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2013 Phys. Scr. 2013 014005

(http://iopscience.iop.org/1402-4896/2013/T158/014005)

IOP PUBLISHING PHYSICA SCRIPTA
Phys. Scr. **T158** (2013) 014005 (8pp) doi:10.1088/0031-8949/2013/T158/014005

Flavor physics: past, present, future

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Received 20 September 2013
Accepted for publication 4 October 2013
Published 6 December 2013
Online at stacks.iop.org/PhysScr/T158/014005

Abstract
In recent years, huge progress in flavor physics and in the physics of CP violation has been achieved by the BaBar, Belle, CDF, D0 and LHCb experiments. This led to a significant theoretical progress. In particular, the Kobayashi–Maskawa mechanism has been proven to be the dominant source of the observed CP violation, and the Cabibbo–Kobayashi–Maskawa mechanism has been proven to be a major player in the observed flavor changing neutral current (FCNC) processes. Two major questions in flavor physics remain however open. Firstly, the Standard Model flavor puzzle is the question of what is the source of the structure—smallness and hierarchy—in the charged fermion flavor parameters. The measurement of neutrino related flavor parameters only added to the complexity of this puzzle. Secondly, the New Physics flavor puzzle is the following question: if there is new physics at the TeV scale, why and how are its contributions to FCNC so strongly suppressed? The high p_T experiments at the LHC, ATLAS and CMS, are likely to solve the latter puzzle, and may even provide hints to the solution of the former.

PACS numbers: 11.30.Er, 11.30.Hv, 12.15.Ff, 14.60.Pq

(Some figures may appear in colour only in the online journal)

1. Past: what have we learned?

CP violation was experimentally established in 1964 [1]. Until the year 2000, only two CP violating parameters have been measured, ϵ which characterizes indirect CP violation in $K \to \pi\pi$, $K \to \pi\ell\nu$ and $K_L \to \pi^+\pi^-e^+e^-$ decays, and ϵ' which characterizes direct CP violation in $K \to \pi\pi$ decays:

$$|\epsilon| = (2.23 \pm 0.01) \times 10^{-3}, \tag{1}$$

$$\mathcal{R}e(\epsilon'/\epsilon) = (1.65 \pm 0.26) \times 10^{-3}. \tag{2}$$

In the present millennium, however, many more CP asymmetries have been observed. The list of observables where CP violation has been observed at a level above 5σ includes the following:

$$S_{\psi K^0} = +0.68 \pm 0.02, \tag{3}$$

$$S_{\eta' K^0} = +0.59 \pm 0.07,\quad S_{\phi K^0} = +0.74^{+0.11}_{-0.13},\quad S_{f_0 K^0} = +0.69^{+0.10}_{-0.12}, \tag{4}$$

$$S_{K^+K^-K_S} = +0.68^{+0.09}_{-0.10}, \tag{5}$$

$$S_{\pi^+\pi^-} = -0.65 \pm 0.07, \tag{6}$$

$$C_{\pi^+\pi^-} = -0.36 \pm 0.06, \tag{7}$$

$$S_{\psi\pi^0} = -0.93 \pm 0.15,\quad S_{D^+D^-} = -0.98 \pm 0.17,\quad S_{D^{*+}D^{*-}} = -0.77 \pm 0.10, \tag{8}$$

$$\mathcal{A}_{\overline{B}^0 \to K^-\pi^+} = -0.087 \pm 0.008, \tag{9}$$

$$\mathcal{A}_{D_+K^\pm} = +0.19 \pm 0.03, \tag{10}$$

$$\mathcal{A}_{B_s^0 \to K^-\pi^+} = +0.27 \pm 0.04. \tag{11}$$

This list exhibits not only a large number of asymmetries, but also a large variety in the types of CP violation observed. As concerns the decaying meson, CP asymmetries have been observed in neutral K, neutral B, charged B and B_s^0 meson decays. The only neutral meson in whose decays CP violation has not been observed (yet?) is the D meson, where, however, an intriguing hint exists,

$$\mathcal{A}_{D \to K^+K^-} - \mathcal{A}_{D \to \pi^+\pi^-} = -0.33 \pm 0.12. \tag{12}$$

Table 1. Measurements related to neutral meson mixing.

Sector	CP-conserving	CP-violating
sd	$\Delta m_K/m_K = 7.0 \times 10^{-15}$	$\lvert\epsilon_K\rvert = 2.3 \times 10^{-3}$
cu	$\Delta m_{\rm d}/m_{\rm d} = 8.7 \times 10^{-15}$	$A_\Gamma/y_{\rm CP} \lesssim 0.2$
bd	$\Delta m_B/m_B = 6.3 \times 10^{-14}$	$S_{\psi K} = +0.67 \pm 0.02$
bs	$\Delta m_{B_s}/m_{B_s} = 2.1 \times 10^{-12}$	$S_{\psi\phi} = -0.04 \pm 0.09$

As concerns the quark level transitions, the above asymmetries are related to $s \to u\bar{u}d$ (1,2), $s \to u\ell\nu$ (1), $b \to c\bar{c}s$ (3), $b \to s\bar{s}s$ (4,5), $b \to u\bar{u}d$ (6,7,11), $b \to c\bar{c}d$ (8), $b \to u\bar{u}s$ (9) and $b \to c\bar{u}s$ and $b \to \bar{c}us$ (10). As concerns the type of CP violation, the asymmetries (3)–(6) and (8) come from CP violation in the interference of mixing and decay, while the asymmetries (7–11) comes from CP violation in decay. CP violation in mixing has been observed only in K decays and is represented by $\mathcal{R}e(\epsilon)$.

Of course, there are many additional CP asymmetries that have been measured above 3σ (but below 5σ), and a long list of searches that provide upper bounds. Such richness of experimental data must lead to progress in theoretical understanding, and indeed it did.

In parallel to the progress in measurements of CP asymmetries, there has been impressive progress in measurements of FCNC processes. For example, the experimental results for CP conserving and CP violating observables related to neutral meson mixing (mass splittings and CP asymmetries in tree level decays, respectively) are given in table 1. Among the recent highlights, we can point out the first evidence for the $B_s^0 \to \mu^+\mu^-$ decay [2] (with branching ratio of order 3×10^{-9}), and the detailed measurement of form factors and angular distribution in the $B \to K^*\mu^+\mu^-$ decay [3].

1.1. Self-consistency of the Cabibbo–Kobayashi–Maskawa (CKM) assumption

The three generation standard model (SM) has room for CP violation, through the Kobayashi–Maskawa (KM) phase η [4] in the quark mixing matrix [5]. (We use here the Wolfenstein parameterization of the CKM matrix.) Yet, one would like to make sure that indeed CP is violated by the SM interactions, namely that $\eta \neq 0$. Once we establish that this is the case, we would further like to know whether the SM contributions to CP violating observables are dominant. Concretely, we would like to put an upper bound on the ratio between the new physics and the SM contributions.

As a first step, one can assume that flavor changing processes are fully described by the SM, and check the consistency of the various measurements with this assumption. Within the SM, quark mixing is described by four parameters, λ, A, ρ and η. The values of λ and A are known rather accurately from, respectively, $K \to \pi\ell\nu$ and $b \to c\ell\nu$ decays:

$$\lambda = 0.2254 \pm 0.0007, \quad A = 0.811^{+0.022}_{-0.012}. \qquad (13)$$

Then, one can express all the relevant observables as a function of the two remaining parameters, ρ and η, and check whether there is a range in the ρ–η plane that is consistent with all measurements. The list of observables includes the following:

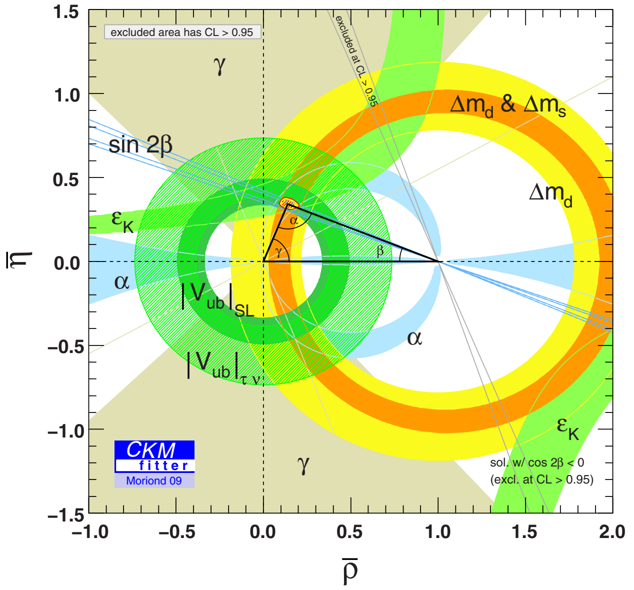

Figure 1. Allowed region in the ρ, η plane. Superimposed are the individual constraints from charmless semileptonic B decays ($|V_{ub}/V_{cb}|$), mass differences in the B^0 ($\Delta m_{\rm d}$) and B_s (Δm_s) neutral meson systems, and CP violation in $K \to \pi\pi$ (ε_K), $B \to \psi K$ ($\sin 2\beta$), $B \to \pi\pi, \rho\pi, \rho\rho$ (α) and $B \to DK$ (γ). Reproduced with permission from [6].

- Charmless semileptonic B decays depend on $|V_{ub}|^2 \propto \rho^2 + \eta^2$;
- The CP asymmetry in $B \to \psi K_s$ depends on $S_{\psi K_s} = \sin 2\beta = \frac{2\eta(1-\rho)}{(1-\rho)^2+\eta^2}$;
- The rates of various $B \to DK$ decays depend on the phase γ, where $e^{i\gamma} = \frac{\rho + i\eta}{\sqrt{\rho^2+\eta^2}}$;
- The rates of various $B \to \pi\pi, \rho\pi, \rho\rho$ decays depend on the phase $\alpha = \pi - \beta - \gamma$;
- The ratio $\Delta m_{B^0}/\Delta m_{B_s^0}$ depends on $|V_{td}/V_{ts}|^2 = \lambda^2[(1-\rho)^2 + \eta^2]$;
- ϵ_K depends in a complicated way on ρ and η.

The resulting constraints are shown in figure 1.

The consistency of the various constraints is impressive. In particular, the following ranges for ρ and η can account for all the measurements:

$$\rho = +0.131^{+0.026}_{-0.013}, \quad \eta = +0.345 \pm 0.014. \qquad (14)$$

One can make then the following statement [7]:

Very likely, CP violation in flavor changing processes is dominated by the KM phase

In the next two subsections, we explain how we can remove the phrase ‘very likely’ from this statement, and how we can quantify the KM-dominance.

1.2. Is the KM mechanism at work?

In proving that the KM mechanism is at work, we assume that charged-current tree-level processes are dominated by the W-mediated SM diagrams (see, for example, [8]). This is a very plausible assumption. I am not aware of any viable well-motivated model where this assumption is not valid. Thus, we can use all tree level processes and fit them to ρ and η, as we did before. The list of such processes includes the following:

(i) Charmless semileptonic B-decays.
(ii) $B \to DK$ decays.
(iii) $B \to \rho\rho$ decays (and, similarly, $B \to \pi\pi$ and $B \to \rho\pi$ decays) with an isospin analysis allow one to determine the relative phase between the tree decay amplitude and the mixing amplitude. By incorporating the measurement of $S_{\psi K_s}$, one can subtract the phase from the mixing amplitude, finally providing a measurement of the angle γ.

In addition, we can use loop processes, but then we must allow for new physics contributions, in addition to the (ρ, η)-dependent SM contributions. Of course, if each such measurement adds a separate mode-dependent parameter, then we do not gain anything by using this information. However, there is a number of observables where the only relevant loop process is $B^0 - \overline{B}^0$ mixing. To take into account new physics contributions to the mixing amplitude M_{12}, one needs to add two parameters, r_d^2 and $2\theta_d$, defined via

$$r_d^2 e^{2i\theta_d} = M_{12}/M_{12}^{SM}. \quad (15)$$

The list of relevant processes includes $S_{\psi K_s}$, Δm_B and the CP asymmetry in semileptonic B decays:

$$\begin{aligned} S_{\psi K_s} &= \sin(2\beta + 2\theta_d), \\ \Delta m_B &= r_d^2 (\Delta m_B)^{SM}, \\ \mathcal{A}_{SL} &= -\mathcal{R}e(\Gamma_{12}/M_{12})^{SM}(\sin 2\theta_d / r_d^2) \\ &\quad + \mathcal{I}m(\Gamma_{12}/M_{12})^{SM}(\cos 2\theta_d / r_d^2). \end{aligned} \quad (16)$$

Since there are two new parameters and three relevant observables, we can further tighten the constraints in the (ρ, η)-plane. Similarly, one can use measurements related to $B_s - \overline{B}_s$ mixing. One gains three new observables at the cost of two new parameters.

The results of such fit, projected on the ρ–η plane, can be seen in figure 2. It gives [6] $\eta = 0.44^{+0.05}_{-0.23}$ (at 3σ). It is clear that $\eta \neq 0$ is well established:

The KM mechanism of CP violation is at work.

The consistency of the experimental results with the SM predictions suggests that the KM mechanism dominates the observed CP violation. In the next subsection, we make this statement more quantitative.

1.3. How much can new physics contribute to $B^0 - \overline{B}^0$ mixing?

All that we need to do in order to establish whether the SM dominates the observed CP violation, and to put an upper bound on the new physics contribution to $B^0 - \overline{B}^0$ mixing, is to project the results of the fit performed in the previous subsection on the $r_d^2 - 2\theta_d$ plane. If we find that $\theta_d \ll \beta$, then the SM dominance in the observed CP violation will be established. The constraints are shown in figure 3(a). Indeed, $\theta_d \ll \beta$.

An alternative way to present the data is to use the h_d, σ_d parameterization,

$$r_d^2 e^{2i\theta_d} = 1 + h_d e^{2i\sigma_d}. \quad (17)$$

While the r_d, θ_d parameters give the relation between the full mixing amplitude and the SM one, and are convenient to apply

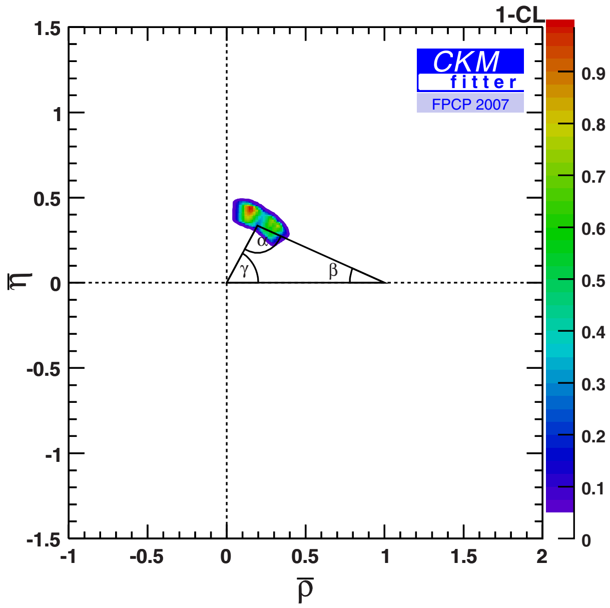

Figure 2. The allowed region in the ρ–η plane, assuming that tree diagrams are dominated by the SM [6].

to the measurements, the h_d, σ_d parameters give the relation between the new physics and SM contributions, and are more convenient in testing theoretical models:

$$h_d e^{2i\sigma_d} = M_{12}^{NP}/M_{12}^{SM}. \quad (18)$$

The constraints in the $h_d - \sigma_d$ plane are shown in figure 3(b). We can make the following two statements:

(i) A new physics contribution to $B^0 - \overline{B}^0$ mixing amplitude that carries a phase that is significantly different from the KM phase is constrained to lie below the 20–30% level.
(ii) A new physics contribution to the $B^0 - \overline{B}^0$ mixing amplitude which is aligned with the KM phase is constrained to be at most comparable to the CKM contribution.

One can summarize the situation concerning CP violation as follows:

- The KM phase is different from zero (the SM violates CP).
- The KM mechanism is the dominant source of CP violation observed in meson decays.
- Complete alternatives to the KM mechanism (such as superweak CP violation and approximate CP) are excluded.
- CP violation in D and B_s^0 decays may still hold surprises.

One can summarize the situation concerning flavor physics as follows:

- There is no evidence for corrections to the CKM mechanism.
- NP contributions to the observed FCNC are at most comparable to the CKM contributions. This statement holds for $s \to d$, $c \to u$, $b \to d$ and $b \to s$ transitions.
- FCNC top decays ($t \to c$, $t \to u$) may still hold surprises.

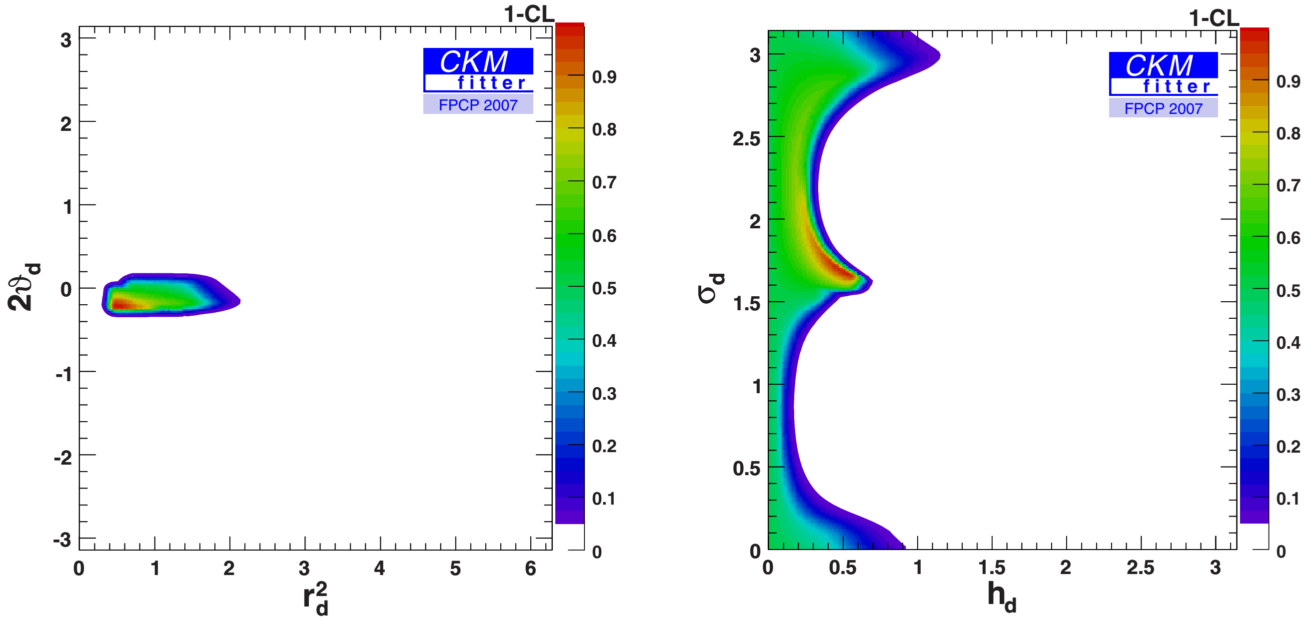

Figure 3. Constraints in the (a) $r_d^2 - 2\theta_d$ plane, and (b) $h_d - \sigma_d$ plane, assuming that NP contributions to tree level processes are negligible [6].

The fact that we can make these statements based on convincing experimental evidence is the outcome of a rich and impressive experimental program, combined with sophisticated theoretical tools (heavy quark effective theory (HQET), soft collinear effective theory (SCET), lattice calculations, etc).

2. Present: the flavor puzzles

There are two major puzzles related to flavor physics, which we will call 'the NP flavor puzzle' and 'the SM flavor puzzle'. The lessons that we have learned in recent years, described in the previous section, have sharpened, broadened and deepened the former. In contrast, there has been no real progress on the latter; neutrino-related data that have been accumulated in recent years only contributed to the confusion in this regard.

2.1. The New Physics flavor puzzle

The SM is only a low energy effective theory. It must be extended at some energy scale $\Lambda_{\rm NP}$ that is higher than the electroweak breaking scale:

- Gravity requires that $\Lambda_{\rm NP} \lesssim m_{\rm Planck} \sim 10^{19}$ GeV.
- $m_\nu \neq 0$ requires that $\Lambda_{\rm NP} \lesssim m_{\rm Seesaw} \lesssim 10^{15}$ GeV.
- The fine-tuning problem of the Higgs mass suggests a scale of $\Lambda_{\rm top-partners} \sim$ TeV.
- The WIMP solution of the dark matter problem suggests a scale of $\Lambda_{\rm wimp} \sim$ TeV.

Thus, when we consider physics at the electroweak scale, we *must* take into account effects of non-renormalizable terms, suppressed by powers of $\Lambda_{\rm NP}$. At dimension-five, we have a very welcome addition: the seesaw terms, $\mathcal{L}_{d=5} \sim \frac{z^\nu_{ij}}{\Lambda_{\rm Seesaw}} L_i L_j \phi\phi$ (where L is a lepton-doublet and ϕ is the Higgs-doublet), which generate neutrino masses and provide an explanation for their lightness. At dimension-six, there are dozens of new operators, and many of them are flavor changing. To explain the implications, we take as a concrete example four of these operators:

$$\mathcal{L}_{d=6} \supset \frac{z_{sd}}{\Lambda^2_{\rm NP}}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda^2_{\rm NP}}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda^2_{\rm NP}}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda^2_{\rm NP}}(\overline{s_L}\gamma_\mu b_L)^2. \quad (19)$$

These four operators contribute, proportionally to $|z_{ij}|$, to the respective mass-splittings presented in table 1 and, proportionally to the relative phase between z_{ij} and the CKM phase of the relevant decay amplitude (we will refer to this, somewhat inaccurately, as $\mathcal{I}m(z_{ij})$), to the respective CP violating observables presented in this table. For example, the contribution of the z_{bd}-term to the mass splitting between the two neutral B-meson mass eigenstates is given by $\Delta m_B/m_B \sim (|z_{bd}|/3)(f_B/\Lambda_{\rm NP})^2$.

As stated in the previous section, and explicitly presented for the neutral B-meson system, NP contributions to neutral meson mixing cannot exceed the SM contribution. Since the SM is consistent with the experimental results, we require that the NP contributions are smaller than the experimental values of table 1. This requirement leads to upper bounds on $|z_{ij}|/\Lambda^2_{\rm NP}$ and on $\mathcal{I}m(z_{ij})/\Lambda^2_{\rm NP}$. If we have an idea of what the dimensionless couplings z_{ij} are, then these constraints can be presented as lower bounds on $\Lambda_{\rm NP}$. Conversely, if we have an idea of what the scale $\Lambda_{\rm NP}$ is, then these constraints can be presented as upper bounds on z_{ij}. In table 2 we give the bounds on $\Lambda_{\rm NP}$ that correspond to $z_{ij} \sim \alpha_W^2$ and the bounds on z_{ij} that correspond to $\Lambda_{\rm NP} \sim$ TeV.

We use the term '*generic flavor structure*' to describe a situation where the dimensionless coefficients z_{ij} are neither hierarchical, nor particularly small, $z_{ij} \sim 1$ or $z_{ij} \sim$ a loop factor (such as α_W^2).

The bounds on $\Lambda_{\rm NP}$ show that if the new physics has a generic flavor structure, then its scale must be above about

Table 2. Lower bounds on the scale of new physics $\Lambda_{\rm NP}$, in units of TeV, from CP conserving observables (the $\Lambda_{\rm NP}^{\rm CPC}$ column), taking $|z_{ij}| = \alpha_W^2$, and from CP violating observables (the $\Lambda_{\rm NP}^{\rm CPV}$ column), taking $\mathcal{I}m(z_{ij}) = \alpha_W^2$, and upper bounds on the dimensionless coefficients z_{ij}, taking $\Lambda_{\rm NP} = 1$ TeV.

ij	$\Lambda_{\rm NP}^{\rm CPC} >$	$\Lambda_{\rm NP}^{\rm CPV} >$	$\|z_{ij}\| <$	$\mathcal{I}m(z_{ij}) <$
sd	30	600	8×10^{-7}	6×10^{-9}
cu	30	100	5×10^{-7}	1×10^{-7}
bd	10	30	5×10^{-6}	1×10^{-6}
bs	2	7	2×10^{-4}	2×10^{-5}

100 TeV. (The bounds from the corresponding four-quark terms with LR structure, instead of the LL structure of equation (19), are even stronger.) If indeed $\Lambda_{\rm NP} \gg$ TeV, it means that we have misinterpreted the hints from the fine-tuning problem and from the dark matter puzzle.

It could be, however, that the scale of new physics is of order TeV. The bounds on z_{ij} tell us that *the flavor structure of TeV-scale NP must be far from generic*. Concretely, if new particles at the TeV scale couple to the SM fermions, then there are two ways in which their contributions to FCNC processes, such as neutral meson mixing, can be suppressed: degeneracy and alignment. Either of these principles, or a combination of the two, signifies non-generic structure.

The New Physics (NP) flavor puzzle refers to a situation that there is new physics at the TeV scale. It is the question of what is the special flavor structure which suppresses its contributions to FCNC in a very strong way, and why does this structure arise.

2.2. The SM flavor puzzle

The SM has thirteen flavor parameters: nine Yukawa couplings of the charged fermions,

$$\begin{aligned} U:&\quad y_t\sim1,\quad y_c\sim10^{-2},\quad y_u\sim10^{-5},\\ D:&\quad y_b\sim10^{-2},\quad y_s\sim10^{-3},\quad y_d\sim10^{-4},\\ E:&\quad y_\tau\sim10^{-2},\quad y_\mu\sim10^{-3},\quad y_e\sim10^{-6},\end{aligned}\tag{20}$$

and four CKM parameters,

$$|V_{us}|\sim0.2,\quad |V_{cb}|\sim0.04,\quad |V_{ub}|\sim0.004,\quad \sin\gamma\sim1.\tag{21}$$

The flavor parameters span six orders of magnitude. Only two of them—y_t and $\sin\gamma$—are clearly of order one. The rest are small and hierarchical. (In contrast, in the four SM couplings that are not flavor parameters,

$$g_s\sim1,\quad g\sim0.6,\quad g'\sim0.3,\quad \lambda\sim0.3,\tag{22}$$

there is neither smallness nor hierarchy.) Thus, the SM parameters seem to exhibit a structure. *The SM flavor puzzle* is the the question of why there is smallness and hierarchy in the SM flavor parameters.

It may be that the set of numerical values in equations (20) and (21) are just accidental. More likely, there is a reason for the smallness and the hierarchy. Various theories have been suggested which can explain this structure in a natural way:

- An approximate Abelian symmetry ('The Froggatt–Nielsen (FN) mechanism' [9]);
- An approximate non-Abelian symmetry (see, e.g. [10]);
- Conformal dynamics ('The Nelson–Strassler mechanism' [11]);
- Location in an extra dimension [12].

2.2.1. The flavor of neutrinos. Five neutrino flavor parameters have been measured in recent years (see e.g. [13]): two mass-squared differences,

$$\begin{aligned}\Delta m_{21}^2 &= (7.5\pm0.2)\times10^{-5}{\rm eV}^2,\\ |\Delta m_{32}^2| &= (2.5\pm0.1)\times10^{-3}{\rm eV}^2,\end{aligned}\tag{23}$$

and the three mixing angles,

$$\begin{aligned}|U_{e2}| &= 0.55\pm0.01,\\ |U_{\mu3}| &= 0.64\pm0.02,\\ |U_{e3}| &= 0.15\pm0.01.\end{aligned}\tag{24}$$

These parameters constitute a significant addition to the thirteen SM flavor parameters and provide, in principle, tests of various ideas to explain the SM flavor puzzle.

The numerical values of the parameters show various surprising features:

- $|U_{\mu3}| >$ any$|V_{ij}|$;
- $|U_{e2}| >$ any$|V_{ij}|$;
- $|U_{e3}|$ is not particularly small ($|U_{e3}| \not\ll |U_{e2}U_{\mu3}|$);
- $m_2/m_3 > 1/6 >$ any m_i/m_j for charged fermions.

These features can be summarized by the statement that, in contrast to the charged fermions, neither smallness nor hierarchy have been observed so far in the neutrino related parameters.

One way of interpretation of the neutrino data comes under the name of neutrino mass anarchy [14]. It postulates that the neutrino mass matrix has no structure, namely all entries are of the same order of magnitude. Normalized to an effective neutrino mass scale, $v^2/\Lambda_{\rm seesaw}$, the various entries are random numbers of order one. Note that anarchy means neither hierarchy nor degeneracy in the neutrino mass spectrum. As concerns lepton mixing, anarchy predicts

$$|U|_{\rm anarchy} = \begin{pmatrix}\mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6)\\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6)\\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6)\end{pmatrix}.\tag{25}$$

If true, the contrast between neutrino mass anarchy and quark and charged lepton mass hierarchy may be a deep hint for a difference between the flavor physics of Majorana and Dirac fermions. The source of both anarchy and hierarchy might, however, be explained by a much more mundane mechanism. In particular, neutrino mass anarchy could be a result of a FN mechanism, where the three left-handed lepton doublets carry the same FN charge. In that case, the FN mechanism predicts parametric suppression of neither neutrino mass ratios nor leptonic mixing angles, which is quite consistent with (23) and (24).

The same data, and in particular the proximity of $|U_{e2}|$ to $1/\sqrt{3}\simeq0.58$ and the proximity of $|U_{\mu3}|$ to $1/\sqrt{2}\simeq0.71$ led to a very different interpretation. This interpretation, termed 'tribimaximal mixing' (TBM), postulates that the leptonic

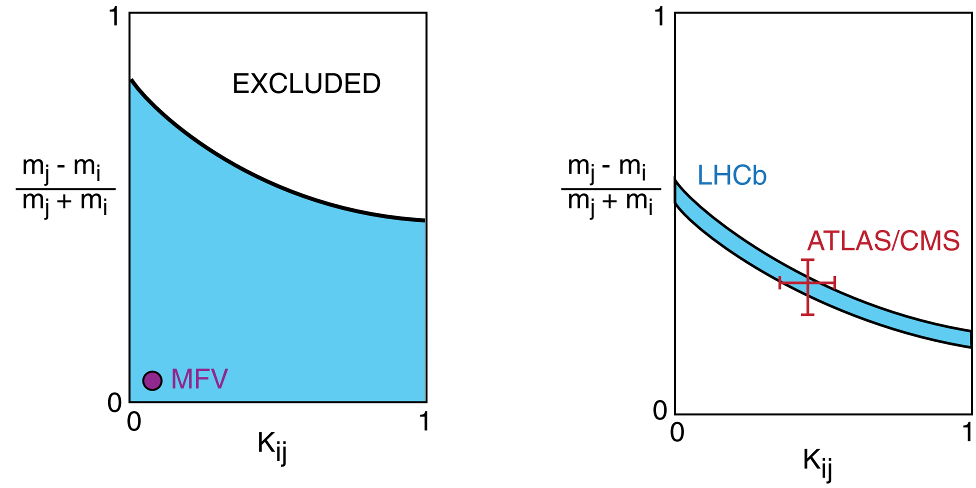

Figure 4. A schematic description of the constraints on the mass splitting $(m_i - m_j)/(m_i + m_j)$, and the mixing angle, K_{ij}, between squarks (or sleptons). Left: a typical present constraint arising from not observing deviations from the SM predictions. The fact that the region of splitting and mixing of order one is excluded constitutes the NP flavor puzzle. Right: A possible future scenario where the mass splitting and the flavor decomposition are measured by ATLAS/CMS and they fit deviations observed in a flavor factory. Reproduced with permission from [20].

mixing matrix is parametrically close to the following special form [15]:

$$|U|_{\text{TBM}} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}. \qquad (26)$$

Such a form is suggestive of discrete non-Abelian symmetries, and indeed numerous models based on an A_4 symmetry have been proposed [16, 17]. A significant feature of of TBM is that the third mixing angle should be close to $|U_{e3}| = 0$. Until recently, there have been only upper bounds on $|U_{e3}|$, consistent with the models in the literature. In the last year, however, a value of $|U_{e3}|$ close to the previous upper bound has been established [18], see equation (24). Such a large value (and the consequent significant deviation of $|U_{\mu 3}|$ from maximal bimixing) puts in serious doubt the TBM idea. Indeed, it is difficult in this framework, if not impossible, to account for $\Delta m^2_{12}/\Delta m^2_{23} \sim |U_{e3}|^2$ without fine-tuning [19].

It is surprising that the same set of data (23) and (24) can give rise to two interpretations that are so radically different from each other such as anarchy (25) and TBM (26). It shows that it will be very difficult to make progress on the SM flavor puzzle if we do not have measurements of new flavor parameters that involve, however, the SM quarks and leptons. If we are fortunate, the LHC might provide us with such measurements.

3. Future: what will we learn?

The high-p_T experiments at the LHC, ATLAS and CMS, and the flavor-factories, such as LHCb, give complementary information. In the absence of NP at ATLAS and CMS, we will lose our hints for a low scale of new physics, based on the Higgs fine-tuning problem and on the WIMP interpretation of the dark matter problem. If deviations from the SM are established in flavor factories, we will regain an upper bound on Λ_{NP}.

If new physics is discovered at ATLAS and CMS, then consistency between its spectrum and flavor decomposition and the measurements of FCNC at the flavor-factories will be necessary in order that we will understand the NP flavor puzzle. In this regard, it is important to search for NP in a variety of FCNC transitions: $c \to u$, $s \to d$, $b \to d$. $b \to s$, $t \to c$, $t \to u$, $\mu \to e$, $\tau \to \mu$ and $\tau \to e$. A schematic description of the present and hypothetical future situation is depicted in figure 4.

The exciting interplay between collider physics and flavor physics has been recently demonstrated in the theoretical interpretation of the intriguingly high value of the forward-backward asymmetry in $t\bar{t}$ production at high $m_{t\bar{t}}$. If the NP is related to a t-channel scalar-mediated contribution to $u\bar{u} \to t\bar{t}$, then collider data constrain the gauge quantum numbers of the scalar, while flavor data require that it has a very specific structure for its Yukawa couplings [21, 22].

The main point to emphasize is that, if there is new physics that couples to the SM quarks and/or leptons, then there are new flavor parameters—spectrum and flavor decomposition of the new particles—that can be measured. There are, in principle, three possibilities for the flavor structure of such new physics:

- Minimal flavor violation (MFV) [23]: there are no new sources of flavor violation beyond the Yukawa matrices of the SM. Gauge-mediated supersymmetry breaking (GMSB) is an example of such new physics.
- The flavor structure of the new physics is related, but not identical, to the SM. For example, it is possible that the structure of both the new couplings and the SM Yukawa couplings is dictated by a the selction rules that follow from an FN symmetry.
- The structure is unrelated to the SM, or may be even anarchical. (In practice, it is impossible to have anarchy in TeV scale new physics, because of the FCNC constraints.)

With any of these possibilities, ATLAS and CMS are almost guaranteed to solve the NP flavor puzzle, at least at the technical level. Either there is no NP at the TeV scale, or its spectrum and flavor decomposition will be measured. In the latter case, we will learn what is the suppression mechanism employed by the new physics, and we are likely to get hints about the physics that generates this structure.

As concerns the SM flavor puzzle, there will be no progress if there is MFV, and we will be even more confused in case of structure that is unrelated to that of the SM. If, however, there is structure that is related but not identical to the SM, then very likely we will be able to test ideas such as approximate, Abelian or non-Abelian, symmetries.

The good news are that a new particle that, very likely, couples to the SM quarks and leptons, has been discovered at ATLAS and CMS [24, 25]. Some thoughts about how the above program of making progress in flavor physics with ATLAS and CMS can be realized with this particle are described in the next subsection.

3.1. The flavor of h

A Higgs-like boson h has been discovered by the ATLAS and CMS experiments at the LHC [24, 25]. The experimental values (see e.g. [26]),

$$R_{ZZ^*} = 1.1 \pm 0.2, \qquad R_{\gamma\gamma} = 1.1 \pm 0.2, \tag{27}$$

where

$$R_f \equiv \frac{\sigma(pp \to h)\mathrm{BR}(h \to f)}{[\sigma(pp \to h)\mathrm{BR}(h \to f)]^{\mathrm{SM}}}, \tag{28}$$

suggest that the h-production via gluon–gluon fusion proceeds at a rate similar to the SM prediction, giving a strong indication that Y_t, the $ht\bar{t}$ Yukawa coupling, is of order one. The determination of Y_t signifies a new arena for the exploration of flavor physics.

In the future, measurements of $R_{b\bar{b}}$ and $R_{\tau^+\tau^-}$ will allow us to extract additional flavor parameters: Y_b and Y_τ. For the latter, the current allowed range is already quite restrictive:

$$R_{\tau^+\tau^-} = 1.0 \pm 0.4. \tag{29}$$

It may well be that the values of Y_b and/or Y_τ will deviate from their SM values. The most likely explanation of such deviations will be that there are more than one Higgs doublets, and that the doublet(s) that couple to the down and charged lepton sectors are not the same as the one that couples to the up sector.

A more significant test of our understanding of flavor physics, which might provide a window into new flavor physics, will come further in the future, when $R_{\mu^+\mu^-}$ is measured. (At present, there is an upper bound, $R_{\mu^+\mu^-} < 9.8$.) The ratio

$$X_{\mu^+\mu^-} \equiv \frac{\mathrm{BR}(h \to \mu^+\mu^-)}{\mathrm{BR}(h \to \tau^+\tau^-)} \tag{30}$$

is predicted within the SM with impressive theoretical cleanliness. To leading order, it is given by $X_{\mu^+\mu^-} = m_\mu^2/m_\tau^2$, and the corrections of order α_W and of order m_μ^2/m_τ^2 to this leading result are known. It is also possible to search for the SM-forbidden decay modes, $h \to \mu^\pm\tau^\mp$ [29–32]. A measurement of, or an upper bound on

$$X_{\mu\tau} \equiv \frac{\mathrm{BR}(h \to \mu^+\tau^-) + \mathrm{BR}(h \to \mu^-\tau^+)}{\mathrm{BR}(h \to \tau^+\tau^-)}, \tag{31}$$

would provide additional information relevant to flavor physics. Thus, it is interesting to understand the implications for flavor physics of measurements of $R_{\tau^+\tau^-}$, $X_{\mu^+\mu^-}$ and $X_{\mu\tau}$ [27, 28].

Table 3. Predictions of various flavor models for the leptonic Yukawa couplings of h: the SM, the minimal supersymmetric standard model (MSSM), two Higgs doublet models with general MFV, and the SM supplemented with non-renormalizable terms that are subject to selection rules from a FN symmetry.

Model	$Y_\tau/Y_\tau^{\mathrm{SM}}$	$(Y_\mu/Y_\tau)/(m_\mu/m_\tau)$	$Y_{\mu\tau}$
SM	1	1	0
MSSM	$\sin\alpha/\cos\beta$	1	0
MFV	$\mathcal{O}(1)$	$\mathcal{O}(1)$	0
FN	$1+\mathcal{O}(v^2/\Lambda_{\mathrm{NP}}^2)$	$1+\mathcal{O}(v^2/\Lambda_{\mathrm{NP}}^2)$	$\mathcal{O}(m_\tau v/\Lambda_{\mathrm{NP}}^2)$

Predictions of various well-motivated flavor models are presented in table 3. It is clear from the table that, in principle, large deviations from the SM are possible and that, furthermore, various ideas about the solution of the NP flavor puzzle (such as natural flavor conservation, MFV and FN mechanism) can be tested. In the case of a FN symmetry, the h-couplings have a structure that is related, but not identical, to the Yukawa couplings of the SM. In this case, further insights into the SM flavor puzzle might be gained.

4. Final comments

As a theorist, I often think of the LHC experiments as ones that might provide answers to six intriguing questions:

- What is the mechanism of electroweak symmetry breaking?
- What separates the electroweak scale from the Planck scale?
- What happened at the electroweak phase transition?
- What are the dark matter particles?
- How was the baryon asymmetry generated?
- What are the solutions of the flavor puzzles?

ATLAS and CMS have made huge progress in answering the first question, and already provide new insights (or challenges, depending on one's point of view) about the second and the third. Progress on the dark matter question depends on whether the dark matter particles are WIMPs and whether they appear in cascade decays of colored particles. Progress on the baryon asymmetry question depends on whether it is the outcome of electroweak baryogenesis.

We are very likely to make progress on the new physics flavor puzzle. The answer could be disappointing: there is no new physics that couples to quarks and leptons at the TeV scale, and therefore there is no puzzle. Hopefully, there is new physics, and the answer is more interesting than that.

We do not know the scale that is related to the SM flavor puzzle, but if there is new physics that is observed at the LHC, we may get indirect hints to the answer. For flavor physics, the newly discovered h-boson does constitute new physics. Measurements of its flavor parameters (including those that are forbidden within the SM) must be pursued. In parallel, precision measurements of FCNC processes and of CP asymmetries at the flavor factories might provide additional clues.

Acknowledgments

YN is the Amos de-Shalit chair of theoretical physics. This research is supported by the I-CORE Program of the Planning and Budgeting Committee and the Israel Science Foundation (grant no 1937/12), by the Israel Science Foundation (grant no 579/11), and by the German-Israeli foundation for scientific research and development (grant no G-1047-92.7/2009).

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