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Flavour Visions

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This decade will allow to improve the resolution of the short distance scales by at least an order of magnitude, extending the picture of fundamental physics down to scales $5 \cdot 10^{-20}$m with the help of the LHC. Further resolution down to scales as short as 10^{-21}m should be possible with the help of high precision experiments in which flavour violating processes will play a prominent role. Will this increase in resolution allow us to see new particles (new animalcula) similarly to what Antoni van Leeuvenhoek saw by discovering bacteria in 1676? The basic question for particle physics is how these new animalcula will look like and which difficulties of the Standard Model (SM) they will help us to solve and which new puzzles and problems they will bring with them. I will describe what role flavour physics will play in these exciting times provided this new world is animalculated.

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1. Overture

The year 1676 was a very important year for the humanity. In this year Antoni van Leeuvenhoek (1632-1723) discovered the empire of bacteria. He called these small creatures *animalcula* (small animals). This discovery was a mile stone in our civilization for at least two reasons:

- He discovered invisible to us creatures which over thousands of years were systematcally killing the humans, often responsible for millions of death in one year. While Antoni van Leeuvanhoek did not know that bacteria could be dangerous for humans, his followers like L. Pasteur (1822-1895), Robert Koch (1843-1910) and other *animalcula hunters* not only realized the danger coming from these tiny creatures but also developed weapons against this empire.

- He was the first human who looked at short distance scales invisible to us, discovering thereby a new *underground world*. At that time researchers looked mainly at large distances, discovering new planets and finding laws, like Kepler laws, that Izaak Newton was able to derive from his mechanics.

While van Leeuvanhoek could reach the resolution down to roughly 10^{-6}m, over the last 335 years this resolution could be improved by twelve orders of magnitude. On the way down to shortest distance scales scientists discovered *nanouniverse* (10^{-9}m), *femtouniverse* (10^{-15}m) relevant for nuclear particle physics and low energy elementary particle physics and finally *attouniverse* (10^{-18}m) that is the territory of contemporary high energy elementary particle physics.

In this decade we will be able to improve the resolution of the short distance scales by at least an order of magnitude, extending the picture of fundamental physics down to scales $5\cdot 10^{-20}$m with the help of the LHC. Further resolution down to scales as short as 10^{-21}m (*zeptouniverse*) should be possible with the help of high precision experiments in which flavour violating processes will play a prominent role.

In this context one should point out that van Leeuvanhoek was really lucky. If the animalcula that he discovered where by an order of magnitude smaller, he would not see them with the microscopes he built. Moreover, the theorists of the 17th century did not make any predictions for this new world. In this sence particle physicists are in a better position. We are all convinced that some new animalcula must exist at the short distance scales explored by the LHC and new high precision experiments. Moreover we have some ideas how they could look like, even if there are different opinions on their possible appearance. This talk deals with the search for new animalcula with the help of flavour physics. More details on this search can be found in [1] as well as [2–6]. I should also warn possible readers that in view of space limitations my list of references is incomplete. This is compensated by approximately 300 references in [1]. There is also some overlap with the latter review but I made an effort to include also new developments that cannot be found there.

2. Beyond the SM

2.1 Preliminaries

The fundamental Lagrangian of the SM consists of four pieces

$$\mathscr{L}_{\text{SM}} = L_{\text{gauge}} + L_{\text{fermion}} + L_{\text{Higgs}} + L_{\text{Yukawa}}, \tag{2.1}$$

of which the first two terms containing kinetic terms of gauge bosons and fermions, invariant under the SM gauge group, have been rather well tested at various laboratories, in particular at CERN and Fermilab. The situation with the last two terms is different.

- L_{Higgs} is responsible for spontaneous breakdown of the electroweak symmetry and the generation of $W^{\pm}$ and Z^0 masses. It provides also the mass for the Higgs boson. The potential in this term driving this breakdown, even if consistent with the gauge symmetry, is rather adhoc. Clearly we are here at the level similar to the Ginzburg-Landau theory of superconductivity. A more dynamical mechanism of electroweak symmetry breakdown is absent in the SM.

- L_{Yukawa} is responsible for the generation of fermion masses through Yukawa-like interactions of fermions with the Higgs system. A natural scale for fermion masses generated in this manner is the value of the vacuum expectation v of the relevant neutral component of the Higgs doublet, this means 246 GeV in my conventions. This works for the top quark but fails totally for the remaining fermions. Their masses are by orders of magnitude smaller than m_t. Consequently in order to describe the observed fermion mass spectrum Yukawa interactions must have a very hierarchical structure. This hierarchical structure is believed to be responsible for the observed hierarchy in flavour violating interactions of quarks. However, a convincing theory behind this hierarchy is still missing.

Thus in spite of the fact that the SM appears to describe the existing data rather well, it does with the help of 28 parameters of which 22 recide in the flavour sector.

Taking all these facts together, the message is clear: in our search for a more fundamental theory we need to improve our understanding of electroweak symmetry breaking and of flavour which would allow us to answer the crucial question:

What is the dynamical origin of the observed electroweak symmetry breaking, of related fermion masses and the reason for their hierarchy and hierarchy of their flavour-changing interactions?

Related important questions are clearly these ones:

- Will the dynamics of electroweak symmetry breaking be driven by an elementary Higgs and be calculable within perturbation theory?

- Will these dynamics be related to a new strong force with a composite Higgs or without Higgs at all?

- Could these dynamics help us to explain the amount of matter-antimatter asymmetry and the amount of dark matter observed in the universe?

- Will these dynamics help us to explain various anomalies observed recently in the flavour data?

Whatever these dynamics will be, we need new particles and new forces in order to answer all these questions and this means new animalcula at the scales explored by the LHC and high precision experiments. But the identification of them is quite challenging both experimentally and theoretically.

In order to illustrate this problematic from the point of view of flavour physics, let us consider the tree level decay $B^+ \to \tau^+\nu_\tau$ which in the SM is just mediated by a W^+ exchange. The resulting branching ratio reads

$$Br(B^+ \to \tau^+\nu_\tau)_{\rm SM} = \left| A \frac{g_2^2}{M_W^2} \right|^2, \tag{2.2}$$

where g_2 is the $SU(2)_L$ coupling constant and A collects all factors that depend on the parameters of the SM.

Let us next assume the presence of a heavy charged boson (scalar or vector) H^+ mediating this decay as well, so that the branching ratio is modified as follows

$$Br(B^+ \to \tau^+\nu_\tau)_{\rm SM+H} = \left| A \frac{g_2^2}{M_W^2} + B \frac{g_H^2}{M_H^2} \right|^2. \tag{2.3}$$

Here g_H is a new coupling constant, M_H is the mass of H^+ and B collects all factors that depend on the parameters of the new physics (NP) model.

Finally let us assume that experiments find the disagreement with the SM prediction:

$$Br(B^+ \to \tau^+\nu_\tau)_{\rm EXP} - Br(B^+ \to \tau^+\nu_\tau)_{\rm SM} \neq 0. \tag{2.4}$$

In principle this deviation could signal the presence of the boson H^+ and by suitably choosing the coupling g_H, the mass M_H and B we could obtain the agreement with the data. Yet, clearly we cannot be sure that this is really the explanation, as many other NP contributions could be responsible for this anomaly. What would definitely help would be the discovery of H^+ in high energy collisions like those taking place at the LHC or TEVATRON, but what if M_H is beyond the reach of of these machines? Moreover, even if H^+ and other new particles could be discovered at the LHC, the measurement of their properties, in particular their flavour interactions, both flavour violating and flavour conserving will be a real challange. Here rare and CP-violating phenomena in low energy, high precision experiment can offer a great help, as they did already in the past 50 years. Yet, as we have seen above, a single measurement of a rare process, even if signalling the presence of new particles, will not be able to tell us what these particles are.

The message is clear: In order to identify new animalcula through flavour physics and generally through high precision experiments we need:

- Many high precision measurements of many observables and precise theory,
- Identification of patterns of flavour violation in various NP models, in particular correlations between many flavour observables that could distinguish between various NP scenarios,
- Identification of correlations between low energy flavour observables and observables measured in high energy collisions.

Despite the impressive success of the CKM picture of flavour changing interactions [7, 8] in which the GIM mechanism [9] for the suppression of flavour changing neutral currents (FCNC) plays a very important role, there are many open questions of theoretical and experimental nature that should be answered before we can claim to have a theory of flavour. Among the basic questions in flavour physics that could be answered in the present decade are the following ones:

1. What is the fundamental dynamics behind the electroweak symmetry breaking that very likely plays also an important role in flavour physics?

2. Are there any new flavour symmetries that could help us to understand the existing hierarchies of fermion masses and the hierarchies in the quark and lepton flavour violating interactions? Are they local or global? Are they continuous or discrete?

3. Are there any flavour violating interactions that are not governed by the SM Yukawa couplings? In other words, is the Minimal Flavour Violation (MFV) the whole story?

4. Are there any additional *flavour violating* and CP-violating (CPV) phases that could explain certain anomalies present in the flavour data and simultaneously play a role in the explanation of the observed baryon-antibaryon asymmetry in the universe (BAU)?

5. Are there any *flavour conserving* CPV phases that could also help in explaining the flavour anomalies in question and would be signalled in this decade through enhanced electric dipole moments (EDMs) of the neutron, the electron and of other particles?

6. Are there any new sequential heavy quarks and leptons of the 4th generation and/or new fermions with exotic quantum numbers like vector-like fermions?

7. Are there any elementary neutral and charged scalar particles with masses below 1 TeV and having a significant impact on flavour physics?

8. Are there any new heavy gauge bosons representing an enlarged gauge symmetry group?

9. Are there any relevant right-handed (RH) weak currents that would help us to make our fundamental theory parity conserving at short distance scales well below those explored by the LHC?

10. How would one successfully address all these questions if the breakdown of the electroweak symmetry would turn out to be of a non-perturbative origin?

An important question is the following one: will some of these questions be answered through the interplay of high energy processes explored by the LHC with low energy precision experiments or are the relevant scales of fundamental flavour well beyond the energies explored by the LHC and future colliders in this century? The existing tensions in some of the corners of the SM to be discussed below and still a rather big room for NP contributions in rare decays of mesons and leptons and CP-violating observables, including in particular EDMs, give us hopes that indeed several phenomena required to answer at least some of these questions could be discovered in this decade.

2.2 Superstars of Flavour Physics in 2011-2016

As far as high precision experiments are concerned a number of selected processes and observables will, in my opinion, play the leading role in learning about the NP in this new territory.

This selection is based on the sensitivity to NP and theoretical cleanness. The former can be increased with the increased precision of experiments and the latter can improve with the progress in theoretical calculations, in particular the non-perturbative ones like the lattice simulations.

My superstars for the coming years are as follows:

- The mixing induced CP-asymmetry $S_{\psi\phi}(B_s)$ that is tiny in the SM: $S_{\psi\phi} \approx 0.04$. The asymmetry $S_{\phi\phi}(B_s)$ is also important. It is also very strongly suppressed in the SM and is sensitive to NP similar to the one explored through the departure of $S_{\phi K_S}(B_d)$ from $S_{\psi K_S}(B_d)$ [10].

- The rare decays $B_{s,d} \to \mu^+\mu^-$ that could be enhanced in certain NP scenarios by an order of magnitude with respect to the SM values.

- The angle γ of the unitarity triangle (UT) that will be precisely measured through tree level decays.

- $B^+ \to \tau^+\nu_\tau$ that is sensitive to charged Higgs particles.

- The rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ that belong to the theoretically cleanest decays in flavour physics.

- The decays $B \to X_s\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$ and $B \to K\nu\bar{\nu}$ that are theoretically rather clean and are sensitive to RH currents.

- Numerous angular symmetries and asymmetries in $B \to K^* l^- l^-$.

- Lepton flavour violating decays like $\mu \to e\gamma$, $\tau \to e\gamma$, $\tau \to \mu\gamma$, decays with three leptons in the final state and $\mu - e$ conversion in nuclei.

- Electric dipole moments of the neutron, the electron, atoms and leptons.

- Anomalous magnetic moment of the muon $(g-2)_\mu$ that indeed seems to be ”anomalous” within the SM even after the inclusion of radiative corrections.

- The ratio ε'/ε in $K_L \to \pi\pi$ decays which is known experimentally within 10% and which should gain in importance in this decade due to improved lattice calculations.

- Precise measurements of two-body B_d and in particular B_s decays which in combination with QCD factorization and various flavour symmetries [3] could teach us more about the interplay of strong and electroweak interactions including NP.

Clearly, there are other stars in flavour physics but I believe that the ones above will play the crucial role in our search for the theory of flavour. Having experimental results on these decays and observables with sufficient precision accompanied by improved theoretical calculations will exclude several presently studied models reducing thereby our exploration of short distance scales to a few avenues.

2.3 Superiority of Top-Down Approach in Flavour Physics

Particle physicists are waiting eagerly for a solid evidence of NP for the last 30 years. Except for neutrino masses, the BAU and dark matter, no clear signal emerged so far. While waiting for experimental signals several strategies for finding NP have been developed. In addition to precision calculations within the SM that allow to find the huge *background* to NP coming from the known dynamics of this model (QCD corrections in flavour physics are reviewed in [11]), one distinguishes between *bottom-up* and *top-down* approaches. Here I would like to express my personal view on these two approaches in the context of flavour physics and simultaneous exploration of short distance physics both through LHC and high precision experiments.

2.3.1 The Bottom-Up Approach

In this approach one constructs effective field theories involving only light degrees of freedom including the top quark in which the structure of the effective Lagrangians is governed by the symmetries of the SM and often other hypothetical symmetries. This approach is rather powerful in the case of electroweak precision studies and definitely teaches us something about $\Delta F = 2$ transitions. In particular lower bounds on NP scales depending on the Lorentz structure of operators involved can be derived from the data [2, 12].

However, except for the case of MFV and closely related approaches based on flavour symmetries, the bottom-up approach ceases, in my view, to be useful in $\Delta F = 1$ decays, because of very many operators that are allowed to appear in the effective Lagrangians with coefficients that are basically unknown [13, 14]. In this approach then the correlations between various $\Delta F = 2$ and $\Delta F = 1$ observables in K, D, B_d and B_s systems are either not visible or very weak, again except MFV and closely related approaches. Moreover the correlations between flavour violation in low energy processes and flavour violation in high energy processes to be studied soon at the LHC are lost. Again MFV belongs to a few exceptions.

2.3.2 The Top-Down Approach

My personal view shared by some of my colleagues is that the top-down approach is more useful in flavour physics. Here one constructs first a specific model with heavy degrees of freedom. For high energy processes, where the energy scales are of the order of the masses of heavy particles one can directly use this “full theory” to calculate various processes in terms of the fundamental parameters of a given theory. For low energy processes one again constructs the low energy theory by integrating out heavy particles. The advantage over the previous approach is that now the coefficients of the resulting local operators are calculable in terms of the fundamental parameters of this theory. In this manner correlations between various observables belonging to different mesonic systems and correlations between low energy and high-energy observables are possible. Such correlations are less sensitive to free parameters than separate observables and represent patterns of flavour violation characteristic for a given theory. These correlations can in some models differ strikingly from the ones of the SM and of the MFV approach.

2.4 Anatomies of explicit models

Having the latter strategy in mind my group at the Technical University Munich, consisting dominantly of diploma students, PhD students and young post–docs investigated in the last decade flavour violating and CP-violating processes in a multitude of models. The names of models analyzed by us are collected in Fig. 1. A summary of these studies before 2011 with brief descriptions of all these models can be found in [1]. Below, I will frequently refer to these results and will briefly mention the most recent results obtained in my group.

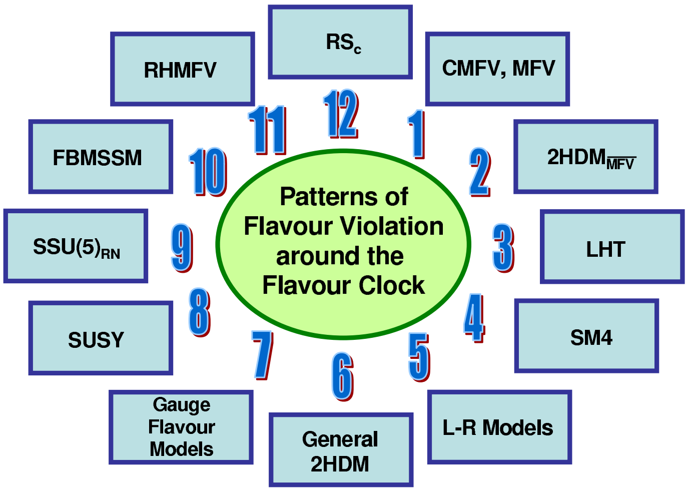

Figure 1: Various patterns of flavour violation around the Flavour Clock.

3. First Messages from New Animalcula

3.1 Preliminaries

While the CKM+GIM picture of flavour and CP Violation describes the existing data surprisingly well, a number of anomalies observed in last years indicate that new Animalcula could be already in sight. Three of these anomalies concern CP violation in K_L, B_d and B_s systems and all three are related to particle-antiparticle mixing. Also the data on the decay $B^+ \to \tau^+ \nu$ seem to depart from the SM expectations. Last but certainly not least the anomalous magnetic moment of the muon, $(g-2)_\mu$, is by 3.2 σ above the SM value. Let me then briefly summarize these anomalies.

3.2 The $\varepsilon_K - S_{\psi K_S}$ Anomaly

It has been pointed out in [16, 17] that the SM prediction for ε_K implied by the measured value of $S_{\psi K_S} = \sin 2\beta$, the ratio $\Delta M_d / \Delta M_s$ and the value of $|V_{cb}|$ turns out to be too small to agree well with experiment. This tension between ε_K and $S_{\psi K_S}$ has been pointed out from a different perspective in [15, 18–20]. These findings have been confirmed by a UTfitters analysis [21]. The CKMfitters having a different treatment of uncertainties find less significant effects in ε_K [22].

Indeed taking the experimental value of $S_{\psi K_S} = 0.672 \pm 0.023$, $|V_{cb}| = 0.0416$, the most recent value of the relevant non-perturbative parameter $\hat{B}_K = 0.724 \pm 0.008 \pm 0.028$ [23] (see also the most recent message from RBC and UKQCD collaborations [24] $\hat{B}_K = 0.749 \pm 0.027$) resulting from unquenched lattice calculations and including long distance (LD) effects in $\mathrm{Im}\Gamma_{12}$ and $\mathrm{Im}M_{12}$

in the $K^0-\bar{K}^0$ mixing [16, 25] as well as recently calculated NNLO QCD corrections to ε_K [26] one finds [26]

$$|\varepsilon_K|_{\rm SM} = (1.90\pm 0.26)\cdot 10^{-3}, \tag{3.1}$$

visibly below the experimental value $|\varepsilon_K|_{\rm exp} = (2.23\pm 0.01)\cdot 10^{-3}$.

On the other hand $\sin 2\beta = 0.85\pm 0.05$ from SM fits of the Unitarity Triangle (UT) is significantly larger than the experimental value $S_{\psi K_S} = 0.672\pm 0.023$. This discrepancy is to some extent caused by the desire to fit ε_K [15–20] and $Br(B^+\to\tau^+\nu_\tau)$ [20]. For the most recent discussions including up to date numerics see [27–29].

One should also recall the tension between inclusive and exclusive determinations of $|V_{ub}|$ with the exclusive ones in the ballpark of $3.5\cdot 10^{-3}$ and the inclusive ones typically above $4.0\cdot 10^{-3}$. As discussed in [30] an interesting solution to this problem is the presence of RH charged currents, which selects the inclusive value as the true value, implying again $\sin 2\beta \approx 0.80$ [31].

As discussed in [15, 16] and subsequent papers of these authors a negative NP phase φ_{B_d} in $B_d^0-\bar{B}_d^0$ mixing would solve both problems, provided such a phase is allowed by other constraints. Indeed we have then

$$S_{\psi K_S}(B_d) = \sin(2\beta + 2\varphi_{B_d}), \qquad S_{\psi\phi}(B_s) = \sin(2|\beta_s| - 2\varphi_{B_s}), \tag{3.2}$$

where the corresponding formula for $S_{\psi\phi}$ in the presence of a NP phase φ_{B_s} in $B_s^0-\bar{B}_s^0$ mixing has also been given. With a negative φ_{B_d} the true $\sin 2\beta$ is larger than $S_{\psi K_S}$, implying a higher value on $|\varepsilon_K|$, in reasonable agreement with data and a better UT-fit. This solution would favour the inclusive value of $|V_{ub}|$ as chosen e.g. by RH currents but as pointed out in [31] this particular solution of the $"V_{ub}-problem''$ does not allow for a good fit to $S_{\psi K_S}$ if large $S_{\psi\phi}$ is required.

3.3 Facing an enhanced CPV in the B_s mixing

The first detailed SM and model independent studies of CP violation in the $B_s^0-\bar{B}_s^0$ mixing in relation to Tevatron and LHCb experiments go back to [32, 33]. Among the recent studies of these authors let me just quote [27, 34].

This topic became rather hot recently. Indeed possibly the most important highlight in flavour physics in 2008, 2009 [35] and even more in 2010 was the enhanced value of $S_{\psi\phi}$ measured by the CDF and D0 collaborations, seen either directly or indirectly through the correlations with various semi-leptonic asymmetries. While in 2009 and in the Spring of 2010 [36], the messages from Fermilab indicated good prospects for $S_{\psi\phi}$ above 0.5, the messages from ICHEP 2010 in Paris, softened such hopes a bit [37]. Both CDF and D0 find the enhancement by only one σ. Yet, this does not yet preclude $S_{\psi\phi}$ above 0.5, which would really be a fantastic signal of NP. Indeed various recent fits indicate that $S_{\psi\phi}$ could be even as high as 0.8 [27]. Let us hope that the future data from Tevatron and in particular from the LHCb, will measure this asymmetry with sufficient precision so that we will know to which extent NP is at work here. One should also hope that the large CPV in dimuon CP asymmetry from D0, that triggered new activities, will be better understood. I have nothing to add here at present and can only refer to numerous papers [22, 38–41].

In what follows I will decribe how different NP scenarios would face a future measurement of a significantly enhanced value of $S_{\psi\phi}$.

The value $S_{\psi\phi} \geq 0.5$ can be obtained in the RSc model due to KK gluon exchanges and also heavy neutral KK electroweak gauge boson exchanges [42]. See also [43]. In the supersymmetric flavour models with the dominance of RH currents double Higgs penguins constitute the dominant NP contributions responsible for $S_{\psi\phi} \geq 0.5$, while in models where NP LH current contributions are equally important, also gluino boxes are relevant. On the operator level LR operators are primarly responsible for this enhancement. Detailed analysis of this different cases can be found in [44]. Interestingly the SM4 having only $(V-A)\times(V-A)$ operator is also capable in obtaining high values of $S_{\psi\phi}$ [45–49]. In the LHT model where only $(V-A)\times(V-A)$ operators are present and the NP enters at higher scales than in the SM4, $S_{\psi\phi}$ above 0.5 is out of reach [50].

All these models contain new sources of flavour and CP violation and it is not surprising that in view of many parameters involved, large values of $S_{\psi\phi}$ can be obtained. The question then arises whether strongly enhanced values of this asymmetry would uniquely imply new sources of flavour violation beyond the MFV hypothesis. The answer to this question is as follows:

- In models with MFV and flavour blind phases (FBPs) set to zero, $S_{\psi\phi}$ remains indeed SM-like.
- In supersymmetric models with MFV even in the presence of non-vanishing FBPs, at both small and large $\tan\beta$, the supersymmetry constraints do not allow values of $S_{\psi\phi}$ visibly different from the SM value [40, 44, 51].
- In the $2\text{HDM}_{\overline{\text{MFV}}}$ in which at one-loop both Higgs doublets couple to up- and down-quarks in the context of MFV, it is possible to obtain $S_{\psi\phi} \geq 0.5$ while satisfying all existing constraints [52].

The driving force for large values of $S_{\psi\phi}$ in this NP scenario are FBPs in interplay with the CKM matrix.[1] Dependently whether these phases appear in Yukawa couplings and/or Higgs potential one can distinguish three scenarios:

A) The FBPs in the Yukawa interactions are the dominant source of new CPV. In this case the NP phases φ_{B_s} and φ_{B_d} are related through [52]

$$\varphi_{B_d} \approx \frac{m_d}{m_s}\varphi_{B_s} \approx \frac{1}{17}\varphi_{B_s}. \tag{3.3}$$

Thus in this scenario large φ_{B_s} required to obtain values of $S_{\psi\phi}$ above 0.5 imply a unique small shift in $S_{\psi K_S}$ that allows to lower $S_{\psi K_S}$ from 0.74 down to 0.70, that is closer to the experimental value 0.672 ± 0.023. This in turn implies that it is $\sin 2\beta = 0.74$ [2] and not $S_{\psi K_S} = 0.67$ that should be used in calculating ε_K resulting in a value of $\varepsilon_K \approx 2.0\cdot 10^{-3}$ within one σ from the experimental value. The direct Higgs contribution to ε_K is negligible because of small masses $m_{d,s}$. We should emphasize that once φ_{B_s} is determined from the data on $S_{\psi\phi}$ by means of (3.2), the implications for ε_K and $S_{\psi K_S}$ are unique. The plots of ε_K and $S_{\psi K_S}$ versus $S_{\psi\phi}$ in [52] show this very transparently.

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[1] Various recent papers on FBPs not discussed here are collected in [53]. See, in particular, in the context of the Aligned two-Higgs-doublet model [54]. Also numerous studies of 2HDM models have been done by Gustavo Branco and his group. See [55] and earlier papers.

[2] The present value value from the most recent UT fit analyses mentioned above is a bit higher and close to 0.80 modifying a bit the numerics below.

On the other hand this scenario does not provide any clue for the difference between inclusive and exclusive determinations of $|V_{ub}|$. Moreover, it appears that (see below) that the effect of FBPs in Yukawa couplings in a MFV framework is a bit to weak to solve quantitatively existing tensions.

B) The FBPs in the Higgs potential are are the dominant source of new CPV. In this case the NP phases φ_{B_s} and φ_{B_d} are related through [38, 40] [3]

$$\varphi_{B_d} = \varphi_{B_s} \tag{3.4}$$

and the plots of ε_K and $S_{\psi K_S}$ versus $S_{\psi\phi}$ are strikingly modified [57]: the dependence is much stronger and even moderate values of $S_{\psi\phi}$ can solve all tensions. However, large values of $S_{\psi\phi}$ are not allowed if one wants to reproduce the experimental value of $S_{\psi K_S}$.

C) Hybrid scenario in which FBPs are present in both Yukawa interactions and Higgs potential so that [57]

$$\varphi_{B_d} = a\frac{m_d}{m_s}\varphi_{B_s} + b\varphi_{B_s} = \kappa\varphi_{B_s}, \tag{3.5}$$

where a, b, κ are real coefficients.

Presently it is not clear which relation between φ_{B_s} and φ_{B_d} fits best the data but the model independent analysis of [38] indicates that $\kappa \approx 1/5$. Which of the two flavour-blind CPV mechanisms dominates depends on the value of $S_{\psi\phi}$, which is still affected by a sizable experimental error, and also by the precise amount of NP allowed in $S_{\psi K_S}$.

3.4 Implications of an enhanced $S_{\psi\phi}$

There are many implications of an enhanced value of $S_{\psi\phi}$ in concrete NP models, which have been worked out in our papers. We have reviewed these implications in some details in [1]. Here we will just collect some of the striking implications:

- Enhanced $\mathrm{Br}(\mathrm{B_s} \to \mu^+\mu^-)$ in SUSY flavour models, $\mathrm{2HDM}_{\overline{\mathrm{MFV}}}$ and SM4,
- Enhanced $\mathrm{Br}(\mathrm{B_d} \to \mu^+\mu^-)$ in $\mathrm{2HDM}_{\overline{\mathrm{MFV}}}$ and in some SUSY flavour models,
- $\mathrm{Br}(\mathrm{B_d} \to \mu^+\mu^-)$ forced to be SM-like in SM4,
- $\mathrm{Br}(\mathrm{K}^+ \to \pi^+\nu\bar\nu)$ and $\mathrm{Br}(\mathrm{K_L} \to \pi^0\nu\bar\nu)$ forced to be SM-like in LHT [50] and RSc models [59] but not in SM4.
- Automatic enhancements of $\mathrm{Br}(\mu \to \mathrm{e}\gamma)$, $\mathrm{Br}(\tau \to \mu\gamma)$, $(g-2)_\mu$ and of EDMs d_e and d_n in SUSY-GUT models [51, 58]

We observe that simultaneous consideration of $S_{\psi\phi}$ and $\mathrm{Br}(\mathrm{B_{s,d}} \to \mu^+\mu^-)$ can already help us in eliminating some NP scenarios. Even more insight will be gained when $\mathrm{Br}(\mathrm{K}^+ \to \pi^+\nu\bar\nu)$ and $\mathrm{Br}(\mathrm{K_L} \to \pi^0\nu\bar\nu)$ will be measured. In particular if $S_{\psi\phi}$ will turn out to be SM-like the branching ratios $\mathrm{Br}(\mathrm{K}^+ \to \pi^+\nu\bar\nu)$ and $\mathrm{Br}(\mathrm{K_L} \to \pi^0\nu\bar\nu)$ can now be strongly enhanced in the LHT model [50] and the RSc model [43, 59] with respect to the SM but this is not guaranteed. These patterns of flavour violations demonstrate very clearly the power of flavour physics in distinguishing different NP scenarios.

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[3] This relation has been postulated already in [16, 56].

3.5 $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$

The branching ratios $\mathrm{Br}(B_{s,d} \to \mu\bar{\mu})$ are very strongly suppressed in the SM:

$$\mathrm{Br}(B_d \to \mu^+\mu^-)_{\mathrm{SM}} = (1.0 \pm 0.1) \times 10^{-10}, \tag{3.6}$$

$$\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.2 \pm 0.2) \times 10^{-9}\,. \tag{3.7}$$

and satisfy in the SM and CMFV models the relation [60]

$$\frac{\mathrm{Br}(B_s \to \mu\bar{\mu})}{\mathrm{Br}(B_d \to \mu\bar{\mu})} = \frac{\hat{B}_d}{\hat{B}_s}\frac{\tau(B_s)}{\tau(B_d)}\frac{\Delta M_s}{\Delta M_d}. \tag{3.8}$$

It involves only measurable quantities except for the ratio $\hat{B}_s/\hat{B}_d$ that is known already now from lattice calculations within 3% [62].

The upper bounds on $\mathrm{Br}(B_d \to \mu^+\mu^-)$ from CDF, D0 and LHCb are still by an order of magnitude larger than the SM predictions but in the coming years LHCb should be able to bring this upper bounds down within a factor two from the SM predictions or to discover NP. In these studies the methodology developed recently in [61] and presented by Niels Tuning at this conference should be very useful. The branching ratios in question can be enhanced even by an order of magnitude in a number of NP scenarios and the relation in (3.8) can also be strongly violated [1].

3.6 EDMs, $(g-2)_\mu$ and $Br(\mu \to e\gamma)$

While I was dominantly discussing quark physics and flavour violating processes, these three observables are also very interesting. They are governed by dipole operators but describe different physics as far as CP violation and flavour violation is concerned. EDMs are flavour conserving but CP-violating, $\mu \to e\gamma$ is CP-conserving but lepton flavour violating and finally $(g-2)_\mu$ is lepton flavour conserving and CP-conserving. A nice paper discussing all these observables simultaneously is [63].

In concrete models there exist correlations between these three observables of which EDMs and $\mu \to e\gamma$ are very strongly suppressed within the SM and have not been seen to date. $(g-2)_\mu$ on the other hand has been very precisely measured and exhibits a 3.2σ departure from the very precise SM value (see [64] and references therein) [4]. Examples of these correlations can be found in [44, 51]. In certain supersymmetric flavour models with non-MFV interactions the solution of the $(g-2)_\mu$ anomaly implies simultaneously d_e and $\mathrm{Br}(\mu \to \mathrm{e}\gamma)$ in the reach of experiments in this decade. In these two papers several correlations of this type have been presented.

The significant FBPs required to reproduce the enhanced value of $S_{\psi\phi}$ in the $2\mathrm{HDM}_{\overline{\mathrm{MFV}}}$ model, necessarily imply large EDMs of the neutron, Thallium and Mercury atoms. Yet, as a detailed analysis in [57] shows the present upper bounds on the EDMs do not forbid sizable non-standard CPV effects in B_s mixing. However, if a large CPV phase in B_s mixing will be confirmed, this will imply hadronic EDMs very close to their present experimental bounds, within the reach of the next generation of experiments. For a recent model independent analysis of EDMs see [66].

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[4] In a very recent paper it is claimed that the SM agrees perfectly with the data [65], confirmation or disproval of this claim would be very important.

3.7 Waiting for precise predictions of ε'/ε

The flavour studies of the last decade have shown that provided the hadronic matrix elements of QCD-penguin and electroweak penguin operators will be known with sufficient precision, ε'/ε will play a very important role in constraining NP models. We have witnessed recently an impressive progress in the lattice evaluation of $\hat{B}_K$ that elevated ε_K to the group of observables relevant for precision studies of flavour physics. Hopefully this could also be the case of ε'/ε already in this decade.

3.8 $B^+ \to \tau^+ \nu_\tau$

Another prominent anomaly in the data not discussed by us sofar is found in the tree-level decay $B^+ \to \tau^+ \nu_\tau$. Within the SM we found [44]

$$\mathrm{Br}(B^+ \to \tau^+ \nu_\tau)_{\mathrm{SM}} = (0.80 \pm 0.12) \times 10^{-4}, \tag{3.9}$$

which agrees well with the result presented by the UTfit collaboration [67].

On the other hand, the present experimental world avarage based on results by BaBar and Belle reads [67]

$$\mathrm{Br}(B^+ \to \tau^+ \nu_\tau)_{\mathrm{exp}} = (1.73 \pm 0.35) \times 10^{-4} \ , \tag{3.10}$$

which is roughly by a factor of 2 higher than the SM value. We can talk about a tension at the 2.5σ level.

With a higher value of $|V_{ub}|$ as obtained through inclusive determination this discrepancy can be decreased significantly. For instance with a value of 4.4×10^{-3}, the central value predicted for this branching ratio would be more like 1.25×10^{-4}. Yet, this would then require NP phases in $B_d^0 - \bar{B}_d^0$ mixing to agree with the data on $S_{\psi K_S}$. In any case values of $\mathrm{Br}(B^+ \to \tau^+ \nu)_{\mathrm{exp}}$ significantly above 1×10^{-4} will signal NP contributions either in this decay or somewhere else. For a very recent discussion of such correlations see [20].

While the final data from BaBar and Belle will lower the exparimental error on $\mathrm{Br}(\mathrm{B}^+ \to \tau^+ \nu)$, the full clarification of a possible discrepancy between the SM and the data will have to wait for the data from Belle II and SFF in Rome. Also improved values for F_B from lattice and $|V_{ub}|$ from tree level decays will be important if some NP like charged Higgs is at work here. As a significant progress made by lattice groups [62] is continuing, there are good chances that around 2015 the picture of $B^+ \to \tau^+ \nu$ will be much clearer. The same applies to many B physics observables as well.

4. Messages from the last moment

Finally, I would like to report on two recent papers from Munich.

In the first paper a minimal theory of fermion masses (MTFM) has been constructed [68]. This amounts to extend the SM by heavy vectorlike fermions with flavour-anarchical Yukawa couplings that mix with chiral fermions such that small SM Yukawa couplings arise from small mixing angles. This model can be regarded as an effective description of the fermionic sector of a large class of existing models and thus might serve as a useful reference frame for a further understanding of flavour hierarchies in the SM. Already such a minimal framework implies modifications in the couplings of $W^{\pm}$, Z and H to fermions and leading to novel FCNC effects with a special structure of their suppression that is different from MFV. This work shows once again that models attempting the explanation of the hierarchies of fermion masses and of its hierarchical flavour violating and CP violating interactions in most cases imply non-MFV interactions. This is also evident from the study of supersymmetric flavour models [44] and more general recent studies [69, 70]. Further phenomenological implications of MTFM will be presented soon.

In the second paper [71] considering a general scenario with new heavy neutral gauge bosons, present in particular in Z' and gauge flavour models, we have pointed out two new contributions to the $\overline{B} \to X_s \gamma$ decay. The first one originates from one-loop diagrams mediated by gauge bosons and heavy exotic quarks with electric charge $-1/3$. The second contribution stems from the QCD mixing of neutral current-current operators generated by heavy neutral gauge bosons and the dipole operators responsible for the $\overline{B} \to X_s \gamma$ decay. The latter mixing is calculated in our paper for the first time. We also discussed general sum rules which have to be satisfied in any model of this type. We emphasise that the neutral gauge bosons in question could also significantly affect other fermion radiative decays as well as non-leptonic two-body B decays, ε'/ε, anomalous $(g-2)_\mu$ and electric dipole moments. Implications of these findings for concrete models will be presented soon.

5. Grand Summary

I hope I convinced the readers that flavour physics is a very rich field which necessarily will be a prominent part of a future theory of fundamental interactions both at large and short distance scales. While MFV could work to first approximation, recent data indicate that at certain level non-MFV interactions could be present.

What role will be played by flavour blind phases in future phenomenology depends on the future experimental data on EDMs. Similar comment applies to LFV. A discovery of $\mu \to e\gamma$ rate at the level of 10^{-13} would be a true mile stone in flavour physics. Also the discovery of $S_{\psi\phi}$ at the level of 0.3 or higher would have a very important impact on quark flavour physics. The measurements of $\mathrm{Br}(\mathrm{B}_{\mathrm{s,d}} \to \mu^+\mu^-)$ in conjunction with $S_{\psi\phi}$, $K^+ \to \pi^+\nu\bar{\nu}$ and at later stage $K_L \to \pi^0\nu\bar{\nu}$ will allow to distinguish between various models. Here the correlations between various observables will be crucial. It is clearly important to clarify the origin of the tensions between ε_K, $S_{\psi K_S}$, $|V_{ub}|$ and $\mathrm{Br}(\mathrm{B}^+ \to \tau^+\nu_\tau)$ but this possibly has to wait until Belle II and later SFF will enter their operation.

In any case I have no doubts that we will have a lot of fun with flavour physics in this decade and that this field will offer very important insights into the short distance dynamics.

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