Two Higgs Doublets Model Run 2

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Abstract

In this poster we present a brief review of Two Higgs Model Doublet with CP-conserving. We begin by the 2HDM potential with softly broken discrete Z_2 symmetry, then we will show that the Z_2 split the Yukawa sector on four types. Then to performing the scan over 2HDM parameter space, we need to take account the usual LHC, Tevatron and LEP bounds (as implemented in `HiggsBounds` and `HiggsSignals`) as well as the theoretical ones (implemented in `2HDMC`), that will be helpful to know which regions are excluded from LHC, LEP and Tevatran.

Introduction

The SM has been a successful achievement in particle physics in terms of explaining the laws of nature, it has been regarded as having inadequacies and incomplete because there are phenomena that it doesn't explain (such as the darkmatter candidate, gravity, the oscillations of neutrinos and the baryonic-asymmetry of the univere). This gives us the impetus to investigate more complete theories that better address these questions, these are what we consider Beyond the SM (BSM). The 2HDM is a BSM theoty which answers some of these questions, such as CP-violation etc. In any such theories there are basically two major constraints which need to be satisfied, first constraint comes from the experimental fact that $\rho = m_W^2/(m_Z^2 \cos^2\theta_W)$ should be very close to 1. Second major theoretical constraint on the Higgs sector comes from severe limits on the existence of flavour-changing neutral currents (FCNC's), which is absent in the minimal Higgs model at tree level and which must also be true in any extended models.

A review of the 2HDM

The most general renormalizable potential for a model of exactly two scalar Electro-Weak (EW) doublets with the quantum numbers which are invariant under $SU(2) \otimes U(1)$, and after introduction of the symmetry Z_2 can be written as [1]

$$\begin{aligned} V(\Phi_1,\Phi_2) =\ & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 + (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}], \end{aligned} \tag{1}$$

where Φ_i, $i = 1,2$ are complex $SU(2)$ doublets with 4 degrees of freedom each and m_i^2, λ_i and m_{12}^2 are real which follows from the hermiticity of the potential. From the initial 8 degrees of freedom, if the $SU(2)$ symmetry is broken, we end up with the aforementioned 5 physical Higgs states, upon the absorption of 3 Goldstone bosons by the $W^\pm$ and Z states. The potential in Eq. (1) has a total of 10 parameters if one includes the vacuum expectation values. In a CP-conserving minimum there are two minimization conditions that can be used to fix the tree-level value of the parameters m_1^2 and m_2^2. The combination $v^2 = v_1^2 + v_2^2$ is fixed as usual by the EW breaking scale through $v^2 = (2\sqrt{2}G_F)^{-1}$. We are thus left with 7 independent parameters, namely $(\lambda_i)_{i=1,...,5}$, m_{12}^2, and $\tan\beta \equiv v_2/v_1$. Equivalently, we can take instead the set m_h, m_H, m_A, $m_{H^\pm}$, $\tan\beta$, $\sin(\alpha-\beta)$ and m_{12}^2 as the 7 independent parameters. The angle β is the rotation angle from the group eigenstates to the mass eigenstates in the CP-odd and charged sector. The angle α is the corresponding rotation angle for the CP-even sector. The parameter m_{12} is a measure of how the discrete symmetry is broken.

Higgs masses

The Higgs masses can now easily be calculated for any choice of Higgs potential and basis. Using the generic potential of eq. (1), one arrives at the relations [2]

$$\begin{aligned} m_A^2 &= \frac{m_{12}^2}{\sin\beta\cos\beta} - v^2\,\lambda_5 \\ m_{H^\pm}^2 &= m_A^2 + \frac{v^2}{2}(\lambda_5 - \lambda_4)\,. \end{aligned} \tag{2}$$

$$m_{H,h}^2 = \frac{1}{2}\left[\mathcal{M}_{11}^2 + \mathcal{M}_{22}^2 \pm \sqrt{\left(\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2\right)^2 + 4\left(\mathcal{M}_{12}^2\right)^2}\,\right]. \tag{3}$$

with $m_H^2 \geq m_h^2$, and

$$s_{2\alpha} = \frac{2\mathcal{M}_{12}}{\sqrt{(\mathcal{M}_{11}-\mathcal{M}_{22})^2 + 4\mathcal{M}_{12}^2}} \quad , \quad c_{2\alpha} = \frac{\mathcal{M}_{11}-\mathcal{M}_{22}}{\sqrt{(\mathcal{M}_{11}-\mathcal{M}_{22})^2 + 4\mathcal{M}_{12}^2}} \tag{4}$$

Yukawa sector

The Most general gauge invariant Lagrangian that couples the Higgs fields to fermions reads [3]

$$-\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} = \sum_{a=1,2} \eta_{ij}^{U,0}\overline{Q}_{iL}^0\widetilde{\Phi}_a U_{jR}^0 + \eta_{ij}^{D,0}\overline{Q}_{iL}^0\Phi_a D_{jR}^0 + \eta_{ij}^{E,0}\overline{l}_{iL}^0\Phi_a E_{jR}^0 + h.c., \tag{5}$$

where $\Phi_{1,2}$ represent the Higgs doublets, $\widetilde{\Phi}_{1,2} \equiv i\sigma_2\Phi_{1,2}$, η_{ij}^0 and ξ_{ij}^0 are non diagonal 3×3 matrices and i,j denote family indices. D_R^0 refers to the three down-type weak isospin quark singlets $D_R^0 \equiv \left(d_R^0, s_R^0, b_R^0\right)^T$, U refers to the three up-type weak isospin quark singlets $U_R^0 \equiv \left(u_R^0, c_R^0, t_R^0\right)^T$ and E_R^0 to the three charged leptons. Finally, $\overline{Q}_{iL}^0$, $\overline{l}_{iL}^0$ denote the quark and lepton weak isospin left-handed doublets respectively. The superscript "0" indicates that the fields are not mass eigenstates yet. After EWSB, the Yukawa Lagrangian can be expressed in terms of mass eigenstates of the neutral and charged Higgs bosons yields as follows [4]

$$\begin{aligned} -\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} =\ & \sum_{f=u,d,\ell}\frac{m_f}{v}\left(\xi_f^h\overline{f}fh^0 + \xi_f^H\overline{f}fH^0 - i\xi_f^A\overline{f}\gamma_5 fA^0\right) \\ & + \left\{\frac{\sqrt{2}V_{ud}}{v}\,\overline{u}\left(m_u\xi_u^A\mathrm{P}_L + m_d\xi_d^A\mathrm{P}_R\right)dH^+ + \frac{\sqrt{2}m_\ell\xi_\ell^A}{v}\,\overline{\nu_L}\ell_R H^+ + \text{h.c}\right\}, \end{aligned} \tag{6}$$

where $v^2 = v_1^2 + v_2^2 = (\sqrt{2}G_F)^{-1}$; P_R and P_L are the right- and left-handed projection operators, respectively. The coefficients ξ_f^h, ξ_f^H and ξ_f^A $(f = u,d,l)$ in the four 2HDM types are given in the Table 1 .

The couplings of h^0 and H^0 to gauge boson $V = W^\pm, Z^0$ are proportional to $\sin(\alpha-\beta)$ and $\cos(\alpha-\beta)$, respectively. Since these are gauge couplings, they are the same for all Yukawa types. As we are considering the scenario where the lightest neutral Higgs state is the 125 GeV scalar, the SM-like Higgs boson h is recovered when $\cos(\beta-\alpha)\approx 0$. As one can see from Tab.1 , for all 2HDM Types, this is also the limit where the Yukawa couplings of the discovered Higgs boson become SM-like. The limit $\cos(\beta-\alpha)\approx 0$ seems to be favored by LHC data, except for the possibility of a wrong sign limit [5, 6], where the couplings to down-type quarks can have a relative sign to the gauge bosons ones, thus oppositely to those of the SM. Our benchmarks will focus on the SM-like limit where indeed $\cos(\beta-\alpha)\approx 0$.

	Type I	Type II	Type-X	Type-Y
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Table 1: Yukawa couplings in terms of mixing angles for the four 2HDM Types

2HDMC, HiggsBounds and HiggsSignals

Now let's go to describe the three code that will help us to study the phenomenology of a general 2HDM. The first code is `2hdmc` [7] (Two-Higgs-Doublet Model Calculator), `2hdmc` is a *C++* code which allows to specify the 2HDM potential in different parametrizations, the Yukawa sector, check theoretical properties of the model (constraints), and also to calculating the 2HDM contribution to the oblique electroweak parameters $(S,T,U,...)$. In addition, decay widths of the Higgs bosons can be calculated. The second is a *Fortran* code called `HiggsBounds` [8], which is a tool to tests each parameter point for 95% Confidence Level (CL) exclusion from Higgs searches at the LHC as well as LEP and Tevatron. First, the code determines the most sensitive experimental search available, as judged by the expected limit, for each additional Higgs boson in the model. Then, only the selected channels are applied to the model, i.e., the predicted signal rate for the most sensitive search of each additional Higgs boson is compared to the observed upper limit. In the case the prediction exceeds the limit, the parameter point is regarded as excluded. The last code is `HiggsSignals` [9], is also a *Fortran* code which allows to test the compatibility of Higgs sector predictions against Higgs rates and masses measured at the LHC or the Tevatron. Arbitrary models with any number of Higgs bosons can be investigated using a model-independent input scheme based on `HiggsBounds`. The test is based on the calculation of a χ^2 measure from the predictions and the measured Higgs rates and masses, with the ability of fully taking into account systematics and correlations for the signal rate predictions, luminosity and Higgs mass predictions. It features two complementary methods for the test.First, the peak-centered method, in which each observable is defined by a Higgs signal rate measured at a specific hypothetical Higgs mass, corresponding to a tentative Higgs signal. Second, the mass-centered method, where the test is evaluated by comparing the signal rate measurement to the theory prediction at the Higgs mass predicted by the model. For models with more than one Higgs boson (our situation) we recommend to use `HiggsSignals` and `HiggsBounds` in parallel to exploit the full constraining power of Higgs search exclusion limits and the measurements of the signal seen at $m_H \approx 125.5$ GeV. Now to link `HiggsBounds` and `HiggsSignals` with `2HDMC`, the libraries libHB.a and libHS.a should be placed in the 2hdmc/lib directory, and in addition two lines should be uncommented in the `2HDMC` Makefile.

Results

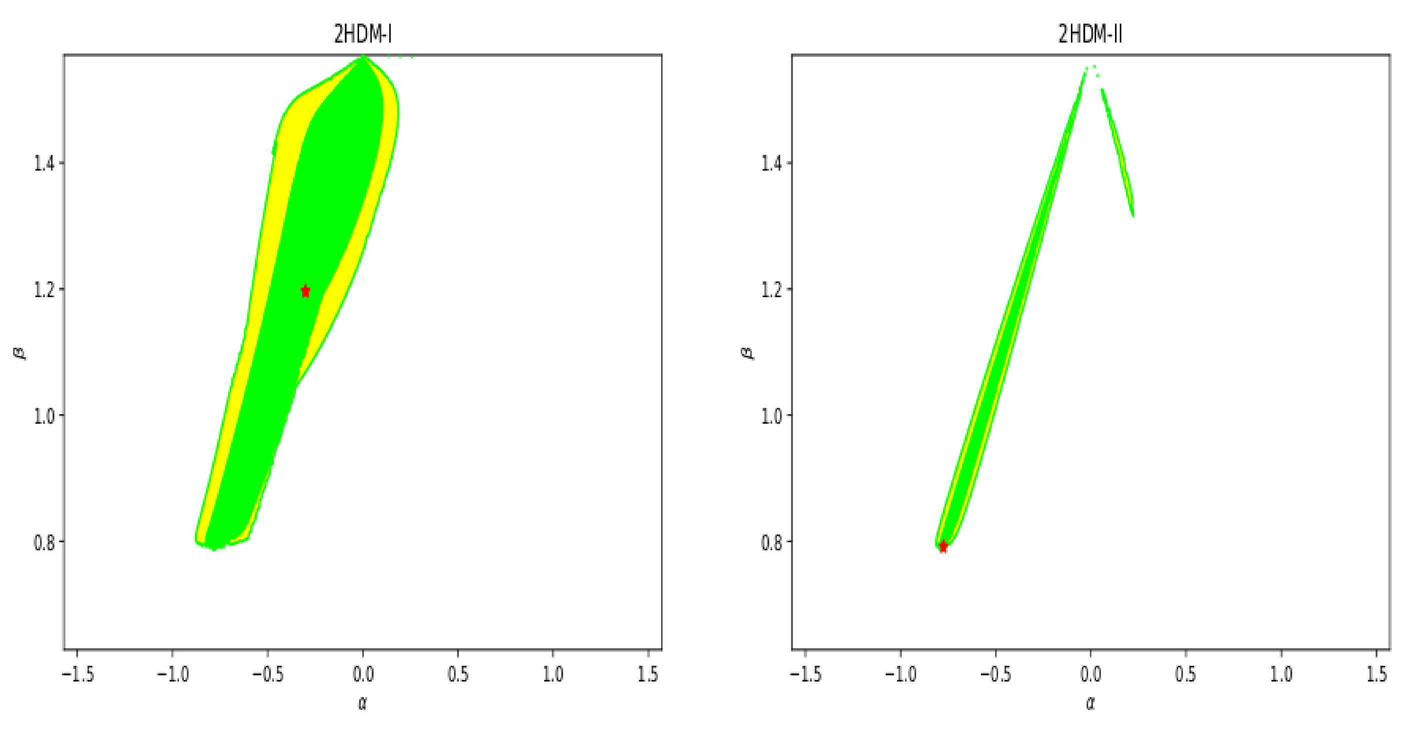

Figure 1: Direct constraints from null heavy Higgs searches at the LHC on the parameter space of the 2HDM Type-I (left), Type-II (right), mapped on the (α, β) plane. The colors indicate compatibility with the observed Higgs signal at 1σ (green), 2σ (yellow) around the best fit points (red stars) [10].

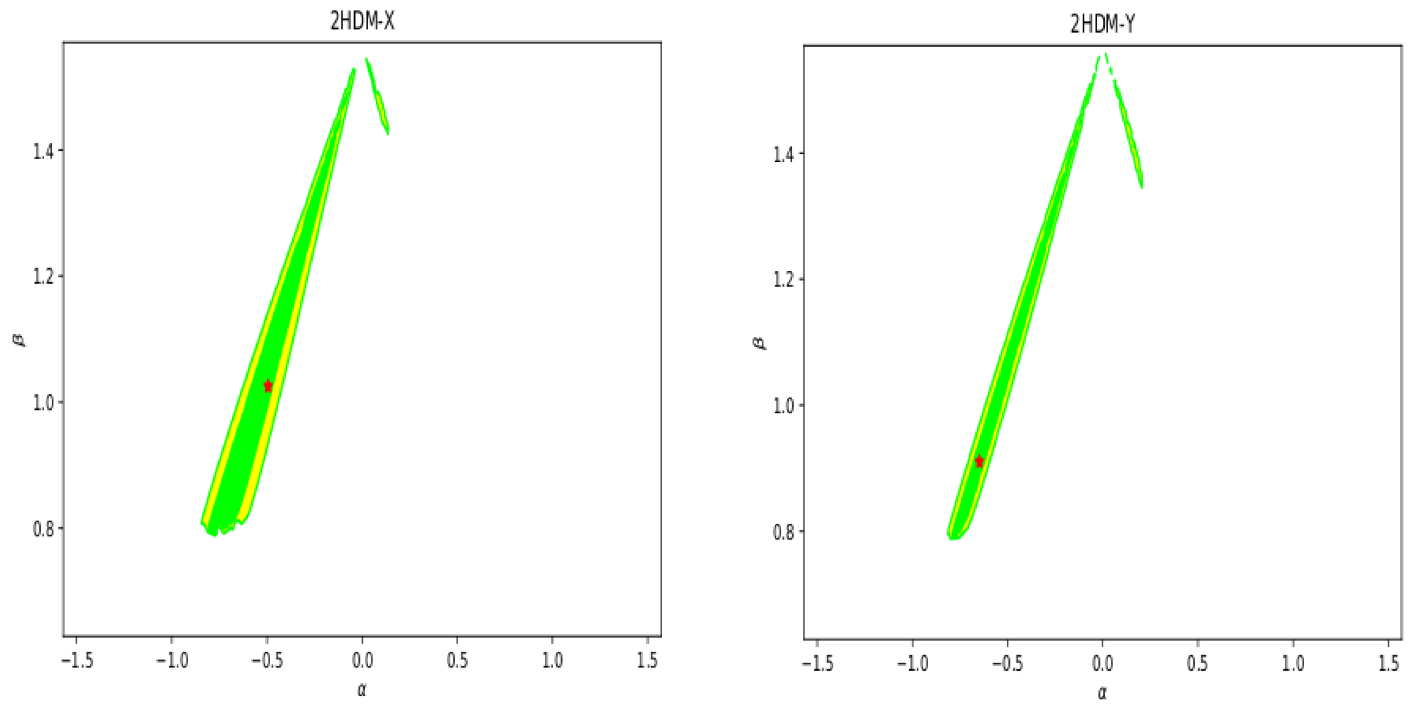

Figure 2: Direct constraints from null heavy Higgs searches at the LHC on the parameter space of the 2HDM Type-X (left) and Type-Y (right) mapped on the (α, β) plane. The colors indicate compatibility with the observed Higgs signal at 1σ (green), 2σ (yellow) around the best fit points (red stars) [10].

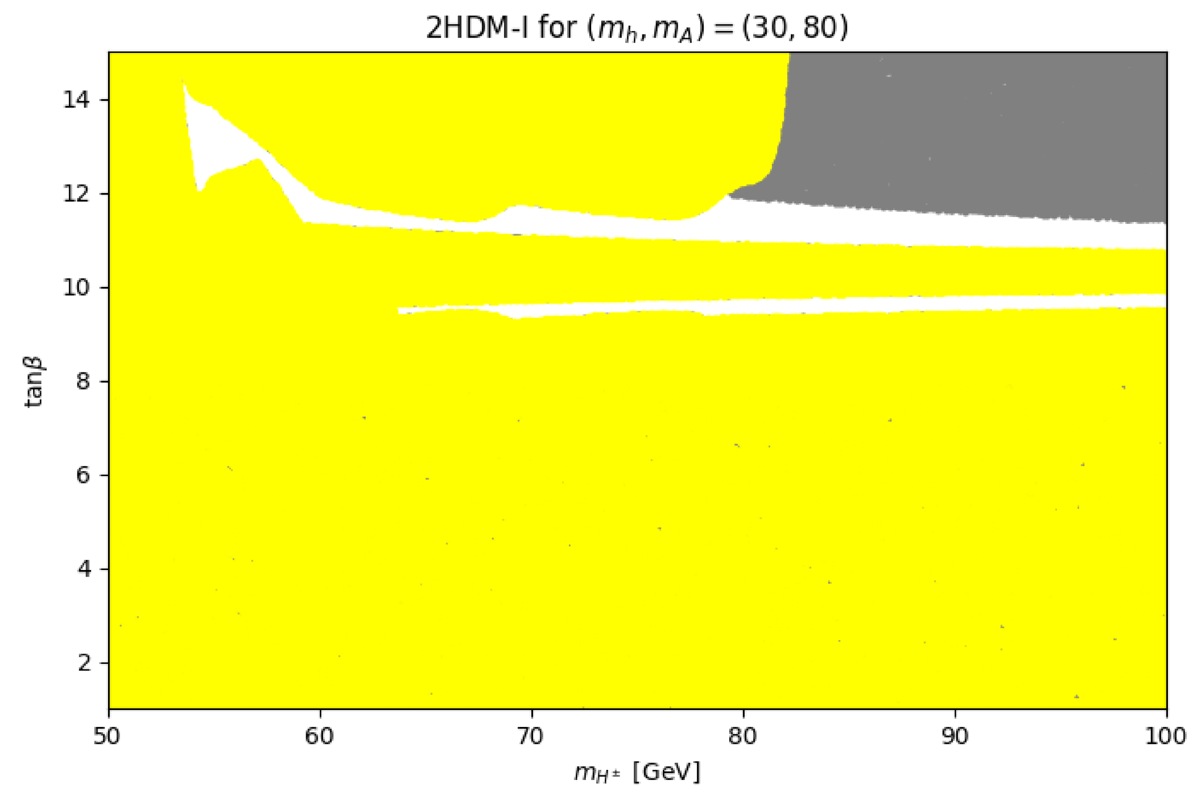

Figure 3: Exclusion regions in the 2HDM Type-I parameter space from LEP for $(m_h, m_A) = (30, 80)$ GeV.

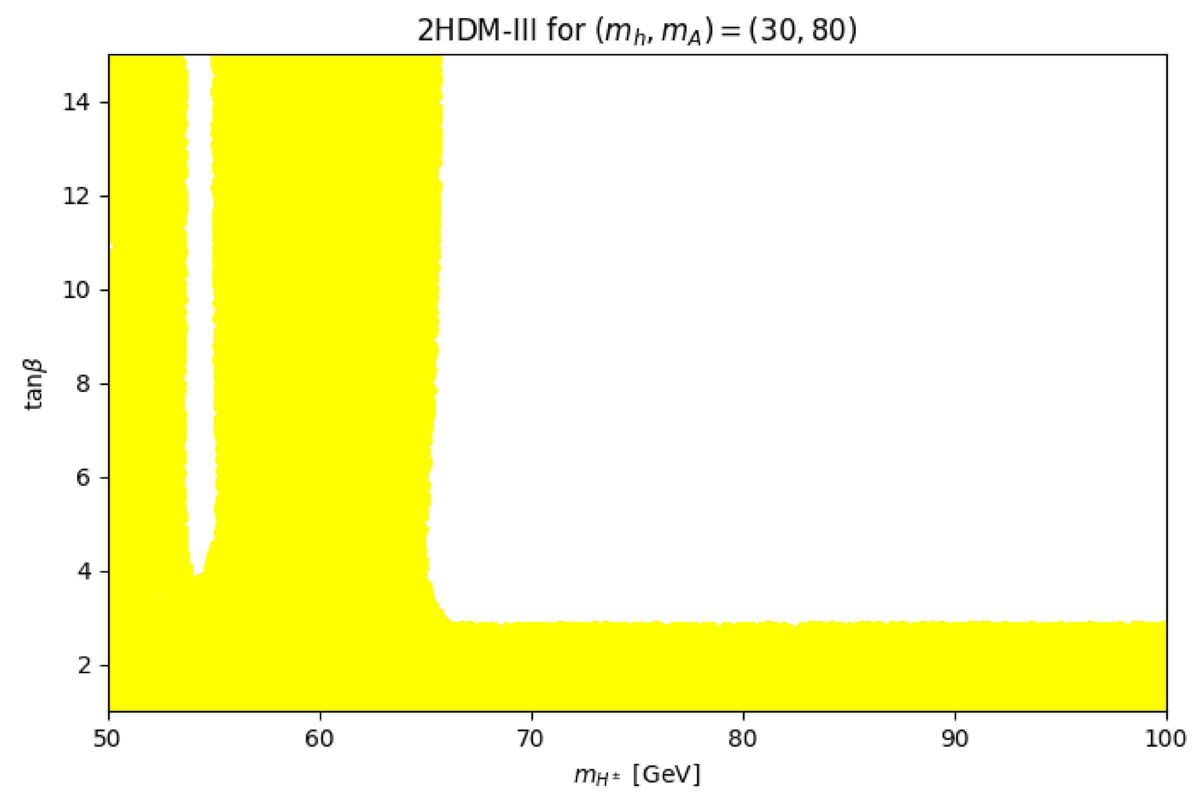

Figure 4: Exclusion regions in the 2HDM Type-X parameter space from LEP (yellow) for $(m_h, m_A) = (30, 80)$ GeV.

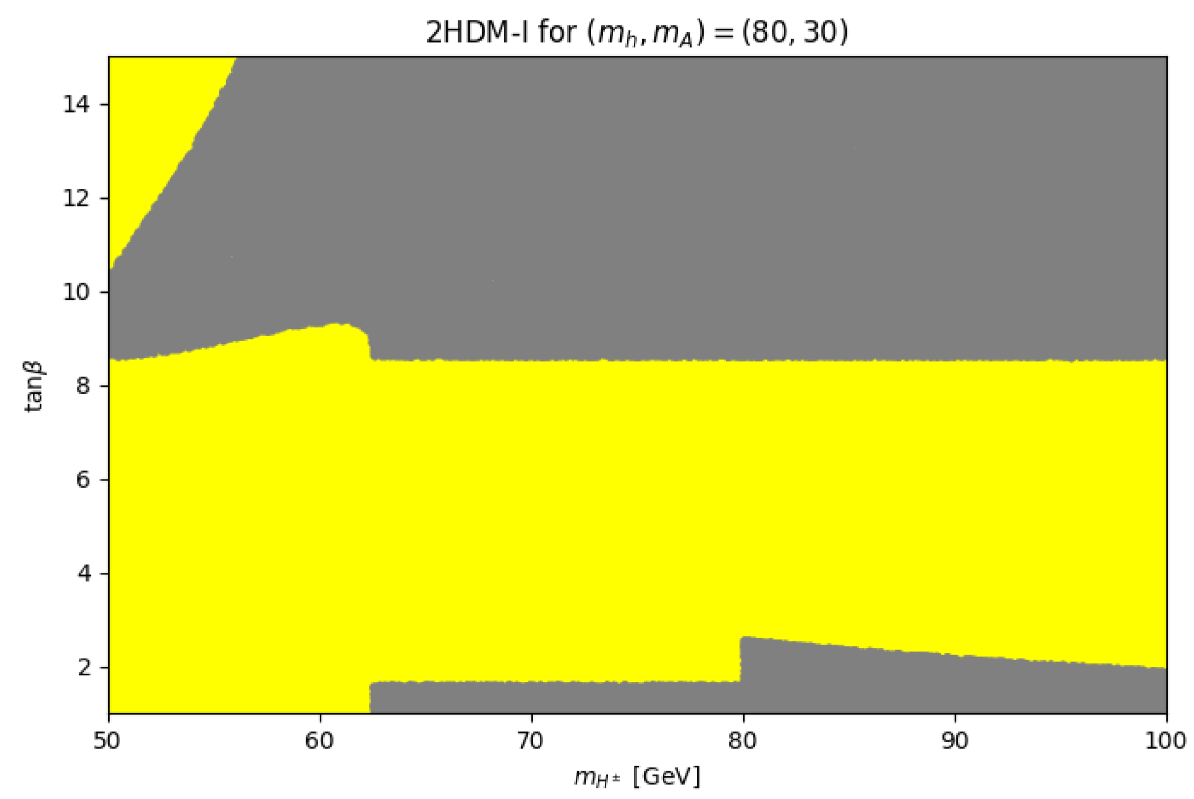

Figure 5: LEP (yellow) and LHC (brown) Exclusion regions in the 2HDM Type-I parameter space from for $(m_h, m_A) = (80, 30)$ GeV.

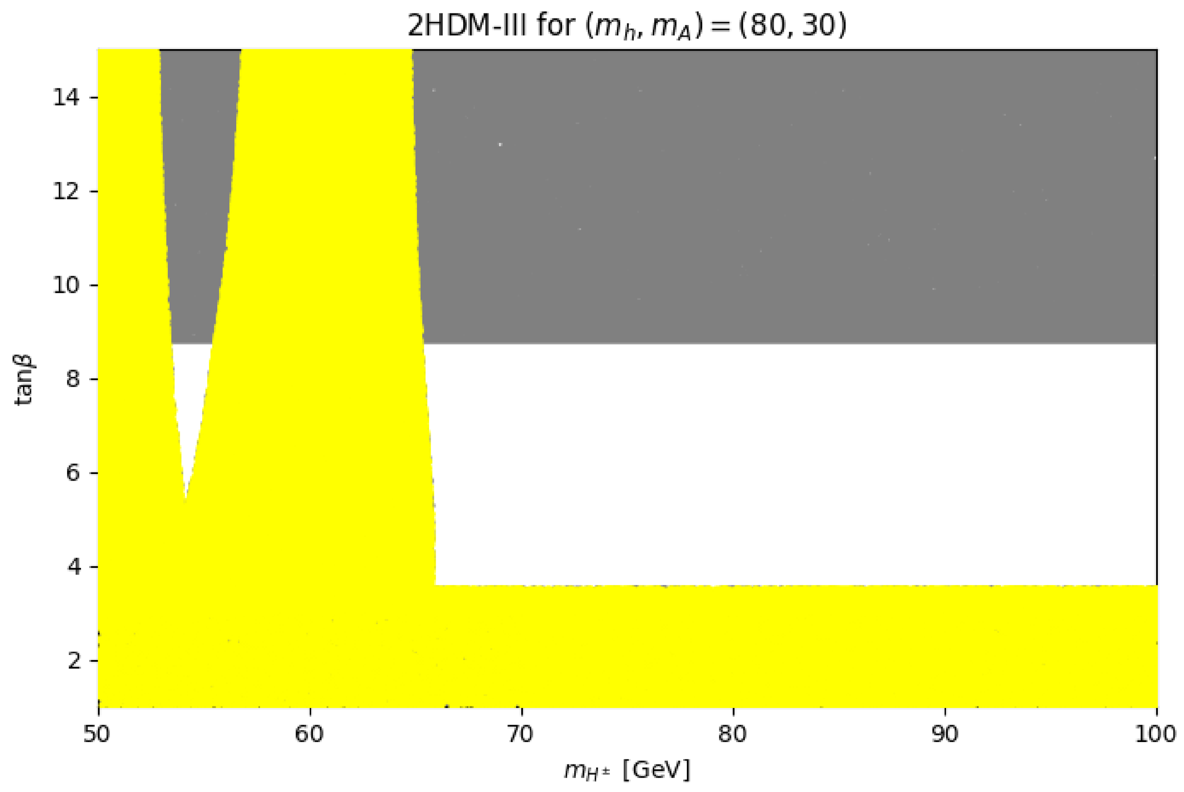

Figure 6: LEP (yellow) and LHC (brown) Exclusion regions in the 2HDM Type-X parameter space from for $(m_h, m_A) = (80, 30)$ GeV.

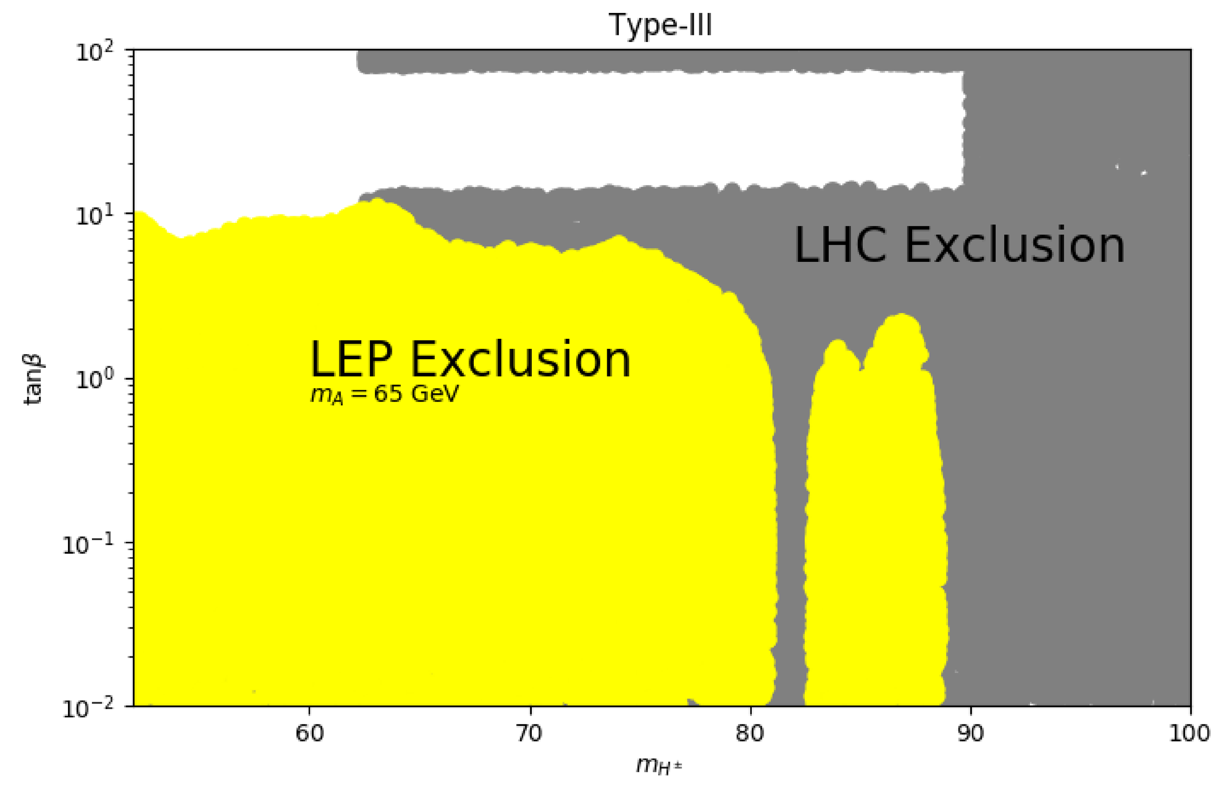

Figure 7: LEP and LHC exclusion region in the 2HDM Type-X parameter space with $m_A = 65$ GeV.

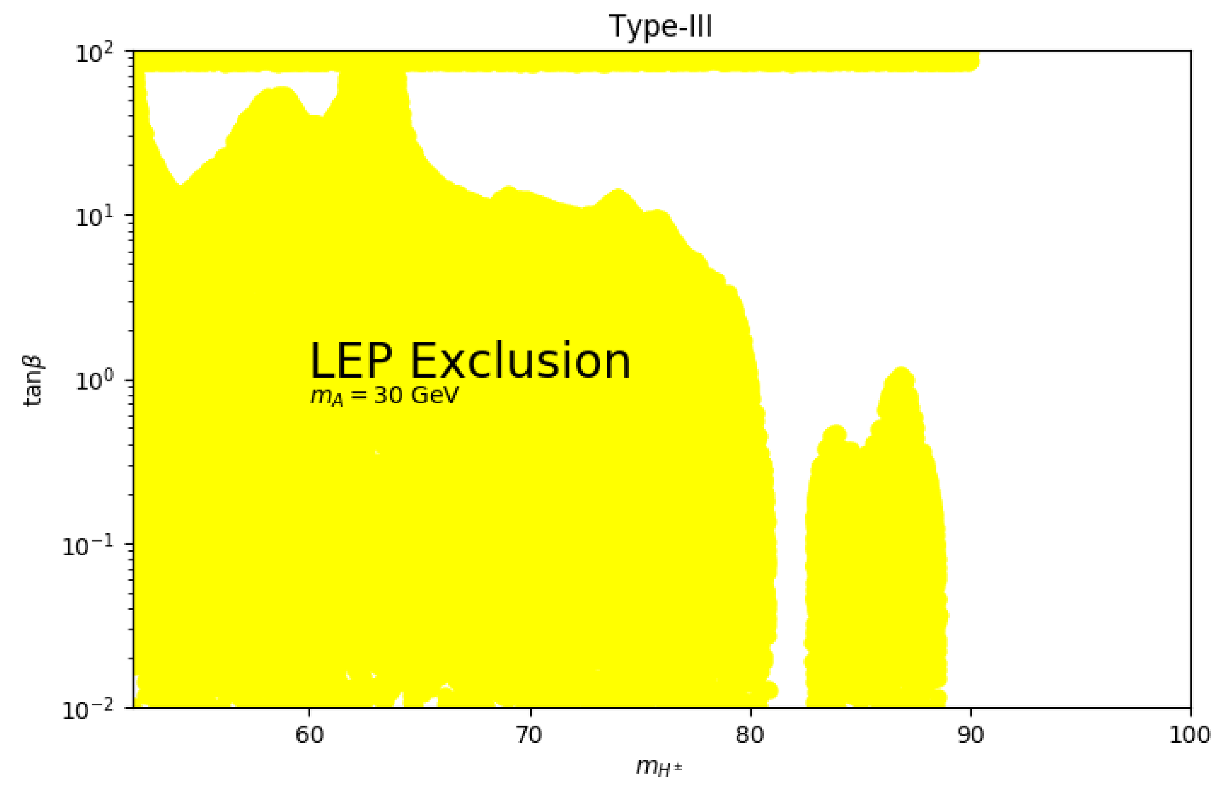

Figure 8: LEP and LHC exclusion region in the 2HDM Type-X parameter space with $m_A = 30$ GeV.

Conclusions

We have discussed the 2HDM potential with softly broken discrete Z_2 symmetry, which gives the Higgs masses spectre and also showed that the symmetry Z_2 split the Yukawa sector on four type I, II, X and Y guarantees the absence of Flavor Changing Neutral Currents $(FCNCs)$. Then we talked about the three codes (`2HDMC, HiggsBounds` and `HiggsSignals`) and how to connect them. Based on such constrained scans, we first illustrate in Fig.[1, 2] , on the (α, β) plane, the best fit points for the four 2HDM Types. Herein, are also shown the compatibility regions with the observed Higgs signal at the 1σ (green) and 2σ level (yellow) around the best fit points (red stars). The graphs (3,4) show the excluded regions from LEP of 2HDM type-(I,X) respectively for $(m_h, m_A) = (30, 80)$, for the graphs (5,6) gives the excluded regions from LHC and LEP of 2HDM type-(I,X) with $(m_h, m_A) = (80, 30)$, finally we show in the graphs (7,8) the exculded regions from LHC and LEP of 2HDM type-X with for ($m_A = 65$,$m_A = 30$) respectively.

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