We discuss the influence of new physics on $CP$-violating observables. Assuming the standard model gives a correct description of tree level processes, we show how a consistent procedure can determine the parameters of the standard model and check its validity also in loop induced processes. A method to include new physics in a systematic way is sketched.

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1 Introduction

Observation of novel phenomena often paves the way to new physics. For instance, \( \beta \) decays, parity and flavor violation required the existence of a new force, the weak interactions. At present, it is often thought that \( CP \)-violation could signal new physics beyond the standard model. Although the latter can indeed account for the observed effects \( \epsilon' / \epsilon \) (even \( \epsilon' / \epsilon \) may be described by the standard model) its predictions are not well tested (compared to physics at LEP) and therefore a comprehensive study of \( CP \)-violation experiments is important. As sketched in figure 1, \( CP \)-violation manifests itself in many areas; only a comparison between them can determine the correct description. In the standard model, all \( CP \)-violation resides in the CKM matrix \( V_{ij} \) which describes the couplings of the W-bosons to the quarks of different charges. Therefore all appreciable \( CP \)-violation occurs within flavor physics. Thus, one obvious strategy to search for new forces and particles would be to look for non-zero \( CP \)-violating effects where no flavour changes are involved, such as in electric dipole moments or asymmetries in nuclear reactions. Unfortunately, the effects of new physics are judged to be quite small (apart from the dipole moments). Therefore more chance is given to the flavor sector instead, that is the physics of Kaons and mostly B-mesons. For a recent extensive review of \( CP \)-violation, see ref. \((\text{[1]}\)).

\[ \text{Theory} \]

\[ \text{K mesons} \]
\[ \text{D-mesons} \]
\[ \text{B mesons} \]
\[ \text{Hyperons} \]
\[ \text{Nucleon, Atoms} \]
\[ \text{Universe} \]
\[ \text{t quark} \]

Figure 1: CP-Violation

\[ ^1 \text{a notable exception is the baryon asymmetry in the universe} \]
\[ ^2 \text{I do not discuss the so-called } \theta \text{ term} \]
The unitarity of the CKM matrix

\[ V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]  

implies among others the triangle relation

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]  

which relates observable products of matrix elements and gives stringent tests of the validity of the standard model. Using the Wolfenstein parametrization and scaling as usual the bottom side to one, we can write for the other sides of the scaled triangle

\[ R_b = \frac{1}{A\lambda^3} V_{ud}V_{ub}^* = \bar{\rho} + i\eta, \quad R_t = \frac{1}{A\lambda^3} V_{td}V_{tb}^* = 1 - (\bar{\rho} + i\eta). \]

Here, following ref. [4], the quantities

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

describe quantities to take into account even higher powers of \( \lambda \).

An elaborate analysis of superallowed \( \beta \) decay, semileptonic Kaon and \( D \)-meson decays and decays of \( B \) mesons into charmed and charmless final states yields [3]

\[ \begin{align*}
V_{ud} &= 0.9736 \pm 0.001 \\
V_{us} &= 0.2205 \pm 0.0018 \\
V_{ub} &= 0.04 \pm 0.002 \\
V_{cd} &= 0.224 \pm 0.016 \\
V_{cs} &= 1.010 \pm 0.16 \\
V_{cb} &= 0.0036 \pm 0.006
\end{align*} \]

Figure 2: Unitarity triangle in the complex \((\bar{\rho}, \eta)\) plane
These are (apart from corrections) all tree-level processes and therefore thought to be governed by the standard model \[^3\]. They are however not sufficient to check unitarity (unless very precise data from $t$ decays would be available, or if the sum of the squares would be significantly away from 1).

Further input comes from loop-induced observables. They can be calculated within perturbation theory and input from hadronic physics. While the former are rather reliable and usually give results accurate to 10 percent or so, the latter are generally difficult to estimate. One usually considers the Kaon-mixing quantity $\epsilon_K$, the mass difference of the $B$ and the $\bar{B}$ mesons (and also of the $B_s$ and $\bar{B}_s$ mesons). This analysis has resulted in the range of values for the three angles $\alpha$, $\beta$ and $\gamma$ of the unitary triangle and its sides. The hadronic uncertainties are summarized in \[^4\] and are reflected by

$$|R_b| = 0.39 \pm 0.07 \quad |R_t| = 0.98 \pm 0.04 - 0.22 \quad (6)$$

and by \[^5\][\[^7\]]

$$(\sin 2\beta)_{SM} = 0.75 \pm 0.20. \quad (7)$$

The new results of last summer and of the beginning of this year concern the angle $\beta$. It was found that the coefficient $a$ of $\sin(\Delta M_{B_d})$ in the asymmetry for $B \to J/\Psi K_S$ is

$$a = 0.79 \pm 0.4(CDF)[8] \quad (8)$$

$$a = 0.58 \pm 0.35(Belle)[9] \quad (9)$$

$$a = 0.34 \pm 0.25(BaBar)[10] \quad (10)$$

In the standard model, one has $a = \sin(2\beta)$; comparing eqs. (7) and (10) we see a surprising inconsistency. Of course, this is a preliminary result, and may disappear as experiments collect more statistics. However, it makes it mandatory to investigate CP-violation in a (standard) model independent way. Unless CP-violation within the standard model is grossly wrong, this program essentially amounts to making many measurements and extracting discrepancies between quantities thought to be the same in the standard model. Many authors have discussed this situation; see e.g. \[^1\][\[^2\][\[^3\][\[^4\][\[^5\].

2 A more general framework

New physics may affect every process. Because the standard model describes the most important weak decays, we will assume that it accounts for semileptonic and tree-level quark decays, at least to the required accuracy. This assumption can be

\[^3\] of course, the small $b \to u$ transition could be due to new physics
tested, by investigating the consistency of different semileptonic decays, bounds from LEP etc. As an example consider the strengths of the effective Hamiltonians

\[ H_{\text{eff}} = G_F (\bar{\tau}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma^\mu c_L) \]  
\[ H_{\text{eff}} = G_F (\bar{\pi}_L \gamma_\mu b_L) (\bar{\pi}_L \gamma^\mu u_L). \]  

In the standard model, they are proportional to \( \lambda^2 \) and \( \lambda^4 \), respectively. On the other hand, a new neutral intermediate boson, say \( Z' \), may exist, coupled to the currents \((\bar{\tau}_L \gamma_\mu b_L)\) and \((\bar{\tau}_L \gamma^\mu c_L)\). If it also couples to quark and lepton pairs, such as \((\bar{\pi}_L \gamma_\mu u_L)\) and \((\bar{\pi}_L \gamma^\mu c_L)\), it would contribute to the above Hamiltonians, to \( B_s \) mixing, to \( B_s \to l^+ l^- \) etc. If the couplings are the same for all these pairs, the effective strength would be the same for the two terms in eqs. (11) and (12). Therefore a new \( Z' \)-mediated interaction would induce a deviation from the standard model result that the couplings of the two interactions have a relative strength of \( \lambda^2 \). Thus detailed studies could in principle also test the first assumption. But of course, there are various experimental and theoretical difficulties to overcome before one will obtain accurate enough results.

From fig. 3 we see that the determination of the angle \( \gamma \) from tree level processes involves the interference of amplitudes proportional to \( V_{ub} \) and \( V_{ub} \) respectively. This is achieved in processes where the two diagrams of fig. 3 contribute. A well known example are the decays \( B \to DK \) \[16,17\]; more recently the advantage of \( B_c \to DD_s \) was stressed \[18\]. The idea is the same as in the previous papers on \( B \to DK \) : One

![Figure 3: two quark diagrams whose interference gives \( \gamma \)]
needs to measure the six amplitudes shown in Fig. 4. However due to the different
CKM elements, the sides of the triangles in Fig. 3 are now of similar length and an
extraction of $\gamma$ seems possible with the $10^{10}$ or so $B_c$-mesons expected at LHC. This
method does not suffer from hadronic uncertainties.

The experimental difficulties associated with these decays have lead to other possi-
bilities. The decays $B \rightarrow K\pi$ are sensitive to the interference of the tree level diagram
(with $V_{ub}$) and the penguin diagram. This also yields the angle $\gamma$ if the penguin graph
has no extra phase. This decay has been discussed by many people [19].

A third possibility that was investigated are the decays $B^0 \rightarrow D^{\pm}K^{\mp}$ [20]. The
usual mixing-decay formalism yields for the time dependent asymmetries the coefficients

$$a \sim \text{Im}(e^{-i(2\phi_{mix}+\gamma)}) \text{const}$$

$$\bar{a} \sim \text{Im}(e^{-i(2\phi_{mix}+\gamma)})/\text{const.}$$

where const is an unknown hadronic number. It cancels in the product which then
yields the combination

$$2\phi_{mix} + \gamma.$$  

Figure 4: The extraction of $\gamma$ from $B_c^\pm \rightarrow D_s^{\pm} \{D^0, \bar{D}^0, D^0\}$ decays.

The $B\bar{B}$ mixing angle $\phi_{mix}$ can be determined as usual from the decay $B \rightarrow J/\Psi K_s$.

The other angles of the triangle cannot be determined independently by a tree
level analysis. But we see, that the tree level analysis allows to determine the unitary
triangle of the standard model. It yields, in principle, also the unknown side $R_t$ and
the angle $\beta$. Any further independent measurement of these quantities checks the standard model with high accuracy, but it requires loop effects.

### 3 New Physics: Phenomenology

Among the $CP$-violating observables, the mixing-decay asymmetry is the cleanest theoretically \[21\]. It is therefore reasonable to start an investigation of new physics with this quantity. Denoting the coefficient of $\sin(\Delta mt)$ by $a$, one has in general

$$a_{M\rightarrow F} = \text{Im}((\frac{p}{q})_M a_1(\frac{p}{q})_F)$$

(16)

where $(\frac{p}{q})$ are the mixing parameters and $a_1$ the amplitudes for $M \rightarrow F$ and $M \rightarrow \overline{F}$, respectively.

Setting for the $B$-meson mixing element $M_{12}$

$$M_{12} = r^2 e^{2i\phi_{NP}} e^{2i\beta} |M_{12}^{SM}|$$

(17)

to account for a possible new phase and magnitude of the mixing, the asymmetry coefficient is given in the table below:

| quarks | $B_d$ | $a$ | $B_s$ | $a$ |
|--------|------|-----|------|-----|
| $b \rightarrow c\bar{c}s$ | $\Psi K_s$ | $\beta + \phi_d^{NP}$ | $DD_s$ | $\phi_s^{NP}$ + $\phi^A$ |
| $b \rightarrow s\bar{s}s$ | $\Phi K_s$ | $\beta + \phi_d^{NP}$ + $\phi^A$ | $\Phi\Phi$ | $\phi_s^{NP}$ + $\phi^A$ |
| $b \rightarrow u\bar{u}s$ | $\pi\pi$ | | |
| $b \rightarrow c\bar{c}d$ | $D^+ D^-$ | | |
| $b \rightarrow u\bar{u}s$ | $\pi^0 K_s$ | | |
| $b \rightarrow s\bar{s}s$ | $\Phi\pi$ | | |

The phase $\phi^A$ takes into account a possible new phase in the decay. The entries left out receive possibly sizeable contributions from penguin diagrams and cannot be brought to the simple form. This result tells us that comparing the different asymmetries, we can check the consistency of the standard model and determine the phases of new physics.

New physics will also influence other $CP$-violating observables, such as the direct asymmetries of, say, charged B-meson decays. In cases such as $B \rightarrow K \pi$, where the asymmetry is small in the standard model new physics may give rise to sizeable asymmetries. Of course, one needs to continue the experimental search for these, but because of the difficulty of calculating direct asymmetries, only quantitative statements are possible.
4 New Physics: Analysis

If new physics is associated with a scale \( \Lambda \) much above the weak scale \( (\sim M_W) \), the total Lagrangian density may be written in the form \[ \mathcal{L} = \mathcal{L}_{SM} + \sum d_i \mathcal{O}_{NP}^i \] (18)

where the \( O_i \) are operators of dimension six induced by new physics and their coefficients \( d_i \) are of order \( (1/\Lambda^2) \). This ‘effective’ Lagrangian is not renormalizable, and therefore one usually uses the new operators only at tree level (see a discussion by). The \( CP \)-violation induced by effective operators \( \mathcal{O}_{NP}^i \) can in most cases only be seen when they are in loops, because the imaginary part (discontinuity) of the corresponding Feynman graph is responsible for \( CP \)-asymmetry. At low energies we then have an effective Hamiltonian

\[ \mathcal{H} = \sum c_i \mathcal{O}_{SM}^i + \sum d_i \mathcal{O}_{NP}^i. \] (19)

The amplitudes for a process \( I \to F \) and the \( CP \) conjugated one \( \overline{I} \to \overline{F} \) then are

\[ A(I \to F) = \sum c_j (R_j + iI_j)^{SM} + \sum d_j (R_j + iI_j)^{NP} \] (20)

where \( R \) and \( I \) are the dispersive and absorptive parts of the matrix elements. For the charge-conjugated process we have similarly

\[ A(\overline{I} \to \overline{F}) = \sum c^*_j (R_j + iI_j)^{SM} + \sum d^*_j (R_j + iI_j)^{NP} \] (21)

When we calculate the \( CP \)-violating asymmetry \( \alpha \sim (|A(I \to F)|^2 - |A(\overline{I} \to \overline{F})|^2) \), we obtain in leading order in QCD and in NP

\[ \alpha \sim Im(c^*d)(R^{SM}I^{NP} - R^{NP}I^{SM}). \] (22)

\( R^{NP} \) is a (finite) tree level amplitude, however also the loop \( I^{NP} \) is finite. Therefore the problems associated with a the non-renormalizable theory \( \sum d_i \mathcal{O}_{NP}^i \) disappear and exact predictions are indeed possible for the the \( CP \)-violating asymmetry. Therefore, an analysis of the effects of new operators is possible also at for \( CP \)-violating asymmetries, and not just at tree level!

5 New Physics: Models

Virtually any model beyond the standard one carries new sources for flavour and \( CP \)-violations. It is therefore more economical to look at them in increasing complexity.

\[ ^4 \text{an exception is the electric dipole moment} \]
The simplest one are the minimal flavour violating ones (MFV) where all sources of
flavour violation reside in the CKM matrix. This results in many cases in a simple
modification of the coefficients in the usual loop expressions. However, there still is
a unitary triangle, but its sizes and angles may change. It was analyzed by Ali and
London [3]; recently Buras and Buras [13] found a clever lower bound on $\sin(2\beta)$.
The idea is simple. For both $\epsilon$ and the $B$-meson mass difference, the standard model
contribution consists mostly of a $W - W - t - t$ box diagram; its value might be
denoted by $F_{tt}$. The MFV modify this to

$$F_{tt} = S_0(m_t) (1 + f).$$

(23)

Then we can write for $\epsilon_K$

$$\epsilon_K \sim \eta \left[ (1 - \bar{\eta}) A^2 \eta_2 F_{tt} + P_c(\varepsilon) \right] A^2 B_K$$

(24)

while the $B$-meson mass difference yields the relation

$$R_t = 1.26 \frac{R_0}{A} \frac{1}{\sqrt{F_{tt}}},$$

(25)

where

$$R_0 = \sqrt{\frac{(\Delta M)_d}{0.47/\text{ps}}} \left[ \frac{200 \text{ mev}}{F_{B_d} B_d} \right] \sqrt{\frac{0.55}{\eta_B}}.$$  

(26)

With

$$\sin 2\beta = \frac{2\eta(1 - \bar{\eta})}{R_t^2}$$

(27)

one gets [2]

$$\sin 2\beta = \frac{1.26}{R_0^2 \eta_2} \left[ \frac{0.226}{A^2 B_K} - \eta P_c(\varepsilon) \right].$$

(28)

Since unitarity implies $\eta \leq R_b$, there exists a lower bound on $\sin 2\beta$. A careful
numerical analysis implies [23]

$$\sin 2\beta \geq 0.42.$$  

(29)

The lower bound in fact corresponds to a $F_{tt}$ which is three times larger than the
standard model value.

Supersymmetry is a attractive candidate for new physics. In general, there are
many new CP-violating phases. Since they can directly affect observables such a
the electric dipole moment, it is natural to take them to be small (approximate CP-
violation, [1]). In this situation, also $CP$-violating effects in the $B$-system are small.
This implies a small angle $\beta$. This is in contrast to the standard model, where the
flavour structure suppresses $CP$-violation. The problem with this scheme is that it is
hard to get $\epsilon_K$ right and that $\epsilon'/\epsilon$ tends to be to small.

Similarly, models with left-right symmetry tend to have small $CP$-violating phases,
thus the effects tend to be small also.
6  **CP-violation in D-mesons**

In the standard model, CP-violation is small in the D-System. This is partly due to the rather large tree-level decay rates and small coupling of the third generation. Therefore one would expect new physics CP-violation mostly in the mixing (see [1] for a more detailed discussion). Recent studies of time-dependent decay rates of $D^0 \rightarrow K^+\pi^-$ by the CLEO collaboration [24] and measurements of the combination of $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow K^-\pi^+$ rates by the FOCUS collaboration [25] gave first information on the mixing.

As usual, one define the mixing quantities

$$x \equiv \frac{m_2 - m_1}{\Gamma}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}. \quad (30)$$

CP-violation in the mixing is defined by the angle $\phi$. The experiments find that the quantity $y\cos\phi$ is significantly larger than the expectation in the standard model. The errors being large, this result is not yet significant, but it shows the potential of D-meson physics.

7  **K-Physics**

Finally let me mention K-physics. Of course, efforts continue in calculating $\epsilon'/\epsilon$ and to overcome the hadronic difficulties, and there will be substantial progress. However, the rare decays $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K^0 \rightarrow \pi^0\nu\bar{\nu}$ provide a theoretically clean way to measure (in the standard model) $|V_{td}|$ and $ImV_{td}$ [26]. Clearly, this can be used as a test of the unitary triangle, however the measurement of the neutral decays is not easy and probably many years away.

8  **Conclusions**

The new results on $\sin 2\beta$ are surprising; they may indicate a failure of the standard model. Several parameters have to be stretched beyond their reasonable values to account for them. One can modify the standard model to accommodate the small value of $\sin 2\beta$, but it is not clear that these modifications are consistent.

Nevertheless, the result brings back the (old) view, that a (standard) model independent and broad analysis of CP-violation is required in order to fully understand this phenomenon and the need for new interaction. This implies in particular measurements of many decay channels.

I have sketched strategies to determine the source of CP-violation for the case that the standard model accounts for tree level processes and given a phenomenological
framework to calculate the effects of new operators. Needless to say that all of this will take many years of hard work on both the experimental and the theoretical side and that also less perfect measurements have to be pursued.

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