$b \to s\ell^+\ell^-$ Transitions in a 2HDM with generic Yukawa couplings

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based on A. Crivellin, D. Müller, C.W. [arXiv:1903.10440]

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Outline

- Why?
  - The $b \to s\ell^+\ell^-$ anomaly
- What?
  - The Two-Higgs-Doublet Model with generic Yukawa couplings
  - Right-Handed Neutrinos
- Phenomenology
  - $b \to s\ell^+\ell^-$
  - $(g-2)_\mu$

Recap of the $b \to s\ell^+\ell^-$ anomaly

Deviations from the SM in a number of observables

- $B \to \phi\mu^+\mu^-$ in $1\mathrm{GeV} < q^2 < 6\mathrm{GeV}$ bin: 3σ
- angular observable P_5' in $B \to K^*\mu^+\mu^-$: $4.30 < q^2 < 8.68\mathrm{GeV}$: 3.7σ
- $R_K = \frac{\mathrm{BR}(B\to K\mu^+\mu^-)}{\mathrm{BR}(B\to Ke^+e^-)}$: 2.5σ
- R_K^*:
  - $0.045 < q^2 < 1.1\mathrm{GeV}$: $2.1 - 2.3\sigma$
  - $1.1 < q^2 < 6.0\mathrm{GeV}$: $2.4 - 2.5\sigma$

$\to$ deviation in $b \to s\mu^+\mu^-$
$\to$ sign of Lepton Flavor Universality violation in $b \to s\ell^+\ell^-$

EFT for $b \to s\ell^+\ell^-$

$$H_{\text{eff}}^{\ell_I\ell_J} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{K=7,8} C_K^{(\prime)} O_K^{(\prime)} + \sum_{K=9,10,S,P} C_K^{(\prime)IJ} O_K^{(\prime)IJ} \right)$$

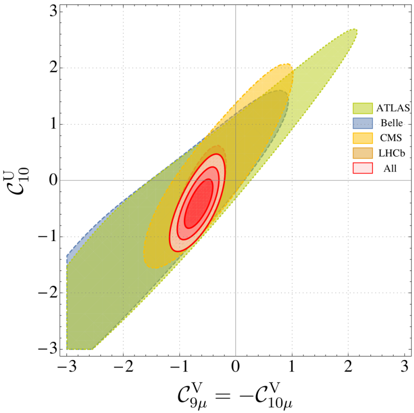
with the operators

$$O_7 = \frac{e}{16\pi^2} m_b \bar{s}\sigma^{\mu\nu} P_R b F_{\mu\nu}\,, \qquad O_8 = \frac{g_s}{16\pi^2} m_b \bar{s}\sigma^{\mu\nu} T^a P_R b G^a_{\mu\nu}\,,$$

$$O_9^{IJ} = \frac{e^2}{16\pi^2} \bar{s}\gamma_\mu P_L b \bar{\ell}_I \gamma^\mu \ell_J\,, \qquad O_{10}^{IJ} = \frac{e^2}{16\pi^2} \bar{s}\gamma_\mu P_L b \bar{\ell}_I \gamma^\mu \gamma_5 \ell_J\,,$$

$$O_S^{IJ} = \frac{e^2}{16\pi^2} \bar{s} P_L b \bar{\ell}_I \ell_J\,, \qquad O_P^{IJ} = \frac{e^2}{16\pi^2} \bar{s} P_L b \bar{\ell}_I \gamma_5 \ell_J$$

Global fit of the anomalies



This scenario:

- $C_{ie}^{NP} = C_i^U$
- $C_{i\mu}^{NP} = C_i^U + C_{i\mu}^V$
- 2D fit:$\{C_{10}^U, C_{9\mu}^V = -C_{10\mu}^V\}$
- p-value: 73.4%

[arXiv:1903.09578, M. Alguero, B. Capdevila, A. Crivellin, S. Descotes-Genon, P. Masjuan, J. Matias and J. Virto]

2HDM with generic Yukawa couplings

- 2 CP even neutral scalars h_0, H_0
- CP odd neutral scalar A_0
- charged scalar $H^\pm$
- two generic Yukawa Matrices
- after diagonalisation of Mass matrix: other Higgs doublet keeps off-diagonal Couplings
- Extra couplings defined as ϵ_{ij}^F
- Introduces flavour dependence

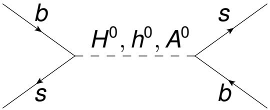
$$\mathcal{L}_Y \supset -\sum_{F=u,d,\ell,\nu} \bar{F}_f\Big(\frac{m_f^F}{v}\delta_{fi}c_{\beta\alpha} - \Big(\varepsilon_{fi}^F P_R + \varepsilon_{if}^{F*} P_L\Big) s_{\beta\alpha}\Big) F_i H^0$$

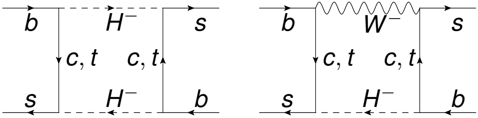
Right-handed Neutrinos

$$
\begin{aligned}
\mathcal{L}_\nu =& i\bar{N}_I \partial\!\!\!/ N_I - (Y^\nu_{IJ} \bar{L}_I \phi_1^c N_J + \varepsilon^\nu_{IJ} \bar{L}_I \phi_2^c N_J + h.c.) \\
&- \frac{1}{2} \left[(M_M)_{IJ} \bar{N}_I^c N_J + h.c. \right]
\end{aligned}
$$

- include right-handed neutrinos with type I see-saw
- ϕ_1 carries the vev: $m_D = vY^\nu$
- $m_D \ll M_M$
- $M_M < 1\text{TeV}$

Dominant constraints: $B_s - \bar{B}_s$ Mixing



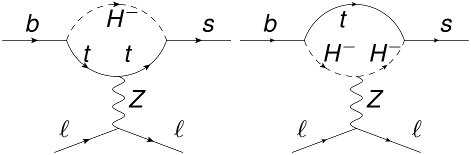


- The tree-level contribution forces ε^d_{ij} to be negligible
- The remaining leading one loop contributions constrain ε^u_{ij}

Other constraints

- $\mathrm{Br}[B \to X_s\gamma]$
- $\mathrm{Br}[B_s \to \ell_I^+\ell_J^-]$
- $\mathrm{Br}[B \to K^{(*)}\ell_I^+\ell_J^-]$
- $\mathrm{Br}[B \to X_s\nu\bar{\nu}]$
- $\mathrm{Br}[\ell_I \to \ell_F\gamma]$
- $\mathrm{Br}[h \to \tau\mu]$

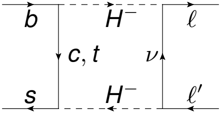
Contributions to $b \to s\ell^+\ell^-$: Z Penguin



$$C_9^U = -\frac{V_{k2}^* \varepsilon_{k3}^u \varepsilon_{n3}^{u*} V_{n3}}{2e^2 V_{tb} V_{ts}^*}\left(1 - 4s_W^2\right)\left(I_1(z_3) - 1\right),$$
$$C_{10}^U = \frac{V_{k2}^* \varepsilon_{k3}^u \varepsilon_{n3}^{u*} V_{n3}}{2e^2 V_{tb} V_{ts}^*}\left(I_1(z_3) - 1\right)$$

- lepton flavour universal contribution
- C_9^U suppressed: $\frac{C_9^U}{C_{10}^U} = -(1 - 4s_w^2)$

Contributions to $b \to s\ell^+\ell^-$: charged Higgs box

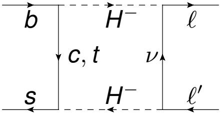


$$C_{9\mu}^{V} = A\big(\varepsilon_{m\mu}^{\ell *}\varepsilon_{m\mu}^{\ell} I_1(z_i) \qquad\qquad\qquad\qquad \big)\,,$$
$$C_{10\mu}^{V} = A\big(\varepsilon_{m\mu}^{\ell *}\varepsilon_{m\mu}^{\ell} I_1(z_i) \qquad\qquad\qquad\qquad \big)$$

Without right-handed neutrinos:

- lepton flavour universality violating
- $C_9 = C_{10}$: wrong sign for the anomaly
- far too small

Contributions to $b \to s\ell^+\ell^-$: charged Higgs box

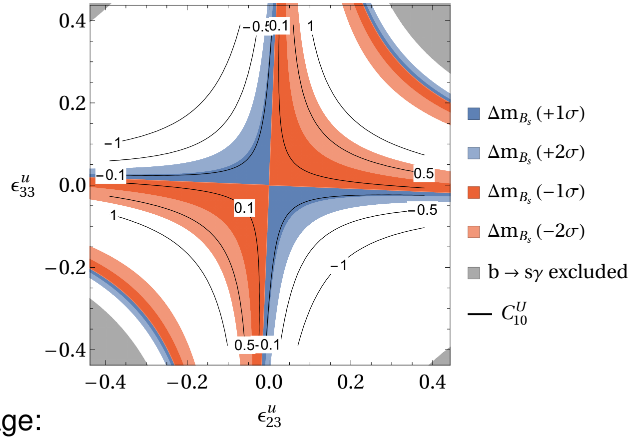


$$C_{9\mu}^V = A\big(\varepsilon_{m\mu}^{\ell *}\varepsilon_{m\mu}^{\ell} I_1(z_i) - U_{\mu p}\varepsilon_{pj}^{\nu}\varepsilon_{mj}^{\nu *}U_{\mu m}^{*} I_8(z_i, x_j)\big)\,,$$
$$C_{10\mu}^V = A\big(\varepsilon_{m\mu}^{\ell *}\varepsilon_{m\mu}^{\ell} I_1(z_i) + U_{\mu p}\varepsilon_{pj}^{\nu}\varepsilon_{mj}^{\nu *}U_{\mu m}^{*} I_8(z_i, x_j)\big)$$

With right-handed neutrinos:

- lepton flavour universality violating
- $C_9 = -C_{10}$: correct sign for the anomaly
- sizeable contributions possible
- mass requirement: $m_{N_i} < 1$TeV

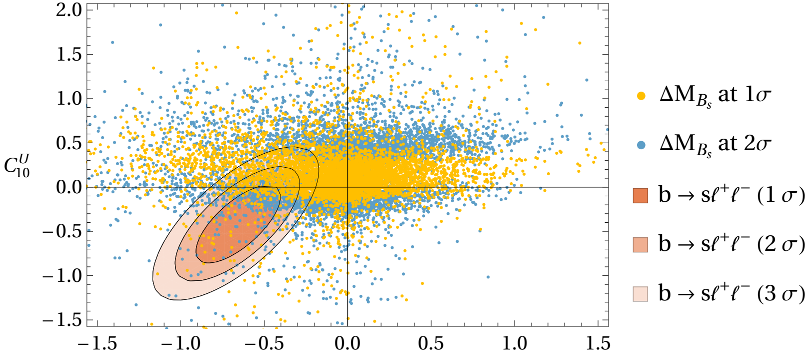
Phenomenology for $b \to s\ell^+\ell^-$



Message:

- Constraint from B_s-Mixing dominant
- preferred region for $b \to s\ell^+\ell^-$anomaly requires $C_{10}^U < 0$

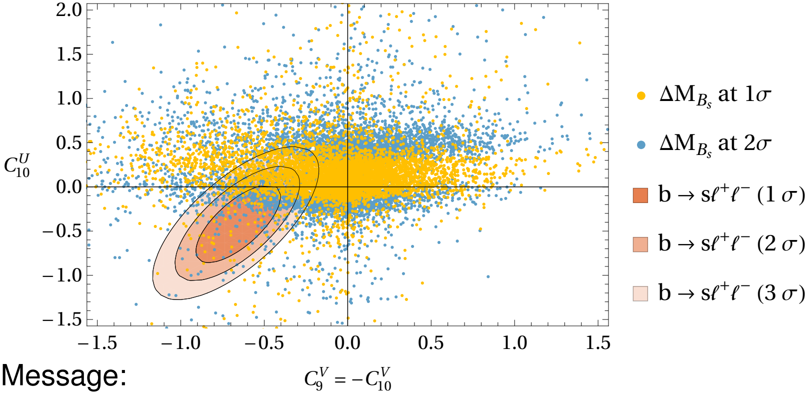
Phenomenology for $b \to s\ell^+\ell^-$



Scan parameters: $C_9^V = -C_{10}^V$

- $\varepsilon^u_{22,23,32,33}$ and $\varepsilon^\nu_{21,22,32,23,33}$ between ± 1.5
- $m_{N_i} \in [100, 1000]$, $m_{H^+} \in [100, 500]$, $\{m_{H_0}, m_{A_0}\} \in [100, 350]$ (GeV)

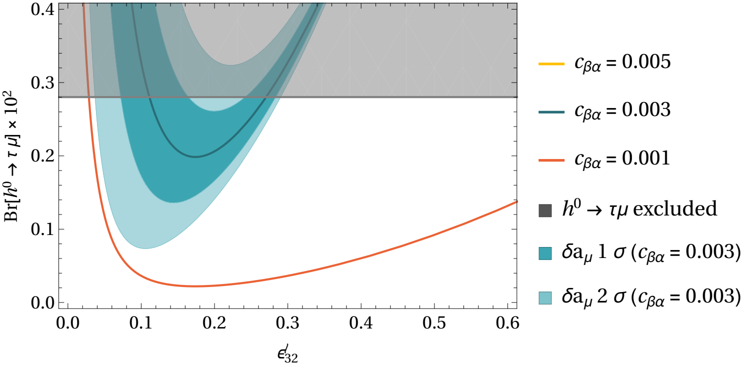
Phenomenology for $b \to s\ell^+\ell^-$



Message:

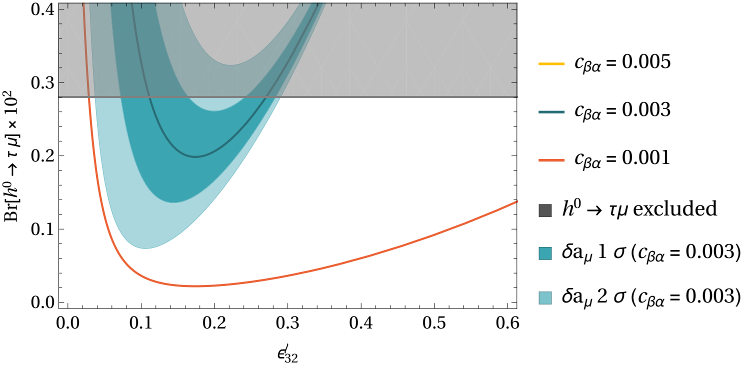
- Central region barely overlaps with the 1σ region of the fit
- below fine-tuning region utilizing all four ε_{ij}^u
- explanation including fine-tuning hard to falsify

$(g-2)_\mu$ in the 2HDM



- ε^{ℓ}_{23} chosen such that $\Delta a_\mu = 270(85) \times 10^{-11}$ is explained
- $M_{H^+} = 400\text{GeV}$
- $\tau \to \mu\gamma$ yields weaker constraint

$(g-2)_\mu$ in the 2HDM



- $c_{\beta\alpha}\varepsilon^{\ell}_{32} < 8.8 \times 10^{-4}$
- 2HDM can account for Δa_μ
- $c_{\beta\alpha}$ pushed towards the alignment limit
- $b \to s\ell^+\ell^-$ and Δa_μ not correlated

Summary

- A 2HDM with generic Yukawa structure can account for the anomalies in $b \to s\ell^+\ell^-$:
  - with some fine tuning
  - Right-handed neutrinos necessary
- A simultaneous explanation of the $(g-2)_\mu$ discrepancy is possible in the alignment limit