B Physics (Experiment)

Michal Kreps

KIT, Wolfgang-Gaede-Straße 1, 77131 Karlsruhe, Germany

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In the past few years flavor physics made an important transition from the work on confirming the standard model of particle physics to the phase of search for effects of new physics beyond the standard model. In this paper we review the current state of the physics of b-hadrons with an emphasis on results with sensitivity to new physics.

1 Introduction

The beginning of b-physics dates back to 1964 when the decay of the long-lived kaon to two pions and thus CP-violation was observed [1]. It did not take very long until a theoretical explanation of CP-violation was proposed. In their famous work, Kobayashi and Maskawa showed that with four quarks there is no reasonable way to include CP-violation [2]. In addition they proposed several models to explain CP-violation in the kaon system, amongst which the six quark model got favored over time.

The explanation of CP-violation in the six quark model of Kobayashi and Maskawa builds on the idea of quark mixing introduced by Cabibbo. The quark mixing introduces a difference between the eigenstates of the strong and weak interactions. CP-violation requires a complex phase in order to provide a difference between a process and its charge conjugate. In the four quark model, the quark mixing is described by a 2×2 unitary matrix. With only four quarks, states can always be rotated in order to keep the mixing matrix real and thus four quark mixing cannot accommodate the CP-violation. Other arguments, which we are not going to discuss here, prevent also the suitable inclusion of the CP-violation in other parts of the theory. With the extension to six quarks, the mixing matrix becomes a 3×3 unitary matrix, called the Cabibbo-Kobayashi-Maskawa matrix, V_{CKM}. In this case there is no possibility to rotate away all phases and one complex phase always remains in the matrix. This complex phase of V_{CKM} provides CP-violation in the standard model. The idea has two important implications: First, in addition to the three quarks known in the early 1970's and the predicted charm quark, it postulates the existence of two additional quarks, called bottom and top. Second, despite the tiny CP-violation in the kaon system, the proposed mechanism predicts large CP-violation in the B-system. It took almost three decades, but both predictions have been confirmed experimentally, first by discovering the bottom quark in 1977 [3], second by the top quark discovery in 1995 [4, 5], and finally by the measurement of large CP-violation in the B^0-system in 2001 [6, 7].

In order to test the Kobayashi-Maskawa mechanism of CP-violation many measurements are performed. Their main aim is to determine V_{CKM} with the highest possible precision. Tests are often presented in the form of the so-called unitarity triangle. It follows from the unitarity requirement of V_{CKM}. The product of the two columns of the matrix has to be zero in the standard model. As the elements of the matrix are complex numbers, this requirement graphically represents a triangle in the complex plane. In the last decade flavor physics moved towards the search for inconsistencies which would indicate the presence of new physics. We omit the charm mixing and CP-violation prospects of starting experiments which are discussed elsewhere in these proceedings. Here we concentrate on the big picture with some emphasis on tensions in various measurements performed by the *BABAR*, Belle, CDF, CLEO-c and DØ experiments.

2 Sides of the unitarity triangle

Looking to the unitarity triangle there are two sets of quantities one can determine, namely angles and sides. In this section we will discuss the status of the determination of sides. They are determined by the V_{td}, V_{ub} and V_{cb} elements of V_{CKM}. To determine those quantities, two principal measurements are used. The first is the measurement of the B^0 oscillation frequency which determines V_{td}. The second is the measurement of the branching fraction of semileptonic B decays, which can be translated to V_{ub} or V_{cb}. As there are no recent results on B mixing, we concentrate on semileptonic decays and the determination of V_{ub} and V_{cb}.

The determination of V_{ub} and V_{cb} is based on the $b \to u\, l\, \nu$ and $b \to c\, l\, \nu$ transitions. The advantage of semileptonic transitions is that all soft QCD effects are contained in a single form factor. In general two complementary approaches exist. The first one is inclusive measurements, where one tries to measure the inclusive rate of $B \to X_{(c,u)}\, l\, \nu$ with $X_{(c,u)}$ denoting any possible hadron containing a charm or an up quark. The second approach uses exclusive measurements where one picks up a well defined hadron like D^* in the case of V_{cb} measurement. The two approaches are complementary; with the inclusive approach being theoretically clean at first order, while the exclusive approach is much cleaner in the experiment, but more difficult in theory. In addition, part of the good properties of the inclusive approach on the theory side is destroyed by the necessity of kinematic requirements on the experimental side. As one needs good control over the background in those measurements, it is practically the domain of e^+e^- B-factories running at the $\Upsilon(4S)$ resonance.

Coming to the current status, determinations of V_{cb} as well as V_{ub} have some issues and inconsistencies [8]. On the one hand, in the inclusive determination of V_{cb} the fit to all information has consistently a too small χ^2. On the other hand, in the exclusive determination using $B \to D^* l\, \nu$ decays, different measurements are not fully consistent with $\chi^2/ndf = 56.9/21$. This inconsistency is due to the differences between the Belle and *BABAR* results rather than inconsistence between old and new measurements. The world average determined from the inclusive measurement is $V_{cb} = (41.5 \pm 0.44 \pm 0.58) \times 10^{-3}$, from $B \to D\, l\, \nu$ we obtain $V_{cb} = (39.4 \pm 1.4 \pm 0.9) \times 10^{-3}$, and from $B \to D^* l\, \nu$ we obtain $V_{cb} = (38.6 \pm 0.5 \pm 1.0) \times 10^{-3}$. Obviously, despite the tension in the experimental information from $B \to D^* l\, \nu$ decays, the two exclusive determinations agree with each other, but the inclusive approach yields a value which is about $2.3\,\sigma$ higher than that from the exclusive determinations.

While the determination of V_{ub} in principle is the same as the determination of V_{cb}, in practice it is much more difficult due to the smallness of the $b \to u\, l\, \nu$ branching fraction compared to that of $b \to c\, l\, \nu$. The $b \to c\, l\, \nu$ decay in this case is a significant background. The kinematic selection to reduce this background destroys the possibilities of the theory for precise and reliable calculations. On the inclusive determination side, there are several groups

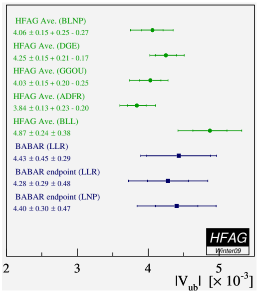

Figure 1: Summary of different inclusive determinations of V_{ub} from semileptonic $b \to u\, l\, \nu$ decays [8].

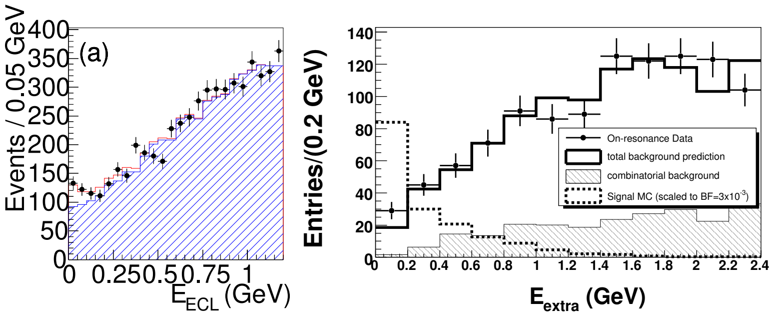

Figure 2: Distribution of the remaining energy in $B \to \tau\, \nu$ searches using semileptonic tag at Belle (left) and fully hadronic tag at *BABAR* (right).

which perform fits to the experimental data of inclusive decays. On the exclusive determination side, the *BABAR* experiment provides new results on $B \to \pi\, l\, \nu$ and $B \to \rho\, l\, \nu$. Using their partial branching fraction in different momentum transfer regions together with lattice QCD calculations they derive $|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3}$ [9], which is about $2\,\sigma$ below the inclusive determinations. If this persists, we have another discrepancy in the sides of the unitarity triangle.

Another way of accessing V_{ub} is to use $B^+ \to \tau\, \nu$ leptonic decays which proceed through weak annihilation. In the standard model its rate is given by the expression

$$BF = \frac{G_F^2 m_B}{8\pi}\, m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B\,, \tag{1}$$

where all quantities except for f_B^2 and V_{ub} are well known. Typically one takes f_B^2 and V_{ub} as input from other measurements and puts constraints on new physics. Alternatively one can take the measured branching fraction together with the prediction for f_B^2 and extract V_{ub}. B-factories recently provided evidence for this decay. Both, Belle and *BABAR* reconstruct one B in a semileptonic or a fully hadronic decay, called tagged, together with identified charged products of the τ decay. In such events, all what should be remaining are neutrinos and therefore one expects zero additional energy in the event. In Fig. 2 we show examples of the distribution of additional energy. The Belle experiment sees evidence on the level of $3.5\,\sigma$ in both tags [10, 11], while the *BABAR* experiment obtains an excess of about $2.2\,\sigma$ [12, 13]. The world average of the branching fraction of $(1.73 \pm 0.35) \times 10^{-4}$ is a little higher than the SM prediction of $(1.20 \pm 0.25) \times 10^{-4}$ and yields a value of V_{ub} which is in some tension with other determinations.

The result of the $B^+ \to \tau\, \nu$ branching fraction brings up the question whether the theory prediction from lattice QCD for f_B^2 is correct. One way to test predictions is to turn to the charm sector where we expect smaller contributions from new physics. The decay $D_s^+ \to \tau^+ \nu$ is a usual testing ground for calculations. The branching fraction is given by the same formula as for $B^+ \to \tau\, \nu$, replacing f_B^2 and V_{ub} by their appropriate counterparts. The branching fraction for $D_s^+ \to \tau^+ \nu$ was measured by the CLEO, *BABAR* and Belle experiments and there used to be some discrepancy between the prediction for f_{D_s} and its value extracted from the $D_s^+ \to \tau^+ \nu$ data. A summary of the evolution of this discrepancy is shown in Fig. 3 [14]. The current

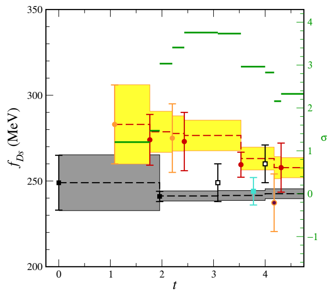

Figure 3: Comparison of the predicted f_{D_s} with experimental results. The circles denote experimental values with the yellow band showing the average. The squares show the prediction and the gray area the theory average. The green lines denote the difference between theory and experiment in Gaussian σ. The time t is measured in years since June 2005.

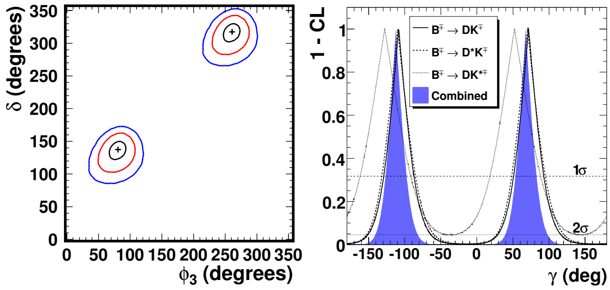

Figure 4: Confidence regions in the plane of the strong phase δ and the CKM angle γ/ϕ_3 from the Belle experiment (left) and 1-CL for the CKM angle γ from the *BABAR* experiment (right). In the left plot, the contours correspond to 1, 2 and 3 standard deviations. In the right plot, separate contours for the decays $B^+ \to D^0K^+$, $B^+ \to D^{*0}K^+$, and $B^+ \to D^0K^{*+}$ and a combination of all are shown.

situation is not too critical anymore as the discrepancy went down from $4\,\sigma$ to $2\,\sigma$. With this we conclude the discussion of sides of the unitarity triangle, where despite a lot of experimental work and large progress several tensions remain.

3 Angles of the unitarity triangle

The angles of the unitarity triangle are defined as

$$\alpha = \arg\left(-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right), \tag{2}$$

$$\beta = \arg\left(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right), \tag{3}$$

$$\gamma = \arg\left(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right). \tag{4}$$

As they are given by the phases of complex numbers, their determination is possible only through measurements of CP-violation. Here we omit the determination of the angle α, briefly mention the status of the angle β, and concentrate on the angle γ which received most of the new experimental information.

The angle β is practically given by the phase of V_{td}. One of the processes where this CKM matrix element enters is the B^0 mixing. Its best determination comes from the measurement of CP-violation due to the interference of decays with and without mixing to a common final state. Using decays to the $c\,\bar{c}$ resonance with a neutral kaon *BABAR* extracts $\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$ using the final dataset [15]. The latest measurement from Belle gives $\sin 2\beta = 0.642 \pm 0.031 \pm 0.017$ [16]. It is worth to note that both experiments are still statistically limited.

The determination of the angle γ provides important information for tests of physics beyond the standard model. It is determined from the interference of tree level $b \to c$ and $b \to u$ transitions and thus has small sensitivity to new physics. While several different decays are suggested for the determination, all current experimental information comes from $B^+ \to D^0K^+$.

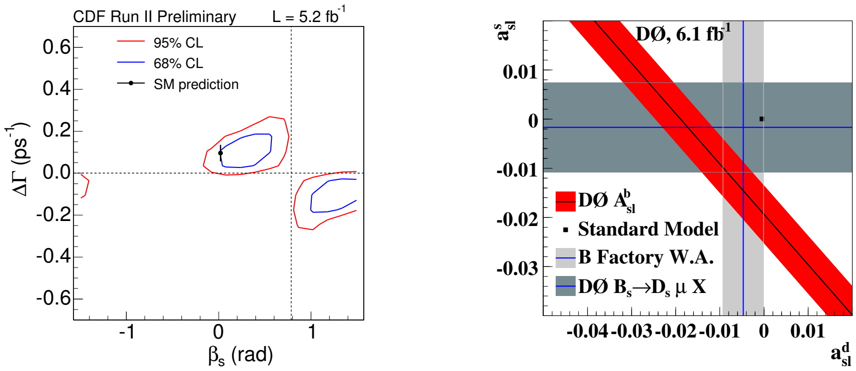

Figure 5: The $\Delta\Gamma_s$-β_s confidence regions in $B_s \to J/\psi\,\phi$ decays from the CDF experiment using 5.2 fb^{-1} of data (right). Latest results on the flavor specific asymmetry in semileptonic B_s decays from the DØ experiment (right).

In those decays, the $b \to c$ transition provides the $B^+ \to D^0K^+$ decay while the $b \to u$ transitions yields the $B^+ \to \bar{D}^0K^+$ final state. Thus measurements of the CP-violation in the final states which are common to D^0 and $\bar{D}^0$ is needed. Three different approaches are currently used: The first one uses the Cabibbo-favored decay $\bar{D}^0 \to K^-\pi^-$ with the doubly Cabibbo-suppressed decay $D^0 \to K^-\pi^+$ [17, 18]. The second method uses Cabibbo-suppressed D^0 decays to final states like $\pi^+\pi^-$ and K^+K^- [19]. The third approach uses a Dalitz plot analysis of $D^0 \to K_s\pi^+\pi^-$ [20]. The main limitation is that the rates are small and up to now there was no significant measurement of CP-violation in those decays. Recently the Belle and *BABAR* experiments announced an approximate $3.5\,\sigma$ evidence for CP-violation in $B^+ \to D^0K^+$ decays with $D^0 \to K_s\pi^+\pi^-$ [21, 22]. The extracted confidence regions on the angle γ are shown in Fig. 4. The Belle experiment extracts $\gamma = (78^{+11}_{-12} \pm 4 \pm 9)^\circ$ and *BABAR* obtains $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$.

4 B_s sector

The CP-violation in the B_s meson sector is currently the most exciting and most widely discussed topic in relation to new physics. Two results, which in many models of new physics are related, are the measurement of the CP-violation in $B_s \to J/\psi\,\phi$ decays and the flavor specific asymmetry in semileptonic B_s decays.

The origin of the first one is in the interference of the decays with and without B_s mixing. The standard model predicts only tiny CP-violation which comes from the fact that all entering CKM matrix elements are almost real. The previous results from the two Tevatron experiments showed about 1.5-1.8$\,\sigma$ deviation from the standard model [23, 24], with their combination being 2.2$\,\sigma$ away. Recently, the CDF collaboration updated its result with more data and a few improvements, which yield better constraints on the CP-violation in $B_s \to J/\psi\,\phi$. The resulting 2-dimensional $\Delta\Gamma_s$-β_s contour is shown in Fig. 5. Overall, the CDF experiment now observes a better agreement between the data and the standard model with a difference of about 0.8$\,\sigma$. More details on this update can be found in [25].

The second measurement we present here is the measurement of the flavor specific asymmetry in semileptonic b-hadron decays. In the standard model, as well as in a large class of new physics models, this quantity is predicted to be small. It can be generated either by direct CP-violation or by an asymmetry in the mixing rate between b- and $\bar{b}$-mesons. Typically, direct CP-violation is zero as we talk about the most allowed decay amplitude $b \to c\,l\,\nu$ which would need a second contribution to interfere with. As it is not easy to construct a model where a second amplitude with reasonable size exists, typically the direct CP-violation is predicted to be zero. The effect of different mixing rates is small for the B^0 due to the small decay width difference and it is small in the standard model for the B_s due to the small phase involved. The DØ experiment announced a new measurement this year, with a highly improved treatment of systematic uncertainties. They measure $A^b_{fs} = (-96 \pm 25 \pm 15) \times 10^{-4}$ which is significantly different from the standard model expectation of $A^b_{fs} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$ [26]. If this result is confirmed, it is a clear sign of physics beyond the standard model. For more details see [27].

5 Rare decays

Rare FCNC transitions are best known outside the flavor physics community for searches of physics beyond standard model. The prime example is the rare $B_s \to \mu^+\mu^-$ decay, where previous results could put strong constraints on some new physics models, even with limits which are far from the standard model expectations. The standard model prediction for the branching fraction of $B_s \to \mu^+\mu^-$ is $(3.6 \pm 0.3) \times 10^{-9}$ [28]. The main difficulty is in suppressing and controlling the background. The search for this decay is dominated by the Tevatron experiments. Recently, the DØ experiment updated its result using 6.1 fb^{-1} of data yielding an upper limit on the branching fraction of 5.2×10^{-8} at 95% C.L. [29]. The best limit at this moment comes from the CDF experiment using 3.7 fb^{-1} of data: 4.3×10^{-8} at 95% C.L. [30]. Those are about an order of magnitude above the standard model prediction.

Another example of a FCNC rare process which generates a lot of excitement these days is a class of decays governed by the $b \to s\,l^+l^-$ quark level transition with l being a charged lepton. The decays $B^{0,\pm} \to K^{0,\pm}\mu^+\mu^-$ and $B^{0,\pm} \to K^{*0,\pm}\mu^+\mu^-$ have already been observed. Recently, the CDF experiment observed also the decay $B_s \to \phi\,\mu^+\mu^-$ with an approximate $6.3\,\sigma$ significance using 4.4 fb^{-1} of data [31]. The measured branching fraction is $(1.44 \pm 0.33 \pm 0.46) \times 10^{-6}$. As those decays proceed even in the standard model through more than one amplitude, there is a rich phenomenology of interferences. From the interference effects, the forward-backward asymmetry of the muons as a function of dimuon invariant mass is the one which is responsible for the excitement. It has been measured in the Belle [32], *BABAR* [33] and CDF [31] experiments and we show the results in Fig. 6. While not statistically significant, all three experiments show some departure in the same direction from the standard model. It is going to be interesting to follow future measurements of this quantity.

6 Conclusions

Globally, except for the flavor specific asymmetry in semileptonic b-decays, there is no significant discrepancy in the global picture of CP-violation. However, there are a few discrepancies which are worth to be followed in the future. In Fig. 7 we show the global status of the CKM fit [34]. Another determination [35] provides a similar picture. Both groups see an approximate $2.5\,\sigma$ improvement of the fit if either the constraint from $B \to \tau\,\nu$ or $\sin 2\beta$ is removed from the fit. Other small discrepancies are in V_{ub} and in the CP-violation parameter ϵ_K in the kaon system.

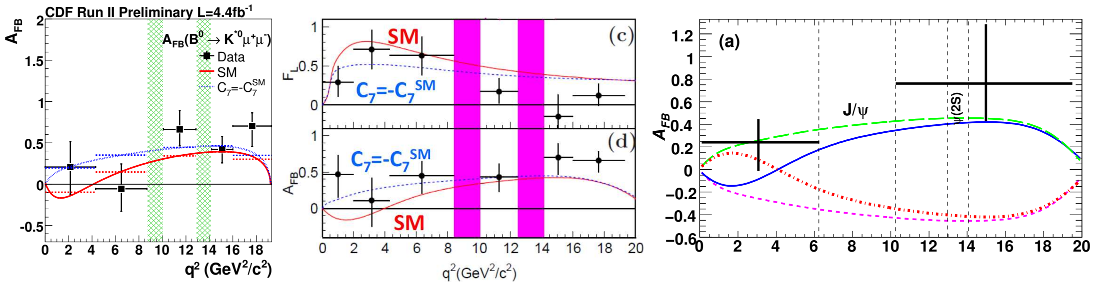

Figure 6: The forward-backward asymmetry of the muon in $B \to K^*\mu^+\mu^-$ decays as a function of the dimuon invariant mass from CDF (left), Belle (middle) and *BABAR* (right). The points represent measurement, the red line in the CDF and Belle cases and the blue line in the *BABAR* result show the standard model prediction and the other curves represent different beyond the standard model scenarios. The areas without data points correspond to the charmonium regions which are excluded from the analysis.

Within the limited space we could not discuss the charm quark sector, which has strong potential. Its status and prospects at the time of the conference can be found in [36]. The prospects of the LHC in the bottom quark sector were discussed in several contributions, the most relevant one with respect to this work being [37]. With large expectations the whole community is positive about future interesting results and the importance of flavor physics for discovering and/or understanding physics beyond standard model.

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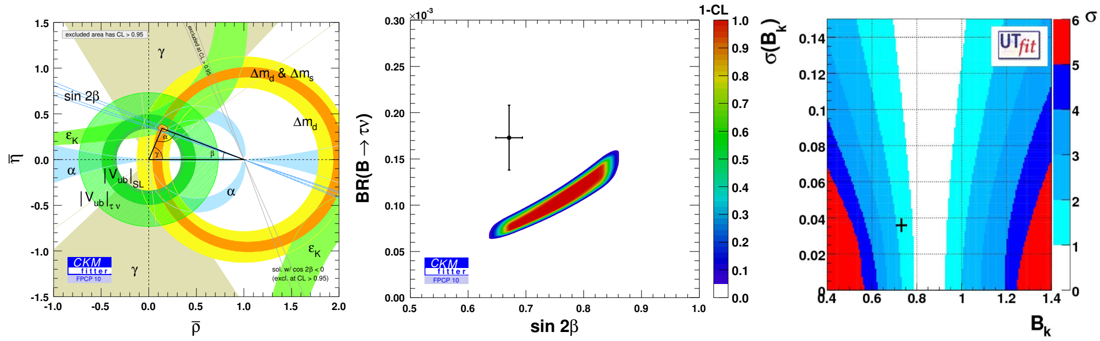

Figure 7: The global status of the unitarity triangle fit from the CKMFitter group (left), the graphical representation of the $B \to \tau\nu$ versus $\sin 2\beta$ disagreement (middle) and the situation with indirect and direct determinations of the parameter proportional to ϵ_K from the UTFit group (right). In the middle plot, colored confidence regions show the expectation for the $B \to \tau\nu$ branching fraction from the fit where two quantities are excluded while the point shows experimental results. In the right plot, the colored areas show the confidence regions of B_K from the fit without constraint from the CP-violation in the kaon system. The cross represents the experimental measurement of the quantity.

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