CP violation in B decays: experimental aspects

L. Widhalm
Institute for High-Energy Physics, Vienna, Austria

Abstract
This lecture, given at the 2005 European School of High-Energy Physics in Austria in succession of the series on CP Violation by Robert Fleischer, sheds light on the topic from a slightly different perspective, which is meant to be a link between theory and the daily work of experimentalists. An overview of B-meson experimental history and phenomenology is followed by a description of B-meson production techniques, facilities worldwide, and a list of important present and future experiments. Current analyses are discussed, and their latest results (as of summer of 2005) are given.

1 Introduction

Studies of CP violation, especially in the B-meson sector, are one of the hottest topics of today's high-energy physics; experiments like BaBar [1] in the USA, or Belle [2] in Japan, have recently started to produce large amounts of B mesons, and recent years have brought numerous new results of high relevance. From the theoretical point of view, several very firm and accurate predictions can be made within the Standard Model, and verified in experiment; New Physics can reveal itself in many places.

This lecture is divided in three main parts. Starting with an experimental history, the first part summarizes the properties of the B meson, with emphasis on how they show up in experiment. A comparison with the K meson stresses the common features as well as the differences (and the reason for these differences). The second part deals with B-meson production and detection techniques, and provides an overview of facilities and experiments worldwide. In the last part, the focus is on a selection of important analyses at these experiments. After a short summary of the theoretical background, recent results and their implications are discussed. The lecture closes with an outlook on the near (and not-that-near) future.

All given experimental numbers, unless some other reference is given, are taken from Particle Data Group (PDG) 2004 [3]. Charge conjugate modes of any given particles are also implied throughout, unless explicitly stated otherwise.

1.1 Disclaimer

The aim of this lecture is not to explain detector physics, experimental setups or analysis techniques in detail, although we give references for further reading about this. It is aimed at students who, after having heard the theoretical lecture on CP violation, would like to be reminded of the key features of B-meson phenomenology, and then get an overview about experimental designs, currently running experiments, and their most important analyses and results. Within the scope of a 90-minutes lecture, the emphasis is on the larger picture rather than on technical (or theoretical) details, addressing experimentalists who are not experts in this field, but would like to understand what is going on.

Although there is very interesting physics with heavier B mesons like the B_s, this lecture will concentrate mainly on the B^0, with some remarks about the $B^{\pm}$.

2 The B meson

2.1 Experimental history and properties

In 1977 the E288 fixed-target experiment at Fermilab (Batavia, USA), studying $\mu\mu$ events, discovered the b-quark in the $\Upsilon(1S)$ resonance [4], and marked the beginning of bottom physics (Table 1). What is remarkable is the extraordinarily small width of this state of just 53.0 ± 1.5 keV, which is the consequence of the fact that its mass of 9460.30 ± 0.26 MeV is too small to allow the fast decay into two B mesons (composed of a b-quark and a light quark, with a mass of 5279 ± 0.5 MeV). While a decay into B mesons would preserve the b-quarks, and can be mediated by the strong interaction, instead both b-quarks have to decay weakly to lighter quarks, which is much slower and thus gives rise to the unusual observed width.

The same remains true even for the excitation states $\Upsilon(2S)$ (observed at DESY in 1978 [5]) at $m = 10023.26 \pm 0.31$ MeV and $\Upsilon(3S)$ at $m = 10355.2 \pm 0.5$ MeV. The excitation $\Upsilon(4S)$ with a mass of 10580.0 ± 3.5 MeV is the first which allows a decay into B mesons, which immediately broadens the width to 20 000 $\pm$ 2000 $\pm$ 4000 keV. This state was observed first in 1979 at the CLEO experiment (CESR, USA) [6]; a review of upsilon spectroscopy can be found, for example, in Ref. [7].

B mesons were discovered a year later, in 1980, also at CESR [8]. A fact that is experimentally quite important is the small mass difference between $\Upsilon(4S)$ and the sum of the two B mesons, which amounts to just 21 MeV. As a consequence, the relative velocity of the B mesons produced via this resonance is very small, and they are produced nearly at rest in the $\Upsilon(4S)$ centre-of-mass frame. Another consequence is that only the lightest B mesons, namely the B^+ (B^0) composed of an anti-b- and a u-quark (d-quark) can be produced via $\Upsilon(4S)$; the required energy for a production of a B_s^0 (with an s-quark instead of the d-quark) is 159 MeV larger than the $\Upsilon(4S)$ mass. Therefore, the production of B mesons at the $\Upsilon(4S)$ threshold is a very clean and efficient process, which is exploited in the so-called B factories discussed later in this lecture (Section 3.1). First evidence of the B_s meson was found much later, at ALEPH (CERN, Switzerland) in 1992 (Ref. [9], and the references therein); the discovery of B_c followed in 1998 at CDF (Fermilab, USA) [10].

1983 was the year of the first measurement of the b-quark inclusive lifetime at PEP (SLAC, USA) and PETRA (DESY, Germany) [11]; the exclusive lifetime of the B mesons was first measured considerably later (1994) at the DELPHI and ALEPH experiments at CERN (Geneva, Switzerland) [12]. Experimentally important is its product with the speed of light, which gives the scale for the spatial separation of primary and secondary decay vertices; it is known today as $c\tau = 501$ μm (461 μm) for B^+ (B^0), which is comparably rather large and is again caused by the fact that the B-meson decay is mediated by a weak transition of the b-quark to a lighter one, which is further suppressed by the CKM-hierarchy as described in Section 2.5.

In 1987, DESY was the first to observe $B^0\bar{B}^0$ oscillations [13]—a feature of neutral meson/anti-meson systems which was already known in the K^0 system, and anticipated also for the B^0. The reason for and the implications of these oscillations will be discussed in more detail in Section 2.4. In the following years, the knowledge of B physics was further improved also by experiments running at LEP (CERN, Geneva) and SLC (Stanford, USA).

The new millennium brought the age of CP violation in B physics: in 2001, the already anticipated large CP violation in the neutral B-meson system was found at both large B-factory experiments at PEP-II (BaBar) and KEKB (Belle) [14]. Only three years later, in 2004, the more subtle direct CP violation was established in B mesons [15] (for comparison: in K physics, three decades lie between the discovery of indirect and direct CP violation). The aspects of CP violation are discussed in Section 2.6.

2.2 The neutral B-meson system

The following discussion assumes B^0 mesons, but is valid generally for any neutral meson. Some important basic features of a system made of a neutral meson B^0 and its antiparticle $\bar{B}^0$ can be derived without the need to know (and independent of) the details of the underlying field theory if one studies the subspace of the complete Hilbert space comprised of just the states $|B^0>=|1>$ and $|\bar{B}^0>=|2>$; in this subspace, the projection of the Hamiltonian H is given by $H_{ij} :=<i|H|j>$, which forms a 2×2 matrix which is—in contrast to the full Hamiltonian—generally *not* Hermitian. Still, any matrix can be

Table 1: B-meson history

Year	Event
1977	Discovery of b-quark in $\Upsilon(1S)$ at FNAL (USA)
1978	$\Upsilon(1S)$ and $\Upsilon(2S)$ at DESY (Germany)
1979	Discovery of $\Upsilon(4S)$ at CESR (USA)
1980	First observation of B mesons at CESR (USA)
1983	Measurement of inclusive b lifetime at PEP and PETRA
1987	$B^0\bar{B}^0$ oscillations discovered at DESY (Germany)
1992	Evidence of B_s
1993	Observation of time-dependent oscillations
1994	Measurement of exclusive B-meson lifetime
1998	Discovery of B_c
2001	CP violation found at PEP-II (USA) and KEKB (Japan)
2004	Direct CP violation established

decomposed into a Hermitian and an anti-Hermitian part. It turns out to be useful to write H as

$$H_{\text{eff}} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = M - \frac{i}{2}\Gamma = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

where—by virtue of the pulled out i—both M and Γ are *Hermitian*, inferring $M_{ij} = M^*_{ji}$ and $\Gamma_{ij} = \Gamma^*_{ji}$. An additional constraint, namely $H_{11} = H_{22}$, comes from the CPT theorem, which states that the combined symmetry of Charge conjugation, Parity transformation and Time reversal holds in a very general class of quantum field theories.

The projected Schrödinger equation

$$H|B\rangle = i\frac{d}{dt}|B\rangle$$

yields the usual solution

$$|B_{H,L}\rangle(t) = \exp^{-iH_{H,L}t}|B_{H,L}\rangle(0)$$

where $H_{H,L}$ denotes the eigenvalues of H, which are under the assumption of CPT symmetry given as

$$H_{H,L} = H_{11} \pm \sqrt{H_{12}H_{21}}$$

and $|B_{H,L}\rangle$ are eigenstates of the form

$$|B_{H,L}\rangle = p|B^0\rangle \mp q|\bar{B}^0\rangle$$

with

$$\frac{q}{p} = -\frac{H_H - H_L}{2H_{12}}\ . \tag{1}$$

Rewriting the time-dependent solution using $H_{H,L} := M_{H,L} - \frac{i}{2}\Gamma_{H,L}$ with real M and Γ, one has

$$|B_{H,L}\rangle(t) = \exp^{-\frac{\Gamma_{H,L}}{2}t}\exp^{-iM_{H,L}t}|B_{H,L}\rangle(0)$$

which is interpreted as two neutral mesons (one Heavier with mass M_H, one Lighter with mass M_L), decaying with (generally different) decay constants $\Gamma_{H,L}$. It is conventional to introduce the mean mass $M := \frac{1}{2}(M_H + M_L)$ and $\Delta M := M_H - M_L$; similarly one introduces Γ and $\Delta\Gamma$.

Note that the above applies for all neutral mesons, while the specific experimental character of the B meson (which is quite different from that of the K meson, for example) is due to the specific values of the above parameters. This will be discussed in Section 2.3.

2.2.1 A short pre-discussion of CP violation

The topic of CP violation in the B-meson system will be discussed in greater depth later (Section 2.6), but it makes sense to discuss immediately some basic properties and connections referred to above.

The CP operator is defined as reversing both charge and parity of a state, i.e., a quark q with momentum p is transformed to $\bar{\mathrm{q}}$ with momentum $-p$. It is an important point to understand that this does not imply that the CP operator acting on $|B^0\rangle$ gives $|\bar{B}^0\rangle$, all that can be concluded is that the result is *proportional* to $|\bar{B}^0\rangle$, which together with the normalization condition gives

$$\mathrm{CP}|B^0\rangle = \exp^{i\xi}|\bar{B}^0\rangle$$

where ξ is an arbitrary phase which can be *defined* to any value, but has to be chosen consistently. To keep formulas simple, we choose $\xi = 0$ which leads to

$$\mathrm{CP}|B^0\rangle = |\bar{B}^0\rangle$$

and similarly

$$\mathrm{CP}|\bar{B}^0\rangle = |B^0\rangle$$

but not without the warning to check for the definition of this phase whenever looking into different papers (to avoid misunderstandings, many theoretical papers explicitly state the phase wherever it occurs).

With this phase convention, the eigenstates of CP are easily found to be

$$|B_{\mathrm{CP}+,\mathrm{CP}-}\rangle = |B^0\rangle \pm |\bar{B}^0\rangle \tag{2}$$

with eigenvalues ± 1. If one assumes CP symmetry, then CP eigenstates are also eigenstates of the Hamiltonian. Comparing the above result with Eq. (1) this infers that $q/p = \pm 1$ and consequently $H_{12} = H_{21}$.

2.3 The different experimental characters of neutral B and K mesons

While the underlying theory is the same, B and K mesons bear rather characteristic (and partly quite different) properties in experiment, especially with respect to CP violation. Table 2 compares the values of some basic parameters for B^0 and K^0. Remarkably, the lifetimes of the two mass eigenstates are practically the same for the B mesons, while they are almost three orders of magnitude different for the K mesons. This is the reason for some of the most characteristic experimental differences between B and K mesons.

For the K mesons, it is natural to think of them in terms of the mass eigenstates, for simple experimental reasons: by just waiting long enough (a couple of τ_L), the lighter component decays away, and one has a pure beam made of the heavier component. On the other hand, if one studies decays immediately after production ($t = \mathcal{O}(\tau_L)$), one mainly observes the lighter component, since it decays much faster. Instead of classifying them into heavier and lighter K mesons, it is usual to speak of a long-lived K_L (which—confusingly—is identified with the heavier kaon state formerly denoted K_H), and a short-lived K_S (formerly K_L).

As the B-meson mass eigenstates—owing to their similar lifetime—do not disentangle equivalently in experiment, frequently they are addressed in terms of the B^0 and $\bar{B}^0$ states (which are the strong eigenstates in which these particles are produced) rather than of the B_H and B_L states. However, it is important to realize that also the K mesons are produced in their strong eigenstates K^0 and $\bar{K}^0$, and the reason for preferring $K_{L,S}$ is only experimentally motivated—in some experiments, it is more useful to think of particles, and in others of waves; consequently, there are also experiments which are better understood in terms of K^0 and $\bar{K}^0$.

A notable property of the B meson is its large lifetime, which is rather surprising given the fact that it is much heavier than the K meson, with much more open decay channels. The reason for this

Table 2: Comparison of B meson with K meson

	B^0	K^0
Mean mass M	5279 MeV/c^2	497 MeV/c^2
Mass difference ΔM	$\approx 3.3 \times 10^{-10}$ MeV/c^2	$\approx 3.5 \times 10^{-12}$ MeV/c^2
Lifetime ($1/\Gamma$)	$\tau_H = 1.5$ ps	$\tau_H = 51800$ ps
	$\tau_L = 1.5$ ps	$\tau_L = 90$ ps
$\lvert q/p \rvert$	≈ 1	≈ 1
$\arg(q/p)$	$\mathcal{O}(\pi/2)$	$\mathcal{O}(10^{-3})$

experimentally very fortunate and welcome property (see, for example, the discussion in Section 5.1) is the CKM hierarchy discussed in Section 2.5, which suppresses transitions of b-quarks to lighter quarks one order of magnitude more than the comparable transition of an s-quark in a K-meson decay.

Concerning the eigenstate parameters p and q, their ratio is about 1 for both B and K mesons, but while for K mesons also the relative phase between p and q is small, it is large for B mesons. Comparing with Eq. (2) this means that the K mesons $K_{L,S}$ are almost CP eigenstates, while the B mesons are not.

Since K mesons are nearly CP eigenstates, the decay of the almost-CP-odd K_L into the kinematically favoured channel $\pi\pi$ is suppressed to a level of $\mathcal{O}(10^{-3})$. As the CP-odd decay into three pions is kinematically suppressed ($3m_\pi \approx m_K$), the K_L acquires its observed long lifetime.

To summarize the comparison: while the K mesons appear in experimentally distinct long- and short-lived mass eigenstates, which are almost CP eigenstates, B mesons bear a large phase relative to CP eigenstates and cannot as easily be separated experimentally into their mass eigenstates. Therefore as will be discussed in the following section, interference between the eigenstates plays a much more central role for B mesons than for K mesons.

2.4 How B mesons show up in experiment

B mesons are produced via strong interactions, therefore in the strong eigenstates B^0 and $\bar{B}^0$. As they cannot decay strongly, their further development with time is governed by weak interactions, and it is advisable to express the strong eigenstates as compositions of the weak mass eigenstates:

$$\begin{aligned} |B^0\rangle &\propto |B_H\rangle + |B_L\rangle \\ |\bar{B}^0\rangle &\propto |B_H\rangle - |B_L\rangle \, . \end{aligned}$$

Since time evolution is different for $|B_H\rangle$ and $|B_L\rangle$, generally *interference* occurs:

$$\begin{aligned} |B^0\rangle(t) &= \exp^{-\frac{t}{2\tau}} \exp^{-iMt} \left[|\cos(\frac{\Delta M}{2}t)|B^0\rangle + i\frac{q}{p}\sin(\frac{\Delta|M}{2}t)|\bar{B}^0\rangle \right] \\ \bar{B}^0\rangle(t) &= |\exp^{-\frac{t}{2\tau}} \exp^{-iMt} \left[i\frac{p}{q}|\sin(\frac{\Delta M}{2}t)|B^0\rangle + \cos(\frac{\Delta|M}{2}t)|\bar{B}^0\rangle \right] \end{aligned}$$

where τ is the mean lifetime, and the very small difference $\Delta\tau$ has been neglected. Obviously there is a damped *oscillation* between B^0 and $\bar{B}^0$ with a frequency determined by the mass difference ΔM. Figure 1 shows three characteristic cases for values of ΔM in relation to $1/\tau$. If ΔM is large compared to $1/\tau$, then many oscillations take place before the majority of the B mesons have been decayed; if ΔM is small, then most of the B mesons decay before the first oscillation occurs. Both cases are unfavourable in experiment; the former because of limits in time resolution, the latter because of limits in statistics. By some lucky coincidence, however, it turns out that for the neutral B meson $\Delta M \approx 0.7/\tau$, which makes one full oscillation well observable, as will be shown later in this lecture.

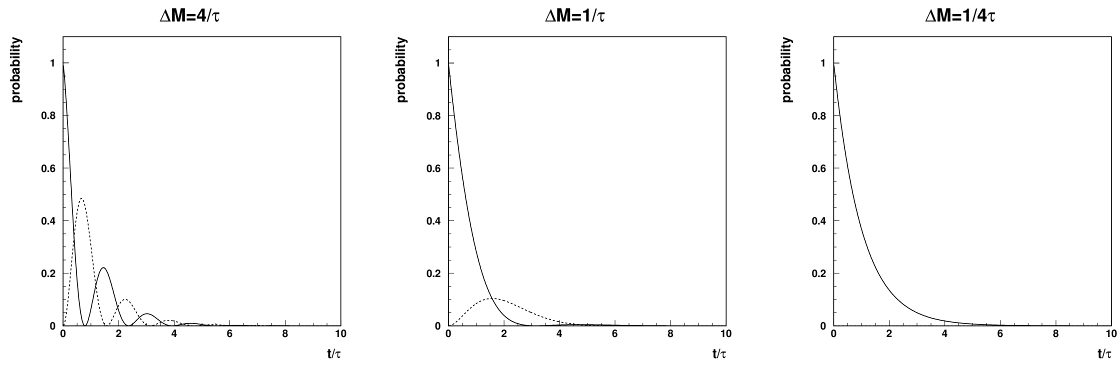

Fig. 1: Oscillation of B mesons: probability to find a B^0 (solid) or $\bar{B}^0$ (dashed) at time t, assuming a B^0 at $t = 0$

From the experimental point of view, it is interesting whether (and how) these interferences can be observed. One precondition is obviously that the *flavour* of the B meson (i.e., whether it is a B^0 or $\bar{B}^0$) can be measured. But it is not sufficient to measure the flavour at the time of decay: if the initial state (at $t = 0$) is unknown, then the interference cancels in the average.

The flavour can be *tagged* by looking for a channel which is only (or at least dominantly) open for either B^0 or $\bar{B}^0$, like, for example, the semileptonic decay $B^0 \to \ell^+ + \text{anything}$ and $\bar{B}^0 \to \ell^- + \text{anything}$, where the charge of the lepton determines (tags) the flavour of the B meson. However, this determines the flavour only at one point in time and does not yet allow one to observe oscillations. To measure the flavour at a second point in time, one could go back to the production at $t = 0$, and determine the flavour at this time using the fact that b-quarks are produced in quark–anti-quark pairs; this works if the second b-quark went into a charged B meson, but only because the charged B meson does not oscillate between its production at $t = 0$ and its later decay, which reveals its charge. If a $B^0\bar{B}^0$ pair is produced at $t = 0$, both neutral B mesons oscillate, and the flavour of both mesons will change with time. However, as the pair builds an *entangled* state, a decay of one B meson at some time t_1 with a certain, tagged flavour forces the opposite flavour for the other B meson *at the same time* t_1. When this second B meson also decays at some later time t_2, flavour oscillation can be observed.

To avoid misunderstandings: the occurrence of oscillations in the B-meson system is *not* an effect of CP violation; as can be seen from the formulae above, it is governed by ΔM, which can be different from zero also when CP symmetry holds. As will be discussed later, the *amplitude* of the oscillations can be connected with the amount of CP violation *in certain decays*.

2.5 The larger picture: CP violation and CKM hierarchy in the Standard Model

To understand the specific properties of B mesons, it is necessary to look at the larger picture: the CKM matrix V_{CKM} describes the conversion between up- and down-type quarks [16]. Within the Standard Model (SM), it is unitary ($V^+V = VV^+ = 1$) which infers that it is defined by nine parameters (three angles and six phases); however, by redefining the quark phases, five of the phases (corresponding to the five relative phases between the quarks; a global phase change does not affect V_{CKM}) can be gauged to zero. Thus, only one phase with physical meaning remains.

It turns out that this single remaining phase is the source of CP violation within the SM (for the scope of this lecture, we do not discuss the strong CP problem [17]), and it is interesting to note that while for only two generations of quarks CP symmetry would necessarily hold, there is no reason for the CP-violating phase to be small in three generations. Experiment shows that it is not, i.e., CP symmetry is not a near miss. However, this does not imply that CP-violating effects are large—on the contrary, it turns out that either the effects are small, or the branching fractions involved.

The hierarchy of the CKM matrix can be illustrated in the approximation

$$V_{\text{CKM}} \approx \begin{pmatrix} 1 & V_{us} & V_{ub}e^{-i\gamma} \\ -V_{us} & 1 & V_{cb} \\ V_{us}V_{cb} - V_{ub}e^{i\gamma} & -V_{cb} & 1 \end{pmatrix}$$

with

$$|V_{us}| = 0.224 \pm 0.003 \ (\lambda) \ , |V_{cb}| = 0.041 \pm 0.002 \ (\mathcal{O}(\lambda^2)) \ , |V_{ub}| = 0.0037 \pm 0.0008 \ (\mathcal{O}(\lambda^3)) \ .$$

The dominant conversions are along the main axis, i.e., among quarks of the same generation. Conversions between the first and second generation are suppressed by about one order of magnitude, characterized by the parameter $\lambda \approx \mathcal{O}(10^{-1})$. Between the second and the third by two orders of magnitude, and finally those between the first and the third by three orders of magnitude. This hierarchy is important to understand certain properties of the B meson.

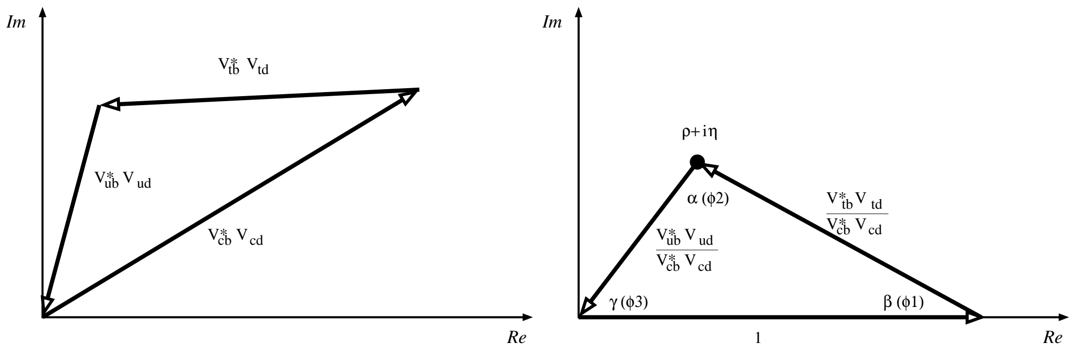

Fig. 2: Unitarity triangles in the complex plane; right the original one, left with one side normalized to 1

To characterize CP violation in the Standard Model, one can utilize the unitarity of the CKM matrix ($V^+V = 1$), which gives nine equations (three in the main diagonal, six off-diagonal). One off-diagonal equation is

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

In the complex plane, the three terms of the above equation can be interpreted as the sides of a triangle (Fig. 2, left). It is conventional to normalize one side of the triangle to 1 by dividing the above equation by $V_{cb}^*V_{cd}$. Introducing the real parameters $\bar{\rho}$ and $\bar{\eta}$ as

$$\bar{\rho} + i\bar{\eta} := \frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}} \ ,$$

one arrives at the *unitarity triangle* (UT) (Fig. 2, right); note that there are six unitarity triangles, as there are six off-diagonal equations from CKM unitarity; however, most of the triangles are rather degenerated, i.e., very flat; the unitarity triangle discussed here is the most famous one, and the one usually referred to when speaking of *the* unitarity triangle. Its three angles are denoted α, β, γ (sometimes also ϕ_2, ϕ_1, ϕ_3).

The area of the unitarity triangle is a direct measure for the amount of CP violation in the CKM matrix [16], i.e., with no CP violation, it would be degenerated to a flat line.

2.6 CP violation in the neutral B-meson system

CP violation (CPV) can reveal itself in experiment in several ways, which we discuss here briefly:

CP violation in mixing is a manifestation of *indirect CP violation*; mixing means that mass eigenstates differ from the CP eigenstates (see discussion above in Section 2.2), and can be measured in asymmetries of semileptonic decays, for example. Note: the mixing of B^0 and $\bar{B}^0$ (i.e., the fact that the mass eigenstates differ from the strong eigenstates) is *not* yet an effect of CP violation. Owing to $|q/p| \approx 1$ this asymmetry is *small* for B mesons (as for K mesons).

As the above asymmetry due to mixing does not require any CP violation in the B decay itself, *CP violation in decay* is another way for CP violation to reveal itself, a manifestation of *direct CP violation*. A non-zero asymmetry requires at least two terms in the amplitude of the decay (i.e., two different Feynman graphs) with a difference in both the strong and weak phases [16].

Since mass eigenstates differ from CP eigenstates, there is interference in the decay to CP eigenstates, and oscillations occur in the corresponding asymmetry (*CP violation in interference*); the oscillation frequency is again determined by ΔM, and the *amplitude* of the oscillation is a measure of CP violation. Generally, the asymmetry is given by $A_{\rm CP}^{\rm dir}\cos(\Delta Mt) + A_{\rm CP}^{\rm mix}\sin(\Delta Mt)$ [16] where because $|q/p| \approx 1$, $A_{\rm CP}^{\rm dir}$ is only different from zero for decay channels with direct CP violation (i.e., channels with at least two contributing Feynman graphs with different phases, see above), i.e., $A_{\rm CP}^{\rm dir}$ *is a measure for direct CP violation*. For channels without direct CP violation, $A_{\rm CP}^{\rm mix}$ depends only on purely electroweak parameters, i.e., $A_{\rm CP}^{\rm mix}$ *measures the unitarity triangle*. Note that the asymmetry cancels when integrated over time, so the time dependence has to be measured if one wants to study this form of CP violation.

Although all above forms of CP violation occur in the B-meson system, most attention is on the last kind (CP violation in interference), because a large effect directly related to angles in the unitarity triangle is predicted (and has already been confirmed experimentally, *cf.* Section 5.1).

Detailed discussions about the phenomenology of CP violation can be found in Ref. [16] or Refs. [18–20].

2.7 New Physics with the B meson

Although CP violation is already accommodated for within the Standard Model, the measured amount is far too small to explain the matter–antimatter asymmetry observed in the Universe [18]. There are many extensions to the Standard Model which predict sizeable differences in CP variables, e.g., SuperSymmetry (SUSY) brings in dozens of additional CP-violating phases. Therefore, the existence of New Physics is rather expected, and potentially can reveal itself in many places in B physics, and also especially in CP violation.

In the Standard Model, where CP violation is controlled by just one single phase, all possible different experiments are determined to give strongly correlated results: as the sides and angles of the unitarity triangle can be measured independently, and usually in more than one way, it is strongly overdetermined. A disagreement would be a sign of physics beyond the Standard Model.

Good candidates to show New Physics are decay channels with sizeable contributions from Feynman graphs involving loops, since such loops may contain (heavy) new particles, which—like the top quark in many Standard Model loops—can have a measurable effect on the amplitudes.

3 Production of B mesons

Precision measurements with B mesons demand a large number of them, and special techniques have evolved with certain advantages and disadvantages, which are briefly discussed here.

3.1 B factories and hadron colliders

Lepton colliders have the advantage of clear environments, but are limited in energy because of synchrotron radiation. An early way to produce b-pairs was via the Z^0 particle, at an energy of about 90 GeV, as done in the LEP experiments at CERN (Geneva, Switzerland) and SLD (Stanford, USA). As these experiments were not designed for the production of B mesons, the production capacity was not very large.

A more efficient way to produce B mesons is to exploit the $\Upsilon(4S)$ resonance at about 10 GeV, as discussed already in Section 2.1. Advantages are that the production is resonantly enhanced, and that the background is comparably small (in addition, it can be comfortably studied by reducing the collision energy to slightly below threshold). However, only B^0 and $B^\pm$ can be produced in this way, the B_s is too heavy. Still, this is currently the state-of-the-art way to produce large amounts of B mesons, as in the so-called *B factories* at PEP-II (Stanford, USA) and KEKB (Tsukuba, Japan); pioneers were DORIS II (Hamburg, Germany) and CESR (Cornell, USA).

An alternative way to produce B mesons is in hadron colliders; just by pure collision energy, B mesons of any kind (B^0, $B^\pm$, B_s, B_c) can be produced copiously in very large numbers, however, the background is very large. This method is currently used in the CDF and D0 experiments at Fermilab (Batavia, USA); and will be soon joined by the LHC experiments at CERN (Geneva, Switzerland).

A possible future linear collider will combine the advantages of lepton colliders (clean environment) with the higher energy of hadron colliders.

3.2 Symmetric vs asymmetric colliders

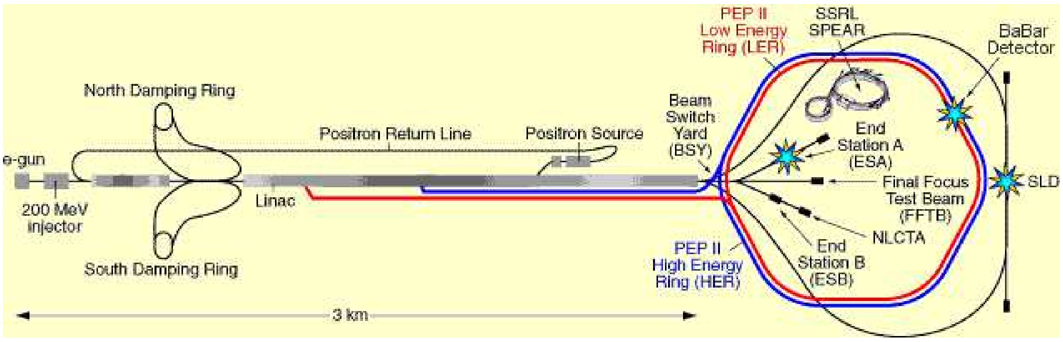

Fig. 3: The PEP-II B factory in Stanford, USA

When B mesons are produced at the $\Upsilon(4S)$ resonance, their relative momentum is very small, since the resonance lies only 24 MeV above the production threshold (*cf.* Section 2.1). In symmetric colliders, where both beams have the same energy, the B mesons are therefore produced nearly at rest, and it is hard (or impossible) to separate their decay vertices (which is important for the measurement of CP violation, see discussion below in Section 5.1). Historically, symmetric colliders were CESR (Cornell, USA) and DORIS (Hamburg, Germany).

Asymmetric colliders, where the beams have different energies, are technologically more demanding, but are essential for modern experiments. In such colliders, the B mesons are boosted in one favoured direction, and their lifetime can be measured via high-resolution vertex detectors. This technology is used in PEP-II (Stanford, USA), Fig. 3, and KEKB (Tsukuba, Japan).

4 B-meson experiments

4.1 B factories and hadron collider experiments

Since 2000, the BaBaR experiment [21] at SLAC (Stanford, USA, see Fig. 4) has been using the PEP-II B factory for precision studies of the B-meson system. A five-layer, double-sided silicon vertex tracker surrounds the interaction point and provides precise reconstruction of track angles and B-decay vertices. A 40-layer drift chamber provides measurements of the transverse momenta of charged particles. An

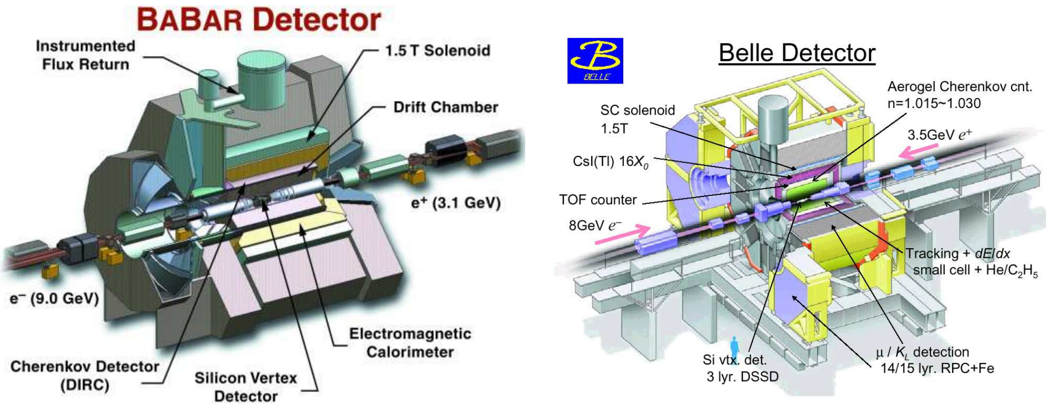

Fig. 4: The BaBaR and Belle detectors

internally reflecting ring-imaging Cherenkov detector is used for particle identification. A CsI(Tl) crystal electromagnetic calorimeter detects photons and electrons. The calorimeter is surrounded by a solenoidal magnet providing a 1.5 T field. The flux return is instrumented with resistive plate chambers used for muon and neutral-hadron identification.

Also since 2000, the Belle experiment at KEK (Tsukuba, Japan, see Fig. 4) with the KEKB B factory has similar goals. The Belle detector [22] is rather similar to that of BaBar: a large-solid-angle magnetic spectrometer that consists of a multilayer silicon vertex detector, a 50-layer central drift chamber, an array of aerogel threshold Cherenkov counters, a barrel-like arrangement of time-of-flight scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons. The old inner detector configuration of a 2.0 cm radius beam pipe and a three-layer silicon vertex detector was upgraded in 2004 to a 1.5 cm radius beam pipe, and a four-layer silicon detector [23].

Besides these two B-factory experiments, there are also two important experiments running at a hadron collider, the Tevatron at Fermilab (Batavia, USA): the CDF II detector [24] consists of a charged-particle tracking system in a magnetic field of 1.4 T, segmented electromagnetic and hadronic calorimeters, and muon detectors. A silicon microstrip detector provides tracking over the radial range 1.5–28 cm and is used to detect displaced secondary vertices. The fiducial region of the silicon detector covers the pseudorapidity range $|\eta| < 2$, while the central tracking system and muon chambers provide coverage for $|\eta| < 1$.

The D0 detector [25] has a silicon microstrip tracker and a central fibre tracker located within a 2 T superconducting solenoidal magnet. The surrounding liquid-argon/uranium calorimeter has a central cryostat covering pseudorapidities $|\eta|$ up to 1.1, and two end-cryostats extending coverage to $|\eta| \approx 4$. A muon system resides beyond the calorimetry, and consists of a layer of tracking detectors and scintillation trigger counters before 1.8 T toroids, followed by two similar layers after the toroids.

Both the CDF II and D0 experiments have a rich physics programme which includes, in addition to B physics, top physics, electroweak physics, and QCD. They are collecting important new results on heavier B mesons like the B_s, which are not accessible to the B-factory experiments.

4.2 The future: experiments at the LHC and super factories

The Large Hadron Collider (LHC), a 14 TeV pp collider at CERN (Geneva, Switzerland), is scheduled to start in 2007. The goal is to get the luminosity to 10^{33} cm^{-2}s^{-1}. Later the luminosity will be increased to nominal 10^{34} cm^{-2}s^{-1}. The launch of the LHC will also bring a whole set of new experiments:

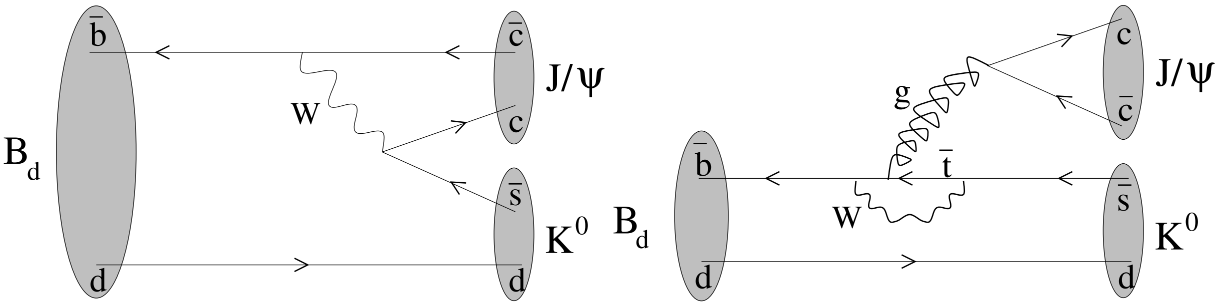

Fig. 5: Tree and penguin diagrams

while ATLAS and CMS have B physics as part of a wider programme, LHCb is a dedicated experiment. LHCb is a single-arm spectrometer covering the range 1.9 $<\ \eta\ <$ 4.9. It consists of a silicon vertex detector [26] which includes a pile-up system surrounding a beam pipe, a magnet and a tracking system, two RICH counters, a calorimeter system and a muon detector. Its construction has started and it will be ready to take data from the start of LHC operation. LHCb will benefit from an unprecedented source of b-hadrons, to substantially improve precision measurements of CP-violation parameters in many different channels. In particular, LHCb will also be capable of measuring CP-violation effects for the first time in decay modes involving B_s mesons.

For the more distant future (around 2010), there are already plans for a super B-factory: Super-Belle is a foreseen successor of the Belle experiment to run at a planned SuperKEKB collider [27], an asymmetric e^+e^- collider with a design luminosity of 5×10^{35} cm^{-2}s^{-1}, which is around 40 times larger than the peak luminosity achieved by the KEKB collider. The Belle detector will be upgraded to Super-Belle to take full advantage of the high luminosity of SuperKEKB. Despite large beam backgrounds, the detector performance will be at least as good as that of the present Belle detector and improvements in several aspects are envisaged.

5 The analyses

The theory behind the analyses is explained in greater detail elsewhere (e.g., Refs. [16, 18–20, 28]), and is only sketched here. For a basic understanding of the relevance of the certain decay channels which are being analysed, it is important to know the two typical Feynman diagrams which contribute to the decay, corresponding to two ways of the transition of the b-quark to a lighter quark: the *tree* diagram (Fig. 5, left), and the *penguin* diagram (Fig. 5, right), which contains a loop. As there are three possibilities for the quark inside the loop (u, c and t), and also three possibilities for the internal gauge boson (g, γ and Z^0—the first known as *strong penguin*, the latter two as *electroweak penguin*), there are in total ten different amplitudes from tree and penguin diagrams which can interfere with each other, and introduce different phases. However, depending on the decay channel, certain amplitudes may be suppressed, which is important for the way a measurement is interpreted.

In the following, a selection of the most important decay channels is briefly discussed, sorted by the amplitudes which dominate the decay.

5.1 Tree-dominated: the golden channel $B^0 \to \Psi K_{S,L}$

This channel is a decay to CP eigenstates, and therefore is expected to exhibit an asymmetry related to CP violation as discussed in Section 2.6. It is known as *golden channel* because it provides both a clear experimental signature, and a clean theoretical situation: it is dominated by the tree graph, there is no contribution from direct CP violation [16], and thus the asymmetry is a pure sine (*cf.* Section 2.6). The

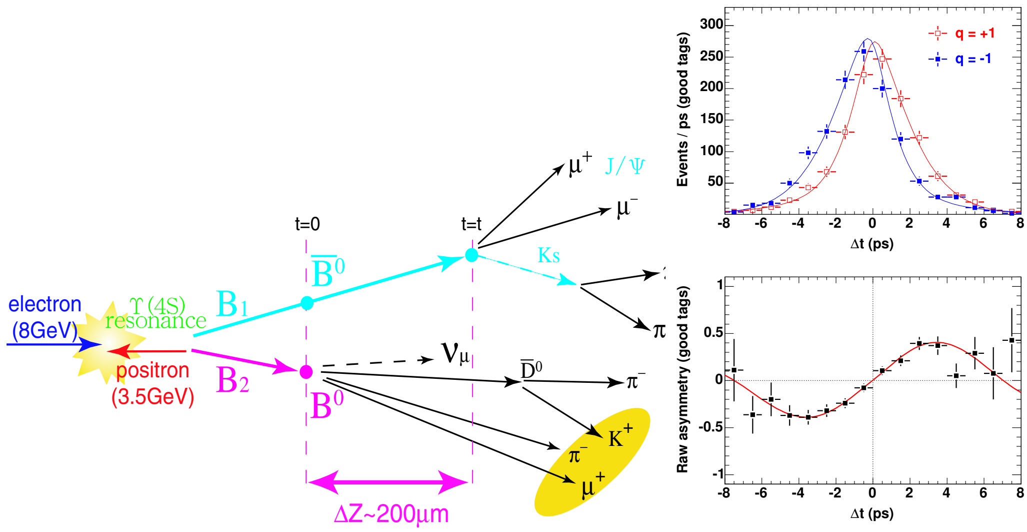

Fig. 6: Scheme of measurement of the time-dependent asymmetry (left), and experimental results from Belle 2005 (right)

amplitude of this sign turns out to be related to angle β of the unitarity triangle:

$$A_{\rm CP}^{\rm mix} = -\sin(2\beta)\ .$$

As the asymmetry cancels when integrated over time, the experimental challenge is to accurately measure the time difference between the decay of the tagging B meson (whose decay determines the flavours of the B meson at this time $t = 0$) and the B meson decaying into the golden channel at some other time t. Figure 6 schematically shows the procedure, which relies on an accurate measurement of the respective decay vertices. Because of the boost of the B mesons in the asymmetric collider, and the relatively long lifetime, the typical distance between the two decay vertices is $\Delta Z = 200\ \mu$m, which is enough to allow a sufficiently accurate measurement with the modern silicon vertex detectors of BaBar and Belle. A more detailed description of the reconstruction method can be found, for example, in Ref. [29].

First results came from both BaBar and Belle in 2001, and have been improved annually since. The 2005 values [14] are in very good agreement with each other (*cf.* Table 3), but also with the Standard Model prediction (using all available other information) of $\sin(2\beta) = 0.68 \pm 0.18$. No indication of a direct CP-violating amplitude was found.

Table 3: Overview of experimental results, as of summer 2005

Channel(s)	**Measurement**	**BaBar**	**Belle**
$B^0 \to \Psi K_{S,L}$	$A_{\rm CP}^{\rm mix}$	$0.722 \pm 0.040 \pm 0.023$	$0.625 \pm 0.039 \pm 0.020$
$B^0 \to \Phi K_{S,L}$	$A_{\rm CP}^{\rm mix}$	$0.50 \pm 0.25 \pm 0.07$	$0.44 \pm 0.27 \pm 0.05$
$B^0 \to \eta' K_{S,L}$	$A_{\rm CP}^{\rm mix}$	$0.36 \pm 0.13 \pm 0.03$	$0.62 \pm 0.12 \pm 0.04$
$B^0 \to \pi\pi$	$A_{\rm CP}^{\rm mix}$	$-0.30 \pm 0.17 \pm 0.03$	$-0.67 \pm 0.016 \pm 0.06$
	$A_{\rm CP}^{\rm dir}$	$-0.09 \pm 0.15 \pm 0.04$	$-0.56 \pm 0.12 \pm 0.06$
$B^0 \to K\pi$	a_d	$0.133 \pm 0.030 \pm 0.009$	$0.113 \pm 0.022 \pm 0.008$
$B^\pm \to D^0 K/\bar{D}^0 K$	γ	$(67 \pm 28 \pm 13 \pm 11)^\circ$	$(68 \pm 15 \pm 13 \pm 11)^\circ$

5.2 Penguin-dominated: $B^0 \to \Phi K_{S,L}$ and the like

Contrary to the golden channel $B^0 \to \Psi K_{S,L}$ discussed above, this channel is dominated by the penguin diagram. However, the direct CP-violating contribution is again suppressed, and the amplitude of the asymmetry is again related to the angle β:

$$A_{\rm CP}^{\rm mix} = \sin(2\beta) \ .$$

The interesting aspect of this channel is that it allows an independent second measurement of β—which tests the Standard Model. Furthermore, it is sensitive to New Physics, as it contains a loop (*cf.* Section 2.7).

Agreement between the BaBar and Belle results in this channel [30] has improved over the years, and no indication of direct CP violation has been found (*cf.* Table 3). Similarly, other channels $B^0 \to XK_{S,L}$ have also been analysed [31]; so far, results are not incompatible with the Standard Model, i.e., the precision result from the golden channel $B^0 \to \Psi K_{S,L}$. However, uncertainties are too large for final conclusions.

5.3 Both tree and penguin: $B^0 \to \pi\pi$ and the like

Although this channel is an example for a mode to which both tree and penguins contribute to a similar extent, it is instructive to discuss the case where the penguin contribution is neglected: in this case, there would be no contribution from direct CP violation, and the amplitude of the asymmetry would be related to another angle of the unitarity triangle:

$$A_{\rm CP}^{\rm mix} = \sin(2\alpha) \ .$$

However, the real situation is more complicated; there might be a non-zero amplitude of the cosine in the asymmetry, $A_{\rm CP}^{\rm dir}$, and the extraction of α is more difficult than in the corresponding measurement of β discussed above. It can be done, for example, by an isospin analysis (comparing the different isospin states of the $\pi\pi$ system) [32].

Starting with a large disagreement in the first 2001 results, agreement between BaBar and Belle has improved over the years, but is still not very good; in addition, no conclusive answer to the question of direct CP violation can be given yet. The latest results from BaBar (2004) and Belle (2005) [33] are given in Table 3.

5.4 Direct CP violation in $B^0 \to K\pi$

Whereas the above analyses studied time-dependent CP violation due to interference, this channel is used to measure direct CP violation. The corresponding asymmetry is given by

$$a_d = \frac{\Gamma(B^0 \to K^+\pi^-) - \Gamma(\bar{B}^0 \to K^-\pi^+)}{\Gamma(B^0 \to K^+\pi^-) + \Gamma(\bar{B}^0 \to K^-\pi^+)}$$

and is a simple counting experiment, with self-tagging modes. Yet, the effect is smaller than that found in interference.

The experimental establishment of direct CP violation in the B-meson system happened very recently, in 2004. Both experiments BaBar and Belle presented results [15] in good agreement with theoretical prediction [16], *cf.* Table 3.

5.5 Interference in production: $B^\pm \to D^0K/\bar{D}^0K$

Another kind of analysis studies this channel, which allows experimental access to the third angle of the unitarity triangle γ. While the previous analyses studied interference between B-meson states or during decay, this one studies interference between two different end states, namely D^0 and $\bar{D}^0$. Interference between the D mesons can be observed in decay channels common to both. Experimentally, there are three established methods which differ by the studied common decay channel: while the GLW method [34], which uses decays into CP eigenstates like $\pi\pi$, and the ADS method [35] (decays into flavour-specific modes, e.g., $K^{\pm}\pi^{\mp}$) both suffer from small sensitivity for γ, the rather new Dalitz method [36] utilizing decays into three-body modes like, for example, $K\pi\pi$ is more promising. Still, the angle γ is certainly the hardest to measure, and the experimental errors are correspondingly large.

The 2005 results [37] listed in Table 3 show good agreement between BaBar and Belle when combining different channels, there is about one sigma difference in the single mode results.

The analyses presented here are only a—to some extent randomly—selected subset of results from BaBar and Belle; a complete listing of all studies would clearly be beyond the scope of this lecture.

6 Conclusions and outlook

As I hope I have demonstrated above, B physics is a very rich and active field; recent years have seen several results of high impact and relevance, deepening our understanding of the Standard Model, which has withstood another precision test: CP violation was found as large as expected in the B-meson system, and so far no disagreement with the Standard Model has been detected (see Fig. 7).

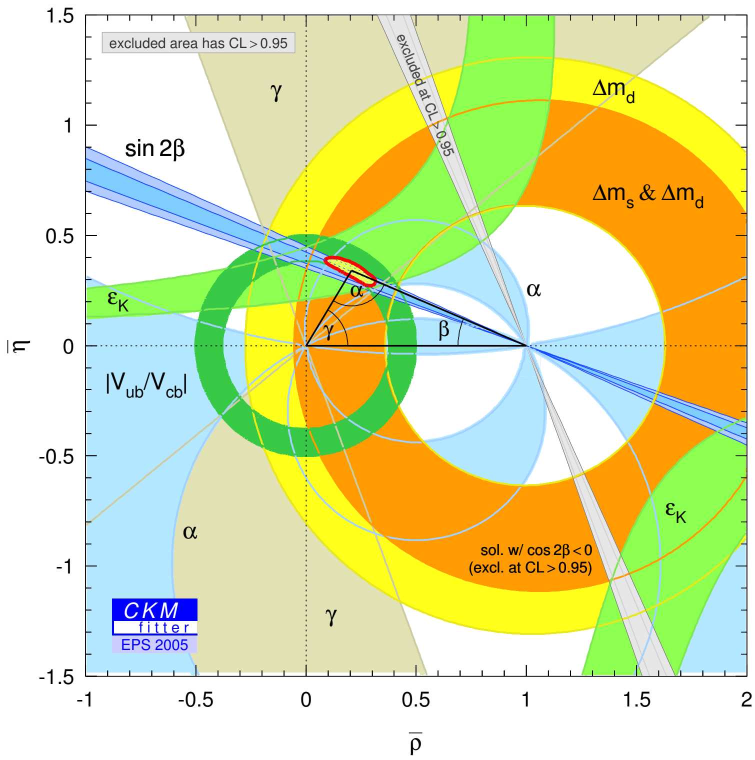

Fig. 7: Current knowledge about the CKM unitarity triangle [38]

However, as the results presented in the previous section show, in several fields no final conclusion can be drawn yet. There are some deviations from the Standard Model predictions which *could* be a hint for New Physics—but some patience is needed until the uncertainties can be further reduced.

Looking into the future, the big running experiments like BaBar, Belle, CDF II and D0 will continue to take data and will further improve their results. In 2007, when the LHC is scheduled to go into operation and bring some orders of magnitude more of data, the dedicated LHCb experiment will enter the game, and the other LHC experiments will also contribute to the field of B physics. This will enable precision measurements of all three angles and the sides of the unitarity triangle, over-constraining it as a strong test of the Standard Model. The B_s meson will be studied in similar precision, and the search for New Physics will extend to rare decays.

For the next decade, the preparations have already started for a super B-factory, with well over one order of magnitude higher luminosity. It will allow precision measurements of whatever the LHC surprises us with.

Maybe the Standard Model will survive once again—but maybe there will be more. And perhaps, you will be there!

Acknowledgements

I wish to thank Robert Fleischer and Manfred Jeitler for a helpful discussion of this lecture. Furthermore, by the nature of such a summary lecture, I gratefully used a lot of material collected from different sources; I tried to give references as far as possible. Last but not least, I owe my gratitude to the Scientific Programme Committee of the European School of High-Energy Physics, who for the first time allowed experimentalists to give summary talks at their School, which we appreciated very much.

References

[1] `http://www-public.slac.stanford.edu/babar/`.

[2] `http://belle.kek.jp` .

[3] S. Eidelman *et al.* [Particle Data Group], Phys. Lett. B **592** (2004) 1.

[4] W. R. Innes *et al.*, Phys. Rev. Lett. **39** (1977) 1240 [Erratum ibid. **39** (1977) 1640].

[5] C. W. Darden *et al.*, Phys. Lett. B **78** (1978) 364.

[6] D. Andrews *et al.* [CLEO Collaboration], Phys. Rev. Lett. **45** (1980) 219;
G. Finocchiaro *et al.* [CUSB Collaboration], Phys. Rev. Lett. **45** (1980) 222.

[7] K. Berkelman, Phys. Rep. **98** (1983) 145.

[8] C. Bebek *et al.*, Phys. Rev. Lett. **46** (1981) 84.

[9] D. Buskulic *et al.* [ALEPH Collaboration], Phys. Lett. B **294** (1992) 145.

[10] P. P. Singh [CDF Collaboration], `arXiv:hep-ex/9807022`.

[11] N. Lockyer *et al.*, Phys. Rev. Lett. **51** (1983) 1316;
M. Althoff *et al.* [TASSO Collaboration], Phys. Lett. B **149** (1984) 524.

[12] P. Abreu *et al.* [DELPHI Collaboration], Z. Phys. C **63** (1994) 3;
D. Buskulic *et al.* [ALEPH Collaboration], Phys. Lett. B **322** (1994) 275.

[13] H. Albrecht *et al.* [ARGUS Collaboration], Phys. Lett. B **192** (1987) 245.

[14] B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **94** (2005) 161803;
K. Abe *et al.* [Belle Collaboration], `arXiv:hep-ex/0507037`.

[15] B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **93** (2004) 131801;
K. Abe *et al.*, `arXiv:hep-ex/0507045`.

[16] R. Fleischer, these proceedings or `arXiv:hep-ph/0405091`.

[17] M. Creutz, `arXiv:hep-th/0303254`.

[18] J. P. Silva, `arXiv:hep-ph/0410351`.

[19] A. J. Buras, Lect. Notes Phys. **629** (2004) 85, `arXiv:hep-ph/0307203`.

[20] Y. Nir, `arXiv:hep-ph/0510413`.

[21] B. Aubert *et al.* [BaBar Collaboration], Nucl. Instrum. Meth. A **479** (2002) 1.

[22] A. Abashian *et al.,* [Belle Collaboration], Nucl. Instrum. Meth. A **479** (2002) 117.

[23] Y. Ushiroda *et al.,* Nucl. Instrum. Meth. A **511** (2003) 6.

[24] D. Acosta *et al.* [CDF II Collaboration], Phys. Rev. D **71** (2005) 032001.

[25] S. Abachi *et al.* [D0 Collaboration], Nucl. Instrum. Methods Phys. Res. A **338** (1994) 185; V. Abazov *et al.* [D0 Collaboration], The upgraded D0 detector, in preparation for submission to Nucl. Instrum. Meth. Phys. Res. A.

[26] S. Klous [LHCb Collaboration], Nucl. Instrum. Meth. A **549** (2005) 55; L. B. A. Hommels [LHCb Outer Tracker Collaboration], CERN-LHCB-2005-014.

[27] A. G. Akeroyd *et al.* [SuperKEKB Physics Working Group], `arXiv:hep-ex/0406071`.

[28] H. Kakuno *et al.*, Nucl. Instrum. Meth. A **533** (2004) 516, `arXiv:hep-ex/0403022`.

[29] W. Trischuk [Belle Collaboration], eConf **C020805**, TW02 (2002) `arXiv:hep-ex/0212059`.

[30] B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **87** (2001) 151801; K. Abe *et al.* [Belle Collaboration], `arXiv:hep-ex/0507037`.

[31] B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **87** (2001) 221802; B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **94** (2005) 041802; B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **93** (2004) 131805; B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **93** (2004) 181805; K. Abe *et al.* [Belle Collaboration], `arXiv:hep-ex/0507037`.

[32] B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **94** (2005) 181802.

[33] B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **95** (2005) 151803; K. Abe *et al.* [Belle Collaboration], `arXiv:hep-ex/0502035`.

[34] M. Gronau and D. Wyler, Phys. Lett. B **265** (1991) 172; M. Gronau and D. London., Phys. Lett. B **253** (1991) 483.

[35] D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. **78** (1997) 3257; Phys. Rev. D **63** (2001) 036005.

[36] A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D **68** (2003) 054018, [`arXiv:hep-ph/0303187`].

[37] B. Aubert *et al.* [BaBar Collaboration], `arXiv:hep-ex/0408088`; P. Krokovny [Belle Collaboration], `arXiv:hep-ex/0506033`.

[38] CKMfitter Group (J. Charles *et al.*), Eur. Phys. J. C **41** (2005) 1–131, `arXiv:hep-ph/0406184`, updated results and plots available at: `http://ckmfitter.in2p3.fr`.