Testing 2HDM at Muon Colliders

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Abstract. One very light neutral Higgs scalar with mass, say, below 40-50 GeV is still allowed in the non-supersymmetric 2HDM (Model II), while the remaining particles of the Higgs sector in this model have to be heavier. The possibility of testing such a scenario at Muon Colliders is discussed.

INTRODUCTION

The Two Higgs Doublet extension of the Standard Model (SM) contains five Higgs particles: two neutral scalars $h, H$ ($M_H > M_h$), one pseudoscalar $A$ and two charged particles $H^\pm$, and is characterized by two parameters $\alpha$ and $\tan\beta$ (for the CP conserved approach), see [1]. Within this extension we study the non-supersymmetric version of the Model II, called here 2HDM. In this framework, unlike in the MSSM, all the masses and $\alpha$ and $\tan\beta$ are independent parameters, which should be constrained one by one.

The present mass limit on the Higgs scalar in the SM is 77 GeV [2]. The non-minimal MSSM neutral Higgs bosons $h$ and $A$, for the considered (as a) typical supersymmetric particle spectra, individually should be heavier than $\sim 60$ GeV (for $\tan\beta > 1$) [3]. In contrast to the above limits the low mass range of the neutral Higgs sector is still allowed in the non-supersymmetric case, i.e. in 2HDM. In particular, one very light neutral Higgs particle $h$ or $A$ may exist, even as light as 10 to 20 GeV yet with the $\tan\beta$ quite large, $\tan\beta \sim 25$ to 45 [4]. Such an object should in principle lead to visible effects. In fact, however, such a scenario is not yet excluded, since some of the effects are surprisingly weak.

One should keep in mind that in 2HDM the mass limits for the lightest neutral Higgs bosons are of the form: $M_h + M_A \gtrsim 90$-110 GeV, therefore there is still a

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2) Note that the Higgs sector of the MSSM also belongs to the Model II.
3) It may be even lighter for the appropriate limit on the allowed range of $\tan\beta$ [5,6,4].
possibility that both of these particles are relatively light, with mass well below $M_Z$. Also it is worth noticing here that a very large mass gap between the neutral Higgs bosons may naturally occur in 2HDM \(^4\).

As far as the charged Higgs boson is concerned it should be at least as heavy as 330 GeV \([7,8]\), leading in most cases to negligible contributions to the observables.

The detailed study on the Higgs boson search at Muon Colliders both for the SM and MSSM, can be found in proceedings of the Muon Colliders workshops and of this workshop, devoted to the physics at the First Muon Collider \([9]\). The aim of my talk is to present unique features of the 2HDM with a possibly one (very) light neutral Higgs boson.

**STATUS OF THE 2HDM WITH A LIGHT HIGGS BOSON**

We start the discussion of the 2HDM with the presentation of widths expected for the lightest neutral Higgs bosons $h$ and $A$. These widths depend crucially on the value of $\tan \beta$, as $h$ and $A$ couple to fermions by the coupling $\sim \left( \cos(\alpha)/\sin(\beta) \right)^\pm$ and $\tan \beta^\pm$ for the states with $I_3=(1/2)^\pm$. In the Fig.1 the LO results are presented for the mass range below 40 GeV, where for simplicity we assume $\alpha = \beta$. The width of the SM Higgs scalar (i.e. for $\tan \beta=1$) is small in the whole considered mass

\[^4\] In MSSM the degeneracy in $M_h$ and $M_A$ is expected for large $\tan \beta$. 

![Figure 1](image-url)
region. For a large $\tan\beta$ the width is considerably larger, reaching for $\tan\beta=20$ and Higgs boson mass 40 GeV the value of 1 GeV. It does not mean that for small $\tan\beta$ the width is always small, see Fig.1 for results for $\tan\beta=0.1$ and 0.02. Note that, for the mass range 3-10 GeV, the widths obtained for $\tan\beta=20$ and 0.1 coincide. Similar effect can be found for the mass above 10 GeV, where the predictions for $\tan\beta=20$ and 0.02 are close to each other.

Similarly to the widths also the preferred decay modes for the studied by us light neutral Higgs bosons strongly depend on the parameters of the model, mainly on $\tan\beta$. Branching ratios of $h$ and of $A$ can be found in Figs. 2a and 2b, where decays of the scalar and pseudoscalar are presented for two choices of $\tan\beta$, $\tan\beta = 0.1$ and $\tan\beta = 20$, respectively (also here for the simplicity we assume that $\alpha = \beta$).

FIGURE 2. The branching ratios for the scalar $h$ with $\alpha = \beta$ (solid and short dashed line) and for the pseudoscalar $A$ (dashed and dotted line) for a) $\tan\beta = 0.1$, b) $\tan\beta = 20$.

The basic LEP limits on the parameters of the considered 2HDM model may be listed as follows:

- the 95% C.L. exclusion derived from the Bjorken process, $e^+e^-\rightarrow Zh$, on $\sin^2(\alpha - \beta)$ for $M_h$ smaller than 70 GeV [10], indicates the small value of $\sin^2(\alpha - \beta)$, e.g. below 0.1 for $M_h \leq 50$GeV.

- one neutral Higgs boson can be very light, as the excluded region from the combined results on $\sin^2(\alpha - \beta)$ and $\cos^2(\alpha - \beta)$ (from the Bjorken process and the Higgs boson pair production $e^+e^-\rightarrow hA$, respectively) has a form $M_h + M_A < 90-110$ GeV [11].

- the 95% C.L limit for $\tan\beta$ for the $M_A$ smallar then 40 GeV [6], obtained from the Yukawa process $e^+e^-\rightarrow f\bar{f}h/A$, allows for $\tan\beta$ up to 20-25 for $M_A \sim 5-10$ GeV and up to 100 for $M_A \sim 40$ GeV.

- measurements of the process $e^+e^-\rightarrow Zh/A\gamma$ for $\tau\tau$, light quarks, $b$-quarks decay channels performed recently at LEP collider by all experimental groups [12].
lead to relatively weak limits on $\tan \beta$ in 2HDM: $\tan \beta \lesssim 0.12$ for $M_A \sim 10$ GeV, as discussed in Ref. [13].

In addition, as it was mentioned above, $M_{H_\pm}$ should be larger than 330-350 GeV as follows from the $b \to s\gamma$ data [7] and the newest NLO calculation [8]. Note that the above limits from LEP, especially from the measurement of the Yukawa process and the $Z \to h/A\gamma$ decay, may be much more stringent if the luminosity will be higher by factor 10 or so.

The present limits on $\tan \beta$ in 2HDM from LEP and TEVATRON [14], $g-2$ measurement for the muon, together with the potential of the improved measurement of $g-2$ for the muon in the E821 experiment at BNL, and of the HERA collider as well as the NL collider [4] can be found in Fig.3.

**SEARCH FOR A LIGHT NEUTRAL HIGGS BOSON AT MUON COLLIDERS**

The present constraints on Higgs boson masses (and other parameters) of the general 2HDM may be used to study the potential of the Muon Colliders for searching for light neutral Higgs bosons, if the tight constraints will not appear earlier.

We will concentrate below on the potential of a direct search of neutral Higgs bosons at the First Muon Collider (FMC). The energy of a collision at FMC is planned to be around the mass of the $Z$ resonance, and in the next stage around 300-500 GeV, with the expected luminosity 1-10 fb$^{-1}$/yr. The end-front search will not be considered here although it may be very useful in the search of a light Higgs particle in 2HDM.
From the point of view of the potential of First Muon Collider one has to distinguish two different Higgs mass ranges allowed in 2HDM:

- **the mass of the lightest Higgs boson is below** $M_Z$
  
  This mass range is unique for the considered by us 2HDM, being excluded in the SM and in the standard scenarios discussed in the MSSM (SUSY) approaches. In such case the study of the Higgs sector similar as at LEP I collider can be performed, so obviously there is a need of a higher luminosity than the one obtained at LEP I.

  Let me first concentrate on the mass of the lightest boson below 40-50 GeV. In this case the analogous production mechanisms as discussed above for LEP I, with a dominating $Z$-boson intermediate state, are possible - in particular the Bjorken process, the Higgs pair production and the Yukawa process.

  In the case of the production of the $h/A +$ photon final state an important difference is expected in comparison to the LEP I measurements. In $\mu^+\mu^-$ collision not only the loop but also the tree diagram contributes, being negligible for $e^+e^-$ collider. Therefore in addition to the $Z$ pole processes the resonance production of the light neutral Higgs $h/A$ is also possible due the return to the pole (tree) process: $\mu^+\mu^- \rightarrow h/A\gamma$ [15,16].

  Note that in principle even two light Higgs bosons $h$ and $A$ with masses around 40-50 GeV may be produced at First Muon Collider.

  If the mass of $h$ or $A$ is close to $M_Z$ the scan in the energy (the mass) planned at FMC will allow to discover the resonant object. For large $\tan \beta$ case the width of a light neutral Higgs boson is not small, also a small $\tan \beta$ (as small as 0.1) may lead to relatively large width (see Fig.1). So no extra requirement referring to the beam energy resolution is needed for such a search.

  The interesting option with two lightest neutral Higgs bosons $h$ and $A$ in the direct reach of the FMC, still being very different in masses (a large mass gap), is also open in the framework of 2HDM. In this case the corresponding processes as listed in the previous section for the LEP I collider are possible, with the $Z$ to be interchanged by the heavier of two bosons. A very attractive possibility of having as a resonance the heavier Higgs boson with the lighter one in the final state may occur, e.g. for $M_A \geq M_h$ the process $\mu^+\mu^- \rightarrow A\rightarrow fh$.

- **the mass of the lightest Higgs boson is above** $M_Z$ but below the energy of the collider
  
  This case may have a similar signature to the MSSM Higgs bosons production. The basic difference to MSSM, beside the fact that $\alpha$ and $\beta$ parameters are not correlated with the masses of Higgs bosons, is the possibility to have a large mass gap between two lightest neutral Higgs particles $h$ and $A$. Both particles may in principle be found as resonances, the difference to the SM Higgs scalar case is that their widths may be large.
To summarize, the general 2HDM may lead to unique signature both in the resonant production of neutral Higgs bosons, and in the higgsstrahlung processes at low energy First Muon Collider. Useful option with $\sqrt{s} \sim M_Z$ requires the luminosity at least by the factor 10 higher than the one achieved at LEP.

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