

# FUTURE DIRECTIONS IN HIGGS PHENOMENOLOGY

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## ABSTRACT

The search for the weakly-coupled Higgs sector at future colliders consists of three phases: discovery of a Higgs candidate, verification of the Higgs interpretation of the signal, and precision measurements of Higgs sector properties. The discovery of one Higgs boson with Standard Model properties is not sufficient to expose the underlying structure of the electroweak symmetry breaking dynamics. It is critical to search for evidence for a non-minimal Higgs sector and/or new physics associated with electroweak symmetry breaking dynamics.

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## Introduction

The discovery of the Higgs boson would begin to address the outstanding problem of elementary particle physics: what is the origin of electroweak symmetry breaking and the nature of the dynamics responsible for it. Higgs hunting at future colliders will consist of three phases. Phase one is the initial Higgs boson search in which a Higgs signal is found and confirmed as evidence for new phenomena not described by Standard Model background. Phase two will address the question: should the signal be identified with Higgs physics? Finally, phase three will consist of a detailed probe of the Higgs sector and precise measurements of Higgs sector observables. Discovery of a Higgs-like signal alone may not be sufficient to earn a place in the Particle Data Group tables. Some basic measurements of the properties of the Higgs candidate will be essential to confirm a Higgs interpretation of the discovery.

It is not unlikely that the first Higgs state to be discovered will be experimentally indistinguishable from the Standard Model Higgs boson ( $h_{\text{SM}}^0$ ). This occurs in many theoretical models that exhibit the decoupling of heavy scalar states [1,2]. In this decoupling limit, the lightest Higgs state,  $h^0$  is a neutral CP-even scalar with properties nearly identical to the  $h_{\text{SM}}^0$ , while the other Higgs bosons of the non-minimal Higgs sector are heavy (compared to the  $Z$ ) and are approximately mass-degenerate. Thus, discovery of  $h^0 \simeq h_{\text{SM}}^0$  may shed little light on the dynamics underlying electroweak symmetry breaking. Precision measurements are critical in order to distinguish between  $h^0$  and  $h_{\text{SM}}^0$  and/or to map out the properties of the non-minimal Higgs states.

Higgs phenomenology at future colliders was recently re-evaluated at the 1996 Snowmass Workshop. This paper reviews some of the principal findings of the Higgs boson working group study. Further details can be found in Refs. [3] and [4].

## Phase 1 – Demonstrate the Observability of a Higgs Signal

In the planning of future collider facilities, the machine and detector characteristics must be developed in such a way that a Higgs signal can be unambiguously

detected above the Standard Model background. In this paper, I shall focus on the Standard Model Higgs boson,  $h_{\text{SM}}^0$ , and the Higgs bosons of the minimal supersymmetric extension of the Standard Model (MSSM):  $h^0$ ,  $H^0$ ,  $A^0$ , and  $H^\pm$ . In the decoupling limit, the discovery reach of  $h_{\text{SM}}^0$  at future colliders also applies to the lightest CP-even neutral Higgs boson ( $h^0$ ) of the MSSM.

Table 1. The  $h_{\text{SM}}^0$  discovery reach of future colliders. A  $5\sigma$  signal above background is required for discovery. Note that Run II at the Tevatron complements the LEP Higgs search only for an integrated luminosity well beyond one year at the design luminosity of the Main Injector. For NLC, both  $\sqrt{s} = 500$  GeV and 1 TeV cases are shown. The discovery reach of a  $\mu^+\mu^-$  collider (FMC) is similar to that of the NLC for the same center-of-mass energy and integrated luminosity.

Collider	Integrated Luminosity	Discovery Reach
LEP-2 ( $\sqrt{s} = 192$ GeV)	150 pb $^{-1}$	95 GeV
Tevatron	5–10 fb $^{-1}$	80–100 GeV
TeV-33	25–30 fb $^{-1}$	120 GeV
LHC	100 fb $^{-1}$	800 GeV
NLC-500	50 fb $^{-1}$	350 GeV
NLC-1000	200 fb $^{-1}$	800 GeV

### 1. The Standard Model Higgs Boson

The  $h_{\text{SM}}^0$  discovery reach of future colliders is summarized above in Table 1. At LEP-2 running at  $\sqrt{s} = 192$  GeV, the discovery reach of  $m_{h_{\text{SM}}^0} \simeq 95$  GeV can be attained by one detector taking data for about one year at design luminosity [5]. With four LEP detectors running, the Higgs mass discovery reach can be achieved sooner (or improve on the significance of any candidate Higgs signal). Additional luminosity cannot significantly extend the Higgs mass reach unless the LEP-2 center-of-mass energy were increased. At Run II of the Tevatron one year of data taking at the Main Injector design luminosity (1–2 fb $^{-1}$ ) is not sufficient to discover a Standard Model Higgs boson above background. However, two detectors running at design luminosity from three to five years can complement the LEP-2 Higgs search. In particular, the associated production of  $Wh_{\text{SM}}^0$  with  $h_{\text{SM}}^0 \rightarrow b\bar{b}$  may be feasible at the Tevatron, given sufficient integrated luminosity. Assuming a total integrated luminosity of 5 [10] fb $^{-1}$ , a Standard Model Higgs mass discovery reach of 80 [100] GeV is attainable [6,7]. The Tevatron Higgs search technique also applies at higher luminosity. For example, initial studies indicate that at TeV-33, a Standard Model Higgs boson with a mass of 120 GeV can be discovered with an integrated luminosity of 25–30 fb $^{-1}$  [6,7]. The significance of the Higgs signal could be enhanced by the detection of the associated production of  $Zh_{\text{SM}}^0$ ,  $h_{\text{SM}}^0 \rightarrow b\bar{b}$  [8]. Implicit in these studies is the assumption that the Standard Model contributions are sufficiently well understood that the Higgs signal can be detected as a small excess above background.

The LHC is required if one wants to extend the Higgs mass discovery reach significantly beyond  $\mathcal{O}(m_Z)$  [4,9,10]. For  $m_{h_{\text{SM}}^0} \gtrsim 2m_Z$ , the “gold-plated mode”  $h_{\text{SM}}^0 \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$  provides a nearly background free signature for Higgs boson production until the production rate becomes too small near the upper end of the weakly-coupled Higgs mass regime. In this case, other signatures (*e.g.*,  $h_{\text{SM}}^0 \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$  and  $h_{\text{SM}}^0 \rightarrow W^+W^- \rightarrow \ell\nu + \text{jets}$ ) provide additional signatures for Higgs discovery. The most troublesome Higgs mass range for hadron colliders is the so-called “intermediate Higgs mass regime”, which corresponds roughly to  $m_Z \lesssim m_{h_{\text{SM}}^0} \lesssim 2m_Z$ . For  $130 \text{ GeV} \lesssim m_{h_{\text{SM}}^0} \lesssim 2m_Z$ , one can still make use of the gold plated mode at the LHC,  $h_{\text{SM}}^0 \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$  (where  $Z^*$  is virtual). Standard Model backgrounds begin to be problematical when the branching ratio  $\text{BR}(h_{\text{SM}}^0 \rightarrow ZZ^*)$  becomes too small. This occurs for  $2m_W \lesssim m_{h_{\text{SM}}^0} \lesssim 2m_Z$  where  $\text{BR}(h_{\text{SM}}^0 \rightarrow W^+W^-)$  is by far the dominant Higgs decay channel, and for  $m_{h_{\text{SM}}^0} \lesssim 140 \text{ GeV}$  where the the virtuality of  $Z^*$  begins to significantly reduce the  $h_{\text{SM}}^0 \rightarrow ZZ^*$  decay rate. A complementary channel  $h_{\text{SM}}^0 \rightarrow WW^{(*)} \rightarrow \ell^+\nu\ell^-\bar{\nu}$  provides a viable Higgs signature for  $155 \text{ GeV} \lesssim m_{h_{\text{SM}}^0} \lesssim 2m_Z$  [11], and closes a potential hole near the upper end of the intermediate Higgs mass range. For  $m_{h_{\text{SM}}^0} \lesssim 130 \text{ GeV}$ , the dominant decay channel  $h_{\text{SM}}^0 \rightarrow b\bar{b}$  has very large Standard Model two-jet backgrounds. Thus, in this regime, it is necessary to consider rarer production and decay modes with more distinguishing characteristics. Among the signatures studied in the literature are: (i)  $gg \rightarrow h_{\text{SM}}^0 \rightarrow \gamma\gamma$ , (ii)  $q\bar{q} \rightarrow V^* \rightarrow Vh_{\text{SM}}^0$  ( $V = W$  or  $Z$ ), (iii)  $gg \rightarrow t\bar{t}h_{\text{SM}}^0$ , (iv)  $gg \rightarrow b\bar{b}h_{\text{SM}}^0$ , and (v)  $gg \rightarrow h_{\text{SM}}^0 \rightarrow \tau^+\tau^-$ . The LHC detectors are being optimized in order to be able to discover an intermediate mass Higgs boson via its rare  $\gamma\gamma$  decay mode (with a branching ratio of about  $10^{-3}$ ). The other signatures could be used to provide consistency checks for the Higgs discovery as well as provide additional evidence for the expected Higgs-like properties of the Higgs boson candidate. A successful intermediate mass Higgs search via the  $\gamma\gamma$  decay mode at the LHC will require maximal luminosity and a very fine electromagnetic calorimeter resolution (at about the 1% level).

In contrast to the Tevatron and LHC Higgs searches, the Standard Model Higgs search at the NLC in the intermediate mass regime is straightforward, due to the simplicity of the Higgs signals, and the relative ease in controlling the Standard Model backgrounds. Higgs production is detected at the NLC via two main signatures. The first involves the extension of the LEP-2 search for  $e^+e^- \rightarrow Zh_{\text{SM}}^0$  to higher energies. In addition, a second process can also be significant: the (virtual)  $W^+W^-$  fusion process,  $e^+e^- \rightarrow \nu\bar{\nu}W^*W^* \rightarrow \nu\bar{\nu}h_{\text{SM}}^0$ . The fusion cross-section grows logarithmically with the center-of-mass energy and becomes the dominant Higgs production process at large  $\sqrt{s}/m_{h_{\text{SM}}^0}$ . For example, at  $\sqrt{s} = 500 \text{ GeV}$ , complete coverage of the intermediate Higgs mass regime below  $m_{h_{\text{SM}}^0} \lesssim 2m_Z$  requires only  $5 \text{ fb}^{-1}$  of data. The only limitation of the NLC in the Higgs search is the center-of-mass energy of the machine which determines the upper limit of the Higgs boson discovery reach. One

would need  $\sqrt{s} \simeq 1$  TeV to fully cover the weakly-coupled Standard Model Higgs mass range [12,13,14].

The techniques for the Standard Model Higgs boson *discovery* at a  $\mu^+\mu^-$  collider (FMC) are, in principle, identical to those employed at the NLC [15,16]. However, one must demonstrate that the extra background resulting from an environment of decaying muons can be tamed. It is believed that sufficient background rejection can be achieved [17]; thus the FMC has the same discovery reach as the NLC at the same center-of-mass energy and luminosity.

## 2. Higgs Bosons of the MSSM

Next, we turn to the discovery potential at future colliders for the Higgs bosons of the MSSM. If  $m_{A^0} \gg m_Z$ , then the decoupling limit applies, and the couplings of  $h^0$  to Standard Model particles are identical to those of  $h_{\text{SM}}^0$ . Thus, unless  $h^0$  decays appreciably to light supersymmetric particles, the discussion given above for  $h_{\text{SM}}^0$  apply without change to  $h^0$ . In general, one can consider two types of MSSM Higgs searches at future colliders. First, one can map out the region of MSSM parameter space where at least one MSSM Higgs boson can be discovered in a future collider Higgs search. If no Higgs state is discovered, then the corresponding region of MSSM parameter space would be excluded. (In some cases, the absence of a Higgs discovery would be strong enough to completely rule out the MSSM!) Note that in this approach, one may simply discover one Higgs state—the light CP-even neutral  $h^0$ —with properties resembling that of  $h_{\text{SM}}^0$ , which would be consistent with MSSM expectations, but would provide no direct proof that low-energy supersymmetry underlies the Higgs sector dynamics. Second, one can examine the discovery potential for specific states of the non-minimal Higgs sector. In the decoupling limit, the non-minimal Higgs states are heavy (compared to the  $Z$ ), nearly degenerate in mass, and weakly-coupled. Discovery of these states at future colliders is far from being assured.

We summarize the MSSM Higgs boson discovery potential at future colliders in Table 2. Consider first the discovery limits for  $h^0$  of the MSSM. The tree-level MSSM predicts that  $m_{h^0} \leq m_Z$  [18]. Suppose that this predicted bound were unmodified (or reduced) after taking radiative corrections into account. Then the non-observation of  $h^0$  at LEP-2 (which will eventually be sensitive to the mass range  $m_{h^0} \lesssim 95$  GeV) would rule out the MSSM. However, for some choices of MSSM parameters, the radiative corrections significantly *increase* the tree-level bound. Based on the most recent analyses of Ref. [19], if superpartner masses are no heavier than a few TeV, then the Higgs mass bound in the MSSM is  $m_{h^0} \lesssim 130$  GeV. Consequently, the absence of a Higgs discovery at LEP-2 and the Tevatron cannot completely rule out the MSSM.

On the other hand, it would appear that the LHC has access to the full MSSM Higgs sector parameter space. After all, we noted above that the LHC will be able to completely cover the intermediate Standard Model Higgs mass regime. However, when  $m_{A^0} \sim \mathcal{O}(m_Z)$ , the decoupling limit does not apply, and the properties of  $h^0$

Table 2. MSSM Higgs boson discovery potential

Collider	Comments
LEP-2	Significant but not complete coverage, via $e^+e^- \rightarrow H^+H^-$ , $e^+e^- \rightarrow Zh^0$ and $e^+e^- \rightarrow h^0A^0$ .
TeV-33	Limited coverage, complements the LEP-2 search.
LHC	(Nearly) complete coverage for the discovery of at least one Higgs boson of the MSSM. Main challenge: the intermediate Higgs mass region [ $m_Z \lesssim m_{h^0} \lesssim 2m_Z$ ] which requires different search strategies depending on the value of $m_{h^0}$ . Some sensitivity to heavier non-minimal Higgs states.
NLC and FMC	Complete coverage for the discovery of at least one Higgs boson of the MSSM. Sensitivity to heavier non-minimal states depends on $\sqrt{s}$ : $\sqrt{s} \gtrsim 2m_A$ for discovery of $H^\pm, H^0, A^0$ via associated production. $\sqrt{s} \sim m_A$ for $\mu^+\mu^- \rightarrow H^0, A^0$ $s$ -channel resonance production.

deviate from those of  $h_{\text{SM}}^0$ . Thus, an independent analysis is required to ascertain the discovery potential of the LHC search for MSSM Higgs bosons. In particular, the LHC detector collaborations must demonstrate the feasibility of  $h^0$  discovery in the mass range  $m_Z \lesssim m_{h^0} \lesssim 130$  GeV. This is precisely the most difficult region for the LHC Higgs search. At this time, one can argue that the LHC coverage of the MSSM Higgs sector parameter space is nearly complete, although the search strategies sometimes depend on the observation of small signals (above significant Standard Model backgrounds) in more than one channel. Moreover, the present estimates of the statistical significance of the Higgs signal rely on theoretical determinations of both signal and background rates as well as simulations of detector performance. Thus, if no Higgs signal is confirmed by the LHC, it might still be difficult to definitively rule out the MSSM.

The NLC (and FMC) provide complete coverage of the MSSM Higgs sector parameter space once the center-of-mass energy is above 300 GeV. In contrast to the LHC Higgs search, the intermediate Higgs mass regime presents no particular difficulty for the high energy lepton colliders. The associated production  $e^+e^- \rightarrow h^0A^0$  provides an additional discovery channel for  $m_{A^0} \lesssim \sqrt{s}/2$ . If no Higgs signal is seen, then the lepton colliders can unambiguously rule out the MSSM.

If only one Higgs boson is discovered, it may closely resemble the  $h_{\text{SM}}^0$ . In this case, one must address the detectability of the non-minimal Higgs states ( $H^0, A^0, H^\pm, \dots$ ) at future colliders. Detection of heavy non-minimal Higgs states at the LHC is difficult due to the very low signal-to-background ratio of the corresponding Higgs boson signals. In particular, heavy Higgs states couple very weakly to gauge bosons, and would have to be detected via their heavy fermion decays. At large  $\tan\beta$ , where the Higgs couplings to down-type fermions is enhanced relative to the Standard Model, it may be possible to observe a heavy neutral Higgs boson via its decay to  $\tau^+\tau^-$ . At

the NLC, the main obstacle for the discovery of non-minimal Higgs states is the limit of the center-of-mass energy. The heavy Higgs states of the MSSM can be produced in sufficient number and detected only if  $\sqrt{s} \gtrsim 2m_{A^0}$  [2]. The discovery reach could in principle be somewhat extended by employing the  $\gamma\gamma$  collider mode of the NLC. In this mode of operation, the search for  $\gamma\gamma \rightarrow A^0$  and  $\gamma\gamma \rightarrow H^0$  can extend the non-minimal Higgs mass discovery reach of the NLC [20].

Finally, the FMC can produce the neutral Higgs states singly via  $s$ -channel  $\mu^+\mu^-$  annihilation, and would permit the discovery of the heavy neutral Higgs states up to  $\sqrt{s} = m_{A^0}$  [15]. The viability of this discovery mode depends on the parameters of the Higgs sector. In the MSSM, the cross-section for  $\mu^+\mu^- \rightarrow H^0, A^0$  is enhanced for values of  $\tan\beta$  above 1. For  $m_{H^0}, m_{A^0} \gg m_Z$ ,  $H^0$  and  $A^0$  are approximately degenerate in mass. Given sufficient luminosity, one can detect  $H^0$  and  $A^0$  (if kinematically accessible) by scanning in  $\sqrt{s}$ , assuming that  $\tan\beta$  is larger than a critical value (which depends on the total luminosity and the Higgs mass). Detection is accomplished via a resonant peak in the Higgs decay to  $b\bar{b}$  (and  $t\bar{t}$  if allowed).

## Phase 2 – After Discovery: Is It a Higgs Boson?

Suppose that the first candidate Higgs signal is detected. What must one do to prove that the produced state is a Higgs boson? We assume that after the initial discovery is made, further collider running confirms the signal and establishes a useful statistical sample of events. A list of the primary Higgs signals at future colliders is given in Table 3.

The first step is to ascertain whether the observed state resembles the Standard Model Higgs boson and/or if it is associated with a non-minimal Higgs sector. If  $h^0 \simeq h_{\text{SM}}^0$ , then one must demonstrate that the discovered state has (i) zero electric and color charge, (ii) spin zero, (iii) CP-even quantum number, (iv) electroweak strength couplings, and (v) couplings proportional to the mass of the state to which it couples. Eventually, one would like to make detailed measurements and verify that the Higgs candidate matches all the properties expected of  $h_{\text{SM}}^0$  to within some precision (small deviations from the  $h_{\text{SM}}^0$  properties will be addressed in Phase 3). If the properties of the discovered state are Higgs-like, but differ in detail from those of  $h_{\text{SM}}^0$ , then it is likely that other non-minimal Higgs states are light and may have been produced in the same experiment. Finding evidence for these states will be crucial in verifying the Higgs interpretation of the data.

At an  $e^+e^-$  collider (LEP-2 and the NLC), many of the Higgs boson properties can be directly measured due to low backgrounds and simple event structures.<sup>1</sup> One can directly measure the spin and CP-quantum numbers of the Higgs candidate through the angular distributions of production and decay. Specific Higgs decay modes can

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<sup>1</sup>In principle, the remarks that follow also apply to the FMC. However, it has not yet been demonstrated that the severe backgrounds arising from the constantly decaying muons can be overcome to make precision measurements.

Table 3. Primary  $h_{\text{SM}}^0$  signatures at future colliders and the corresponding Higgs mass range over which detection of a statistically significant signal is possible.

Collider	Signature	Mass Range
LEP-2	$e^+e^- \rightarrow Zh_{\text{SM}}^0$	$\lesssim 95$ GeV
TeV-33 <sup>a</sup>	$W^* \rightarrow Wh_{\text{SM}}^0 \rightarrow \ell\nu b\bar{b}$	60–120 GeV
	$Z^* \rightarrow Zh_{\text{SM}}^0 \rightarrow \begin{cases} \ell^+\ell^-b\bar{b} \\ \nu\bar{\nu}b\bar{b} \end{cases}$	
LHC	$W^* \rightarrow Wh_{\text{SM}}^0 \rightarrow \ell\nu b\bar{b}$	80–100 GeV
	$h_{\text{SM}}^0 + X \rightarrow \gamma\gamma + X$	90–140 GeV
	$h_{\text{SM}}^0 \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$	130–180 GeV
	$h_{\text{SM}}^0 \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu}$	155–180 GeV
	$h_{\text{SM}}^0 \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$	180–700 GeV
	$h_{\text{SM}}^0 \rightarrow ZZ \rightarrow \nu\bar{\nu}\ell^+\ell^-$	600–800 GeV
	$h_{\text{SM}}^0 \rightarrow W^+W^- \rightarrow \ell\nu + \text{jets}$	600–1000 GeV [21]
NLC	$\left. \begin{aligned} e^+e^- &\rightarrow Zh_{\text{SM}}^0 \\ e^+e^- &\rightarrow \nu\bar{\nu}h_{\text{SM}}^0 \\ e^+e^- &\rightarrow e^+e^-h_{\text{SM}}^0 \end{aligned} \right\}$	$\lesssim 0.7\sqrt{s}$
FMC	$\left. \begin{aligned} \mu^+\mu^- &\rightarrow Zh_{\text{SM}}^0 \\ \mu^+\mu^- &\rightarrow \nu\bar{\nu}h_{\text{SM}}^0 \\ \mu^+\mu^- &\rightarrow \mu^+\mu^-h_{\text{SM}}^0 \end{aligned} \right\}$	$\lesssim 0.7\sqrt{s}$
	$\mu^+\mu^- \rightarrow h_{\text{SM}}^0$	up to $\sqrt{s} < 2m_W$

<sup>a</sup>The TeV-33 Higgs signatures listed above are also relevant for lower luminosity Tevatron searches over a more restricted range of Higgs masses, as indicated in Table 1.

be separated and individually studied. Accurate measurements of  $\sigma(h^0)\text{BR}(h^0 \rightarrow X)$  can be made for a number of final states, including  $X = b\bar{b}$  and  $\tau^+\tau^-$ . A recent breakthrough was made which demonstrates that detection of  $h^0 \rightarrow c\bar{c}$  is possible with appreciable efficiency and low mis-identification [22]. Thus, at the lepton colliders,  $h^0 \simeq h_{\text{SM}}^0$  can be confirmed with some precision.

The verification of a Higgs interpretation of a Higgs signal discovered at a hadron collider is much more involved. One must examine in detail a variety of possible Higgs signatures (see Table 3) and evaluate the potential of each channel for supporting the Higgs interpretation of the signal. Taken one by one, each channel provides limited information. However, taken together, such an analysis might provide a strong confirmation of the Higgs-like properties of the observed state as well as providing a



phenomenological profile that could be compared to the predicted properties of the Standard Model Higgs boson.

The quantum numbers of the Higgs candidate may be difficult to measure directly at a hadron collider. However, note that if  $h_{\text{SM}}^0 \rightarrow \gamma\gamma$  is seen, then the  $h_{\text{SM}}^0$  cannot be spin-1 (by Yang's theorem). This does not prove that  $h_{\text{SM}}^0$  is spin-zero, although it would clearly be the most likely possibility. If the coupling  $h_{\text{SM}}^0 VV$  is seen at a tree-level strength, then this would confirm the presence of a CP-even component. Unfortunately, any CP-odd component of the scalar state couples to  $VV$  at the loop level, so one would not be able to rule out *a priori* a significant CP-odd component for  $h_{\text{SM}}^0$ .

The most problematical Higgs mass range is  $100 \text{ GeV} \lesssim m_{h_{\text{SM}}^0} \lesssim 130 \text{ GeV}$ . Higgs bosons in this mass range are not accessible to LEP-2 or Run II of the Tevatron. At the LHC, the most viable signatures in this mass range involve the production of  $h_{\text{SM}}^0$  followed by  $h_{\text{SM}}^0 \rightarrow \gamma\gamma$ . However, the Higgs can be produced via a number of different possible mechanisms: (i)  $gg \rightarrow h_{\text{SM}}^0$ , (ii)  $q\bar{q} \rightarrow q\bar{q}h_{\text{SM}}^0$  via  $t$ -channel  $W^+W^-$  fusion, (iv)  $q\bar{q} \rightarrow Vh_{\text{SM}}^0$  via  $s$ -channel  $V$ -exchange, and (v)  $gg \rightarrow t\bar{t}h_{\text{SM}}^0$ . The  $gg \rightarrow h_{\text{SM}}^0$  mechanism dominates, and it will be an experimental challenge to separate out the other production mechanisms. It may be possible to separate  $gg \rightarrow h_{\text{SM}}^0$  and  $W^+W^- \rightarrow h_{\text{SM}}^0$  events using a forward jet tag which would select out the  $W^+W^-$  fusion events. It may also be possible to distinguish  $Vh_{\text{SM}}^0$  ( $V = W^\pm$  or  $Z$ ) and  $t\bar{t}h_{\text{SM}}^0$  events based on their event topologies. If these other production mechanisms can be identified, then it would be possible to extract information about relative couplings of the Higgs candidate to  $VV$  and  $t\bar{t}$ . Otherwise, one will be forced to rely on matching  $\sigma(h_{\text{SM}}^0)\text{BR}(h_{\text{SM}}^0 \rightarrow \gamma\gamma)$  to Standard Model expectations in order to confirm the Higgs interpretation of  $h_{\text{SM}}^0$ .

In some circumstances, it might be possible to observe the decays  $h_{\text{SM}}^0 \rightarrow b\bar{b}$  or  $h_{\text{SM}}^0 \rightarrow \tau^+\tau^-$  (after a formidable background subtraction), or identify the Higgs boson produced via  $gg \rightarrow b\bar{b}h_{\text{SM}}^0$ . One could then extract the relative coupling strengths of  $h_{\text{SM}}^0$  to  $b\bar{b}$  and/or  $\tau^+\tau^-$  final states. These could be compared with the corresponding  $VV$  and  $t\bar{t}$  couplings, and confirm that the Higgs candidate couples to particles with coupling strengths proportional to the particle masses.

As a result of these considerations, Ref. [4] concludes that in some Higgs parameter range, LHC can make a convincing case for the “expected” Higgs-like properties of a Higgs signal. Ratios of Higgs couplings to different final states may be measured to roughly 20–30%.

### Phase 3 – Precision Measurements of Higgs Properties

Let us suppose that the Higgs candidate (with a mass no larger than a few times the  $Z$  mass) has been confirmed to have the properties expected of the  $h_{\text{SM}}^0$  (to within the experimental error). One would then be fairly confident that the dynamics that is responsible for electroweak symmetry breaking is weakly-coupled. Unfortunately, the details of the underlying physics responsible for electroweak symmetry breaking

would still be missing. As a consequence of the decoupling of heavy Higgs states, it is possible to construct many models of scalar dynamics that produce a light scalar state with the properties of the  $h_{\text{SM}}^0$ . To distinguish among such models, additional properties of the scalar sector must be uncovered. It is the non-minimal Higgs states that encode the structure of the electroweak symmetry breaking dynamics. In order to provide experimental proof of the existence of a non-minimal Higgs sector, one must either demonstrate that the properties of  $h^0$  differ (even if by a small amount) from those of  $h_{\text{SM}}^0$ , or one must directly produce and detect the heavier Higgs states ( $H^0, A^0, H^\pm, \dots$ ). In general, precision measurements of both light and heavy Higgs properties are essential for distinguishing among models of electroweak symmetry breaking dynamics.

Table 4. Anticipated experimental errors in the measured values of the  $h_{\text{SM}}^0$  branching ratios, the partial decay rate,  $\Gamma(h_{\text{SM}}^0 \rightarrow \gamma\gamma)$ , and total width,  $\Gamma_{h_{\text{SM}}^0}^{\text{tot}}$ , in percent, for various ranges of  $m_{h_{\text{SM}}^0}$ . The notation “?” indicates that a reliable simulation or estimate is not yet available or that the number indicated is a very rough guess, while “—” means that the corresponding observable cannot be reliably measured. The results listed below are primarily derived from a multi-year run at the NLC. For  $h_{\text{SM}}^0 \rightarrow \gamma\gamma$ , data from LHC and the  $\gamma\gamma$  collider are also employed to improve the quoted errors. The total Higgs decay rate can be obtained indirectly (by combining measurements of related quantities); the comparison with the direct determination via  $s$ -channel Higgs resonance production at the FMC is shown. See the text and Ref. [4] for further details.

Observable	$m_{h_{\text{SM}}^0}$ range (GeV)			
	80–130	130–150	150–170	170–300
$\text{BR}(h_{\text{SM}}^0 \rightarrow b\bar{b})$	5–6%	6–9%	20% ?	—
$\text{BR}(h_{\text{SM}}^0 \rightarrow c\bar{c})$	$\sim 9\%$	?	?	—
$\text{BR}(h_{\text{SM}}^0 \rightarrow WW^*)$	—	16–6%	6–5%	5–14%
$\text{BR}(h_{\text{SM}}^0 \rightarrow \gamma\gamma)$	15%	20–40%	?	—
$\Gamma(h_{\text{SM}}^0 \rightarrow \gamma\gamma)$	12–15%	15–31%	?	13–22%
$\Gamma_{h_{\text{SM}}^0}^{\text{tot}}$ (indirect)	19–13%	13–10%	10–11%	11–28%
$\Gamma_{h_{\text{SM}}^0}^{\text{tot}}$ (FMC)	3% <sup>a</sup>	4–7%	—	—

<sup>a</sup>Near the  $Z$  peak, the expected FMC uncertainty in  $\Gamma_{h_{\text{SM}}^0}^{\text{tot}}$  is about 30%.

The precision measurements of Higgs properties include branching ratios, cross-sections, and quantum numbers as previously discussed. In Phase 3, it is important to be able to separate cross-sections and branching ratios (instead of simply measuring the product of the two). More challenging will be the measurement of absolute partial widths, which requires a determination of the total Higgs width. Below  $ZZ$  threshold, the Standard Model Higgs width is too small to be directly measured, and other strategies must be employed. As an illustration, Table 4 presents the anticipated

errors in the measurements of some  $h_{\text{SM}}^0$  branching ratios, the partial decay rate for  $h_{\text{SM}}^0 \rightarrow \gamma\gamma$ , and the total Higgs width,  $\Gamma_{h_{\text{SM}}^0}^{\text{tot}}$ , for  $80 \leq m_{h_{\text{SM}}^0} \leq 300$  GeV. The quoted errors are determined primarily by considering the data that would be collected by the NLC at  $\sqrt{s} = 500$  GeV with a total integrated luminosity of  $L = 200 \text{ fb}^{-1}$ . For  $\text{BR}(h_{\text{SM}}^0 \rightarrow \gamma\gamma)$ , the NLC analysis has been combined with results from an LHC analysis; while the measurement of  $\Gamma(h_{\text{SM}}^0 \rightarrow \gamma\gamma)$  relies on data taken from a  $50 \text{ fb}^{-1}$  run in the  $\gamma\gamma$  collider mode of the NLC (with an  $e^+e^-$  center-of-mass energy of  $\sqrt{s} \sim 1.2m_{h_{\text{SM}}^0}$ ). These quantities also contribute to the net accuracy of the total Higgs width,  $\Gamma_{h_{\text{SM}}^0}^{\text{tot}}$ , following the indirect procedure<sup>2</sup> described in Ref. [4]. Note that  $\Gamma_{h_{\text{SM}}^0}^{\text{tot}}$  can be measured directly only in the  $s$ -channel Higgs production at the FMC. For comparison with the indirect determination of  $\Gamma_{h_{\text{SM}}^0}^{\text{tot}}$ , the FMC scan results listed in Table 4 assume that a total luminosity of  $L = 200 \text{ fb}^{-1}$  is devoted to the scan. With the exception of the case where  $m_{h_{\text{SM}}^0} \simeq m_Z$ , the FMC would provide the most precise measurement of the total Higgs width for values of the Higgs mass below the  $W^+W^-$  threshold.

In models of non-minimal Higgs sectors, precision measurements of the branching ratios and partial (and total) decay rates of the lightest CP-even Higgs boson could prove that  $h^0 \neq h_{\text{SM}}^0$ , thereby providing indirect evidence of the non-minimal Higgs states. Once the non-minimal Higgs bosons are directly discovered, detailed measurements of their properties would yield significant clues to the underlying structure of electroweak symmetry breaking. For example, if the Higgs sector arises from a two-doublet model, then precision studies of the heavy Higgs states can provide a direct measurement of the important parameter  $\tan\beta$  (the ratio of Higgs vacuum expectation values).<sup>3</sup> The measurement of  $\tan\beta$  can also provide a critical self-consistency test of the MSSM, since the parameter  $\tan\beta$  also governs the properties of the charginos and neutralinos (and can in principle be determined in precision measurements of supersymmetric processes). Moreover, the couplings of Higgs bosons to supersymmetric particles will provide invaluable insights into both the physics of electroweak symmetry breaking and the structure of low-energy supersymmetry. The possibility that the heavy non-minimal Higgs states have non-negligible branching ratios to supersymmetric partners can furnish an additional experimental tool for probing the Higgs boson–supersymmetry connection.

As in the case of the  $h_{\text{SM}}^0$  discussed above, the lepton colliders (assuming that  $\sqrt{s} \gtrsim 2m_{A^0}$  for the NLC and  $\sqrt{s} \sim m_{A^0}$  for the FMC) provide the most powerful set of tools for extracting the magnitudes of the Higgs couplings to fermion and vector boson pairs. The Higgs couplings to vector boson pairs directly probe the mechanism of electroweak symmetry breaking. The Higgs coupling to two photons, depends (through their one-loop contributions) on all charged states whose masses

<sup>2</sup>For  $m_{h_{\text{SM}}^0} \lesssim 130$  GeV, the indirect procedure relies on the  $h_{\text{SM}}^0 \rightarrow \gamma\gamma$  measurements. In the case of  $m_{h_{\text{SM}}^0} \gtrsim 130$  GeV, one may also make use of the  $WW h_{\text{SM}}^0$  coupling strength extracted from data.

<sup>3</sup>Note that in the decoupling limit (where  $h^0$  cannot be distinguished from  $h_{\text{SM}}^0$ ), measurements of processes involving  $h^0$  alone cannot yield any information on the value of  $\tan\beta$ .

are generated by their couplings to the Higgs sector. Precision measurements of the Higgs couplings to fermions are sensitive to other Higgs sector parameters [18] (*e.g.*,  $\tan\beta$  and the neutral Higgs mixing parameter  $\alpha$  in a two-Higgs-doublet model). Additional information can be ascertained if Higgs self-interactions could be directly measured. This would in principle provide direct experimental access to the Higgs potential. Unfortunately, there are very few cases where the measurement of Higgs self-couplings has been shown to be viable [23].

## Conclusions

The methods by which the first Higgs signal will be identified are well known and have been studied in great detail. However, the most outstanding challenge facing the Higgs searches at future colliders lies in identifying and exploring in detail the properties of the Higgs states. Precision measurements may be able to distinguish between the Higgs boson of the Standard Model and the lightest scalar of a non-minimal Higgs sector. It is also crucial to directly detect and explore the properties of the non-minimal Higgs states. A successful exploration will have a profound effect on our understanding of TeV-scale physics.

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