QUARK FLAVOUR PHYSICS

M. Kreps, M.Kreps@warwick.ac.uk, University of Warwick

ABSTRACT

The quark flavour sector plays a crucial rôle in searches for a new physics beyond standard model as well as for understanding the details of it if observed. We review the flavour structure of the standard model with emphasis on neutral meson mixing and *CP* violation. On example of kaons we explain the basic concepts as well as the idea of accessing yet unobserved physics from precision low energy measurements. Then we turn attention to the testing of standard model with Kobayashi-Maskawa mechanism for *CP* violation. Finally we discuss ideas behind main measurements sensitive to physics beyond standard model including main experimental techniques necessary for such measurements.

INTRODUCTION

The current experimental results of the particle physics can be described by the single theory, so-called standard model. Parameters of the standard model are three coupling constants which give strength of interactions, two Higgs parameters related to the spontaneous symmetry breaking, and 12 fermion masses (6 for quarks and 6 for leptons) along with 4 quark mixing parameters and 4 lepton mixing parameters. The field of flavour physics is defined by the parameters giving quark masses and mixing parameters.

In this short write-up we briefly summarize main points of the lectures on quark flavour physics with aim to provide a good summary of references for further study of presented ideas. The lectures are split into three parts. The first one is dealing with kaon physics and building standard model. The second one explains how the confidence in the standard model was built while last part is discussing searches for a breakdown of the standard model and thus observation of a new physics. All three parts should be useful to any particle physicist to understand modern flavour physics measurements. While the last part is probably not too important for non-particle physicists, first part on kaon physics still provides useful material, which opens up basic understanding of modern flavour physics.

KAON PHYSICS AND BUILDING OF STANDARD MODEL

Historically kaon physics played a crucial role during buildup of the flavour structure of the standard model. It provided all necessary information to arrive to the existing theory of flavour transitions. The field started by discovery of K^0 and K^+ in 1947 [1]. From the discovery it was apparent that those new particles are produced by the strong interaction while they decays are mediated by weak interactions. Skipping history of introducing strangeness quantum number and arrival to three quarks (down, up, strange) which can be found for instance in Ref. [2] we continue at point of introducing decays of kaons into the theory. The main observed decays modes were

$$\mathrm{K}^+ \to \mu^+\nu_\mu, \quad \mathrm{K}^+ \to \pi^0\mathrm{e}^+\nu_\mathrm{e}, \quad \mathrm{K}^0 \to \pi^+\pi^-, \quad \mathrm{K}^0 \to \pi^0\pi^0. \tag{1}$$

As the K^+ is composed of s and $\overline{\mathrm{u}}$ and the K^0 of d and $\overline{\mathrm{s}}$ it is easy to find out that on the quark level we need transition s $\to$ u in order to allow those decays. In the same time as lifetime of the kaons is rather long, the transition behind their decay has to be relatively weak. Elegant way of achieving this goal in theory was proposed by N. Cabibbo in paper from 1963 [3]. Here he postulated two ideas, universality of weak interactions and mixing between different quarks. The mixing effectively means that while the strong interaction works with d and s, the weak interaction couples to a weak doublet defined as

$$\begin{pmatrix} \mathrm{u} \\ \mathrm{d}' \end{pmatrix} = \begin{pmatrix} \mathrm{u} \\ \mathrm{d}\cos(\theta_C) + \mathrm{s}\sin(\theta_C) \end{pmatrix} \tag{2}$$

where θ_C is mixing angle also known as Cabibbo angle. This mixing angle has to be determined experimentally and originally ratio of rates between $\mathrm{K}^+ \to \mu^+\nu_\mu$ and $\pi^+ \to \mu^+\nu_\mu$ was used for this purpose. One of the nice features of this proposal was that it helped to resolve discrepancy in Fermi constant of weak interaction as determined in μ^- and nuclear β decays. The quark mixing in this case gives amplitude which is proportional to $\cos(\theta_C)$ while muon decay amplitude remains unmodified. While the quark mixing introduced by Cabibbo successfully solved some of questions of the time, it also introduced new issue in the theory, which had to be fixed. Issue arises from the fact that if W^+ couples to u with d', than also Z^0 could couple to d'$\overline{\mathrm{d}}$'. In terms of original quarks, this coupling translates to

$$\mathrm{u}\overline{\mathrm{u}} + \mathrm{d}\overline{\mathrm{d}}\cos^2\theta_C + \mathrm{s}\overline{\mathrm{s}}\sin^2\theta_C + (\mathrm{s}\overline{\mathrm{d}} + \overline{\mathrm{s}}\mathrm{d})\sin\theta_C\cos\theta_C \tag{3}$$

which would allow flavour changing neutral current (FCNC) decays like $\mathrm{K}^+ \to \pi^+\mathrm{e}^+\mathrm{e}^-$ at the tree level. But such decays are not observed experimentally and from the experiment itself it was known that

$$\frac{\Gamma(\mathrm{K}^+ \to \pi^+\mathrm{e}^+\mathrm{e}^-)}{\Gamma(\mathrm{K}^+ \to \pi^0\mathrm{e}^+\nu_\mathrm{e})} < 10^{-5}. \tag{4}$$

Thus we need some way to suppress FCNC decays. In 1970, Glashow, Iliopoulos and Maiani proposed a solution to this issue by introducing fourth quark [4] and forming a second doublet taking place in weak interaction. This doublet has form

$$\begin{pmatrix} \mathrm{c} \\ \mathrm{s}' \end{pmatrix} = \begin{pmatrix} \mathrm{c} \\ \mathrm{s}\cos(\theta_C) - \mathrm{d}\sin(\theta_C) \end{pmatrix}. \tag{5}$$

The second doublet has similar cross terms as first one, but with opposite sign, so at the tree level FCNC decays are exactly cancelled. At higher order levels, in limit of equal masses for up and charm quarks FCNC diagrams cancel each other exactly. If masses of up and charm quark are not equal, than residual effect of FCNC decays would be observable and its size will depend on the ratio of masses of two up type quarks. With this, a fourth quark is predicted at the time when quarks itself were not fully accepted and thus the model not only explained experimental results, but also provided very strong prediction of the existence of fourth quark. Before moving on, we should answer question, why down type quark mix together while up type quarks are left untouched. In fact one could equally well introduce it to the up type quarks and leave down type quarks unaffected or mix both up and down type quarks. But as we have the freedom to rotate quark fields, we can always reduce it to mixing in down type quarks without experimentally observable consequences. So only reason for using down type quark is convention and probably fact that when Cabibbo introduced quark mixing, only single up type quark was needed, thus he naturally had to choose down type quarks.

The next puzzle to deal with concerns neutral kaons. At the time, experiments observed two particles produced in the same way by the strong interaction having the same charge and mass, but significantly different lifetimes. First one with $\tau \approx 9 \times 10^{-11}$ s decaying to two pions and second one with $\tau \approx 5 \times 10^{-8}$ s decaying to three pions. The way to understand this is that in the strong interaction K^0 or $\overline{\mathrm{K}}^0$ are produced with their distinct strangeness content. But when we start to look to decays governed by the weak interaction eigenstates of the strong interaction are not eigenstates any more as the weak interaction does not conserve strangeness. Recalling CP symmetry, which transforms particles into antiparticles we have

$$\begin{aligned} CP \mid \pi^+\pi^-\rangle &= +\mid \pi^+\pi^-\rangle, \\ CP \mid \pi^+\pi^-\pi^0\rangle &= -\mid \pi^+\pi^-\pi^0\rangle. \end{aligned} \tag{6}$$

If we for the moment assume that the CP is conserved also in weak interactions and that CP eigenstates are the eigenstates of weak interaction, than we can easily explain the large difference in lifetimes. Lets call the CP-even eigenstate K_1 while the CP-odd eigenstate will be called K_2. With CP conserved, K_1 will decay only to two pions, while K_2 only to three pions. Now we have to turn to the formula used to calculate the decay width, which is inverse of lifetime,

$$d\Gamma = \frac{(2\pi)^4}{2M}|\mathcal{M}|^2 d\Phi_n \tag{7}$$

where

$$d\Phi_n = \delta^4(P - \sum p_i) \prod \frac{d^3p_i}{(2\pi)^3 2E_i}. \tag{8}$$

While the matrix element $\mathcal{M}$ is of same order for both cases, the phase space integral defined by the equation 8 yields significant difference as in the decay of K_1 we have more energy available than in the decay of K_2. With this, lifetimes can be explained, but now we need to connect two sets of eigenstates together. As we already mixed quarks, it is quite natural idea that the weak interaction eigenstates would be mixtures of the strong interaction eigenstates. Defining positive CP parity for K^0 and $\overline{\mathrm{K}}^0$ we can define

$$\mid \mathrm{K}_1\rangle = \frac{1}{\sqrt{2}}\left(\mid \mathrm{K}^0\rangle + \mid \overline{\mathrm{K}}^0\rangle\right), \quad \mid \mathrm{K}_2\rangle = \frac{1}{\sqrt{2}}\left(\mid \mathrm{K}^0\rangle - \mid \overline{\mathrm{K}}^0\rangle\right). \tag{9}$$

It is easy to verify that K_1 and K_2 have in this case proper CP properties to explain different lifetimes. When concerned about the propagation through space, weak interaction is of importance. This suggests that time propagation will be given as

$$\begin{aligned} \mid \mathrm{K}_1(t)\rangle &= e^{-im_1t-\Gamma_1 t/2} \mid \mathrm{K}_1\rangle, \\ \mid \mathrm{K}_2(t)\rangle &= e^{-im_2t-\Gamma_2 t/2} \mid \mathrm{K}_2\rangle. \end{aligned} \tag{10}$$

Other way to look at it is that K_1 and K_2 have well defined lifetimes, so those are correct states which should decay exponentially. It is useful to check what happens to the initially pure K^0 beam after some time. To start, we can write

$$\mid \mathrm{K}^0\rangle = \frac{1}{\sqrt{2}}\left(\mid \mathrm{K}_1\rangle + \mid \mathrm{K}_2\rangle\right) \tag{11}$$

and perform time evolution. At any specific time t we can find out amount of K^0 by calculating $\langle \mathrm{K}^0(t) \mid \mathrm{K}^0(t)\rangle$. For our case we find

$$\begin{aligned} 2\langle \mathrm{K}^0(t) \mid \mathrm{K}^0(t)\rangle &= \langle \mathrm{K}_1^* \mid \mathrm{K}_1\rangle + \langle \mathrm{K}_2^* \mid \mathrm{K}_2\rangle + \langle \mathrm{K}_1^* \mid \mathrm{K}_2\rangle + \langle \mathrm{K}_2^* \mid \mathrm{K}_1\rangle \\ &= e^{-\Gamma_1 t} + e^{-\Gamma_2 t} + e^{\frac{\Gamma_1+\Gamma_2}{2}t}\cos\left[(m_2 - m_1)t\right], \end{aligned} \tag{12}$$

where $\Gamma_{1,2}$ and $m_{1,2}$ are decay width and mass of $K_{1,2}$. Starting again from pure K^0 at time $t = 0$ we can also find number of $\overline{K}^0$ to be

$$2\langle\overline{K}^0(t) \mid \overline{K}^0(t)\rangle = e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - e^{\frac{\Gamma_1+\Gamma_2}{2}t}\cos\left[(m_2 - m_1)t\right]. \tag{13}$$

What this means is that the initially pure K^0 beam will not only decay, but will also oscillate to pure $\overline{K}^0$ and back with oscillation frequency given by the mass difference between two weak interaction eigenstates.

The oscillating behaviour is also experimentally observable. A nice example of such experiment is CPLEAR experiment at CERN [5]. The experiment consists of symmetric detector around beam axis with tracking, calorimeter and muon detection subsystems. It uses low energy $\overline{p}$ beam impinging on a hydrogen target. Energy of the beam is tuned so that only $K^+ \pi^- \overline{K}^0$ and $K^- \pi^+ K^0$ final states involving kaons are possible. The charged kaon determines whether a neutral kaon was produced as K^0 or $\overline{K}^0$. Using semileptonic decays like $K^0 \to \pi^- e^+ \nu_e$ which determine flavour at the decay, one can measure a time dependent asymmetry

$$A(t) = \frac{N(K^0 \to K^0) + N(\overline{K}^0 \to \overline{K}^0) - N(K^0 \to \overline{K}^0) - N(\overline{K}^0 \to K^0)}{N(K^0 \to K^0) + N(\overline{K}^0 \to \overline{K}^0) + N(K^0 \to \overline{K}^0) + N(\overline{K}^0 \to K^0)}. \tag{14}$$

The obtained asymmetry from Ref. [6] is shown in Fig. 1. From the time dependence one can extract mass difference between two weak eigenstates, which is in the case of this measurement $\Delta m = (529.5 \pm 2.0(\mathrm{stat}) \pm 0.3((sys)) \times 10^{-7}\hbar$ s^{-1}.

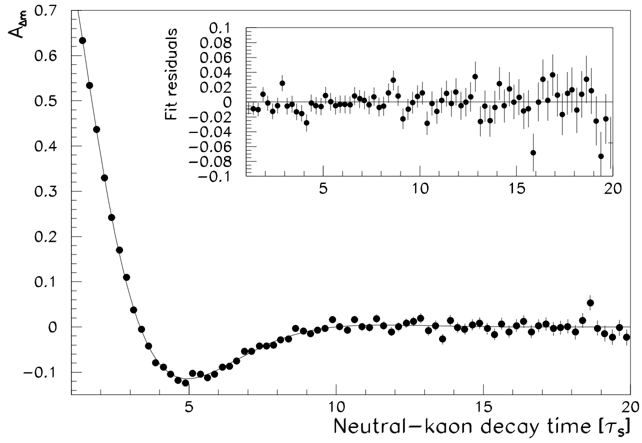

Fig. 1. The asymmetry defined by eq. 14 measured by CPLEAR experiment [6]. The measurement clearly demonstrates that neutral kaons are mixing.

Up to now we assumed that the *CP* is conserved both by strong and weak interactions. What happens if we remove this requirement for the weak interaction? Immediate consequence is that the K_1 can decay to three pions and the K_2 to two pions. Is this something which experiments can support? In 1964, Christenson, Cronin, Fitch and Turlay performed an experiment to find out whether *CP* is conserved in weak interactions or not [7]. Specifically, using a beam of long lived K_2 mesons they searched for its decay to two charged pions. The experiment consisted of two arm spectrometer capable to reconstruct tracks of two pions. If the K_2 decays to two pions, then the vector sum of their momenta should point along the beam axis, while for three body decays this points in all possible directions. In Fig. 2 we reproduce the principal result of Ref. [7], which clearly shows that there are K_2 mesons decaying to $\pi^+ \pi^-$ pairs and thus the *CP* is violated in weak interactions. The experiment measured

$$R = \frac{N(K_2 \to \pi^+\pi^-)}{N(K_2 \to \text{all charged})} = (2 \pm 0.4) \times 10^{-3}. \tag{15}$$

What does it mean for the model we are putting together? First, the K_1 and K_2 are not eigenstates of the weak interaction. The eigenstates are still slightly different and usually named K_S^0 and K_L^0 for short and long lived one respectively. Given that observed *CP* violation is small, the K_S^0 and K_L^0 are mostly composed of appropriate *CP*-eigenstate with a small admixture of wrong *CP*-eigenstate, which formally can be written as

$$\mid K_S^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(\mid K_1\rangle - \epsilon \mid K_2\rangle\right), \quad \mid K_L^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(\mid K_2\rangle + \epsilon \mid K_1\rangle\right). \tag{16}$$

It is easy to check that the parameter ϵ is related to the size of the *CP* violation and the rate of decay $K_L^0 \to \pi^+ \pi^-$ is proportional to ϵ^2. From the result of original experiment one finds $\epsilon \approx 2.3 \times 10^{-3}$.

While phenomenologically the *CP* violation can be included, in terms of the standard model which describes the interaction of quarks the *CP* violation is not included. In 1973 Kobayashi and Maskawa in their topical paper

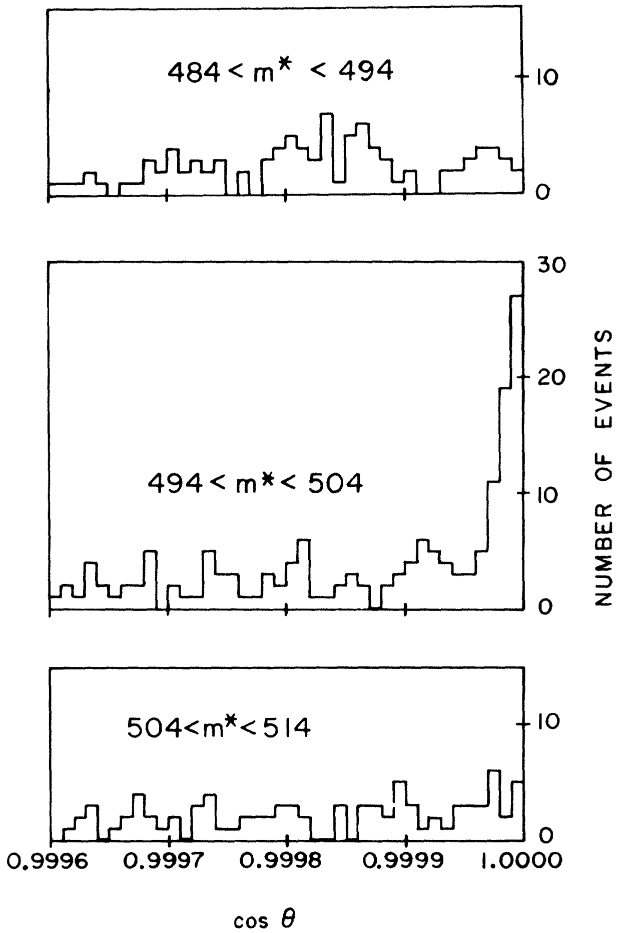

Fig. 2. The distribution of the angle between K_2 beam and the vector sum of the momenta of two detected charged pions for pion pair invariant mass below the K_2 mass (top), in the K_2 mass region (center) and above the K_2 mass (bottom). A clear peak at $\cos\theta \approx 1$ is visible, which is sign of the *CP* violation. The figure is reproduced from Ref. [7].

showed that with four quarks it is practically impossible to introduce the *CP* violation into theory [8]. In this paper they also proposed to add third generation of quarks into the theory to explain the *CP* violation observed about decade ago. With three generations, the quark mixing can be described by unitary 3×3 matrix called Cabibbo-Kobayashi-Maskawa matrix. While in case of two generations, quark fields can be always rotated to remove the complex phase from mixing matrix, in case of three generations, one complex phase always remains. The quark mixing can be written as

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{17}$$

where primed quarks are those entering the weak interaction while non primed are quarks of the strong interaction. While each element is a complex number, unitarity of the matrix together with possibility to rephase quark fields reduces all parameters down to 4 independent ones. Those are three mixing angles and one complex phase which is responsible for the *CP* violation in the standard model. Very popular parametrization was suggested by Wolfenstein [9], which expands all elements in terms of small parameter $\lambda = \sin\theta_C$ and has form

$$V_{\text{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4). \tag{18}$$

Reader should be aware that while this parametrization is useful and catches main features it is just approximation which does not provide all details. In any case, Wolfenstein parametrization provides to first order right answers about the *CP* violation and the size of quark transitions. Now we shortly turn back to the neutral kaon mixing. The Feynman diagrams for the mixing of neutral kaons are shown in Fig. 3. With those together with information we already discussed we can say that mixing is rather small. This is a consequence of the GIM suppression of contributions from up and charm quark in the loop and the strong CKM suppression (V_{td}) for top quark contribution. In addition, to a first order, top contribution is one which introduces the CKM phase into process

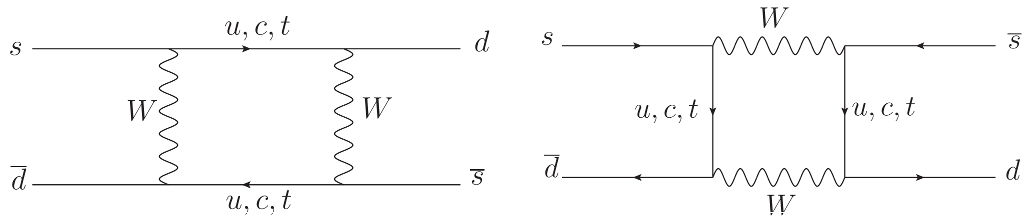

Fig. 3. Feynman diagrams for the neutral kaon mixing.

and thus the *CP* violation is also small in this case. On the other hand, if we find a process which would be dominated by contribution with top quark coupling to down quark, we could expect large *CP* violation in such process.

With this we summarized main features of the standard model and how one could arrive to it. Discussion outlined here can be found in many standard textbooks on particle physics. Some examples are Refs. [2, 10, 11]. Another useful reference, specially for particle physics students are lecture notes of G. Buchalla [12] which are exclusively devoted to the kaon physics.

DISCOVERY OF NEW QUARKS

When Kobayashi and Maskawa proposed their explanation of the *CP* violation, only three quarks were needed to explain all observed hadrons and quarks were not fully accepted. Their idea together with GIM mechanism implied three more quarks to exists, which should be observable by experiments. Experiments searching for new quarks followed rather quickly the theoretical development and in 1974 particle physics witnessed so-called November revolution in which first observation of hadrons with charm quark was announced. Two different experiments with two different technique made the discovery of same particle with a third experiment confirming result in extremely short time. The first experiment at Brookhaven lead by S. Ting, measured the cross section for producing e^+e^- pairs in pBe interactions as a function of the invariant mass of e^+e^- pair [13]. The second experiment was performed at SLAC and lead by B. Richter [14]. It studied the e^+e^- annihilation as a function of energy of the system. The principal results of the two experiments are shown in Fig. 4. The particle they discovered is now known under the name J/ψ where J is name suggested by Ting and ψ by Richter. When G. Belletini heard about results, he pushed the e^+e^- accelerator at Frascati to the necessary energy and repeated experiment from SLAC and provided the confirmation of observation [15]. It should be noted that while J/ψ is now interpreted as a $c\bar{c}$ bound state, at the time of discovery it was not obvious this is charm and further work was necessary to conclude that this is indeed the charm quark discovery.

The next step in the search for additional quarks followed very quickly. Just three years after the discovery of charm quark, experiments pushed studies of dileptons to high enough energy to see a next resonance. Experiment lead by L. Lederman used proton beam shot on a nucleus target and similar to the experiment of S. Ting, also here a peak in the invariant mass of dimuons showed up [16]. The invariant mass distribution from this work is reproduced in Fig. 5. With this observation, five quarks turned up to be present, so there was no doubt that sixth will follow and it is only a matter of time to achieve a high enough energy and statistics to observe it. But there was difference as top quark is much heavier than any others and its lifetime is shorter than a typical time scale on which hadrons are formed. Thus in the search for top quark experiments at the end did not search for a hadron containing the top quark, but directly for the quark decay. It turned out that top quark with its mass of about 170 GeV/c^2 was hard enough to observe that it took until 1995 when CDF and D0 experiments finally saw it [17, 18].

The fact that at the time when quarks were not fully accepted and only three were know one could predict other three and construct the standard model just based on measurements available is quite remarkable. Nevertheless before Nobel prize was awarded for the explanation of the *CP* violation one more important measurement had to be done. Also at this point we will depart from rather historical line and discuss rest in a more logical connections.

CP VIOLATION

In the next step we will look to the classification of *CP* violation. But first lets go back to the basic quantum mechanics and observables in it. As we know, in the quantum mechanics all observable quantities are given by the square of the wave function. This also means that phase of the wave function is not really observable. On the other hand, if we look to a system which is described by a sum of wave functions, then thanks to the interference the difference in phases of wave functions can be observed. Given this if we want to have an observable *CP* violation in some process, then the process has to proceed through more than one amplitude which would potentially introduce observable phase difference. It also means that decays dominated by a single amplitude will in first order not exhibit observable *CP* violation.

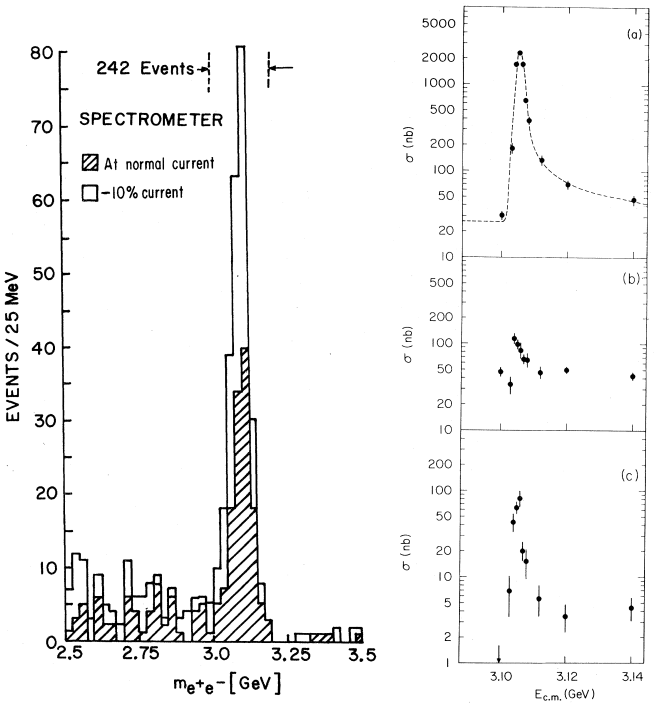

Fig. 4. The invariant mass distribution of e^+e^- pairs produced in the pBe interactions [13] (left) and for various particle productions in the e^+e^- annihilation as a function of energy [14] (right). Those two results mark the observation of J/ψ, first particle with charm quark.

To classify different types of the *CP* violation, we first define few quantities. First ones are decay amplitudes

$$\begin{aligned} A_f &= \langle f|H|M\rangle, & \overline{A}_f &= \langle f|H|\overline{M}\rangle, \\ A_{\overline{f}} &= \langle \overline{f}|H|M\rangle, & \overline{A}_{\overline{f}} &= \langle \overline{f}|H|\overline{M}\rangle. \end{aligned} \tag{19}$$

The first line gives amplitudes for particle and antiparticle to decay to a given final state f while the second line are amplitudes for decays to the *CP* conjugated state $\overline{f}$. Those four amplitudes can be defined for any particle including charged mesons or baryons. In addition for neutral mesons mixing plays a role. This is governed by a Schrödinger type equation

$$i\frac{d}{dt}\begin{pmatrix} |B(t)\rangle \\ |\overline{B}(t)\rangle \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} |B(t)\rangle \\ |\overline{B}(t)\rangle \end{pmatrix}, \tag{20}$$

where B and $\overline{B}$ are flavour eigenstates of given meson (while we use B, it means K^0, D^0, B^0 or B^0_s). By diagonalization of the Hamiltonian composed of the mass matrix $\hat{M}$ and the decay matrix $\hat{\Gamma}$ we arrive to mass eigenstates

$$|B_H\rangle = p\,|B\rangle + q\,|\overline{B}\rangle, \quad |B_L\rangle = p\,|B\rangle - q\,|\overline{B}\rangle \tag{21}$$

with

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}. \tag{22}$$

Having those definitions, we can describe all types of *CP* violation in terms of phase invariant variables

- $|\overline{A}_{\overline{f}}/A_f|$,
- $|q/p|$,
- $\lambda_f = (q/p)(\overline{A}_f/A_f)$.

Three different types of the *CP* violation exist. They can be categorized as

1. *CP* violation in decay: It is defined by $|\overline{A}_{\overline{f}}/A_f| \neq 1$. For charged mesons and baryons it can be measured as asymmetry

$$A = \frac{\Gamma(M^- \to f^-) - \Gamma(M^+ \to f^+)}{\Gamma(M^- \to f^-) + \Gamma(M^+ \to f^+)} = \frac{|\overline{A}_{f^-}/A_{f^+}|^2 - 1}{|\overline{A}_{f^-}/A_{f^+}|^2 + 1}. \tag{23}$$

   This is the only possible *CP* violation for charged mesons and baryons.

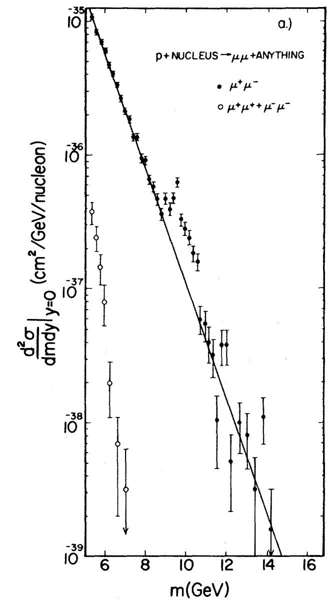

Fig. 5. The invariant mass distribution of dimuon pairs produced in a p-Nucleus interactions [16].

2. CP violation in mixing: This type is given by $|q/p| \neq 1$ and is essentially difference in rate for meson turning into antimeson and vice versa. It is this type of CP violation which original discovery in 1964 observed. Typically it is measured by an asymmetry

$$A = \frac{d\Gamma/dt[\overline{M} \to f^+] - d\Gamma/dt[M \to f^-]}{d\Gamma/dt[\overline{M} \to f^+] + d\Gamma/dt[M \to f^-]} = \frac{1-|q/p|^4}{1+|q/p|^4}, \tag{24}$$

where the flavour of meson is defined at a production time, final state is chosen such that it flags flavour at a decay time (e.g. semileptonic decays) and experiments are looking to decays, which cannot occur directly, but must happen through mixing. Thus this asymmetry measures directly the mixing rate difference.

3. CP violation in interference of decays with and without mixing is determined by $\mathrm{Im}(\lambda_f) \neq 0$: This CP violation occurs in decays to final states accessible to both meson and antimeson and exploits interference of the direct decay of meson M with the amplitude of first M oscillating to $\overline{M}$ followed by the decay of $\overline{M}$. It is measured by a time dependent asymmetry

$$A(t) = \frac{d\Gamma/dt[\overline{M} \to f_{CP}] - d\Gamma/dt[M \to f_{CP}]}{d\Gamma/dt[\overline{M} \to f_{CP}] + d\Gamma/dt[M \to f_{CP}]}, \tag{25}$$

where again the flavour of the meson is determined at a production time. For case of zero decay width difference between two mass eigenstates and no CP violation in mixing ($|q/p| = 1$) this has a simple form of

$$A(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t) \tag{26}$$

with

$$S_f = \frac{2Im(\Lambda_f)}{1+|\lambda_f|^2}, \quad C_f = \frac{1-|\lambda_f|^2}{1+\lambda_f|^2}. \tag{27}$$

The prime example of this kind of CP violation is one observed in the decay $\mathrm{B}^0 \to \mathrm{J}/\psi \mathrm{K}^0_\mathrm{S}$ which we will discuss shortly.

Short summary of this classification can be found also in chapter 12 of Ref. [19].

DETERMINATION OF CKM MATRIX AND UNITARITY TRIANGLE

While Kobayashi and Maskawa proposed the mechanism how to generate the CP violation, the elements of CKM matrix have to be determined experimentally. Theory does not say anything about their magnitudes and phases. If we look to magnitudes only, basically each of the elements can be determined in a measurement which can be interpreted in terms of a single CKM matrix element. Short summary of these determinations can be found in Chapter 11 of Ref. [19]. Discussion of the details and issues related to the determination of each element would became quickly long. Here we just summarize main ideas:

- $|V_{ud}|$: Determined in super allowed $0^+ \to 0^+$ nuclear β decays.
- $|V_{us}|$: Two ways are used here, semileptonic or leptonic kaon decays or hadronic decays of τ lepton.
- $|V_{cd}|$: Semileptonic decays of charm mesons or production of charm mesons in neutrino interaction. The second way is actually more precise in these days.
- $|V_{cs}|$: Information comes from semileptonic D or leptonic D_s decays.
- $|V_{cb}|$: Determined in semileptonic B decays to charm meson.
- $|V_{ub}|$: Comes from semileptonic B decays which do not have a charm meson in the decay chain. We will discuss issues little later.
- $|V_{td}|$ and $|V_{ts}|$: These elements are determined by measuring the oscillation frequency of B^0 and B_s^0 mesons. Again we will touch those measurements little later.
- $|V_{tb}|$: Only lower limit exist up to now and is determined by the electroweak single top quark production and decays of top quark.

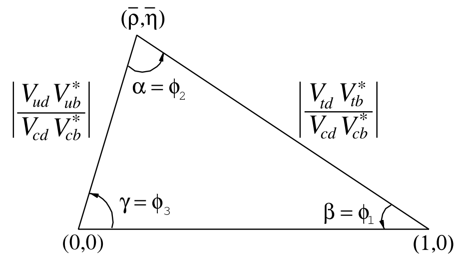

Fig. 6. Definition of the unitarity triangle. Please note that it is usually used in form where base is rescaled to a unit length.

Before we turn our attention to phases, lets first exploit the fact that CKM matrix in the standard model is unitary matrix. While general 3×3 complex matrix has 18 parameters, unitarity condition reduces this number down to 9 parameters. In addition possibility to rephase quark fields without visible effect on physics observables removes additional 5 parameters, leaving us with only four parameters available in the standard model. Another consequence of the unitarity requirement is that product of any two rows or two columns is equal to zero. If we take any of the products, it can be visualized as a triangle in complex plane and those triangles are called unitarity triangles. One, which is a product of first and third column, is picked up as the unitarity triangle. The definition of this triangle in graphical form is in Fig. 6. The three angles of the triangle are defined as

$$\begin{aligned}
\beta &= \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \\
\alpha &= \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \\
\gamma &= \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).
\end{aligned} \tag{28}$$

As they are related to complex phase of the CKM matrix, they are extracted from measurements of CP violation. Various measurements can then be used to extract either sides of the unitarity triangle or its angles and check for the consistency with the standard model (unitarity) can be performed. This check is typically done in a form of global fit to all measurements and recent example is shown in Fig. 7 [20]. There are two other groups performing such fits, one is UTFit group [21] and last one consists of E. Lunghi and A. Soni with their latest results in Ref. [22]. In the rest of this section we will briefly discuss how different bands in Fig. 7 are obtained. Rather detailed description of the earlier version can be found in Ref. [23]. While it is probably too difficult for non-particle physicists, experts who are interested can find all details with large number of references in there.

First constraint comes from the CP violation in neutral kaon system $|\epsilon_K|$. It is determined by the rate of $K_L^0 \to \pi^-\pi^+$. It relates to the unitarity triangle via

$$|\epsilon_K| = C_\epsilon B_K A^2 \lambda^6 \bar{\eta} \left\{\eta_1 S_0(x_c)(1-\lambda^2/2)|\eta_3 S_0(x_c,x_t) + \eta_2 S_0(x_t) A^2 \lambda^4 (1-\bar{\rho})\right\}. \tag{29}$$

Here S_0 is Inami-Lim function, B_K contains non-perturbative part describing hadrons. Three terms are contributions from charm, up and top quark in the kaon mixing box diagram. On the theoretical side, the main uncertainty comes from hadronic physics with B_K typically calculated using lattice QCD. This process is loop induced, so there is in principle sensitivity to a new physics beyond the standard model.

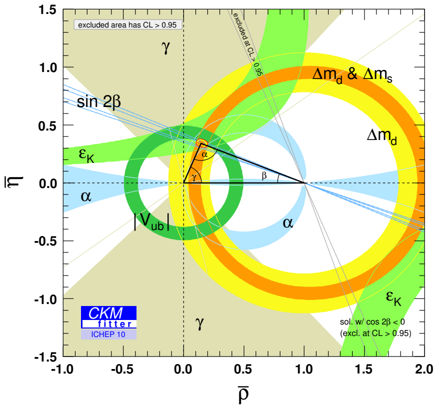

Fig. 7. Example of the global fit of the unitarity triangle from CKMFitter group [20]

.

The sides of the unitarity triangle are basically determined by the V_{ub} and V_{td} elements of the CKM matrix. The first one can be obtained using semileptonic decays of $\mathrm{B} \to \mathrm{X}_u \ell \nu$ where X_u denotes any charmless (not containing charm quark anywhere in decay chain) hadronic system. Both inclusive and exclusive determinations are used. The inclusive determination is in principle cleaner for the theory, but very difficult in experiment as one has to distinguish the signal from much more abundant B to charm decays. To do this experiments introduce some kinematical requirements which turns the theory predictions more difficult. The exclusive approach is easier on experimental side as it uses a better defined final state, but the theory is more difficult as it has to deal with hadronic physics. There is another option of using leptonic decays of B^+ mesons, but those could be sensitive to a new physics and we will discuss them later. As it is determination of the length of triangle side in Fig. 7 it provides a constraint of the shape of circle around zero point.

The V_{td} element as we already mentioned is extracted from the B meson mixing frequency. The mixing frequency is given by

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 |V_{tb}|^2 |V_{td}|^2. \tag{30}$$

Experimentally the most precise measurements come from B-factories experiments Belle and *BABAR*. Detector descriptions can be found in Ref. [24, 25]. Here we concentrate on the technique used by those experiments. Both of them collide $\mathrm{e}^+\mathrm{e}^-$ at the energy of $\Upsilon(4\mathrm{S})$ resonance. The $\Upsilon(4\mathrm{S})$ mass is just above the threshold for decays to a pair of B mesons and thus in events with B mesons, only pairs of $\mathrm{B}^0\ \overline{\mathrm{B}}^0$ or $\mathrm{B}^+\ \mathrm{B}^-$ are possible without any other particles. Thus the two B mesons are described by a common wave function up to the point when first one is detected. The core is to measure a time dependent asymmetry

$$A(t) = \frac{N_{\mathrm{mixed}} - N_{\mathrm{unmixed}}}{N_{\mathrm{mixed}} + N_{\mathrm{unmixed}}} = \cos(\Delta m_d t), \tag{31}$$

where N_{mixed} (N_{unmixed}) is the number of events which had opposite (same) flavour at the time of the decay of first B meson and the time of decay of second meson. The first meson is typically reconstructed only inclusively by forming a vertex from existing tracks and running so-called flavour tagging algorithms to determine the flavour. The physics of flavour tagging at B-factories can be found in Refs. [26, 27]. Alternatively one can use also information provided by the B_s^0 mixing. Its relation to the theory is the same as for B^0, just CKM matrix elements, mass and hadronic part has to be exchanged appropriately. The use of B_s^0 exploits unitarity of the matrix and has no special advantage on the experimental side, but on the theoretical side it improves constraints as ratio of hadronic part can be calculated more precisely than corresponding quantities for a single meson. The B_s^0 mixing was measured by CDF experiment at Tevatron. The detector from the point of view of flavour physics is described in Ref. [28, 29]. The principle of measurement is same as for B^0 except that not only two B_s^0 mesons are produced but also many other particles, thus effectively each b hadron is evolving independently in time. As a result, the decay time is measured from collision time and the flavour tagging has some differences to B-factories. Details of the flavour tagging at hadron colliders like Tevatron or LHC can be found in Refs. [29, 30]. Recently also the LHCb experiment provided significant and precise measurement of the B_s^0 mixing frequency. The detector is described in Ref. [31] with measurement itself in Ref. [32].

The angles are extracted from the measurement of *CP* violation. For the angle β, the main contribution containing complex phase is CKM element V_{td}, so we need a process governed by this element. The golden one is decay $\mathrm{B}^0 \to \mathrm{J}/\psi \mathrm{K}^0$ in which the *CP* violation due to interference of decays with and without mixing occurs. The time dependent asymmetry is given by eqs. 26 and 27 with $|\lambda_f| = 1$ in the standard model. The most precise measurements are available from B-factories [33, 34]. It should be noted, that *CP* violation in this process was predicted to be large already in early 1980s. The initial results confirmed this prediction [35, 36] and provided the final stone to confirmation of Kobayashi-Maskawa mechanism of the *CP* violation in the standard model.

The angle α is the phase between $V_{tb}^{*}V_{td}$ and $V_{ub}^{*}V_{ud}$. Its determination therefore involves strongly suppressed decays governed by the $\mathrm{b} \to \mathrm{u\bar{u}d}$ transition. As first term is clearly related to the B^0 mixing box diagram, measurements of the *CP* violation in decays like $\mathrm{B}^0 \to \pi^+\pi^-$ are of prime interest here. While decays happen at the tree level through wanted transition, as the tree level is suppressed by the CKM matrix element V_{ub}, the higher order processes can also effectively contribute, which makes extraction of α less clean. In order to deal with contamination by higher order processes, several other decays are included and involved isospin analysis is performed. Some details including the current experimental status is available in Ref. [37].

Finally we come to the angle γ, which plays a crucial role in defining what the standard model is. This angle is given by the elements V_{cb} and V_{ub} which also suggests that we need to use *CP* violation in decays where both $\mathrm{b} \to \mathrm{c}$ and $\mathrm{b} \to \mathrm{u}$ transitions contribute. The decays used up to now are of type $\mathrm{B}^+ \to \mathrm{D}^0\mathrm{K}^+$. Using D^0 decay which is accessible to both D^0 and $\overline{\mathrm{D}}^0$ one can observe interference between two types of transition and the corresponding *CP* violation. Three different methods are typically discussed depending on the D^0 final state:

- GLW method [38, 39]: Based on the two-body final states which are *CP*-eigenstates. Typical examples are decays $\mathrm{D}^0 \to \pi^+\pi^-$ or $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$. Those final states are accessible by both D^0 and $\overline{\mathrm{D}}^0$ with the same probabilities. Advantage of the method is that branching fraction is rather large and thus experiments see signal. On the other hand as $\mathrm{b} \to \mathrm{c}$ amplitude is much larger than $\mathrm{b} \to \mathrm{u}$ amplitude, the interference term is rather small comparing to the dominant amplitude which reflects also into the small *CP* violation. Question arises how interference can occur given the different decay chains. To resolve this we would like to remind the original work which is formulated in terms of D_1 and D_2, the *CP*-eigenstates analogous to K_1 and K_2. In such formulation the question of interference is naturally answered. Unfortunately most of the work these days is not formulated in terms of D_1 and D_2.

- ADS method [40, 41]: In this method one the exploits fact that D^0 can decay also through doubly Cabibbo suppressed decay to a final state which has opposite charge assignment as the Cabibbo allowed decay. As an example D^0 normally decays through Cabibbo allowed decay to $\mathrm{K}^-\pi^+$, but with much smaller probability can also decay to $\mathrm{K}^+\pi^-$. Thus using $\mathrm{K}^+\pi^-$ final state one effectively picks up the $\mathrm{b} \to \mathrm{c}$ transition followed by the doubly Cabibbo suppressed decay and the $\mathrm{b} \to \mathrm{u}$ transition followed by the Cabibbo favoured decay of D^0. Advantage of this method is that two amplitudes are now of comparable size and thus the *CP* violation can be large. On the other hand, experiments has to search for rare decays which are hard to observe. Only recently those decays were seen by the experiments [42, 43].

- Dalitz plot method [44]: Exploits three body final states like $\mathrm{K}_\mathrm{S}^0\ \pi^+\ \pi^-$. This final state has many different contributions of quazi two-body final states and is effectively some mixture of two previous methods depending on the position in Dalitz plot. This method is used by B-factories [45, 46] and up to recently provided the most significant information about angle γ.

As we already said, angle γ is of paramount importance for the standard model. This is due to the fact that it is determined in decays governed by the tree level Feynman diagrams and thus we do not expect significant contribution of a possible new physics. Therefore it can provide phase of the CKM matrix which is unlikely to be significantly affected by a new physics. This is not case for other angles, which are due to the loop processes and new physics can significantly affect them. Without having angle γ it would be much more difficult to a observe new physics in comparison of precision measurements with the standard model predictions.

To mention the status, it is shown in Fig. 7. As one can see, all constraints provide a consistent picture of the unitarity triangle confirming Kobayashi-Maskawa mechanism as the dominant source for the *CP* violation we observe. This statement does not mean that there is no place for new physics, but tells us that new physics is going to be correction of the standard model in the processes we study.

WHY NEW PHYSICS?

Up to now we discussed the quark flavour physics from a point of view of the standard model of particle physics. At the end of previous section we saw that the standard model is rather successful in describing existing measurements (which also holds more generally and not only for quark flavour physics) and thus one could ask a question whether we need any new physics beyond the standard model. Beyond success of the standard model in explaining existing measurements, there are several questions on which the standard model cannot say anything. If we restrict ourself only to the part related to the quark flavour sector, we do not know why we have three generations of particles or whether there are really only three of them. The standard model has no real say about masses of fermions. With Higgs mechanism we can introduce fermion masses into the standard model without destroying it, but mass itself remain free parameters (often called Yukawa couplings which give strength of the interaction between Higgs field and fermions). Also the four parameters of the CKM matrix are only determined by the experiment and the standard model does not have any explanation why we see hierarchical structure we see. Cosmology also suggests exists of a dark matter for which we do not have explanation in terms of fundamental particles in the standard model. Any explanation of the dark matter in terms of particles needs new particles beyond standard model ones. Finally perhaps one of the strongest argument comes from the baryogenesis in Universe.

As we know, Universe is now composed of only baryons and not antibaryons while the standard model of Universe start by Big Bang when the number of particles and antiparticles was same. In 1967 A. Sakharov formulated three necessary conditions to produce the baryon-antibaryon asymmetry in the Universe [47]. Those three conditions are:

- Existence of baryon number violation. The standard model surprisingly contains such violation, but it is a non-perturbative effect of strong interaction, thus in domain which is not too well understood.
- Existence of CP violation. As we discussed the standard model has CP violation incorporated, but when we look to the size needed we find that the CP violation in standard model is too small by several orders of magnitude to produce the observed content of the Universe. Thus we need some additional sources of the CP violation for this task.
- Interaction out of equilibrium, which is essentially expansion. But with the standard model particles only, this is again hard to achieve and thus some new physics is needed to drive the expansion.

From this and several other arguments, there are good reasons to believe that the standard model is not the final theory and which makes search for new physics exciting. While there are several approaches possible for such search, the flavour physics plays a crucial role not only for the discovery of a new physics, but also for the discrimination between different models of new physics. In fact, the flavour physics can access higher scales than direct an on-shell production of new particles. Moreover many models predict similar effects for on-shell production, but often substantially differ in flavour observables and correlations between them. Thus without the flavour physics we might be able to observe new physics, but we would be unable to gain its full understanding. Several examples of such correlations in different new physics scenarios are discussed in Ref. [48].

NEW PHYSICS MEASUREMENTS IN FLAVOUR SECTOR

In this final section we are going to shortly discuss few key measurements and analyses which are relevant for the search for a new physics in quark flavour observables. Each of the topics could easily fill many pages, but we will restrict ourself to discuss only main ideas to understand why a given topic is important, how measurement is done in principle with a brief mention of results complemented by references to original work or useful summaries.

$B_s^0 \to \mu^+\mu^-$ decays

Rare decay $\mathrm{B_s^0} \to \mu^+\mu^-$ is one of the most sensitive probe for new physics. In the standard model its branching fraction is predicted to be $(3.2 \pm 0.2) \times 10^{-9}$ [49, 50]. At the same time, new physics can enhance it by several orders of magnitude, so even before observing this decay experimentally, there was a huge potential for constraining models of new physics. As example, in one of the simple usually discussed supersymmetry models called MSSM the branching fraction additional to the standard model is

$$\mathcal{B} \propto \frac{m_b^2 m\mu^2 \tan^6\beta}{M_{A0}^4}, \tag{32}$$

where M_{A0} is mass of the supersymmetric Higgs boson and β is ratio of vacuum expectation values of Higgs fields. Example of Feynman diagrams in the standard model and supersymmetry are shown in Fig. 8. All major

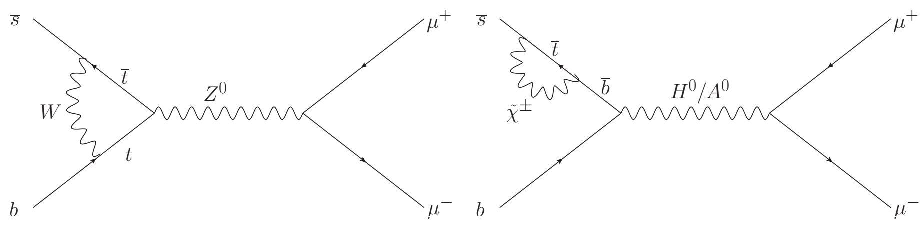

Fig. 8. Example of the Feynman diagram for $\mathrm{B_s^0} \to \mu^+\ \mu^-$ decay in standard model (left) and supersymmetry (right).

experiments search for this kind of decay with recent results available from D0 [51], CDF [52], LHCb [53] and CMS [54]. The combination of LHCb and CMS results is available in Ref. [55]. Main issue is to suppress and control background in order to be able to see signal. None of the experiments observe signal at this point and set mainly upper limits on the branching fraction itself. Exception is the CDF experiment, which observes more events than expected and if the excess is interpreted as signal, the branching fraction of $\mathcal{B} = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$ is obtained. On the other hand, from the detailed analysis the excess does not look exactly like signal and in the same time it is unlikely that there would be any issue with the background prediction. CDF itself concludes that most likely the excess is caused by a statistical fluctuation. In the same time, LHCb and CMS give limits with are in some tension with the CDF branching fraction. For completeness, extracted limits at 95% confidence level (C.L.) are 5.1×10^{-8} at D0, 3.9×10^{-8} at CDF, 1.9×10^{-8} at CMS and 1.5×10^{-8} at LHCb. The stringent limit is about factor 5 above the standard model prediction. It should be noted that each experiment reached sensitivity when some signal events from the standard model are expected in dataset, so we might easily witness situation where limits do not improve quickly but in the same time amount of data would be insufficient to claim the observation.

B_s^0 mixing phase

Second topic to discuss is the phase of $\mathrm{B_s^0}$ mixing diagram. As the $\mathrm{B_s^0}$ mixing is dominated by the top quark contribution, its phase is very close to zero. In the same time if new physics is present its contribution to the loop can increase phase significantly. Without going to details, a best way to search for new physics contributions is to exploit decays like $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ or $\mathrm{B_s^0} \to \mathrm{J}/\psi \mathrm{f_0}(980)$ to measure the *CP* violation in interference of decays with and without mixing. In Feynman diagrams those two processes are shown in Fig. 9. While this *CP* violation

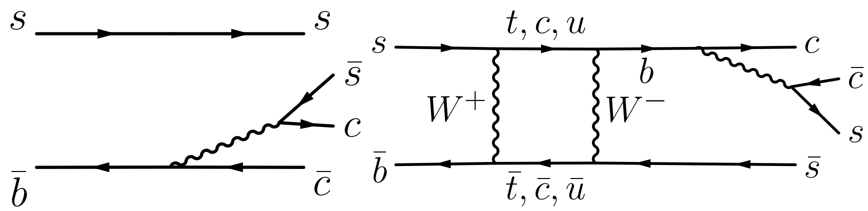

Fig. 9. Feynman diagrams for the direct $\mathrm{B_s^0} \to \mathrm{J}/\psi \mathrm{s\bar{s}}$ (left) and the decay where $\mathrm{B_s^0}$ first oscillates and then decays (right). There is another diagram with mixing which is not shown and is principally same except of using second mixing box diagram.

does not measure directly the phase of $\mathrm{B_s^0}$ mixing, in the standard model it is small and a new physics affects it in the same way as pure mixing diagram. Thus large phase measured here directly means large phase in the $\mathrm{B_s^0}$ mixing diagram. Major experimental challenge is in need of very good time resolution in order to resolve the fast $\mathrm{B_s^0}$ oscillation.

The time evolution in the most general way can be written as [56]

$$\begin{aligned}\Gamma(M(t) \to f) &= \mathcal{N}_f\, |A_f|^2\, e^{-\Gamma t} \left\{ \frac{1+|\lambda_f|^2}{2} \cosh\frac{\Delta\Gamma\, t}{2} + \frac{1-|\lambda_f|^2}{2} \cos(\Delta M\, t) \right. \\ &\qquad \left. - \mathrm{Re}\,\lambda_f \sinh\frac{\Delta\Gamma\, t}{2} - \mathrm{Im}\,\lambda_f \sin(\Delta M\, t) \right\}, \end{aligned} \tag{33}$$

$$\begin{aligned}\Gamma(\overline{M}(t) \to f) &= \mathcal{N}_f\, |A_f|^2\, \frac{1}{1-a}\, e^{-\Gamma t} \left\{ \frac{1+|\lambda_f|^2}{2} \cosh\frac{\Delta\Gamma\, t}{2} - \frac{1-|\lambda_f|^2}{2} \cos(\Delta M\, t) \right. \\ &\qquad \left. - \mathrm{Re}\,\lambda_f \sinh\frac{\Delta\Gamma\, t}{2} + \mathrm{Im}\,\lambda_f \sin(\Delta M\, t) \right\}. \end{aligned} \tag{34}$$

For the *CP* conjugate final state time evolution reads

$$\begin{aligned}\Gamma(M(t) \to \overline{f}) &= \mathcal{N}_f\, \left|\overline{A}_{\overline{f}}\right|^2 e^{-\Gamma t} (1-a) \left\{ \frac{1+|\lambda_{\overline{f}}|^{-2}}{2} \cosh\frac{\Delta\Gamma\, t}{2} - \frac{1-|\lambda_{\overline{f}}|^{-2}}{2} \cos(\Delta M\, t) \right. \\ &\qquad \left. - \mathrm{Re}\,\frac{1}{\lambda_{\overline{f}}} \sinh\frac{\Delta\Gamma\, t}{2} + \mathrm{Im}\,\frac{1}{\lambda_{\overline{f}}} \sin(\Delta M\, t) \right\}, \end{aligned} \tag{35}$$

$$\begin{aligned}\Gamma(\overline{M}(t) \to \overline{f}) &= \mathcal{N}_f\, \left|\overline{A}_{\overline{f}}\right|^2 e^{-\Gamma t} \left\{ \frac{1+|\lambda_{\overline{f}}|^{-2}}{2} \cosh\frac{\Delta\Gamma\, t}{2} + \frac{1-|\lambda_{\overline{f}}|^{-2}}{2} \cos(\Delta M\, t) \right. \\ &\qquad \left. - \mathrm{Re}\,\frac{1}{\lambda_{\overline{f}}} \sinh\frac{\Delta\Gamma\, t}{2} - \mathrm{Im}\,\frac{1}{\lambda_{\overline{f}}} \sin(\Delta M\, t) \right\}. \end{aligned} \tag{36}$$

While those expressions are lengthy they contain all information about the time evolution of neutral mesons, so specific decays can be easily obtained from this. For $\mathrm{B_s^0}$, we can safely put $(1-a) = 1$ as a is at most 1% even in the presence of a new physics. Lets first discuss the case of $B_s^0 \to J/\psi f_0(980)$ decay which is a CP-eigenstate which simplifies situation. Starting from eqs. 33 and 34 we can easily obtain time evolution once we use $|\lambda_f| = 1$ (we are not going to discuss why). For cases where we flavour tag events for B_s^0 in initial state we have

$$\frac{1+\cos(\phi)}{2}e^{-\Gamma_H t} + \frac{1-\cos(\phi)}{2}e^{-\Gamma_L t} - e^{-\Gamma t}\sin(\phi)\sin(\Delta m t). \tag{37}$$

Close inspection reveals that the decay time distribution has two pure exponentials with the slope defined by the lifetimes of two mass eigenstate and third exponential modulated by the sin term. Interestingly enough, if we do not flavour tag initial state, then sin term cancels out and we are left with two exponentials with two distinct lifetimes and proportion of the two exponentials is given by the amount of CP violation. In fact in case of untagged decays, one is in principle performing similar experiment as original CP violation discovery [7]. Unfortunately two lifetimes are not too different, so analysis is much more complicated than in the kaon system.

Experimentally, two experiments exploited decay $B_s^0 \to J/\psi f_0(980)$ to learn something about the time evolution of B_s^0 mesons. The CDF experiment measured effective lifetime from which one can extract information about the CP violation. As the measured lifetime is slightly higher than the standard model expectation for lifetime of heavy eigenstate, the result is consistent with the standard model which holds also for the CP violation [57]. In this analysis no attempt was made to convert it into the constraint on CP violation. Second experiment exploiting those decays is LHCb, which performed full time dependent measurement using flavour tagging. The analysis uses input on lifetimes of two mass eigenstates from the $B_s^0 \to J/\psi\phi$ analysis and obtains $\phi_S^{J/\psi s\bar{s}} = -0.44 \pm 0.44 \pm 0.02$ again consistent with the standard model [58]. In Fig. 10 we show the likelihood profile of LHCb measurement.

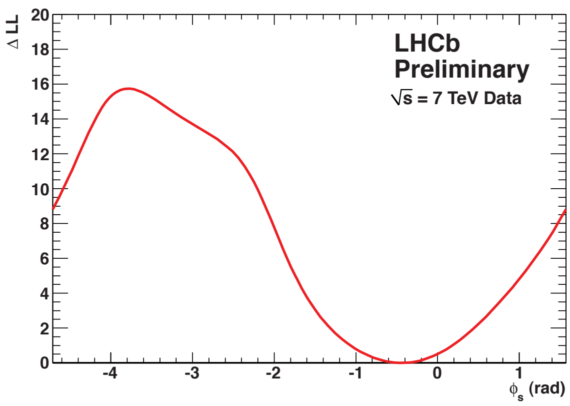

Fig. 10. The likelihood profile from $B_s^0 \to J/\psi f_0(980)$ CP violation analysis performed by the LHCb experiment [58]. A second solution exists which is not shown and is related to the one shown by transformation $\phi_S^{J/\psi s\bar{s}} \to \pi - \phi_S^{J/\psi s\bar{s}}$.

The case of the decay $B_s^0 \to J/\psi\phi$ is same with same physics. The only difference, which complicates live further is the fact that both J/ψ and ϕ are spin 1 particles and thus experiments observe mixture of CP-eigenstates which has to be disentangled by the angular analysis. While this decay is more sensitive than the $B_s^0 \to J/\psi f_0(980)$ due to the available statistics, discussion of details is beyond benefit of general student. With this in mind we refer interested reader to review on this analysis [30] where detailed discussion is available. It discusses results from Refs. [59, 60, 61]. The D0 and LHCb result discussed there are superseded by now by Refs. [62] and [63]. The results for the CP violating phase are $\phi_s \in [-3.1, -2.16] \cup [-1.04, -0.04]$ at 68% C.L. at CDF [59], $\phi_s = -0.55^{+0.38}_{-0.36}$ at D0 [62] and $\phi_s = 0.13 \pm 0.18 \pm 0.07$ at LHCb [63]. All those show good agreement with the standard model, but it is premature to exclude a new physics contributions of moderate size.

Decays governed by $b \to s\mu^+\mu^-$ transition

The most famous decay in this category is decay $B^0 \to K^*(892)\mu^+\mu^-$. In the standard model those decays proceed through the so-called penguin or box diagrams which are shown in Fig. 11. The final state is flavour specific, so in analysis we know flavour at the decay time. As decay proceed only through loop diagrams, new physics can add larger contributions. It also provides very rich possibilities of what can be measured and there are several layers of studies of those decays. Currently the most sensitive output from those studies is the measurement of forward-backward asymmetry as a function of invariant mass of dimuon pair. To measure it, we use angle of the positive muon in the dimuon rest frame and compare the number of events in forward and backward direction. The forward-backward asymmetry can vary significantly depending on the new physics scenarios. The first measurements from B-factories, shown in Fig. 12, provided some hints of a non-standard model physics [64, 65]. Latest results from CDF [66] and LHCb [67] shown in Fig. 13 provide picture which is much more consistent with the standard model.

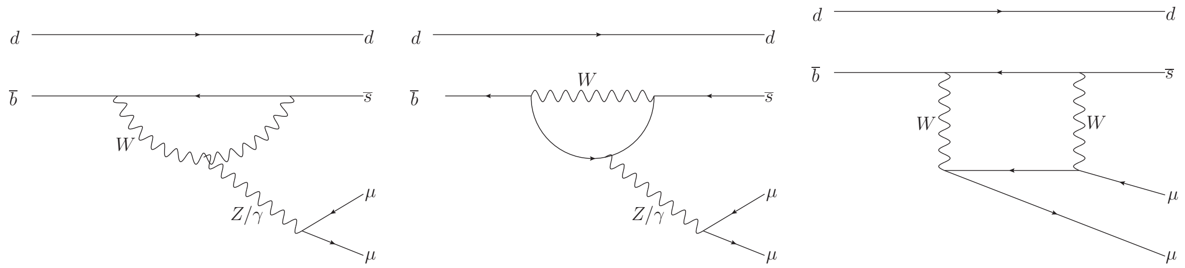

Fig. 11. Feynman diagrams for the decay $B^0 \to K^*(892)\mu^+\mu^-$ in the standard model.

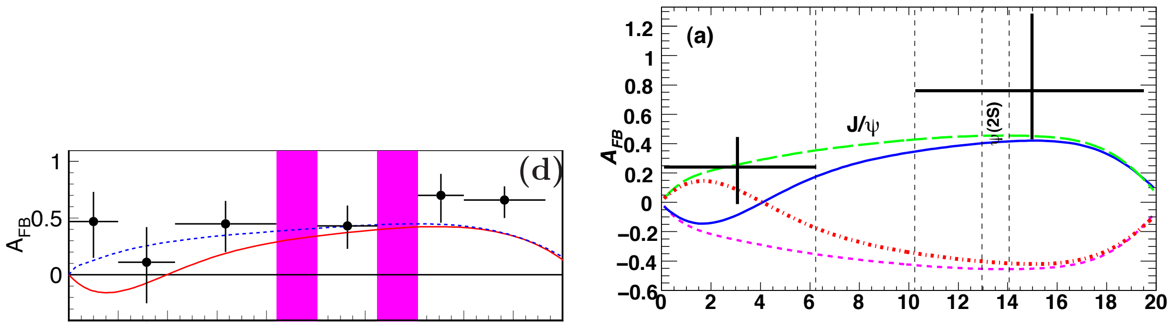

Fig. 12. Forward-backward asymmetry in the $B^0 \to K^*(892)\mu^+\mu^-$ decay from Belle experiment (left) and *BABAR* (right) as a function of dimuon invariant mass. Horizontal scale on both plots is same. The red (left) and blue (right) line shows the standard model prediction with other lines depicting new physics.

Charm mixing and CP violation

Charm mixing and *CP* violation is from the physics point of view same as those topics in the B meson system. The main difference is that as charm mesons contain up type quark, down type quarks are entering the mixing box diagram. Thus charm mixing provides a complementary information to B mesons as it probes the coupling of up type quarks to a new physics. Unfortunately theory predictions are much more difficult in the charm sector. To understand the reason we can split mixing process to two parts, short distance part described by box diagram similar to Fig. 3 and a long distance which happens through rescattering of hadronic final states. The rescattering can be viewed as a decay of D^0 meson to a final state common to D^0 and $\overline{D}^0$ (e.g. $\pi^+\pi^-$) followed by the interaction of final state particles and forming $\overline{D}^0$. While the long distance contribution exists also in the case of B mesons, the short distance part is much larger there and thus the long distance part can be neglected. In the case of D mesons situation is different as short distant part is very small. This is due to the GIM suppression of down and strange quark contribution and the strong CKM suppression of bottom quark contribution. Given all this, also oscillation is very slow. One thing which can be predicted with a reasonable confidence is practically zero *CP* violation in the charm system with upper bounds in a region of 5×10^{-3}. This is also consequence of the strong CKM suppression of bottom quark in the mixing box diagram.

Experimentally measurements are difficult as the oscillation frequency is very small and the lifetime difference is non-zero but small as well. This requires to use huge statistics for measurements to reach decay times of order of magnitude larger than the D^0 lifetime. For the oscillation itself experiments use decays to *CP* eigenstates together with decays $D^0 \to K\pi$. Three main measurements measure the lifetime difference by comparing lifetime in $\pi^+\pi^-$ or K^+K^- final states with a lifetime extracted in "flavour" specific final state $K^-\ \pi^+$ [68, 69], studying a time dependent rate of decays $D^0 \to K^+\pi^-$ (so called wrong sign events) [70, 71] and three body final states using Dalitz plot analyses. Here we briefly discuss measurements using the wrong sign D^0 decays.

In the decays $D^0 \to K^+\pi^-$ we can measure ratio

$$R_{\mathrm{WS}} = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)} = e^{-\Gamma t}|A_{\overline{f}}|^2 \left[1 + \lambda_{\overline{f}} y'(\Gamma t) + \frac{|\lambda_{\overline{f}}|^2}{4}(x'^2 + y'^2)\right]. \tag{38}$$

In this expression we already performed Taylor expansion as the frequency is very small. The x' and y' are linear combinations of the mass difference $x = \Delta m/\Gamma$ and the decay width difference $y = \Delta\Gamma/2\Gamma$. The idea behind is basically same as in the B mixing, but now decay to wrong sign is possible not only through mixing, but also through a doubly Cabibbo suppressed diagram which is responsible for the 1 in brackets in above expression and the second term which is interference between the mixing and the doubly Cabibbo suppressed decay. To tag flavour at the production time, experiments use D^0 decays originating from $D^{*+} \to D^0\pi^+$ as the charge of the pion tags flavour. Other difficulty in experiments is due to the B mesons production, which have charm mesons in

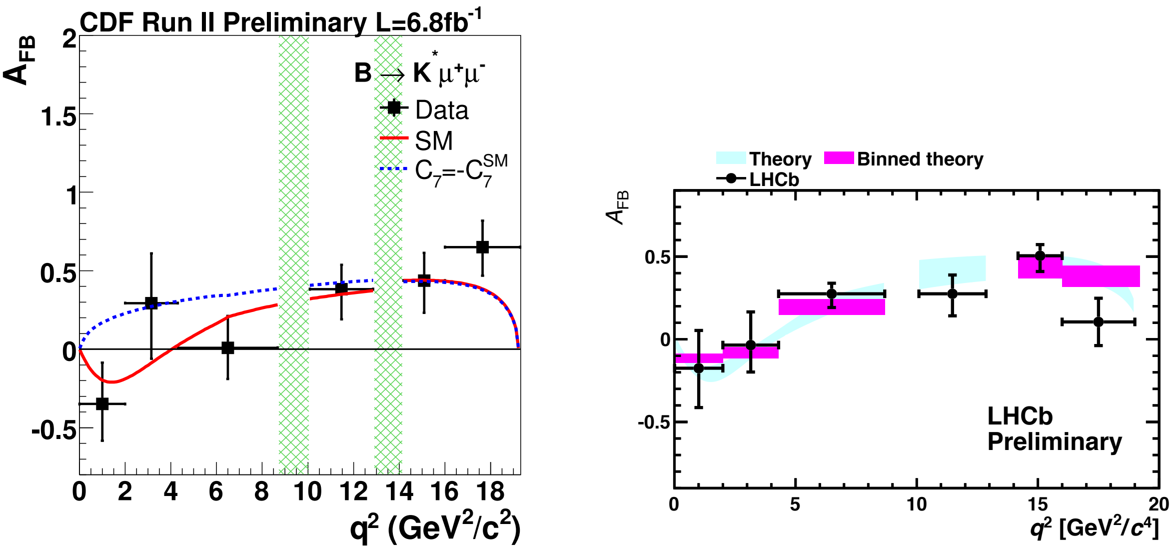

Fig. 13. Forward-backward asymmetry in the $B^0 \to K^*(892)\mu^+\mu^-$ decay from CDF (left) and LHCb (right) as a function of dimuon invariant mass. The red line (left) and boxes (right) show the standard model prediction.

the decay chain as those would have typically misreconstructed decay time. Charm mesons coming from B decays are typically removed by momentum requirements at B-factories and by study of impact parameters of charm mesons at hadron machines. In Fig. 14 we show example of such measurement together with the world average of all information on the D^0 mixing.

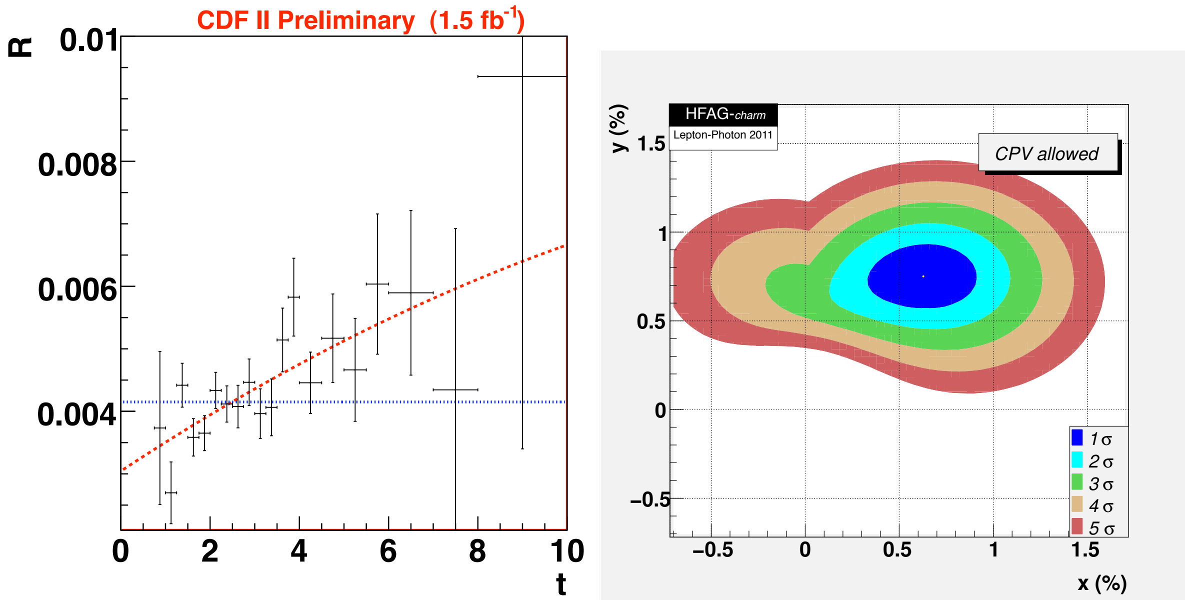

Fig. 14. Example of time dependence of $R_{\rm WS}$ from the CDF experiment [71] (left) with blue line representing no mixing hypothesis and the red line best fit. The combination of all D^0 mixing results by HFAG group [72, 73] (right).

The *CP* violation in neutral charm mesons is usually measured by a time integrated analysis. While normally the *CP* violation due to the interference of decays with and without mixing would cancel out as experiments in this case see only very first part of the oscillation pattern, it remains accessible even after time integration. Measurements are performed in decays to *CP*-eigenstate like $\pi^+\pi^-$ or K^+K^- using flavour tagging by $D^{*\pm}$. The measured asymmetry can be related to the physical *CP* violation as

$$A_{CP}(h^+h^-) = a_{CP}^{\rm dir} + \frac{\langle t\rangle}{\tau} a_{CP}^{\rm ind}, \tag{39}$$

where $\langle t\rangle$ is the average decay time of the sample and τ is the lifetime of the D^0. Thanks to this, measurements with different decay time acceptance are to some extend complementary as they allow to disentangle two contributions. The most precise measurement up to now is from CDF experiment [74] with other measurements available from Belle [75] and *BABAR* [76]. LHCb experiment has another complication as it prefers to produce particles over antiparticles and therefore they measure difference in the asymmetry between decays $\pi^+\pi^-$ and K^+K^- which is mainly sensitive to the direct *CP* violation [77]. None of the measurements sees significant signal yet with allowed region being pushed to the area where it will be impossible to claim a new physics even with significant *CP* violation being observed. A recent overview of existing results on charm mixing and *CP* violation can be found in Ref. [78].

$B^+ \to \tau^+\nu_\tau$ *and global status of UT fit*

The last decay we would like to discuss is decay $B^+ \to \tau^+\nu_\tau$. In the standard model its branching fraction is given by

$$\mathcal{B} = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B. \tag{40}$$

Numerical prediction is $(1.2 \pm 0.25) \times 10^{-4}$ and one can use measurements to either extract f_B which parametrizes hadronic physics or $|V_{ub}|$ if we take f_B from theory. As the decay involves many neutrinos in the final state and practically only single track from the τ decay, measurement is challenging and only possible at B-factories. To perform the measurement, experiments reconstruct one B hadron (called tagging B) and a track which would be τ daughter and then check that no other tracks or calorimeter clusters are within the event. Two principal methods exist, the one called semileptonic tag uses semileptonic B decays [79, 80] and the other one called hadronic tag uses fully reconstructed tagging B [81, 82]. Some details of how hadronic tag is reconstructed and selected in upcoming Belle analysis are available in Ref. [83]. Both Belle and *BABAR* use both methods with results which are consistent with each other. The extracted branching fraction is about 1.7×10^{-4} which is somewhat higher than the standard model expectation. The results are often interpreted as constraints on the charged Higgs boson, which would contribute in this case on the tree level and can effectively compete with the standard model contribution.

The last point to touch is the global fit shown in Fig. 7. While general impression from there is that all measurements fit together, there are some tensions in the fit. What usually can be done is removal of some input and predict it from the global fit of remaining inputs which can be then compared to the experiment. Interestingly enough, if branching fraction for $B^+ \to \tau^+\nu_\tau$ or $\sin(2\beta)$ is removed from the fit, its quality improves significantly by about 2.5σ. Also the branching fraction of $B^+ \to \tau^+\nu_\tau$ is above the standard model prediction, which can be interpreted as a hint of new physics or a hint on something we do not understand when we extract the V_{ub} CKM matrix element from other measurements. Together with this tension, also the *CP* violation in the kaon system which enters as $|\epsilon_K|$ does not fully agree with the global fit. While none of those tensions is significant, it is interesting to see whether its significance will increase with new data or diminish with next round of improvements by experiments. Interesting discussion about those tensions is available in Ref. [22].

CONCLUSIONS

In these notes we attempted to provide short description of important points of the quark flavour physics. We started from the early days of kaon physics and its puzzles, which lead to the development of standard model with its quark mixing and Kobayashi-Maskawa mechanism for the *CP* violation. The mechanism provided good predictions, which could be tested by experiments and about 30 years after Kobayashi and Maskawa made their proposal, the standard model was confirmed and they received Nobel Prize for the idea. With successful confirmation of the standard model which we briefly discussed attention shifted to searches for a new physics. In the area of search for new physics we made short description of the most important measurement and rather than listing long list of results, we hopefully succeeded in providing the main ideas why given measurement is important and how it is performed. To conclude on this part, we can say that while no significant signal of new physics is present in today's experimental results (except some tensions or results which needs confirmation and not discussed here) room for a new physics with significant effects are still possible. Finally with high expectation that new physics exists the flavour physics should play an important role in building theory which would become the next standard model of particle physics.

REFERENCES

1. G.D. Rochester and C.C. Butler, *Nature* **160**, 855–857 (1947).
2. R.N. Cahn and G. Goldhaber. *THE EXPERIMENTAL FOUNDATIONS OF PARTICLE PHYSICS* (Cambridge University Press, 2009).
3. Nicola Cabibbo, *Phys.Rev.Lett.* **10**, 531–533 (1963).
4. S.L. Glashow, J. Iliopoulos, and L. Maiani, *Phys.Rev.* **D2**, 1285–1292 (1970).
5. `http://cplear.web.cern.ch`.
6. A. Angelopoulos et al., *Phys.Lett.* **B444**, 38–42 (1998).
7. J.H. Christenson, J.W. Cronin, V.L. Fitch, and R. Turlay, *Phys.Rev.Lett.* **13**, 138–140 (1964).

8. Makoto Kobayashi and Toshihide Maskawa, *Prog.Theor.Phys.* **49**, 652–657 (1973).
9. Lincoln Wolfenstein, *Phys.Rev.Lett.* **51**, 1945 (1983).
10. D.H. Perkins. *Introduction to high energy physics* (Cambridge University Press, 1982).
11. F. Halzen and A.D. Martin. *Quarks and Leptons: An Introductory Course in Modern Particle Physics* (John Wiley & Sons, 1984).
12. Gerhard Buchalla (2001), `hep-ph/0103166`.
13. J.J. Aubert et al., *Phys.Rev.Lett.* **33**, 1404–1406 (1974), technical report 96.
14. J.E. Augustin et al., *Phys.Rev.Lett.* **33**, 1406–1408 (1974).
15. C. Bacci, R.Balbini Celio, M. Berna-Rodini, G. Caton, R. del Fabbro, et al., *Phys.Rev.Lett.* **33**, 1408 (1974).
16. S.W. Herb, D.C. Hom, L.M. Lederman, J.C. Sens, H.D. Snyder, et al., *Phys.Rev.Lett.* **39**, 252–255 (1977).
17. F. Abe et al., *Phys.Rev.Lett.* **74**, 2626–2631 (1995), `hep-ex/9503002`.
18. S. Abachi et al., *Phys.Rev.Lett.* **74**, 2632–2637 (1995), `hep-ex/9503003`.
19. K. Nakamura et al., *J.Phys.G* **G37**, 075021 (2010).
20. `http://ckmfitter.in2p3.fr/www/html/ckm_main.html`.
21. `http://www.utfit.org/UTfit/`.
22. E. Lunghi and Amarjit Soni, *Phys.Lett.* **B697**, 323–328 (2011), `1010.6069`.
23. J. Charles et al., *Eur.Phys.J.* **C41**, 1–131 (2005), `hep-ph/0406184`.
24. Bernard Aubert et al., *Nucl.Instrum.Meth.* **A479**, 1–116 (2002), `hep-ex/0105044`.
25. A. Abashian, K. Gotow, N. Morgan, L. Piilonen, S. Schrenk, et al., *Nucl.Instrum.Meth.* **A479**, 117–232 (2002).
26. H. Kakuno et al., *Nucl.Instrum.Meth.* **A533**, 516–531 (2004), `hep-ex/0403022`.
27. Bernard Aubert et al., *Phys.Rev.* **D66**, 032003 (2002), `hep-ex/0201020`.
28. D. Acosta et al., *Phys.Rev.* **D71**, 032001 (2005), `hep-ex/0412071`.
29. Michal Kreps, *PoS* **BEAUTY2009**, 032 (2009), `0912.0110`.
30. Michal Kreps, *Mod.Phys.Lett.* **A26**, 2007–2028 (2011), * Temporary entry *, `1108.6257`.
31. A.Augusto Alves et al., *JINST* **3**, S08005 (2008).
32. The LHCb Collaboration (2011), lHCb-ANA-2011-005.
33. Bernard Aubert et al., *Phys.Rev.* **D79**, 072009 (2009), `0902.1708`.
34. `http://belle.kek.jp/belle/talks/moriondEW11/poluektov.pdf`.
35. K. Abe et al., *Phys.Rev.Lett.* **87**, 091802 (2001), `hep-ex/0107061`.
36. Bernard Aubert et al., *Phys.Rev.Lett.* **87**, 091801 (2001), ¡a href=/slac/media-info/20010706/cpviolation.html¿ **Press release**¡/a¿, `hep-ex/0107013`.
37. Gagan B. Mohanty (2011), * Temporary entry *, `1109.1343`.
38. Michael Gronau and David London, *Phys.Lett.* **B253**, 483–488 (1991).
39. Michael Gronau and Daniel Wyler, *Phys.Lett.* **B265**, 172–176 (1991).
40. David Atwood, Isard Dunietz, and Amarjit Soni, *Phys.Rev.Lett.* **78**, 3257–3260 (1997), `hep-ph/9612433`.
41. David Atwood, Isard Dunietz, and Amarjit Soni, *Phys.Rev.* **D63**, 036005 (2001), `hep-ph/0008090`.
42. Y. Horii et al., *Phys.Rev.Lett.* **106**, 231803 (2011), `1103.5951`.
43. T. Aaltonen et al., *Phys.Rev.D* (2011), * Temporary entry *, `1108.5765`.
44. Anjan Giri, Yuval Grossman, Abner Soffer, and Jure Zupan, *Phys.Rev.* **D68**, 054018 (2003), `hep-ph/0303187`.
45. I. Adachi, K. Adamczyk, and H. Aihara (2011), * Temporary entry *, `1106.4046`.
46. P. del Amo Sanchez et al., *Phys.Rev.Lett.* **105**, 121801 (2010), `1005.1096`.
47. A.D. Sakharov, *Pisma Zh.Eksp.Teor.Fiz.* **5**, 32–35 (1967), reprinted in *Kolb, E.W. (ed.), Turner, M.S. (ed.): The early universe* 371-373, and in *Lindley, D. (ed.) et al.: Cosmology and particle physics* 106-109, and in Sov. Phys. Usp. 34 (1991) 392-393 [Usp. Fiz. Nauk 161 (1991) No. 5 61-64].
48. Andrzej J. Buras, *PoS* **EPS-HEP2009**, 024 (2009), `0910.1032`.
49. Elvira Gamiz, Christine T.H. Davies, G.Peter Lepage, Junko Shigemitsu, and Matthew Wingate, *Phys.Rev.* **D80**, 014503 (2009), `0902.1815`.
50. Andrzej J. Buras, Maria Valentina Carlucci, Stefania Gori, and Gino Isidori, *JHEP* **1010**, 009 (2010), `1005.5310`.
51. Victor Mukhamedovich Abazov et al., *Phys.Lett.* **B693**, 539–544 (2010), `1006.3469`.
52. T. Aaltonen et al. (2011), `1107.2304`.
53. The LHCb Collaboration (2011).
54. Serguei Chatrchyan et al. (2011), * Temporary entry *, `1107.5834`.
55. The CMS and LHCb Collaborations (2011), lHCb-ANA-2011-039.
56. Ulrich Nierste 1–38 (2009), `0904.1869`.
57. T. Aaltonen et al., *Phys.Rev.D* (2011), `1106.3682`.
58. The LHCb Collaboration (2011), lHCb-ANA-2011-056.
59. T. Aaltonen et al., *CDF Public Note* 10206 (2010).
60. V.M. Abazov et al., *D0 Conference Note* 6098–CONF (2010).
61. The LHCb Collaboration (2011), lHCb-CONF-2011-006.
62. Victor Mukhamedovich Abazov et al. (2011), * Temporary entry *, `1109.3166`.
63. The LHCb Collaboration (2011), lHCb-CONF-2011-049.

64. Bernard Aubert et al., *Phys.Rev.* **D79**, 031102 (2009), 0804.4412.
65. J.-T. Wei et al., *Phys.Rev.Lett.* **103**, 171801 (2009), 0904.0770.
66. T. Aaltonen et al. (2011), long author list - awaiting processing, 1108.0695.
67. The LHCb Collaboration (2011), lHCb-ANA-2011-022.
68. M. Staric et al., *Phys.Rev.Lett.* **98**, 211803 (2007), hep-ex/0703036.
69. Bernard Aubert et al., *Phys.Rev.* **D80**, 071103 (2009), 0908.0761.
70. Bernard Aubert et al., *Phys.Rev.Lett.* **98**, 211802 (2007), hep-ex/0703020.
71. T. Aaltonen et al., *Phys.Rev.Lett.* **100**, 121802 (2008), 0712.1567.
72. D. Asner et al. (2010), 1010.1589.
73. http://www.slac.stanford.edu/xorg/hfag/.
74. T. Aaltonen et al., *CDF Public Note* 10296 (2010).
75. M. Staric et al., *Phys.Lett.* **B670**, 190–195 (2008), 0807.0148.
76. Bernard Aubert et al., *Phys.Rev.Lett.* **100**, 061803 (2008), 0709.2715.
77. The LHCb Collaboration (2011), lHCb-ANA-2011-010.
78. A. Zupanc (2011), * Temporary entry *, 1109.1362.
79. K. Hara et al., *Phys.Rev.* **D82**, 071101 (2010), 1006.4201.
80. Bernard Aubert et al., *Physical Review D* (2009), 0912.2453.
81. K. Ikado et al., *Phys.Rev.Lett.* **97**, 251802 (2006), hep-ex/0604018.
82. P. del Amo Sanchez et al. (2010), 1008.0104.
83. Michael Feindt, Fabian Keller, Michal Kreps, Thomas Kuhr, Sebastian Neubauer, et al., *Nucl.Instrum.Meth.* **A654**, 432–440 (2011), 1102.3876.