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Nuclear Physics B 926 (2018) 167–178

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Implication of quadratic divergences cancellation in the two Higgs doublet model

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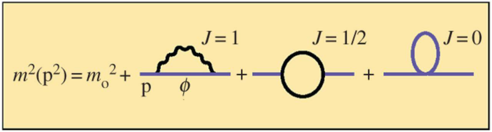
Received 29 September 2017; received in revised form 30 October 2017; accepted 31 October 2017
Available online 6 November 2017
Editor: Tommy Ohlsson

29th November 2017

Cancellation of the quadratic divergences

- One of the basic problems of the SM is **Hierarchy problem**.
- There are unnatural tuning between the tree-level Higgs mass and the mass from the radiative corrections.



$$(M_{\text{Higgs}})_{\text{experiment-tree level}} \ll (M_{\text{Higgs}})_{\text{naturalness}}$$

- These radiative corrections are sensitive to the largest scale in the theory.
- Veltman $\rightarrow$ These radiative corrections to the scalar mass either vanish or are kept at a manageable level.
- Implication of Cancellation quadratically Divergences in the 2HDM.

Two Higgs Doublet Model (2HDM)

- 2HDM consists of two SU(2) scalar doublets ϕ_1 and ϕ_2.

$$Z_2 \text{ transformation}: \ \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2$$

- Potential for 2HDM (soft Z_2 symmetry breaking)

$$\begin{aligned} V &= \frac{\lambda_1}{2}(\phi_1^+\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^+\phi_2)^2 + \lambda_3\left(\phi_1^+\phi_1\right)\left(\phi_2^+\phi_2\right) \\ &+ \lambda_4\left(\phi_1^+\phi_2\right)\left(\phi_2^+\phi_1\right) + \left(\frac{1}{2}\lambda_5(\phi_1^+\phi_2)^2 + h.c.\right) \\ &- \frac{m_{11}^2}{2}\left(\phi_1^+\phi_1\right) - \frac{m_{22}^2}{2}\left(\phi_2^+\phi_2\right) - \left(\frac{m_{12}^2}{2}(\phi_1^+\phi_2) + h.c.\right). \end{aligned}$$

- Positivity and the perturbativity constraints

$$\lambda_1 > 0, \ \ \lambda_2 > 0, \ \ \lambda_3 > -\sqrt{\lambda_1\lambda_2}, \ \ |\lambda_5| < \lambda_3 + \lambda_4 + \sqrt{\lambda_1\lambda_2}$$
$$\lambda < 4\pi.$$

- 2HDM II for Yukawa interaction

$$<\phi_1>= v_1/\sqrt{2} \neq 0, \ <\phi_2>= v_2/\sqrt{2} \neq 0$$
$$v^2 = v_1^2 + v_2^2, \ \ \tan\beta = v_2/v_1$$
$$\text{D quarks} \to \phi_1, \ \ \text{U quarks} \to \phi_2$$

There are 5 physical Higgs particle with these masses: $M_h, M_H, M_A, M_{H\pm}$

Implication of cancellation of one loop quadratic divergences in the 2HDM

- Applying Cancellation of one loop quadratic divergences in the 2HDM leads to two set of conditions [Newton&Wu 1994]:

$$
\begin{aligned}
6M_W^2 + 3M_Z^2 + v^2\left(3\lambda_1 + 2\lambda_3 + \lambda_4\right) &= \frac{12}{\cos^2\beta} {m^2}_D, \\
6M_W^2 + 3M_Z^2 + v^2\left(3\lambda_2 + 2\lambda_3 + \lambda_4\right) &= \frac{12}{\sin^2\beta} {m^2}_U .
\end{aligned}
$$

- The SM-like h and H scenarios are defined as:
  - $M_H = 125$ GeV (SM-like $H_\pm$ scenario)

$$\cos(\beta - \alpha) \sim \pm 1$$

  - $M_h = 125$ GeV (SM-like h scenario)

$$\sin(\beta - \alpha) \sim +1$$

Approximate solutions of the cancelation conditions

- For the SM-like scenarios, with $\sin(\beta-\alpha)=1$, $\cos(\beta-\alpha)=1$:

$$SM-like\ h \quad : \quad \lambda_1-\lambda_2=(\tan^2\beta-\frac{1}{\tan^2\beta})(\frac{M_H^2}{v^2}-\nu),$$

$$SM-like\ H_+ \quad : \quad \lambda_1-\lambda_2=(\tan^2\beta-\frac{1}{\tan^2\beta})(\frac{M_h^2}{v^2}-\nu).$$

- The solutions of equations, in terms of masses and angle β are:

$$\lambda_1-\lambda_2=\frac{4}{v^2}(\frac{m_b^2}{\cos^2\beta}-\frac{m_t^2}{\sin^2\beta})=\frac{4m_b^2}{v^2}(1-\frac{m_t^2/m_b^2}{\tan^2\beta})(1+\tan^2\beta).$$

- The expressions for masses squared of the partner of the SM-like Higgs particle is:

$$M^2=4m_b^2\frac{\tan^2\beta-\frac{m_t^2}{m_b^2}}{\tan^2\beta-1}+\nu v^2.$$

SM-like h and H scenarios

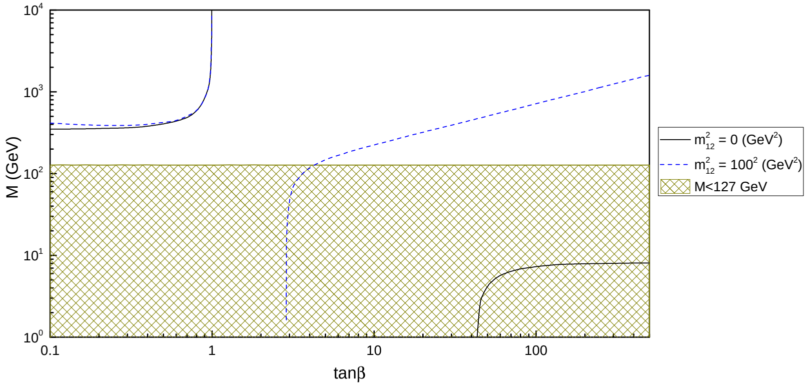


Figure: The mass of the partner of the SM-like $h(H)$ Higgs particle versus $\tan\beta$ for $m_{12}^2 = 0$ and $m_{12}^2 = 100^2$ GeV^2.

SM-like h and H scenarios

$$6M_W^2 + 3M_Z^2 + v^2\left(3\lambda_1 + 2\lambda_3 + \lambda_4\right) = \frac{12}{\cos^2\beta}{m_D}^2,$$
$$6M_W^2 + 3M_Z^2 + v^2\left(3\lambda_2 + 2\lambda_3 + \lambda_4\right) = \frac{12}{\sin^2\beta}{m_U}^2.$$

- Inserting λ in the term of mass and including only top and bottom quarks:

$$\delta_1 = \frac{12m_b^2}{\cos^2\beta} - 6M_W^2 - 3M_Z^2 - 2M_{H\pm}^2 - M_A^2 + \frac{m_{12}^2}{2\sin\beta\cos\beta}[1 + 3\tan^2\beta],$$
$$\delta_2 = \frac{12m_t^2}{\sin^2\beta} - 6M_W^2 - 3M_Z^2 - 2M_{H\pm}^2 - M_A^2 + \frac{m_{12}^2}{2\sin\beta\cos\beta}[1 + 3\cot^2\beta],$$

$$\binom{\delta_1}{\delta_2} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}\binom{M_h^2}{M_H^2}$$

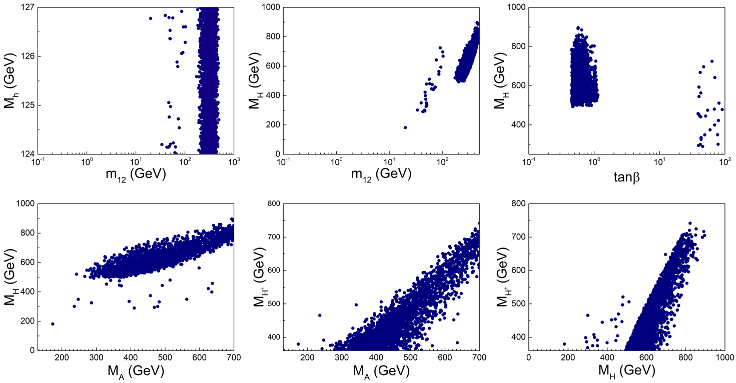
Scanning:

$$-\pi/2 < \alpha < \pi/2, \quad M_{H\pm} \in [360, 800]\ \text{GeV}, \quad m_{12}^2 \in [-400^2, 400^2]\ \text{GeV}^2,$$
$$0 < \beta < \pi/2, \quad M_h < M_H \leq 1000\ \text{GeV}, \quad M_A \in [130, 700]\ \text{GeV}.$$

Results:

Solution exist only for masses in SM-like h scenario

Considering only theoretical constraint:



Experiment constraints:

- ATLAS+CMS collaboration:
  - ∗ Higgs mass:125.09 ± 0.24 GeV
  - ∗ The relative Higgs couplings:

$$\chi_i = \frac{g_i}{g_i^{SM}}$$

$$\chi_t^h = 1.43^{+0.23}_{-0.22} \quad \chi_b^h = 0.57 \pm 0.16$$

  - ∗ Higgs signal strength:

$$\mathcal{R}_{XX} = \frac{\sigma(gg \to h_1)}{\sigma(gg \to \phi_{SM})} \frac{\text{BR}(h_1 \to XX)}{\text{BR}(\phi_{SM} \to XX)} \simeq \frac{\Gamma(h_1 \to gg)}{\Gamma(\phi_{SM} \to gg)} \frac{\text{BR}(h_1 \to XX)}{\text{BR}(\phi_{SM} \to XX)}.$$

$$R_{ZZ}^h = 1.29^{+0.26}_{-0.23},\ R_{\gamma\gamma}^h = 1.14^{+0.19}_{-0.18},\ R_{Z\gamma}^h < 9$$

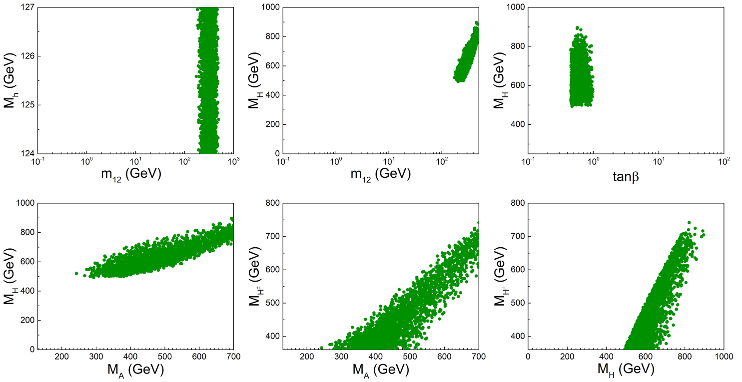
  - ∗ The total Higgs decay width:

$$\frac{\Gamma_h^{tot}}{\Gamma_h^{tot}|_{SM}} < 5.4$$

- Gfitter Group Collaboration:

$$S_{exp} = 0.05 \pm 0.11, \qquad T_{exp} = 0.09 \pm 0.1, \qquad U_{exp} = 0.01 \pm 0.11$$

Considering theoretical and experiment constraints:



- Solutions exits only in low $tan\beta$ below 1.
- Lower and upper bounds on M_H between: 500 GeV $< M_H <$ 900 GeV
- Lower bound on M_A: 250 GeV $< M_A$
- Lower bound on m_{12}^2: 170 GeV^2 $< m_{12}^2$

Benchmarks

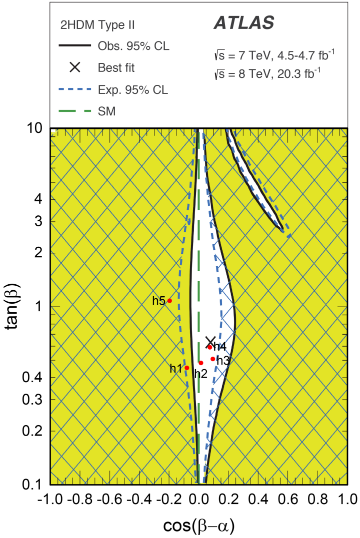


Table: SM-like h for $\sin(\beta-\alpha)\sim 1$, Higgs bosons masses (in GeV)

B mark	M_h	M_H	M_A	$M_H^{\pm}$	m_{12}^2
h1	124.426	573.832	444.16	454.424	$(281.0690)^2$
h2	124.082	505.298	266.59	375.488	$(191.9640)^2$
h3	124.242	736.961	567.37	598.392	$(352.9160)^2$
h4	125.252	826.947	650.08	645.560	$(421.8410)^2$
h5	125.771	605.931	448.48	438.628	$(309.6770)^2$

Benchmarks

Table: SM-like h for $\sin(\beta-\alpha)\sim 1$, Higgs bosons masses (in GeV)

B point	M_H	χ_t^H	χ_b^H	$R_{\gamma\gamma}^H$	$R_{Z\gamma}^H$	$\frac{\Gamma_H^{tot}}{\Gamma_H^{tot\,SM}}$
h1	573.832	-2.30	0.34	69.14	0.62	0.88
h2	505.298	-2.06	0.49	14.88	0.31	1.09
h3	736.961	-1.86	0.59	152.71	1.21	0.78
h4	826.947	-1.61	0.66	49.95	1.44	0.53
h5	605.931	-1.10	0.85	72.79	0.79	0.28

•These are calculated with respect to the would be SM Higgs with the considered mass.

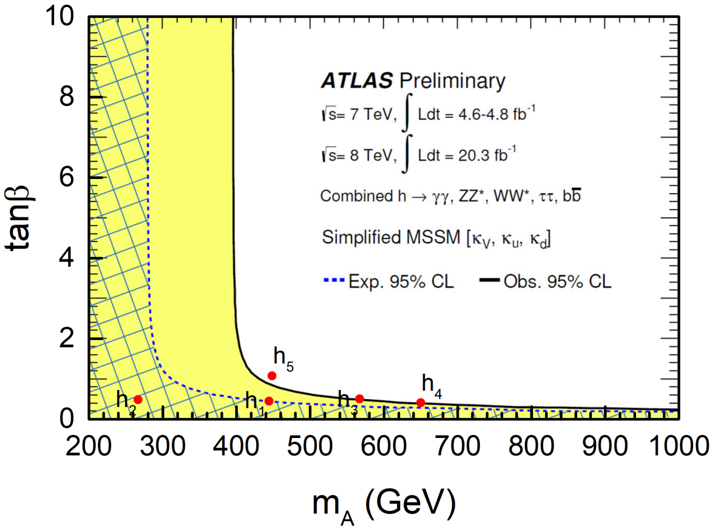
Summary and Conclusion

- Applying cancellation of one loop quadratic divergences in the 2HDM leads to two set of conditions.
- We have considered two possible scenarios, with the SM like-h and the SM like-H bosons.
- We have found that solution exist in SM-like h scenario (within the shown boundaries).
- We found theoretical constraints for mass of heavy scalars in SM-like h scenario.
- Our solution are in agreement with the recent experimental data.

Back up

Problems of the Veltman condition

- The Veltman condition, which claims to be a way to ameliorate the hierarchy problem, is known not to satisfy this goal.
- Cutoff regularization assumes that the cutoff is the same on all sectors of the theory that couple to the Higgs.
- In ultraviolet completions like a supersymmetric SM, the cutoff in each sector is related to the mass of a physical particle, which can be different for each sector.
- It is further not clear how to extend the Veltman condition beyond one loop.



ATLAS Preliminary
√s= 7 TeV, ∫ Ldt = 4.6-4.8 fb⁻¹
√s= 8 TeV, ∫ Ldt = 20.3 fb⁻¹
Combined h → γγ, ZZ*, WW*, ττ, bb̄
Simplified MSSM [κV, κu, κd]
Exp. 95% CL
Obs. 95% CL
h5
h4
h3
h2
h1
tanβ
0
2
4
6
8
10
200
300
400
500
600
700
800
900
1000
mA (GeV)

The ratio of the coupling constant (g_i) of the neutral Higgs boson to the corresponding SM coupling g_i^{SM}, called the relative couplings

$$\chi_i = \frac{g_i}{g_i^{SM}},$$

	$\chi_V (W \text{ and } Z)$	χ_u(up-type quarks)	χ_d(down-type quarks)
h	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)+\frac{1}{\tan\beta}\cos(\beta-\alpha)$	$\sin(\beta-\alpha)-\tan\beta\cos(\beta-\alpha)$
H	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)-\frac{1}{\tan\beta}\sin(\beta-\alpha)$	$\cos(\beta-\alpha)+\tan\beta\sin(\beta-\alpha)$
A	0	$-i\gamma_5\cot\beta$	$-i\gamma_5\tan\beta$

Tree-level couplings of the neutral Higgs bosons to gauge bosons and fermions in 2HDM (II).

Two Higgs Doublet Model(2HDM)

- The minimization conditions:

$$m_{11}^2 = v_1^2\lambda_1 + v_2^2(\lambda_{345} - 2\nu)$$

$$m_{22}^2 = v_2^2\lambda_2 + v_1^2(\lambda_{345} - 2\nu)$$

$$\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5, \quad \nu \equiv m_{12}^2/(2v_1v_2)$$

- There are five Higgs particles:

$M_{h,H}^2$ are the eigenvalues of the mass squared matrix $\mathcal{M}^2$

$$\mathcal{M}^2 = \begin{bmatrix} \cos^2\beta\lambda_1 + \sin^2\beta\nu & (\lambda_{345} - \nu)\cos\beta\sin\beta \\ (\lambda_{345} - \nu)\cos\beta\sin\beta & \sin^2\beta\lambda_2 + \cos^2\beta\nu \end{bmatrix} v^2$$

$$\mathcal{M}^2 = \begin{bmatrix} M_h^2\sin^2\alpha + M_H^2\cos^2\alpha & \left(M_H^2 - M_h^2\right)\sin\alpha\cos\alpha \\ \left(M_H^2 - M_h^2\right)\sin\alpha\cos\alpha & M_H^2\sin^2\alpha + M_h^2\cos^2\alpha \end{bmatrix}.$$

$$M_A^2 = (\nu - \lambda_5)v^2$$

$$M_{H^\pm}^2 = (\nu - \frac{1}{2}(\lambda_4 + \lambda_5))v^2$$