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PROCESS $Z \to h(A) + \gamma$ IN THE 2HDM AND THE EXPERIMENTAL CONSTRAINTS FROM LEP

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Abstract

The one-loop branching ratios for the process $Z \to h(A) + \gamma$ are calculated in the general Two Higgs Doublet Model (Model II) taking into account existing constraints on the model parameters. For Higgs boson masses below 50 GeV and $\tan\beta$ $\mathcal{O}(1-10)$ the fraction of such Z decays are at the level of 10^{-7}, but can be significantly stronger for very low or high $\tan\beta$, where the dependence of these results on other model parameters like $\sin(\beta-\alpha)$ and the mass of the charged Higgs boson is found to be of little importance. The results are compared to the LEP measurements, which are sensitive to branching ratios of $Z \to h(A) + \gamma$ of the order 10^{-5} for masses ≥ 20 GeV, but approach 10^{-6} for low masses. Relating the expectation to the experimental limits, constraints on the parameter space of the 2HDM are derived.

1 Introduction

The Two Higgs Doublet extension of the Standard Model leads to five physical Higgs particles: two neutral scalars h, H (with the mass relation $M_H > M_h$), one pseudoscalar A and two charged particles $H^{\pm}$. In case of CP conservation, their interaction with fermions and gauge bosons is characterized by only two additional parameters α and β, describing the mixing within the neutral scalar system and the ratio of the vacuum expectation values, respectively [1]. The Higgs bosons couple also to themselves and this self-coupling requires an extra parameter λ_5. A lot of attention has been devoted to Two Higgs Doublet models embedded in the Minimal Supersymmetric Model (MSSM). Here strong relations between the various masses and also with the parameters α and β exist, such that at the tree level there are only two independent parameters and stringent experimental limits on Higgs masses can be set. In this paper we discuss the CP-conserving Two Higgs Doublet Model II, denoted 2HDM, which has a Higgs sector as in MSSM, but where these relations do not exist and the masses of the Higgs particles are very weakly constrained.

In this model the couplings of the pseudoscalar A to fermions are given in terms of β. Couplings to gauge bosons AWW and AZZ are forbidden. The couplings of the scalar h to fermions (and gauge bosons) depend in addition on α. For example, the coupling hZZ boson contains factors $\sin(\beta-\alpha)$, and is thus suppressed for $\alpha \sim \beta$. Theoretically the allowed ranges of α and β are only constrained through the requirement of the perturbativity of calculations which suggests $\tan\beta$ to be between ~ 0.1 and 200-300 [2].

Important constrains on the neutral sector of the general 2HDM are due to searches for Higgs boson production in Z decays. From the absence of evidence for the Higgs-strahlung process ($Z \to Z + h$) limits on the $\sin^2(\beta-\alpha)$ as a function of M_h can be inferred. At least for up to $M_h \sim 50$ GeV they imply $\mid \sin^2(\beta-\alpha) \mid < 0.1$ and thus $\alpha \sim \beta$ [3, 4, 5, 6]. Complementary to the Higgs-strahlung, the decay $Z \to h + A$ is proportional to $\cos^2(\beta-\alpha)$. Also for the Higgs pair production process no evidence has been found. Combining the sensitivities reached for these two production mechanisms, one can derive a limit on the sum of the two Higgs masses: $M_h + M_A$ has to be larger than about 50 GeV [7, 8, 4, 5]. For the Model II, if embedded in supersymmetry, the same measurements exclude both a pseudoscalar or scalar neutral Higgs boson of less than $\sim$ 77 GeV for $\tan\beta > 0.8$ [7]. However, in the 2HDM, because of the absence of relations between masses and between other parameters, no limits on the masses of individual Higgs bosons can be set: even a very light neutral Higgs particle is not excluded.

Another potential production mechanism for a Higgs particle at LEP is a Yukawa process where Higgs particles are radiated from heavy fermions, namely $Z \to b\bar{b}h(A)$, $Z \to \tau^+\tau^- h(A)$. As yet measurements [9] have only been interpreted in terms of limits on $\tan\beta$ and M_A. For $\tan\beta > 25$, only Higgs boson masses of less than ~ 2 GeV are excluded by these data and much larger values for $\tan\beta$ are allowed for higher Higgs boson masses. For small masses an interpretation of the data in terms of M_h production would yield stronger limits on $\tan\beta$ (see [10]). Some further constraints on neutral Higgs bosons are obtained from non-LEP experiments. The present data of $g-2$ for muons limit the allowed $\tan\beta$ for the pseudoscalar or scalar mass below 2 GeV to values of 4 at M_h=0.1 GeV [11], for higher masses the limits on $\tan\beta$ are weaker than those from the Yukawa process [9]. The measurement of the Wilczek process $J/\psi, \Upsilon \to h(A)+\gamma$ points to possible constraints for the $M_{h(A)}$ below 10 GeV [12, 13], unfortunately the interpretation suffers both from theoretical uncertainties and lack of experimental considerations of some aspects of the 2HDM. In conclusion, only very weak limits exist for this rather simple extension of the Higgs sector. It is therefore important to search for additional relevant experimental data, particularly if it constrains the masses of h and A bosons independently.

In this paper we study the 2HDM contribution to $Br(Z \to h(A) + \gamma) = \Gamma(Z \to h(A) + \gamma)/\Gamma(Z \to all)$, where the Γ denote the partial, respectively, total width of the Z, and compare these to experimental data. For the theoretical evaluation we take into account existing LEP limits on the model parameters. In detail, the calculations include the following results, which are all valid at 95% confidence:

1. The exclusion on $\sin^2(\beta-\alpha)$ for M_h smaller than 60 GeV [6] [1].
2. The limit on $\tan\beta$ for M_A smaller then 40 GeV [9].
3. The excluded region of M_h versus M_A [8].

In addition the result from the NLO analysis of the $b \to s+\gamma$ process is invoked:

4. The mass of the charged Higgs boson should be larger than 330-350 GeV [14] [2]. Alternatively we also consider the mass limit for a charged Higgs from the direct search at LEP yielding to $M_{H^\pm} > 54.5$ GeV [22][3].

Relevant experimental results from LEP1 on the search for $Z \to h+\gamma$ have been published by all four LEP experiments [23, 24, 25, 26]. The decay modes considered include $h \to b\bar{b}$, $\tau^+\tau^-$ and inclusive hadrons, which are independent of quark flavours and applicable also to decays into a pair of gluons. The mass range covered is between 5 and 85 GeV. The experiments are typically sensitive to branching ratios $Br(Z \to h+\gamma) \cdot Br(h \to X)$ of $\mathcal{O}(10^{-5})$ but approach 10^{-6} for low M_h and X = hadrons or $\tau^+\tau^-$. Note that since the angular distribution for the h and A final state are identical up to a normalization factor [27] these experimental results should also hold for the pseudoscalar A.

In this paper we will first address the theoretical aspects of this process, the production rates and decay modes for a neutral Higgs boson as a function of its mass and for various values of $\tan\beta$. The dependence on the charged Higgs boson mass and their coupling to the neutral scalar is also discussed. We then summarise the experimental situation and finally conclude on its relevance for constraining the parameter space of the 2HDM.

In this paper we restrict ourselves to the one-loop contributions to decays of on-shell Z's. This decay in the SM were studied in [28]a-c [4], in [29] the SM, 2HDM and MSSM was also discussed. A more general theoretical analysis of $h(A)+\gamma$ production which also addresses energies above the Z peak can be found, for example in [28]b-e, [31].

[1] Recently limits on $\sin^2(\beta-\alpha)$ became available from other experiments as well [3, 4, 5] which in addition extend towards higher Higgs masses. Because of lack of detailed information we refrain from combining these individual limits. In addition, because of the experimental sensitivity the constraints on $\sin^2(\beta-\alpha)$ for high masses would not add significantly to our conclusion.

[2] This limit is based on the published CLEO data [15]. Recently the ALEPH collaboration has published a new analysis [16] and CLEO released new preliminary results [17]. The results tend to relax the limits on the charged Higgs boson, a new theoretical analysis leads to a lower limit of 165 GeV [18]. Note that also the Tevatron searches for $t \to H^\pm X$ [19] lead to constraints only in a limited region of parameter space in the 2HDM [20]. See also [21].

[3] Preliminary results from LEP data at 183 GeV set limits of up to 59 GeV [7].

[4] Note that the QCD corrections were calculated in [30], they were found to be small.

2 The process $Z \to h + \gamma$ in the Standard Model

As a reference we summarise the theoretical results on the Z decay into $h + \gamma$ within the Standard Model. Here the process would be mediated by W and fermion loops [1], [28]a-c, [29]. In Fig. 1a the branching ratio $Br(Z \to h + \gamma)$ is shown as a function of the scalar Higgs boson mass. Also the individual contributions to the branching ratios are displayed. As can be seen the W-loop contributes almost exclusively to this process. Note that there is a relative minus sign between the W- and fermion terms.

As can be seen from Fig. 1a, the Standard Model branching ratio is below $5 \cdot 10^{-6}$ in the whole mass range and thus beyond the experimental sensitivity. Anyhow, a Standard Model Higgs of mass less than 89.9 GeV has been excluded from searches at LEP for the Higgs-strahlung [32]. As discussed in the introduction, these limits do not apply in the 2HDM. Here the Z decay into $h(A) + \gamma$ can be in principle stronger and may provide the most prominent signal for Higgs production for some regions in parameter space.

3 The process $Z \to h(A) + \gamma$ in the 2HDM

We start our analysis of Z decays into photons and $h(A)$ within the 2HDM (see also [1] and especially [29]) by listing the Higgs couplings to quarks and gauge bosons in a form which will make our discussion more transparent [33]. For the coupling to fermions the SM factor $(-igm_f/2M_W)$ is modified by factors which differ for the two fermion isospins, for example for bottom and top quarks:

$$h b\bar{b}: \quad \frac{-\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \tag{1}$$

$$h t\bar{t}: \quad \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \frac{1}{\tan\beta}\cos(\beta-\alpha) \tag{2}$$

The h couples to ZZ with a SM factor $(igM_Z/\cos\theta_W\ g^{\mu\nu})$ times

$$hZZ: \quad \sin(\beta-\alpha). \tag{3}$$

For our further considerations two extreme cases of parameters are of interest:

- case A
  $$\cos(\beta-\alpha) = 0 \text{ (equivalently } \sin(\beta-\alpha) = +1)^5$$
  which corresponds to the SM case, since for both the $hb\bar{b}$ and $ht\bar{t}$ as well as for the hZZ couplings the factors of eqs. 1-3 are unity. Note that there is a relative minus sign between fermionic and gauge coupling. There is no dependence on $\tan\beta$.

- case B
  $$\sin(\beta-\alpha) = 0 \text{ (equivalently } \cos(\beta-\alpha) = +1 \text{ or } \alpha = \beta)$$

[5] For the purpose of our analysis the other sign will not be considered.

which leads to a scenario that is totally different from the Standard Model one. Here the hZZ coupling disappears, moreover $hb\bar{b}$ and $ht\bar{t}$ couplings have opposite signs, independent of whether we choose $\cos(\beta-\alpha)$=1 or -1. So even $\tan\beta$ =1 does not necessarily correspond to the SM prediction although, for special cases, i.e. if one contribution dominates, it looks like the Standard Model. Note that for a large value of $\tan\beta$ the Higgs scalar h may have a larger coupling to the bottom quark, than to top, despite the larger top quark mass.

For the coupling of the pseudoscalar A to fermions the corresponding factors are

$$Ab\bar{b}: \quad -i\gamma_5 \tan\beta \tag{4}$$

$$At\bar{t}: \quad -i\gamma_5 \frac{1}{\tan\beta}. \tag{5}$$

The AZZ, AWW couplings are absent in the considered model [1].

3.1 $Z \to h + \gamma$

In the 2HDM [1, 29] W, charged leptons or down-type quarks, and up-type quarks contribute to the matrix element for the $Z \to h + \gamma$ decay with factors given above. An additional contribution, not existent in the Standard Model, is due to loops involving charged Higgs scalars. However, for masses of $M_{H^+} > 330$ GeV, as required by some $b \to s + \gamma$ analysis, it is negligible. As will be discussed in Sec. 5, this does not change for lower masses of $H^\pm$ in an important way.

The branching ratios $Br(Z \to h + \gamma)$ in the 2HDM are presented in Fig. 1b,c,d for low, medium and high values of $\tan\beta$. The two solid curves for each $\tan\beta$ correspond to the cases of $\sin(\beta-\alpha)$=0 and of the maximum allowed value of $\sin(\beta-\alpha)$ from [6]. The experimental constraints on $\sin^2(\beta-\alpha)$ lead to the wiggles in the upper curves. The possible range of h production in the 2HDM for the masses M_h and $\tan\beta$ shown in Fig. 1b,c,d is bounded by the two corresponding solid curves.

For $M_h < 60$ GeV, where the experimental constraint on $\sin^2(\beta-\alpha)$ [6] is relevant, the branching ratio increases with increasing $\tan\beta$ for $\tan\beta$ larger than ~ 5 (see also figures discussed in Sec. 5,6). For $\tan\beta$ of $\mathcal{O}(1-10)$ the decay fraction is significantly below the expected yield for a Standard Model Higgs. This is because of the large suppression of the W contribution for the small $\sin^2(\beta-\alpha)$ allowed by experiments. Only for very high $\tan\beta$ the loop of bottom quarks, which contributes with $(\sin\alpha/\cos\beta)^2 \sim \tan^2\beta$, dominates such that branching ratios comparable to the Standard Model ones are reached. In contrast the top quark loop contributes only by $1/\tan^2\beta$ and is therefore negligible.

A large rate can be also obtained for very small $\tan\beta$, see Figs. 1b and figures discussed in Secs. 5, 6. Here the roles of t and b quarks are reversed.

For $M_h > 60$ GeV no relevant constraint exists on $\sin^2(\beta-\alpha)$ in [6] and $\sin^2(\beta-\alpha)$=1 (case A above) was assumed. As discussed above, this implies the same coupling of the Higgs boson to fermions and gauge bosons as in the Standard Model.

3.2 $Z \to A + \gamma$

In the considered 2HDM with CP conservation, because of the forbidden AWW and AH^+H^- couplings, the $Z \to A + \gamma$ decay is mediated only by fermions [1, 29]. Charged leptons and down-type quarks (up-type quarks) contribute to the branching ratio with the factors, relative to the SM case, of $\tan^2\beta$ ($\tan^{-2}\beta$) independent of α. Thus down-type quarks dominate for large $\tan\beta$ whereas up-type quarks dominate for $\tan\beta \ll 1$.

The results for corresponding $\tan\beta$=0.1, 5 and 100 are presented in Fig. 1b,c,d together with the results for scalar boson production, see also figures discussed in Secs. 5, 6. The branching fraction $Br(Z \to A + \gamma)$ is larger than the one for scalars for masses of up to 30-40 GeV for $\tan\beta$=0.1 and 100. For the intermediate $\tan\beta$ the pseudoscalar production is lower than for the scalar. The $\tan\beta$ dependence will be discussed further in Secs. 5 and 6.

Given the strongly decreasing production yield for higher masses, we will limit the following discussion to $M_{h,A} \leq 40$ GeV. Note that for this mass range the experimental constraints on $\sin^2(\beta - \alpha)$ are strong and will always be taken into account in the following discussion.

4 Decay modes in the 2HDM

The preferred decay modes of Higgs bosons depend on the parameters of the model. For the condition $\alpha = \beta$ and masses of up to 40 GeV the decay branching fractions of scalar and pseudoscalar Higgs bosons are presented in Figs. 2a and b for the two choices $\tan\beta = 0.1$ and $\tan\beta = 20$. They do not change significantly for smaller, respectively larger values of $\tan\beta$ and masses of up to ~ 80 GeV.

The decay branching ratios are fairly similar for h and A, they differ only around the production thresholds of the various fermion pairs. In the case of $\tan\beta \gg 1$ and masses above 4 GeV, both h and A decay to almost 100% into τ's, or, once their threshold is passed, into beauty quarks. For $\tan\beta \ll 1$ they decay almost exclusively into gluons and, for $M_{h,A} > 2m_c$, into charm quarks. With increasing $M_{h,A}$ the decay into gluons rises again and reaches some 10% around 40 GeV.

The branching fractions for decays of the scalar bosons depend through $\sin^2(\beta - \alpha)$ also on the parameter α. For $\tan\beta = 0.1$ these fractions are compared in Fig. 3 for $\alpha = \beta$ and the maximum $\sin^2(\beta - \alpha)$ allowed by data [6]. No difference of relevance for experimental studies is observed: the dominant decay modes are hardly affected and only extremely suppressed branching fractions exhibit some sensitivity. Also for larger $\tan\beta$ (not shown) the leading decay modes are not affected by the value of $\sin^2(\beta - \alpha)$.

5 Sensitivity to charged Higgs boson contribution

Compared to the Standard Model an additional contribution involving loops of charged Higgs bosons has to be included for the production of a scalar h. The relevant hH^+H^- coupling in the general 2HDM [1, 29, 33] is more complicated than the Higgs couplings to fermions and gauge bosons. It depends on the masses of both M_h and $M_{H^\pm}$ and an additional parameter λ_5, remaining from the original Higgs potential:

$$g_{hH^+H^-} = \frac{M_h^2 - \lambda_5 v^2}{M_W^2}\frac{\cos(\beta+\alpha)}{\sin 2\beta} + \frac{2M_{H^\pm}^2 - M_h^2}{2M_W^2}\sin(\beta-\alpha) \qquad (6)$$

where λ_5 is an arbitrary parameter and the vacuum expectation value: v=246 GeV (with a normalization, up to the sign, as for the gauge boson in the SM, see Eq. 3).

In the following analysis we will assume that λ_5=0, which corresponds to the assumption of the strict symmetry of the Lagrangian under the scalar Higgs doublet transformation $\phi_1 \to -\phi_1$. In general, our results should be correct for $|\lambda_5 v^2| \ll M_h^2$. Even for such small λ_5 it is still possible to have both a decoupling and a non-decoupling of the heavy charged Higgs particle. In contrast to the belief stated eg. in [29] that the $\Gamma(Z \to h+\gamma)$ will be hardly sensitive to the charged Higgs particle loop, there are interesting parameter regions where one may expect to see such an effect.

Let us discuss this dependence in more detail. We start by considering different values of $\sin(\beta-\alpha)$. If $\sin(\beta-\alpha)$=0 we have the so called decoupling case, as only the first term of $g_{hH^+H^-}$ (Eq. 6) contributes and therefore the overall contribution to the branching ratio due to the charged Higgs loop is given by

$$\frac{g_{hH^+H^-}}{M_{H^\pm}^2} \propto \frac{M_h^2}{M_{H^\pm}^2}(\frac{1}{\tan\beta} - \tan\beta), \qquad (7)$$

leading to the negligible contribution for a very heavy charged Higgs boson. (Here factors not relevant to our discussion are omitted.) Note that the W contribution, otherwise dominating the branching ratio for intermediate $\tan\beta$, becomes negligible for $\sin(\beta-\alpha) \sim 0$ and the effects due to the charged Higgs boson might be eventually seen if the mass of the charged Higgs is not too large, see below. For both very small and very large $\tan\beta$ the $H^\pm$ may contribute with a strength that is almost comparable to those from heavy quarks or W-bosons. The difference in sign between the small and large $\tan\beta$ scenarios may result in the constructive or destructive interference with bottom, or top quark, or W contributions. For $\tan\beta$=1 the contribution from charged Higgs bosons disappears.

For $\sin(\beta-\alpha) \neq$0 and for $M_{H^\pm} \gg M_h$ the non-decoupling limit is obtained, and

$$\frac{g_{hH^+H^-}}{M_{H^\pm}^2} \propto \sin(\beta-\alpha), \qquad (8)$$

independent of the mass of Higgs bosons and $\tan\beta$.

The effect of charged Higgs bosons, assuming λ_5=0, on ratios $BR(Z \to h+\gamma)\cdot BR(h \to f\bar{f})$ is shown in Figs. 4 and 5 for the 'hadronic', i.e. the $qq+gg$, decay mode and the tau decay channel. The product branching ratios are presented as a function of $\tan\beta$ for masses of the charged Higgs boson of 54.5 and 330 GeV (which gives a similar result as for masses of 1000 GeV or greater) and for masses of the scalar particle h of 8, 12, and 40 GeV. For $\sin^2(\beta-\alpha)=0$ a smaller product branching ratio is observed, as expected.

For a lower scalar mass of 8-12 GeV and for almost the whole range of $\tan\beta$ the expected product branching ratios are insensitive to the value of $M_{H^\pm}$. However, with increasing mass M_h, the sensitivity to the mass of the charged Higgs boson becomes more prominent (cp. Eq. 7). The contribution of charged Higgs boson increases the h production rate with diminishing $M_{H^\pm}$ for $\tan\beta \gg 1$, but decreases it for $\tan\beta \ll 1$ (cp. Eq. 7). (Note that the lower dashed curves (2) in Figs. 5a,b can be treated as a bare fermionic contributions.) The value of $M_{H^\pm}$ affects the branching ratio stronger for large $\tan\beta$ than for small $\tan\beta$, where the top loop interferes destructively with the charged Higgs boson contribution. At $\tan\beta$=1 the charged Higgs boson does not contribute for $\sin^2(\beta-\alpha)=0$, the point where its contribution disappears (observe cross over points between solid and dashed lines in Fig. 5b) is shifted to slightly larger $\tan\beta$ value for the $\sin^2(\beta-\alpha)=0.25$, the experimental limit for M_h=40 GeV [25].

As we already mentioned above, the figures show a non-negligible dependence on the parameter $\sin(\beta-\alpha)$ which governs the couplings W^+W^-h, H^+H^-h and also (partly) $hf\bar{f}$. In Figs. 4 and 5 the branching ratio with $\sin(\beta-\alpha)$=0 is compared to the one accounting for the experimental limit on $\sin(\beta-\alpha)$. The difference due to $\sin^2(\beta-\alpha)$ is one to two orders of magnitude in the branching ratios for intermediate values of $\tan\beta$ but much less for the extreme values of $\tan\beta$ where it has effects at the 30 - 50 % level.

The effect due to charged Higgs boson loop should be larger for larger M_h and will be studied elsewhere for different assumptions on λ_5 [34].

6 The experimental results

All LEP experiments have searched for Z decays into a scalar particle S and a photon. Such particles would appear as a resonance peak of rather narrow width over a background, which is mainly due to photons emitted from the final state fermions. Results have been presented for the decay modes:

- $S \rightarrow \tau^+\tau^-$ [23, 24].
- $S \rightarrow q\bar{q}$ without flavour tag [23, 24, 25, 26]. This can also be interpreted in terms of a decay into two gluons.
- $S \rightarrow b\bar{b}$ [24, 26].

In addition decays into muons, electrons, neutrinos and photons have been considered, but are of less interest in the context of Higgs searches in the 2HDM. No single experiment has observed any significant structure, the corresponding limits are shown in Fig. 6. From this figure it becomes apparent that also a combination of the results would not reveal any significant peak. Thus, there exists no indication of a production of a Higgs boson in this process.

The LEP experiments considered explicitely only the production of a scalar particle. Since the angular distribution of Z decays into a pseudoscalar and the photon is identical, the experimental limits, taking into account the different normalization, can be directly applied also to the pseudoscalar Higgs boson A.

The typical individual limits are $Br(Z \to S+\gamma)\cdot Br(S \to X) \sim 10^{-5}$ for $X = q\bar{q}$ and $b\bar{b}$. A notable exception is the result of [23] which sets limits of less than 10^{-6} for $M_S \sim$ 10 GeV and $S \to q\bar{q}$. For $X = \tau^+\tau^-$ limits have been set between $2{\cdot}10^{-6}$ at $M_S \sim 5$ - 20 GeV and 10^{-5} at $M_S \sim 85$ GeV. Without more detailed information, for example about the mass dependent backgrounds, data yields and efficiencies, it is impossible to combine the results from the various experiments in a rigorous manner. Generally one expects the limits to improve by some factor $\sqrt{2}$ - 2. In the absence of this detailed information we will consider the most restrictive limit from all experiments. This is justified because of the absence of a consistent indication of a signal. In general, though not necessarily everywhere, this approach should be conservative.

For $\tan\beta \ll 1$ the h and A decay into charm quarks and gluons to almost 100%. Limits on both of these decays are not explicitely provided by the experiments. However, since charm as well as gluon jets are rather similar to those of other flavours, no significant change of the experimental efficiency compared to the study of inclusive quark decays should be expected [6]. In considering the low $\tan\beta$ region, we therefore apply the limits from inclusive decays into quarks (and gluons).

7 Results

The product branching ratios $Br(Z \to h(A)+\gamma)\cdot Br(h(A) \to X)$ are plotted in Figs.4,5 discussed above for the scalar case and in Figs. 7a,b,c,d as a function of $\tan\beta$ for h and A masses of 8, 12 and 40 GeV. Because the experimental sensitivity to other decay modes is rather limited, only the $qq+gg$ decay mode denoted 'hadronic' and the decay into τ's (for $M_{h(A)}$=8 GeV) are considered. The experimental limits on $\sin(\beta-\alpha)$ and on the mass of the charged Higgs particle are taken into account.

These product branching ratios agree within up to about a factor two for scalar and pseudoscalar Higgs bosons and values of $\tan\beta$ of less than ~ 0.2 and larger than ~ 50. They differ drastically for intermediate values of $\tan\beta$, where the pseudoscalar production rate can be lower by some two orders of magnitude. This difference is mainly due to the additional contribution of W loops for the h production (see for example Figs. 7b,c).

One sees that in general the experimental limits on the product branching ratio $Br(Z \to h(A)+\gamma)\cdot Br(h(A) \to X)$ of $\sim 10^{-5} - 10^{-6}$ are significantly above the ex-

[6] The ALEPH collaboration has explicitely studied $S \to gg$ and obtains limits which are almost identical to those for S decays into inclusive quark flavours [23].

pected rates for a wide range of $\tan\beta$ values. An exception are the extremely high and low values of $\tan\beta$. Here the data impose additional constraints on the 2HDM. This is especially true in the mass region $\sim$ 10 GeV, where an experimental sensitivity of below 10^{-6} is reached. Limits on $\tan\beta$ as a function of the h and A masses are shown in Fig. 8. The constraints in the two extreme regions of $\tan\beta$ can be summarized as follows.

- In the region of $\tan\beta \ll 1$ the product branching ratio $Br(Z \to h(A) + \gamma) \cdot Br(h(A) \to X)$ is larger than 10^{-6} for masses of up to 40 GeV. Here the non-observation of associated $h(A) + \gamma$ decays leads to new constraints. Unfortunately only around 10 GeV the data exclude values of $\tan\beta$ that are not disfavoured by theoretical arguments.
- Also in the region of high $\tan\beta$, $\mathcal{O}(100)$, the data limit the $\tan\beta$ range. It is constrained to be smaller than 75 (55) (for $M_h(M_A) = 10$ GeV) and smaller than $\mathcal{O}(300)$ (for $M_{h(A)} = 35$ GeV). These constraints are around 10 GeV more stringent than the limits from todays $(g\text{-}2)_\mu$ data [7]. They are, however, less restrictive than the constraints from the Yukawa process [8].

The limits on $\tan\beta$ as a function of M_h and M_A were obtained for λ_5=0 and a charged Higgs mass 330 GeV and for comparison also for mass 54.5 GeV, but, as long as it is above 200 GeV the limits will change only marginally. The dependence (for h only) on the assumption on the $\sin^2(\beta - \alpha)$ on the obtained limits is weak, and the exclusion plot in Fig. 8 corresponds to the tightest limit on $\tan\beta$ corresponding to the experimental limits on $\sin^2(\beta - \alpha)$. Assuming $\alpha = \beta$ the limit will be weaker, being shifted up and down by approximately factor of 1.4 for the mass of 40 GeV, for lower masses the change will be much smaller.

Also shown in Fig. 8 is a dependence on the mass of the charged Higgs boson for the h and larger M_h values (a difference by the solid curves "1" ($M_{H^\pm}$=54.5 GeV) and "2" (330 GeV)).

8 Conclusion and outlook

The one-loop result to the process $Z \to h + \gamma$ in the general Two Higgs Doublet Model (Model II) is compared to the experimental limits from LEP, which is of the order $BR(Z \to h + \gamma) \cdot BR(h \to X) \sim 10^{-6} - 10^{-5}$. Taking into account the existing limits on $\sin^2(\beta - \alpha)$ we analysed the light mass of neutral scalar Higgs bosons scenarios with large and small $\tan\beta$. We find that the process constrains the parameter space to $\tan\beta$ between 0.15 and 70 for masses $M_h \sim 10$ GeV.

[7] Those are expected to be improved soon by the E821 experiment at BNL [35].

[8] As mentioned in the introduction, the experimental results for the Yukawa process have as yet been presented only for pseudoscalars A. However, an interpretation in terms of a potential scalar production would yield stronger limits on $\tan\beta$.

We studied the dependence of the scalar production yield a $\sin^2(\beta-\alpha)$ and the mass of the charged Higgs boson. The parameter $\sin^2(\beta-\alpha)$ induces dependence for intermediate $\tan\beta$, but affects only mildly the product branching ratios at extreme values of $\tan\beta$. The dependence on the charged Higgs mass, in the limits of 54.5 to 330 GeV becomes stronger with higher mass M_h.

The product branching ratios for the associated production of a pseudoscalar A and a photon is similar to the one for scalars for $\tan\beta$ below 0.2 and $\tan\beta$ above 50. Thus similar limits to those for the scalar h can be derived. They differ drastically for intermediate values of $\tan\beta$, where the pseudoscalar production rate is much lower, than for scalars because of the strong W contribution in the latter case.

For a large parameter space of the 2HDM the data have no sensitivity to the expected yields. Only for extremely high or low values of $\tan\beta$ some constraints can be derived. The large $\tan\beta$ region of the 2HDM can be constrained by the data. These limits are stronger than those from the present $g-2$ data for muons for both a light scalar and a light pseudoscalar Higgs boson. For the light pseudoscalar scenario the existing data from the Yukawa process at LEP lead to stronger limits, but for mass around 10 GeV the $Z \to A+\gamma$ decay becomes competitive.

Constraints on the 2HDM model can also be obtained for the low values of $\tan\beta$ for both scalar (similar remarks as above for the large $\tan\beta$ case hold here as well) and pseudoscalar production. Also these limits are of interest, although they just touch the region of $\tan\beta \ll 1$, which is required by perturbative calculations.

To summarize, the process discussed here leads to constraints of the parameters of the 2HDM for very large and very low $\tan\beta$ for both scalar and pseudoscalar production. The one-loop calculation applied here may be improved in the future by taking into account higher order corrections.

Finally let us consider possible experimental improvements. Although data taking at the Z has been completed, some improvements may be expected from the data since not the whole statistics has been used up to now for the various analyses and improvements seem possible. Only one experiment has fully exploited the $\tau\tau\gamma$ channel, the low mass region ≤ 20 GeV has also not been addressed by all experiments and finally most experiments have improved their beauty tagging compared to what has been published. Assuming in addition a proper combination of the final data it may be possible to gain some factor 2-4 in sensitivity. This would imply a sensitivity to branching ratios of some 10^{-6}. The drastically lower cross section at the high energies of 160 - 200 GeV of LEP and also the increased background from initial state photons above the Z pole, renders it unlikely that a sensitivity close to the expected yields within the 2HDM can be reached. On the other hand, higher masses can be reached which in itself makes it important to consider this process. A first look [36], however, did not reveal any new particle production. The interpretation of experimental results require a more general theoretical analysis which includes not only the production of on-shell Z decays.

The high luminosities which are envisaged at a new linear e^+e^- collider or $\mu^+\mu^-$ collider may allow some sensitivity to the associated $h(A)+\gamma$ production. However a detailed experimental study is still missing.

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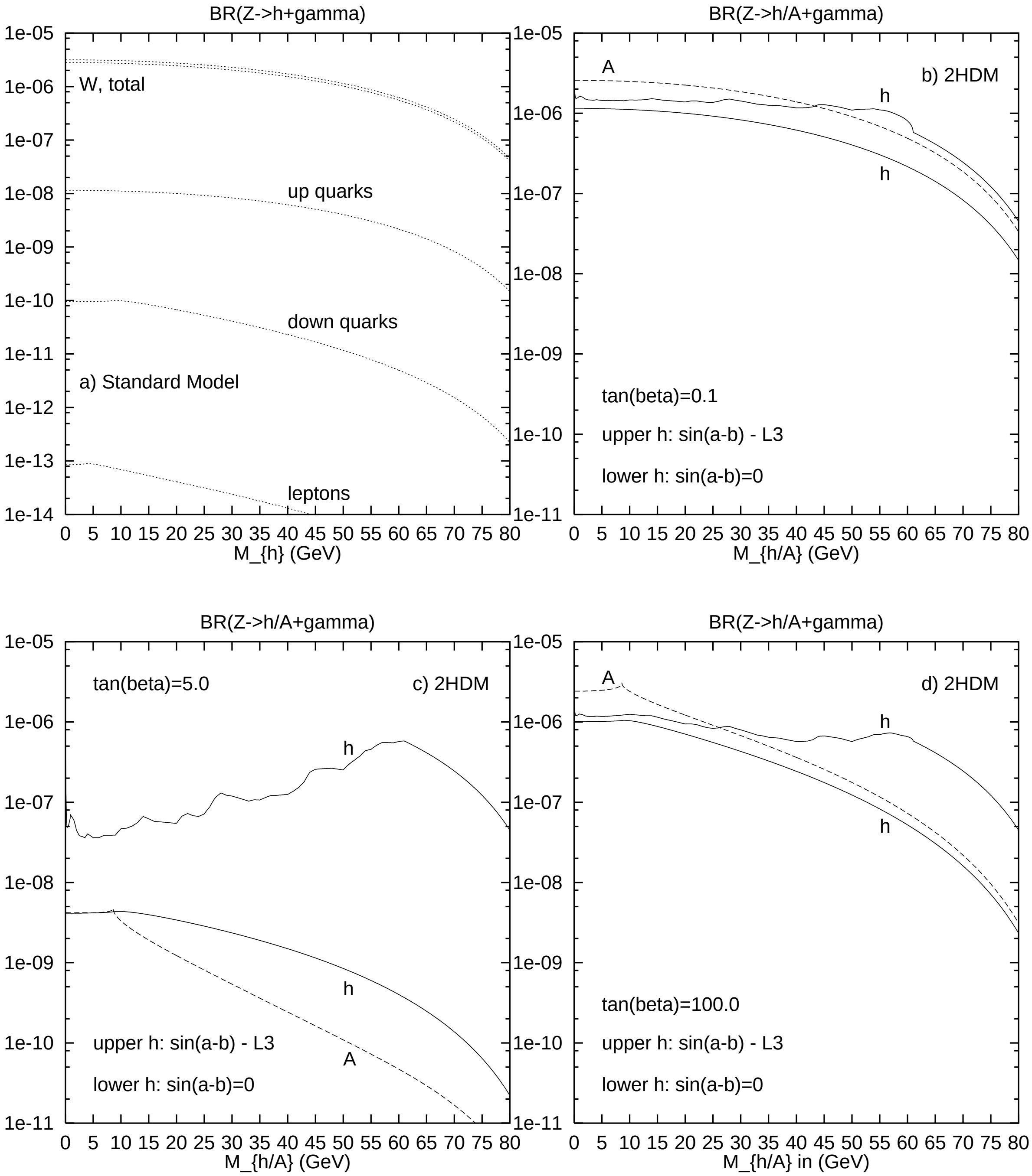

Figure 1: *a)The scalar production in SM (dotted lines) - W and total, up-type quarks, down-type quarks, leptons contributions. b,c,d) The production of a scalar (solid line, h) and pseudoscalar (dashed line, A) in the 2HDM for* $\tan\beta = 0.1,\ 5,\ 100$*, respectively. Limits on* $\sin^2(\beta-\alpha)$ *are included for upper solid curves and for lower solid curves* $\sin(\beta-\alpha)=0$ *is assumed;* $M_{H\pm}$ *is set to 330 GeV.*

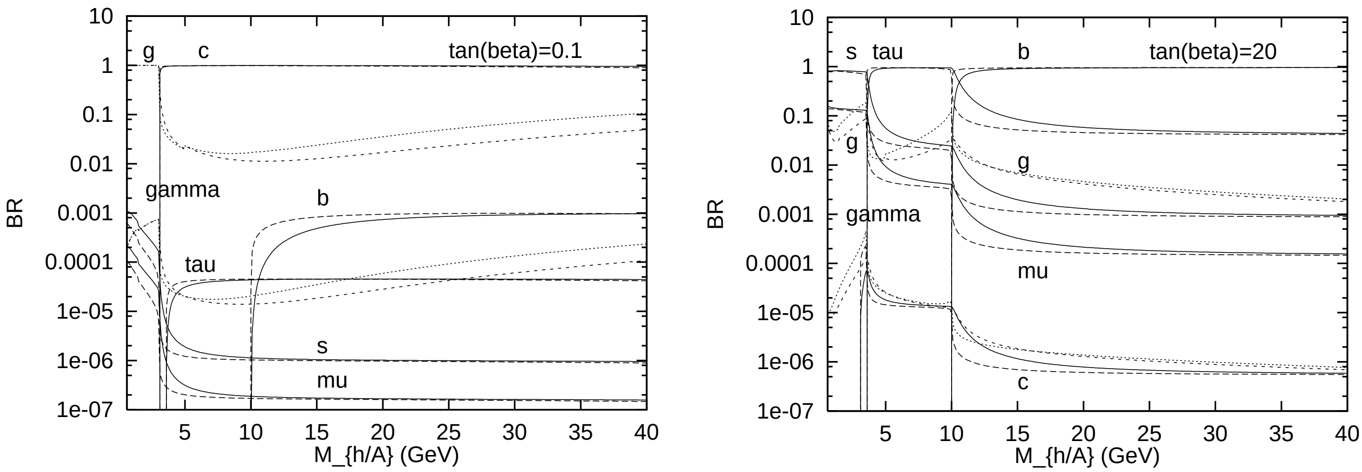

Figure 2: *The branching ratio for a scalar boson decay with $\alpha = \beta$ (solid lines for the fermionic modes) and for a pseudoscalar one (dashed lines for the fermionic modes). The corresponding decays into gluons and photons are denoted by short-dashed (scalar) and the dotted (pseudoscalar) lines. a)* $\tan\beta = 0.1$, *b)* $\tan\beta = 20$.

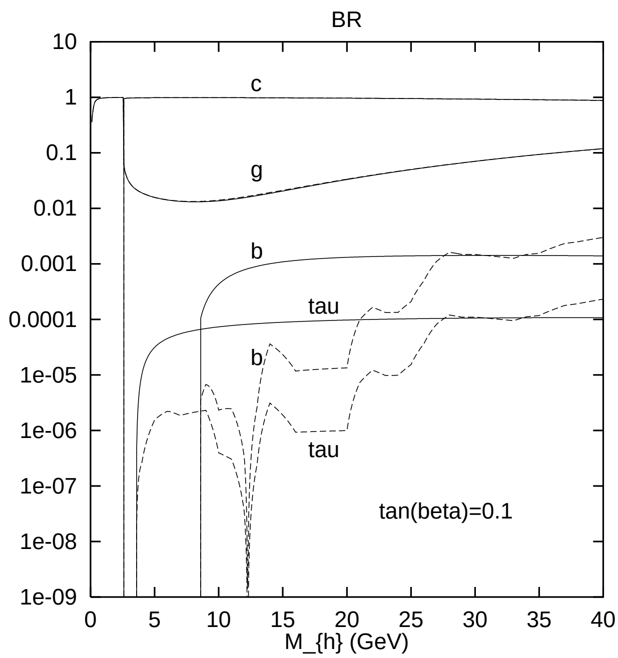

Figure 3: *The branching ratio for a scalar boson decay with the experimental limit on the* $\sin^2(\beta - \alpha)$ *(dashed line) and with $\alpha = \beta$ (solid line) for* $\tan\beta = 0.1$.

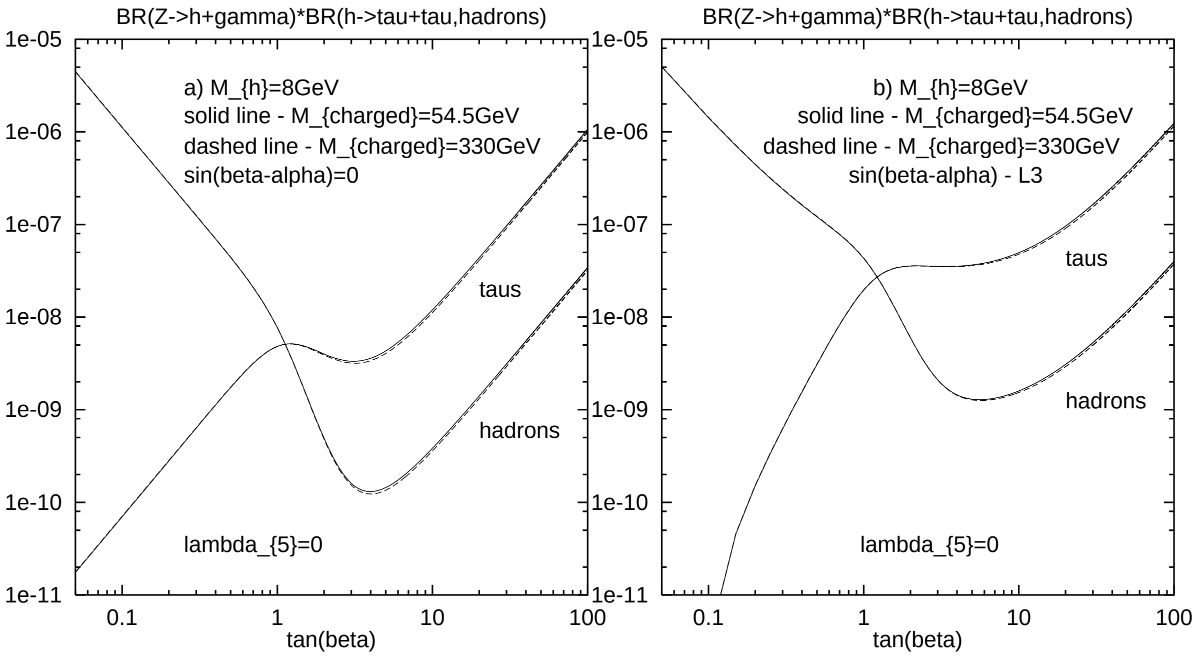

Figure 4: *The branching ratio as a function of* $\tan\beta$ *for a scalar boson decay with* M_h=*8 GeV with a)* $\alpha = \beta$ *and b) the experimental limit on* $\sin^2(\beta - \alpha)$*. The mass of charged Higgs boson is equal to 54.5 and 330 GeV.*

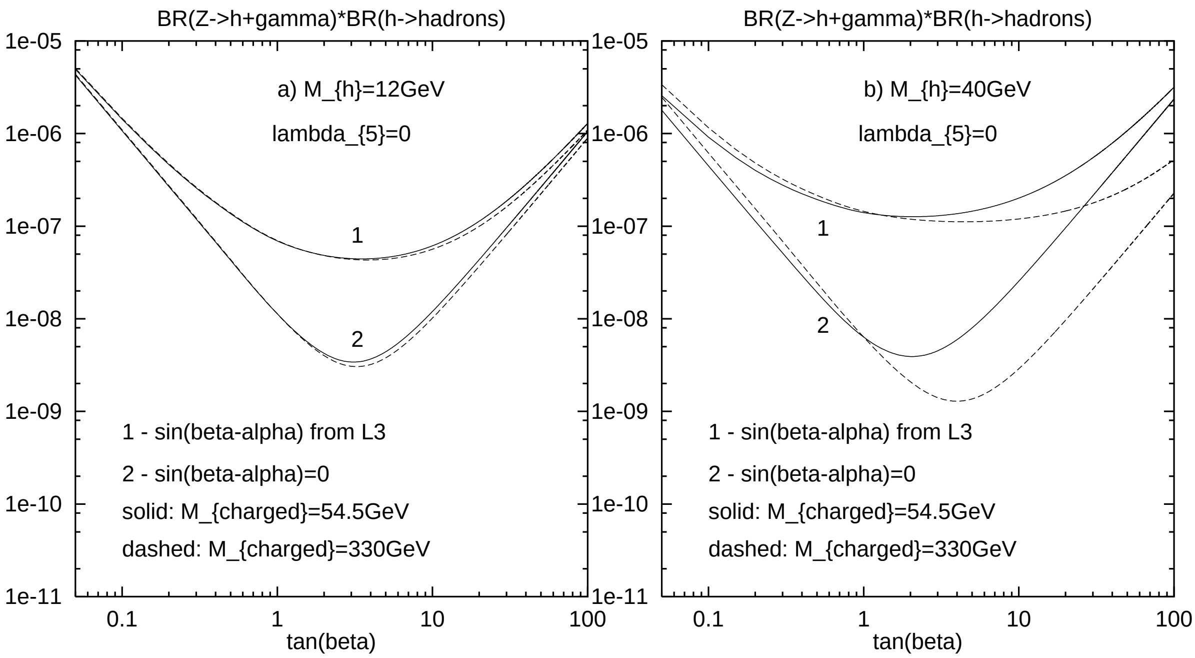

Figure 5: *The branching ratio as a function of* $\tan\beta$ *for a scalar boson decay with a)* M_h=*12 GeV and b)* M_h=*40 GeV . The results obtained with the assumption* $\alpha = \beta$ *and with the experimental limit on* $\sin^2(\beta - \alpha)$ *are plotted. The mass of charged Higgs boson is equal to 54.5 and 330 GeV.*

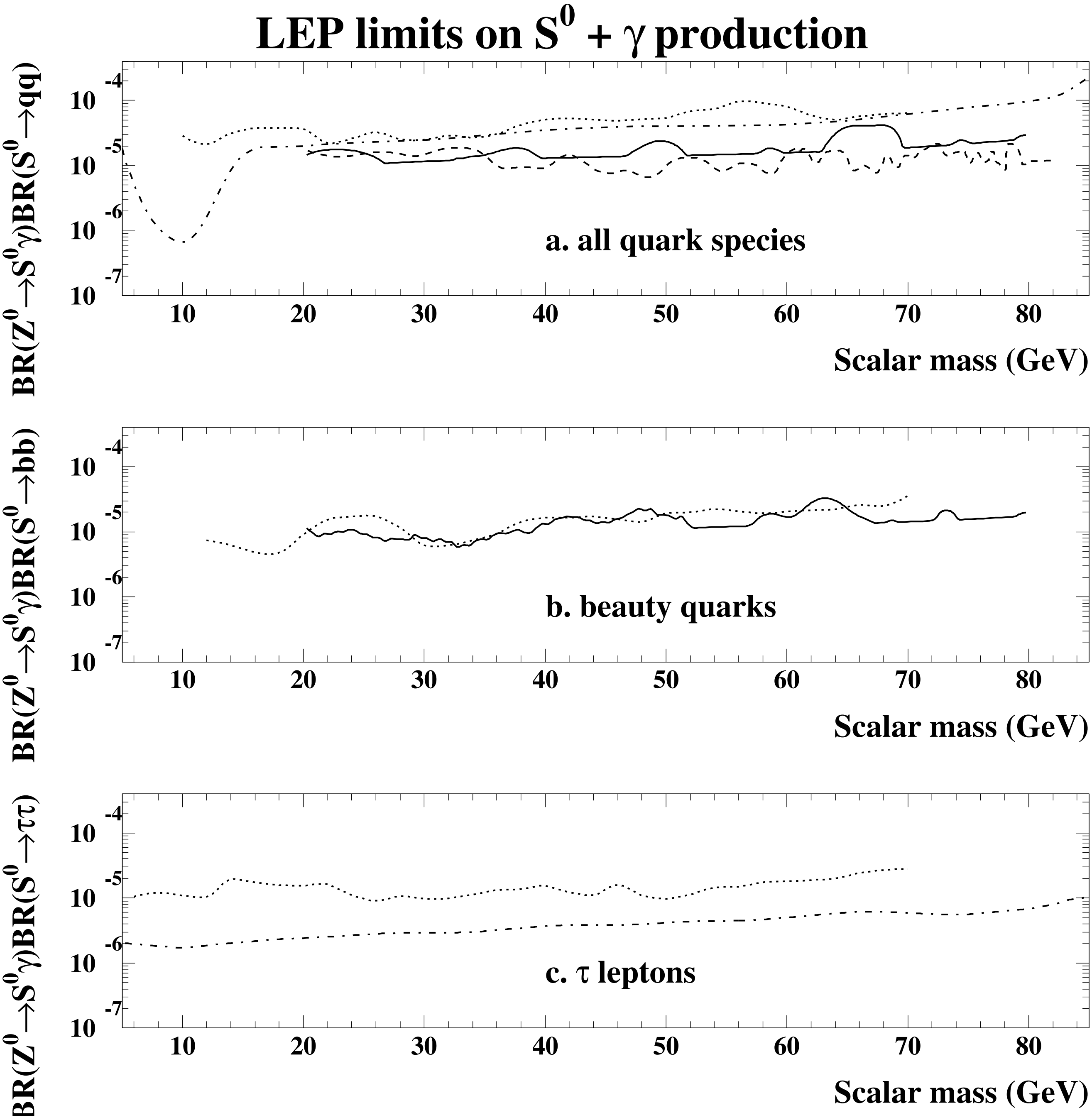

Figure 6: *Limits on the branching ratio $Z^0 \to S + \gamma$ from the various LEP experiments. Shown are the limits for the cases that the S decays into any kind of quarks or gluons (a), into beauty quarks (b), or into τ pairs (c). ALEPH [23]: dashed - dotted, DELPHI [24]: dotted, L3 [25]: dashed, OPAL [26]: full.*

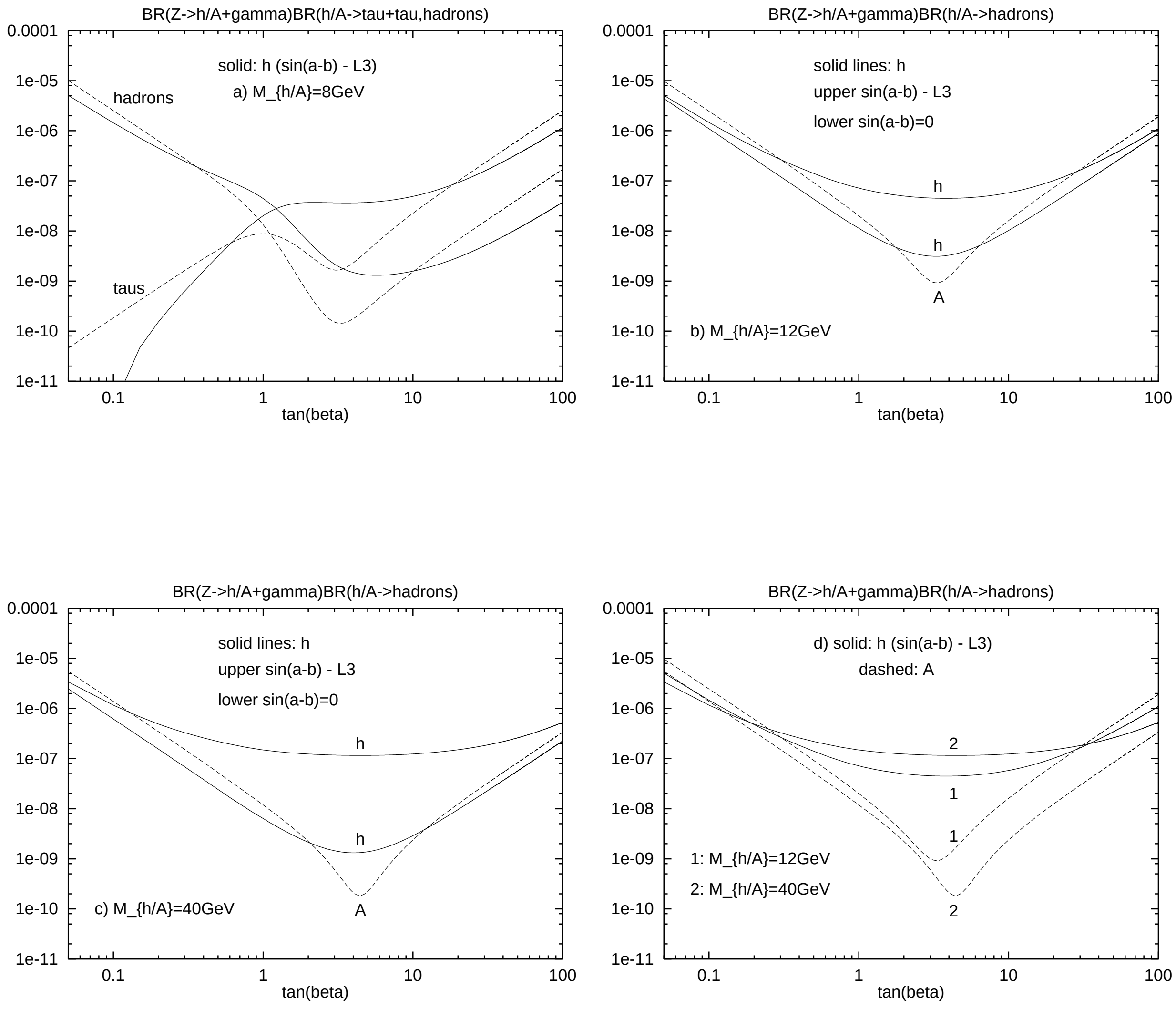

Figure 7: *a) The branching ratio for a pseudoscalar boson (dashed line) compared to the scalar case (solid line) for* $M_{h(A)}$=a) *8, b) 12, and c) 40 GeV, respectively. The h curves take into account the experimental limits on* $\sin^2(\beta-\alpha)$ *and assume* $M_{H\pm}$=*330 GeV. The* $X = qq + gg$ *is denoted by 'hadrons', while* $X = \tau\tau$ *is described by 'taus'. In d) a comparison is made for two masses 12 and 40 GeV.*

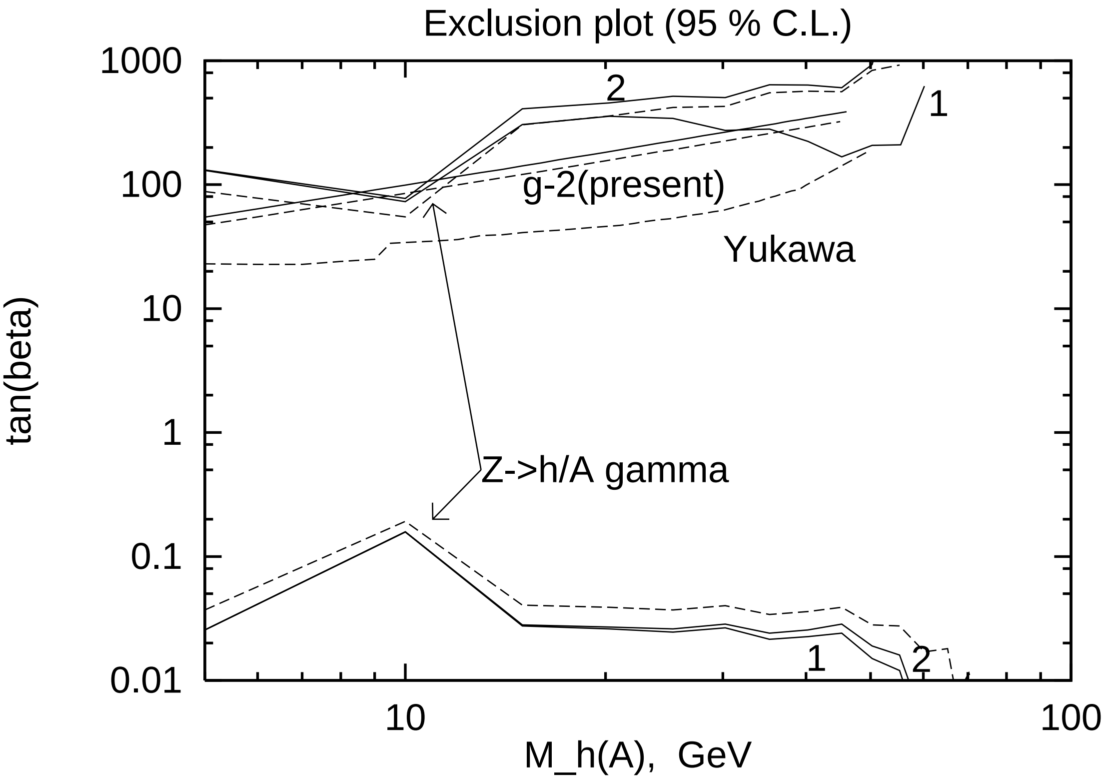

Figure 8: *The exclusion plot (95% C. L.) for the* $\tan\beta$ *versus mass of the scalar (with experimental limits on* $\sin(\beta-\alpha)$*, solid line) or the pseudoscalar(dashed line) obtained from the data on* $Br(Z \to h(A) + \gamma)$ *for the hadronic final state with an exception of the lowest mass uses the tau-channel, data from OPAL, L3 and ALEPH (below 20 GeV). For scalar production two masses for the charged Higgs boson were used: 1 – 54.5 GeV and 2 – 330 GeV. For comparison exclusion based on ALEPH data from Yukawa process and present g-2 for muon measurement is shown. The area above upper and below lower curves is excluded.*