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Quark flavour observables in 331 models in the flavour precision era

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I discuss a new Physics scenario, the 331 model, based on the gauge group $SU(3)_c \times SU(3)_L \times U(1)_X$. In particular, I elaborate on correlations between flavour observables in the B_d and B_s systems that can help constraining the model parameters.

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1. Motivations

Small tensions exist between the Standard Model (SM) predictions and data on flavour observables. Understanding whether they represent signals of new Physics (NP) requires a strong reduction in the uncertainty affecting such observables, both from the theoretical and experimental point of view. Among such tensions, one can mention the anomalies observed in the angular analysis of the decay $B \to K^* \mu^+ \mu^-$ [1] as well as unexpectedly large branching fractions of semileptonic B decays to a τ lepton in the final state. While improved measurements of the branching ratio of the purely leptonic $B \to \tau \bar{\nu}_\tau$ mode [2] are close to theory predictions, a discrepancy between experimental data [3] and theory holds in the case of the processes $B \to D^{(*)} \tau \bar{\nu}_\tau$, which seem to be anomalously enhanced with respect to SM predictions [4]. NP models that might explain the anomaly without contributing to $\mathcal{B}(B \to \tau \bar{\nu}_\tau)$ have been proposed [5] and await improved experimental data to be contrasted to.

A intriguing question concerns the value of $|V_{ub}|$, since the determination from exclusive B decays turns out to be smaller than the one from inclusive modes. Denoting by scenario 1 (S1) that in which $|V_{ub}|$ assumes the smaller value $|V_{ub}| = 3.1\ 10^{-3}$ and scenario 2 (S2) that in which $|V_{ub}| = 4.0\ 10^{-3}$, there are several observables for which the agreement of the SM prediction with data depends whether S1 or S2 are realized. In particular, the following conclusions can be drawn in S1:

- S1 requires NP enhancing of $\mathcal{B}(B \to \tau \nu_\tau)$;
- it reproduces the experimental value for the CP asymmetry $S_{J/\psi K_s}$ in $B \to J/\psi K_s$;
- it suppresses ε_K with respect to experiment.

The opposite conclusions are reached in S2. As for the mass differences $\Delta M_{d,s}$ in the $B_{d,s} - \bar{B}_{d,s}$ systems, their dependence on $|V_{ub}|$ is mild, so that in both cases agreement with experiment is found within the uncertainties, even though NP models that predict a small suppression of these quantities are slightly favoured.

This discussion shows that in order to understand whether in the LHC era a number of NP scenarios may be discarded and the space of parameters of others can be constrained, more precise data and theoretical inputs are required. In view of this, it is interesting to try to predict what will happen in the flavour precision era, ahead of us, in which we can assume that

- experimental data are affected by a much reduced uncertainty;
- non perturbative parameters have been precisely calculated;
- CKM matrix elements have been determined by means of tree-level decays (except for $|V_{ub}|$).

In this paper, following [6], I discuss a NP model, the so-called 331 model, assuming that this era is already realized, showing the predicions for a number of flavour observables in $B_{d,s}$ systems.

2. The model

The name 331 encompasses a class of models based on the gauge group $SU(3)_c \times SU(3)_L \times U(1)_X$ [7], that is at first spontaneously broken to the Standard Model group $SU(3)_c \times SU(2)_L \times U(1)_Y$ and then undergoes the spontaneous symmetry breaking to $SU(3)_c \times U(1)_Q$. The extension of the gauge group with respect to SM leads to interesting consequences. The first one is that the requirement of anomaly cancelation together with that of asymptotic freedom of QCD implies that the number of generations must necessarily be equal to the number of colours, hence giving an explanation for the existence of three generations. Furthermore, quark generations should transform differently under the action of $SU(3)_L$. In particular, two quark generations should transform as triplets, one as an antitriplet. Choosing the latter to be the third generation, this different treatment could be at the origin of the large top mass.

A fundamental relation holds among some of the generators of the group: $Q = T_3 + \beta T_8 + X$ where Q indicates the electric charge, T_3 and T_8 are two of the $SU(3)$ generators and X is the generator of $U(1)_X$. β is a key parameter that defines a specific variant of the model. Here I focus on the case $\beta = \frac{1}{\sqrt{3}}$ ($\overline{331}$ model), since the resulting scenario turns out to be phenomenologically more interesting than other variants. Moreover, the new gauge bosons, that are present due to the enlarged gauge group, have integer charges for this value of β.

The model comprises several new particles. There are new gauge bosons Y and V, whose charges depend on the considered variant. In $\overline{331}$ they are a singly charged $Y^{\pm}$ boson and a neutral one $V^0(\bar{V}^0)$. In all the variants a new neutral gauge boson Z' is present. This represents a very appealing feature, since Z' mediates tree level flavour changing neutral currents (FCNC) in the quark sector (couplings to leptons are instead universal). An extended Higgs sector is also present, with three $SU(3)_L$ triplets and one sextet. Finally, new heavy fermions are predicted; I will not consider them in this discussion.

As in the SM, quark mass eigenstates are defined upon rotation of flavour eigenstates through two unitary matrices U_L (for up-type quarks) and V_L (for down-type ones). The relation $V_{CKM} = U_L^{\dagger} V_L$ holds in analogy with the SM case. However, while in SM V_{CKM} appears only in charged current interactions and the two rotation matrices never appear individually, in this model only one matrix between U_L and V_L can be expressed in terms of V_{CKM} and the other one; the remaining rotation matrix enters in the Z' couplings to quarks. One can choose V_L to be the surviving rotation matrix and parametrize it as follows:

$$V_L = \begin{pmatrix} \tilde{c}_{12}\tilde{c}_{13} & \tilde{s}_{12}\tilde{c}_{23}e^{i\delta_3} - \tilde{c}_{12}\tilde{s}_{13}\tilde{s}_{23}e^{i(\delta_1-\delta_2)} & \tilde{c}_{12}\tilde{c}_{23}\tilde{s}_{13}e^{i\delta_1} + \tilde{s}_{12}\tilde{s}_{23}e^{i(\delta_2+\delta_3)} \\ -\tilde{c}_{13}\tilde{s}_{12}e^{-i\delta_3} & \tilde{c}_{12}\tilde{c}_{23} + \tilde{s}_{12}\tilde{s}_{13}\tilde{s}_{23}e^{i(\delta_1-\delta_2-\delta_3)} & -\tilde{s}_{12}\tilde{s}_{13}\tilde{c}_{23}e^{i(\delta_1-\delta_3)} - \tilde{c}_{12}\tilde{s}_{23}e^{i\delta_2} \\ -\tilde{s}_{13}e^{-i\delta_1} & -\tilde{c}_{13}\tilde{s}_{23}e^{-i\delta_2} & \tilde{c}_{13}\tilde{c}_{23} \end{pmatrix} . \tag{2.1}$$

With this parametrization, considering the Feynmann rules for Z' couplings to quarks, it can be noticed that the B_d system involves only the parameters $\tilde{s}_{13}$ and δ_1 while the B_s system depends on $\tilde{s}_{23}$ and δ_2. Stringent correlations between observables in $B_{d,s}$ sectors and in the kaon sector are found since kaon physics depends on $\tilde{s}_{13}$, $\tilde{s}_{23}$ and $\delta_2 - \delta_1$. I refer to [6] for the analysis of these correlations and for predictions on kaon observables; in the next section I analyse the $B_{d,s}$ phenomenology, exploiting data on $\Delta F = 2$ processes to constrain the above parameters in restricted

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oases and to predict correlations between $\Delta F = 1$ observables that might allow to identify the right oasis, if any exists, which would mean that the model has a chance to be realized in Nature.

3. Determining the optimal oasis in the parameter space

As a preliminary, I fix the mass of the Z' in the range $1 \leq M_{Z'} \leq 3$ TeV, in the reach of LHC. FCNC mediated by Z' involve only left-handed quarks and have the structure

$$i\mathscr{L}_L(Z') = i\left[\Delta_L^{sd}(Z')(\bar{s}\gamma^\mu P_L d) + \Delta_L^{bd}(Z')(\bar{b}\gamma^\mu P_L d) + \Delta_L^{bs}(Z')(\bar{b}\gamma^\mu P_L s)\right] Z'_\mu \,, \tag{3.1}$$

where $P_L = \frac{1-\gamma_5}{2}$ and the effective couplings Δ depend on the parameters $\tilde{s}_{13}$, $\tilde{s}_{23}$ and δ_1, δ_2.

I consder $\Delta F = 2$ observables, namely the $B_{d,s} - \bar{B}_{d,s}$ mass differences $\Delta M_{d,s}$, the CP asymmetries $S_{J/\psi K_s}$ in the decay $B_d \to J/\psi K_s$ and $S_{J/\psi\phi}$ in the mode $B_s \to J/\psi\phi$. Imposing that $\Delta M_{d,s}$ vary in a range within $\pm 5\%$ of their experimental central value, while $S_{J/\psi K_s}$ and $S_{J/\psi\phi}$ vary within a 2σ range of their experimental measurements [8], the resulting constraints

$$\begin{aligned} 0.48\,\mathrm{ps}^{-1} \leq \;& \Delta M_d \;\leq 0.53\,\mathrm{ps}^{-1} \\ 0.64 \leq \;& S_{J/\psi K_s} \;\leq 0.72 \\ 16.9\,\mathrm{ps}^{-1} \leq \;& \Delta M_s \;\leq 18.7\,\mathrm{ps}^{-1} \\ -0.15 \leq \;& S_{\psi\phi} \;\leq 0.15 \end{aligned} \tag{3.2}$$

permit to find allowed oases for the four parameters under consideration. The result is shown in

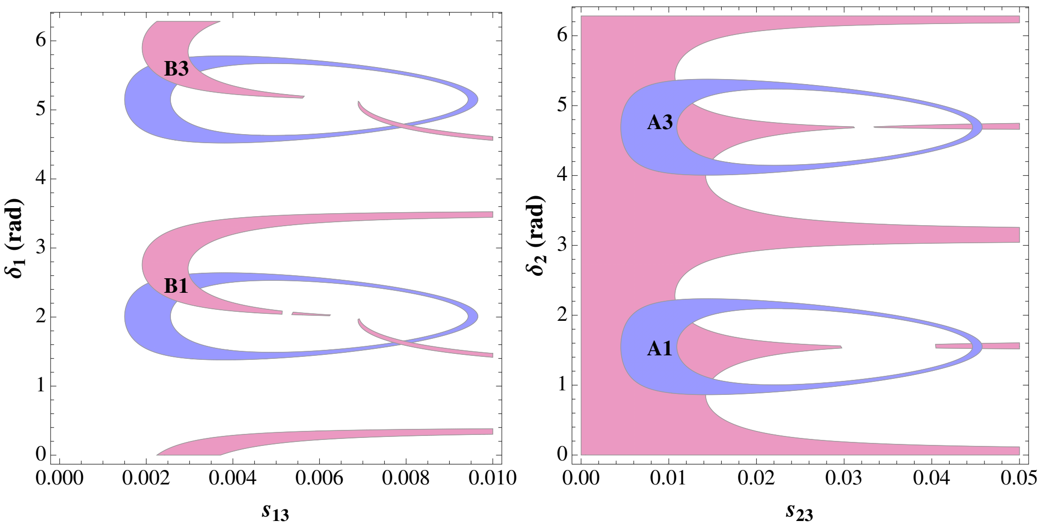

Figure 1: Left panel: Ranges for ΔM_d (violet region) and $S_{\psi K_s}$ (pink region). Right panel: Ranges for ΔM_s (violet region) and $S_{\psi\phi}$ (pink region).

fig.1 in which the left panel refers to the B_d case, the right one to the B_s case, both in S1 scenario. Four oases are found in each case constraining the pairs $(\tilde{s}_{13}, \delta_1)$ (from B_d) and $(\tilde{s}_{23}, \delta_2)$ (from B_s). In both cases two large oases (A1, A3 for B_s, B1, B3 for B_d, indicated in fig.1) are present together with two small ones; the latter can be discarded by imposing further experimental constraints on the mixing phase. Therefore I am going to discuss how to find the optimal oasis for the parameters $(\tilde{s}_{13},\delta_1),(\tilde{s}_{23},\delta_2)$ among the four pairs (A_1,B_1), (A_1,B_3), (A_3,B_1), (A_3,B_3).

For this purpose, other observables should be considered. Important modes are $B_{s,d}\to\mu^+\mu^-$ [9], that have been recently observed by the LHCb and CMS Collaborations [10, 11]. The experimental analysis was optimized for B_s case, and the result is in agreement with the SM. In the case of B_d the SM prediction is below the data, but the analysis still needs to be optimized for B_d before conclusions can be reached.

From the theory point of view, the SM effective hamiltonian for these decays depends only on a single real function $Y_0(x_t)$ $(x_t=\frac{m_{top}^2}{M_W^2})$, which is independent of the decaying meson and of lepton flavour. Its expression can be found e.g. in [12]. The new Z' contribution modifies this function to a new one $Y(B_q)$ that now is different for B_d and B_s and has a complex phase $\theta_Y^{B_q}$, $q=d,s$ [6] . As a consequence, a CP asymmetry can be predicted in these modes, which reads: $S^q_{\mu^+\mu^-}=\sin(2\theta_Y^{B_q}-2\phi_{B_q})$, ϕ_{B_q} being a new phase entering in the mixing $B_q-\bar{B}_q$ that is absent in SM. Therefore, these modes provide two observables: their branching ratio and the CP asymmetry. I discuss as an example the case of B_s system and show how the correlation between these observables and those related to $\Delta F=2$ processes can uniquely identify the optimal oasis. Indeed, from fig.2 one can

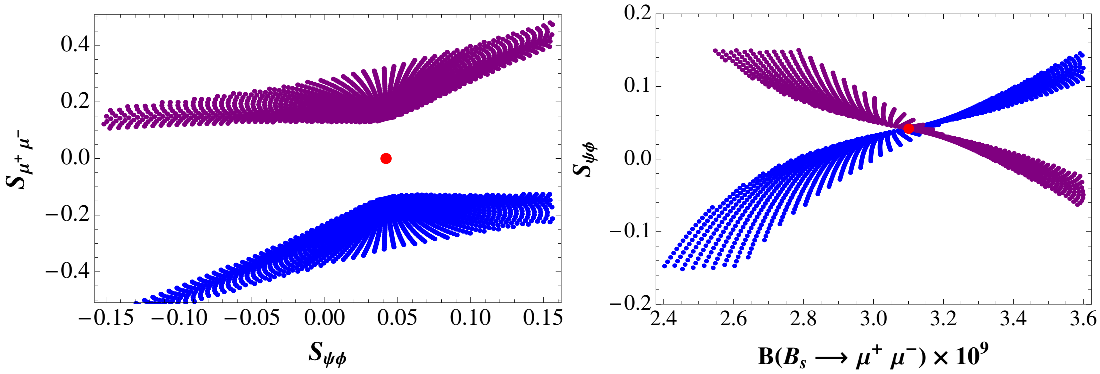

Figure 2: Left panel: $S^s_{\mu^+\mu^-}$ vs $S_{\psi\phi}$. Right panel: $S^s_{\mu^+\mu^-}$ vs $BR(B_s\to\mu^+\mu^-)$. Blue regions correspond to the contribution of oasis A1, purple regions to the contribution of A3. The red points represent the SM predictions.

see a triple correlation. The plot in the left panel shows the two CP asymmetries $S^s_{\mu^+\mu^-}$ versus $S_{\psi\phi}$. Measuring $S^s_{\mu^+\mu^-}$ above its SM value, represented by the red point, would select the oasis A3, while in the opposite case the oasis A1 should be chosen. Once this has been done, the right panel can be considered as a test of the model. In fact, it shows that $S_{\psi\phi}$ and the branching fraction $B(B_s\to\mu^+\mu^-)$ are correlated in oasis A1 and anticorrelated in A3. This means that if A_1 has been selected, $S_{\psi\phi}$ above (below) its SM value would imply $B(B_s\to\mu^+\mu^-)$ also above (below) its SM value, while the opposite correlation occurs in A_3. Measured incoherence between these two plots would mean that the model has to be discarded.

Many other observables can be considered, that can help further in the search for the optimal oasis; in [6] a comprehensive analysis of $B_{d,s}$ and K phenomenology can be found. It is worth mentioning that the model can produce values of ε_K in agreeement with experiment both in S1 and S2 scenarios, i.e. independently of the value of $|V_{ub}|$.

4. Conclusions

331 models are interesting extensions of the SM, with dominant new Physics contributions from tree level Z' exchanges. In this framework it is possible to remove existing tensions between the SM and experimental data when the mass of Z' is varied in the range $1 \leq M(Z') \leq 3$ TeV. In this case, the parameters of the model can be constrained in restricted oases using data on $\Delta F = 2$ observables. Correlations among other quantities of interest, in particular processes induced by $\Delta F = 1$ transitions, might allow to identify the optimal oasis and, simultaneously, serve as test of the model. I have shown this in a particular case, i.e. underlying a triple correlation existing in the B_s sector.

If the mass of Z' is increased, it is still possible to find allowed oasis. However, the deviations from SM become smaller, so that the model could be hardly tested in this case. The model provides also a concrete example of a scenario in which a new Z' boson is predicted to exist. A model independent analysis of correlations in the three systems of B_d, B_s and K mesons can be found in [13].

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