STATUS OF 2HDM WITH A LIGHT HIGGS PARTICLE

M. KRAWCZYK

Institute of Theoretical Physics, Warsaw University, Hoża 69, Warsaw, 00-681, POLAND

Present data do not rule out the light neutral Higgs particle \( h \) or \( A \) with mass below 40–50 GeV in the framework of the general 2HDM ("Model II"). The status of this model in a light of existing LEP I data and a potential of the new muon experiment \((g-2)\), the measurement of photon-gluon and gluon-gluon fusion at HERA as well as photon-photon fusion at low energy \( \gamma\gamma \) NLC is discussed.

1 Introduction

The mechanism of spontaneous symmetry breaking proposed as the source of mass for the gauge and fermion fields in the Standard Model (SM) leads to a neutral scalar particle, the minimal Higgs boson. According to the LEP I data, based on the Bjorken process \( e^+e^- \rightarrow HZ^* \), it should be heavier than 66 GeV\(^1\),\(^2\), also the MSSM neutral Higgs particles have been constrained by LEP1 data to be heavier than \( \sim 45 \) GeV\(^2\),\(^3\). The general two Higgs doublet model (2HDM) may yet accommodate a very light (\( \lesssim 45 – 50 \) GeV) neutral scalar \( h \) or pseudoscalar \( A \) as long as \( M_h + M_A \gtrsim M_Z \). Note that the lower limit for the charged Higgs boson \( M_{H^\pm} = 44 \) GeV/c was obtained at LEP I from process \( Z \rightarrow H^+H^- \) (moreover in the MSSM version one expect \( M_{H^\pm} > M_W \)).

In the minimal extension of the Standard Model there are two Higgs doublets, the observed Higgs sector is enlarged to five scalars: two neutral Higgs scalars (with masses \( M_H \) and \( M_h \) for heavier and lighter particle, respectively), one neutral pseudoscalar (\( M_A \)), and a pair of charged Higgses (\( M_{H^+} \) and \( M_{H^-} \)). The neutral Higgs scalar couplings to quarks, charged leptons and gauge bosons are modified with respect to analogous couplings in SM by factors that depend on additional parameters: \( \tan \beta \), which is the ratio of the vacuum expectation values of the Higgs doublets \( v_2/v_1 \), and the mixing angle in the neutral Higgs sector \( \alpha \). Further, new couplings appear, e.g. \( Zh(H)A \) and \( ZH^+H^- \).

1.1 The status of 2HDM Model after LEP I

In this talk I will focus on the "Model II" of the two Higgs doublet extensions of SM, where one Higgs doublet with vacuum expectation value \( v_2 \) couples only to the "up" components of fermion doublets while the other one couples to the "down" components\(^4\). In particular, fermions couple to the pseudoscalar \( A \) with a strength proportional to \( (\tan \beta)^\pm \) whereas the coupling of the fermions to the scalar \( h \) goes as \( \pm (\sin \alpha/\cos \beta)^\pm \), where the sign \( \pm \) corresponds to isospin \( \mp 1/2 \) components.

In the well known supersymmetric model (MSSM) belonging to this class the relations among the parameters required by the supersymmetry appear, leaving only two parameters free (at the tree level) e.g. \( M_A \) and \( \tan \beta \). In general case, which we call the general 2 Higgs Doublet Model (2HDM), masses and parameters \( \alpha \) and \( \beta \) are not constrained by the model. Therefore the same experimental data may lead to very different consequences depending on which version of two Higgs doublet extension of SM, supersymmetric or nonsupersymmetric, is considered (see below).

For neutral Higgs particles \( h \) and \( A \) there are two main and complementary sources of information:\(^5\)
tion at LEP I: the Bjorken processes $Z \to Z'h$, which constrain $g_{ZZh}^2 \sim \sin^2(\alpha - \beta)$ for $M_h$ below 50-60 GeV (Fig. 1a) and pair production $Z \to hA$, constraining the $g_{ZhA}^2 \sim \cos^2(\alpha - \beta)$ for $M_h + M_A \lesssim M_Z$. The Higgs pair production cross section depends also on the masses $M_h$, $M_A$ and $M_Z$. Combined results on $\sin^2(\alpha - \beta)$ and $\cos^2(\alpha - \beta)$ can be translated into the limits on neutral Higgs boson masses $M_h$ and $M_A$. In the MSSM, due to relations among parameters, the above data allow to draw limits for the masses of individual particles: $M_h \gtrsim 45$ GeV for any $\tan \beta$ and $M_A \gtrsim 45$ GeV for $\tan \beta \gtrsim 1$. In the general 2HDM the implications are quite different, here the large portion of the $(M_h, M_A)$ plane, where both masses are in the range between 0 and $\sim 50$ GeV, is excluded (Fig. 1b) (for comparison the corresponding plot obtained for MSSM is presented in Fig. 2). The third basic process in search of a neutral Higgs particle at LEP I is the Yukawa process, $i.e.$ the bremsstrahlung production of the neutral Higgs boson $h(A)$ from the heavy fermion, $e^+e^- \to f\bar{f}h(A)$, where $f$ means here $b$ quark or $\tau$ lepton. This process plays a very important role since it constrains the production of a very light pseudoscalar even if the pair production is forbidden kinematically, $i.e.$ for $M_h + M_A > M_Z$. It allows also to look for a light scalar, being an additional, and in case of $\alpha = \beta$ the most important, source of information. New analysis of the Yukawa process by ALEPH collaboration, contributed to this conference, led to the exclusion plot (95%) on the $\tan \beta$ versus the pseudoscalar mass, $M_A$ (Fig. 1c). The obtained limits are rather weak allowing for the existence of a light $A$ with large $\tan \beta$ (for mass below 10 GeV $\tan \beta$ till 20-30, whereas for $M_A = 40$ GeV $\tan \beta$ up to 100 is allowed!) For scalar $h$ similar exclusion limits should hold also (with the replacement in coupling $\tan \beta \to \sin \alpha / \cos \beta$).

As far as other experimental data, especially from low energy measurements, they cover only part of the parameter space of 2HDM, moreover some of them like the Wilczek process have large theoretical uncertainties due both to the QCD and relativistic corrections.

In light of the above experimental results there is still the possibility of the existence of one light neutral Higgs particle with mass below $\sim 40 - 50$ GeV in 2HDM. In the following we will study this model assuming, according to LEP I data, the following mass relation between the lightest neutral Higgs boson $h$ and $\tan \beta$:

$$M_h \lesssim 45 \text{ GeV for any } \tan \beta$$

$$M_h \lesssim 50 \text{ GeV for } \tan \beta \lesssim 1$$

for the off shell production

$c$ Larger differences one should expect however in region of mass below $10$ GeV where more stringent limits should be obtained.

$M_A \gtrsim 45 \text{ GeV for } \tan \beta \gtrsim 1$
Higgs particles: \( M_h + M_A \geq M_Z \). We specify the model further by choosing particular values for the parameters \( \alpha \) and \( \beta \) within the present limits from LEP I, we simply take \( \alpha = \beta \).

As we described above the existing limits for a light neutral Higgs scalar/pseudoscalar boson in 2HDM are rather weak. Therefore it is extremely important to check if more stringent limits can be obtained from other measurements.

1.2 Constraints on the parameters of 2HDM from present \((g - 2)\) data for muon.

The present experimental data limits on \((g - 2)\) for muon, averaged over the sign of the muon electric charge, is given by \( -11.79 \leq \delta a_{\mu} \leq 21.25 \) at the 95\% C.L. We specify the uncertainty in the last digit. The theoretical SM prediction: the difference between the experimental data and theoretical SM prediction: \( a_{\mu}^{\exp} - a_{\mu}^{SM} \equiv \delta a_{\mu} \).

\[
a_{\mu}^{\exp} \equiv \frac{(g - 2)_{\mu}}{2} = 1 165 923 \, (8.4) \cdot 10^{-9}.
\]

The quantity within parenthesis, \( \sigma_{\exp} \), refers to the uncertainty in the last digit. The theoretical (SM) result

\[
a_{\mu}^{SM} = a_{\mu}^{QED} + a_{\mu}^{had} + a_{\mu}^{EW},
\]

has error, mainly due to the hadronic contribution, which is smaller than \( \sigma_{\exp} \). Still there is a large discrepancy between theoretical results. We will consider two cases, so called case A, based on Refs. [13,3,4], with relatively small error in the hadronic part and case B (Refs. [14,5,6,7]), corresponds to the two times larger error in the hadronic part.

| case | A [in \(10^{-9}\)] | B [in \(10^{-9}\)] |
|------|-------------------|-------------------|
| QED  | 1 165 847.06 (0.02) | 1 165 847.06 (0.02) |
| had  | 69.70 (0.76)       | 68.82 (1.54)       |
| EW   | 1.51 (0.04)        | 1.51 (0.04)        |
| tot  | 1 165 918.27 (0.76) | 1 165 917.39 (1.54) |

The room for new physics is given basically by the difference between the experimental data and theoretical SM prediction: \( a_{\mu}^{\exp} - a_{\mu}^{SM} \equiv \delta a_{\mu} \).

Below the difference \( \delta a_{\mu} \) for these two cases, A and B, is presented together with the error \( \sigma \), obtained by adding the experimental and theoretical errors in quadrature; also the 95\% C.L. limits are shown:

\[
\begin{array}{ccc}
\delta a_{\mu}(\sigma) & A & B \\
\hline
\text{lim} & -11.79 \leq \delta a_{\mu} \leq 21.25 & -11.13 \leq \delta a_{\mu} \leq 22.35 \\
\text{lim}_\pm & -13.46 \leq \delta a_{\mu} \leq 19.94 & -13.71 \leq \delta a_{\mu} \leq 20.84 \\
\end{array}
\]

One can see that at 1 \( \sigma \) level the difference \( \delta a_{\mu} \) can be of positive and negative sign. For that scenarios in which both positive and negative \( \delta a_{\mu} \) may appear, the 95\% C.L. bound can be calculated in a straightforward way (denoted above by \( \text{lim}_\pm \)). For the model where the contribution of only one sign is physically accessible (i.e. positive or negative \( \delta a_{\mu} \)), the other sign being unphysical, the 95\% C.L. limits should be calculated separately for positive and for negative contributions (\( \text{lim}_\pm \)).

We will use above bounds for the constraining the 2HDM: so we take \( \delta a_{\mu} = a_{\mu}^{(2HDM)} \) with contribution from scalar \( h(a_h^0) \), pseudoscalar \( A(a_A^0) \) and charged Higgs boson \( H^\pm (a_{\mu}^{HDM}) \) ("full" 2HDM contribution, relevant formulae can be found in the Appendix in Refs. [13,3]). Each of these terms disappears in the limit of large mass, at small mass the contribution reaches its maximum (or minimum if negative) value.

In the following we assume, according to the LEP I, mass limits for charged and neutral Higgs particles in following way: for scenario a) with a light pseudoscalar we take \( a_{\mu}^{(2HDM)}(M_A) = a_A^0(M_A) + a_h^0(M_h^0 = M_Z - M_A) + a_{\mu}^{(2HDM)}(M_h^0) \), while for a light scalar scenario b): \( a_{\mu}^{(2HDM)}(M_h) = a_h^0(M_h) + a_{\mu}^0(M_A^0 = M_Z - M_h) + a_{\mu}^{HDM}(M_h^0) \). Here mass limit of \( H^\pm \) was used \( M_{h^\pm} = 44 \text{ GeV} \). Since the contribution \( a_{\mu}^{(2HDM)}(M_A) \) is for the scenario a) positive, whereas the pseudoscalar boson \( a_{\mu}^0(M_A) \) gives a negative contribution, also the charged boson contribution is negative.

In the following we assume, according to the LEP I, mass limits for charged and neutral Higgs particles in following way: for scenario a) with a light pseudoscalar we take \( a_{\mu}^{(2HDM)}(M_A) = a_A^0(M_A) + a_h^0(M_h^0 = M_Z - M_A) + a_{\mu}^{(2HDM)}(M_h^0) \), while for a light scalar scenario b): \( a_{\mu}^{(2HDM)}(M_h) = a_h^0(M_h) + a_{\mu}^0(M_A^0 = M_Z - M_h) + a_{\mu}^{HDM}(M_h^0) \). Here mass limit of \( H^\pm \) was used \( M_{h^\pm} = 44 \text{ GeV} \). Since the contribution \( a_{\mu}^{(2HDM)}(M_A) \) is for the scenario a) positive, whereas for the scenario a) negative we will use bounds provided by \( \text{lim}_\pm \) introduced above. In the contrast to the “full” 2HDM contribution the simple approach is based on only pseudoscalar or scalar contribution in case a) or case b), respectively. It reproduces the full 2HDM prediction below mass say 30 GeV (see Refs. [13,3]).

The case A gives more stringent limit for both positive and negative \( \delta a_{\mu} \) (see table), therefore this case was used in constraining parameters of the 2HDM. The obtained 95\% C.L. exclusion plots for \( \tan \beta \) for light \( h \) or \( A \) is presented in Fig. 3. If one compare the upper curve resulting from the
present $g-2$ data with the ALEPH results one can find that in the pseudoscalar case there appear additional restriction for mass below 2 GeV. Still $\tan \beta$ about 10-15 is allowed for mass around 1 GeV. Case B will lead to similar limits with the rescaling curves by factor 1.022(1.009) for a light scalar (a light pseudoscalar) case.

**Exclusion plot, 95% C.L: comparison**

![Figure 3: The 95% exclusion plots for light scalar(solid lines) or light pseudoscalar (dashed lines) in 2HDM (simple approach). The limits derivable from present $(g-2)_\mu$ measurement (upper lines) and from existing LEP I results (Yukawa process) for the pseudoscalar (dotted line) are shown. The lower lines correspond to the future $(g-2)$ data (see text). Parameter space above the curves can be ruled out.](image)

The resulting exclusion plots for two scenarios in 2HDM obtained in the same manner as in Sec. 1.2 (simple approach) can be found in Fig. 3 (lower curves). They will be discussed together with others exclusion plots in Sec. 2.3. Here we would like only to mention that the assumed by us $\delta a^\mu_{\text{new}}$ cover both positive and negative region, but if the actual $\delta a^\mu_{\text{new}}$ will turn out to be positive/negative then the light pseudoscalar(scalar) is no more allowed.

## 2 Potential of future experiments

The role of future measurements: $(g-2)$ for muon, photon/gluon-gluon fusion at HERA collider and $\gamma\gamma$ fusion at low energy NLC are discussed.

### 2.1 Future $(g-2)$ data for muon

Since presently the dominant uncertainty in $\delta a^\mu_\mu$ is due to the experimental error, the role of the forthcoming E821 experiment is crucial in testing the SM or probing a new physics. The expected new high-precision E821 Brookhaven experiment has design sensitivity of $\delta a^\mu_{\text{new}} = 4 \cdot 10^{-10}$ (later even $1-2 \cdot 10^{-10}$, see Ref.4) instead of the above $84 \cdot 10^{-10}$ (see talk at this conference presented by B. L. Roberts). It is of great importance to reach similar accuracy in the theoretical analysis.

One expects the improvement in the calculation of the hadronic contribution such that the total uncertainty will be basically due to the experimental error. Below we will assume that the accessible range for the beyond SM contribution, in particular 2HDM with a light scalar or pseudoscalar, would be smaller by factor 20 as compared with the present $\lim_{\pm}95\%$ bounds for case A (Sec.1.2). So, we consider the following option for future $(g-2)$ measurement (in $10^{-9}$):

$$\lim_{\pm}^n_{\text{new}}(95\%) : -0.69 \leq \delta a^\mu_{\text{new}} \leq 1.00.$$  

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### 2.2 Photon-gluon and gluon-gluon fusion at HERA

The gluon-gluon fusion via a quark loop, $gg \to h(A)$, can be a significant source of light non-minimal neutral Higgs bosons at HERA collider due to the hadronic interaction of quasi-real photons with protons. In addition the production of the neutral Higgs boson via $\gamma g \to bh(A)$ may also be substantial. Note that the latter process also includes the lowest order contributions due to the resolved photon, like $\gamma b \to bh(A)$, $bb \to h(A)$, $bg \to h(A)b$ etc. We study the potential of both $gg$ and $\gamma g$ fusions at HERA collider.

It was found that for mass below $\sim 30$ GeV the $gg$ fusion via a quark loop clearly dominates the cross section. In order to detect the Higgs particle it is useful to study the rapidity distribution $d\sigma/dy$ of the Higgs bosons in the $\gamma p$ centre of mass system. The (almost) symmetric shape of the rapidity distribution found for the signal is extremely useful to reduce the background and to separate the $gg \to h(A)$ contribution.

The main background for the Higgs mass range between $\tau\tau$ and $bb$ thresholds is due to $\gamma\gamma \to \tau^+\tau^-$. In the region of negative rapidity the cross section $d\sigma/dy$ is very large, e.g. for the $\gamma p$ energy equal to 170 GeV ~ 800 pb at the edge of phase space ($y \sim -4$), then it falls down rapidly approaching $y = 0$. At the same time signal reaches...
at most 10 pb (for $M_h=5$ GeV). The region of positive rapidity is not allowed kinematically for this process since here one photon interacts directly with $x_\gamma = 1$, and therefore $y_{+\tau^-} = -\frac{1}{2} \log \frac{1}{x_\gamma} \leq 0$. Moreover, there is a relation between rapidity and invariant mass: $M_{+\tau^-}^2 = e^{y_{+\tau^-} - S_{\gamma p}}$. Significantly different topology found for $\gamma\gamma \rightarrow \tau^+\tau^-$ events than for the signal should allow to get rid of this background. The other sources of background are $q\bar{q} \rightarrow \tau^+\tau^-$ processes. These processes contribute to positive and negative rapidity $y_{+\tau^-}$, with a flat and relatively low cross sections in the central region (see for more details Ref. [10]).

To show the potential of HERA collider the exclusion plot based on the $gg$ fusion via a quark loop at HERA may lead to even more stringent limits for the mass range 5–15 (5–25) GeV, provided the luminosity will reach 25 (500) pb$^{-1}$ and the efficiency for $\tau^+\tau^-$ final state will be high enough.1 The other production mechanisms like the $g\gamma$ fusion and processes with the resolved photon are expected to improve further these limits.

In the very low mass range the additional limits can be obtained from the low energy $\gamma\gamma$ NL collider. The results based on $\gamma\gamma \rightarrow h(A) \rightarrow \mu^+\mu^-$ for the luminosity $\mathcal{L}_{ee}$ 10 fb$^{-1}$ are presented in Fig.4 (from Ref.[10]).

2.3 Exclusion plots for 2HDM

In Fig.4 the 95% C.L. exclusion curves for the $\tan\beta$ in the general 2HDM (“Model II”) obtained by us for a light scalar (solid lines) and for a light pseudoscalar (dashed lines) are presented in mass range below 40 GeV. For comparison results from LEP I analysis (Yukawa process) for pseudoscalar is also shown (dotted line). The region of $(\tan\beta, M_{h(A)})$ above curves is excluded.

The present $(g-2)_\mu$ data improve limits obtained recently by ALEPH collaboration on $\tan\beta$ for low mass of the pseudoscalar: $M_A \lesssim 2$ GeV. Similar situation should hold for a 2HDM with a light scalar, although here the Yukawa process may be more restrictive for $M_h \lesssim 10$ GeV. The future improvement in the accuracy by factor 20 in the forthcoming $(g-2)_\mu$ experiment may lead to more stringent limits than provided by LEP I up to mass of a neutral Higgs boson $h$ or $A$ equal to 30 GeV, if the mass difference between scalar and pseudoscalar is $\sim M_A^2$ (or to higher $M_{h(A)}$ for a larger mass difference). Note however that there is some arbitrariness in the deriving the expected bounds for the $\delta a^\mu_{\text{new}}$.

The search at HERA in the gluon-gluon fusion via a quark loop at HERA may lead to even more stringent limits for the mass range 5–15 (5–25) GeV, provided the luminosity will reach 25 (500) pb$^{-1}$ and the efficiency for $\tau^+\tau^-$ final state will be high enough.1 The other production mechanisms like the $g\gamma$ fusion and processes with the resolved photon are expected to improve further these limits.

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3 Conclusion

To conclude, in the framework of 2HDM a light neutral Higgs scalar or pseudoscalar, in mass range below 40 GeV, and $\tan\beta$ even as large as 15-20 is not ruled out by the present data. The future experiments may clarify the status of the general 2HDM with the light neutral Higgs particle. The role of the forthcoming $(g-2)_\mu$ measurement seems to be crucial in clarifying which scenario of 2HDM is allowed: with a light scalar or with...

\footnote{In this analysis the 100% efficiency has been assumed. If the efficiency will be 10% the corresponding limits will be larger by factor 3.3}
a light pseudoscalar. Then farther constraints on the coupling of the allowed light Higgs particle one can obtained from the HERA collider, which is very well suitable for this. The very low energy region of mass may be studied in addition in low energy $\gamma\gamma$ NLC machines. It is not clear however if the low energy option will come into operation.

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