Constraining the Two Higgs Doublet Model

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28.08.2012

Workshop on Multi-Higgs Models, Lisbon, Portugal

Outline

1. Review of 2HDMs
2. Constraints
    1. vacuum stability, conditions determining type of the vacuum
    2. perturbative unitarity condition
    3. EWPT
3. Results
    1. parameters λ
    2. Inert Model
    3. Mixed Model
4. Summary

Motivation

- 2HDM - one of the simplest extensions of the SM with 2 scalar doublets ϕ_S, ϕ_D.
- $\rho = 1$, at the tree-level.
- possible CP violation - baryon asymmetry.
- DM candidates (if $\mathbb{Z}_2$ symmetry).

Potential

[N. G. Deshpande, E. Ma, Phys. Rev. D 18 (1978) 2574, J. F. Gunion, H. E. Haber, G. Kane, S. Dawson, *The Higgs Hunter's Guide*, 1990 Addison-Wesley, I. F. Ginzburg, K. A. Kanishev, M. Krawczyk, D. Sokołowska, Phys. Rev. D 82 (2010) 123533]

$$V = -\frac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S) + m_{22}^2(\phi_D^\dagger\phi_D)\right] + \frac{1}{2}\left[\lambda_1(\phi_S^\dagger\phi_S)^2 + \lambda_2(\phi_D^\dagger\phi_D)^2\right] +$$
$$+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D) + \lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) +$$
$$\frac{1}{2}\lambda_5\left[(\phi_S^\dagger\phi_D)^2 + (\phi_D^\dagger\phi_S)^2\right]$$

- $\mathbb{Z}_2$ symmetry (D symmetry): $\phi_D \to -\phi_D$, $\phi_S \to \phi_S$
- Positivity constraints:
  a) $\lambda_1 > 0$, $\lambda_2 > 0$, b) $\lambda_3 + \sqrt{\lambda_1\lambda_2} > 0$,
  c) $\lambda_3 + \lambda_4 + \lambda_5 + \sqrt{\lambda_1\lambda_2} > 0$

Possible vacua

There are 5 types of possible vacua:

- Electroweak-symmetric
- Charge Breaking
- Inert-Like
- Inert
- Mixed

Different vacua $\Rightarrow$ different particle spectra.

The Inert vacuum

- $\langle \phi_S \rangle = \frac{v}{\sqrt{2}}$, $\langle \phi_D \rangle = 0$
- 5 physical scalars: $h, H, A, H^{\pm}$ (h - the Higgs boson)
- The Inert vacuum can be realized only if:

$$m_{11}^2 > 0, \quad \lambda_1 > 0, \quad \lambda_3 v^2 \geqslant m_{22}^2,$$
$$(\lambda_3 + \lambda_4 \pm \lambda_5) v^2 \geqslant m_{22}^2, \quad \frac{m_{11}^2}{\sqrt{\lambda_1}} > \frac{m_{22}^2}{\sqrt{\lambda_2}}$$

The Inert Doublet Model (IDM)

[N. G. Deshpande, E. Ma, Phys. Rev. D 18 (1978) 2574, R. Barbieri, L. J. Hall, V. S. Rychkov, Phys. Rev. D 74 (2006) 015007, Q.-H. Cao, E. Ma, G. Rajasekaran, Phys. Rev. D 76 (2007) 095011]

IDM

A 2HDM with potential V, Inert vacuum state and Model I of Yukawa interactions (i.e. only ϕ_S couples to fermions).

- D symmetry conserved in $\mathcal{L}$ and in the vacuum - the lightest neutral D-odd particle stable - a DM candidate (H if $\lambda_4 + \lambda_5 < 0$).
- h couples to gauge bosons and fermions like SM Higgs. We assume $M_h = 125$ GeV.
- Parametrized by: $(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{22}^2)$ or $(M_h, M_H, M_A, M_{H^\pm}, m_{22}^2, \lambda_2)$

The Mixed vacuum

- $\langle \phi_S \rangle = v_S$, $\langle \phi_D \rangle = v_D$, $\quad v_S, v_D \neq 0$
- 5 physical Higgs bosons: $h, H, A, H^\pm$
- Two mixing angles: α and β, $\tan\beta = \frac{v_D}{v_S}$
- The Mixed vacuum can be realized only if:

$$v_S^2 = \frac{m_{11}^2\lambda_2 - \lambda_{345}m_{22}^2}{\lambda_1\lambda_2 - \lambda_{345}^2} > 0, \quad v_D^2 = \frac{m_{22}^2\lambda_1 - \lambda_{345}m_{11}^2}{\lambda_1\lambda_2 - \lambda_{345}^2} > 0,$$

$$\lambda_4 + \lambda_5 < 0, \quad \lambda_5 < 0, \quad \lambda_1\lambda_2 - \lambda_{345}^2 > 0$$

$$(\lambda_{345} := \lambda_3 + \lambda_4 + \lambda_5)$$

The Mixed Model

The Mixed Model

A 2HDM with potential V, the Mixed vacuum state, Model II of Yukawa interactions.

- $\mathbb{Z}_2$ symmetry spontaneously broken
- SM-like Mixed Model:
  - $\sin(\beta - \alpha) = 1 \Rightarrow h$ couples to SM fields like SM Higgs
  - $\cos(\beta - \alpha) = 1 \Rightarrow H$ couples to SM fields like SM Higgs
- Parametrized by: $(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{11}^2, m_{22}^2)$ or $(M_h, M_H, M_A, M_{H^\pm}, \tan\beta, \sin\alpha)$

Perturbative unitarity condition

[B. W. Lee, C. Quigg, H. B. Thacker, Phys. Rev. Lett. 38 (1977) 883, S. Kanemura, T. Kubota, E. Takasugi Phys. Lett. B 313 (1993) 155, A. G Akeroyd, A. Arhrib, E. Naimi Phys. Lett. B 490 (2000) 119, I. F. Ginzburg, I. P. Ivanov, Phys. Rev. D 72 (2005) 115010, B. Gorczyca, Master Thesis at the University of Warsaw (2011)]

$$|\Re(a_0^0(s))| < \frac{1}{2}$$

Scattering matrix $\mathcal{M}(\mathbf{25} \times \mathbf{25})$ (*doubly charged channels included-B.G.*) for the scalar sector in the high energy limit - $|\text{eigenvalues}| < 8\pi$

$$\mathcal{M} = \begin{pmatrix} \mathcal{M}_1 & & & & & \\ & \mathcal{M}_2 & & & & \\ & & \mathcal{M}_3 & & & \\ & & & \mathcal{M}_4 & & \\ & & & & \mathcal{M}_5 & \\ & & & & & \mathcal{M}_6 \end{pmatrix}$$

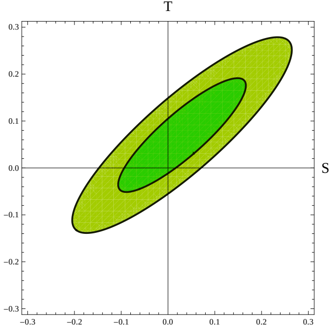
- We get constraints for $(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{11}^2, m_{22}^2)$ or $(M_h, M_H, M_A, M_{H^\pm}, m_{22}^2, \lambda_2)$ or $(M_h, M_H, M_A, M_{H^\pm}, \tan\beta, \sin\alpha)$.

Electroweak Precision Tests

[M. E. Peskin, T. Takeuchi, Phys. Rev. Lett. 65 (1990) 964, W. Grimus, L. Lavoura, O. M. Ogreid, P. Osland, Nucl. Phys. B 801 (2008) 81; R. Barbieri, L. J. Hall, V. S. Rychkov, Phys. Rev. D 74 (2006) 015007, K. Nakamura *et al.* (Particle Data Group), JPG 37 (2010) 075021]

$$S = 0.03 \pm 0.09$$
$$T = 0.07 \pm 0.08$$
$$\rho = 87\%$$

- Calculate values of S and T and check whether they fall into the 2σ ellipse.



The method

Random scan over the parameter space.

We check

- theoretical constraints:
  - positivity constraints
  - perturbative unitarity
  - conditions determining the type of the vacuum
  - $\lambda_5 < 0$ and $\lambda_4 + \lambda_5 < 0$
- experimental constraints:
  - EWPT*

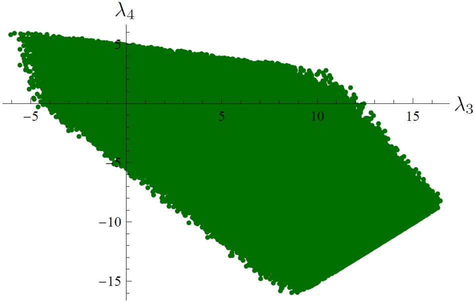
Constraints on parameters λ and their correlations

[B. Gorczyca, Master Thesis at the University of Warsaw (2011)]

Region of perturbativity of the theory.

$$\begin{aligned} 0 \leqslant \lambda_1 &\leqslant 8.38, \\ 0 \leqslant \lambda_2 &\leqslant 8.38, \\ -6.05 \leqslant \lambda_3 &\leqslant 16.44, \\ -15.98 \leqslant \lambda_4 &\leqslant 5.93, \\ -8.34 \leqslant \lambda_5 &\leqslant 0. \end{aligned}$$

Compare with the traditionally used $|\lambda_i| \leqslant 4\pi \approx 12.57$.

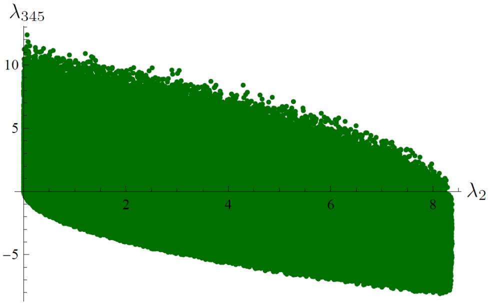


Constraints on couplings in the IDM

In the Inert Model the couplings of physical particles - simple combinations of λ_i ($\lambda_{ij} = \lambda_i + \lambda_j$, $\lambda^-_{ij} = \lambda_i - \lambda_j$).

e.g. $\lambda_{345} \to hhHH$, $\lambda^-_{345} \to hhAA$, $\lambda_3 \to hH^+H^-$, $3\lambda_2 \to HHHH$

$$-8.10 \leqslant \lambda_{345} \leqslant 12.38,$$
$$-7.76 \leqslant \lambda^-_{345} \leqslant 16.45,$$
$$-8.28 \leqslant \frac{1}{2}\lambda_{45} \leqslant 0,$$
$$-7.97 \leqslant \frac{1}{2}\lambda^-_{45} \leqslant 6.08,$$
$$-7.77 \leqslant \lambda_{34} \leqslant 13.25.$$



Constraints on masses in the Inert Doublet Model

We set $M_h = 125\,\text{GeV}$

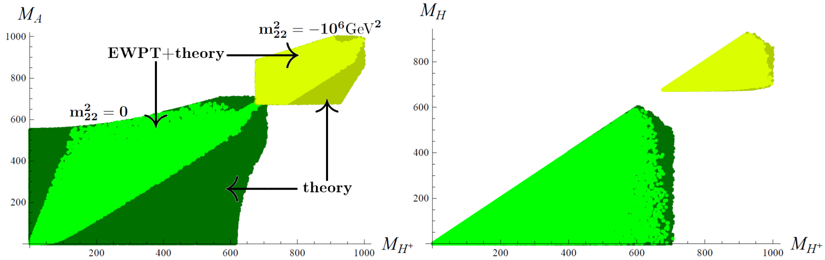
- Constraints on masses depend on value of m_{22}^2.
- For $m_{22}^2 = 0$:

$$\begin{aligned} M_H &\leqslant 602\,\text{GeV}, \\ M_{H^\pm} &\leqslant 708\,\text{GeV}, \\ M_A &\leqslant 708\,\text{GeV}. \end{aligned}$$

- For $|m_{22}^2| \leqslant 10^4\,\text{GeV}^2$ results hardly change w.r.t. $m_{22}^2 = 0$.
- For big negative values of m_{22}^2 allowed masses (including DM mass) are big $\longrightarrow$

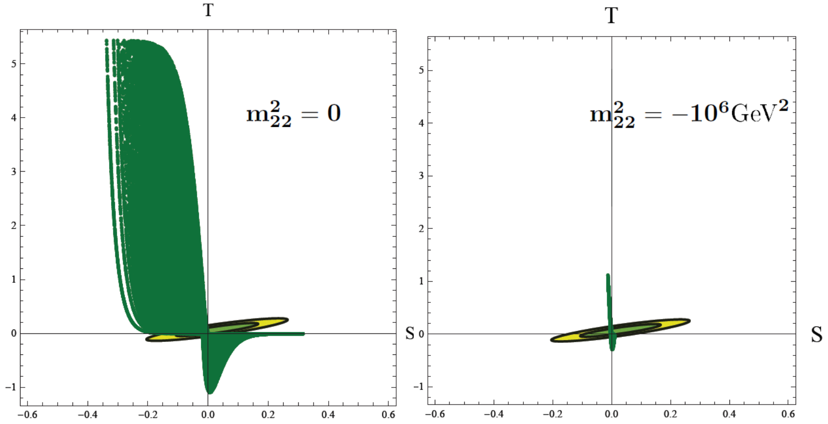
see also: [A. Arhrib, R. Benbrik, N. Gaur, Phys. Rev. D85 (2012) 095021, E. M. Dolle, S. Su, Phys. Rev. D 80 (2009) 055012, M. Gustafsson, S. Rydbeck, L. Lopez-Honorez, E. Lundstrom, hep-ph/1206.6316v1]

Allowed regions of masses in the Inert Model



- Regions for $m^2_{22} = 0$ and $m^2_{22} = -10^6$ GeV^2 have empty intersection.
- Lower bounds on masses arise.
- Very heavy DM excluded for moderate values of m^2_{22}.

The values of S and T



Huge part of the parameter space excluded!

Remarks

- m_{22}^2 does not enter the scattering matrix but can be constrained with use of:
  - condition on Inert vacuum: $\frac{m_{11}^2}{\sqrt{\lambda_1}} > \frac{m_{22}^2}{\sqrt{\lambda_2}}$ $(m_{11}^2 = M_h^2, \lambda_1 = \frac{M_h^2}{v^2})$
  - the constraint on λ_2: $\lambda_2 \leqslant 8.38$

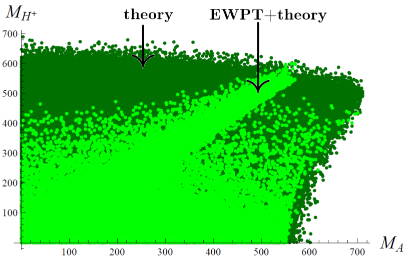
$$\Rightarrow m_{22}^2 < \sqrt{\lambda_2} M_h v \lesssim 9 \cdot 10^4 \text{ GeV}^2.$$

- Important to take into account conditions determining type of vacuum.

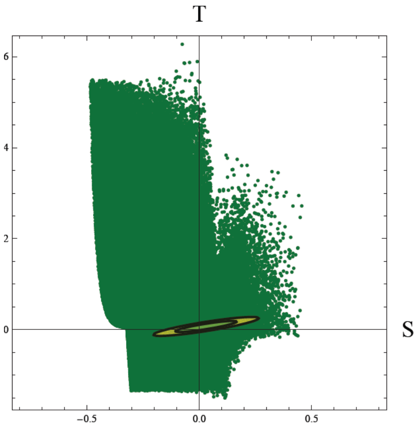
Constraints on masses in the Mixed Model

see also: [S. Kanemura, Y. Okada, H. Taniguchi, K. Tsumura, Phys. Lett. B704 (2011) 303-307, H. S. Cheon, S. K. Kang, hep-ph/1207.1083v2]

Region of masses allowed in the Mixed Model.



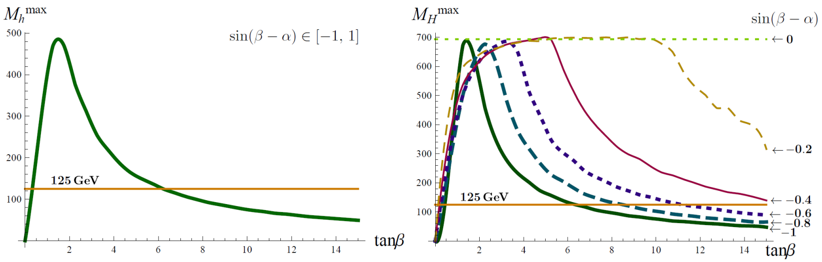
The results agree at the level of 1-2% with analytical results of [J. Hořejší, M. Kladiva, Eur. Phys. J. C 46 (2006) 81]



similar analysis in: [G. Funk, D. O'Neil, R. M. Winters, Int. J. Mod. Phys. A 27 (2012) 1250021.]

Constraining $\tan\beta$

Maximal values of masses: M_h (left) and M_H (right) versus $\tan\beta$ allowed in the Mixed Model.



- Correlation between M_H^{max} and $\tan\beta$ depends on $\sin(\beta-\alpha)$.
- Lower bound on $M_h \Rightarrow$ constraints on $\tan\beta$

SM-like Mixed Model

[B. Gorczyca, M. Krawczyk, arXiv:hep-ph/1112.5086v2]

SM-like Mixed Model

$\sin(\beta-\alpha)=1,\ M_h=125\,\mathrm{GeV}.$

$$\mathbf{0.18} \lesssim \tan\beta \lesssim \mathbf{5.59}$$

Also true when $\sin(\beta-\alpha)\neq 1$

SM-like Mixed Model

$\sin(\beta-\alpha)=0,\ M_H=125\,\mathrm{GeV}.$

$\tan\beta$ unconstrained

Summary

1. Consistent analysis of the parameter spaces of different incarnations of 2HDM: IDM and Mixed Model.
2. Included: positivity constraints, conditions determining type of the vacuum, perturbative unitarity constraints, EWPT and $M_h = 125\,\text{GeV}$.
3. Very heavy DM in the IDM excluded in wide region of values of m_{22}^2.
4. In the Mixed Model with $M_h = 125\,\text{GeV}$ $\mathbf{0.18} \lesssim \tan\beta \lesssim \mathbf{5.59}$.
5. Bounds on $\tan\beta$ without specifying model of Yukawa interactions and without constraining couplings with gauge bosons.
6. In the SM-like Mixed Model with $M_H = 125\,\text{GeV}$ $\tan\beta$ unconstrained.

Backup

How do bounds on M_h constrain $\tan\beta$?

$$M_h^2 \to \frac{v^2}{2}\left(\lambda_2 - \sqrt{\lambda_2^2}\right) = 0 \text{ for } \tan\beta \to \infty$$

$$M_h^2 \to \frac{v^2}{2}\left(\lambda_1 - \sqrt{\lambda_1^2}\right) = 0 \text{ for } \tan\beta \to 0.$$

- Lower bound on $M_h \Rightarrow$ upper and lower bounds on $\tan\beta$.

Dark matter

[D. Sokołowska, arXiv:hep-ph/1107.1991v1]

- In the Inert Model good DM candidate - H.
- For most values of the DM particle's mass the energy relic density too low to fit in the astrophysical observations.
- Only three regions are considered: $M_{\rm DM} \lesssim 10\,\text{GeV}$, $40 \lesssim M_{\rm DM} \lesssim 80\,\text{GeV}$ or $M_{\rm DM} \gtrsim 500\,\text{GeV}$.
- Our results strongly constrain the last option for $|m_{22}^2| < 10^4\,\text{GeV}^2$.

Perturbative unitarity condition

- $SS^\dagger = \mathbf{1} \Rightarrow$ partial wave amplitudes of elastic scatterings lie on the Argand circle.
- In the high energy limit: $|\Re(a^0(s))| < \frac{1}{2}$.