Quark flavour mixing with right-handed currents: an effective theory approach

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Outline

1. **Part 1: Motivation and Introduction of RHMFV**
2. **Part 2: $\Delta F = 2$ Processes**
3. **Part 3: Rare decays and $Z \to b\bar{b}$**

Based on:

Buras, KG, Isidori [arXiv:1007.1993]

Motivation

Right-handed (RH) currents arise in various new physics frameworks, in particular in models with an underlying $SU(2)_R \times SU(2)_L$ symmetry

A recent flavour physics motivation [Crivellin '09]: right-handed currents can help remove the discrepancy between inclusive and exclusive determinations in V_{ub}

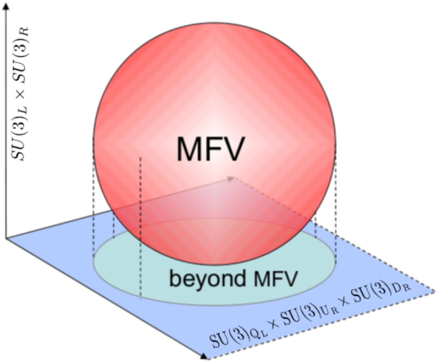
our goal:
to investigate whether the RH currents motivated by the V_{ub} problem are consistent with other flavour observables ($\Delta F = 2$, rare decays)

The RHMFV model

- in the spirit of an effective approach to MFV
  [Ambrosio, Giudice, Isidori, Strumia '02]
- assume only the global symmetry and the pattern of breakdown

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$	- electroweak symmetry
$SU(3)_L \times SU(3)_R$	- flavour symmetry

- left-right symmetric flavour symmetry only explicitly broken by Yukawas
- only $SU(2)_L$ and $U(1)_Y$ are effectively gauged below the TeV scale



The method

- construct dimension six operators formally invariant under LR symmetric flavour group
- new bilinears e.g. $\bar{Q}_R \Gamma Y_u^\dagger Y_u Q_R$ contribute with respect to MFV

Yukawa insertions:

$$
\begin{aligned}
(Y_u Y_u^\dagger)_{i\neq j}\,\big|_{d-\mathrm{base}} &= (V^\dagger \lambda_u^2 V)_{ij} \approx y_t^2 \overbrace{V_{3i}^* V_{3j}}^{\text{CKM matrix}} \\
(Y_u^\dagger Y_u)_{i\neq j}\,\big|_{d-\mathrm{base}} &= (\widetilde{V}^\dagger \lambda_u^2 \widetilde{V})_{ij} \approx y_t^2 \underbrace{e^{i(\phi_i^d-\phi_j^d)} (\widetilde{V}_0)_{3i}^* (\widetilde{V}_0)_{3j}}_{\text{new RH CKM with new phases}}
\end{aligned}
$$

$Y_u Y_u^\dagger$ - known from MFV
$Y_u^\dagger Y_u$ - new! characterizing the strength of RH mediated FCNC

The right-handed mixing matrix

- due to misalignment of the Yukawas in the down-type sector a RH mixing matrix $\widetilde{V}$ appears
- $\widetilde{V}$ controls flavour-mixing in the right-handed sector

Parametrization:

$$\widetilde{V} = D_U \widetilde{V}_0 D_D^\dagger$$

$\widetilde{V}_0$	- “CKM-like” mixing matrix, one non-trivial phase
$D_{U,D}$	- diagonal matrices, five new CP-violating phases

What are the bounds on $\widetilde{V}$?

- ⋆ charged currents data
- ⋆ unitarity
- ⋆ phenomenological bounds

1 bounds from charged currents data

- determine $\widetilde{V}$ using data on tree level charged current transitions, in particular $u \to d$, $u \to s$, $b \to u$ and $b \to c$

$$|\widetilde{V}| \sim \begin{pmatrix} < 1.4 & < 1.4 & 1.0 \pm 0.4 \\ - & - & < 2.0 \\ - & - & - \end{pmatrix} \times \left(\frac{10^{-3}}{\epsilon_R} \right)$$

- elements of $\widetilde{V}$ and ϵ_R appear in combination
- the size of the effective RH charged current coupling ϵ_R is given by

$$\epsilon_R = -\frac{c_R v^2}{2\Lambda^2}$$

- here the coeffcient c_R is the coupling of the RH charged current before rotation to mass eigenstates

1 bounds from charged currents data

the V_{ub} problem - a more detailed look at the $b \to u$ transition

$$\mathcal{B}(B \to \pi \ell \nu) \sim |V_{ub} + \epsilon_R \widetilde{V}_{ub}|^2$$

$$\mathcal{B}(B \to X_u \ell \nu) \sim (|V_{ub}|^2 + |\epsilon_R \widetilde{V}_{ub}|^2)$$

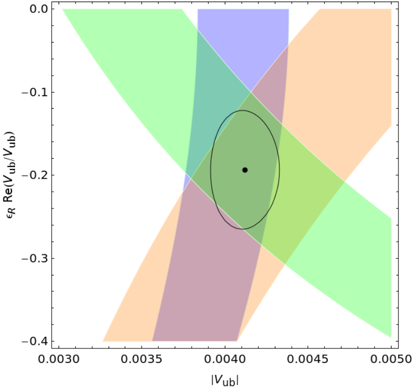
$$\mathcal{B}(B \to \tau \nu) \sim |V_{ub} - \epsilon_R \widetilde{V}_{ub}|^2$$

UTfit:

$$|V_{ub}|^{B\to\pi}_{\text{SM-exp}} = (3.38 \pm 0.36) \times 10^{-3}$$

$$|V_{ub}|^{\text{incl}}_{\text{SM-exp}} = (4.11 \pm 0.28) \times 10^{-3}$$

$$|V_{ub}|^{B\to\tau}_{\text{SM-exp}} = (5.14 \pm 0.57) \times 10^{-3}$$



the tension between inclusive and exclusive determinations of $|V_{ub}|$ can be resolved. [Crivellin '09]

1. **bounds from charged currents data**
2. **bounds from unitarity**
   - constraint from first row:

$$|\epsilon_R| = \left(|\epsilon_R \widetilde{V}_{ud}|^2 + |\epsilon_R \widetilde{V}_{us}|^2 + |\epsilon_R \widetilde{V}_{ub}|^2\right)^{1/2} = (1.0 \pm 0.5) \times 10^{-3}$$

   - agreement with naive estimate using

$$c_R = \mathcal{O}(1) \quad \text{and} \quad \Lambda = 4\pi v \approx 3 \text{ TeV}$$

   we find

$$\epsilon_R \sim \frac{c_R v^2}{2\Lambda^2} \sim \mathcal{O}(10^{-3})$$

   - third column: large $|\widetilde{V}_{ub}|$ constrains the maximal value of $|\widetilde{V}_{tb}|$

1. **bounds from charged currents data**
2. **bounds from unitarity**
3. **phenomenological bounds**

- large value of $|\widetilde{V}_{tb}|$ welcome since:
  i) it minimizes the values of $|\widetilde{V}_{ts}|$ and $|\widetilde{V}_{td}|$ $\Leftrightarrow$ FCNCs
  ii) it maximizes the impact of right-handed currents in $Z \rightarrow b\bar{b} \Leftrightarrow$ agreement with experiments?
  $\Rightarrow$ maximize $|\widetilde{V}_{tb}|$

- global fit $\Leftrightarrow$ RH mixing matrix is well described by the following ansatz

$$\widetilde{V}_0^{(\mathrm{II})} = \begin{pmatrix} \pm\tilde{c}_{12}\frac{\sqrt{2}}{2} & \pm\tilde{s}_{12}\frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \\ -\tilde{s}_{12} & \tilde{c}_{12} & 0 \\ \tilde{c}_{12}\frac{\sqrt{2}}{2} & \tilde{s}_{12}\frac{\sqrt{2}}{2} & \pm\frac{\sqrt{2}}{2} \end{pmatrix}$$

$\Delta F = 2$ Processes - some theoretical aspects

- **Relevant operators:** $\rightarrow$ focus on $\bar{Q}_R Y_u^\dagger Y_u \gamma^\mu Q_R$ bilinear

$$\begin{aligned} \mathcal{O}_{RR}^{(6)} &= [\bar{Q}_R^i (Y_u^\dagger Y_u)_{ij} \gamma_\mu Q_R^j]^2 \\ \mathcal{O}_{LR}^{(6)} &= [\bar{Q}_L^i (Y_u Y_u^\dagger)_{ij} \gamma^\mu Q_L^j][\bar{Q}_R^i (Y_u^\dagger Y_u)_{ij} \gamma_\mu Q_R^j] \end{aligned}$$

- **effective Hamiltonian of new contributions:**

$$\mathcal{L}^{\Delta F=2} = \frac{c_{RR}}{\Lambda^2} \mathcal{O}_{RR}^{(6)} + \frac{c_{LR}}{\Lambda^2} \mathcal{O}_{LR}^{(6)}$$

- c_{RR} and c_{LR} are **flavour-blind** by construction and therefore the same in the K, B_d and B_s system
- hence the RH mixing is only determined by the elements of the RH mixing matrix in particular by $\tilde{c}_{12}$, $\tilde{s}_{12}$ and CP violating phases

RH contributions to flavour mixing

Mixing term	K-mixing $s \to d$	B_d-mixing $b \to d$	B_s-mixing $b \to s$
$\widetilde{V}_{ti}^* \widetilde{V}_{tj}$	$\frac{1}{2}\tilde{c}_{12}\tilde{s}_{12}e^{i(\phi_2^d - \phi_1^d)}$	$\pm\frac{1}{2}\tilde{c}_{12}e^{i(\phi_3^d - \phi_1^d)}$	$\pm\frac{1}{2}\tilde{s}_{12}e^{i(\phi_3^d - \phi_2^d)}$

- **K system:** strong constraints points towards small $\tilde{c}_{12}$ or $\tilde{s}_{12}$ unless c_{RR} and c_{LR} are very small
- **$\mathbf{B_s}$ system:** hints for sizable NP contributions from CDF and DO collaborations, in particular in $S_{\psi\phi}$

$$\Longrightarrow \quad \tilde{c}_{12} \ll 1 \to \tilde{s}_{12} \approx 1$$

$$\left|\widetilde{V}_0\right| \sim \begin{pmatrix} 0 & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \\ 1 & 0 & 0 \\ 0 & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{pmatrix}$$

large CPV phases in B_s mixing + small NP effects allowed by ε_K
$\Rightarrow$ negligible effects of RH currents in B_d mixing

Combined fit of ε_K and B_s mixing

- Constraints from B_s mixing:

$$\frac{(\Delta M_s)_{\rm exp}}{(\Delta M_s)_{\rm SM}} \approx 0.96 \pm 0.15$$
$$S_{\psi\phi} \approx 0.6 \pm 0.3$$

- Solution when assuming e.g $c_{RR} \gg c_{LR}$:

$$c_{RR} \approx \pm 7.3 \times 10^{-3} \quad \text{and} \quad \sin(2\phi_{32}^d) \approx \mp 0.30\,,$$
$$c_{RR} \approx \pm 2.3 \times 10^{-3} \quad \text{and} \quad \sin(2\phi_{32}^d) \approx \mp 0.95\,.$$

Fine-tuning?

operator	size of coefficient	suppression
RH charged current	$\mathcal{O}(1)$	tree level
$\Delta F = 2$	$1/(16\pi^2) \approx 6 \times 10^{-3}$	loop

- $c_{RR,LR} = \mathcal{O}(10^{-3}\text{–}10^{-2}) \rightarrow$ small enough to satisfy kaon bounds

Effects due to $\sin(2\beta)$ enhancement

SM: $|V_{ub}|$ is averaged over different determinations

$$\sin(2\beta)^{\rm SM}_{\rm tree} = 0.734 \pm 0.034 \quad \text{(UTfit)}$$

RHMFV: $|V_{ub}|$ enhanced, close to inclusive determination

$$\sin(2\beta)^{\rm RH}_{\rm tree} = 0.77 \pm 0.05$$

- ε_K **Problem:**

$$\varepsilon_K^{\rm exp} = (2.229 \pm 0.01) \times 10^{-3} \quad \text{(PDG)}$$
$$\varepsilon_K^{\rm SM} = (1.85 \pm 0.21) \times 10^{-3}$$

The $\sin(2\beta)$ enhancement removes ε_K problem automatically.

Effects due to $\sin(2\beta)$ enhancement

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RHMFV: $|V_{ub}|$ enhanced, close to inclusive determination

$$\sin(2\beta)^{\mathrm{RH}}_{\mathrm{tree}} = 0.77 \pm 0.05$$

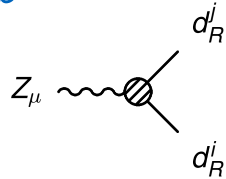
- $S_{\psi K_S}$ **Problem:**

$$S^{\mathrm{exp}}_{\psi K_S} = \sin(2\beta)^{\mathrm{exp}}_{\psi K_S} = 0.672 \pm 0.023 \quad \text{(HFAG)}$$
$$S^{\mathrm{RH}}_{\psi K_S} = \sin(2\beta + \underbrace{\varphi_{B_d}}_{\text{too small since small } B_d \text{ mixing}})$$

The 2σ tension between the experimental value of $S_{\psi K_S}$ and $S^{\mathrm{RH}}_{\psi K_S}$ cannot be resolved. $S_{\psi K_S}$ cannot be explained by RH currents alone in this framework!

Analysis of rare decays and $Z \to b\bar{b}$

- new dimension six operators generate effective $\bar{d}^i_R \gamma^\mu d^j_R Z_\mu$ coupling

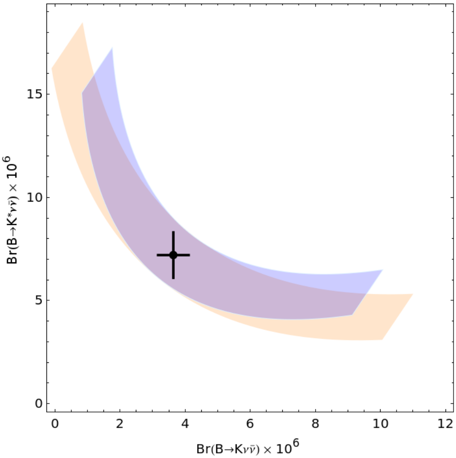


the constraints from $B_{s,d} \to \ell^+\ell^-$ eliminate the possibility of removing the known anomaly $Z \to b\bar{b}$

more B decays:

- constraint from $B_s \to X_s \ell^+\ell^-$ [Altmannshofer et al '09] precludes $B_s \to \mu^+\mu^-$ near present experimental bound
- while $\mathcal{O}(1)$ deviation from the SM in $\mathcal{B}(B_s \to \mu^+\mu^-)$ can be found, effects of RH currents in $\mathcal{B}(B_d \to \mu^+\mu^-)$ are small and negligible after imposing constraints from $S_{\psi\phi}$

Correlation between $\mathcal{B}(B \to K\nu\bar{\nu})$ and $\mathcal{B}(B \to K^*\nu\bar{\nu})$



- the two bands correspond to the two values of $|\sin(2\phi^d_{32})|$ obtained from taking $S_{\psi\phi}$ large
- factor 2 enhancement with respect to SM value in both decays possible
- clear anti-correlation

black dot = SM value	
blue:	$\lvert\sin(2\phi^d_{32})\rvert = 0.95$
orange:	$\lvert\sin(2\phi^d_{32})\rvert = 0.30$

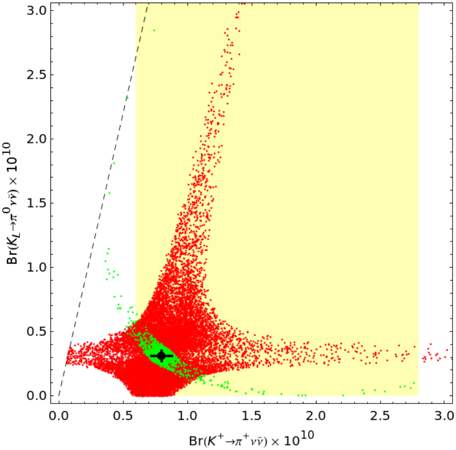
Correlation between $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ & $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$

red: $c_{RR} \gg c_{LR}$

- $\mathcal{O}(1)$ deviations from the SM predictions possible in both modes
- larger deviations: fine-tuned scenario where the phase ϕ^d_{12} such that ε_K constraint is avoided

green: $c_{LR} \gg c_{RR}$

- situation more constraint
- different correlation, since different $\Delta S = 2$ condition on phases



impose the constraints from ε_K and $S_{\psi\phi}$

Conclusions for RHMFV:

- RH currents provide a solution to the V_{ub} problem
- the $S_{\psi\phi}$ and ε_K anomalies can be understood

- $Zb\bar{b}$ cannot be solved
- strengthens the tension between $\sin 2\beta$ and $S_{\psi K_S}^{\text{exp}}$

more phenomenology:

- if large B_s mixing then negligible contributions to B_d mixing
- if the RH contribution to $S_{\psi\phi}$ is large, no significant enhancement is expected in $B_d \to \mu^+\mu^-$
- well-defined pattern of correlations in $B \to \{K, K^*\}\nu\bar{\nu}$ & $K \to \pi\nu\bar{\nu}$

Rare decays and $Z \to b\bar{b}$ - theoretical aspects

- **Relevant operators:** $\to$ generate $\bar{d}^i_R \gamma^\mu d^j_R Z_\mu$

$$\mathcal{O}^{(6)}_{R_{Z1}} = i\bar{Q}^i_R (Y_u^\dagger Y_u)_{ij} \gamma^\mu H^\dagger D_\mu H Q^j_R$$
$$\mathcal{O}^{(6)}_{R_{Z2}} = i\bar{Q}^i_R (Y_u^\dagger Y_u)_{ij} \gamma^\mu \tau_i Q^j_R \ \mathrm{Tr}\left(H^\dagger D_\mu H \tau^i\right)$$

- **effective Hamiltonian of new contributions:**

$$\mathcal{L}^{\Delta F=1} = \frac{c_{R_{Z1}}}{\Lambda^2}\mathcal{O}^{(6)}_{R_{Z1}} + \frac{c_{R_{Z2}}}{\Lambda^2}\mathcal{O}^{(6)}_{R_{Z2}}$$

- Effectively the following combination appears:

$$c^{\mathrm{eff}}_{Z_R} = (c_{R_{Z1}} + 2c_{R_{Z2}})\frac{(3\ \mathrm{TeV})^2}{\Lambda^2}$$

For $\Lambda = 3$ TeV and $c_{R_{Z_i}} = \mathcal{O}(1)$
$\Rightarrow c^{\mathrm{eff}}_{Z_R} = \mathcal{O}(1)$

$Z \to b\bar{b}$

- disagreement between data and SM expectation in the RH sector:

$$(\Delta g_R^{bb})_{\rm exp} = (g_R^{bb})_{\rm exp} - (g_R^{bb})_{\rm SM} = (1.9 \pm 0.6) \times 10^{-2} .$$

- the generated effective coupling reads:

$$(\Delta g_R^{bb})_{RH} \approx -0.15 \times 10^{-2} \times c_{Z_R}^{\rm eff}$$

$\Longrightarrow$ too small correction for $c_{Z_R}^{\rm eff} = \mathcal{O}(1)$
$Z \to b\bar{b}$ anomaly cannot be solved

- combined constraints of the decays $B_d \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ imply even stronger bound:

$$\left|c_{Z_R}^{\rm eff}\right| < 0.62 \Rightarrow \left|(\Delta g_R^{bb})_{RH}\right| < 1 \times 10^{-3}$$

$B_{s,d} \to \mu^+\mu^-$ and $B_{s,d} \to X_s\ell^+\ell^-$

$$\mathcal{B}(B_s \to \ell^+\ell^-) = \mathcal{B}(B_s \to \ell^+\ell^-)_{\rm SM} \left|1 \mp 7.8 \times \tilde{s}_{12} e^{i\phi^d_{32}}\ c^{\rm eff}_{Z_R}\right|^2$$

$$\mathcal{B}(B_d \to \ell^+\ell^-) = \mathcal{B}(B_d \to \ell^+\ell^-)_{\rm SM} \left|1 \pm 37 \times \tilde{c}_{12} e^{i\phi^d_{31}}\ c^{\rm eff}_{Z_R}\right|^2$$

- maximal enhancement of $\mathcal{B}(B_s \to \mu^+\mu^-)$ over its SM expectation
  $\Rightarrow$ factor of 5
- constraint from $B_s \to X_s\ell^+\ell^-$: $\left|\tilde{s}_{12} c^{\rm eff}_{Z_R}\right| < 0.15$
  $\Rightarrow$ precludes $B_s \to \mu^+\mu^-$ near present experimental bound
- assume $\mathcal{O}(1)$ deviation from the SM in $\mathcal{B}(B_s \to \mu^+\mu^-)$
  $\Rightarrow \mathcal{B}(B_d \to \mu^+\mu^-)$ close to SM value
- combined with constraints from $S_{\psi\phi}$ ($\tilde{s}_{12} \approx 1$ and $\tilde{c}_{12} < 10^{-2}$)
  $\Rightarrow$ effects of RH currents in $\mathcal{B}(B_d \to \mu^+\mu^-)$ are negligible