Flavor Physics and New Physics

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Abstract: This is a written version of part of a series of lectures aimed at graduate students in particle theory familiar with the basics of the Standard Model. We explain the implications of flavor physics for new physics. We emphasize the "new physics flavor puzzle". We explain how the ATLAS and CMS experiments can solve the new physics flavor puzzle and perhaps shed light on the standard model flavor puzzle. For a detailed, pedagogical introduction to flavor physics, within and beyond the Standard Model, the reader may consult Ref. [1].

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Abstract

This is a written version of part of a series of lectures aimed at graduate students in particle theory familiar with the basics of the Standard Model. We explain the implications of flavor physics for new physics. We emphasize the "new physics flavor puzzle". We explain how the ATLAS and CMS experiments can solve the new physics flavor puzzle and perhaps shed light on the standard model flavor puzzle. For a detailed, pedagogical introduction to flavor physics, within and beyond the Standard Model, the reader may consult Ref. [1].

1 The new physics flavor puzzle

It is clear that the Standard Model (SM) is not a complete theory of Nature:

1. It does not include gravity, and therefore it cannot be valid at energy scales above $m_{\rm Planck} \sim 10^{19}$ GeV:
2. It does not allow for neutrino masses, and therefore it cannot be valid at energy scales above $m_{\rm seesaw} \sim 10^{15}$ GeV;
3. The fine-tuning problem of the Higgs mass and the puzzle of the dark matter suggest that the scale where the SM is replaced with a more fundamental theory is actually much lower, $\Lambda_{\rm NP} \lesssim 1$ TeV.

Given that the SM is only an effective low energy theory, non-renormalizable terms must be added to the SM Lagrangian. These are terms of dimension higher than four in the fields which, therefore, have couplings that are inversely proportional to the scale of new physics $\Lambda_{\rm NP}$. For example, the lowest dimension non-renormalizable terms are dimension five:

$$-\mathcal{L}^{\rm dim-5}_{\rm Yukawa} = \frac{Z^\nu_{ij}}{\Lambda_{\rm NP}} L^I_{Li} L^I_{Lj} \phi\phi + {\rm h.c.}. \quad (1)$$

These are the seesaw terms, leading to neutrino masses.

As concerns quark flavor physics, consider, for example, the following dimension-six, four-fermion, flavor changing operators:

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2. \quad (2)$$

Each of these terms contributes to the mass splitting between the corresponding two neutral mesons. For example, the term $\mathcal{L}_{\Delta B=2} \propto (\overline{d_L}\gamma_\mu b_L)^2$ contributes to Δm_B, the mass difference between the two neutral B-mesons. We use $M_{12}^B = \frac{1}{2m_B}\langle B^0|\mathcal{L}_{\Delta F=2}|\overline{B}^0\rangle$ and

$$\langle B^0|(\overline{d_{La}}\gamma^\mu b_{La})(\overline{d_{Lb}}\gamma_\mu b_{Lb})|\overline{B}^0\rangle = -\frac{1}{3}m_B^2 f_B^2 B_B. \quad (3)$$

Analogous expressions hold for the other neutral mesons. This leads to $\Delta m_B/m_B = 2|M_{12}^B|/m_B \sim (|z_{bd}|/3)(f_B/\Lambda_{\rm NP})^2$. Experiments give, for CP conserving observables (the experimental evidence for Δm_D is at the 3σ level) [2, 3, 4, 5]:

$$\begin{aligned} \Delta m_K/m_K &\sim 7.0\times 10^{-15}, \\ \Delta m_D/m_D &\sim 8.7\times 10^{-15}, \\ \Delta m_B/m_B &\sim 6.3\times 10^{-14}, \\ \Delta m_{B_s}/m_{B_s} &\sim 2.1\times 10^{-12}, \end{aligned} \quad (4)$$

nd for CP violating ones

$$\begin{aligned} \epsilon_K &\sim 2.3\times 10^{-3}, \\ A_\Gamma/y_{\rm CP} &\lesssim 0.2, \\ S_{\psi K_S} &= 0.67\pm 0.02, \\ S_{\psi\phi} &\lesssim 1. \end{aligned} \quad (5)$$

hese measurements give then the following constraints (the bounds from the corresponding four-fermi terms with LR structure, instead of the LL structure of Eq. (2), are even stronger):

$$\Lambda_{\rm NP} \gtrsim \begin{cases} \sqrt{z_{sd}}\ 1\times 10^3\ TeV & \Delta m_K \\ \sqrt{z_{cu}}\ 1\times 10^3\ TeV & \Delta m_D \\ \sqrt{z_{bd}}\ 4\times 10^2\ TeV & \Delta m_B \\ \sqrt{z_{bs}}\ 7\times 10^1\ TeV & \Delta m_{B_s} \end{cases} \quad (6)$$

and, for maximal phases,

$$\Lambda_{\rm NP} \gtrsim \begin{cases} \sqrt{z_{sd}}\ 2\times 10^4\ TeV & \epsilon_K \\ \sqrt{z_{cu}}\ 3\times 10^3\ TeV & A_\Gamma \\ \sqrt{z_{bd}}\ 8\times 10^2\ TeV & S_{\psi K} \\ \sqrt{z_{bs}}\ 7\times 10^1\ TeV & S_{\psi\phi} \end{cases} \quad (7)$$

If the new physics has a generic flavor structure, that is $z_{ij} = \mathcal{O}(1)$, then its scale must be above $10^3 - 10^4$ TeV (or, if the leading contributions involve electroweak loops, above $10^2 - 10^3$ TeV).

If indeed $\Lambda_{\rm NP} \gg TeV$, it means that we have misinterpreted the hints from the fine-tuning problem and the dark matter puzzle. There is, however, another way to look at these constraints:

$$\begin{aligned} z_{sd} &\lesssim 8\times 10^{-7}\ (\Lambda_{\rm NP}/TeV)^2, \\ z_{cu} &\lesssim 5\times 10^{-7}\ (\Lambda_{\rm NP}/TeV)^2, \\ z_{bd} &\lesssim 5\times 10^{-6}\ (\Lambda_{\rm NP}/TeV)^2, \\ z_{bs} &\lesssim 2\times 10^{-4}\ (\Lambda_{\rm NP}/TeV)^2, \end{aligned} \tag{8}$$

$$\begin{aligned} z^I_{sd} &\lesssim 6\times 10^{-9}\ (\Lambda_{\rm NP}/TeV)^2, \\ z^I_{cu} &\lesssim 1\times 10^{-7}\ (\Lambda_{\rm NP}/TeV)^2, \\ z^I_{bd} &\lesssim 1\times 10^{-6}\ (\Lambda_{\rm NP}/TeV)^2, \\ z^I_{bs} &\lesssim 2\times 10^{-4}\ (\Lambda_{\rm NP}/TeV)^2. \end{aligned} \tag{9}$$

It could be that the scale of new physics is of order TeV, but its flavor structure is far from generic.

One can use that language of effective operators also for the SM, integrating out all particles significantly heavier than the neutral mesons (that is, the top, the Higgs and the weak gauge bosons). Thus, the scale is $\Lambda_{\rm SM} \sim m_W$. Since the leading contributions to neutral meson mixings come from box diagrams, the z_{ij} coefficients are suppressed by α_2^2. To identify the relevant flavor suppression factor, one can employ the spurion formalism (see next Section). For example, the flavor transition that is relevant to $B^0 - \overline{B}^0$ mixing involves $\overline{d_L} b_L$ which transforms as $(8,1,1)_{SU(3)^3_q}$. The leading contribution must then be proportional to $(Y^u Y^{u\dagger})_{13} \propto y_t^2 V_{tb} V_{td}^*$. Indeed, an explicit calculation (using VIA for the matrix element and neglecting QCD corrections) gives

$$\frac{2M_{12}^B}{m_B} \approx -\frac{\alpha_2^2}{12}\frac{f_B^2}{m_W^2} S_0(x_t)(V_{tb}V_{td}^*)^2, \tag{10}$$

where $x_i = m_i^2/m_W^2$ and

$$S_0(x) = \frac{x}{(1-x)^2}\left[1 - \frac{11x}{4} + \frac{x^2}{4} - \frac{3x^2 \ln x}{2(1-x)}\right]. \tag{11}$$

Similar spurion analyses, or explicit calculations, allow us to extract the weak and flavor suppression factors that apply in the SM:

$$\begin{aligned}\mathcal{I}m(z_{sd}^{\rm SM}) &\sim \alpha_2^2 y_t^2 |V_{td}V_{ts}|^2 \sim 1\times 10^{-10},\\ z_{sd}^{\rm SM} &\sim \alpha_2^2 y_c^2 |V_{cd}V_{cs}|^2 \sim 5\times 10^{-9},\\ z_{bd}^{\rm SM} &\sim \alpha_2^2 y_t^2 |V_{td}V_{tb}|^2 \sim 7\times 10^{-8},\\ z_{bs}^{\rm SM} &\sim \alpha_2^2 y_t^2 |V_{ts}V_{tb}|^2 \sim 2\times 10^{-6}.\end{aligned} \tag{12}$$

We did not include $z_{cu}^{\rm SM}$ in the list because it requires a more detailed consideration. The naively leading short distance contribution is $\propto \alpha_2^2 (y_s^4/y_c^2)|V_{cs}V_{us}|^2 \sim 5\times 10^{-13}$. However, higher dimension terms can replace a y_s^2 factor with $(\Lambda/m_D)^2$ [6]. Moreover, long distance contributions are expected to dominate. In particular, peculiar phase space effects [7, 8] have been identified which are expected to enhance Δm_D to within an order of magnitude of the its measured value.)

It is clear then that contributions from new physics at $\Lambda_{\rm NP} \sim 1\ TeV$ should be suppressed by factors that are comparable or smaller than the SM ones. Why does that happen? This is the new physics flavor puzzle.

The fact that the flavor structure of new physics at the TeV scale must be non-generic means that flavor measurements are a good probe of the new physics. Perhaps the best-studied example is that of supersymmetry. Here, the spectrum of the superpartners and the structure of their couplings to the SM fermions will allow us to probe the mechanism of dynamical supersymmetry breaking.

2 Flavor at the LHC

The LHC will study the physics of electroweak symmetry breaking. There are high hopes that it will discover not only the Higgs, but also shed light on the fine-tuning problem that is related to the Higgs mass. Here, we focus on the issue of how, through the study of new physics, the LHC can shed light on the new physics flavor puzzle.

2.1 Minimal flavor violation (MFV)

If supersymmetry breaking is gauge mediated, the squark mass matrices have the following form at the scale of mediation m_M:

$$\begin{aligned}\tilde M^2_{U_L}(m_M) &= \left(m^2_{\tilde Q_L} + D_{U_L}\right)\mathbf{1} + M_u M_u^\dagger,\\ \tilde M^2_{D_L}(m_M) &= \left(m^2_{\tilde Q_L} + D_{D_L}\right)\mathbf{1} + M_d M_d^\dagger,\\ \tilde M^2_{U_R}(m_M) &= \left(m^2_{\tilde U_R} + D_{U_R}\right)\mathbf{1} + M_u^\dagger M_u,\\ \tilde M^2_{D_R}(m_M) &= \left(m^2_{\tilde D_R} + D_{D_R}\right)\mathbf{1} + M_d^\dagger M_d,\end{aligned} \tag{13}$$

here $D_{q_A} = (T_3)_{q_A} - (Q_{\rm EM})_{q_A} s_W^2 m_Z^2 \cos 2\beta$ are the D-term contributions. Here, the only source of the $SU(3)_q^3$ breaking are the SM Yukawa matrices.

This statement holds also when the renormalization group evolution is applied to find the form of these matrices at the weak scale. Taking the scale of the soft breaking terms $m_{\tilde{q}_A}$ to be somewhat higher than the electroweak breaking scale m_Z allows us to neglect the D_{q_A} and M_q terms in (13). Then we obtain

$$\begin{aligned} \tilde{M}^2_{Q_L}(m_Z) &\sim m^2_{\tilde{Q}_L}\left(r_3 \mathbf{1} + c_u Y_u Y_u^\dagger + c_d Y_d Y_d^\dagger\right), \\ \tilde{M}^2_{U_R}(m_Z) &\sim m^2_{\tilde{U}_R}\left(r_3 \mathbf{1} + c_{uR} Y_u^\dagger Y_u\right), \\ \tilde{M}^2_{D_R}(m_Z) &\sim m^2_{\tilde{D}_R}\left(r_3 \mathbf{1} + c_{dR} Y_d^\dagger Y_d\right). \end{aligned} \tag{14}$$

ere r_3 represents the universal RGE contribution that is proportional to the gluino mass ($r_3 = \mathcal{O}(6) \times (M_3(m_M)/m_{\tilde{q}}(m_M))$) and the c-coefficients depend logarithmically on m_M/m_Z and can be of $\mathcal{O}(1)$ when m_M is not far below the GUT scale.

Models of gauge mediated supersymmetry breaking (GMSB) provide a concrete example of a large class of models that obey a simple principle called *minimal flavor violation* (MFV) [9]. This principle guarantees that low energy flavor changing processes deviate only very little from the SM predictions. The basic idea can be described as follows. The gauge interactions of the SM are universal in flavor space. The only breaking of this flavor universality comes from the three Yukawa matrices, Y_U, Y_D and Y_E. If this remains true in the presence of the new physics, namely Y_U, Y_D and Y_E are the only flavor non-universal parameters, then the model belongs to the MFV class.

Let us now formulate this principle in a more formal way, using the language of spurions. The Standard Model with vanishing Yukawa couplings has a large global symmetry:

$$G_{\rm global}(Y^{u,d,e} = 0) = SU(3)_q^3 \times SU(3)_\ell^2 \times U(1)^5, \tag{15}$$

where

$$\begin{aligned} SU(3)_q^3 &= SU(3)_Q \times SU(3)_U \times SU(3)_D, \\ SU(3)_\ell^2 &= SU(3)_L \times SU(3)_E, \\ U(1)^5 &= U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{\rm PQ} \times U(1)_E. \end{aligned} \tag{16}$$

n this section we concentrate only on the quarks. The non-Abelian part of the flavor symmetry for the quarks is $SU(3)_q^3$ of Eq. (16) with the three generations of quark fields transforming as follows:

$$Q_L(3,1,1), \quad U_R(1,3,1), \quad D_R(1,1,3). \tag{17}$$

The Yukawa interactions,

$$\mathcal{L}_Y = \overline{Q_L} Y_D D_R H + \overline{Q_L} Y_U U_R H_c, \tag{18}$$

($H_c = i\tau_2 H^*$) break this symmetry. The Yukawa couplings can thus be thought of as spurions with the following transformation properties under $SU(3)_q^3$:

$$Y_U \sim (3, \overline{3}, 1), \qquad Y_D \sim (3, 1, \overline{3}). \tag{19}$$

When we say "spurions", we mean that we pretend that the Yukawa matrices are fields which transform under the flavor symmetry, and then require that all the Lagrangian terms, constructed from the SM fields, Y_D and Y_U, must be (formally) invariant under the flavor group $SU(3)_q^3$. Of course, in reality, $\mathcal{L}_Y$ breaks $SU(3)_q^3$ precisely because $Y_{D,U}$ are *not* fields and do not transform under the symmetry.

The idea of minimal flavor violation is relevant to extensions of the SM, and can be applied in two ways:

1. Consider the SM as a low energy effective theory. Then all higher-dimension operators, constructed from SM-fields and Y-spurions, are formally invariant under $G_{\rm global}$.

2. Consider a full high-energy theory that extends the SM. Then all operators, constructed from SM and the new fields, and from Y-spurions, are formally invariant under $G_{\rm global}$.

Examples of MFV models include models of supersymmetry with gauge-mediation or with anomaly-mediation of its breaking. If the LHC discovers new particles that couple to the SM fermions, then it will be able to test solutions to the new physics flavor puzzle such as MFV [10]. Much of its power to test such frameworks is based on identifying top and bottom quarks.

To understand this statement, we notice that the spurions Y_U and Y_D can always be written in terms of the two diagonal Yukawa matrices λ_u and λ_d and the CKM matrix V:

$$Y^d = \lambda_d, \quad Y^u = V^\dagger \lambda_u, \tag{20}$$

$$\lambda_d = {\rm diag}(y_d, y_s, y_b), \quad \lambda_u = {\rm diag}(y_u, y_c, y_t), \tag{21}$$

Thus, the only source of quark flavor changing transitions in MFV models is the CKM matrix. Next, note that to an accuracy that is better than $\mathcal{O}(0.05)$, we can write the CKM matrix as follows:

$$V = \begin{pmatrix} 1 & 0.23 & 0 \\ -0.23 & 1 & 0 \\ 0 & 0 & 1 \\ . & . & . \end{pmatrix} \tag{22}$$

We learn that the third generation of quarks is decoupled, to a good approximation, from the first two. This, in turn, means that any new particle that couples to an odd number of the SM quarks (think, for example, of heavy quarks in vector-like representations of $G_{\rm SM}$), decay into either third generation quark, or to non-third generation quark, but not to both. For example, in Ref. [10], MFV models with additional charge $-1/3$, $SU(2)_{\rm L}$-singlet quarks – B' – were considered. A concrete test of MFV was proposed, based on the fact that the largest mixing effect involving the third generation is of order $|V_{cb}|^2 \sim 0.002$: Is the following prediction, concerning events of B' pair production, fulfilled:

$$\frac{\Gamma(B'\overline{B'} \to X q_{1,2} q_3)}{\Gamma(B'\overline{B'} \to X q_{1,2} q_{1,2}) + \Gamma(B'\overline{B'} \to X q_3 q_3)} \lesssim 10^{-3}. \quad (23)$$

If not, then MFV is excluded.

2.2 Supersymmetric flavor at the LHC

One can think of analogous tests in the supersymmetric framework [11, 16, 17, 12, 13, 14, 15]. Here, there is also a generic prediction that, in each of the three sectors (Q_L, U_R, D_R), squarks of the first two generations are quasi-degenerate, and do not decay into third generation quarks. Squarks of the third generation can be separated in mass (though, for small $\tan\beta$, the quasi-degeneracy in the $\tilde{D}_R$ sector is threefold), and decay only to third generation quarks.

It is not necessary, however, that the mediation of supersymmetry breaking is MFV. Examples of natural and viable solutions to the supersymmetric flavor problem that are not MFV include the following:

1. The leading contribution to the soft supersymmetry breaking terms is gauge mediated, and therefore MFV, but there are subleading contributions that are gravity mediated and provide new sources of flavor and CP violation [11, 17]. The gravity mediated contributions could either have some structure (dictated, for example, by a Froggatt-Nielsen symmetry [11] or by localization in extra dimensions [18]) or be anarchical [19].

2. The first two sfermion generations are heavy, and their mixing with the third generation is suppressed (for a recent analysis, see [20]). These features can come, for example, from conformal dynamics [21].

Such framework have different predictions concerning the mass splitting between sfermion generations and the flavor decomposition of the sfermion mass eigenstates. Note that measurements of flavor changing neutral current processes are only sensitive to the products of the form

$$\delta_{ij} = \frac{\Delta\tilde{m}^2_{ij}}{\tilde{m}^2}\ K_{ij} K^*_{jj}, \quad (24)$$

where $\Delta\tilde{m}^2_{ij}$ is the mass-squared splitting between the sfermion generations i and j, $\tilde{m}^2$ is their average mass-squared, and K is the mixing matrix of gaugino couplings to these sfermions. On the other hand, the LHC experiments – ATLAS and CMS – can, at least in principle, measure the mass splitting and the mixing separately [14, 15].

The present situation is depicted schematically in Fig. 1(a). Flavor factories have provided only upper bounds on deviations of FCNC processes, such as $\mu \to e\gamma$ or $D^0 - \overline{D}^0$ mixing, from the standard model predictions. In the supersymmetric framework, such bounds translate into an upper bound on a δ_{ij} parameter of Eq. (24), corresponding to the blue region in the figure. The supersymmetric flavor puzzle can be stated as the question of why the region in the upper right corner – where the flavor parameters are of order one – is excluded. MFV often puts us in the lower left corner of the plot, far from the experimental constraints. (This is particularly true for δ_{12} parameters.)

The optimal future situation is depicted schematically in Fig. 1(b). Imagine that a flavor factory does provide evidence for new physics, such as observation of $\Gamma(\mu \to e\gamma) \neq 0$ or CP violation in $D^0 - \overline{D}^0$ mixing. This will constrain the corresponding δ parameter, which is shown as the blue region in the Figure. If ATLAS/CMS measure the corresponding sfermion mass splitting and/or mixing, we will get a small allowed region in this flavor plane.

If we have at our disposal such three consistent measurements (rate of FCNC process, spectrum and splitting), then we will understand the mechanism by which supersymmetry has its flavor violation suppressed. This will provide strong hints about the mechanism of supersymmetry breaking mediation.

If the sfermions are quasi-degenerate, then the mixing is determined by the small corrections to the unit mass-squared matrix. As mentioned above, the structure of such corrections may be dictated by the same symmetry or dynamics that gives the structure of the Yukawa couplings. If that is the case, then the measurement of the flavor decomposition might shed light on the Standard Model flavor puzzle.

We conclude that measurements at the LHC related to new particles that couple to the SM fermions are likely to teach us much more about flavor physics.

3 Concluding Comments

The present status and near-future prospects of flavor physics can be summarized as follows:

(i) Measurements of CP violating B-meson decays have established that the Kobayashi-Maskawa mechanism is the dominant source of the observed CP violation.

(ii) Measurements of flavor changing B-meson decays have established the the Cabibbo-Kobayashi-Maskawa mechanism is a major player in flavor violation.

(iii) The consistency of all these measurements with the CKM predictions sharpens the new physics flavor puzzle: If there is new physics at, or below, the TeV scale, then its flavor structure must be highly non-generic.

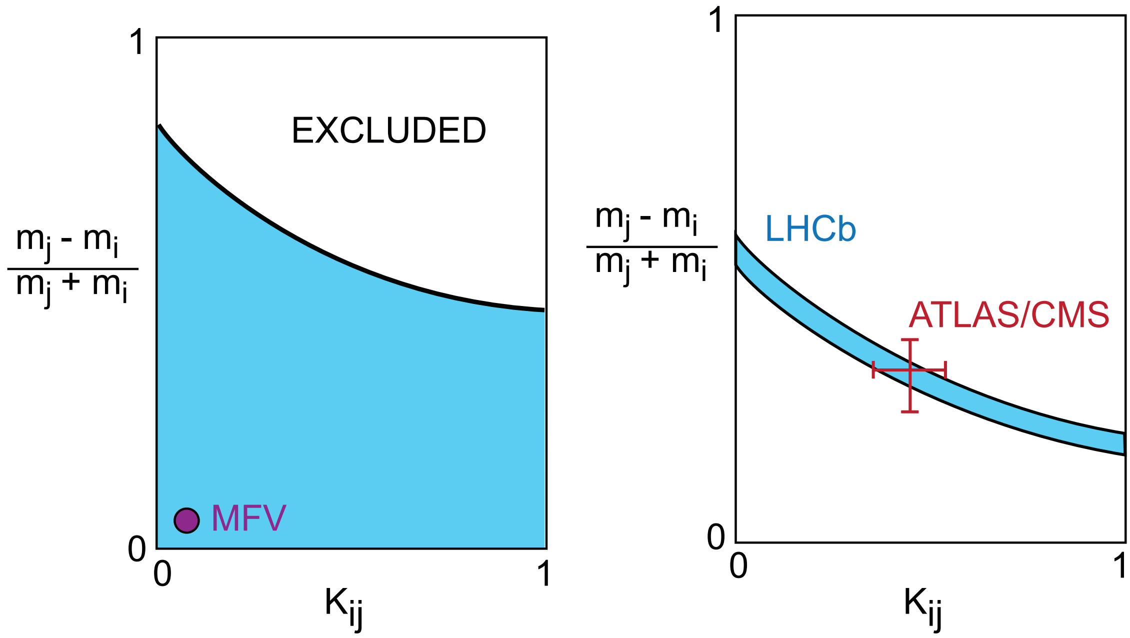

Figure 1: Schematic description of the constraints in the plane of sfermion mass-squared splitting, $\Delta\tilde{m}^2_{ij}/\tilde{m}^2$, and mixing, $K_{ij}K^*_{jj}$: (a) Upper bounds from not observing any deviation from the SM predictions in present experiments; (b) Hypothetical future situation, where deviations have been observed in flavor factories (such as LHCb, a super-B factory, a $\mu\to e\gamma$ measurement, etc.) and the mass splitting and flavor decomposition have been measured by ATLAS/CMS.

(iv) Measurements of $D^0-\overline{D}^0$ mixing imply that alignment by itself cannot solve the supersymmetric flavor problem. The first two squark generations must be quasi-degenerate.

(v) Measurements of neutrino flavor parameters have not only not clarified the standard model flavor puzzle, but actually deepened it. Whether they imply an anarchical structure, or a tribimaximal mixing, it seems that the neutrino flavor structure is very different from that of quarks.

(vi) If the LHC experiments, ATLAS and CMS, discover new particles that couple to the Standard Model fermions, then, in principle, they will be able to measure new flavor parameters. Consequently, the new physics flavor puzzle is likely to be understood.

(vii) If the flavor structure of such new particles is affected by the same physics that sets the flavor structure of the Yukawa couplings, then the LHC experiments (and future flavor factories) may be able to shed light also on the standard model flavor puzzle.

The huge progress in flavor physics in recent years has provided answers to many questions. At the same time, new questions arise. We look forward to the LHC era for more answers and more questions.

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