DETERMINATION OF HIGGS-BOSON COUPLINGS AT THE LHC

M. DÜHRSSEN¹, S. HEINEMEYER², H. LOGAN³, D. RAINWATER⁴, G. WEIGLEIN⁵ and D. ZEPPENFELD⁶

¹Physikalisches Institut, Universität Freiburg, D–79104 Freiburg, Germany
²CERN TH Division, Dept. of Physics, CH-1211 Geneva 23, Switzerland
³Dept. of Physics, University of Wisconsin, Madison, Wisconsin 53706 USA
⁴DESY Theory, Notkestr. 85, D–22603 Hamburg, Germany
⁵Institute for Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, UK
⁶Institut für Theoretische Physik, Universität Karlsruhe, D–76128 Karlsruhe, Germany

We investigate the determination of Higgs boson couplings to gauge bosons and fermions at the LHC from data on Higgs boson production and decay. We demonstrate that very mild theoretical assumptions, which are valid in general multi-Higgs doublet models, are sufficient to allow the extraction of absolute values of the couplings rather than just ratios of the couplings. For Higgs masses below 200 GeV we find accuracies of 10⁻⁴⁰% for the Higgs couplings and the total Higgs boson width after several years of LHC running. The sensitivity of the Higgs coupling measurements to deviations from the Standard Model predictions is studied for an MSSM scenario.

1 Introduction

If the Higgs mechanism is realized in nature, it is very likely that at least one Higgs boson will be discovered at the LHC. Within the Standard Model (SM), the Higgs boson can be observed in a variety of channels, in particular if its mass lies in the intermediate mass region, 114 < m_H < 250 GeV, as suggested by direct searches¹ and electroweak precision data². The situation is similar for Higgs bosons in this mass range in many extensions of the SM. Once a Higgs-like state is discovered, a precise measurement of its couplings will be mandatory in order to experimentally verify (or falsify) the Higgs mechanism.

The various Higgs couplings determine Higgs production cross sections and decay branching fractions. By measuring the rates of multiple channels, various combinations of couplings can be determined. A principal problem at the LHC is that there is no technique analogous to the measurement of the missing mass spectrum at a linear collider³ which would directly determine the total Higgs production cross section. In addition, some Higgs decay modes cannot be observed at the LHC. For example, H → gg or decays into light quarks will remain hidden below overwhelming QCD dijet backgrounds. The H → bb decay, which has by far the dominant branching ratio for a light SM-like Higgs, will be detectable but suffers from large experimental uncertainties. As a consequence of the strong correlations in the measurements of different Higgs couplings, only ratios of couplings (or partial widths) can be determined if no additional theoretical are made, see e.g. the analysis of Ref.⁴.

¹Talk given by G. Weiglein
It is therefore interesting to investigate whether absolute determinations of couplings become possible if suitable theoretical assumptions are employed. In Refs. 5, 6 (see also Ref. 7), such a strategy has been outlined, assuming the absence of unexpected decay channels and a SM ratio of the $H \to b\bar{b}$ and $H \to \tau\tau$ partial widths. These assumptions are valid, however, in only a restricted class of models. They can be violated, for instance, in the Minimal Supersymmetric Standard Model (MSSM).

In the present analysis, we make only a very mild theoretical assumption, which is valid in general multi-Higgs doublet models (with or without extra Higgs singlets; this class of models contains in particular the MSSM). In this class of models the strength of the Higgs–gauge-boson couplings does not exceed the SM value. We will demonstrate that the existence of such an upper bound on the Higgs–gauge-boson couplings is already sufficient to allow the extraction of absolute couplings rather than coupling ratios.

In the present analysis, we consider the expected accuracies at various stages of the LHC program: after 30 fb$^{-1}$ of low luminosity ($10^{33}$ cm$^{-2}$ sec$^{-1}$) running, 300 fb$^{-1}$ at high luminosity ($10^{34}$ cm$^{-2}$ sec$^{-1}$), and a mixed scenario where the weak boson fusion channels are assumed to suffer substantially from pile-up problems under high luminosity running conditions (making forward jet tagging and central jet veto fairly inefficient).

In order to investigate the sensitivity of the coupling measurements at the LHC to deviations from the SM predictions we consider as a specific example the no-mixing benchmark scenario of the MSSM as defined in Ref. 10. Other MSSM benchmark scenarios have been analyzed in Refs. 8, 9.

2 Strategy

In order to determine the properties of a physical state such as a Higgs boson, one needs at least as many separate measurements as properties to be measured, although two or more measurements can be made from the same channel if different information is used, e.g., total rate and an angular distribution. Fortunately, the LHC will provide us with many different Higgs observation channels. In the SM there are four relevant production modes: gluon fusion (GF; loop-mediated, dominated by the top quark), which dominates inclusive production; weak boson fusion (WBF), which has an additional pair of hard and far-forward/backward jets in the final state; top-quark associated production ($t\bar{t}H$); and weak boson associated production ($WH, ZH$), where the weak boson is identified by its leptonic decay.

Although a Higgs boson is expected to couple to all SM particles, not all these decays would be observable. Very rare decays (e.g., to electrons) would have no observable rate, and other modes are unidentifiable QCD final states in a hadron collider environment (gluons or quarks lighter than bottom). In general, however, the LHC will be able to observe Higgs decays to photons, weak bosons, tau leptons and $b$ quarks, in the range of Higgs masses where the branching ratio (BR) in question is not too small.

For a Higgs in the intermediate mass range, the total width, $\Gamma$, is expected to be small enough to use the narrow-width approximation in extracting couplings. The rate of any channel (with the $H$ decaying to final state particles $xx$) is, to good approximation, given by

$$\sigma(H) \times \text{BR}(H \to xx) = \frac{\sigma(H)}{\Gamma_p} \frac{\Gamma_p \Gamma_x}{\Gamma},$$

(1)

where $\Gamma_p$ is the Higgs partial width involving the production couplings, and where the Higgs branching ratio for the decay is written as $\text{BR}(H \to xx) = \Gamma_x/\Gamma$. Even with cuts, the observed rate directly determines the product $\Gamma_p \Gamma_x/\Gamma$ (normalized to the calculable SM value of this product). The LHC will have access to (or provide upper limits on) combinations of
\( \Gamma_g, \Gamma_W, \Gamma_Z, \Gamma_\gamma, \Gamma_\tau, \Gamma_b \) and the square of the top Yukawa coupling, \( Y_t. \)

We use the following channels in our analysis \( ^8 \): GF \( gg \rightarrow H \rightarrow ZZ \), WBF \( qq H \rightarrow qq ZZ \), GF \( gg \rightarrow H \rightarrow WW \), WBF \( qq H \rightarrow qq WW \), \( W H \rightarrow W WW \) (2\( l \) and 3\( l \) final state), \( t \bar{t} H (H \rightarrow WW, t \rightarrow W b) \) (2\( l \) and 3\( l \) final state), inclusive Higgs boson production: \( H \rightarrow \gamma \gamma \), WBF \( qq H \rightarrow qq \gamma \gamma \), \( t \bar{t} H (H \rightarrow \gamma \gamma) \), \( W H (H \rightarrow \gamma \gamma) \), \( Z H (H \rightarrow \gamma \gamma) \), WBF \( qq H \rightarrow qq \tau \tau \), \( t \bar{t} H (H \rightarrow b \bar{b}) \).

The production and decay channels listed above refer to a single Higgs resonance, with decay signatures which also exist in the SM. The Higgs sector may be much richer, of course. For instance, the MSSM with its two Higgs doublets predicts the existence of three neutral and one pair of charged Higgs boson, and the LHC may be able to directly observe several of these resonances. Within SUSY models, additional decays, e.g., into very light super-partners, may be kinematically allowed. The additional observation of super-partners or of heavier Higgs bosons will strongly focus the theoretical framework and restrict the parameter space of a Higgs couplings analysis. For our present analysis we ignore the information which would be supplied by the observation of additional new particles. Instead we ask the question of how well LHC measurements of the above decay modes of a single Higgs resonance can determine the various Higgs boson couplings or partial widths.

While from the channels listed above ratios of couplings (or partial widths) can be extracted in a fairly model-independent way, see e.g. Ref. \( ^4 \), further theoretical assumptions are necessary in order to determine absolute values of the Higgs couplings to fermions and bosons and of the total Higgs boson width. The only assumption that we will make in the following is that the strength of the Higgs-gauge-boson couplings does not exceed the SM value,

\[
\Gamma_V \leq \Gamma_V^{\text{SM}}, \quad V = W, Z . \tag{2}
\]

This assumption is justified in any model with an arbitrary number of Higgs doublets (with or without additional Higgs singlets), i.e., it is true for the MSSM in particular.

While eq. (2) constitutes an upper bound on the Higgs coupling to weak bosons, the mere observation of Higgs production puts a lower bound on the production couplings and, thereby, on the total Higgs width. The constraint \( \Gamma_V \leq \Gamma_V^{\text{SM}} \), combined with a measurement of \( \Gamma_V^2/\Gamma \) from observation of \( H \rightarrow VV \) in WBF, then puts an upper bound on the Higgs total width, \( \Gamma \). Thus, an absolute determination of the Higgs total width is possible in this way. Using this result, an absolute determination also becomes possible for Higgs couplings to gauge bosons and fermions.

We obtain the expected LHC accuracies from a fit based on experimental information for the channels listed above. For details of the fitting procedure, see Refs. \( ^{11,13} \). The statistical errors for the results presented in Sec. \( ^8 \) are obtained for the case that the channels listed above are observed with SM rates. In the fit we allow for undetected Higgs decays (giving rise to additional partial widths) and additional contributions to the loop-induced Higgs couplings to photon pairs or gluon pairs due to non-SM particles running in the loops. The estimated systematic errors\( ^{11,13} \) include a 5\% luminosity error, uncertainties on the reconstruction/identification of leptons (2\%), photons (2\%), b-quarks (3\%), \( \tau \)-jets (3\%) and forward tagging jets and veto jets (5\%), error propagation for background determination from side-band analyses (assuming an error from 0.1\% for \( H \rightarrow \gamma \gamma \) to 5\% for \( H \rightarrow WW \) and \( H \rightarrow \tau \tau \) to 10\% for \( H \rightarrow b \bar{b} \) on the shape plus the statistical error of the background sample used for normalization) and theoretical and parametric uncertainties on Higgs boson production (20\% GF, 15\% \( t \bar{t} H \), 7\% \( W H/ZH \), 4\% WBF) and decays (1\%, as a future expectation). For the WBF channels there is an additional uncertainty on the minijet veto and jet tagging efficiency (combined) of 5\%, as well as an added 10\% contribution from \( gg \rightarrow H g g \)\( ^{11} \), which has its own theory uncertainty of a factor of 2.

\( ^4 \)We do not write this as a partial width, \( \Gamma_\gamma \), because, for a light Higgs, the decay \( H \rightarrow t \bar{t} \) is kinematically forbidden.
The 1σ uncertainties on each parameter are determined in the fit by finding the maximum deviation of that parameter from its best fit value that lies on the Δχ2 = 1 surface. We repeat the procedure for each Higgs mass value in the range 110 ≤ m_H ≤ 190 GeV in steps of 10 GeV.

We perform the fits under three luminosity assumptions for the LHC:

- 30 fb\(^{-1}\) at each of two experiments, denoted 2 × 30 fb\(^{-1}\);
- 300 fb\(^{-1}\) at each of two experiments, of which only 100 fb\(^{-1}\) is usable for WBF channels at each experiment, denoted 2 × 300 + 2 × 100 fb\(^{-1}\);
- 300 fb\(^{-1}\) at each of two experiments, with the full luminosity usable for WBF channels, denoted 2 × 300 fb\(^{-1}\).

The second case allows for possible significant degradation of the WBF channels in a high luminosity environment, while the third case serves to investigate the possible physics gain of additional improvements in WBF studies at high luminosity.

In both cases the Higgs boson mass is not fitted, i.e. it is assumed that the mass of the Higgs boson can be measured with high precision (Δm_H/m_H < 1%) in \(H \rightarrow Z^(*) Z^(*) \rightarrow 4\ell\) or \(H \rightarrow \gamma \gamma\). If both channels go unobserved, the theoretical predictions of Higgs boson branching ratios receive a large error due to the relatively low precision and larger systematic errors of \(m_H\) measurements in WBF \(H \rightarrow \tau \tau\) or \(H \rightarrow WW\).

### 3 Results for general multi-Higgs-doublet models

We obtain the results for the Higgs couplings-squared in general multi-Higgs-doublet models using the assumption that

\[
g^2(H, W) < 1.05 \cdot g^2(H, W, SM), \quad g^2(H, Z) < 1.05 \cdot g^2(H, Z, SM) .
\]

Any model that contains only Higgs doublets and singlets will satisfy the relations \(g^2(H, W) \leq g^2(H, W, SM)\) and \(g^2(H, Z) \leq g^2(H, Z, SM)\). The extra 5% margin allows for theoretical uncertainties in the translation between couplings-squared and partial widths, and also for small admixtures of exotic Higgs states, like SU(2) triplets. As explained above, we allow for the possibility of additional particles running in the loops for \(H \rightarrow \gamma \gamma\) and \(gg \rightarrow H\), fitted by a positive or negative new partial width to these contributions.

The results for the constraints on the new partial widths are shown in Fig. 1 as a function of Higgs mass for the 2 × 30 fb\(^{-1}\) and 2 × 300 + 2 × 100 fb\(^{-1}\) luminosity scenarios assuming that SM rates are observed. The new partial width for \(H \rightarrow \gamma \gamma\) is most tightly constrained for 120 ≤ m_H ≤ 140 GeV, being less than ±(25 − 35)% of \(\Gamma_{\gamma}^{SM}\) for 2 × 30 fb\(^{-1}\) and ±(10 − 15)% for 2 × 300 + 2 × 100 fb\(^{-1}\). The new partial width for \(gg \rightarrow H\) is less well constrained, being less than ±(30 − 90)% of \(\Gamma_{g}^{SM}\) for 2 × 30 fb\(^{-1}\) and ±(30 − 45)% for 2 × 300 + 2 × 100 fb\(^{-1}\) over the whole range of Higgs masses.

Additional light hadronic decays of the Higgs boson are fitted with a partial width for undetected decays. (Invisible decays, e.g. to neutralinos could still be observable\(^{12}\)) This undetected partial width can be constrained to be less than 15 − 55% of the total fitted Higgs width for 2 × 30 fb\(^{-1}\) and 15 − 30% for 2 × 300 + 2 × 100 fb\(^{-1}\), at the 1σ level. This undetected partial width is most tightly constrained for Higgs masses above 160 GeV.

The resulting precisions on the Higgs boson couplings squared are shown in Fig. 2 as a function of Higgs mass for the same luminosity scenarios, 2 × 30 fb\(^{-1}\) and 2 × 300 + 2 × 100 fb\(^{-1}\), assuming SM rates. For 2 × 300 + 2 × 100 fb\(^{-1}\), typical accuracies range between 20 and 30% for Higgs masses below 150 GeV. Above W-pair threshold the measurement of the then-dominant \(H \rightarrow WW, ZZ\) partial widths improves to the 10% level. The case of 2 × 300 fb\(^{-1}\) yields only small improvements over the right-hand panel in Fig. 2 except in the case of \(g^2(H, \tau)\) which shows moderate improvement. However, since this happens for Higgs masses below ∼ 140 GeV,
Figure 1: Relative precisions of fitted new partial widths as a function of the Higgs mass assuming that SM rates are observed with 30 fb$^{-1}$ at each of two experiments (left) and 300 fb$^{-1}$ at each of two experiments for all channels except WBF, for which 100 fb$^{-1}$ is assumed (right). The new partial width can be due to new particles in the loops for $H \rightarrow \gamma \gamma$ and $gg \rightarrow H$ or due to unobservable decay modes. See text for details. Here we make the weak assumption that $g_2^2(H, t) \cdot g_2^2(H, V, SM) (V = W, Z) < 1.05$.

this effect can be relatively important in the case of MSSM analyses, see Sec. 4. This can be understood because the $H \rightarrow \tau \tau$ decay is measured only in WBF, and $g(H, \tau)$ does not have a large effect on the Higgs total width or loop-induced couplings.

The results shown in Fig. 2 reflect present understanding of detector effects and systematic errors. One should note that improved selection and higher acceptance will decrease the statistical errors. At least as important is work on the reduction of systematic errors. In Fig. 2 the thin lines show expectations with vanishingly small systematics: systematic errors contribute up to half the total error, especially at high luminosity.

For a Higgs boson mass below 140 GeV the main contribution to the systematic uncertainty is the background normalization from sidebands. The largest contribution is from $H \rightarrow b \bar{b}$. For this channel the signal to background ratio is between 1:4 and 1:10. For the background normalization we assume a systematic error of 10%. This leads to a huge total systematic error on the measurement of $\Gamma_b$, which is the main contribution to the total width $\Gamma_H$ (the BR($H \rightarrow b \bar{b}$) is between 80% and 30%). But a measurement of absolute couplings needs $\Gamma_H$ as input, as discussed above, so all measurements of couplings share the large systematic uncertainty on $H \rightarrow b \bar{b}$.

For a Higgs boson mass above 150 GeV there are two dominant contributions to the systematic error: the background normalizations in GF, WBF and $t\bar{t}H$ (systematic error between 5% and 15%) and the QCD uncertainty in the cross section calculations for GF (20%) and $t\bar{t}H$ (15%) from given Higgs boson couplings. This is especially evident in the measurement of the top coupling which is based on the $t\bar{t}H$ channel. Here the systematic uncertainties contribute...
Figure 2: Relative precision of fitted Higgs couplings-squared as a function of the Higgs mass for the $2 \times 30$ fb$^{-1}$ (left) and the $2 \times 300 + 2 \times 100$ fb$^{-1}$ (right) luminosity scenarios. We make the weak assumption that $g^2(H,V) < 1.05 \cdot g^2(H,V,SM)$ ($V = W, Z$) but allow for new particles in the loops for $H \to \gamma\gamma$ and $gg \to H$ and for unobservable decay modes. See text for details.

half of the total error.

The precision of the extracted couplings improves if more restrictive theoretical assumptions are applied, see Refs. 8, 9 for a discussion.

4 Sensitivity to deviations from the Standard Model

If the values obtained for the Higgs boson couplings differ from the SM predictions, one can investigate at which significance the SM can be excluded from LHC measurements in the Higgs sector alone. As a specific example of physics beyond the SM, we consider here the MSSM.

If supersymmetric partners of the SM particles were detected at the LHC, this would of course rule out the SM. It would nevertheless be of interest in such a situation to directly verify the non-SM nature of the Higgs sector. Besides the possible detection of the additional states of an extended Higgs sector, a precise measurement of the couplings of the lightest (SM-like) Higgs boson will be crucial.

For definiteness let us assume that the pseudoscalar Higgs and the charged Higgs are fairly heavy ($M_A \gtrsim 150$ GeV, and they may, but need not, have been observed directly) so that they do not interfere with the $h$ signal extraction. We furthermore assume that only decays into SM particles are detected. A fit of the Higgs couplings can then be performed as outlined above, where the rates are obtained according to a certain MSSM scenario. A quantitative, global measure of how well the LHC can distinguish the SM from a specific MSSM scenario is provided by a $\chi^2$-analysis of the deviations expected for this SUSY scenario.

As a specific example we consider the no-mixing scenario scenario of Ref. 10 (for results in
the other benchmark scenarios of Ref.\cite{10}, see Ref.\cite{8}). We calculate the mass and branching fractions of the MSSM Higgs boson using HDECAY3.0\cite{14}, using the FeynHiggsFast1.2.2\cite{15,16} option to compute the MSSM Higgs masses and couplings. Assuming that, for a given $M_A$ and $\tan \beta$, the corresponding SUSY model is realized in nature, we may ask at what significance the SM would be ruled out from $h$ measurements alone.

![Figure 3: Fit within the no-mixing benchmark scenario of the MSSM in the $M_A$–$\tan \beta$ plane for three luminosity scenarios. The two panels show the region (to the left of the curves) which would yield a $\geq 5\sigma$ ($\Delta \chi^2 \geq 25$) or $\geq 3\sigma$ ($\Delta \chi^2 \geq 9$) discrepancy from the SM. The mostly-horizontal dotted lines are contours for different values of $m_h$.](image)

The resulting contours are shown in Fig. 3 for the three luminosity assumptions defined above. In the areas to the left of the contours the SM can be rejected with more than $5\sigma$ or $3\sigma$ significance, respectively. The $\chi^2$ definition in Fig. 3 assumes the same systematic errors as our analysis in Sec. 3. Event rates and resulting statistical errors, however, are those expected for the MSSM. For $2 \times 300 + 2 \times 100 \text{ fb}^{-1}$ a deviation from the SM can be established at the $3\sigma$ level in this scenario up to $M_A \simeq 350$ GeV and at the $5\sigma$ level up to $M_A \simeq 250$ GeV.

The source of the MSSM analysis sensitivity can be understood as follows. For $M_A \gtrsim 200$ GeV, the couplings of $h$ to SM particles all essentially obtain their SM values except for the $hbb$ and $h\tau\tau$ couplings, due to the slower decoupling behavior of the latter. In this scenario the SUSY threshold corrections to the $b$ mass are also quite small, so that the ratio of the $hbb$ and $h\tau\tau$ couplings essentially takes its SM value. The $h \to b\bar{b}$ decay mode dominates the Higgs total width in this scenario. The pattern of Higgs coupling deviations can then be summarized as follows: all the Higgs production cross sections considered in our study are SM-like. The partial widths into $b\bar{b}$ and $\tau\tau$ are equally enhanced (but with SM-like branching ratios since the total width is dominated by $b\bar{b}$ and $\tau\tau$ decays). This results in a larger total width for the Higgs boson. The branching ratios into all other final states ($WW^*, ZZ^*, \gamma\gamma$) are smaller than in the SM, reflecting this total width enhancement.

It should be noted that the shown sensitivity to $M_A$ cannot directly be translated into indirect bounds on $M_A$. In order to establish realistic bounds on $M_A$, a careful analysis of the experimental errors arising from the incomplete knowledge of the spectrum of supersymmetric particles and of the theoretical uncertainties from unknown higher-order corrections is necessary.
5 Conclusions

Measurements of the Higgs sector are expected to provide many complementary signatures after several years of LHC running. Combining these measurements allows one to extract information on Higgs partial widths and Higgs couplings to fermions and gauge bosons. Because significant contributions from unobservable channels cannot easily be ruled out at the LHC, model-independent analyses produce large correlations between extracted partial widths. We have shown that a reduction of correlations and hence an absolute determination of Higgs boson couplings and the total Higgs width can be achieved if weak theory assumptions are made. We have analyzed the constraint valid in generic multi-Higgs-doublet models, namely that $HVV$ couplings cannot be larger than within the SM. Within such models, the LHC can measure Higgs couplings to the top quark, tau lepton, and $W$ and $Z$ bosons with accuracies in the $10-30\%$ range once $300 \text{ fb}^{-1}$ of data have been collected. If, on the other hand, the SLHC will be realized, one could hope for significant improvements over the results presented here. This applies in particular for the bottom Yukawa coupling determination.

Within the MSSM, significant deviations in the Higgs sector should be observable at the LHC, provided that the charged and the pseudoscalar Higgs masses are not too heavy, i.e., that decoupling is not completely realized. Within the no-mixing benchmark scenario and with $300 \text{ fb}^{-1}$ of data, the LHC can distinguish the MSSM and the SM at the $3\sigma$ level up to $M_A \simeq 350 \text{ GeV}$ and with $5\sigma$ significance up to $M_A \simeq 250 \text{ GeV}$ with the Higgs data alone. The LHC will thus provide a surprisingly sensitive first look at the Higgs sector, even though it cannot match the precision and model-independence of analyses which are expected for a linear $e^+e^-$ collider.

So far we have investigated the situation where no important channel suffers substantial suppression. Scenarios where such a suppression occurs will be analyzed in a forthcoming publication.

Acknowledgments

We would like to thank M. Carena for enjoyable discussions during early stages of this work. H.L. was supported in part by the U.S. Department of Energy under grant DE-FG02-95ER40896 and in part by the Wisconsin Alumni Research Foundation. This work has been supported by the European Community’s Human Potential Programme under contract HPRN-CT-2000-00149 Physics at Colliders. G.W. thanks the organizers of the XXXIXth Rencontres de Moriond for the kind invitation and the pleasant atmosphere enjoyed at La Thuile.

References

1. R. Barate et al. [LEP Higgs working group], Phys. Lett. B 565 (2003) 61 [arXiv:hep-ex/0306033].
2. M. W. Grünewald, arXiv:hep-ex/0304023 updated as: S. Roth, talk given at “Rencontres de Moriond: QCD and Hadronic interactions”, La Thuile (Italy), March 28 - April 4 2004, see: moriond.in2p3.fr/QCD/2004/ThursdayAfternoon/Roth.pdf; see also: lepewwg.web.cern.ch/LEPEWG/Welcome.html.
3. P. Garcia-Abia and W. Lohmann, Eur. Phys. J. directC 2 (2000) 2 [arXiv:hep-ex/9908065].
4. M. Dührssen, ATL-PHYS-2003-030, available from http://cdsweb.cern.ch.
5. A. Djouadi et al., [arXiv:hep-ph/0002258]
6. D. Zeppenfeld, R. Kinnunen, A. Nikitenko and E. Richter-Was, Phys. Rev. D 62 (2000) 013009 [arXiv:hep-ph/0002036].
7. A. Belyaev and L. Reina, JHEP 0208, 041 (2002) arXiv:hep-ph/0205270.
8. M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein and D. Zeppenfeld, arXiv:hep-ph/0406323.
9. K. A. Assamagan et al., arXiv:hep-ph/0406152.
10. M. Carena, S. Heinemeyer, C. E. M. Wagner and G. Weiglein, Eur. Phys. J. C 26 (2003) 601 arXiv:hep-ph/0202167.
11. V. Del Duca et al., Phys. Rev. Lett. 87, 122001 (2001) arXiv:hep-ph/0105129.
12. O. J. P. Eboli and D. Zeppenfeld, Phys. Lett. B 495 (2000) 147 arXiv:hep-ph/0009158; R. M. Godbole, M. Guchait, K. Mazumdar, S. Moretti and D. P. Roy, Phys. Lett. B 571, 184 (2003) arXiv:hep-ph/0304137.
13. J. Cammin and M. Schumacher, ATL-PHYS-2003-024.
14. A. Djouadi, J. Kalinowski and M. Spira, Comput. Phys. Commun. 108 (1998) 56 arXiv:hep-ph/9704448.
15. S. Heinemeyer, W. Hollik and G. Weiglein, arXiv:hep-ph/0002213.
16. S. Heinemeyer, W. Hollik and G. Weiglein, Phys. Lett. B 455 (1999) 179 arXiv:hep-ph/9903404.
17. J. A. Aguilar-Saavedra et al. [ECFA/DESY LC Physics Working Group Collaboration], arXiv:hep-ph/0106315.
18. T. Abe et al. [American Linear Collider Working Group Collaboration], in Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001) ed. N. Graf, arXiv:hep-ex/0106056.
19. K. Abe et al. [ACFA Linear Collider Working Group Collaboration], arXiv:hep-ph/0109166.