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Abstract

The particle discovered in the Higgs boson searches at the LHC with a mass of about 125 GeV can be identified with one neutral Higgs boson in a variety of Beyond the Standard Model (BSM) theories with an extended Higgs sector. Limits on the couplings between additional Higgs fields to the electroweak gauge-bosons in such theories can be obtained by model-independent Higgs searches at lepton colliders. We present an extrapolation of the limits obtained at LEP for a future lepton collider and can show that the ILC with polarized beams and a total luminosity of $\mathcal{L} = 2000\ \text{fb}^{-1}$ is very sensitive to such reduced Higgs-gauge-boson couplings up to about 4%. We apply the extrapolated limits on BSM models with an extended Higgs-sector.

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1 Introduction

With the discovery of a Higgs boson in the year 2012, the Standard Model (SM) seems to be completed. Within the current experimental accuracy, the observed properties of the Higgs boson coincide very well with the predictions for a Higgs boson in the SM. Additional Higgs bosons appear in a large class of new physics models as, for instance, in a singlet extended SM, two-Higgs-doublet model (2HDM) and in supersymmetric models (MSSM, NMSSM, etc.). These new Higgs fields can mix, but their couplings to gauge bosons have to fulfill a sum rule:

$$(g_{HVV}^{\rm SM})^2 = \sum (g_{\phi VV})^2, \quad \text{where} \quad V \in \{W, Z\}. \tag{1}$$

In physics models Beyond the Standard Model (BSM) the Higgs boson couplings get further contributions, however, only within the per cent level. Therefore, measurements with high precision will be mandatory to be sensitive to deviations from the SM. The measurements of all Higgs bosons to gauge bosons will therefore be an important consistency test for the closure of the SM or for opening the window to new physics.

As already mentioned, in many BSM models additional Higgs bosons appear. In the Minimal Supersymmetric extension of the Standard Model (MSSM), for instance, a Higgs boson at 125 GeV would uniquely point to a SM-like Higgs boson at this mass without any further lighter Higgs masses. However, already in the Next-to-Minimal Supersymmetric Model (NMSSM) the additional Higgs singlet relieves the bounds and offers light Higgs bosons below 125 GeV. Since such bosons necessarily have a reduced couplings to gauge bosons, very light Higgs bosons —that escaped LEP and Tevatron bounds— are still not yet excluded and provide a very interesting framework for new physics.

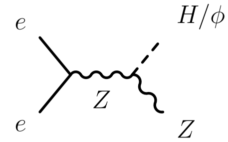
In the current paper we study the sensitivity of the ILC in its first stage of $\sqrt{s} = 250$ GeV cms energy to such light Higgs bosons far below the LEP limit. Due to the clean environment, the low beamstahlung, the precise knowledge on the beam energy and the availability of polarized beams, the ILC is perfectly suited to be sensitive to such light additional Higgs bosons.

The two main production processes for Higgs bosons are Higgs-strahlung ($e^+e^- \to H/\phi Z$), dominant at lower masses and energies, and via WW-fusion ($e^+e^- \to H\nu\bar{\nu}$) dominant at higher Higgs masses and cms energies. In the current study, we concentrate therefore on the Higgs-strahlung process and use two approaches: we either study the Higgs decay process $H \to b\bar{b}$ and use the Z-decay into $\mu^+\mu^-$ for validation (perfomed at LEP) or use the recoil method and expoit only the Z-decays, here $Z \to \mu^+\mu^-$, (perfomed at the OPAL experience).

As criteria whether a light Higgs boson is accessible, the statistical method S_{95} has been applied for the two approaches, the details are explained in Sect. 2. In Sect. 3 the method is validated with the results obtained at LEP and in Sect. 4 the discovery potential of the ILC for such light Higgs bosons is discussed. Conclusions are given in Sec. 5.

2 Details on the applied methods

We consider the 'Higgs-strahlung' process



(2)

with the Z-boson and the scalar H, ϕ decaying into fermions,

$$e^- + e^+ \to Z + \{H/\phi\} \to b + \bar{b} + \mu^- + \mu^+. \tag{3}$$

In order to study the sensitivity to lighter Higgs masses, we evaluate a hypothetical signal process, where the SM-Higgs in Eq. 3 is replaced by a new scalar ϕ. The new scalar ϕ is assumed to have the same couplings as the SM-Higgs scalar, but to have a different mass m_ϕ.

We use the statistical method called S_{95}, described in refs. [1,2], here used in a simplified approach, see also [3], where event samples for the two hypotheses 'all events are generated by the background only' or 'all events are generated by the background plus a hypothetical signal'. The quantity

$$S_{95} = \frac{\hat{\sigma}}{\sigma_{\mathrm{ref}}} = \frac{\hat{n}}{n} \tag{4}$$

gives an upper limit $\hat{\sigma}$ on a cross-section, that is compatible with the 'background only' hypothesis at the 95% confidence level, normalized on a reference cross section σ_{ref}. As reference process we regard in Eq. 3 the scalar to be the Higgs boson of the SM. This quantity S_{95} is equal to the maximal allowed signal rate $\hat{n}$ normalized on the total signal rate n. Since it is assumed that ϕ has SM-coupling but only a different mass, Eq. 4 can be interpreted as the ratio between the squared couplings of the scalars ϕ (H) with the Z-boson, $g^2_{\phi Z}$ (g^2_{HZ}), respectively:

$$S_{95} \mathrel{\hat{=}} \left| \frac{g^2_{\phi Z}}{g^2_{HZ}} \right|. \tag{5}$$

The event samples for

$$e^- + e^+ \to b + \bar{b} + \mu^- + \mu^+ \tag{6}$$

are generated with the Monte Carlo generator `Whizard-2.4.1` and contain the signal processes of Eq. 3.

For the given process gauge invariance forbids to generate signal and background events separately. The obtained events are ordered by either the invariant or recoil mass m of the quark- or lepton-system for this analysis. The obtained signal rate in the i-th bin is obtained by the difference of the event rates for the background plus signal (sb_i) and the background only hypotheses (b_i), and the signal rate s_i is obtained by $sb_i - b_i$. Negative rates for signal events are cut, $s_i = \max(0,\ sb_i - b_i)$.

The obtained events are identified by either the invariant or recoil mass m of the quark- or lepton-system for this analysis.

We assume that the number of potential signal events d_i in each of the i bins are distributed according to a Poisson distribution with the expected values b_i for the 'background only' and $s_i + b_i$ for the 'background plus signal' hypotheses, respectively. The test statistic

$$Q = \frac{L_{s+b}}{L_b} = e^{-n} \prod_{\text{bins } i} \frac{(s_i + b_i)^{d_i}}{(b_i)^{d_i}} \tag{7}$$

orders the outcome of test experiments according to their 'signal likeness'. While the expectation values of the Poisson distributions have to be determined *a priori*, the numbers of potential signal events d_i have to be determined experimentally. For this work we consider only simulated events, and thus $d_i = s_i$. The logarithm of the test-statistic reveals the weights for the number of potential signal events per bin as

$$w_i = \log\left(1 + \frac{s_i}{b_i}\right). \tag{8}$$

This definition requires the presence of at least one background event per considered bin. In order to accommodate this, we choose the luminosity for the simulation large enough that at least one event can be found in each bin, i.e. $b_i \geq 1$, and scale the luminosity afterwards with a factor c to the desired value. The weights w_i are not affected by the scaling procedure.

With the weight factors of Eq. (8), the scaling factor S_{95}, given in Eq. (4) can be expressed [2] as

$$S_{95} = \frac{\hat{n}}{n} = \frac{K \cdot \sigma_{sb}}{\langle X \rangle_s} = \frac{1.96 \cdot \sigma_{sb}}{\langle X \rangle_s}, \tag{9}$$

where K denotes the number of standard deviations for the significance: $K = 1.96$ corresponds to a c.l. of 5% for the signal hypothesis, the variance σ_{sb} is given by $\sigma_{sb}^2 = \sum_{\text{bins } i} w_i^2 (s_i + b_i)$ and $\langle X \rangle_s = \sum_{\text{bins } i} w_i s_i$.

3 Validation of the methods with results from LEP I and LEP II

In order to test the method we apply it in a first step on the obtained data from LEP and try to recover the published results and the interpretation for new physics [1, 4]. Furthermore, in a second step, we reproduce the results of the OPAL collaboration that performed also Higgs analysis with the recoil method [5].

We simulated the process $e^+ + e^- \to b + \bar{b} + \mu^+ + \mu^-$ with the SM implementation of `Whizard 2.4.1` [6, 7]. This process contains the decays of the scalar and Z-boson in the Higgs-strahlung process, where we consider only the dominant process with the Higgs decaying into b-quarks and the Z-boson decaying into the μ-leptons. Our 'background only' and 'background plus signal' hypotheses are generated by adapting the mass of the implemented SM-Higgs field, correspondingly, i.e. concerning the 'background only' hypothesis we chose the mass m_ϕ of the implemented scalar beyond the kinematic accessibility of the LEP experiments.

For LEP I we consider the integrated luminosity at the center-of-mass energy of 91.2 GeV. For LEP II we simulate the experiment with the integrated luminosity per year with the highest achieved energy in each period, with exception of the last year, where we assume the lowest energy of 206 GeV [8]. The considered luminosity per experiment is given in tab. 1.

Table 1: LEP luminosity $\int dt\mathcal{L}$ integrated over the run time at specified center of mass energies $\sqrt{s}$ taken at the maximal achieved c.m. energy per year, with the exception of the last year, where the luminosity at the lowest energy of $\sqrt{s} = 206$ was assumed, see [8].

$\sqrt{s}$/GeV	91.2	172	184	189	202	206
$\int dt\mathcal{L}/\text{pb}^{-1}$	208.44	24.7	73.4	199.7	253	233.4

For the simulation, however we generated a luminosity that was 400 times the LEP-luminosity in order to obtain finite weight factors w_i (Eq. 8) and to reduce the statistical error.

We do not consider hadronization effects of the b-quarks or detector effects. This simplification leads to an over-optimistic estimate for the signal efficiency and thus for the observed signal rates. This effect is countered, however, by the restraint to only one decay mode for the scalar and Z-bosons.

Since the signal rates are not explicitly given for the LEP experiments [3], we scale the event rates of our results by a factor c, which yields an effective luminosity $\mathcal{L}_{\text{eff}}$ of

$$\mathcal{L}_{\text{eff}} = c_{\text{trad}} \cdot \mathcal{L} = c_{\text{recoil}}\epsilon \cdot \mathcal{L}, \tag{10}$$

where $\mathcal{L}$ is the actual luminosity derived from the values given in tab. 1. The scaling factors c_{trad}, c_{recoil} depend on the parameters of the experiment and the analysis. We determined the factors via comparison with the official numbers from LEP for S_{95}. Such a scaling factor can only approximate the effects of an exact analysis. In case that the decay modes $H/\phi \to b\bar{b}$ and $Z \to \mu^+\mu^-$ are considered —we call this the 'traditional' method at LEP— it is expected to obtain $\sim 30\times$ the luminosity (for an ideal detector). Assuming a median signal efficiency of 50% for the signal rates, the coefficients c_{trad} should therefore be not larger than ≈ 15. Applying the recoil method, used by the OPAL experiment, only the decay mode $Z \to \mu^+\mu^-$ has been used and explicit efficiency ϵ have been published, therefore the corresponding coefficients c_{recoil} are smaller. The coefficients are given in tab. 2.

Table 2: Luminosity scaling factors c_{trad} and c_{recoil} derived via comparison with official S_{95} results from LEP for different center of mass energies.

$\sqrt{s}$/GeV	91.2	> 91.2
traditional	$c_{\text{trad}} = 12$	$c_{\text{trad}} = 4$
recoil	$c_{\text{recoil}} = 4$	$c_{\text{recoil}} = 1$

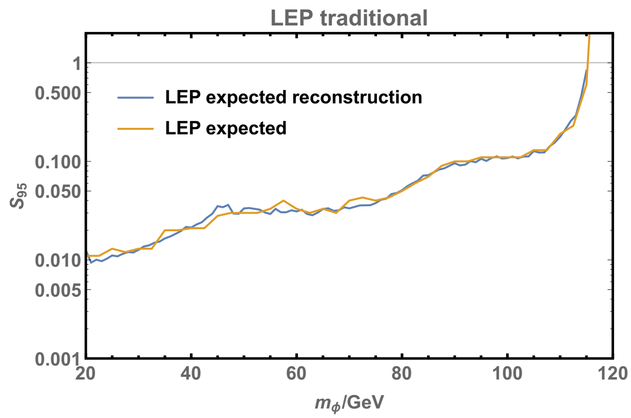


Figure 1: The LEP expected result compared with our approach to derive S_{95} for the process $e^+e^- \to ZH/\phi- > \mu^+\mu^- b\bar{b}$ ('traditional method'). The scaling factor $c_{\rm trad}$, see Table 2, had to be used to account for detector effects and the restriction to $b\bar{b}$ only.

3.1 Comparison with LEP data using the H/ϕ decay mode – 'LEP Traditional'

In order to compare with LEP data, event samples for the process $e^+ + e^- \to H/\phi Z \to b\bar{b}\mu^+\mu^-$ are generated. However, this process depends on the width via $1/\Gamma_{H,\phi}$. Changing the mass would therefore also induce to adjust the width. However, we obtain the best consistency results when assuming a constant width of the scalar

$$\Gamma_\phi(m_\phi) = \Gamma_H^{(\rm SM)}(125~\text{GeV}) \approx 3~\text{MeV}. \tag{11}$$

The events for 'background only', b_i, and 'background plus signal', $b_i + s_i$, are taken from the $b\bar{b}$ decay channel. The $\mu^+\mu^-$-decay channel is used only for validation that one observes both a signal from a scalar and a Z-boson. A challenging region for this analysis is if the scalar m_ϕ is close to m_Z, since a large number of background events close to the Z-boson mass M_Z, weakens the result for S_{95}; in this region we fit the expected background events to emulate a more detailed analysis: we extrapolate the expected background events in an interval around the M_Z and fit these points with a third order polynomial to obtain the number of events in the bins around M_Z as the value of the fit function at the central mass of each bin.

Our result concerning the reconstruction of the LEP expectation for S_{95} are given in Fig.1 including scaling factors $c_{\rm trad}$, corresponding to Table 2, that accounts for detector effects and the restriction to the $b\bar{b}$-channel only. As can be seen from Fig.1, the expected limits are very well reconstructed with our method.

3.2 Comparison with OPAL data using the recoil method – 'LEP Recoil'

The OPAL experiment also used the recoil method for analyzing the data, i.e. exploiting the recoil of H, ϕ on the Z-boson and analyzing the Z-decay only. This method has the great advantage of being completely independent of the H, ϕ decay channels.

The OPAL analysis used the decay modes $Z \to \mu^+\mu^-$, e^+e^- [5]. We restrict our analysis to the decay mode $Z \to \mu^+\mu^-$ only, but extrapolated in a second step the luminosity taken by OPAL to the full LEP luminosity, see Table 1. We include only bins close to M_Z (interval [84 GeV, 98 GeV]), so that the weighted mean of the central masses of the bins is in a small interval around M_Z

$$\frac{\sum_{i=1}^{N} d_i m_i}{\sum_{j=1}^{N} d_j} \in [91.1 \text{ GeV},\ 91.3 \text{ GeV}] \tag{12}$$

with the number of events d_i in the i-th of N bins with the central mass m_i.

The events from the μ-lepton pairs are ordered by their total energy E_i into bins and for each bin we calculated the respective recoil mass $m_i^{(\text{rec})}$,

$$m_i^{(\text{rec})} = \sqrt{s + M_Z^2 - 2E_i\sqrt{s}}, \tag{13}$$

to obtain the event rates for background , $b_i \equiv b_i(m_i^{(\text{rec})})$, and signal, $s_i \equiv s_i(m_i^{(\text{rec})})$.

A mass-dependent width is taken into account,

$$\Gamma_\phi(m_\phi) = \Gamma_H^{(\text{SM})}(m_\phi). \tag{14}$$

Since the OPAL experiment published the used signal efficiency in ref. [5], we estimated a mean signal efficiency of $\varepsilon = 30\%$ for our approach and obtained the effective luminosity $\mathcal{L}_{\text{eff}}$ as

$$\mathcal{L}_{\text{eff}} = \varepsilon\ c_{\text{recoil}}(\sqrt{s})\ \mathcal{L}, \tag{15}$$

where the obtained values for the scaling factor c_{recoil} are given in Tab. 2. Practically $c_{\text{recoil}} = 1$, since the used efficiency is given. It turned out that neglecting hadronization as well as detector effects practically compensated our disregard of the $Z \to e^+e^-$-channel.

The reconstructed results for S_{95} for OPAL and our comparison are shown in Fig.2, as well as the distribution to the full LEP luminosities. A you can see, also the reconstruction of the recoil results seem to be very promising.

4 Discovery potential at the ILC for light Higgs

After having validated the method with the LEP data, we turn our analysis now into expectation for the ILC at $\sqrt{s} = 250$ GeV. We assume a beam polarization of $P_{e^-} = -80\%$ for the electron beam and $P_{e^+} = +30\%$ for the positron beam, corresponding to the baseline design [9]. We assume a total luminosity of $\mathcal{L} = 2000$ fb^{-1} expected to be collected within 15 years [10].

We compare the S_{95} projections for the ILC both for the case, where the $H, \phi \to b\bar{b}$-decays have been taken into account, corresponding to the 'LEP traditional' method, and the recoil method, where only $Z \to \mu^+\mu^-$ has been used. Of course, a mass-dependent width for H, ϕ has been calculated and taken into account. We compare these new results with the derived curve for LEP. As one can see in Fig. 3, we gain about a factor 10 compared to LEP with the ILC, already with only a cms of $\sqrt{s} = 250$ GeV.

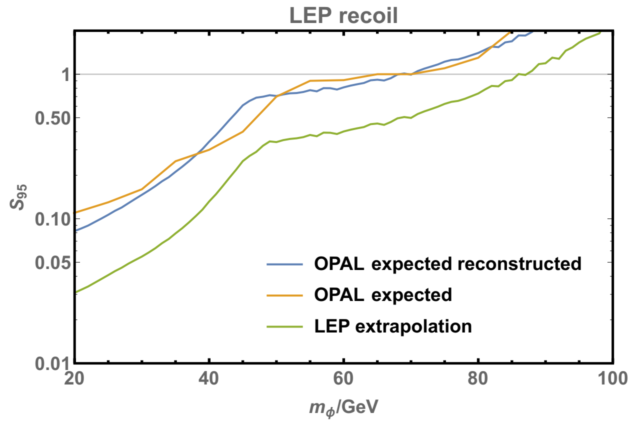


Figure 2: Reconstruction of the expected results for S_{95} with the recoil method at OPAL and extrapolated to the full LEP luminosity.

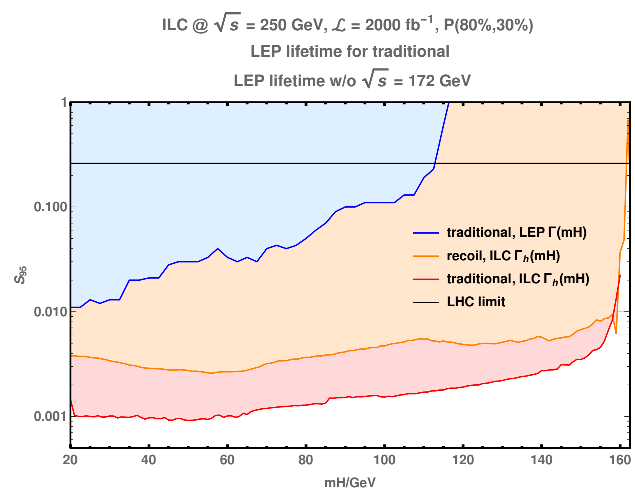


Figure 3: Depicted are the S_{95} expectations of the ILC with $\sqrt{s} = 250$ GeV, $\mathcal{L} = 2000$ fb^{-1} polarized beams ($P_{e^-} = -80\%$ and $P_{e^+} = +30\%$) for both approaches, using the Higgs decay channel ('traditional') and the recoil method ('recoil') and compare it with the S_{95} results at LEP ('traditional'). The solid horizontal line denotes the projection from future LHC accuracy on the couplings of a scalar state at 125 GeV [11, 12].

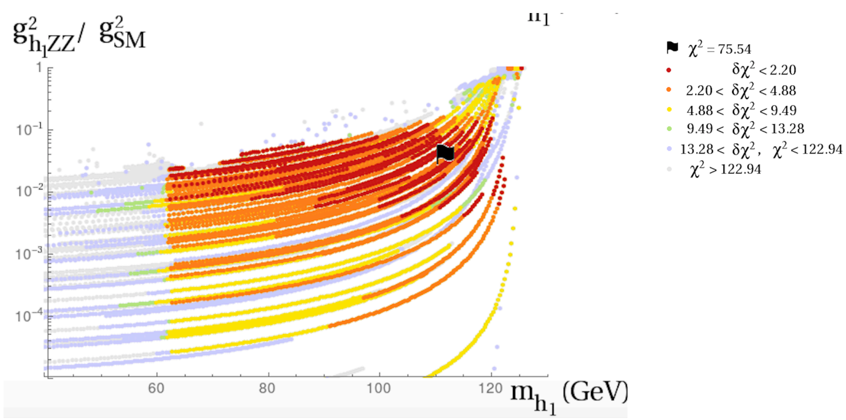


Figure 4: Squared coupling of a singlet-like Higgs state to the Z-boson in the NMSSM normalized to the SM value, taken from [13]. The best fit value corresponds to 5%. The ILC at $\sqrt{s} = 250$ GeV covers therefore the light singlet mass region down to about 60 GeV and a reduced Higgs-gauge-boson coupling of up to only a few percent.

From Fig. 3 we derive the following limits for S_{95}:

$$S_{95} \in [0.001, 0.002] \quad \text{with ILC 'traditional'}, \tag{16}$$
$$S_{95} \in [0.003, 0.005] \quad \text{with ILC 'recoil'}. \tag{17}$$

With respect to Eq. 5, these limits predict a sensitivity of the ILC to deviations from Standard-Model gauge boson-Higgs couplings up to

$$\text{ILC 'traditional'}: \quad g_{\phi Z}/g_{HZ}^{\text{SM}} \in [0.032, 0.045], \tag{18}$$
$$\text{ILC 'recoil'}: \quad g_{\phi Z}/g_{HZ}^{\text{SM}} \in [0.055, 0.071]. \tag{19}$$

These limits for a reduced coupling in the light scalar sector can be easily accommodated within a large class of new physics models, 2HDM, MSSM, NMSSM. Taking the NMSSM, for instance, scanning through the $\{\kappa, \lambda\}$ plane and performing a global fit and comparing with the Standard Model as done in [13], see Fig. 4, allows perfectly well these range of S_{95} limits. As can be seen from Fig. 4, where the fit value of the reduced squared coupling of a singlet-like Higgs state to the Z-boson is given in dependence of the light singlet Higgs mass, the ILC at $\sqrt{s} = 250$ GeV would be sensitive to the light singlet mass region down to about 60 GeV and a reduced Higgs-gauge-boson coupling of up to only a few percent.

Such a sensitivity greatly enhances the physics potential of the ILC at $\sqrt{s} = 250$ GeV. If, for instance, a signal around $m_\phi \sim 95$ GeV, see Fig. 5 (left) (corresponding to Fig. 7 in [14]), would become reality, then one could provide strict bounds for the new Scalar-gauge-boson couplings in different BSM models. One should remember that also at LEP, there was a

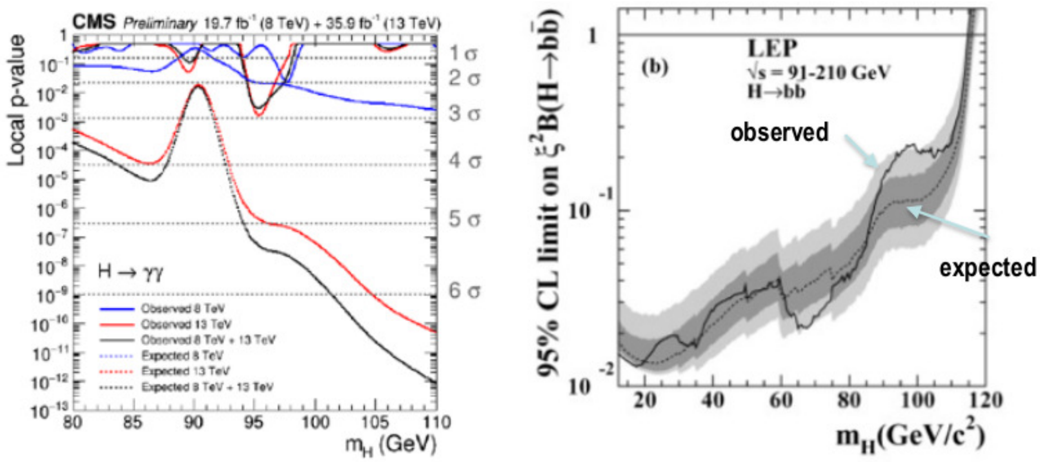


Figure 5: Left panel: CMS result on $H \to \gamma\gamma$ in the mass region $m_H \in [80, 110]$ GeV on 10.7 fb^{-1} (8 TeV) and on 35.0 fb^{-1} (13 TeV), taken from [14]. There is a local $\sim 2.8\sigma$ and a global $\sim 1.3\sigma$ significance at $m_\phi = 95.3$ GeV. Right panel: Slight excess at LEP data in $H \to b\bar{b}$ in the region of about $m_H = [95, 97]$ GeV, taken from [1].

slight excess for a light scalar $m_h \in [95, 97]$ GeV, see Fig. 5 (right) (corresponding to Fig. 10 in [1]).

At the ILC, one therefore would expect at this mass a limit of $S_{95} = 0.0015$, cf. 3, which would allow that a gauge-boson-scalar-coupling of such a new scalar at 95 GeV is only about 3.9% of the SM-coupling. Such reduced couplings in the light scalar sector can be accommodated with a large class of new physics models, as, for instance, in the NMSSM, see discussion above.

5 Conclusion

In the current study we could show that an ILC at $\sqrt{s} = 250$ GeV has a large, still unexplored, physics potential for the discovery of light, non-SM-like Higgs masses. The sum rule for Higgs-gauge-boson-couplings is very restrictive w.r.t. new physics models and allows only small admixtures. We use the S_{95} method to estimate the sensitivity to non SM-like couplings and cross sections. We validate the S_{95} method with LEP data both the traditional method, i.e. using Higgs decays and Z-decays, as well as the recoil method where only the decays of the Z-boson are exploited within the Higgs-strahlungs process. With an ILC at $\sqrt{s} = 250$ GeV and an integrated luminosity of about $\mathcal{L} = 2000$ fb^{-1} and with a polarization configuration of $(P_{e^-}, P_{e^+}) = (-80\%, +30\%)$, one has an impressive higher sensitivity up to one order of magnitude in this channel, comparing LEP/LHC data for masses in the range $m_\phi = [20, 115]$ GeV. Furthermore one can probe the hypothesis of an current excess at $m^\phi = 95$ GeV with regard to the new scalar-gauge-boson and we show that the ILC could be sensitive to a respective couplings of only $g_{VV\phi}/g^{SM}_{ZZH} \sim 4\%$. That's an impressive improvement compared to LHC results. The ILC already at its first energy stage of $\sqrt{s} = 250$ GeV will therefore provide essential steps towards new physics, is highly sensitive to such non-SM-like Higgs couplings opening a window to a large class of new phyics models as 2HDM, MSSM, NMSSM.

Acknowledgments

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