The $Zb\bar{b}$ vertex in a CP-conserved Lef-Right model

Darius Jurčiukonis[1], Duarte Fontes[2], and Luís Lavoura[3]

[1] Vilnius University, Institute of Theoretical Physics and Astronomy
darius.jurciukonis@tfai.vu.lt

[2] Department of Physics, Brookhaven National Laboratory
dfontes@bnl.gov

[3] Universidade de Lisboa, Instituto Superior Técnico, CFTP
balio@cftp.tecnico.ulisboa.pt

October 11, 2022

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′2022]

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

- 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].

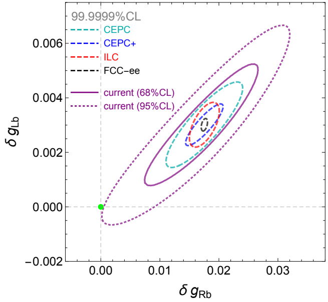


Figure: The preferred regions, given by the global fit of the future measurements [Gori, *et al.*'2016].

The couplings

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

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

- 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

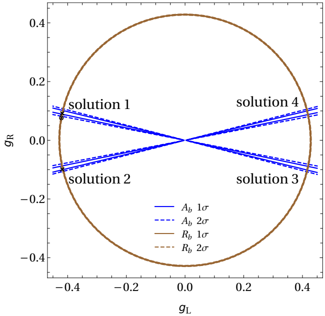
$$s_b = (1-6\mu_b)\left(g_L - g_R\right)^2 + \left(g_L + g_R\right)^2,$$

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, '2021].

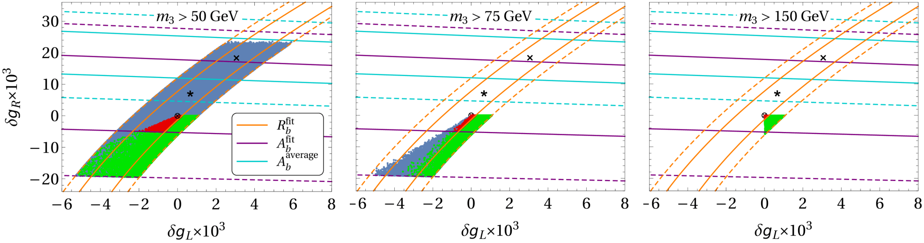
solution	g_L	g_R
1^{fit}	-0.420206	0.084172
2^{fit}	-0.419934	-0.082806
3^{fit}	0.420206	-0.084172
4^{fit}	0.419934	0.082806
1^{average}	-0.417814	0.095496
2^{average}	-0.417504	-0.094139
3^{average}	0.417814	-0.095496
4^{average}	0.417504	0.094139



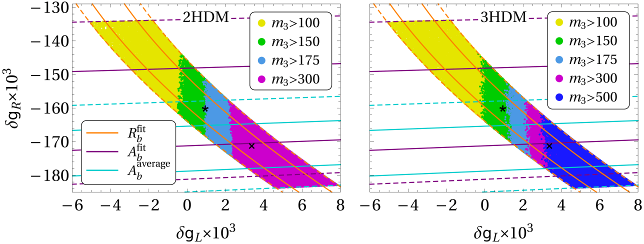
- Solutions 3 and 4 have a much too large δg_L and are not really experimentally valid [Choudhury *et al.*'2002] therefore we discard those solutions.
- Solution 1 seems to be preferred over solution 2 because it has much smaller $|\delta g_R|$.

The aligned 2HDM and aligned 3HDM

- The computations for solution 1



- The computations for solution 2



A Left-Right model (LRM)

- We consider a *CP-conserving* left–right model *i.e.* a model with gauge group $SU(2)_L \times SU(2)_R \times U(1)_X$. The gauge coupling constant of $SU(2)_L$ is g; the gauge coupling constant of $SU(2)_R$ is l; the gauge coupling constant of $U(1)_X$ is h.
- The scalar multiplets of our LRM consist of an $SU(2)_L$ doublet H_L, an $SU(2)_R$ doublet H_R, and a 'bi-doublet'–*i.e.*, a doublet both of $SU(2)_L$ and of $SU(2)_R$–Φ. Thus,

$$H_L = \begin{pmatrix} m \\ n \end{pmatrix}, \quad H_R = \begin{pmatrix} p \\ q \end{pmatrix}, \quad \Phi = \begin{pmatrix} b^* & c \\ -a^* & d \end{pmatrix}, \quad \tilde{\Phi} = \begin{pmatrix} d^* & a \\ -c^* & b \end{pmatrix},$$

where m, n, p, q, a, b, c, and d are complex Klein–Gordon fields.

The vacuum expectation values

- The vacuum expectation values (VEVs) are

$$\langle 0 \,|m|\, 0\rangle = \langle 0 \,|p|\, 0\rangle = \langle 0 \,|a|\, 0\rangle = \langle 0 \,|c|\, 0\rangle = 0,$$

$$\langle 0 \,|n|\, 0\rangle = u_L, \quad \langle 0 \,|q|\, 0\rangle = u_R, \quad \langle 0 \,|b|\, 0\rangle = v_1, \quad \langle 0 \,|d|\, 0\rangle = v_2.$$

  Since we assume our model to be CP-conserving, $u_{L,R}$ and $v_{1,2}$ are taken to be real.
- We expand the neutral-scalar fields about their VEVs as

$$n = u_L + \frac{\rho_L + i\eta_L}{\sqrt{2}}, \quad q = u_R + \frac{\rho_R + i\eta_R}{\sqrt{2}}, \quad b = v_1 + \frac{\rho_1 + i\eta_1}{\sqrt{2}}, \quad d = v_2 + \frac{\rho_2 + i\eta_2}{\sqrt{2}},$$

  where $\rho_{L,R,1,2}$ and $\eta_{L,R,1,2}$ are real Klein–Gordon fields. Because of CP invariance, the fields $\rho_{L,R,1,2}$ (*viz.* the scalars) mix among themselves, but they do not mix with the fields $\eta_{L,R,1,2}$ (*viz.* the pseudoscalars).
- The fields a, c, m and p give charged scalars.

The scalar potential

- The scalar potential is $V = V_H + V_\Phi + V_{H\Phi}$, where

$$
\begin{aligned}
V_H &= \{H_L, H_R; \mu_L, \mu_L, \lambda_L, \lambda_R, \lambda_{LR}\}, \\
V_\Phi &= \left\{\Phi, \tilde{\Phi}; \mu_1, \mu_2, \lambda_1, \lambda_2, \lambda_3, \lambda_4\right\}, \\
V_{H\Phi} &= \left\{H_L, H_R, \Phi, \tilde{\Phi}; m_1, m_2, \lambda_{3L}, \lambda_{3R}, \lambda_{4L}, \lambda_{4R}, \lambda_{5L}, \lambda_{4R}\right\}.
\end{aligned}
$$

- The parameters λ_L, λ_R, λ_{LR}, λ_1, λ_2, λ_3, λ_4, λ_{3L}, λ_{3R}, λ_{4L}, λ_{4R}, λ_{5L}, and λ_{5R} are dimensionless; the parameters m_1 and m_2 have mass dimension; the parameters μ_L, μ_R, μ_1, and μ_2 have mass-squared dimension.
- All these parameters are real because of the assumed CP conservation.

The Yukawa couplings

- In our simplified LRM we only consider the third generation quarks, *viz.* t_L, b_L, t_R, and b_R; we disconsider both the lepton sector and the other two quark generations (*because of the negligible impact to the* $Zb\bar{b}$ *couplings*).
- The Yukawa couplings are given by

$$\mathcal{L}_{\rm Yukawa} = -\begin{pmatrix} \bar{t}_L, & \bar{b}_L \end{pmatrix} \left(y_1 \Phi + y_2 \tilde{\Phi} \right) \begin{pmatrix} t_R \\ b_R \end{pmatrix} + \text{H.c.},$$

where y_1 and y_2 are real because of the assumed CP invariance of the model.
- When b and d acquire real VEVs v_1 and v_2, respectively, upper equation produces quark masses

$$m_t = y_1 v_1 + y_2 v_2, \qquad m_b = y_1 v_2 + y_2 v_1.$$

Parameter counting

- Our left–right model has in its Lagrangian the following parameters:
  - The gauge coupling constants g, l, and h.
  - The parameters of the potential μ_i, m_j, and λ_k.
  - The Yukawa couplings y_1 and y_2.

  This makes 24 independent real parameters.
- Since there are 24 parameters, we must use as input of the renormalization procedure 24 observable (measurable) quantities. The quantities at our disposal thus are:
  - The electromagnetic coupling constant.
  - 4 masses of the gauge bosons.
  - 8 masses of the scalars.
  - The masses the top and bottom quarks.
  - 10 mixing angles.

  This makes a total of 25 observables. There is one more observable than there are parameters of the model. This means that there is one constraint among the 25 observables.

Renormalization

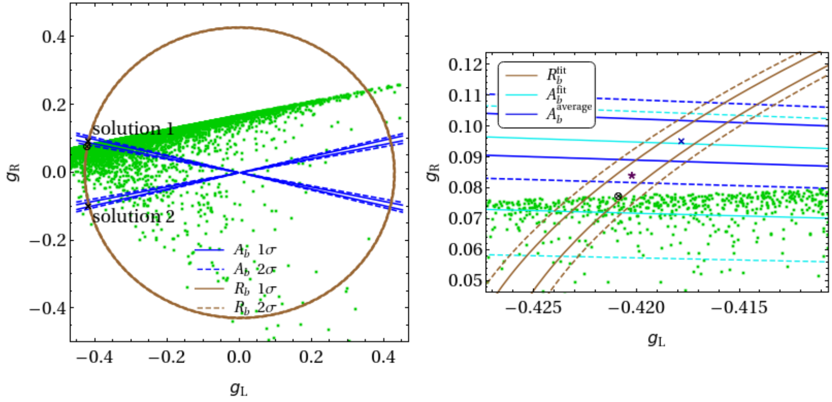
- There are computed 32 one-loop diagrams contributing to the process $Z \to b\bar{b}$.
- The renormalization is done using FeynMaster [Fontes and Romão.'2020].
- The UV divergences cancels after computations of the counterterms.
- Diagrams with photon and gluon's contain IR divergences, which are eliminated by subtracting the SM contribution (which have the same IR divergences).
- Initially, the renormalization was done in Faynman gauge, later in arbitrary gauge.
- In both cases we checked numerically finiteness of the computed couplings using LoopTools and Collier library.

Theoretical and experimental restrictions

- unitarity requirements,
- bounded-from-below requirements,
- vacuum stability conditions,
- experimental restrictions to the Yukawa couplings [CMS, Eur.Phys.J.C 79 (2019) 5, 421],
- heavy gauge bosons mass and mixing angle restrictions from the global fits.

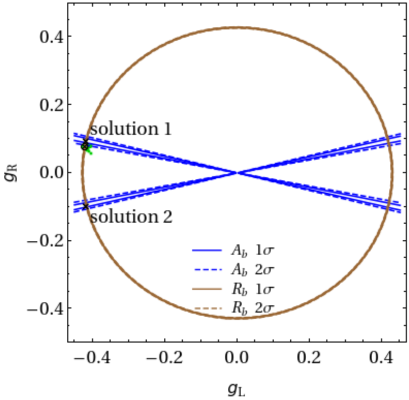
No restrictions

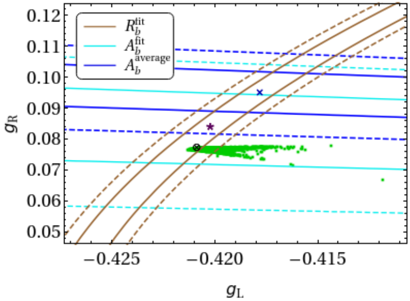
- The confrontation between experiment and the computed values g_L and g_R.



With restrictions

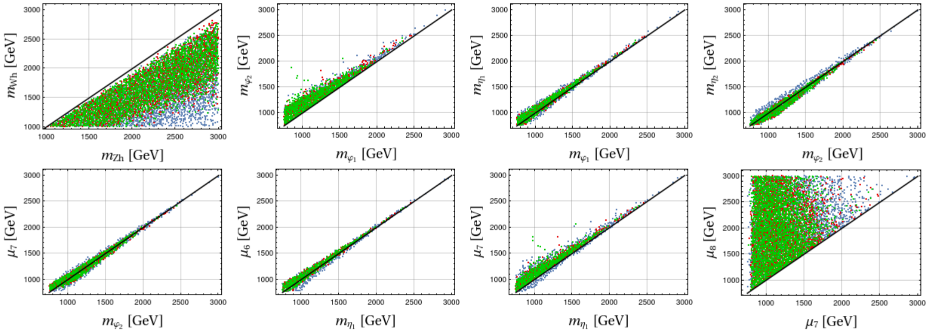
- The confrontation between experiment and the computed values g_L and g_R.





The masses of the new particles

- For all points Yukawa conditions are applied.
- Blue points: only UNI conditions are added additionally.
- Red points: UNI and BFB conditions are applied.
- Green points: all restrictions are applied.



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 LRM cannot solve this problem either (like many other models).
- An alternative solution of the g_R coupling can only be achieved with an unconstrained model.
- The constrained model gives small corrections to the $Zb\bar{b}$ couplings.
- An investigation is still underway trying to explain the negative δg_R.

The End