Constraints on new physics from the quark mixing unitarity triangle

(UTfit Collaboration)

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The status of the Unitarity Triangle beyond the Standard Model including the most recent results on \( \Delta m_s \), on dilepton asymmetries and on width differences is presented. Even allowing for general New Physics loop contributions the Unitarity Triangle must be very close to the Standard Model result. With the new measurements from the Tevatron, we obtain for the first time a significant constraint on New Physics in the \( B_s \) sector. We present the allowed ranges of New Physics contributions to \( \Delta F = 2 \) processes, and of the time-dependent CP asymmetry in \( B_s \to J/\Psi \Phi \) decays.

In the last decade, flavour physics has witnessed unprecedented experimental and theoretical progress, opening the era of precision flavour tests of the Standard Model (SM). The advent of \( B \) factories, with the measurements of the angles of the Unitarity Triangle (UT), has opened up the possibility of the simultaneous determination of SM and New Physics (NP) parameters in the flavour sector. As shown below, with the most recent improvements obtained at the \( B \) factories and at the Tevatron, the UT analysis in the presence of NP has reached an accuracy comparable to the SM analysis, providing at the same time very stringent constraints on NP contributions to \( \Delta F = 2 \) processes.

While in general all the constraints have been improved, three remarkable results have boosted the precision of the UT analysis beyond the SM. First, the CDF collaboration presented the first measurement of \( B_s \to \bar{B}_s \) mass difference \( \Delta m_s \), which reduces the uncertainty of the SM fit and has a strong impact on the determination of the Universal Unitarity Triangle (UUT) in models with Minimal Flavour Violation (MFV). Moreover, it allows for the first time to put a bound on the absolute value of the amplitude for \( B_s \) oscillations.

Second, the measurement of the dimuon asymmetry in \( p \bar{p} \) collisions by the D0 experiment can be translated into a bound on the phase of the same amplitude. Third, the measurements of the width difference for \( B_s \) mesons provide another constraint on the phase of the mixing amplitudes, complementary to the one given by dilepton asymmetries.

In this Letter, we first discuss extensions of the SM with MFV, in which no new source of flavour and CP violation is present beyond the SM Yukawa couplings. We analyze the impact of \( \Delta m_s \) on the UUT determination, where the ratio \( \Delta m_d/\Delta m_s \) plays a crucial role since it is independent of NP contributions. We find that the UUT analysis has now an accuracy very close to the SM UT fit. Using instead the information coming from the individual measurements of \( \Delta m_s \), \( \Delta m_d \) and \( \varepsilon_K \), we constrain NP contributions to the \( \Delta F = 2 \) Hamiltonian, both in the small and large tan \( \beta \) regimes. We find improved constraints on the NP scale \( \Lambda \) that suppresses non-renormalizable effective interactions.

We then turn to the most general case in which NP contributions with an arbitrary phase are allowed in all sectors, and obtain a fully model-independent determination of the CKM parameters \( \rho \) and \( \eta \). We simultaneously obtain the allowed range for the \( \Delta F = 2 \) amplitudes which can be used to test any extension of the SM, and the prediction for the time-dependent CP asymmetry \( S_{J/\Psi \Phi} \). For all our analyses we use the method described in refs. 10–11 and the input values listed in ref. 12.

In the context of MFV extensions of the SM, it is possible to determine the parameters of the CKM matrix independently of the presence of NP, using the UUT construction, which is independent of NP contributions. In particular, all the constraints from tree-level processes and from the angle measurements are valid and the NP contribution cancels out in the \( \Delta m_d/\Delta m_s \) ratio; the only NP dependent quantities are \( \varepsilon_K \) and (individually) \( \Delta m_d \) and \( \Delta m_s \), because of the shifts \( \delta S_0 \) and \( \delta S_0^B \) of the Inami-Lim functions in \( K \to \bar{K} \) and \( B_{d,s} \to \bar{B}_{d,s} \) mixing processes. With only one Higgs doublet or at small tan \( \beta \), these two contributions are dominated by the Yukawa coupling of the top quark and are forced to be equal. For large tan \( \beta \), the additional contribution from the bottom Yukawa coupling cannot be neglected and the two quantities are in general different. In both cases, one can use the output of the UUT given in Tab. 1 and the bottom plot of Fig. 1 to obtain a constraint on \( \delta S_0^{K,B} \) using \( \varepsilon_K \) and \( \Delta m_d \). We get \( \delta S_0 = \delta S_0^K = \delta S_0^B = -0.12 \pm 0.32 \) for small tan \( \beta \), while for large tan \( \beta \) we obtain \( \delta S_0^B = 0.26 \pm 0.72 \) and \( \delta S_0^K = -0.18 \pm 0.38 \). Using the procedure detailed in 5, these bounds can be translated into lower bounds.
on the MFV scale $\Lambda$:
\[
\Lambda > 5.9 \text{ TeV} \oplus 95\% \text{ Prob. for small } \tan \beta \\
\Lambda > 5.4 \text{ TeV} \oplus 95\% \text{ Prob. for large } \tan \beta
\] (1)
significantly stronger than our previous results $\Lambda > 3.6$ TeV and $\Lambda > 3.2$ TeV for small and large $\tan \beta$ respectively [11].

FIG. 1: Determination of $\bar{\rho}$ and $\bar{\eta}$ from the constraints on $\alpha$, $\beta$, $\gamma$, $|V_{cb}/V_{ub}|$, $\Delta m_d/\Delta m_s$ (UUT fit, left) and from the constraints on $\alpha$, $\beta$, $\gamma$, $|V_{cb}/V_{ub}|$, $\Delta m_d$, $\Delta m_s$, $\epsilon K$, $A_{SLL}$, $A_{CH}$ and $\Delta \Gamma_q/\Gamma_q$ (generalized NP fit, right). In the right plot, only tree-level constraints are shown.

| Parameter | Output | Parameter | Output |
|-----------|--------|-----------|--------|
| $\bar{\rho}$ | $0.154 \pm 0.032$ | $\bar{\eta}$ | $0.347 \pm 0.018$ |
| $\alpha^{[\circ]}$ | $91 \pm 5$ | $\beta^{[\circ]}$ | $22.2 \pm 0.9$ |
| $\gamma^{[\circ]}$ | $66 \pm 5$ | $\sin 2\beta$ | $0.037 \pm 0.002$ |
| $|V_{ub}/V_{cb}|$ | $3.69 \pm 0.15$ | $V_{cb}/10^{-2}$ | $4.18 \pm 0.07$ |
| $|V_{cd}/V_{ub}|$ | $8.6 \pm 0.3$ | $|V_{cd}/V_{ub}|$ | $0.210 \pm 0.008$ |
| $R_b$ | $0.381 \pm 0.015$ | $R_t$ | $0.915 \pm 0.033$ |

TABLE I: Determination of UUT parameters from the constraints on $\alpha$, $\beta$, $\gamma$, $|V_{cb}/V_{ub}|$, and $\Delta m_d/\Delta m_s$ (UUT fit).

We now turn to the UT analysis in the presence of arbitrary NP. Following ref. [11], we incorporate general NP loop contributions in the fit in a model independent way, parametrizing the shift induced in the $B_q^-\bar{B}_q$ mixing frequency (phase) with a parameter $C_{B_q}$ ($\phi_{B_q}$) having expectation value of one (zero) in the SM [13]:
\[
C_{B_q} e^{2i\phi_{B_q}} = \frac{(B_q|H_{\text{SM}}^{\text{eff}}|B_q)}{(B_q|H_{\text{eff}}^{\text{SM}}|B_q)} = 1 + A_{\text{NP}}^{B_q} A_{\text{SM}}^{B_q} e^{2i\phi_{\text{NP}}} (2)
\]
with $q = d, s$, plus an additional parameter $C_{\epsilon K} = \text{Im}(K^0|H_{\text{SM}}^{\text{eff}}|K^0)/\text{Im}(K^0|H_{\text{SM}}^{\text{SM}}|K^0)$. As shown in refs. [11] [14], the measurements of UT angles strongly reduced the allowed parameter space in the $B_d$ sector. On the other hand, in previous analyses the $B_s$ sector was completely untested in the absence of stringent experimental constraints. Recent experimental developments allow to improve the bounds on NP in several ways. First, the measurement of $\Delta m_s$ [11] and of $\Delta \Gamma_s$ [13] provide the first constraints on the $\phi_{B_s}$ vs. $C_{B_s}$ plane. Second, the improved measurement of $A_{SLL}$ in $B_d$ decays [17] and the recently measured CP asymmetry in dimuon events ($A_{CH}$) [18] further constrain the $C_{B_d}$ and $\phi_{B_d}$ parameters. They also strongly disfavour the solution with $\bar{\rho}$ and $\bar{\eta}$ in the third quadrant, which now has only 1.0% probability. Finally, $\Delta \Gamma_d$ [17] helps in reducing further the uncertainty in $C_{B_d}$.

The use of $A_{CH}$ and $\Delta \Gamma_d$ to bound $C_{B_d}$ and $\phi_{B_d}$ deserve some explanation, while for all the other constraints we refer the reader to ref. [11]. The dimuon charge asymmetry $A_{CH}$ can be written as:
\[
\frac{(\chi - \bar{\chi})(P_1 - P_3 + 0.3 P_3^*)}{\xi(P_1 + P_3) + (1 - \xi)P_2 + 0.28 P_2 + 0.5 P_2^* + 0.69 P_{13}}
\]
in the notation of ref. [11], where the definition and the measured values for the $P$ parameters can be found. We have $\chi = f_d \chi_d + f_s \chi_s$, $\bar{\chi} = f_d \bar{\chi}_d + f_s \bar{\chi}_s$ and $\xi = \chi + \bar{\chi} - 2\chi \bar{\chi}$, where we have assumed equal semileptonic widths for $B_d$ and $B_s$ mesons, $f_d = 0.397 \pm 0.010$ and $f_s = 0.107 \pm 0.011$ are the production fractions of $B_d$ and $B_s$ mesons respectively [15] and $\chi_q$ and $\bar{\chi}_q$ are given by the expression
\[
\chi_q = \frac{\Delta \Gamma_{\bar{q}}}{\Gamma_q}^2 + 4 \frac{\Delta m_q}{\Gamma_q}^2 \left( z_q^2 - 1 \right) + 4 \left( \frac{z_q^*}{z_q} \right) \frac{\Delta m_q}{\Gamma_q}^2 \left( 1 + z_q \right) (3)
\]
with $z_q = |q/p_q|^2$ and $\bar{z}_q = |p_q/q|^2$. Finally, using the results of [19] and following the notation of [11], we have
\[
\frac{\Delta \Gamma_q}{\Delta m_q} = \Re \mathcal{P} , \quad |q/p_q| - 1 = -\frac{1}{2} \text{Im} \mathcal{P} (4)
\]
where
\[
\mathcal{P} = -2 \frac{\kappa}{C_{B_q}} \left\{ e^{2i\phi_{B_q}} \left( n_1 + n_9 B_2 + n_{11} \right) - e^{i\phi_{\text{SM}} + 2i\phi_{B_q}} \left( n_2 + n_7 B_2 + n_{12} \right) + e^{2i\phi_{\text{SM}} + i\phi_{B_q}} \left( n_3 + n_8 B_2 + n_{13} \right) \right\} R_t^d (5)
\]
they are actually a measurement of $\Delta \Gamma_s \cos 2(\phi_{B_d} - \beta_s)$ in the presence of NP \[12\]. To assess the constraining power of leptonic asymmetries and width differences, we compare the SM predictions and the experimental results with the predictions in the presence of NP, see Tab. III and Fig. 4. We see that NP can produce dilepton asymmetries (\[8\]) and $\Delta \Gamma_s / \Gamma_s$ in the SM or in the presence of NP, obtained without including these observables in the fit.

\begin{table}[h]
\centering
\begin{tabular}{lccc}
\hline
 & SM & SM+NP & exp & ref \\
\hline
$10^3 A_{\text{SL}}$ & $-0.71 \pm 0.12$ & see Fig. 3 & $-0.3 \pm 5$ & [16] \\
$10^3 A_{\text{CH}}$ & $-0.23 \pm 0.05$ & see Fig. 3 & $-13 \pm 12 \pm 8$ & [7] \\
$10^3 \Delta \Gamma_d / \Gamma_d$ & $3.3 \pm 1.9$ & $2.0 \pm 1.8$ & $9 \pm 37$ & [17] \\
$\Delta \Gamma_s / \Gamma_s$ & $0.10 \pm 0.06$ & $0.00 \pm 0.08$ & $0.25 \pm 0.09$ & [15] \\
\hline
\end{tabular}
\caption{Predictions for $A_{\text{SL}}$, $A_{\text{CH}}$ and $\Delta \Gamma_s / \Gamma_s$ in the SM or in the presence of NP, obtained without including these observables in the fit.}
\end{table}

FIG. 3: Predictions for $A_{\text{SL}}$ and $A_{\text{CH}}$ in the presence of NP, obtained without including these observables in the fit. The lower peak in the p.d.f.'s correspond to values of $\rho$ and $\eta$ in the third quadrant.

In the presence of NP, for each value of $(C_{B_s}, \phi_{B_s})$ we compute $A_{\text{SL}}$, $A_{\text{CH}}$ and $\Delta \Gamma_s \cos 2(\phi_{B_d} - \beta_s)$ and use the experimental values to compute the weight of the given configuration. In ref. [8], the measurement of $A_{\text{CH}}$ was used in a different way: $A_{\text{CH}}$ was combined with the experimental value of $A_{\text{SL}}$ to obtain a value for $A_{\text{SL}}^{*}$. In principle, our method takes into account the correlations between the theoretical predictions for $A_{\text{SL}}$ and $A_{\text{SL}}^*$. In addition, using $A_{\text{CH}}$ instead of $A_{\text{SL}}$ is more constraining since the theoretical range for $A_{\text{SL}}$ is smaller than the present experimental error. In practice, however, these two effects are rather small.

The result of the fit is summarized in Tab. III. The table includes $\rho$ and $\eta$ is also shown in right plot of Fig. 1 while the bounds on the two $\phi_B$ vs. $C_B$ planes are given in Fig. 2 together with the corresponding regions in the $\phi_{B_s}^{NP}$ vs. $A_{\text{NP}}^B / A_{\text{SM}}^B$ planes. The distributions for $C_{B_s}$, $\phi_{B_s}$ and $\phi_{K}$ are shown in Fig. 4. We see that the non-standard solution for the UT with its vertex in the third quadrant, which was present in the previous analysis [11], is now absent thanks to the improved value of $A_{\text{SL}}$ by the BaBar Collaboration and to the measurement of $A_{\text{CH}}$ by the D0 Collaboration (the lower peaks in Fig. 4 correspond to the non-standard solution and are now excluded). Furthermore, the measurement of $\Delta m_s$ strongly constrains $C_{B_s}$, so that $C_{B_s}$ is already known better than $C_{B_d}$. Finally, $A_{\text{CH}}$ and $\Delta \Gamma_s$ provide stringent constraints on $\phi_{B_d}$. Taking these constraints into account, we obtain

$$S_{J/\phi} = 0.09 \pm 0.60,$$

leaving open the possibility of observing large values of $S_{J/\phi}$ at LHCb. We point out an interesting correlation between the values of $C_{B_d}$ and $C_{B_s}$ that can be seen in Fig. 3. This completely general correlation is present since lattice QCD determines quite precisely the ratio $\xi^2$ of the matrix elements entering $B_s$ and $B_d$ mixing amplitudes respectively.

We conclude by noting that the fit produces a nonzero central value of $\phi_{B_d}$. This is due to the difference in the SM fit between the angles measurement (in particular $\sin 2\beta$) and the sides measurement (in particular $V_{ub}$ inclusive). More details on this difference can be found in ref. [2]. Further improvements in experimental data and in theoretical analyses are needed to tell whether this is just a fluctuation or we are really seeing a first hint of...
FIG. 4: Constraints on $\phi_{B_d}$, $C_{B_d}$, and $C_{sK}$ coming from the NP generalized analysis. The correlation between $C_{B_d}$ and $C_{B_s}$ is also shown.

NP in the flavour sector.

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TABLE III: Determination of UT and NP parameters from the NP generalized fit.

| Parameter | Output | Parameter | Output |
|-----------|--------|-----------|--------|
| $C_{B_d}$ | $1.25 \pm 0.43$ | $\phi_{B_d}[\pi]$ | $-2.9 \pm 2.0$ |
| $C_{B_s}$ | $1.13 \pm 0.35$ | $\phi_{B_s}[\pi]$ | $(-3 \pm 19) \cup (94 \pm 19)$ |
| $C_{sK}$ | $0.92 \pm 0.16$ | $\overline{\beta}$ | $0.20 \pm 0.06$ |
| | | $\overline{\eta}$ | $0.36 \pm 0.04$ |
| | | $\alpha[\pi]$ | $93 \pm 9$ |
| | | $\beta[\pi]$ | $24 \pm 2$ |
| | | $\gamma[\pi]$ | $62 \pm 9$ |
| | | $\Im \lambda_1[10^{-3}]$ | $14.6 \pm 1.4$ |
| | | $V_{ud}[10^{-3}]$ | $4.01 \pm 0.25$ |
| | | $|V_{td}|[V_{ts}|]$ | $4.15 \pm 0.07$ |
| | | $R_q | V_{td}|[V_{ts}|] | 0.203 \pm 0.015 |
| | | $R_0 | V_{td}|[V_{ts}|] | 0.416 \pm 0.027$ |
| | | $R_t | V_{td}|[V_{ts}|] | 0.887 \pm 0.063$ |
| | | $\sin 2\beta | V_{td}|[V_{ts}|] | 0.748 \pm 0.040$ |
| | | $\sin 2\beta | V_{td}|[V_{ts}|] | 0.039 \pm 0.004$ |
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