CMFV models facing the recent progress in lattice calculations of $B_{s,d}$ mixing

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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**: 

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

**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 $\gamma$

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)**

compare to FLAG (2016) values

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

$$f_{B_d} \sqrt{\hat{B}_{B_d}} = (227.7 \pm 9.8) \text{ MeV}$$

$$f_{B_s} \sqrt{\hat{B}_{B_s}} = (274.6 \pm 8.8) \text{ MeV}$$

$$\xi = \frac{f_{B_s} \sqrt{\hat{B}_{B_s}}}{f_{B_d} \sqrt{\hat{B}_{B_d}}} = 1.206 \pm 0.019$$

- discrepancies between measured values of $\Delta M_d$, $\Delta M_s$, and $\Delta M_d/\Delta M_s$ and SM predictions (global fit) at $1.8\sigma$, $1.1\sigma$, and $2.0\sigma$

**What is the origin of this tension?**
Constrained 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

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

The universal unitarity triangle

Universal unitarity triangle holding within all CMFV models

- $|V_{us}|$ from tree-level decays
- angle $\beta$ 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 $\xi$

\[
\rho_{\text{UUT}} = 0.170 \pm 0.013 \quad \eta_{\text{UUT}} = 0.333 \pm 0.011
\]
Implications from the UUT: the angle $\gamma$

construction of UUT yields

$\gamma_{UUT} = (63.0 \pm 2.1)^\circ$

compare to:

$\gamma_{\text{tree}} = (72.2^{+6.8}_{-7.2})^\circ$

Problem for CMFV?

More precise $\gamma$ measurements by LHCb and Belle II will tell!
Implications from the UUT: the ratio $|V_{ub}|/|V_{cb}|$

Strategies to fully determine CKM matrix:

$S_1$: $\Delta M_s$ is used to determine $|V_{cb}|$ as function of $S(v)$

$S_2$: $\varepsilon_K$ is used to determine $|V_{cb}|$ as function of $S(v)$

$|V_{ub}|/|V_{cb}|_{\text{UUT}} = 0.0864 \pm 0.0025$
$|V_{cb}|$ from $\Delta M_s$ and $\varepsilon_K$

Comparing results of $S_1$ and $S_2$:

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

MB, Buras (2016)

$|V_{cb}|S_1 = (39.7 \pm 1.3) \cdot 10^{-3} \left[ \frac{2.322}{S(v)} \right]^{1/2}$

$|V_{cb}|S_2 = (43.3 \pm 1.1) \cdot 10^{-3} \left[ \frac{2.322}{S(v)} \right]^{1/4}$
Tension between $\Delta M_{s,d}$ and $\varepsilon_K$

**$S_1$:** small $|V_{cb}|$ from $\Delta M_s \gg \varepsilon_K$ significantly below the data

**$S_2$:** large $|V_{cb}|$ from $\varepsilon_K \gg \Delta M_{s,d}$ significantly above the data
More SM numerics

**CKM elements** (|\(V_{ij}\)| in units of \(10^{-3}\), \(\lambda_t\) in units of \(10^{-4}\))

|     | \(|V_{ts}|\) | \(|V_{td}|\) | \(|V_{cb}|\) | \(|V_{ub}|\) | Im\(\lambda_t\) | Re\(\lambda_t\) |
|-----|-------------|-------------|-------------|-------------|---------------|--------------|
| \(S_1\) | 39.0(13)   | 8.00(29)   | 39.7(1.3)   | 3.43(15)    | 1.21(8)       | −2.88(19)    |
| \(S_2\) | 42.6(11)   | 8.73(26)   | 43.3(1.1)   | 3.74(14)    | 1.44(7)       | −3.42(18)    |

**Rare decay branching ratios**

<table>
<thead>
<tr>
<th></th>
<th>(\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}))</th>
<th>(\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}))</th>
<th>(\overline{\mathcal{B}}(B_s \to \mu^+\mu^-))</th>
<th>(\mathcal{B}(B_d \to \mu^+\mu^-))</th>
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<tbody>
<tr>
<td>(S_1)</td>
<td>7.00(71) \cdot 10^{-11}</td>
<td>2.16(25) \cdot 10^{-11}</td>
<td>3.23(24) \cdot 10^{-9}</td>
<td>0.90(8) \cdot 10^{-10}</td>
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<tr>
<td>(S_2)</td>
<td>8.93(74) \cdot 10^{-11}</td>
<td>3.06(30) \cdot 10^{-11}</td>
<td>3.85(24) \cdot 10^{-9}</td>
<td>1.08(8) \cdot 10^{-10}</td>
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Breaking the flavour universality

flavour-universal CMFV contribution

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

cannot explain the tension in \( \Delta F = 2 \) data

Possible ways out:

- relax lower bound on \( \Delta S(v) \)
  - possible but difficult to achieve in concrete models
  - inconsistencies with tree-level values of \( |V_{cb}| \) and \( \gamma \)

- introduce flavour non-universal contributions

  \[ S_0(x_t) \rightarrow S_i = |S_i|e^{i\varphi_i} \quad i = K, d, s \]

  - 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:

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

Consequences:

- $\varepsilon_K$ can only be enhanced w. r. t. the SM
- $\gamma = (63.0 \pm 2.1)\degree$ also holds in $U(2)^3$ models
- $S_{\psi K_S}$ affected by $\varphi_{\text{new}}$, but correlated with $\phi_s$

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

1 new lattice data allow for a precise theory prediction for $\Delta M_d$, $\Delta M_s$ and in particular their ratio

2 within CMFV models this implies

$$\gamma = (63.0 \pm 2.1)^\circ \quad \frac{|V_{ub}|}{|V_{cb}|} = 0.0864 \pm 0.0025$$

3 determining $|V_{cb}|$ from $\Delta M_s$ or from $\varepsilon_K$ yields inconsistent results, putting all CMFV models under pressure

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