Various perspectives of 2HDMS

Ambalika Biswas, Amitabha Lahiri
Department of Theoretical Sciences, S. N. Bose National Centre for Basic Sciences,India.

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Introduction

Motivations for two Higgs doublets

- ⋈ Simplest extension of **BSM** Physics.
- ⋈ Embedded in **MSSM** and **SUSY**.
- ⋈ The extended scalar sector provides scope for viable **Dark Matter** candidates.
- ⋈ CP violating terms explain **Baryon Asymmetry**.

The two SU(2) complex scalar Higgs Doublets:

$$\Phi_a = \begin{pmatrix} w_a^+(x) \\ \frac{(v_a + h_a(x) + i z_a(x))}{\sqrt{2}} \end{pmatrix}; \quad a = 1, 2$$

$$\tan\beta = \frac{v_2}{v_1}, \quad v = \sqrt{v_1^2 + v_2^2} = 246\text{GeV}$$

Mass Eigen States : The **Physical Higgs fields** and the **Goldstone bosons**.

$$\begin{pmatrix} \omega^\pm \\ \xi^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} w_1^\pm \\ w_2^\pm \end{pmatrix},$$

$$\begin{pmatrix} \zeta \\ A \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} z_1 \\ z_2 \end{pmatrix},$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix},$$

Symmetry and 2HDM Lagrangian

U(1) symmetry imposed to avoid **FCNCs**

$$\mathcal{V} = \lambda_1(\Phi_1^\dagger\Phi_1 - \frac{v_1^2}{2})^2 + \lambda_2(\Phi_2^\dagger\Phi_2 - \frac{v_2^2}{2})^2 + \lambda_3(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2 - \frac{v_1^2 + v_2^2}{2})^2 + \lambda_4((\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) - (\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)) + \lambda_5|\Phi_1^\dagger\Phi_2 - \frac{v_1 v_2}{2}|^2$$

$$\mathcal{L}_Y = \sum_{i=1,2}[-\bar{l}_L\Phi_i G_e^i e_R - \bar{Q}_L\tilde{\Phi}_i G_u^i u_R - \bar{Q}_L\Phi_i G_d^i d_R + \text{H.c.}]$$

Veltman Conditions

Obtained from **Cancellation of the quadratic divergences** of the 2HDM. [C. Newton and T. T. Wu, Z. Phys. C 62, 253 (1994).]

$$2\text{Tr}G_e^1G_e^{1\dagger} + 6\text{Tr}G_u^{1\dagger}G_u^1 + 6\text{Tr}G_d^1G_d^{1\dagger} = \frac{9}{4}g^2 + \frac{3}{4}g'^2 + 6\lambda_1 + 10\lambda_3 + \lambda_4 + \lambda_5$$

$$2\text{Tr}G_e^2G_e^{2\dagger} + 6\text{Tr}G_u^{2\dagger}G_u^2 + 6\text{Tr}G_d^2G_d^{2\dagger} = \frac{9}{4}g^2 + \frac{3}{4}g'^2 + 6\lambda_2 + 10\lambda_3 + \lambda_4 + \lambda_5$$

$$2\text{Tr}G_e^1G_e^{2\dagger} + 6\text{Tr}G_u^{1\dagger}G_u^2 + 6\text{Tr}G_d^1G_d^{2\dagger} = 0 + \text{H.c}$$

Stability and Unitarity conditions

★ **Stability Conditions** [Ref:M.Sher,Phys.Rept.**179**(1989)273]

$$\lambda_1 + \lambda_3 > 0$$

$$2\sqrt{(\lambda_1+\lambda_3)(\lambda_2+\lambda_3)} + 2\lambda_3 + \lambda_4 > 0$$

$$\lambda_2 + \lambda_3 > 0$$

$$2\sqrt{(\lambda_1+\lambda_3)(\lambda_2+\lambda_3)} + 2\lambda_3 + \lambda_5 > 0$$

★ **Perturbative Unitarity** [Ref:J.Maalampi, J.Sirkka and I.Vilja, Phys.Lett.B **265**,371(1991)]

$$|2\lambda_3 - \lambda_4 + 2\lambda_5| \le 16\pi$$
$$|2\lambda_3 + \lambda_4| \le 16\pi$$
$$|2\lambda_3 + \lambda_5| \le 16\pi$$
$$|2\lambda_3 + 2\lambda_4 - \lambda_5| \le 16\pi$$

$$|\pm\sqrt{9(\lambda_1-\lambda_2)^2 + (4\lambda_3+\lambda_4+\lambda_5)^2} + 3(\lambda_1+\lambda_2+2\lambda_3)| \le 16\pi$$

$$|\pm\sqrt{(\lambda_1-\lambda_2)^2 + (\lambda_4-\lambda_5)^2} + (\lambda_1+\lambda_2+2\lambda_3)| \le 16\pi$$

$$|(\lambda_1+\lambda_2+2\lambda_3) \pm (\lambda_1-\lambda_2)| \le 16\pi.$$

New Physics correction

$$\rho = \frac{m_W^2}{\cos\theta_w^2 m_Z^2}$$

Including new physics effects modifies this relation into

$$\rho = \frac{1}{1-\delta\rho}$$

Recent bounds on $\delta\rho$ is $\delta\rho = -0.0002 \pm 0.0007$

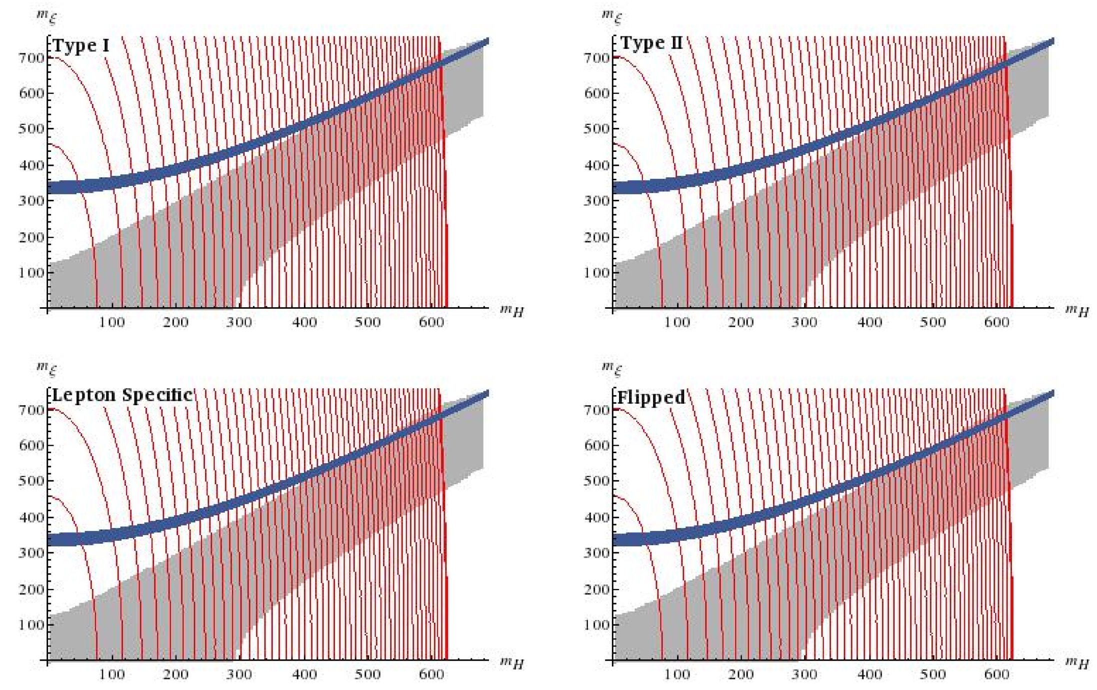
[**Particle Data Group** Collaboration, K. Olive *et al.*, **C38** (2014)090001.].

Alignment Limit

h as the SM Higgs

- $\beta - \alpha = \frac{\pi}{2}$
- $h_{VV} = h_{VV,SM}$
- $h_{ff} = h_{ff,SM}$
- $m_h = 125\text{GeV}$

The allowed mass range plots



Results for SM-like limit

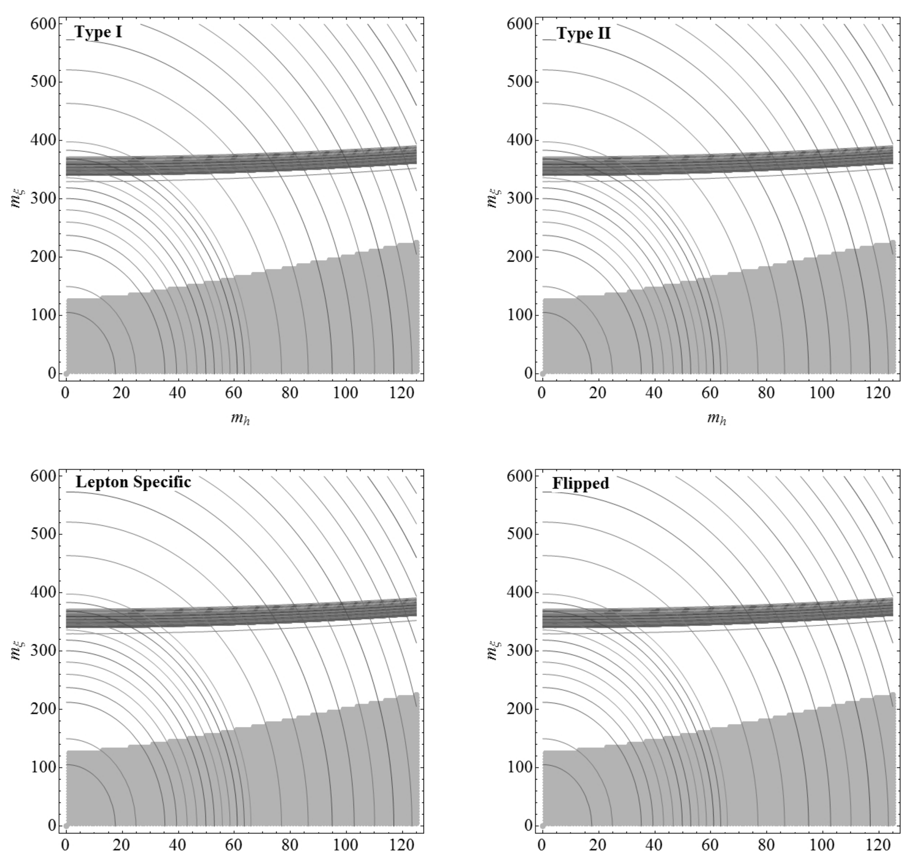
- ★ $450\text{GeV} \lesssim m_H \lesssim 620\text{GeV}$
- ★ $550\text{GeV} \lesssim m_\xi \lesssim 700\text{GeV}$
- ★ The above mass ranges vary between a few GeV for the various 2HDMs.
- ★ Direct searches: $m_\xi > 100\text{GeV}$ and our results agree with this lower bound. [K.A. Olive et al. (Particle Data Group), Chin. Phys. C38 , 090001 (2014)]
- ★ The degeneracy in the masses of the physical Higgs bosons for large enough $\tan\beta$ is evident from our plots.

Reverse Alignment Limit

H as the SM Higgs

- $\beta \approx \alpha$
- $H_{VV} = h_{VV,SM}$
- $H_{ff} = h_{ff,SM}$
- $m_H = 125\text{GeV}$

The allowed mass range plots



Results for Reverse Alignment limit

As seen from the plots in figure we find that there is no common region of intersection which obeys all the constraints. Thus *Reverse alignment limit* is not consistent with *Naturalness*.

Wrong Sign Limit

- $\frac{h\bar{D}D}{hVV} < 0$ or,
- $\frac{h\bar{U}U}{hVV} < 0$

Here h is the SM-like Higgs. [P. M. Ferreira *et al.* arxiv: 1410.1926v1 [hep-ph].]

Wrong Sign Limit and Alignment Limit

Type-II Higgs-fermion Yukawa couplings normalized w.r.t. SM:

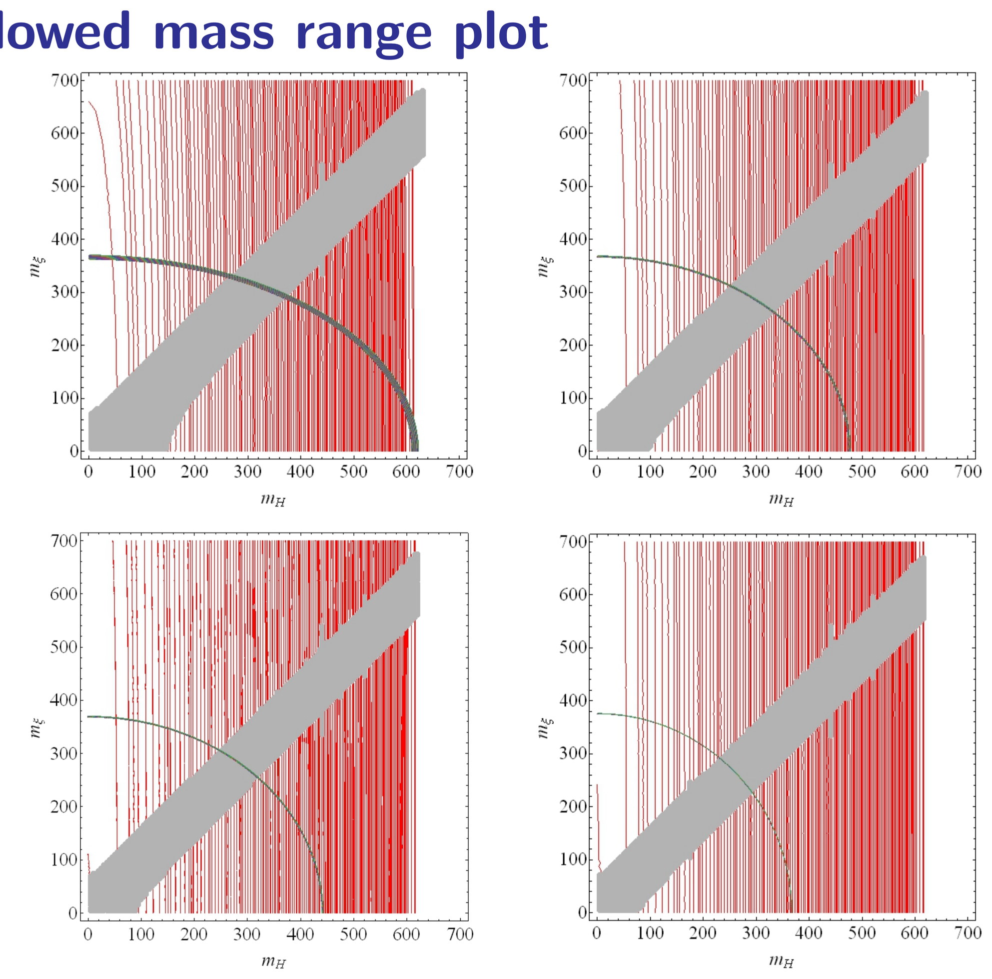
$$h\bar{D}D : -\frac{\sin\alpha}{\cos\beta} = -\sin(\beta+\alpha) + \cos(\beta+\alpha)\tan\beta$$

$$h\bar{U}U : \frac{\cos\alpha}{\sin\beta} = \sin(\beta+\alpha) + \cos(\beta+\alpha)\cot\beta$$

- $\sin(\beta+\alpha) = 1 \Rightarrow h\bar{D}D = -1$ and $h\bar{U}U = +1$.
- Wrong Sign + Alignment limit $\Rightarrow \sin(\beta-\alpha) \sim 1$ and $\sin(\beta+\alpha) \sim 1$.
- The wrong sign limit approaches the alignment limit for $\tan\beta \approx 17$ [P. M. Ferreira *et al.* arxiv: 1410.1926v1 [hep-ph].]

Wrong Sign Limit contd...

Allowed mass range plot



for $\tan\beta$ 10, 17, 20 and 30 respectively.

Results

- ★ For $\tan\beta = 17$, $250\text{GeV} \lesssim m_H \lesssim 330\text{GeV}$
- ★ $260\text{GeV} \lesssim m_\xi \lesssim 310\text{GeV}$
- ★ At higher values of $\tan\beta$, both ranges become narrower and move down on the mass scale.

Diphoton Decay Width

Diphoton decay width in Wrong sign and Alignment limits

$$\Gamma(h \to \gamma\gamma) = \frac{G_\mu\alpha^2 m_h^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c Q_f^2 g_{hff} A_{1/2}^h(\tau_f) + g_{hVV}A_1^h(\tau_W) + \frac{m_W^2\lambda_{h\xi^+\xi^-}}{2c_W^2 M_{\xi^\pm}^2}A_0^h(\tau_{\xi^\pm})\right|^2$$

$$g_{htt} = \frac{\cos\alpha}{\sin\beta}, \ g_{hbb} = -\frac{\sin\alpha}{\cos\beta} \text{ and } g_{hWW} = \sin(\beta-\alpha)$$

$$\lambda_{h\xi^+\xi^-} = \cos 2\beta\sin(\beta+\alpha) + 2c_W^2\sin(\beta-\alpha) = \lambda_{hAA} + 2c_W^2 g_{hVV}$$

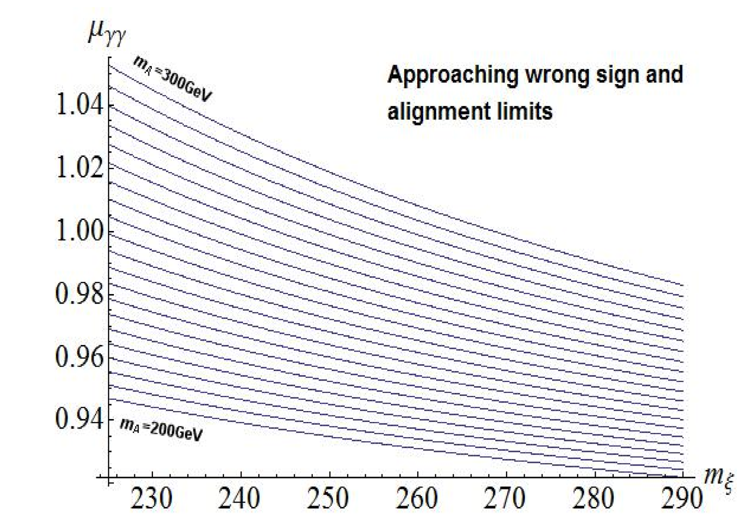
where $c_W = \cos\theta_W$, θ_W being the Weinberg angle.

$$A_{1/2}^h = 2[\tau + (\tau-1)f(\tau)]\tau^{-2}$$
$$A_1^h = -[2\tau^2 + 3\tau + 3(2\tau-1)f(\tau)]\tau^{-2}$$
$$A_0^h = -[\tau - f(\tau)]\tau^{-2}$$

$$\tau_x = m_h^2/4m_x^2$$

$$f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau}, & \tau \le 1 \\ -\frac{1}{4}[\log\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi]^2, & \tau > 1 \end{cases}$$

Plot for diphoton decay



Results for diphoton decay width

- ★ The relative diphoton decay width increases as m_A increases.
- ★ Maximum value of about **6%** as compared to the SM value.
- ★ Throw light on BSM Physics.

Conclusion

- ★ $\Gamma(h \to \gamma\gamma)$ receives a maximum of **6%** additional contributions from $\xi^\pm \Rightarrow$ Can be probed at the next LHC run.
- ★ Possible DM candidate.
- ★ Though a peak at 750 GeV was observed by ATLAS and CMS, but 2HDMs will not advocate it if *Naturalness* holds.

ani73biswas@gmail.com