Multi-Higgs solution to flavor anomalies and implications for neutrino physics

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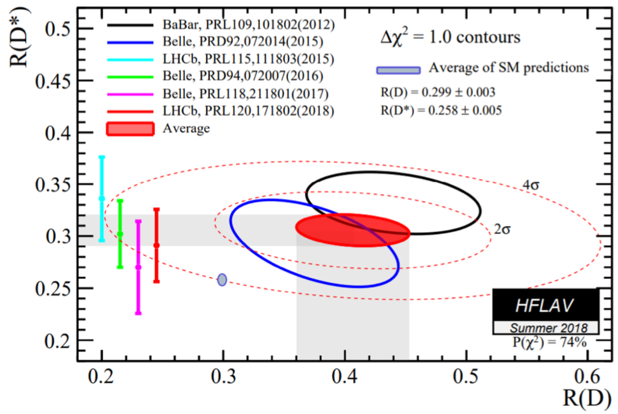
The R_D and R_K - before Moriond 2019

- R_D

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu})},$$

$$R_D^{SM} = 0.300 \pm 0.008, \qquad R_D^{exp} = 0.407 \pm 0.039 \pm 0.024,$$
$$R_{D^*}^{SM} = 0.252 \pm 0.003, \qquad R_{D^*}^{exp} = 0.306 \pm 0.013 \pm 0.007,$$



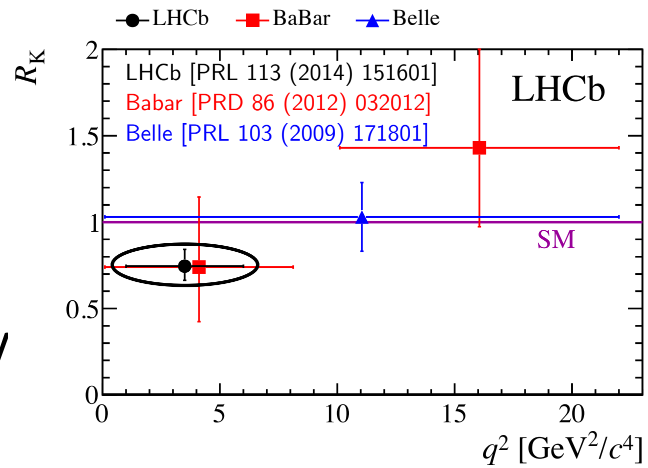
Several ~2σ deviations by BaBar, Belle, LHCb combine to a 4.1σ anomaly

- R_K

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \qquad R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

$$R_K^{SM} = 1.0004 \pm 0.0002, \qquad R_K^{exp} = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad \text{for } 1\,\text{GeV}^2 \le q^2 \le 6\,\text{GeV}^2,$$

$$R_{K^*}^{SM} = \begin{cases} 0.926 \pm 0.003, \\ 0.9965 \pm 0.0005, \end{cases} \qquad R_{K^*}^{exp} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03 & \text{for } 0.045\,\text{GeV}^2 \le q^2 \le 1.1\,\text{GeV}^2, \\ 0.69^{+0.11}_{-0.07} \pm 0.05 & \text{for } 1.1\,\text{GeV}^2 \le q^2 \le 6\,\text{GeV}^2, \end{cases}$$



The LHCb measurements combine to almost ~5σ anomaly

The R_D and R_K - after Moriond 2019

- R_D by Belle

$$\mathcal{R}_D^{\rm Belle} = 0.307 \pm 0.037 \pm 0.016 \qquad \text{and} \qquad \mathcal{R}_{D^*}^{\rm Belle} = 0.283 \pm 0.018 \pm 0.014\,,$$ 1.2σ dev.

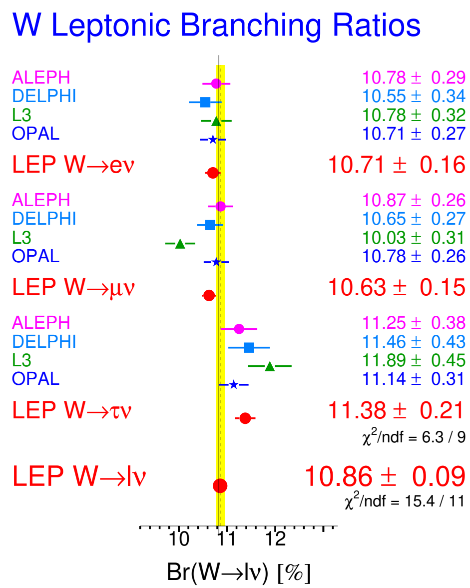
- R_K by LHCb and R_{K^*} by Belle

$$R_K = \frac{\mathrm{BR}(B \to K\mu\mu)}{\mathrm{BR}(B \to Kee)} = 0.846\ {}^{+0.060}_{-0.054}\ {}^{+0.016}_{-0.014}\,, \qquad \text{for } 1.1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2\,,$$ 2.5σ dev.

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu\mu)}{\mathrm{BR}(B \to K^*ee)} = \begin{cases} 0.90^{+0.27}_{-0.21} \pm 0.10\,, & \text{for } 0.1\,\mathrm{GeV}^2 < q^2 < 8\,\mathrm{GeV}^2\,, \\ 1.18^{+0.52}_{-0.32} \pm 0.10\,, & \text{for } 15\,\mathrm{GeV}^2 < q^2 < 19\,\mathrm{GeV}^2\,. \end{cases}$$

- The overall picture has not changed much. The significance has been mildly reduced, the same NP explanations are valid.

The peculiar properties of the anomalies require an explanation



[PR 532 (2013) 119]

- Lepton flavor universality violation!
  - In the SM this refers to the scalar sector interactions.
- Very different scales of new physics
  - R_D - NP competes with tree level SM amplitude – requires 1 TeV scale NP + large coupling
  - R_K – NP competes with loop level SM amplitude – requires 10 TeV scale NP

Is a common NP explanation needed and possible?

Should we work on anomalies?

Should we work on anomalies?

We do not have a choice!

Every discovery is preceded by a deviation but the opposite is not true

Remain reasonable with interpretations, use your common sense

Is a common NP explanation possible?

- Need NP with many freely adjustable parameters

- Majority of flavor physics community has adopted leptoquark explanation to the anomalies

Extraordinary claim requires extraordinary evidence

What is my interest to the anomalies?

- To show that non-exotic, ``SM-like NP" can simultaneously fit data
- To show that models with many scalars can fit the data
- To determine the minimal scalar model that can explain both observables

Notice: we do allow for GeV scale right-handed neutrinos – new interactions available

Model independent explanations to the anomalies

$$\mathcal{L}_{eff}^{b\to c\ell\bar\nu} = \frac{2G_F V_{cb}}{\sqrt{2}} \Big(C_{VL}^\ell\, \mathcal{O}_{VL}^\ell + C_{AL}^\ell\, \mathcal{O}_{AL}^\ell + C_{SL}^\ell\, \mathcal{O}_{SL}^\ell + C_{PL}^\ell\, \mathcal{O}_{PL}^\ell + C_{VR}^\ell\, \mathcal{O}_{VR}^\ell + C_{AR}^\ell\, \mathcal{O}_{AR}^\ell + C_{SR}^\ell\, \mathcal{O}_{SR}^\ell + C_{PR}^\ell\, \mathcal{O}_{PR}^\ell \Big) ,$$

$$\begin{aligned} \mathcal{O}_{VX}^\ell &= [\bar c \gamma^\mu b]\, [\bar\ell \gamma_\mu P_X \nu_\ell] , \\ \mathcal{O}_{AX}^\ell &= [\bar c \gamma^\mu \gamma_5 b]\, [\bar\ell \gamma_\mu P_X \nu_\ell] \\ \mathcal{O}_{SX}^\ell &= [\bar c b]\, [\bar\ell P_X \nu_\ell] , \\ \mathcal{O}_{PX}^\ell &= [\bar c \gamma_5 b]\, [\bar\ell P_X \nu_\ell] , \end{aligned}$$

$$C_{VL} = -C_{AL} = 1.$$

$$-\mathcal{L}_{bs} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\,\pi^2} \sum_i \left(\mathcal{C}_i \mathcal{O}_i + \mathcal{C}_i' \mathcal{O}_i' \right)$$

$$\begin{aligned} \mathcal{O}_7 &= (\bar s\, P_L\, b)(\bar l l) , & \mathcal{O}_7' &= (\bar s\, P_R\, b)(\bar l l) , \\ \mathcal{O}_8 &= (\bar s\, P_L\, b)(\bar l \gamma_5 l) , & \mathcal{O}_8' &= (\bar s\, P_R\, b)(\bar l \gamma_5 l) , \\ \mathcal{O}_9 &= (\bar s\, \gamma_\mu P_L\, b)(\bar l \gamma^\mu l) , & \mathcal{O}_9' &= (\bar s\, \gamma_\mu P_R\, b)(\bar l \gamma^\mu l) , \\ \mathcal{O}_{10} &= (\bar s\, \gamma_\mu P_L\, b)(\bar l \gamma^\mu \gamma_5 l) , & \mathcal{O}_{10}' &= (\bar s\, \gamma_\mu P_R\, b)(\bar l \gamma^\mu \gamma_5 l) . \end{aligned}$$

$$C_9 - C_9^{SM} \simeq -1.21 \text{ or } C_9 - C_9^{SM} = -\left(C_{10} - C_{10}^{SM} \right) \simeq -0.67$$

0. Vector (or axial vector) operators are strongly favoured by global fits to data in both cases
1. Small fraction of scalar contribution improves the global fit

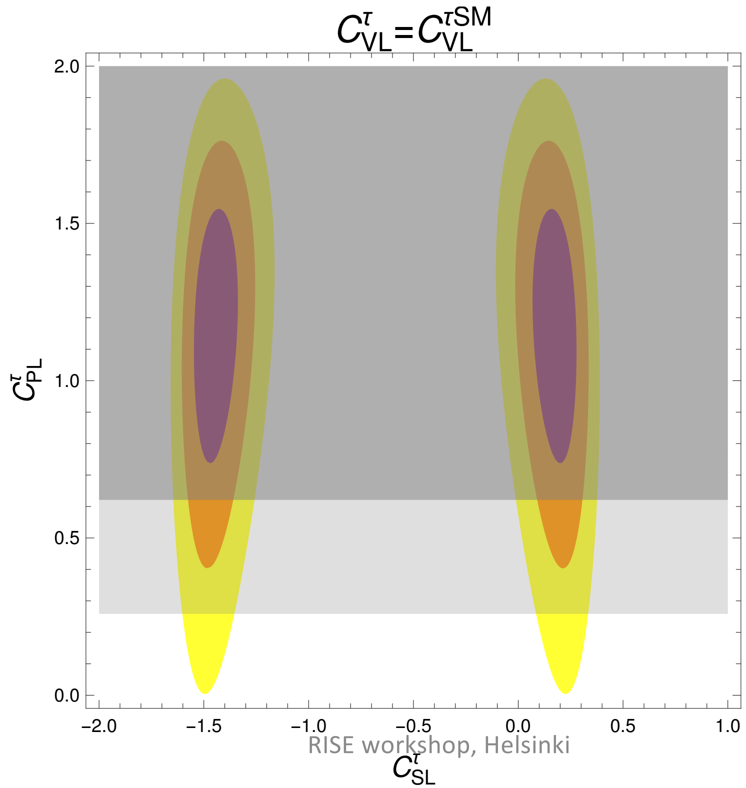
R_D model independently

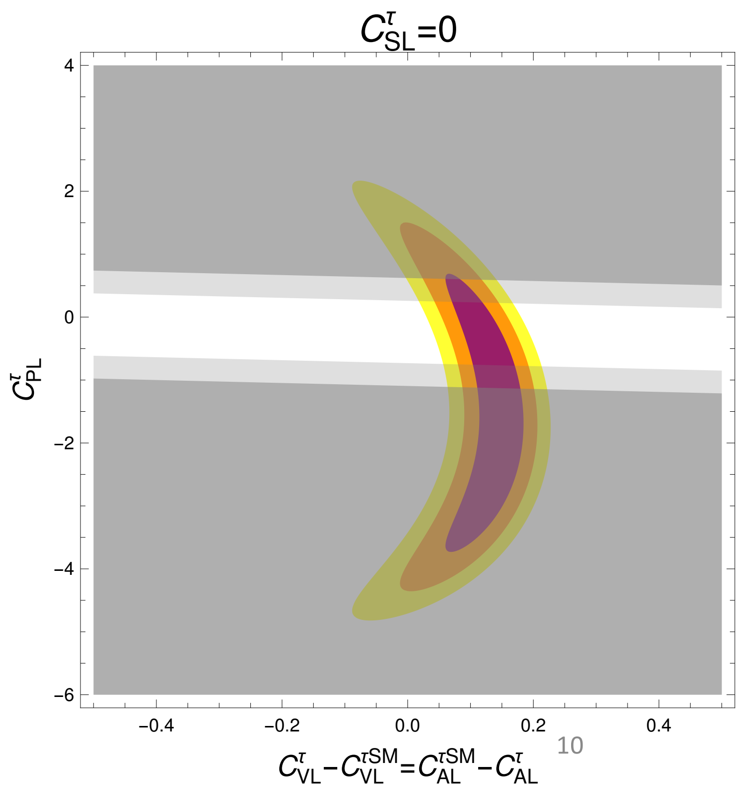
$$R_{D^{(*)}} = \frac{\mathcal{B}_\tau^{D^{(*)}}(m_\tau, \mathbf{C}^\tau)}{\mathcal{B}_{\mu/e}^{D^{(*)}}(m_{\mu/e}, \mathbf{C}^{\mu/e})} .$$

$$\mathcal{B}_{\tau\nu} = \frac{m_{B_c} m_\tau^2 f_{B_c}^2 G_F^2 |V_{cb}|^2}{8\pi \Gamma_{B_c^-}} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left| \frac{m_{B_c}^2}{m_\tau(m_b + m_c)} C_{PL}^\tau - C_{AL}^\tau \right|^2$$

- Scalar operators strongly constrained by B_c lifetime allowing 10% (30%) deviations

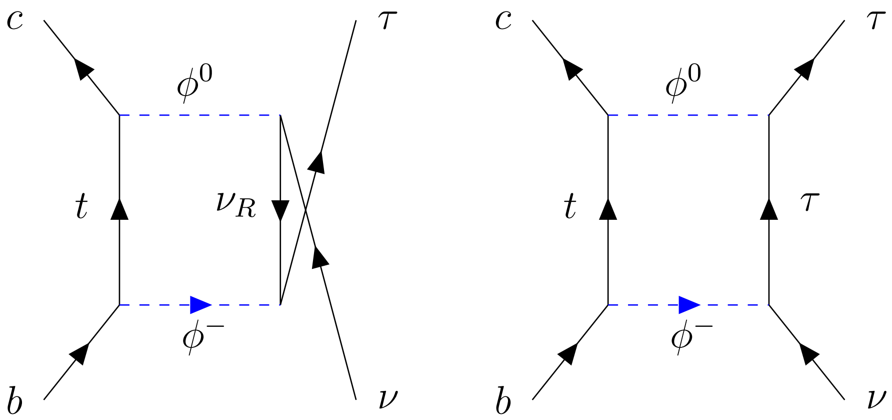
- Vector operators are OK





The idea

- Simplified model



$$
\begin{aligned}
-\mathcal{L} \supset\ & \xi_{\bar{c}_L t_R}\phi^{0*}\bar{c}_L t_R + \xi_{\bar{t}_R b_L}\phi^{+}\bar{t}_R b_L + \xi_{\bar{\tau}_L \tau_R}\phi^{0}\bar{\tau}_L \tau_R - \xi_{\bar{\tau}_R \nu_L}\phi^{-}\bar{\tau}_R \nu_L + \\
+\ & \xi_{\bar{\tau}_L \nu_R}\phi^{-}\bar{\tau}_L \nu_R + \xi_{\bar{\nu}_R \nu_L}\phi^{0}\bar{\nu}_R \nu_L + h.c.\,,
\end{aligned}
$$

$$
C^1_{VL} = -C^1_{AL} = -\left(\frac{m_W^2}{8\pi^2 V_{cb} g_w^2}\right)\left(\xi_{c_L t_R}\xi_{t_R b_L}\xi_{\nu_R \nu_L}\xi_{\tau_L \nu_R}\right) D_{dd00}[m^2_{\nu_R}, m^2_t, m^2_{\phi^0}, m^2_{\phi^-}]
$$

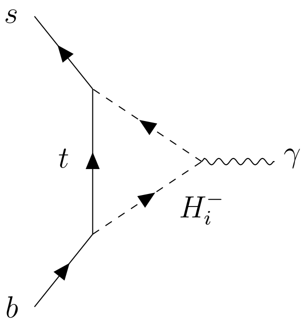
$$
C^2_{VL} = -C^2_{AL} = -\left(\frac{m_W^2}{8\pi^2 V_{cb} g_w^2}\right)\left(\xi_{c_L t_R}\xi_{t_R b_L}\xi_{\tau_L \tau_R}\xi_{\tau_R \nu_L}\right) D_{dd00}[m^2_t, m^2_{\phi^0}, m^2_{\phi^-}, m^2_\tau]\,.
$$

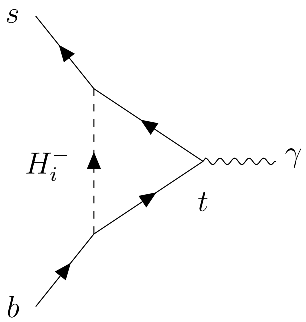
New RH interactions

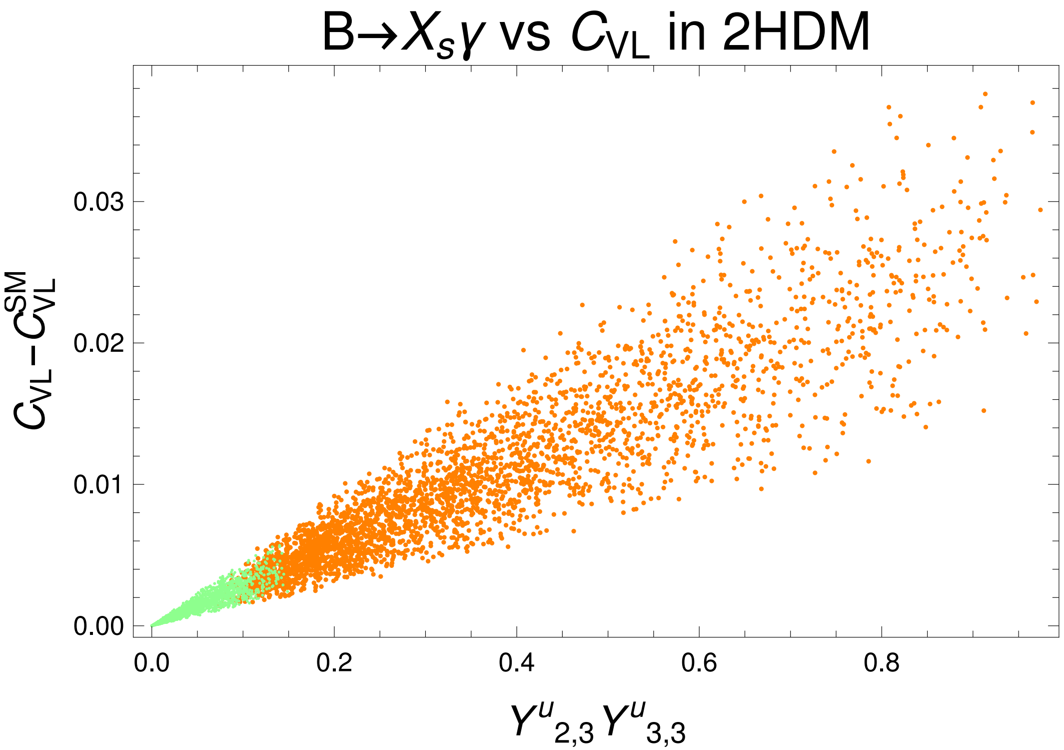
Enhancement by light, GeV mass RHNs

Does 2HDM+ν_R work?

$B \to X_s \gamma$







NO! Existing constraints are too strong. Not enough free parameters (Yukawas) to fit all data!

3HDM+ν_R

$$H_0 = \begin{pmatrix} H_0^+ \\ H_0^0 \end{pmatrix}, \quad H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

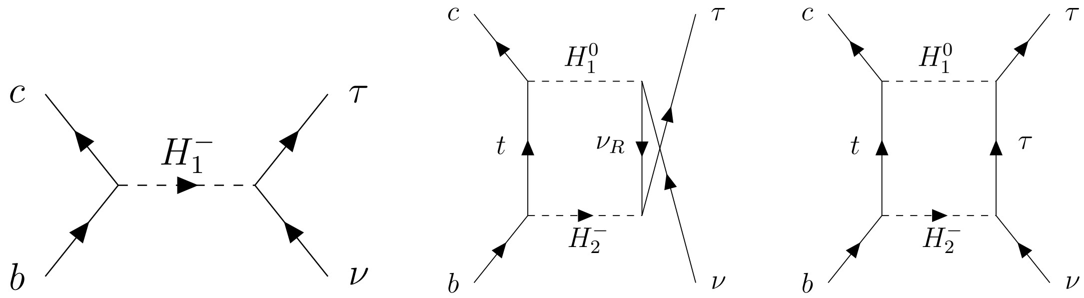
$$-\mathcal{L} \supset \bar{Q}_L \tilde{H}_1 \mathcal{Y}_1^u u_R + \bar{Q}_L \tilde{H}_2 \mathcal{Y}_2^u u_R + \bar{L}_L H_1 \mathcal{Y}_1^\ell \ell_R + \bar{L}_L H_2 \mathcal{Y}_2^\ell \ell_R + \bar{L}_L \tilde{H}_1 \mathcal{Y}_1^\nu \nu_R + \bar{L}_L \tilde{H}_2 \mathcal{Y}_2^\nu \nu_R + \bar{Q}_L H_1 \mathcal{Y}_1^d d_R + h.c.$$

$$\mathcal{Y}_1^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & f_{\bar{c}_L t_R} \\ 0 & f_{\bar{b}_L c_R} & 0 \end{pmatrix}, \quad \mathcal{Y}_1^d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & f_{\bar{c}_L b_R} \\ 0 & 0 & 0 \end{pmatrix}, \quad \mathcal{Y}_2^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & g_{\bar{b}_L t_R} \end{pmatrix},$$

$$\mathcal{Y}_1^\nu = \begin{pmatrix} 0 & 0 & 0 \\ 0 & f_{\bar{\nu}_L \nu_R} & 0 \\ 0 & 0 & f'_{\bar{\nu}_L \nu_R} \end{pmatrix}, \quad \mathcal{Y}_1^\ell = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & f_{\bar{\tau}_L \tau_R} \end{pmatrix}, \quad \mathcal{Y}_2^\nu = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_{\bar{\nu}_L \nu_R} & 0 \\ 0 & 0 & g'_{\bar{\nu}_L \nu_R} \end{pmatrix}, \quad \mathcal{Y}_2^\ell = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & g_{\bar{\nu}_L \tau_R} \end{pmatrix}$$

Textures constructed to fit all observables simultaneously consistently with constraints

R_D in our model



$$C_{VL}^{\tau\,(1)} = -C_{AL}^{\tau\,(1)} = \left(-\frac{m_W^2}{8\pi^2 V_{cb} g_w^2}\right)\left(f_{\bar{c}_L t_R}\, g_{\bar{b}_L t_R}\, f'_{\bar{\nu}_L \nu_R}\, g'_{\bar{\nu}_L \nu_R}\right) D_{dd00}[m_{\nu_R}^2, m_t^2, m_{H_1^0}^2, m_{H_2^-}^2]\,,$$

$$C_{VL}^{\tau\,(2)} = -C_{AL}^{\tau\,(2)} = \left(-\frac{m_W^2}{8\pi^2 V_{cb} g_w^2}\right)\left(f_{\bar{c}_L t_R}\, g_{\bar{b}_L t_R}\, f_{\bar{\tau}_L \tau_R}\, g_{\bar{\nu}_L \tau_R}\right) D_{dd00}[m_t^2, m_{H_1^0}^2, m_{H_2^-}^2, m_\tau^2]\,,$$

$$C_{SL}^{\tau} = -\frac{2\, m_W^2}{V_{cb} g_w^2 m_{H_1^-}^2} f_{\bar{\nu}_L \tau_R}\left(f_{\bar{b}_L c_R} - f_{\bar{c}_L b_R}\right)\,,$$

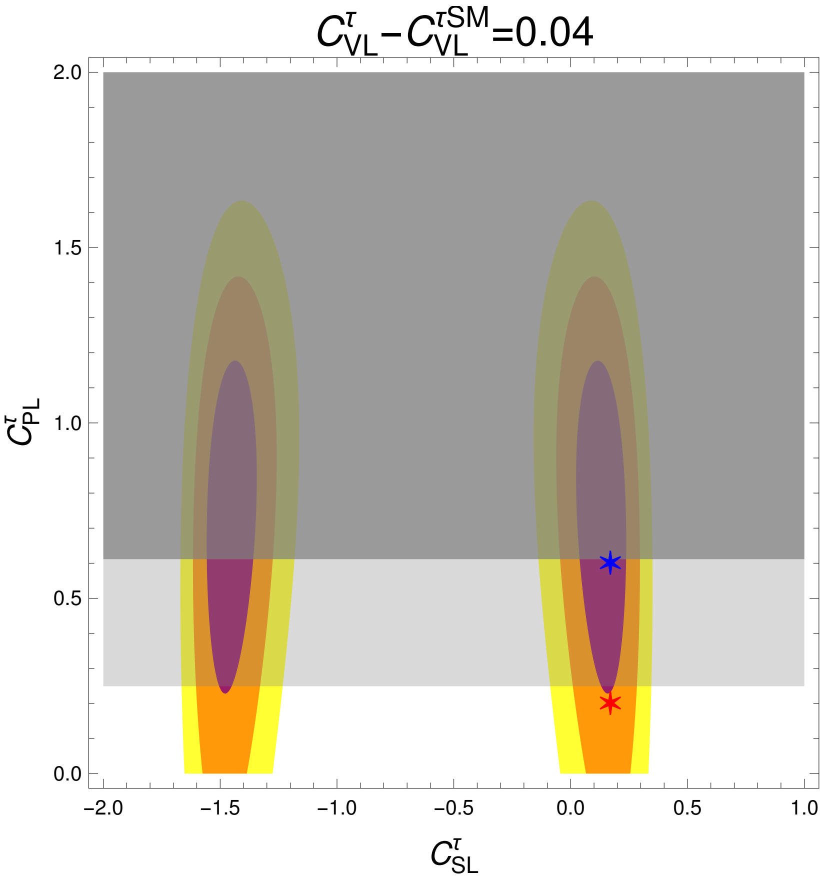
$$C_{PL}^{\tau} = -\frac{2\, m_W^2}{V_{cb} g_w^2 m_{H_1^-}^2} f_{\bar{\nu}_L \tau_R}\left(f_{\bar{b}_L c_R} + f_{\bar{c}_L b_R}\right)\,,$$

Must be maximized

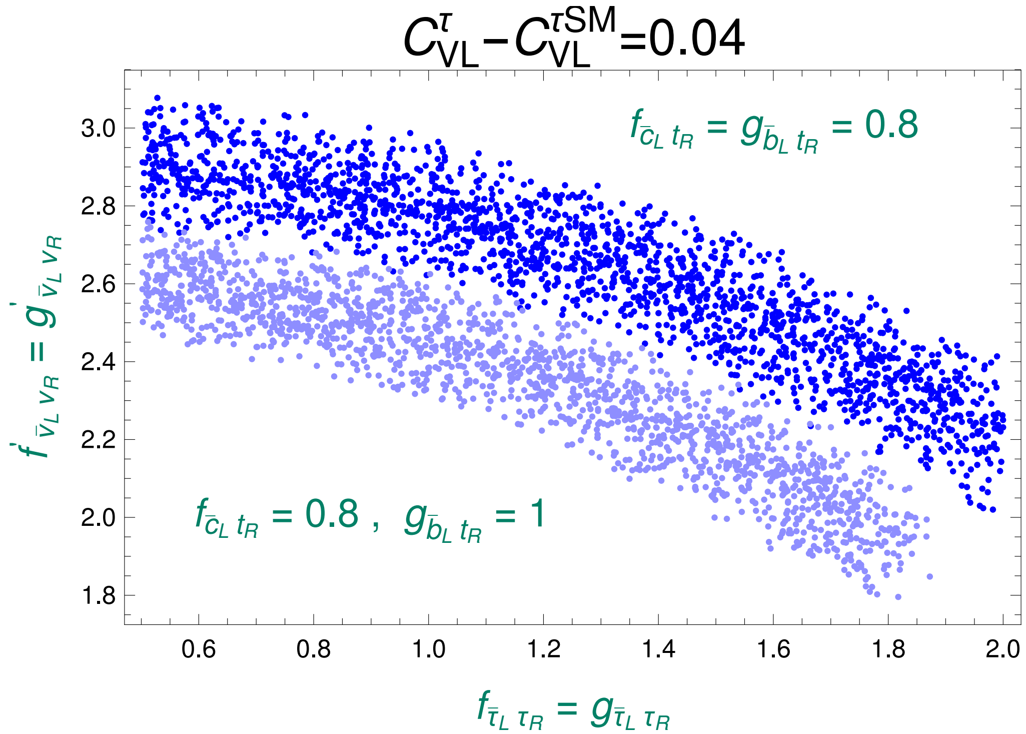
Must be minimized

We require that all existing exp. constraints are satisfied

Benchmark points for R_D and vector operators

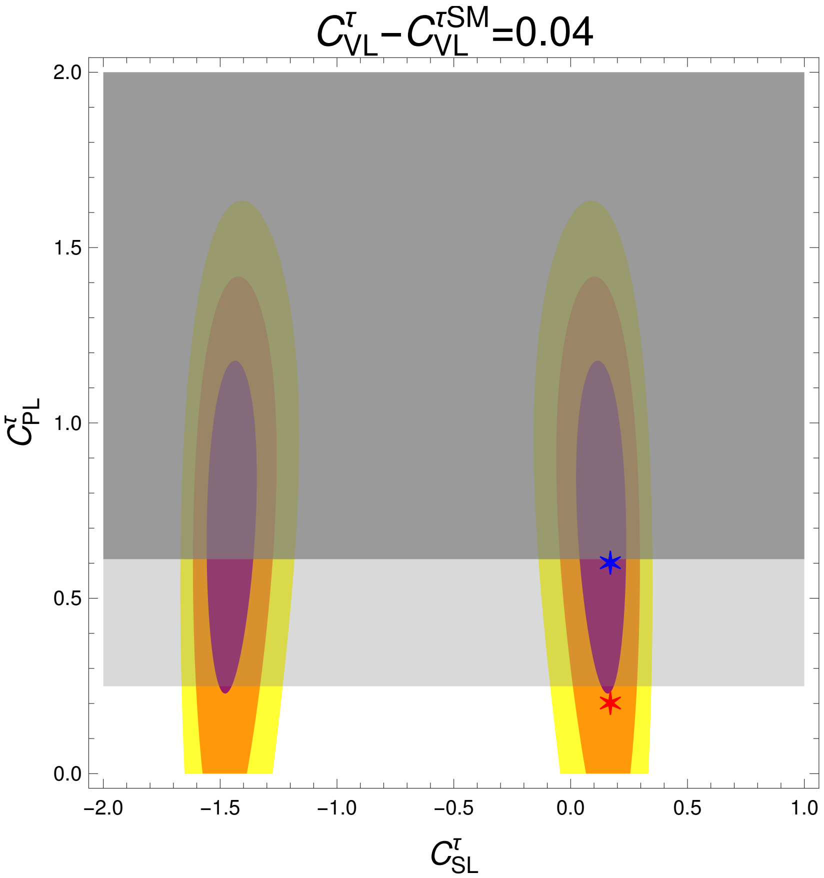


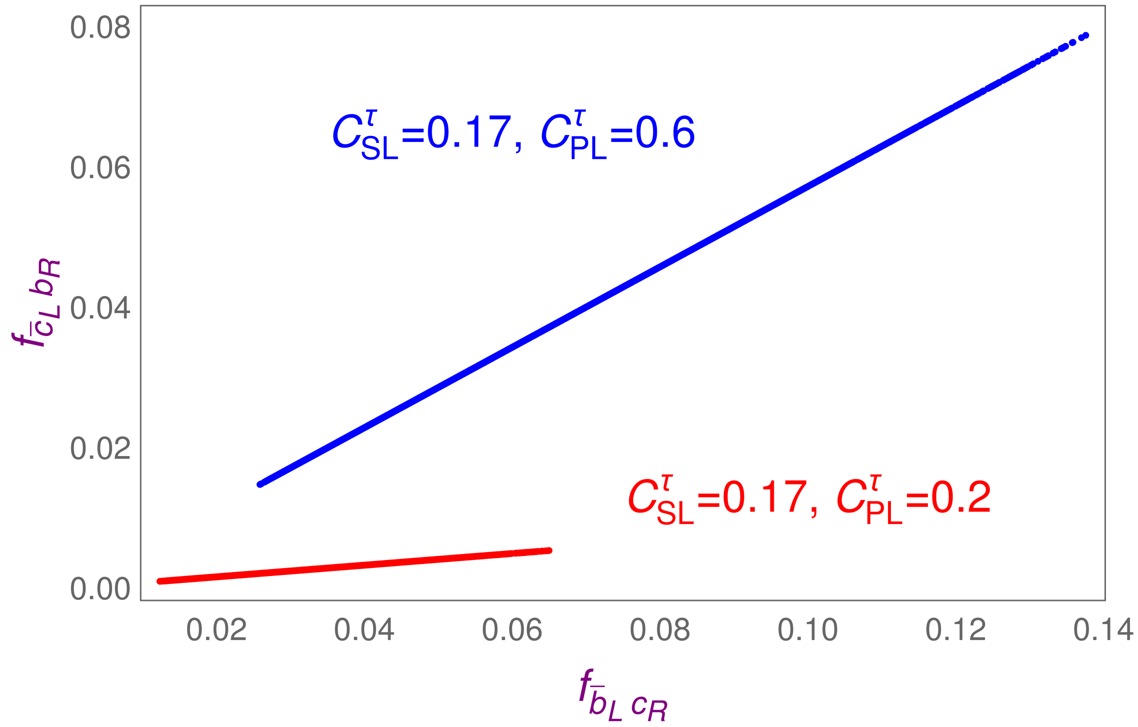
350 GeV < M < 400 GeV



Yukawa couplings of order 1 are needed

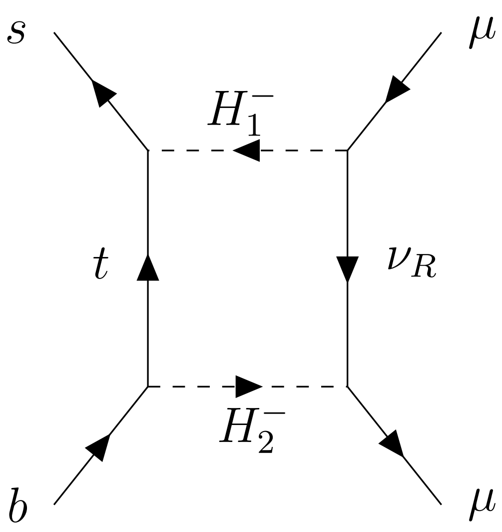
Benchmark points for R_D and scalar operators





The related Yukawa couplings must be small

R_K in our model



$$-\mathcal{L} \supset f_{\bar{\mu}_L \nu_R} H_1^- \bar{\mu}_L \nu_R + g_{\bar{\mu}_L \nu_R} H_2^- \bar{\mu}_L \nu_R + h.c.\,,$$

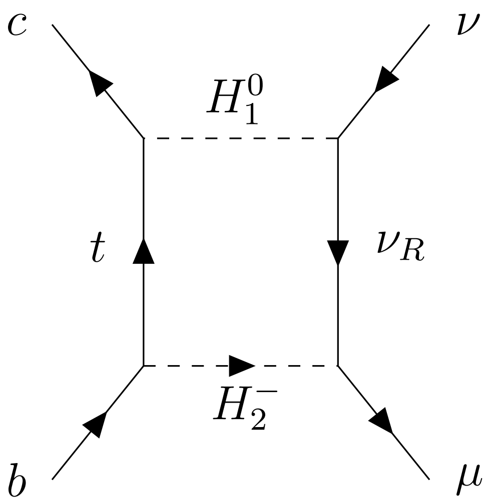
$$-C_9 = C_{10} = -\frac{m_W^2}{4\pi\,\alpha g_w^2} \frac{V_{cs}^*}{V_{ts}^*} \left(f_{\bar{c}_L t_R} g_{\bar{b}_L t_R} f_{\bar{\mu}_L \nu_R} g_{\bar{\mu}_L \nu_R}\right) D_{dd00}[m_t^2, m_{H_1^-}^2, m_{H_2^-}^2]\,,$$

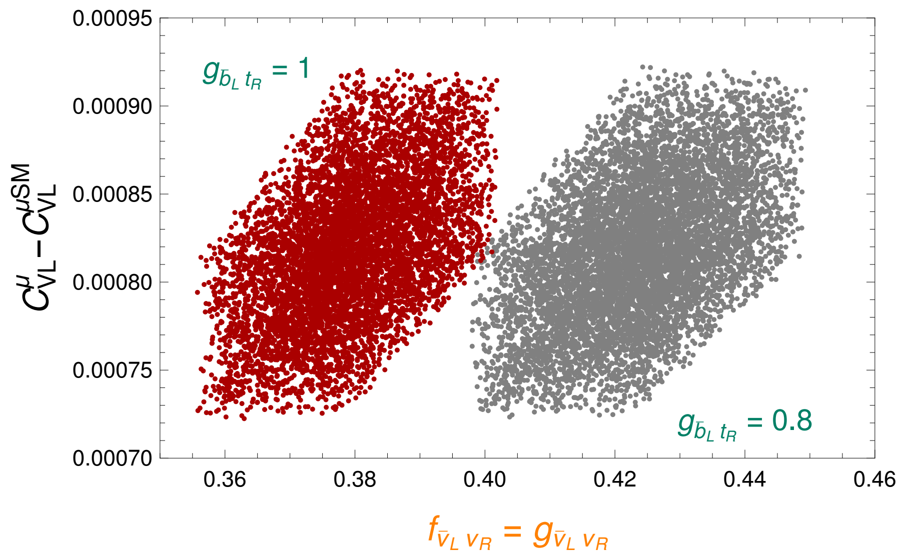
$$O_9 = -O_{10} = -0.67$$

Is needed to explain the R_K anomaly

Can R_K be explained simultaneously? Yes!

- Couplings inducing R_K enter to denominator of $R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu})}$





Any correlation is numerically small

ε'/ε anomaly?

$$Re(\epsilon'/\epsilon) = 1.38(5.15)(4.59) \times 10^{-4} \,, \qquad Re(\epsilon'/\epsilon)_{exp} = (16.6 \pm 2.3) \times 10^{-4} \,.$$

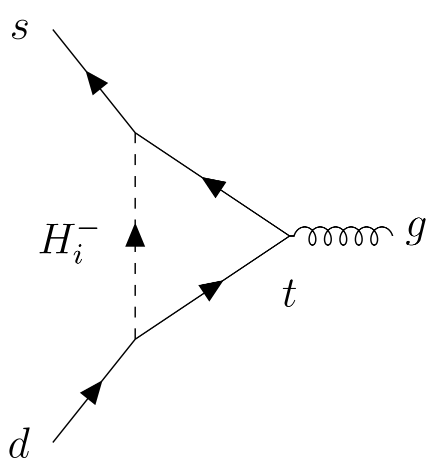
If there is an anomaly, no problem to explain it simultaneously with others. There is enough free parameters.

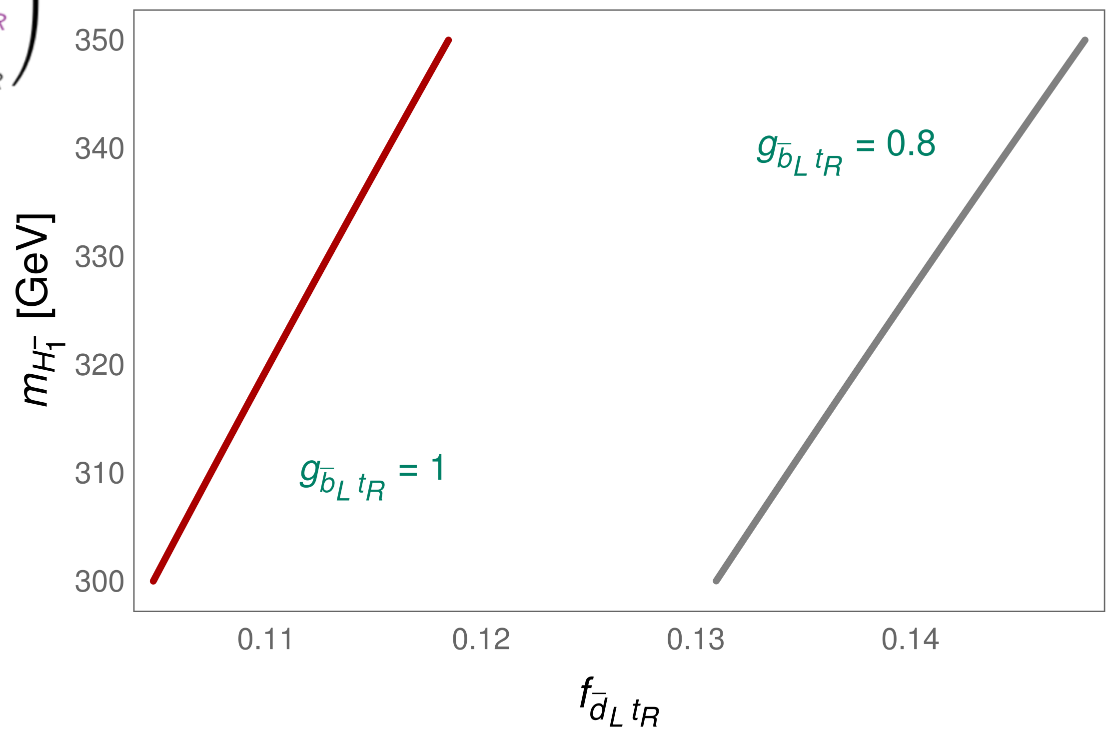
$$Re\,(\epsilon'/\epsilon)_{8g} \sim -\left(1.85 \times 10^5 GeV\right) \times Im\left(C_{8g}^-\right) \,,$$

$$C_{8g}^- = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{td} \left(m_d C'_{8g} - m_s C_{8g}\right) \,.$$

ε'/ε anomaly in our model

$$\mathcal{Y}_1^d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & f_{\bar{c}_L b_R} \\ 0 & 0 & 0 \end{pmatrix} \quad \rightarrow \quad \mathcal{Y}_1^d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & f_{\bar{c}_L b_R} \\ 0 & 0 & f_{\bar{s}_L t_R} \end{pmatrix}$$





$$Re\left(\epsilon'/\epsilon\right)_{8g} = 10^{-3}$$

Can easily be explained in our model

Distinctive prediction of the scenario

- RH neutrino masses must be below 10 GeV

$m_{\nu R} < 10$ GeV

- Flavour anomalies are related to the leptogenesis and neutrino masses

- ν_R can be produced and discovered at SHIP

This scenario is predictive and testable

Conclusions

- All the considered flavor anomalies can be simultaneously explained in 3HDM+ν_R
- RH neutrinos must be light, induce baryogenesis and neutrino masses, and may show up at SHIP experiment