# From the KM ansatz to the search of New Physics in ΔF=2 FCNC

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# From the KM ansatz to the search of New Physics in $|\Delta B| = 2$ FCNC

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We present the current status of the metrology of the CKM matrix using a frequentist global fit. The current experimental data are found consistent with the Standard-Model framework establishing the KM mechanism as the dominant source of CP violation at the electroweak scale. Yet, measurements exhibit an ongoing discrepancy between the fit prediction and the direct measurement of $\mathscr{B}(B \to \tau\nu)$ and $\sin 2\beta$. This discrepancy has little to do with the semileptonic extraction of $|V_{ub}|$ or the lattice QCD calculation of $f_{B_d}$. Model-independent constraints on the $B$-$\bar{B}$ mixing in the $B_d$ and $B_s$ systems are then given. The discrepancy $\sin 2\beta$ versus $\mathscr{B}(B \to \tau\nu)$ can be accommodated by a new CP-violation phase in the $B_d$ mixing, in agreement with the latest $A_{SL}(D0)$ measurement.

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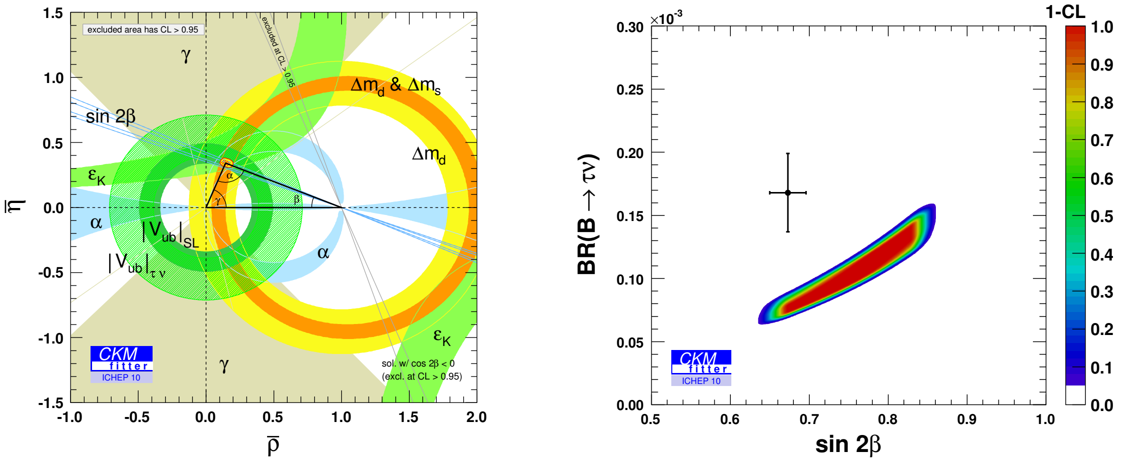


**Figure 1:** On the left: 95% CL constraints on the UT from the SM global fit. On the right: Constraint in the $(\sin 2\beta, \mathscr{B}(B \to \tau\nu))$ plane. The colored constraint represents the prediction for these quantities from the global fit when these inputs are removed while the cross represents the measurements with a $1\sigma$ uncertainty.

## 1. Standard Model Quark-Mixing Matrix

The Standard Model (SM) of electroweak interactions describes CP violation in weak interactions as a consequence of a single non-vanishing complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1], known as the KM mechanism or ansatz. The CKM matrix, $V$, depends on four real parameters which are fundamental constants. They can be defined as: $\lambda^2 = |V_{us}|^2/(|V_{ud}|^2+|V_{us}|^2)$, $A^2\lambda^4 = |V_{cb}|^2/(|V_{ud}|^2+|V_{us}|^2)$, $\bar{\rho}+i\bar{\eta} = V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)$. They provide a unitary-exact Wolfenstein-like parametrization and rephasing-invariant quantities. These quantities are determined experimentally by tree-level charged-current processes. $\lambda$ is determined from $|V_{ud}|$ (superallowed nuclear transitions) and $|V_{us}|$ (semileptonic kaon decays) to a combined precision of 0.4%. $A$ is determined from $|V_{cb}|$ (inclusive and exclusive semileptonic $B$ decays) to a combined precision of about 2.5%. While $\lambda$ and $A$ are well-known, the parameters $\bar{\rho}$ and $\bar{\eta}$ are more uncertain (about 17% for $\bar{\rho}$ and 5% for $\bar{\eta}$).

The metrology of the CKM matrix is performed with a global fit, whose inputs are observables where the theoretical uncertainties are quantitatively under control in order to test the SM: $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$ (to fix the length scale of the UT and the constraints on $A$ and $\lambda$), and the following quantities that are sensitive to $(\bar{\rho},\bar{\eta})$, i.e., $|V_{ub}|$, $\mathscr{B}(B\to\tau\nu)$, $|\varepsilon_K|$, $\Delta m_d$, $\Delta m_d \& \Delta m_s$, $\sin 2\beta$, $\cos 2\beta$, $\alpha$ and $\gamma$. In this review, a frequentist statistical framework is used, where estimates and confidence intervals are obtained from statistical significance (p-value) functions. The test statistic used is the normed likelihood ratio to assess evidence against the SM hypothesis. A dedicated Rfit scheme [2] is used for the treatment of theoretical systematics, as bounds in the minimization (constrained fit) for these theoretical parameters and no other a priori information is assumed where none is available. The outcome of the global fit is shown on Fig. 1 and the result for the four real parameters describing the CKM matrix are $A = 0.812^{+0.013}_{-0.027}$, $\lambda = 0.22543 \pm 0.00077$, $\bar{\rho} = 0.144 \pm 0.025$ and $\bar{\eta} = 0.342^{+0.016}_{-0.015}$.

All measurements used in the global fit are consistent with their predictions within $\pm 1\sigma$ except for $\mathscr{B}(B\to\tau\nu)$ and $\sin 2\beta$ which showed a discrepancy of $2.8\sigma$ and $2.6\sigma$ respectively. The combination of $\mathscr{B}(B\to\tau\nu)$ and $\sin 2\beta$ defines two solutions for the UT apex that are in contradiction with the other observables $\Delta m_d\&\Delta m_s$ and $\alpha$. There is a specific correlation between $\mathscr{B}(B\to\tau\nu)$ and $\sin 2\beta$ in the global fit which is a bit at odds with their measurements, as viewed on Fig. 1. The low value of the prediction of $\mathscr{B}(B\to\tau\nu)$ is mainly driven by the measured value of $\sin 2\beta$: the discrepancy has little to do with the semileptonic extraction of $|V_{ub}|$ or the lattice QCD calculation of $f_{B_d}$.

## 2. Bounds on NP in $|\Delta B|=2$ FCNC

Despite the fact that experimental data are, up to now, consistent with the SM, flavor dynamics leaves open too many unanswered questions. The SM electroweak theory, viewed as an effective theory at the electroweak scale, is thus the minimal theory of flavor dynamics. The coming decade in flavor physics is to progress towards a theory of flavor dynamics of a more fundamental theory at higher energy scales [3] that will supersede the SM. If New Physics (NP) is discovered by the so-called energy-frontier experiments (ATLAS and CMS), flavor physics will play a key role in constraining the NP flavor structure.

A natural place to start looking for NP is the $b\to s$ transitions, the least tested by previous experiments, with the $B_s-\bar{B}_s$ mixing [4] where NP is parametrized by only a complex amplitude in a model-independent approach. The $B_q-\bar{B}_q$ ($q=d$ or $s$) mixing depends on three parameters: the modulus of the dispersive and absorptive amplitudes of the box diagram, $|M_{12}^q|$ and $|\Gamma_{12}^q|$ and their relative phase $\phi_{12}^q=\arg(-M_{12}^q/\Gamma_{12}^q)$. The observables to determine them are the mass and width differences between the light and heavy $B_L^q$ and $B_H^q$ physical states: $\Delta M_q=M_H^q-M_L^q=2|M_{12}^q|$, $\Delta\Gamma_q=\Gamma_L^q-\Gamma_H^q=2|\Gamma_{12}^q|\cos\phi_{12}^q$, up to numerically irrelevant corrections of order $m_b^2/M_W^2$. A third quantity is the CP asymmetry in flavor specific decays: $a_{fs}^q=Im(\Gamma_{12}^q/M_{12}^q)=(\Delta\Gamma_q/\Delta M_q)\tan\phi_{12}^q$. The effect of NP is to barely unaffect $\Gamma_{12}^q$ which stems from tree-level decays unlike $M_{12}^q$ which is very sensitive to virtual effects of new heavy particles. We thus assume that NP only affects short distance physics in $|\Delta B|=2$ amplitudes and parametrize it with a complex amplitude $\Delta_q(=|\Delta_q|e^{i\phi_q^\Delta})$: $M_{12}^q=M_{12}^{SM,q}.\Delta_q$. To identify or constrain NP, both the magnitude and phase of $M_{12}$ are to be measured.

To fix the SM parameters, a reference UT is constructed using inputs which are not affected by NP in mixing: $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$, $\mathscr{B}(B\to\tau\nu)$, $\gamma$ and $\gamma(\alpha)=\pi-\beta_{c\bar{c}}-\alpha$. On the other hand, we use several observables potentially affected by NP to determine $\Delta_d$ and $\Delta_s$: the oscillation frequencies $\Delta M_q$, the decay width difference $\Delta\Gamma_s$ supplemented by the constraint on the flavor-specific $B_s$ lifetime, the time dependent CP asymmetries related to $\phi_q^\Delta$ , the semileptonic untagged and tagged asymmetries $a_{fs}^q$ and $A_{SL}$, and finally $\alpha$ (from interference between decay and mixing). In Fig. 2, we show the results in the complex $\Delta_d$ and $\Delta_s$ planes, respectively. $\Delta_d$ and $\Delta_s$ are taken as independent but some of the constraints correlate them, such that $A_{SL}$ from the inclusive dimuon asymmetry, and the ratio $\Delta M_d/\Delta M_s$. The figures should be understood as two dimensional projections of a single multidimensional fit, and not as independent computations.

In the (Re$\Delta_d$,Im$\Delta_d$) plane, the dominant constraints come from $\sin 2\beta$ and $\Delta M_d$ (the two rings are from the two solutions for the apex of the reference UT with $a_{fs}^d$ excluded from the list of



PoS(ICHEP 2010)269

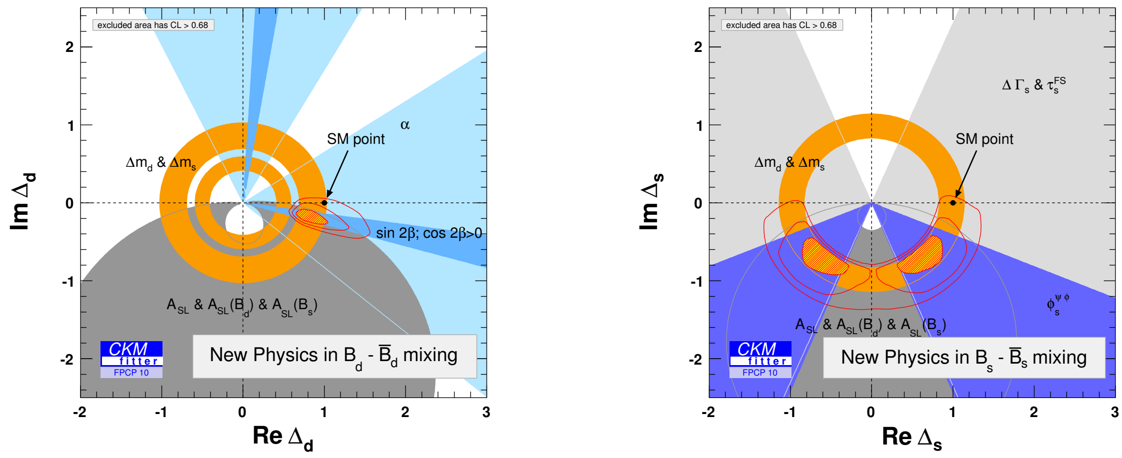


**Figure 2:** Constraint on the complex parameter $\Delta_d$ and $\Delta_s$. For the individual constraints the colored areas represent regions with CL < 68.3 %. For the combined fit the red area shows the region with CL < 68.3 % while the two additional contour line inscribe the regions with CL < 95.5 %, and CL < 99.7 %, respectively.

inputs. This highlights the power of the $a^d_{fs}$ measurement to exclude a large region of the possible NP parameter space.) The 2D SM hypothesis ($\Delta_d = 1$) is excluded at $2.5\sigma$, mainly driven by the $\sin 2\beta$ versus $\mathscr{B}(B\to\tau\nu)$ discrepancy (it can be accommodated by a NP phase of $(-13^{+9}_{-5})^\circ$ at 95% CL). There is still a sizable NP contribution possible at the level of 40%. In the (Re$\Delta_s$,Im$\Delta_s$) plane, the dominant constraints come from $\Delta M_s$, $\phi_s^{\psi\phi}$ and $A_{SL}$. The disagreement with the SM is driven in same direction by $\phi_s^{\psi\phi}$ and $A_{SL}$. The 2D SM hypothesis ($\Delta_s = 1$) is excluded at $2.7\sigma$.

## 3. Conclusion

The KM mechanism is at work at the EW scale. The UT shows an overall consistency at the $2\sigma$ level, with an ongoing discrepancy between $\sin 2\beta$ and $\mathscr{B}(B\to\tau\nu)$. In the New Physics in $|\Delta B| = 2$ mixing, the discrepancy $\sin 2\beta$ versus $\mathscr{B}(B\to\tau\nu)$ can be accommodated by a new CPV phase in the $B_d$ mixing, in agreement with the latest $A_{SL}(D0)$ measurement. There is still a lot of room for NP in the $B_s$ sector, even with the latest CDF and D0 measurements of $\phi_s^{\psi\phi}$. This new decade will be the era of precision flavor physics to unravel the flavor structure of New Physics which will require to revisit many assumptions and to have a consensus average of lattice QCD quantities.

## References

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