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**CP VIOLATION IN B MESONS DECAYS:  
A REVIEW AFTER FIVE YEARS OF B-FACTORIES**

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## ***1 Introduction.***

The beginning of data taking at KEK-B and PEP-II, in early summer 1999, marked the onset of a new era in B-Physics. These two high luminosity  $e^+e^-$  colliders, operating at the c.m. energy of the  $Y(4S)$  mass, started running practically simultaneously, one in Japan at the KEK Laboratory, the other in California on the SLAC site. Each is equipped with one interaction region, where a state of the art detector is installed, BABAR at PEP-II and BELLE at KEK-B.

The main motivation behind the construction of these machines was to discover CP violation effects in the B system, and to prove that the Standard Model picture of CP violation was correct; the hope was to find discrepancies which would shed light on new Physics. In this paper I will try to summarize what we have learned so far, as well as the prospects for the near future.

The large number of clean BB events, approximately half a billion, produced in five years of operation of the b-factories has allowed significant advances in many areas of B, charm and  $\tau$  physics. These machines have already achieved their primary goal and produced a wealth of important results, which essentially prove that the Standard Model picture is correct. More detailed tests are still necessary to uncover hints for new Physics. A current debate in the community is whether it is worth to proceed with the design and construction of a much more luminous Super-B factory, or if future dedicated hadron colliders experiments will suffice for further B-studies.

In order to introduce the language and the formalism, I will start with a brief description of the theory. In literature there are several excellent, more in depth, reviews and books, and the interested reader is referred to them [1]. After the theory, I will present a selection of experimental results from BABAR and BELLE, which, since I could not possibly cover all the issues involved, might be incomplete or not up to date. My aim is limited to reviewing the results related to CP violation, and discussing how they can, or cannot, over-constrain the Standard Model parameters, in particular the angles of the Unitarity Triangle.

Very important contributions to our present knowledge of B-Physics come from LEP, SLC and the experiments at hadron machines, both fixed target or colliders. The reason I am not discussing them here is uniquely that the scope of this paper is limited to an overview of the results obtained in five years of operation of the b-factories.

The results that I will discuss in this paper, as well as the ones that I am forced to overlook because of time and space constraints, were obtained by the hard and ingenious work of a very large number of dedicated physicists, engineers and technicians; they were also made possible by the effort of the machine physicists and their teams. Progress at B factories proceeds at such a pace that many of the results which were new at the time of this writing will be out of date when the paper will be published, and some of the choices that I am making in selecting the topics to discuss might be proven wrong.

Finally, it is likely that in reviewing such a broad subject, I will be omitting very relevant work and missing important references; I apologize in advance to the affected authors; if this happens, it is most definitely an involuntary mistake on my part.

### *1.1 A short history of CP violation.*

CP symmetry means invariance under the inversion of all spatial coordinates (P parity) and replacement of all particles with their antiparticles (C conjugation). It is experimentally known that the P and C symmetries both hold in strong and

electromagnetic interactions, while they are broken by the weak interactions; these, however, are generally invariant under their combination CP. Before the b-factories, the only known exception was the decay of the K mesons. It should be noted that the combination CPT, where T is time inversion, is an exact symmetry in any local Lagrangian field theory; so CP violation also means T violation. All observations to date are consistent with exact CPT symmetry.

In 1963 a historical experiment carried out by J. H. Christensen, W. Cronin, V. L. Fitch, and R. Turlay measured the decay  $K_L \rightarrow \pi^+ \pi^-$ ; the original paper [2] was published in 1964 and sparked a great flurry of interpretations. It was subsequently a fundamental paper [3] by Wu and Yang to lay the grounds for a phenomenological analysis of the experiment, based on CP violation. At the time it was thought that this phenomenon was restricted to the neutral kaon physics, and Wolfenstein proposed [4] a new  $\Delta S = 2$  *superweak* interaction, which has existed as a possibility until recently.

In 1967, another historical paper [5] by A. D. Sakharov, listed CP violation as one of the requirements to explain the matter-antimatter asymmetry in the Universe.

In 1973 Kobayashi and Maskawa, wrote a paper [6], which went largely unnoticed for several years, where it was shown for the first time that if there are at least 3 generations of quarks, the unitary matrix that governs quark transitions does not need to be real. In the case of 3 generations, there are 4 independent parameters which can be written as 3 rotation angles and a phase that cannot be eliminated by redefinitions of the fields. As the authors pointed out, the fact that the matrix is complex, introduces an imaginary part in the Lagrangian, and CP violation can naturally occur, as we will discuss later. This paper is now one of the most referenced ever, and still provides the only mechanism for CP violation to occur in the Standard Model.

For many years after the original discovery, the only example of CP violation was the non zero value (of the order of  $10^{-3}$ ) of the parameter  $\epsilon$  which measures the amount of CP violation in the  $K^0 - \bar{K}^0$  oscillation (usually referred to as *indirect CP violation*). This was a tiny effect, and could not be directly related to any parameter of the SM, leaving the superweak theory as still a possibility. Dedicated experiments were designed and built to attempt the more difficult measurement of “direct” CP violation in Kaon decays (measured by the parameter  $\epsilon'$ ).

The first round of experiments, at BNL and at CERN, were not conclusive, due to lack of statistical significance. In the 80's two experiments, NA31 at CERN and E731 at FERMILAB took data for several years; after lengthy and painstakingly analysis, NA31 found [7] a positive value:  $\text{Re}(\epsilon'/\epsilon) = (2.30 \pm 0.65) \times 10^{-3}$ ; but this was not confirmed by the competing E731 experiment which found [8]  $\text{Re}(\epsilon'/\epsilon) = (0.74 \pm 0.52 \pm 0.29) \times 10^{-3}$ , consistent with zero. In the following decade, more sophisticated, second generation experiments, after several more years of data analysis were able to establish [9] this kind of CP violation and disprove the superweak theory. A recent, in depth, review of CP violation in the Kaon system can be found, for example, in ref [10]

A different technique for studying the decays of K mesons, exploiting the fact that they are produced in correlated coherent pairs from the  $\Phi$  decay, is actually being pursued in the KLOE [11] experiment at the DAΦNE  $e^+e^-$  storage ring, at the Frascati INFN National Laboratory.

### 1.2 A short history of the b quark

The discovery of the  $J/\psi$  [12] in 1974, followed by the charmed flavoured hadrons [13] in 1976, seemed to complete the picture of the elementary fermions,

with a second family (c,s, $\nu_\mu$ ,  $\mu$ ) entirely analogous to the well known set (u,d, $\nu_e$ ,e). The GIM mechanism [14] was proven to work, and the Standard Model started to emerge as the theory that included all known phenomena in Particle Physics.

The discovery in 1975 of a third, much heavier, lepton [15] and its neutrino presaged a new family (t, b, $\nu_\tau$ ,  $\tau$ ), and spurred the hunt for a new pair of quarks, using the same techniques that had uncovered the charmed quark. In literature the new (t, b) pair was dubbed *top-bottom* or alternatively *truth-beauty*; now the most common denomination is *top-beauty*.

The b-quark, was first discovered in 1977, when the Y narrow resonances ( $b\bar{b}$  bound states) were seen in hadron interactions [16]. In 1980 the much wider resonance Y(4S) was discovered [17] at the  $e^+e^-$  collider CESR, at the Cornell Laboratory (USA); This is the lowest state to decay into the b-flavoured hadrons dubbed  $B^0$  and  $B^+$ . These particles have been invaluable for our understanding of fundamental interactions; and the so called b-Physics has been the object of an enormous amount of theoretical as well as experimental work for the last 25 years after the discovery of the Y(4S) resonance and the b-flavoured hadrons the so called b-Physics has been the object of an enormous amount of theoretical as well as experimental work for the last 25 years. This field is far from exhausted, as proven by the fact that more experiments [18] completely devoted to study b's b Physics, are now being built for operation in the near future.

The t quark was discovered much later [19] in 1995, and found so heavy that cannot be used to probe the weak interactions: its mass is greater than the W's, so it decays very rapidly, before it even has time to form a hadron!

Most of our present knowledge on b-hadrons comes from a number of  $e^+e^-$  colliders: the early work was done at DORIS and CESR,  $e^+e^-$  colliders which were originally built to run at 7 GeV and 16 GeV c.m. energies, respectively. These machines were operated for several years in the 10 GeV region, and allowed extensive studies of the  $b\bar{b}$  bound states, and B mesons production and decay at threshold. In the 80's B physics was also studied at higher energy at the PEP and PETRA colliders, whose main goal was initially supposed to be the hunt for the sixth quark. In the 90's a wealth of new and more precise measurements were provided by the LEP and SLC experiments, which produced large samples of all b particle species from  $Z^0$  decays.

In spite of the large number of B mesons produced by these machines, it became soon clear that we were still short of the more ambitious goal: verify that the CP symmetry was indeed violated in the B meson decays, and compare the amount of violation with the Standard Model prediction. Starting in the late 80's several workshops were held, with the aim of studying the feasibility of a high luminosity B-factory and sharpening the issues involved in measuring CP violation effects in B decays. This work led to two detailed proposals which were approved in 1994; construction of machines and detectors started immediately in Japan (KEK-B and BELLE) and in the USA (PEP-II and BABAR). These projects were completed on schedule, and started stable operation at the end of 1999: CP violation in the B system was first observed [20] about one year later.

In the meantime great progress was made by the experiments operating at hadron machines: in spite of huge backgrounds and high multiplicities, they were able to identify events containing B particles and study their properties, taking advantage of the much larger production cross section.

## 2 The Standard Model Framework

### 2.1 The CKM matrix

In the Standard Model (often labelled SM in the following) the charge-changing transition (by W-emission or absorption) of a left-handed down-type quark  $j$  to a left-handed up-type quark  $i$  is described by the element  $V_{ij}$  of a unitary matrix  $V$ . With only two generations of quarks, it can be shown that  $V$  is real, and has just one independent parameter (whose value is left to experiment) represented by a rotation angle, the well known Cabibbo angle  $\theta_c$  [21]. Starting with three generations, as first shown by Kobayaski and Maskawa, the matrix becomes complex. For 3 generations the nine complex entries depend on nine real parameters, once the unitarity is required. However, five phases can be absorbed by redefining the quark fields, thus we are left with four parameters, three mixing angles and a phase. This phase is the only source of CP violation in flavour changing transitions in the SM.

Several representations have been suggested for the 3x3 matrix  $V$  (which is now commonly referred to as CKM, from the initials of the three main players); for our purposes the most convenient is the Wolfenstein approximation [22] of the Maiani representation [23]:

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

where the power of the parameter  $\lambda$  emphasizes the hierarchy in the size of the couplings, which has been experimentally observed.

The 4 parameters are free in the SM, and empirically we know that  $\lambda$  is very close to  $\sin\theta_c$  and is measured to be  $0.2240 \pm 0.0036$ , and  $A$  is measured to be close to 1 (in the range 0.77-0.88);  $\eta$  is the CP-violating parameter, since couplings in which  $\eta$  appears are complex. The determination of the parameters  $\rho$  and  $\eta$  is the main purpose of the B factories; these machines produce large samples of B mesons, so can also improve significantly in the direct measurements of  $|V_{ub}|$ ,  $|V_{cs}|$ ,  $|V_{cb}|$  and indirect measurements, via loop processes, of  $|V_{tb} V_{td}|$ .

### 2.2 The B Meson decays

Since the  $B^0$  and the  $B^+$  mesons are the lightest of the  $b$ -flavoured hadrons, they must decay via weak interactions. The mass of a  $b$ -quark is much larger than its partner quark ( $d$  or  $u$ ), and much larger than the scale of QCD ( $\Lambda_{\text{QCD}}$ ), so  $B$  meson decays are mostly described by the decay of the  $b$  quark (spectator model). The dominant decay mode of a  $b$ -quark is  $b \rightarrow cW$ , where the virtual  $W$  eventually materializes either into a pair of leptons (semileptonic decay), or into a pair of quarks (hadronic decays). Analogous diagrams with a  $b \rightarrow uW$  transition are suppressed roughly by a factor  $\lambda^2$  (and this is commonly referred to as CKM suppression). These diagrams, shown in Fig. 1 and Fig. 2, are also called *tree*, because of the graphical representation. If the quarks from the  $W$  decay hadronize separately, then their ‘‘colour’’ must match that of the initial state quarks; these are also called ‘‘internal’’ diagrams and are expected to be somewhat

suppressed (up to a factor 9), Note that all these decay modes must include the spectator quarks (u or d) in the final state. The inclusive semileptonic branching fractions are roughly 10% each for electron and muon, i.e. about one every 5 B's decays into a lepton and a neutrino plus one (or more) hadron, which most of the time is a D or a D\* meson. The sign of the lepton determines the b flavour.

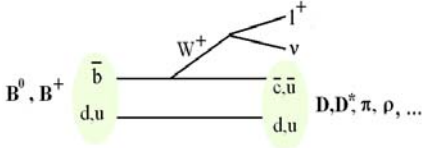


Fig 1 Spectator tree diagram: semileptonic decays of B mesons

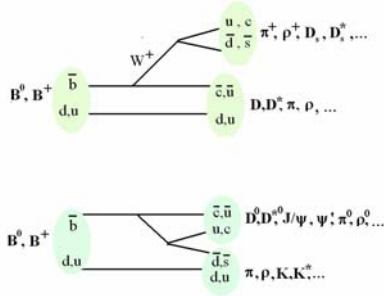


Fig 2 Hadronic decays of B mesons; top: external tree diagram; bottom: internal (or colour suppressed) tree diagram

the neutral B through an exchange diagram (Fig 5), both of which are “non spectator”. These diagrams are however even more suppressed than the penguin, because they require the two quarks in the B meson to be a short distance apart on the scale of  $\Lambda_{\text{QCD}}$ . Finally, the pure leptonic mode of the charged B's is further suppressed by the helicity structure.

From the variety of diagrams we have shown, it is clear that most final states can be reached in more than one way, and this is crucial for the CP violation discussion that will follow.

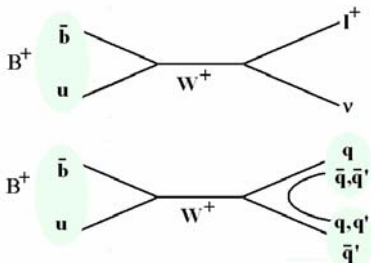


Fig 4 Annihilation diagrams for the B<sup>+</sup>: top leptonic mode, bottom hadronic modes

These diagrams are not the only possible; as proven, for example, by the observation of the decay  $B \rightarrow \Phi K$ , which cannot proceed via any of the above, because there are three strange quarks in the final state. The SM forbids, at tree level, FCNC, and such decay must proceed via a two steps loop transition, the so called penguin diagrams, which allow effective flavour changing neutral currents  $b \rightarrow s$  and  $b \rightarrow d$ . Fig. 3 shows the  $b \rightarrow s$  diagram. Because of the GIM mechanism, the loop is dominated by the t quark, since it has, by far, the highest mass. The rates are therefore sensitive to  $V_{ts}$  and  $V_{td}$ , respectively. The top in the loop can radiate not only a gluon, but also a photon, real or virtual, or a  $Z^0$ ; the penguin diagrams are respectively called radiative, or electroweak.

All the diagrams we have discussed so far are “spectator”, since the light quark in the B meson does not participate in the decay, and is always present in the final state. The charged B mesons could decay via an annihilation diagram (Fig. 4) and

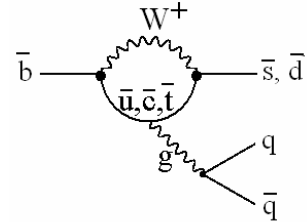


Fig 3 Penguin diagram, which allows the  $b \rightarrow s$  and  $b \rightarrow d$  transitions

These diagrams, however, are an oversimplification of the physical decay process: quarks are confined inside hadrons, bound by the exchange of soft gluons; the diagrams and names of the various topologies that we have described, are a useful way to categorize the processes and to compare various channels, not a tool for precision calculation. The simple quark-line graphs as well as the CKM elements for the couplings, refer to quark interactions, while the measurements deal

with hadrons, so one must take into account QCD effects in all stages of the process under study. Theoretical uncertainties, arising from model dependence in interpreting data, or in the use of specific hadronic matrix elements to relate the actual measurement to the weak quark transition, are a non negligible, in some cases prevalent, part of the overall uncertainty. This is particularly true for loop diagrams and must be taken into account when comparing measurements and theory.

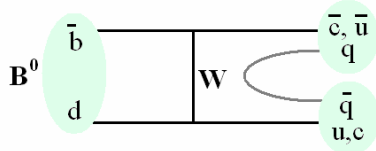


Fig. 5 Exchange diagram for the  $B^0$  meson: final states without a  $d$  quark are possible.

A complicated interplay between the weak and strong forces characterizes the phenomenology of hadronic weak decays, thus often rendering calculations often not too reliable, especially when light quarks are involved; in many cases the experimental error in the determination of a BR is smaller than the theoretical uncertainties; progress is underway also in the theory, and more precise lattice calculation may improve the situation in the near future.

### 2.3 The Unitarity Triangle

The weak interaction gauge symmetry requires that the CKM matrix is unitary, unless there are additional quark types beyond the three generations of the Standard Model. The unitarity constraints, which have been built into this parameterization, take the form:

$$\sum_{i=u,c,t} V_{ij} V_{ik}^* = \delta_{jk} \quad \text{and} \quad \sum_{i=u,c,t} V_{ij} V_{kj}^* = \delta_{ik}$$

The off-diagonal relationships can each be represented as a closed triangle of vectors in the complex plane (a sum of three complex numbers is equal to zero). These are called the Unitarity triangles. All these triangles are related; the statement that there is only one independent CP-violating parameter in the matrix is the condition that all these triangles

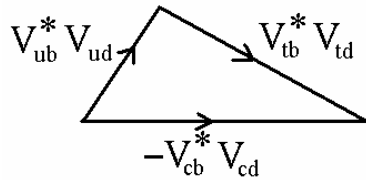


Fig. 6 The Unitarity Triangle (UT) relevant to  $b$  Physics

have the same area, which is small but non zero, if the quark masses are non degenerate, if all the mixing angles are different from zero ( or  $90^\circ$ ), and the phase does not vanish. The shapes of the triangles are very different: four of them almost collapse in a line (because one side is smaller by a factor  $\lambda^4$  ( $i=d, j=s$ ) or  $\lambda^2$  ( $i=s, j=b$ )), while in the case  $i=d$  and  $j=b$  all the sides are of the same order ( $\sim \lambda^3$ ), and the angles can be quite large, leading to potentially large CP-violation from phases between the CKM elements.

In  $B$  physics the triangle, commonly referred as the Unitarity Triangle (UT in the following) is the one depicted in Fig 6 and defined by the relation:

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

Since the length of the side  $|V_{cd} V_{cb}|$  is well known, it is convenient to rescale the sides by this quantity and place the side of unit length on the real axis (fig 7); the apex of the triangle is the point  $(\bar{\rho}, \bar{\eta})$  in the complex plane where:

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

In literature the angles of this triangle have, unfortunately, two conventionally used sets of names, they are either  $\alpha, \beta, \gamma$  (as in fig 7), or  $\varphi_2, \varphi_1, \varphi_3$ , where the first named is at the apex, and the order is clockwise around the triangle.

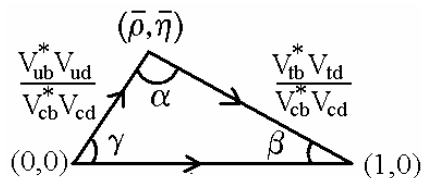


Fig 7: The rescaled Unitarity triangle in the complex plane

The values of the angles in terms of the CKM elements are:

$$\alpha \equiv \arg \left[ \frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} \right], \quad \beta \equiv \arg \left[ \frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right], \quad \gamma \equiv \arg \left[ \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right]$$

The lengths of the sides of the UT can be derived from measurements of quantities which are all CP-conserving: semileptonic decays, b lifetime,  $B_d$  and  $B_s$  oscillation, etc; the angles are all related to CP violation effects, as we will discuss in the following.

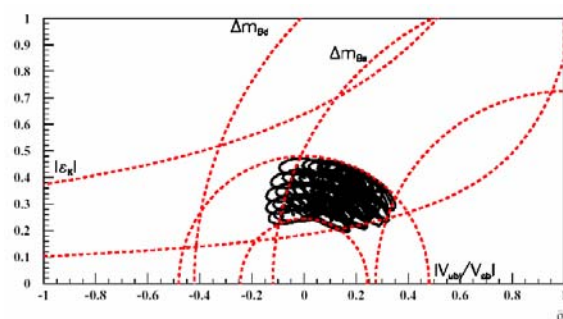


Fig 8: Constraints on the apex of the UT in 1998 (from the BABAR Physics Book). See ref [24] for more details

Before the era of B-factories the constraints on the position of the apex of the UT were quite loose; the BABAR Physics Book [24] presented the graph here shown in Fig.8, obtained with the best knowledge in 1998 of the measured values of  $|V_{ub}|, |V_{cb}|, |\varepsilon_k|, \Delta m_B$  (for both  $B_d$  and  $B_s$ ),  $m_t$  and the model dependent ranges for QCD parameters and B factors and decay constants.

The convolution of the 95% CL contour plots obtained in the  $(\bar{\rho}, \bar{\eta})$  plane with

one fixed set of theoretical parameters define the allowed area for the apex of the UT; a range of 0.4-0.8 was derived (at 95% CL), for  $\sin 2\beta$ , while practically no restriction was possible for the angle  $\alpha$ .

#### 2.4 Flavour – antiflavour oscillations

The measurement of a lifetime much longer than anticipated for the B mesons [25] was considered a preamble for the possibility to observe flavour anti-flavour oscillation for the neutral state  $B^0$ . The fact that a flavour eigenstate may not be a mass eigenstate, and the observable particle could be a mixture of flavour and antiflavour has been well explored in the case of the kaons.

We will recall here briefly the main points: the time evolution of a state is described by the Schrödinger equation,

$$i \frac{\partial}{\partial t} \begin{pmatrix} |P^0(t)\rangle \\ |\bar{P}^0(t)\rangle \end{pmatrix} = \left( M - \frac{i}{2} \Gamma \right) \begin{pmatrix} |P^0(t)\rangle \\ |\bar{P}^0(t)\rangle \end{pmatrix}$$

where the mass mixing matrix,  $M$  and the decay mixing matrix  $\Gamma$ , are  $2 \times 2$  Hermitian matrices. CPT invariance implies  $M_{11} = M_{22}$  and  $\Gamma_{11} = \Gamma_{22}$ . The mass eigenstates  $P_1$  and  $P_2$  are the eigenvectors of  $M - i\Gamma/2$ :



$$|P_1\rangle = p |P^0\rangle + q |\bar{P}^0\rangle$$

$$|P_2\rangle = p |P^0\rangle - q |\bar{P}^0\rangle$$

Evolving with time as:  $|P_{1,2}(t)\rangle = e^{-(iM_{12} + \Gamma_{12}/2)t} |P_{1,2}\rangle$

with the normalization condition:  $|p|^2 + |q|^2 = 1$

Of p and q, only the ratio has physical significance, since it is independent of phase convention. If the quark-W couplings were all real, CP would be an exact symmetry and the two CP-eigenstates  $(|P^0\rangle \pm |\bar{P}^0\rangle)/\sqrt{2}$  would have to be the mass eigenstates, and thus  $|q/p| = 1$ . The two physical states have a mass difference  $\Delta M$  and a width difference  $\Delta\Gamma$ ; if we call M and  $\Gamma$  the average (half of the sum) mass and width of the two states, the parameters normally used to describe the mixing are:  $x = \frac{\Delta M}{\Gamma}$ ,  $y = \frac{\Delta\Gamma}{2\Gamma}$ .

Flavour-antiflavour oscillations are spectacular for the kaon system ( $\Delta\Gamma \sim \Delta M$ , i.e.  $y \sim x$ ), because of the very different lifetimes, the two mass eigenstates can be experimentally distinguished. For D mesons the effects of mixing are very difficult to detect, as these mesons decay so rapidly on the scale of their mass difference that the initial coherent superposition of the two mass eigenstates scarcely has time to evolve. The opposite case is the  $B_s$  which has a very large value of x, with an experimental lower limit of  $14\text{ps}^{-1}$  for  $\Delta M$ ; the oscillation could be so fast to be difficult to measure. For the  $B_d$ , or  $B^0$ , as we will call the  $(\bar{b}d)$  state in the following, the situation is quite interesting, since the mixing is dominated by  $\Delta M$ , not  $\Delta\Gamma$  ( $x \gg y$ ), but the oscillation is not too fast on the lifetime scale, so that can easily be studied experimentally.

Finding the eigenvalues of the Schrödinger equation, one gets for the  $B^0$  system:

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

and for the ratio q/p :

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

The two physical states of the  $B^0$  cannot be experimentally distinguished (as the  $K_s$  and  $K_L$ ), because of the too small  $\Delta\Gamma$  ( $\Delta\Gamma/\Gamma = O(10^{-2})$ ); we can neglect  $\Delta\Gamma$  and write the quantum evolution of the observable states. Following the usual notation [26] we define the state  $B_{\text{phys}}^0$  as the physical particle that at time  $t=0$  is a pure  $B^0$  and evolves as a time dependent superposition of a  $B^0$  and a  $\bar{B}^0$ . In the approximation  $\Delta\Gamma/\Gamma \rightarrow 0$ , the previous expressions simplify to:  $\Delta m_B = 2|M_{12}|$ ,  $\Delta\Gamma_{12} = 2\text{Re}(M_{12}\Gamma_{12}^*)/|M_{12}|$ ,  $q/p = |M_{12}|/M_{12}$ . The quantum evolution equations are simplified, and a state that begins as a pure  $B^0$  will become at time t the mixture:

$$B_{\text{phys}}^0(t) = \left( e^{-\frac{\Gamma}{2}t} e^{iMt} \cos \frac{\Delta M}{2} t \right) B^0 + i \left( \frac{q}{p} \right) \left( e^{-\frac{\Gamma}{2}t} e^{iMt} \sin \frac{\Delta M}{2} t \right) \bar{B}^0$$

and the state which at time  $t=0$  is a pure  $\bar{B}^0$  evolves with time as:

$$\bar{B}_{\text{phys}}^0(t) = i \begin{pmatrix} p \\ q \end{pmatrix} \left( e^{-\frac{\Gamma}{2}t} e^{iMt} \sin \frac{\Delta M}{2} t \right) B^0 + \left( e^{-\frac{\Gamma}{2}t} e^{iMt} \cos \frac{\Delta M}{2} t \right) \bar{B}^0$$

where it is interesting to note that the time  $t$  in these equations can be negative. This is a bit artificial since it would describe states which evolve with time toward  $t=0$  to become a pure  $B^0$  or  $\bar{B}^0$ ; it is, however, very useful in the case of production at the B-factories, as we will discuss in the following.

### 2.5 CP Violation in the decay

A first type of CP violation is the difference in the amplitude  $A$  for any particle decay into a final state  $f$ , and the amplitude  $\bar{A}$  for the antiparticle decay into the final state  $\bar{f}$ . This is generally known as *direct* CP violation, or CP violation in the decay; it can occur for both charged and neutral particle decays, and requires:  $|A/\bar{A}| \neq 1$ , so that the rate for the process and its CP conjugate are different. The amplitude  $A$  is a complex quantity and is usually written with two types of phases: the weak phases  $\varphi_i$ , which occur in the mixing matrices that parameterize the charged current weak interactions and the strong phases  $\delta_i$  from absorptive parts in the amplitude that appear in re-scattering or decay amplitudes.

The CP conjugate amplitude has opposite weak phase (because of the complex conjugate couplings) while the strong phase is the same (since strong interactions are CP invariant). If there is a single amplitude, the observable quantity, the decay rate (squared modulus amplitudes in quantum mechanics) would be the same for  $P$  and  $\bar{P}$ , and no difference can be measured. The presence of at least two interfering amplitudes is required to have a measurable effect, so we need at least two Feynman diagrams contributing to the same process  $P \rightarrow f$ ; then  $A$  can be written as:

$$A = A_1 e^{i\varphi_1} e^{i\delta_1} + A_2 e^{i\varphi_2} e^{i\delta_2}$$

and the CP conjugate amplitude is given by

$$\bar{A} = A_1 e^{-i\varphi_1} e^{i\delta_1} + A_2 e^{-i\varphi_2} e^{i\delta_2}$$

the difference  $\varphi_1 - \varphi_2$  is phase convention invariant, and can have physical consequences, while the individual values of the phases are convention dependent, and hence have no physical meaning. The difference in rates is:

$$|A|^2 - |\bar{A}|^2 = -4A_1A_2 \sin(\varphi_1 - \varphi_2) \sin(\delta_1 - \delta_2)$$

the sum:

$$|A|^2 + |\bar{A}|^2 = 2A_1^2 + 2A_2^2 + 4A_1A_2 \cos(\delta_1 - \delta_2) \cos(\varphi_1 - \varphi_2)$$

and the measurable asymmetry:

$$A_f = \frac{\Gamma(P \rightarrow f) - \Gamma(\bar{P} \rightarrow \bar{f})}{\Gamma(P \rightarrow f) + \Gamma(\bar{P} \rightarrow \bar{f})} = \frac{1 - |\bar{A}/A|^2}{1 + |\bar{A}/A|^2}$$

if there are only two channels leading to  $f$  is:

$$A_f = \frac{-2 A_1 A_2 \sin(\delta_1 - \delta_2) \sin(\varphi_1 - \varphi_2)}{A_1^2 + A_2^2 + 2 A_1 A_2 \cos(\delta_1 - \delta_2) \cos(\varphi_1 - \varphi_2)}$$

A CP-violating rate difference of this type requires that both the weak and strong phases are different for the two terms in the amplitude. From the above expression it is also clear that in order to have a large asymmetry, the two interfering amplitudes must be of comparable magnitude. The best decay modes in which to look for direct CP violation are therefore the ones in which the dominant, lowest-order (tree level) graphs are suppressed (by Cabibbo suppression or by some other selection rule), and there is a competing higher-order graph (penguin) of comparable magnitude.

In B Physics, purely leptonic and semileptonic decays are dominated by a single diagram, and thus are unlikely to exhibit any measurable direct CP violation. On the other hand, hadronic decays have often contributions from at least two types of processes (but all tree diagrams have the same weak phase). The best candidates for direct CP violation are decays where there is contribution from a tree (suppressed) and a penguin, or from two penguins with different phases. When there are more than two graphs, the additional phases complicate the picture. Theoretical estimates of the asymmetries are however always difficult, because they depend on the calculation of strong interaction phases. Thus, it is generally very difficult to use an observation of direct CP violation to pin down theoretical parameters, or make a stringent test of the Standard Model.

## 2.6 CP violation in the mixing

This kind of CP violation effect can occur only in the neutral  $P^0$  states, if the two mass eigenstates are not CP eigenstates, or  $|q/p| \neq 1$ . This violation has been observed in the kaon system, where the parameter commonly used is  $\varepsilon$ , linked to  $p$  and  $q$  by the relation:  $\frac{q}{p} = \frac{1-\varepsilon}{1+\varepsilon}$ . It is straightforward to verify that the condition  $|q/p|=1$  implies

$\text{Re}(\varepsilon)=0$ . In the kaon system  $\varepsilon_k$  is of the order  $10^{-3}$ . The experimental signature of this effect for the B system would be quite clear: if CP is violated in the mixing, the rate of  $B^0 \rightarrow \bar{B}^0$  would be different than  $\bar{B}^0 \rightarrow B^0$ , and we would have a different number of events with two negative leptons from:

$$B^0 \rightarrow \bar{B}^0 \rightarrow l^- X \qquad \bar{B}^0 \rightarrow l^- X$$

and events with positive lepton pairs from:

$$B^0 \rightarrow l^+ X \qquad \bar{B}^0 \rightarrow B^0 \rightarrow l^+ X$$

resulting into a measurable asymmetry:  $a_{sl} = \frac{N(l^-l^-) - N(l^+l^+)}{N(l^-l^-) + N(l^+l^+)}$

In the B system, after some algebra, one arrives at

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

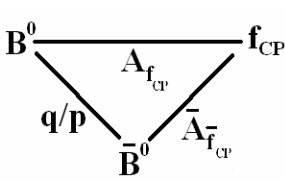
This shows that in the Standard Model the expected effect is tiny:  $|q/p|$  can be written as:

$$\left| \frac{q}{p} \right|^2 \approx 1 - \text{Im} \frac{\Gamma_{12}}{M_{12}}$$

and is close to 1 since  $\text{Im}(\Gamma_{12}/M_{12})$  is expected to be small (but the calculation of  $\Gamma_{12}$  and  $M_{12}$  involves large uncertainties, due to model dependence in the hadronization). The Standard Model predicts this asymmetry to be [27] in the range:  $-1.3 \times 10^{-3} < a_{\text{sl}} < -0.5 \times 10^{-3}$ ; if this is the case, a measurement is still out of reach; on the other hand, a larger value would be an indication of new Physics. Recent measurements [28] are consistent with zero asymmetry and set a limit at the  $O(10^{-2})$  level.

### 2.7 CP violation in the interference between decay and mixing

A third kind of CP violation can occur in the decay of the neutral pseudoscalar state  $P^0$ , if the final state is a CP eigenstate  $f_{\text{CP}}$ , which can be reached also by  $\bar{P}_0$ . An interference term can indeed arise between, the direct decay, and the decay after mixing, as sketched in Fig.9. If we can measure the rate of  $\Gamma(\bar{B}_{\text{phys}}^0(t) \rightarrow f_{\text{CP}})$  and  $\Gamma(B_{\text{phys}}^0(t) \rightarrow f_{\text{CP}})$  the measurable quantity for CP violation is the time dependent asymmetry:



$$a_{f_{\text{CP}}}(t) = \frac{\Gamma(\bar{B}_{\text{phys}}^0(t) \rightarrow f_{\text{CP}}) - \Gamma(B_{\text{phys}}^0(t) \rightarrow f_{\text{CP}})}{\Gamma(\bar{B}_{\text{phys}}^0(t) \rightarrow f_{\text{CP}}) + \Gamma(B_{\text{phys}}^0(t) \rightarrow f_{\text{CP}})}$$

where the physical  $B^0$  particles, and the time variable  $t$ , have been previously defined in par.2.4.

We define for each final state the parameter

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

Fig. 9. Two patterns for  $B^0$  to reach  $f_{\text{CP}}$ :  $B^0 \rightarrow f_{\text{CP}}$  and  $B^0 \rightarrow \bar{B}^0 \rightarrow f_{\text{CP}}$

and using our definition of the physical B states, the decay rate  $f_{\pm}$  ( $f_{\pm}$ ) as a function of time  $t$  of a  $B^0$  ( $\bar{B}^0$ ) into a final state  $f$ , is given by:

$$f_{\pm}(t) \propto e^{-\Gamma t} \left[ \cosh\left(\frac{\Delta\Gamma}{2} t\right) - 2 \text{Re}(\lambda_f) \sinh\left(\frac{\Delta\Gamma}{2} t\right) \mp \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \cos(\Delta M t) \pm \frac{2 \text{Im}(\lambda_f)}{1 + |\lambda_f|^2} \sin(\Delta M t) \right]$$

In the B system we can neglect  $\Delta\Gamma$  and write:

$$f_{\pm}(t) \propto e^{-\Gamma t} \left[ 1 \mp \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \cos(\Delta M t) \pm \frac{2 \text{Im}(\lambda_f)}{1 + |\lambda_f|^2} \sin(\Delta M t) \right]$$

And for the asymmetry:

$$a_{f_{\text{CP}}}(t) = \frac{\Gamma(\bar{B}^0 \rightarrow f) - \Gamma(B^0 \rightarrow f)}{\Gamma(\bar{B}^0 \rightarrow f) + \Gamma(B^0 \rightarrow f)} = \frac{-(1 - |\lambda_f|^2) \cos(\Delta M t) + 2 \text{Im}(\lambda_f) \sin(\Delta M t)}{1 + |\lambda_f|^2}$$

if we define:

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad S_f = \frac{2 \text{Im}(\lambda_f)}{1 + |\lambda_f|^2}$$

the time dependent asymmetry can be written as:

$$a_{f_{\text{CP}}}(t) = -C_f \cos(\Delta M t) + S_f \sin(\Delta M t)$$

(sometimes the quantity  $A_f = -C_f$  is used. The BABAR Collaboration uses  $C_f$ , BELLE uses  $A_f$ ; the choice of the phase convention is also the opposite in part of literature).

It is interesting to note that this kind of CP violation can occur even if there is no direct CP violation,  $|\bar{A}/A|=1$  and no indirect CP violation,  $|q/p|=1$ ; actually this would be the best situation for the measurement, because we would have  $|\lambda_f|=1$ , and therefore  $C_f=0$ , and:  $S_f = \text{Im}(\lambda_f)$ ; and  $a_f$  simplifies to

$$a_f(t) = \text{Im}(\lambda_f) \sin(\Delta Mt)$$

Then the imaginary part of  $\lambda_f$  directly measures the phase difference between the mixing and the decay amplitudes, a quantity that is cleanly predicted in the Standard Model. It is convenient, for the measurement, to define  $\lambda$  as a function of the CP eigenvalue  $\eta_f = \pm 1$  of the final state  $f$ , with  $\eta_f = +1$  for CP even, and  $\eta_f = -1$  for CP odd states:

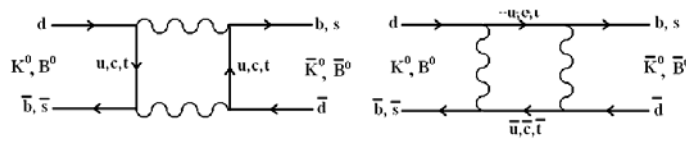
$$\lambda_f = \eta_f \frac{q}{p} \frac{\bar{A}_f}{A_f} \quad \text{because } A_f \text{ and } \bar{A}_f \text{ are related by the CP transformation.}$$

### 2.8 Testing the Standard Model by measuring CP Violation

From the previous discussion, it emerges that CP violation in the decay of a B meson to a final state  $f$  involves  $\lambda \neq \pm 1$ , and each type of CP violation we have discussed requires that one of the following conditions is verified:

- a)  $|\bar{A}/A| \neq 1$  direct CP violation (charged or neutral B's)
- b)  $|q/p| \neq 1$  indirect CP violation (neutral B's only)
- c)  $\text{Im}(\lambda) \neq 0$  CP violation in the interference between mixing and decay (neutral B's only)

In the first case, asymmetries could be large, especially in rare modes, but it would be very difficult to link measurements to SM parameters, or otherwise test the model, because of the difficulties in the calculation of the amplitudes. In the second case we expect a tiny effect: in the SM  $|q/p|$  is very close to 1 (in the kaon system  $\epsilon_K$  is of the order  $10^{-3}$ , and a similar value is expected for the B system). The most interesting case is the third, when  $|\lambda|=1$  and  $\text{Im}(\lambda) \neq 0$ , i.e. there is only one weak phase in the amplitude (and no direct CP violation). In this case, the only effect is CP violation in the interference between mixing and decay, and  $\text{Im}(\lambda)$  can be directly related to the angles of the Unitarity triangle.



**Fig. 10** SM diagrams for  $\Delta F=2$  transitions.

In the SM the mixing, i.e.  $P^0 \rightarrow \bar{P}^0$  transitions ( $\Delta F=2$ ), are described by the so called box diagrams, shown in Fig 10, with two W exchanges. The loops are dominated by a transition via a virtual top. The large mass of the  $B^0$  mesons makes the QCD calculation of these quantities much more reliable than the corresponding calculation for  $K^0$  mixing: We have, in the Wolfenstein approximation:

$$\left(\frac{q}{p}\right)_B = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = \frac{1 - \bar{\rho} - i\bar{\eta}}{1 - \bar{\rho} + i\bar{\eta}}$$

The angle  $\beta$  of the unitarity triangle, in the same approximation is:  $\beta = \text{tg}^{-1} \frac{\bar{\eta}}{1 - \bar{\rho}}$  and:

$$\sin 2\beta = \frac{2\bar{\eta}(1 - \bar{\rho})}{(1 - \bar{\rho})^2 + \bar{\eta}^2}, \quad \cos 2\beta = \frac{(1 - \bar{\rho})^2 - \bar{\eta}^2}{(1 - \bar{\rho})^2 + \bar{\eta}^2}$$

So we can write:

$$\left(\frac{q}{p}\right)_B = e^{-2i\beta} \quad \text{and} \quad \lambda_f = \eta_f \left| \frac{\bar{A}}{A} \right| e^{-2i\beta}$$

Final states that are CP eigenstates, and are dominated by a single weak phase, will measure:

- $\sin 2\beta$  if A is real (CKM enhanced modes),
- $\sin(2\beta + 2\gamma) = \sin 2\alpha$  if A includes a  $V_{bu}$  term (CKM suppressed modes).

The angle  $\gamma$  is more difficult to measure in  $B_d$  decays, and we will see in Chapter 6 several approaches to this problem.

Since in the Standard Model CP violation arises from a single phase, and there are many final states available for  $B^0$  decay, all asymmetries must be correlated. Testing the whole pattern, allows a powerful test of the SM. If discrepancies are found, then other sources must exist for CP violation and many scenarios of new Physics introduce new sources of CP violation.

If we consider for example the decays  $b \rightarrow cW^- \rightarrow c\bar{c}d$  we have:

$$\lambda_{c\bar{c}d} = \left(\frac{q}{p}\right)_B \frac{V_{cb}^* V_{cd}}{V_{cb} V_{cd}^*} \quad \text{and} \quad \text{Im}(\lambda_{c\bar{c}d}) = -\eta_f \sin(2\beta)$$

For the decay  $b \rightarrow uW^- \rightarrow u\bar{u}d$  we have:

$$\lambda_{u\bar{u}d} = \left(\frac{q}{p}\right)_B \frac{V_{ub}^* V_{ud}}{V_{ub} V_{ud}^*} \quad \text{and} \quad \text{Im}(\lambda_{u\bar{u}d}) = \eta_f \sin(2\alpha)$$

where we have used the Wolfenstein approximation of the CKM matrix and the definition of the angles in par. 2.3.

The time dependent asymmetry measurement for a CP final state reached by these quark processes, as for example  $B^0 \rightarrow D^+ D^-$  or  $B^0 \rightarrow \pi^+ \pi^-$  would be a sinusoid, with frequency given by  $\Delta M$  and amplitude equal to  $\sin(2\phi)$ ,  $\phi$  being the angles  $\beta$  or  $\alpha$ , respectively. These are just two examples, there are several more quark transitions, both for  $B^0$  or  $B_s$ , where  $\text{Im}(\lambda_f)$  is linked to one of the angles of the unitarity triangle, or a combination of  $\beta$  and  $\gamma$ . It must however be kept in mind that this holds if a number of requirements are satisfied: the final state must be a CP eigenstate, and there should be no direct CP violation.

### 3 CP asymmetries at $e^+e^-$ B-Factories

#### 3.1 KEK-B and PEP-II

In order to measure the CP asymmetries  $a_i(t)$ , we need, first of all, to produce a very large amount of  $B^0$  mesons ( $>10^7$  events in one year of running); in the late eighties the community of particle physicists, both theorists and experimentalists, interested in B Physics, was actively studying the issues related to how to perform such measurements. Many well attended and productive workshops were organized, and several projects put forward. There were different opinions on which machine to build, but there was consensus that at least one was needed.

The Y(4S) resonance is generally considered the natural “B-factory”, since it decays practically exclusively into B pairs. An  $e^+e^-$  collider running at the c.m. energy of 10.774 GeV (the Y(4S) mass) produces monochromatic B mesons, and the final state does not have any extra particles: such a clean environment is a major plus in favour of this solution. The Y(4S) cross section is about 1nb and, in order to produce the large data set necessary to measure CP violation ( $>10^7$  events in one year of running), a luminosity in excess of  $10^{33}$  is needed, i.e. current techniques used at the time for  $e^+e^-$  colliders had to be improved by at least one order of magnitude.

The luminosity of a colliding beam machine is given by

$$L = \frac{N_+ N_-}{A} f$$

where  $N_+$  and  $N_-$  are the number of particles per bunch,  $f$  is the collision frequency, and  $A$  is the effective collision area. Therefore, the high luminosity required by the B-factories demands a combination of a large number of particles per bunch, high collision frequency, and small collision area. This was a tough challenge for the machine physicists, who also had to satisfy the experimentalists requirements for free space in the interaction region, where the detector had to be positioned.

The measurement of CP violation effects requires a certain care, since time integrated asymmetries are zero at the Y(4S), because of the coherent production of the  $B^0$  pair. The asymmetries must therefore be measured as a function of time, but the flight path of the two decays is very short, because the two B’s are produced with  $p \approx 340$  MeV/c in the Y(4S) rest frame.

The B’s are better separated when produced with higher energy; at  $e^+e^-$  colliders, the signal to background ratio is much less favourable in the continuum, the final states have higher multiplicity and therefore complete reconstruction is more difficult. The probability of assigning the wrong flavour is also higher, because of the lack of coherent production.

In 1987 P. Oddone [29] made an ingenious proposal that solved the dispute: retain the advantage of the Y(4S) production, by using an  $e^+e^-$  collider with a c.m. energy equal to the Y(4S) mass, but use beams of different energy. Because of the relativistic boost, the annihilation would produce clean B pairs with decay vertices far enough from the interaction point, to be measurable by state of the art vertex detectors. Design work started immediately, and detailed proposals were put forth.

Selecting the boost for an optimal physics performance required balancing two conflicting effects:

a) the average  $B$  decay vertex separation in  $z$  is related to the quantity  $\gamma\beta c\tau$ , where  $\tau$  is the  $B$  lifetime. Thus increasing the boost would result in an increase in the separation of the  $B$  decay vertices, making it easier to measure their distance.

b) the momenta of the  $B$  decay products will be boosted in the forward direction, increasing the boost would degrade the detector performance, by allowing too many particles to escape undetected through the dead region around the beam axis.

In 1993 the PEP-II proposal was approved; construction started in 1994, operation in 1998, with first stable collisions in June 1999. PEP-II [30] is located in the old PEP tunnel, on the SLAC site; has a circumference of 2.2 km and uses some of the existing

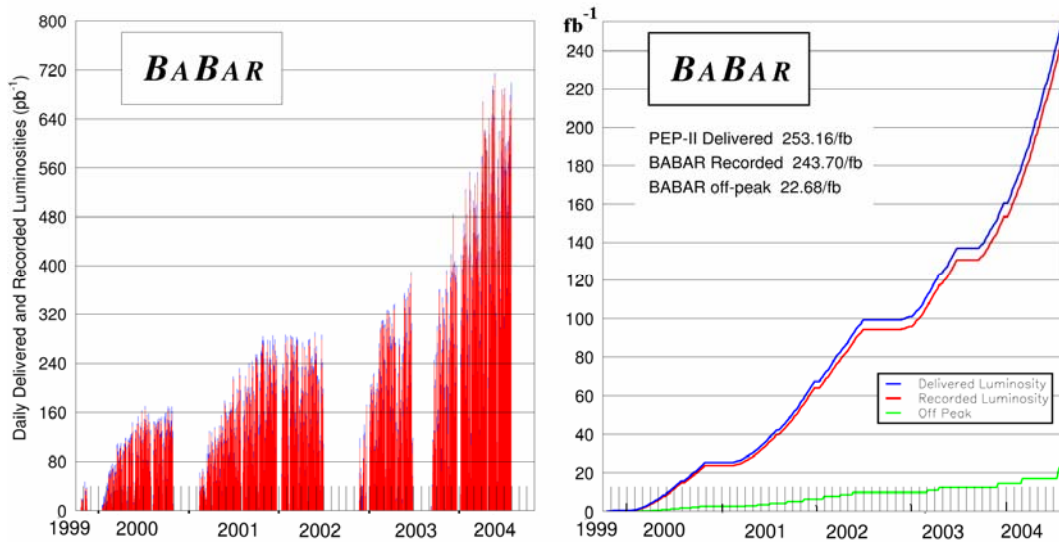


Fig. 11 Left: Daily recorded luminosity ( $pb^{-1}$ ) by BABAR at PEP-II from fall 1999 to July 2004; right total integrated luminosity ( $fb^{-1}$ ) in the same time period: the top curve indicates the luminosity delivered by PEP-II; the middle is the recorded luminosity by BABAR, the lower curve indicates off-resonance runs.

infrastructures from the old machine. Electrons and positrons are injected with their nominal energy of 9.1 and 3.0 GeV, respectively, from the 3 km long SLAC linear accelerator. The energy asymmetry leads to an Y(4S) motion with  $\beta\gamma \approx 0.55$ . The luminosity in the only intersection region has now reached  $L = 9.2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ , corresponding to  $\approx 10$  produced Y(4S) mesons per second, more than 3 times the original design luminosity of  $3 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ . To obtain this luminosity, the circulating currents are 1.55A (electrons) and 2.45A (positrons); the number of bunches is 1588. Both beams are colliding head-on, *i.e.* with zero crossing angle; total delivered luminosity at the end of July 2004 was  $254 \text{fb}^{-1}$ .

At about the same time, the KEK-B [31] project was approved, for a new machine to be built in the TRISTAN tunnel of the KEK Laboratory at Tsukuba, Japan. This machine was built with a schedule very similar to that of PEP-II, and also started successfully operation in 1999.

KEK-B has a circumference of 3Km and slightly less asymmetry: 8 GeV electrons collide with 3.5 GeV positrons, with a crossing angle of 11mrad. The relativistic boost is  $\beta\gamma = 0.425$ . The design luminosity of  $10^{34} \text{cm}^{-2}\text{sec}^{-1}$  has been



surpassed and a world record of  $1.39 \times 10^{34} \text{cm}^{-2} \text{sec}^{-1}$  has been achieved with the circulating electron current of 1.20A, the positrons current of 1.58A; and 1289 bunches. By July 1, 2004 a total integrated luminosity of  $288 \text{fb}^{-1}$  was collected, of which  $253 \text{fb}^{-1}$  at the Y(4S), the remaining at slighter inferior energy, for background studies. One reason for the higher luminosity, compared to PEP-II, is the beam crossing angle of 22 mrad at the interaction point.

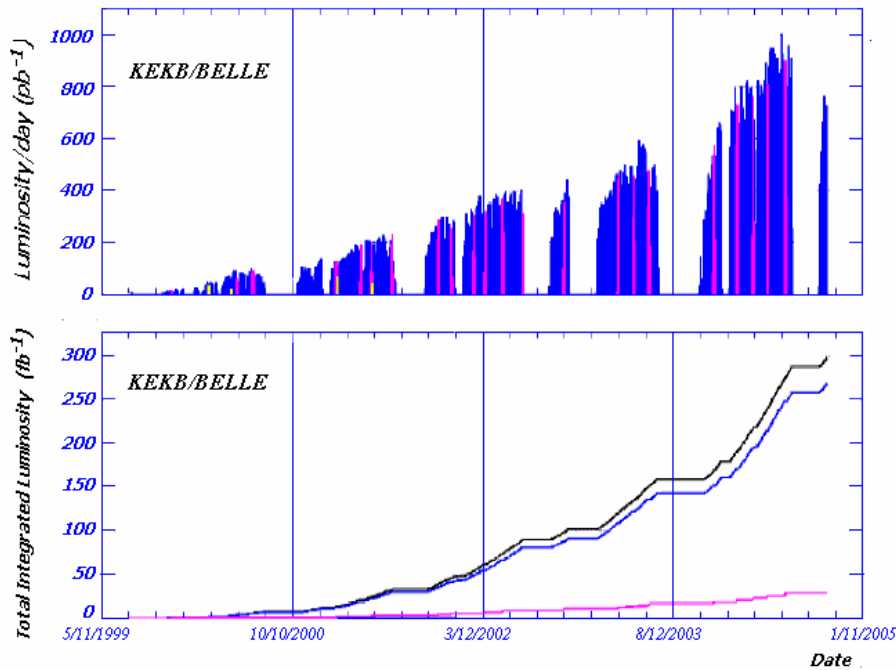


Fig. 12. Top: daily recorded luminosity ( $\text{pb}^{-1}$ ) by BELLE at KEK-B from end of 1999 to September 2004. Bottom: total integrated luminosity ( $\text{fb}^{-1}$ ) in the same time period: the top curve indicates the luminosity delivered by KEK-B; the middle is the recorded luminosity by BELLE, the lower curve indicates off-resonance runs.

Both machines have provided a spectacular performance over the past five years: the factory-type operation calls for minimum down time and efficient injection; this has to be balanced with the needs of machine studies, to improve the performance, and detector maintenance and upgrades. The steady increase of the luminosity in these five years is documented in Fig 11 for PEP-II and Fig.12 for KEK-B, where the daily delivered luminosity, and the total integrated luminosity are reported, from October 1999 to July 2004.

### 3.2 BABAR and BELLE

These two detectors were designed, built and are being operated, by a large number of physicists and engineers; the BABAR collaboration consists of about 650 people from 75 Institutions from 10 Countries, with the US component being about 50% of the total. The BELLE collaboration includes approximately 400 physicists from 56 Institutions in ASIA, North America, Europe and Australia.

The main design criteria are the same for both detectors, and were dictated by the asymmetry of the colliders, and the requirements to measure the mixing induced CP asymmetries. To reach this goal, the detector must have a very good vertex resolution along the beam axis, and must cover as much as possible of the solid angle, especially in the forward direction. Furthermore, multiple scattering in front of the e.m. calorimeter must be reduced at a minimum, charged hadrons should be cleanly identified up to momenta of  $3.5 \text{ GeV}/c$ , low energy photons (down to a few  $\text{MeV}$  energy) should be measured with great precision, neutral hadrons should be detected, and their energy measured, muons should be well separated from hadrons.

It is not surprising that the two detectors are quite similar, even if some of the technical choices for the sub-detectors are different, as in the area of hadron identification; each consists of a central part (barrel) a forward, and a rear component; BELLE has better coverage in the backward direction, BABAR somewhat compromises the performance in this region where most of the cables and other services are housed, to favour the forward cone.

BABAR's vertex detector (SVT) consists of 5 layers of double sided silicon strips. The

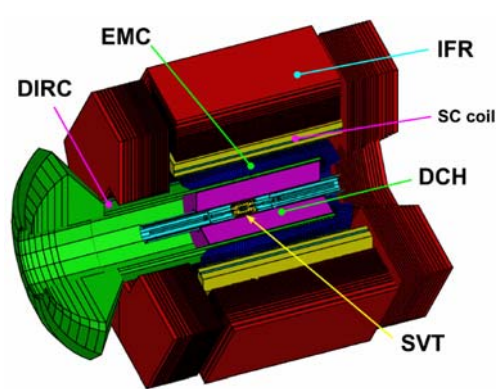


FIG. 13: Sketch of the BABAR Detector; the main sub-detectors are indicated by the arrows.

tracking is completed by a 40 layers small cell drift chamber (DCH). The gas in the drift chamber is a low mass helium based mixture, to minimize multiple scattering, the main factor for the resolution of low momentum tracks. The hadron species are identified by the DIRC, a novel concept of Cherenkov ring imaging detector, based on total internal reflection, which uses long, rectangular quartz bars, oriented parallel to the beam axis, as both radiator and light guide. The Cherenkov radiation is transmitted to the photon detector array ( $\approx 11000$  photomultipliers), located at the backward end of the detector, which gives the detector its peculiar asymmetric aspect. Additional separation, especially at low momentum is obtained with  $dE/dx$  information from the drift chamber and the silicon tracker. The  $K-\pi$  separation is of at least three standard deviations for B decay products with momentum greater than  $250 \text{ MeV}/c$  in the laboratory, up to few  $\text{GeV}/c$ . The finely segmented electromagnetic calorimeter, EMC, consists of 6580 Thallium-doped CsI crystals, mounted with minimum material in front, to preserve excellent measurement at low energy. It is used to detect photons and neutral hadrons, and also to identify electrons. All these detectors are immersed in a magnetic field of 1.5 T, provided by a superconducting solenoid. The iron for the flux return is segmented to house the muon and neutral hadron detectors (IFR). The iron segmentation is finer in the inner 9 layers ( $\approx 1$  absorption length) to optimize  $K_L$  detection, and is coarser in the outer layers. The active detectors are plastic (bakelite) resistive plate chambers. A sketch of the BABAR components is shown in Fig. 13.

The BELLE detector is a similar large-solid-angle general purpose spectrometer; the tracking is performed by a silicon vertex detector (DSSD), and a central drift chamber (CDC); both using the same techniques as BABAR. The original vertex detector had 3

layers and a resolution in the  $z$  direction of about  $70 \mu\text{m}$  for a fully reconstructed  $B$  meson. In October 2003 a new detector was installed, with 4 layers, larger acceptance ( $17^\circ < \theta < 150^\circ$ ) and smaller inner radius (thanks to a new beam pipe, reduced from 2 cm to 1.5 cm in radius). With the new vertex detector, the resolution in  $z$  is now  $55 \mu\text{m}$ .

The drift chamber has 50 layers of anode wires, including 18 layers of stereo wires, and covers the polar angle region  $17^\circ < \theta < 150^\circ$ . The particle identification system

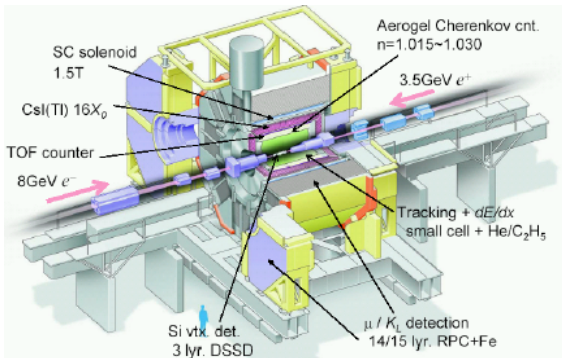


FIG 14: Sketch of the BELLE detector positioned in the KEK-II interaction region; the main sub-detectors are indicated by the arrows.

consists of an array of aerogel threshold Cherenkov counters (ACC), and one of time-of-flight scintillation counter (TOF), which can distinguish kaons from pions up to momenta of  $3.5 \text{ GeV}/c$  with 90 % efficiency and a fake rate of less than 5%. There are 1188 aerogel blocks with refractive indices between 1.01 and 1.03, depending on the polar angle. The effective number of photoelectrons is approximately 6 for  $\beta = 1$  particles. The TOF consists of 128 plastic scintillators, viewed on both ends by fine-mesh photo-multipliers. Their time resolution is 95 ps (*rms*) for

minimum-ionizing particles.

The electromagnetic calorimeter (ECL) is very similar to BABAR's, and is comprised of 8736 crystal blocks, of Csl(Tl), 16.1 radiation lengths thick, located inside a superconducting solenoid coil, 1.7m radius, that provides 1.5T magnetic field. The outermost spectrometer subsystem is a  $K_L$  and muon detector (KLM), which consists of 14 layers of iron absorber (4.7 cm thick) alternating with glass resistive plate counters (RPC).

A sketch of the BELLE detector is shown in Fig 14; detailed descriptions of the BABAR and BELLE detectors and discussion of performances of each sub-system can be found elsewhere [32].

### 3.3 The experimental method to measure the angles of the $UT$

The  $Y(4S)$  production cross section is  $\approx 1.1 \text{ nb}$ , on top of a continuum ( $c\bar{c}$ ,  $s\bar{s}$ ,  $u\bar{u}$ ,  $d\bar{d}$  production) of  $\approx 3 \text{ nb}$ ;  $B\bar{B}$  events have a spherical topology in the c.m. frame, while the continuum events are jet-like, and this makes possible a good separation, using topological variables. Continuum background can be measured by taking data, a fraction of the time, at energy slightly inferior to the  $Y(4S)$  mass, where no  $B$ 's are produced. Both experiments take periodically runs off resonance for this purpose.

In the laboratory frame the relativistic boost forces the  $B$ 's roughly along the direction of the high energy beam (usually defined as  $z$  axis) and the separation in time of the two decays is measured by the separation in decay distance along  $z$ .

Since the  $Y(4S)$  has  $J^{PC} = 1^{--}$  quantum numbers, it decays into a p-wave pair of neutral  $B$  mesons: these must then oscillate coherently (Einstein-Podolsky-Rosen effect). At the time when the first particle decays, the flavour of the other one is determined to be opposite: from that time on, the surviving particle is free to oscillate (until its own decay)

following the quantum evolution equation, with  $t=0$  being the time of the companion particle decay. In the events of interest for the time dependent asymmetry measurements, one  $B^0$  decays into a CP final state, the other in a flavour specific mode.

In order to determine the b flavour at time  $t=0$ , i.e.  $B_{phys}^0$  or  $\bar{B}_{phys}^0$ , one must observe the *tag* (flavour dependent) final state, for example a semileptonic decay; from the sign of the lepton, it is then possible to state which particle, at time  $t=0$ , was a  $B^0$  and which one was a  $\bar{B}^0$ .

If the tag decay is the first to happen, its time defines  $t=0$ , and the CP decay will follow at  $t > 0$ . If the flavour dependent final state is the later one, the definition of the time  $t=0$  still holds, and the time of the CP decay has a negative value. The two situations are graphical depicted in Fig 15, where one of the two B's, the *tag*, decays in a flavour specific mode and the other B decays in a CP final state, which does not distinguish flavour. The difference  $t_{CP} - t_{tag}$  is then the definition of time  $t$  in the time evolution equation for the asymmetry (see par.2.7), and can be positive or negative.

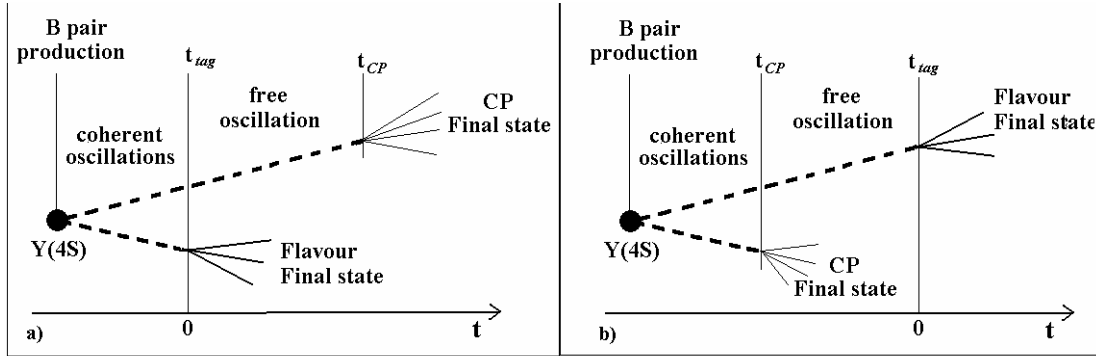


Fig 15: Time evolution of the B's from the Y(4S) decay: the first B to decay determines the flavour of the other B, at  $t = 0$ . Time dependent asymmetries are measured as a function of  $t = t_{CP} - t_{tag}$ ; the parameter  $t$  can be positive (a) or negative (b).

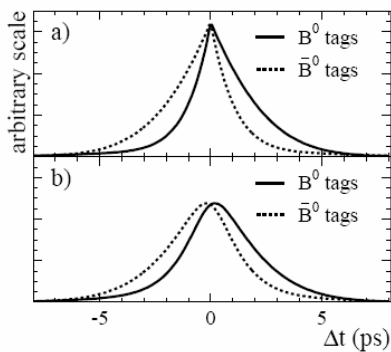


Fig. 16: a) "ideal" distribution of the number of  $B^0$  s (dotted line) and  $\bar{B}^0$  (solid line) decaying into a  $f_{CP}$  final state, for a  $\sin 2\beta$  value of 0.7 b) distributions when typical experimental resolution and tagging error are taken into account.

At the Y(4S) the total number of  $B^0$ 's and  $\bar{B}^0$ 's decaying into the final state  $f_{CP}$  is the same when integrated over time, and no CP violation can be observed if  $\Delta t$  is not measured, (or the tag not identified), even if CP is violated! In the experiment one determines  $\Delta t$  from the measurement of the distance between the decay vertices of the two Bs, and studies the dependence of the asymmetry  $a_f$  for the final state  $f_{CP}$  as a function of  $\Delta t$ . As previously noted, the ability to measure  $\Delta t$  depends on the motion of the Y(4S) in the laboratory rest frame, since  $\Delta z \approx \beta \gamma c \Delta t$  ( $z$  being the boost axis). The ideal time evolution for a  $B^0$  for  $\Delta t < 0$  is the same as the  $\bar{B}^0$  at  $\Delta t > 0$ , and vice versa, as shown in Fig. 16a). Experimental resolutions and wrong assignments of the B flavour somewhat smear this distribution,

diluting the measured asymmetry, and leading typically to the distribution depicted in Fig. 16 b).

The analysis proceeds essentially in four steps: a) search for the candidate events for the final state  $f_{CP}$ , under study; b) determination of the flavour of the other B (tag) c) measurement of the separation  $\Delta z$  of the two vertices, hence determination of the  $\Delta t$  for the event. d) fitting procedure to extract  $\text{Im}(\lambda_f)$ . The experimental resolution in the vertex measurement, the probability of assigning the *wrong* flavour to the B tag, the presence of background, etc somewhat modify the distribution in Fig. 16, so the detector effects, and the analysis techniques must be carefully simulated by Monte Carlo and other means, and each step of the procedure validated. The analyses differ in several aspects between the two experiments and, in the same experiment, depending on the final state under study. In the following we will briefly describe the four steps in general terms, to offer the reader an idea of the analysis strategies more commonly used.

### 3.4 Final state reconstruction.

For each final state of interest, the B candidates are selected from tracks and energy clusters in the event, with charged hadron identification provided by the Cherenkov detector. Track finding algorithms start from pattern recognition for the drift chamber clusters and have efficiency well above 90% in both experiments, when the transverse momentum is more than  $200 \text{ MeV}/c$ .

Energy clusters in the e.m. calorimeter not associated with a charged track define photons, which are then used to identify  $\pi^0$ 's and  $\eta$ 's; typical resolutions in invariant mass for these particles are  $\approx 7 \text{ MeV}$  and  $\approx 16 \text{ MeV}$ , respectively. Electron candidates are identified primarily by the ratio  $E/p$  of the energy in the electromagnetic calorimeter to the momentum of the track pointing to shower centroid.

Muon candidates are essentially identified by the measured number of hadronic interaction lengths traversed, and the difference between the actual and the predicted penetration depth for a muon of the same momentum and angle. For each particle species there is a classification of the identification quality, and different analysis uses different criteria as to the required quality. Neural network algorithms are also used to combine information on a single particle from several detector components.

The reconstruction of B mesons typically involves multiple decay chains for the charm daughters or other short lived decay products. Virtual *composite* particles and their error matrices are constructed from the original daughter particles, and then used to replace the daughters in subsequent fits and analysis.

B candidates in all modes, except the ones involving  $K_L$  or neutrinos, are completely reconstructed using two largely independent kinematics variables:

$$\Delta E = E_B^* - E_{beam}^* \quad m_{ES} = \sqrt{E_{beam}^{*2} - |p_B^*|^2} \quad \text{with } E_{beam}^* = \frac{\sqrt{s}}{2}$$

where the asterisk denotes the Y(4S) rest frame, and the subscript B denotes the reconstructed B. One looks for central values of these variables peaked respectively at  $\Delta E = 0$  and  $m_{ES} = m_B$ . The resolutions of these two variables are given by:

$$\sigma_{m_{ES}}^2 = \frac{1}{4} \sigma_{\sqrt{s}}^2 + \left( \frac{p^*}{m_B} \right)^2 \sigma_{p^*}^2 \approx \frac{1}{4} \sigma_{\sqrt{s}}^2 \quad \text{dominated by the beam energy spread}$$

$$\sigma_{\Delta E}^2 = \frac{1}{4}\sigma_{\sqrt{s}}^2 + \sigma_{E^*}^2 \approx \sigma_{E^*}^2 \quad \text{dominated by the energy resolution}$$

Typical values are:  $\sigma_{m_{ES}} \approx 2.6 \text{ MeV} / c^2$ ,  $\sigma_{\Delta E} \approx 10 \leftrightarrow 40 \text{ MeV}$

Crucial to the analysis is the accurate evaluation of the background, which can be due to several causes. There are essentially two kinds of background: the first one arises from random combinations of charged tracks and neutral showers, both from  $B$  mesons or from continuum events. This background is smoothly distributed in  $m_{ES}$  and does not peak near the  $B$  mass.

The second type, or *peaking* background is due, for example, to a slow pion from the reconstructed  $B$  meson being replaced by an other track in the event; this background must be treated with care, since has time-dependent properties; usually it is studied with Monte Carlo simulations.

Both real data and simulated events are used to evaluate the background and its characteristics. Background from non BB events is studied directly in the data, with events collected when running at energy  $\approx 40 \text{ MeV}$  below the  $Y(4S)$  peak. Backgrounds from BB events are studied using Monte Carlo events, with complete simulation of the detector's geometry, its performances and the interaction of particles when going through the different materials.

In some cases, as the  $\pi\pi$ ,  $\pi K$  or  $KK$  two-body decays for example, each signal is a background for the others; instead of separating the components prior to fitting, all candidates are considered, and a maximum likelihood procedure is applied to separate each decay.

### 3.5 Tagging.

Full reconstruction is not needed for the *tag* B; we only must know its decay point and whether it's a  $B^0$  or a  $\bar{B}^0$ . The tracks left over from the reconstruction of the other B in the event, are examined to determine the recoil B vertex and to deduce its flavour. The resolution on  $\Delta z$ , of which the largest contribution comes from tag side, is  $\approx 180 \mu\text{m}$  (or in  $\Delta t \approx 1:25 \text{ ps}$ ), and is similar for BABAR and BELLE.

Flavour tagging signatures include the sign of charge for leptons or kaons (because  $B^0 \rightarrow l^+ X$ ,  $B^0 \rightarrow \bar{D}^0 \rightarrow K^+$ ), leading charged track, soft pions from  $D^*$  decay,  $\Lambda \rightarrow p\pi$  decays, etc. The discriminating power of each tagging category is the effective tagging efficiency  $Q_i = \varepsilon_i (1 - 2w_i)^2$ , where  $\varepsilon_i$  is the fraction of events associated to the tagging category  $i$  and  $w_i$  is the corresponding *mistag* fraction, i.e. the probability of incorrectly assigning the tag. The statistical errors in the measurements of  $\sin 2\beta$  and  $\Delta M$  are inversely proportional to  $\sqrt{\sum_i Q_i}$

The efficiency  $\varepsilon_i$ , and mistag fraction  $w_i$ , for each algorithm are measured from the data, using events where a B decays into a final state with a definite flavour ( $B_{\text{flav}}$ ) and is completely reconstructed. If the other B is “tagged” with opposite flavour, the event is labelled “unmixed”, otherwise is defined “mixed” ( $B^0 B^0$  or  $\bar{B}^0 \bar{B}^0$ ) event. The *mixing* asymmetry as a function of time is the cosine function  $\cos \Delta M t$  (corresponding to perfect  $\Delta t$  measurement and flavor tagging) times the resolution function  $R$  (due to the less than perfect time measurement) and with the amplitude reduced by a dilution factor  $D=1-2w$ , where  $w$  is the wrong tag fraction. In both experiments the tagging techniques

are continuously improved, as larger data samples become available, and new ideas are set forth.

BABAR has introduced neural network methods to increase the tagging efficiency, and assigns each event to one of six tagging categories if the estimated mis-tag probability is less than 45%. The combined factor of merit recently quoted is

$$\varepsilon_{eff} = \sum_{l=1}^6 Q_l = \sum_{l=1}^6 \varepsilon_l (1 - 2w_l)^2 = 0.305 \pm 0.004$$

BELLE uses the likelihood ratios of the properties of the charged particles to estimate the wrong tag rate for each individual event, and then ranks events into six categories based on their estimated mis-tag rate. They define a parameter  $r$  which ranges from  $r = 0$  for no flavor discrimination to  $r = 1$  for unambiguous flavor assignment. The total effective tagging efficiency is determined by summing the six categories:

$$\varepsilon_{eff} = \sum_{l=1}^6 Q_l = \sum_{l=1}^6 \varepsilon_l (1 - 2w_l)^2 = 0.287 \pm 0.005$$

### 3.6 Vertex separation

The decay point of the reconstructed  $B$  is obtained by applying a *vertexing* algorithm to the tracks; since the  $B$  is fully measured, its decay vertex position is the best known. The direction of the  $B_{rec}$  is obtained from the daughters tracks (tracks from  $K_S$  and  $D$  candidates are first fit to a separate vertex and the resulting parent momentum and position are used in the fit to the  $B_{rec}$  vertex); it points to a small area in the beam interaction region around the interaction point (see Fig.17). The decay vertex of the  $B_{tag}$  is obtained from the remaining tracks in the event.

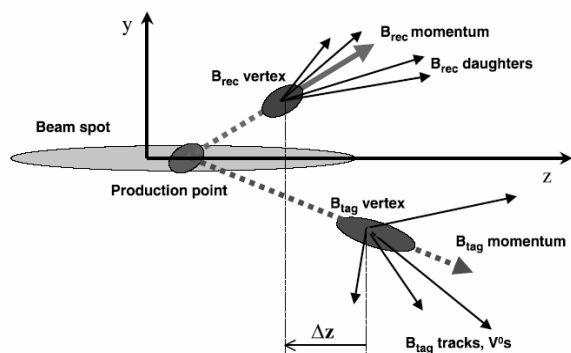


Fig. 17: Schematic view of the geometry in the  $yz$  plane for a  $Y(4S) \rightarrow BB$  decay. (the scale in the  $y$  direction is magnified compared to that in the  $z$  direction).

The line of flight of the  $B_{tag}$  can be estimated from the (reverse) momentum vector and the vertex position of  $B_{rec}$ , and from the beam spot position in the  $xy$  plane and the  $Y(4S)$  average boost.

BABAR requires the  $B_{tag}$  vertex to be consistent with the line of flight computed from the beam spot position, the  $Y(4S)$  momentum and the  $B_{rec}$  momentum. BELLE requires the  $B_{tag}$  vertex position to be consistent with the interaction region profile, determined run-by-run, smeared in the  $r-\phi$  plane to account for the  $B$  meson decay length.

The dominant limitation on the accuracy with which  $\Delta t$  is determined from the measured decay length difference  $\Delta z$ , is the experimental resolution on the  $\Delta z$  measurement. The next most significant limitation is the  $B$  meson momentum of about  $340 \text{ MeV}/c$  in the  $Y(4S)$  rest frame. The impact on the  $\Delta t$  measurement of the spread in the two beam energies, which results in a distribution of  $Y(4S)$  momenta with a Gaussian width of about  $6 \text{ MeV}/c$ , is negligible.

In first approximation, neglecting the B momentum in the Y(4S) rest frame, the time difference  $\Delta t$  is related to the distance  $\Delta z$  between the two vertices along the boost axis by the relation:  $\Delta z = \gamma \beta c \Delta t$ ; small corrections which take into account the B momentum improve the resolution in  $\Delta t$  by approximately 5%.

The  $\Delta t$  measurement is tuned on the sample of  $B_{\text{flav}}$  which is statistically much richer; since the resolution is determined essentially by the tag side, no difference is expected. Comparisons are also made with Monte Carlo events, to be sure that all effects are well understood.

The resolution in  $\Delta t$  for the sample of fully reconstructed B decays is 1.1 ps for BABAR and 1.4 ps for BELLE, the difference mostly due to the lesser boost at KEK-B.

### 3.7 Fit procedure.

Once the final CP state has been reconstructed, the other B in the same event has been flavour tagged and the time difference between the two decays has been evaluated, the event enters a complex fit procedure which takes into account the imperfect tagging, the resolution of each measurement, the background contamination, etc.

The same tagging procedure and  $\Delta t$  measurement, as previously discussed, is applied to a set of events with a completely reconstructed final state of definite flavour ; the tagging is used to distinguish between unmixed ( $B^0 \bar{B}^0$ ) or mixed ( $B^0 B^0$  or  $\bar{B}^0 \bar{B}^0$ ) events; the respective decay rates are given by:

$$f_{\pm}^{\text{flav}}(t) \propto e^{-\Gamma t} \left[ 1 \pm (1-2w) \cos(\Delta M \cdot t) \otimes R(t, \sigma(t)) \right]$$

Where the plus sign indicates opposite flavour, the minus same flavour,  $w$  is the wrong tag probability (mistag) and  $R$  is the resolution function

For the CP final state sample the decay rates are

$$f_{\pm}^{CP}(t) \propto e^{-\Gamma t} \left[ 1 \mp \eta_f (1-2w) \sin 2\phi \sin(\Delta M \cdot t) \otimes R(t, \sigma(t)) \right]$$

where  $\eta_f$  is  $\pm 1$ , depending on the CP even or odd of the final state,  $w$  and  $R$  are the same as for the flavour sample;  $\phi$  is one of the angles of the UT. The values of  $B^0$  lifetime ( $1/\Gamma$ ) and  $\Delta M$  have been measured by both BABAR and BELLE with better precision than previous experiments, performing an unbinned maximum-likelihood fit to the tagged  $B_{\text{flav}}$  sample.

The fit for  $\sin 2\beta$  is performed on the combined flavour-eigenstate and CP samples, with a likelihood constructed from time distributions that depend on whether the event is signal or any of a variety of backgrounds, on the tag category, on the tag flavor, and on the type of reconstructed final state. Each such component has its own probability density function (PDF)



## 4) Measurements of the angle $\beta$

### 4.1 The angle $\beta$ .

Of the three angles of the unitarity triangle, the angle  $\beta$ , also called in literature  $\phi_1$ , is by far the easiest to deal with, both for theorists and experimentalists: penguin pollution is small and/or under control, the final states involved have large branching ratios, experimental signatures are clean.

The Standard Model provides a wide variety of  $B^0$  decays useful to measure  $\sin 2\beta$  from CP asymmetries in the interference of mixing and decay. We have already discussed in par.2.8 how the  $B^0$  mixing introduces a phase  $2\beta$ , and the interference with a (approximately) real amplitude leads to the measure of  $\sin 2\beta$ . The useful final states fall essentially into three categories:

a) the *golden* modes with a charmonium plus a neutral kaon. In this case the asymmetries measure  $\sin 2\beta$  (practically) without theoretical assumptions.

b) the *penguin polluted* modes, where the tree diagram is Cabibbo suppressed and penguin amplitudes, difficult to calculate, could introduce more phases. The comparison of these asymmetries with the golden modes can give important information on the size of the penguin contribution.

c) *pure penguin* modes, particularly sensitive to new Physics, since “new “ particles in the loop could change both the branching ratios and the asymmetries. Large deviation of these asymmetries respect to the golden modes would be evidence of phenomena beyond the Standard Model.

We will now discuss the experimental results from BABAR and BELLE for these three categories.

### 4.2 Charmonium $b \rightarrow c\bar{c}s$ processes

The  $J/\psi K_S$  decay of the  $B^0$  has always been considered the best means to measure the angle  $\beta$  and early, crude measurements were already performed several years ago at LEP [33]. The  $J/\psi$ , as well as other charmonium particles, is produced via the tree diagram

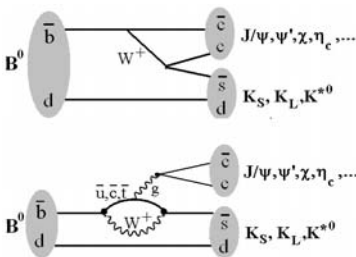


Fig. 18 *Leading tree and penguin Feynman diagrams for the decay modes  $b \rightarrow c\bar{c}s$*

shown in Fig.18, where the two charm quarks are produced from the  $\bar{b} \rightarrow \bar{c}W^+$  and  $W^+ \rightarrow c\bar{s}$  transitions, both Cabibbo favoured. This is likely to be the dominant graph (although somewhat suppressed by the colour match of the two c quarks). The same final state can be obtained via the Penguin diagram, also shown in Fig 18; both graphs, however, happen to have the same weak phase [34] up to  $\mathcal{O}(\lambda^2)$  suppressed terms. So, to a very good accuracy and without assumptions,  $|\lambda|$  is equal to unity, and direct CP violation (CPV) is expected to be absent, even if penguin contribution are not negligible.

In deriving  $\lambda$  for these processes, it is important to take into account also the  $K^0$  oscillation, in addition to that of the  $B^0$  (the interference is actually possible because of the  $K^0$  mixing). The value of the parameter  $\lambda$  is given by:

$$\lambda_{b \rightarrow c\bar{c}s} = \left(\frac{q}{p}\right)_B \frac{\bar{A}_f}{A_f} = e^{-2i\beta} \eta_f \left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right) \left(\frac{q}{p}\right)_K = e^{-2i\beta} \eta_f \left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right) \left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right)$$

the imaginary part of  $\lambda$  is  $-\eta_f \sin 2\beta$ , and the time dependent asymmetry

$$a_f(t) = -\eta_f \sin 2\beta \sin(\Delta M \cdot t)$$

where  $\eta_f$  is equal to +1 for the decays into a  $K_L$ , and to -1 for the  $K_S$ .

The final state  $J/\psi K_S$  can be measured in the decays  $J/\psi \rightarrow l^+ l^-$  and  $K_S \rightarrow \pi^+ \pi^-$ : the experimental signature is quite easy, and practically there is no background. For these reasons this CP state has been considered the benchmark in the design of the detectors, and was the first to be addressed at B-factories. At present it provides the more precisely measured CP asymmetry. To increase the statistics, the  $J/\psi$  can be reconstructed also in hadronic final states, and the  $K_S$  in the neutral  $\pi^0 \pi^0$  mode.

BELLE and BABAR have both the ability to detect the  $K_L$  by measuring its direction from the energy deposition in the e.m. calorimeter and the first part of the instrumented flux return. Since only the direction is measured, the mass of the  $B^0$  candidate must be constrained to the B mass and, as a consequence, there is only one parameter left to define the signal region, which is taken to be  $|\Delta E| < 10\text{MeV}$ . This leads to a higher background level than the modes with a  $K_S$ .

The final state  $J/\psi K^{*0}$  has also been studied by both experiments, it must be treated with care; since it is not a CP eigenstate, but a mixture of CP-even (orbital moment  $L=0, 2$ ) and CP-odd ( $L=1$ ), with predominance of the CP-even. An angular analysis is needed to separate the two components and add each contribution with the correct sign, otherwise the measured asymmetry is reduced by a factor  $|1-2R_\perp|$ , where

$R_\perp$  is the fraction of the  $L=1$  contribution. BABAR [35] has separated the two contributions with an angular analysis and measured  $R_\perp = 0.230 \pm 0.015 \pm 0.004$ , which gives an effective  $\eta_f = 0.51 \pm 0.04$ , after acceptance corrections.

The first measurements of  $\sin 2\beta$  with a non zero compatible result were done by BABAR and BELLE approximately one year after achieving stable data taking, and published in 2001: BABAR [36] using a sample of  $23.3 \times 10^6$  events found:  $\sin 2\beta = 0.34 \pm 0.20$  (stat)  $\pm 0.05$  (syst.) in the modes  $J/\psi K_S$ ,  $\psi(2S) K_S$ ,  $J/\psi K_L$ , for a total of 529 events. At the same time BELLE [37] published the result  $\sin 2\beta = 0.58^{+0.32}_{-0.34}$  (stat)

$^{+0.09}_{-0.10}$  (syst.) based on a  $10.5 \text{ fb}^{-1}$  data sample, and the same final states used by BABAR, plus the additional modes:  $\chi_{c1} K_S$ ,  $\eta_c K_S$ , and  $J/\psi \pi^0$ .

After these early results, the two experiments have kept updating and refining

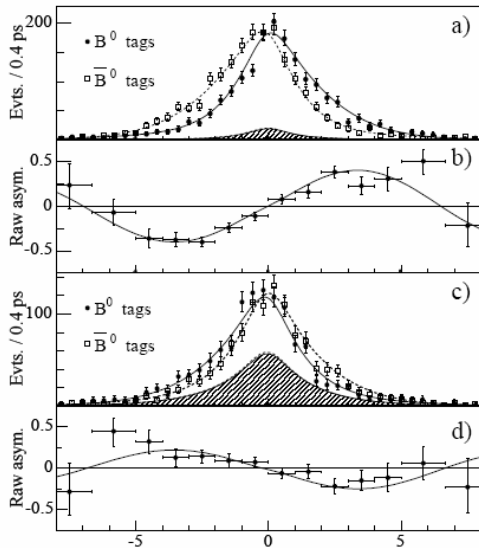


Fig.19. a) Number of  $\eta_f = -1$  candidates in the signal region for each tag b) the raw asymmetry as a function of  $\Delta t$  c) and d) are the corresponding plots for  $J/\psi K_L$ . The solid (dashed) curves represent the fit projections in  $\Delta t$  for  $B^0$  ( $\bar{B}^0$ ) tags. The shaded regions represent the estimated background contributions.

their analyses, using more final states and more sophisticated algorithms. In 2002 the precision was high enough that a positive measurement was claimed for the first time. From a 34-parameters likelihood fit to 2641 tagged events (with 78% purity), BABAR [38] confirmed the Standard Model prediction with the result  $\sin 2\beta = 0.741 \pm 0.067 \pm 0.034$ . At the same time, the BELLE announced the measurement [39], from 2958 tagged events with 81% purity, of  $\sin 2\beta = 0.719 \pm 0.074 \pm 0.035$ , in excellent agreement with BABAR.

A recent paper by BABAR [40] reports an analysis which makes use of the complete data sample ( $227 \times 10^6$  BB events); the decay modes used are  $J/\psi K_S$ ,  $\psi(2S)K_S$ ,  $\chi_{c1}K_S$ ,  $\eta_c K_S$  ( $\eta_f = -1$ ) and  $J/\psi K_L$  ( $\eta_f = +1$ ). The  $\psi(2S)$  is reconstructed via  $J/\psi \pi^+ \pi^-$ , the  $\chi_{c1}$  via  $J/\psi \gamma$ ; the decays used for the  $\eta_c$  are  $K_S K^- \pi^+$ ,  $K^+ K^- \pi^0$ , and  $p \bar{p}$  modes. The combined result is  $\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$ , where, as usual, the first error is statistical, the second reflects the systematic effects. The distribution as a function of  $\Delta t$  for signal events and raw asymmetries are shown in Fig.19 where, despite the dilution from the vertex resolution, background events and incorrect flavor tagging, the asymmetry is clearly visible, as well as its sinusoidal behaviour as a function of time. The partial results on  $\sin 2\beta$  for each mode are listed in Table I, so that the relative values can be compared.

TABLE I : *BABAR's results from the analysis of  $227 \times 10^6$   $B\bar{B}$  events (ref. 40 ); for charmonium decay modes. The number of events, the signal purity (%) and the value of  $\sin 2\beta$  are reported for each final state, as well as the average values of  $\sin 2\beta$  for CP even and CP odd modes.*

Decay Mode	# of events	% Purity	$\sin 2\beta$
$J/\psi K_S (K_S \rightarrow \pi^+ \pi^-)$	2751	96	$0.79 \pm 0.05$
$J/\psi K_S (K_S \rightarrow \pi^0 \pi^0)$	653	88	$0.65 \pm 0.12$
$\psi(2S)K_S (K_S \rightarrow \pi^+ \pi^-)$	485	82	$0.88 \pm 0.14$
$\chi_{c1} K_S$	194	81	$0.69 \pm 0.23$
$\eta_c K_S$	287	64	$0.17 \pm 0.25$
<b>Total <math>\eta_f = -1</math></b>	<b>4370</b>	<b>90</b>	<b><math>0.75 \pm 0.04</math></b>
$J/\psi K_L$	2788	56	$0.57 \pm 0.09$
$J/\psi K^* (K^* \rightarrow K_S \pi^0)$	572	68	$0.96 \pm 0.32$
<b>Total</b>	<b>7730</b>	<b>76</b>	<b><math>0.722 \pm 0.040</math></b>

At the 2004 ICHEP conference BELLE presented [41] an updated result, based on 4347 signal events from a sample of  $156 \times 10^6$  BB events, using the same final states as BABAR, the result is:  $\sin 2\beta = 0.728 \pm 0.056 \pm 0.023$ . To convey an idea of the charmonium samples purity, Fig 20 shows the B signal, in this BELLE analysis, as seen

in the invariant mass for all candidates, excluding  $J/\psi K_L$  and the B momentum distribution, in the  $Y(4S)$  c.m. for the  $J/\psi K_L$  candidates.

The  $\sin 2\beta$  value is obtained from the measured asymmetries, assuming no direct CP violation; the assumption  $|\lambda_{J/\psi K}|=1$  is tested using the high purity sample  $\eta_f=-1$  and performing a separate fit, where the value  $|\lambda|$  is left as unknown; BABAR's result is in fact consistent with zero direct CP violation:  $|\lambda_{J/\psi K}|=0.950 \pm 0.031 \pm 0.013$ ; BELLE finds the value:  $|\lambda_{J/\psi K}|=1.007 \pm 0.041 \pm 0.033$ , again confirming the SM prediction. Both experiments validate their analysis, and look for possible biases, studying also the charged Bs decaying into a charmonium particle, plus a  $K^+$  or  $K^{*+}$ .

The error on the  $\sin 2\beta$  measurement is already below 10%, and is still statistics dominated; the contribution of systematic effects is 2.5 times smaller, so it will take of the order of  $1.5 \text{ ab}^{-1}$  of integrated luminosity, for each experiment, to be limited by systematics. The main sources of systematic errors include the uncertainties in the level and CP asymmetry of the peaking background, the assumed parameterization of the  $\Delta t$  resolution function, possible differences between the  $B_{\text{flav}}$  and  $B_{\text{CP}}$  mistag fractions, the knowledge of the event-by-event beam spot position, and the less than perfect knowledge of  $|\lambda|$  and  $\Delta\Gamma$ . For some of these, improvements are possible with larger data samples and more refined analysis techniques.

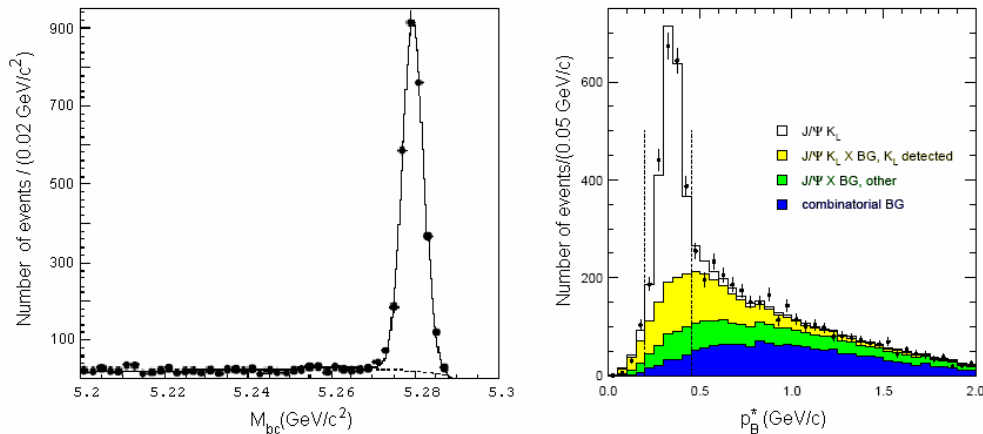


Fig. 20. Left: BELLE invariant mass distribution for charmonium+ $K_S$  candidates; right: B momentum distribution in the  $Y(4S)$  c.m. for  $J/\psi K_L$  candidates. The estimated background is also shown in both plots.

From the  $\sin 2\beta$  measurement there is a four-fold discrete ambiguity in deriving the value of  $\beta$ ; work on reducing this ambiguity has already started; BABAR uses the s- and p-wave interference in angular analysis of the decay  $B \rightarrow J/\psi K^*(K_S \pi^0)$ . The measurement of the decay amplitudes of the three helicity states can be obtained by the time-integrated angular analysis to flavour specific decays: the comparison of the amplitudes between flavour-separated samples probes the direct CP violation. The time-dependent angular analysis, in addition to provide additional information on  $\sin 2\beta$ , is used to measure  $\cos 2\beta$ , which appears in the interference terms.

The sign of  $\cos 2\beta$  can be used to eliminate two of the four solutions for the value of the angle  $\beta$ . The BABAR determination [42] of  $\cos 2\beta$  rules out, at 87% C.L., the solutions with  $\cos 2\beta < 0$ .

Only one of the two remaining solutions for  $\beta$  is allowed by the SM, when the  $|V_{ub}|$  measurement is included, as seen in Fig 21, where two global fits from the CKM fitter group [43] is shown. The first one, on the left, does not include the  $\sin 2\beta$  measurements, so the determination of the apex relies only on the CP conserving measurements (some of which, however, have been considerably improved at b-factories) and the theoretical uncertainties are quite large. The effect of the  $\sin 2\beta$  data is clear when comparing the plot on the right: not only the allowed region is much smaller, but also the theoretical uncertainties become practically negligible.

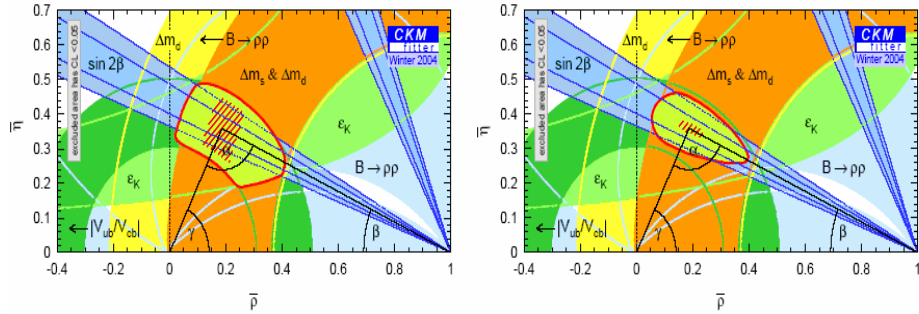


Fig 21. Confidence levels in the  $(\bar{\rho}, \bar{\eta})$  plane for the global fit by the CKM fitter group. The shaded regions indicate the regions of  $\geq 5\%$  CLs. For  $\sin 2\beta$  the  $\geq 32\%$  and  $\geq 5\%$  constraints are shown. The left (right) plot excludes (includes) the  $\sin 2\beta$  measurements. The hatched area in the center of the fit indicates the region where theoretical errors dominate.

#### 4.3 The $b \rightarrow c\bar{c}d$ processes

B decays to  $D^{(*)+}D^{(*)-}$  or  $J/\psi \pi^0$  are examples of  $b \rightarrow c\bar{c}d$  quark processes. The tree diagrams have a Cabibbo suppressed transition in the W decay, so penguin contributions could be non negligible, although expected small, and the interference would lead to direct CPV. The leading diagrams are shown in Fig. 22. In absence of Penguin pollution, the value of the parameter  $\lambda$  would be the same as for the  $b \rightarrow c\bar{c}s$  transition:

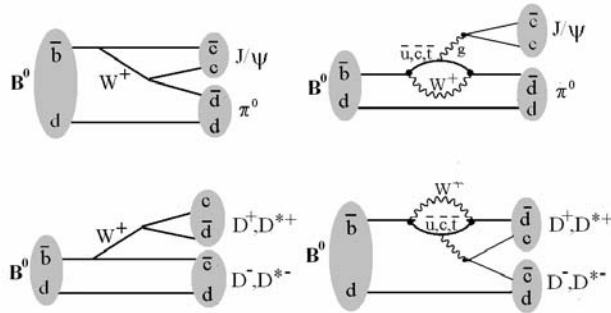


Fig. 22 Examples of tree and penguin diagrams for the transition  $b \rightarrow c\bar{c}d$

backgrounds higher; theoretically are less clean because of the presence of the penguin amplitudes. BABAR and BELLE have studied several of these modes and also the corresponding decays of the charged B mesons, in order to verify if there are effects of

$$\lambda_{b \rightarrow c\bar{c}s} = \left( \frac{q}{p} \right)_B \frac{\bar{A}_f}{A_f} = e^{-2i\beta} \eta_f \left( \frac{V_{cd}^* V_{cb}}{V_{cd} V_{cb}^*} \right)$$

direct CP violation would be absent, and  $Im(\lambda_f) = -\eta_f \sin(2\beta)$ .

These modes are more difficult experimentally, since decay rates are lower (by a factor  $\lambda^2$ ) and

direct CP violation. To take into account the possibility of direct CP violation, both terms  $S_f$  and  $C_f$  are measured from the fit to the time dependent asymmetry:

$$a_f(t) = \frac{\Gamma(\bar{B}^0 \rightarrow f) - \Gamma(B^0 \rightarrow f)}{\Gamma(\bar{B}^0 \rightarrow f) + \Gamma(B^0 \rightarrow f)} = -C_f \cos(\Delta Mt) + S_f \sin(\Delta Mt)$$

We will now briefly review these measurements, and summarize the results published, or submitted to Conferences, in Summer 2004.

$B^0 \rightarrow J/\psi \pi^0$  :

in the SM this decay has a tree and a penguin diagram with the same phase, plus an additional penguin diagram with different phase. The tree and each penguin amplitude are equal to leading order in  $\lambda_{CKM}$ , therefore this decay may have a CP asymmetry that differs from that of  $B^0 \rightarrow J/\psi K_S$ , and the difference can be used as a probe of the penguin decay amplitudes.

The first results from BABAR and BELLE are consistent with the expected picture, with the value of the term  $S$  close, within the errors, to  $-\sin 2\beta$ , and  $C \approx 0$ , but are not precise enough for a real test. BABAR [44] finds, from the likelihood fit, 40 events in a selected sample of 438 (starting from 88 million BB events); BELLE [45] finds 91 candidates in a sample of 152 million events, with a purity of  $(84 \pm 11)\%$ . The results on the parameters of time-dependent CP asymmetry are:

$S_{J/\psi \pi^0} = 0.05 \pm 0.49 \pm 0.16$	$C_{J/\psi \pi^0} = 0.38 \pm 0.41 \pm 0.09$	BABAR
$S_{J/\psi \pi^0} = -0.72 \pm 0.42 \pm 0.09$	$C_{J/\psi \pi^0} = -0.01 \pm 0.29 \pm 0.03$	BELLE

$B^0 \rightarrow D^* D$  :

These final states are not CP eigenstate and 4 flavour-charge combinations should be considered:  $B^0(\bar{B}^0) \rightarrow D^{*\pm} D^\mp$ ; if the amplitude  $\Gamma(B^0 \rightarrow D^{*+} D^-)$  is equal to  $\Gamma(\bar{B}^0 \rightarrow D^{*-} D^+)$  (no direct CP violation) at tree level

$$C_{+-} = C_{-+} = 0 \quad S_{+-} = S_{-+} = \sin 2\beta.$$

Penguin pollution is expected to be small, but a number of processes from non SM physics could provide additional sources of CP violation and lead to a significantly different result, with differences up to  $\Delta\beta \approx 0.6$  [46]. The BABAR measurement [47] on the first 88M  $B^0 \bar{B}^0$  events gives:

$S_{+-} = -0.24 \pm 0.69 \pm 0.12$	$S_{-+} = -0.82 \pm 0.75 \pm 0.14$
$C_{+-} = -0.22 \pm 0.37 \pm 0.10$	$C_{-+} = -0.47 \pm 0.40 \pm 0.12$

and, for the time independent ratio of the rates,

$$A_{D^{*+} D^-} = \frac{\Gamma(B^0 \rightarrow D^{*+} D^-) + \Gamma(\bar{B}^0 \rightarrow D^{*-} D^+)}{\Gamma(B^0 \rightarrow D^{*-} D^+) + \Gamma(\bar{B}^0 \rightarrow D^{*+} D^-)} = -0.03 \pm 0.11 \pm 0.05$$

BELLE [48] analyzes 152M  $B^0 \bar{B}^0$  events and employs two methods of  $B^0$  reconstruction: full and partial. In the full reconstruction method all daughter particles of the  $B^0$  are required to be detected; the partial reconstruction technique requires a fully reconstructed  $D^-$  and only a slow pion from the  $D^{*+} \rightarrow D^0 \pi^+$  decay. They define the significance of non-zero CP asymmetry as  $\sqrt{-2 \ln(L_0 / L_{\max})}$ , where  $L_{\max}$  is the likelihood returned by the combined fit to the two samples, and  $L_0$  is determined from a fit with the parameters corresponding to zero CP violation:  $A = 0$ ,  $S_+ = -S_-$  and  $C_+ = -C_-$ .

They find the significance of non-zero CP asymmetry to be 2.7 standard deviations. For the asymmetry, they measure:  $A_{D^*+D^-} = +0.07 \pm 0.08$ . The CP asymmetry parameters are measured to be:

$$\begin{aligned} S_{+,-} &= -0.96 \pm 0.43 \pm 0.12 & S_{+,-} &= -0.55 \pm 0.39 \pm 0.12 \\ C_{+,-} &= 0.23 \pm 0.25 \pm 0.06 & C_{+,-} &= -0.37 \pm 0.22 \pm 0.06 \end{aligned}$$

Once again, these values are not inconsistent with the SM, but the errors are too large to determine if there is, or not, a discrepancy.

$B^0 \rightarrow D^* D^*$ :

This is not a CP finale state: when a pseudo-scalar meson decays into two vector mesons, there are contributions from three partial waves with different CP parities: even for the S and D waves, odd for the P. The CP odd contribution is expected [49] to be small ( $\approx 6\%$ ) To extract the CP-odd fraction, one needs to perform a time integrated analysis of the angular distribution in the transversity basis, where three angles are defined:  $\theta_1$  is the angle between the momentum of the slow pion from the  $D^{*-}$  (in the  $D^{*-}$  rest frame) and the direction of the  $D^{*-}$  in the B rest frame; the angle  $\theta_{tr}$  is the polar angle between the normal to the  $D^{*-}$  decay plane and the direction of the slow pion from the  $D^{*+}$  in the  $D^{*+}$  rest frame; the angle  $\phi_{tr}$  is the corresponding azimuthal angle.

The result from BABAR [50] based on a sample with  $156 \pm 14$  signal events (from  $88M B^0 \bar{B}^0$ ) is  $R_{\perp} = 0.063 \pm 0.055 \pm 0.009$ ; where the quantity  $R_{\perp}$  is the fraction of the CP-odd component. The measurement confirms that  $B^0 \rightarrow D^{*+} D^{*-}$  is mostly CP-even. The CP asymmetry parameters are measured to be: ,

$$|\lambda_{CP+}| = 0.75 \pm 0.19 \pm 0.02 \quad \text{Im } \lambda_{CP+} = 0.05 \pm 0.29 \pm 0.10$$

$$\text{or } S_{D^*D^*} = 0.06 \pm 0.37 \pm 0.13 \quad C_{D^*D^*} = 0.28 \pm 0.23 \pm 0.02$$

the value of  $S_{D^*D^*}$  is about  $2. \sigma$  away from  $\sin 2\beta$  as measured in the  $b \rightarrow c\bar{c}s$  modes; and there is no evidence of direct CP violation.

BELLE [51] from the analysis of a sample corresponding to an integrated luminosity of  $140\text{fb}^{-1}$ , finds a CP odd fraction of  $0.19 \pm 0.08 \pm 0.01$  and measures:

$$S_{D^*D^*} = -0.75 \pm 0.56 \pm 0.12, \quad C_{D^*D^*} = 0.26 \pm 0.26 \pm 0.04$$

consistent with the SM, but with too large an error for a significant test.

All these measurements are dominated by the statistical errors, so a more significant check of the theory will be done when the results on much larger data samples will be available.

#### 4.4 The $b \rightarrow sq\bar{q}$ processes.

One of the most promising ways to look for *new physics* at B-factories is to measure  $\sin 2\beta$  in several B decay modes sensitive to different short-distance physics. Time-dependent CP

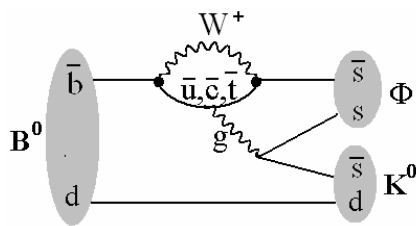


Fig.23 Penguin diagram for  $B^0 \rightarrow \Phi K^0$

asymmetries of B decays dominated by penguin type diagrams  $\bar{b} \rightarrow \bar{s}s\bar{s}$  (which lead to final states such as  $\Phi K^0$ ,  $\eta' K^0$ ,  $K^+ K^- K^0$ , and  $f_0(980) K^0$ ) are the best candidates. Neglecting CKM suppressed amplitudes, these decays carry the same weak phase as the decay  $B^0 \rightarrow J/\psi K^0$ . There is no direct CP violation expected in these decays since, in the SM, they are dominated by a single amplitude. As a

consequence, their mixing-induced CP-violation asymmetries are expected to measure  $\text{Im } \lambda = \eta_f \sin 2\beta$ . Due to the large virtual masses occurring in the penguin loops, additional diagrams with non-SM heavy particles in the loops and new CP-violating phases may contribute. Measurements of CP violation in these channels and their comparisons with the SM expectation are therefore sensitive probes for *new physics*.

In the SM, the  $B \rightarrow \Phi K$  decay is practically a pure  $\bar{b} \rightarrow \bar{s}s\bar{s}$  penguin transition, as shown in Fig. 23, (other diagrams are strongly suppressed), and the major contribution in the loop is due to the top quark. With only one weak phase, direct CP violation should be negligible ( $|\lambda_{\Phi K}|=1$  up to a few % level [52]) and  $\text{Im } \lambda_{\Phi K} = \eta_f \sin 2\beta$ . Theoretically this is the cleanest of the penguin diagrams, since QCD uncertainties are smaller, and therefore the most sensitive to new Physics in the loop, where non SM particles, e.g. SUSY, could substitute the off-shell particles (top quark and/or W).

In the BELLE and BABAR measurements, both  $B^0 \rightarrow \Phi K_S$  and  $B^0 \rightarrow \Phi K_L$  are reconstructed; preliminary plots of the signals for BABAR are shown in Fig. 24. The daughter decays used in the analysis are:  $\Phi \rightarrow K^+ K^-$ ,  $K_S \rightarrow \pi^+ \pi^-$ ; the  $K_L$  is observed via its hadronic interactions. Fig 25 shows the  $\Delta t$  distribution, for the two different tag types, and the time dependent asymmetry for  $B^0 \rightarrow \Phi K_S$  and  $B^0 \rightarrow \Phi K_L$  separately, as obtained, still in a

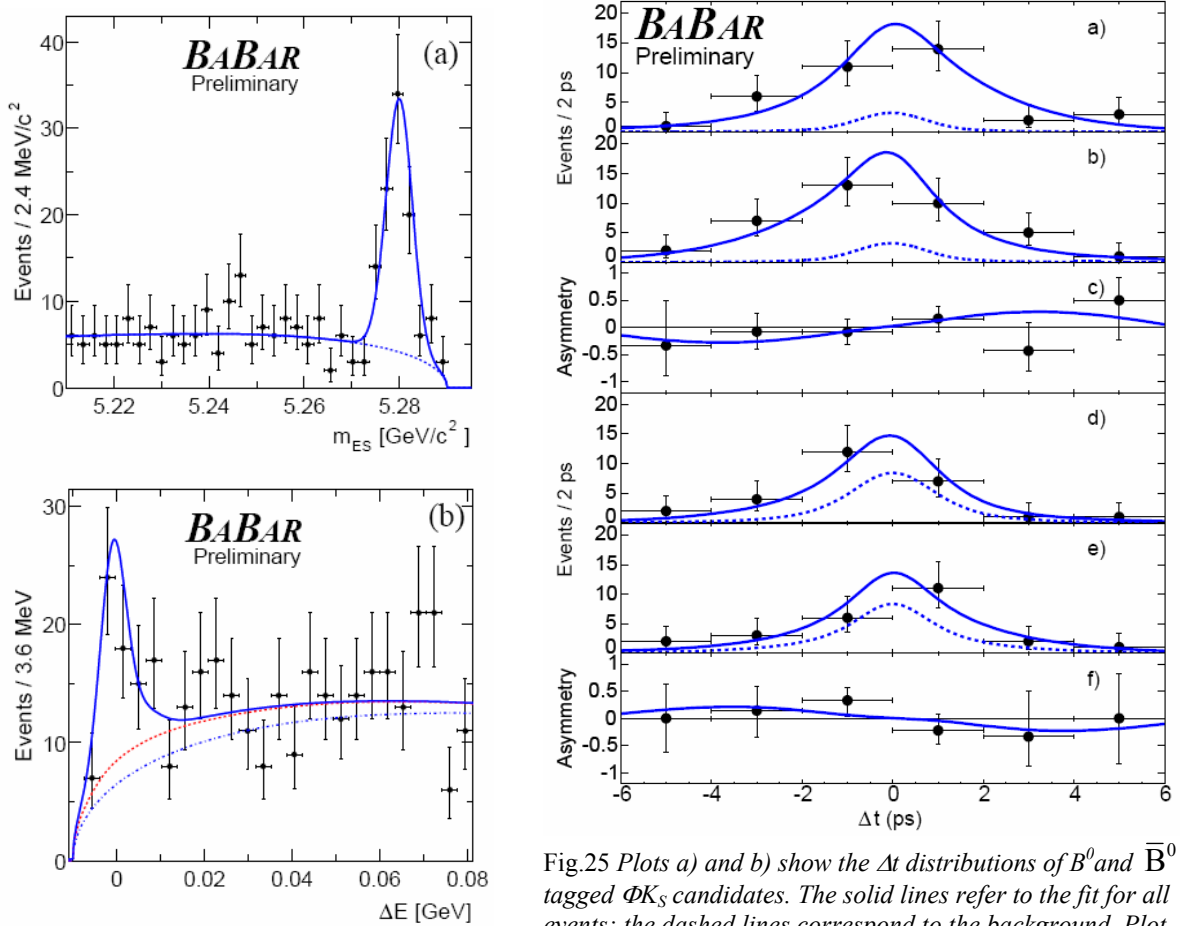


Fig. 24. a)  $m_{ES}$  for  $\Phi K_S$  candidate, b)  $\Delta E$  for the  $\Phi K_L$  candidates. The solid line represents the fit result for the total event yield and the dotted line for the total background. The lower line in b) represents the continuum background only.

Fig. 25 Plots a) and b) show the  $\Delta t$  distributions of  $B^0$  and  $\bar{B}^0$  tagged  $\Phi K_S$  candidates. The solid lines refer to the fit for all events; the dashed lines correspond to the background. Plot c) shows the asymmetry. Plots d), e), and f) are the corresponding plots for  $\Phi K_L$  candidates. For each final state, a requirement is applied on the event likelihood to suppress background.



preliminary form, by BABAR.

Earlier results for this channel from BABAR [53] and BELLE [54] were not in agreement. New results, still preliminary, were recently presented by both experiments on the full data samples, and, within the errors, there is no disagreement anymore:

$$\begin{aligned} S_{\Phi K} &= 0.06 \pm 0.33 \pm 0.09 & C_{\Phi K} &= -0.08 \pm 0.22 \pm 0.09 & \text{(BELLE) [55]} \\ S_{\Phi K} &= 0.50 \pm 0.25 \pm 0.07 & C_{\Phi K} &= -0.00 \pm 0.23 \pm 0.05 & \text{(BABAR) [56]} \end{aligned}$$

These values are obtained merging the results for  $B^0 \rightarrow \Phi K_S$  and  $B^0 \rightarrow \Phi K_L$ ; (BABAR, in the same reference quotes  $0.29 \pm 0.31$  and  $1.05 \pm 0.51$  respectively for the parameter S), the average value of  $S_{\Phi K}$  for the two experiments deviates of about  $2\sigma$  from the  $\sin 2\beta$  measurement (mostly because of the value consistent with zero found by BELLE). This has produced speculation that we could, for the first time, observe an inconsistency with the SM; the results however, have an upward trend with time, so an early fluctuation is conceivable; much more data are needed, for both experiments, for a significant comparison, so to date any claim appears premature.

The absence of a sizeable direct CP violation is confirmed by the ACP asymmetry measured in the decay  $B^+ \rightarrow \Phi K^+$ :  $A_{CP} = 0.054 \pm 0.056 \pm 0.012$  (also preliminary, from ref [56]) and  $A_{CP} = 0.01 \pm 0.12 \pm 0.05$  [57]

BABAR and BELLE have measured the time dependent asymmetry for the non resonant process  $B^0 \rightarrow K^+ K^- K_S$  which is not a CP eigenstate; they measure, however, the CP even fraction to dominate ( $\approx 97\%$ ) and the CP asymmetries:

$$\begin{aligned} S_{K^+ K^- K_S} &= 0.49 \pm 0.18 \pm 0.04 & C_{K^+ K^- K_S} &= 0.12 \pm 0.07 & \text{BELLE [55]} \\ S_{K^+ K^- K_S} &= 0.55 \pm 0.22 \pm 0.04 & C_{K^+ K^- K_S} &= 0.10 \pm 0.14 \pm 0.06 & \text{BABAR [58]} \end{aligned}$$

again consistent, given the still large experimental errors, with the SM for a CP even state. Using all decays in  $K^+ K^- K_S$ , that do not contain a  $\phi$  meson, could in future lead to a more precise measurement of  $\sin 2\beta$  in the  $b \rightarrow s$  modes, since the branching ratio is several times larger than the  $B \rightarrow \phi K_S$  mode.

The  $B \rightarrow \eta' K_S$  decay is also a dominantly  $\bar{b} \rightarrow \bar{s} s \bar{s}$  transition. However, because the  $\eta$  and  $\eta'$  mesons have non-negligible  $d\bar{d}$  and  $u\bar{u}$  components, the decay may also receive additional  $\bar{b} \rightarrow \bar{s} u \bar{u}$  and  $\bar{b} \rightarrow \bar{s} d \bar{d}$  penguin contributions, with a different weak phase, and a possible contribution from a tree suppressed  $b \rightarrow u$  diagram. The uncertainty in the expected match of the asymmetry measured in these processes to that for  $J/\psi K_S$  is larger, but the predictions are that the size of the non-penguin contribution is relatively small. The branching ratio for  $\eta' K$  is quite large  $(6.3 \pm 0.7) \times 10^{-5}$  and could result from a constructive interference of these diagrams.

The  $\eta' K_S$  final state is completely reconstructed; the daughter decays used in the analysis are:  $\eta' \rightarrow \rho^0 \gamma$ ,  $\eta' \rightarrow \eta \pi^+ \pi^-$  for the  $\eta'$ ,  $\eta \rightarrow \gamma \gamma$  and  $\eta \rightarrow \pi^+ \pi^- \pi^0$  for the  $\eta$ ;  $K_S \rightarrow \pi^+ \pi^-$  (also  $K_S \rightarrow \pi^0 \pi^0$  for BABAR). The preliminary results presented at the ICHEP04 Conference are:

$$\begin{aligned} -S_{\eta' K} &= 0.27 \pm 0.14 \pm 0.03 & C_{\eta' K} &= -0.21 \pm 0.10 \pm 0.03 & \text{BABAR [59]} \\ -S_{\eta' K} &= 0.65 \pm 0.18 \pm 0.04 & C_{\eta' K} &= 0.19 \pm 0.11 \pm 0.05 & \text{BELLE [57]} \end{aligned}$$

(where the minus sign in front of  $S_{\eta' K}$  is due to the fact the the final state is CP odd).

The  $B \rightarrow f_0(980) K_S$  decay proceeds through similar diagrams as the  $\rightarrow \eta' K_S$  but is CP even. Both experiments study this channel using the  $f_0(980) \rightarrow \pi^+ \pi^-$  decay mode and find:

$$S_{f_0 K} = 0.95^{+0.23}_{-0.32} \pm 0.10 \quad C_{f_0 K} = -0.24 \pm 0.31 \pm 0.15 \quad \text{BABAR [60]}$$

$$S_{\text{FK}} = -0.47 \pm 0.41 \pm 0.08 \quad C_{\text{FK}} = 0.39 \pm 0.27 \pm 0.08 \quad \text{BELLE [57]}$$

BELLE has also measured the more difficult mode  $K_S K_S K_S$  (the B decay distance must be reconstructed from the flight direction of the 3  $K_S$ , which decay far away); the preliminary result recently announced [61] has an even larger error:

$$S_{K_S K_S K_S} = -1.26 \pm 0.68 \pm 0.18, \quad C_{K_S K_S K_S} = 0.54 \pm 0.34 \pm 0.08$$

Additional modes which have been studied are  $\pi^0 K_S$  and  $\omega K_S$ , which proceed through a  $\bar{b} \rightarrow \bar{u}u\bar{s}$  tree diagram, CKM and color suppressed, and a  $\bar{b} \rightarrow \bar{s}d\bar{d}$  penguin amplitude, which carries a weak phase  $\sin 2\beta$ . The bound on the deviation from  $\sin 2\beta$  due to Standard Model contributions with a different weak phase respect to the pure penguin, is model dependent; for example it is  $\approx 0.2$  from SU(3) flavour symmetry [62] and  $\approx 0.1$  in QCD calculations [63]. Both experiments have presented at the ICHEP04 Conference preliminary, updates of the previous published results:

$$S_{\pi^0 K_S} = 0.35^{+0.30}_{-0.33} \pm 0.04 \quad C_{\pi^0 K_S} = 0.06 \pm 0.18 \pm 0.06 \quad \text{BABAR [64]}$$

$$S_{\pi^0 K_S} = 0.30 \pm 0.59 \pm 0.11 \quad C_{\pi^0 K_S} = 0.12 \pm 0.20 \pm 0.07 \quad \text{BELLE [57]}$$

$$S_{\omega K_S} = 0.75 \pm 0.64^{+0.13}_{-0.16} \quad C_{\omega K_S} = -0.26 \pm 0.48 \pm 0.15 \quad \text{BELLE [57]}$$

In Fig.26 we report the signals obtained by BELLE in the invariant mass distributions for all these modes, to convey the idea of the relative statistical significance and background contributions

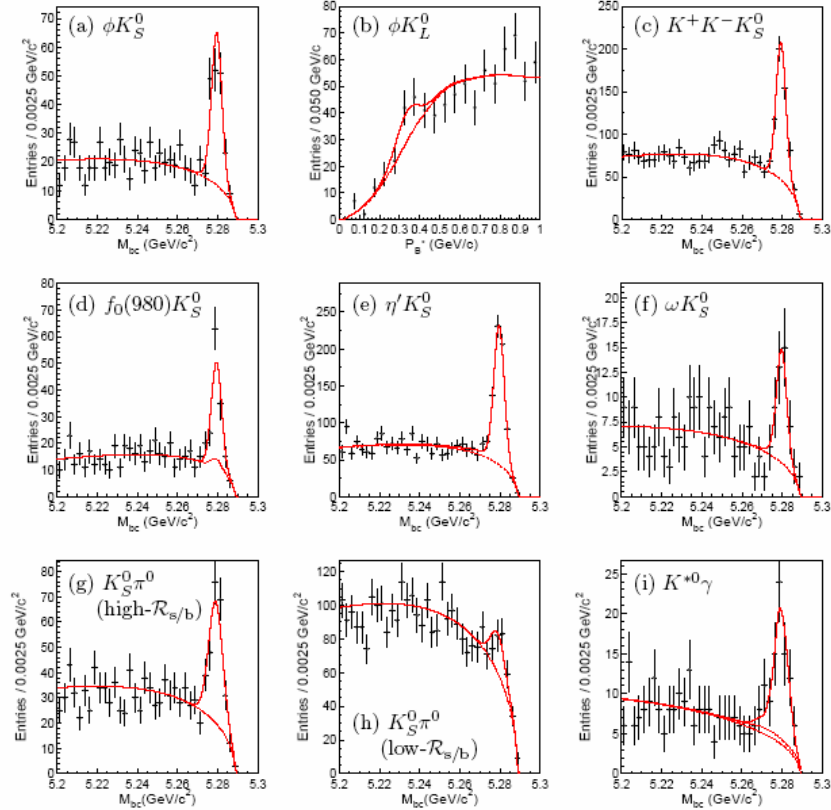


Fig. 26 Invariant mass distribution for candidate events (within the  $\Delta E$  signal region) in final states from  $b \rightarrow s$  transitions (BELLE); for the  $\Phi K_L$  mode (b) the distribution of the reconstructed B momentum in the  $Y(4S)$  c.m. is reported. The curves show the fit to signal plus background distributions, and the background contributions.

#### 4.5 Summary on the angle $\beta$ .

The value of  $\sin 2\beta$ , measured by BABAR and BELLE in the *golden* charmonium modes, is now known with a statistical error less than 0.04; each experiment quotes a systematic uncertainty 0.23. The central values are very close (0.722 and 0.728) and right on mark of the SM prevision from indirect measurements. The present results on  $\sin 2\beta$ , using the less clean modes from the quark process  $b \rightarrow c\bar{c}d$  are consistent, but suffer of large statistical uncertainties and there is still room for surprises.

The most enticing hint of a possible discrepancy with the SM comes from the results on the penguin dominated quark process  $b \rightarrow s\bar{s}s$ ; Fig. 27 and Fig. 28 show the HFAG (Heavy Flavour Averaging Group) [65] average value of the quantity  $\eta_f S$  measured in these modes and the comparison with the average value of  $\sin 2\beta$  measured in charmonium decays, for BABAR and BELLE respectively. The quantity  $\eta_f S$  measured by BABAR using the penguin modes is  $2.7\sigma$  away from the central value of  $\sin 2\beta$ ; for BELLE the difference is  $2.4\sigma$ .

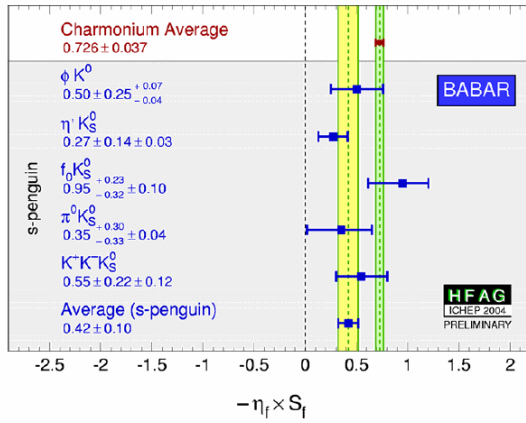


Fig. 27 HFAG average of BABAR results for  $\sin 2\beta$  for  $b \rightarrow s$  modes and comparison with the average of charmonium modes

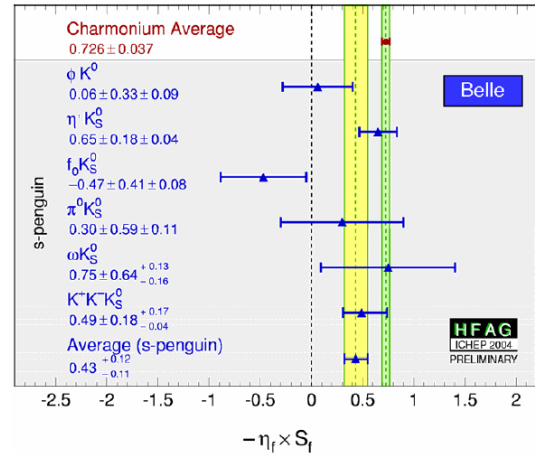


Fig. 28 HFAG average of BELLE results for  $\sin 2\beta$  for  $b \rightarrow s$  modes and comparison with the average of charmonium modes

It is intriguing that in both cases  $S$  from the penguin modes is on the low side of the  $\sin 2\beta$  results, but the statistical significance is not enough for each experiment to claim a disagreement with the SM. There are, on the other hand, large fluctuations in each set of measurements and in some channels the agreement between BABAR and BELLE is quite poor, so that it does not seem appropriate to average all the results, which would lead to claim a significant discrepancy. Even if the agreement was satisfactory, we want to point out that one cannot trivially average the results in the various s-penguin modes, because of the different types of pollutions which could occur.

Finally, a discrepancy would not automatically prove effects of *New Physics*, since  $\eta_f S$  is not a measure of  $\sin 2\beta$ , unless  $C=0$ . The absence of direct CP violation in these decays still has to be proven, and more data are necessary to both experiments for measuring  $|\lambda|$  with the necessary accuracy.

## 5 Measurements of the angle $\alpha$ .

The angle  $\alpha$  ( $\phi_1$  in the notation preferred by BELLE) is given by:

$$: \alpha = -\arg \left| \frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} \right|;$$

using the Wolfenstein approximation, in terms of the  $\eta$  and  $\rho$  parameters, we have:

$$\sin 2\alpha = 2\eta \frac{\eta^2 - \rho(1-\rho)}{(\rho^2 + \eta^2)(\eta^2 + (1-\rho)^2)}$$

a B decays to a CP final state decay dominated by tree contribution, with the quark process  $b \rightarrow u\bar{u}d$   $b \rightarrow u\bar{u}d$  with only the tree contribution would give::

$$\lambda_{f_{CP}}(b \rightarrow u\bar{u}d) = \left( \frac{p}{q} \right)_B \frac{\bar{A}}{A} = \xi \left( \frac{V_{tb}^* V_{td}}{V_{ib} V_{id}^*} \right) \left( \frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*} \right) = \eta_f \frac{(1-\rho-i\eta)(\rho-i\eta)}{(1-\rho+i\eta)(\rho+i\eta)}$$

and  $\text{Im}|\lambda_{u\bar{u}d}| = \eta_f \sin 2\alpha$ , with  $\eta_f = \pm 1$ , depending on the CP odd or even eigenstate value of the final state.

Unfortunately, for the angle  $\alpha$  there is no *golden* channel, since all decay modes from this quark process are CKM suppressed, so the contribution from loop diagrams could be non negligible. The uncertainties in the calculation of the Penguin size lead to a sizeable uncertainty in the relation between S and  $\sin 2\alpha$ , usually the deviation from  $\alpha$  is expressed through a quantity  $\alpha_{\text{eff}}$  defined by:  $S = \eta_f \sin 2\alpha_{\text{eff}} = \eta_f \sin 2(\alpha + \Delta\alpha)$ . On the other end, the fact that these are rare decays (BR of the order of  $10^{-5}$ ) with a possible interference between comparable amplitudes, with different weak and strong phases, make these decays good candidates for direct CP violation.

From the experimental point of view, these modes are difficult to study because of small signals over a large background, mainly due to continuum events; in addition excellent particle ID at high momenta is required to distinguish pions from kaons. To suppress the background, BELLE uses the likelihood ratio calculated from two variables: the modified Fox-Wolfram moments[66] that are combined using a Fisher discriminant into a single variable, and the angle of the B flight direction with respect to the beam axis. BABAR uses the angle between the sphericity axis of the B candidate and the sphericity axis of the remaining particles in the event, and the Fisher discriminant calculated from the momenta of remaining particles and the angles between their momenta and the thrust axis of the B candidate, in the cm frame.

### 5.1 $B^0 \rightarrow \pi\pi$

The decay  $B^0 \rightarrow \pi^+ \pi^-$ : is the natural candidate to measure the angle  $\alpha$ :  $\pi^+ \pi^-$  is a CP eigensate ( $\eta_{\pi\pi} = +1$ ); the tree amplitude is proportional to  $V_{ub}^* V_{ud}$ , and can be written  $A e^{i\gamma}$ , so in absence of other weak phases, we would have  $\lambda_{\pi\pi} = e^{-2i(\beta+\gamma)} = e^{2i\alpha}$  and  $S_{\pi\pi} = -\sin 2\alpha$ .

The problem here is that the tree decay is CKM suppressed; so penguin pollution may be not negligible[67]. Other CP violating effects may in fact arise from the interference between the T and P terms, or from interference between mixing and P amplitudes. These effects not only have different weak phase dependences, but also depend on the amplitude ratio  $|P/T|$  and the strong phase  $\arg(P/T)$ . These complicate the

relationship between the measured CP violation and the phase  $\alpha$ , and  $S_{\pi\pi}$  may therefore differ from  $\sin 2\alpha$ .

As we will discuss later in 7.1, the BF measurements for  $\pi\pi$  and  $\pi K$  modes suggest that the penguin contribution is indeed sizeable. Decay diagrams are shown in Fig:29; the penguin term is proportional to  $V_{id}^*V_{ib}$  and can be written  $Pe^{-i\beta}$ ; the quantity  $\lambda_{\pi\pi}$  is then::

$$\lambda_{\pi\pi} = \left(\frac{p}{q}\right)_B \frac{Te^{-i\gamma} + Pe^{i\beta}}{Te^{i\gamma} + Pe^{-i\beta}} = e^{-2i\beta} e^{-2i\gamma} \frac{1 + P/Te^{i(\beta+\gamma)}}{1 + P/Te^{-i(\beta+\gamma)}} = e^{2i\alpha} \frac{1 + P/Te^{-i\alpha}}{1 + P/Te^{i\alpha}} \equiv |\lambda_{\pi\pi}| e^{2i\alpha_{\text{eff}}}$$

where P and T are complex amplitudes, dominated by tree and penguin topologies,

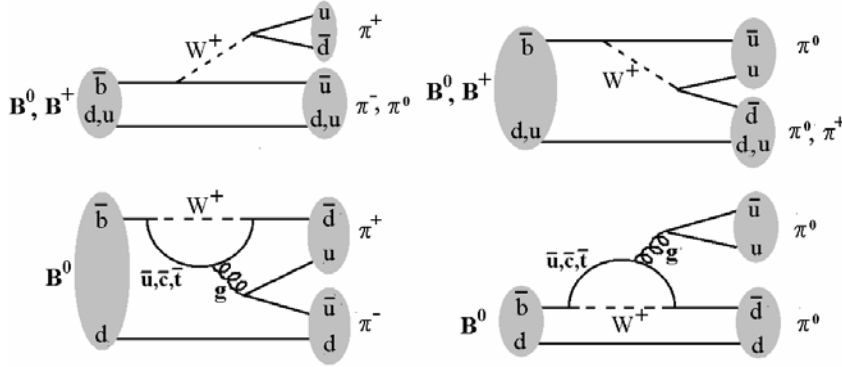


Fig. 29 B decays into  $\pi\pi$ ; top tree diagrams, bottom penguin diagrams

respectively. The quantity  $\text{Im}(\lambda_{\pi\pi})$  is not equal to  $\sin(2\alpha)$ , and the difference depends on the penguin contribution, which is hard to calculate. Usually this is reflected in the definition of a quantity called  $\alpha_{\text{eff}}$ , previously introduced, such that:

$$\text{Im}(\lambda_{\pi\pi}) = \sin 2\alpha_{\text{eff}} = \sin(2\alpha + \delta)$$

A possible way to deal with a sizeable Penguin contribution, based on isospin symmetry of strong interactions, has been suggested [68]: if we call  $A^{00}$ ,  $A^{+-}$  and  $A^{0+}$  the amplitudes  $A(B^0 \rightarrow \pi^0 \pi^0)$ ;  $A(B^0 \rightarrow \pi^+ \pi^-)$ ;  $A(B^+ \rightarrow \pi^0 \pi^+)$ , and use a similar notation for antiparticle decays, the following triangular relations, depicted in Fig hold:

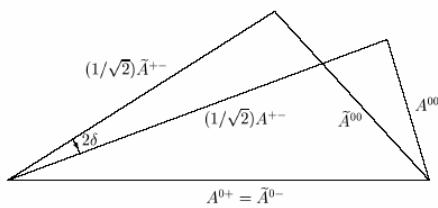


Fig 30. Triangular relations between the various  $\pi\pi$  amplitudes

$$A^{00} + \frac{1}{\sqrt{2}} A^{+-} = A^{0+} \quad \text{and} \quad \bar{A}^{00} + \frac{1}{\sqrt{2}} \bar{A}^{+-} = \bar{A}^{0-}$$

and since only a single isospin amplitude contributes to the charged B decay (no penguin amplitude, since  $\Delta I=3/2$ ), we have  $|\bar{A}^{0-}| = |A^{0+}|$

and we can superimpose the triangles as in the Fig.30. We have six unknown amplitudes and seven measurable quantities: 3 branching ratios,

and  $S_{\pi^+\pi^-}, C_{\pi^+\pi^-}, S_{\pi^0\pi^0}, C_{\pi^0\pi^0}$  :. The quantity  $S_{\pi^0\pi^0}$  is very difficult, probably impossible, to measure, so we are left with 6 measurements. This is, in principle, a clean way of measuring the angle  $\alpha$ , once a large enough data sample is available; one should note, however, that measuring the magnitudes of all the sides does not define the relative orientation of the two triangles, and this leads to a fourfold ambiguity in the value of  $\delta$ .

We will discuss the branching ratio measurements in section 7.1, and discuss here the results on the terms  $C_{\pi\pi}$  and  $S_{\pi\pi}$ , as obtained from the multivariable fits to the measured asymmetries. The early measurements from BABAR and BELLE (with  $41.8 \text{ fb}^{-1}$ ) were in disagreement, although the errors were quite large:

$$S_{\pi^+\pi^-} = +0.02 \pm 0.34 \pm 0.05 \quad C_{\pi^+\pi^-} = -0.30 \pm 0.25 \pm 0.04 \quad \text{BABAR [69]}$$

$$S_{\pi^+\pi^-} = -1.21_{-0.27-0.13}^{+0.38+0.16} \quad C_{\pi^+\pi^-} = -0.94_{-0.25}^{+0.31} \pm 0.09 \quad \text{BELLE [70]}$$

Later analysis with increased statistics have somewhat reduced the disagreement, although this remains the only area where the two experiments still show a discrepancy. BELLE claims evidence of direct CP violation, which is not confirmed by the BABAR's results. The more recent results on the asymmetry parameters are:

$$S_{\pi^+\pi^-} = -0.30 \pm 0.17 \pm 0.03 \quad C_{\pi^+\pi^-} = -0.09 \pm 0.15 \pm 0.04 \quad \text{BABAR [71]}$$

$$S_{\pi^+\pi^-} = -1.00 \pm 0.21 \pm 0.07 \quad C_{\pi^+\pi^-} = -0.58 \pm 0.15 \pm 0.07 \quad \text{BELLE [72]}$$

$$C_{\pi^0\pi^0} = -0.12 \pm 0.56 \pm 0.06 \quad \text{BABAR [73]}$$

$$C_{\pi^0\pi^0} = -0.43 \pm 0.51_{-0.17}^{+0.16} \quad \text{BELLE [74]}$$

Existing measurements only give a weak constraint on  $|\alpha_{\text{eff}} - \alpha|$ ; more precise results are needed, together with more input from the theory, to exploit this channel for measuring the angle  $\alpha$ . Even a projected integrated luminosity of  $0.5 \text{ ab}^{-1}$  would still be inadequate, by a factor at least 20, to discriminate between the solutions for  $|\alpha_{\text{eff}} - \alpha|$ , as discussed in ref.[75].

## 5.2 $B^0 \rightarrow \rho\pi$

This decay  $B^0 \rightarrow \pi^+\pi^-\pi^0$  is dominated by the  $\rho$  intermediate resonances; unlike the  $\pi\pi$ , the  $\rho^\pm\pi^\mp$  is not a CP eigenstate and four decay modes with different charge and flavour combinations must be considered:

$$A^{+-} \equiv A(B^0 \rightarrow \rho^+\pi^-), A^{-+} \equiv A(B^0 \rightarrow \rho^-\pi^+), \bar{A}^{-+} \equiv A(\bar{B}^0 \rightarrow \rho^-\pi^+), \bar{A}^{+-} \equiv A(\bar{B}^0 \rightarrow \rho^+\pi^-)$$

To further complicate the matter, the  $\rho$  resonance can be in the ground state  $\rho(770)$  or in the radial excitations  $\rho(1450)$  or  $\rho(1700)$ . In a quasi-two-body approach, the strategy is to limit the analysis to the areas of the Dalitz plot dominated by the  $\rho^\pm(770)$  and neglect interference terms. The time dependent decay rates are then proportional to:

$$e^{-\Gamma\Delta t} \left( 1 \pm A_{\text{CP}}^{\rho\pi} \right) \times \left\{ 1 + Q_{\text{tag}} \left[ S_{\rho\pi} \pm \Delta S_{\rho\pi} \right] \sin(\Delta M\Delta t) - \left[ C_{\rho\pi} \pm \Delta C_{\rho\pi} \right] \cos(\Delta M\Delta t) \right\}$$

$$\text{where: } Q_{\text{tag}} = 1 \text{ for } B^0 \text{ tag and } Q_{\text{tag}} = -1 \text{ for } \bar{B}^0 \text{ tag; } A_{\text{CP}}^{\rho\pi} = \frac{N(\rho^+\pi^-) - N(\rho^-\pi^+)}{N(\rho^+\pi^-) + N(\rho^-\pi^+)}$$

is the time and flavour integrated asymmetry.

The mixing induced CP violation parameter  $S_{\rho\pi}$  is related to the angle  $\alpha$ , while  $C_{\rho\pi}$  is the direct CP violation parameter;  $\Delta S_{\rho\pi}$  describes the strong phase difference between the amplitudes  $A_+$  and  $A_-$ ;  $\Delta C_{\rho\pi}$  describes the asymmetry between  $\Gamma(B^0 \rightarrow \rho^+\pi^-) + \Gamma(\bar{B}^0 \rightarrow \rho^-\pi^+)$  and  $\Gamma(B^0 \rightarrow \rho^-\pi^+) + \Gamma(\bar{B}^0 \rightarrow \rho^+\pi^-)$ ; both have no CP content.

A model independent extraction of  $\alpha$  from time-dependent CP-asymmetry measurements requires an isospin analysis of the decay rates of all the  $\rho\pi$  decay modes

[76]. A method has been proposed [77] assuming SU3 symmetry, and using other measured branching fractions for  $B^0 \rightarrow K^{*\pm} \pi^\mp, \rho^\mp K^\pm$  and similar decays for the charged B's

The decay amplitudes of the isospin-related final states obey the pentagonal relations

$$\sqrt{2}(A^{+0} + A^{0+}) = 2A^{00} + A^{+-} + A^{-+}$$

$$\sqrt{2}(\bar{A}^{+0} + \bar{A}^{0+}) = 2\bar{A}^{00} + \bar{A}^{+-} + \bar{A}^{-+}$$

where  $A^{ij}$  refers to the decay into a  $\rho$  with charge  $i$  and a  $\pi$  of charge  $j$ .

The use of these relations together with the measurements of all branching ratios and asymmetries could lead to the determination of  $\alpha$ , but present measurements only set weak limits, and a much higher precision is needed, especially in the decay rates. Results are available from BELLE [78] and BABAR [79] on samples respectively of  $140\text{fb}^{-1}$  and  $113\text{fb}^{-1}$ ; the two experiments also measure separately the two asymmetries:

$$A_{\text{CP}}^{+-} = \frac{N(\bar{B}^0 \rightarrow \rho^- \pi^+) - N(B^0 \rightarrow \rho^+ \pi^-)}{N(\bar{B}^0 \rightarrow \rho^- \pi^+) + N(B^0 \rightarrow \rho^+ \pi^-)}, A_{\text{CP}}^{-+} = \frac{N(\bar{B}^0 \rightarrow \rho^+ \pi^-) - N(B^0 \rightarrow \rho^- \pi^+)}{N(\bar{B}^0 \rightarrow \rho^+ \pi^-) + N(B^0 \rightarrow \rho^- \pi^+)}$$

and quote the results listed in Table II, with no evidence for large mixing induced, or direct, CP asymmetries.

TABLE II: *BABAR's and BELLE's results from the CP analysis of the decay  $B^0 \rightarrow \rho^\pm \pi^\mp$ ; see text for the parameters definition*

Parameter	BABAR	BELLE
$C_{\rho\pi}$	$0.35 \pm 0.13 \pm 0.05$	$0.25 \pm 0.17^{+0.02}_{-0.06}$
$\Delta C_{\rho\pi}$	$0.20 \pm 0.13 \pm 0.05$	$0.38 \pm 0.18^{+0.02}_{-0.04}$
$S_{\rho\pi}$	$-0.13 \pm 0.18 \pm 0.04$	$-0.28 \pm 0.23^{+0.10}_{-0.08}$
$\Delta S_{\rho\pi}$	$0.33 \pm 0.18 \pm 0.03$	$-0.30 \pm 0.24 \pm 0.09$
$A_{\text{CP}}^{\rho\pi}$	$-0.114 \pm 0.062 \pm 0.027$	$-0.16 \pm 0.10 \pm 0.02$
$A_{\text{CP}}^{+-}$	$-0.18 \pm 0.13 \pm 0.05$	$-0.02 \pm 0.16^{+0.05}_{-0.02}$
$A_{\text{CP}}^{-+}$	$-0.52^{+0.17}_{-0.19} \pm 0.07$	$-0.53 \pm 0.29^{+0.09}_{-0.04}$

A more sophisticated method, which makes use, on the full data sample, of the time dependent Dalitz plot analysis, and takes into account the interference terms, was presented by BABAR[80] to the 2004 ICHEP Conference; the result, still preliminary, is

$$\alpha = (113^\circ_{-31^\circ}^{+28^\circ} \pm 6^\circ)$$

### 5.3 $B^0 \rightarrow \rho\rho$

The decay  $B^0 \rightarrow \rho^+\rho^-$  holds promise to a better determination of the angle  $\alpha$  because has the advantage of a larger decay rate (about 5 times more than  $\pi^+\pi^-$ ) and smaller uncertainty in penguin contributions. The extraction of  $\alpha$  from measurements made with this decay mode requires an understanding of the contributing amplitudes. Since there are two vector particles in the final state, it also requires proper accounting for CP-even and CP-odd components in the decay amplitude.

The measurements of the  $B^+ \rightarrow \rho^+\rho^0$ , and the upper limit on the  $B^0 \rightarrow \rho^0\rho^0$  [81] branching fractions place experimental limits on the contribution of penguin amplitudes [82]. The CP analysis of B decays to  $\rho^+\rho^-$  is complicated by the presence of three helicity states ( $h = 0, +1, -1$ ). The  $h=0$  state corresponds to longitudinal polarization and is CP-even, while neither the  $h = +1$  nor the  $h = -1$  state are CP eigenstates. The longitudinal polarization fraction  $f_L$  is defined as the fraction of the helicity zero state in the decay and has been measured to be close to unity. The BABAR result [83] on a sample of  $89 \times 10^6$  BB events is  $f_L = 0.99 \pm 0.03(\text{stat}) \pm 0.03(\text{syst})$

The small value of  $B^0 \rightarrow \rho^0\rho^0$ , compared to the other modes, makes it possible to use the Grossman-Quinn bound [84]:

$$|\alpha - \alpha_{\text{eff}}| = \frac{\Gamma(B^0 \rightarrow \rho^0\rho^0)}{\Gamma(B^0 \rightarrow \rho^+\rho^-)}$$

with the measured rates for  $B \rightarrow \rho^\pm\rho^0, \rho^0\rho^0$  BABAR puts a limit  $|\alpha_{\text{eff}} - \alpha| < 13^\circ$  (68% C.L.). Ignoring possible non-resonant contributions, interference with  $\rho\pi\pi^0, \pi\pi^0\pi\pi^0$ , or  $a_1\pi$ , and  $I = 1$  amplitudes, one can relate the CP parameters  $S_L$  and  $C_L$  to  $\alpha$ , up to a four-fold ambiguity. Selecting the solution closest to the CKM best fit average, the measured CP parameters of the longitudinal polarization correspond to

$$\alpha = 96^\circ \pm 10^\circ (\text{stat}) \pm 4^\circ (\text{syst}) \pm 1^\circ (\text{model})$$

where the last term comes from the uncertainty in the knowledge of the branching ratio of  $B \rightarrow \rho^0\rho^0$  (BABAR preliminary result presented at the ICHEP04 Conference)

### 5.4 Summary on the angle $\alpha$

Prior to the B-factories there were practically no bounds on the angle  $\alpha$ , since it was very poorly constrained by the indirect measurements (all CP conserving). The measurement has proven to be considerably more difficult than anticipated because of the small branching ratios, large backgrounds and, most of all, the *penguin pollution*, which makes difficult the interpretation of the data. The best constraints now come from the  $B \rightarrow \rho^+\rho^-$  mode, which is more abundant, has smaller penguin contribution and, as we now know from the angular analysis, is practically a pure CP eigenstate.

BABAR and BELLE have published, or made public, results on the asymmetries on all three modes:  $\pi\pi, \rho\rho, \rho\pi$ . None is very stringent, but when considered together, they restrict significantly the allowed range for  $\alpha$ . Averaging the confidence level curves from the  $\pi\pi$  and  $\rho\rho$  isospin analyses, as well as the  $\rho\pi$  Dalitz plot study, leads to the combined constraint:  $90^\circ < \alpha < 109^\circ$  ( $\pm 1 \sigma$  interval) or  $80^\circ < \alpha < 129^\circ$  ( $\pm 2 \sigma$  interval); a graphical representation of the fits for the three modes  $\pi\pi, \rho\pi$  and  $\rho\rho$  and the combined fit (by the CKM fitter group [85]) is shown in fig 31.



The combined results from BABAR and BELLE on  $\alpha$  start to be significant also to limit the apex region in the  $(\bar{\rho}, \bar{\eta})$  plane; fig. 32 shows the bounds on the apex of the triangle derived exclusively from the B-factories measurements of the angles  $\beta$  and  $\alpha$  as calculated by the CKM fitter group. The colour code indicates different CL areas.

To improve in the measurement of  $\alpha$  it is necessary to measure more precisely the branching ratios of all the isospin related modes, some of which are experimentally very challenging, as  $\pi^0 \pi^0$ . A precise measurement of  $\alpha$ , however, requires further theoretical work, to pin down the corrections due to the penguin contribution.

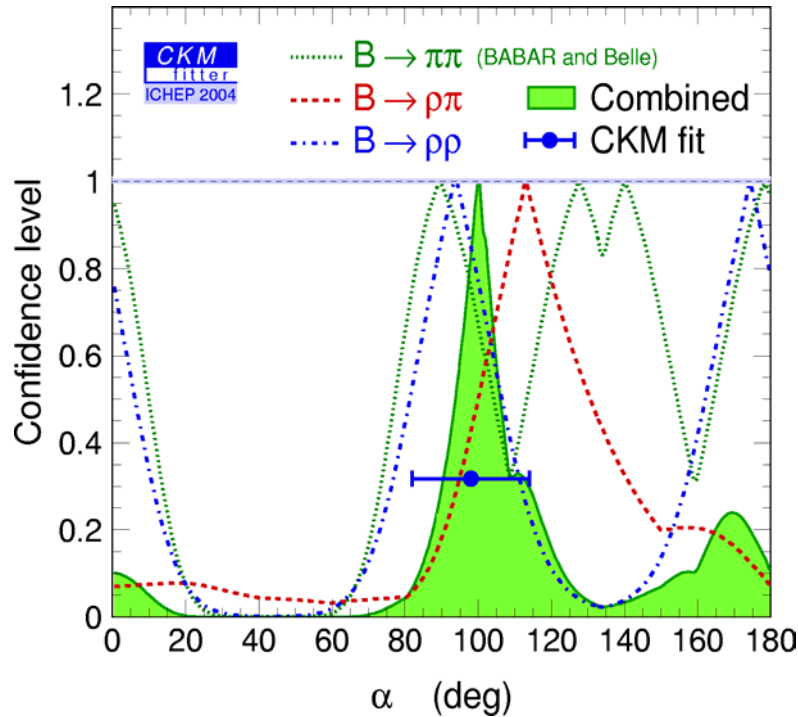


Fig. 31 Bounds on the value of  $\alpha$  from the CKM fitter group for the separate final states  $\pi\pi$ ,  $\rho\pi$  and  $\rho\rho$  and combined. The value from the CKM global fit is also indicated.

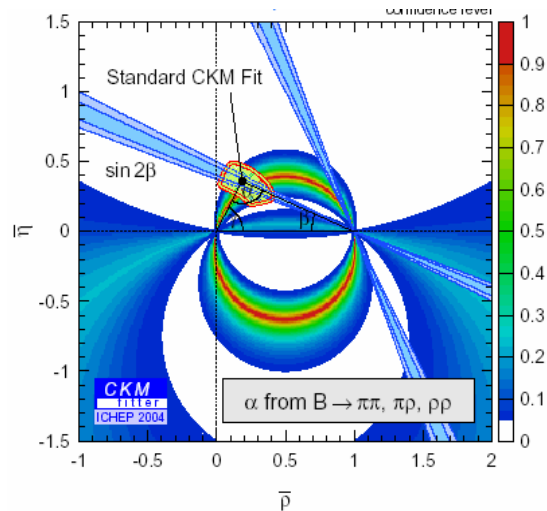


Fig. 32 Bounds in the  $(\bar{\rho}, \bar{\eta})$  plane (as determined by the CKM fitter group), from the combined measurement of the angles  $\alpha$  and  $\beta$  at the B-factories. The colour code indicates the CLs

## 6 Measurements of the angle $\gamma$ .

The third angle of the unitarity triangle is given by  $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ ; in the Wolfenstein approximation all the  $V_{ij}$  involved are real but  $V_{ub}$ , so  $\gamma \approx \arg V_{ub}$ . Thus measurements of  $\gamma$  typically use B decays with a  $b \rightarrow u$  quark transition, which is CKM suppressed, so have small branching fractions and are experimentally quite challenging.

Several methods have been suggested for measurements possible at B-factories using  $B^0$  or  $B^+$  decays into DK (or  $D\pi$ ) modes and subsequent D decays into CP eigenstates. The possibility of observing direct CP violation in  $B \rightarrow DK$  decays was first discussed by I. Bigi and A. Sanda [86]. These methods are based on the following observations:

- CP violation in  $D^0$  decays is small and can be assumed to be negligible
- neutral  $D^0$  and  $\bar{D}^0$  mesons can decay to a common final state (for example  $K_s\pi^+\pi^-$ ) or  $K\pi^+$  (Cabibbo favoured for the  $D^0$ , doubly Cabibbo suppressed for the  $\bar{D}^0$ )
- the decays  $B^+ \rightarrow D^{(*)}K^+$  ( $B^+ \rightarrow D^{(*)}\pi^+$ ) can produce neutral D mesons of both flavours via  $\bar{b} \rightarrow \bar{c}u\bar{s}$  ( $\bar{b} \rightarrow \bar{c}u\bar{d}$ ) and  $\bar{b} \rightarrow \bar{u}c\bar{s}$  ( $\bar{b} \rightarrow \bar{u}c\bar{d}$ ) transitions, with a relative phase  $\theta_+$  between the two interfering amplitudes that is the sum,  $\delta + \gamma$ , of strong and weak interaction phases

If we consider the  $B^+$  decays into  $D^0K^+$  or  $D^0\pi^+$ , whose diagrams are shown in Fig. 33, for the  $D^0K^+$  decay both amplitudes are of the order  $A\lambda^3$  (the interference could lead to large asymmetries) and the weak phase difference is  $\gamma$ . For the  $D^0\pi^+$  final state the first amplitude is of the order  $A\lambda^2$ , the second  $A\lambda^4$  and the interference should lead to somewhat smaller asymmetries.

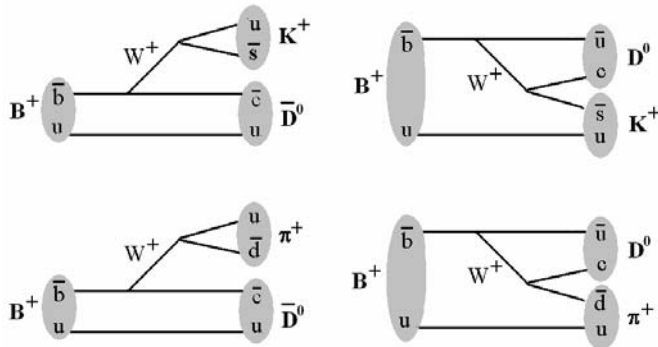


Fig. 33 Feynman diagrams for CKM favoured  $B^+ \rightarrow K^+ \bar{D}^0$ ,  $B^+ \rightarrow \pi^+ \bar{D}^0$  and the corresponding suppressed modes

The amount of the interference depends on the ratio

$$r_B = \left| \frac{A(b \rightarrow u)}{A(b \rightarrow c)} \right|$$

which is not well constrained by the theory; the larger  $r_B$ , bigger the interference, hence greater sensitivity for  $\gamma$ .

The use of the branching fractions alone, for charged and neutral B

decays requires additional information to obtain  $\gamma$ ; this is provided either by determining the branching fractions of D decays to flavour eigenstates (GLW method) or by using different neutral D final states (ADS method). Another method uses a single  $B^+$  decay mode, plus a Dalitz plot analysis on a 3-body  $D^0$  decay. We will now discuss briefly the methods and the experimental results. Combining all methods is essential for a better determination of  $\gamma$ . The critical parameter is  $r_B$ : as it gets smaller, the sensitivity of the measurements deteriorates.

### 6.1 The GLW method

The original idea of Gronau and Wyler [87] was to measure two rates arising from  $b \rightarrow c \bar{u} s$  and  $b \rightarrow u \bar{c} s$  amplitudes, and a third one that involves their interference. Thus one can gain sensitivity to the weak phase between the two amplitudes, which is related to  $\gamma$ . Assuming that there is no CP violation in the D sector (which is a very good approximation in the SM), and defining the CP-even and odd states as

$$|D_{\pm}^0\rangle = \frac{1}{\sqrt{2}} (|D^0\rangle \pm |\bar{D}^0\rangle),$$

imply the following amplitude relations,

$$\begin{aligned} \sqrt{2} A(B^+ \rightarrow K^+ D_+^0) &= A(B^+ \rightarrow K^+ D^0) + A(B^+ \rightarrow K^+ \bar{D}^0), \\ \sqrt{2} A(B^- \rightarrow K^- D_+^0) &= A(B^- \rightarrow K^- D^0) + A(B^- \rightarrow K^- \bar{D}^0). \end{aligned}$$

In the first relation, for example, we can see from the graphs in Fig. 33 that  $B^+ \rightarrow \bar{D}^0 K^+$  is a  $b \rightarrow c$  transition,  $B^+ \rightarrow D^0 K^+$  is a  $b \rightarrow u$  transition, and  $B^+ \rightarrow D_+^0 K^+$  receives contributions from both. Then the triangle construction in Fig. 34 determines the weak phase between the  $\bar{b} \rightarrow \bar{u}$  and  $b \rightarrow u$  transitions, which is  $2\gamma$ . There is again a four-fold ambiguity corresponding to the reflections of the triangles.

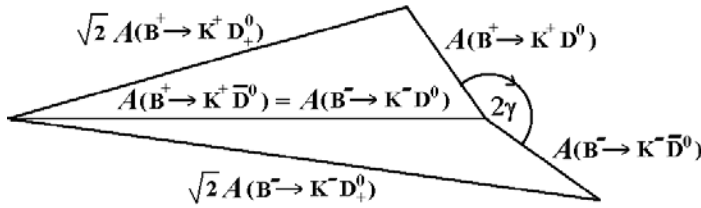


Fig. 34 Triangle constructed from the amplitudes of  $B^{\pm} \rightarrow D^0 K^{\pm}$  decays

This method requires the measurement of a number of branching ratios which are accessible with present data sets, but the construction of the triangles is experimentally very difficult, since they are quite squashed, because, based on naïve factorization the ratio of the side  $A(B^+ \rightarrow D^0 K^+)$  to the base is small:

$$\frac{|A(B^+ \rightarrow K^+ D^0)|}{|A(B^+ \rightarrow K^+ \bar{D}^0)|} \sim \left| \frac{V_{ub} V_{cs}^*}{V_{cb} V_{us}^*} \right| \frac{1}{N_c} \sim 0.15,$$

(where  $N_c=3$  for 3 colours).

BABAR and BELLE measurements for the asymmetries:

$$A_{\pm} = \frac{\Gamma(B^- \rightarrow D_{\pm} K^-) - \Gamma(B^+ \rightarrow D_{\pm} K^+)}{\Gamma(B^- \rightarrow D_{\pm} K^-) + \Gamma(B^+ \rightarrow D_{\pm} K^+)} = \frac{\pm 2r_B \sin \delta \sin \gamma}{1 + r_B^2 + 2r_B \cos \delta \cos \gamma}$$

and the ratios: :

$$R_{\pm} = 2 \frac{\Gamma(B^- \rightarrow D_{\pm} K^-) + \Gamma(B^+ \rightarrow D_{\pm} K^+)}{\Gamma(B^- \rightarrow D^0 K^-) + \Gamma(B^+ \rightarrow \bar{D}^0 K^+)} = 1 + r_B^2 \pm 2r_B \cos \delta \cos \gamma$$

are obtained combining several CP=+1 and CP=-1  $D^0$  final states. In principle we have 4 observables to determine 3 unknowns ( $r_B, \delta, \gamma$ ), but the branching ratios are small!

Available results are listed in Table III

TABLE III: *BABAR's and BELLE's results from the CP analysis of the decays  $B^- \rightarrow D^0 K^-$ ,  $B^0 \rightarrow D^0 K^*$ ,  $B^- \rightarrow D^{*0} K^-$ ; see text for the parameters definition. For each analysis the sample size is reported.*

Sample	BABAR [88],[89]		BELLE [90],[91]	
$D_{CP}^0 K^-$	$N_{BB}=214 \times 10^6$	$A_+ = 0.40 \pm 0.15 \pm 0.08$ $R_+ = 0.87 \pm 0.14 \pm 0.06$ $A_- = 0.21 \pm 0.17 \pm 0.07$ $R_- = 0.80 \pm 0.14 \pm 0.08$	$N_{BB}=274 \times 10^6$	$A_+ = 0.07 \pm 0.14 \pm 0.06$ $R_+ = 0.98 \pm 0.18 \pm 0.10$ $A_- = -0.11 \pm 0.14 \pm 0.05$ $R_- = 1.29 \pm 0.16 \pm 0.08$
$D_{CP}^0 K^{*-}$	$N_{BB}=227 \times 10^6$	$A_+ = -0.09 \pm 0.20 \pm 0.06$ $R_+ = 1.77 \pm 0.37 \pm 0.12$ $A_- = -0.33 \pm 0.34 \pm 0.10$ § $R_- = 0.76 \pm 0.29 \pm 0.06$ §	$N_{BB}=96 \times 10^6$	$A_+ = -0.02 \pm 0.33 \pm 0.07$ - $A_- = -0.19 \pm 0.50 \pm 0.04$ -
$D^{*0} K^-$	$N_{BB}=123 \times 10^6$	$A_+ = -0.02 \pm 0.24 \pm 0.05$ $R_+ = 1.09 \pm 0.26 \pm 0.10$	$N_{BB}=274 \times 10^6$	$A_+ = -0.27 \pm 0.25 \pm 0.04$ $R_+ = 1.43 \pm 0.28 \pm 0.06$ $A_- = 0.26 \pm 0.26 \pm 0.03$ $R_- = 0.94 \pm 0.28 \pm 0.06$

§ additional uncertainties from possible interference effects in the final states with  $\omega$  and  $\phi$  resonances.

The experimental errors are still too large, and the present data may only give loose bound on  $\gamma$  and  $r_B$ . The statistical errors, however, are typically a factor 2÷3 bigger than the systematic ones; so by the end of the B-factories program, the two contributions should be of the same order, and the precision of several of these measurement will be limited by systematic uncertainties.

### 6.2 The ADS method

A variation of the GLW method has been proposed [92] (ADS method), again to measure  $\gamma$  from  $DK^+$  decays of the charged  $B^+$  meson; this exploits the interference between the

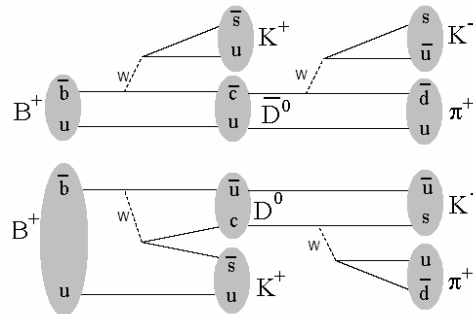


Fig35  $B^+$  decays diagrams for the ADS method:

Top:  $b \rightarrow c$  transition, followed by a doubly Cabibbo suppressed  $D^0$  decay.

Bottom: CKM suppressed  $b \rightarrow u$  transition followed by favoured  $D^0$  decay

colour suppressed  $b \rightarrow u$  transition, followed by a Cabibbo allowed hadronic  $D^0$  decay,

and a colour allowed  $b \rightarrow c$  transition, followed by a double suppressed  $D^0$  decay; the two graphs are shown in Fig.35. The following relations hold:

$$R_{ADS} = \frac{\Gamma(B^- \rightarrow (K^+ \pi^-) K^-) + \Gamma(B^+ \rightarrow (K^- \pi^+) K^+)}{\Gamma(B^- \rightarrow (K^- \pi^+) K^-) + \Gamma(B^+ \rightarrow (K^+ \pi^-) K^+)} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos \gamma$$

$$A_{ADS} = \frac{\Gamma(B^- \rightarrow (K^+ \pi^-) K^-) - \Gamma(B^+ \rightarrow (K^- \pi^+) K^+)}{\Gamma(B^- \rightarrow (K^+ \pi^-) K^-) + \Gamma(B^+ \rightarrow (K^- \pi^+) K^+)} = 2r_B r_D \cos(\delta_B + \delta_D) \sin \gamma / R_{ADS}$$

and also the strong phase in D decays plays a role; from D decays we know [93] that

$$r_D = \frac{A(D^0 \rightarrow K^+ \pi^-)}{A(D^0 \rightarrow K^- \pi^+)} = 0.060 \pm 0.003$$

Unfortunately the double suppressed D decays have a very small branching ratio and this measurement is still out of experimental reach: first attempts by BABAR [94] and BELLE [95] fail to set significant bounds on  $\gamma$ . In the future, however, adding results obtained with this method to other determinations of  $\gamma$  could help.

### 6.3 The Dalitz plot analysis

Additional recent results from BABAR and BELLE use still another approach to extract meson the value of the angle  $\gamma$  from the decays  $B^+ \rightarrow D^0 K^+$  or  $B^+ \rightarrow D^{*0} K^+$ . This method [96] allows to obtain all the information required for determination of  $\gamma$  in a single decay mode], uses the interference of  $B^+ \rightarrow K^+ D^0$  with  $B^+ \rightarrow K^+ \bar{D}^0$ , when both the  $D^0$  and the  $\bar{D}^0$  go to the same 3-body final state (for example  $K_S \pi^+ \pi^-$ ), and requires the analysis of the Dalitz plot of D decay. The statistical accuracy of the  $\gamma$  extraction can be improved by adding decay modes with the excited states of the K and/or more 3-body  $D^0$  decays.

There are several advantages to this method: the D decays involved are Cabibbo favoured, so the branching ratios are large; the final state consists of all charged particles, so the reconstruction efficiency is higher and the background lower; finally one expects large strong phase difference, because of the presence of the resonances, hence greater sensitivity in  $\gamma$  extraction. The price to pay is that one needs to perform the Dalitz plot analysis of the data.

BELLE was the first to publish [97] a measurement, based on this technique. The sample used was from  $140 \text{ fb}^{-1}$  integrated luminosity, and the modes  $B^+ \rightarrow DK^+$ ,  $B^+ \rightarrow D^* K^+$ ,  $D^* \rightarrow D\pi^0$  and conjugates, followed by the  $D^0 (\bar{D}^0) \rightarrow K_S \pi^+ \pi^-$ . They define the amplitudes for the  $B^+$  and the  $B^-$  decays to be respectively:

$$M_- = f(m_-^2, m_+^2) + r e^{-i(\gamma-\delta)} f(m_+^2, m_-^2)$$

$$M_+ = f(m_+^2, m_-^2) + r e^{i(\gamma+\delta)} f(m_-^2, m_+^2)$$

where  $\delta$  is the strong phase,  $m_+$  and  $m_-$  are the squared invariant masses of the  $K_S \pi^+$  and  $K_S \pi^-$  combinations, respectively,  $r$  is the ratio between the two interfering amplitudes (for the decays  $B^+ \rightarrow \bar{D}^0 K^+$  and for  $B^+ \rightarrow D^0 K^+$ ) and  $f(m_+, m_-)$  is the complex amplitude for

the decay  $\bar{D}^0 \rightarrow K_S \pi^+ \pi^-$ , which they model from the abundant, flavour tagged, D meson production in the continuum. Once the functional form of  $f$  is fixed, they perform a simultaneous fit to the two Dalitz plots, with  $r$ ,  $\gamma$ , and  $\delta$  as free parameters. The result of the combined fit to the modes  $B^+ \rightarrow D^0 K^+$  or  $B^+ \rightarrow D^{*0} K^+$ , is:  $\gamma = 77^{+17}_{-19} \pm 13^\circ \pm 11^\circ$  where the first error is statistical, the second systematic, the third comes from the model uncertainties. BABAR presented [98] in Summer 2004 a preliminary result, using the same decay modes plus the corresponding one with a  $D^* \rightarrow D\pi^0$  and a larger data sample ( $211 \times 10^6$  BB events):

$$\gamma = 73^\circ \pm 45^\circ(\text{stat}) \pm 10^\circ(\text{syst}) \pm 10^\circ(\text{model})$$

$$r < 0.18 \text{ (90\% C.L.)}$$

$$\delta = 130^\circ \pm 45^\circ \pm 8^\circ \pm 10^\circ$$

Recently BELLE has updated [99] the analysis to the full data sample (  $275 \times 10^6$  BB events)

and quotes the combined preliminary result:

$$\gamma = 64^\circ \pm 19^\circ(\text{stat}) \pm 13^\circ(\text{syst}) \pm 11^\circ(\text{model})$$

$$r = 0.21 \pm 0.08(\text{stat}) \pm 0.03(\text{syst}) \pm 0.04(\text{model})$$

$$\delta = 157^\circ \pm 19^\circ \pm 11^\circ \pm 21^\circ$$

The interval quoted by BELLE for  $\gamma$  corresponding to two standard deviations (and including all uncertainties) is  $22^\circ < \gamma < 113^\circ$ , consistent with SM expectation from indirect measurements ( $57^\circ \pm 9^\circ$ ), but still too wide to further constrain the area of the apex of the unitarity triangle.

#### 6.4 Time dependent asymmetry in $B^0 \rightarrow D^{(*)0} K_S$

The  $B^0$  and the  $\bar{B}^0$  can both decay to the same final state  $D^{(*)0} K_S$  through the diagrams shown in Fig 36 Both are colour-suppressed tree amplitudes, of order  $|V_{cb}| |V_{us}| \approx |V_{ub}| |V_{cs}| \approx \lambda^3$ . The weak phase difference between the two decay amplitudes is  $\gamma$ , and  $B^0$  mixing introduces a phase  $2\beta$ .

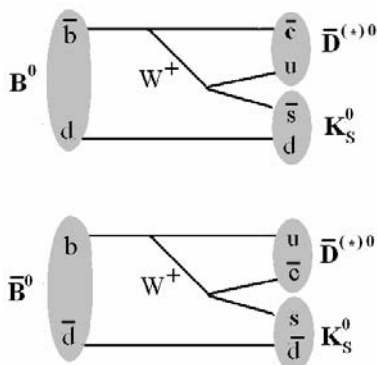


Fig.36 Feynman-diagrams for the decay  $B^0 \rightarrow D^{(*)0} K_S$  and charge conjugate

Thus the time-dependent CP-asymmetries for the final states  $D^0 K^0$ ,  $\bar{D}^0 K^0$  are sensitive to  $\sin(2\beta + \gamma + \delta)$ , where  $\delta$  represents the strong phase difference between the two decay trees.

BELLE has observed for the first time [100] the decays  $B^0 \rightarrow D^0 K_S$  and  $B^0 \rightarrow D^0 K^{*0}$  and searched for  $B^0 \rightarrow D^{*0} K$ ,  $B^0 \rightarrow D^{*0} K^*$  in a sample corresponding to  $78 \text{ fb}^{-1}$  of integrated luminosity, with the  $D^0$  reconstructed in  $K^- \pi^+$ ,  $K^- \pi^+ \pi^- \pi^+$ ,  $K^- \pi^+ \pi^0$ , the  $K_S$  in  $\pi^+ \pi^-$ , the  $D^{*0}$  in  $D^0 \pi^0$ , the  $K^{*0}$  in  $K^+ \pi^-$ . The reconstruction method makes use of the usual  $\Delta E$  and  $M_{ES}$  variables to identify the candidate events; particle identification is used to separate pions and kaons.

BABAR has presented the first evidence for the decay  $B \rightarrow D^{*0} K_S$  and measurements of the branching fractions  $\text{Br}(B^0 \rightarrow D^0 K_S)$  and  $\text{Br}(\bar{B}^0 \rightarrow D^0 \bar{K}^{*0})$ , and a 90% C.L. upper limit for the  $\text{Br}(\bar{B}^0 \rightarrow \bar{D}^0 \bar{K}^{*0})$ ,

The samples of signals events, however, are not yet large enough for measuring CP violation effects. The fact that the  $\bar{B}^0 \rightarrow \bar{D}^0 \bar{K}^{*0}$  is not observed, while  $\bar{B}^0 \rightarrow D^0 \bar{K}^{*0}$  has been measured, sets a limit on the ratio of the two contributions  $b \rightarrow u$ ,  $b \rightarrow c$ , which is critical for the sensitivity of the  $\gamma$  measurement.

### 6.5 Time dependent asymmetry in $B^0 \rightarrow D^{(*)\mp} \pi^\pm, B^0 \rightarrow D^{(*)\mp} \rho^\pm$

The decay  $B^0 \rightarrow D^{(*)\mp} \pi^\pm$  can proceed through a CKM favoured amplitude proportional to the CKM matrix elements  $V_{cb} V_{ud}$  or through a doubly-CKM-suppressed amplitude proportional to the CKM matrix elements  $V_{cd} V_{ub}$ . The Feynman diagrams for both amplitudes are shown in Fig. 37. As in the previous case, the relative weak phase between the two decay amplitudes is  $\gamma$ , and  $2\beta$  is introduced by  $B^0$  mixing. Comparing with the  $B \rightarrow DK$  decays, the  $V_{cb}$  mediated amplitude is less suppressed, and the  $V_{ub}$  is more strongly suppressed. This leads to a much larger decay rate for  $B^0 \rightarrow D^{(*)\mp} \pi^\pm$  with a much smaller CP asymmetry.

The time dependent decay rate is given by:

$$f^\pm(t) = \frac{e^{-\frac{t}{\tau}}}{4\tau} \left[ 1 \mp \eta C \cos(\Delta m \cdot t) \pm S_\eta \sin(\Delta m \cdot t) \right]$$

Fig. 37. Feynman diagrams for the  $B^0$  and the  $\bar{B}^0$  decays into  $D^{(*)\pm} \pi^\mp$

Where  $\eta = +1(-1)$  for the final state  $D^{*-} \pi^+$  ( $D^{*+} \pi^-$ ); Where  $S_\pm$  and  $C$  are given in term of the ratio between the amplitudes of the two diagrams:  $r_{D^* \pi} = |A_u/A_c|$ ; and their strong phase difference  $\delta_{D^* \pi}$ :

$$C \equiv \frac{1 - r_{D^* \pi}^2}{1 + r_{D^* \pi}^2}, \quad S_\pm \equiv \frac{2r_{D^* \pi}}{1 + r_{D^* \pi}^2} \sin(2\beta + \gamma \pm \delta_{D^* \pi})$$

Similar equations hold for the charge conjugate decays; we expect  $r_{D^* \pi} \approx 0.02$ . The doubly Cabibbo suppressed amplitude  $A_u$  is too small to be measured with present data sample. It has been suggested [101] that, using the SU(3)-based symmetry relations,  $r^{(*)}$  can be inferred as:

$$r^{(*)} = \tan \theta_C \sqrt{\frac{\text{Br}(B^0 \rightarrow D_s^{(*)+} \pi^-) f_{D^{(*)}}}{\text{Br}(B^0 \rightarrow D^{(*)-} \pi^+) f_{D_s^{(*)}}}}$$

Where  $\theta_C$  is the Cabibbo angle,  $f_D$  are the D meson form factors; BABAR [102] uses the known value of  $\theta_C$ , the measured branching ratios for the  $D^{(*)} \pi$  [103] and  $D_s^{(*)} \pi$  [104] decays and the form factors from lattice QCD calculations [105], and evaluates:  $r = 0.019 \pm 0.004$ ,  $r^* = 0.017 + 0.005 - 0.007$ ; increasing the error by 30% to

take into account theoretical uncertainties, they pose the limit:  $|\sin(2\beta + \gamma)| > 0.69$  at 68% C.L. and exclude no CP violation ( $\sin(2\beta + \gamma)=0$ ) at 83% c.l.

### 6.6 Summary on the angle $\gamma$

In the SM, from the global fit to the measurements related to the Unitarity Triangle, we expect the angle  $\gamma$  to be approximately  $(57 \pm 9)^\circ$ ; a direct measure would be a significant test of the consistency of the Model.

In the past, it was common wisdom that the measurement of the angle  $\gamma$  required the study of the  $B_s$  mesons decay, not accessible in  $e^+e^-$  annihilation at the energy of the Y(4S) mass. The threshold for  $B_s$  production is at the Y(5S); the c.m. energy at an asymmetric b-factory cannot be easily changed; in addition, the signal to background ratio is considerably worse at the Y(5S), and the fast oscillations of the  $B_s$  complicates even more the experimental picture. Both collaborations have therefore chosen not to run at the Y(5S). In the meantime several ideas have been put forward to measure  $\sin(2\beta + \gamma)$  or  $\sin \gamma$  using  $B_d$  and  $B_u$  decays. None of these modes are *golden*, but the combination can be effective in providing an independent check on the consistency of the theory.

From the measurement of  $\sin(2\beta + \gamma)$  the value of  $\gamma$  is determined with a fourfold ambiguity, and the bounds in the  $(\bar{\rho}, \tilde{\eta})$  plane have the shape shown in Fig 38, where the fit from the CKM fitter group is reported.

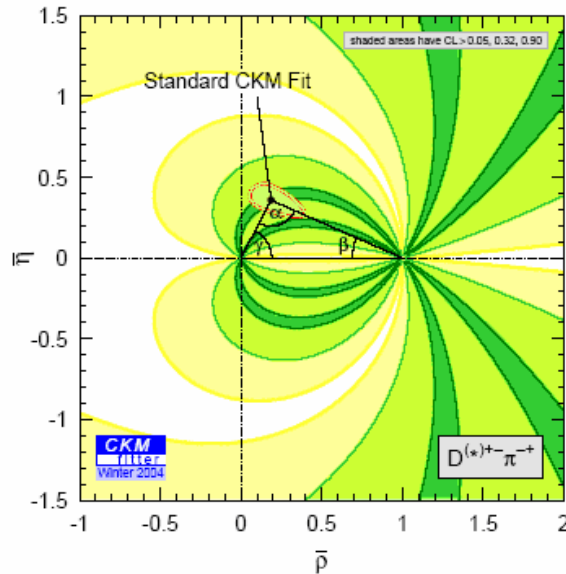


Fig 38: Bounds in the  $(\bar{\rho}, \tilde{\eta})$  plane (as determined by the CKM fitter group), from the measurement of the angle  $\gamma$  from  $D^* \pi$  decays. The colours indicate the CLs, from lighter (>5%) to darkest (>90%). Also shown the CL > 5% region of the standard CKM fit.



## 7 Rare B decays and direct CP violation

The definition of *rare* B decays usually refers to modes with a branching fraction of the order of  $10^{-5}$  or less. These are typically decays which do not proceed through the CKM favoured  $b \rightarrow c$  transition, so do not involve charmed particles; if the final state contains hadrons they are also called *charmless*. Rare decays include  $b \rightarrow u$  suppressed tree and  $b \rightarrow s$  or  $b \rightarrow d$  penguin transitions, but also annihilation, exchange or more exotic diagrams, which are even more suppressed.

The interest for rare decays generally lies in the fact that processes with a very small SM amplitude could be modified in a sensible way by contributions from *new* Physics, providing a window on what lies beyond the Standard Model. It is however necessary to keep in mind that SM predictions for hadronic processes have uncertainties due to model dependence. In case of discrepancies between expected and measured values of branching ratios or CP asymmetries, before claiming new Physics, a careful evaluation of the approximations, assumptions and model dependence of the calculation must be performed.

When the tree diagram is suppressed, there is often a penguin process with different weak and strong phases, and comparable amplitude; such cases are excellent candidates for searching effects of direct CP violation.

### 7.1 Charmless two body $\pi\pi$ , $\pi K$ , $KK$ final states

Charmless B decays are CKM suppressed; each of them has a set of possible diagrams. We will discuss here just the graphs described in 2.2 (main contributors in the SM) and start with PP two body final states:  $\pi\pi$ ,  $K\pi$ ,  $KK$ . We have already discussed in 5.1 the  $\pi\pi$  diagrams (Fig. 29). Table IV indicates for each final state the two leading diagrams and the size of the CKM elements involved (for a in depth classification and discussion see ref [106]).

A naïve comparison would lead to the conclusion that, if the tree diagrams were dominant, the amplitude for the  $K\pi$  mode would be suppressed (by a factor  $\lambda$ ) respect to the  $\pi\pi$ , while the opposite would hold if the penguin were dominant. The branching ratios for all these decay modes have been measured by BABAR and BELLE, refining the earlier measurements, or upper limits, by CLEO (see listing in Table V)

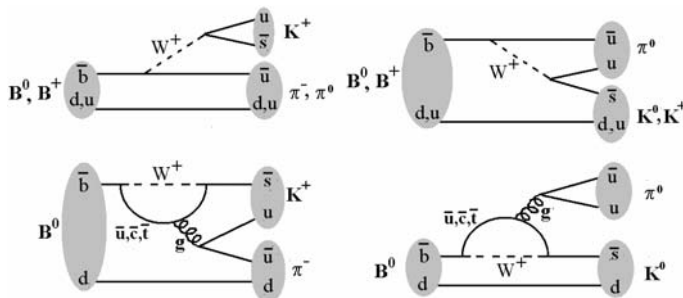


Fig. 39 Feynman diagrams for B decays into  $K\pi$

The  $K\pi$  mode has similar diagrams as the  $\pi\pi$  (as shown in Fig. 39), and a BF about a factor 3 larger. This represents a clear indication that the Penguin contributions are relevant, and these modes are good candidates for direct CP violation.

The  $KK$  final state cannot be reached via a tree diagram in the SM; possible Feynman graphs are a penguin, an exchange. (for the  $B^0$ ) or an annihilation (for the  $B^+$ ), as shown in Fig 40; all these are highly suppressed. None of the  $KK$  mode have been seen yet, and only upper limits have been set by BABAR and BELLE.

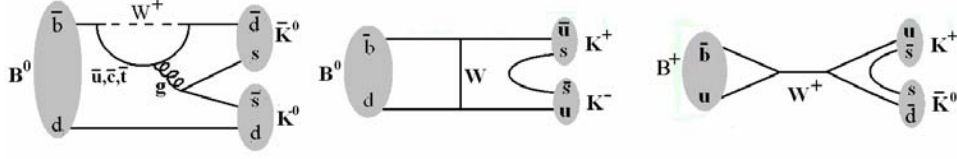


Fig. 40 Possible graphs for B decays to KK

Experimentally the measurements of all these charmless decays are difficult because one must look for a tiny signal (the branching ratios are in the range  $1 \div 25 \times 10^{-6}$ ) over a huge background, mostly due to two jets events from production of light quarks pairs (usually referred to as *continuum* events). In order to reduce this kind of background, topological and angular cuts are applied: only events which are not jet-like, and where the two hadrons do not come from opposite sides are selected.

A further problem is the requirement of K- $\pi$  separation at high momenta (typically over 3 GeV/c) to identify each final state. Both BABAR and BELLE have excellent hadron identification capability, and assign to each track the probability to be a pion or a kaon. Fig 41 shows, for example, the expected Cherenkov angle as a function of momentum for the BABAR DIRC detector. Reconstruction efficiencies for these final states are typically in the 20-40 % range.

TABLE IV: Two-body charmless decays: for each mode type and amplitude of the two leading diagrams are listed; the possibility of observing direct CP violations is also indicated

Final state	Graph I		Graph II		Direct CPV ?	Comments
	Type	Ampl $\propto$ to:	Type	Ampl $\propto$ to		
$\pi^+\pi^-$	Tree	$\lambda^3 e^{-i\gamma}$	Penguin	$\lambda^3 e^{i\beta}$	Yes	Penguin <i>pollution</i> , <i>direct CPV</i>
$\pi^+\pi^0$	Tree	$\lambda^3 e^{-i\gamma}$	Tree colour suppressed	$\lambda^3 e^{-i\gamma}$	No	No strong penguin for Isospin symmetry
$\pi^0\pi^0$	Penguin	$\lambda^3 e^{i\beta}$	Tree colour suppressed	$\lambda^3 e^{-i\gamma}$	Yes	Measured BR smaller than $\pi^+\pi^-$
$K^+\pi^-$	Tree	$\lambda^4 e^{-i\gamma}$	Penguin	$\lambda^2$	Yes	Penguin should dominate
$\pi^+K^0$	Penguin	$\lambda^2$	Annihilation	$\lambda^4 e^{-i\gamma}$	No	Penguin should dominate
$K^+\pi^0$	Tree, and Tree c.s.	$\lambda^4 e^{-i\gamma}$	Penguin	$\lambda^2$	Yes	As $K^+\pi^-$ , with more diagrams
$\pi^0K^0$	Penguin	$\lambda^2$	Tree, colour suppressed	$\lambda^3 e^{-i\gamma}$	No	Penguin should dominate
$K^+K^-$	Exchange.	$\lambda^3 e^{-i\gamma}$	-----	-----	No	Tiny BR expected
$K^+K^0$	Penguin	$\lambda^3 e^{i\beta}$	Annihilation	$\lambda^3 e^{-i\gamma}$	No	Penguin should dominate
$K^0K^0$	Penguin	$\lambda^3 e^{i\beta}$	-----	-----	No	Penguin dominated

These modes are background to one another, so a maximum likelihood combined fit is performed to disentangle each contribution, for example  $B^0 \rightarrow h^+ h^-$  or  $B^+ \rightarrow h^+ \pi^0$ , where  $h$  is a pion or a kaon. The signal yields are then simultaneously determined.

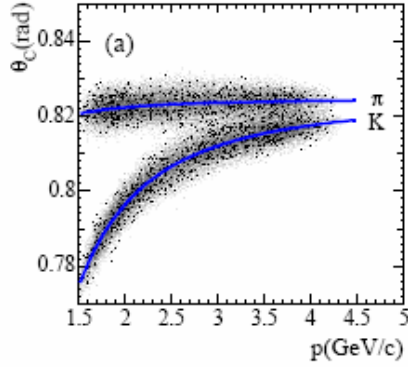


Fig.41. The measured Cherenkov angle distribution for pions and kaons from BABAR data. The lines show the expected angle  $\theta_c$  as a function of laboratory momentum

The  $\pi^0 \pi^0$  mode is particularly challenging to measure, and has been now firmly established at both B-factories.

All measurements, including the previous CLEO results, are in excellent agreement. The  $K\pi$  modes are at least a factor four higher than the  $\pi\pi$  modes, and this indicates that the Penguin contributions are large.

In a very naïve approximation, if we simply treat the amplitude in Table IV as real, from  $A_{K\pi} \geq 2A_{\pi\pi}$ , we find  $P/T \geq 0.6$ .

TABLE V: BABAR's, BELLE's and CLEO's measured branching fractions of two-body charmless B mesons decays.

Final state	BABAR BF/ ( $10^{-6}$ )	Refs.	BELLE BF/ ( $10^{-6}$ )	Refs.	CLEO BF/ ( $10^{-6}$ )	Refs.
$\pi^+ \pi^-$	$4.7 \pm 0.6 \pm 0.2$	69	$4.4 \pm 0.6 \pm 0.3$	107	$4.6^{+1.4+0.5}_{-1.2-0.4}$	108
$\pi^0 \pi^0$	$1.17 \pm 0.32 \pm 0.10$	73	$2.32 \pm^{+0.44+0.22}_{-0.48-0.18}$	74	$< 4.4$	108
$\pi^+ \pi^0$	$5.8 \pm 0.6 \pm 0.4$	73	$5.0 \pm 1.2 \pm 0.5$	107	$4.6^{+1.8+0.6}_{-1.6-0.7}$	108
$K^+ \pi^-$	$17.9 \pm 0.9 \pm 0.7$	69	$18.5 \pm 1.0 \pm 0.7$	107	$18.0^{+2.3+1.2}_{-2.1-0.9}$	108
$K^+ \pi^0$	$12.0 \pm 0.7 \pm 0.6$	73	$12.0 \pm 1.3^{+1.3}_{-0.9}$	107	$12.9^{+2.4+1.2}_{-2.2-1.1}$	108
$K_S \pi^0$	$11.4 \pm 0.9 \pm 0.6$	64	$11.7 \pm 2.3^{+1.2}_{-1.3}$	107	$12.8^{+4.0+1.7}_{-3.3-1.4}$	108
$K_S \pi^+$	$26.0 \pm 1.3 \pm 1.0$	109	$22.0 \pm 1.9 \pm 1.1$	107	$18.8^{+3.7+2.1}_{-3.3-1.8}$	108
$K^+ K^-$	$< 0.6$	69	$< 0.7$	107	$< 0.8$	108
$K^+ \bar{K}^0$	$1.45^{+0.53}_{-0.46} \pm 0.11$	109	$< 3, 3$	107	$< 3.3$	108
$K^0 \bar{K}^0$	$1.19^{+0.40}_{-0.35} \pm 0.13$	109	$< 1.5$	107	$< 3.3$	108

## 7.2 Observation of direct CP violation in B decays

The first claim to observation of direct CP violation in B decays was made by BELLE with the result [72] reported in 5.1 on the asymmetry in  $B^0 \rightarrow \pi^+ \pi^-$ . In a sample of  $152 \times 10^6$  million events, the unbinned maximum likelihood fit to the 1529 candidates (801  $B^0$  tags and 728  $\bar{B}^0$  tags), containing  $372 \pm 32$   $\pi^+ \pi^-$  signal events, yields  $C_{\pi\pi} = -0.58 \pm 0.15(\text{stat}) \pm 0.07(\text{syst})$ . This was interpreted as a greater than  $3.2\sigma$  evidence of direct CP violation in the  $\pi^+ \pi^-$  channel, but was not confirmed by BABAR, who found [71] a value consistent with zero ( $C_{\pi\pi} = -0.09 \pm 0.15(\text{stat}) \pm 0.04(\text{syst})$ ).

A statistically significant asymmetry was recently reported [110] by BABAR in the  $B^0$  decay into  $K^+ \pi^-$  versus the  $\bar{B}^0$  into  $K^- \pi^+$ ; by analyzing the full sample of  $B \bar{B}$  events (227 millions) BABAR finds  $1606 \pm 51$  decays, with an asymmetry (also clearly visible from the  $m_{ES}$  plot shown in Fig. 42):

$$A_{K^+ \pi^-} = \frac{N_{K^- \pi^+} - N_{K^+ \pi^-}}{N_{K^- \pi^+} + N_{K^+ \pi^-}} = -0.133 \pm 0.030 \pm 0.009$$

This value is  $4.2 \sigma$  away from zero, and consistent with previous, less precise measurements. The background asymmetry (also shown in Fig. 42), is  $0.001 \pm 0.008$ .

This result was soon after confirmed by BELLE [111] (see Fig 43), with the value:

$$A_{K^+ \pi^-} = -0.101 \pm 0.025 \pm 0.005$$

which was also obtained with the full sample of available events. The combined result is more than  $5\sigma$  away from zero, so we can conclude that direct CP violation has definitely been observed in B decays. No asymmetry has been observed in the charged channels  $K^0 \pi^+$  or  $K^+ \pi^0$ .

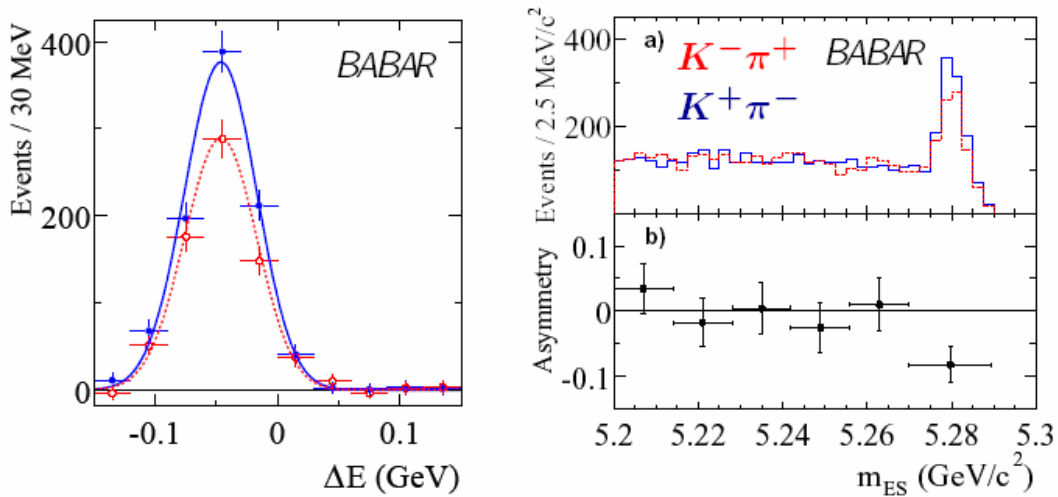


Fig.42. Left: Distribution of  $\Delta E$  in data (points with error bars) and the PDFs (curves) used in the maximum likelihood fit for  $K^+ \pi^-$  (solid circles and solid curve) and  $K^- \pi^+$  (open circles and dashed curve). Right: Distribution of  $M_{ES}$  enhanced in  $K^+ \pi^-$  (solid) and  $K^- \pi^+$  (dashed) in the top plot and CP asymmetry calculated for different ranges of  $M_{ES}$  in the bottom plot.

The two experiments are in good agreement, except for the already discussed  $3\sigma$  discrepancy in the  $\pi^+ \pi^-$  final state. The statistical errors still dominate in these

results, so much more data are needed for a detailed comparison with the many theoretical models.

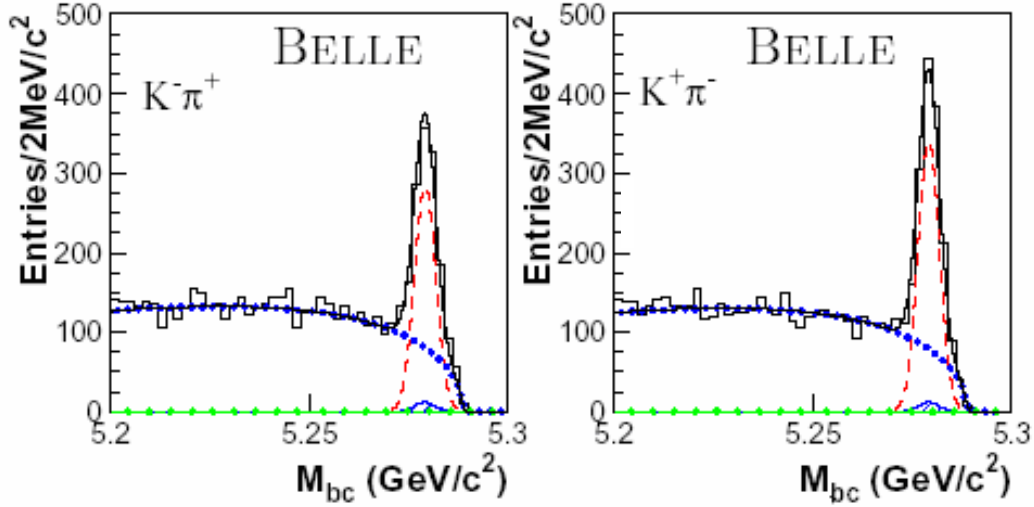


Fig.43. *BELLE* invariant mass distributions for  $K^-\pi^+$  (left) and  $K^+\pi^-$  (right); The histograms represent the data, while the curves represent the various components from the fit: signal (dashed), continuum (dotted), three-body  $B$  decays (dash-dotted), background from mis-identification (hatched), and sum of all components (solid)

A summary on the results obtained for the coefficients  $C$  and  $S$  for the time dependent asymmetries in neutral  $B$  decays to CP eigenstates, and the time integrated asymmetries  $A_f$  in the self tagging neutral or charged modes are reported in Table VI.

TABLE VI: *BABAR's* and *BELLE's* results from the CP analysis of  $B^0$  two-body charmless decays; the parameters  $S$ ,  $C$  and  $A$  are defined in the text.

Mode	BABAR		BELLE	
	C	S	C	S
$\pi^+\pi^-$	$-0.09 \pm 0.15 \pm 0.04$	$-0.30 \pm 0.17 \pm 0.03$	$-0.58 \pm 0.15 \pm 0.07$	$-1.00 \pm 0.21 \pm 0.07$
$\pi^0\pi^0$	$0.12 \pm 0.56 \pm 0.06$		$0.43 \pm 0.51 \pm 0.17$	
$\pi^0K^0$	$0.06 \pm 0.18 \pm 0.06$	$0.35^{+0.30}_{-0.33} \pm 0.59 \pm 0.04$	$0.12 \pm 0.20 \pm 0.07$	$0.30 \pm 0.59 \pm 0.11$
	A		A	
$\pi^+\pi^0$	$0.01 \pm 0.10 \pm 0.02$		$-0.02 \pm 0.10 \pm 0.01$	
$K^+\pi^-$	$-0.133 \pm 0.030 \pm 0.009$		$-0.101 \pm 0.025 \pm 0.005$	
$\pi^+K^0$	$-0.087 \pm 0.046 \pm 0.010$		$0.05 \pm 0.05 \pm 0.01$	
$K^+\pi^0$	$0.06 \pm 0.06 \pm 0.01$		$0.04 \pm 0.05 \pm 0.01$	
$K^+K^0$	$1.15^{+0.33}_{-0.35} \pm 0.03$			

### 7.3 Charmless two body $\eta\pi$ , $\eta K$ , $\eta'\pi$ , $\eta'K$ , $\omega\pi$ , $\omega K$ final states

The large number, and the cleanness, of BB events at the B-factories, combined with the excellent performances of the detectors, have made possible the discovery of many rare decay modes, including two-body charmless final states with a  $\eta$ ,  $\eta'$  or  $\omega$  particle accompanied by a pion or a kaon. Charmless decays with kaons are usually expected to be dominated by penguin amplitudes, while  $b \rightarrow u$  tree transitions

are typically larger for the decays into pions. The  $B \rightarrow \eta K$  decays are especially interesting since they are suppressed relative to the  $B \rightarrow \eta' K$  modes due to destructive interference between two penguin amplitudes [112].

The CKM-suppressed  $b \rightarrow u$  amplitudes may interfere significantly with the suppressed penguin amplitudes and this may lead to large direct CP violation in the  $\eta K^+$  decay as well as  $\eta \pi^+$ , and  $\eta' \pi^+$  [113] and some numerical estimates can be found in literature [114]. These decays are also useful to test the accuracy of theoretical predictions such as QCD factorization [115]. Phenomenological fits to the branching fractions and charge asymmetries can be used to understand the importance of tree and penguin contributions and may even provide sensitivity to the CKM angle  $\gamma$  [116].

BABAR and BELLE have measured the branching fractions and the CP asymmetries for the charged B mesons decays; the experimental methods they use to identify these final states are similar: the  $\eta$  is reconstructed from  $\gamma\gamma$  and  $\pi^+ \pi^- \pi^0$ , the  $\omega$  in the  $\pi^+ \pi^- \pi^0$  mode, the  $K_S$  in  $\pi^+ \pi^-$ . The more recent results are shown in Table VII. There are a few points that it is worth to mention on these measurements:.

- The branching ratio for the decay  $B^0 \rightarrow \eta' K^0$  is 3-10 times larger than originally expected [117] and this has initiated a number of possible explanations, including positive interference between penguin diagrams in which the spectator quark is contained in the  $\eta'$  or in the Kaon [118].

TABLE VII: *Results from BABAR and BELLE for the branching ratios and CP asymmetries (charged modes) of 2-body charmless decays with an  $\eta$ ,  $\eta'$  or  $\omega$  meson.*

Mode	BABAR BF( $\times 10^{-6}$ ) Refs. [119]	BELLE BF( $\times 10^{-6}$ ) Refs [120]	BABAR $A_{CP}$	BELLE $A_{CP}$
$B^0 \rightarrow \eta \pi^0$		$1.2 \pm 0.7 \pm 0.1$		
$B^0 \rightarrow \eta K_S$	$2.5 \pm 0.8 \pm 0.1$	$0.3^{+0.9}_{-0.7} \pm 0.1$		
$B^0 \rightarrow \eta \eta$		$0.7^{+0.7}_{-0.6} \pm 0.1$		
$B^+ \rightarrow \eta \pi^+$	$5.3 \pm 1.0 \pm 0.3$	$4.8 \pm 0.7 \pm 0.3$	$-0.44 \pm 0.18 \pm 0.01$	$0.07 \pm 0.15 \pm 0.03$
$B^+ \rightarrow \eta K^+$	$3.4 \pm 0.8 \pm 0.2$	$2.1 \pm 0.6 \pm 0.2$	$-0.52 \pm 0.24 \pm 0.01$	$-0.49 \pm 0.31 \pm 0.07$
$B^0 \rightarrow \eta \omega$	$1.2 \pm 0.6 \pm 0.2$			
$B^0 \rightarrow \omega \pi^0$	$< 1.2$	$< 1.9$		
$B^+ \rightarrow \omega \pi^+$	$5.5 \pm 0.9 \pm 0.5$	$5.7^{+1.4}_{-1.3} \pm 0.6$	$0.03 \pm 0.16 \pm 0.01$	$0.50^{+0.23}_{-0.20} \pm 0.02$
$B^0 \rightarrow \omega K_S$	$5.9^{+1.6}_{-1.3} \pm 0.5$	$< 7.6$ (90% c.l.)		
$B^+ \rightarrow \omega K^+$	$4.8 \pm 0.8 \pm 0.4$	$6.5^{+1.3}_{-1.2} \pm 0.6$	$-0.09 \pm 0.17 \pm 0.01$	$0.06^{+0.21}_{-0.18} \pm 0.01$
$B^0 \rightarrow \eta' \pi^0$	$< 5.7$	$< 3.7$		
$B^0 \rightarrow \eta' K^0$	$60.6 \pm 5.6 \pm 4.6$	$68 \pm 10^{+9}_{-8}$		
$B^+ \rightarrow \eta' \pi^+$	$2.7 \pm 1.2 \pm 0.3$		$24 \pm 19 \pm 1$	
$B^+ \rightarrow \eta' K^+$	$76.9 \pm 3.5 \pm 4.4$	$78 \pm 6 \pm 9$		

- Although uncertainties are still large, due to the small branching ratios and large continuum background, the values of the asymmetries for modes where a small value is expected, as in the modes containing  $\omega$  mesons, are indeed consistent with zero. The asymmetries for  $B^+ \rightarrow \eta \pi^+$  and  $B^+ \rightarrow \eta K^+$  where large values have been

anticipated [121] are consistent with zero within less than  $3\sigma$ , but 3 out of the 4 central values are quite high. As before, all numbers from contributed papers to the 2004 ICHEP Conference must be considered preliminary.

#### 7.4 Charmless two body $VV$ final states

The decays to two vector particles are of special interest because their angular distributions reflect both strong and weak interaction dynamics [122]. The asymmetries constructed from the number of B decays with each flavour and with each sign of a triple product are sensitive to CP violation or to final state interactions (FSI) [123]. The triple product is defined as  $(\mathbf{q}_1 - \mathbf{q}_2) \cdot \mathbf{p}_1 \times \mathbf{p}_2$ , where  $\mathbf{q}_1$  and  $\mathbf{q}_2$  are the momenta of the two vector particles in the B frame and  $\mathbf{p}_1$  and  $\mathbf{p}_2$  represent their polarization vectors (see Fig. 44 for the decay  $B^0 \rightarrow \phi K^{*0}$ , followed by  $\phi \rightarrow K^+ K^-$ ,  $K^{*0} \rightarrow K^+ \pi^-$ )

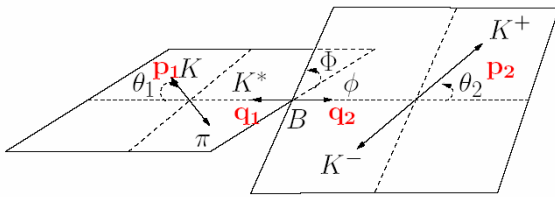


Fig. 44 Helicity frames for the decay  $B^0 \rightarrow \phi K^{*0}$ , followed by  $\phi \rightarrow K^+ K^-$ ,  $K^{*0} \rightarrow K^+ \pi^-$

The first evidence for the decays of B mesons to pairs of charmless vector mesons was provided by CLEO [124] with the observation of  $B \rightarrow \phi K$ . The CLEO experiment also set upper limits on the B decay rates for several other vector-vector final states [125]

BABAR and BELLE have measured a number of vector-vector

B meson decays involving  $\phi$ ,  $\rho$ , and  $K^*$  (892) resonances, with full reconstruction of the charged and neutral decay products, including the intermediate states  $\phi \rightarrow K^+ K^-$ ,  $K^{*0} \rightarrow K^+ \pi^-$  and  $K^0 \pi^0$ ,  $K^{*+} \rightarrow K^+ \pi^0$  and  $K^0 \pi^+$ ,  $\rho^0 \rightarrow \pi^+ \pi^-$ ,  $\rho^+ \rightarrow \pi^+ \pi^0$ , with  $\pi^0 \rightarrow \gamma\gamma$  and  $K_S \rightarrow \pi^+ \pi^-$  (inclusion of the charge conjugate states is implied).

We have already discussed how the  $B \rightarrow \phi K^*$  decays proceed via pure  $b \rightarrow s$  penguin diagrams, while the decay  $B^+ \rightarrow \rho^+ \rho^0$  is a tree-dominated  $b \rightarrow u$  process; the decay  $B \rightarrow \rho K^*$  is expected to have both loop and tree contributions. The comparison of the branching ratios values for all these modes would provide interesting information on the relative importance of the implicated amplitudes.

In Table VIII the branching ratios and the asymmetries from BABAR and BELLE are listed. All results presented at the Summer 2004 conferences (see bibliography) should be considered preliminary; the scope of the table, however, is just to present a picture of the experimental situation, and point out that statistical errors are still large (but in several cases approach the systematic uncertainties), and a stringent test of the SM is not yet possible.

The rates for  $B^+ \rightarrow \rho^+ \rho^0$  and  $B^0 \rightarrow \rho^+ \rho^-$  are larger than that of the  $\pi\pi$  modes; the rates for  $\rho K^*$  are not significantly larger than  $\pi K$ ; this experimental picture suggests that the penguin contributions are much smaller in the  $\rho\rho$  than in the  $\pi\pi$ , making the former a better candidate for the  $\sin 2\alpha$  measurement

In addition to rate asymmetries,  $B \rightarrow VV$  decays provide opportunities to search for direct CP and/or T violation through angular correlations between the vector meson decay final states. In these decays three helicity states are possible: 0, +1, -1. The SM predicts, assuming naive factorization, almost complete (>90%) longitudinal polarization with the relations:  $R_0 \gg R_T = (R_\perp + R_\parallel)$ , and [126]  $R_\perp \approx R_\parallel$ , where  $R_0$  ( $R_T$ ,  $R_\perp$ ,  $R_\parallel$ ) is the longitudinal (transverse, perpendicular, parallel) polarization fraction in the transversity basis [127].

The data [128] indicate that the  $\rho^0\rho^+$ ,  $\rho^+\rho^-$  and the  $\rho^0K^{*+}$  final states are indeed almost completely longitudinally polarized, while the  $\Phi K^{*0}$  and  $\Phi K^{*+}$  are only about 50%. Furthermore, the decay  $B\rightarrow\phi K^*$  does not agree with the SM expected hierarchy of the amplitudes:  $|A_0|\gg|A_{+1}|$ , while it agrees with  $|A_{+1}|\gg|A_{-1}|$ ; this is commonly referred to as the  $\Phi K^*$  puzzle and needs more investigation, both theoretically and experimentally.

TABLE VIII: Results from BABAR and BELLE for the branching ratios and CP asymmetries for vector-vector B decays.

Mode	BABAR BF( $\times 10^{-6}$ ) Refs. [128,129]	BELLE BF( $\times 10^{-6}$ ) Refs [130]	BABAR $A_{CP}$	BELLE $A_{CP}$
$B^+\rightarrow\rho^+K^{*0}$	$17.0\pm 2.9^{+2.0}_{-2.8}$	$6.6\pm 2.2\pm 0.8$	$-0.14\pm 0.17\pm 0.04$	
$B^+\rightarrow\rho^0K^{*+}$	$10.6^{+3.0}_{-2.6}\pm 2.4$	----	$0.20^{+0.32}_{-0.29}\pm 0.04$	
$B^+\rightarrow\phi K^{*+}$	$12.7^{+2.2}_{-2.0}\pm 1.1$	$6.7^{+2.1+0.7}_{-2.0-1.0}$	$0.16\pm 0.17\pm 0.03$	$0.13\pm 0.29^{+0.08}_{-0.11}$
$B^+\rightarrow\rho^+\rho^0$	$22.5^{+5.7}_{-5.4}\pm 5.8$	$31.7\pm 7.1^{+3.8}_{-6.7}$	$-0.19\pm 0.23\pm 0.03$	$0.00\pm 0.22\pm 0.03$
$B^0\rightarrow\rho^0K^{*0}$		$< 2.6$		
$B^0\rightarrow\rho^-K^{*+}$	$< 24$	----		
$B^0\rightarrow\rho^+\rho^-$	$30\pm 4\pm 5$			
$B^0\rightarrow\phi K^{*0}$	$9.2\pm 0.9\pm 0.5$	$10.0^{+1.6+0.7}_{-1.5-0.8}$	$0.04\pm 0.12\pm 0.02$	$0.07\pm 0.15^{+0.05}_{-0.03}$
$B^0\rightarrow\rho^0\rho^0$	$< 1.1$			
$B^0\rightarrow\phi\phi$	$< 1.5$			

### 7.5 Radiative Penguins

Rare B decays into a final state with a photon or a lepton pair plus a strange particle proceed through a FCNC process, typically a  $b\rightarrow s\gamma$  which is forbidden at tree level and requires a penguin loop, as in Fig 45, or other higher order diagrams. If the photon is virtual, or if a  $Z^0$  is emitted instead, the final state includes a lepton pair. In the Standard Model the dominant loop contribution contains a top quark, with other contributions being suppressed by CKM factors and the GIM mechanism. The lack of interference between comparable amplitude contributions leads to a rather small predicted direct asymmetry  $A_{CP}$ .

These processes are of great interest since they are sensitive to the effects of non-SM particles, charged Higgs or SUSY particles for example, that may enter the loop. The radiative rate  $b\rightarrow s\gamma$  is not too tiny; these decays were first discovered by CLEO in 1993 and studied also by the LEP experiments before the B-factories era. In the last five years BABAR and BELLE have performed the measurements of several exclusive final states, and improved the precision for the inclusive  $B\rightarrow X_s\gamma$  branching fraction.

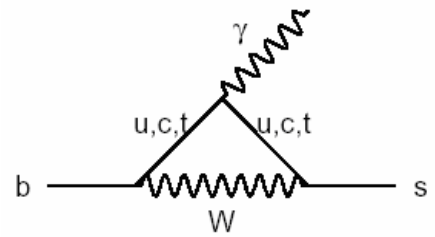


Fig. 45: the  $b\rightarrow s\gamma$  penguin diagram



In the inclusive process, the photon energy spectrum is mainly concentrated in the 2.0 to 2.7 GeV region, and has a peak at approximately half of the b quark mass, the signal, however, is submerged in a huge background; the main contribution is from high energy photons from  $\pi^0$  and  $\eta$  decays in the continuum, and radiative  $e^+e^- \rightarrow q\bar{q}\gamma$  events, These non-B backgrounds can be subtracted using the off Y(4S) peak data, while the contribution from B events can only be estimated using Monte Carlo samples. B events background mostly contribute in the lower photon energy region, so a cut is necessary, which determines a loss of the signal.

To determine the inclusive branching fraction it is therefore necessary to extrapolate the spectrum below this  $E_{\gamma\text{min}}$  cut using a theoretical calculation such as that of Neubert and Kagan [131]. The inclusive photon spectrum is a relevant measurement, since the branching ratio is theoretically freer from uncertainties than the exclusive modes; the  $A_{\text{CP}}$  asymmetry provides an additional test to the SM and has little sensitivity to the photon energy cut-off or to the distribution of hadronic final states.

a) Inclusive measurements.

Several published results are summarized in Table IX; the 2004 PDG average of  $(3.3 \pm 0.4) \times 10^{-4}$  is in good agreement with the theoretical SM prediction [132] of  $(3.57 \pm 0.30) \times 10^{-4}$ ; such an agreement poses quite tight constraints to new physics effects. Models where the only effect of new Physics is a constructive interference with the SM processes are not favoured; many SUSY models can, however, accommodate the addition of a destructive amplitude which could cancel the constructive one. The experimental error is already at the level of the theoretical uncertainties (and the quoted results refer to less than one half of the data now available); for a more meaningful comparison, both more precise measurements (decreasing the energy cut would help) and improved theory calculations are needed.

TABLE IX: *Inclusive measurements for the branching ratio  $b \rightarrow s\gamma$  decay; the sample size and the reference are also indicated*

Experiment	Sample	BF( $b \rightarrow s\gamma$ ) $\times 10^{-4}$	Reference
BABAR	54.8 fb <sup>-1</sup>	3.88 $\pm$ 0.36 $\pm$ 0.37	[133]
ALEPH	4.1 M Z <sup>0</sup>	3.11 $\pm$ 0.80 $\pm$ 0.72	[134]
CLEO	9.1 fb-1	3.21 $\pm$ 0.43 $\pm$ 0.27	[135]
BELLE	140 fb-1	3.35 $\pm$ 0.32 $\pm$ 0.30	[136]

BABAR has measured the  $A_{\text{CP}}$  for the inclusive process, by reconstructing  $b \rightarrow s$  decays as the sum of twelve exclusive, and flavour specific, final states; the result [137]:

$$A_{\text{CP}}(b \rightarrow s) = 0.025 \pm 0.050(\text{stat.}) \pm 0.015(\text{syst.})$$

can be expressed as a 90%CL for  $A_{\text{CP}}$  being in the range  $-0.06 \div 0.11$ ; BELLE uses a pseudo-reconstruction technique to reconstruct the hadronic recoil system Xs and finds [138]:

$$A_{\text{CP}}(b \rightarrow s) = 0.002 \pm 0.050(\text{stat.}) \pm 0.030(\text{syst.})$$

Both experiments in their analysis require a kaon in the recoil system to the photon, to eliminate  $b \rightarrow d$  contamination, since it is expected [139] that CP asymmetries in  $b \rightarrow d$  and  $b \rightarrow s$  cancel; the results are consistent with the SM expectation of small asymmetry.

b) Exclusive modes.

The large data samples collected at the B-factories have allowed also semi-inclusive and exclusive measurements, for final states, with a photon, a kaon and a

number of up to four pions. This method has the advantage of being experimentally much cleaner, since powerful cuts on the beam substituted mass  $M_{ES}^2 = E_{Beam}^2 - p_B^2$  and the energy difference  $\Delta E = E_B^* - E_{beam}^*$  can be applied, but suffers from additional model dependent theoretical uncertainties.

Unfortunately there are large uncertainties associated with the hadronization of the s quark into a meson, so that these more precise measurements cannot be reliably translated into a determination of the rate at parton level. The dominant mode is the  $B \rightarrow K^* \gamma$  decay, and this is the best measured both for neutral and charged Bs; the results from CLEO, BABAR [140] and BELLE [141] are in good agreement and are shown in Table X.

Comparing with the inclusive result, we observe from table X that (35±6)% of the total  $B \rightarrow X_s \gamma$  rate is measured to be either  $B \rightarrow K^* \gamma$  (12.5%),  $B \rightarrow K^{*2} \gamma$  (4% after excluding  $K\pi\pi\gamma$ ),  $B \rightarrow K^* \pi \gamma$  (9%),  $B \rightarrow K \rho \gamma$  (9%) or  $B \rightarrow K \phi \gamma$  (1%). The remaining (65 ± 6)% may be accounted for by decays with multi-body final states, baryonic decays, modes with  $\eta$  and  $\eta'$ , multi-kaon final states other than  $K\phi\gamma$  or in the large  $X_s$  mass range

TABLE X: *BABAR and BELLE results, together with earlier CLEO measurements for some exclusive  $b \rightarrow s \gamma$  final states.*

Mode	BABAR BF ( $10^{-5}$ )	BELLE 143 BF ( $10^{-5}$ )	CLEO BF ( $10^{-5}$ )
$B^0 \rightarrow K^{*0}(892) \gamma$	$3.92 \pm 0.20 \pm 0.24$	$4.01 \pm 0.21 \pm 0.17$	$4.55 \pm 0.70 \pm 0.34$
$B^0 \rightarrow K^{*0}(1410) \gamma$		<13	$0.08 \pm 0.13 \pm 0.03$
$B^0 \rightarrow K_2^{*0}(1430) \gamma$	$1.22 \pm 0.25 \pm 0.11$	$1.3 \pm 0.5 \pm 0.1$	
$B^+ \rightarrow K^{*+}(892) \gamma$	$3.87 \pm 0.28 \pm 0.26$	$4.25 \pm 0.31 \pm 0.24$	$3.76 \pm 0.86 \pm 0.28$
$B^+ \rightarrow K^{*0} \pi^+ \gamma$		$2.0 \pm 0.7 \pm 0.2$	
$B^+ \rightarrow K^+ \rho^0 \gamma$		< 2	
$B^+ \rightarrow K^+ \phi \gamma$		$0.34 \pm 0.09 \pm 0.04$	

### c) Asymmetries

Much of the theoretical uncertainties in the branching fractions cancel in the ratios defining the isospin asymmetry:

$$\Delta_{0-} = \frac{\Gamma(\bar{B}^0 \rightarrow \bar{K}^{*0} \gamma) - \Gamma(B^- \rightarrow \bar{K}^{*-} \gamma)}{\Gamma(\bar{B}^0 \rightarrow \bar{K}^{*0} \gamma) + \Gamma(B^- \rightarrow \bar{K}^{*-} \gamma)}$$

and the direct CP asymmetry:

$$A_{CP} = \frac{\Gamma(\bar{B} \rightarrow \bar{K}^* \gamma) - \Gamma(B \rightarrow K^* \gamma)}{\Gamma(\bar{B} \rightarrow \bar{K}^* \gamma) + \Gamma(B \rightarrow K^* \gamma)}$$

hence these are stringent tests of the SM. A further advantage of these asymmetries is that some of the experimental systematic uncertainties also cancel in the ratios. The SM predicts a positive value of  $\Delta_{0-}$  between 5 and 10%, while in some SM extensions it may have an opposite sign [142] and  $|A_{CP}|$  less than 1%. A large CP-asymmetry would be a clear sign of new physics, and these references also indicate how new physics contributions can modify these values significantly.

BABAR [140] finds the isospin asymmetry to be in the range  $-0.046 \div 0.146$  and the CP asymmetry to be  $-0.074 \div 0.049$ , both at 90% c.l., BELLE [143] has also performed the  $A_{CP}$  measurement finding:

$$\Delta_{0+} = +0.012 \pm 0.044(\text{stat}) \pm 0.026(\text{syst})$$

$$A_{CP}(B \rightarrow K^* \gamma) = -0.015 \pm 0.044(\text{stat}) \pm 0.012(\text{syst}).$$

both experiments are therefore consistent with SM predictions.

BABAR has also measured the first time dependent asymmetry in a  $b \rightarrow s\gamma$  process, through the exclusive decay  $B^0 \rightarrow K^{*0}\gamma$ . Such measurement probes the polarization of the photon, which is dominantly left-handed for  $b \rightarrow s\gamma$  in the SM, but is mixed in various new physics scenarios, as pointed out in ref [144].

The CPV asymmetry due to interference between decays with or without mixing is expected to be very small,  $\approx 2(m_s/m_b) \sin 2\beta$ , and any significant deviation would indicate phenomena beyond the SM. BABAR [145] finds:  $S_{K^*\gamma} = 0.25 \pm 0.63 \pm 0.14$  and

$C_{K^*\gamma} = -0.57 \pm 0.32 \pm 0.09$ , where the first error is statistical and the second systematic, consistent with the SM expectation.

#### d) $b \rightarrow d\gamma$

If the  $s$  quark in Figure 45 is replaced by a  $d$  quark, the final state will be  $\rho\gamma$ ,  $\omega\gamma$ , etc. Also in this case the amplitude is dominated by a  $t$  quark in the loop, so the  $B \rightarrow Xd$  yield is reduced compared to  $B \rightarrow Xs$  by a factor approximately  $(|V_{td}|/|V_{ts}|)^2 \approx 0.04$ , where the uncertainty is due to the lack of precise knowledge of  $V_{td}$ . Measurements of these exclusive branching fractions could help in improving the constraints on  $V_{td}$  in the context of the SM, and the sensitivity to physics beyond the SM that is complementary to that from  $b \rightarrow s\gamma$ .

The first searches for these rare decays have targeted the exclusive states, with a  $\rho$  or a  $\omega$  light meson plus a photon. Recent calculations [146] of the branching ratio for  $B \rightarrow (\rho/\omega)\gamma$  in the SM indicate a range of  $(0.9 - 2.7) \times 10^{-6}$ ; in literature [147] there are a number of speculations on how contributions of new particles in the loop could modify this estimate.

Recent searches from BABAR [148] and BELLE [149] were performed using the full sample of available data; the main backgrounds come from continuum events, where the accidental combination of a  $\rho$  or an  $\omega$  with a photon fakes a B candidate. Both experiments use event shape and other topological cuts to suppress this background, as well as the separation between the vertex of the tracks of the B candidate and the other tracks in the event. Significant backgrounds also come from  $B \rightarrow K^*\gamma$ , additional  $B \rightarrow X_s \gamma$  processes,  $B \rightarrow \rho\pi^0$  and  $\rightarrow \omega\pi^0$ , and other charmless decays.

The signal yields, obtained after the fitting procedure is applied, have too small statistical significance so only upper limits, at the 90% confidence level, are

quoted; these are already in the SM range, as reported in Table XI. The upper limits (90% c.l.) on  $|V_{td}|/|V_{ts}|$  that the two experiments obtain using the indications of ref [146] are 0.21 (BELLE) and 0.19 (BABAR), consistent with fits of the CKM matrix which use different processes.

TABLE XI: *BABAR and BELLE results on their full data sample (as of Summer 2004) for the modes  $B \rightarrow \rho \gamma$  and  $B \rightarrow \omega \gamma$ . For each experiment reconstruction efficiencies and measured branching ratios are reported; the BABAR numbers for the signal yields give an idea of the statistics.*

Mode	BABAR (211 M BB)			BELLE (274M BB)	
	Yield	$\epsilon(\%)$	BF ( $10^{-6}$ ) 90% c.l.	$\epsilon(\%)$	BF ( $10^{-6}$ ) 90% c.l.
$B^0 \rightarrow \rho^0 \gamma$	$0.3^{+7.2+1.7}_{-5.4-1.6}$	$15.8 \pm 1.9$	$< 0.4$	$3.9 \pm 0.3$	$< 0.8$
$B^+ \rightarrow \rho^+ \gamma$	$26^{+15+2}_{-14-2}$	$13.2 \pm 1.4$	$< 1.8$	$5.5 \pm 0.4$	$< 2.2$
$B^0 \rightarrow \omega \gamma$	$8.3^{+5.7+1.3}_{-4.5-1.9}$	$8.6 \pm 0.9$	$< 1.0$	$3.9 \pm 0.4$	$< 0.8$

## 7.6 Electroweak Penguins

The  $B \rightarrow X_s \ell^+ \ell^-$  modes proceed through an electromagnetic penguin loop, or a  $Z^0$  penguin loop; a weak box diagram is also possible, as shown in Fig.46. The presence of three SM electroweak amplitudes makes these processes more interesting; the presence, however, of the long-distance contributions due to  $c \bar{c}$  resonances decaying into  $\ell^+ \ell^-$  pairs, makes the theoretical uncertainties on

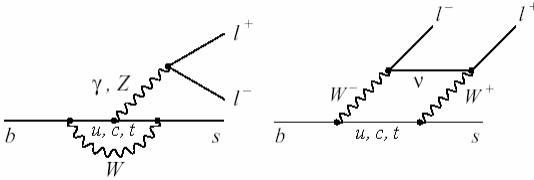


Fig. 46: *Diagrams for  $b \rightarrow s \ell^+ \ell^-$  transitions*

the rates quite high.

In the framework of the operator product expansion (OPE) the decay rate is factorized into short-distance contributions that are parameterized by scale-dependent Wilson coefficients, and non-perturbative long-distance effects that are represented by local four quark operators. Operator mixing occurring in next-to-leading order perturbation theory leads to three effective scale-dependent Wilson coefficients  $C_7$ ,  $C_9$  and  $C_{10}$ , sensitive to new physics contributions [150]. To disentangle all of them it is necessary to measure  $d\Gamma/d\hat{s}$ , the branching fraction as a function of  $\hat{s}=q^2/m_b^2$ , and the forward-backward asymmetry  $dA_{FB}/d\hat{s}$ .

This would allow to determine completely these coefficients, including their sign; it has been shown [151] that non SM contributions could change the sign, without affecting the branching ratio.

The decay  $B \rightarrow K \ell^+ \ell^-$  was first observed by BELLE [152] using a  $29\text{fb}^{-1}$  data sample and confirmed by BABAR [153] with  $78\text{fb}^{-1}$ ; more recent results refer to larger data samples and improved analysis techniques. These are quite similar for the two experiments: the final state reconstruction relies in the usual variables  $M_{\text{ES}}$  and  $\Delta E$ ; the main background comes from charmonium decays, with the charmonium state decaying into a lepton pair, and is removed by a cut in the windows around the  $J/\psi$  and  $\psi'$  masses.

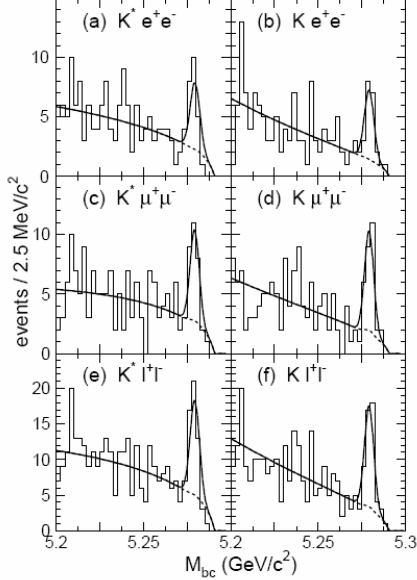


Fig 47: Invariant mass distributions for several electroweak decays obtained by BELLE using their full statistics. The solid and dashed curves are the fit results of the total and background contributions.

Additional backgrounds come from  $K\pi^+\pi^-$  modes, two leptons from semileptonic decays combined with a random  $K^{(*)}$ , continuum, and  $K^{(*)}\gamma$ , where the photon converts in  $e^+e^-$ , or  $K^{(*)}\pi^0$ , with  $\pi^0 \rightarrow e^+e^- \gamma$  decay

In the Standard Model the branching fractions are predicted to be within the ranges:

$$\text{Br}(B \rightarrow K \ell^+ \ell^-) = (0.23 \div 0.97) \times 10^{-6},$$

$$\text{Br}(B \rightarrow K^* \mu^+ \mu^-) = (0.81 \div 2.64) \times 10^{-6} \quad \text{and}$$

$\text{Br}(B \rightarrow K^* e^+ e^-) = (1.09 \div 3.0) \times 10^{-6}$ . The most recent measured branching fractions for exclusive states from BABAR (published results) and BELLE (preliminary results) are reported in Table XII.; BABAR's errors are statistical and systematic. BELLE adds the model dependent uncertainty. Fig 47 shows the invariant mass distribution for each channel and for the sum of electron and muon pairs, as obtained by BELLE with the full data sample (ref. [155]).

TABLE XII: Branching ratios for several  $b \rightarrow s \ell^+ \ell^-$  modes, as measured by BABAR and BELLE

Mode	BABAR [154] ( $123 \times 10^6$ BB events) BR( $\times 10^{-7}$ )	BELLE [155] ( $275 \times 10^6$ BB events) BR( $\times 10^{-7}$ )
$B^0 \rightarrow K^0 e^+ e^-$	$-2.1^{+2.3}_{-1.6} \pm 0.8$	$< 3$ (90% c.l.)
$B^0 \rightarrow K^0 \mu^+ \mu^-$	$16.3^{+8.2}_{-6.3} \pm 1.4$	$6.26^{+2.17+0.38}_{-1.81-0.41} \pm 0.04$
$B^0 \rightarrow K^*(892) e^+ e^-$	$11.1^{+5.6}_{-4.7} \pm 1.1$	$18.5^{+5.5}_{-4.9} \pm 1.1 \pm 1.5$
$B^0 \rightarrow K^*(892) \mu^+ \mu^-$	$8.6^{+7.9}_{-5.8} \pm 1.1$	$18.5^{+3.5}_{-3.1} \pm 1.0 \pm 0.3$
$B^+ \rightarrow K^+ e^+ e^-$	$10.5^{+2.5}_{-2.2} \pm 0.7$	$6.40^{+1.50+0.29}_{-1.34-0.31} \pm 0.05$
$B^+ \rightarrow K^+ \mu^+ \mu^-$	$0.7^{+1.9}_{-1.1} \pm 0.2$	$6.28^{+1.19+0.30}_{-1.08-0.31} \pm 0.13$
$B^+ \rightarrow K^{*+}(892) e^+ e^-$	$2.0^{+13.4}_{-8.7} \pm 2.8$ §	$16.0^{+10.4+1.2}_{-8.7-1.8} \pm 0.7$
$B^+ \rightarrow K^{*+}(892) \mu^+ \mu^-$	$30.7^{+25.8}_{-17.8} \pm 4.2$ §	$16.3^{+6.4+0.9}_{-5.4-1.2} \pm 0.5$

The inclusive measurements are even more challenging because the lepton pair alone is not sufficient to suppress the background from semileptonic decays; BABAR and BELLE obtain the inclusive result by summing up a number of final states with a

kaon ( $K^+$  or  $K_S$ ) and up to four pions. This approach allows to reconstruct a large fraction of the total inclusive rate. If the fraction of modes containing a  $K_L^0$  is assumed equal to that containing a  $K_S^0$ , the missing states represent  $\approx 30\%$  of the total rate and can be calculated using theoretical models, and this constitutes the dominant source for the uncertainty. The BABAR result<sup>156</sup> is

$$\text{Br}(B \rightarrow X_s \ell^+ \ell^-) = 5.6 \pm 1.5(\text{stat}) \pm 0.6(\text{exp syst}) \pm 1.3(\text{model syst})$$

and the BELLE<sup>157</sup> preliminary, updated value:

$$\text{Br}(B \rightarrow X_s \ell^+ \ell^-) = 4.11 \pm 0.83 (\text{stat}) \pm 0.7 (\text{syst})$$

can be compared with the SM prediction<sup>158</sup> of  $(4.6 \pm 0.8) \times 10^{-6}$ , integrated over the same dilepton mass range of  $M(\ell^+ \ell^-) > 0.2 \text{ GeV}$  used by the experiments.

A first attempt by BELLE to measure the forward backward asymmetry:

$$A_{FB} = \frac{\Gamma(\cos \theta_{Bl^+} > 0) - \Gamma(\cos \theta_{Bl^+} < 0)}{\Gamma(\cos \theta_{Bl^+} > 0) + \Gamma(\cos \theta_{Bl^+} < 0)}.$$

defined as the partial rate asymmetry between the positive and negative regions of  $\cos \theta_{Bl^+}$ , where  $\theta_{Bl^+}$  is the angle between the directions of the B meson and the positive lepton momenta, is consistent with zero for the  $Kl^+ \ell^-$  mode, as expected in the SM (this expectation is essentially unchanged by new physics<sup>159</sup>); in the more interesting mode  $K^* \ell^+ \ell^-$  the statistical significance is not enough to distinguish between SM and physics beyond.

While the measured errors on the branching fractions are already close to the SM uncertainties, and model dependent variations, it is too early to fit the  $q^2$  distributions, or the  $A_{FB}$  asymmetries, to more tightly constrain new Physics. Even bigger data samples are necessary for these detailed studies, maybe available at a future Super-B-factory!

The lepton pair in the final state could also be a neutrino pair: the decay  $B \rightarrow K \nu \bar{\nu}$  involves only the weak penguin diagram and does not have the interference of charmonium decays, so it is theoretically much cleaner; experimentally instead, it is very challenging, since only one charged track is present as B daughter. BABAR has tried two methods: looking for a single kaon track left over from events with a completely reconstructed B, or using partially reconstructed charged B (with a  $D^0$  and a lepton for example, to tag the charge) and look for a high energy kaon of the opposite sign in the event; the present upper limit of  $7.0 \times 10^{-5}$  90% C.L. is still an order of magnitude higher than the SM prediction<sup>160</sup>. This is one more example of an important process still out of reach for the B-factories.

## 8 Summary and outlook

BABAR and BELLE have already reached their primary goal: they have proven that CP is violated in B decays, and have measured both direct and mixing induced CP violation. The violation in the mixing, which was the first effect to be measured in Kaon physics, is not yet established, but the overall picture is very consistent with the Standard Model. Consequently, it is very likely that the CKM matrix is the dominant source of CP violation in flavour changing processes at the electroweak scale; this model has passed its first real test, and the angle  $\beta$  has become the most precisely known ingredient in the unitarity triangle.

These two experiments have also demonstrated that the measurement of the angle  $\alpha$  cannot be performed as simply as  $\beta$ , using  $\pi^+\pi^-$  instead of  $J/\psi K_S$ ; the use of  $\rho\pi$  and, even better,  $\rho\rho$  have recently made it possible to reach a precision in the value of  $\alpha$  that was not anticipated a few years ago. Progress in the theory, and use of sophisticated analysis techniques, have also made it possible to measure the third angle  $\gamma$ ; while in the past it was common belief that  $B_s$  mesons were necessary for this purpose.

In the last five years we also learned from B factories that the CKM contributions to rare decays are probably the dominant ones, as they are for CP violation in  $B \rightarrow J/\psi K_S$ . This is supported by at least three measurements; a) the branching ratio of  $B \rightarrow X_s \gamma$ , which agrees with the SM at the 15% level and already provides stringent constraints on the supersymmetric (SUSY) parameter space<sup>161</sup>, b) the branching ratios  $B \rightarrow X_s l^+ l^-$  and  $B \rightarrow Kl^+ l^-$ , which are in the ballpark of the SM expectation; c) the non-observation of direct CP violation in  $b \rightarrow s \gamma$ , which is expected to be tiny in the SM. These results make it unlikely that new physics could yield order-of-magnitude enhancement of any rare decay.

BABAR and BELLE are generally in excellent agreement, within the errors; there are a few areas where the agreement is not so satisfactory, and a couple of results which differ by more than  $3\sigma$ , the direct CP asymmetry in the  $\pi\pi$  channel and the  $\sin 2\beta$  measurement in  $B^0 \rightarrow f_0 K_S$ .

Most intriguing are the results on the asymmetry in the pure penguin modes which are lower than  $\sin 2\beta$  measured in  $J/\psi K_S$  by more than two standard deviations, in each experiment, once all the modes are summed together. We have already pointed out that averaging BABAR's and BELLE's results, and claiming a discrepancy, is premature because of the large fluctuations and poor agreement in some channels. Summing the various  $b \rightarrow s$  modes to increase the statistical significance could be simply wrong, because of the differences in the contributing amplitudes;  $\Phi K$  and  $\eta' K$ , for example, cannot be trivially added together.

Even if the present discrepancy between the asymmetries in  $\Phi K$  and  $J/\psi K_S$  will be confirmed with increased statistics, it might not be easy to claim effects of new physics on this basis alone: what is measured in  $\Phi K$  is the quantity  $S$ ; this differs from  $\sin 2\beta$  of up to few % only if there is no direct CP violation and no extra (CKM) phases contribute. The amount of difference is also somewhat model dependent, and only a large, statistically significant, discrepancy could sustain the claim of new Physics.

In conclusion, B mesons provide multiple channels that have been used to measure various combinations of Standard Model parameters. Over-determinations of the parameters obtained by different measurements are an excellent probe for physics

beyond the Standard Model. To be interesting, however, any inconsistency with Standard Model relationships must be large compared to both experimental and theoretical uncertainties. The CP asymmetries in the  $b \rightarrow s$  process are clearly an area to be closely watched in the future; rare decays are maybe the most promising tool for uncovering new phenomena; in both cases much larger data sets are needed, since we already know that, if there are discrepancies with the SM, they must be rather small.

Much has been learned in five years, and we expect more from B-factories in the next few years; still many measurements will remain limited by statistics and fall short of the goal of attaining an error comparable with the theoretical uncertainty. This will be especially true for the rare decays, some of which we have discussed, and some which are more rare, and have barely been attacked up to now, such as the pure leptonic, and those which are forbidden in the SM; a few are listed in Table XIII, where the present limits are compared with SM expectations.

TABLE XIII : *Present limits on a number of interesting rare B decays, compared with Standard Model expected rates.*

Decay mode	Approximate SM rate	Present status
$B \rightarrow X_s \gamma$	$3.6 \times 10^{-4}$	$(3.4 \pm 0.4) \times 10^{-4}$
$B \rightarrow X_s \nu \bar{\nu}$	$4 \times 10^{-5}$	$< 7.7 \times 10^{-4}$
$B \rightarrow \tau \nu$	$4 \times 10^{-5}$	$< 5.7 \times 10^{-4}$
$B \rightarrow X_s \ell^+ \ell^-$	$5 \times 10^{-6}$	$(6 \pm 2) \times 10^{-6}$
$B_s \rightarrow \tau^+ \tau^-$	$1 \times 10^{-6}$	
$B \rightarrow X_s \tau^+ \tau^-$	$5 \times 10^{-7}$	
$B \rightarrow \mu \nu$	$2 \times 10^{-7}$	$< 6.5 \times 10^{-6}$
$B_s \rightarrow \mu^+ \mu^-$	$4 \times 10^{-9}$	$< 2 \times 10^{-6}$
$B \rightarrow \mu^+ \mu^-$	$1 \times 10^{-10}$	$< 2.8 \times 10^{-7}$

By the year 2009 it is likely that the total integrated luminosity by KEK-B and PEP-II will be of the order of one  $\text{at}^{-1}$  each; at the same time LHC-b, BTeV and the LHC experiments will be taking data and producing the first physics results. The hadron machines have two main advantages: a much larger B cross section, and the capability to produce all B species; it has been pointed out many times, however, how hadron and  $e^+e^-$  machines are complementary and there are several processes that can be studied only at  $e^+e^-$  colliders,  $B^0 \rightarrow \pi^0 \pi^0$ , for example, and modes with neutral particles or neutrinos.

The experience gained by BABAR and BELLE, and by the machine physicists, in five years of running allow us to reliably extrapolate what it will be



possible to achieve with samples 10 or 100 times larger than attainable with present machines, also taking into account harsher machine backgrounds and higher rates.

Feasibility studies for an asymmetric  $e^+e^-$  collider with luminosity in the range  $(5\div 10)\times 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}$  have been performed both at KEK and at SLAC. The background situation is obviously expected to become much worse, so the detectors should undergo major upgrades; possible techniques for operating in a much harsher environment are already at hand: pixel vertex detectors, silicon trackers, etc

The Physics case for a Super B-factory does not rest with a single well defined goal, as it was for PEP-II and KEK-B. In practically all areas of B Physics which have been touched in this review, there is a long list of measurements, which need to be carried out or improved, in order to test the flavour sector of the SM in depth. A precision test is motivated by more than one reason: almost all extensions of the SM contain new sources of CP and flavour violation; moreover, the flavour sector sets constraints for any model, and may allow to differentiate between new physics models.

Only if the scale of new flavour physics is much higher than the electroweak scale, there will be no observable discrepancy with the SM in B decays, and the B factories will allow precise measurements of the free parameters. If, however, there is new flavour physics near the electroweak scale, then deviations from the SM predictions are possible, large enough to be detected, and the B factories would provide detailed information on new physics by performing many “redundant” measurements.

The program as a whole is a lot more interesting than any single measurement and in the next decade a B-factory with one order of magnitude higher luminosity will provide excellent opportunity to complement B physics experiments at hadron machines: the combination of large statistics and clean events will allow the study of rare decays and a significantly improved sensitivity to observables which vanish in the SM. For example, the forward backward asymmetry in the  $sl^+l^-$  decays is a detailed study which is out of reach at present machines and is considered an excellent “clean” indicator of new Physics.

What is considered theoretically clean, however, changes with time; there has been significant progress toward understanding hadronic physics since the start of the B-factories program, but more is expected in the future, and more precise experimental results should continue to proceed in parallel.

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