Maximal deviations of the scalar boson couplings if no further particle is seen

Rick S. Gupta[A], Heidi Rzehak[B,a,b], James D. Wells[B,C]
[A] *IFAE, Universitat Autonoma de Barcelona, 08193 Bellaterra, Barcelona, Spain*
[B] *CERN, PH-TH, 1211 Geneva 23, Switzerland*
[C] *Physics Department, University of Michigan, Ann Arbor, MI USA*

In the light of the discovery of a Higgs boson like particle and no evidence of particles beyond the Standard Model the question arises: How much can the coupling of the Higgs boson to other particles deviate from the Standard Model Higgs couplings if no further particles will be discovered at the LHC and how precise have Higgs coupling measurements to be to capture these deviations? In the context of three different models (a model with a singlet Higgs boson mixed-in, a composite Higgs boson model and the Minimal Supersymmetric Standard Model) these questions will be answered.

1 Introduction

Last year, a particle has been discovered [1] which is compatible with the Standard Model Higgs boson. The Higgs boson is the physical particle connected to the gauge invariant mass generation mechanism [2] and the last missing piece in the Standard Model (SM). Besides this great discovery, no further particles have been found yet at the LHC. Moreover, electroweak precision test constrain possible deviations from the Standard Model. At this point, the properties of this new particle have to be measured to ensure that it actually is the Higgs boson or, maybe, a Higgs boson embedded in a different way than in the Standard Model. Questions arising are: Can Higgs couplings give a hint about the underlying model? And how large can the deviations of the couplings actually be if no further particle will be found at the LHC? - leading to the follow-up question of how precisely at least the Higgs couplings have to be measured to capture these deviations. Of course, these questions cannot be answered completely model independently and will be discussed in the context of three different models: "Mixed-in Singlet Model", "Composite Higgs Model" and "Minimal Supersymmetric Standard Model (MSSM)" [3]. A discussion of how much the triple Higgs self couplings can deviate can be found in [4].

2 Higgs Couplings in a Mixed-in Singlet Model

Additionally to the Standard Model part, this model contains a hidden sector with no Standard Model quantum numbers. The hidden sector exhibits an extra gauge symmetry which is broken via a Higgs boson singlet [5,6]. The only observable sign of this hidden sector at a collider are the physical components of this Higgs singlet. The Higgs singlet S mixes with the Standard Model Higgs doublet H_{SM} via the operator $|H_{SM}|^2|S|^2$. This mixing leads to two CP-even mass eigenstates h, H and can be described by a mixing angle θ_h. The couplings squared g_h^2, g_H^2 to

[a] speaker
[b] On leave from: Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, Freiburg, Germany.

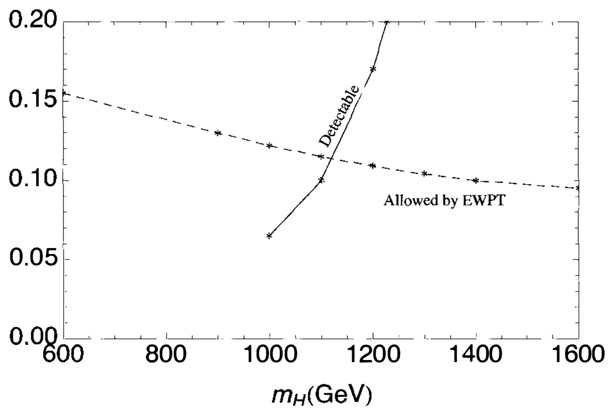

Figure 1: The solid line indicates the estimated LHC reach for the Higgs boson; for smaller masses of the heavy Higgs boson m_H the heavy Higgs boson is detectable. For parameter values of m_H and s_h^2 corresponding to the region below the dashed line the electroweak precision constraints (S and T parameter) are fulfilled.

all other particles will then be suppressed with respect to the SM one, $g^2_{\rm SM}$,

$$g_h^2 = c_h^2\, g^2_{\rm SM} \;, \qquad g_H^2 = s_h^2\, g^2_{\rm SM} \;. \tag{1}$$

with $s_h = \sin\theta_h$ and $c_h = \cos\theta_h$. In the following we will assume that h is the SM-like Higgs boson and hence, $c_h^2 \geq 0.5$. The other Higgs boson is assumed to be heavier and might be detectable at the LHC if it is light enough.

In Fig. 1 an estimate of the discovery potential of the heavy Higgs boson for the 14 TeV LHC and a luminosity of 100 fb^{-1} based on Ref.[6] is shown as well as the s_h^2–m_H region for which the electroweak precision constraints are fulfilled. The latter has been determined by calculating the S and T parameters

$$S = c_h^2 S_{SM}(m_h) + s_h^2 S_{SM}(m_H) \tag{2}$$
$$T = c_h^2 T_{SM}(m_h) + s_h^2 T_{SM}(m_H) \tag{3}$$

where the one-loop expressions of Ref.[7] have been used. We fixed the Higgs mass to $m_h = 125$ GeV and imposed the requirement that the contributions to the S and T parameters are within the 90% CL $S-T$ contour in Ref.[8] where U is appropriately fixed to 0.

The maximal value for the sine squared of the mixing angle for which neither the heavy Higgs boson will be discovered nor the electroweak precision tests are violated can be read of Fig. 1 as

$$s_h^2 = 0.12 \tag{4}$$

which corresponds to a maximal deviation of

$$\frac{\Delta g_h}{g_{\rm SM}} \approx -\frac{s_h^2}{2} \approx -6\ \% \;. \tag{5}$$

with $\Delta g_h = g_h - g_{\rm SM}$. All couplings of the Higgs boson to other particles will be affected in the same way.

3 Higgs Couplings in Composite Higgs Models

In a Composite Higgs Model the Higgs boson is a pseudo-Goldstone boson stemming from a Higgs multiplet belonging to a strong sector which exists in addition to the SM vector bosons

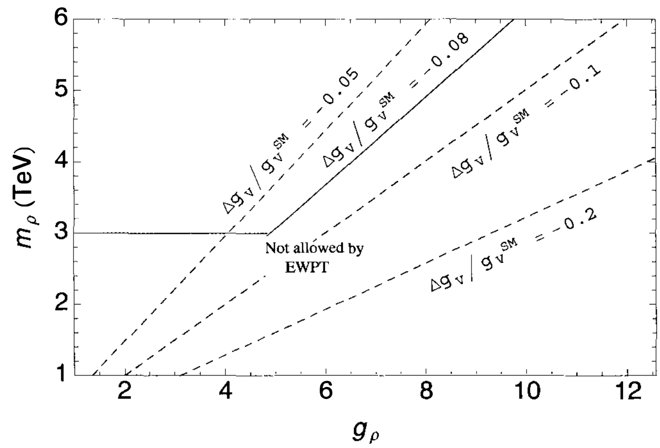

Figure 2: The region in the parameter plane m_ρ-g_ρ which is not allowed by electroweak precision tests is shown in yellow. Also, lines indicating different deviations of the vector couplings from the Standard Model $\Delta g_V/g_V^{SM}$ with $\Delta g_V = g_V - g_V^{SM}$ are presented.

and fermions. To be independent of the exact realisation of the model we study the deviations of the couplings adapting the effective Lagrangian for a strong interacting light Higgs boson (SILH) [9]. Here, we list only the operators relevant for our study:

$$\mathcal{L}_{\rm SILH} = \left(\frac{c_y y_f}{f^2} H^\dagger_{SM} H_{\rm SM} \bar{f}_L H_{\rm SM} f_R + \frac{c_S g g'}{4m_\rho^2} \left(H^\dagger_{SM} \sigma_I H_{\rm SM} \right) B_{\mu\nu} W^{I\mu\nu} + h.c. \right) + \frac{c_H}{2f^2} \partial^\mu \left(H^\dagger_{SM} H_{\rm SM} \right) \partial_\mu \left(H^\dagger_{SM} H_{\rm SM} \right) + \ldots \quad (6)$$

with y_f and g (g') being the Yukawa coupling and the $SU(2)$ ($U(1)$) gauge coupling. The Higgs boson doublet, the right- and the left-handed fermion fields, the $U(1)$ and the $SU(2)$ gauge field strength are denoted as H_{SM}, f_R and f_L, $B_{\mu\nu}$ and $W^{I\mu\nu}$, respectively. The decay constant f, analogous to the pion decay constant, is given by

$$m_\rho = g_\rho f \quad (7)$$

where m_ρ and g_ρ are the mass and the coupling of the new resonance. The coefficients c_y, c_S and c_H are of the order $O(1)$ according to the Naive Dimensional Analysis [9,10].

In Fig. 2, the region in the parameter plane m_ρ-g_ρ which is not allowed by electroweak precision tests is shown in yellow. Two constraints result in this region: The coupling of the second operator in Eq. (6), c_S/m_ρ^2, is proportional to the S parameter and the constraint $m_\rho \geq$ 3 GeV can be derived [9]. The second constraint comes from cancellations between Higgs boson and gauge boson contributions which occur completely in the Standard Model but only partially in the Composite Higgs Models due to the reduced couplings to gauge bosons. This leads to a logarithmically divergent contribution to the precision observables [11]. At 90% CL this results in the constraint [12] $c_H\xi \leq 0.15$ with a Higgs mass of 125 GeV. Direct LHC probes are expected to be much less sensitive.

The maximal deviation of the coupling of the Higgs boson to the gauge bosons is then $\Delta g_V/g_V^{SM} \approx -(c_H\xi)/2 \approx -8\%$, where Δg_i is the difference $\Delta g_i = g_i - g_i^{SM}$ with i indicating the specific coupling. From that we can also calculate the deviations of the fermion couplings as $\Delta g_f/g_f^{SM} \approx -c_H\xi/2 + c_y\xi \approx -8\% - 15\% \, c_y/c_H$. The loop-induced coupling of the Higgs boson to gluons receives the same deviations as the one to fermions as the coupling is mediated by

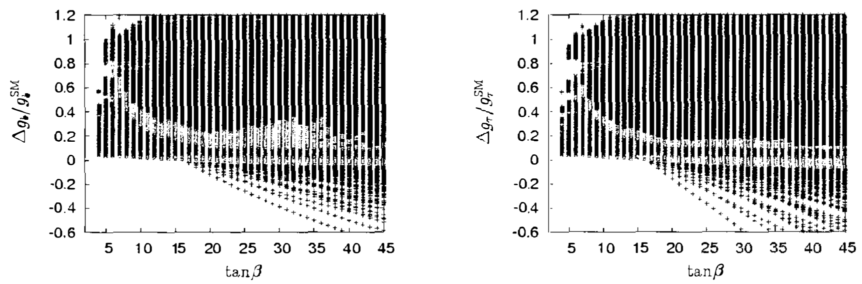

Figure 3: Deviation of the Higgs coupling to bottom quark normalized to the Standard Model value in dependence on $\tan\beta$. The colour code is the following: Red means several Higgs bosons can be discovered at the LHC, only a single one for all other points. Blue points denote exclusion by the branching ratio of $BR(b \to s\gamma)$. Lightblue, yellow and green stand for at least one stop quarks is lighter than 1 TeV, both are heavier than 1 TeV but not all heavier than 1.5 TeV, and all are heavier than 1.5 TeV, respectively.

fermion loops, $\Delta g_g/g_g^{\rm SM} \approx -c_H\xi/2 + c_y\xi \approx -8\% - 15\%\, c_y/c_H$. The coupling of Higgs bosons to photons is mediated by fermion and gauge boson loops. Taking both contributions into account gives the deviation $\Delta g_\gamma/g_\gamma^{\rm SM} \approx -c_H\xi/2 + 0.3c_y\xi \approx -8\% - 5\% c_y/c_H$.

4 Higgs Couplings in the Minimal Supersymmetric Standard Model

The minimal supersymmetric extension of the Standard Model, the MSSM, contains two Higgs doublets in order to give mass to up-type as well as down-type fermions and to keep the theory anomaly-free. These two Higgs doublets result in five physical Higgs bosons where the lightest one is neutral and CP-even (in the case of real parameters). In the following we will assume that the lightest Higgs boson, h, is the SM-like one. Depending on the point in parameter space the other Higgs bosons can be discovered at the LHC. We modelled the Higgs boson discovery potential for $300{\rm fb}^{-1}$ and a 14 TeV LHC after Fig. 1.21 in Ref. [14] (which has been taken from Ref. [13]). Additionally the MSSM comprises superpartners, partner fields to the Standard Model fields, which might be discovered at the LHC. For the discussion of the Higgs coupling deviations the most relevant superpartner are the top squarks, the superpartners of the top quarks. We discuss the maximal deviations depending on the mass of the top squark to get an estimate on how much a non-discovery of top squarks will influence the maximal deviations.

In Fig. 3, the deviations of the coupling of the Higgs boson to bottom quarks and to tau leptons normalised to the Standard Model one, $\Delta g_b/g_b^{SM}$ and $\Delta g_\tau/g_\tau^{SM}$, are shown on the left and right, respectively. Points shown in red correspond to parameter regions in the $\tan\beta$-M_A plane (where $\tan\beta$ is the ratio of the Higgs vacuum expectation values of the two Higgs doublets and M_A the mass of the CP-odd Higgs boson) for which several Higgs bosons are expected to be discovered while all other parameter points correspond to the single Higgs boson discovery region. The blue points for large $\tan\beta$ indicate an exclusion by the branching ratio of $\mathrm{BR}(b \to s\gamma)$ [15]. The lightblue, yellow and green points indicate stop quarks where at least one is lighter than 1 TeV, both are heavier than 1 TeV but not all heavier than 1.5 TeV, and all are heavier than 1.5 TeV, respectively. The scan has been performed using the program `FeynHiggs2.8.6` [16] and the scanned parameters are the CP-odd Higgs boson mass M_A from 200 to 800 GeV, $\tan\beta$ from 2 to 45, the diagonal soft breaking top squark masses $M_{L_{\tilde{Q}_3}} = M_{R_{\tilde{t}}}$ from 100 to 3000 GeV, the Higgs superfield mixing parameter μ between ± 1 TeV, and the top squark mixing parameter X_t between $\pm 150{\rm GeV} \cdot n_{max}$ where n_{max} is the nearest smaller integer to $2M_{L_{\tilde{Q}_3}}/150{\rm GeV}$. All the points fulfil the Higgs mass constraint of 123 GeV $\leq m_h \leq$ 127 GeV.

The largest deviation, up to 100%, can be found for $\tan\beta = 5$. At this point the single Higgs boson discovery region reaches to the lowest value of the CP-odd Higgs boson mass of 200 GeV.

Table 1: Summary of the approximate maximal coupling deviations in the three different models if no other particle is found at the LHC: Mixed-in Singlet Model, Composite Higgs Model, MSSM. For the $\Delta h\bar{b}b$ values in the MSSM, the superscript a refers to large $\tan\beta > 20$ and heavy top squarks and b to all other cases with a maximum of 100% for $\tan\beta = 5$. The last line gives the anticipated 1 σ sensitivities at the 14 TeV LHC with $3\,\mathrm{ab}^{-1}$ of accumulated luminosity.

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet Model	6%	6%	6%
Composite Higgs Model	8%	tens of %	tens of %
MSSM	< 1%	3%	10%^{a}, 100%^{b}
LHC 14 TeV, $3\,\mathrm{ab}^{-1}$	8%	10%	15%

As the deviation of the Higgs coupling to bottom quarks as well as to tau leptons decreases with $1/M_A^2$, a lower value of the CP-odd Higgs boson mass leads to a larger deviation. For larger $\tan\beta$ the maximal deviations are of the order of 10%.

For lighter top squarks, larger deviations can be found for large $\tan\beta$ in the case of the Higgs coupling to bottom quarks. This is due to $\tan\beta$ enhanced Δ_b effects [17] which arise due to a loop-induced coupling of the Higgs field H_u to the bottom quarks, where H_u is the Higgs field coupling to only the up-type quarks at tree-level. As the bottom squark masses are not completely independent of the top squarks masses, heavier top squarks lead to at least one heavier bottom squark which diminishes the Δ_b effect. In the case of the coupling to tau leptons, no corresponding effects are taken into account. They are expected to be smaller as they are pure electroweak effects.

The maximal deviations of the Higgs coupling to the gauge bosons are very small, below 1%, and for the Higgs coupling to top quarks they amount to roughly 3%.

5 Conclusion

The question of how large the maximal deviations from the SM Higgs couplings can be if no new physics is discovered by the LHC experiments has been discussed in the context of three different models, the Mixed-in Singlet Model, the Composite Higgs Model and the MSSM. In Tab. 1 the found approximate maximal deviations are summarized and for comparison the anticipated 1 σ sensitivities at the LHC with center of mass energy of 14 TeV with $3\,\mathrm{ab}^{-1}$ of accumulated luminosity [18] are listed. The deviations of the Higgs coupling to gauge bosons are less than 10% in all cases and tiny in the case of the MSSM. For the Higgs coupling to top quarks, the deviations can be several tens of percents in the case of the Composite Higgs Model depending on the actual scenario and less then 10% in all other cases. The largest variation can be found for the Higgs coupling to bottom quarks that can be of the order of several percents in the Composite Higgs model and, for $\tan\beta = 5$, up to 100% in the MSSM. For larger values of $\tan\beta$ and heavier top squarks the deviations can reach about 10 % in the MSSM.

Acknowledgments

H.R. would like to thank the organisers of "Rencontres de Moriond EW 2013" for financial support and a very enjoyable meeting.

References

1. G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716** (2012) 1 [arXiv:1207.7214 [hep-ex]]; S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716** (2012) 30 [arXiv:1207.7235 [hep-ex]].
2. F. Englert and R. Brout, Phys. Rev. Lett. **13** (1964) 321; P. W. Higgs, Phys. Lett. **12** (1964) 132; Phys. Rev. Lett. **13** (1964) 508; G. S. Guralnik, C. R. Hagen and T. W. B. Kibble, Phys. Rev. Lett. **13** (1964) 585; P. W. Higgs, Phys. Rev. **145** (1966) 1156; T. W. B. Kibble, Phys. Rev. **155** (1967) 1554.
3. R. S. Gupta, H. Rzehak and J. D. Wells, Phys. Rev. D **86** (2012) 095001 [arXiv:1206.3560 [hep-ph]].
4. R. S. Gupta, H. Rzehak and J. D. Wells, [arXiv:1305.6397 [hep-ph]].
5. R. Schabinger and J. D. Wells, Phys. Rev. D **72** (2005) 093007 [hep-ph/0509209].
6. M. Bowen, Y. Cui and J. D. Wells, JHEP **0703** (2007) 036 [hep-ph/0701035].
7. K. Hagiwara, S. Matsumoto, D. Haidt and C. S. Kim, Z. Phys. C **64**, 559 (1994) [Erratum-ibid. C **68**, 352 (1995)] [hep-ph/9409380].
8. W. M. Yao *et al.* [Particle Data Group Collaboration], J. Phys. GG **33**, 1 (2006).
9. G. F. Giudice, C. Grojean, A. Pomarol and R. Rattazzi, JHEP **0706** (2007) 045 [hep-ph/0703164].
10. A. Manohar and H. Georgi, Nucl. Phys. B **234**, 189 (1984).
11. J. R. Espinosa, C. Grojean and M. Mühlleitner, JHEP **1005**, 065 (2010) [arXiv:1003.3251 [hep-ph]].
12. R. Contino, C. Grojean, D. Pappadopulo, R. Rattazzi and A. Thamm, to appear.
13. L. Linssen *et al.* [CLIC], arXiv:1202.5940 [physics.ins-det].
14. ATLAS Collaboration (1999) "ATLAS: Detector and physics performance technical design report. Volume 2," CERN-LHCC-99-15.
15. M. S. Carena, D. Garcia, U. Nierste and C. E. M. Wagner, Phys. Lett. B **499** (2001) 141 [hep-ph/0010003]; T. Hahn, W. Hollik, J. I. Illana and S. Penaranda, hep-ph/0512315.
16. S. Heinemeyer, W. Hollik and G. Weiglein, Comput. Phys. Commun. **124** (2000) 76 [hep-ph/9812320]; S. Heinemeyer, W. Hollik and G. Weiglein, Eur. Phys. J. C **9** (1999) 343 [hep-ph/9812472]; G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, Eur. Phys. J. C **28** (2003) 133 [hep-ph/0212020]; M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak and G. Weiglein, JHEP **0702** (2007) 047 [hep-ph/0611326]; K. E. Williams, H. Rzehak and G. Weiglein, Eur. Phys. J. C **71** (2011) 1669 [arXiv:1103.1335 [hep-ph]]; see `www.feynhiggs.de` .
17. M. S. Carena, D. Garcia, U. Nierste and C. E. M. Wagner, Nucl. Phys. B **577** (2000) 88 [hep-ph/9912516]; L. Hofer, U. Nierste and D. Scherer, JHEP **0910** (2009) 081 [arXiv:0907.5408 [hep-ph]].
18. M. Klute, R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, arXiv:1205.2699 [hep-ph].