Profile of Two-Higgs-Doublet-Model Parameter Space

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We review recent work on constraining the parameter space of the Two-Higgs-Doublet Model by theoretical and experimental results. Some characteristics of the model, in particular the distribution of masses in the surviving parameter space, are discussed.

1 Introduction

We report on recent work on constraining the multi-dimensional parameter space of the Two-Higgs-Doublet Model by theoretical and experimental results \([1, 2]\). As compared with the Standard Model (SM), the Two-Higgs-Doublet Model (2HDM) allows for an additional mechanism for CP violation \([3]\). This is one of the main reasons for continued strong interest in the model \([4]\).

Several experimental constraints restrict its parameter space. The \(B \to X_s \gamma\) rate excludes low values of the charged-Higgs mass, \(M_{H^\pm}\) \([5]\), whereas \(B-\bar{B}\) oscillations and the branching ratio \(R_b\) for \(Z \to b\bar{b}\) exclude low values of \(\tan\beta\). The precise measurements at LEP of the \(\rho\) parameter constrain the mass splitting in the Higgs sector, and force the masses to be not far from the \(Z\) mass scale \([6]\).

From the theoretical point of view, there are also consistency conditions. The potential has to be positive for large values of the fields \([7, 8]\). Furthermore, we require the tree-level Higgs–Higgs scattering amplitudes to be unitary \([9]\). Together, these constraints dramatically reduce the allowed parameter space of the model. In particular, the unitarity constrain excludes large values of \(\tan\beta\), unless \(\mu\) is reasonably large. This limit is basically the decoupling limit \([10]\).

Our recent study \([2]\), restricted to the so-called “Type II” version, where up-type and down-type quarks couple to different Higgs doublets, uses rather complete and up-to-date experimental results, as well as accurate theoretical predictions for the above quantities. We consider a model with the \(Z_2\) symmetry respected by the quartic couplings, i.e., no \(\lambda_6\) and \(\lambda_7\) couplings. Otherwise, we allow for full generality. In particular, we allow for \(CP\) violation, taking \(\lambda_5\) complex. (For a definition of the potential, see \([2]\).) The neutral Higgs boson sector will thus contain three bosons, described by a \(3 \times 3\) mixing matrix \(R\). These three neutral Higgs bosons will in general all have \(CP\)-violating Yukawa couplings. A related study, focused more on large values of \(\tan\beta\), was also presented at this Workshop \([11]\).

2 Results

We parametrize the model in terms of the masses of the two lightest neutral Higgs bosons, together with the charged Higgs boson mass, \(\tan\beta\), the soft parameter \(\mu^2\), and the rotation matrix \(R\) of the neutral sector. The third (heaviest) neutral mass is then calculable, as well as the quartic couplings, \(\lambda_i\) (see \([12, 13]\)).
We establish allowed regions in the $\tan\beta - M_{H^\pm}$ plane by the following procedure: For each point in this plane, we scan over the parameters $\alpha = \{\alpha_1, \alpha_2, \alpha_3\}$, defining the mixing matrix $R$ in the neutral-Higgs sector, imposing the absolute theory constraints of positivity and unitarity. At each point, we evaluate a $\chi^2$ penalty corresponding to the experimental constraints, adopting the “best” point (lowest $\chi^2$) in $\alpha$.

For two values of $\mu$ (200 and 500 GeV), we show in Fig. 1 the allowed regions in the $\tan\beta - M_{H^\pm}$ plane, taking into account the theoretical constraints mentioned above, the LEP2 non-discovery, the very precise $\Delta \rho$ measurements at LEP, as well as the $B$-physics constraints ($B \rightarrow X_s \gamma$, mainly), and $R_b$. The masses of the two lightest neutral Higgs bosons are here kept fixed, at $M_1 = 100$ GeV and $M_2 = 300$ GeV or 500 GeV.

The over-all surviving regions of parameter space depend significantly on the “soft” parameter $\mu^2$. At low or negative values, the unitarity constraint will cut off the allowed region already at moderate values of $\tan\beta$. We have therefore shown results for a couple of positive values of $\mu^2$, the higher one approaching the so-called decoupling limit.

3 Distribution of Higgs masses

It turns out that, if $\mu$ is comparable with $M_2$, or smaller, the distribution of $M_3$-values will be very narrow, especially at large values of $\tan\beta$. This is illustrated in Fig. 2 for $M_1 = 100$ GeV, and two sets of $(M_2, \mu)$ values: (300, 200) GeV and (500, 500) GeV. Also, we note that for $M_2 = 500$ GeV and $\mu = 500$ GeV (lower panels), low values of $M_{H^\pm}$ are excluded. This is basically because of the $\Delta \rho$ constraint.
Figure 2: Distribution of $M_3$-values for fixed $M_1 = 100$ GeV. Top: $M_2 = 300$ GeV and $\mu = 200$ GeV; bottom: $M_2 = 500$ GeV and $\mu = 500$ GeV. Three slices of $\tan\beta$-values are shown.

On the other hand, if $\mu$ is larger than $M_2$, the distribution can be considerably wider, as is seen in Fig. 3.

4 Summary

We have shown that the constraints of positivity and tree-level unitarity of Higgs–Higgs scattering, $B$-physics results, together with the precise LEP measurements, in particular of the $\rho$-parameter at LEP, exclude large regions of the 2HDM (II) parameter space. High values of $\tan\beta$ are excluded unless $\mu$ is large, allowing $M_2$ and $M_3$ both to be heavy. Furthermore, $M_2$ and $M_3$ should be reasonably close to each other. Improved precision of the $\bar{B} \rightarrow X_s\gamma$ measurement could significantly reduce the remaining part of the parameter space, but it appears unlikely that the model could be excluded other than by a negative search at the LHC.

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Figure 3: Distribution of $M_3$-values for $M_1 = 100$ GeV, $M_2 = 300$ GeV and $\mu = 500$ GeV. Three slices of $\tan\beta$-values are shown, increasing to the right.

Acknowledgments

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