The $Zb\bar{b}$ couplings in models with extended Higgs sectors

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Observables

The process $Z \to b\bar{b}$ yields two observable quantities, R_b and A_b.

- R_b is the hadronic branching ratio of Z to b quarks

$$R_b \equiv \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \mathrm{hadrons})}.$$

- A_b is the b-quark asymmetry
  - the Z-pole forward–backward asymmetry measured at LEP-1

$$A_{FB}^{(0,b)} = \frac{\sigma\left(e^- \to b_F\right) - \sigma\left(e^- \to b_B\right)}{\sigma\left(e^- \to b_F\right) + \sigma\left(e^- \to b_B\right)} = \frac{3}{4} A_e A_b,$$

  - the left–right forward–backward asymmetry measured by the SLD collaboration

$$A_{LR}^{FB}(b) = \frac{\sigma_{LF} + \sigma_{RB} - \sigma_{LB} - \sigma_{RF}}{\sigma_{LF} + \sigma_{RB} + \sigma_{LB} + \sigma_{RB}} = \frac{3}{4} A_b,$$

where $\sigma_{XY} = \sigma\left(e_X^- \to b_Y\right)$; $e_{L,R}^-$ are left and right handed initial–state electrons and $b_{F,B}$ are final–state b-quarks moving in the forward and backward directions.

Measurements

- An overall fit of many electroweak observables gives [PDG′2020]

$$R_b^{\rm fit} = 0.21629 \pm 0.00066 \implies 0.7\sigma \text{ above the SM},$$
$$A_b^{\rm fit} = 0.923 \pm 0.020 \implies 0.6\sigma \text{ below the SM [SLD measurements]}.$$

- Extracting A_b from $A_{FB}^{0,b}$ when $A_e = 0.1501 \pm 0.0016$ leads to $A_b = 0.885 \pm 0.0017$, which is 2.9σ below the SM prediction [LEP-1 measurements].
- The combined value $A_b^{\rm average} = 0.901 \pm 0.013$ deviates from the SM value by 2.6σ.
- These discrepancies in A_b could be an evidence of New Physics, but they could also be due to a statistical fluctuation or another experimental effect in one of asymmetries; more precise experiments are needed.

Experiments

- A direct measurement of the $Zb\bar{b}$ couplings at the **LHC** is challenging because of the large backgrounds for the process $Z \to b\bar{b}$.
- Lepton colliders of the next generation, the **CEPC**, **ILC**, or **FCC-ee** offer great opportunities for further studies of the $Zb\bar{b}$ vertex, because they could collect a large amount of data around the Z^0 pole.
- If its results are SM-like, a future lepton collider can provide strong constraints on models beyond the SM.
- If the $A_{FB}^{0,b}$ discrepancy found at LEP does come from New Physics, then any of the three next-generation e^+e^- colliders will be able to rule out the SM with more than 5σ significance [Gori, *et al.*'2016].

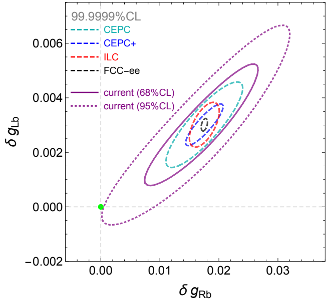


Figure: The preferred regions, given by the global fit of the future measurements [Gori, *et al.*'2016].

The couplings

- We focus on the $Zb\bar{b}$ couplings

$$\mathcal{L}_{Zbb} = \frac{g}{c_w} Z_\mu \, \bar{b}\gamma^\mu \left(g_L P_L + g_R P_R \right) b.$$

- At tree level,

$$g_L^{\rm tree} = \frac{s_w^2}{3} - \frac{1}{2}, \quad g_R^{\rm tree} = \frac{s_w^2}{3}.$$

- The Standard Model prediction is

$$g_L^{\rm SM} = -0.420875, \quad g_R^{\rm SM} = 0.077362.$$

- In the presence of New Physics, we write

$$g_L = g_L^{\rm SM} + \delta g_L, \quad g_R = g_R^{\rm SM} + \delta g_R.$$

- The couplings $g_{L,R}$ are related to A_b

$$A_b = \frac{2 r_b \sqrt{1 - 4\mu_b}}{1 - 4\mu_b + (1 + 2\mu_b)\, r_b^2},$$

where $r_b = (g_L + g_R)/(g_L - g_R)$ and $\mu_b = \left[m_b \left(m_Z^2 \right) \right]^2 \Big/ \, m_Z^2$.

- The couplings $g_{L,R}$ are related to R_b

$$R_b = \frac{s_b \, c^{\rm QCD} \, c^{\rm QED}}{s_b \, c^{\rm QCD} \, c^{\rm QED} + s_c + s_u + s_s + s_d},$$

where c^{QCD} and c^{QED} are QCD and QED radiative correction factors and

$$s_b = (1 - 6\mu_b)\left(g_L - g_R \right)^2 + \left(g_L + g_R \right)^2,$$

and $s_c + s_u + s_s + s_d = 1.3184$.

Solutions

- We can solve the above equations for g_L and g_R in terms of the experimentally measured values for R_b and A_b [DJ & Lavoura, arXiv:2103.16635].

solution	g_L	g_R	δg_L	δg_R
1^{fit}	−0.420206	0.084172	0.000669	0.006810
2^{fit}	−0.419934	−0.082806	0.000941	−0.160168
3^{fit}	0.420206	−0.084172	0.841081	−0.161534
4^{fit}	0.419934	0.082806	0.840809	0.005444
1^{average}	−0.417814	0.095496	0.003061	0.018134
2^{average}	−0.417504	−0.094139	0.003371	−0.171501
3^{average}	0.417814	−0.095496	0.838688	−0.172858
4^{average}	0.417504	0.094139	0.838379	0.016777

- Solutions 3 and 4 have a much too large δg_L and are not really experimentally valid [Choudhury *et al.*'2002] therefore we discard those solutions.
- Solution 1 seems to be preferred over solution 2 because it has much smaller $|\delta g_R|$. Still, in this work we shall also consider solution 2.

The aligned nHDM

- The scalar doublets $\Phi_1, \ldots \Phi_n$ in the charged Higgs basis are written

$$\Phi_1 = \begin{pmatrix} S_1^+ \\ \left(v + H + iS_1^0\right) \big/ \sqrt{2} \end{pmatrix}, \quad \Phi_k = \begin{pmatrix} S_k^+ \\ \left(R_k + iI_k\right) \big/ \sqrt{2} \end{pmatrix} \quad (k = 2, \ldots, n),$$

  where $S_2^+, \ldots, S_n^+$ are physical charged scalars with masses $m_{C2} \leq m_{C3} \leq \cdots \leq m_{Cn}$.
- For the sake of simplicity, we assume alignment. This means that $H \equiv S_2^0$ is a physical neutral scalar, with mass $m_2 \approx 125\,\text{GeV}$, that does not mix with the fields R_k and I_k.
- We order the physical neutral scalars S_j^0 through $m_3 \leq m_4 \leq \ldots \leq m_{2n}$. Notice that, in principle, one or more of these masses may be lower than m_2.
- To compute the one-loop corrections to the $Zb\bar{b}$ vertex in the nHDM, we make the simplifying assumption that only the top and bottom quarks exist and the $(t,\, b)$ CKM matrix element is 1. The relevant part of the Yukawa Lagrangian is [Fontes, Lavoura *et al.*'2020]

$$\mathcal{L}_{\text{Yukawa}} = -\begin{pmatrix} \bar{t}_L & \bar{b}_L \end{pmatrix} \sum_{k=2}^{n} \left[\frac{f_k}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, S_k^+ \\ R_k + iI_k \end{pmatrix} b_R + \frac{e_k}{\sqrt{2}} \begin{pmatrix} R_k - iI_k \\ -\sqrt{2}\, S_k^- \end{pmatrix} t_R \right] + \text{H.c.},$$

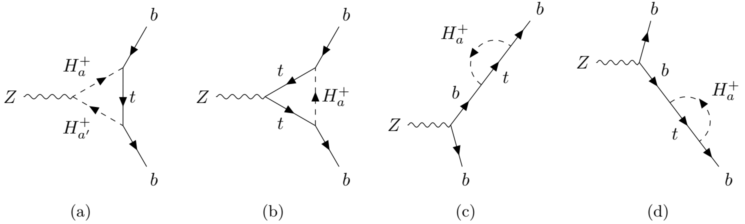
  where the e_k and f_k are the Yukawa coupling constants.

The scalar contributions

In the nHDM at the one-loop level, both δg_L and δg_R are the sum of a two contributions

$$\delta g_L = \delta g_L^c + \delta g_L^n, \quad \delta g_R = \delta g_R^c + \delta g_R^n.$$

- The charged-scalar contribution (having charged scalars and top quarks in the internal lines of the loop) [Haber & Logan'2000]

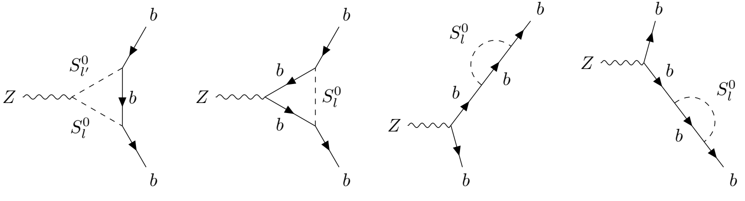


$$\delta g_L^c = \frac{1}{16\pi^2} \sum_{k=2}^{n} |e_k|^2 \, f_L\left(m_{Ck}^2\right), \quad \delta g_R^c = \frac{1}{16\pi^2} \sum_{k=2}^{n} |f_k|^2 \, f_R\left(m_{Ck}^2\right),$$

where the functions f_L and f_R are defined through various PV functions.

The scalar contributions

- The neutral-scalar contribution (with neutral scalars and bottom quarks in the internal lines of the loop) [Fontes, Lavoura *et al.*'2020; DJ & Lavoura'2021]



$$\delta g_L^n = \frac{1}{16\pi^2} \sum_{j=3}^{2n-1} \sum_{j'=j+1}^{2n} \mathcal{A}_{jj'} \, \mathrm{Im}\left[\left(\mathcal{V}^\dagger \mathcal{F}^*\right)_j \left(\mathcal{V}^T \mathcal{F}\right)_{j'}\right] h_L\left(m_j^2,\, m_{j'}^2\right),$$

$$\delta g_R^n = \frac{1}{16\pi^2} \sum_{j=3}^{2n-1} \sum_{j'=j+1}^{2n} \mathcal{A}_{jj'} \, \mathrm{Im}\left[\left(\mathcal{V}^\dagger \mathcal{F}^*\right)_j \left(\mathcal{V}^T \mathcal{F}\right)_{j'}\right] h_R\left(m_j^2,\, m_{j'}^2\right),$$

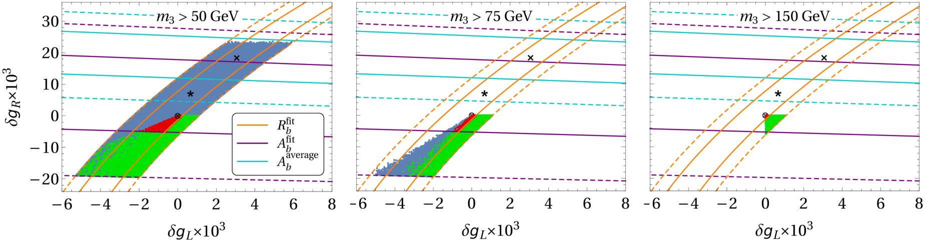
where $\mathcal{A} := \mathrm{Im}\left(\mathcal{V}^\dagger \mathcal{V}\right) = \mathcal{R}^T \mathcal{I} - \mathcal{I}^T \mathcal{R}$ is the real antisymmetric matrix, $\mathcal{F}_k = f_k$ for $k = 2, \ldots, n$, and the functions h_L and h_R are defined through various PV functions.

The aligned 2HDM and the aligned 3HDM

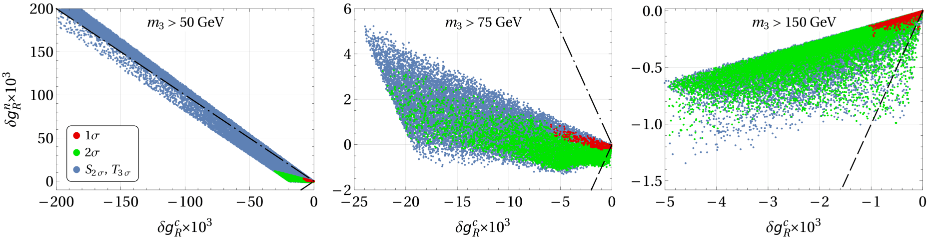
- The aligned 2HDM. New scalars: m_{C2} and $m_{3,4}$. Restrictions to the scalar potential: because of alignment, $\lambda_1 = \frac{m_2^2}{v^2}$, $\lambda_6 = 0$ and for simplicity $\lambda_{2,7} = 0$.
- The aligned 3HDM. New scalars: $m_{C2,C3}$ and $m_{3,4,5,6}$. Restrictions to the scalar potential: we discard from the quartic part of the potential all the terms that either do not contain Φ_1 or are linear in Φ_1.
- Theoretical and experimental constraints
  - unitarity requirements,
  - bounded-from-below requirements,
  - vacuum stability conditions,
  - phenomenological constraint: $T = 0.03 \pm 0.12$ and $S = -0.01 \pm 0.10$ [PDG'2020].

The aligned 2HDM, solution 1

- The confrontation between experiment and the computed values of δg_L and δg_R

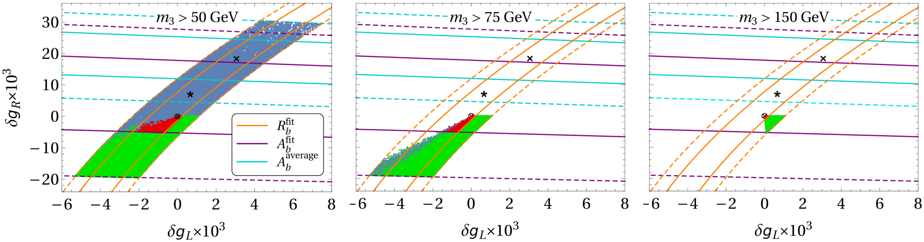


- δg_R^n *versus* δg_R^c in the aligned 2HDM ($m_{C2} > 150$ GeV for all panels)



The aligned 3HDM, solution 1

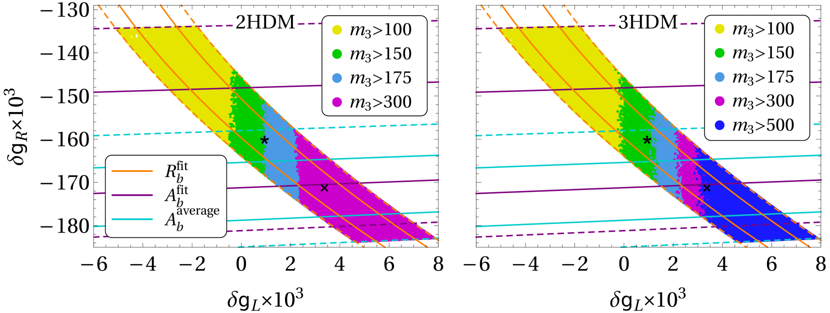
- The confrontation between experiment and the computed values of δg_L and δg_R



- Only when one allows both for a laxer S- and T-oblique parameters constraints and for a very low neutral-scalar mass $m_3 \lesssim 60\,\text{GeV}$ are the central values of both solutions 1^{fit} and 1^{average} attainable.
- In the 3HDM, just as in the 2HDM, the better agreement occurs through an extensive finetuning where $\delta g_L^n \approx -\delta g_L^c$ and $\delta g_R^n \approx -\delta g_R^c$.

Solution 2

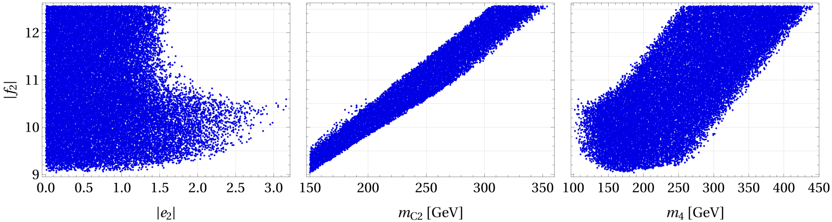
- The confrontation between experiment and the computed values of δg_L and δg_R



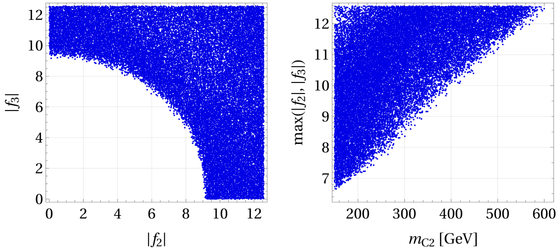
- All points obey S- and T-oblique parameters 1σ constraints
- One can attain the best-fit points both of solution $2^{\rm fit}$ and of solution $2^{\rm average}$
- In the 3HDM the lightest neutral scalar m_3 may be as heavy as 620 GeV, while in the 2HDM $m_3 < 420$ GeV

Solution 2^{average}

- The 2HDM case: points fit solution 2^{average} at the 1σ level, and have $m_3 > 100$ GeV.



- The 3HDM case: points fit solution 2^{average} at the 1σ level, and have $m_3 > 100$ GeV.



Conclusions

- The SM has a slight problem in fitting the $Zb\bar{b}$ vertex, since it produces a g_R smaller than what is needed to reproduce the measured A_b.
- The nHDM can solve that but with very light new scalars and too-large oblique parameters S and T.
- There exist an alternative fit of the $Zb\bar{b}$ vertex, wherein g_R has the opposite sign from the one predicted by the SM but is easy to obtain in a nHDM.
- This solution, though, also works only if the new scalars are relatively light and if at least one of the Yukawa couplings is quite large.

The End