

The Precision of Higgs Boson Measurements and Their Implications

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J. Conway,¹ K. Desch,² J.F. Gunion,³ S. Mrenna,⁴ and D. Zeppenfeld⁵

¹*Dept. of Physics, Rutgers University, Piscataway, NJ USA*

²*Dept. of Physics, Univ. of Hamburg*

³*Davis Institute for HEP, Univ. of California, Davis, CA USA*

⁴*Fermilab, Batavia, IL USA*

⁵*Department of Physics, U. of Wisconsin, Madison, WI USA*

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The prospects for a precise exploration of the properties of a single or many observed Higgs bosons at future accelerators are summarized, with particular emphasis on the abilities of a Linear Collider (LC). Some implications of these measurements for discerning new physics beyond the Standard Model (SM) are also discussed.

I. INTRODUCTION

Despite the experimental verification of the Electroweak Symmetry-Breaking pattern $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$, the origin of the Higgs mechanism remains unknown. The simplest proposal is the existence of a fundamental, complex scalar field which is an $SU(2)_L$ doublet, the neutral component of which acquires a vacuum expectation value $v = 246$ GeV. The one physical degree of freedom is the Standard Model (SM) Higgs boson h_{SM} , which couples to each fermion and electroweak gauge boson in proportion to its mass. The analysis of precision Electroweak data strongly suggests the existence of a light, SM-like Higgs boson, which should be discovered in the next generation of hadron-collider experiments. This report addresses the question of how well the properties of this Higgs boson can be measured at planned and proposed colliders, and whether there are associated experimental signatures that would reveal additional structure to the Higgs sector.

II. THE STANDARD MODEL HIGGS BOSON

The SM Higgs boson is a spin-0, CP-even scalar with tree level couplings to fermions $\propto m_f/v$ and to the $V = W$ and Z bosons $\propto M_V \times M_W/v$. The Higgs boson mass $m_{h_{SM}}$ is $v\sqrt{\lambda}$, where λ is the self-coupling of the Higgs field that also sets the strength of the Higgs cubic and quartic self-interactions. Because the Higgs boson has the largest couplings to the heaviest Standard Model particles, promising Higgs production modes at colliders are in association with W or Z bosons [$V^* \rightarrow Vh_{SM}$ or $VV \rightarrow h_{SM}$] or t quarks [$f\bar{f}, gg \rightarrow t\bar{t}h_{SM}$]. At hadron colliders, the largest production process is $gg \rightarrow h_{SM}$, which is formally one-loop, but is enhanced by the large gluon density in the proton. At an e^+e^- linear collider (LC), the dominant production mechanisms are $e^+e^- \rightarrow Zh$ and $\rightarrow \nu_e\bar{\nu}_e h$. Specialized colliders using muon beams (μC) or photon beams (γC) overcome small couplings to h_{SM} with beams tuned near the resonance energy. SM Higgs boson decays are dominated by the heaviest, kinematically accessible particles. Thus, for $m_{h_{SM}} \lesssim 135$ GeV, the largest SM decay is $h_{SM} \rightarrow b\bar{b}$, but other sizable decays in this mass range are $h_{SM} \rightarrow gg, \tau\tau, c\bar{c}$, and W^*W^* . Despite the dominance of only a few decay channels, it is nonetheless important to calculate all decay rates to high precision. For example, even though $BR(h_{SM} \rightarrow \gamma\gamma)$ is typically $\mathcal{O}(10^{-3})$, it may be the easiest decay mode to observe at the LHC for a light Higgs boson, because of a very clear signal and excellent Higgs mass resolution. As $m_{h_{SM}}$ increases, $h_{SM} \rightarrow WW^*$ then $h_{SM} \rightarrow WW + ZZ$ become the dominant decays, even above the $h_{SM} \rightarrow t\bar{t}$ threshold.

A. Discovery/Observation

The best direct bounds on the SM Higgs boson mass come from the CERN LEP collider, where searches for the process $e^+e^- \rightarrow Z^* \rightarrow Zh_{SM}$ exclude $m_{h_{SM}} < 114.1$ GeV at the 95% C.L.[1]. A slight (2σ) excess of events has been observed near the kinematic limit, which is consistent with $m_{h_{SM}} = 115.6$ GeV. The indirect bounds from precision Electroweak observables are consistent with this number, and imply $m_{h_{SM}} < 196$ GeV at the 95% C.L. [2].

The next collider experiments that are sensitive to the SM Higgs boson are at the Tevatron $p\bar{p}$ collider ($\sqrt{s} = 2$ TeV) and the CERN Large Hadron pp Collider [LHC] ($\sqrt{s} = 14$ TeV). At the Tevatron, the most accessible search channels are $p\bar{p} \rightarrow Wh_{SM} + X$ and $p\bar{p} \rightarrow Zh_{SM} + X$ with leptonic gauge boson decays and $h_{SM} \rightarrow b\bar{b}$ [3]. For $m_{h_{SM}} > 130$ GeV, the decay $h_{SM} \rightarrow WW^*$ can provide additional sensitivity. Over the lifetime of the

experiment, no single channel can yield enough signal-like events to claim discovery. However, the statistical combination of CDF and DØ data in all search channels has significant sensitivity. The integrated luminosity needed for exclusion and discovery, respectively, are shown in Fig. 1 as a function of the Higgs mass. With $2(10) \text{ fb}^{-1}$ per experiment, $m_{h_{\text{SM}}} < 120(190) \text{ GeV}$ can be excluded. With 30 fb^{-1} per experiment, discovery at the $3\text{--}5\sigma$ level can be achieved over the entire mass range up to 180 GeV . Roughly $2(5) \text{ fb}^{-1}$ will cover the region of the LEP excess at 95% C.L. (3σ).

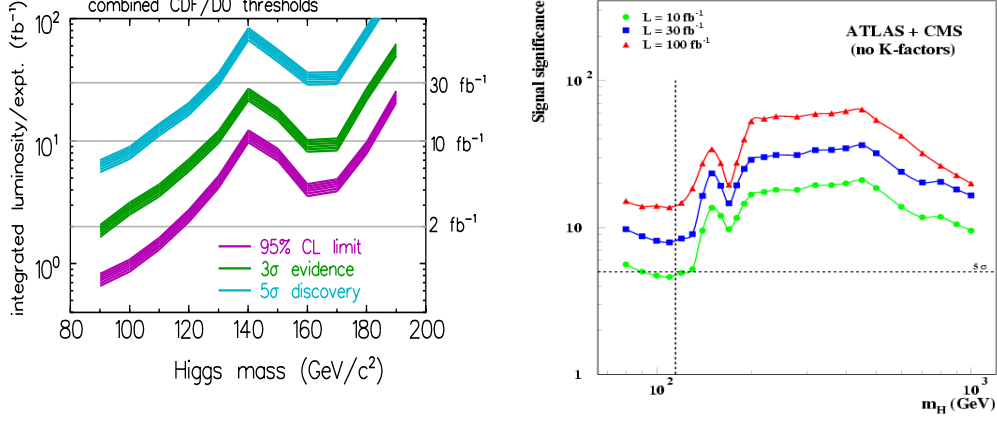


FIG. 1: (left) Required integrated luminosity to achieve different levels of statistical significance for SM Higgs boson searches at the Tevatron; (right) Statistical significance of SM Higgs boson searches for different amounts of integrated luminosity at the LHC.

At the LHC, there are at least three highly promising channels for Higgs boson discovery: $gg \rightarrow h_{\text{SM}} \rightarrow \gamma\gamma$ for $m_{h_{\text{SM}}} \lesssim 150 \text{ GeV}$ and $gg \rightarrow h_{\text{SM}} \rightarrow ZZ^* \rightarrow 4\ell$ and $gg \rightarrow h_{\text{SM}} \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu}$ for $m_{h_{\text{SM}}} \gtrsim 130 \text{ GeV}$. Additional sensitivity comes from $gg, q\bar{q} \rightarrow t\bar{t}h_{\text{SM}}(h_{\text{SM}} \rightarrow b\bar{b}, \gamma\gamma)$ at low $m_{h_{\text{SM}}} \lesssim 120 \text{ GeV}$ and from $gg \rightarrow h_{\text{SM}} \rightarrow WW^*$ or $WW \rightarrow \ell\nu q\bar{q}$, both at the highest $m_{h_{\text{SM}}}$ and also for $m_{h_{\text{SM}}} \sim 160 \text{ GeV}$ where the opening of the on-shell WW channel suppresses the ZZ^* signal. With an integrated luminosity of 10 fb^{-1} (out of a projected $100\text{--}300 \text{ fb}^{-1}$), discovery at the $\approx 5\sigma$ level is guaranteed over the whole theoretically allowed mass range if information from these channels and from both experiments, ATLAS and CMS, are combined (see Fig. 1) [4–6]. Additional improvements are expected from the separate observation of weak boson fusion (WBF) channels, $qq \rightarrow qqh_{\text{SM}}$ with $h_{\text{SM}} \rightarrow \gamma\gamma$ [7], $h_{\text{SM}} \rightarrow WW^*$ [8, 9], and $h_{\text{SM}} \rightarrow \tau^+\tau^-$ [10, 11].

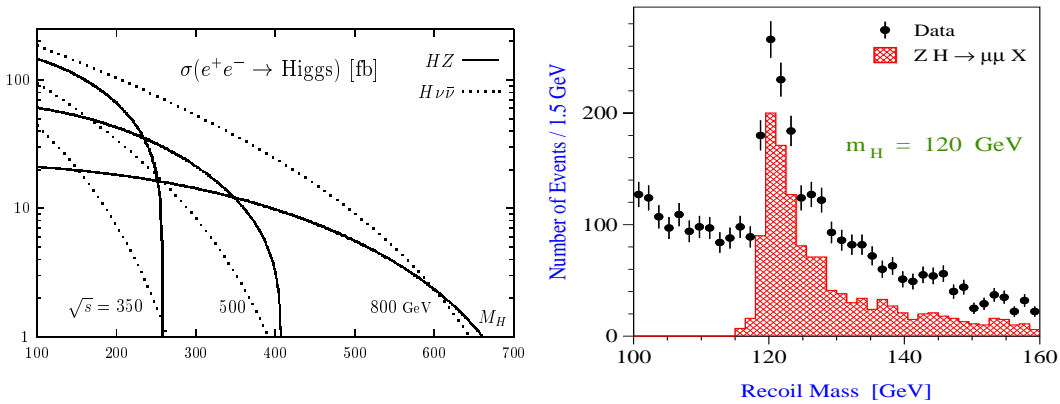


FIG. 2: (left) Higgsstrahlung and WW -fusion cross sections for SM Higgs boson production at a LC for various \sqrt{s} ; (right) Recoil mass spectrum for $e^+e^- \rightarrow Zh$ with $Z \rightarrow \mu^+\mu^-$ signal and continuum background at a $\sqrt{s} = 350 \text{ GeV}$ LC with 500 fb^{-1} of data and $m_h = 120 \text{ GeV}$.

Proposed colliders, such as the LC, μC , and Very Large Hadron Collider (VLHC), would be SM Higgs boson factories. The potential of a VLHC for performing precision Higgs studies is not well-studied, and it is premature to make quantitative statements. At the LC, the SM Higgs boson is produced mainly in the $e^+e^- \rightarrow Zh_{\text{SM}}$

(Higgsstrahlung) and $e^+e^- \rightarrow \nu_e \bar{\nu}_e h_{\text{SM}}$ (WBF) channels. Production rates for a light Higgs boson are on the order of 10^5 Higgs bosons for accumulated luminosity of 500 fb^{-1} (corresponding to 1–2 years of running) at $\sqrt{s} \sim 350 \text{ GeV}$. The production cross sections as a function of $m_{h_{\text{SM}}}$ for various center-of-mass energies are shown in Fig. 2(a). The Higgsstrahlung channel offers the unique possibility to tag Higgs bosons independently of their decay [Fig. 2 (b)], thus allowing for a model-independent observation of any Higgs boson with sufficient coupling to the Z^0 . In contrast to hadron colliders, Higgs bosons with any decay mode can be selected at a LC with high efficiency [$\mathcal{O}(50\%)$] and small backgrounds ($S/B \gtrsim 1$).

The LC is sensitive to a SM-like Higgs boson with a mass less than or near the kinematic limit. If the Higgs coupling to W and Z bosons is reduced from the SM value, the reach will be reduced accordingly. The sensitivity to Higgs bosons with reduced couplings to the W and Z bosons has not been well-studied, but the results would be of great interest.

Observation of the Higgs boson in the recoil spectrum could also be compromised if the Higgs is sufficiently wide to wash out the signal. This could occur if the Higgs has a substantial decay width into pseudo-Goldstone bosons, additional Higgs singlets [12], etc. The exact sensitivity to such a case has also not been well studied.

The LC can be turned into a γC by converting beam electrons into highly energetic photons through back-scattering of laser light. At a γC , Higgs bosons can be produced at resonance in the process $\gamma\gamma \rightarrow h$ with a large cross section. The one-loop $\gamma\gamma$ coupling is typically large enough, even for a Higgs boson with suppressed tree-level couplings to the W and Z bosons, that a γC has potential for discovering Higgs bosons that cannot be seen in e^+e^- collisions either by reason of couplings or mass. The μC also allows the possibility of Higgs boson production as an s-channel resonance. High rates are predicted so long as the Higgs total width is not large. Especially useful will be SM Higgs production for $m_{h_{\text{SM}}} < 180 \text{ GeV}$ and production of the H, A of the MSSM [13, 14].

B. Properties: Mass, Total Decay Width, Quantum Numbers, and Couplings

1. Mass $m_{h_{\text{SM}}}$

The SM Higgs boson mass is fixed by the self-coupling λ , which is constrained from above by perturbativity arguments [$\lambda^2/(4\pi) < 1$], and constrained from below by the requirement of vacuum stability [$\lambda > 0$]. At the Tevatron, the statistical error on the Higgs mass measurement using the $b\bar{b}$ invariant mass in $h_{\text{SM}} \rightarrow b\bar{b}$ decays will be approximately 1 GeV for $m_{h_{\text{SM}}} = 120 \text{ GeV}$ and 10 fb^{-1} of data. A conservative estimate including systematic errors is 2 GeV, but the nearby Z peak will be quite useful as a calibration. At the LHC, for light Higgs bosons ($m_{h_{\text{SM}}} \lesssim 150 \text{ GeV}$), the Higgs mass can be measured from the di-photon invariant mass in $h_{\text{SM}} \rightarrow \gamma\gamma$ decays. The mass resolution is determined by both the energy and angular resolution of the electromagnetic calorimeters in the ATLAS and CMS detectors. If an absolute normalization of the calorimeter energy scale of 0.1% can be achieved, the mass resolution σ_M/M is about 0.1–0.4 % for 300 fb^{-1} . For larger Higgs masses, the $h_{\text{SM}} \rightarrow ZZ \rightarrow 4\ell$ decay provides similar precision.

At the LC, the Higgs mass is best reconstructed in the Higgsstrahlung process either from the invariant mass recoiling against the Z^0 or from a kinematic fit to the $Zh \rightarrow q\bar{q}b\bar{b}$ final state. The achievable precision is around 5×10^{-4} for $m_{h_{\text{SM}}} = 120 \text{ GeV}$. For realistic operating scenarios, a γC cannot provide any further improvement of the accuracy of the Higgs mass determination. Precision beyond the LC measurement can be obtained at the μC from a scan of the $\mu^+\mu^- \rightarrow h$ resonance. Due to the expected excellent control of the beam energy, a precision of roughly 10^{-6} is envisaged.

2. Total Width Γ_{tot}

The total decay width of the SM Higgs boson is predicted to be below 1 GeV for $m_{h_{\text{SM}}} < 200 \text{ GeV}$, which is too small to be resolved directly except at the μC . However, indirect methods can be employed both at the LHC and the LC.

At the LHC, a variety of combinations of (partial) widths can be measured directly. A few additional assumptions, which are appropriate for a SM-like Higgs, then allow the total width to be extracted [15]. From the weak boson fusion processes $q\bar{q} \rightarrow q\bar{q}h$ with $h \rightarrow WW^*$, $h \rightarrow \gamma\gamma$, and $h \rightarrow \tau\tau$, the quantities $X_W = \Gamma_W^2/\Gamma$, $X_\gamma = \Gamma_W\Gamma_\gamma/\Gamma$, and $X_\tau = \Gamma_W\Gamma_\tau/\Gamma$ can be measured. The gluon-fusion induced processes $gg \rightarrow h \rightarrow \gamma\gamma, ZZ^*, WW^*$ provide measurements of $Y_i = \Gamma_g\Gamma_i/\Gamma$ for $i = \gamma, W, Z$. If $SU(2)$ invariance holds for the WWh and ZZh couplings, if the ratio $y = \Gamma_b/\Gamma_\tau$ has its SM value and if the partial widths of decay channels other than $ZZ, WW, b\bar{b}, \tau^+\tau^-, gg, \gamma\gamma$ are small, then Γ_W can be approximately determined from the quantities $X_W, X_\tau, X_\gamma, Y_Z, Y_W$ and Y_γ . Thus, the total width can be reconstructed under this assumption as $\Gamma = \Gamma_W^2/X_W$.

The achievable accuracy is shown in Fig. 3 and is estimated to be about 20 (10) % for $m_h = 120(200)$ GeV. Despite the assumptions made, this method is useful, since the observation of a width that substantially differs from the SM value (predicted for a given $m_{h_{\text{SM}}}$) would indicate new physics. Another valid consistency check of the SM is to simply use the rate for Higgs production in WBF, with subsequent decay $h_{\text{SM}} \rightarrow WW^*$, to infer the total width assuming that $g_{WW^*h}^2$ and, hence, $\Gamma(h \rightarrow WW)$ have their SM values. The latter is a good approximation for the lightest Higgs boson of extensions of the SM Higgs sector when in the decoupling limit.

At the LC, the total width of a SM-like h can be computed in a model-independent manner. For $m_h \gtrsim 120$ GeV, the best method is to first measure both inclusive $e^+e^- \rightarrow Zh$ production and $e^+e^- \rightarrow Zh(\rightarrow WW^*)$ and compute $\text{BR}(h \rightarrow WW^*)$ from the ratio. The rate for $e^+e^- \rightarrow \nu\bar{\nu}h(\rightarrow WW^*)$ determines $g_{WW^*h}^2 \text{BR}(h \rightarrow WW^*)$ so that g_{WW^*h} can be extracted and $\Gamma(h \rightarrow WW)$ computed. The total h width is then obtained in a model-independent manner as $\Gamma_{\text{tot}} = \Gamma_W / \text{BR}(h \rightarrow WW)$. For $m_{h_{\text{SM}}} = 120$ GeV, an accuracy of about 5% can be achieved [16]. Alternatively, the measurement of $\text{BR}(h \rightarrow \gamma\gamma)$ at the LC can be combined with the measurement of $\Gamma(h \rightarrow \gamma\gamma)$ at the γC , yielding a somewhat larger error on the total width $\sim 20\%$, due to the limited statistics of the $\text{BR}(h \rightarrow \gamma\gamma)$ measurement.

Note that new physics contributions need not contribute democratically to production and decay processes, so that some ambiguity may exist in indirect extractions of the Higgs boson width due to higher-order corrections. For example, within the MSSM, certain box diagram contributions to the $e^+e^- \rightarrow Zh$ production process that are absent for decay can modify the inclusive cross section by 10% [17] for certain choices of soft-breaking parameters. Therefore, the effective g_{ZZh} coupling would not be the same one used in the calculation of the partial width. It remains to be seen whether such corrections can modify the WW -fusion process with a similar magnitude, or whether the choice of soft-breaking parameters would necessarily provide a sparticle signature at the same or other colliders. While loop effects appear to be a complication, an alternative view is that precise measurements of the Higgs-strahlung cross section will provide additional information about MSSM parameters [18].

For $m_{h_{\text{SM}}} \gtrsim 200$ GeV, the total width can be directly obtained from resolving the Higgs boson line-shape. At the LHC, the 4-lepton invariant mass spectrum from $h_{\text{SM}} \rightarrow ZZ \rightarrow 4\ell$ yields a precision of about 25% for $m_{h_{\text{SM}}} = 240$ GeV, improving to about 5% at 400 GeV and then slightly degrading again [6]. At the LC, preliminary results at $m_{h_{\text{SM}}} = 240$ GeV show, that from a kinematic fit to the $h_{\text{SM}}Z \rightarrow ZZZ, WWZ$ final states with one Z decaying into a charged lepton pair and the other gauge bosons decaying hadronically, a precision of about 10% on the total width can be obtained [19].

At the μC , the total width can be measured directly from a scan of the Higgs line-shape. The expected accuracy for the h_{SM} is of order 20% at $m_{h_{\text{SM}}} \sim 120$ GeV (i.e. poorer than the indirect LC technique but comparable to the LHC). For masses $m_{h_{\text{SM}}} > 180$ GeV, the μC does not yield an observable $\mu^+\mu^- \rightarrow h_{\text{SM}}$ signal [13].

3. Quantum Numbers J^{PC}

The SM Higgs boson has $J^{PC} = 0^{++}$. The observation of the $h \rightarrow \gamma\gamma$ decay (e.g., at the LHC) would rule out $J = 1$ and require $C=[+]$. At the LC, the spin of the Higgs boson can be determined unambiguously by examining the threshold dependence of the Higgsstrahlung cross section and the angular distributions of the Z and Higgs bosons and their decay products in the continuum [20–25]. Using optimal observables, a CP-odd component of a Higgs boson coupling with strength η relative to an essentially SM-like CP-even component can be distinguished at the $|\eta| \sim 3\% - 4\%$ level. Of course, in conventional Higgs sector scenarios (such as the general 2HDM or the MSSM with complex-valued soft-breaking parameters) η is roughly given by the fraction of the Higgs boson that is CP-odd f_{CP-} times a one loop factor, resulting in a value of $|\eta|$ that is too small to be detected. However, in more general scenarios (in particular, ones in which there are anomalous sources of ZZ couplings such as those that can arise in composite Higgs models), η could be of measurable size. The azimuthal distribution of the tagging jets in weak boson fusion observed at the LHC is also sensitive to the appearance of non-renormalizable CP-odd (and CP-even) operators [26]. A simplified analysis implies sensitivity at the $|\eta| \sim 30\%$ level.

At the LC, the (presumably dominant) CP-conserving production processes $Z^* \rightarrow Zh, WW \rightarrow h$ can provide CP information through correlations between the τ decay products in the decays $h \rightarrow \tau^+\tau^-$ [27–29], but this is challenging experimentally [30].

In the $\gamma\gamma$ collision mode, the polarization of the photons can be tuned to select different CP components of the Higgs boson [29, 31, 32] and a reasonably good determination of the CP nature of any Higgs boson observable in this mode is possible. In the case of a SM-like Higgs boson with $m_h = 120$ GeV, a highly realistic NLC study [33] concludes that a CP-odd component f_{CP-} of about 20% can be excluded at the 95% C.L. after one year of operation for expected luminosities.

At the μC , the transverse polarization of the muon beams can be adjusted to select different CP components [34]. After accounting for polarization precession there is some dilution of the transverse polarization, but a good measurement will still be possible [35]. For reasonable assumptions about proton source intensity and bunch merging, one year of running will yield $b_\mu/a_\mu \lesssim 0.2 - 0.3$ at the 1σ level assuming that in actuality $a_\mu = 1$ and $b_\mu = 0$, where a_μ and b_μ are the CP-even and CP-odd couplings of the Higgs boson to the muon defined by $\mathcal{L}_{\text{int}} = -\frac{gm_\mu}{2m_W}\bar{\mu}(a_\mu + ib_\mu\gamma_5)\mu h$.

Another promising method for directly observing CP violation is to study the kinematics of Higgs bosons produced in association with fermions as influenced by the relative sizes of a_t and b_t in the $t\bar{t}h$ coupling $\mathcal{L}_{\text{int}} = -\frac{gm_t}{2m_W}\bar{t}(a_t + ib_t\gamma_5)th$. The reactions $p\bar{p} \rightarrow t\bar{t}h$ and $e^+e^- \rightarrow t\bar{t}h$ are sensitive to the CP nature of the Higgs h at the LHC [36] and LC [37, 38], respectively. Theoretical analyses find that for $m_h \sim 120$ GeV the value of b_t relative to the SM value of $a_t = 1$ can be measured at about the 40% level at the LHC (using the $\gamma\gamma$ Higgs decay mode and for 300 fb^{-1} per detector) and with an accuracy of $\sim 20\%$ at the LC with $\sqrt{s} = 1$ TeV and $L = 500 \text{ fb}^{-1}$. Detailed experimental analyses are not yet available.

Finally, for any type of Higgs sector, an incontrovertible signature of CP violation would be the observation of 2 separate, neutral Higgs bosons in $f\bar{f} \rightarrow Zh_1$, $f\bar{f} \rightarrow Zh_2$ and $f\bar{f} \rightarrow h_1h_2$ [39]. Of course, this requires $\sqrt{s} > m_{h_1} + m_{h_2}$, while the study of $t\bar{t}h$ requires $\sqrt{s} > 2m_t + m_h$.

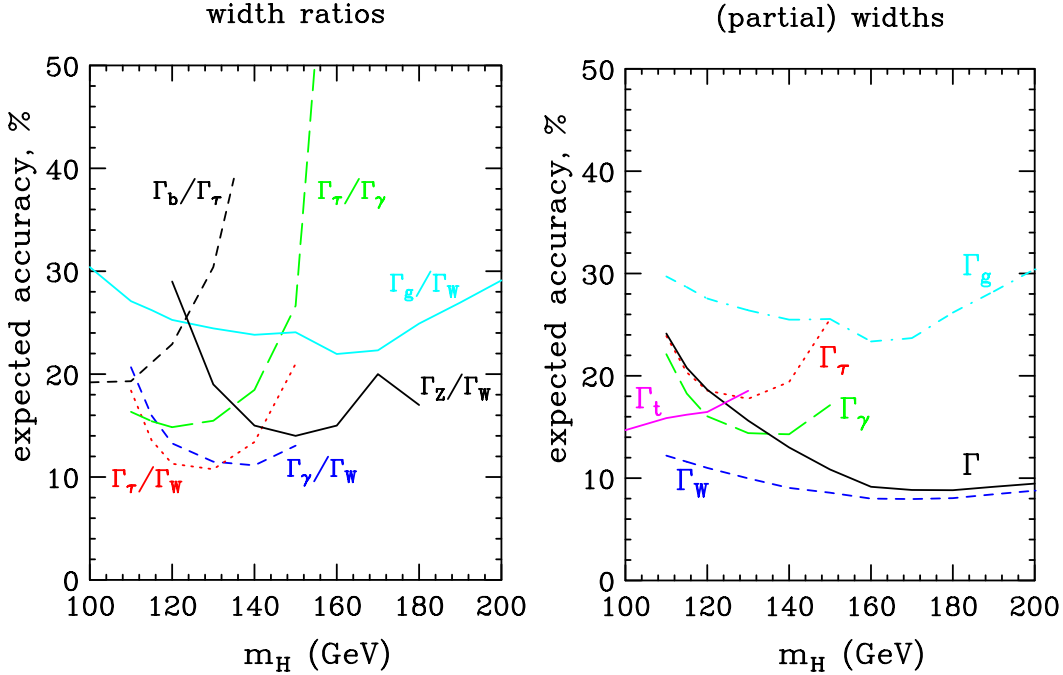


FIG. 3: Relative accuracy expected at the LHC with 200 fb^{-1} of data for (a) various ratios of Higgs boson partial widths and (b) the indirect determination of partial and total widths $\tilde{\Gamma}$ and $\tilde{\Gamma}_i = \Gamma_i(1 - \epsilon)$. Simulations have been performed at the parton level for WBF processes. Width ratio extractions only assume W, Z universality, which can be tested at the 15 to 30% level (solid line). Indirect width measurements assume b, τ universality in addition and require a small branching ratio ϵ for unobserved modes like $H \rightarrow c\bar{c}$ and decays beyond the SM.

4. Gauge and Yukawa Couplings

For a light Higgs boson, the Tevatron can observe two separate production channels with the same Higgs boson decay. The number of $Zh(\rightarrow b\bar{b})$ and $Wh(\rightarrow b\bar{b})$ final states could test the ratio g_{ZZh}^2/g_{WWH}^2 to about 40% for $m_{h_{\text{SM}}} = 120$ GeV and 10 fb^{-1} . The LHC is sensitive to many different production and decay processes, which provide direct measurements of the ratios of several partial decay widths. The expected accuracy of such measurements is given in Fig. 3, for 100 fb^{-1} of data in each of the two detectors [15]. This corresponds

to several years of running at lower luminosities, where pile-up effects are not very important. For several channels, significant improvements can be expected with higher integrated luminosities. However, a complete analysis of all channels, including pile-up at $\mathcal{L} = 10^{34} \text{cm}^{-2} \text{sec}^{-1}$, is not available at this time.

The measurement of Γ_b/Γ_τ indicated in Fig. 3 is assumed to originate from the $Wh_{\text{SM}}(\rightarrow b\bar{b})$ [40] and $qq \rightarrow qqh_{\text{SM}}(\rightarrow \tau\tau)$ channels, where the former relies only on the CMS analysis for 300fb^{-1} . A QCD uncertainty of 10% on the ratio of production cross sections is added in quadrature. A better handle on $h_{\text{SM}} \rightarrow b\bar{b}$ decays is expected from $t\bar{t}h_{\text{SM}}(\rightarrow b\bar{b})$ events [6, 41] which provide a measurement of the combination $\Gamma_t\Gamma_b/\Gamma$ with a statistical accuracy of 12–14% (for $m_{h_{\text{SM}}} < 130 \text{ GeV}$ and 200fb^{-1}). This is smaller than the NLO cross section uncertainty, which is taken to be 10% [42]. The dependence on the unknown top-Yukawa coupling $g_{h_{\text{SM}}t}^2 \propto \Gamma_t$ can be eliminated in principle, by assuming top-quark dominance in the $h_{\text{SM}}gg$ triangle graphs or by measuring $t\bar{t}h_{\text{SM}}$ production with subsequent decay $h_{\text{SM}} \rightarrow \gamma\gamma$ or $h_{\text{SM}} \rightarrow WW^*$ [43].

A global fit, using these techniques, is not available yet. Instead, tau-bottom universality is assumed for the extraction of Higgs Yukawa couplings at the LHC [15] and a conservative 7% error is assigned to the predicted $\text{BR}(h \rightarrow \tau^+\tau^-)/\text{BR}(h \rightarrow b\bar{b})$ ratio. Expected accuracies for squared couplings, or, equivalently, (partial) decay widths, are given in Fig. 3 [44]. For $m_h = 120 \text{ GeV}$ they are compared with LC expectations in Table I. The errors on $\Gamma_t \propto g_{h_{\text{SM}}t}^2$ and Γ_g are dominated by systematics, namely QCD uncertainties at NLO and NNLO of 15 and 20% for the $t\bar{t}h_{\text{SM}}$ and $gg \rightarrow h_{\text{SM}}$ cross sections.

A LC can significantly improve these measurements in a model-independent way. The expected experimental uncertainties in the measurement of BRs at the LC for a 120 GeV SM-like Higgs boson are summarized in Table I. The first row shows the results assuming 500fb^{-1} of integrated luminosity at $\sqrt{s} = 350 \text{ GeV}$ [45]. The second row of Table I shows the results of a similar study [46] for the branching ratios of a 120 GeV SM-like Higgs boson with 500fb^{-1} at $\sqrt{s} = 500 \text{ GeV}$. Note the very different predictions in Table I for the precisions of $\text{BR}(c)$ and $\text{BR}(g)$, which depend on very good charm and light quark separation. The origin of this difference is not yet fully understood, and is not simply a result of using different collider energies. Finally, the entry in the last row is based on the results of a dedicated study of the $\text{BR}(\gamma)$ measurement [47] for $\sqrt{s} = 350$ and 500 GeV , both without and with beam polarization (80% left-handed electron polarization and 40 or 60% right-handed positron polarization) chosen to enhance the Higgsstrahlung and WW fusion cross sections. At $\sqrt{s} = 500 \text{ GeV}$ and the highest polarizations, a measurement of $\text{BR}(\gamma)$ with an experimental uncertainty of 9.6% is possible with 1ab^{-1} . Scaling this to 500fb^{-1} to compare with the other studies yields a precision of about 14%, as shown in the third row of Table I. Without beam polarization, this deteriorates to 16% (23%) with 1ab^{-1} (500fb^{-1}).

Decay mode:	$b\bar{b}$	WW^*	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$									
Ref. [45]	2.4%	5.1%	5.0%	8.5%	5.5%	19%	$g_{h_{\text{SM}}WW}^2$	$g_{h_{\text{SM}}ZZ}^2$	$g_{h_{\text{SM}}bb}^2$	$g_{h_{\text{SM}}\tau\tau}^2$	$g_{h_{\text{SM}}cc}^2$	$g_{h_{\text{SM}}gg}^2$	$g_{h_{\text{SM}}t\bar{t}}^2$	$g_{h_{\text{SM}}\gamma\gamma}^2$	
Ref. [46]	2.9%	9.3%	7.9%	39%	18%		LHC	11%	11%	–	19%	–	28%	16%	16%
Ref. [47] (scaled)						14%	LC expt	2.4%	2.4%	4.4%	6.6%	7.4%	7.4%	10%	–
theory uncertainty	1.4%	2.3%	2.3%	23%	5.7%	2.3%	theory	–	–	3.5%	–	24%	3.9%	2.5%	–

TABLE I: (left) Expected fractional uncertainty of BR measurements at an e^+e^- LC for a 120 GeV SM-like Higgs boson. Results are shown for (500fb^{-1} at $\sqrt{s} = 350 \text{ GeV}$) (first row); (500fb^{-1} at $\sqrt{s} = 500 \text{ GeV}$) (second row); and (1ab^{-1} at $\sqrt{s} = 500 \text{ GeV}$, scaled to 500fb^{-1}) (third row). The theoretical uncertainty of the predicted Standard Model branching ratios is given in the fourth row. (right) Expected uncertainty of measurements of squared couplings (equivalently partial widths) for a 120 GeV SM-like Higgs boson. LHC results correspond to Fig. 3. LC estimates are from HFITTER [45, 48], assuming 500fb^{-1} at $\sqrt{s} = 500 \text{ GeV}$, except for the measurement of $g_{h_{\text{SM}}t\bar{t}}^2$ which assumes 1ab^{-1} at $\sqrt{s} = 800 \text{ GeV}$. The last line shows the theoretical uncertainty.

At the LC, the extraction of the absolute couplings of the Higgs boson is straightforward. The coupling $g_{h_{\text{SM}}ZZ}$ is inferred directly from the production cross section using the recoil method (modulo the comment above – this is true at the tree level). Furthermore, most other couplings can be inferred from BR measurements once Γ_{tot} has been extracted using $\text{BR}(h \rightarrow WW)$ and $\sigma(\nu_e \bar{\nu}_e h)$. The results of a χ^2 minimization using HFITTER [45, 48] are summarized in Table I. The coupling $g_{h_{\text{SM}}t\bar{t}}$ can be measured indirectly from the LC measurements of $h \rightarrow gg$ and $h \rightarrow \gamma\gamma$ if one assumes that non-SM loop contributions are small compared to experimental uncertainties. A direct measurement of $g_{h_{\text{SM}}t\bar{t}}^2$ can be obtained from the $e^+e^- \rightarrow t\bar{t}h$ cross section [38, 49–51]. Such a measurement requires running at higher $\sqrt{s} = 800\text{--}1000 \text{ GeV}$ in order to avoid kinematic suppression of the cross section; the result in Table I assumes 1000fb^{-1} at $\sqrt{s} = 800 \text{ GeV}$.

Sources of theoretical uncertainty include higher order loop corrections to Higgs decay rates not yet computed and parametric uncertainties due to the choice of input parameters. The largest sources of uncertainty arise from the choice of α_s , m_c and m_b used in the numerical prediction: $\alpha_s = 0.1185 \pm 0.0020$, $m_c(m_c) = 1.23 \pm 0.09 \text{ GeV}$ [52] and $m_b(m_b) = 4.17 \pm 0.05 \text{ GeV}$ [53]. The variation of these input parameters leads to the theoretical

fractional uncertainties for the Higgs branching ratios quoted in Table I. For the Higgs squared-couplings listed in Table I, the only significant theoretical uncertainties reside in g_{hbb}^2 and g_{hcc}^2 , due to the uncertainties in the b and c quark masses and in α_s (which governs the running of the quark masses from the quark mass to the Higgs mass). The resulting theoretical uncertainties for g_{hbb}^2 and g_{hcc}^2 (for a SM Higgs boson of mass 120 GeV) are 3.5% and 24%, respectively. In addition, a theoretical uncertainty in g_{hgg}^2 of 3.9% arises due to the uncertainty in α_s . The observed uncertainty in m_t has only a small effect on the predictions for the $h \rightarrow gg$ and $h \rightarrow \gamma\gamma$ decay rates.

For a SM Higgs boson with $m_h = 120$ GeV, about 2/3 of the width is due to $h \rightarrow b\bar{b}$. The theoretical fractional uncertainties for the Higgs branching ratios to WW^* , $\tau^+\tau^-$ and $\gamma\gamma$ listed in Table I are due primarily to the fractional uncertainty of the total width, which for a SM Higgs boson with $m_h = 120$ GeV is mainly governed by the corresponding uncertainty in the $h \rightarrow b\bar{b}$ width. For larger values of the Higgs mass, the $h \rightarrow b\bar{b}$ branching ratio is smaller and the uncertainty in the total width, which is now dominated by $h \rightarrow WW^{(*)}$, is correspondingly reduced. The large uncertainty in the $h \rightarrow c\bar{c}$ decay rate, arising from the relatively large uncertainty in the charmed quark mass, limits the usefulness of charm quark branching ratio and coupling measurements. Further improvements in theory and lattice computational techniques [54] may ameliorate the situation.

Finally, a scan of the $t\bar{t}$ threshold at the LC will reduce the uncertainty on m_t to about 100 MeV [55]. Thus, the theoretical error expected for the Standard Model Higgs coupling to $t\bar{t}$ due to the top-quark mass uncertainty will be negligible. The remaining uncertainty in g_{htt}^2 is due to uncalculated higher order QCD corrections to the $e^+e^- \rightarrow t\bar{t}h$ cross section. We estimate this uncertainty to be about 2.5% based on the renormalization scale dependence in the NLO QCD result for $m_h = 120$ GeV and $\sqrt{s} = 1$ TeV [56, 57].

Another Higgs coupling that is potentially accessible in collider experiments is $g_{h\mu\mu}$. Of course, the μC relies on the existence of such a coupling for s -channel production of the Higgs boson. The μC will allow a $\sim 2\%$ measurement of $g_{h\mu\mu}$ by computing $g_{h\mu\mu}^2 \propto \sigma(\mu^+\mu^- \rightarrow h \rightarrow b\bar{b})/\text{BR}(b)$, where $\text{BR}(b)$ is assumed to be measured with the above noted precisions at the LC (see [14] and references therein). The small theoretical error in the predicted value of $g_{h\mu\mu_{\text{SM}}}$ would make this a particularly valuable check of the SM expectation. Recently, the prospects for measuring $g_{h\mu\mu}$ at other colliders have been considered. A CLIC analysis claims an error for $g_{h\mu\mu}$ of $\sim 4\%$ from WBF followed by $h \rightarrow \mu^+\mu^-$ [58]. This latter result relies on an order-of-magnitude improvement in muon momentum resolution, as assumed in many LC detector designs. A precision of about 15% would be expected from operating at $\sqrt{s} = 800$ GeV. Based on a 5σ “discovery” in WBF with 300 fb^{-1} of data, a VLHC ($\sqrt{s} = 200$ TeV, pp collider) would provide a 10% measurement [59].

5. Self Coupling and Higgs Potential

Further evidence of a fundamental scalar as the source of EWSB would be the reconstruction of the Higgs potential, i.e. measurement of the self-coupling λ . The first kinematically accessible process with sensitivity to λ is $f\bar{f} \rightarrow Zh\bar{h}$ [60, 61]. A **full** reconstruction of the Higgs potential requires measurement of $m_{h_{\text{SM}}}$ (which is quite precise), the trilinear coupling (which is good), and the quartic coupling. Presently, there are no claims for measurement of the quadratic coupling. The impact of this measurement can be phrased in the language of non-renormalizable operators that will arise from a theory beyond the SM which has a single, SM Higgs as its effective theory. In this case, the Higgs potential can have the form:

$$V(\Phi) = \lambda(\Phi^\dagger\Phi - v^2)^2 + \mathcal{C}\frac{(4\pi)^2}{\Lambda^2}(\Phi^\dagger\Phi - v^2)^3 + \dots \quad (1)$$

Expanding Φ into the physical Higgs component $v+H$, the first term determines the coefficient of H^2 or the mass term, which we define as $\lambda_{H^2}v^2$. The first and second terms contribute to the coefficient of the H^3 term, which we define as $\lambda_{H^3}v$. In the renormalizable theory, $\lambda_{H^2} = \lambda_{H^3}$. However, the LC measurement can only constrain this relation at the 20% level, i.e. $\lambda_{H^3} = (1.0 \pm .2)\lambda_{H^2}$, which bounds the relation $\lambda_{H^3} = \lambda_{H^2} + 8\mathcal{C}\frac{(4\pi)^2v^2}{\Lambda^2}$. Assuming a Higgs boson m_H that is equal to v and $\mathcal{C} = 1$, the expected precision will be sensitive to $\Lambda \lesssim 20$ TeV. In the MSSM, the measured self-coupling must obtain the Standard Model value once the decoupling region is reached. Some past studies have emphasized that the existence of the trilinear coupling for the light Higgs boson will be *verifiable* over most of the MSSM parameter space, but, for the most part, it will not deviate from the Standard Model expectations [62, 63]. It is worth noting that some models of strong dynamics predict a light, composite Higgs boson that also has a decoupling limit [64]. Therefore, the reconstruction of the Higgs potential would not be incontrovertible evidence of a fundamental scalar.

III. SUPERSYMMETRIC HIGGS BOSONS

The Standard Model, with the Higgs mechanism manifested by a single, fundamental Higgs doublet that acquires a vacuum expectation value, is believed to be an incomplete description of nature. There is only a limited region of Higgs boson masses where the theory remains perturbative through a desert up to a very high energy scale. Even in this limited region, the theory is extremely fine-tuned. Furthermore, the apparent existence of a GUT structure, as implied by the apparent unification of the gauge bosons near the GUT scale, raises the question of how a stable hierarchy can be maintained between the Electroweak and GUT scales.

One appealing solution to the fine-tuning and hierarchy problems is the existence of a broken, Electroweak-scale supersymmetry. The simplest form of supersymmetry requires an extended Higgs sector with two Higgs doublets, one responsible for the masses of up-quark-like fermions [H_2^0] and one for down-quark-like fermions [H_1^0]. The Higgs mechanism then generates 5 physical Higgs bosons, labeled h, H [$CP = +$], A [$CP = -$], and H^\pm, H^\mp . Furthermore, the Higgs boson self-coupling is no longer a free parameter, but is proportional to (the square of) gauge couplings. This implies a calculable upper bound to one of the Higgs bosons of the theory.

A. Is a light h supersymmetric in origin?

To answer this question, we must understand the expected properties of Higgs bosons in theories of Electroweak-scale supersymmetry (Susy) breaking. The properties of the Higgs sector are influenced primarily by several soft-Susy-breaking mass parameters with values of $\mathcal{O}(1 \text{ TeV})$ and the Susy-conserving, dimensionless parameter $\tan\beta$. Lacking a clear picture of the Susy-breaking mechanism, we vary these parameters over their allowed ranges, subject to theoretical and experimental constraints, and examine the consequences.

The properties of the SM-like Higgs bosons can be derived from the squared-mass matrix of the CP-even neutral MSSM Higgs bosons h and H [$m_h < m_H$], which is given in the (H_1^0, H_2^0) basis by:

$$\mathcal{M}^2 \equiv \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} = \begin{pmatrix} m_A^2 s_\beta^2 + m_Z^2 c_\beta^2 & -(m_A^2 + m_Z^2) s_\beta c_\beta \\ -(m_A^2 + m_Z^2) s_\beta c_\beta & m_A^2 c_\beta^2 + m_Z^2 s_\beta^2 \end{pmatrix} + \delta\mathcal{M}^2. \quad (2)$$

The contribution $\delta\mathcal{M}^2$ is a consequence of the radiative corrections that depend on the SM and Susy parameters. Solving the eigen-problem for this matrix yields the physical masses m_h and m_H and the mixing angle α , which appears in the Higgs couplings to fermions and gauge bosons. The tree level prediction $m_h \leq m_Z |\cos 2\beta| \leq m_Z$ is essentially ruled out by searches at LEP2. However, the radiative corrections raise the theoretical upper bound on m_h substantially above m_Z . For a fixed value of $\tan\beta$ and a specified set of MSSM parameters, m_h grows with increasing m_A and reaches an asymptotic value $m_h^{\max}(\tan\beta)$. If $\tan\beta$ is now allowed to vary while holding all other free parameters fixed, $m_h^{\max}(\tan\beta)$ increases with $\tan\beta$ and typically reaches an asymptotic value for $\tan\beta \gtrsim 10$. For large values of $\tan\beta$, $m_h \simeq m_h^{\max}$ and $m_H \simeq m_A$ for $m_A > m_h^{\max}$. Conversely, if $m_A < m_h^{\max}$ then $m_h \simeq m_A$ and $m_H \simeq m_h^{\max}$. Based on a scan of MSSM parameters, the largest value obtained for any reasonable choice of MSSM parameters is $m_h^{\max} \lesssim 135 \text{ GeV}$. Observation of a SM-like Higgs boson heavier than this would rule out a simple [or even CP-violating] MSSM Higgs sector. In the NMSSM, which includes an additional Higgs singlet, m_h^{\max} can be increased from its MSSM value for some choice of parameters. The inclusion of the dominant two-loop contributions to the effective potential have reduced the previous upper-bound to around 135 – 140 GeV [65, 66]. However, based on using a similar approximation in the MSSM, one can expect a further shift of several GeV after including sub-leading contributions.

Must such a Higgs boson be observed in the next generation of collider experiments? This will be the case if the light MSSM Higgs boson has substantial tree level coupling to W and Z bosons. In the MSSM, this follows from the fact that the couplings of h [H] to the W and Z are given by $\sin(\beta - \alpha)$ [$\cos(\beta - \alpha)$] times the corresponding SM Higgs coupling and from the CP-even Higgs boson sum rule [67–69]

$$m_H^2 \cos^2(\beta - \alpha) + m_h^2 \sin^2(\beta - \alpha) = [m_h^{\max}(\tan\beta)]^2. \quad (3)$$

In particular, if $m_A < m_h^{\max}$ and $\tan\beta$ is large one finds $m_H \sim m_h^{\max}$ and $\cos(\beta - \alpha) \sim 1$ while for $m_H \gg m_h^{\max}$ (as occurs in the $m_A \gg m_Z$ decoupling limit) the sum rule requires $m_h \sim m_h^{\max}$ and $\sin(\beta - \alpha) \sim 1$ (for any $\tan\beta$).

Will this Higgs boson be sufficiently different to exclude the SM? To answer this question, we must address the decoupling limit in more detail. In the decoupling limit, we find that $\sin(\beta - \alpha) = 1$ [or equivalently $\cos(\beta - \alpha) = 0$], in which case the couplings of h are identical to those of the h_{SM} . This behavior, which is easy to verify for the tree-level expressions, continues to hold when radiative corrections are included. However, the

onset of decoupling can be significantly affected by the radiative corrections. In general,

$$\cos(\beta - \alpha) = \frac{(\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2) \sin 2\beta - 2\mathcal{M}_{12}^2 \cos 2\beta}{2(m_H^2 - m_h^2) \sin(\beta - \alpha)} = \frac{m_Z^2 \sin 4\beta + (\delta\mathcal{M}_{11}^2 - \delta\mathcal{M}_{22}^2) \sin 2\beta - 2\delta\mathcal{M}_{12}^2 \cos 2\beta}{2(m_H^2 - m_h^2) \sin(\beta - \alpha)}. \quad (4)$$

Since $\delta\mathcal{M}_{ij}^2 \sim \mathcal{O}(m_Z^2)$, and $m_H^2 - m_h^2 = m_A^2 + \mathcal{O}(m_Z^2)$, one obtains

$$\cos(\beta - \alpha) = c \left[\frac{m_Z^2 \sin 4\beta}{2m_A^2} + \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\right) \right]; \quad c \equiv 1 + \frac{\delta\mathcal{M}_{11}^2 - \delta\mathcal{M}_{22}^2}{2m_Z^2 \cos 2\beta} - \frac{\delta\mathcal{M}_{12}^2}{m_Z^2 \sin 2\beta}; \quad (5)$$

Eq. (5) exhibits the expected decoupling behavior for $m_A \gg m_Z$, but also reveals another way in which $\cos(\beta - \alpha) = 0$ can be achieved—Nature must simply choose the supersymmetric parameters (that govern the Higgs mass radiative corrections) such that c vanishes. Remarkably, the vanishing of c is independent of m_A , and has a large $\tan \beta$ solution at

$$\tan \beta \simeq \frac{2m_Z^2 - \delta\mathcal{M}_{11}^2 + \delta\mathcal{M}_{22}^2}{\delta\mathcal{M}_{12}^2}. \quad (6)$$

Explicit solutions depend on ratios of Susy parameters and so are mostly insensitive to the overall Susy mass scale.

The behavior of the MSSM Higgs couplings as the decoupling limit is approached is revealed by expressing them in terms of c :

$$\frac{g_{hVV}^2}{g_{h_{\text{SM}}VV}^2} = \sin^2(\beta - \alpha) \simeq 1 - \frac{c^2 m_Z^4 \sin^2 4\beta}{4m_A^4}, \quad (7)$$

which quickly assumes the SM value as m_A increases. At large $\tan \beta$, the approach to decoupling is even faster, since $\sin 4\beta \simeq -4 \cot \beta$.

The couplings of h to up-type fermions may be written (explicitly for t):

$$\frac{g_{htt}^2}{g_{h_{\text{SM}}tt}^2} = [\sin(\beta - \alpha) + \cot \beta \cos(\beta - \alpha)]^2 \left[1 - \frac{\Delta_t \tan \beta}{1 + \Delta_t} (\cot \beta + \tan \alpha) \right]^2 \simeq 1 + \frac{cm_Z^2 \sin 4\beta \cot \beta}{m_A^2} \quad (8)$$

where the couplings are expressed in terms of $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$ in order to better illustrate the decoupling behavior. The Susy vertex corrections, expressed as Δ_t , are absent from the final expression since they are not enhanced with $\tan \beta$ and the prefactor $\cot \beta + \tan \alpha \simeq \cos(\beta - \alpha) / \sin^2 \beta$ is small in the decoupling limit. Similar expressions can be written for the charm quark, in which case the Susy vertex corrections are entirely negligible. The approach to decoupling is significantly slower [by a factor of m_A^2/m_Z^2] than in the case of the hVV coupling [Eq. 7]. At large $\tan \beta$, the approach to decoupling is faster due to the additional suppression factor of $\cot^2 \beta$ as in the case of the hVV coupling.

For the coupling of h to down-type fermions, Susy vertex corrections cannot be neglected. Focusing on the $b\bar{b}$ coupling, and neglecting corrections which are not $\tan \beta$ -enhanced, it follows that

$$\frac{g_{hbb}^2}{g_{h_{\text{SM}}bb}^2} = [\sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha)]^2 \left[1 - \frac{\Delta_b \cot \beta}{1 + \Delta_b} (\tan \beta + \cot \alpha) \right]^2 \simeq 1 - \frac{4cm_Z^2 \cos 2\beta}{m_A^2} \left[\sin^2 \beta - \frac{\Delta_b}{1 + \Delta_b} \right]. \quad (9)$$

The approach to decoupling is again slower as compared to g_{hVV} . However, in contrast to the previous two cases, there is no suppression at large $\tan \beta$. In fact, since $\Delta_b \propto \tan \beta$, the approach to decoupling is further delayed, unless $c \simeq 0$. A similar expression can be written for the τ coupling. The function Δ_τ is also $\tan \beta$ enhanced, but is of order g^2 instead of g_s^2 and y_t^2 , and is thus expected to be of less importance.

B. Coverage of Susy parameter space with the Light Higgs Boson

Sensitivity to the supersymmetric origin of a light Higgs boson from Higgs coupling measurements depends on the closeness to the decoupling limit. Since Higgs widths are approximately quadratic in the couplings, the greatest deviations from the SM are expected in $\Gamma(b)$ and $\Gamma(\tau)$, since these quantities approach the decoupling limit slowly. Determining the “coverage” of Susy parameter space is a biased endeavor. It is commonly phrased in terms of coverage in the $m_A - \tan \beta$ plane for fixed values of all other soft- Susy-breaking parameters.

The projected reach of the LHC for a Standard Model Higgs boson implies that a light, CP-even Higgs boson as predicted by the MSSM will also be observable over the entire $m_A - \tan\beta$ plane. For $m_A \gtrsim 110$ GeV, it is the h that is SM-like and which will be detected. For lower m_A , where $\sin^2(\beta - \alpha)$ is suppressed, the observed SM-like Higgs would be the heavier H . The ability to always detect the SM-like Higgs boson survives even when supersymmetric particles are included in the one-loop hgg and $h\gamma\gamma$ couplings. This is because it is essentially impossible to simultaneously suppress these couplings, and hence the $gg \rightarrow h \rightarrow \gamma\gamma$ rate, while also suppressing the $t\bar{t}h(\rightarrow b\bar{b})$ or $WW \rightarrow h(\rightarrow \tau^+\tau^-)$ processes that, as has been discussed, provide very good signals in the SM Higgs case [67]. While observation of a light, SM-like Higgs boson at the LHC will be consistent with a supersymmetric origin, this alone would not be incontrovertible evidence for Susy. The existence of sparticle-like signatures would be supporting, but not conclusive, evidence.

The LC has increased sensitivity to the properties of h from BR and coupling measurements. Nonetheless, even the LC will not be able to distinguish the light CP-even Higgs of the MSSM from a Higgs boson with precisely SM-like properties if the MSSM lies in the decoupling limit. Furthermore, this decoupling can occur much more rapidly than expected based purely on dimensional analysis, i.e. $m_A \gg M_Z$. If the MSSM parameters are such that the m_A -independent decoupling is realized, then the experimental sensitivity to m_A is greatly compromised. One way to present coverage of Susy parameter space is to consider “benchmark” scenarios that lead to very different behaviors of the SM-like Higgs boson of the MSSM. Three such scenarios are summarized in Table II, and correspond approximately to those discussed in Ref. [70]. All MSSM parameters are specified at the electroweak scale. The three benchmark scenarios have the following properties:

No-mixing scenario: The top squark mixing angle $\theta_{\tilde{t}}$ is zero. This scenario yields the lowest value of $m_h^{\max}(\tan\beta)$ for given values of $\tan\beta$ and M_S . For simplicity, the scenarios are defined in terms of $M_{\text{Susy}} \equiv M_{\tilde{Q}} = M_{\tilde{U}} = M_{\tilde{D}}$, where the latter are third generation squark mass parameters. For $M_{\text{Susy}} \gg m_t$, as is true in the scenarios considered here, $M_{\text{Susy}} \simeq M_S$ [where $M_S^2 \equiv .5(M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2)$]. Here, a large value for $M_{\text{Susy}} = 1.5$ TeV is chosen in order to obtain a sufficiently large value of $m_h^{\max}(\tan\beta)$, comparable to that obtained in the other two scenarios (the case of $M_{\text{Susy}} = 1$ TeV is at the edge of the region excluded by LEP2).

Maximal-mixing scenario: The top squark mixing is chosen to give the maximal value of $m_h^{\max}(\tan\beta)$ for given values of $\tan\beta$ and M_S .

Benchmark	Mass parameters [TeV]					
	μ	$X_t \equiv A_t - \mu \cot\beta$	A_b	M_{Susy}	$M_{\tilde{g}}$	m_h^{\max} [GeV]
No-Mixing	-0.2	0	A_t	1.5	1	118
Maximal-Mixing	-0.2	$\sqrt{6}$	A_t	1	1	129
Large μ and A_t	± 1.2	$\mp 1.2(1 + \cot\beta)$	0	1	0.5	119

TABLE II: MSSM parameters for our benchmark scenarios, and the derived maximal mass for the SM-like Higgs boson.

Large μ and A_t scenario: Large radiative corrections occur to both the mixing angle α and through Δ_b . In particular, \mathcal{M}_{12}^2 can exhibit extreme variations in magnitude depending on the sign of $A_t\mu$ and the magnitude of A_t . The two possible sign combinations for A_t and μ (for a fixed sign of $A_t\mu$) yield small differences in \mathcal{M}_{12}^2 through the dependence of h_t and h_b on Δ_t and Δ_b , respectively. The vertex correction Δ_b is dominated by the bottom squark-gluino contribution, which can enhance or suppress the Yukawa coupling h_b for negative or positive μ , respectively. In the following, two possible sign combinations for A_t and μ are considered with $A_t\mu < 0$.

To be conservative, relatively large values for the Susy breaking parameters, on the order of 1 TeV, are chosen so that some supersymmetric particles may not be kinematically accessible at the LC. However, for simultaneously large μ and $M_{\tilde{g}}$, the size of the Δ_b corrections may drive the bottom Yukawa coupling out of the perturbative region. Thus the gluino mass is taken as $M_{\tilde{g}} = 0.5$ TeV for large μ and $M_{\tilde{g}} = 1$ TeV for moderate μ . The other gaugino mass parameters are $M_2 = 2M_1 = 200$ GeV (M_2 is relevant for the one-loop $h \rightarrow \gamma\gamma$ amplitude). Finally, the masses of the remaining squarks and sleptons are set to 1 TeV.

The LC studies summarized earlier for branching ratio and coupling measurements were conducted for $m_{h_{\text{SM}}} = 120$ GeV, and thus are directly applicable to the study of a SM-like Higgs boson of the MSSM with a mass near 120 GeV, especially near the decoupling limit. Deviations from SM behavior can be probed using $\delta\text{BR} \equiv |1 - \text{BR}_{\text{MSSM}}/\text{BR}_{\text{SM}}|$ or $\delta\Gamma$ (defined similarly). Since the overall sensitivity is similar, only results for δBR are shown.

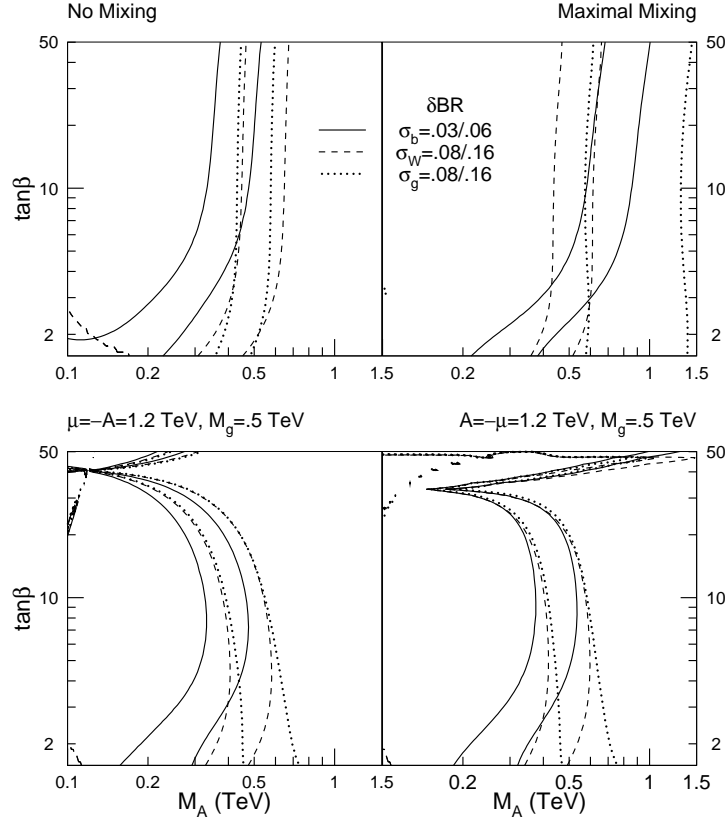


FIG. 4: Contours of $\delta\text{BR}(b) = 3$ and 6% (solid), $\delta\text{BR}(W) = 8$ and 16% (long-dashed) and $\delta\text{BR}(g) = 8$ and 16% (short-dashed) in the three benchmark scenarios.

In the four panels of Fig. 4, the solid, long-dashed, and short-dashed lines are contours of $\delta\text{BR}(b)$, $\delta\text{BR}(W)$ and $\delta\text{BR}(g)$, respectively [71]. Although $\delta\Gamma(b)$ is quite large over much of the parameter space, $\delta\text{BR}(b)$ is smaller because the increase in $\Gamma(b)$ also significantly increases Γ_{tot} . Because $\delta\Gamma(W)$ quickly approaches zero for increasing m_A , $\delta\text{BR}(W)$ indicates variation in the total Higgs width, and is more sensitive than $\delta\text{BR}(b)$, except for the case of maximal mixing. In regions of parameter space where $\delta\Gamma(g)$ approaches zero, $\delta\text{BR}(g)$, like $\delta\text{BR}(W)$, is sensitive to variations in the total width.

For the maximal-mixing scenario, the mass of the SM-like Higgs boson near the decoupling limit is roughly 10 GeV heavier than in the other benchmarks (see Table II), so that the relative contribution of $\Gamma(b)$ to Γ_{tot} is decreased. Therefore, deviations in g_{hbb} are not as diluted in the BR measurement as in the other scenarios, and the measurement of $\delta\text{BR}(b)$ yields superior sensitivity at large $\tan\beta$, around $m_A \lesssim 600\text{--}700$ GeV at 2σ . One should interpret this result with caution, however, since the accuracies for BR measurements are based on the simulation of a 120 GeV SM Higgs boson. In the maximal-mixing scenario, $\text{BR}(g)$ deviates by more than 8% from its SM value for $m_A \lesssim 1.4$ TeV. At 2σ the reach in $\delta\text{BR}(g)$ is roughly $m_A \lesssim 600$ GeV. In the no-mixing scenario, $\delta\text{BR}(g)$ and $\delta\text{BR}(W)$ give comparable reach in m_A ; at 2σ the reach is $m_A \lesssim 425$ GeV. For comparison, in the no-mixing scenario deviations in $\text{BR}(b)$ yield sensitivity at 2σ for $m_A \lesssim 300$ GeV for $\tan\beta \gtrsim 5$.

In the large μ and A_t scenarios, $\text{BR}(g)$ gives the greatest reach in m_A , allowing one to distinguish the MSSM from the SM Higgs boson at 2σ for $m_A \lesssim 350\text{--}450$ GeV, depending on the value of $\tan\beta$. At larger values of $\tan\beta$, the large μ and A_t scenarios have regions of m_A -independent decoupling where the SM-like MSSM Higgs boson cannot be distinguished from the SM Higgs boson even for very low values of m_A .

Clearly, the regions of the m_A — $\tan\beta$ plane in which the MSSM and SM Higgs bosons can be distinguished from one another at the LC by measuring the properties of the light Higgs boson depend strongly on the supersymmetric parameters, and the sensitivity comes from different measurements for different sets of MSSM parameters. In the following section, the impact of other Susy Higgs measurements will be considered.

C. Coverage of Susy parameter space and Heavy H/A and H^\pm Bosons

In or near the decoupling limit, measurements of the properties of the light Higgs boson in the MSSM will most likely not deviate significantly from the SM expectations. Of course, it is possible that H ($m_H < 135$ GeV) is the SM-like Higgs boson and hA production occurs ($m_h < m_H$ and $m_h \sim m_A$), but this is far from the decoupling limit. When h is very SM-like, it becomes urgent to observe one or more of the heavier Higgs bosons. The relevant couplings of the neutral Higgs bosons are:

$$\begin{aligned} g_{HVV}/g_{h_{SM}VV} &= \cos(\beta - \alpha); \quad g_{AVV}/g_{h_{SM}VV} = 0 \\ g_{Htt}/g_{h_{SM}tt} &= \cos(\beta - \alpha) + \sin(\beta - \alpha) \cot \beta; \quad g_{Att}/g_{h_{SM}tt} = \cot \beta \\ g_{Hbb}/g_{h_{SM}bb} &= [\cos(\beta - \alpha) + \sin(\beta - \alpha) \tan \beta] \frac{1}{1 + \Delta_b} [1 - \Delta_b \cot^2 \beta]; \quad g_{Abb}/g_{h_{SM}bb} = \tan \beta \frac{1}{1 + \Delta_b}. \end{aligned} \quad (10)$$

There are similar expressions with $t \rightarrow c$ and $b \rightarrow \tau$. As $\cos(\beta - \alpha) \rightarrow 0$, the H boson couplings approach those of the A boson, which has no significant coupling to W and Z bosons. While the true pseudoscalar still has γ_5 in its interaction Lagrangian, differences in the predictions of production and decay properties for the H and A bosons depend on the kinematic mass of the associated fermions, and are difficult to observe. Also, the effects of Susy vertex corrections can have important effects on the H and A properties. Finally, there is a ZHA coupling proportional to $\sin(\beta - \alpha)$, which is maximal in the decoupling limit.

For the charged Higgs boson H^\pm , where there is no SM analog, it is more convenient to write the interaction Lagrangian between fermions and the charged Higgs boson:

$$\begin{aligned} \mathcal{L} = & (h_b + \bar{\delta}h_b)H^- \bar{b}_R t_L \sin \beta + \bar{\Delta}h_b \cos \beta H^- \bar{b}_R t_L \\ & + (h_t + \bar{\delta}h_t)H^+ \bar{t}_R b_L \cos \beta + \bar{\Delta}h_t H^+ \bar{t}_R b_L \sin \beta + h.c., \end{aligned} \quad (11)$$

with similar expressions for $\tau - \nu_\tau$ and $c - s$. The presence of the couplings $\bar{\delta}h_{b,t}$ and $\bar{\Delta}h_{b,t}$ [72] indicate deviations from the tree-level expectations, and their effect is similar in nature to the $\Delta_i = \Delta h_i/h_i$ corrections introduced earlier. Finally, there are also $\gamma H^+ H^-$ and $ZH^+ H^-$ couplings, as well as other couplings which are not important near the decoupling limit.

The pseudoscalar A boson can be produced at a substantial rate at hadron colliders either in association with b quarks [$q\bar{q}, gg \rightarrow b\bar{b}A$ or $g b(\bar{b}) \rightarrow b(\bar{b})A$] or through $gg \rightarrow A$ when b or \bar{b} loops dominate, provided that the parameter $\tan \beta$ is large enough. Because of the large heavy-quark backgrounds, search strategies have focused on the decays $\tau^+ \tau^-$. In much of Susy parameter space, except for the region near $m_A \simeq m_h^{\max}$, one of the CP-even Higgs bosons has very similar properties to A [except for CP], thereby increasing the expected signal (the present studies have not treated carefully the mass splitting between A and either h or H and how the displaced mass peaks affect the estimate of the “continuum” background shape). In the decoupling limit, the charged Higgs also has a mass similar to that of A and H , and can be produced in the process $gb \rightarrow tH^-$, for example. The expected coverage in the $m_A - \tan \beta$ plane at the LHC is displayed in Fig. 5, for a conservative set of Susy parameters and neglecting any Susy vertex effects, i.e. Δ_b and Δ_τ . While a light SM-like Higgs boson is observable over the entire unexcluded region, its properties can be indistinguishable from a true SM Higgs boson, and thus shed no light on the underlying physics. However, for $\tan \beta \gtrsim 10$, the H^\pm, A and H bosons can be discovered through production in association with t or b quarks and decays into τ leptons, with coverage deteriorating somewhat at larger values of m_A .

The effect of Δ_b on the $b\bar{b}$ couplings of the heavy MSSM Higgs bosons does *not* decouple for $m_A \gg m_Z$ (i.e., for $\tan \alpha \tan \beta = -1$). Thus Δ_b could potentially have a significant effect on the discovery of the heavy Higgs bosons at the Tevatron and LHC by modifying production cross sections and decay branching ratios. The full impact of the Susy vertex corrections for hadron colliders has not been adequately explored; they will at least cause ambiguity in the interpretation of a purported value of $\tan \beta$. Here, we estimate their effect. The hadron collider production rate for $b\bar{b}\phi(\rightarrow b\bar{b}) + X$ scales roughly as $\tan^2 \beta / (1 + \Delta_b)^2$ as long as the b decay is still dominant, while the rate for $b\bar{b}\phi(\rightarrow \tau^+ \tau^-) + X$ is mainly unaffected and scales as $\tan^2 \beta$, due to a cancellation between changes in the production rate and changes to the total width. Ignoring uncertainties from higher-order QCD corrections and other sources, discovery of the H and A will allow an extraction of $\tan \beta / (1 + \Delta_\tau)$ with a relative error of about 10%. The impact on the charged Higgs discovery and interpretation should be similar, since modifications to the production rate are similarly canceled by the change to the total width. Studies described in the ATLAS TDR [73] show a relative error of 6% (7%) on the extraction of $\tan \beta$ from $H/A \rightarrow \tau^+ \tau^-$ decays assuming large $\tan \beta$, 300 fb $^{-1}$ of data, and $m_A = 150(350)$ GeV. The relative error decreases to about 5 – 6% using the rarer decays to muon pairs. However, these methods are sensitive to any Higgs decays into particles.

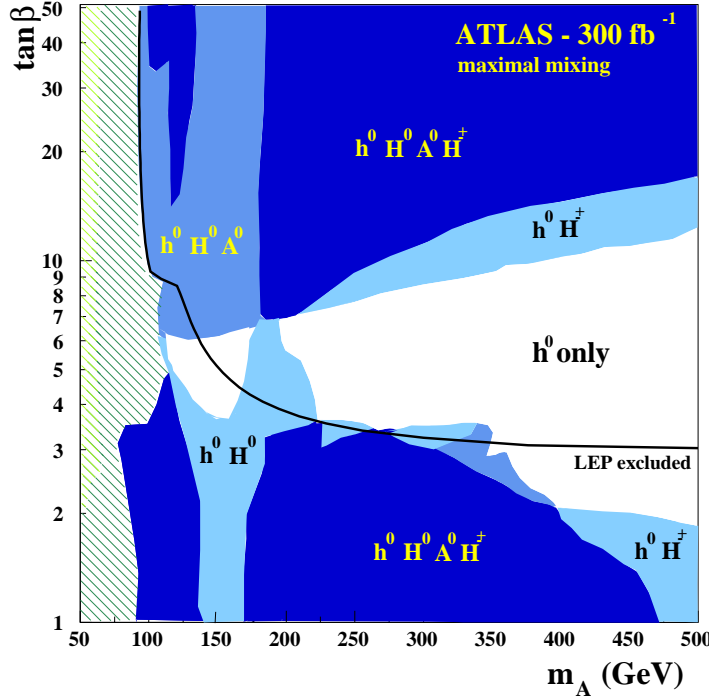


FIG. 5: LHC coverage of the $m_A - \tan \beta$ plane for a conservative Susy model, but neglecting potentially large corrections at large $\tan \beta$.

At a LC, the relevant production processes for heavy Higgs bosons are $(\gamma/Z)^* \rightarrow b\bar{b}(t\bar{t})H/A$, $(\gamma/Z)^* \rightarrow H^+H^-$, and $Z^* \rightarrow HA$. The $b\bar{b}H/A$ process requires rather large values of $\tan \beta$, whereas $t\bar{t}H/A$ requires small $\tan \beta$ and $\sqrt{s} > 350 \text{ GeV} + m_{H/A}$ [74, 75]. Small $\tan \beta$ is theoretically disfavored, since it typically leads to a lighter SM-like Higgs boson that should have been observed at LEP. HA [H^+H^-] production is fairly independent of $\tan \beta$, but requires $\sqrt{s} > m_H + m_A[2m_{H^\pm}]$. Thus, for high enough \sqrt{s} , the LC can observe heavy Higgs bosons in the moderate $\tan \beta$ region where the LHC does not have 5σ sensitivity. Note that the 5σ criterion is quite stringent, but analyses of the 95% CL and 3σ limits possible at the LHC are not yet available. The kinematic reconstruction of Higgs decay products in pair production at the LC will also allow a fairly good determination of the Higgs masses [76, 77], on the order of 1%.

The large μ and A_t scenario introduced above demonstrates the complementarity of the LC and the hadron colliders. For $\tan \beta \lesssim 10 - 20$, where the heavy MSSM Higgs bosons can be missed at the LHC, $\text{BR}(g)$ gives the greatest reach in m_A , allowing one to distinguish the MSSM from the SM Higgs boson at 2σ for $m_A \lesssim 350 - 450 \text{ GeV}$, depending on the value of $\tan \beta$. At larger values of $\tan \beta$, the large μ and A_t scenarios have regions of m_A -independent decoupling where the SM-like MSSM Higgs boson cannot be distinguished from the SM Higgs boson even for very low values of m_A . In fact, in these scenarios it is possible for h to be indistinguishable from the SM Higgs boson at the LC, while at the same time $m_A < 250 \text{ GeV}$ so that the heavy Higgs bosons will be directly observed at a 500 GeV LC through $e^+e^- \rightarrow HA, H^+H^-$. Where the m_A -independent decoupling occurs, for $\tan \beta \simeq 40$ [$\tan \beta \simeq 33$], the heavy MSSM Higgs bosons would be discovered at the LHC even for m_A above 500 GeV [6, 73]. Note also that for large μ and A_t and large $\tan \beta$, the correction Δ_b is quite large.

A very accurate determination of $\tan \beta$, mainly through Higgs production rates and Higgs decays, is also possible at a LC [78]. This is important, since it is fairly difficult to obtain a robust measurement of this parameter from other observables at hadron colliders or even a LC. As an example, assuming $\mathcal{L} = 2 \text{ ab}^{-1}$, $m_A \sim m_H \sim 200 \text{ GeV}$ and $\sqrt{s} = 500 \text{ GeV}$, measurements of the total H and A widths from calorimetry alone will yield accuracy $\Delta \tan \beta / \tan \beta \sim 0.1$ (~ 0.02) for $\tan \beta \sim 20$ (~ 50), while ratios of branching ratios yield $\Delta \tan \beta / \tan \beta < 0.1$ for $\tan \beta \leq 13$; $b\bar{b}A + b\bar{b}H$ production yields $\Delta \tan \beta / \tan \beta < 0.1$ for $\tan \beta \geq 40$. These different techniques are highly complementary and will, in combination, allow a very accurate determination of $\tan \beta$. Charged Higgs production should also be visible at the LC when HA production is, and this will provide additional information. At the LC, the processes $e^+e^- \rightarrow \tau^+\nu H^-$ and $\rightarrow t\bar{b}H^-$ show some sensitivity, but the most promising channel is $(\gamma/Z)^* \rightarrow H^+H^-$. While these results are promising, the analysis also ignored the dependence on Susy vertex corrections. The extracted value of “ $\tan \beta$ ” only represents an effective coupling. At large $\tan \beta$, where only a few decay modes dominate, the vertex corrections can have a significant impact. From the above discussion, however, it appears that a combination of LHC and LC measurements can give a

determination of $\tan\beta$ **and** the radiative corrections. Clearly, LC data would be of great value for disentangling the Δ_b dependence, so that the value of $\tan\beta$ extracted from heavy Higgs boson measurements can be compared to the value obtained from other sectors of the theory.

At a γC , the $(\gamma\gamma \rightarrow H) + (\gamma\gamma \rightarrow A)$ signal is observable in the $b\bar{b}$ final state for many $m_A - \tan\beta$ parameter choices. In particular, for almost all of the moderate- $\tan\beta$ wedge region with $250 \text{ GeV} \lesssim m_A \lesssim 500 \text{ GeV}$ of Fig. 5 in which only the light h of the MSSM can be detected at the LHC (with a similar wedge of non-detection being present at a LC operating in the e^+e^- collision mode [74, 79]), the combined $(\gamma\gamma \rightarrow H) + (\gamma\gamma \rightarrow A)$ signal will be observable at the 4σ level [33] after about 3 years of operation at $\sqrt{s} = 630 \text{ GeV}$ using the NLC design. The factor of two larger luminosity at TESLA would yield full coverage of this wedge region after 3 years of operation. (See also [80] and references therein.) Of course, the LHC and LC wedge regions in which H, A discovery will not be possible extend to arbitrarily high masses beyond 500 GeV, spanning an increasingly large range of $\tan\beta$ as m_A increases. Discovery of the H/A signal at the γC for masses above 500 GeV would require higher energy for the electron beams at the LC; roughly, H/A masses $\lesssim 0.8\sqrt{s}$ could be explored — a detailed study is needed to determine the amount of luminosity required to achieve 4 to 5 sigma signals throughout this entire kinematically accessible mass range for all $\tan\beta$ in the wedge region when operating at a fixed high \sqrt{s} .

Finally, at a μC , direct observation of H/A is possible through the $\tan^2\beta$ enhancement in $\sigma(\mu^+\mu^- \rightarrow H/A)$ [14, 34]. The strength of the H, A signals at the γC and μC are sensitive to the Δ_b radiative corrections and could be enhanced or suppressed relative to the tree-level expectations employed in the above studies.

D. CP violation

In the MSSM, CP need not be a good quantum number once one-loop effects are included in the Higgs potential. Mixing between the scalars and the pseudoscalar arises if there is a phase mismatch between several combinations of soft Susy-breaking parameters, i.e. if $\arg(A_t\mu) \neq 0$ [72, 81]. As a result, each of the three neutral Higgs bosons can have a CP-even admixture, and, thus, couple to the W and Z bosons. Observation of 3 separate Higgs bosons with couplings to W and Z might be possible, depending upon the precise mixing, the Higgs masses and (at the LC) the available energy. Also, all 3 of the couplings $Z \rightarrow h_1h_2, h_1h_3$ and h_2h_3 would be significant in general, allowing observation of all these pair processes at a LC with sufficient energy. As noted earlier, observation of $Z^* \rightarrow h_iZ, Z^* \rightarrow h_jZ$ and $Z^* \rightarrow h_ih_j$ for any $i \neq j$ is a direct signal of CP violation ([82] and references therein). CP-violating effects in the MSSM are most important for $m_{H^\pm} \lesssim 170 \text{ GeV}$ and $\tan\beta \lesssim 7$ [83], implying that all the Higgs boson mass eigenstates would typically have masses in this same range, making all 6 of the above processes kinematically accessible at a $\sqrt{s} \gtrsim 350 - 500 \text{ GeV}$ machine. Since $e^+e^- \rightarrow H^+H^-$ would be visible for $\sqrt{s} = 350 \text{ GeV}$ for $m_{H^\pm} \sim 150 \text{ GeV}$, we would be alerted to the possibility of this scenario even at an early stage LC. Susy QCD effects can render such a charged Higgs invisible in top quark decays or even in direct production at a hadron collider [84].

As sketched earlier, direct observation of CP violation via final state distributions in Higgs-strahlung production of a single Higgs boson is very difficult. In particular, in the MSSM the coupling of the CP-odd part of a Higgs eigenstate to WW, ZZ is one-loop suppressed so that Higgs-strahlung would be dominated by the CP-even component of the Higgs (or else have a very small cross section if the CP-even component is very small). Better opportunities are afforded via $t\bar{t}h$ final state distributions and γC and μC polarization asymmetries (obtained by varying the polarizations for the colliding γ 's and μ 's, respectively).

IV. EXOTIC HIGGS SECTORS

While a single Higgs doublet is the most economical way to manifest the Higgs mechanism, simple extensions of the Higgs sector include: (i) one or more singlet Higgs fields [This leads to no particular theoretical problems (or benefits) but Higgs discovery can be much more challenging, especially if there are many singlets], (ii) more Higgs doublet fields, the simplest case being the general two-Higgs-doublet model (2HDM) [In the general 2HDM, CP violation can arise in the Higgs sector and possibly be responsible for all CP-violating phenomena], (iii) $(SU(2)_L)$ triplet fields [In order for $\rho \sim 1$ to be a prediction of the theory (especially to avoid loop infinities that would require renormalization), the vev of any neutral member of the triplet representation must vanish [85]. Triplets are highly motivated in left-right symmetric models for the neutrino mass see-saw mechanism. In this case, a right-handed $(SU(2)_R)$ triplet Higgs representation, with non-zero vev for its neutral member to generate neutrino masses, requires a partner left-handed $(SU(2)_L)$ triplet, whose neutral member should have zero vev in order that $\rho = 1$ be natural], (iv) special choices of T and Y for an exotic Higgs multiplet, the next simplest after $T = 1/2, |Y| = 1$ being $T = 3, |Y| = 4$, that yield $\rho = 1$ at tree level and finite loop corrections to ρ even if the neutral field has non-zero vev (see [86] and references therein).

Coupling constant unification provides further motivation for considering an extended SM Higgs sector. For appropriate choices of Higgs representations, it is possible to achieve coupling constant unification for SM matter content (i.e. no Susy) [87], although not at as high a scale as the standard $M_{\text{GUT}} \sim 10^{16}$ GeV. For example, the combination of two $T = 1/2, Y = 1$ and one $T = 1, Y = 0$ representations gives unification with $\alpha_s(m_Z) = 0.115$ and $M_{\text{GUT}} = 1.6 \times 10^{14}$ GeV. Still lower unification scales, as perhaps appropriate in theories with extra dimensions, can be achieved for more complicated Higgs sectors. Thus, one should not discard complicated Higgs sectors out of hand.

In what follows, we very briefly address the implications for discovery and precision measurements for some unusual Higgs sectors. For more theoretical and experimental discussion, see [88].

A. Multi-Singlet Models

Neither precision electroweak constraints nor LEP2 data rule out a complicated Higgs sector. In fact, the LEP2 exclusion plots for a single SM-like Higgs boson – which demonstrate a flat 2σ systematic difference between the expected and observed background rates – can be interpreted as indicating a spread-out Higgs signal, *e.g.* several Higgs bosons in the < 114 GeV region, each with an appropriate fraction of the SM ZZ coupling. Such a situation was considered in [69]. The simplest way to achieve this is to add a modest number of singlet Higgs fields to the minimal one-doublet SM Higgs sector. For an appropriate Higgs potential that mixes the many neutral fields, the physical Higgs bosons would be mixed states sharing the WW/ZZ coupling strength squared. If these Higgs bosons had masses spread out every 10–20 GeV (*i.e.* smaller than the detector resolution in a typical decay channel), a broad/diffuse ‘continuum’ Higgs signal would be the result.

Precision electroweak constraints and also perturbativity for Higgs sector couplings for all scales between 1 TeV to M_{GUT} both imply that the Higgs mass eigenstates with significant WW, ZZ coupling must, on average, have mass below 200 – 250 GeV. As shown in [69], this implies that the broad diffuse excess in the recoil M_X mass distribution for $e^+e^- \rightarrow ZX$ will be observable for $L \gtrsim 200 \text{ fb}^{-1}$ at a $\sqrt{s} = 500$ GeV LC. With 1 ab^{-1} of data, it would be possible to map out the ZZ coupling strength as a function of location in M_X and possibly explore branching ratios to various channels as a function of M_X . In contrast, this broad excess would most likely be very difficult to detect at the LHC. This would typically be true even for the $\gamma\gamma$ discovery mode where it might be hoped that the excellent mass resolution would allow observation of a series of narrow peaks. While such peaks should be carefully searched for even if no other Higgs signal is seen, they would typically be very suppressed compared to the SM expectation. This is because the suppression of the WW coupling to each of the Higgs bosons implies suppression of the crucial W -loop contribution to the $\gamma\gamma h$ coupling, which would then cancel substantially against the top-loop contribution.

B. General Two-Higgs-Doublet Models

In the conventional decoupling limit of a general 2HDM, there will be a light SM-like Higgs boson which can be consistent with precision Electroweak constraints and will be easily detected at both the LHC and the LC. However, there are non-decoupling scenarios in which the situation is very different. One such case is that considered in [89] where the only light Higgs boson has no WW/ZZ couplings (for example, it could be a light A) and all the other Higgs bosons have mass $\gtrsim 1$ TeV, including a SM-like CP-even state. The large negative ΔT arising from the heavy SM-like Higgs boson can be compensated by an even larger positive ΔT coming from a small mass splitting between the non-SM-like heavy Higgs bosons so that the net S, T parameters fall within the current 90% precision electroweak ellipse. The light Higgs boson without WW/ZZ couplings would be very hard to see at the LHC or a $\sqrt{s} \sim 800$ GeV LC if $\tan\beta$ is moderate and its mass is above ~ 300 GeV. (For lower masses, $e^+e^- \rightarrow \bar{\nu}\nu$ plus two light Higgs would allow discovery of the light Higgs.) The heavy SM-like Higgs boson would be seen at the LHC but not at the LC until $\sqrt{s} \gtrsim 1$ TeV is reached. Giga- Z constraints on S, T would be very valuable in fully exploring this type of scenario. The γC and μC would both be able to detect the light, decoupled Higgs boson over substantial portions of the $\tan\beta$ -Higgs mass parameter region for which it could not otherwise be seen (see [33] and [14], respectively).

C. Extended Higgs sectors in supersymmetric models

A very attractive extension of the MSSM is the NMSSM (next-to-minimal supersymmetric model) in which one singlet Higgs superfield is added to the model [90]. The trilinear superpotential term with the two Higgs doublet superfields and the singlet superfield yields a natural explanation for the μ parameter of the MSSM

when the scalar component of the Higgs singlet superfield acquires a vev. The prospects for discovering the three CP-even and two CP-odd Higgs bosons (for purposes of discussion, we assume CP is conserved) have been explored (see [91] and references therein). Discovery of at least one of the CP-even Higgs bosons would be guaranteed at a LC with $\sqrt{s} = 500$ GeV and $L \gtrsim 100 \text{ fb}^{-1}$. Discovery of one of the CP-even Higgs bosons at the LHC can also be guaranteed for those regions of NMSSM parameter space in which heavier Higgs bosons do not decay into lighter Higgs bosons. Particularly important for this latter conclusion is the recent development of viable methods for detecting the $t\bar{t}h(\rightarrow b\bar{b})$ and $WW \rightarrow h \rightarrow \tau^+\tau^-$ LHC signals. However, for NMSSM parameter choices such that there is a light (*e.g.* 30 to 50 GeV) pseudoscalar Higgs boson into which the heavier CP-even Higgs bosons can decay, there is currently no certainty that even one of the NMSSM Higgs bosons will be detected at the LHC. A very important future task will be to develop LHC detection modes that will fill this void. Still, it is clear that the LC might be absolutely essential to discover the NMSSM Higgs bosons and would certainly be required in order to fully explore their properties.

More complicated extensions of the MSSM Higgs sector are certainly possible, but it is only singlet superfields that can be easily added without upsetting the nearly perfect coupling constant unification. Addition of more doublet and or triplet superfields (in pairs, as required for anomaly cancellation) will destroy coupling unification unless a carefully chosen set of intermediate-scale matter superfields are also incorporated in the model. Coupling constant unification can be retained without intermediate-scale matter only for certain complicated and carefully chosen sets of additional Higgs representations [87]. However, the unification scale for such models is always well below 10^{16} GeV. If we stick to the addition of singlets, the general no-lose theorem of [69] guarantees that a signal for one of the CP-even Higgs bosons, or perhaps a spread-out signal from several, will be detectable at a $\sqrt{s} = 500$ GeV LC. However, for much of the parameter space of such a model, LHC detection of even one Higgs boson would not be possible.

D. Radions from Extra Dimensions

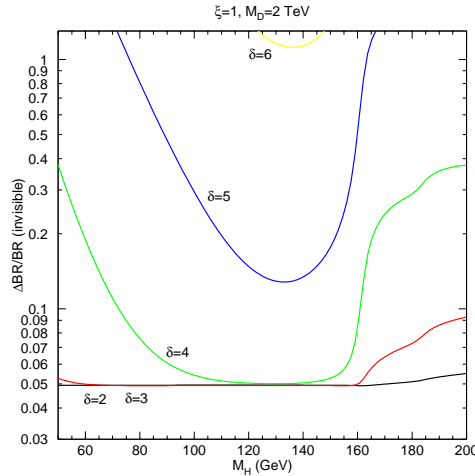


FIG. 6: Resolution on invisible decays of the Higgs boson in the ADD scenario with conformal factor $\xi = 1$ and reduced Planck constant $M_D = 2$ TeV.

Extra dimensions and related ideas can have a tremendous impact on Higgs phenomenology. Most intriguing are the impacts of the graviscalars present in such theories. These new scalar degrees of freedom can significantly alter Higgs boson phenomenology. In principle, the graviscalars can mix with the ordinary Higgs boson through a coupling to the Ricci scalar. Most of the relevant phenomenology was addressed in Ref. [92]. For the ADD scenario, the large number of graviscalar states can overcome their weak coupling, providing a sizable invisible width for the Higgs boson. Perhaps the best way to bound the invisible width is to use the excellent measurement of the visible width at the LC. As demonstrated in Fig. 6, a good measurement of the $\text{BR}(h \rightarrow \text{invisible})$ is possible for large ξ and relatively small scales M_D (the invisible width scales as $\xi^2 m_h^{1+\delta}/M_D^{2+\delta}$). This plot is based on applying simulations for $m_h = 120$ GeV to all Higgs boson masses; better (worse) resolution is expected for higher (lower) masses [93]. Even in the limit $\xi = 0$, direct graviscalar production is possible at colliders (*e.g.* $e^+e^- \rightarrow ZH^{(n)}$), but the effect is weak and the signal from spin-2 KK excitations will be substantially larger. In the RS scenario (with a non-factorizable geometry) there is only one radion, characterized by its scale Λ_ϕ .

The radion interaction with fermions and electroweak gauge bosons is similar to the SM one, but scaled by the factor v/Λ_ϕ . The production of the radion through the typical tree-level processes is then suppressed by the factor $(v/\Lambda_\phi)^2$. This compromises LC searches through the channels $Z^* \rightarrow Z\phi, WW \rightarrow \phi, b\bar{b}\phi$, etc. However, the radion has a coupling to gg and $\gamma\gamma$ pairs through trace anomalies, and the largest partial width can be $\Gamma(\phi \rightarrow gg)$, thereby dominating the radion decays, for $m_\phi < 2M_W$. Additionally, the ξ term induces a mixing between the pure radion and Higgs boson. For $|\xi| \sim .5$ and $v/\Lambda_\phi \sim .1 - .2$, observable deviations from the SM width should be observable at a LC [94]. Typically, the direct production rate of the radion, even through gg fusion at the LHC, is small enough to avoid detection. Surprisingly, one of the most promising modes at the LHC could be the observation of $gg \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ in a rather-narrow invariant mass range.

V. SUMMARY AND CONCLUSION

The analysis of precision Electroweak observables indicates a high likelihood for the existence of a light SM-like Higgs boson, which will be discovered possibly at the Tevatron and definitely at the LHC. While it is possible to obtain agreement with precision Electroweak data by canceling the large negative ΔT coming from a heavy SM-like Higgs boson against even more positive ΔT contributions from new physics [89, 95], this is only possible if the SM-like Higgs boson has mass below about 1 TeV (and hence is observable at the LHC) and if there is other new physics below or at this same scale.

Whatever the nature of the Higgs sector, it will ultimately be essential not only to observe all the Higgs bosons but also to determine their properties at the precision level. If only a single Higgs boson is observed with decays and production rates that suggest it is SM-like, it will be crucial to search for any deviations of its properties from those predicted for the SM Higgs boson. A complete program will require the verification that the observed particle carries the Higgs boson quantum numbers, and that it is responsible for the generation of gauge boson and fermion masses through the model-independent measurements of its couplings to the SM particles. Deviations from SM predictions could indicate that the SM-like Higgs boson is part of an extended Higgs sector. In this case, observation of the other Higgs bosons becomes mandatory. In the MSSM, the other Higgs bosons are most likely to be heavier if the observed Higgs boson is light and SM-like. In more general models this need not be the case — for example, a CP-odd Higgs boson of moderate mass can easily escape discovery at both the LHC and at a LC of modest energy.

A full exploration of the Higgs sector can be carried out by a sequence of collider experiments in the coming decades. While the potential for precise measurements of an observed Higgs boson at the Tevatron is marginal due to luminosity and energy limitations, the LHC will yield a first quantitative picture of the Higgs sector, once a significant amount of integrated luminosity ($\sim 200 \text{ fb}^{-1}$) is accumulated. Assuming the Higgs is SM-like, this picture consists of a precise measurement of the Higgs boson mass, constraints on its spin and quantum numbers, a model-dependent determination of its total width, and a measurement of its coupling to electro-weak gauge bosons at the 5% level. Access to the Yukawa couplings is more limited at the LHC. For a light Higgs boson, only the coupling to the τ lepton and the top-quark can be measured, with $\sim 10\%$ precision ($\sim 20\%$ for partial widths). Beyond that, in a large part of the MSSM parameter space, heavier Higgs bosons (H, A, H^\pm) can be observed for large ($\gtrsim 10$) and small ($\lesssim 3$) values of $\tan\beta$, for masses up to several hundred GeV.

The measurements of the couplings of a SM-like Higgs boson at the LHC require stringent assumptions, namely b/τ universality and absence of important unexpected decay modes. Lifting these assumptions will increase coupling errors substantially. Ultimately, the precision of coupling measurements at hadron colliders is systematics limited, by unknown higher order QCD corrections to the production cross sections, unknown normalization of the background, and detector effects. Some ratios of couplings can be determined more precisely, but these ratios give incomplete information on the Higgs sector. If the Higgs sector is more complicated and the hadron colliders discover more than one Higgs-like signal, an unambiguous interpretation of these signals will be even more challenging. Therefore, one concludes that another collider facility will be necessary to precisely determine the properties of a SM-like Higgs boson and/or fully delineate the Higgs sector.

An electron positron linear collider with center-of-mass energy up to ~ 1 TeV will significantly increase our knowledge about the Higgs sector. If the lightest Higgs boson is SM-like and has a mass in the region favored by EW precision data, already a first stage with $\sqrt{s} \sim 500$ GeV is sufficient for a measurement of the essential properties of a Higgs boson at the percent level. These properties include the mass, quantum numbers and couplings to the gauge bosons Z, W^\pm and fermions b, c, τ . Furthermore, for $m_h \lesssim 140$ GeV, a first measurement of the Higgs trilinear coupling will be possible, with a relative accuracy of 20%. At higher energy (~ 1 TeV) additional important information can be obtained from a direct measurement of the top quark Yukawa coupling. For the specific case of the MSSM, measurements of these couplings may reveal distinct differences from the SM that were not accessible at hadron colliders. However, it is always possible in the MSSM, and many extensions of the SM, that the Higgs sector parameters are sufficiently into the decoupled regime that the lightest Higgs

boson is very SM-like. In this case, LC operations at a higher energy could discover heavier Higgs bosons for which the LHC and a lower energy LC did not provide any evidence. For example, for a range of values of $\tan\beta$ and $m_A \gtrsim 300$ GeV, the H/A of the MSSM will not be directly visible at the LHC or a low energy LC and the MSSM parameters can be chosen so that decoupling applies to a very good approximation, implying that the light h is very SM-like. Nonetheless, the H/A would yield visible signals at a LC with high energy. (Masses up to $\sim \sqrt{s}/2$ for e^+e^- collisions and up to $\sim 0.8\sqrt{s_{ee}}$ for $\gamma\gamma$ collisions become accessible). Even if these heavier Higgs bosons are observable at the LHC, the LC operating at $\sqrt{s} \sim 1$ TeV will provide complementary and generally much more precise measurements of the couplings of the heavy Higgs bosons.

To summarize, the proposed e^+e^- linear collider, operating at energies up to $\sqrt{s} \sim 1$ TeV, will allow precision measurements of the properties of those Higgs bosons which are kinematically accessible, which will almost certainly include a relatively SM-like (or collection of somewhat SM-like Higgs bosons). But, there are cases (e.g. Susy near the decoupling limit) in which a complete exploration of the Higgs sector will require multi-TeV colliders (multi-TeV- e^+e^- -LC, μ C, VLHC) to complete the exploration of the Higgs sector through the observation of very heavy Higgs bosons.

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