Future prospects of $B$ physics

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In recent years, the CKM picture of flavor and $CP$ violation has been confirmed, mainly due to $B$ decay data. Yet, it is likely that there are small corrections to this picture. We expect to find new physics not much above the weak scale. This new physics could modify flavor changing processes compared to their SM expectations. Much larger $B$ decay data sets, which are expected from LHCb and super-$B$-factories, will be used to search for these deviations with much improved sensitivity. The combination of low and high energy data will be particularly useful to probe the structure of new physics.

§1. Introduction

The aim of high energy physics is to understand the fundamental interactions among the elementary particles in Nature. The mathematical tool that is used to describe these interactions is quantum field theory, and high energy physics aims to determine the Lagrangian of Nature. The standard model (SM) has so far proven to be a good description of Nature up to energies of the order of the electroweak scale, $m_W \sim 100$ GeV. In particular, the electroweak gauge sector of the SM has been verified to an accuracy better than 1%, mainly by the LEP, SLC, and Tevatron experiments.\footnote{1}

In recent years, our understanding of the flavor sector has improved dramatically, due to the $e^+e^-$ $B$ factories, $B\bar{B}$, Belle, and CLEO, and the Tevatron experiments. With over $10^9$ decays of $B$ hadrons analyzed, the SM picture of the flavor sector has been tested with impressive accuracy.\footnote{1}

One sector where deviations from the SM predictions have been found is the lepton sector. The experimental pieces of evidence for neutrino flavor transitions contradict the prediction of massless neutrinos. The SM can be modified in a simple way to accommodate this result. If we consider the SM to be a low energy effective theory, nonrenormalizable terms should be included in the SM action. In particular, the only dimension-five operators that can be added generate neutrino masses. The observed coefficients of these operators suggest a suppression scale that is very high, well beyond direct probe.

The least tested sector of the SM is the Higgs sector. The Higgs boson is the only SM particle that has not yet been discovered. There are numerous alternatives to the SM Higgs sector. These range from mild modifications, such as having additional Higgs doublets, to rather radical alternatives where the mechanism that breaks the...
electroweak symmetry is not the vacuum expectation value of an elementary scalar. One of the most disturbing aspects of the SM is related to the Higgs sector. Once the SM is viewed as an effective theory, the fact that the Higgs mass is not very high becomes puzzling: radiative corrections involving heavy particles would drive the Higgs mass close to the cutoff scale. This well known fine tuning problem is often interpreted as an indication for new physics at the weak scale. Indeed, this is the main motivation to look for new effects at the weak scale with the LHC.

Flavor physics, in particular $B$ physics, has provided strong upper bounds on contributions from new physics models. This situation leads to the “new physics flavor puzzle”, which is the mismatch between the relatively low scale required to solve the fine tuning problem, and the high scale that is seemingly required to suppress the non-SM contributions to flavor changing processes. Let us expand a little on this point. The flavor sector of the SM is impressively successful. This success is linked to the fact that the SM flavor structure is special. First, the CKM matrix is unitary and contains small mixing angles. Second, flavor-changing neutral currents (FCNCs) are highly suppressed. These features are crucial to explain the observed pattern of weak decays. Any extension of the SM must preserve these successful features. Consider a model where the only suppression of new flavor changing interactions comes from the large masses (of scale $\Lambda \gg m_W$) of the new particles that mediate them. Flavor physics, in particular measurements of meson mixing and $CP$ violation, put severe lower bounds of order $\Lambda \gtrsim 10^{4}$ TeV. There is therefore a tension. The hierarchy problem can be solved with new physics at a scale $\Lambda \sim 1$ TeV. Flavor bounds, on the other hand, require $\Lambda \gtrsim 10^{4}$ TeV. This tension implies that any TeV-scale new physics cannot have a generic flavor structure. The new physics flavor puzzle is thus the question of why, and in what way, the flavor structure of the new physics is non-generic.

Flavor physics has been mainly an input to model building, not an output. The flavor predictions of most new physics models are not a consequence of their generic features but rather of the special structure that is imposed specifically to satisfy the existing severe flavor bounds. Therefore, flavor physics is a powerful indirect probe of new physics. We hope that new physics not far above the weak scale will be discovered at the LHC. A major issue will then be to understand its flavor structure. While it is not easy to directly probe this flavor structure at high energy, a lot can be learned from low energy flavor physics.

The precision with which we can probe the high scale physics in flavor physics experiments is limited by theoretical uncertainties (once experimental precision becomes good enough). Thus, the important questions are the following:

1. What are the expected deviations from the SM predictions induced by new physics at the TeV scale?
2. What are the theoretical uncertainties?
3. What can we expect in terms of experimental precision?
4. What will the measurements teach us if deviations from the SM are [not] seen?

In the following we discuss these questions in detail. The main lines of our answers read as follows:

1. The expected deviations from the SM predictions induced by new physics at the
TeV scale with generic flavor structure are already ruled out by many orders of magnitudes. We can thus expect any size of deviation below the current bounds. In a large class of scenarios we expect deviations at the $10^{-2}$ level.

2. The theoretical limitations are highly process dependent. Some measurements are already limited by theoretical uncertainties (mostly due to hadronic, strong interaction, effects), while in various other cases the theory has very small uncertainties, and is more precise than the expected sensitivity of future experiments.

3. Experimentally, the useful data sets can increase by a factor of order one hundred at LHC-b and a super-$B$ factory. Such improvements will therefore probe into the region of fairly generic new physics predictions.

4. The new low energy flavor data will be complementary with the high-$p_T$ part of the LHC program. The synergy of both data sets can teach us a lot about the new physics at the TeV scale.

In the next section we briefly review the current status of (quark) flavor physics. Sections 3–6 discuss questions 1–4, respectively. Section 7 contains our conclusions.

§2. Current status

In the standard model, the distinction between quarks of different generations comes from their Yukawa couplings to the Higgs field. In the mass basis, this flavor physics is manifest in quark masses, in $CP$ violation, and in all flavor changing phenomena described by the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix.\(^2,3\) In the SM all flavor-changing phenomena are described by only a handful of parameters, and therefore intricate correlations are predicted between dozens of different decays of $s$, $c$, $b$, and $t$ quarks, and in particular between $CP$ violating observables. Possible deviations from the CKM paradigm may modify (i) correlations between various measurements (e.g., inconsistent constraints from $B$ and $K$ decays, or from $CP$ asymmetries in different decay modes, for example, $B \to \psi K$ and $B \to \phi K$); (ii) predictions for FCNC transitions (e.g., enhanced $B_{(s)} \to \ell^+\ell^-$); (iii) enhanced $CP$ violation, (e.g., in $B \to K^*\gamma$ or in $B_s \to \psi\phi$).

Over the past decade, much progress has been made in precision measurements of the flavor parameters and in testing the SM flavor sector by many overconstraining measurements. To visualize the constraints from many measurements, it is convenient to use the Wolfenstein parameterization\(^4\) of the CKM matrix,

\[
V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar{\rho} - i\bar{\eta}) \\
-\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\
A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1
\end{pmatrix} + \ldots,
\]

(2.1)

This parameterization exhibits the hierarchical structure of the CKM matrix by expanding in a small parameter, $\lambda \simeq 0.23$; however, recent CKM fits use definitions of the $\lambda$, $A$, $\bar{\rho}$ and $\bar{\eta}$ parameters that obey unitarity exactly.\(^5\) The unitarity of $V$ implies

\[
\sum_i V_{ij}V_{ik}^* = \sum_i V_{ji}V_{ki}^* = \delta_{jk}.
\]

(2.2)
Each of the six vanishing combinations can be represented by a triangle in the complex plane. The most commonly used such triangle, often called “the unitarity triangle,” arises from rescaling the

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

relation by \( V_{cd} \) and choosing two vertices of the resulting triangle to be \((0,0)\) and \((1,0)\). The definition

\[ \bar{\rho} + i \bar{\eta} = -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}, \]  

ensures that the apex of the unitarity triangle is \((\bar{\rho}, \bar{\eta})\).

The asymmetric-energy \( B \) factory experiments, \( \text{BABAR} \) and \( \text{Belle} \), have measured many \( CP \) violating observables (around 20 with more than 3\( \sigma \) significance), of which the most precise is the \( CP \) asymmetry in \( B \to \psi K_S \) and related modes,

\[ S_{\psi K} = \sin 2\beta = +0.671 \pm 0.024, \]  

with only a 4\% experimental uncertainty\(^\text{1)}\). As shown in Fig. 1(a), the result of this and other measurements is that the \( CP \) violating parameter \( \bar{\eta} \) (or, equivalently, the Jarlskog invariant, \( J \)) has been determined with a 5\% uncertainty. This figure indicates that the existing measurements are consistent with the CKM picture of quark mixing, and, in particular, with the KM phase\(^3)\) being responsible for the observed \( CP \) violation.

The implications of the level of agreement between these various measurements is often overstated, however. Fig. 1(a) does not directly address how well the existing measurements constrain additional non-SM contributions to flavor changing processes. This cannot be easily discussed in a model independent fashion, since the most general low energy effective Hamiltonian contains about a hundred dimension-six operators, which parameterize the leading corrections to the SM. In a large class of

\(^1\) In the literature there are two common ways to refer to the angles of the unitarity triangle. We use the \( \alpha, \beta \) and \( \gamma \) notation. The other notation is, respectively, \( \phi_2, \phi_1, \) and \( \phi_3 \).
models, however, the new physics modifies the mixing amplitude of neutral mesons, while leaving tree level decays unaffected. This effect can be parameterized with just two real parameters for each mixing amplitude. For $B^0 - \bar{B}^0$ mixing, we write
\[ M_{12} = M_{12}^{SM} (1 + h_d e^{2i\sigma_d}). \] (2.6)

Fig. 1(b) shows the constraints on $h_d$ and $\sigma_d$, indicating that order 10$−20\%$ corrections to $|M_{12}|$ are still allowed, for (almost) any value of the phase of the new physics contribution. If this phase is aligned with the SM, $2\sigma_d = 0 \mod \pi$, then the new physics contribution to $|M_{12}|$ may still be comparable to the SM one. Similar conclusions apply to new physics contributions to many other FCNC transition amplitudes, though those analyses tend to be more complicated and (strong interaction) model dependent.

The fact that such large deviations from the SM are not yet excluded gives a very strong motivation to continue low energy flavor measurements in order to observe deviations from the SM predictions or establish a stronger hierarchy between the SM and new physics contributions.

§3. Typical effects of TeV-scale new physics

There are at least two good reasons to think that there is new physics at (or below) the TeV scale. First, the fine-tuning problem of the Higgs mass implies that either there are some symmetry partners of (at least) the particles that couple to the Higgs with order one couplings (the top quark, the $W$- and $Z$-bosons, and the Higgs itself), or gravity changes its nature at this scale. Second, if the dark matter particles are weakly interacting massive particles (WIMPs), then their annihilation cross section is of order $1/\text{TeV}^2$. The first argument for TeV-scale physics further implies that the new physics has nontrivial flavor structure, because some of its effects must be related to the top Yukawa coupling. In this section we describe the flavor effects expected from TeV-scale new physics.

The effects of new physics can be parameterized by nonrenormalizable operators, made of the standard model fields, obeying the standard model gauge symmetries, and suppressed by inverse powers of the scale of the new physics. In particular, there is a large number of dimension-six four-fermion operators that contribute to FCNCs. Let us take as an example the following four-quark $\Delta B = 2$ operator:
\[ \frac{z_{1}^{bd}}{A_{NP}^2} (\overline{d} \gamma_{\mu} b) (\gamma_{\mu} c L)^2, \] (3.1)
where $z_{1}^{bd}$ is a dimensionless coefficient and $A_{NP}$ is the scale of new physics. This operator contributes to $B^0 - \bar{B}^0$ mixing. Its absolute value is then constrained by $\Delta m_B$ and its imaginary part (in the basis where the leading decay amplitudes are real) by $S_{\psi KS}$. For a detailed analysis, the reader is referred to Ref.7

Let us now focus on
\[ A_{NP} \lesssim 1 \text{ TeV}. \] (3.2)
If the contribution of the new physics comes at tree level, with complex couplings of order one, then the contribution of (3.1) will be 5–6 orders of magnitude above
the experimental bounds. If the contribution comes at the loop level, say $O(\alpha_s^2)$ as in the standard model, but there are no additional suppression factors, then the contribution is still 2–3 orders of magnitude above the experimental bounds. The contribution from operators with a different Lorentz structure, in particular

$$\frac{z_{bd}^4}{A_{NP}} (\bar{d}_R b_L)(\bar{d}_L b_R),$$  

(3.3)

is even two orders of magnitude larger (for the same loop suppression factors). These facts lead to two important conclusions:

- New physics at the TeV scale can easily saturate the upper bounds on FCNC. Conversely, even a mild improvement in the experimental sensitivity may lead to signals of new physics in $B$ decays.
- New physics at the TeV scale must have a highly non-generic flavor structure. This special structure might involve alignment, particularly with the down sector, or some level of flavor degeneracy, or a combination of the two.

For $B$ decays, and with $O(10^{-3})$ flavor-blind suppression, the flavor factors must suppress, for example, $z_{bd}^1$ and $z_{bd}^4$ by order $10^{-3}$ and $10^{-5}$, respectively. Suppose that the suppression of $z_{bd}^1$ comes from both a loop factor of order $10^{-3}$ and flavor alignment similar in size to that of the standard model:

$$z_{bd}^1 \sim 10^{-3} (V_{tb} V_{td}^*)^2 \sim 10^{-7}. \quad \text{(3.4)}$$

This is a few percent effect in $B^0 - \bar{B}^0$ mixing, which is too small to be observed in $\Delta m_B$. If, however, the new phase carried by $z_{bd}^1$ is of order one, then the effect on $S_{\psi K_S}$ is also of order a few percent, which may be observed in the future. Note that, in general, we do not expect flavor degeneracy in $z_{bd}^1$ because the global $SU(3)_Q$ symmetry is strongly broken even within the standard model. The analogous naive estimate for $z_{bd}^4$, based on supersymmetric models of alignment, gives

$$z_{bd}^4 \sim 10^{-3} (m_d/m_b) \sim 10^{-6}, \quad \text{(3.5)}$$

which can saturate the bounds.

Finally, it is possible that $z_{bd}^1$ is not just of the order of $(V_{tb} V_{td}^*)^2$, but actually proportional to it. This happens in a class of models called minimal flavor violation (MFV). An example of such a model is low-energy gauge-mediated supersymmetry breaking. Then the phase of $z_{bd}^1$ is the same as the one carried by the standard model, and there will be no deviation from the standard model prediction for $S_{\psi K_S}$. Furthermore, in this class of models, flavor changing operators involving right-handed quarks, such as (3.3), are highly suppressed.

Similar considerations apply to other operators that contribute to $B^0 - \bar{B}^0$ mixing, as well as operators that contribute to FCNC decay amplitudes, for example $b \rightarrow s \ell^+ \ell^-$. With new physics at the TeV scale, the new contributions can be as large as the present upper bounds. With loop and flavor suppression factors, there could be effects of order a few percent, which can lead to observable $CP$ violating effects. Finally, if the new physics contributions are loop suppressed and carry the
CKM angles and phases, then the effects on the theoretically cleanest CP asymmetries vanish, while the contributions to CP conserving observables tend to be smaller than the theoretical uncertainties.

§4. Theoretical limitations

In order to have a convincing signal of new physics, we need its effect to be larger than both the experimental and the theoretical uncertainties. The most interesting observables are thus those with small theoretical uncertainties and good experimental precision. Since we search for deviations from the SM, the relevant theoretical uncertainties are those of the SM predictions.

There are in general two kinds of theoretical uncertainties, usually labeled perturbative and nonperturbative. Perturbative uncertainties come from the truncation of expansions in small (or not-so-small) coupling constants, such as $\alpha_s(m_b) \simeq 0.2$. There are always higher order terms that have not been computed. In principle, such errors can be reduced by performing the higher order calculations; however, the calculations become very demanding. So far, when the precision of a perturbative QCD calculation was the limiting uncertainty, the necessary calculations were possible to carry out. A prime example is the next-to-next-to-leading order calculation (four-loop running, three-loop matching and matrix elements) of $B \to X_s\gamma$.

The second kind of uncertainty is due to nonperturbative effects. They arise because QCD becomes strongly interacting at low energies, and one can no longer expand in the coupling constant. In general, there is no systematic method to deal with nonperturbative effects. There are cases, however, when we can get at the fundamental physics even in the presence of such effects. One way to proceed is to find observables where all (or most) of the hadronic parameters cancel or can be extracted from data. Many interesting processes involve hadronic parameters which can neither be measured nor calculated in perturbation theory. In some cases other tools can be used, such as lattice QCD or exploiting symmetries of the strong interaction which arise in certain limits, such as chiral symmetry or the heavy quark expansion. Then the limiting uncertainty is often due to the increasing number of hadronic matrix elements as one goes to higher order. These methods often use experimental data from related processes to constrain the uncertainties. Thus, experimental progress will not only reduce the measurement errors, but can also reduce the theoretical uncertainties. Here we do not discuss in detail the predictions for many modes, but focus on a few representative examples. Discussions about other modes can be found in many reviews.

Our first example is extracting $\gamma$ from $B \to D K$. This is arguably the cleanest measurement in terms of theoretical uncertainties. Basically, all the necessary hadronic quantities can be measured. The idea of all $B \to D K$ based analyses is to consider decays of the type

$$B \to D(\bar{D}) K(X) \to f_D K(X),$$

where $f_D$ is a final state that is accessible from both $D$ and $\bar{D}$ and $X$ represents possible extra particles in the final state. The crucial point is that, in the inter-
mediate state, the \( D \) or \( \bar{D} \) are not measured (and in particular their flavor is not tagged), and are thus in a coherent state. On the other hand, the \( D \) is on-shell, and therefore the \( B \to D \) and the \( D \to f_D \) amplitudes are factorized. Thus, we have quantum coherence and factorization at the same time. Using several \( B \to DKX \) decays modes (say, \( n \) different \( X \) states), and several \( D \to f_D \) modes (say \( k \)), one can perform \( nk \) measurements, which depend on \( n + k \) hadronic decay amplitudes. For large enough \( n \) and \( k \), there is a sufficient number of measurements to determine all hadronic parameters, as well as the weak phase we are after. Since all hadronic matrix elements can be measured, the theoretical uncertainties are much below the sensitivity of any foreseeable future experiment.

Next in terms of theoretical cleanliness are cases where the leading hadronic matrix elements cancel. The uncertainties then depend on the ratio of leading and subleading amplitudes. The subleading terms can be suppressed by small CKM matrix elements and/or by loop factors and/or by symmetry breaking corrections (see examples below). The question is to estimate the relative size of the subleading matrix elements.

Consider the time dependent \( CP \) asymmetries in neutral \( B \) decay into three different \( CP \) eigenstates: \( \psi K_S \), \( \phi K_S \), and \( \pi^0 K_S \). Using CKM unitarity, Eq. (2.3), we can write the relevant decay amplitudes in the form\(^\text{19}\)

\[
A = V_{us} V_{ub}^* A_u e^{i\delta} + V_{cs} V_{cb}^* A_c,
\]

such that \( A_i \), which are real and positive, and \( \delta \), the \( CP \) conserving phase, are mode dependent. The hierarchy of the CKM elements

\[
\frac{|V_{us} V_{ub}^*|}{|V_{cs} V_{cb}^*|} \sim \lambda^2,
\]

suggests that in all three decays we are considering the term proportional to \( A_u \) is subleading. Indeed, to first approximation, this is the case, and all three decays determine \( \beta \). This approximation would fail, however, if \( A_u \gg A_c \) due to hadronic physics. Even if \( A_u \lesssim A_c \), we would like to estimate the corresponding uncertainty, so we need to estimate the ratio

\[
r \equiv A_u/A_c.
\]

Here is where hadronic physics enters the analysis, and the three cases differ.

For \( B \to \psi K_S \), the final state contains \( cc\bar{s}\bar{d} \) quarks, and therefore the quark level decay is dominantly \( b \to c\bar{c}s \). Thus, \( A_c \) is a tree level decay amplitude, while \( A_u \) is a loop (or rescattering) effect. Consequently, \( r \ll 1 \) and the theoretical error in \( S_{\psi K_S} \) is tiny.\(^\text{20-23}\) Another comparable effect proportional to \( \epsilon_K \) is due to the fact that \( K_S \) is not a pure \( CP \) eigenstate.\(^\text{21}\)

For \( B \to \phi K_S \), the final state contains \( ss\bar{s}\bar{d} \) quarks, and therefore the decay is dominantly mediated by \( b \to s\bar{s}s \). The dominant contributions to both \( A_c \) and \( A_u \) come from loop diagrams, so we expect \( r \sim 1 \). The theoretical uncertainty in interpreting \( S_{\phi K} \) is then suppressed by \( \lambda^2 \), and is of order a few percent.\(^\text{24-26}\)

For \( B \to \pi^0 K_S \), the final state has \( u\bar{u}s\bar{d} \) quarks and therefore the quark level decay is \( b \to u\bar{u}s \). Thus, \( A_u \) is generated at tree level while \( A_c \) is generated at one
loop and we expect $r \gg 1$. Therefore, the correction to $S^0_{\pi^0 K_S}$ due to the subleading amplitude cannot be neglected a-priori. However, it is possible to analyze a set of $B \to K\pi$ measurements using isospin symmetry relations among them to reduce the theoretical error on the $CP$ asymmetries.\(^{27}\) The remaining theoretical uncertainty is at the level of a few percent, due to isospin breaking. Calculations based on the heavy quark limit also predict small uncertainty in $S^0_{\pi^0 K_S}$.\(^{26,28}\)

In some cases, approximate symmetries — isospin or $SU(3)$ — can be used to reduce the theoretical uncertainties, allowing clean extractions of fundamental parameters. The size of $SU(3)$ and $U$-spin breaking are comparable, so while we often use only $U$-spin, we generally refer to it as $SU(3)$. The theoretical errors associated with these symmetries are at the few percent level for isospin, and $O(20\%)$ for $SU(3)$. Thus, in an era of much higher precision, when the accuracy of some measurements will be comparable to isospin breaking, $SU(3)$ may become of limited use.

Isospin has been used in many cases, in particular in $B \to \pi\pi$,\(^{29}\) $B \to K\pi$, and decays with more pions in the final states. Isospin is very important in measuring $\alpha$ in decays that proceed via the $b \to u\bar{u}d$ quark-level transition, like $B \to \pi\pi$. The theoretical uncertainties arise from electroweak penguin amplitudes and from isospin breaking in the matrix elements. The overall theoretical uncertainties are expected to be at the few percent level.\(^{30}-32\)

In $B \to K\pi$, isospin is also crucial in reducing the theoretical errors. There are many relations between the decay rates and $CP$ asymmetries of the various $B \to K\pi$ modes.\(^{33}-35\) Here, due to CKM enhancement, the effect of the electroweak penguin amplitude is larger than that in $B \to \pi\pi$. Yet, its calculation is considered reliable and thus precise relations are obtained that can be used to test the SM.\(^{36,37}\) The residual errors are due to isospin breaking and uncertainties about the magnitude of the electroweak penguin amplitude. In most cases, we expect the isospin breaking to enter at first order, and thus to have theoretical uncertainties at the few percent level. There is, however, one case, the so-called Lipkin sum rule,\(^{34,35}\) where isospin breaking affects the result only at second order.\(^{38}\) Thus, this sum rule has theoretical uncertainties at the percent level.

Other important theoretical tools come from expanding about the heavy quark limit, $m_b(c) \gg \Lambda_{\text{QCD}}$. There are several formalisms to do this. For spectroscopy and exclusive semileptonic decays, extra symmetries of the Lagrangian emerge in the $m \gg \Lambda_{\text{QCD}}$ limit. These heavy quark spin-flavor symmetries (HQS)\(^{39}\) imply, for example, that exclusive semileptonic $B \to D^{(*)}\ell\bar{\nu}$ decays are described by a universal Isgur-Wise function in the symmetry limit, providing some model-independent predictions. For inclusive semileptonic $B$ decays an operator product expansion (OPE) can be used to compute sufficiently inclusive rates.\(^{40}-42\) The leading order result is given by free quark decay, the $\Lambda_{\text{QCD}}/m_b$ terms vanish, and the $\Lambda_{\text{QCD}}^2/m_b^2$ corrections are parameterized by just two hadronic matrix elements, which can be determined from data. Thus, the theoretical uncertainties for inclusive semileptonic rates are at the few percent level. A prime application is the extraction of $|V_{ub}|$; the theoretical uncertainties are at the few percent level both in the inclusive and exclusive analysis. When severe phase space cuts are imposed experimentally, such as for many determinations of $|V_{ub}|$ from inclusive decays, the expansion is less powerful, since the usual
OPE in terms of local matrix elements is replaced by a “nonlocal OPE” in which the hadronic matrix elements are functions rather than numbers, and $\Lambda_{\text{QCD}}/m_b$ corrections do occur. The heavy quark expansion in fully hadronic decays becomes yet more complicated, and motivated many developments in soft-collinear effective theory (SCET). In most such applications, we do not have a complete categorization of even the leading power corrections. Furthermore, the corresponding matrix elements have substantial uncertainties. Thus, the theoretical uncertainties are at least at the 10% level, and often larger. One of the possible exceptions is the difference of $CP$ asymmetries, $A_{K^+\pi^0} - A_{K^+\pi^-} = 0.15 \pm 0.03$, which appears hard to reconcile with the heavy quark expansion and any set of assumptions about the $\Lambda_{\text{QCD}}/m_b$ corrections popular in the literature.

A theoretical tool where significant improvements are expected in the next few years is lattice QCD. In principle, lattice QCD enables us to calculate many non-perturbative matrix elements. In practice, however, several approximations have to be used to keep the computational time under control, e.g., because the $b$ quark is too heavy to be simulated directly. Yet, we can hope to see improvements in the next few years as new algorithms and more powerful computers are used. One may hope that matrix elements which contain at most one (stable) hadron in the final state may be calculated with percent level uncertainties. Matrix elements involving states with sizable widths, e.g., $\rho$ and $K^*$, are more challenging. Matrix elements containing more than one hadron in the final state are much more complicated, and it would require major developments to be able to do calculations with small and reliable uncertainties. Thus, the theoretical errors are expected to shrink especially for measurements that relate to meson mixing, leptonic and semileptonic decays.

While our main focus is $B$ physics, there are interesting and theoretically clean observables in $K$ and $D$ decays. In particular, the decay rates of $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ are very clean, with theoretical errors at the few percent level. In the neutral $D$ system, the calculations of the mass and width differences suffer from large hadronic uncertainties. Yet, the general prediction of the SM is that all $CP$ asymmetries in tree level decays are below the $10^{-2}$ level. The reason is that charm decay and mixing involve to a good approximation only the two lighter generations, and are thus insensitive to the SM $CP$ violation. Consequently, if $CP$ violation is observed in charm mixing or decay, it will be a good probe of new flavor physics.

Finally, we mention lepton flavor violating decays, such as $\tau \to \mu\mu\mu$. Such decays can be studied in future $B$ factories, and are very clean theoretically. The SM prediction is zero for all such decays. Adding neutrino masses to the SM via the see-saw mechanism yields lepton flavor changing operators suppressed by the see-saw scale. The resulting lepton flavor violating branching ratios are tiny, many orders of magnitude below the experimental sensitivities. Thus, these decays are very clean probes of TeV-scale physics.

Our conclusion is that there are many observables with theoretical uncertainties at the few percent level, and some with even smaller errors. This is an important conclusion, since many of these observables are expected to be measured with a percent-level accuracy, which will allow us to discover small contributions from new
physics. As argued above, this is also the level of deviations expected from many interesting new physics models.

§5. Expected sensitivity to deviations from the SM

Most of the currently available $B$ decay data is from the two $B$ factories, BaBar and Belle, and from the Tevatron experiments, CDF and DØ. Not much more data is expected from the $B$ factories: BaBar finished its data taking and Belle will stop running in its current configuration soon. While CDF and DØ are still running, the expected increase in integrated luminosity is at most a factor of few. Much more data is expected to be accumulated by future experiments. First, LHCb will start to operate soon. They expect $10 \text{ fb}^{-1}$ of data collected by 2015 or so. Beyond that, an LHCb upgrade is planned with 10 times larger luminosity. This hadron collider data is complementary to the $e^+e^-$ data. The statistics is much higher and the sensitivity to the various decay modes is different. There are also proposals for higher luminosity $e^+e^-$ machines. One proposal is to upgrade KEK-B to reach a luminosity near $10^{36}/\text{cm}^2/\text{s}$. The other proposal is to build a new machine in Italy with a luminosity of $10^{36}/\text{cm}^2/\text{s}$ or possibly even higher.

Any attempt to assess the sensitivity of future measurements, with a factor of 100 larger statistics than currently available, is unavoidably subject to significant uncertainties. For example, for the expected super-$B$-factory sensitivities, various studies\(^{57}-^{59}\) assume quite different beam conditions and detectors. In Table II we list the current status\(^60\) and expected sensitivities in some of the channels we view as important. The LHCb expectations are taken from Refs.\(^{61}-^{63}\). We emphasize that this table is not comprehensive and the entries in the last two columns necessarily have significant uncertainties.

The simplest extrapolations can be done for those measurements in which the experimental uncertainty is expected to be dominated by statistical errors for any foreseen data sets, and the theoretical uncertainties are negligible. An example of this is the determination of the CKM angle $\gamma$. In other cases, theoretical uncertainties may still be very small, but the experimental systematic errors become important. An example of this is $A_{d,s}^{d,s}$. In less favorable modes, systematic errors may become dominant on both the experimental and the theoretical sides. Interestingly, the gold-plated measurement of BaBar and Belle, $S_{\psi K}$, is in this category. None of the reports\(^{57}-^{59}\) expect the uncertainty to decrease by a factor of 10 with 100 times more data. As discussed above, at the 0.005 error level, the relation between $S_{\psi K}$ and $\sin 2\beta$ is sensitive to hadronic physics. Similar is the determination of $\alpha$, where some of the uncertainties not yet addressed in the current analysis (e.g., isospin violation) may become relevant when the experimental precision improves. To what extent they can be controlled using the data\(^{31}\) is hard to foresee.

The magnitudes of CKM elements are important for constraining new physics by comparing the information from tree-dominated and loop-mediated processes. Some $|V_{cb}|$ and $|V_{ub}|$ analyses are already theory limited, while some of the theoretically cleaner (and experimentally less efficient) methods will benefit from more data. In particular, the experimental implementation of many of the theoretically cleaner
analyses is based on the full-reconstruction tag method, in which the “other” $B$ meson is fully reconstructed. This way, the four-momenta of both the leptonic and the hadronic systems can be measured. It also gives access to a wider kinematic region due to improved signal purity, and is only possible in the $e^{+}e^{-}$ environment. The possibility to precisely determine $|V_{cb}|$ and $|V_{ub}|$ from exclusive decays is almost entirely in the hands of lattice QCD. While a lot of progress is expected, we will need experience to assess under what circumstances one can prove the presence of new physics if there is significant tension between data and lattice QCD predictions (e.g., how the $f_{D_s}$-problem is going to be resolved). At present, there is also some tension between the inclusive and exclusive measurements of both $|V_{cb}|$ and $|V_{ub}|$, which prompted the PDG in 2008 for the first time to inflate the errors.

Many rare FCNC decays are sensitive probes of various extensions of the SM. In most cases the theory is under better control for inclusive decays, which are very hard (if not impossible) to measure at hadron colliders. Final states with neutrinos or $\tau$
leptons producing final states with large missing energy\textsuperscript{65)–67)} are only possible at $e^+e^-$ colliders. At the same time, the constraints on the very important $B_s \rightarrow \mu^+\mu^-$ and $B \rightarrow \mu^+\mu^-$ modes are, and will be, dominated by hadron collider data.

The two exclusive decay modes at the bottom of the table are listed for the following reasons. The $K\nu\bar{\nu}$ mode\textsuperscript{68)} may be the only final state in $B \rightarrow X_s\nu\bar{\nu}$ decays that can be measured with good precision. For the $K^*\ell^+\ell^-$ mode, there are many interesting differential observables, such as the zero of the forward-backward asymmetry, which LHCb expect to measure with a 0.3 GeV$^2$ uncertainty with 10 fb$^{-1}$ data, giving a determination of $C_7^{\text{eff}}/C_9^{\text{eff}}$ with 7% statistical error.

The role of LHCb is even more important than Table\textsuperscript{I} might indicate. First, at this time, it is the only future dedicated $B$ physics experiment which will definitely take data. Its expected measurement of $B_s \rightarrow \mu^+\mu^-$ is particularly sensitive to some extensions of the SM not well constrained so far. Furthermore, if we parameterize new physics in $B^0_s-\overline{B}^0_s$ mixing with $h_s$ and $\sigma_s$, similar to Eq. (2.6), then the measurement of $\beta_s$ will give constraints similarly strong as those on $h_d, \sigma_d$\textsuperscript{69)}.

While we concentrate on the future of $B$ physics, a super-$B$-factory will also be sensitive to other kinds of physics. It will probe lepton flavor violating decays at a much improved level. For example, sensitivity down to $B(\tau \rightarrow \mu\gamma) \sim 2 \times 10^{-9}$ may be achieved. The corresponding bound on the ratio $B(\mu \rightarrow e\gamma)/B(\tau \rightarrow \mu\gamma)$ will be useful to constrain various new physics models. Similarly, decays of the type $\tau^- \rightarrow \ell^-_1\ell^-_2\ell^+_3$ will also be constrained at a level around $B(\tau \rightarrow \mu\mu\mu) \sim 2 \times 10^{-10}$. Again, the ratio $B(\tau \rightarrow \mu\mu\mu)/B(\tau \rightarrow \mu\gamma)$ is an interesting probe of new physics; for example, if new physics generates the operators $\bar{\tau}_R\sigma_{\alpha\beta}F^{\alpha\beta}\mu_L$ and $(\bar{\tau}_L\gamma^\alpha\mu_L)(\bar{\mu}_L\gamma^\alpha\mu_L)$ with coefficients of very different magnitudes, then either decay mode can be more sensitive to a particular model. A super-$B$-factory will also be able to do precision QCD studies and look for yet unobserved resonances. It may even be able to find direct signals of new physics, such as a very light Higgs boson or light particles\textsuperscript{70)} predicted in some models of dark matter\textsuperscript{71)–74)}.

§6. Synergy and complementarity with LHC new particle searches

The LHC will soon start its operation. As can be learned from Table\textsuperscript{II}, the LHCb experiment will contribute to our understanding of flavor via measurements of $B$ and $B_s$ decays. ATLAS and CMS will also probe FCNC top quark decays at orders of magnitude better level than the current bounds\textsuperscript{75), 76)} There is, however, another aspect where the LHC is expected to be relevant to flavor physics, and that is the interplay between the high-$p_T$ physics of the ATLAS and CMS detectors and the low energy measurements of the flavor factories.

Let us first comment on a rather pessimistic scenario, where no new physics is observed at ATLAS/CMS. In that case, we will lose the two main clues that we have had to new physics at the TeV scale. First, we have probably misinterpreted the fine-tuning problem of the Higgs mass. Second, the dark matter particles are perhaps not WIMPs. It will be difficult then to argue that a collider with a center of mass energy of, say, 50 or 100 TeV, is likely to discover new physics. It is this point where flavor physics might play an important role. If deviations from the standard
model predictions for FCNC processes are established in the flavor factories, they can be used to put an upper bound on the scale of new physics. This might be then the only argument for a relatively low energy new physics. Depending on the pattern of deviations, one might get further clues about the nature of this new physics, and perhaps propose an experimental program that can directly produce and study the new physics.

A much more exciting scenario is one where new physics is observed at ATLAS and CMS. In this case, the interplay between collider physics and flavor physics is expected to be very fruitful:

- It is very likely that we will understand how the new physics flavor puzzle is solved, namely what are the special flavor features of the new physics that are at work in suppressing its contribution to FCNC processes.
- Under some favorable circumstances, we may also get clues about the solution to the standard model flavor puzzle, namely why there is hierarchy and smallness in the Yukawa couplings.
- Understanding the flavor structure of the new physics might teach us about its inner structure and perhaps about physics at a scale much higher than the LHC scale.

In the rest of this section, we explain these three points in more detail.

If new particles are discovered at the LHC, and if they couple to the standard model quarks and/or leptons, then there are new flavor parameters that can, at least in principle, be measured. These include the spectrum of the new particles, and their flavor decomposition, \( i.e. \), their decay branching ratios. Realistically one can expect that ATLAS/CMS will be able to measure the leptonic flavor decomposition and, for the quark sector, separate third generation final states (bottom and top) from first two generation final states. Even this limited information might complement in a significant way the information on flavor from FCNC measurements.

As an example of how this information will allow us to make progress in solving the new physics flavor puzzle, consider the principle of minimal flavor violation (MFV).\(^77\)–\(^80\) Within the standard model, there is a large global symmetry, \([U(3)]^5\), which is broken only by the Yukawa matrices. Models of new physics where this is still true, namely where there are no new sources of flavor violation beyond the standard model Yukawa matrices, are said to obey the principle of MFV. A well known example of an MFV model is that of gauge mediated supersymmetry breaking. The scale of MFV models can be as low as order TeV without violating the bounds from FCNC, thus solving the new physics flavor puzzle.

Within models of MFV, the only quark flavor changing parameters are the CKM elements. Since the CKM elements that couple the third generation to the lighter ones are very small, new particles in MFV models that decay to a single final quark decay to either a third generation quark or to a first two generation quark, but (to \(\mathcal{O}(10^{-3})\) approximation) not to both.\(^81\) As a concrete example, consider extra heavy quarks in vector-like representations of the standard model gauge group. If ATLAS/CMS discover such a heavy quark and can establish that it decays to both third generation and light quarks, it will prove that MFV does not hold and is not the solution to the new physics flavor puzzle.\(^81\)
Within supersymmetry, the predictive power of MFV is even stronger. It implies that the first two squark generations are quasi-degenerate and decay only to light quarks, while the third generation squarks are separated in mass (except for $SU(2)$-singlet down squarks if $\tan \beta$ is small) and decay to only third generation quarks.\(^{82}\) If these features can be tested, it will provide us not only with deeper understanding of how the supersymmetric flavor puzzle is solved, but also open a window to the mechanism that mediates supersymmetry breaking, which is physics at a scale much higher than those accessible to the LHC.\(^{83}\)

The standard model flavor parameters – fermion masses and mixing angles – seem to have a structure. In particular, there is smallness and hierarchy in the Yukawa sector. An explanation to this structure might lie in some high scale physics, perhaps an approximate symmetry, such as the Froggatt-Nielsen mechanism,\(^{84}\) or a dynamical mechanism, such as the Nelson-Strassler mechanism.\(^{85}\) If new physics is discovered at the LHC, then we might ask whether its flavor structure is determined by the same mechanism as the Yukawa couplings. For example, the mixing among sleptons in a certain class of supersymmetric models can test the Froggatt-Nielsen mechanism.\(^{83}\)

The only information that we have at present on flavor aspects of possible new physics models is coming from low energy measurements. Such measurements put constraints on the product of the flavor alignment and flavor degeneracy factors (see, however,\(^{86}\)). For example, within supersymmetry, measurements of $b \to s$ transitions constrain the product of the mass splitting between the second and third generation down squarks, and their mixing. If in the future we discover the new physics, then we can in principle measure the flavor alignment and flavor degeneracy separately. If, in addition, future $B$ factories establish a deviation from the standard model for such a process, then the overall consistency of the direct measurements and the low energy measurement will assure us that we fully understand the flavor structure of the new physics and how the new physics flavor puzzle is solved. The present situation and an (optimistic) future scenario are schematically depicted in Fig. 2.

### §7. Conclusions

We are now in a transition period in flavor physics. In the past, flavor physics led the way to the three generation SM, with the CKM picture of flavor and $CP$ violation. The 2008 Nobel Prize in Physics, awarded to Kobayashi and Maskawa, is a formal recognition that this task is, to large extent, completed. We know that the CKM matrix is the dominant source of flavor and $CP$ violation.

Here we discussed the future of flavor physics, in particular, that of $B$ physics. The question at hand is not less important: Given that the SM is only a low energy effective theory that is very likely to be supplemented by new physics at a scale close to TeV, how can flavor physics help in understanding the ultraviolet completion of the SM? The fine tuning problem of the Higgs mass and the dark matter puzzle lead us to think that there is new physics at the TeV scale. Flavor bounds tell us, in turn, that such new physics must have a special flavor structure.
To make sure that the future of flavor physics may be as successful as its past, we need much more data. Present constraints imply that the new physics, while perhaps not minimally flavor violating, is likely to have flavor suppression factors that are similar to, or stronger than, the SM ones. Since the new physics contributions are further suppressed by a scale somewhat above the electroweak scale, we expect to see small deviations from the SM prediction. A more quantitative statement would be both model dependent and mode dependent, but the main idea is clear: “small deviations” mean that more data is required to discover them. Conversely, with more data, it is not unlikely that deviations will indeed be discovered.

Three facts combine to make the future look promising:

• The technology to collect much more flavor data exists. This includes the LHC experiments that will operate in a hadron environment, and the proposed super-B-factories that will be high luminosity $e^+e^-$ machines.
• Many measurements are not theory limited. That is, the new data can be compared to solid theoretical predictions.
• In many modes we expect deviations to be found at the level of the experimental sensitivity and above the SM theoretical errors.

We may thus be optimistic about obtaining convincing pieces of evidence for new physics in the flavor sector. Together with the anticipated direct discovery of new particles at the LHC, we will be able to learn a great deal about the way that Nature...
works at a very fundamental level.

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