Hints for new sources of flavour violation in meson mixing

MB, Buras – arXiv:1602.04020

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The race is on!

Lots of progress in particle physics!

Experiment

- LHC @ 13 TeV
- Belle II
- various LFV experiments
- ...

Theory

- studies of BSM pheno
- SM precision calculations
- non-pertubative methods
- ...

Where will new physics show up first?

New physics in the flavour sector?

Where will new physics show up first?

Some hints emerged over the past years, in particular in the flavour sector.

Goals of this talk

- ➢ to draw your attention to the recent progress in meson mixing
- ➢ to point out that we might be facing new physics in $\Delta F = 2$
- ➢ to convince you that non-minimally flavour violating interactions are required to solve the tension

CKM matrix and unitarity triangle

Flavour and CP violation in SM described by CKM matrix:

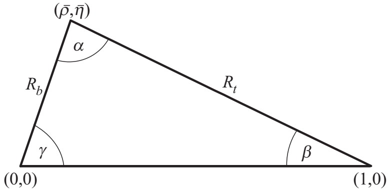
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\mathsf{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitarity implies $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

➢ **Unitarity triangle**

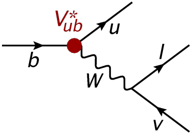
$$R_b = \left| \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right|$$

$$R_t = \left| \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} \right|$$



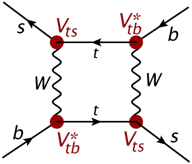
Determination of the unitarity triangle

1. **from tree level decays**



- direct sensitivity to relevant CKM element
- small impact of BSM contributions
- sizable uncertainty from $|V_{ub}|$ and γ

2. **from meson mixing observables** $(\Delta F = 2)$



- strong suppression in the SM
- high sensitivity to BSM contributions

➢ inconsistency would reveal new physics in $\Delta F = 2$ observables

Recent news from the lattice

Fermilab Lattice and MILC Collaborations (2016)

recent precise determination of $B_{d,s}$ mixing parameters

$$f_{B_d}\sqrt{\hat{B}_{B_d}} = 229.4(9.0)(2.3)\,\text{MeV}$$

$$f_{B_s}\sqrt{\hat{B}_{B_s}} = 276.0(8.0)(2.8)\,\text{MeV}$$

$$\xi = \frac{f_{B_s}\sqrt{\hat{B}_{B_s}}}{f_{B_d}\sqrt{\hat{B}_{B_d}}} = 1.203(17)(6)$$

- ➢ discrepancies between measured values of ΔM_d, ΔM_s, and $\Delta M_d/\Delta M_s$ and SM predictions (global fit) at 2.1σ, 1.3σ, and 2.9σ

What is the origin of this tension?

Constrained Minimal Flavour Violation

Buras et al. (2000)

see also D'Ambrosio et al. (2002); MB, Buras, Guadagnoli, Tarantino (2006)

Comstrained Minimal Flavour Violation (CMFV)

- flavour symmetry $U(3)_q \times U(3)_u \times U(3)_d$ only broken by Yukawa couplings Y_u, Y_d
- no new sources of CP-violation
- only SM effective operators

Consequences:

- BSM contributions suppressed by smallness of CKM elements
- CMFV contributions to $\Delta F = 2$ observables can be parameterised by a single real and flavour-universal function $S(v)$ with the lower bound

$$S(v) \geq S_0(x_t) = 2.322$$

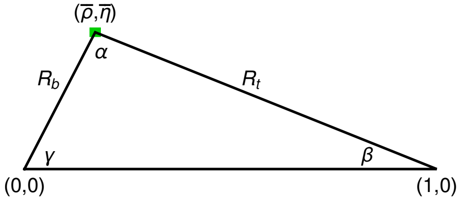
MB, Buras (2006)

The universal unitarity triangle

Universal unitarity triangle holding within all CMFV models

- $|V_{us}|$ from tree-level decays
- angle β determined from time-dependent CP-asymmetry $S_{\psi K_S}$
- side R_t determined from $\Delta M_d/\Delta M_s$

➢ few % precision, main uncertainties in $S_{\psi K_S}^{\text{exp}}$ and ξ

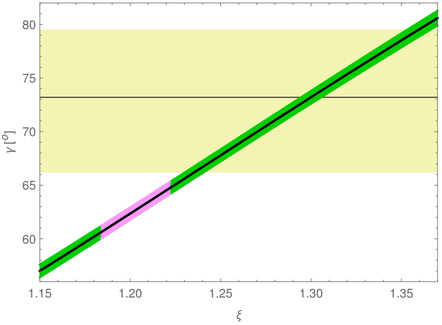


$$\bar{\rho}_{\text{UUT}} = 0.172 \pm 0.013 \qquad \bar{\eta}_{\text{UUT}} = 0.332 \pm 0.011$$

MB, Buras (2016)

Implications from the UUT: the angle γ

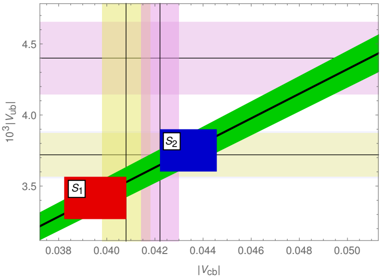
MB, Buras (2016)



➢ $\gamma_{\mathsf{UUT}} = (62.7 \pm 2.1)^\circ$

Implications from the UUT: the ratio $|V_{ub}|/|V_{cb}|$

MB, Buras (2016)

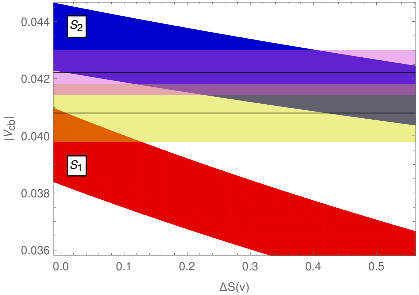


➢ $|V_{ub}|/|V_{cb}|_{\text{UUT}} = 0.0864 \pm 0.0025$

➢ **Strategies to fully determine CKM matrix:**
$\boldsymbol{S_1}$: ΔM_s is used to determine $|V_{cb}|$ as function of $S(v)$
$\boldsymbol{S_2}$: ε_K is used to determine $|V_{cb}|$ as function of $S(v)$

$|V_{cb}|$ from ΔM_s and ε_K

MB, Buras (2016)



$$|V_{cb}|_{S_1} = (39.5 \pm 1.3) \cdot 10^{-3} \left[\frac{2.322}{S(v)}\right]^{1/2}$$

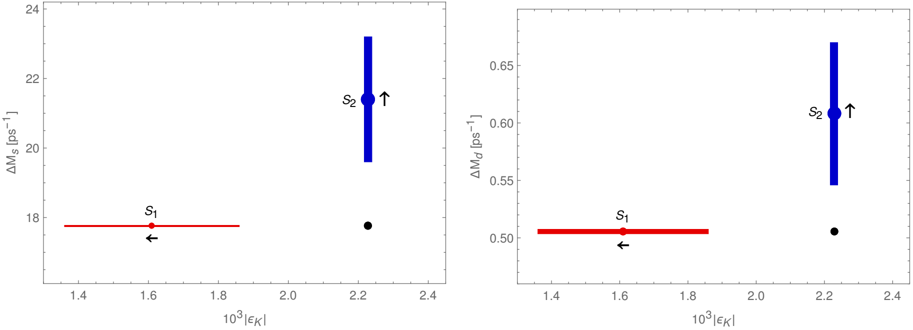
$$|V_{cb}|_{S_2} = (43.4 \pm 1.2) \cdot 10^{-3} \left[\frac{2.322}{S(v)}\right]^{1/4}$$

Comparing results of S_1 and S_2:

- inconsistent results for $|V_{cb}|$
- tension smallest for SM case $\Delta S(v) = 0$

Tension between $\Delta M_{s,d}$ and ε_K

MB, Buras (2016)



S_1: small $|V_{cb}|$ from ΔM_s ➢ ε_K significantly below the data

S_2: large $|V_{cb}|$ from ε_K ➢ $\Delta M_{s,d}$ significantly above the data

More SM numerics

MB, Buras (2016)

CKM elements ($|V_{ij}|$ in units of 10^{-3}, λ_t in units of 10^{-4})

	$\lvert V_{ts}\rvert$	$\lvert V_{td}\rvert$	$\lvert V_{cb}\rvert$	$\lvert V_{ub}\rvert$	$\mathrm{Im}\lambda_t$	$\mathrm{Re}\lambda_t$
S_1	$38.9(13)$	$7.95(29)$	$39.5(1.3)$	$3.41(15)$	$1.20(8)$	$-2.85(19)$
S_2	$42.7(12)$	$8.74(27)$	$43.4(1.2)$	$3.75(15)$	$1.44(8)$	$-3.44(19)$

Rare decay branching ratios

	$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)$	$\mathcal{B}(B_d \to \mu^+\mu^-)$
S_1	$6.88(70) \cdot 10^{-11}$	$2.11(25) \cdot 10^{-11}$	$3.14(22) \cdot 10^{-9}$	$0.84(7) \cdot 10^{-10}$
S_2	$8.96(79) \cdot 10^{-11}$	$3.08(32) \cdot 10^{-11}$	$3.78(23) \cdot 10^{-9}$	$1.02(8) \cdot 10^{-10}$

Breaking the flavour universality

flavour-universal CMFV contribution

$$S(v) = S_0(x_t) + \Delta S(v) \quad \text{with } \Delta S(v) > 0$$

cannot explain the tension in $\Delta F = 2$ data

Possible ways out:

- relax lower bound on $\Delta S(v)$ MB, Buras (2006)
  - ➢ possible but difficult to achieve in concrete models
  - ➢ inconsistencies with tree-level values of $|V_{cb}|$ and γ
- introduce flavour non-universal contributions

$$S_0(x_t) \to S_i = |S_i| e^{i\varphi_i} \qquad i = K, d, s$$

  - ➢ in general possible to fit $\Delta F = 2$ data
  - ➢ correlations with rare decays needed to test given model

Models with $U(2)^3$ flavour symmetry

Barbieri et al. (2012); Buras, Girrbach (2012); MB, Buras (2016)

minimally broken $U(2)^3$ flavour symmetry:

$$S_K = r_K S_0(x_t) \quad \text{with } r_K > 1$$
$$S_d = S_s = r_B S_0(x_t) e^{i\varphi_{\text{new}}}$$

Consequences:

- ε_K can only be enhanced w. r. t. the SM
- $\gamma = (62.7 \pm 2.1)^\circ$ also holds in $U(2)^3$ models
- $S_{\psi K_S}$ affected by φ_{new}, but correlated with ϕ_s

➢ $U(2)^3$ models in better shape than CMFV, but might get in trouble with more precise determinations of γ, $|V_{ub}/V_{cb}|$, and ϕ_s

Conclusions

1. new lattice data allow for a precise theory prediction for ΔM_d, ΔM_s and in particular their ratio

2. within CMFV models this implies

$$\gamma = (62.7 \pm 2.1)^\circ \qquad \frac{|V_{ub}|}{|V_{cb}|} = 0.0864 \pm 0.0025$$

3. determining $|V_{cb}|$ from ΔM_s or from ε_K yields incosistent results, putting all CMFV models under pressure

Are $\Delta F = 2$ transitions subject to new sources of flavour violation?