Flavour physics, supersymmetry and grand unification

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A global fit to quark flavour-physics data disfavours the Standard Model with 3.6 standard deviations and points towards new CP-violating physics in meson-antimeson mixing amplitudes. Tevatron data call for a new $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing phase and new physics in $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ mixing alleviates the tension on the unitarity triangle driven by $B(B \to \tau\nu)$. In supersymmetric GUT models the large atmospheric neutrino mixing angle can influence $b \to s$ transitions. I present the results of a recent analysis in an SO(10) GUT model which accomodates the large $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing phase while simultaneously obeying all other experimental constraints.

1 Introduction

On May 17, 2010, *The New York Times* wrote:

> *Physicists at the Fermi National Accelerator Laboratory are reporting that they have discovered a new clue that could help unravel one of the biggest mysteries of cosmology: why the universe is composed of matter and not its evil-twin opposite, antimatter.*

This phrase was contained in an article featuring a measurement by the DØ collaboration presented three days earlier by Guennadi Borissov in the talk

Evidence for an anomalous like-sign dimuon charge asymmetry.

DØ has studied the decays of pair-produced hadrons into final states with muons [1]. If, for example, a $(b, \overline{b})$ pair hadronises into a Λ_b baryon, a B^+ meson, and several lighter hadrons, the semileptonic decays of Λ_b and B^+ will result in leptons of opposite charges. However, if the b or $\overline{b}$ quark ends up in a neutral B meson, $\mathrm{B}-\overline{\mathrm{B}}$ oscillations may lead to a "wrong-sign" muon charge: While a B meson contains a $\overline{b}$ quark decaying into a μ^+, $\mathrm{B}-\overline{\mathrm{B}}$ mixing permits the process $B \to \overline{B} \to X\mu^-\overline{\nu}_\mu$ resulting in a muon with negative charge. The data sample with like-sign dimuons is therefore enriched with events which involve a mixed neutral meson. By further comparing the numbers of (μ^-, μ^-) and (μ^+, μ^+) pairs in the final states DØ has quantified the CP violation in $\mathrm{B}-\overline{\mathrm{B}}$ mixing for a data sample composed of B_d and B_s mesons. The central value of the measured CP asymmetry exceeds the theory prediction [2] by a factor of 42 and the statistical significance of the discrepancy is 3.2 standard deviations.[a] A new-physics interpretation of the measurement requires a large effect in $\mathrm{B_s}–\overline{\mathrm{B}}_\mathrm{s}$ mixing, because the precision measurements at the B factories limit the size of a possible new CP phase in $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ mixing.

The Standard-Model (SM) predictions for the $\mathrm{B}-\overline{\mathrm{B}}$ mixing amplitudes involve elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which are found from global fits to many observables of flavour physics. CP-violating quantities depend in a crucial way on the parameters $\overline{\rho}$ and $\overline{\eta}$, which define the apex of the CKM unitarity triangle (UT) (see Fig. 1). $\overline{\rho}$ and $\overline{\eta}$ also govern the sizes of $b \to u$ and $b \to d$ transitions. Among the quantities used in global fits to the UT are the precisely measured $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ mixing and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing oscillation frequencies, the CP phase in $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ mixing measured in the decay $B_d \to J/\psi K_S$, and ϵ_K, which quantifies CP violation in $\mathrm{K}-\overline{\mathrm{K}}$ mixing. Several authors have noticed a tension in the Standard-Model (SM) fit of the UT to data [4]. Meson-antimeson mixing amplitudes are $\Delta F = 2$ amplitudes, meaning that the flavour quantum number $F = B, S, \ldots$ changes by two units. In a wide class of models beyond the SM $\Delta F = 2$ transitions receive larger new-physics corrections than the $\Delta F = 1$ decay amplitudes. The relation of the measured quantities to the CKM elements will be altered if new physics affects the $\Delta F = 2$ amplitudes. A proper theoretical assessment of the quoted DØ measurement and of the tensions in the over-constrained CKM matrix therefore

[a] After this conference DØ has updated the analysis with a larger data sample and found a discrepancy of 3.9 standard deviations with respect to the SM prediction [3].

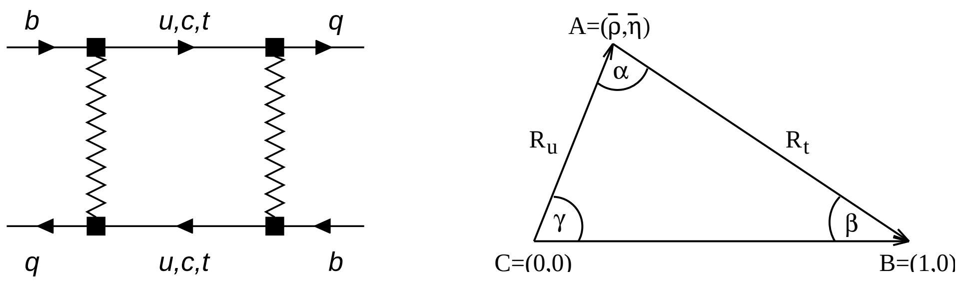


Figure 1: Left: SM box diagram describing $B_q - \overline{B}_q$ mixing, with $q = d$ or s. Right: Standard unitarity triangle.

calls for a global analysis which fits the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix simultaneously with complex parameters quantifying new physics in $K-\overline{K}$, $B_d-\overline{B}_d$, and $B_s-\overline{B}_s$ mixing. Such an analysis has been performed in Ref. [5]. In this talk I first summarise the results of this analysis in Sec. 2. Subsequently, in Sec. 3 I interpret the results within a supersymmetric grand unified theory (GUT). In Sec. 4 I conclude.

2 Anatomy of new physics in $B-\overline{B}$ mixing

In this section I present the essentials of the analysis in Ref. [5], which shows evidence for new physics (NP) in $B-\overline{B}$ mixing. While I use the numerical ranges for experimental and theoretical input quantities compiled in this reference, I use two simplifications in this talk: First, for clarity of the presentation my quoted errors contain statistical, systematic and theoretical errors added in quadrature. By contrast, the original analysis in Ref. [5] has used the more conservative Rfit procedure [6], which scans over systematic and theoretical uncertainties. Second, whenever possible I present simplified derivations of the tensions between experimental results and SM predictions. In this way the main sources of the quoted tensions become transparent.

Flavour-changing neutral current (FCNC) processes are known to be very sensitive to NP. Schematically, any contribution to an FCNC $\Delta F = 1$ decay amplitude is proportional to $\delta_{\rm FCNC}/M^2$, where $\delta_{\rm FCNC}$ is a small flavour-violating parameter and M is some heavy mass scale. In a SM diagram, $\delta_{\rm FCNC}$ is the product of two CKM elements and the relevant scale M is the W boson mass entering the FCNC loop diagrams. $\Delta F = 2$ amplitudes, however, scale like $\delta^2_{\rm FCNC}/M^2$, for instance the $\Delta B = 2$ box diagram of Fig. 1 is proportional to $(V_{tb}V_{tq}^*)^2/M_W^2$. One realises that $\Delta F = 2$ amplitudes are more sensitive to NP than $\Delta F = 1$ transitions in a wide class of models: Whenever $|\delta^{\rm NP}_{\rm FCNC}| > |\delta^{\rm SM}_{\rm FCNC}|$, which must come with $M > M_W$ to keep the NP contribution smaller than the SM one, the relative impact of NP on a $\Delta F = 1$ transition is smaller by factor of $|\delta^{\rm SM}_{\rm FCNC}|/|\delta^{\rm NP}_{\rm FCNC}|$ with respect to the $\Delta F = 2$ case. In extensions of the SM with new sources of flavour violation the case $|\delta^{\rm NP}_{\rm FCNC}| > |\delta^{\rm SM}_{\rm FCNC}|$ is the default situation, because off-diagonal CKM elements are small. Moreover, $\Delta F = 1$ FCNC decays hardly enter the global fit determining the CKM elements. It is therefore well-motivated to fit these elements in scenarios in which the NP effects are confined to $\Delta F = 2$ processes [5].

2.1 The $|V_{ub}|$ puzzle

The CKM matrix

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

is fixed by the measurements of

$$|V_{us}| = 0.2254 \pm 0.0013, \qquad |V_{cb}| = (40.9 \pm 0.7) \cdot 10^{-3}, \qquad (1)$$

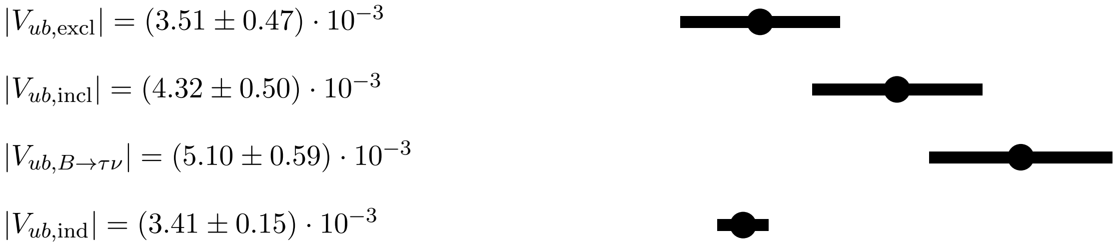


Figure 2: Measurements of $|V_{ub}|$. The fourth value is indirectly obtained from the side R_u of the UT.

and the values of $\overline{\rho}$ and $\overline{\eta}$, which define the apex of the unitarity triangle (UT) depicted in Fig. 1:

$$\overline{\rho} + i\overline{\eta} \;\equiv\; -\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} \;\equiv\; R_u e^{i\gamma} \qquad (2)$$

Currently $|V_{ub}|$ is measured in three ways, from i) the exclusive decays $B \to \pi\ell\nu$, ii) the inclusive decays $B \to X\ell\nu$, and iii) the leptonic decay $B^+ \to \tau^+\nu_\tau$. $B(B^+ \to \tau^+\nu_\tau)$ has been measured by both the BaBar and Belle collaboration, each with two methods using either a leptonic or a hadronic tag [7], resulting in[b]

$$B^{\mathrm{exp}}(B^+ \to \tau^+\nu_\tau) \;=\; (1.68 \pm 0.31) \cdot 10^{-4}.$$

The theory prediction involves the B meson decay constant f_B, which is calculated with the help of lattice QCD:

$$B(B^+ \to \tau^+\nu_\tau) \;=\; 1.13 \cdot 10^{-4} \cdot \left(\frac{|V_{ub}|}{4 \cdot 10^{-3}}\right)^2 \left(\frac{f_B}{200\ \mathrm{MeV}}\right)^2$$

With $f_B = (191 \pm 13)$ MeV one finds

$$\begin{aligned} |V_{ub,B\to\tau\nu}| &= \left[5.10 \pm 0.47|_{\mathrm{exp}} \pm 0.35|_{\mathrm{f_B}}\right] \cdot 10^{-3} \\ &= [5.10 \pm 0.59] \cdot 10^{-3}. \end{aligned}$$

The measurement of $|V_{ub}|$ constrains the side R_u of the UT, because $|V_{ub}| \propto |V_{cb}| R_u$ (see Eq. (2)). However, in the global fit to the UT the dominant constraint on R_u stems from the precise measurement of the mixing-induced CP asymmetry $A_{\mathrm{CP}}^{\mathrm{mix}}(B_d \to J/\psi K_S)$. If the SM describes $\mathrm{B_d} - \overline{\mathrm{B}}_\mathrm{d}$ mixing correctly, this quantity determines the UT angle $\beta = 21.15^\circ \pm 0.89^\circ$. Using further $\alpha = 89^\circ{}^{+4.4^\circ}_{-4.2^\circ}$, we find $R_u = \sin\beta / \sin\alpha = 0.361 \pm 0.015$ with a negligible impact of the error in α. This value is in excellent agreement with the result of the full global fit to the UT. With our number for R_u we can determine $|V_{ub}|$ indirectly through Eq. (2):

$$|V_{ub}|_{\mathrm{ind}} \;=\; (3.41 \pm 0.15) \cdot 10^{-3}.$$

The four determinations of $|V_{ub}|$ are shown in Fig. 2. We observe no significant discrepancy between the individual direct measurements of $|V_{ub}|$. However, there is a 2.9 σ tension between $B^+ \to \tau^+\nu$ and the indirect determination of $|V_{ub}|$ driven by $A_{\mathrm{CP}}^{\mathrm{mix}}(B_d \to J/\psi K_S)$.

Several authors have studied NP contributions to $B^+ \to \tau^+\nu$ [9–11]. While a charged Higgs boson can contribute to $B^+ \to \tau^+\nu$, the contribution typically decreases the branching fraction and therefore cannot solve the $|V_{ub}|$ puzzle. (A control channel for charged-Higgs effects is $B \to D\tau\nu$ [12].) A more promising NP explanation of the $|V_{ub}|$ puzzle has been pointed out by Crivellin, who has observed that an effective right-handed W coupling $\overline{b}_R \gamma^\mu u_R W_\mu$ can simultaneously shift $|V_{ub,\mathrm{excl}}|$ upwards and $|V_{ub,B\to\tau\nu}|$ downwards [10]. The effect of a right-handed W coupling on $|V_{ub,\mathrm{ind}}|$ is model-dependent.

[b] After this conference the average $(1.64 \pm 0.34) \cdot 10^{-4}$ has been presented [8].

Since the direct determinations of $|V_{ub}|$ agree up to normal statistical fluctuations, I argue that the simplest solution to the $|V_{ub}|$ puzzle is NP in the $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ mixing amplitude. In the presence of a new contribution ϕ_d^Δ to the $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ mixing phase the well-measured $A_{\rm CP}^{\rm mix}(B_d \to J/\psi K_S)$ determines $\sin(2\beta+\phi_d^\Delta)$. With $\phi_d^\Delta < 0$ the true value of β will be larger than $\beta = 21.15^\circ \pm 0.89^\circ$ inferred from the SM analysis. Since β is also constrained by other measurements, a global fit is required [5].

2.2 New physics in $\mathrm{B}-\overline{\mathrm{B}}$ *mixing*

$\mathrm{B_q}-\overline{\mathrm{B}}_\mathrm{q}$ mixing involves two hermitian 2×2 matrices, the mass matrix M^q and the decay matrix Γ^q. The off-diagonal elements M_{12}^q and Γ_{12}^q are calculated from the dispersive and absorptive parts of the $\overline{B}_q \to B_q$ transition amplitude, respectively. In the SM M_{12}^q is dominated by the box diagram in Fig. 1 with internal top quarks, while Γ_{12}^q stems from box diagrams with only charm and up quarks on the internal lines. The SM expression for M_{12}^q including NLO QCD corrections has been calculated in Ref. [13]; the corresponding results for Γ_{12}^q have been obtained in Ref. [2, 14]. The numerical predictions in Ref. [2] have been recently updated with present-day values of CKM elements, quark masses and hadronic parameters in Refs. [5,15]. As a consequence of $\mathrm{B_q}-\overline{\mathrm{B}}_\mathrm{q}$ mixing, the mass eigenstates B_q^H and B_q^L (with "H" and "L" denoting "heavy" and "light") found by diagonalising $M^q - i\Gamma^q/2$ are linear combinations of B_q and $\overline{B}_q$. The mass and width differences between B_q^H and B_q^L are given by

$$\Delta M_q \;=\; M_H^q - M_L^q \;\simeq\; 2|M_{12}^q|\,, \qquad\qquad \Delta\Gamma_q \;=\; \Gamma_L^q - \Gamma_H^q \;\simeq\; 2|\Gamma_{12}^q|\cos\phi_q\,.$$

The CP asymmetry in flavour-specific decays (such as $B_s \to X\ell^+\nu_\ell$) reads

$$a_{\rm fs}^q \;=\; \frac{|\Gamma_{12}^q|}{|M_{12}^q|}\sin\phi_q$$

with the CP-violating phase

$$\phi_q \;\equiv\; \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right). \tag{3}$$

The DØ measurement of the like-sign dimuon asymmetry [1,3] involves a sample which is almost evenly composed of B_d and B_s mesons. The measured value is[c]

$$\begin{aligned} a_{\rm fs} \;&=\; (0.506\pm 0.043)a_{\rm fs}^d + (0.494\pm 0.043)a_{\rm fs}^s \\ &=\; (-9.57\pm 2.51\pm 1.46)\cdot 10^{-3} \end{aligned} \tag{4}$$

Averaging with an older CDF measurement yields

$$a_{\rm fs} = (-8.5\pm 2.8)\cdot 10^{-3}. \tag{5}$$

The numbers in Eqs. (4) and (5) are 3.2σ and 2.9σ away from the SM prediction $a_{\rm fs}^{\rm SM} = (-0.20\pm 0.03)\cdot 10^{-3}$ [15], respectively.

Γ_{12}^s originates from Cabibbo-favoured tree-level decays and is insensitive to new physics.[d] While Γ_{12}^d involves some Cabibbo suppression, it is nevertheless difficult to engineer a sizable new-physics contribution to Γ_{12}^d without running into conflict with the plethora of measured exclusive B decay branching fractions. It is therefore safe to assume that NP contributions to $\Gamma_{12}^{d,s}$ are irrelevant in view of today's experimental errors. In our analysis in Ref. [5] we

[c] The 2011 value is $a_{\rm fs} = (-7.87\pm 1.72\pm 0.93)\cdot 10^{-3}$ [3].

[d] Any NP competing with the tree-level $b\to s\overline{c}c$ decays constituting Γ_{12}^s will alter the $b\to s\overline{c}c$ decay rates of all b-flavoured hadrons in conflict with the precisely measured charm content n_c of B decay final states and/or the semileptonic branching fraction [5].

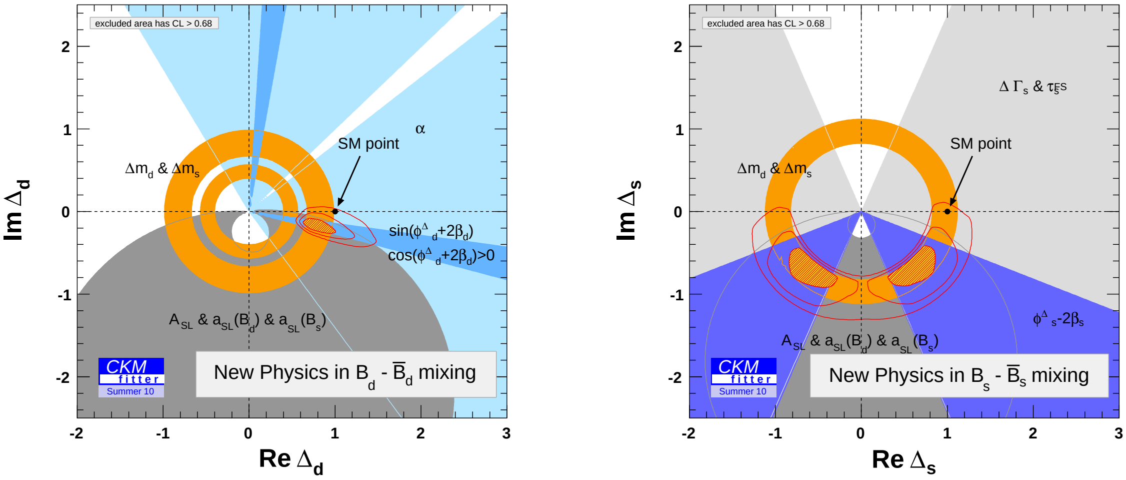


Figure 3: Allowed regions for Δ_d (left) and Δ_s (right) from the global fit [5].

have fitted the CKM elements together with complex quantities parametrising new physics in meson-antimeson mixing. For $\mathrm{B_q}-\overline{\mathrm{B}}_\mathrm{q}$ mixing these parameters are defined as

$$\Delta_q \;\equiv\; \frac{M_{12}^q}{M_{12}^{q,\mathrm{SM}}}, \qquad \Delta_q \;\equiv\; |\Delta_q| e^{i\phi_q^\Delta}, \qquad \text{with } q=d \text{ or } s.$$

For $\mathrm{K}-\overline{\mathrm{K}}$ mixing one needs three such parameters. We have considered three scenarios, with i) new physics with arbitrary flavour structure, ii) minimally flavour-violating (MFV)[e] new physics with small bottom Yukawa coupling, and iii) MFV new physics with large bottom Yukawa coupling. These scenarios correspond to i) Δ_d, Δ_s complex and unrelated, ii) $\Delta \equiv \Delta_d = \Delta_s$ real, and iii) $\Delta \equiv \Delta_d = \Delta_s$ complex, respectively. In the first and third scenario the constraint from ϵ_K is simply absent, because $\mathrm{K}-\overline{\mathrm{K}}$ mixing is unrelated to $\mathrm{B}-\overline{\mathrm{B}}$ mixing, while in scenario ii) the $\mathrm{K}-\overline{\mathrm{K}}$ mixing NP parameters can be expressed in terms of Δ. In scenario i) we obtain an excellent fit, the preferred regions in the complex $\Delta_{d,s}$ planes are shown in Fig. 3. The point $\Delta_d = 1$ is disfavoured by 2.7σ, and this discrepancy is mainly driven by $B^+ \to \tau\nu$ as discussed in Sec. 2.1. ϵ_K plays a minor role in our analysis because of our conservative error estimate of the hadronic parameter B_K. For a discussion of this issue see Soni's talk at this conference [16]. Δ_s deviates from its SM value $\Delta_s = 1$ by 2.7σ as well, with a_{fs} as the main driver. Yet also the CDF and DØ measurements of the CP phase in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing through $B_s \to J/\psi\phi$ contribute here: Both measurements favour $\phi_s < 0$, in agreement with the conclusion drawn from a_{fs} in Eq. (5). The SM point $\Delta_d = \Delta_s = 1$ is disfavoured with 3.6 standard deviations, establishing evidence of new physics. Choosing a different statistical test, $\mathrm{Im}\,\Delta_d = \mathrm{Im}\,\Delta_s = 0$ is even disfavoured at a level of 3.8σ.

It is instructive to compare our best-fit result $\phi_s^\Delta = (-52^{+32}_{-25})^\circ$ at 95% CL with the 2010 Tevatron measurements. (I do not discuss the mirror solution $\phi_s^\Delta = (-130^{+28}_{-28})^\circ$ in the third quadrant of the complex Δ_s plane here.) The results of Ref. [17] read $\phi_s^\Delta = (-29^{+44}_{-49})^\circ$ (CDF) and $\phi_s^\Delta = (-44^{+59}_{-51})^\circ$ (DØ) at 95%CL . The naive average is $\phi_s^{\mathrm{avg}} = (-36 \pm 35)^\circ$ at 95% CL. While the Tevatron measurements of ϕ_s^Δ alone contain only weak hints to new physics, they perfectly agree with our best-fit value within normal statistical fluctuations. If one discards a_{fs} in Eq. (5) altogether and instead predicts it from the fit, one finds $a_{\mathrm{fs}} = \left(-4.2^{+2.9}_{-2.7}\right) \cdot 10^{-3}$ at

[e] In MFV models all quark flavour violation is governed by the same CKM elements as in the SM.

95%CL , which is just 1.5σ away from the DØ/CDF average in Eq. (5). In total a consistent picture of new physics in $\mathrm{B}-\overline{\mathrm{B}}$ mixing emerges, with a normal upward statistical fluctuation of a_{fs} and a mild downward fluctuation of the CDF value for ϕ_s^{Δ} from $B_s \to J/\psi\phi$.

Scenario iii) also gives a reasonable fit to the data, but scenario ii) is as bad as the SM. This is bad news for the popular Constrained Minimal Supersymmetric Standard Model (CMSSM) and its variant minimal supergravity (mSUGRA), which are realisations of scenario ii).

3 Supersymmetry and grand unification

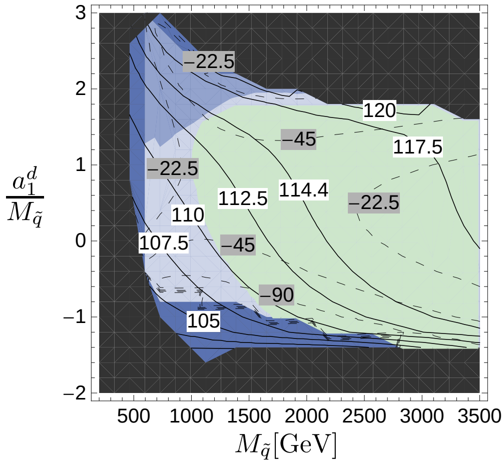
The MSSM has many new sources of flavour violation, all of which reside in the supersymmetry-breaking sector. It is easy to get big effects in $\mathrm{B_s}$–$\overline{\mathrm{B}}_\mathrm{s}$ mixing, and the challenge is to suppress big effects elsewhere. MFV variants of the MSSM cannot produce large effects in $\mathrm{B_s}$–$\overline{\mathrm{B}}_\mathrm{s}$ mixing [18]. An attractive way to deviate from MFV in a controlled way (i.e. without producing too large FCNC in observables agreeing with the SM) emerges if one embeds the MSSM into a grand unified theory (GUT). In a GUT quarks and leptons reside in the same symmetry multiplets, which opens the possibility of quark-flavour transitions driven by the leptonic mixing matrix U_{PMNS} [19, 20]. Consider SU(5) multiplets:

$$\overline{\mathbf{5}}_\mathbf{1} = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ e_L \\ -\nu_e \end{pmatrix}, \qquad \overline{\mathbf{5}}_\mathbf{2} = \begin{pmatrix} s_R^c \\ s_R^c \\ s_R^c \\ \mu_L \\ -\nu_\mu \end{pmatrix}, \qquad \overline{\mathbf{5}}_\mathbf{3} = \begin{pmatrix} b_R^c \\ b_R^c \\ b_R^c \\ \tau_L \\ -\nu_\tau \end{pmatrix}.$$

If the observed large atmospheric neutrino mixing angle stems from a rotation of $\overline{\mathbf{5}}_\mathbf{2}$ and $\overline{\mathbf{5}}_\mathbf{3}$, it will also affect the b_R and s_R superfields. While rotations of quark fields in flavour space are unphysical, this is not the case for the corresponding squark fields $\widetilde{b}_R$ and $\widetilde{s}_R$ because of the supersymmetry-breaking terms. The key ingredients of the idea of Refs. [19, 20] is the following: In a weak basis with diagonal up-type Yukawa matrix the down-type Yukawa matrix Y_d is diagonalised as $\mathsf{Y}_d = V_{\mathrm{CKM}}^* \mathrm{diag}\,(y_d, y_s, y_b) U_{\mathrm{PMNS}}$. In this basis the right-handed down-squark mass matrix has the form $\mathsf{m}_{\tilde{d}}^2 = \mathrm{diag}\,(m_{\tilde{d}}^2,\, m_{\tilde{d}}^2,\, m_{\tilde{d}}^2 - \Delta_{\tilde{d}})$ with a calculable real parameter $\Delta_{\tilde{d}}$ generated by top-Yukawa renormalisation group effects. Rotating now Y_d to diagonal form puts the large atmospheric neutrino mixing angle into $\mathsf{m}_{\tilde{d}}^2$:

$$U_{\mathrm{PMNS}}^\dagger\, \mathsf{m}_{\tilde{d}}^2\, U_{\mathrm{PMNS}} = \begin{pmatrix} m_{\tilde{d}}^2 & 0 & 0 \\ 0 & m_{\tilde{d}}^2 - \frac{1}{2}\Delta_{\tilde{d}} & -\frac{1}{2}\Delta_{\tilde{d}}\, e^{i\xi} \\ 0 & -\frac{1}{2}\Delta_{\tilde{d}}\, e^{-i\xi} & m_{\tilde{d}}^2 - \frac{1}{2}\Delta_{\tilde{d}} \end{pmatrix}$$

As a result we find large new transitions between right-handed $\widetilde{b}$ and $\widetilde{s}$ squarks while keeping all other quark FCNC transitions MFV-like. Moreover, the CP phase ξ affects $\mathrm{B_s}$–$\overline{\mathrm{B}}_\mathrm{s}$ mixing! The GUT boundary conditions further connect $b_R \to s_R$ with $\tau_L \to \mu_L$ transitions, so that $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing is correlated with $\tau \to \mu\gamma$. The CMM model realises this idea using the GUT symmetry breaking chain SO(10)$\to$ SU(5) $\to$ SU(3)$\times$SU(2)$_L\times$U(1)$_Y$. In Ref. [21] we have performed a global analysis of the CMM model, considering flavour physics data, vacuum stability bounds and the lower bounds on sparticle masses and the mass of the lightest Higgs boson. All MSSM parameters involved depend on just seven CMM-model parameters. We find that we can accommodate a large $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing phase while simultaneously obeying all other experimental constraints (see Fig. 4). In the CMM model eight of the twelve squark masses are essentially degenerate and are typically larger than 1 TeV, as can be seen from Fig. 4. Finally, corrections to the Yukawa couplings from dimension-5 terms can leak some of the CMM contribution in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing to $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ and $\mathrm{K}-\overline{\mathrm{K}}$ mixing and alleviate the tension in the fit to the UT [22].



Black: unphysical soft masses
Light blue: excluded by $\tau \to \mu\gamma$
Medium blue: excluded by $b \to s\gamma$
Dark blue: excluded by $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing
Green: allowed

Figure 4: Predictions of the CMM model for $m_{\tilde g_3} = 500$ GeV, $\tan\beta = 6$ and $\mu > 0$. $M_{\tilde q}$ is the (essentially degenerate) squark mass of the first two generations and a_1^d is the trilinear supersymmetry-breaking term of the down squarks. The dashed lines with grey labels show the value of $\phi_s \simeq \phi_s^\Delta$ in degrees, the solid lines with white labels show the mass of the lightest neutral Higgs boson. The black and blue regions are excluded.

4 Conclusions

Precision data of flavour physics put the Standard Model under pressure. The global analysis of Ref. [5] disfavours the SM at a level of 3.6σ and reveals a consistent picture of new CP-violating physics in meson-antimeson mixing. The data cannot be accommodated in the popular CMSSM and mSUGRA scenarios. However, the large CP phase in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing can naturally be explained in GUT models which link the large atmospheric neutrino mixing angle to novel $b \to s$ transitions [19, 20]. Our recent quantitative analysis, which relates FCNC observables, the Higgs mass and other theoretical and experimental constraints to just seven parameters, has found that this idea is indeed viable and permits large effects in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing [21].

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