CKM fits as of winter 2009 and sensitivity to New Physics

Vincent Tisserand, on behalf of the CKMfitter group
LAPP (UMR5814), Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux, France

We present the status of the CKM matrix parameters in the framework of the Standard Model. We perform a model independent analysis to set constraints on additional effective parameters accounting for possible New Physics effects and to evaluate the present allowed space for these effects both from B_d and B_s mesons.

The unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix [1] describes the mixing of the quark flavors within the framework of the Standard Model (SM). Profs. Kobayashi and Maskawa have just been awarded the Nobel prize for their early 70's work on such a 3×3 (3 quark generations) unitary matrix that accounts for violation of CP symmetry through Electro-Weak (EW) couplings. It has 4 real parameters, among which one single non-vanishing phase. We employ an exact Wolfenstein-like parametrization [2,3] that describes the strong hierarchy in these couplings where unitarity holds to an arbitrary power of the Cabibbo angle $\lambda = \sin(\theta_C)$, it is also re-phasing invariant:

$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}, \qquad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}, \qquad \bar\rho + i\bar\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}.$$

The parameter λ is accurately determined (at 0.3 % level) from super-allowed nuclear transitions ($|V_{ud}|$) and in semi-leptonic kaon decays ($|V_{us}|$). The parameter A ($|V_{cb}|$) is measured from charmed B semi-leptonic decays with an accuracy at the level of 3 %. The apex of the Unitary Triangle (UT), i.e. the complex number $(\bar\rho + i\bar\eta)$, is less constrained.

The accurate measurement of these parameters and especially of the UT sides and angles, possibly in a redundant way, allows to check the consistency of the Kobayashi-Maskawa (KM) mechanism within the SM. Any significant departure could suggest contributions from New Physics (NP). The challenge, both for experimentalists and theorists, is that precise extraction of observables related to these EW parameters is complicated by the presence of strong interaction effects.

We perform a global fit to the CKM parameters within a frequentist approach including a specific treatment to deal with theoretical uncertainties (i.e. flat likelihood *à la Rfit*)[3], where we only use the observables from K and B sectors on which we have a good theoretical control, to avoid to claim pseudo departures from SM. Table 1 displays the various key ingredients used (more details on the world averages (WA) exp. and theo. inputs and related references are given at [3]). Among all these observables, only the branching ratio (BR) of the $B^+ \to \rho^+\rho^0$ channel updated by the BaBar collaboration [4] is a new input since our last summer 2008 update.

Several hadronic inputs are mandatory for the fits. They mainly limit the precision on the determination of the observables involving processes with loops such as Δm_d, Δm_s, $|\varepsilon_K|$,

Phys. params.	Experim. input	Theory method/ingredient
$\lvert V_{ud}\rvert$	super-allowed β decays	Towner and Hardy (08)
$\lvert V_{us}\rvert$	K_{l3} SL kaon decays (WA, Flavianet [5])	$f_+^{K\pi}(0) = 0.964(5)$ (RBC-UKQCD (07))
$\lvert V_{cb}\rvert$	$B \to X_c l\nu$ (HFAG [6]: excl. + incl.)	$40.59(38)(58) \times 10^{-3}$ (FF and/or OPE)
$\lvert V_{ub}\rvert_{SL}$	$B \to X_u l\nu$ (HFAG [6]: excl. + incl.)	$3.87(9)(46) \times 10^{-3}$ (FF and/or OPE) and own syst. treatment
$\lvert V_{ub}\rvert_{lept.}$	BR($B^+ \to \tau^+\nu$) annihilation (B-factories)	[$f_{B_s} = 228(3)(17)$ MeV, $f_{B_s}/f_{B_d} = 1.196(8)(23)$]
Δm_s	$B_s - \bar{B}_s$ mixing (CDF II)	ΔB=2 amp. [$\hat{B}_s = 1.23(3)(5)$, f_{B_s}, $\bar{m}_t$, η_B]
Δm_d	$B_d - \bar{B}_d$ mixing (HFAG [6])	ΔB=2 amp. [$\hat{B}_{B_s}/\hat{B}_{B_d} = 1.05(2)(5)$, f_{B_s}/f_{B_d}, η_B]
$\lvert\varepsilon_K\rvert$	$K\bar{K}$ mixing (PDG 08 [7]: KLOE, NA48, KTeV...)	ΔS=2 amp. [$B_K = 0.721(5)(40)$, η_{cc} , η_{ct}, η_{tt}]
β/ϕ_1	Charmonium B decays (HFAG [6])	-
α/ϕ_2	$B \to \pi\pi, \rho\rho, \rho\pi$ (B-factories: rates + asym.)	Isopsin $SU(2)$ (Gronau, London (90))
γ/ϕ_3	$B^- \to D^{(*)}K^{(*)-}$ (B-factories: rates + asym.)	GLW/ADS/GGSZ

Table 1: Various relevant inputs to the CKMfitter global fit. Many LQCD inputs in these table are from our own average (see text). The upper (lower) part of the table corresponds to CP conserving (violating) parameters.

and also the tree decay $B^+ \to \tau^+\nu$. The hadronic contributions to K_{l3} decay are surprisingly under excellent control. We mostly rely on lattice QCD (LQCD) simulations to estimate these quantities, since the accuracy of such first-principle computations can be improved in a controlled way (at least in principle). The presence of results from different collaborations with various statistics and systematics makes it all the more necessary to combine them in a careful and reproducible way. It has been pointed out[8] that *"if experts cannot agree, it is unlikely the rest of the community would believe a claim of NP"*. Therefore we have recently set up our own average of these results [a].

Figure 1 (Left) shows the global CKM fit results in the ($\bar{\rho}$,$\bar{\eta}$) plane. The CKM parameters are: $A = 0.8116^{+0.0097}_{-0.0241}$, $\lambda = 0.22521 \pm 0.00082$, $\bar{\rho} = 0.139^{+0.025}_{-0.027}$, and $\bar{\eta} = 0.341^{+0.016}_{-0.015}$. A good overall consistency at 95 % CL is seen, probing the fact that the KM mechanism is at work for CP violation and dominant in B decays. It is also visible that there is a tension between the measurement of $\sin(2\beta)$ from charmonium B decays and the determination of $|V_{ub}|$ from the decay $B^+ \to \tau^+\nu$. When removing one of the last paramaters from the global fit, the χ^2 at minimum drops respectively by 2.3 and 2.4 σ.

This tension is mainly originated from the recent BR($B^+ \to \tau^+\nu$) measurements by BaBar

[a] We apply the averaging procedure [3]:

- First of all, we collect the relevant calculations of the quantity that we are interested in: we take only unquenched results with 2 or 2+1 dynamical fermions, from published papers or proceedings. In these results, we separate the error estimates into a Gaussian part and a flat part (Rfit). The Gaussian part should collect the uncertainties from purely statistical origin, but also the systematics that can be controlled and treated in a similar way (e.g., interpolation or fitting in some cases). The remaining systematics constitute the Rfit error. If there are several sources of error in the Rfit category, we add them linearly, keeping in mind that in many papers in the literature, this combination is done in quadrature and the splitting between different sources is not published. If Rfit is taken stricto sensu and the individual likelihoods are combined in the usual way (by multiplication), the final uncertainty can be underestimated, in particular in the case of marginally compatible values.
- We correct this effect by adopting the following averaging recipe. We first combine the Gaussian uncertainties by combining likelihoods restricted to their Gaussian part. Then we assign to this combination the smallest of the individual Rfit uncertainties. The underlying idea is twofold: (1) the present state of art cannot allow us to reach a better theoretical accuracy than the best of all estimates, and (2) this best estimate should not be penalized by less precise methods (as it would happen be the case if one would take the dispersion of the individual central values as a guess of the combined theoretical uncertainty). It should be stressed that the concept of a theoretical uncertainty is ill-defined, and the combination of them even more. Thus our approach is only one among the alternatives that can be found in the literature. In contrast to some of the latter, ours is algorithmic and can be reproduced. We found a very good agreement between our previous inputs (taken from lattice reviews) and our current set (obtained from the above recipe).

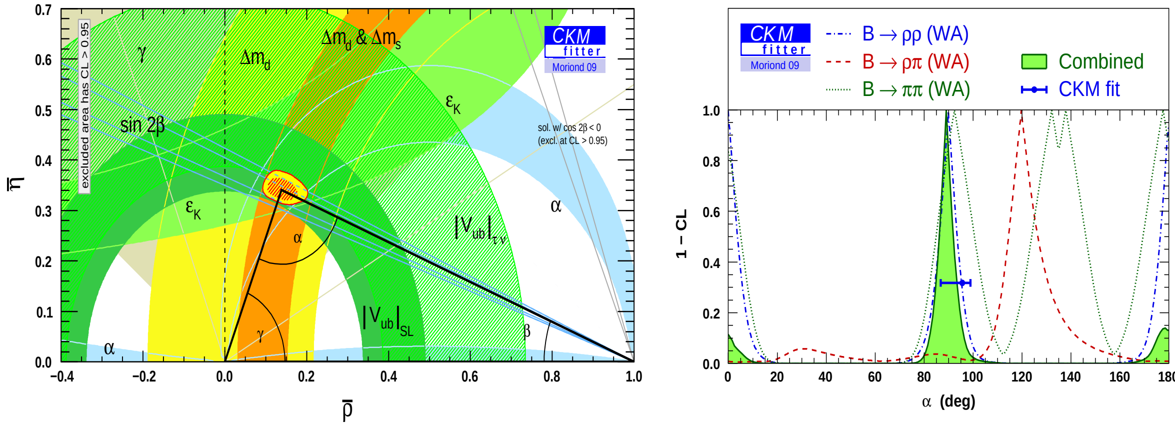

Figure 1: 95 % CL individual and global constraints in the ($\bar{\rho}$,$\bar{\eta}$) plane from the global CKM fit (Left). The red hashed region of the global combination corresponds to 68 % CL. CL profile for α with the present world average of the 3 $B \to \pi\pi, \rho\rho, \rho\pi$ channels (Right).

and Belle [3,9]. All these measurements are consistent and their WA is $(1.73 \pm 0.35) \times 10^{-4}$, while our global CKM fit predicts it to be at a lower value of $(0.80^{+0.15}_{-0.09}) \times 10^{-4}$. Such a higher BR is not necessarily accommodated for by models with 2 Higgs boson doublets [10] (2HDM). In addition one can see on Fig. 1 that both semi-leptonic and purely leptonic B decays $|V_{ub}|$ determinations agree pretty well. In between the 2 semi-leptonic methods $\sin(2\beta)$ prefers the exclusive one, while the inclusive one is still compatible in the CKMfitter approach. Doing the computation of the ratio of the BR of this B annihilation decay over the mixing parameter Δm_d removes the dependance to the decay factor f_{B_d}. The combination of these 2 constraints releases therefore partially some LQCD related uncertainties and gives a direct access to the parameter B_{B_d} [9]. When doing so we obtain the value $B_{B_d} = 1.18 \pm 0.14$ that is 2.7 σ away from the CKM global fit: $0.52^{+0.15}_{-0.11}$. The tension arising from the BR$(B^+ \to \tau^+\nu)$ is clearly not yet an evidence for NP, but it motivates more accurate measurements at BaBar and Belle and at possible future super-B factories.

It has been suggested [11] that the recent LQCD improvements in the determination of the parameter $\hat{B}_K$ alights a so far neglected additional multiplicative factor in the determination of the parameter $|\varepsilon_K|$, this is the so called κ_ε parameter computed and estimated to be equal to 0.92 ± 0.02 . This factor accounts for CP violation effects in $K - \bar{K}$ mixing and may hint for CP violation contributions originated from NP. The computed value of $|\varepsilon_K|$ from this recent work and within the SM is $(1.78 \pm 0.25) \times 10^{-3}$, while the current experimental WA [7] is $(2.229 \pm 0.10) \times 10^{-3}$. This suggests an additional tension at the level of 2 σ mainly with respect to $\sin(2\beta)$. Our fit[10], even while accounting for κ_ε, shows that the uncertainty of $|\varepsilon_K|$ is rather likely to be of the order of 0.5×10^{-3}. This tension arises while dealing with pure convoluted Gaussian uncertainties for all the parameters and including all the uncertainties on LQCD computations, that are obviously not overwhelmed by statistical effects. It therefore vanishes while using the Rfit procedure.

Figure 1 (Right) shows that the angle α is now determined with a good accuracy, at the level of 5 % or less: $\alpha = (89.0^{+4.4}_{-4.2})^\circ$, while the angle β is measured within a precision of 4 %. The isospin analysis on the $\rho\rho$ channels almost fully drives it. It is in excellent agreement with the global fit $(95.6^{+3.3}_{-8.8})^\circ$ (without the related measurement in the fit) and the uncertainties have been reduced by more than 20 % with respect to last summer. This is due to the new measurement on the BR$(B^+ \to \rho^+\rho^0)$ by BaBar [4] that dominates the WA for this observable. It has increased from $(18.2 \pm 3.0) \times 10^{-6}$ up to $(24.0 \pm 1.9) \times 10^{-6}$. In the $\rho\rho$ system, the Penguin to Tree amplitude ratio is much more favorable than in the case of charmless B decays to $\rho\pi$ and $\pi\pi$ [3,12], allowing therefore a relatively smaller $|\Delta\alpha|$ isospin bound.

The BR of both channels $\rho^+\rho^0$ and $\rho^+\rho^-$ are now very similar [6] and almost 25 times as big as that of $\rho^0\rho^0$ (the Penguin transition), the B and $\bar{B}$ related isospin amplitudes triangles are basically flat and do not close, i.e. for B : $|A^{+-}|/\sqrt{2} + |A^{00}| < |A^{+0}|$ (but this is still consistent within uncertainties). As a consequence the mirror solutions that possibly arise while experimentally measuring the effective angle α_{eff} (Penguin dilution), are degenerated into a single peak. As it can be seen on Fig. 1 the expected 8-fold ambiguities from the isospin analysis degenerate into the only 4 $\Delta\alpha$ geometric solutions, in the vicinity of 0°, ± 90°, and ± 180°.

The isospin analysis for the $\rho\rho$ system is performed using [6] the 3 BRs, time-dependent CP-asymmetry parameters C^{+-}, S^{+-}, C^{00}, and C^{00}, and the 3 longitudinal fractions (f_L) of these VV channels that are not stricto-sensu CP-eigenstates, thought the f_L are very close to 1 which eases the analysis. The α angle is determined to be $(89.9 \pm 5.4)^\circ$ and the isospin bound $\Delta\alpha$ close to 0° with a good accuracy: $(1.4 \pm 3.7)^\circ$ (at summer time we had: $\alpha = (90.9^{+6.7}_{-14.9})^\circ$). To test what is the expected uncertainties for this measurement, we have performed 1000 pseudo experiments (toys). We have generated the above experimental observables with $\pm 1\ \sigma$ around their best fitted value (from global fit), where the σ are the currently measured uncertainties. We measure that the average expected uncertainty is 7.5°, slightly higher than the 5.4° that we measure. The uncertainty distribution has a long tail up to about 20°, it corresponds to revival of pseudo mirror solutions, above the 1 σ CL(α). About 34 % of the toys where isospin triangles close and have similar uncertainties or higher than that of last summer configuration. This is a message for future experiments, such as LHCb, that better uncertainties of the various $\rho\rho$ observables may not necessarily lead to better accuracy on α.

Due to the reached precision, it is legitimate to investigate for possible isospin breaking effects [12] beyond the Gronau-London $SU(2)$ method. Not all the breaking effects can be calculated at present, but we can list a few of them: the u and d quarks have different electric charges and masses (breaking of the order: $(m_u - m_d)/\Lambda_{QCD} \sim 1$ %), the isospin transitions $\Delta I = 5/2$ may be no more negligible, we may need to extend the basis of EW-Penguin operators: $Q_{7,...,10}$ ($\Delta\alpha_{EWP} \sim 1.5^\circ$), the mass and isospin eigenstates are different ($\rho - \omega$ mixing at the level of 2 %), the ρ natural width is large enough such that $I = 1$ contributions are possible ($\mathcal{O}(\Gamma^2_\rho/m^2_\rho) \sim 4$ %) ... There are possible ways out such as exploiting the $B^+ \to K^\star\rho^+$ channels through $SU(3)$ constraints. In order to break the triangle closure we apply the procedure as described in [3]. The amplitudes A^{+0} and $\bar{A}^{+0}$ are corrected by additional Tree (Δ_T) and Penguin (Δ_P) contributions weighted as: $\sqrt{2}\Delta A^{+0} = V_{ud}V^\star_{ub}\Delta_T T^{+-} + V_{td}V^\star_{tb}\Delta_P P^{+-}$ (the strong phases are set arbitrarily). We tested $|\Delta A^{+0}|$ as big as 4, 10, and 15 %. The 2 first corrections break $SU(2)$ at 90° and restore it in the vicinity of 0°, while the largest is needed to restore it at the α SM solution. Anyway when combining the $\pi\pi$ and $\rho\pi$ the determination on α is mostly unaffected at 1 σ CL.

We have updated [3] the constraint on $|V_{td}/V_{ts}|$ accessible through the ratio of branching ratio for $B \to V\gamma$ decays, where V holds respectively for (ρ, ω) and $K^\star$ vector mesons. These penguins processes complement the box diagrams involved in the measurement of $\Delta m_{(d,s)}$. Any inconsistency in between the 2 approaches would teach us in which direction to look for NP. We use the parametrization for hadronic effects as described in [13]. The sophisticated description of the amplitudes has non trivial sensitivity to the CKM parameters. Our new analysis benefits from the recent updated BR measurements of all of the above decays [6]. The improvement is such that at 95 % CL these new measurements constrain the ($\bar{\rho}$,$\bar{\eta}$) plane as accurately as Δm_d alone, and at 68 % CL they have similar precision as that from $\Delta m_{(d,s)}$ at 95 % CL.

There has been a standing issue due to apparently non SM BR measurements for leptonic decays of D_s mesons [13,14], by the B-factory and the CLEO-c experiments. These decays give access to the measurement of the decay parameter f_{Ds} and to $|V_{cs}|$. The charm sector, where $m_c \sim \Lambda_{QCD}$, is an ideal laboratory to validate LQCD against experiment. The recent most accurate BR measurements by CLEO-c [15] on annihilation decays $D_s \to (\tau, \mu)\nu$ allow to compute

$f_{Ds} = (259.5 \pm 6.6 \pm 3.1)$ MeV, while our average on LQCD results is $(246.3 \pm 1.2 \pm 5.3)$ MeV. There is still some discrepancy at the 2 σ level, but it is almost twice as less as what it used to be. Converting this into a $|V_{cs}|$ determination and averaging CLEO-c and LQCD measurements of f_{Ds}, one computes $|V_{cs}| = 1.027 \pm 0.051$, in good agreement with the global fit that yields 0.97347 ± 0.00019. This comparison alighted a 2 σ tension one year ago and the measurements led to a unitarity violation of the CKM matrix [13].

We also updated the constraint from the measured BR of the $K^+ \to \pi^+ \nu\bar{\nu}$ rare decay, for which a recent update of the E789 and E949 experiments has been done with 5 signal candidates [16]. We parameterize the BR using the calculations by Brod and Gorbahn at NLO QED-QCD and accounting for EW corrections to the charm quark contribution. The global fit predicts BR=$(0.811^{+0.027}_{-0.021}{}_{exp.} \pm 0.096_{theo.}) \times 10^{-10}$ while the experiments measure $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$. The agreement is good and the constraint in the $(\bar{\rho},\bar{\eta})$ plane is such that in the vicinity of the point (1,0) a non negligible area is forbidden at 95 % CL for the first time. This effect clearly motivates a $\mathcal{O}(100)$ signal event experiment, such as the future NA62.

Finally we reiterate [17,9] the analysis to compute the constraints set on NP from $B_{q=d,s}$-meson mixing. We consider that NP only affects the short distance part of the $\Delta B = 2$ transitions. In addition we assume that the tree-level mediated decays proceeding through a Four Flavor Change get only SM contributions (SM4FC hypothesis: $b \to q_i \bar{q}_j q_k$ $(i \neq j \neq k)$), the observables $|V_{ij}|$ (including $B^+ \to \tau^+\nu$), γ, and $\gamma(\alpha) = \pi - \beta_{c\bar{c}} - \alpha$ are not affected by the NP contribution and can be used in a (SM+NP) global fit to fix the SM CKM parameters. We also consider only 3 generations of quarks. The oscillation parameters, the weak phases, the semi-leptonic asymmetries and the B-meson lifetime differences are affected by the phase and/or the amplitude of the NP contribution and allow to constrain the NP deviation to SM quantified through out the model-independent parametrization: $\langle B_q | M_{12}^{\rm SM+NP} | \bar{B}_q \rangle = \Delta_q^{\rm NP} \langle B_q | M_{12}^{\rm SM} | \bar{B}_q \rangle$.

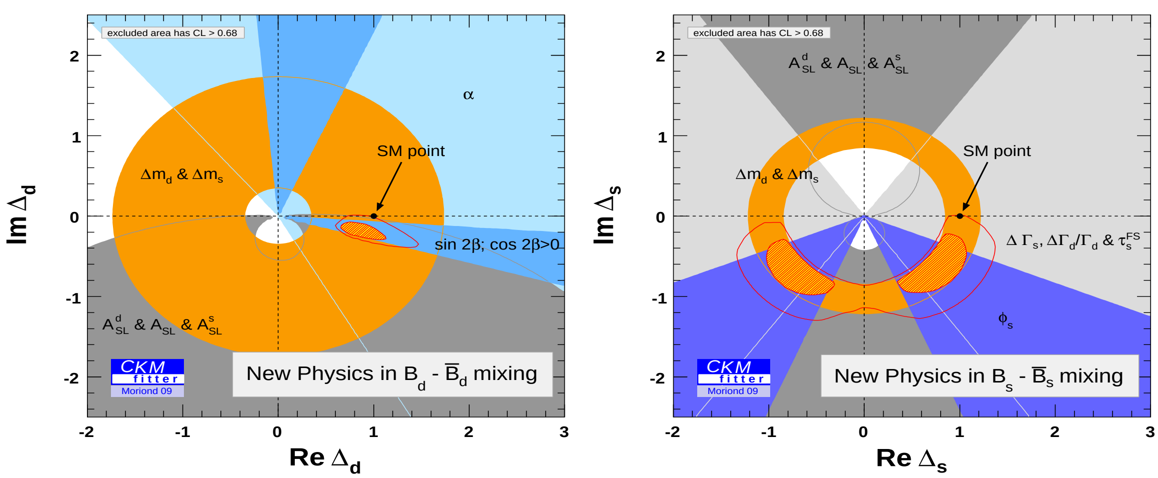

Figure 2: 68 % CL contours for $\Delta_q^{\rm NP}$ in $B_d - \bar{B}_d$ system (Left) and in $B_s - \bar{B}_s$ system (Right).

In Figure 2 we present the deviations to the SM ($\Delta_q^{\rm NP} = 1$) using the intuitive Cartesian coordinates parametrization [17]: $\Delta_q^{\rm NP} = ({\rm Re} + i\ {\rm Im})\, \Delta_q^{\rm NP}$. This parametrization is statistically more robust as uncertainties have Gaussian behavior in the vicinity of $|\Delta_q^{\rm NP}| = 0$. In the B_d case, the tension in between $\sin(2\beta)$ and $|V_{ub}|_{\tau\nu}$ pushes the best fitted $\Delta_d^{\rm NP}$ 2.1 σ away from the SM point (while it is only 0.6 σ away when $B^+ \to \tau^+\nu$ is removed). In the case of B_s, the deviation is 1.9 σ, it's mainly driven by the recent TeVatron measurements of $(2\beta_s, \Delta\Gamma_s)$ [6]. This measurement is performed with the time dependent analysis of the decay $B_s \to J/\psi\phi$. It deviates by 2.2 σ from the SM expected value. In both cases $\Delta m_{q=d,s}$ constrain the modulus $|\Delta_{q=d,s}^{\rm NP}|$ to be in the vicinity of 1 or below. this is the evidence of the KM mechanism dominance for the sensitivity to NP effects. If one tests the Minimal Flavor Violation (MFV) scenario (i.e. no additional NP phase and Yukawa couplings only: $\mathrm{Im}\Delta_q^{\mathrm{NP}} = 0$ and $\Delta_d^{\mathrm{NP}} = \Delta_s^{\mathrm{NP}}$), no tension with respect to SM is observed, as theses effects arise at the present time only through EW phases: $\sin(2\beta)$ vs. $|V_{ub}|_{\tau\nu}$ and ϕ_s, in both $B_{q=d,s}$ systems.

To conclude the KM mechanism is at work and dominates the sensitivity to CP violation and to NP in the b quark sector. Anyway there is still substantial room for NP both in B_d-meson and B_s-meson physics. Some few deviations to the SM global fit exist at the present time and at most at the 2 σ level. It is therefore fundamental to finalize the analyzes of the present B-factory datasets and to wait for the next generation experiments at the LHC (huge b quark cross-section production), or at the future super-B factories, at KEK and possibly at Frascati ($\mathcal{L} = 10^{35-36} cm^{-2} s^{-1}$). They will allow for high precision measurements of rare effects. Finally, continuous progress in LQCD are currently achieved, but even more accurate calculations, in a coherent motion of that community, are mandatory and expected to fully exploit the potential of the physics program in that field.

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