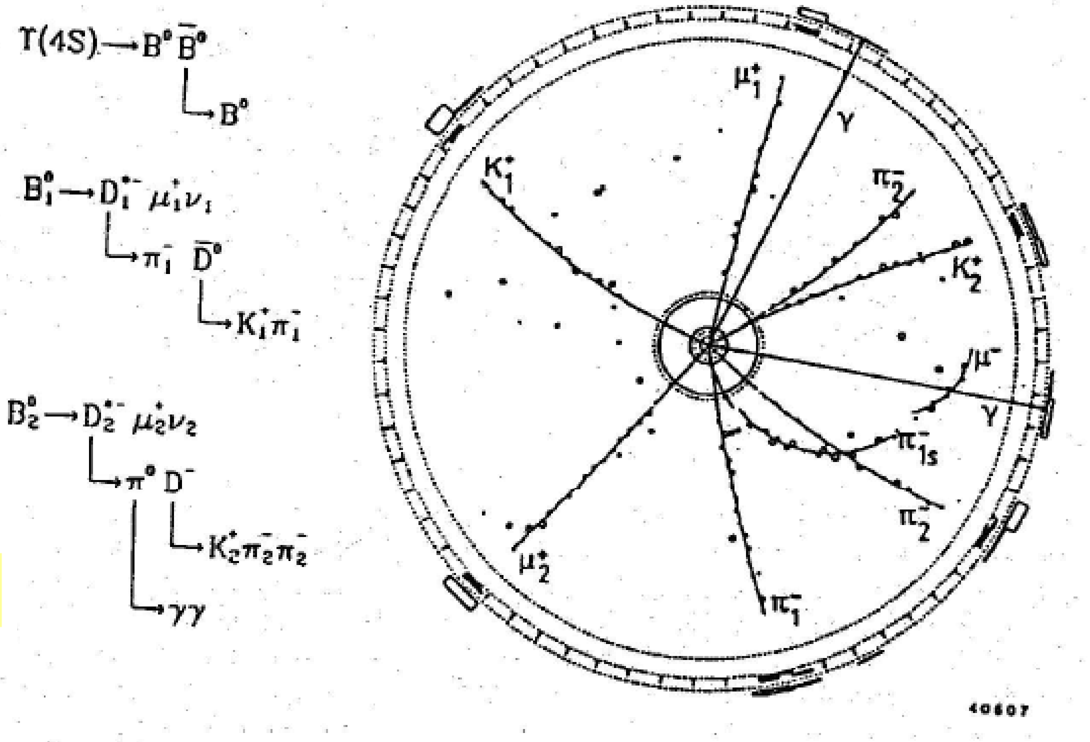
Large solid angle, excellent tracking and good particle identification (TOF, dE/dx, EM calorimeter, muon chambers).



Mixing in the B^0 system

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

Reconstructed event



$\chi_d = 0.17 \pm 0.05$

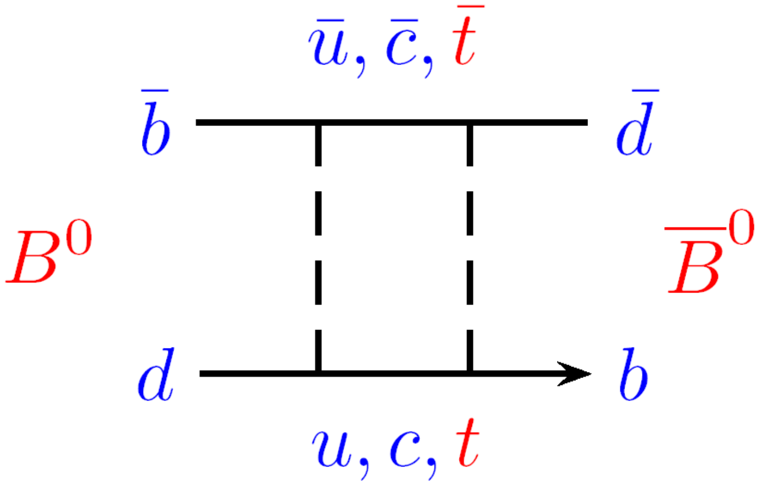
ARGUS, PL B **192**, 245 (1987)

cited >1000 times.

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

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

Mixing in the B^0 system



$$\Delta m \propto$$

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

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

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

The top quark has only been discovered seven years later!

Systematic studies of B mesons at Y(4s)

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

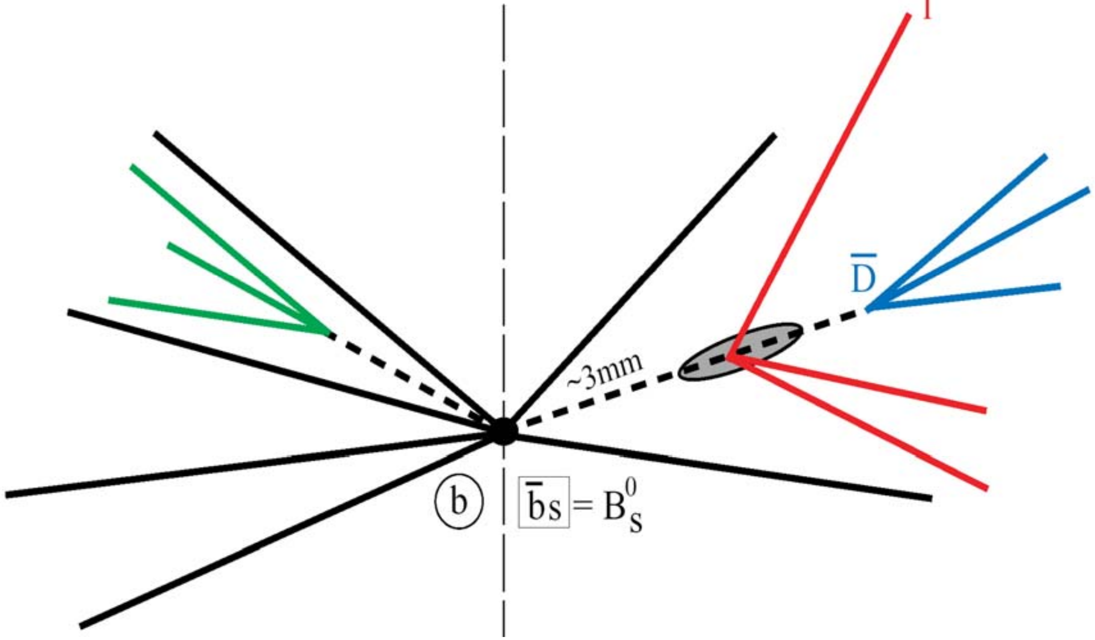
- B mesons
- D mesons
- τ^- lepton
- and even a measurement of ν_τ mass.

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

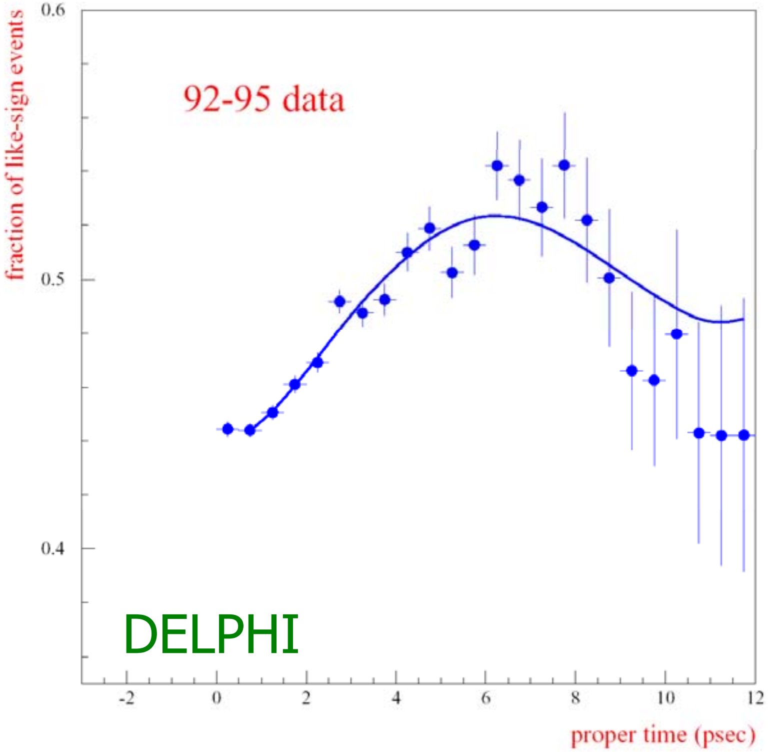
Studies of B mesons at LEP

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

- Large solid angle, excellent tracking, vertexing, particle identification
- Boost of B mesons → time evolution (lifetimes, mixing)
- Separation of one B from the other → inclusive rare b→u



Studies of B mesons at LEP and SLC



B^0 → anti-B^0 mixing, time evolution

Fraction of events with like sign lepton pairs

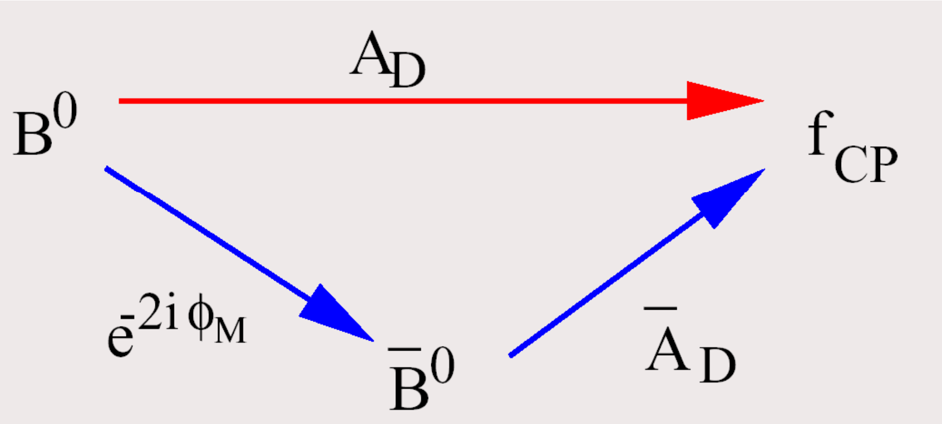
Almost measured mixing in the B_s system (bad luck...)

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

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

CPV through interference of decay amplitudes

CPV through interference of mixing diagram



CPV through interference between mixing and decay amplitudes

Directly related to CKM parameters in case of a single amplitude

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

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

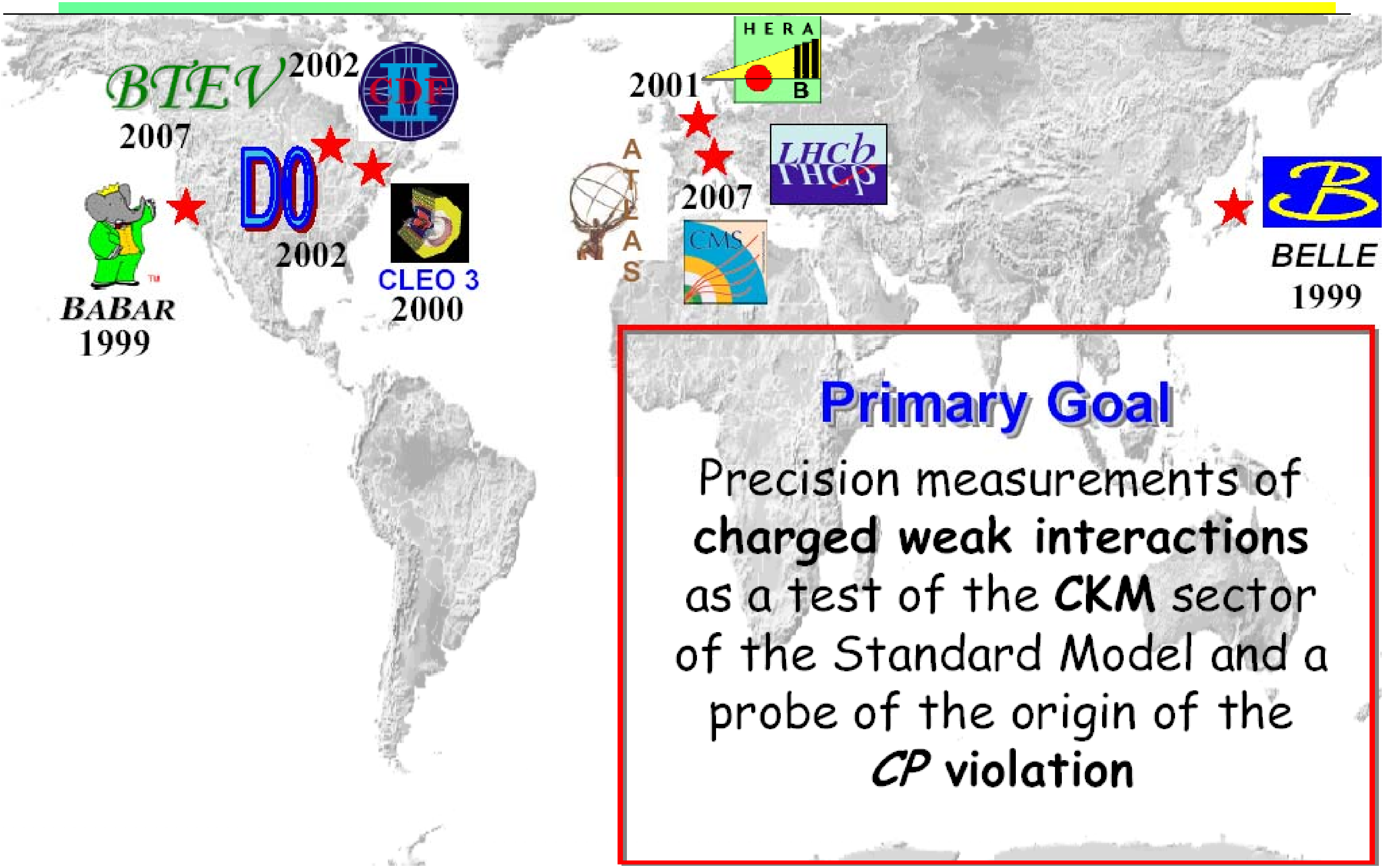
Theoretically clean way to one of the parameters ($\sin 2\phi_1$)

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

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

→ A lot of physicists were after this holy grail

Genesis of Worldwide Effort



Primary Goal

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

Time evolution in the B system

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

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

is governed by a time-dependent Schroedinger equation

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

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

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

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

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

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

with the eigenvalue differences

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

They are determined from the M and Γ matrix elements

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

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

The ratio p/q is

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

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

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

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

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

→ **$\Delta\Gamma_B << \Delta m_B$**

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

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

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

and

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

= a phase factor

or to the next order

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

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

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

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

Time evolution

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

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

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

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

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

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

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

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

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

→mixing

Time evolution of B's

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

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

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

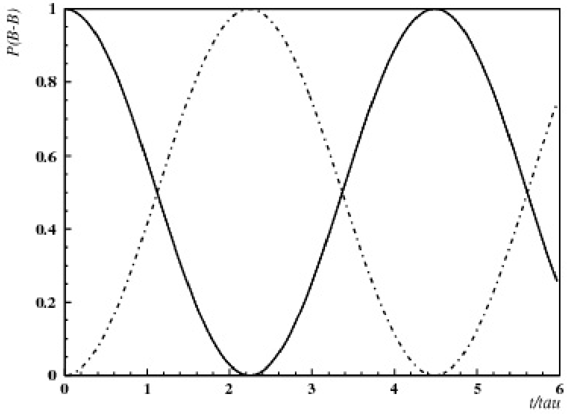
with

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

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

$M = (M_H+M_L)/2$

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



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

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

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

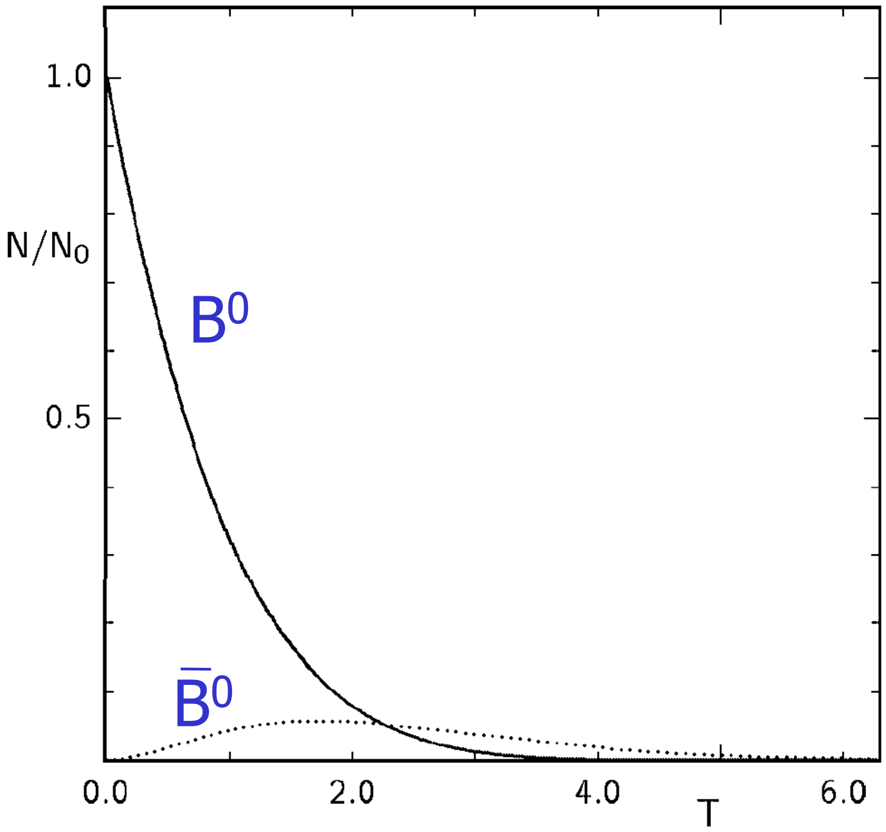
$$\left|\left\langle \overline{B}^0 \middle| B^0_{phys}(t)\right\rangle\right|^2 = |q/p|^2 |g_-(t)|^2 = |q/p|^2 \sin^2(\Delta m t/2)$$

→Probability that a B remains a B

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

→Expressions familiar from quantum mechanics of a two level system

B mesons of course do decay →



B^0 at t=0

Evolution in time

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

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

Decay probability

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

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

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

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

Decay amplitude as a function of time:

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

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

... and similarly for the anti-B

CP violation: three types

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

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

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

Define a parameter λ

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

Three types of CP violation (CPV):

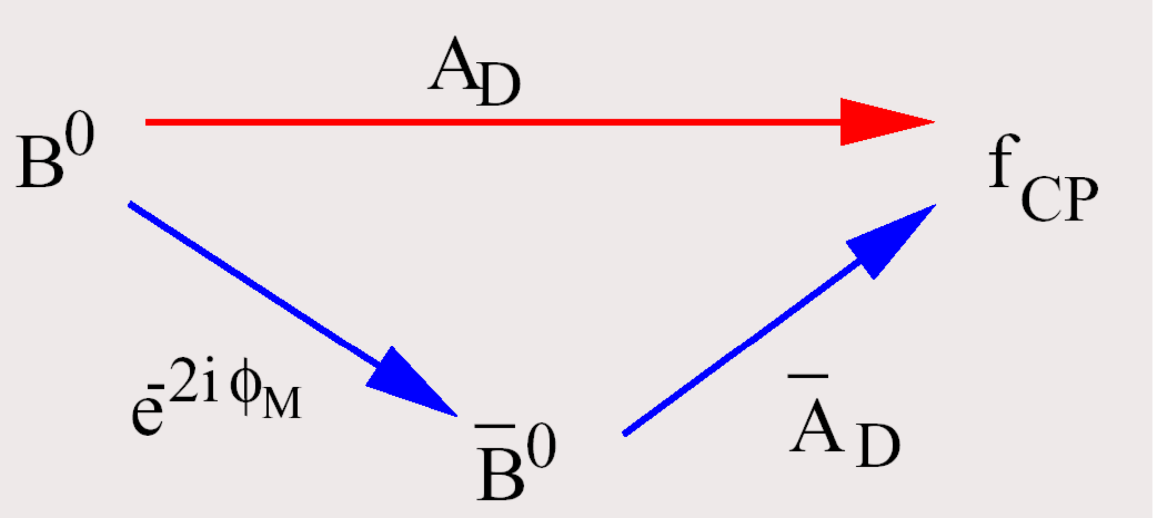
$$\left.\begin{array}{l} \cancel{CP}\text{ in decay: } |\bar{A}/A| \neq 1 \\ \\ \cancel{CP}\text{ in mixing: } |q/p| \neq 1 \end{array}\right\} \; |\lambda| \neq 1$$

$\cancel{CP}$ 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

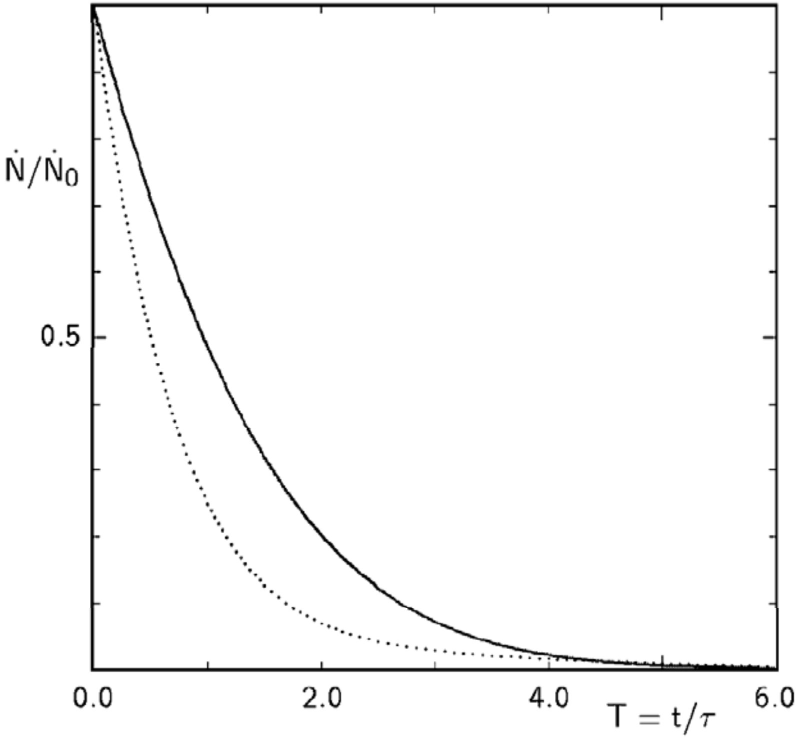
- one decays to a CP eigenstate f_{CP} (e.g. $\pi\pi$ or $J/\psi K_S$) at time t_{fCP} and
- the other at t_{ftag} to a flavor-specific state f_{tag} (=state only accessible to a B^0 and not to a anti-B^0 (or vice versa), e.g. $B^0 \to D^0\pi$, $D^0 \to K^-\pi^+$)

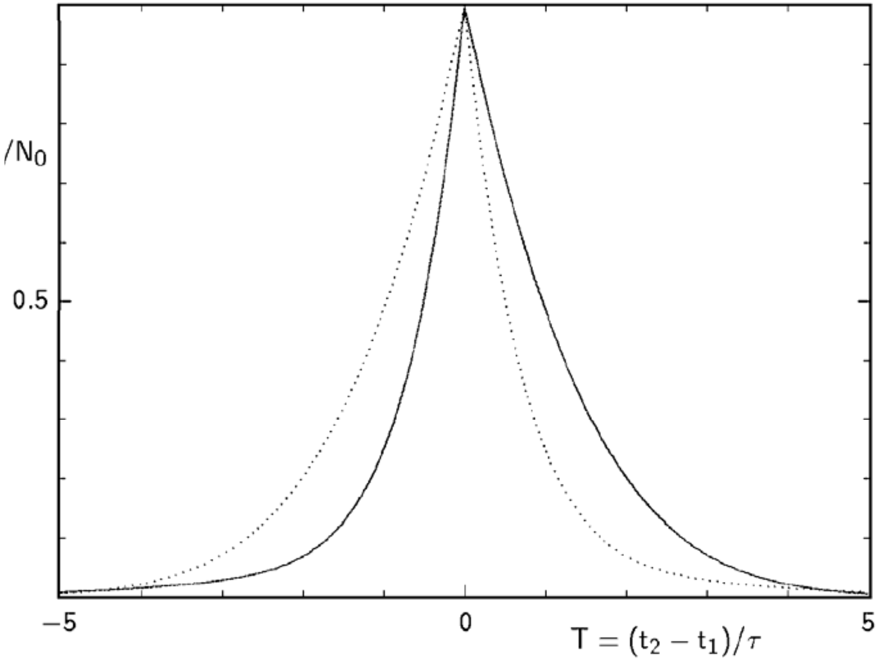
also known as 'tag' because it tags the flavour of the B meson it comes from

Decay rate to f_{CP}

Incoherent production
(e.g. hadron collider)

coherent production
at Y(4s)

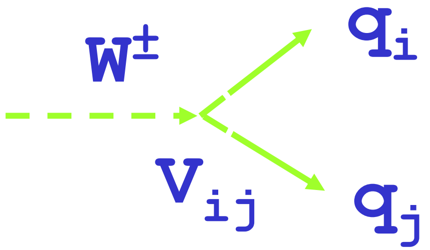




At Y(4s): Time integrated asymmetry = 0

CP violation in SM

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



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

CKM matrix

3x3 ortogonal matrix: 3 parameters - angles

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

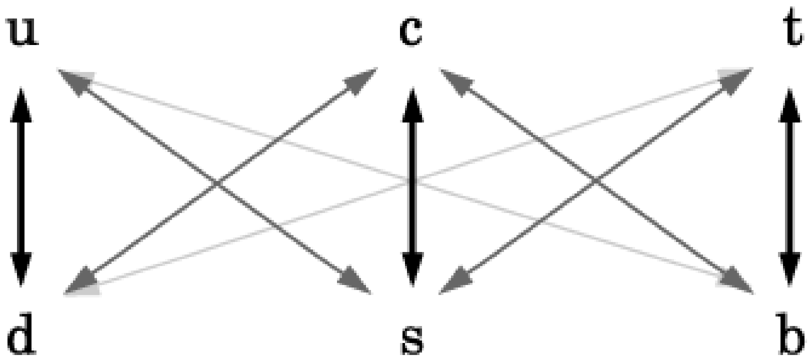
6 quarks: 5 relative phases can be transformed away (by redefinig the quark fields)

1 phase left -> the matrix is in general complex

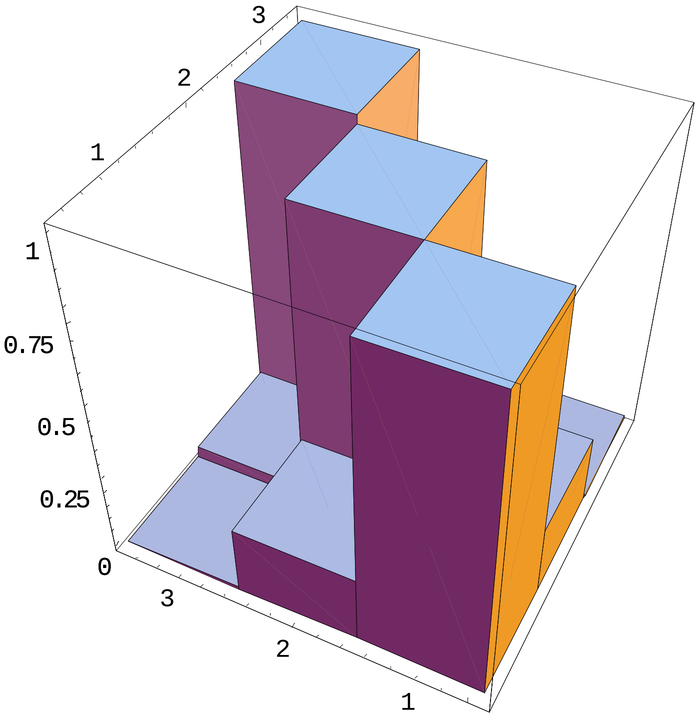
$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{13} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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

CKM matrix



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



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

CKM matrix

Almost a diagonal matrix, but not completely ->

Wolfenstein parametrisation: expand in the parameter λ (=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

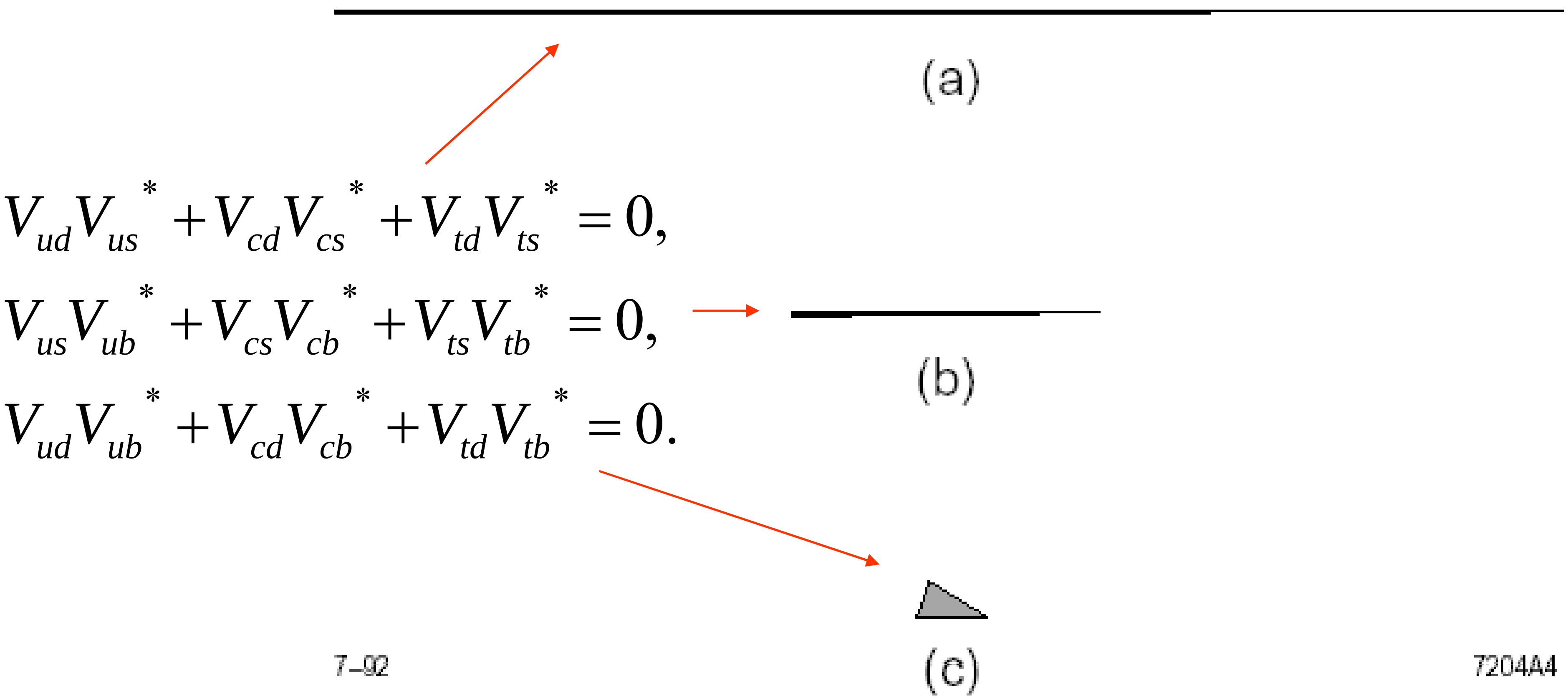
Rows and columns of the V matrix are orthogonal

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 $4\mathrm{x}10^{-5}$)

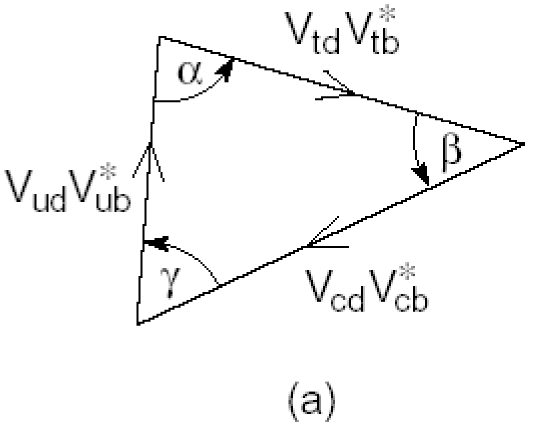
$$J=c_{12}c_{23}c_{13}^{2}s_{12}s_{23}s_{13}\sin\delta$$

Jarlskog invariant

Unitarity triangle

THE unitarity triangle:

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

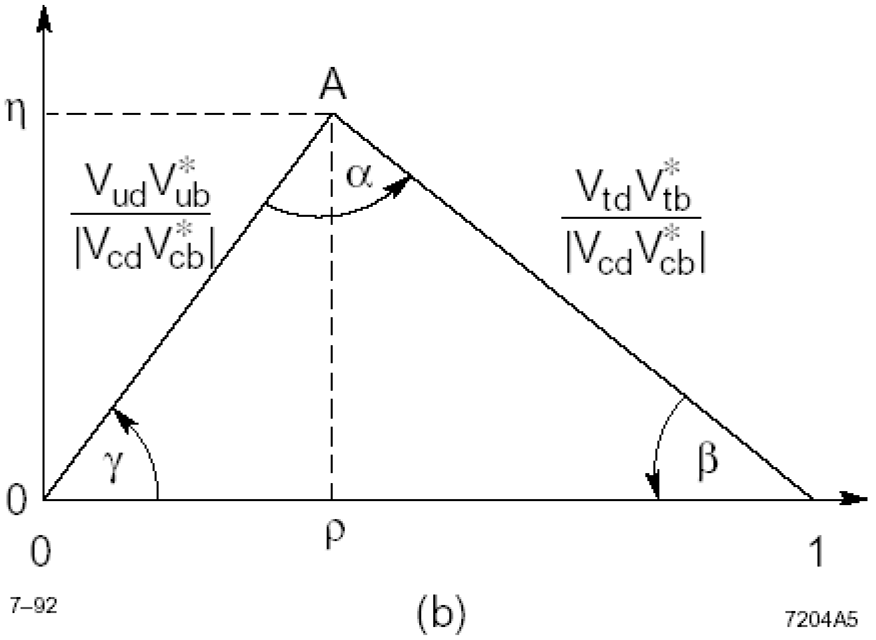


Two notations:

$\phi_1=\beta$

$\phi_2=\alpha$

$\phi_3=\gamma$

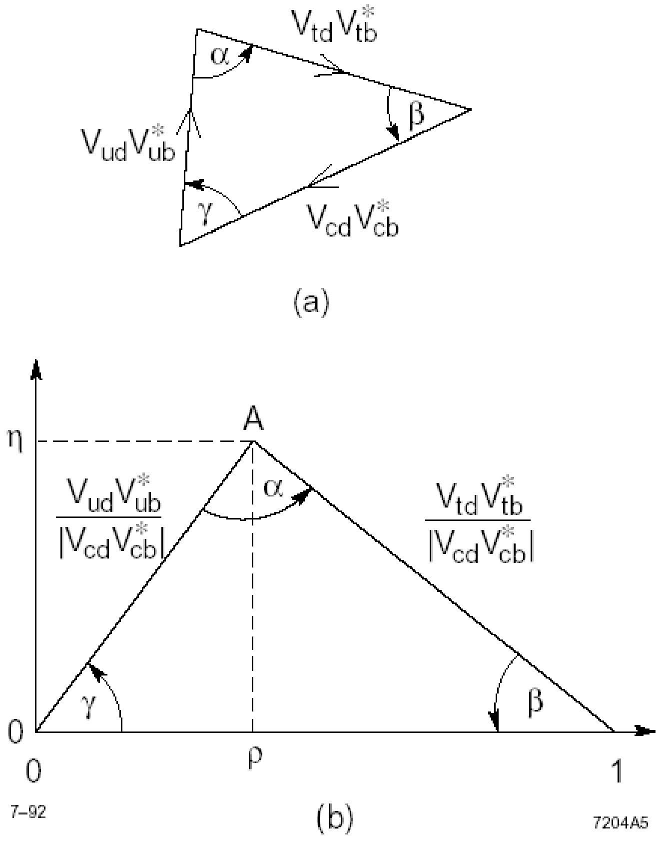


Angles of the unitarity triangle

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

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

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

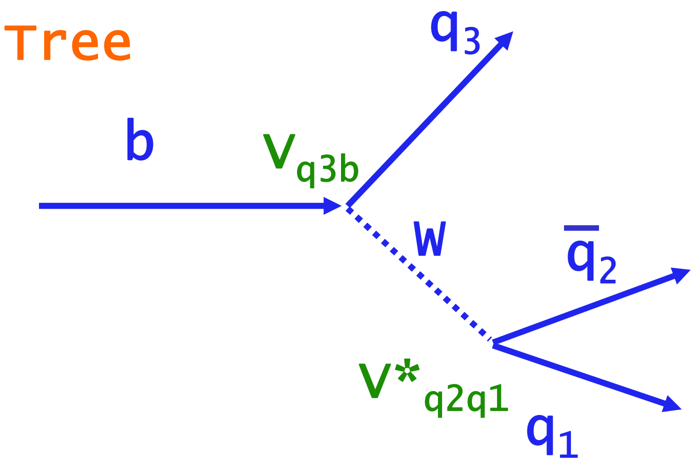


(a)

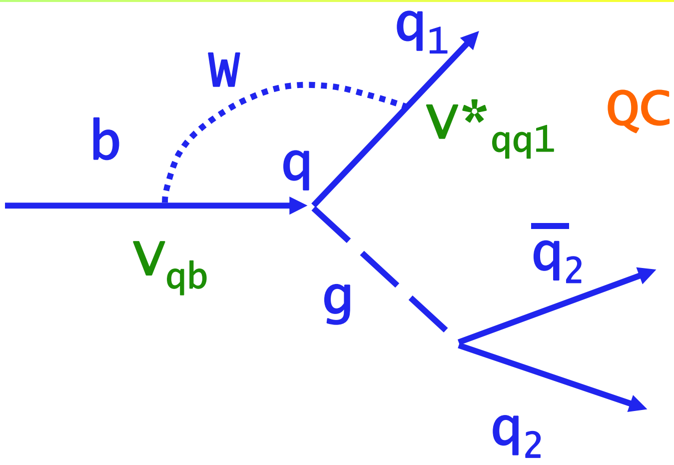
(b)

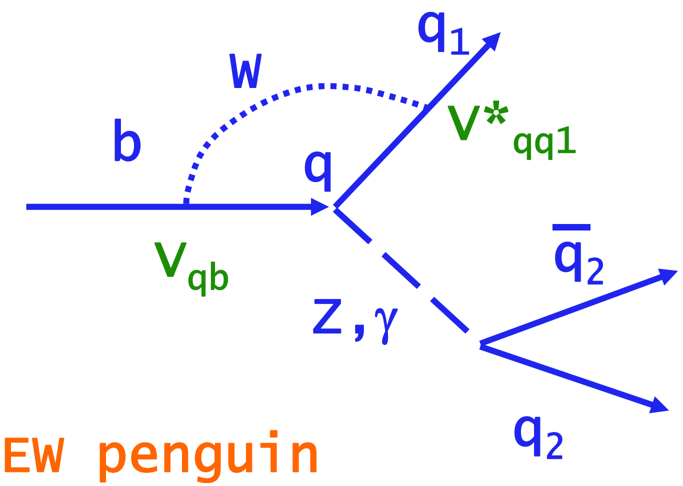
b decays

Tree



QCD penguin

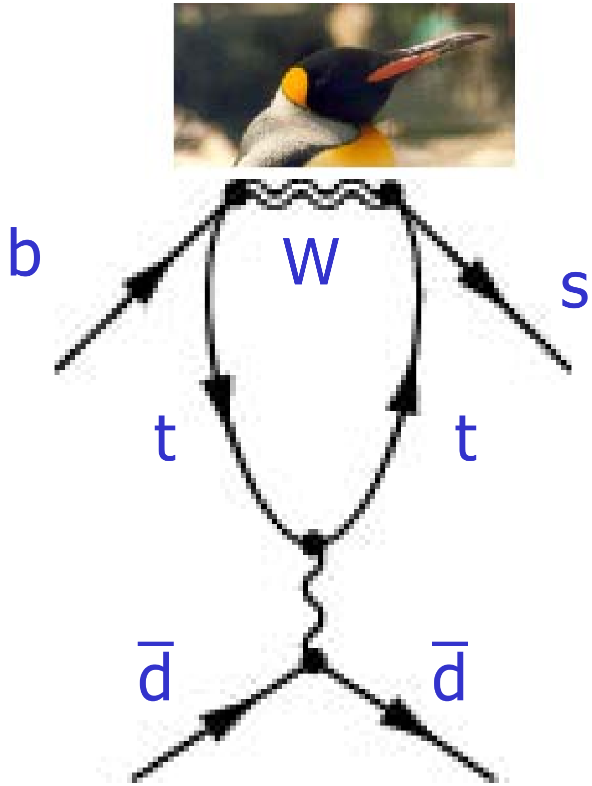




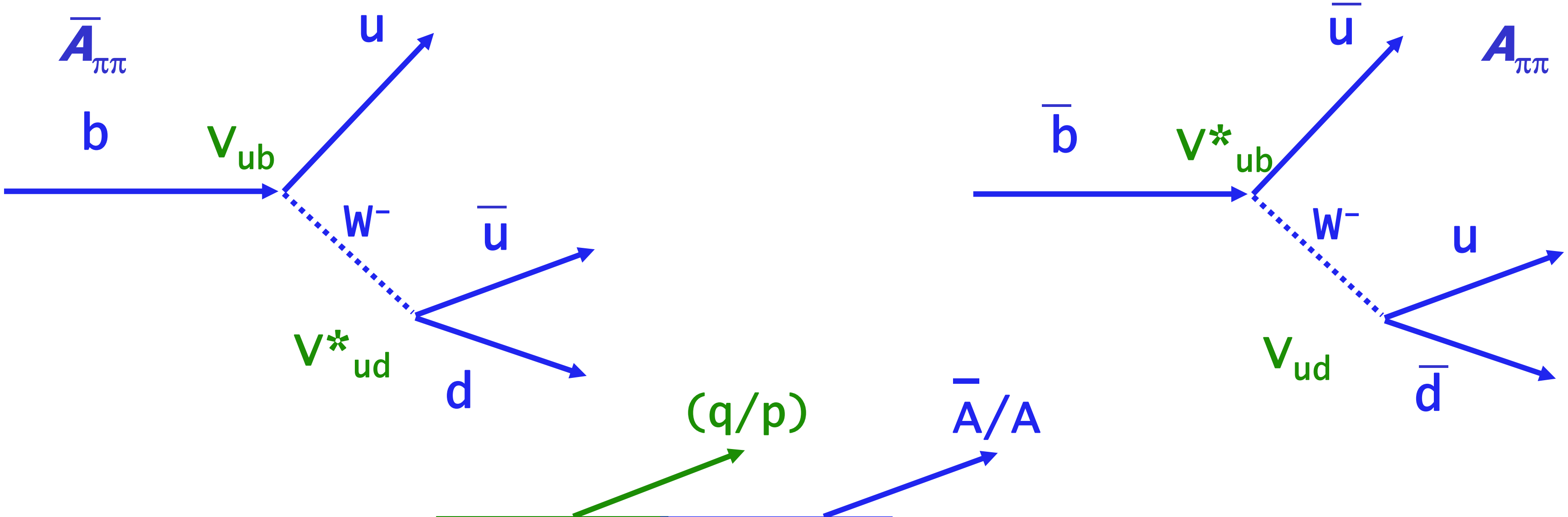
EW penguin

Why penguin?

Example: b→s transition



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



$$\lambda_{\pi\pi} = \eta_{\pi\pi} \boxed{\left(\frac{V_{tb}^{\;*} V_{td}}{V_{tb} V_{td}^{\;*}}\right)} \boxed{\left(\frac{V_{ud}^{\;*} V_{ub}}{V_{ud} V_{ub}^{\;*}}\right)}$$

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

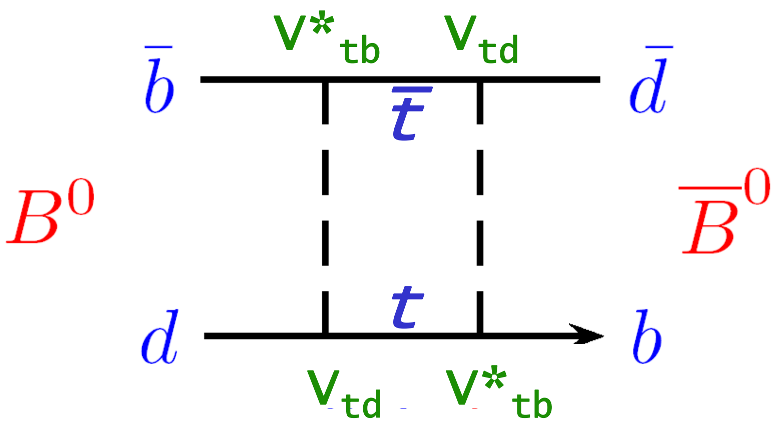
$$\alpha \equiv \phi_2 \equiv \arg\left(\frac{V_{td} V_{tb}^{\;*}}{V_{ud} V_{ub}^{\;*}}\right)$$

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

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

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

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

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

b → c anti-c s
CP=+1 and CP=-1 eigenstates

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

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

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

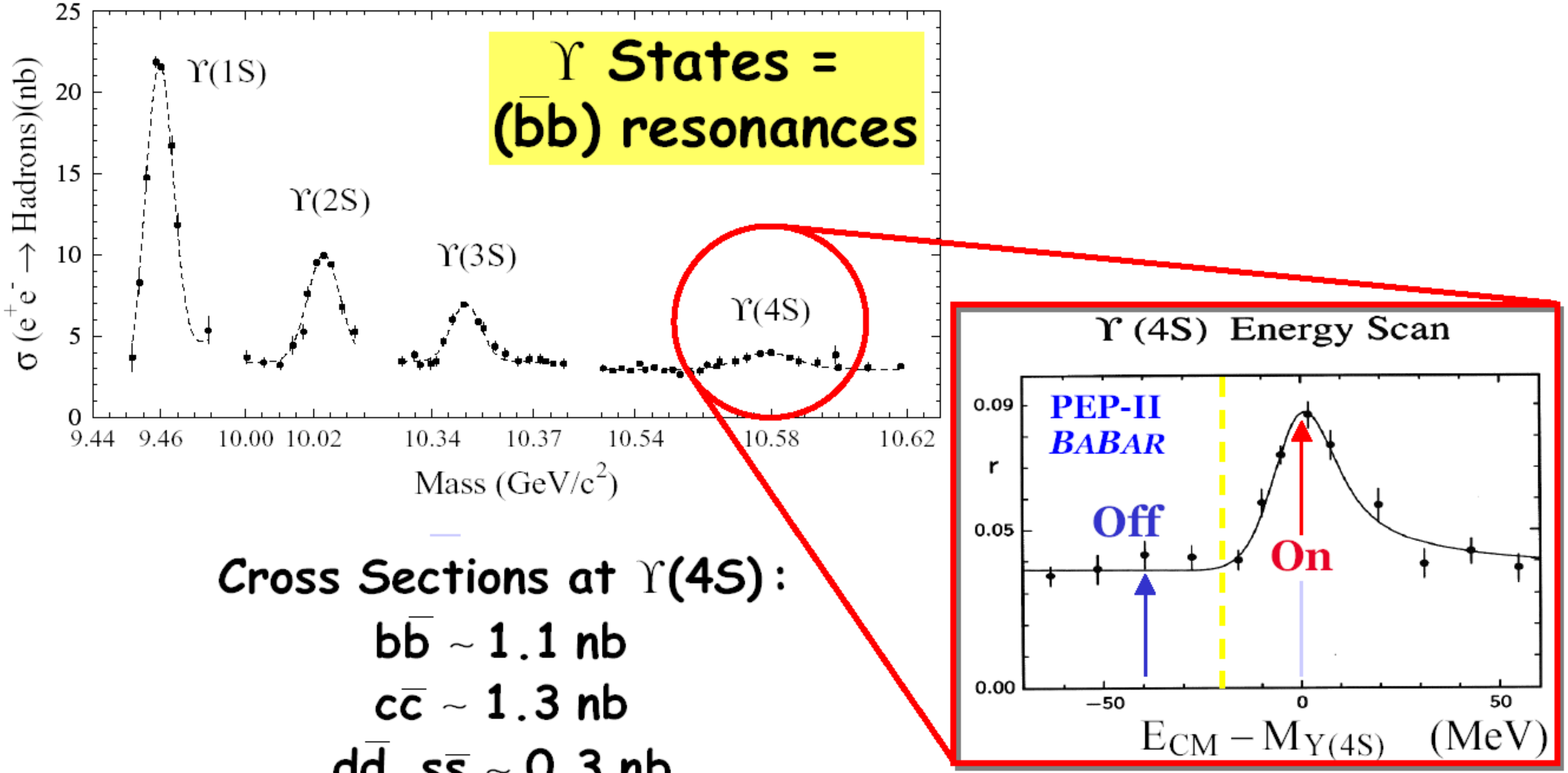
$J/\psi\ K_S\ (\pi^+\pi^-)$: CP=-1

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

B meson production at Υ(4s)



Υ States = $(b\bar{b})$ resonances

Cross Sections at Υ(4S):

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

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

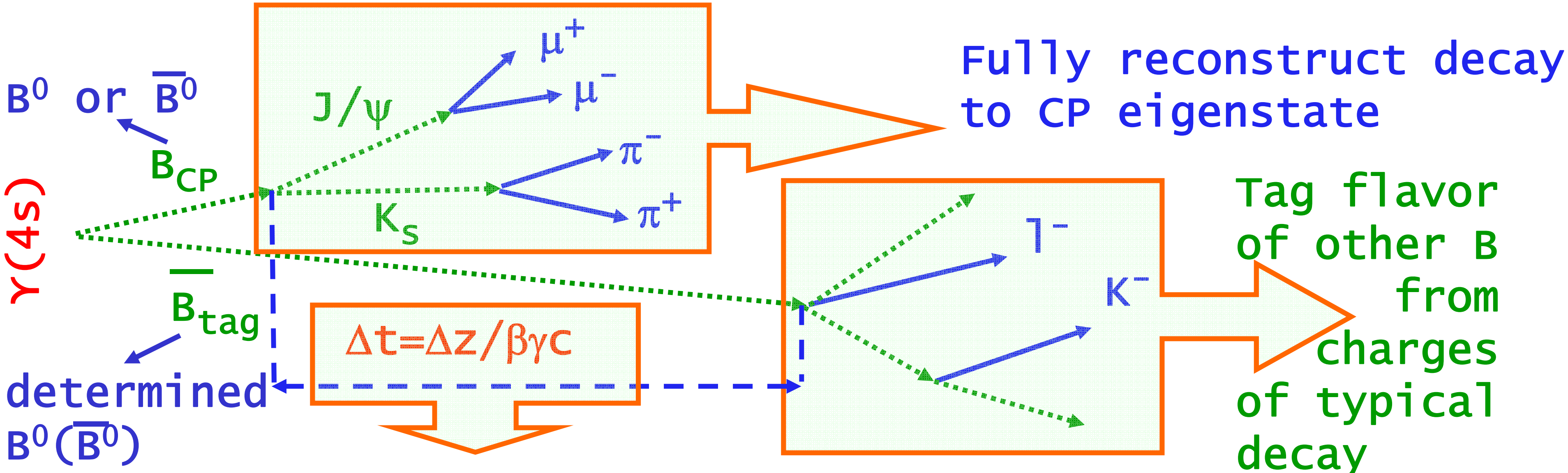
$d\bar{d}$, $s\bar{s} \sim 0.3$ nb

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

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

$$L = 1 \text{ state}$$

Principle of measurement



Fully reconstruct decay to CP eigenstate

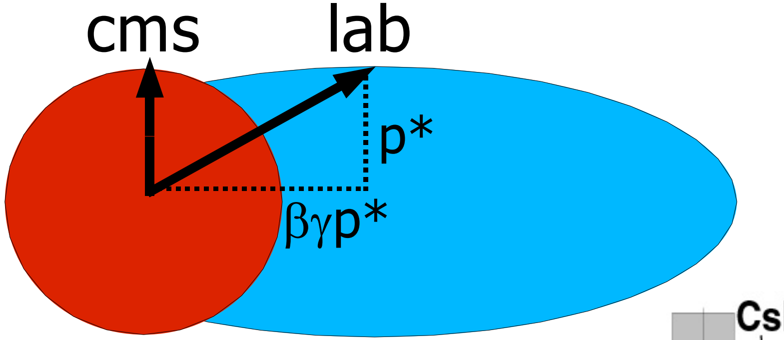
Tag flavor of other B from charges of typical decay products

Determine time between decays

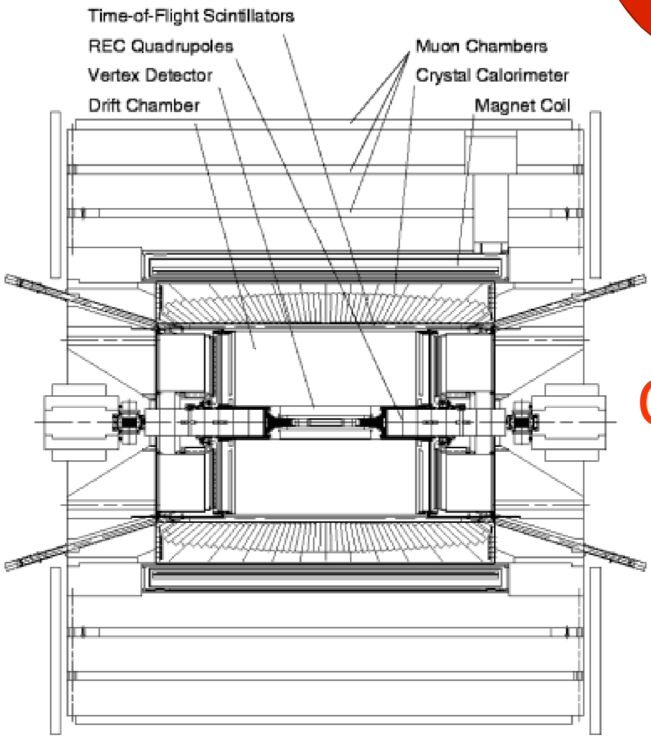
Transform distance into time: need a moving center-off-mass system → asymmetric collider

Experimental considerations

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

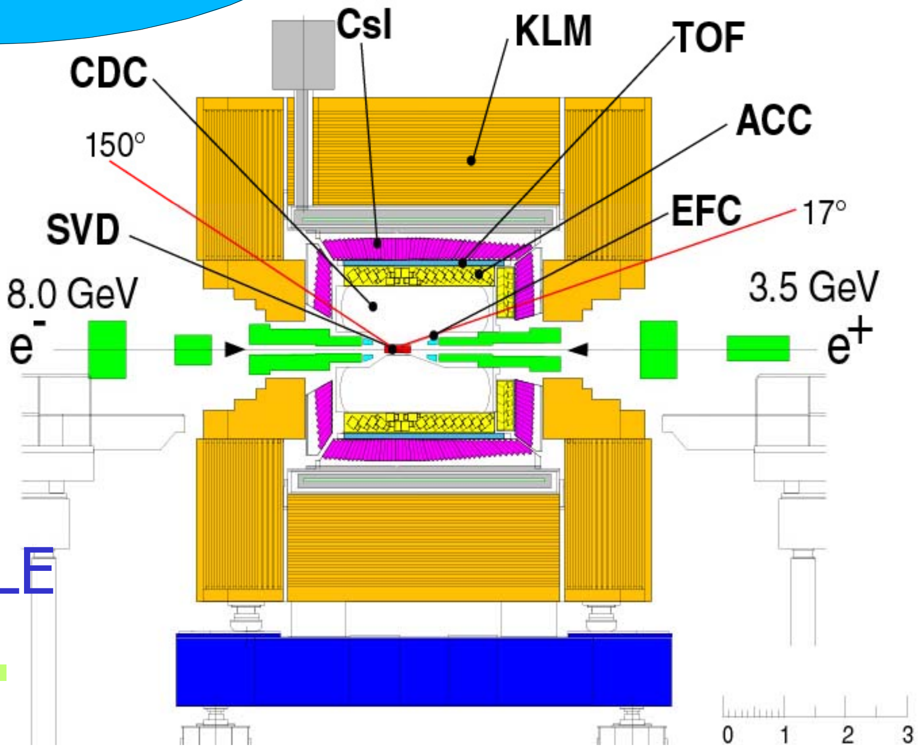


Exaggerated plot: in reality $\beta\gamma=0.5$



CLEO

BELLE



How many events?

Rough estimate:

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

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

BR(B-> J/ψ K^0)=$8.4\ 10^{-4}$

BR(J/ψ -> ee or $\mu\mu$)=11.8%

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

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

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

How to produce 140 M BB pairs?

Want to produce 140 M pairs in two years

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

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

Observed rate of events = Cross section x Luminosity

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

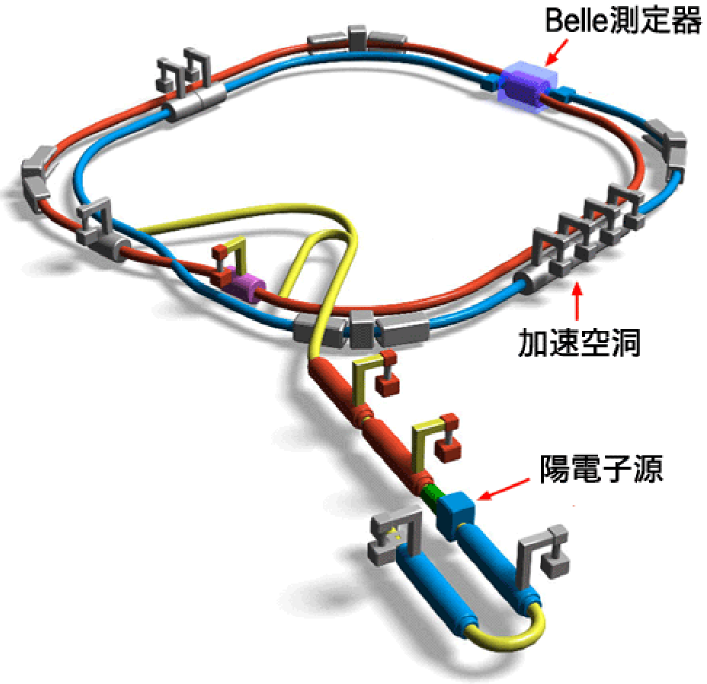
Cross section for Y(4s) production: 1.1 nb = 1.1 10^{-33} cm^2

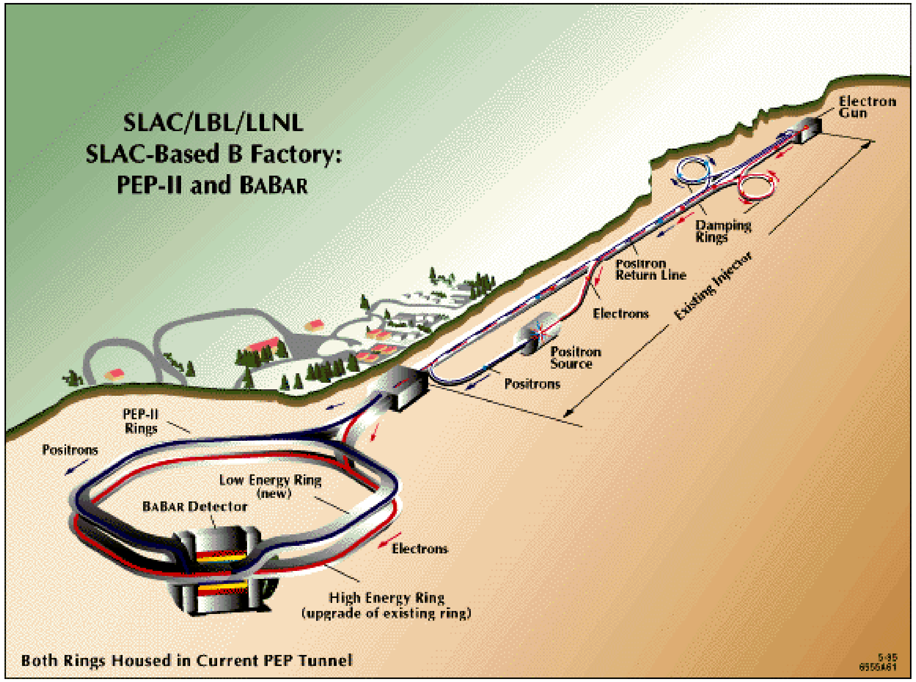
→ Accelerator figure of merit - luminosity - has to be

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

This is much more than any other accelerator achieved before!

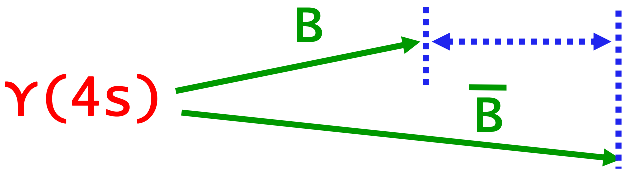
Colliders: asymmetric B factories





$\sqrt{s}=10.58$ GeV

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



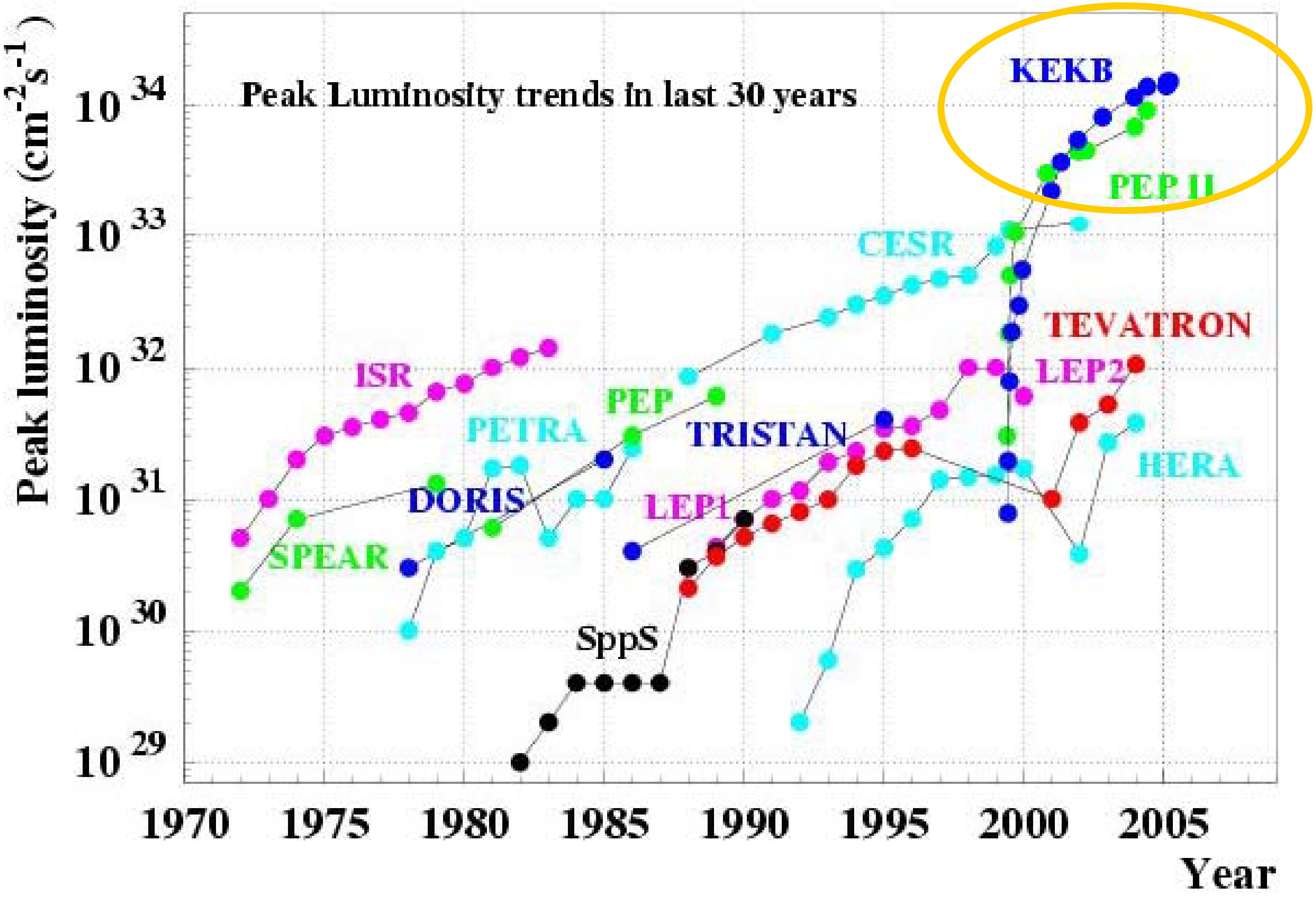
$\Delta z \sim c\beta\gamma\tau_B$
$\sim 200\mu m$

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

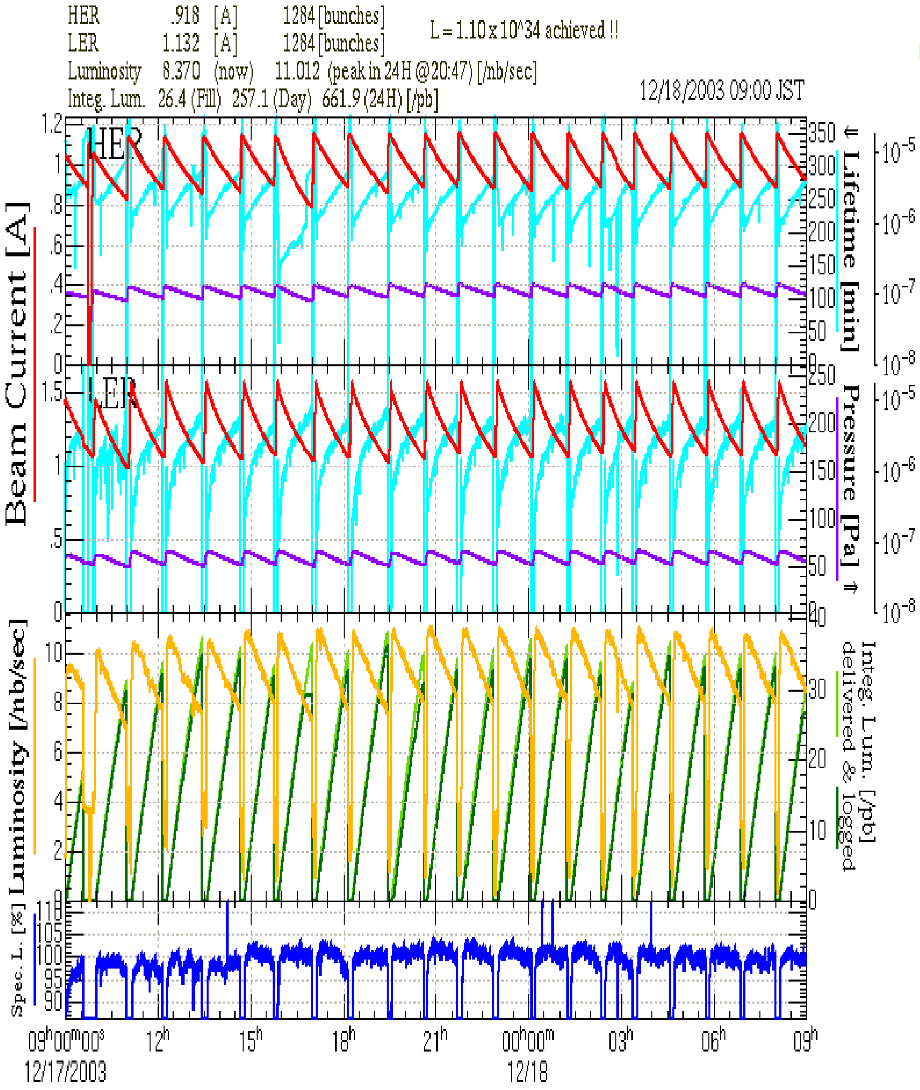
KEKB records: L_{peak} = 17/nb/sec (=$1.7\text{x}10^{34}$ $s^{-1}cm^{-2}$)

L_{int}= 852/fb → ~900 M BB pairs

Accelerator performance



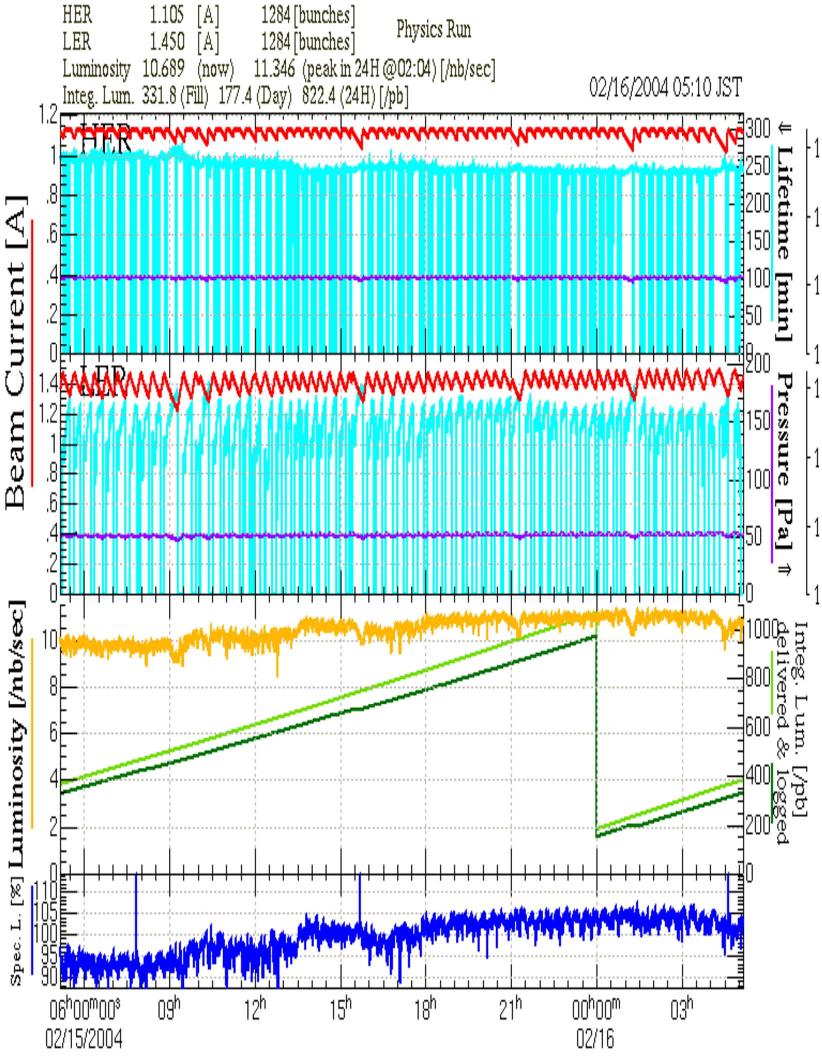
Normal injection


HER .918 [A] 1284 [bunches]
LER 1.132 [A] 1284 [bunches]
Luminosity 8.370 (now) 11.012 (peak in 24H @20:47) [/nb/sec]
Integ. Lum. 26.4 (Fill) 257.1 (Day) 661.9 (24H) [/pb]

L = 1.10 x 10^34 achieved !!

12/18/2003 09:00 JST

Continuous injection


HER 1.105 [A] 1284 [bunches]
LER 1.450 [A] 1284 [bunches]
Luminosity 10.689 (now) 11.346 (peak in 24H @02:04) [/nb/sec]
Integ. Lum. 331.8 (Fill) 177.4 (Day) 822.4 (24H) [/pb]

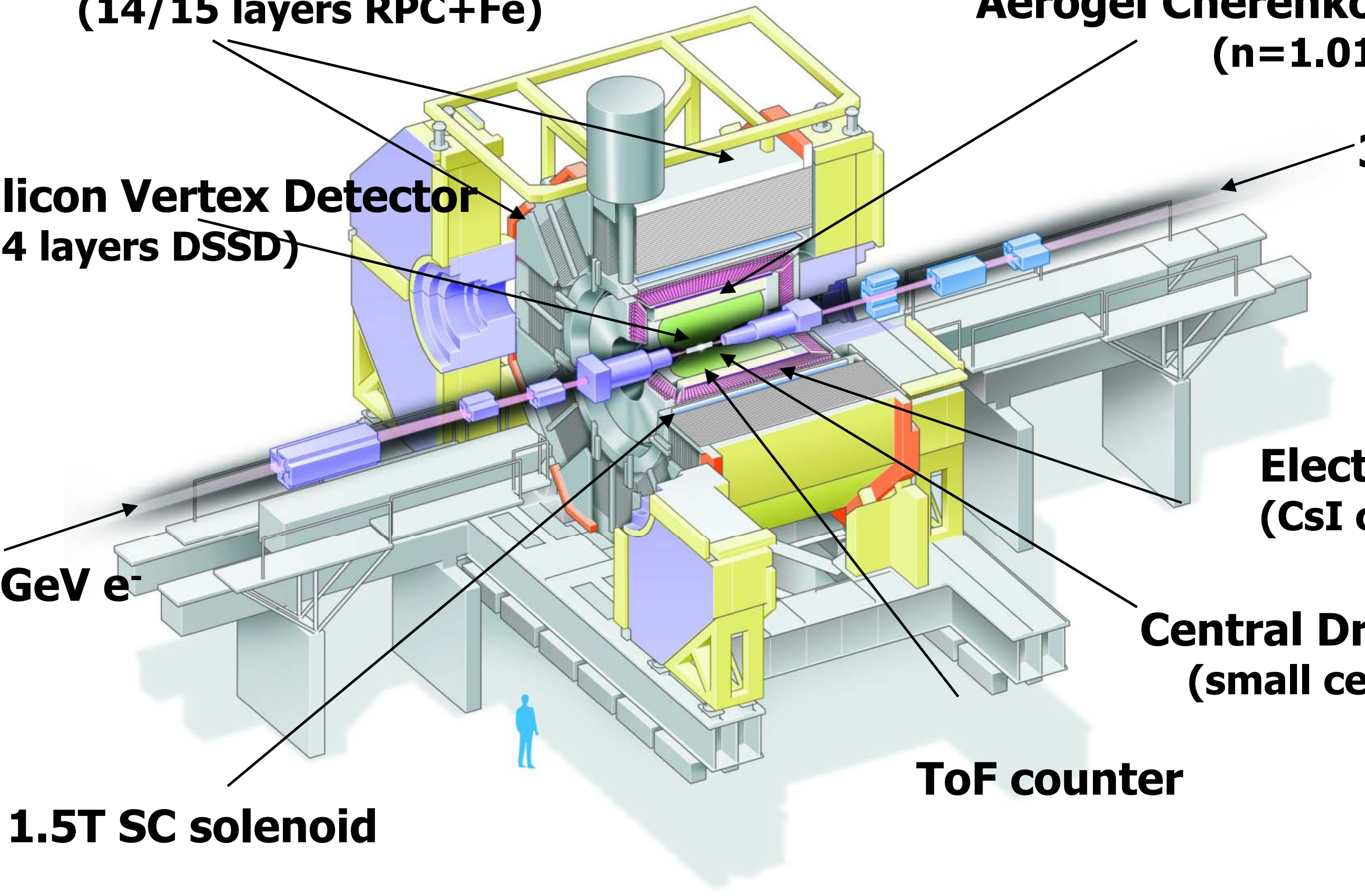
Physics Run

02/16/2004 05:10 JST

661/pb/day

→1182/pb/day

Belle spectrometer at KEK-B



μ and K_L detection system
(14/15 layers RPC+Fe)

Aerogel Cherenkov Counter
(n=1.015-1.030)

3.5 GeV e^+

Silicon Vertex Detector
(4 layers DSSD)

Electromag. Cal.
(CsI crystals, $16X_0$)

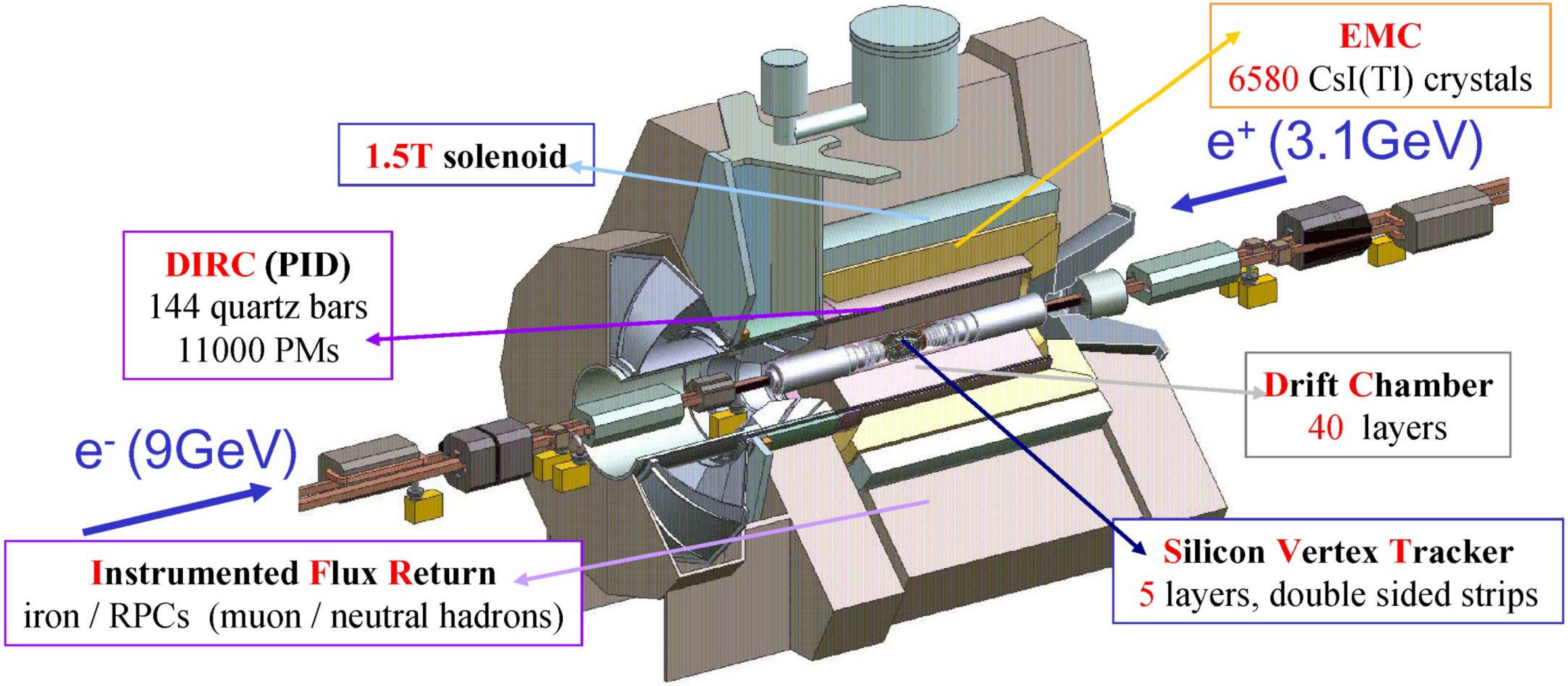
8 GeV e^-

Central Drift Chamber
(small cells, He/C_2H_6)

ToF counter

1.5T SC solenoid

BaBar spectrometer at PEP-II



EMC
6580 CsI(Tl) crystals

e^+ (3.1GeV)

1.5T solenoid

DIRC (PID)
144 quartz bars
11000 PMs

Drift Chamber
40 layers

e^- (9GeV)

Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)

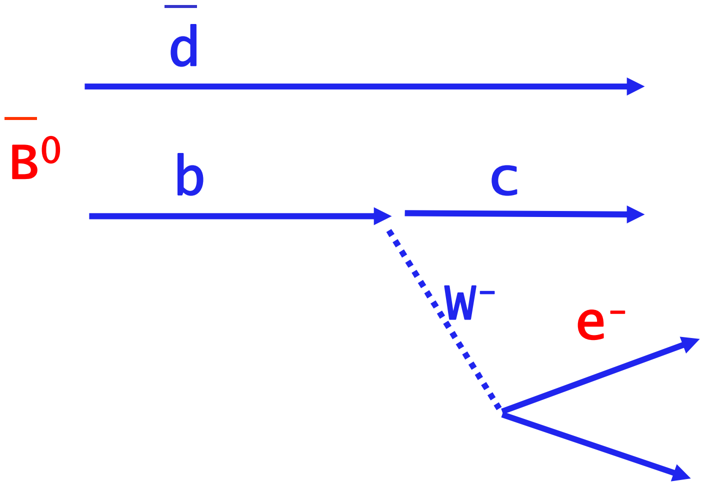
Silicon Vertex Tracker
5 layers, double sided strips

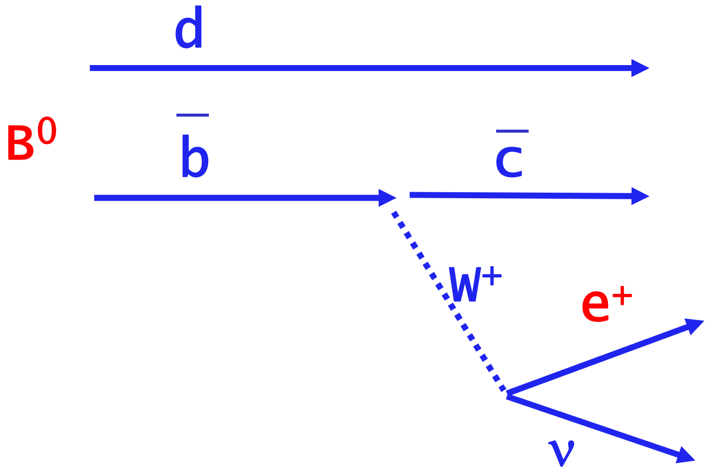
Flavour tagging

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?

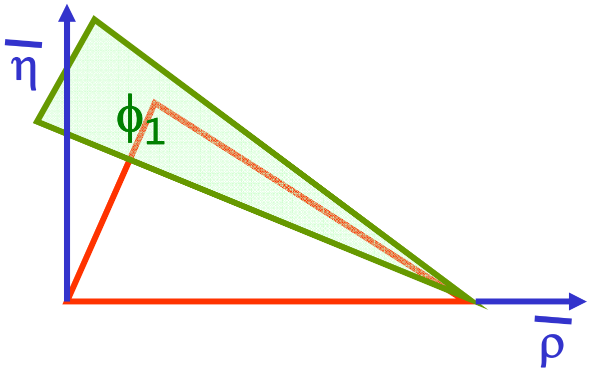
Look at the decay products of the associated B

- 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

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

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

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

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).

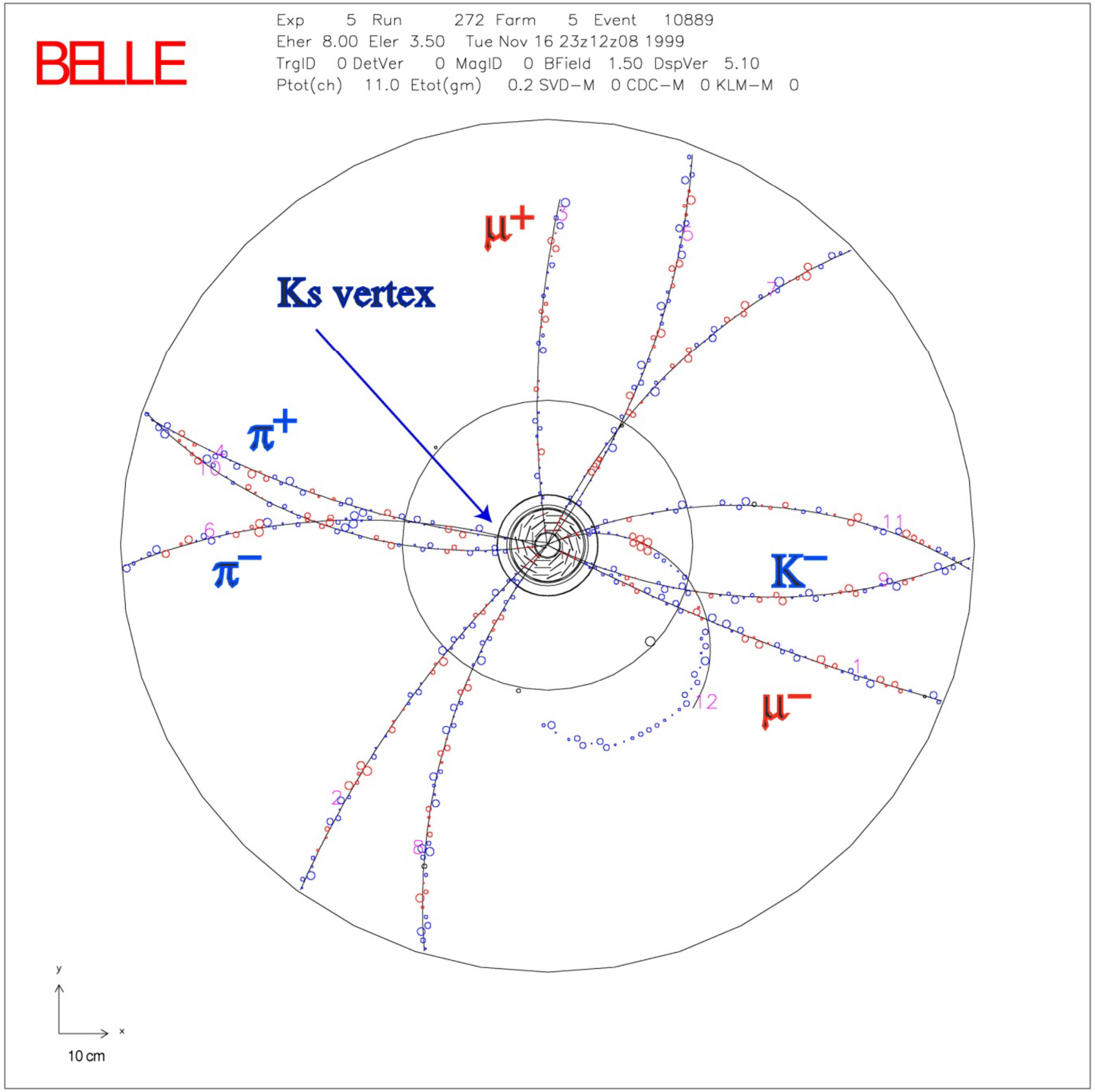
Reconstructing chamonium states

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):

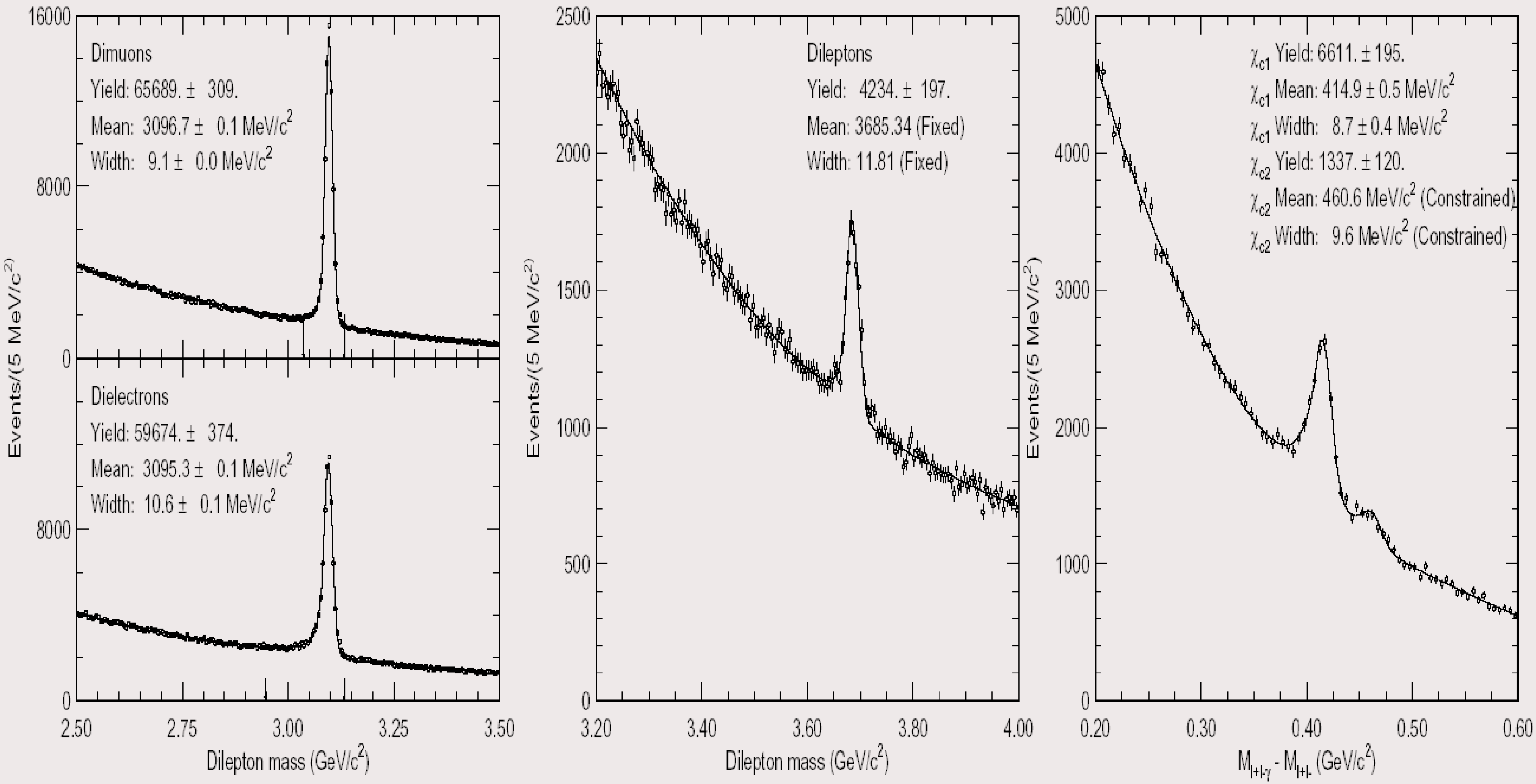
$$M = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2}$$

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

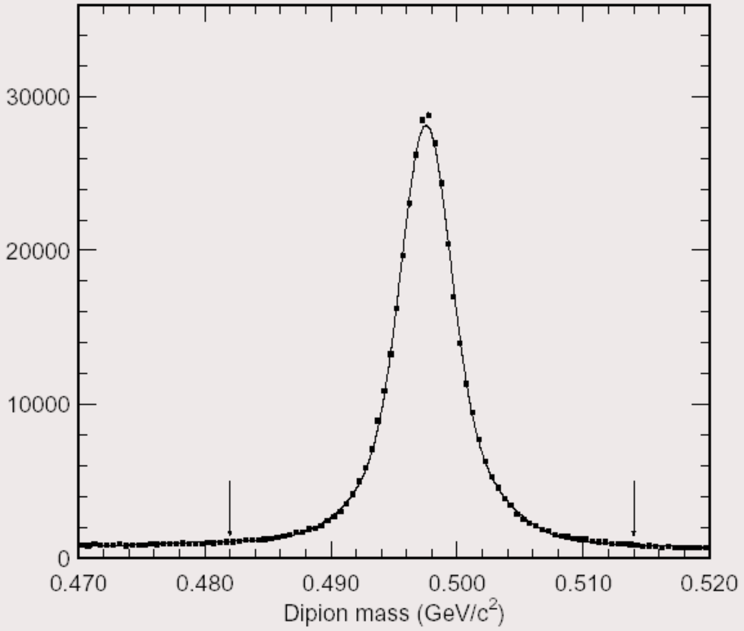


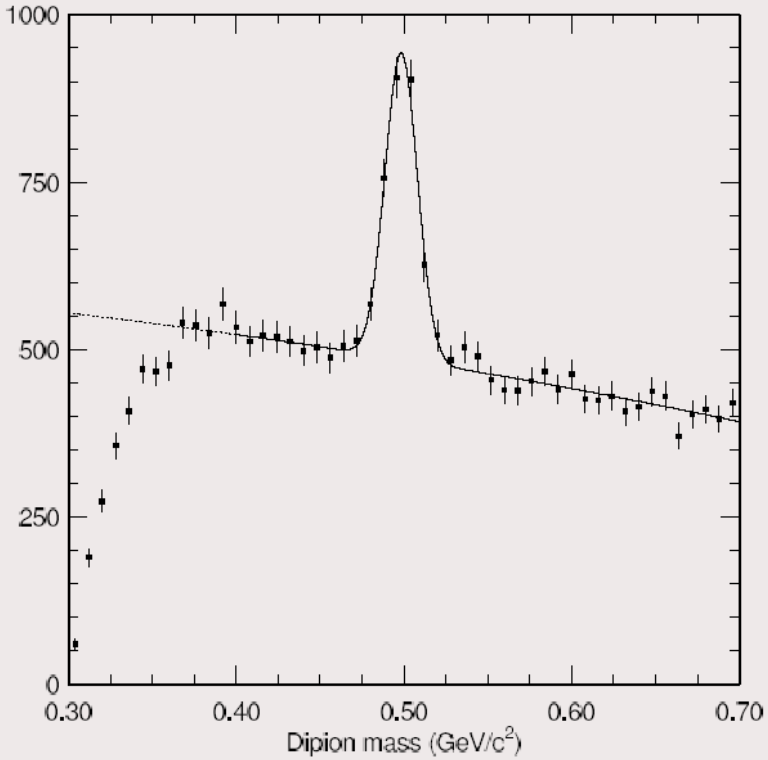
$J/\psi \rightarrow \mu^+\mu^-, e^+e^-$	$\psi(2s) \rightarrow \mu^+\mu^-, e^+e^-$	$\chi_{c1}, \chi_{c2} \rightarrow J/\psi\gamma$
$\sigma_M = 9.6(10.7)\mathrm{GeV}/c^2$	$\sigma_M = 12.1\mathrm{GeV}/c^2$	$\sigma_{\Delta M} = 7.0\mathrm{GeV}/c^2$

Reconstructing K^0_S

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

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

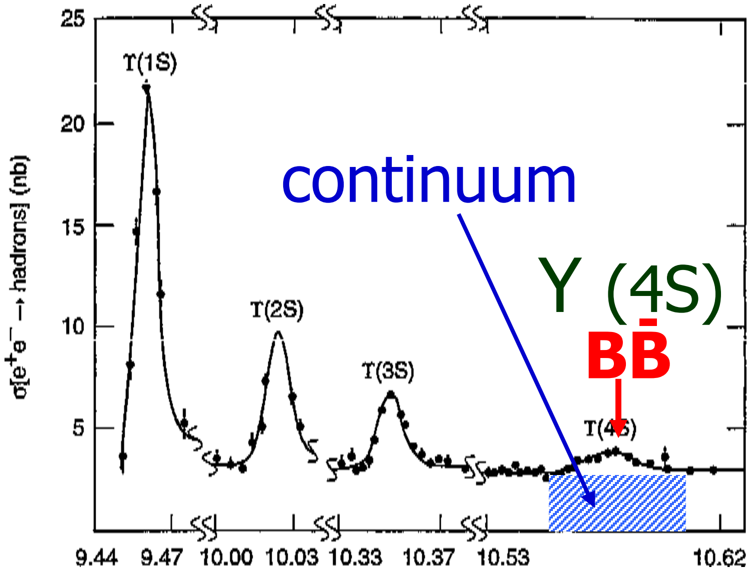




$K_S \to \pi^0\pi^0$

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

Continuum suppression



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

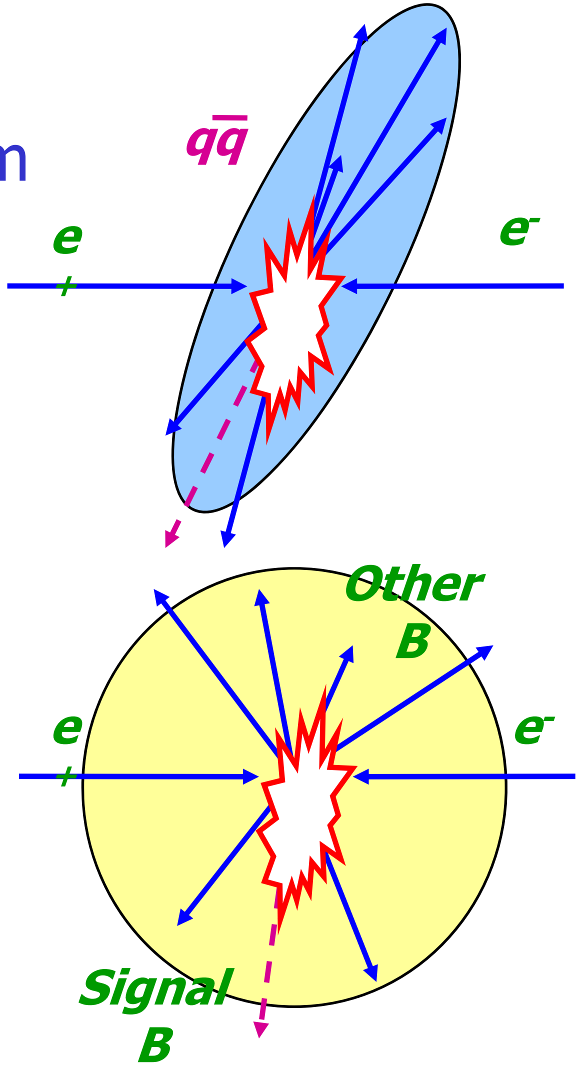
To suppress: use event shape variables

Continuum

Jet-like

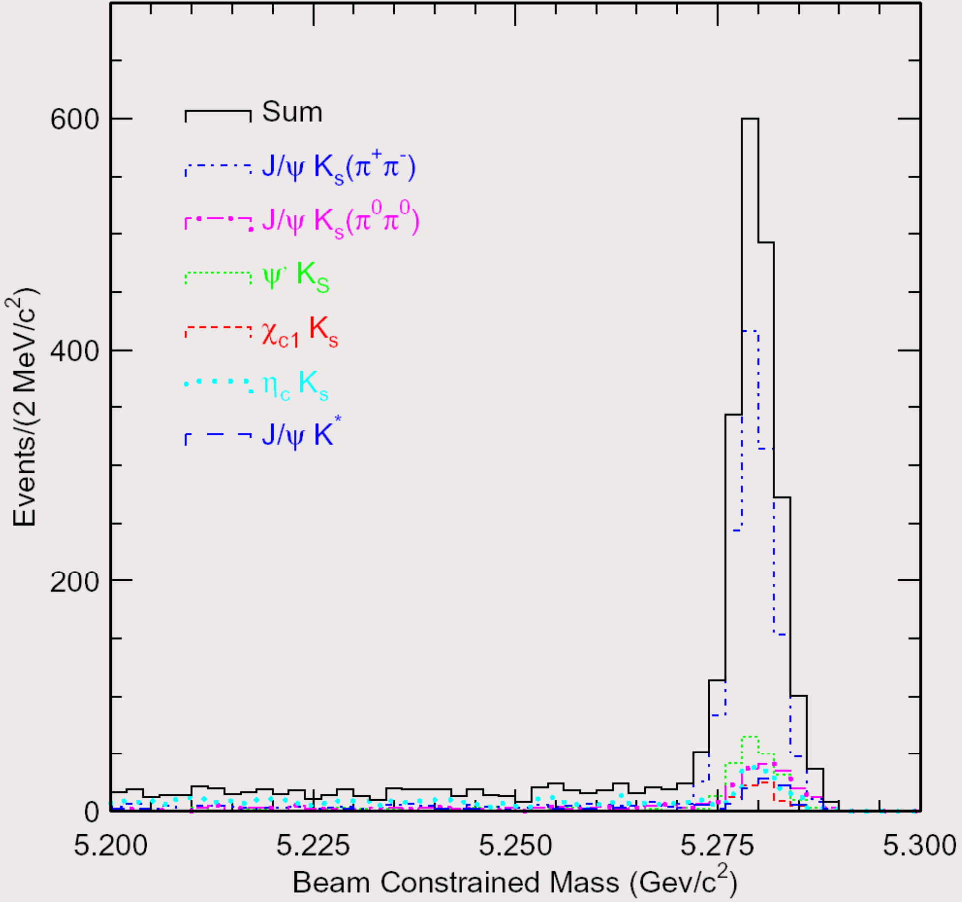
BB

spherical



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

Reconstructed decay modes for 78/fb, 85M B B pairs, Belle 2002 result



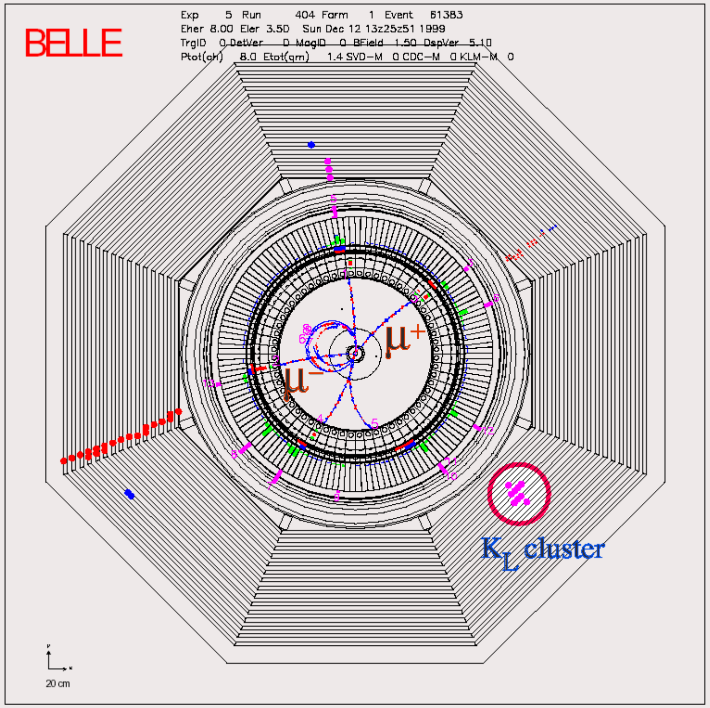
$B^0 \rightarrow$	events	$\frac{S}{S+N}$
$J/\psi K_S(K_S \rightarrow \pi^+\pi^-)$	1285	.976
$J/\psi K_S(K_S \rightarrow \pi^0\pi^0)$	188	.824
$\psi(2S)K_S$		
$(\psi(2S) \rightarrow \ell^+\ell^-)K_S$	91	.957
$(\psi(2S) \rightarrow J/\psi\pi^+\pi^-)$	112	.911
$\chi_{c1}K_S$	77	.958
$\eta_c(\eta_c \rightarrow K_S K\pi)K_S$	72	.646
$\eta_c(\eta_c \rightarrow K K\pi^0)K_S$	49	.725
$\eta_c(\eta_c \rightarrow p\bar{p})K_S$	21	.936
$J/\psi K^*(K^* \rightarrow K_S\pi^0)$	101	.917
total $CP = -1$	1996	.935
$J/\psi K_L$, $CP = +1$	1330	.627
Total	3326	.807

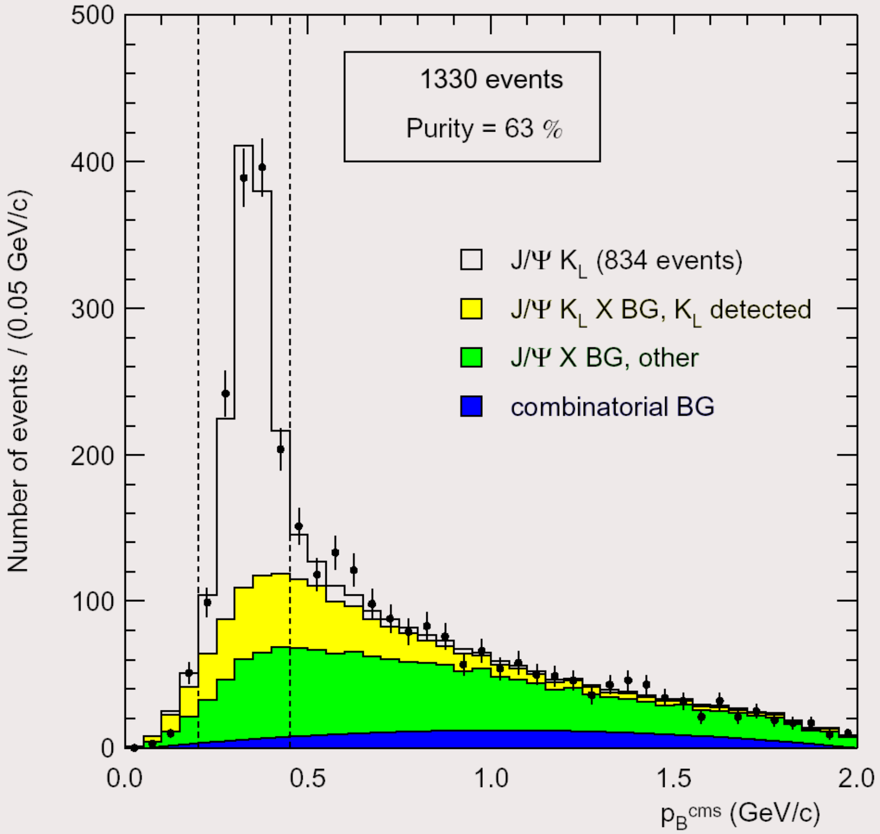
$$M_{bc} = \sqrt{E_{\mathrm{beam}}^2 - \vec{p}_{\mathrm{Bcandidate}}^2}$$

2958 events are used in the fit

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

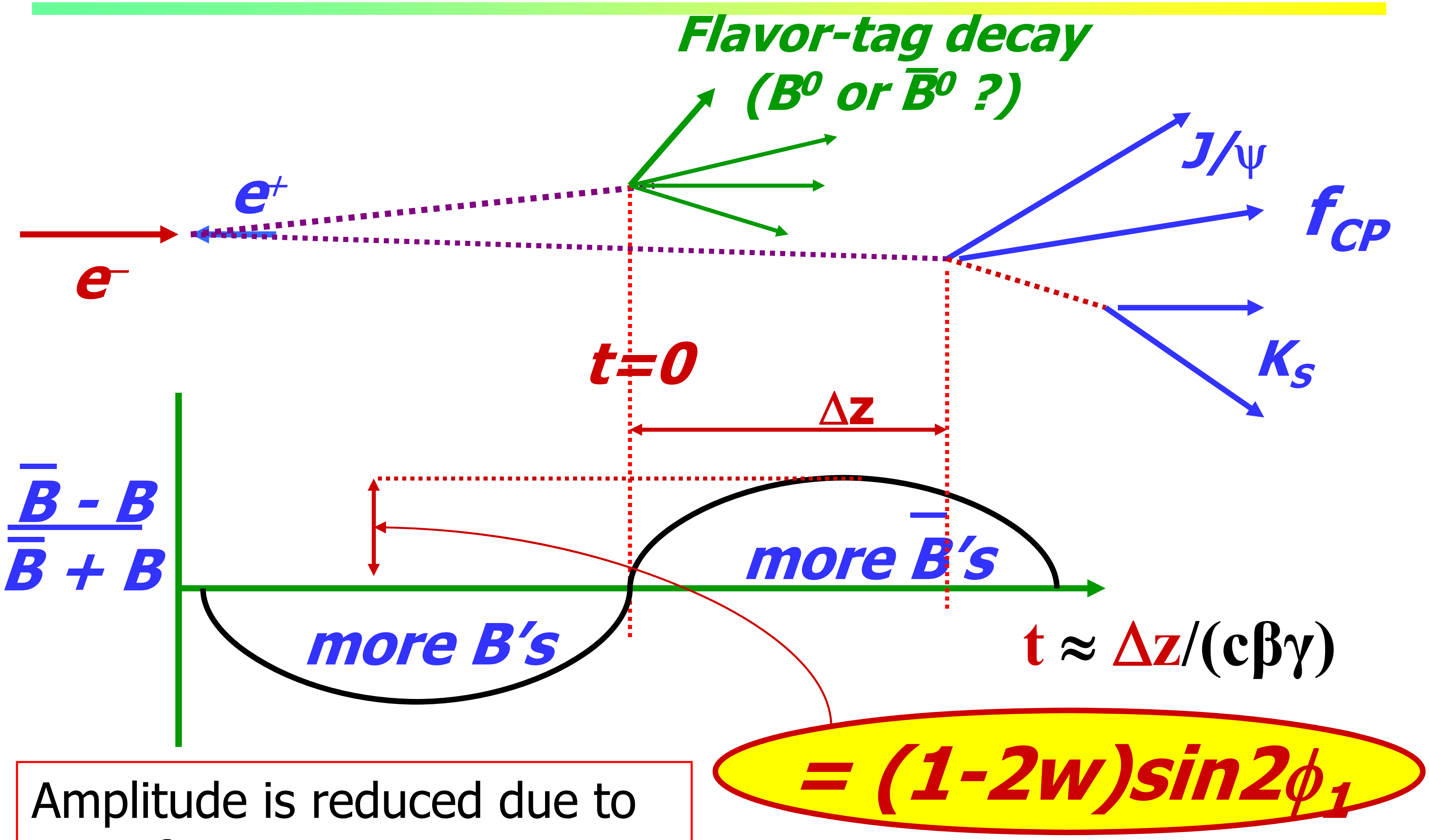
- detection of K_L in KLM and ECL
- K_L direction, no energy





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

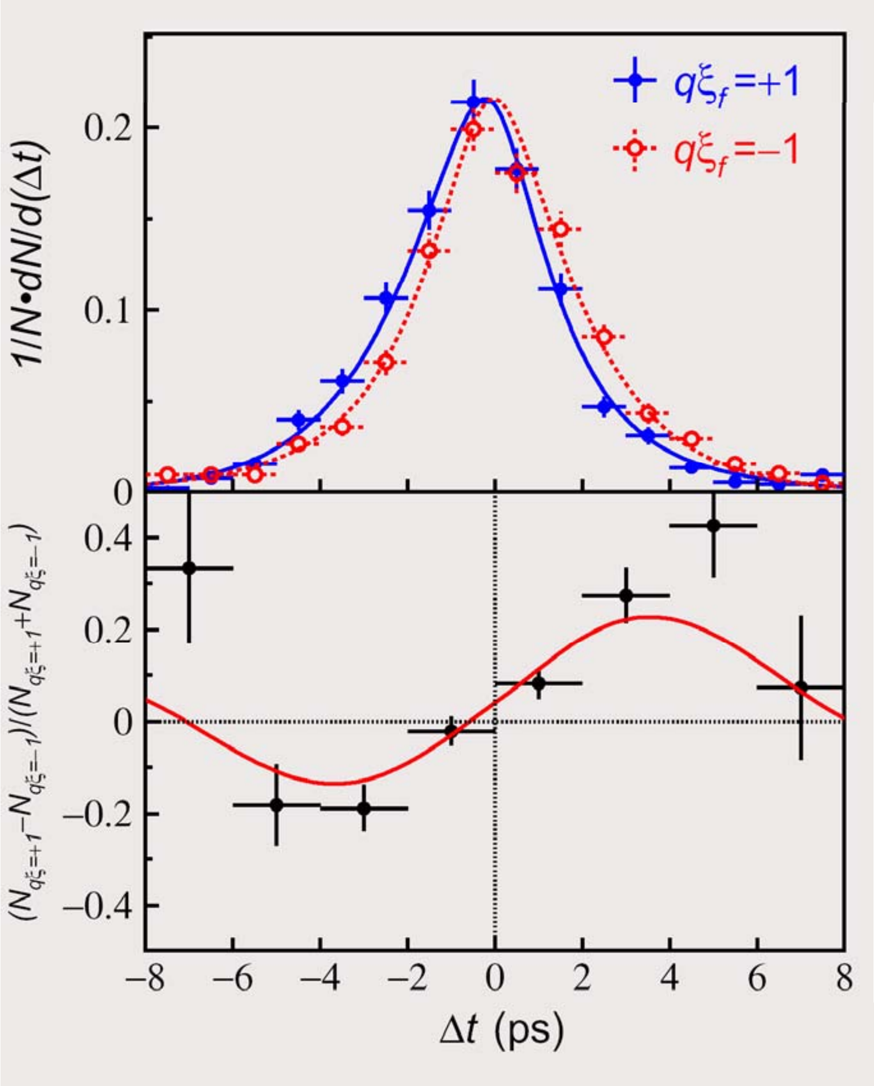
Principle of CPV Measurement



$= (1-2w)\sin 2\phi_1$

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, …**

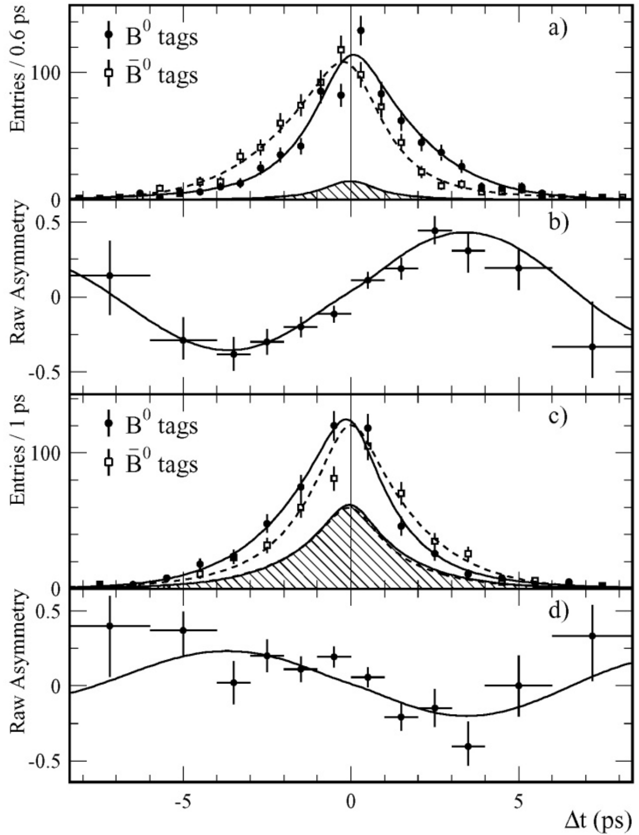
q=+1 or =-1 (B or anti-B on the tag side)

Fitting: unbinned maximum likelihood fit event-by-event

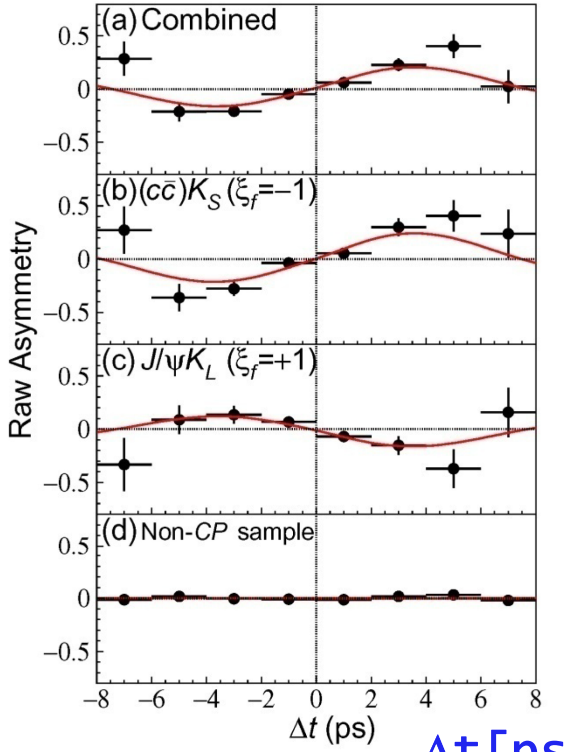
Fitted parameter: Im(λ)

BaBar vs Belle sin2ϕ_1

asymmetry



Δt[ps]



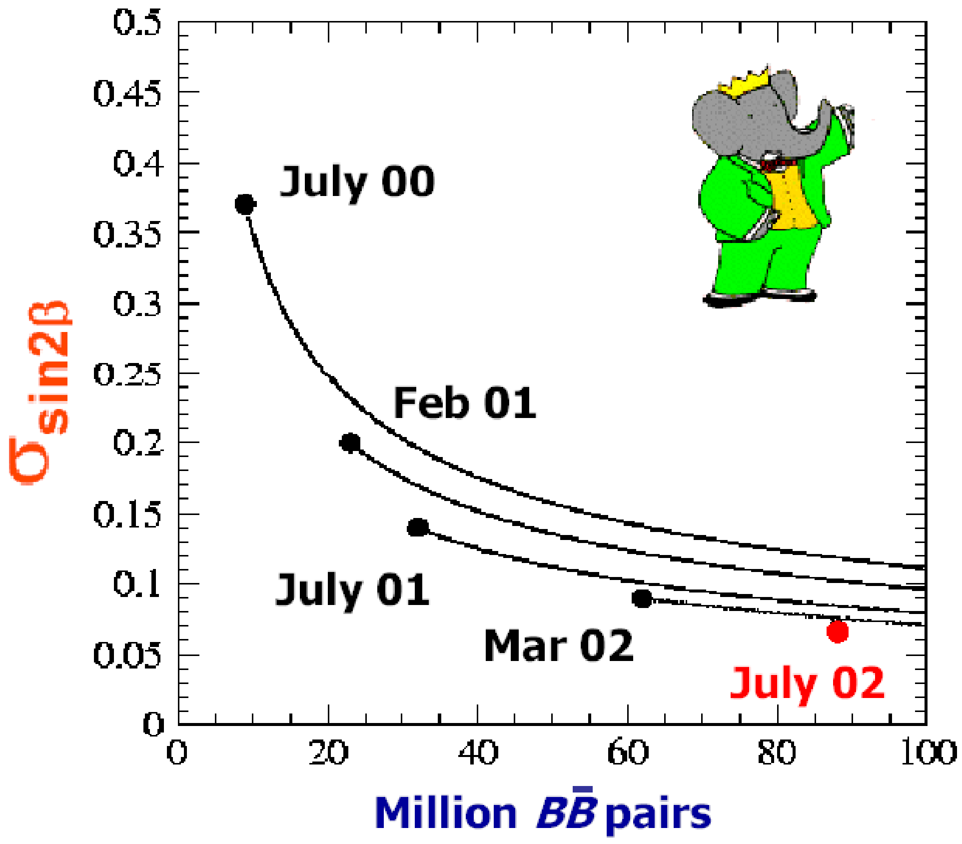
Δt[ps]

sin2ϕ_1=0.741±0.067±0.034 (BaBar)
sin2ϕ_1=0.719±0.074±0.035 (Belle)

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 → 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

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

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

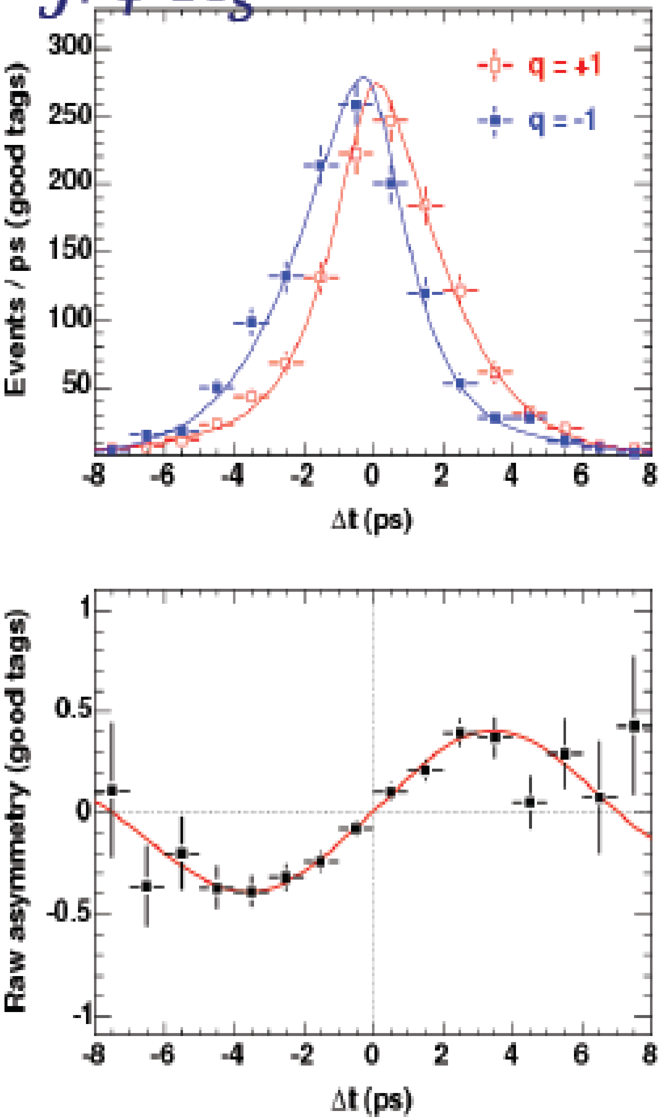
- J/ψ: P=-1, C=-1 (vector particle $J^{PC}=1^{--}$): CP=+1
- K_S (->$\pi^+ \pi^-$): CP=+1, orbital ang. momentum of pions=0 ->
  P $(\pi^+ \pi^-)=(\pi^- \pi^+)$, C$(\pi^- \pi^+)$ $=(\pi^+ \pi^-)$
- orbital ang. momentum between J/ψ and K_S l=1, $P=(-1)^1=-1$

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

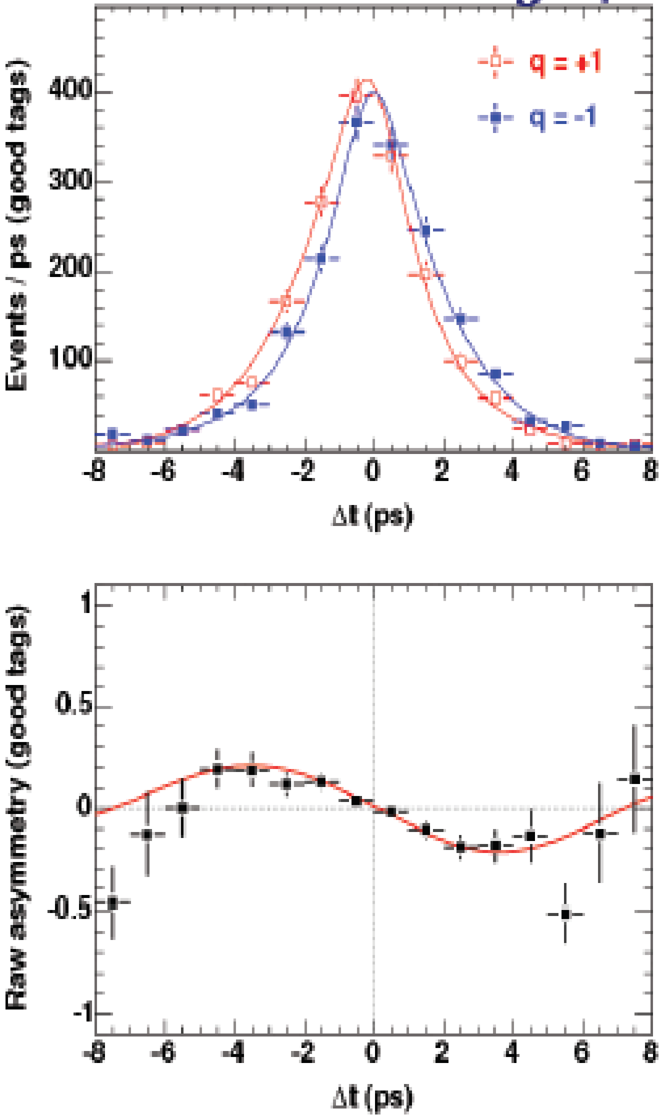
Opposite parity to $J/\psi\ K_S\ (\pi^+ \pi^-)$, because $K_L(3\pi)$ has CP=-1

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

$J/\psi\,K_S$

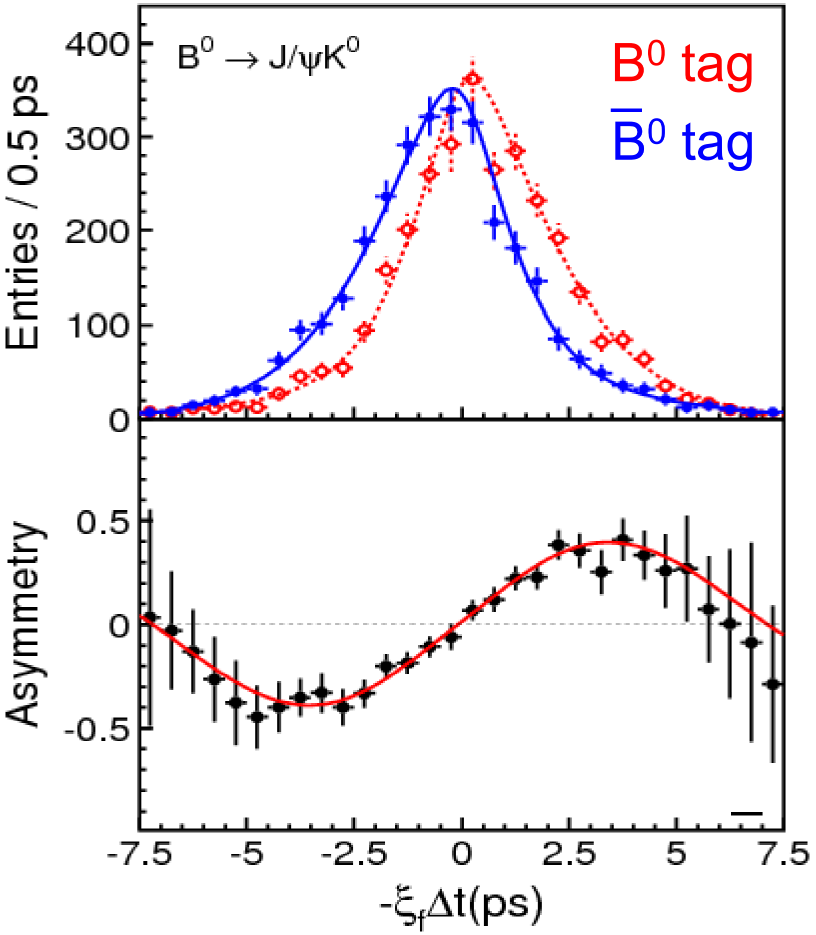


$J/\psi\,K_L$



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)



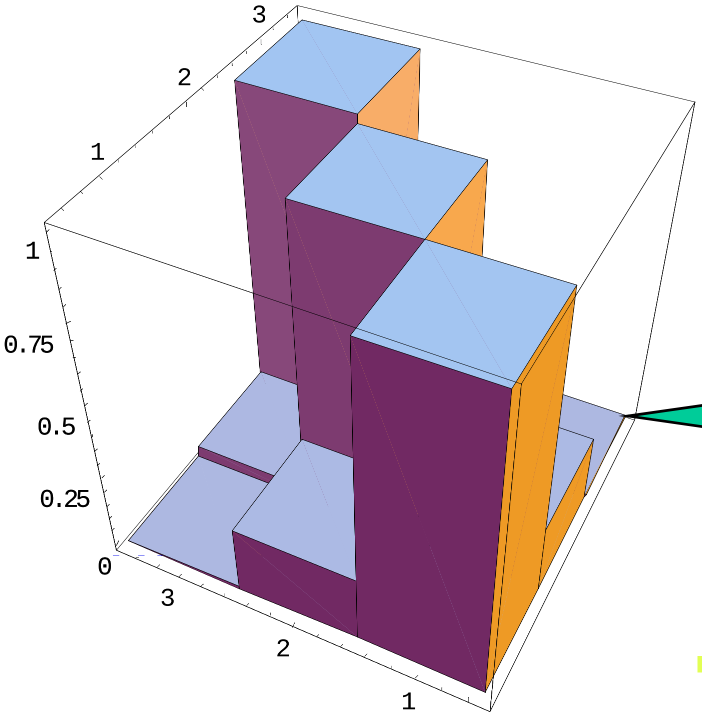
$\sin 2\phi_1 = \sin 2\beta$ from $b \rightarrow ccs$

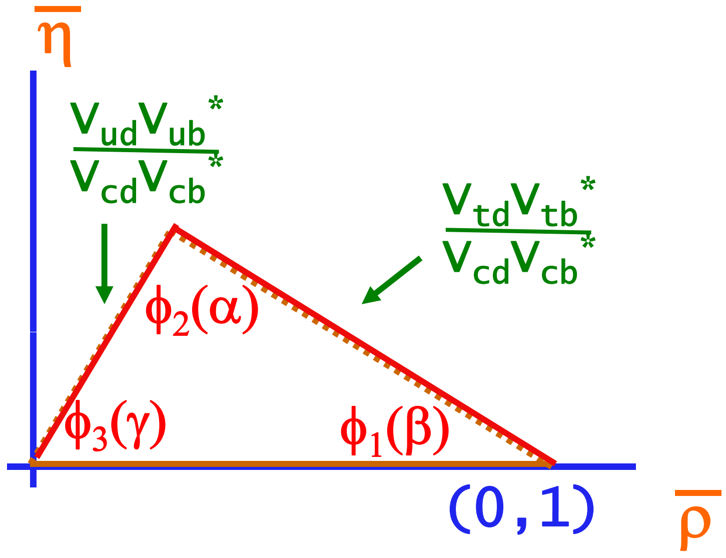
535 M $B\overline{B}$ pairs

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

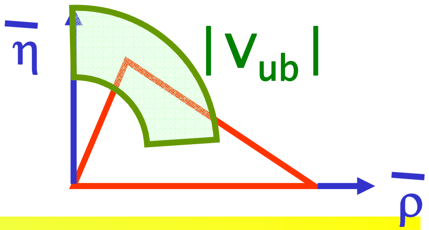
Unitary triangle: one of the sides is determined by V_{ub}

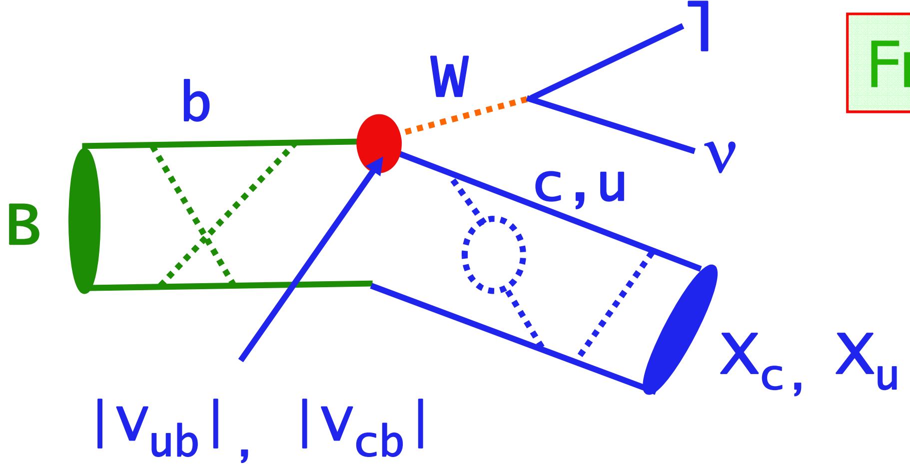
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$





$|V_{ub}|$ measurements





From semileptonic B decays

b→clν background typically an order of magnitude larger.

Traditional inclusive method: fight the background from b→clν decays by using only events with electron momentum above the b→clν kinematic limit. Problem: extrapolation to the full phase space→ large theoretical uncertainty.

New method: fully reconstruct one of the B mesons, check the properties of the other (semileptonic decay, low mass of the hadronic system)

- Very good signal to noise
- Low yield (full reconstruction efficiency is 0.3-0.4%)

Fully reconstructed sample

Fully reconstructed sample

Clean environment but small sample: **$\varepsilon_{reco} \approx 3 \cdot 10^{-3}$**

Exclusive method: 180 decay channels

Reconstructed channels:

$B^0 \to D^{(*)-}\pi^+ / D^{(*)-}\rho^+ / D^{(*)-}a_1^+ / D^{(*)-} D_s^{(*)+}$

$B^+ \to D^{(*)0}\pi^+ / D^{(*)0}\rho^+ / D^{(*)0}a_1^+ / D^{(*)0} D_s^{(*)+}$

$D^{*0} \to D^0\pi^0$

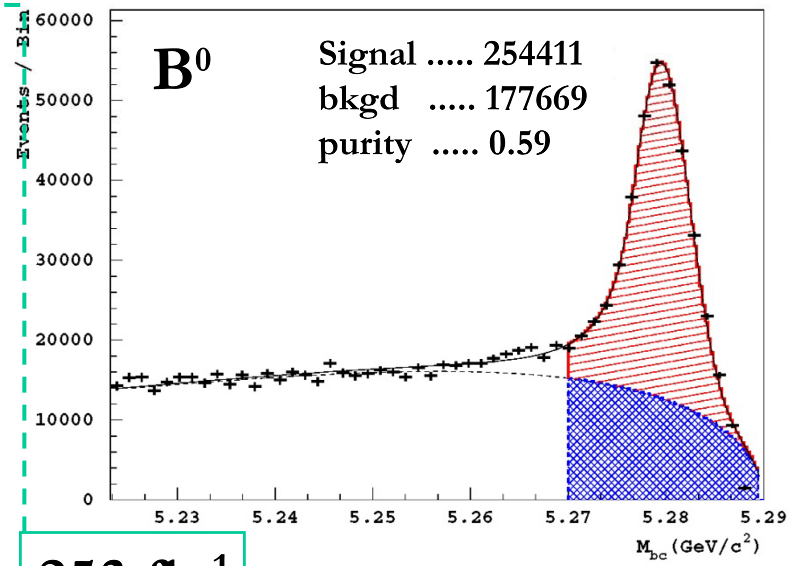
$D^* \to D^0\pi / D\pi^0$

$D_s^* \to D_s\gamma$

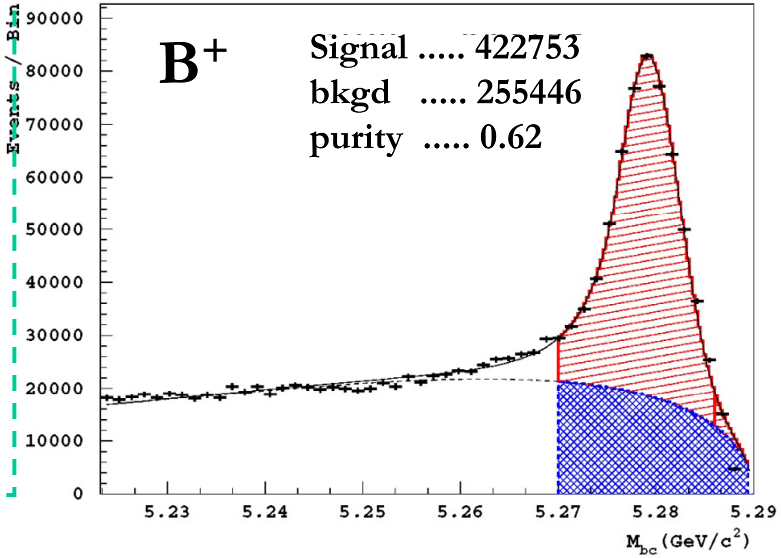
$D^0 \to K\pi / K\pi\pi^0 / K\pi\pi\pi / K_s\pi^0 / K_s\pi\pi / K_s\pi\pi\pi^0 / KK$

$D \to K\pi\pi / K\pi\pi\pi^0 / K_s\pi / K_s\pi\pi^0 / K_s\pi\pi\pi / KK\pi$

$D_s \to K_sK\pi / KK\pi$



$253\ fb^{-1}$



M_x analysis

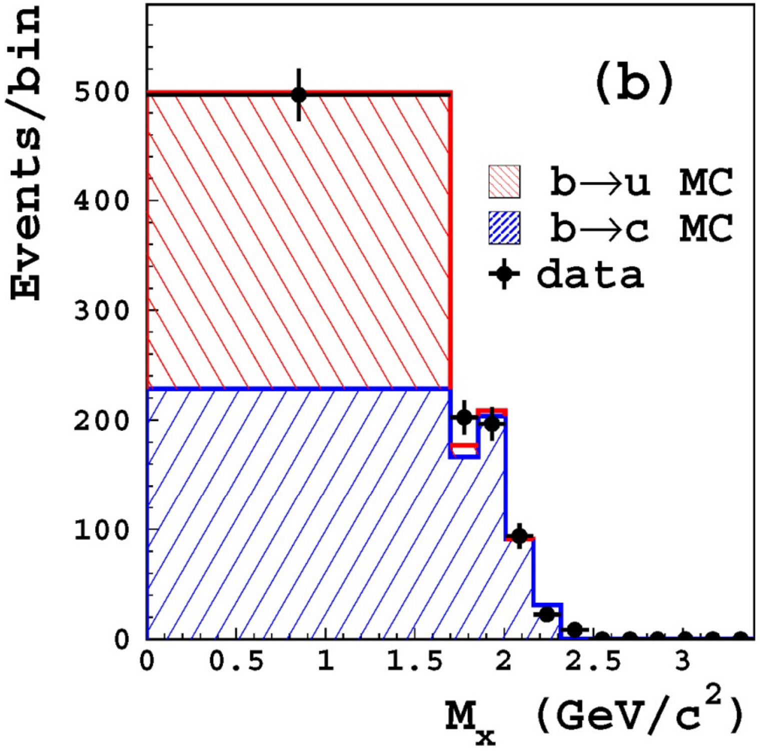
Use the mass of the hadronic system M_x as the discriminating variable against $b \rightarrow c l \nu$

M_x = mass of all hadrons from the B decay.

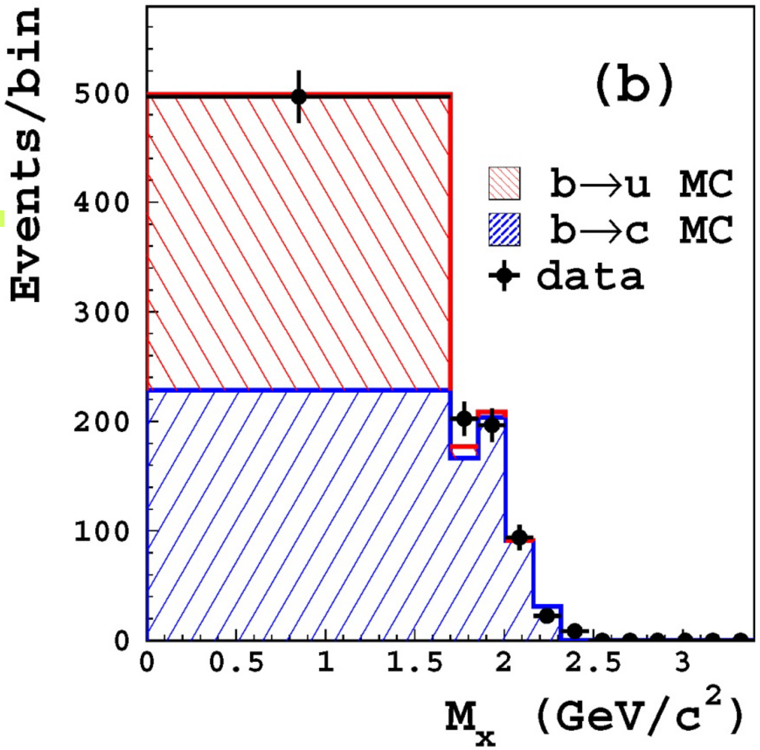
Expect:

- M_x for b → $c l \nu$ to be above 1.8 GeV (b → $c l \nu$ results in a D meson with >1.8 GeV)

- M_x for b → $u l \nu$ to mainly below 1.8 GeV ($B \rightarrow \pi l \nu$, $\rho l \nu$, $\omega l \nu$ ...)



M_x analysis



M_x<1.7 GeV/c^2 / q^2>8 GeV^2/c^2

Total error on $|V_{ub}|$ 12%

253 fb^{-1}

$$|V_{ub}| = (4.93 \pm 0.25 \pm 0.22 \pm 0.15 \pm 0.13 \pm 0.46 \, {}^{+0.20}_{-0.22}) \times 10^{-3}$$

stat syst b→u b→c SF theo
model dep.

- - -

M_x<1.7 GeV/c^2 / no q^2 cut : total error on $|V_{ub}|$ 11%

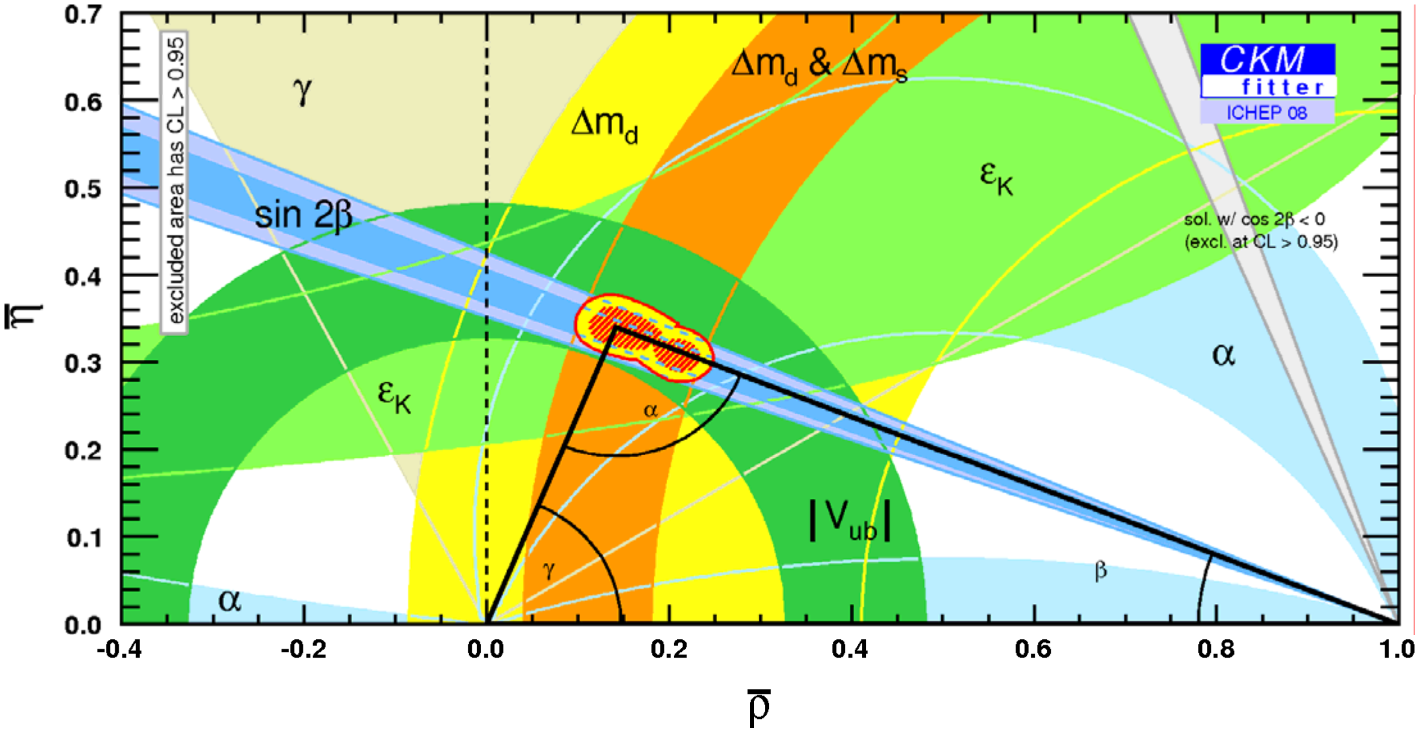
253 fb^{-1}

$$|V_{ub}| = (4.35 \pm 0.20 \pm 0.15 \pm 0.13 \pm 0.05 \pm 0.40 \, {}^{+0.13}_{-0.14}) \times 10^{-3}$$

stat syst b→u b→c SF theo
model dep.

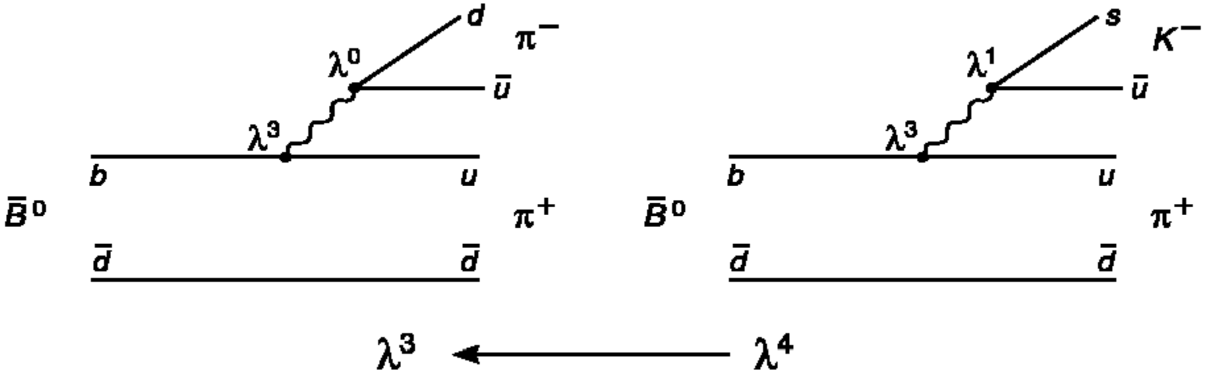
All measurements combined...

Constraints from measurements of angles and sides of the unitarity triangle →



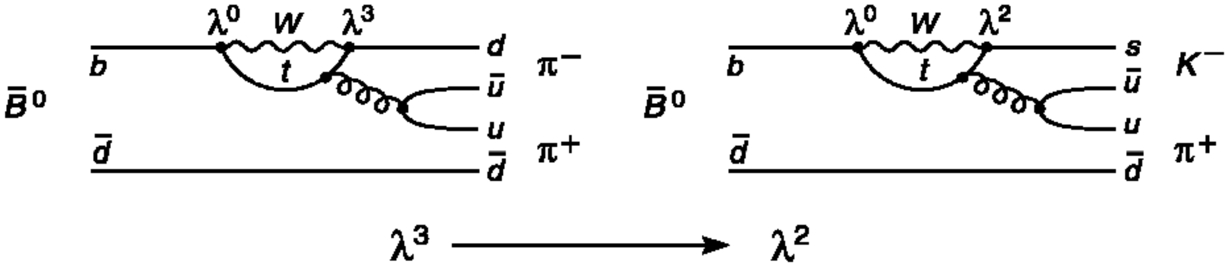
→Remarkable agreement

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

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.

A difference in the direct violation of CP symmetry in B^+ and B^0 decays to $K\pi$

nature International weekly journal of science

nature Vol 452 | 20 March 2008 | doi:10.1038/nature06827

LETTERS

Difference in direct charge-parity violation between charged and neutral *B* meson decays

The Belle Collaboration*

CP asymmetry

$$\mathcal{A}_f = \frac{N(\overline{B} \to \overline{f}) - N(B \to f)}{N(\overline{B} \to \overline{f}) + N(B \to f)}$$

Difference between B^+ and B^0 decays

In SM expect $\mathcal{A}_{K^\pm\pi^\mp} \approx \mathcal{A}_{K^\pm\pi^0}$

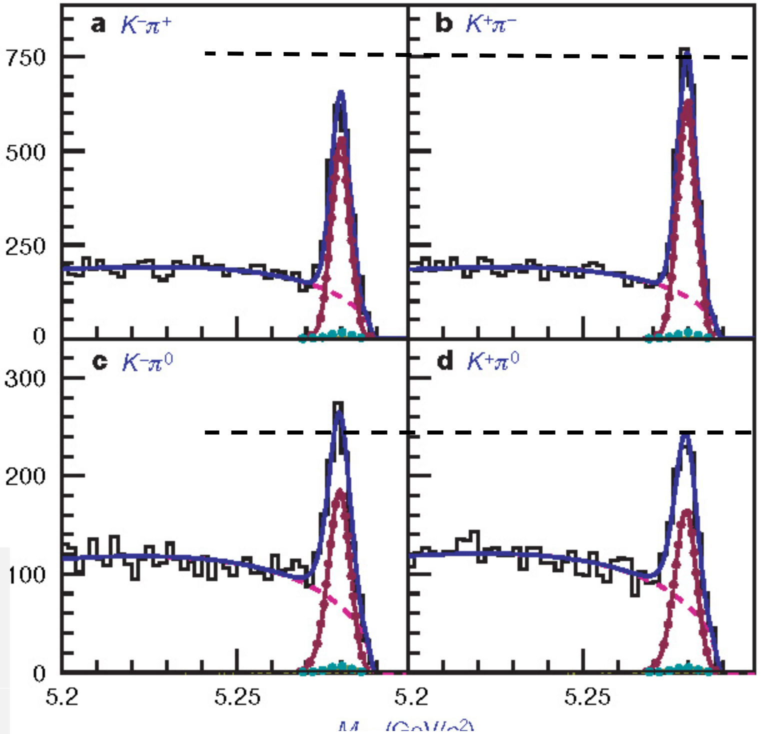
Measure:

$$\mathcal{A}_{K^\pm\pi^\mp} = -0.094 \pm 0.018 \pm 0.008$$

$$\mathcal{A}_{K^\pm\pi^0} = +0.07 \pm 0.03 \pm 0.01$$

$$\Delta\mathcal{A} = +0.164 \pm 0.037$$

A problem for a SM explanation
(in particular when combined with other measurements)
A hint for new sources of CP violation?



~1 in 10^5 B mesons decays in this decay mode

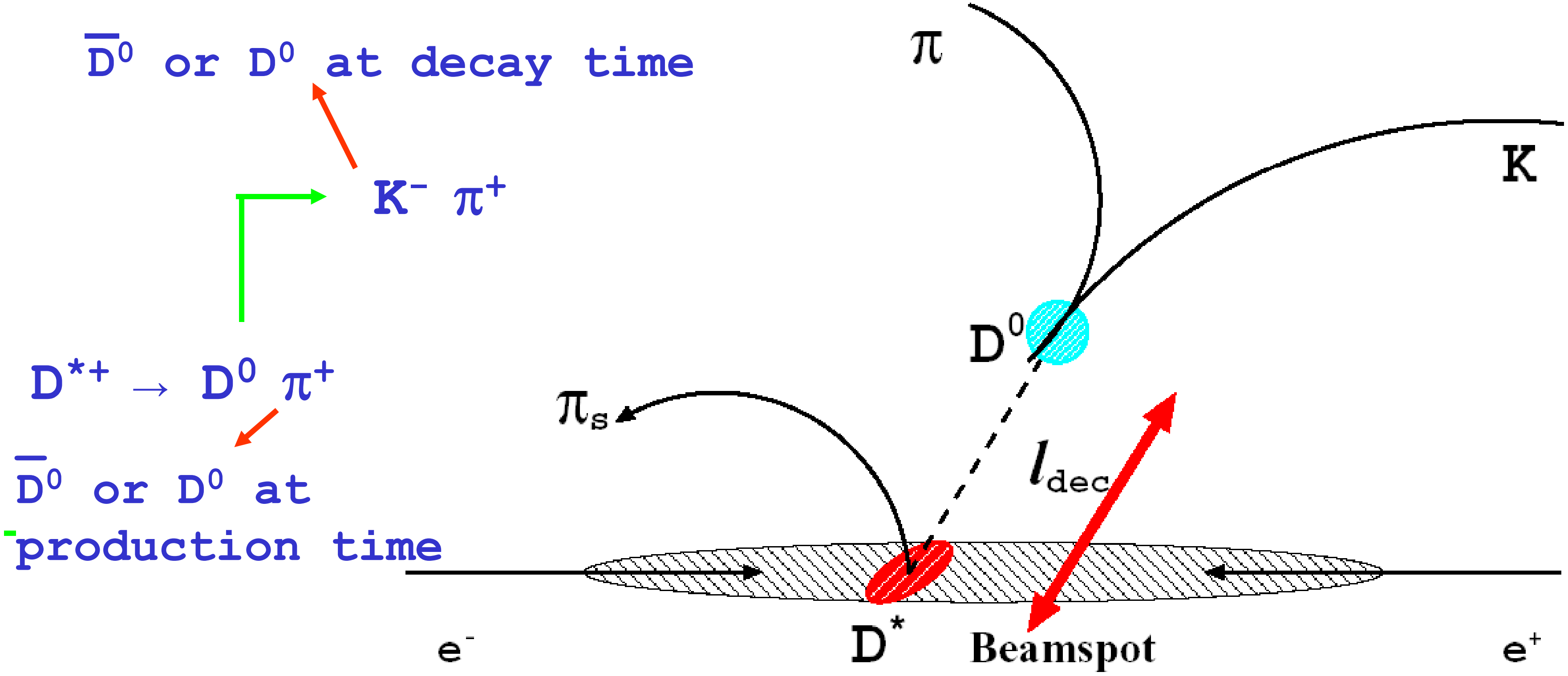
Belle, Nature 452, 332 (2008)

Experimental methods in D^0 mixing searches

The method: investigate D decays in the decay sequence:

$D^{*+} \to D^0\pi^+$, $D^0 \to$ specific final states

Used for tagging the initial flavour and for background reduction



$\bar{D}^0$ or D^0 at decay time

$K^- \pi^+$

$D^{*+} \to D^0 \pi^+$

$\bar{D}^0$ or D^0 at production time

$p_{cms}(D^*) > 2.5$ GeV/c eliminates D meson production from b → c

D^0 mixing in K^+K^-, $\pi^+\pi^-$

$D^0 \to K^+K^- / \pi^+\pi^-$

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

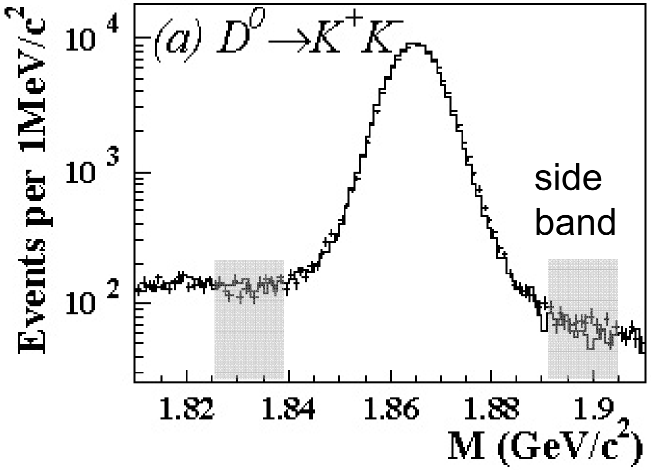
CP even final state;
in the limit of no CPV: $CP|D_1\rangle = |D_1\rangle$
$\Rightarrow$ measure $1/\Gamma_1$

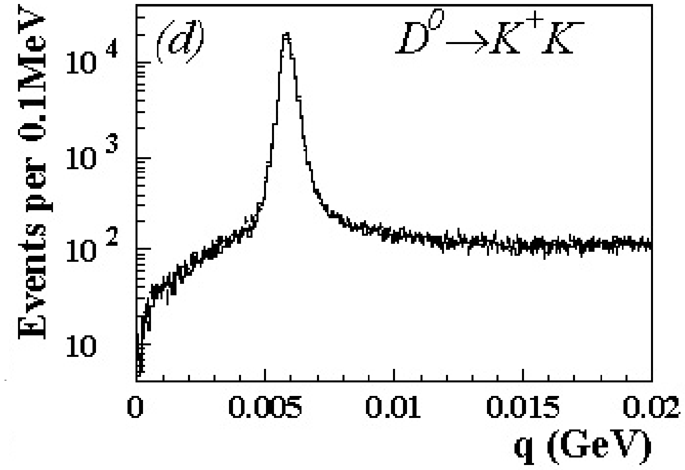
$$\boxed{y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1} = y\cos\varphi - \frac{1}{2}A_M x\sin\varphi =$$

$$\boxed{\underset{no\,CPV}{=} y}$$

S. Bergman et al., PLB486, 418 (2000)

A_M, ϕ: CPV in mixing and interference





Signal: $D^0 \to K^+K^- / \pi^+\pi^-$ from D^*

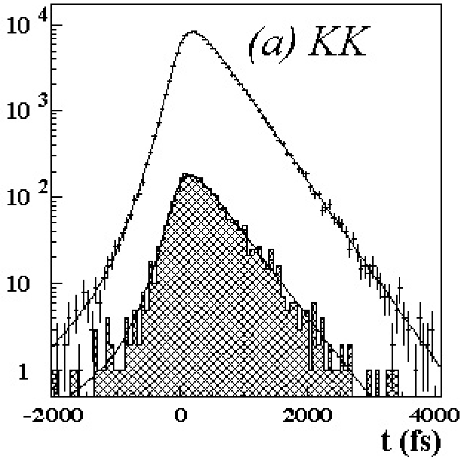
M, Q, σ_t selection optimized in MC

	K^+K^-	$K^-\pi^+$	$\pi^+\pi^-$
N_{sig}	111×10^3	1.22×10^6	49×10^3
purity	98%	99%	92%

PRL 98, 211803 (2007), 540fb^{-1}

D^0 mixing in K^+K^-, $\pi^+\pi^-$

Decay time distributions for KK, ππ, Kπ



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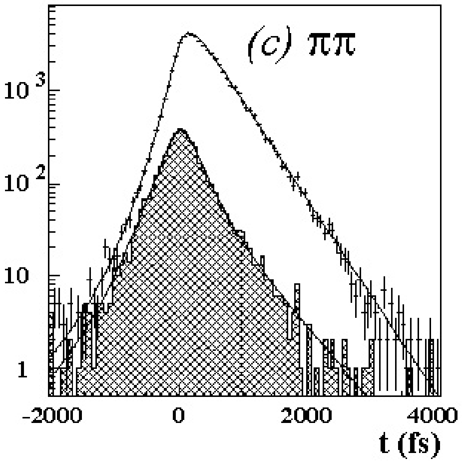
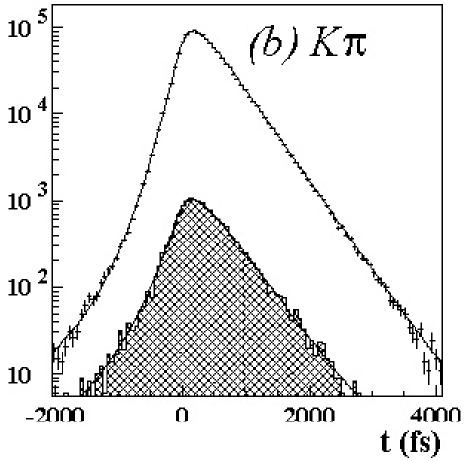
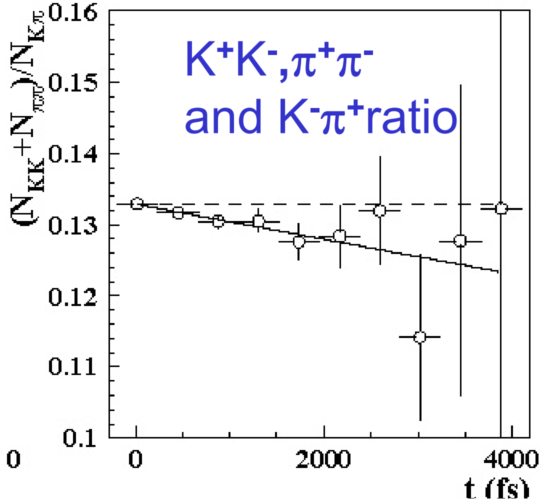




Difference of lifetimes visually observable in the ratio of the distributions →



Real fit:

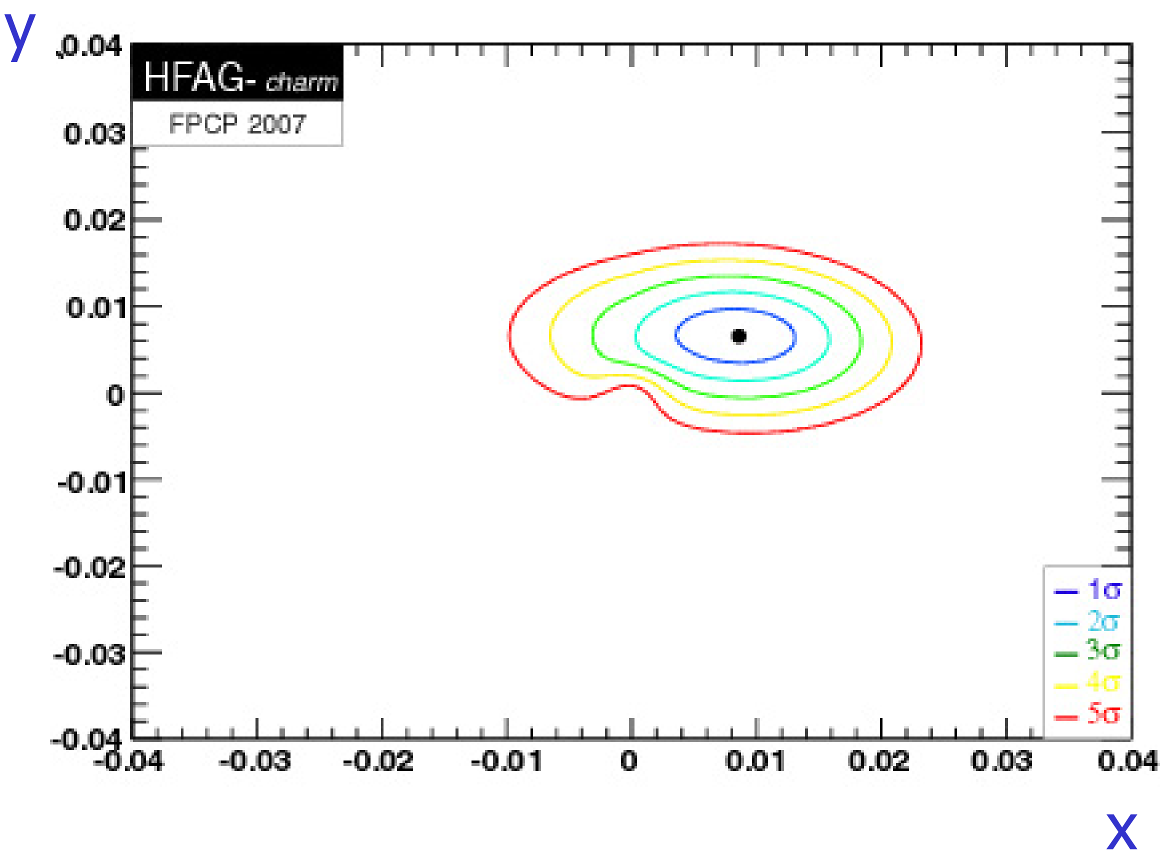
$$\boxed{y_{CP} = (1.31 \pm 0.32 \pm 0.25)\,\%}$$

evidence for D^0 mixing

(regardless of possible CPV)

→y_{CP} is on the high side of SM expectations

D^0 mixing: all results combined



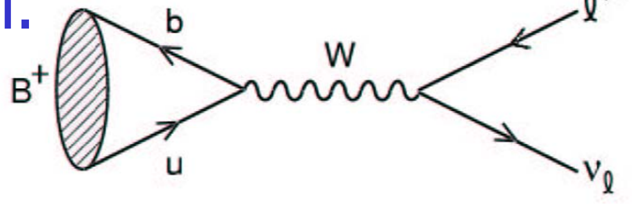
Assuming no CPV

$x = (0.87 \pm ^{\mathbf{0.30}}_{\mathbf{0.34}})\ \%$
$y = (0.66 \pm ^{\mathbf{0.21}}_{\mathbf{0.20}})\%$
$\delta = 0.33 \pm ^{\mathbf{0.26}}_{\mathbf{0.29}}$

(x,y)=(0,0) excluded by >5σ

Purely leptonic decay B→τ ν

- Challenge: B decay with at least two neutrinos
- Proceeds via W annihilation in the SM.



- Branching fraction

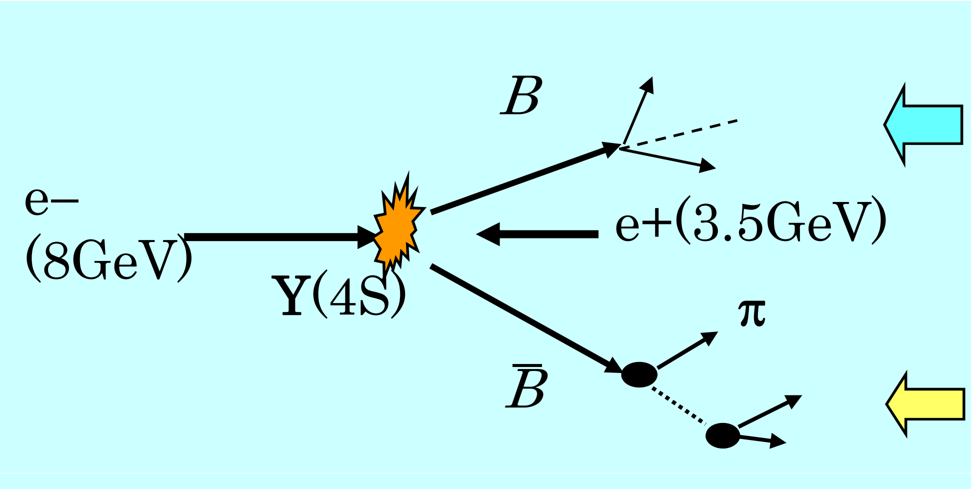
$$\mathcal{B}(B^- \to \ell^- \bar{\nu}) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

- Provide information of $f_B|V_{ub}|$
  - $|V_{ub}|$ from $B \to X_u\, l\, \nu$ ➡ f_B ⟺ cf) Lattice
  - $Br(B \to \tau\nu)/\Delta m_d$ ➡ $|V_{ub}|\,/\,|V_{td}|$
- Limits on charged Higgs

Full Reconstruction Method

Fully reconstruct one of the B's to

- Tag B flavor/charge
- Determine B momentum
- Exclude decay products of one B from further analysis



Decays of interest
B→X_u l ν,
B→K ν ν
B→Dτν, τν

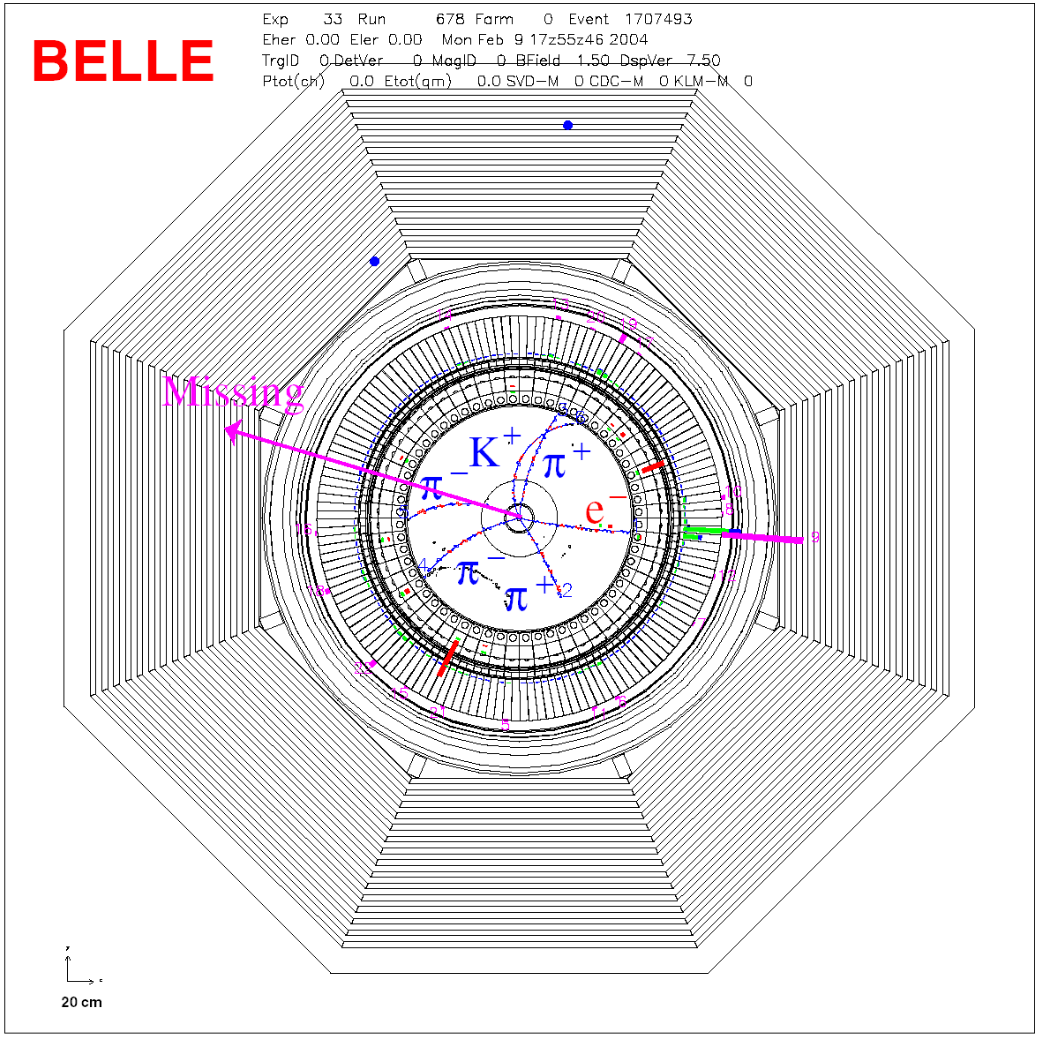
full reconstruction
B→Dπ etc. (0.1~0.3%)

→ Offline B meson beam!

Powerful tool for B decays with neutrinos

Event candidate $B^- \rightarrow \tau^- \nu_\tau$

$$B^+ \to D^0\pi^+$$
$$(\to K\pi^-\pi^+\pi^-)$$
$$B^- \to \tau(\to e\nu\bar{\nu})\nu$$



B→τ ν

τ decay modes

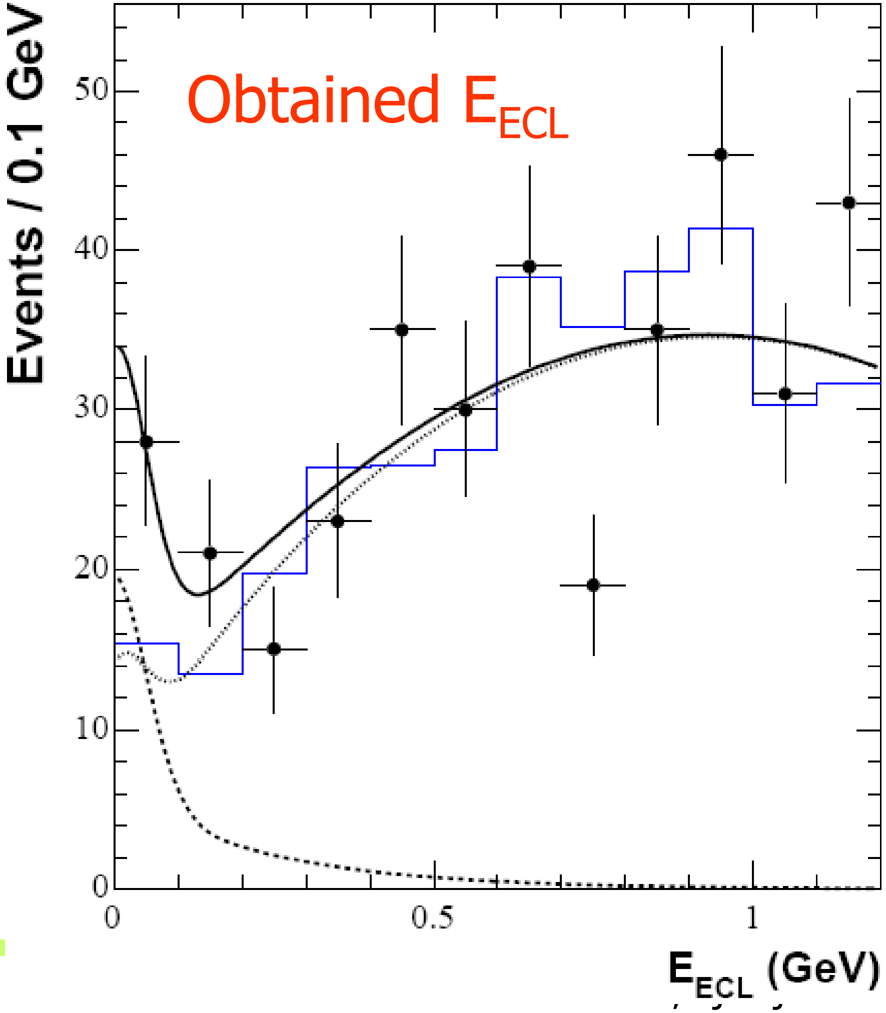
$$\tau^- \to \mu^- \nu\bar{\nu}, e^- \nu\bar{\nu}$$

$$\tau^- \to \pi^- \nu, \pi^- \pi^0 \nu, \pi^- \pi^+ \pi^- \nu$$

- Cover 81% of τ decays
- Efficiency 15.8%

Event selection

- Main discriminant: extra neutral ECL energy



Fit to $E_{residual}$ → $17.2^{+5.3}_{-4.7}$ signal events.

→3.5**σ** significance including systematics

B → $\tau\ \nu_\tau$

$$\boxed{BF(B^+ \to \tau^+\nu_\tau) = (1.79^{+0.56+0.46}_{-0.49-0.51}) \times 10^{-4}}$$

$$\Gamma^{SM}(B^+ \to \ell^+\nu) = \frac{G_F^2}{8\pi}\left|V_{ub}\right|^2 f_B^2 m_B m_\ell^2 \left(1-\frac{m_\ell^2}{m_B^2}\right)$$

→ Product of B meson decay constant f_B and CKM matrix element $|V_{ub}|$

$$f_B \times V_{ub} = \left(10.1^{+1.6+1.3}_{-1.4-1.4}\right) \times 10^{-4}\, GeV$$

Using $|V_{ub}| = (4.39 \pm 0.33)\times 10^{-3}$ from HFAG

$$\boxed{f_B = 229^{+36+34}_{-31-37}\, MeV}$$

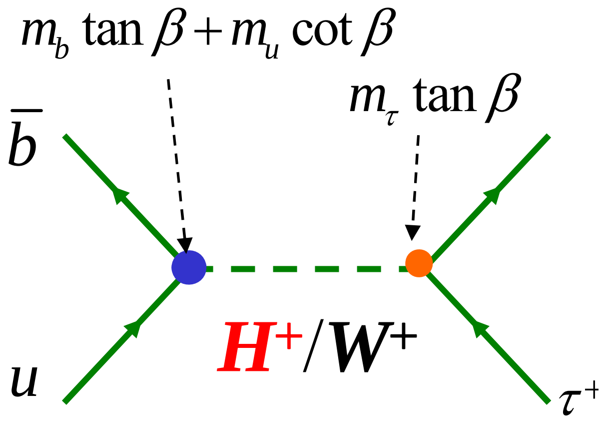
15%   15% = 13%(exp.) + 8%(V_{ub})

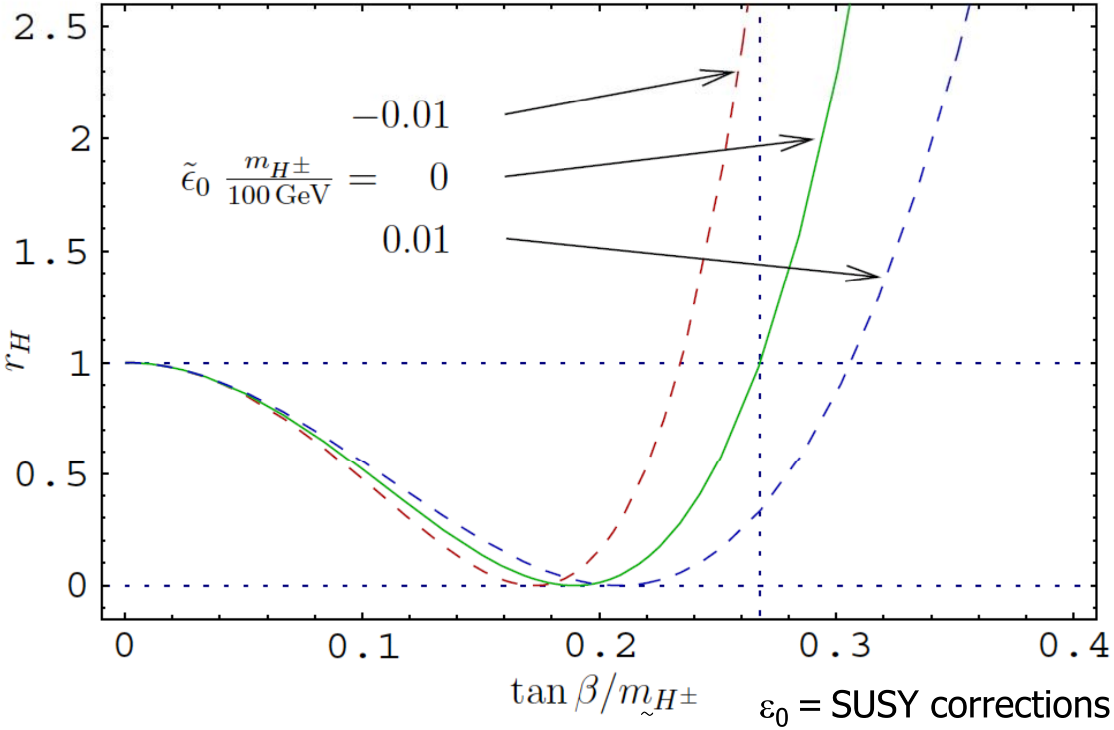
First measurement of f_B!

f_B = (216 ± 22) MeV from unquenched lattice calculation

[HPQCD, Phys. Rev. Lett. 95, 212001 (2005)]

Charged Higgs contribution to B→τ ν





ε_0 = SUSY corrections to b Yukawa coupling

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\rm SM} \times r_H,$$

$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

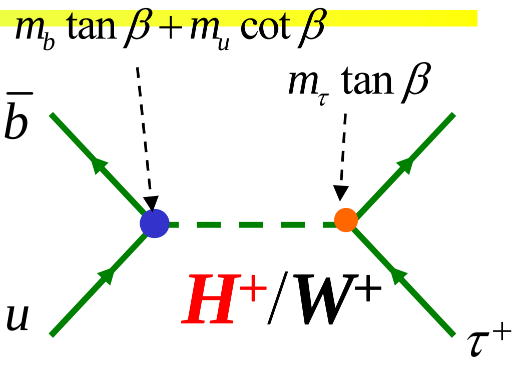
The interference is destructive in 2HDM (type II). $B > B_{SM}$ implies that H^+ contribution dominates

Phys. Rev. D **48**, 2342 (1993)

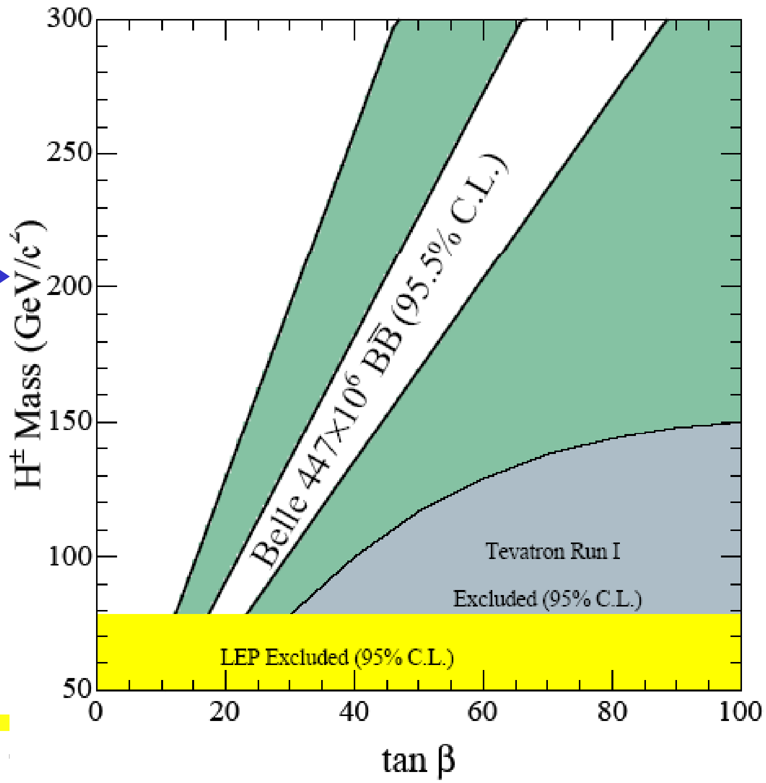
Charged Higgs limits from B$^-$ → $\tau^- \nu_\tau$

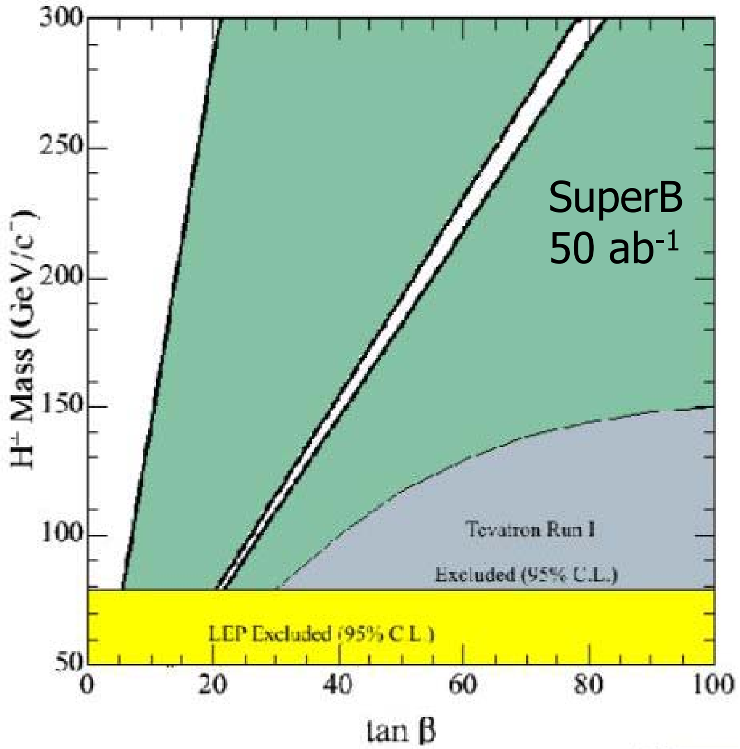
If the theoretical prediction is taken for $\mathbf{f_B}$

→ limit on charged Higgs mass vs. tanβ



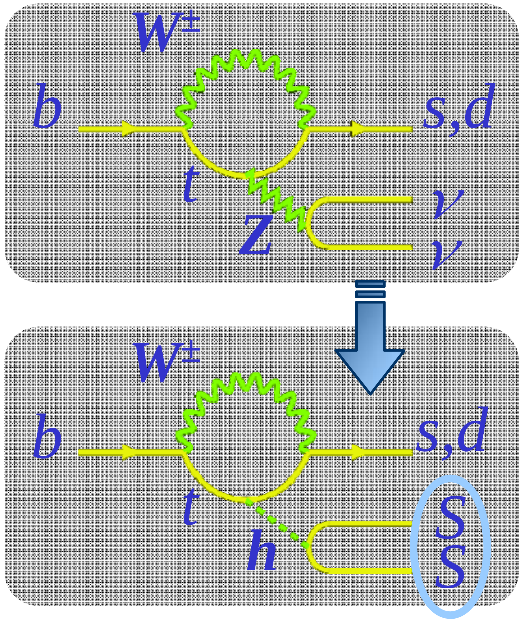
$$r_H = \frac{BF(B\to\tau\nu)}{BF(B\to\tau\nu)_{SM}} = \left(1-\frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

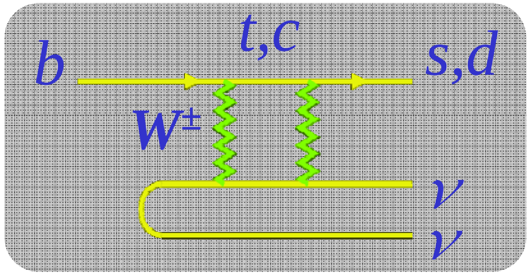




$B \to K^{(*)} \nu\nu$

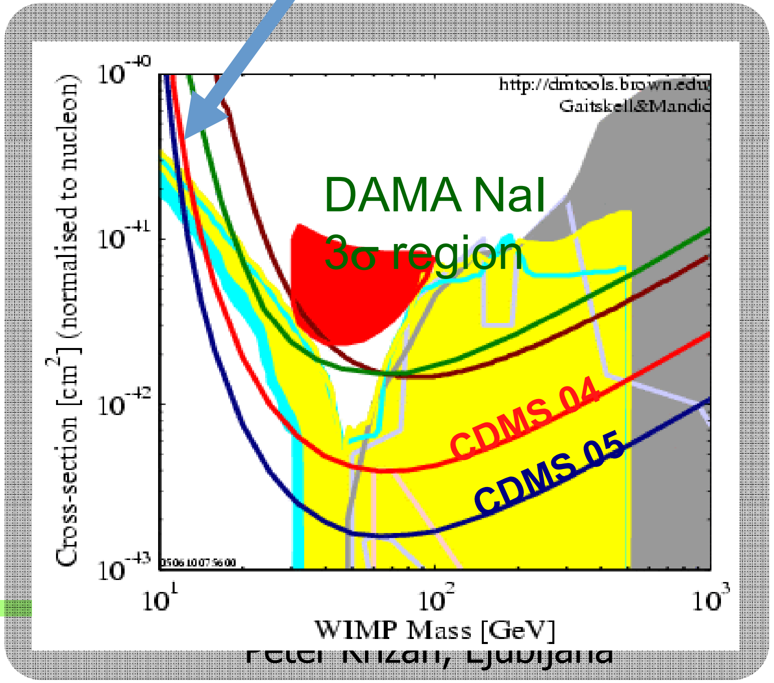
- Proceed through electroweak penguin + box diagram.
- Sensitive to New Physics in the loop diagram.
- Theoretically clean: no long distance contributions.
- May be sensitive to light dark matter (C. Bird, PRL 93, 201803 (2004))



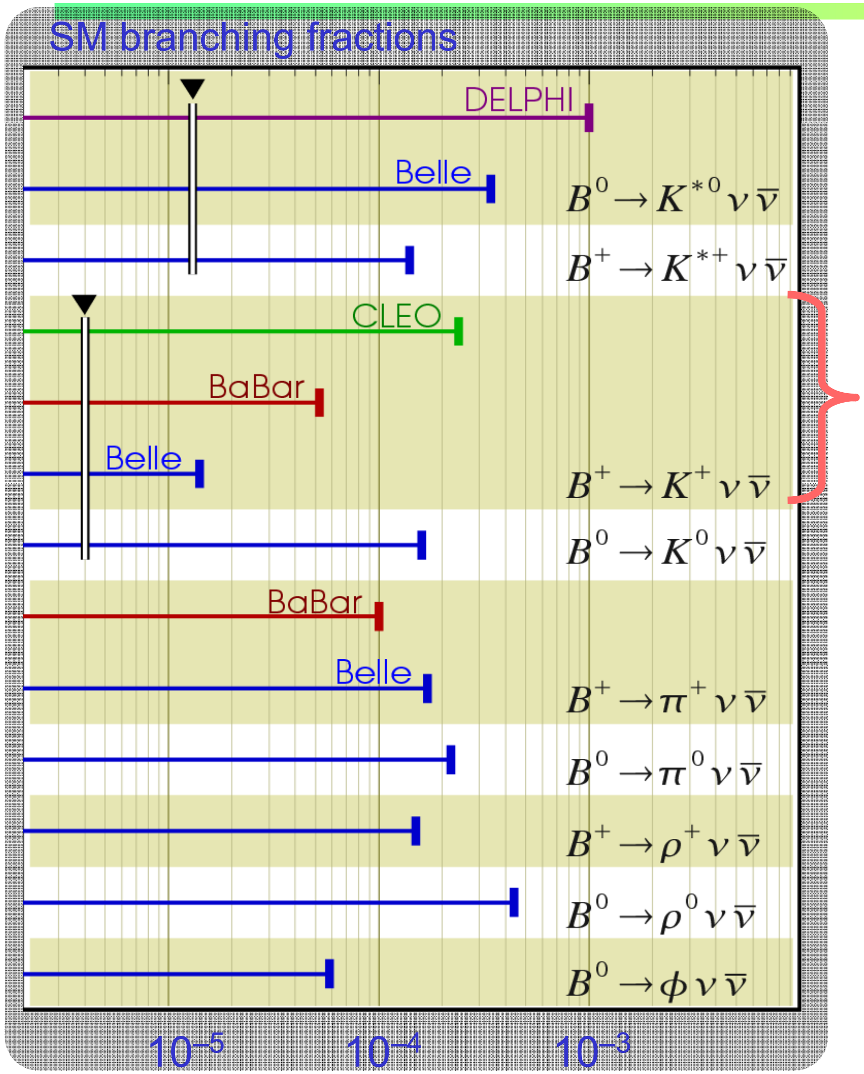


$b \to s$ + Missing E may be enhanced by this extra diagram.

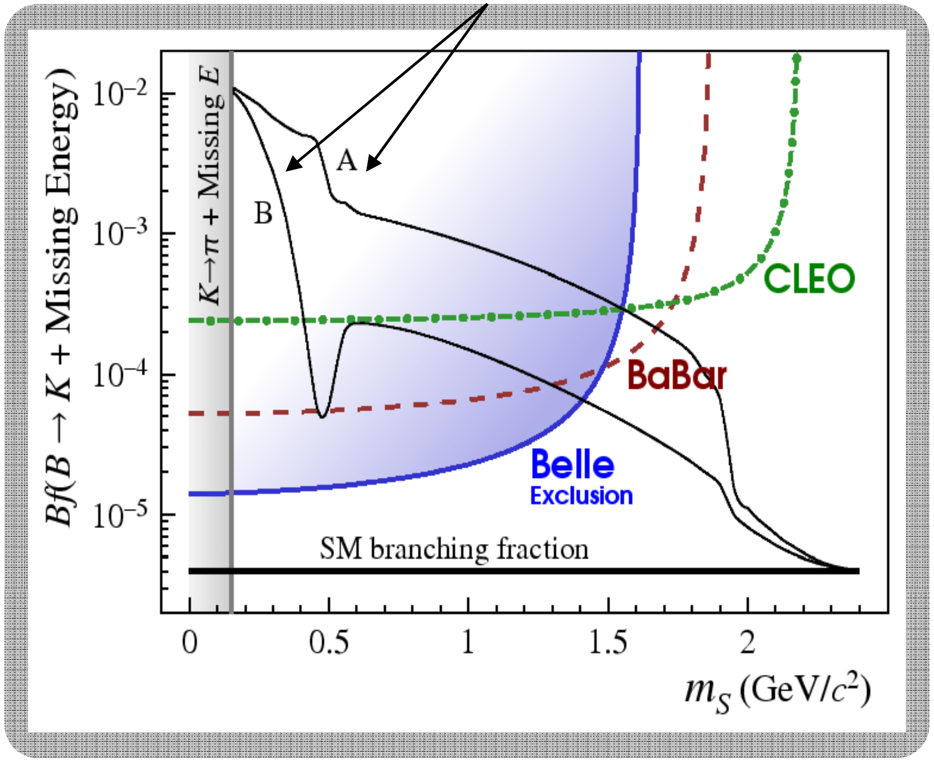
No sensitivity to light dark matter (M<10 GeV) in direct searches



$B\to K^{(*)}\nu\nu$: present limits



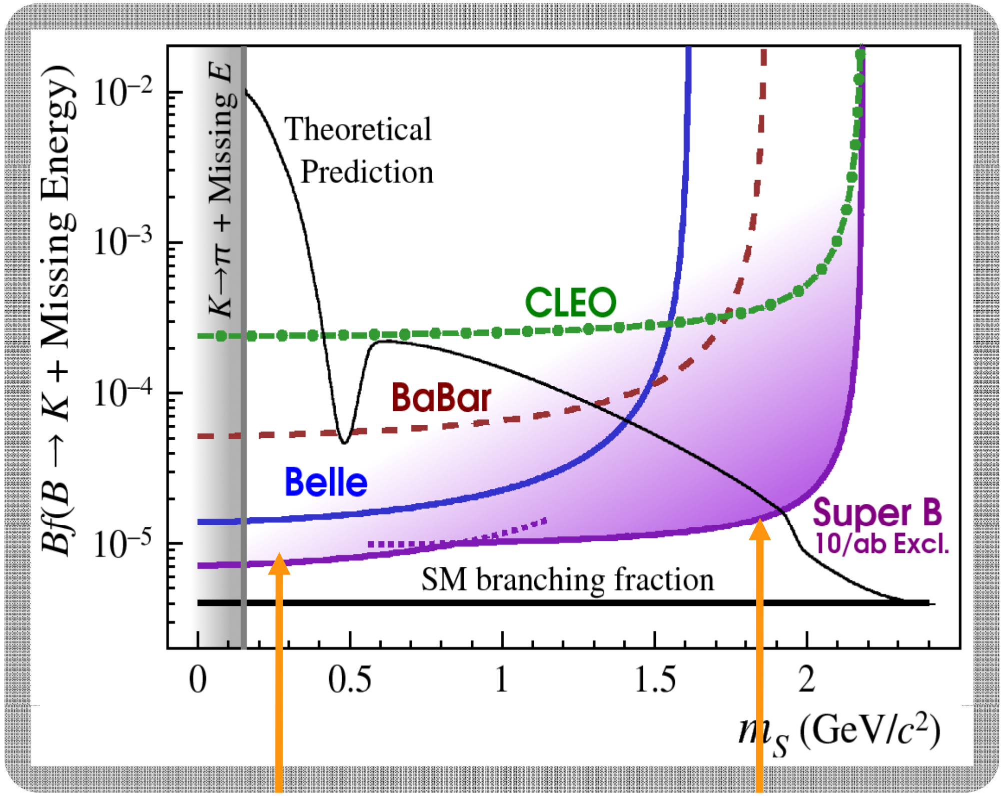
- Limit on light dark matter based on the $K^+\nu\nu$ limits (using theory predictions, C. Bird, PRL 93, 201803 (2004)



- Limit depends on P*(K) momentum cut

$B \to K^{(*)} \nu\nu$: prospects for 10/ab

- Assuming no changes in the analysis & detector:

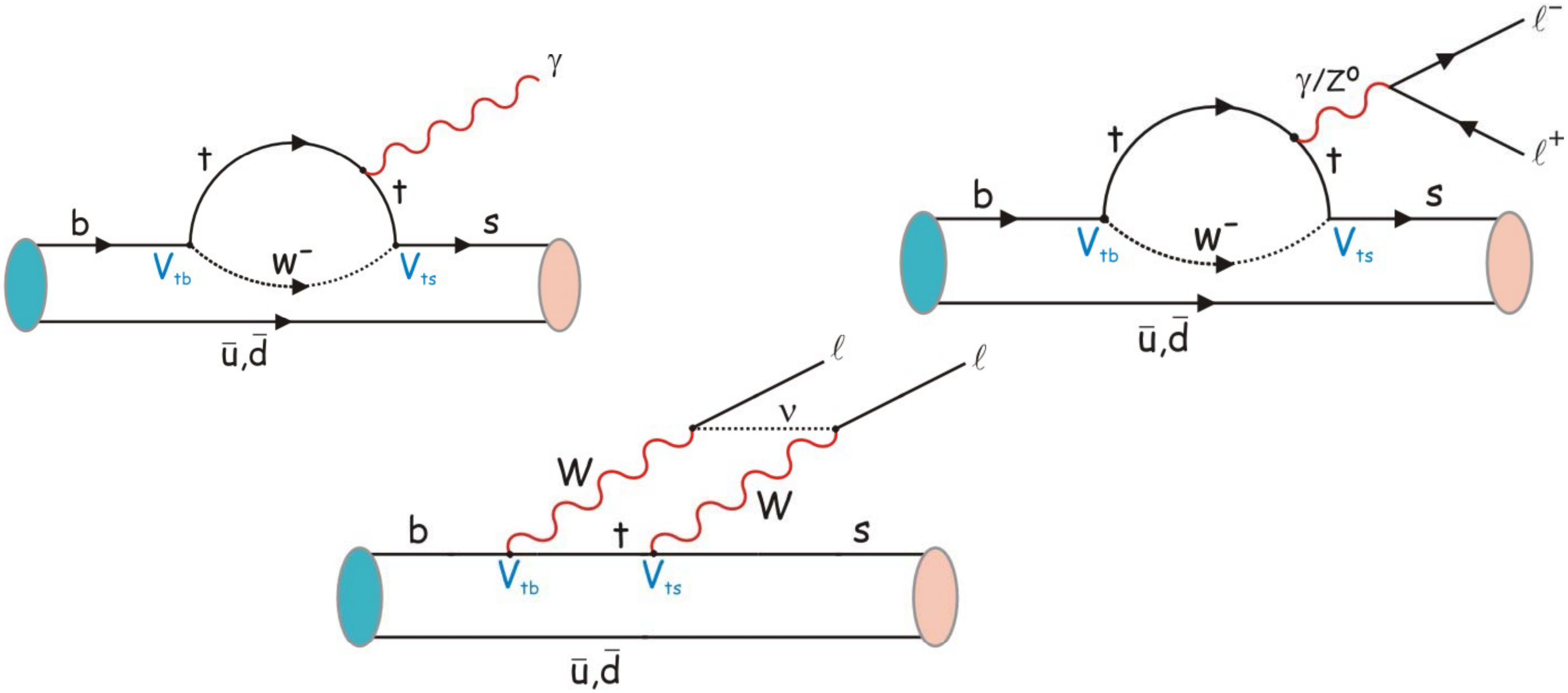


with the same $P^*(K)$ threshold (1.6 GeV)

with a lower $P^*(K)$ threshold (0.7 GeV)

Why FCNC decays?

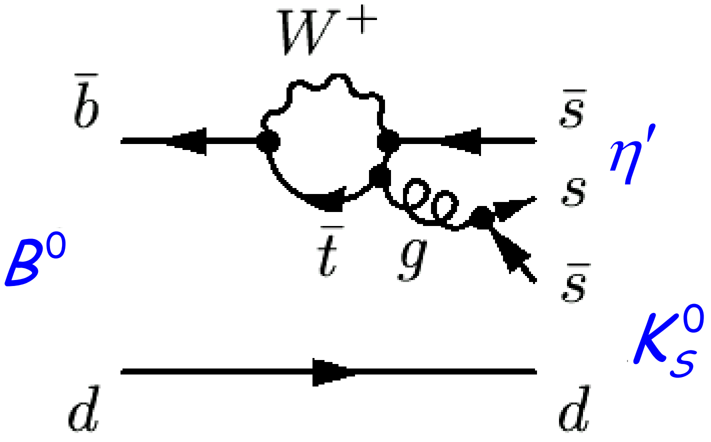
Flavour changing neutral current (FCNC) processes (like b→s, b→d) are fobidden at the tree level in the Standard Model. Proceed only at low rate via higher-order loop diagrams. Ideal place to search for new physics.



How can New Physics contribute to b→s?

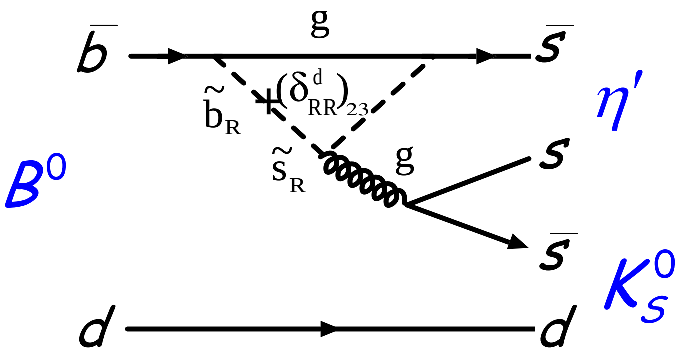
For example in the process:

$$B^0 \to \eta' K^0$$



Ordinary penguin diagram with a t quark in the loop

Diagram with supersymmetric particles

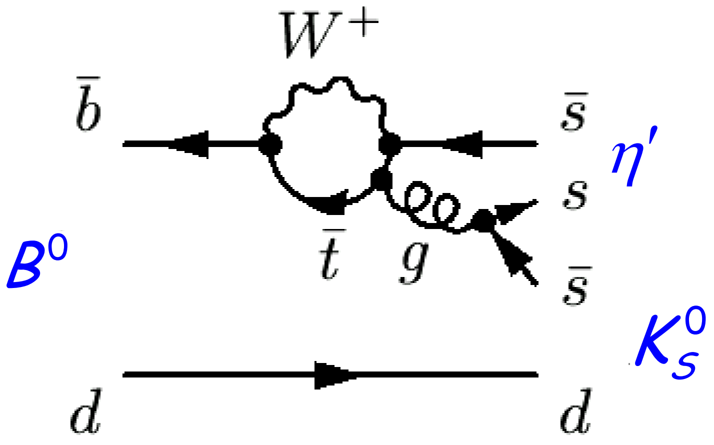


Searching for new physics phases in CP violation measurements in b→s decays

Prediction in SM:

$B^0 \to \eta' K^0$

$$a_f = -\mathrm{Im}(\lambda_f)\sin(\Delta m t)$$

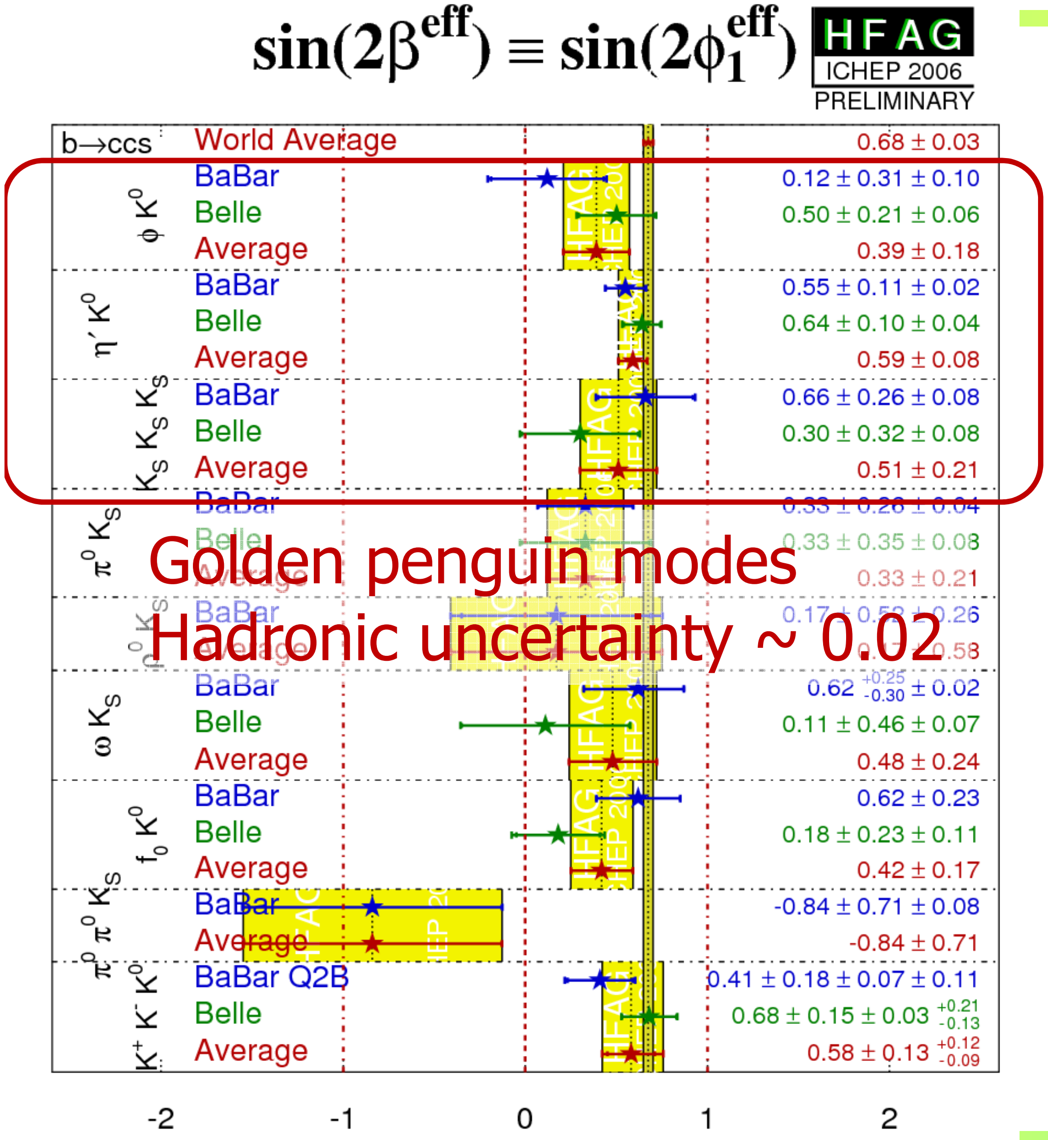


$$\boxed{\mathrm{Im}(\lambda_f) = \xi_f \sin 2\phi_1}$$

The same value as in the decay $B^0 \to J/\psi\, K_S$!

This is only true if there are no other particles in the loop! In general the parameter can assume a different value $\sin 2\phi_1^{\mathrm{eff}}$

Search for NP: $b \to s\bar{q}$



Golden penguin modes

Hadronic uncertainty ~ 0.02

ICHEP08

BaBar

Belle

Naïve average

0.26±0.25±0.04

$0.67\pm^{0.25}_{0.27}\pm0.07$

0.45±0.18

0.57±0.08±0.02

0.64±0.10±0.04

0.60±0.07

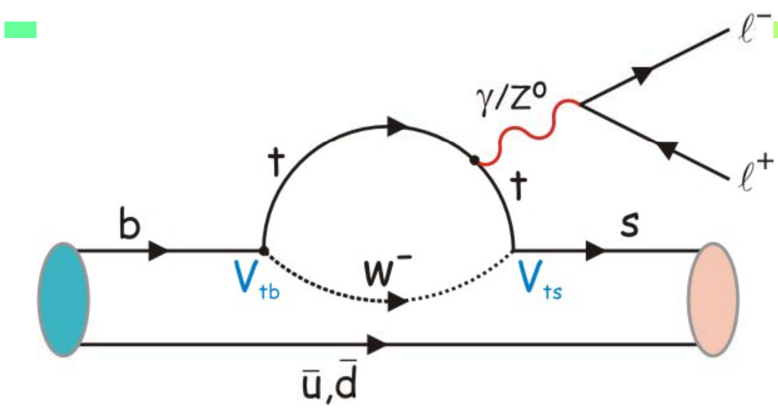
0.71±0.24±0.04

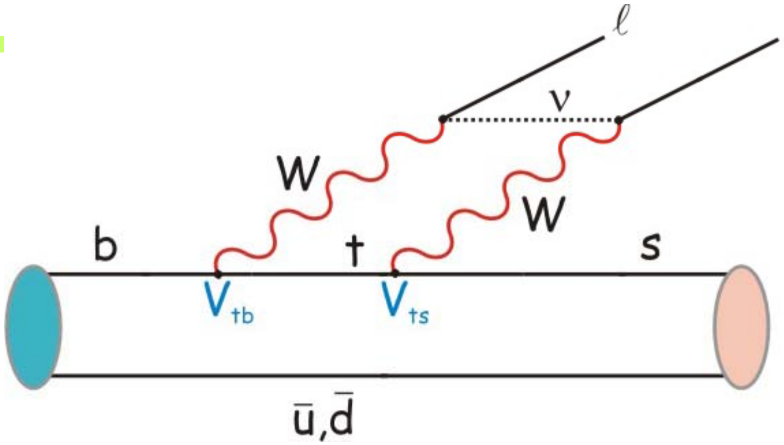
0.30±0.32±0.08

0.57±0.20

Need much more data (x50) to clarify the issue

Another FCNC decay: B → $K^* l^+ l^-$





b → s l^+l^- was first measured in B → K l^+l^- by Belle (2001).

Important for further searches for the physics beyond SM

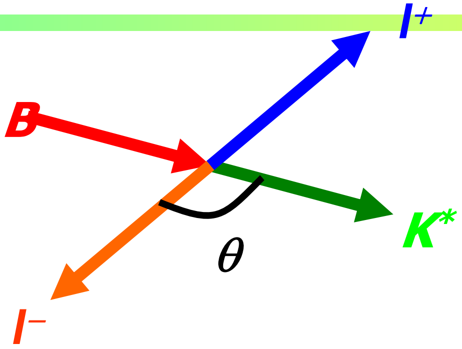
Particularly sensitive: backward-forward asymmetry in $K^* l^+l$

$$A_{FB} \propto \Re\left[C_{10}^{*}\left(sC_9^{eff}(s)+r(s)C_7\right)\right]$$

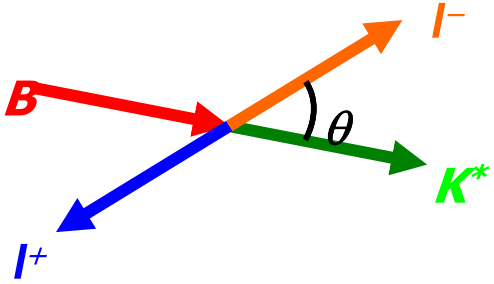
C_i : Wilson coefficients, abs. value of C_7 from b→sγ

s=lepton pair mass squared

Backward-forward asymmetry in $K^* l^+ l$

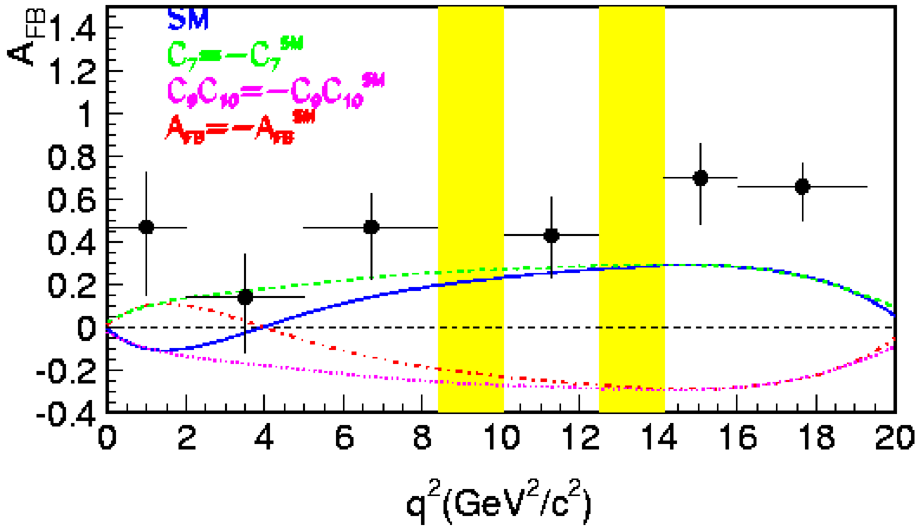


Backward event



Forward event

[γ* and Z* contributions in B→K^* l l interfere and give rise to forward-backward asymmetries c.f. $e^+e^- \rightarrow \mu^+ \mu^-$]

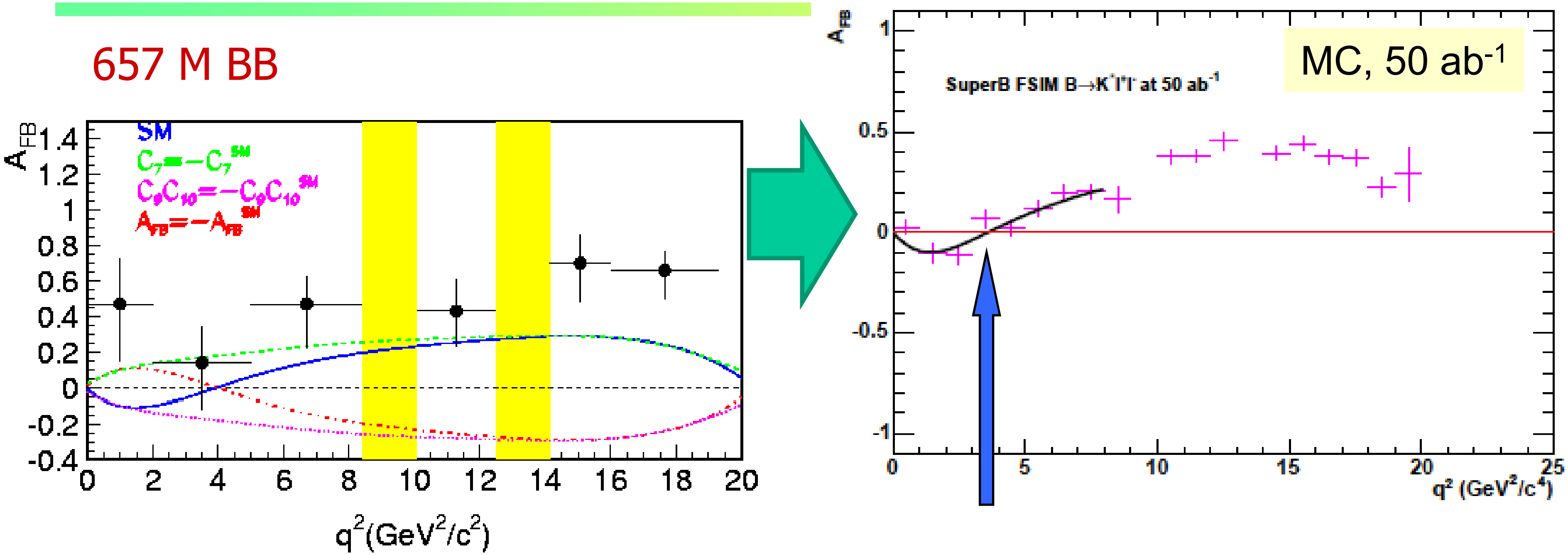


657 M BB

$$A_{FB} \propto \Re\left[C_{10}^{*}\left(sC_{9}^{eff}(s)+r(s)C_{7}\right)\right]$$

$A_{FB}(B \to K^* l^+ l^-)[q^2]$ at a Super B Factory

657 M BB

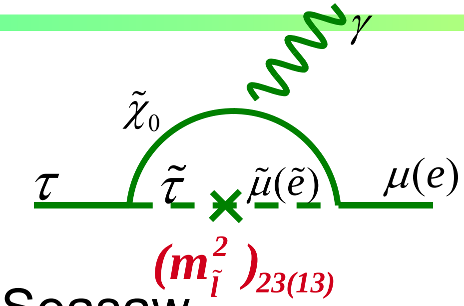


- Zero-crossing q^2 for A_{FB} will be determined with a 5% error with $50 ab^{-1}$.

Strong competition from LHCb and ATLAS/CMS

LFV and New Physics

τ→lγ

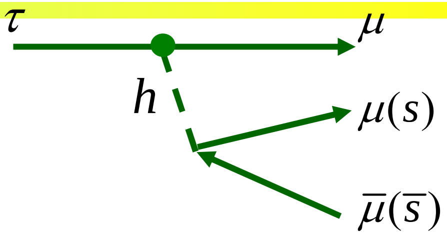


- SUSY + Seasaw
- Large LFV $Br(\tau \to \mu\gamma)=O(10^{-7\sim 9})$

$$Br(\tau \to \mu\gamma) \simeq 10^{-6} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\overline{m}^2_{\tilde{L}}} \right) \left(\frac{1\,TeV}{m_{SUSY}} \right)^4 \tan^2\beta$$

=

τ→3l,lη



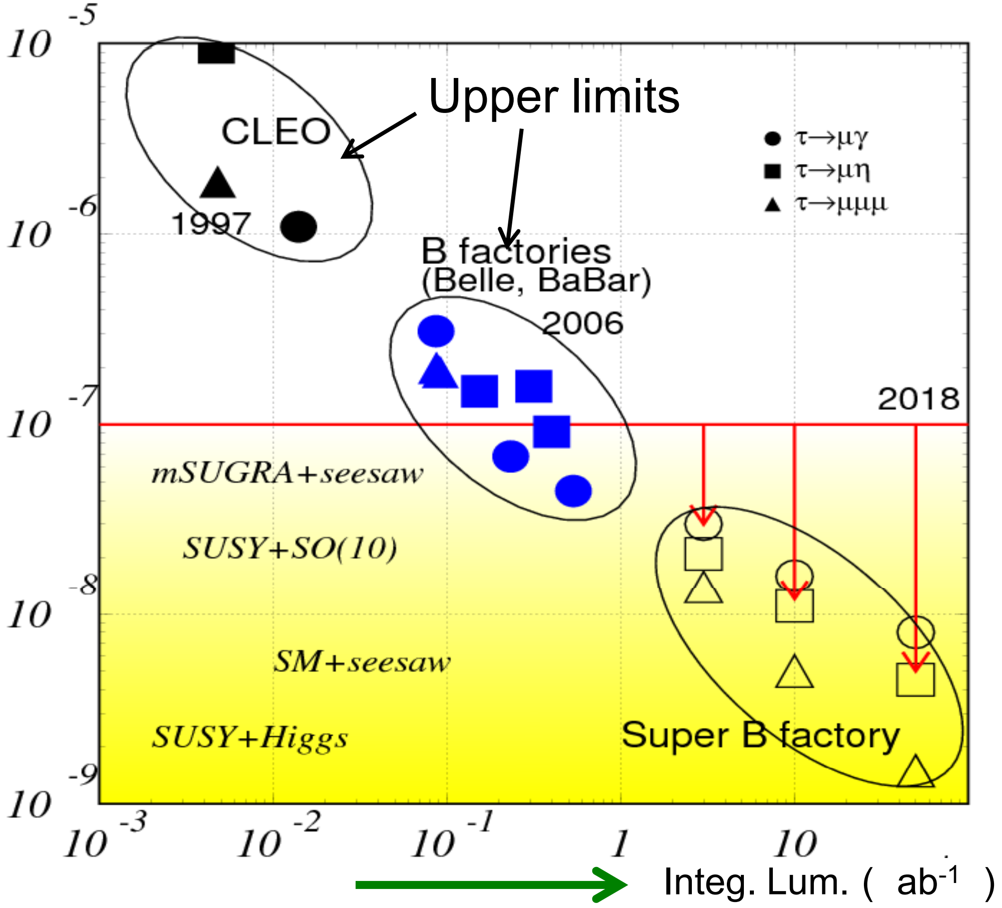
- Neutral Higgs mediated decay.
- Important when MSUSY >> EW scale.

$$Br(\tau \to 3\mu) = 4\times 10^{-7} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\overline{m}^2_{\tilde{L}}} \right) \left(\frac{\tan\beta}{60} \right)^6 \left(\frac{100GeV}{m_A} \right)^4$$

model	Br(τ→μγ)	Br(τ→lll)
mSUGRA+seesaw	10^{-7}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-Universal Z’	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-7}

Precision measurements of τ decays

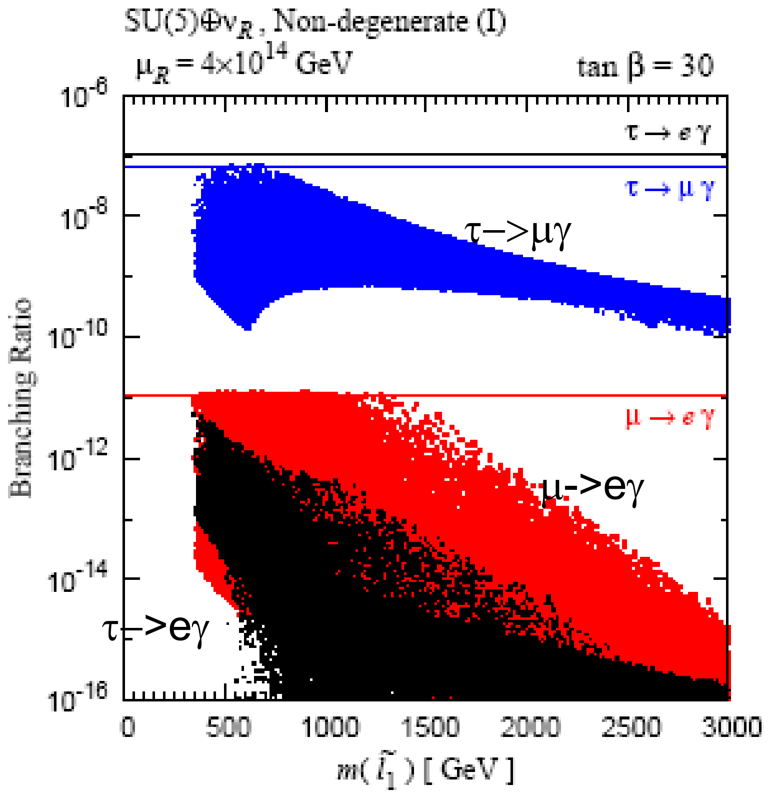
LF violating τ decay?



Reach of B factories

Upgraded KEKB

Theoretical predictions compared to present experimental limits



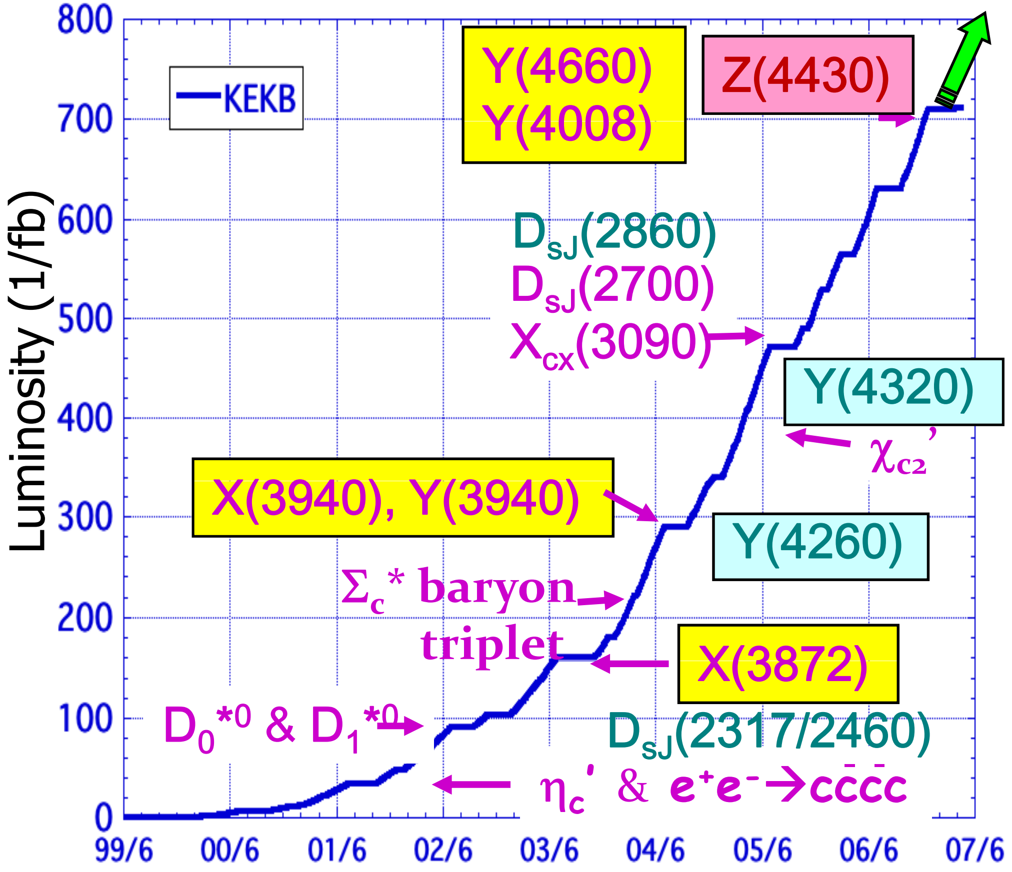
T.Goto et al., 2007

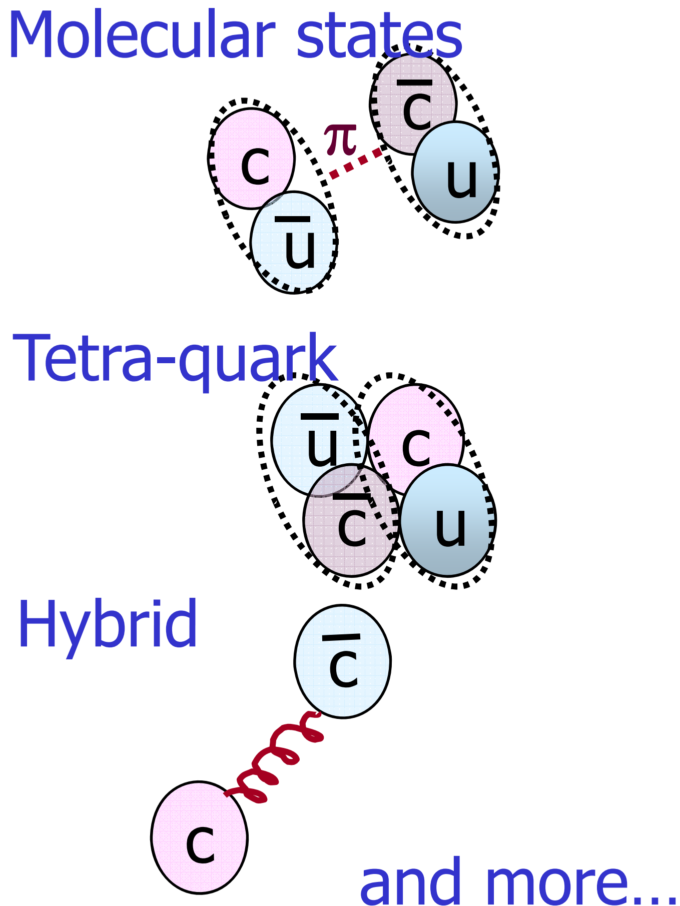
B factories: a success story

- Measurements of CKM matrix elements and angles of the unitarity triangle
- Observation of direct CP violation in B decays
- Measurements of rare decay modes (e.g., $B \to \tau\nu$, $D\tau\nu$) by fully reconstructing the other B meson
- Observation of D mixing
- CP violation in $b \to s$ transitions: probe for new sources if CPV
- Forward-backward asymmetry (A_{FB}) in $b \to s l^+ l^-$ has become a powerfull tool to search for physics beyond SM.
- Observation of new hadrons

New hadrons at B-factories

Discoveries of many new hadrons at B-factories have shed light on new class of hadrons beyond the ordinary mesons.





Molecular states

Tetra-quark

Hybrid

and more…

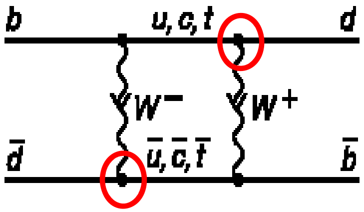
Physics at a Super B Factory

- There is a good chance to see new phenomena:
  - **CPV in B decays from the new physics (non KM)**
  - **Lepton flavor violations in τ decays.**
- They will help to diagnose (if found) or constraint (if not found) new physics models.
- Even in the worst case scenario (such as MFV), $B \rightarrow \tau\nu$, $D\tau\nu$ can probe the charged Higgs in large tanβ region.
- **Physics motivation is independent of LHC**.
  - If LHC finds NP, precision flavour physics is compulsory.
  - If LHC finds no NP, high statistics B/τ decays would be an unique way to search for the TeV scale physics.

Super B Factory Motivation 2

- A lesson from history: the top quark

<u>Physics of top quark</u>
First estimate of mass: BB mixing → ARGUS
Direct production, Mass, width etc. → CDF/D0
Off-diagonal couplings, phase → BaBar/Belle

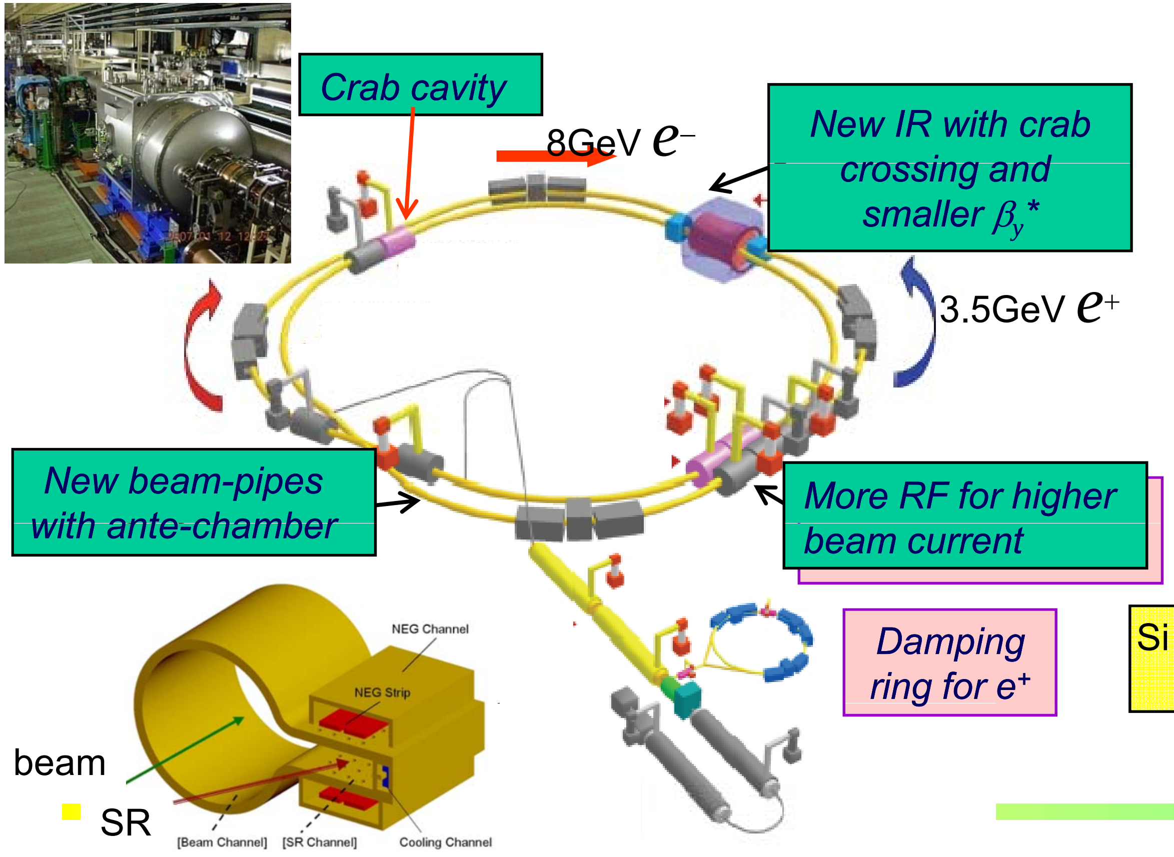


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ \boxed{V_{td}} & V_{ts} & V_{tb} \end{pmatrix}$$

- There are many more topics: CPV in charm, new hadrons, …

KEKB Upgrade Plan : Super-B Factory at KEK

- *Asymmetric energy e^+e^- collider at $E_{CM}=m(\Upsilon(4S))$ to be realized by upgrading the existing KEKB collider.*
- *Initial target:* *10×higher luminosity* $\cong 2\times10^{35}$/cm^2/sec after 3 year shutdown
  $\rightarrow 2\times10^{9}\ \overline{B}B$ *and* $\tau^+\tau^-$ *per yr.*
- *Final goal:* $L=8\times10^{35}$/cm^2/sec *and* $\int L\,dt$ = 50 ab^{-1}



Crab cavity

8GeV e^-

*New IR with crab crossing and smaller β_y**

3.5GeV e^+

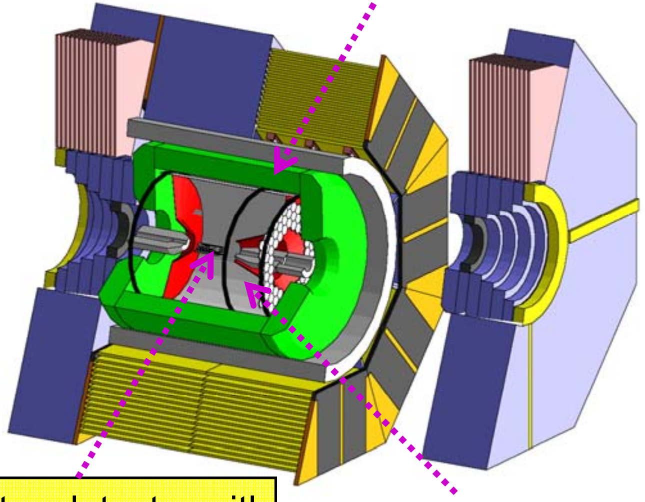
New beam-pipes with ante-chamber

More RF for higher beam current

Damping ring for e$^+$

beam

SR

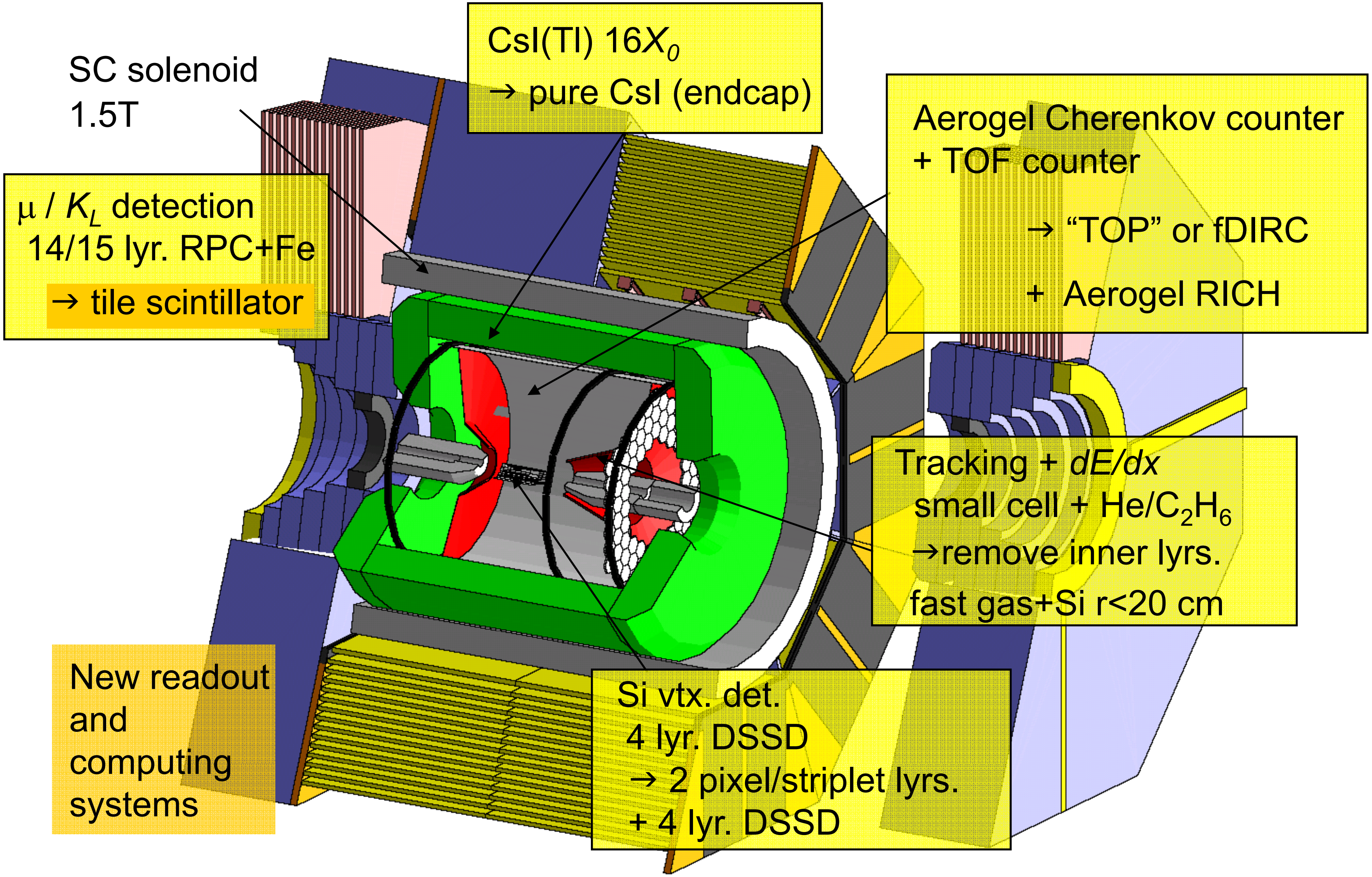


Faster calorimeter with wave form sampling and pure CsI

Si vertex detector with very short strips

Background tolerant small cell drift chamber

Belle Upgrade for Super-B



SC solenoid
1.5T

CsI(Tl) $16X_0$
→ pure CsI (endcap)

Aerogel Cherenkov counter
+ TOF counter
→ "TOP" or fDIRC
+ Aerogel RICH

μ / K_L detection
14/15 lyr. RPC+Fe
→ tile scintillator

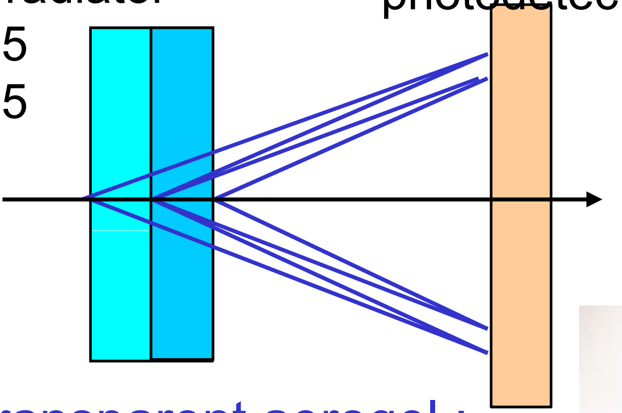
Tracking + dE/dx
small cell + He/C_2H_6
→remove inner lyrs.
fast gas+Si r<20 cm

New readout
and
computing
systems

Si vtx. det.
4 lyr. DSSD
→ 2 pixel/striplet lyrs.
+ 4 lyr. DSSD

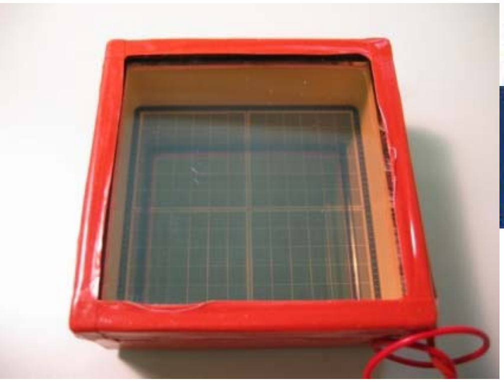
Aerogel RICH

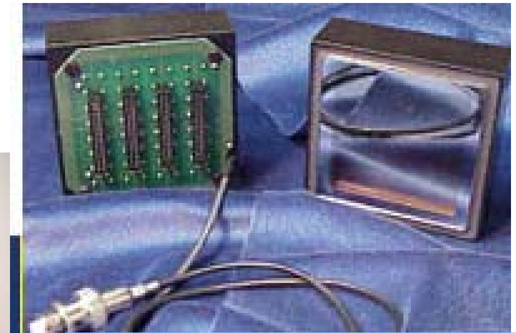
- Proximity focusing RICH with multilayer aerogel radiator with different indices.

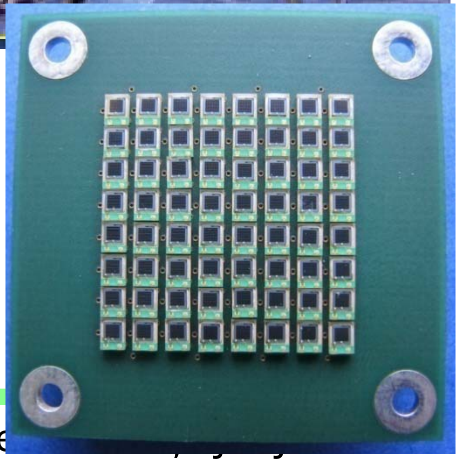


Multi-pixel photodetector to measure single photon positions in B=1.5T
→ HAPD/MCP-PMT/G-APD

Highly transparent aerogel :
$\Lambda_t > 40$mm (λ=400nm)

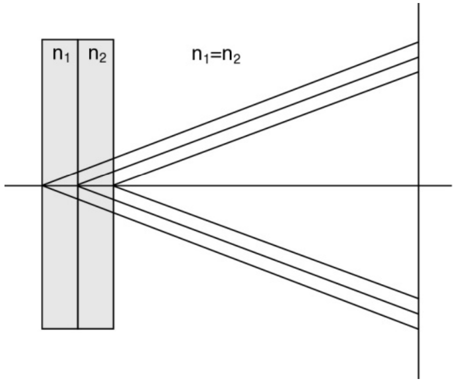


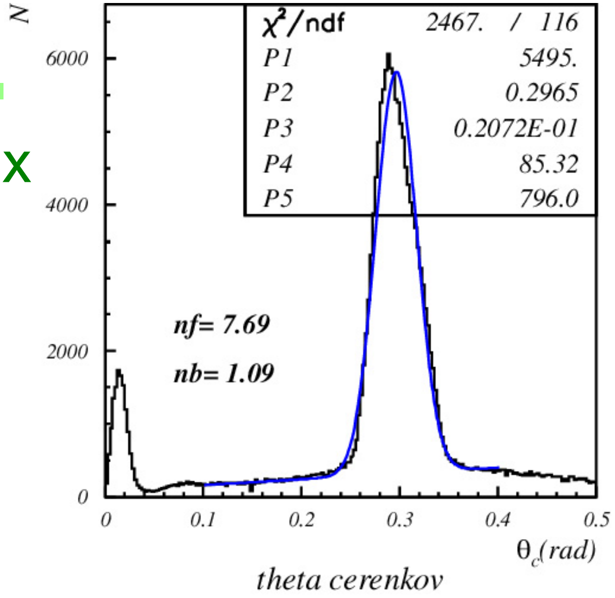




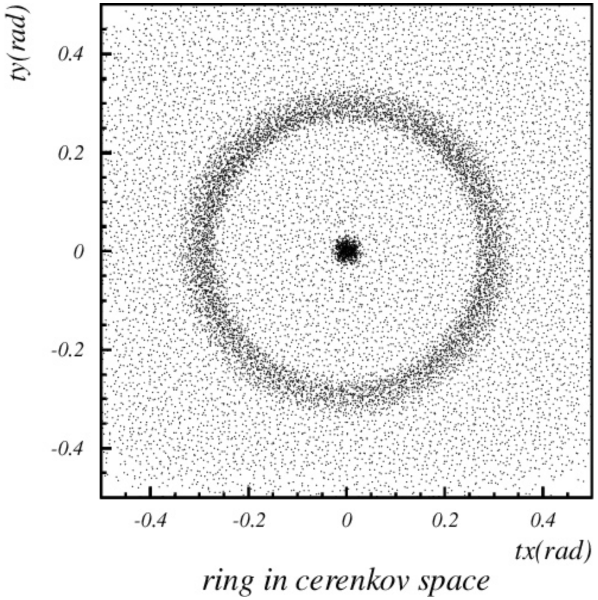
Aerogel RICH – test results

4cm aerogel single index



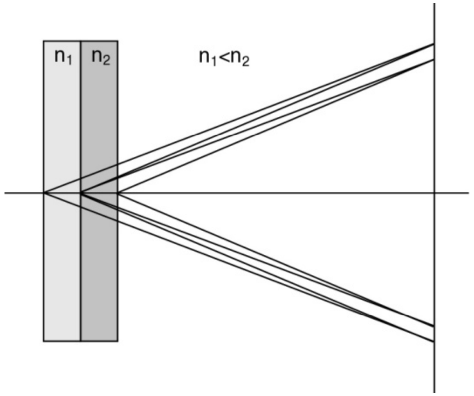


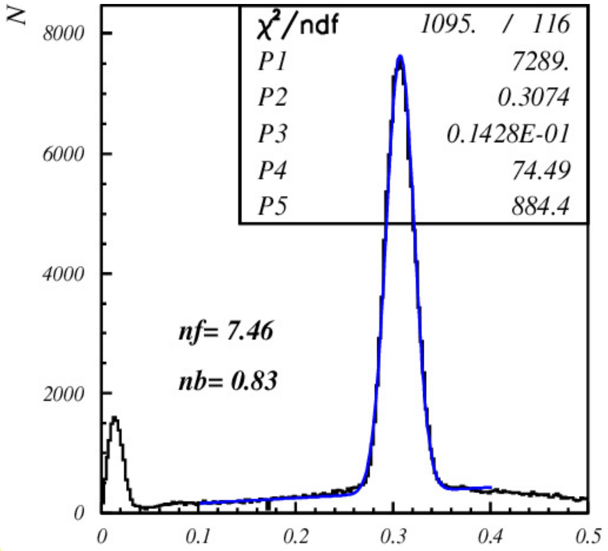
theta cerenkov

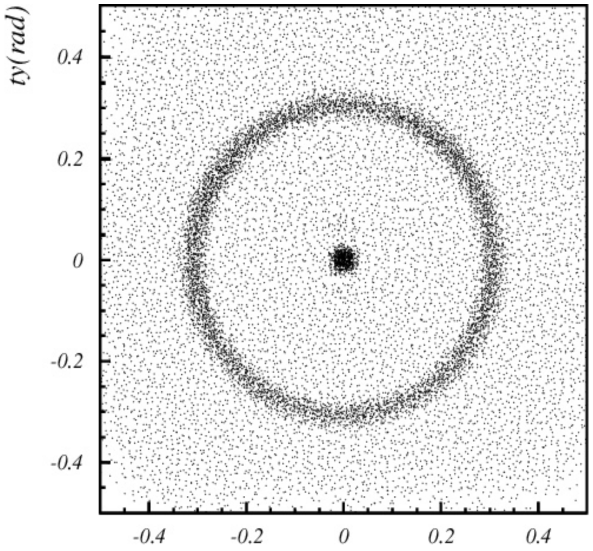


ring in cerenkov space

2+2cm aerogel







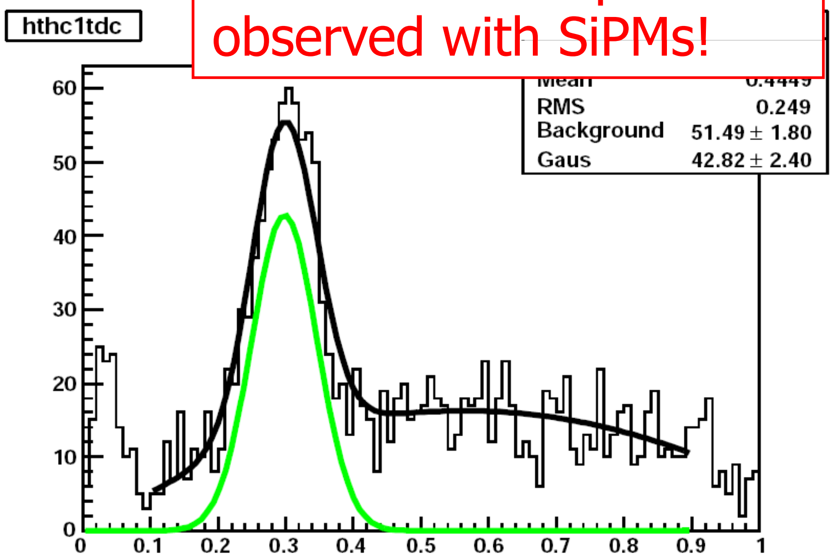
→NIM A548 (2005) 383

SiPMs for Aerogel RICH

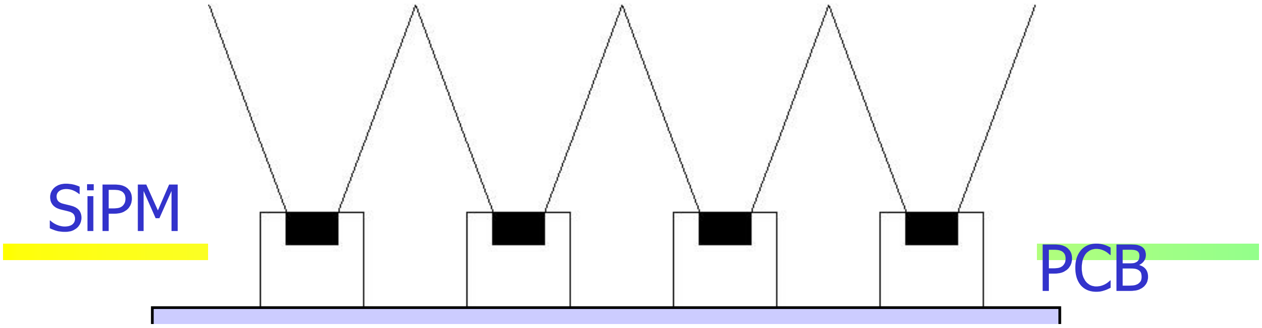
Main challenge: R+D of a photon detector for operation in high magnetic fields (1.5T). Candidates:

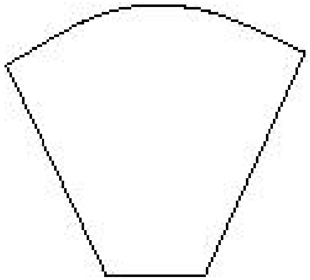
- MCP PMT: excellent timing, could be also used as a TOF counter
- HAPD: development with HPK
- SiPMs: easy to handle, but never before used for single photon detection (high dark count rate with single photon pulse height) → use a <u>narrow time window</u> and <u>light concentrators</u>

First Cherenkov photons observed with SiPMs!



→NIM A594 (2008) 13

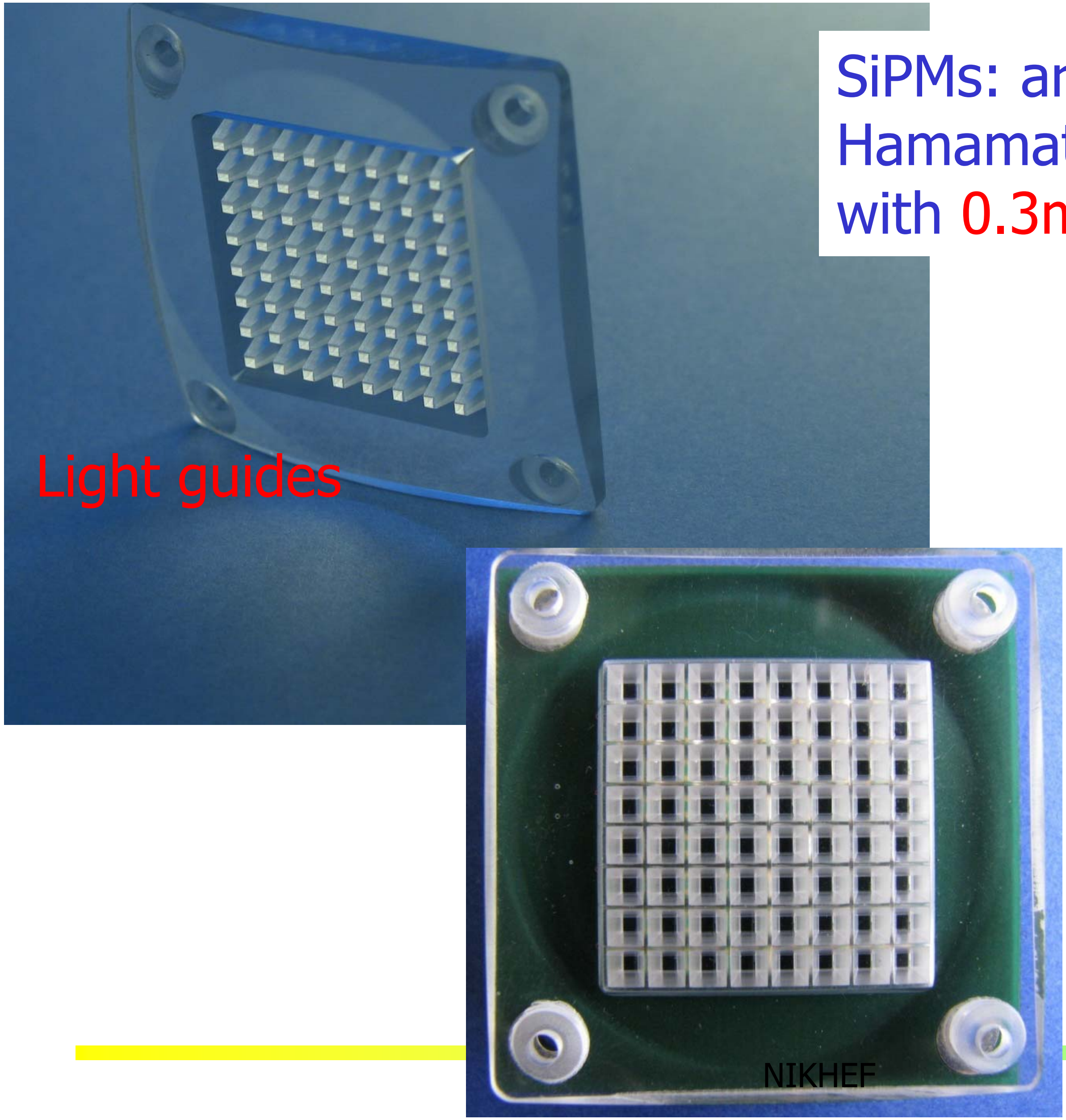




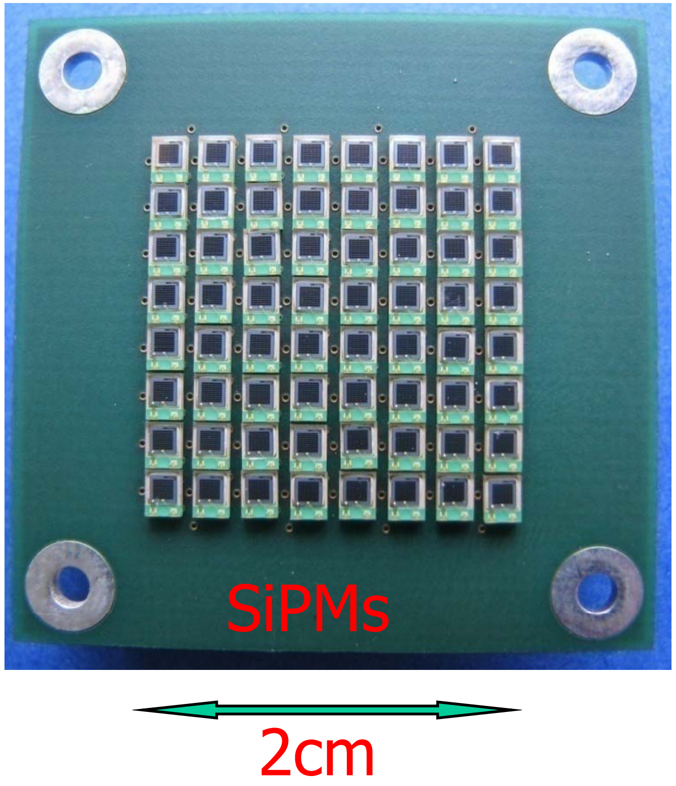
or combine a lens and mirror walls

Detector module for beam tests at KEK

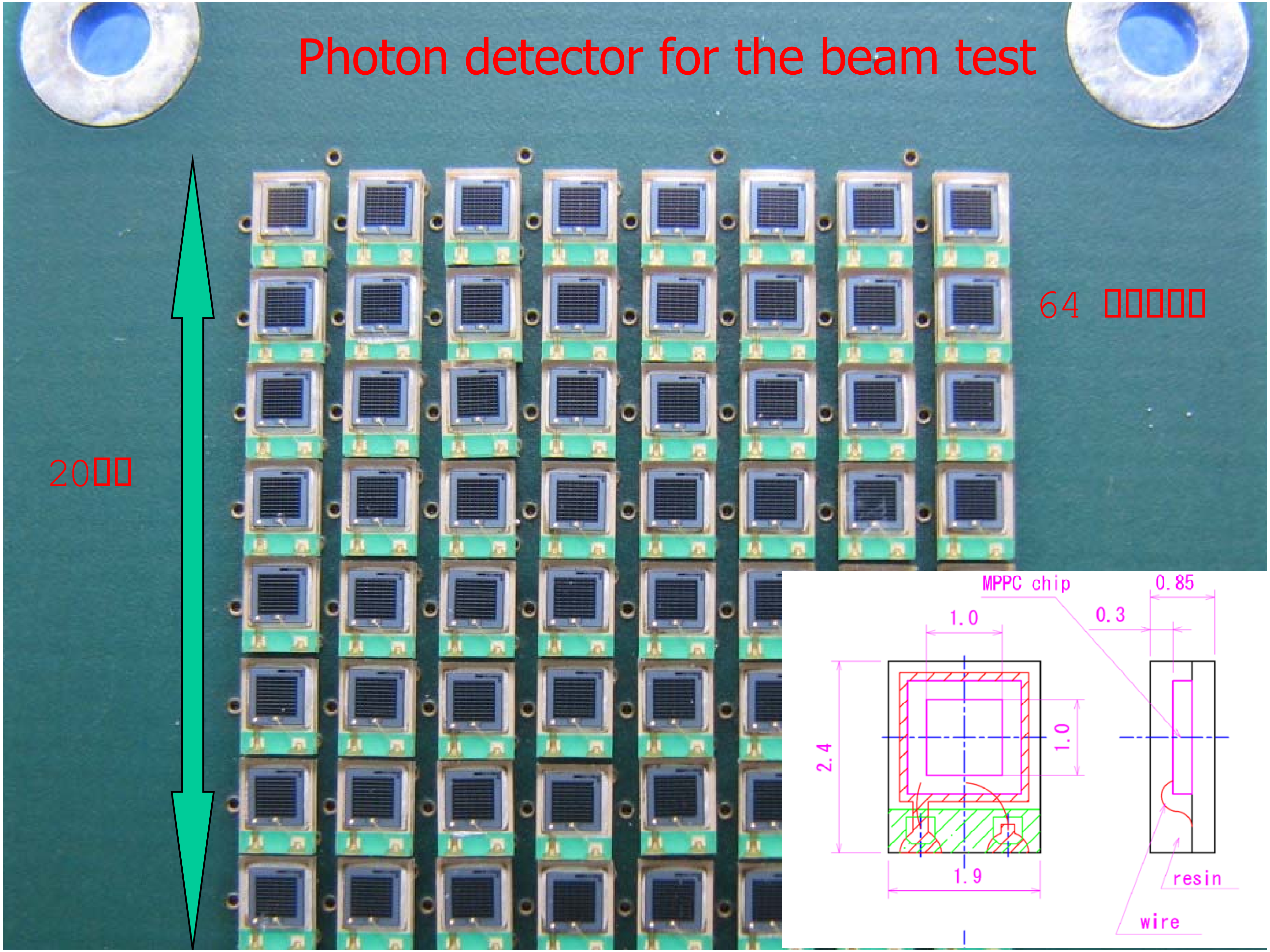
SiPMs: array of 8x8 SMD mount Hamamatsu S10362-11-100P with 0.3mm protective layer



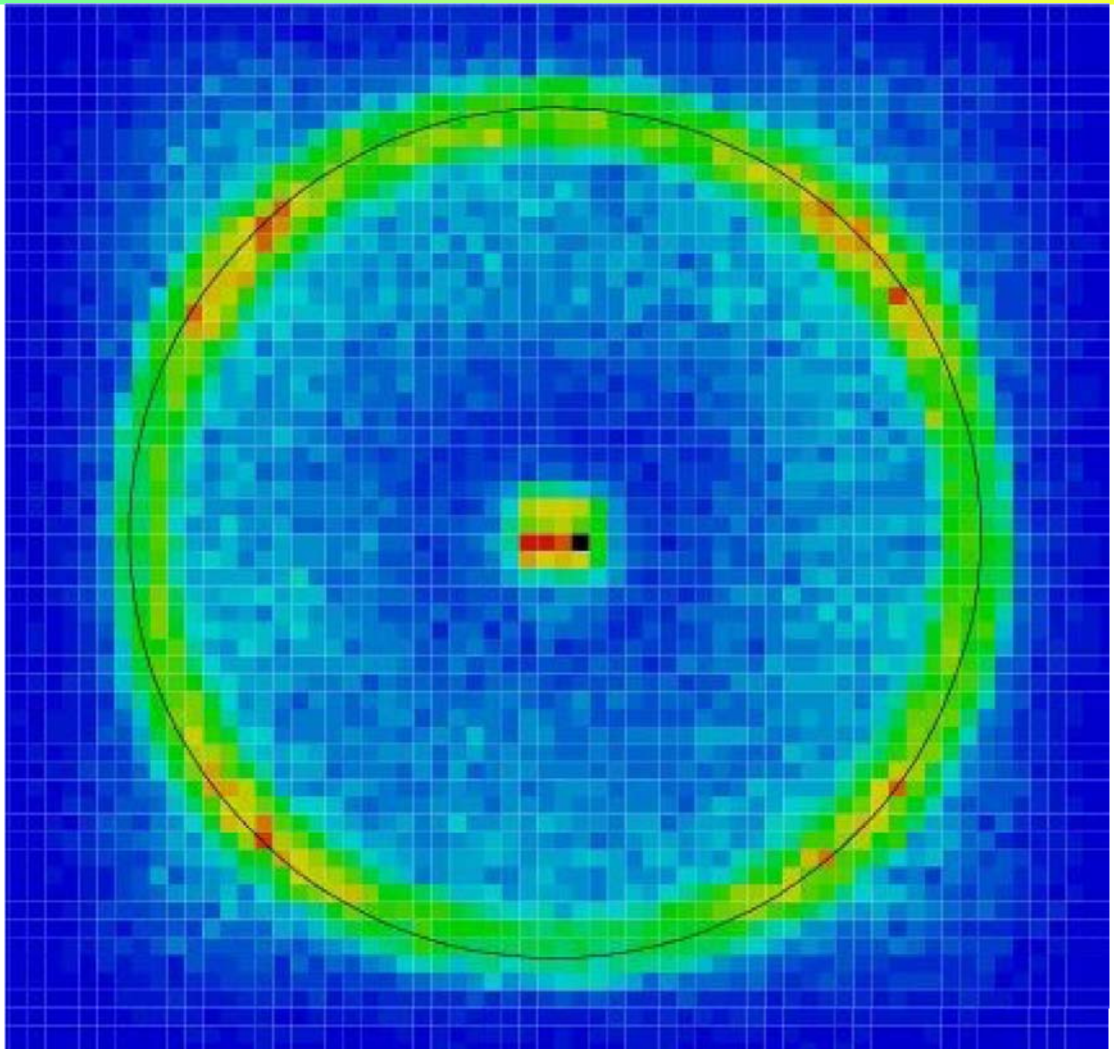
SiPMs + light guides



Photon detector for the beam test



Cherenkov ring with SiPMs



Summary

- B factories have proven to be an excellent tool for flavour physics, with reliable long term operation, constant improvement of the performance.
- Major upgrade in 2009-12 → Super B factory, L x10 → x40
- Strong competetion from LHCb
- Expect a new, exciting era of discoveries, complementary to LHC

Back-up slides

Introduction to CP

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

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

nb. baryons (matter) ←

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

→ **Nb of photons (microvawe backg)**

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

How did we get from

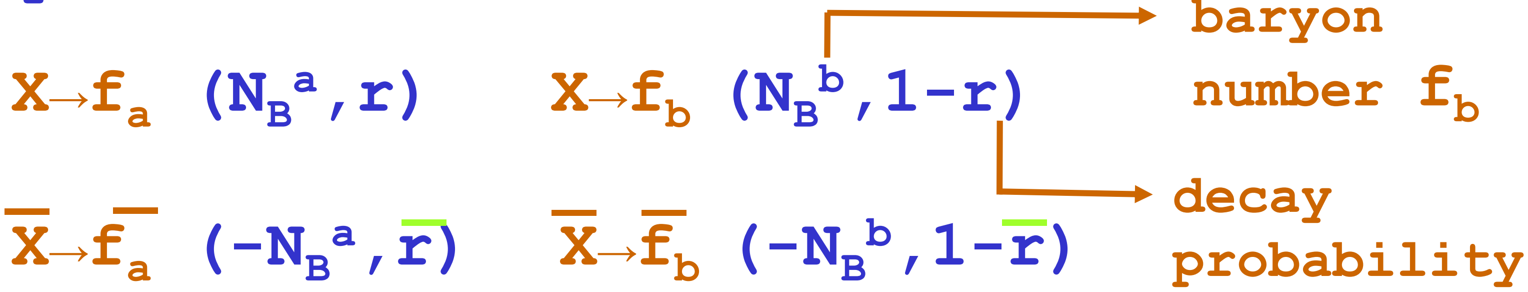
$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 0 \quad \text{to} \quad \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 10^{-10} - 10^{-9} \text{ ?}$$

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

Introduction to CP

Three conditions (A.Saharov, 1967):

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



$X \rightarrow f_a \quad (N_B^a, r) \qquad X \rightarrow f_b \quad (N_B^b, 1-r)$

$\overline{X} \rightarrow \overline{f}_a \quad (-N_B^a, \overline{r}) \qquad \overline{X} \rightarrow \overline{f}_b \quad (-N_B^b, 1-\overline{r})$

baryon number f_b

decay probability

Change in baryon number in the decay of X:

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

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

Introduction to CP

$$N_B - N_{\bar{B}} = \Delta B n_X =$$

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

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

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

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

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

Introduction to CP

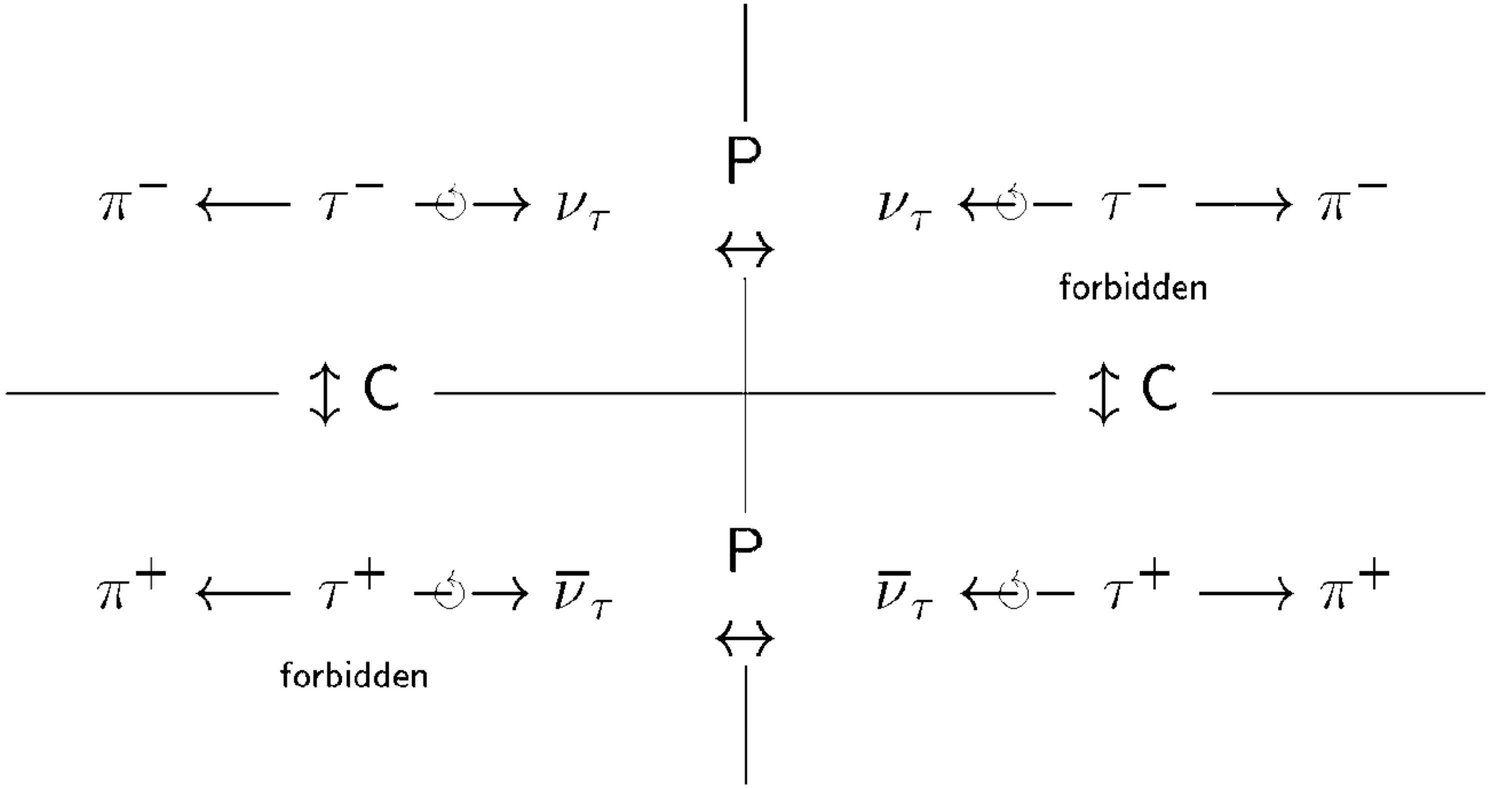
C: charge conjugation $C|B^0> = |\overline{B}^0>$

P: space inversion $P|B^0> = -|B^0>$

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

Introduction to CP

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



C or P transformed processes: forbidden.

CP transformed process: allowed

CP violation in decay

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

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

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

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

Also possible for the neutral B.

CP violation in decay

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

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

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

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:

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

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

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

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

CP violation in SM

$$\mathcal{L} = \underbrace{V_{ij}}\overline{U}_i \gamma^\mu (1-\gamma_5) D_j W_\mu^+ + \underbrace{V_{ij}^*}\overline{D}_i \gamma^\mu (1-\gamma_5) U_j W_\mu$$

$$\Updownarrow CP$$

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

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

CKM matrix

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

Then to O(λ⁶)

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

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

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

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

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

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