Particle Physics - VI

Juliet Lee-Franzini

Laboratori Nazionali Frascati

Karlsruhe University

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url: www-ttp.physik.uni-karlsruhe.de/~juliet/

4.3 Formalism

We define, analogously to the $K^0\overline{K}^0$ system,

$$B_{\mathsf{L}} = p\,|\,B^0\,\rangle + q\,|\,\overline{B}^0\,\rangle$$
$$B_{\mathsf{H}} = p\,|\,B^0\,\rangle - q\,|\,\overline{B}^0\,\rangle$$

with $p^2 + q^2 = 1$

Here L, H stand for light and heavy. The B_d's also have different masses but very similar decay widths.

Mixing is calculated in the SM by evaluating the standard "box" diagrams with intermediate u, c, t and W states. We define:

$$\Delta M = M_H - M_L, \quad \Delta\Gamma = \Gamma_H - \Gamma_L$$

note that ΔM is positive by definition.

The ratio q/p is given by:

$$q/p = (\Delta M - i/2\Delta\Gamma)/2(M_{12} - i/2\Gamma_{12}) =$$
$$2(M_{12}^* - i/2\Gamma_{12}^*)/(\Delta M - i/2\Delta\Gamma)$$

where

$$\Gamma_{12} \propto [V_{ub}V_{ud}^* + V_{cb}V_{cd}^*]^2 m_b^2 = (V_{tb}V_{td}^*)^2 m_b^2$$

and $M_{12} \propto (V_{tb}V_{td}^*)^2 m_t^2$, so they have almost the same phase.

x and y, for B_d and B_s mesons are:

$$x_{d,s} = \Delta M_{d,s}/\Gamma_{d,s}, \qquad y_{d,s} = \Delta\Gamma_{d,s}/\Gamma_{d,s}$$

y_d is less than 10^{-2}, and x_d is about 0.7, and if we ignore the width difference between the two B_d states,

$$\frac{q}{p}\Big|_{B_d} \approx \frac{(V_{tb}^* V_{td})}{(V_{tb}V_{td}^*)} = e^{-2i\beta}$$

6. CP Violation in the B system

Semileptonic decays of Bs allow, in principle, to observe $\not{C}\not{P}$ by studying the dilepton and total lepton charge asymmetries.

This however has turned to be rather difficult because of the huge background and so far yielded no evidence for $\not{C}\not{P}$ in B.

We can estimate the magnitude of the leptonic asymmetry from

$$4\Re\epsilon_B = \Im(\frac{\Gamma_{12}}{M_{12}}) \sim \frac{|\Gamma_{12}|}{|M_{12}|}\mathrm{Arg}(\frac{\Gamma_{12}}{M_{12}})$$

or approximately

$$\frac{m_b^2}{m_t^2} \times \frac{m_c^2}{m_b^2}$$

which is $\mathcal{O}(10^{-4})$.

6.1 α, β and γ

Sensitivity to CP violation in the B system is usually discussed in terms of the 3 interior angles of the U_{13} triangle.

$$\alpha = \text{Arg}(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}) \quad \beta = \text{Arg}(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}) \quad \gamma = \text{Arg}(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$$

The favorite measurements are asymmetries in decays of neutral B decays to CP eigenstates, f_{CP}, in particular $J/\psi(1S)K_S$ and possibly $\pi\pi$, which allow a clean connection to the CKM parameters. The asymmetry is due to interference of the amplitude A for $B^0 \to J/\psi\, K_S$ with the amplitude A' for $B^0 \to \overline{B}^0 \to J/\psi\, K_S$.

As is the case in the K system, direct $\not{C}\!\not{P}$ needs interference of two different amplitudes, more precisely amplitudes with different phases.

If A is the amplitude for decay of say a B^0 to a CP eigenstate, given by $A = \sum_i A_i e^{i(\delta_i + \phi_i)}$, the amplitude $\bar{A}$ for the CP conjugate process is $\bar{A} = \sum_i A_i e^{i(\delta_i - \phi_i)}$. The strong phases δ do not change sign while the weak phases (CKM related) do.

Direct CP violation requires $|A| \neq |\bar{A}|$, while indirect CP violation only requires $|q/p| \neq 1$.

The time-dependent CP asymmetry is:

$$
\begin{aligned}
a_{f_{CP}}(t) &\equiv \frac{I(B^0(t) \to J/\psi\, K_S) - I(\overline{B}^0(t) \to J/\psi\, K_S)}{I(B^0(t) \to J/\psi\, K_S) + I(\overline{B}^0(t) \to J/\psi\, K_S)} \\
&= \frac{(1 - |\lambda_{f_{CP}}|^2)\cos(\Delta M t) - 2\Im(\lambda_{f_{CP}})\sin(\Delta M t)}{1 + |\lambda_{f_{CP}}|^2} \\
&= \Im\lambda_{f_{CP}} \sin(\Delta M t)
\end{aligned}
$$

with

$$\lambda_{f_{CP}} \equiv (q/p)(\bar{A}_{f_{CP}}/A_{f_{CP}}), \quad |\lambda_{f_{CP}}| = 1.$$

In the above, $B^0(t)$ ($\overline{B}^0(t)$) is a state tagged as such at time t, for instance by the sign of the decay lepton of the other meson in the pair.

The time integrated asymmetry, for a $B^0(t)$ state is given by

$$a_{f_{CP}} = \frac{I(B^0 \to J/\psi\, K_S) - I(\overline{B}^0 \to J/\psi\, K_S)}{I(B^0 \to J/\psi\, K_S) + I(\overline{B}^0 \to J/\psi\, K_S)} = \frac{x}{1+x^2}\Im\lambda_{f_{CP}}$$

At a B-factory $a_{f_{CP}}$ vanishes because we have a $B^0\overline{B}^0$ pair in a C-odd state. Staring at box diagrams, with a little poetic license one concludes

$$a_{f_{CP}} \propto \Im\lambda_{f_{CP}} = \sin 2\beta.$$

or

$$a_{f_{CP}} \approx 0.5 \sin 2\beta \sim 1$$

The license involves ignoring penguins, which is probably OK for the decay to $J/\psi\, K_S$, presumably a few % correction.

For the $\pi\pi$ final state, the argument is essentially the same. However the branching ratio for $B \to \pi\pi$ is extraordinarily small and penguins *are* important.

The asymmetry is otherwise proportional to $\sin(2\beta+2\gamma) = -\sin 2\alpha$. Here we assume $\alpha + \beta + \gamma = \pi$, which is something that we would instead like to prove.

The angle γ can be obtained from asymmetries in B_s decays and from mixing, measurable with very fast strange Bs.

6.2 CDF and DØ

CDF at the Tevatron was the first to profit from the idea suggested first by Toni Sanda, to study asymmetries in the decay of tagged B^0 and of $\overline{B}^0$ to a final state which is a CP eigenstate. They find

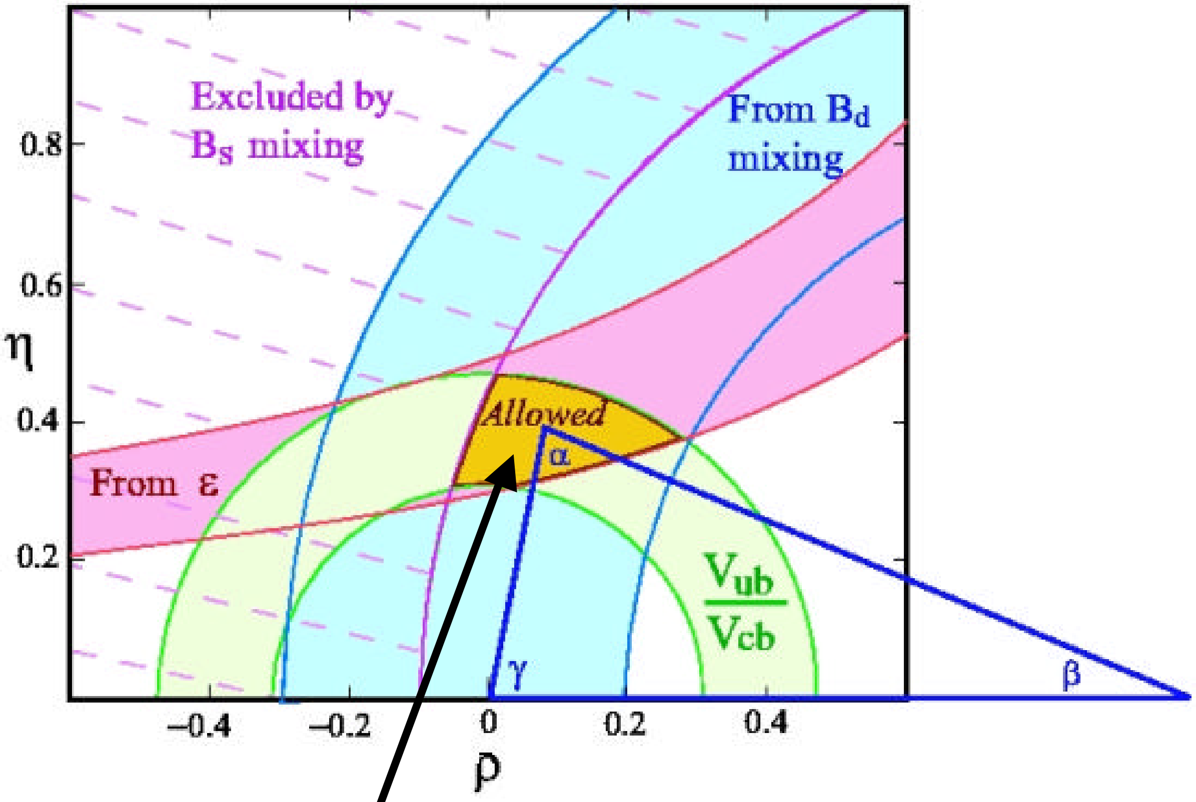
$$\sin 2\beta = 0.79^{+0.41}_{-0.44}, \quad 0.0 \leq \sin 2\beta < 1 \quad \text{at 93\% CL}$$

Their very lucky central value agrees with the aforementioned SM fit, but there is a two fold ambiguity in the determination of β. Their error does not allow to chose one of the two values.

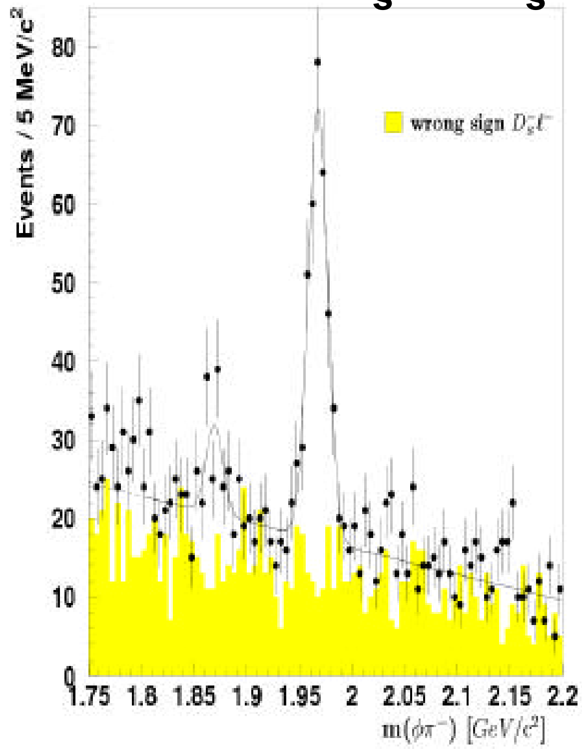
In the coming Tevatron runs, CDF and DØ expect to reach an accuracy of $\delta \sin 2\beta \approx 0.1$, and to measure $\sin(2\alpha)$ from the asymmetry in $B^0 \to \pi^+\pi^-$ and $\overline{B}^0 \to \pi^+\pi^-$, to a similar accuracy.

Being optimistic, they hope to get a first measurement of $\sin(\gamma)$

CP Violation and CKM Matrix



CDF Run I $B_s \rightarrow D_s\, l^+\nu$



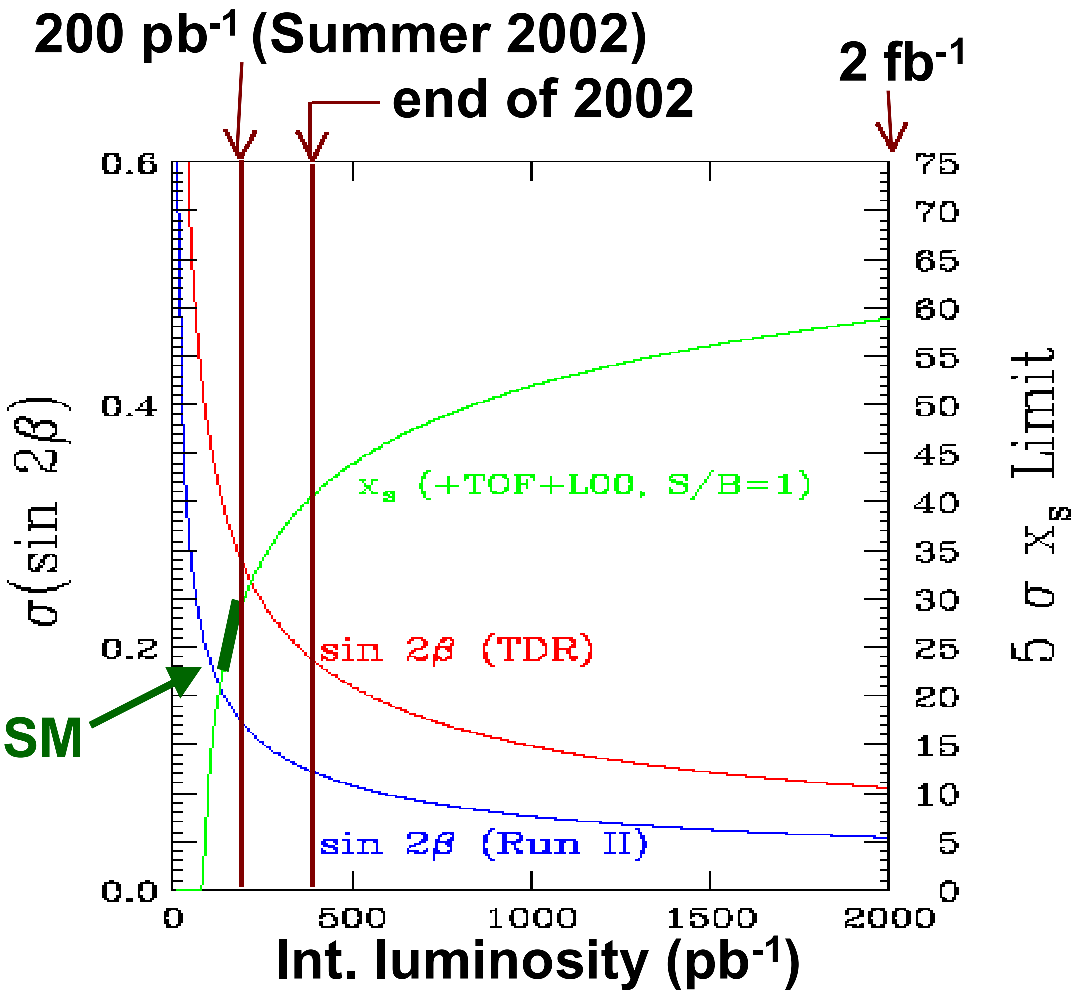
B_s mixing measurement is important for complete picture of the unitarity triangle.

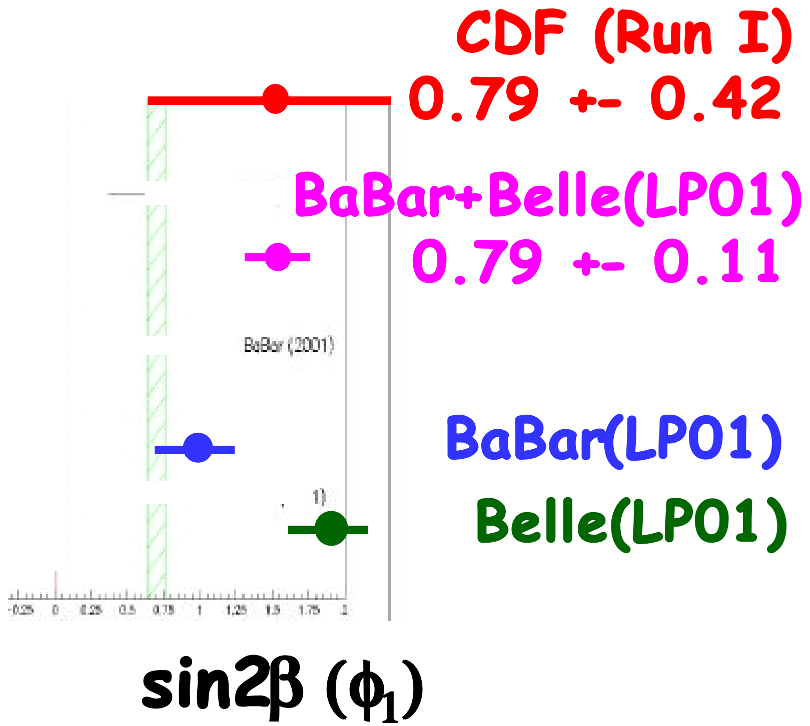
LP01, Young-Kee Kim, The Tevatron's Run II

CP Violation & CKM Matrix (cont.)

With data by next summer,

- **B_s mixing : SM predicted region ~fully covered.**
- **$\delta(\sin 2\beta)$ ~ 0.14**





LP01, Young-Kee Kim, The Tevatron's Run II by using $B_s^0/\bar{B}_s^0 \to D_s^{\pm} K^{\mp}$ from about 700 signal events.

DØ will have the same sensitivity

6.3 B-factories

In order to overcome the short B lifetime problem, and still profit from the coherent state property of B's produced on the $\Upsilon(4S)$, two asymmetric e^+e^- colliders have been built, PEP-II and KEKB.

The two colliders both use a high energy ≈9 GeV beam colliding against a low energy, ≈ 3.1 GeV, beam, so that the center of mass energy of the system is at the $\Upsilon(4S)$ energy, but the B's are boosted in the laboratory, so they travel detectable distances before their demise.

In order to produce the large number of $B^0\overline{B}^0$ pairs, the accelerators must have luminosities on the order of 3×10^{33} cm^{-2}s^{-1}, about one orders of magnitude greater than that of CESR.

Both factories have achieved luminosities of 3×10^{33} cm^{-2} s^{-1}. There is talk now to try for 1×10^{36}!!

One of the highlights at LP01 is that both experiments reported definitive measurements of β from about 30 pb^{-1}. We shall have a dedicated seminar on the subject, and just to whet your appetite I attach here a few transparencies shown at LP01.

Incidentally, B-factories will likely provide the best measurements of $|V_{cb}|$ and $|V_{cb}|$.

CPV àla Kobayashi-Maskawa

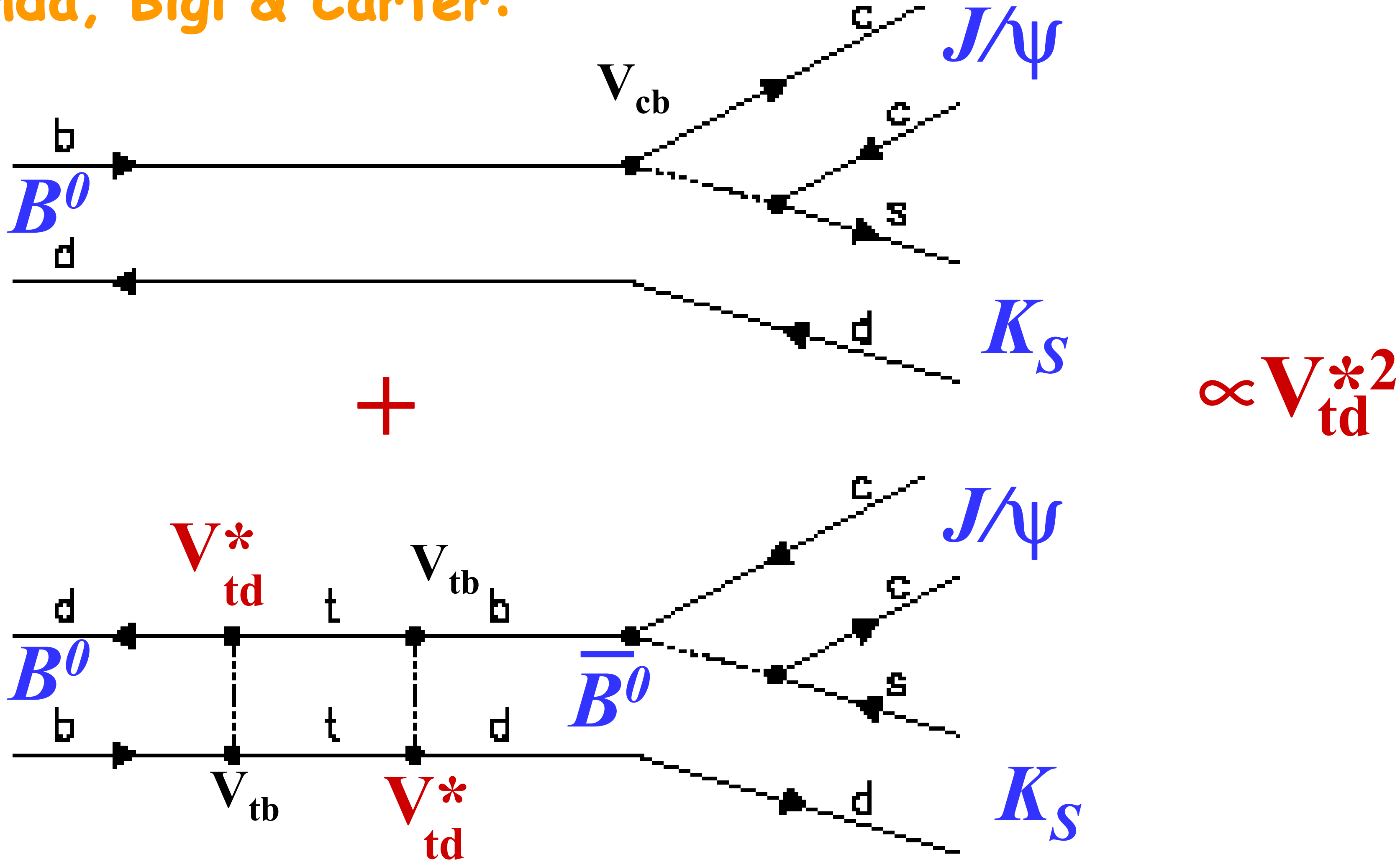
CPV due to complex phases in the Quark generation mixing matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Usually put in the V_{td} and V_{ub} corners

$\sin 2\phi_1$ from $B \to f_{CP} + B \leftrightarrow \overline{B} \to f_{CP}$ interf.

Sanda, Bigi & Carter:

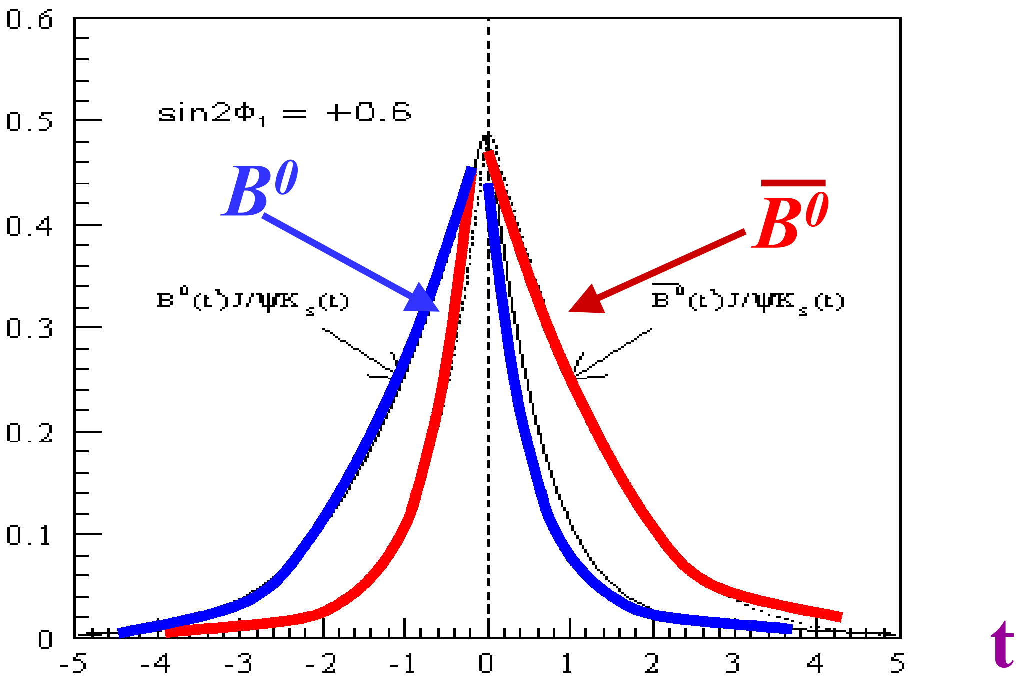


Mixing-induced CPV asymmetry

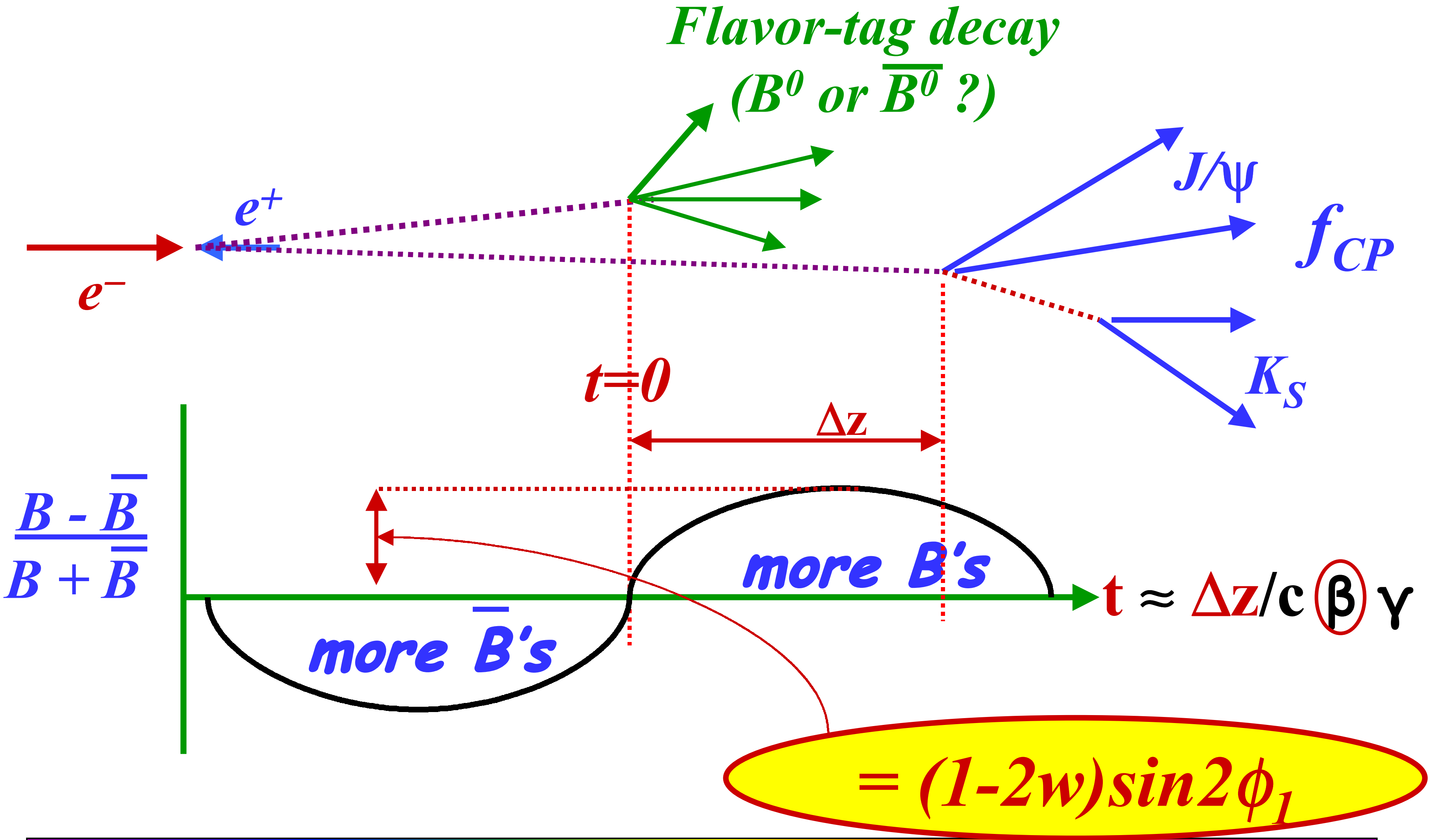
$\xi_f = \pm 1$ *for* $CP = \pm 1$

$$A(t) \equiv \frac{\Gamma(\overline{B_d^0} \to f_{CP}) - \Gamma(B_d^0 \to f_{CP})}{\Gamma(\overline{B_d^0} \to f_{CP}) + \Gamma(B_d^0 \to f_{CP})} = -\xi_f \sin 2\phi_1 \sin \Delta m t$$

PDG notation!

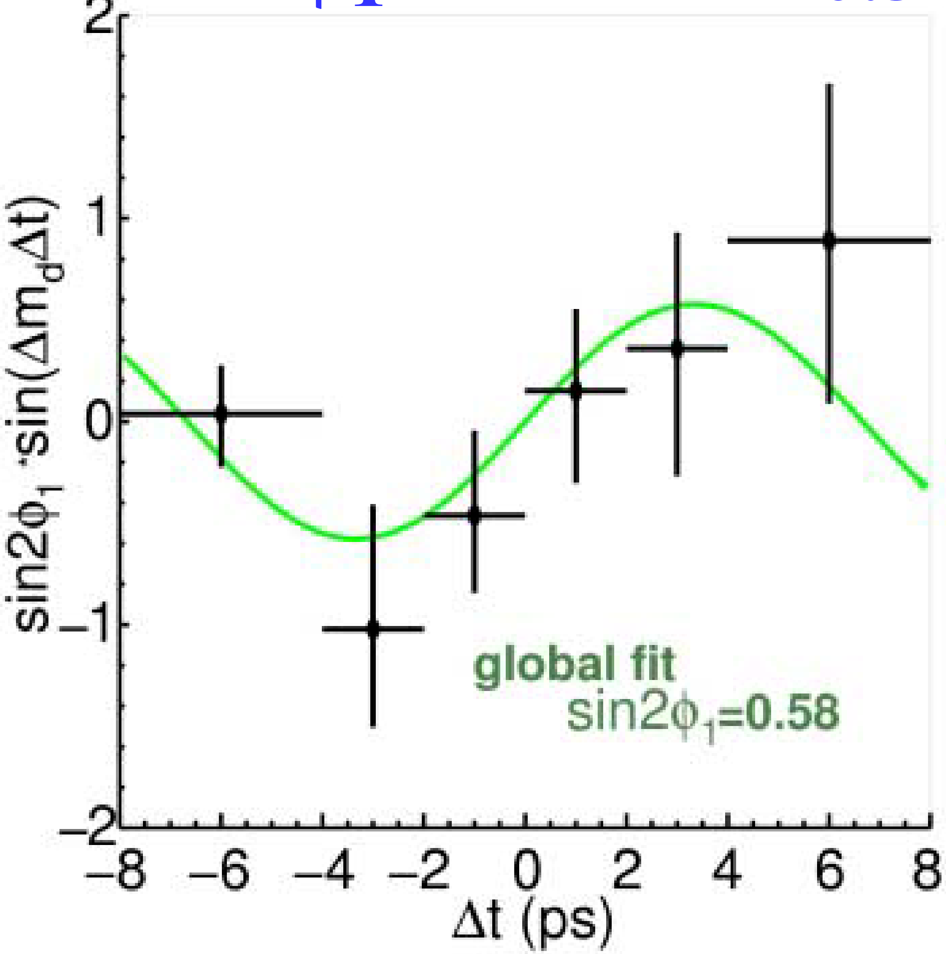


What do we measure?



Previous result (using 10.5 fb^{-1})

$$\sin 2\phi_1 = 0.58 \,{}^{+0.32}_{-0.34}\,{}^{+0.09}_{-0.10}$$

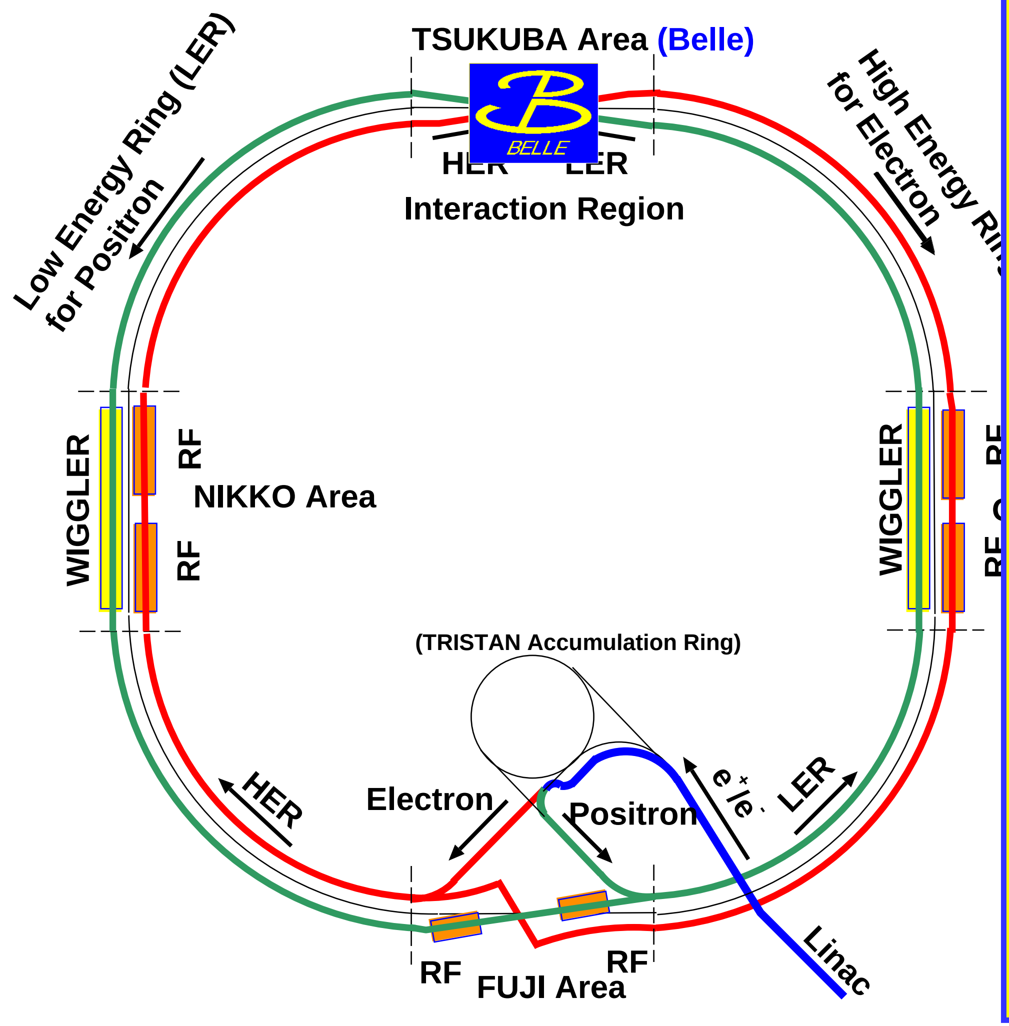


Today:
Results from
29.1 fb^{-1}
4x more events

What's needed?

- Lots of B mesons ($Br\,(B \to f_{CP}) \sim 10^{-3}$)
  - very high Luminosity $\Rightarrow$ KEKB
- Find CP eigenstate decays
  - high quality ~4π detector $\Rightarrow$ Belle
- Tag other B's flavor
  - good particle id
- Measure decay-time difference
  - Asymmetric energies
  - good vertexing (@KEKB: $\gamma\beta c\tau \approx 200\mu m$)

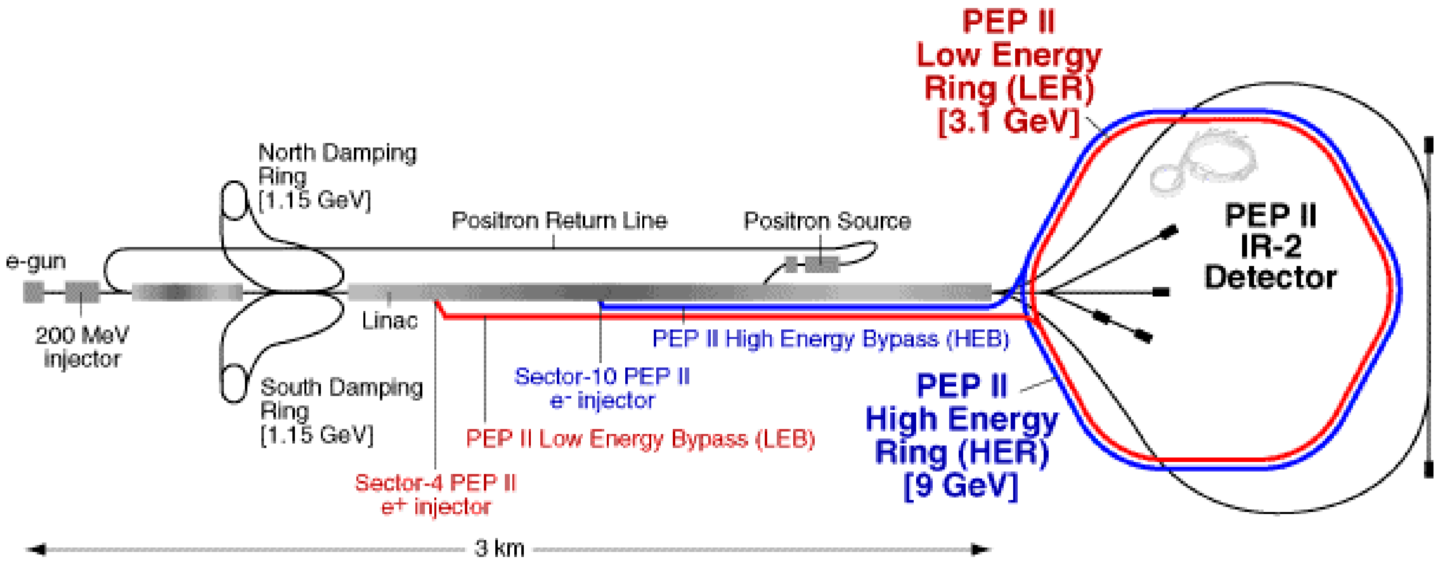
KEKB asymmetric e^+e^- collider



- Two separate rings
  - e^+ (LER) : 3.5 GeV
  - e^- (HER) : 8.0 GeV
- E_{CM} : 10.58 GeV at Y(4S)
- Luminosity
  - target: 10^{34} cm^{-2}s^{-1}
  - achieved: 4×10^{33} cm^{-2}s^{-1}
- ±11 mrad crossing angle
- Small beam sizes:

  $\sigma_y \approx 3\ \mu\text{m};\ \ \sigma_x \approx 100\ \mu\text{m}$

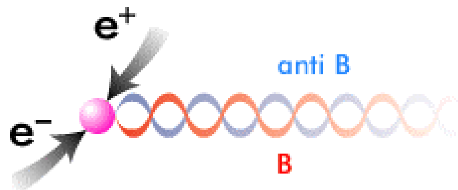
PEP-II Asymmetric *B* Factory



9GeV e^- on 3.1GeV e^+ :

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B^0}$$

- **coherent neutral B pair production and decay (p-wave)**

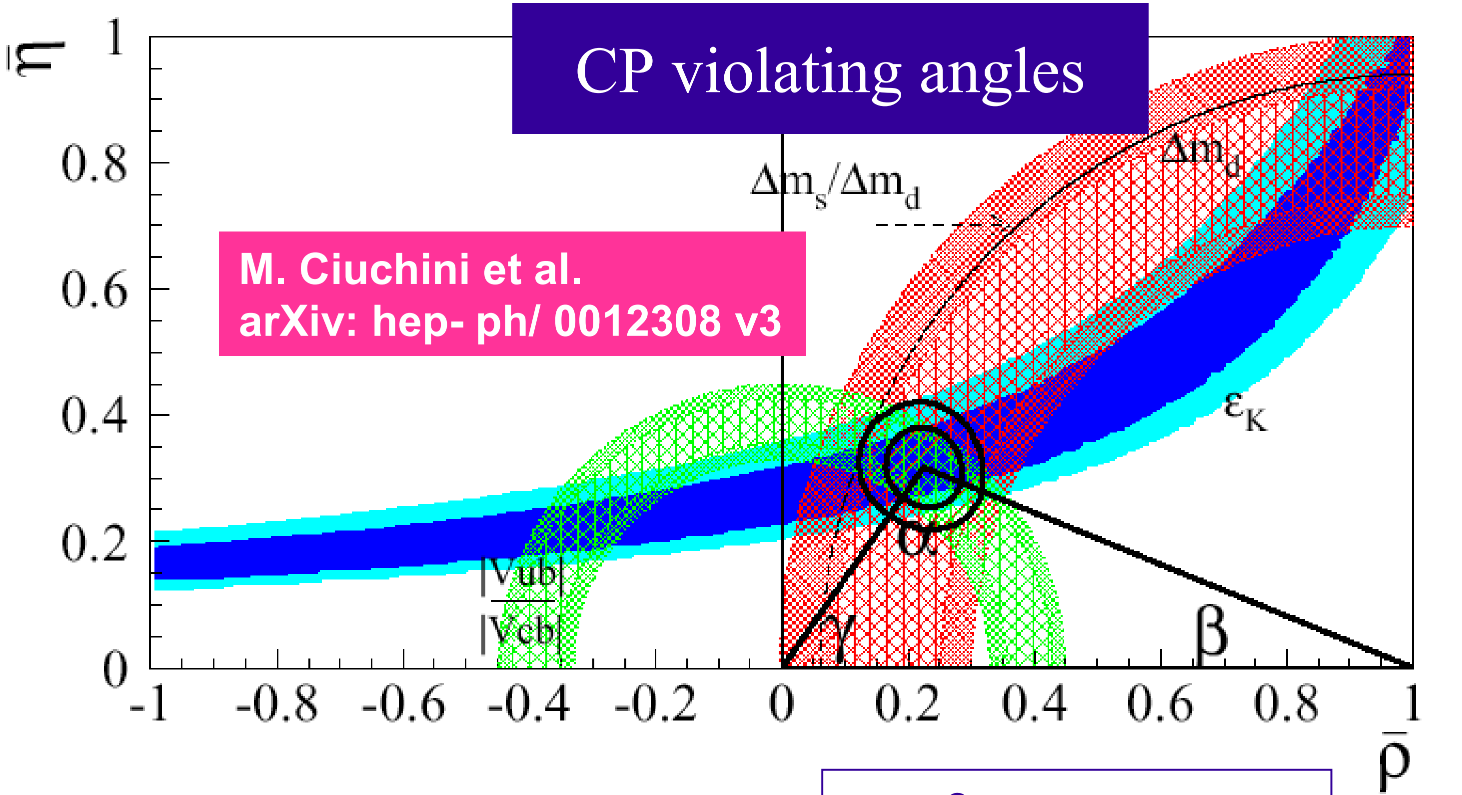


- **boost of Υ(4S) in lab frame : $\beta\gamma$=0.56**

6.4 LHC

The success of CDF shows that LHCB, BTeV, ATLAS and CMS will attain, some day, accuracies ten times better than Belle and Babar.

In particular the possibility of studying very high energy strange B's or B_s at the LHC, will allow them to measure the mixing oscillation frequency, something which was not possible at LEP.



$\sin(2\beta) = 0.692 \pm 0.065$

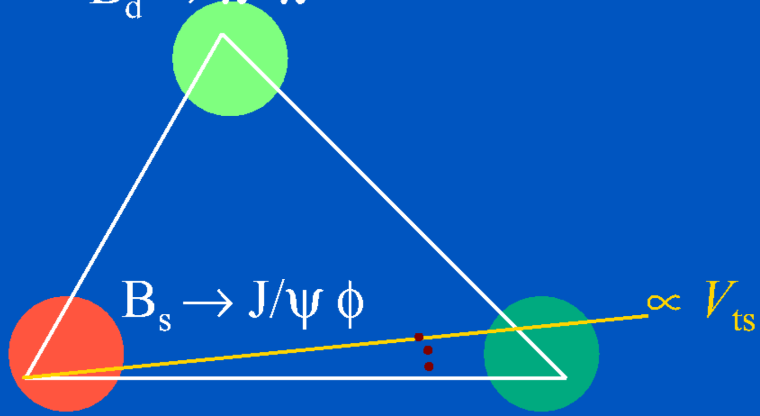
The allowed regions for ρ and η (contours at 68%, 95%) are compared with the uncertainty bands (at 68% and 95% probabilities) for | Vub| / | Vcb | , | ε_K| , Δm_d and the limit on Δm_s / Δm_d (dotted curve).

BaBar:
$\sin 2\beta = 0.590 \pm 0.14$ (stat) ± 0.05 (syst)
Belle:
$\sin 2\beta = 0.99 \pm 0.14$ (stat) ± 0.06 (syst)

Some decay channels for measuring four angles of the CKM triangles

The LHCb Experiment

$B_d \rightarrow \rho^{\pm}\pi^{\mp}$, $\rho^0\pi^0$
$B_d \rightarrow \pi^+\pi^-$



$B_d \rightarrow J/\psi\ K_S$

$B_d \rightarrow D^{*\pm}\pi^{\mp}$
$B_s \rightarrow D_s^{\mp}K^{\pm}$
$B_d \rightarrow \pi^+\pi^- + B_s \rightarrow K^+K^-$
$B_{u,d} \rightarrow K\pi$
$B_d \rightarrow D\ K^{*0}$

High $B_{u,d,s,c}$, b-hadrons statistics @ LHC
$\sim 10^{12} b\bar{b}$/year
Lepton, γ and Hadron P_T trigger
+ Vertex trigger
Decay time resolution (B_s: 40 fs)
Particle ID (π/K)
Mass resolution ($\pi^+\pi^-$: 18 MeV)