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Towards the Identification of New Physics through Correlations between Flavour Observables

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We emphasize the power of correlations between flavour observables in the search for New Physics and identify a number of correlations that could allow to discover New Physics even if it would appear at the level of 15% of the Standard Model contributions. After presenting the simplest correlations in CMFV and $U(2)^3$ models we address the recent data on $B_{s,d} \to \mu^+\mu^-$ as well as anomalies in $B_d \to K^*\mu^+\mu^-$ in the context of Z'-models and SM Z, both with tree-level FCNC couplings. A strategy consisting of twelve steps which concentrate on theoretically clean observables, to be measured in this decade, could one day allow us to reach the Zeptouniverse. The related DNA charts based on the correlations between enhancements and suppressions of various observables in a given New Physics scenario relative to the Standard Model predictions allow a transparent distinction between various extensions of this model.

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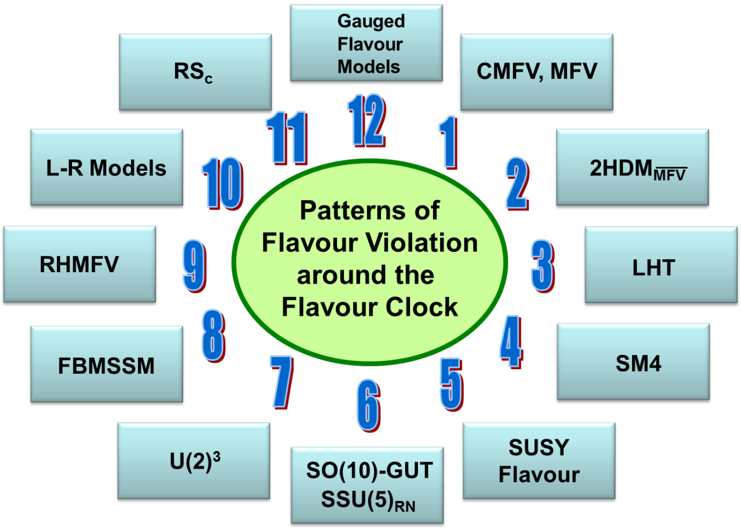

Figure 1: *Studing Multitude of Extensions of the Standard Model.*

1. Overture and Strategy

In spite of tremendous efforts of experimentalists and theorists to find New Physics (NP) beyond the Standard Model (SM), no clear indications for NP beyond dark matter, neutrino masses and matter-antimatter asymmetry in the universe have been observed. Yet, not only for these three reasons we expect that some new particles and new forces have to exist. The present talk discusses what flavour physics can contribute to the identification of these particles. In this context I will discuss some of the strategies for reaching this goal developed in my group at the Technical University in Munich during last ten years. They are summarized in [1].

The identifcation of NP through rare processes will require many precise measurements of many observables and precise theory. Moreover it will require intensive studies of correlations between many observables in a given extension of the SM with the goal to identify patterns of deviations from the SM expectations characteristic for this extension. Having this in mind we have investigated flavour violating and CP-violating processes in a multitude of models. The names of models analyzed by us until June 2012 are collected in Fig. 1. A summary of these studies can be found in [2, 3]. Here, I will concentrate on most recent analyses that have been performed after the second of these two reviews and are not shown in Fig. 1. They are reviewed in [1].

2. Simplest Correlations

The first one is in models with contrained Minimal Flavout Violation (CMFV) [4]

$$\frac{\mathcal{B}(B_s \to \mu^+\mu^-)}{\mathcal{B}(B_d \to \mu^+\mu^-)} = \frac{\hat{B}_d}{\hat{B}_s}\frac{\tau(B_s)}{\tau(B_d)}\frac{\Delta M_s}{\Delta M_d} r, \qquad \frac{\hat{B}_d}{\hat{B}_s} = 0.99 \pm 0.02 \tag{2.1}$$

where the departure of r from unity measures effects which go beyond CMFV. This relation does not involve F_{B_q} and CKM parameters. It involves only measurable quantities except for the ratio

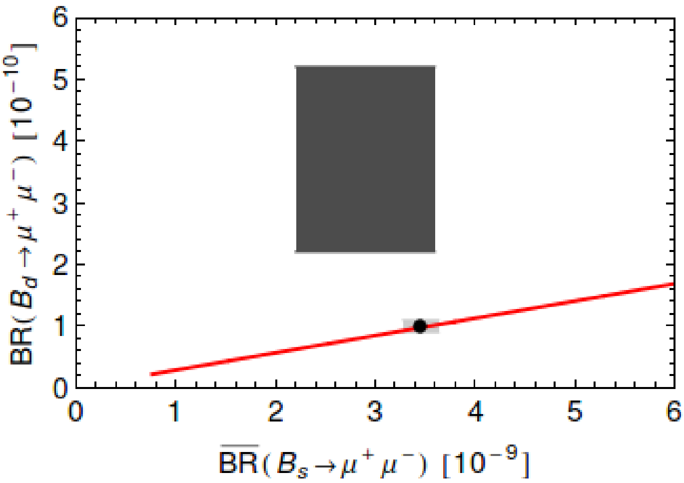

Figure 2: *$\mathscr{B}(B_d \to \mu^+\mu^-)$ vs $\overline{\mathscr{B}}(B_s \to \mu^+\mu^-)$ in models with CMFV. SM is represented by the light grey area with black dot. Dark gray region: Overlap of exp 1σ ranges for $\overline{\mathscr{B}}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \cdot 10^{-9}$ and $\mathscr{B}(B_d \to \mu^+\mu^-) = (3.6^{1.6}_{-1.4}) \times 10^{-10}$. From [1].*

$\hat{B}_s/\hat{B}_d$ that is known from lattice calculations with impressive accuracy of roughly $\pm 2\%$ [5]. The precision with which r.h.s of this equation is known should allow to identify possible NP in $B_{s,d} \to \mu^+\mu^-$ decays and also in $\Delta M_{s,d}$ even if it was only at the level of $10-15\%$ of the SM contributions.

We compare (2.1) with the most recent data from LHCb and CMS in Fig. 2. The SM predictions [6, 7] and the most recent averages from LHCb [8] and CMS [9] are given as follows:

$$\overline{\mathscr{B}}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.56 \pm 0.18) \cdot 10^{-9}, \quad \overline{\mathscr{B}}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}, \tag{2.2}$$

$$\mathscr{B}(B_d \to \mu^+\mu^-)_{\rm SM} = (1.05 \pm 0.07) \times 10^{-10}, \quad \mathscr{B}(B_d \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}. \tag{2.3}$$

The "bar" in the case of $B_s \to \mu^+\mu^-$ indicates that $\Delta\Gamma_s$ effects have been taken into account. From these data we find $r_{\rm exp} = 0.23 \pm 0.11$ to be compared with $r = 1$ in CMFV. Even if in view of large experimental uncertainties one cannot claim that here NP is at work, the plot in Fig. 2 invites us to investigate whether the simplest NP models beyond CMFV could cope with the future more precise data in which the central experimental values in (2.2) and (2.3) would not change by much.

In CMFV and MFV, that are both based on the $U(3)^3$ flavour symmetry, the measurement of the mixing induced asymmetry $S_{\psi K_S}$ together with the unitarity of the CKM implies that the analogous asymmetry in the $B_s^0 - \bar{B}^0$ system, $S_{\psi\phi} = 0.036 \pm 0.002$. Presently the data give $S_{\psi K_S} = 0.679 \pm 0.020$ and $S_{\psi\phi} = -0.01 \pm 0.07$ and although $S_{\psi\phi}$ is found to be small [11] it can still significantly differ from its SM value, in particular if it had negative sign.

If this indeed turned out to be the case, one possible solution would be to decrease the flavour symmetry down to $U(2)^3$. As pointed out in [12] in the simplest versions of these models there is a stringent triple correlation $S_{\psi K_S} - S_{\psi\phi} - |V_{ub}|$ that constitutes an important test of this NP scenario. It is shown in Fig. 3. Yet, in this simple scenario the relation (2.1) is still valid [12] and in order to explain the data in Fig. 2 we have to look for other alternatives.

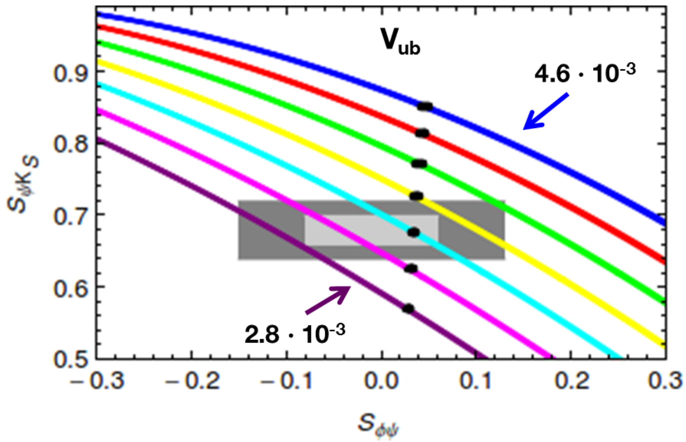

Figure 3: $S_{\psi K_S}$ *vs.* $S_{\psi\phi}$ *in models with* $U(2)^3$ *symmetry for different values of* $|V_{ub}|$ *and* $\gamma \in [58^\circ, 78^\circ]$. *From top to bottom:* $|V_{ub}| = 0.0046$ *(blue),* 0.0043 *(red),* 0.0040 *(green),* 0.0037 *(yellow),* 0.0034 *(cyan),* 0.0031 *(magenta),* 0.0028 *(purple). Light/dark gray: experimental* $1\sigma/2\sigma$ *region.*

3. Correlations between Flavour Observables in Models with Tree Level FCNCs

During the last year we have studied flavour observables in models in which FCNC processes are mediated at tree-level by neutral gauge bosons [13–15] and neutral scalars or pseudoscalars [7, 16]. While such processes have been studied in the literature for the last three decades, we still could contribute to this field by identifying certain correlations between several flavour observables.

These models have a small number of parameters: in addition to the mass $M_{Z'}$ only the left-handed and/or right-handed couplings of Z' to quarks $\Delta^{ij}_{A,B}$ with $(A,B) = (L,R)$ and $i, j = d, s, b$. Once these couplings are constrained by $\Delta F = 2$ observables, predictions for rare decays and in particular for correlations between various observables can be made [14, 16]. It is interesting that the pattern of these correlations depends on whether a gauge boson, a scalar or pseudoscalar mediates the FCNC transition. As the scalar contributions cannot interfere with SM contributions, only enhancements of branching ratios are possible in this case. A tree-level gauge boson contribution and pseudoscalar contribution interfer generally with the SM contribution but the resulting correlations between observables have different pattern because of the i in the coupling $i\gamma_5$ of pseudoscalar to leptons. In Fig. 4 we show the correlation between $S_{\psi\phi}$ and $\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)$ in the case of pure left-handed Z', pseudoscalar and scalar couplings. One should only note rather spectacular differences between these three NP scenarios, that can be distinguished from each other provided the departures from SM values are sufficiently large. More details can be found in [14, 16].

4. Tree-Level FCNCs Facing New Data

In addition to new results on $B_{s,d} \to \mu^+\mu^-$, LHCb collaboration reported anomalies in angular observables in $B_d \to K^*\mu^+\mu^-$ [20, 21]. Also the data on the observable F_L, consistent with LHCb value in [20], reported by CMS [22] are a bit below its SM value. These anomalies in $B_d \to K^*\mu^+\mu^-$ triggered two sophisticated analyses [17, 18]. Both analyses point toward NP contributions to the Wilson coefficients $C_{7\gamma}$ and C_9 with $C^{\rm NP}_{7\gamma} < 0$ and $C^{\rm NP}_9 < 0$. Other possibilities,

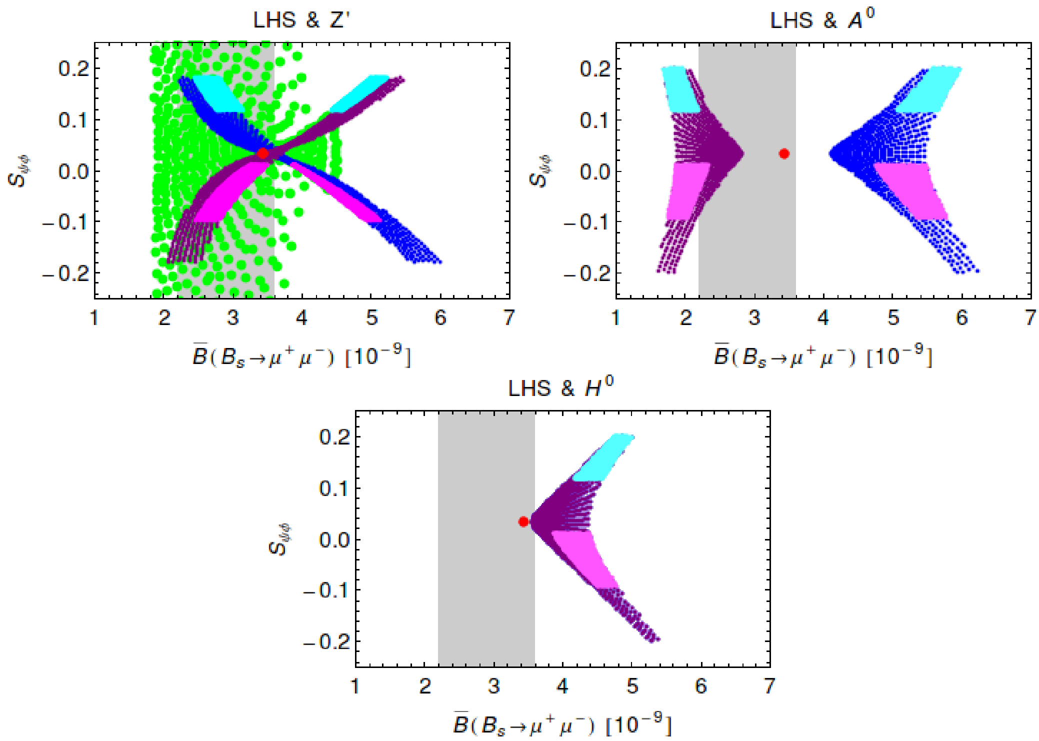

Figure 4: *$S_{\psi\phi}$ versus $\overline{\mathscr{B}}(B_s \to \mu^+\mu^-)$ in different tree-level NP scenarios as explained in the text with $M_{Z'} = M_{A^0} = M_{H^0} = 1$ TeV. Gray region: exp 1σ range $\overline{\mathscr{B}}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \cdot 10^{-9}$. Red point: SM central value.*

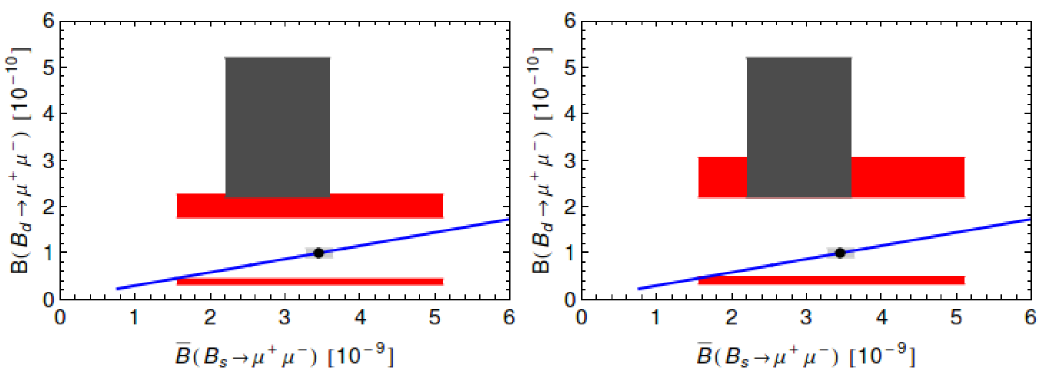

Figure 5: $\mathscr{B}(B_d \to \mu^+\mu^-)$ versus $\bar{\mathscr{B}}(B_s \to \mu^+\mu^-)$ for $|V_{ub}| = 0.0034$ (left) and $|V_{ub}| = 0.0040$ (right) and $C_{B_d} = 1.04 \pm 0.01$, $C_{B_s} = 1.00 \pm 0.01$. Z' case.

in particular involving right-handed currents, have been discussed in [18]. Assuming that these anomalies are not statistical fluctuations and/or the result of underestimated theoretical errors we have investigated in [19] whether tree-level Z' and Z-exchanges could simultaneously explain the $B_d \to K^*\mu^+\mu^-$ anomalies and the most recent data on $B_{s,d} \to \mu^+\mu^-$. The outcome of this rather extensive analysis can be briefly summarized as follows.

The so-called LHS scenario for Z' or Z FCNC couplings (only left-handed couplings are

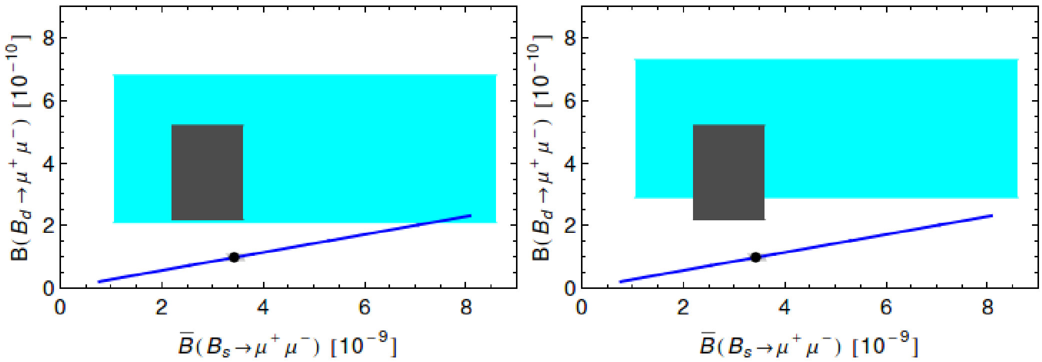

Figure 6: $\mathscr{B}(B_d \to \mu^+\mu^-)$ versus $\bar{\mathscr{B}}(B_s \to \mu^+\mu^-)$ for $|V_{ub}| = 0.0034$ (left) and $|V_{ub}| = 0.0040$ (right) and $C_{B_d} = 0.96 \pm 0.01$, $C_{B_s} = 1.00 \pm 0.01$. Z-case.

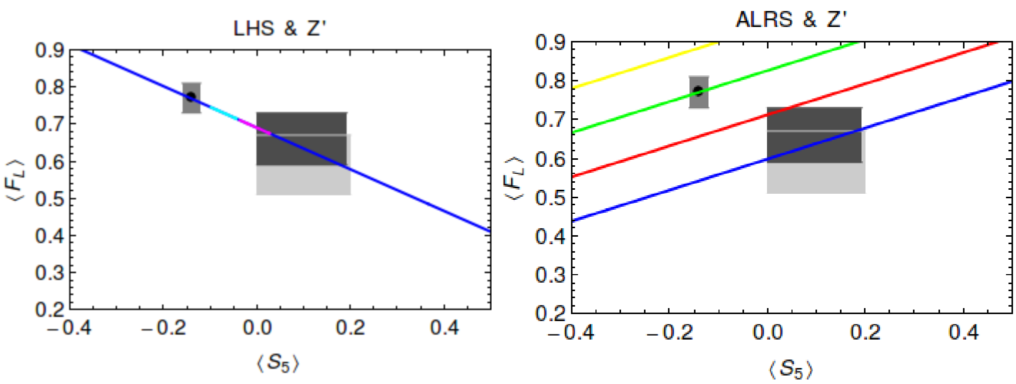

Figure 7: Left: $\langle F_L \rangle$ versus $\langle S_5 \rangle$ in LHS where the magenta line corresponds to $C_9^{\rm NP} = -1.6 \pm 0.3$ and the cyan line to $C_9^{\rm NP} = -0.8 \pm 0.3$. Right: The same in ALRS for different values of $C_9^{\rm NP}$: -2 (blue), -1 (red), 0 (green) and 1 (yellow). The light and dark gray area corresponds to the experimental range for $\langle F_L \rangle$ with all data and only LHCb+CMS data, taken into account, respectively. The black point and the gray box correspond to the SM predictions from [18].

flavour violating) provides a simple model that allows for the violation of the CMFV relation in (2.1). The plots in Figs. 5 and 6 for Z' and Z illustrate this. To achieve this in the case of Z' the value of ΔM_s must be very close to its SM value and ΔM_d is favoured to be by 5% *larger* than $(\Delta M_d)_{\rm SM}$. $S_{\psi\phi}$ can still deviate significantly from its SM value. In the case of Z, both ΔM_s and $S_{\psi\phi}$ must be rather close to their SM values while ΔM_d is favoured to be by 5% *smaller* than $(\Delta M_d)_{\rm SM}$. As far as the anomalies in $B \to K^*\mu^+\mu^-$ are concerned Z' with only left-handed couplings is capable of softening the anomalies in the observables F_L and S_5 in a correlated manner as proposed [17, 18]. However, a better description of the present data is obtained by including also right-handed contributions with the RH couplings of approximately the same magnitude but opposite sign. This is so-called ALRS scenario of [14]. We illustrate this in Fig. 7. Several analogous correlations can be found in [19]. The SM Z boson with FCNC couplings to quarks cannot describe the anomalies in $B \to K^*\mu^+\mu^-$ due to its small vector coupling to muons.

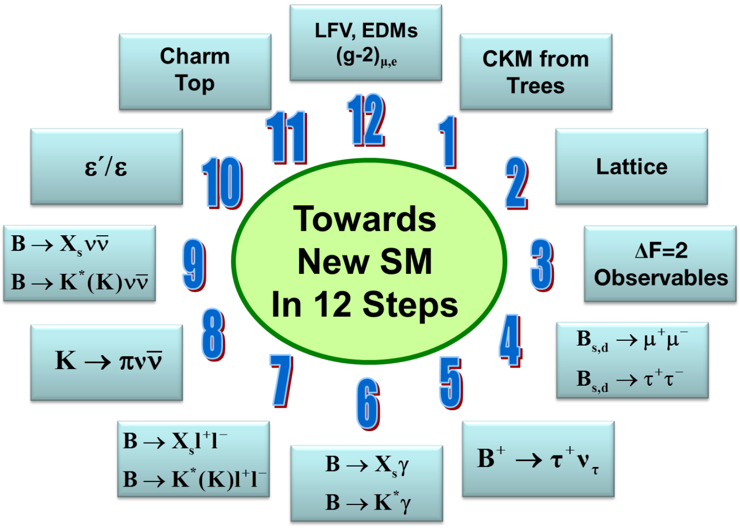

Figure 8: *Towards New Standard Model in 12 Steps.*

5. Towards the new SM in 12 Steps and DNA-Charts

The identification of NP indirectly will require many measurements. The most important are shown in Fig. 8 taken from [1], where we have outlined a strategy consisting of 12 steps for identifying the correct extension of the SM. Finding the deviations from SM predictions for the observables listed there and studying correlations between these deviations should allow at least to identify some routes to be followed that one day could bring us to the Zeptouniverse.

As emphasized in [1] already the pattern of signs of departures from SM expectations in various observables and the correlations or anti-correlations between these departures could exclude or support certain scenarios. In order to depict various possibilities in a transparent manner a DNA-Chart has been proposed to be applied separately to each NP scenario. In Fig. 9 we show the DNA-chart of CMFV and the corresponding chart for $U(2)^3$ models is shown in Fig. 10. The DNA-charts representing models with left-handed and right-handed flavour violating couplings of Z and Z' can be found in Fig. 11. The interested reader may check that these charts summarize compactly the correlations that are discussed in detail at various places in [1]. In summary there are exciting times ahead of us and following the 12 Steps in Fig. 8 we may one day reach Zeptouniverse.

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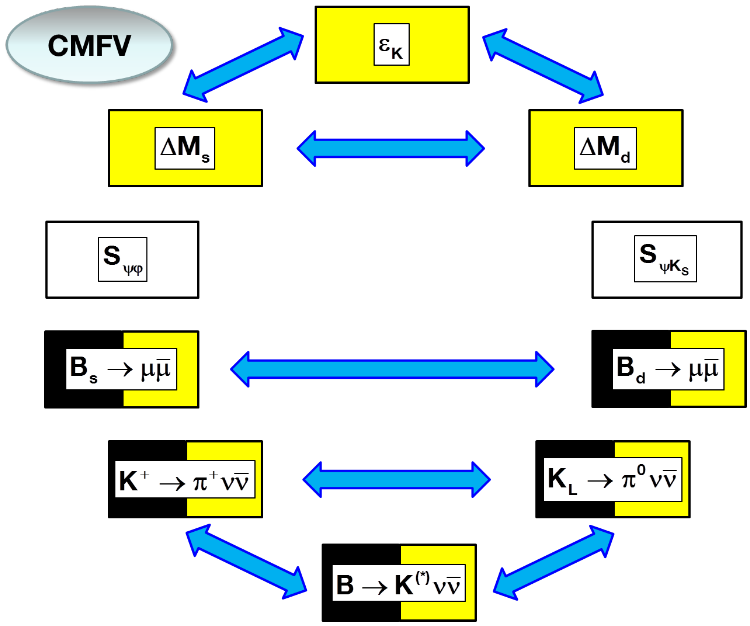

Figure 9: *DNA-chart of CMFV models. Yellow means* *enhancement*, *black means* **suppression** *and white means* *no change*. *Blue arrows* ⇔ *indicate correlation and green arrows* ⇔ *indicate anti-correlation.*

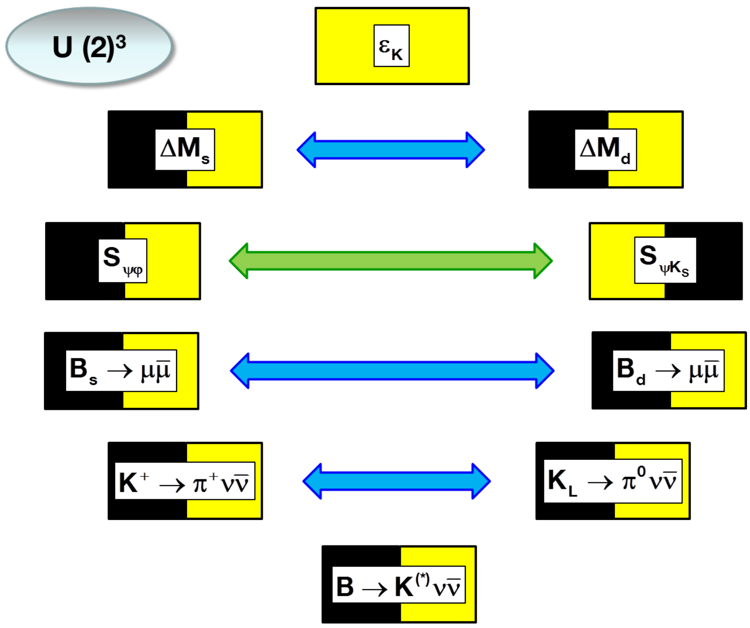

Figure 10: *DNA-chart of* $U(2)^3$ *models. Yellow means* *enhancement*, *black means* **suppression** *and white means* *no change*. *Blue arrows* ⇔ *indicate correlation and green arrows* ⇔ *indicate anti-correlation.*

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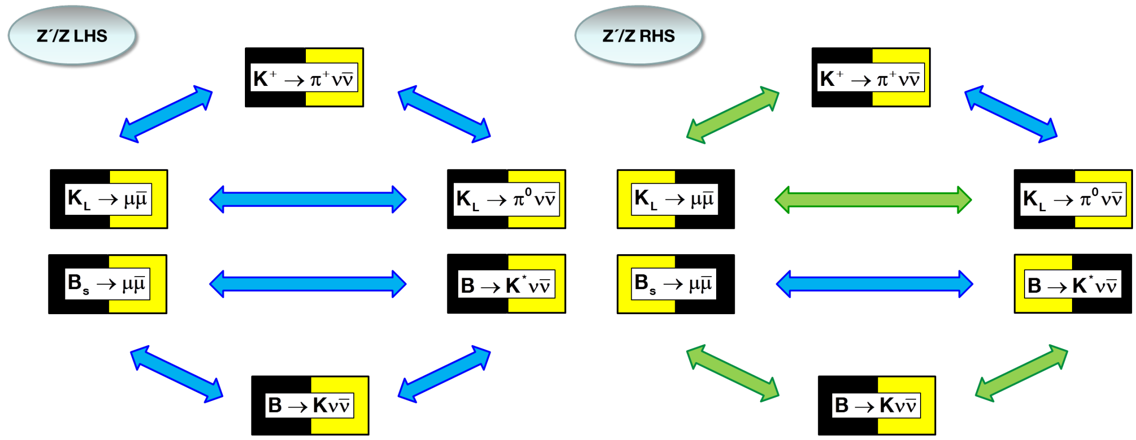

Figure 11: *DNA-charts of Z' models with LH and RH currents. Yellow means* *enhancement*, *black means* **suppression** *and white means* *no change*. *Blue arrows* ⇔ *indicate correlation and green arrows* ⇔ *indicate anti-correlation.*

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