

# Theoretical Summary Lecture for Higgs Hunting 2012

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## ABSTRACT

In this lecture, I review some of the perspectives on the Higgs boson discussed at the Higgs Hunting 2012 Workshop and discuss the short- and long-term aspects of Higgs physics.

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## 1 Introduction

It is a rare pleasure to have attended the 2012 meeting of the Higgs Hunters at LAL Orsay [1]. The meeting was held two weeks after the remarkable July 4 seminar at CERN that announced the discovery of a new boson of mass roughly 125 GeV, decaying to  $\gamma\gamma$  and  $ZZ^*$  [2]. The euphoria in the High Energy Physics community was still evident, and, I think it will continue for some time. It has been a long time since I have had the pleasure of lecturing to an auditorium full of so many so happy people.

I myself am a bundle of emotions. I am, all at the same time,

- Awestruck
- Impatient
- Poised for the future

A discussion of the thoughts pulling me in these three directions gives as good a framework for discussing the current state of Higgs physics as any other.

## 2 Awestruck

I am awestruck by this discovery.

The discovery is not unexpected. The situation is quite the reverse: We have been waiting a long time for it. I do not have space for a complete history, but here are crucial elements of the Higgs timeline:

- **1967:** Weinberg and Salam create their weak interaction theory that requires the Higgs boson [3,4].
- **1975:** Ellis, Gaillard, and Nanopoulos present the complete phenomenological profile of the Standard Model Higgs boson [5].
- **1976:** Ioffe and Khoze and Bjorken discuss the  $hZZ$  coupling as a means for discovering the Higgs boson [6,7].
- **1981:** Okun declares the discovery of the Higgs to be “Problem Number 1” in high-energy physics [8].
- **1982:** The Snowmass 1982 workshop focuses high-energy physicists on the problem of electroweak symmetry breaking and the TeV scale [9].

- **1984:** The ECFA-CERN Workshop on a Large Hadron Collider initiates the LHC [10].
- **1987:** Gunion, Kane, and Wudka discuss  $h \rightarrow \gamma\gamma$  and  $h \rightarrow ZZ^*$  as means for discovering the Higgs boson [11].
- **1993:** The Superconducting SuperCollider is cancelled, dealing a setback to Higgs hunters.
- **1995:** The discovery of the top quark sharpens the precision electroweak implications for the Higgs boson, predicting a low value for the Higgs mass [12]
- **2000:** LEP runs at 209 GeV in its last days, giving hope but not success in the search for the Higgs boson [13]

We can add July 4, 2012, to this history.

It is not only the time scale of the Higgs boson search that is impressive. Those of us who scribble equations for a living are humbled by the enormous effort it takes to find out whether those equations are relevant to the real world. I felt this already in the days when physicists explored energies of just a few GeV in teams of thirty to fifty. It is even more awe-inspiring to watch the ATLAS and CMS experiments pursue their analyses. The enormous scale of the endeavor is measured in some obvious ways—the 27 km scale of the accelerator, the highest energy particles accelerated by man, the world’s largest cryogenic system, the 5-story-high particle detectors, the 3000 physicists contributing to each publication. But there is more. I would like to highlight three more items.

First, the discovery of the Higgs boson is the world’s hardest data problem. Many scientists and engineers today tout their analyses of Big Data. But nothing is bigger than this. The Higgs boson appears, in the decay modes used for the discovery, in fewer than 1 in  $10^{12}$  proton-proton collisions. To search for the Higgs, ATLAS and CMS push out an enormous stream of raw data, 100 Tb/sec. The permanent databases of these experiments are tens of Pb. It is dangerously close to true that there are not enough computers or human brains in the world physics community to understand this data, so a crucial part of the logistics of the experiments is the global sharing and analysis of these huge databases. The day before the workshop, the Herald Tribune reminded us that, in July 1962, the Telstar satellite began the global information revolution with the first television pictures broadcast live across the Atlantic [14]. Fifty years later, it is our community that is at the cutting edge.

Second, the LHC and the ATLAS and CMS experiments have relied on the intense commitment of scientists and laboratories over the past 25 years. At the workshop, Daniel Denegri told a part of this story [15]. Most moving to me are the stories of the people who began with ATLAS and CMS in the mid-1980’s as young postdocs and

have devoted their whole careers to preparing the infrastructure for this discovery. The list of these people includes recent spokesmen of the collaborations—Jim Virdee and Fabiola Gianotti—but there are many others to thank. These include our LAL hosts Louis Fayard and Daniel Fournier, who played a key role in enabling the ATLAS electromagnetic calorimetry to see the Higgs decay to  $\gamma\gamma$ . I must also point to the amazing institutional continuity and persistence of CERN—across 6 DG terms—to realize the LHC project, and the continued support of the taxpayers of Europe. I know how difficult this is; we tried a similar effort in the United States, but we could not make it work.

Finally, I am impressed by the enormous effort in QCD calculation that has been carried out over decades to produce reliable theoretical predictions for signal and background in Higgs boson searches. These were reviewed at the workshop by Robert Harlander, who is one of the important contributors to this effort [16,17]. These calculations are among the most difficult that have ever been done in physics. They require not only persistence but also great creativity.

These amazing achievements brought us to the July 4 discovery. After July 4, we find ourselves in a new era of particle physics. Many questions that we had before have become irrelevant. Other questions need to be posed anew. And, some questions whose importance we could not see before the discovery have now become central.

### 3 Impatient

Let us, then, turn to the discussion of what we know and what we need to know. I am impatient to know more about this particle. I sketch below a framework for organizing the questions.

#### 3.1 Is it the Higgs boson?

The first question is: Do we actually have grounds to call the newly discovered particle the Higgs boson? The issue is obviously not settled. However, there is an argument that is surprisingly strong for the current early stage in the study of this particle.

The fact that the particle decays to  $\gamma\gamma$  implies that the particle must be a boson and, by the Landau-Yang theorem [18,19], cannot be spin 1. Then we already know that it is a new type of elementary particle, one different from all other particles of the Standard Model. It is very difficult to exclude spin 2 and higher, because these theories can mimic spin 0, but certainly spin 0 is the simplest choice.

Many types of spin 0 particles can couple to  $\gamma\gamma$  and to  $gg$  through loop diagrams.

However, couplings to  $WW$  are more restricted. The Standard Model Higgs boson has an order 1 coupling to  $WW$  generated from its gauge-invariant kinetic term. Starting from

$$\mathcal{L} = |D_\mu\varphi(x)|^2, \quad (1)$$

we assume that the field  $\varphi$  acquires a vacuum expectation value  $v$ . Let  $h(x)$  be the field that corresponds to a space-time variation of this vacuum expectation value. Then (1) becomes

$$\begin{aligned} \mathcal{L} &= \frac{g^2}{4}(v + h(x))^2 W_\mu^+ W^{-\mu} \\ &= m_W^2 W_\mu^+ W^{-\mu} + \frac{2m_W^2}{v} h W_\mu^+ W^{-\mu} + \dots \end{aligned} \quad (2)$$

This argument generates a similar Higgs coupling to  $ZZ$  with strength  $2m_Z^2/v$ .

A spin 0 field that does not have a vacuum expectation value can also couple to  $WW$  and  $ZZ$  in a manner symmetric under  $SU(2) \times U(1)$  through dimension 5 operators involving the  $W$  and  $Z$  field strengths. In a weak-coupling theory, these operators are generated by loops and so are suppressed by a power of  $\alpha$ . These terms have the form

$$\mathcal{L} = A \frac{\alpha}{4\pi} \frac{1}{M} h F_{\mu\nu} F^{\mu\nu} + B \frac{\alpha}{4\pi} \frac{1}{M} h \epsilon_{\mu\nu\lambda\sigma} F^{\mu\nu} F^{\lambda\sigma} \quad (3)$$

We see the new particle coupling to  $WW$  and  $ZZ$  with a strength similar to that predicted in the Standard Model, rather than two orders of magnitude smaller. From the choice of vertices above, this is *prima facie* evidence that the new particle is a CP even spin 0 field with a vacuum expectation value that breaks  $SU(2) \times U(1)$ . This is exactly what we call a ‘‘Higgs boson’’.

This argument is hardly airtight. Vertices of the type (3) with order 1 coefficients can be generated in strong-coupling theories of TeV scale physics. Spin 2 particles can have direct non-derivative couplings to  $WW$  and  $ZZ$ .

However, we can find further support for the Higgs field interpretation by studying the spin correlations in the process [20,21]

$$pp \rightarrow ZZ^* \rightarrow \ell^+ \ell^- \ell^+ \ell^- \quad (4)$$

The reconstruction of the new particle in the four lepton final state allows us to measure the five angles shown in Fig. 1. The angle  $\theta^*$  is sensitive to the production dynamics and discriminates production of an  $s$ -channel resonance from the background process  $q\bar{q} \rightarrow ZZ$ . However, the angles  $\theta_1$ ,  $\theta_2$ , and  $\Phi_1 - \Phi_2$  are sensitive to the decay dynamics. In particular, they distinguish the vertex in (2), in which the two  $Z$ s are dominantly longitudinally polarized, from (3), in which the two  $Z$ s are transversely polarized. This angular analysis was described at the workshop in the talk of Baffioni on the CMS observation of the new particle in  $ZZ^*$  [22]. This angular

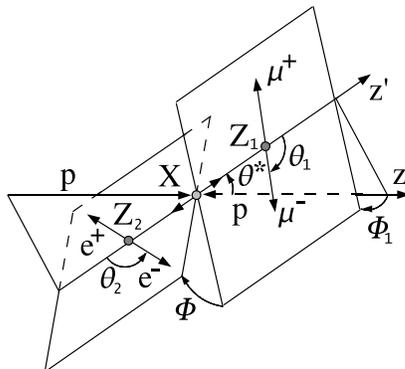


Figure 1: Angles used in the spin analysis of the new particle in its 4-lepton final state, from [20].

analysis already distinguishes the scalar and pseudoscalar cases at about 1 sigma. Baffioni reported that 3 sigma separation is possible with  $30 \text{ fb}^{-1}$  at 8 TeV.

From here on, I will call the new particle “the Higgs Boson” without further apology.

We must still find out whether this particle has the properties predicted for the Higgs boson in the Standard Model. The Standard Model insists that the Higgs boson is the unique source of mass for all quarks, leptons, and gauge bosons. This implies that the couplings of the boson to all quarks, leptons, and gauge boson are precisely in the ratio of their masses, up to simple factors reflecting the particle spins. It is really so?

The mass of 125 GeV makes the Standard Model Higgs boson exceptionally hard to find. However, once we have found the particle, this special mass confers an advantage. At this mass, the Standard Model Higgs boson has a large number of decay channels with substantial branching fractions available for study. As Fabiola Gianotti put it in her July 4 lecture: “Thank you, Nature.”

Mele reviewed the phenomenology of the Standard Model Higgs boson at the mass of 126. GeV, referring to its properties as “the new set of Standard Model reference parameters” [23,24]. The predicted width of the boson is 4.2 MeV. The major branching fractions are:

$b\bar{b}$	56%	$\tau^+\tau^-$	6.2%	$\gamma\gamma$	0.23%
$W W^*$	23%	$Z Z^*$	2.9%	$\gamma Z$	0.16%
$gg$	8.5%	$c\bar{c}$	2.8%	$\mu^+\mu^-$	0.02%

For all of these modes except  $c\bar{c}$ , there is a strategy to observe the decay at the LHC.

Our understanding of the new boson will proceed in stages. I foresee three stages:

- Are the major decay modes present?
- Is the boson Standard Model-like, or not?
- Are there small deviations from the Standard Model predictions?

Let's discuss these questions one by one.

### 3.2 Are the major decay modes present?

Already by the time of this meeting, many of the key qualitative properties of a Standard Model Higgs boson are being confirmed. Further information was provided after the conference in the papers submitted by ATLAS [25], CMS [26], and the Tevatron experiments [27]. Here is a list of the most important nine items, and the current status of each:

1.  $\gamma\gamma$  decay mode: Observed (4.5  $\sigma$  in ATLAS, 4.1  $\sigma$  in CMS) .
2.  $ZZ^*$  decay mode: Observed (3.6  $\sigma$  in ATLAS, 3.2  $\sigma$  in CMS) .
3.  $WW^*$  decay mode: Observed (2.8  $\sigma$  in ATLAS, 1.6  $\sigma$  in CMS) .
4.  $b\bar{b}$  decay mode. So far, this is seen only by the Tevatron experiments, at 2.8  $\sigma$  in the CDF/DO combination. CMS seems to be making good progress toward the observation at the LHC. [28]
5.  $\tau\tau$  decay mode: This is not yet observed; CMS reports a deficit with respect to the expectation.
6. Spin-Parity: As noted above, there is a preliminary indication from the CMS spin analysis of the  $ZZ^*$  decay.
7. Gluon Fusion production mode: This is the dominant production model for the observation of the boson in  $\gamma\gamma$ .
8. Vector Boson Fusion production mode: ATLAS claims that the rate of Vector Boson Fusion production and  $\gamma\gamma$  observation is nonzero at 2.7  $\sigma$  significance. CMS claims 3.5  $\sigma$  significance for  $\gamma\gamma$  production with a "VBF tag", a weaker statement.
9. Higgsstrahlung production mode: Seen at the Tevatron only, in the  $b\bar{b}$  final state listed above.

This is quite an impressive scorecard. It is very likely that all of the issues listed here will be settled, at the yes/no level, with the full 2012 data set from the LHC.

### 3.3 Is the Higgs Standard Model-like, or not?

There is much interest now in parsing the deviations from the Higgs boson production and decay rates predicted by the Standard Model. These rates are determined by a combination of Higgs properties, as I will discuss in a moment. A measurement of the rate for production of the Higgs boson at the LHC gives the *relative signal strength*  $\mu$ , defined by

$$\mu = \sigma \cdot BR / (\sigma \cdot BR)|_{SM} , \quad (5)$$

where  $\sigma$  is the Higgs production cross section in the measurement under consideration and  $BR$  is the branching ratio of the Higgs into the final state observed in the analysis. Here and below,  $SM$  denotes the Standard Model prediction. The production cross section will in general be a combination of the Gluon Fusion, Vector Boson Fusion, and other elementary cross sections, as defined by the particular set of cuts used in the measurement.

The ATLAS and CMS experiments and the Tevatron experiments have presented values of  $\mu$  for a variety of final states and cross section tags. These are shown in Fig. 2. The fact that the central value of  $\mu$  is close to 2 in several channels, in particular, in the LHC  $\gamma\gamma$  signal and  $\mu$  in several channels, in particular, for the LHC  $\gamma\gamma$  signals and the Tevatron  $b\bar{b}$  signal, has excited much interest. However, we are still at an early stage in the study of the Higgs, and these large signals are consistent with the expected size of fluctuations.

The analysis of  $\mu$  deviations is very much fun for theorists. There are many interesting model-building solutions that give order 1 modifications of the Higgs boson signal strengths. These typically involve new particles with masses of the order of 200 GeV or below [30]. A nontrivial part of the game is to suggest new particles that are not excluded by the LHC experiments. Possible new particles influencing the Higgs rates include new bosons from an extended Higgs sector [31,32], new color-singlet matter particles such as the tau slepton [33], or new colored particles such as light top squarks that are stealthy at the LHC [34]. Strong interactions in the Higgs sector can also influence the Higgs signal strengths; a compositeness scale close to 1 TeV is required for a large effect [35,36]. Carena gave examples of many of these scenarios in her talk at the workshop [37].

There are many groups now that fit the measured signal strengths to look for insight. Some of these fits were reviewed at the workshop by Espinosa [38]. At the moment, fits to the current measurements tend to be 2-parameter fits under specific model hypotheses. They give insight if the particular scheme assumed for modifying the Standard Model is correct.

It is important to realize, though, that analyses of the Higgs properties in terms of a small number of parameters bring in assumptions that might well be incorrect. It is easy to construct models that tweak individual Higgs couplings away from their

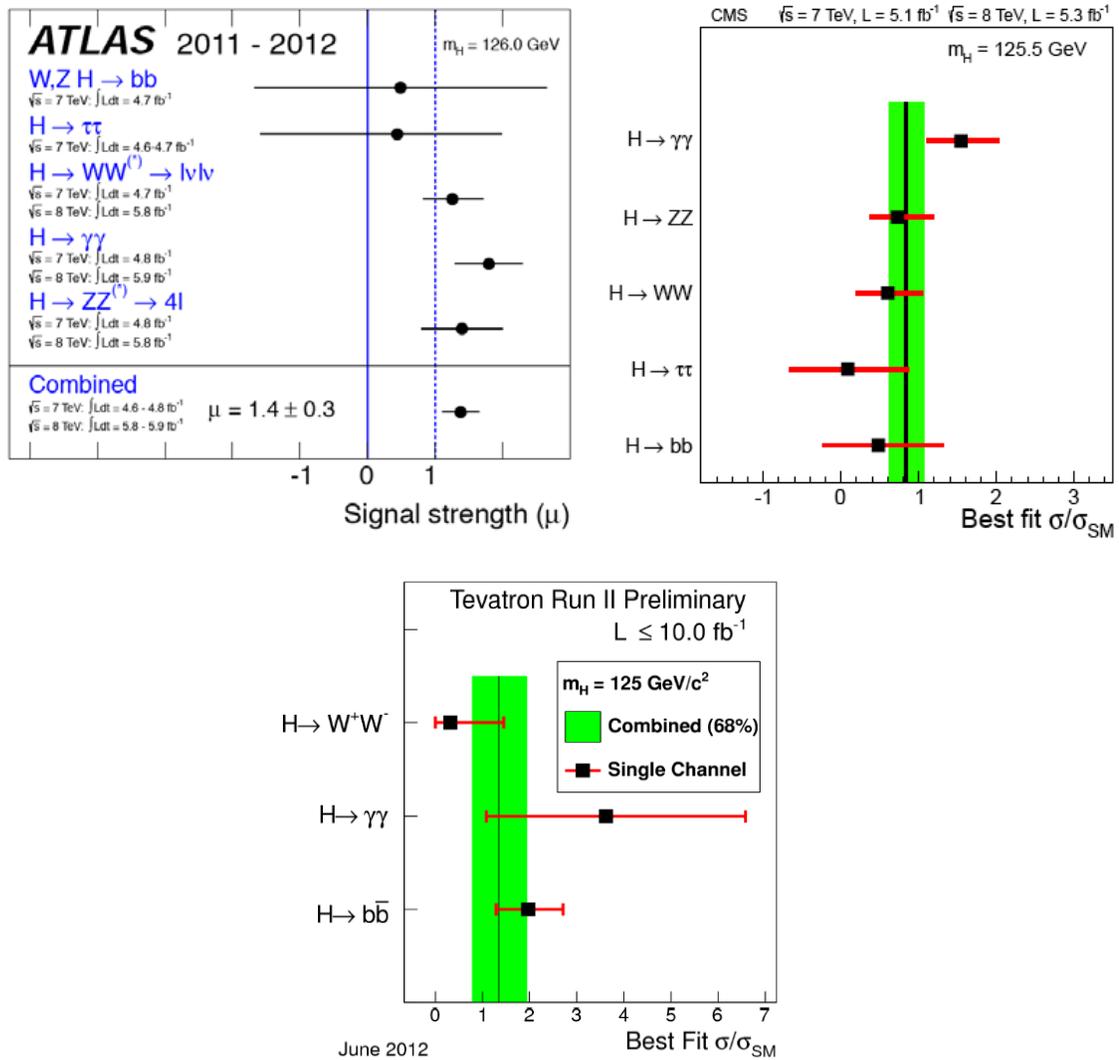


Figure 2: Measured relative signal strength  $\mu$  in many channels of the ATLAS, CMS, and Tevatron Higgs searches: (a) from ATLAS [25], (b) from CMS [26], (c) from the CDF and DO combination [29].

Standard Model values without affecting other couplings. Models with two Higgs doublets can modify the Higgs couplings to up-type quarks, down-type quarks, or leptons without changing the couplings to other matter particles. Introduction of new particles that appear in loops can modify the Higgs couplings to  $\gamma\gamma$  and  $gg$  while having small effects on the other couplings.

This means that a deviation of a signal strength  $\mu$  from 1 gives ambiguous information, pointing in several different directions. A given  $\mu$  parameter refers to a production channel  $A\bar{A} \rightarrow h$  (where  $A\bar{A}$  might, for example, be  $gg$  or  $WW$ ) and a decay channel  $h \rightarrow B\bar{B}$ . Since  $\mu$  contains the branching ratio, the total width of the Higgs also enters. In all

$$\mu(A\bar{A} \rightarrow h \rightarrow B\bar{B}) = \frac{\Gamma(A)\Gamma(B)}{\Gamma_T} / SM, \quad (6)$$

where  $\Gamma(A)$  is the partial width for Higgs decay to  $A\bar{A}$ ,  $\Gamma_T$  is the total width of the Higgs, and  $SM$  is the Standard Model value of the numerator. An excess in the rate for Higgs production by Gluon Fusion and observation in  $\gamma\gamma$  might be due to:

- an enhancement of  $\Gamma(\gamma)$
- an enhancement of  $\Gamma(g)$
- a suppression of  $\Gamma(b)$ , the dominant component of  $\Gamma_T$ .

or any combination of these effects. A small enhancement could be due to a suppression of  $\Gamma(W)$ .

At our current state of experimental uncertainty, global fits to the Higgs couplings that allow all of these deviations to fluctuate independently are unstable. We will need more data, and, probably, more data than the LHC will provide in 2012, to resolve the ambiguities.

However, if this problem will not be solved this year, there are good prospects for a qualitative understanding of the Higgs properties from the LHC run at 14 TeV. In principle, we would like to make global fits to the rates of Higgs production and decay processes that include the couplings to all of the Higgs decay modes listed at the end of Section 3.1, plus the Higgs couplings to  $t\bar{t}$  and to invisible decay product. This is an ambitious goal, but, with the help of a weak theoretical assumption, it is within the reach of the LHC.

There are two problems on the path to getting the inputs required for such global fits. The first is that the dominant decay mode of a Standard Model Higgs boson of mass 125 GeV, the decay  $h \rightarrow b\bar{b}$ , is very difficult to observe at the LHC. The problem is the enormous background from QCD production of  $b\bar{b}$  pairs, at the  $\mu b$

level compared to the pb level for Higgs production. To overcome this problem, it is necessary to observe the Higgs in particular characteristic reactions, especially, in associated production with  $W$ ,  $Z$ , or  $t\bar{t}$ . This does not solve the problem, however. A reaction that has a much higher cross section than  $pp \rightarrow Wh$  is  $pp \rightarrow Wg$ , with subsequent gluon splitting to  $b\bar{b}$ . Even after a cut on mass of the  $b\bar{b}$  system around the known Higgs mass, the Higgs signal is submerged in background.

Recently, a solution to this problem was proposed by Butterworth, Davison, Rubin, and Salam [39]. These authors begin from the idea that, if the Higgs is highly boosted, the  $b$  and  $\bar{b}$  jets are merged into a single anti- $k_T$  jet. They then note that the internal structure of this jet is different from that of a gluon jet with splitting to  $b\bar{b}$ . The Higgs jet has fewer soft subjects, a consequence of its color-singlet rather than color-octet origin, and its major two component subjects share their energy more equally, a consequence of its origin as a massive particle. With these features in mind, Butterworth *et al.* devised a “jet grooming” strategy that removes the gluon background. Plehn, Salam, and Spannowsky proposed a similar grooming strategy for the measurement of the cross section for  $pp \rightarrow t\bar{t}h$  [40]. The study of boosted objects and jet grooming is now of interest for many applications to LHC physics; the subject has recently been reviewed in [41] and in Salam’s presentation to this workshop [42].

The second problem is to control the branching ratio of the Higgs to final states that are not visible to the LHC experiments. An example is the decay  $h \rightarrow c\bar{c}$ , for which, currently, there is no strategy for its observation at the LHC. This requires a theoretical argument that this branching ratio cannot be large. Such an argument can be made by using the idea that, if there are many fields with vacuum expectation values that contribute to the  $W$  and  $Z$  masses, each makes a positive contribution, and these sum to the observed vector boson masses. This idea implies the inequalities

$$\Gamma(W) \leq \Gamma(W)|_{SM} \quad \Gamma(Z) \leq \Gamma(Z)|_{SM} \quad (7)$$

Gunion, Haber, and Wudka have shown that these inequalities are generally true in models with no CP violation in the Higgs sector and no doubly charged Higgs bosons [44]. Dührssen and collaborators introduced the use of these inequalities in Higgs parameter fitting in [45]. Using this assumption, it is possible to make a controlled fit to LHC data with the full set of free parameters listed above.

Following this idea, I made an estimate of the accuracy to which the LHC results available by the end of the decade would constrain the Higgs couplings in such a model-independent fit [43]. The analysis makes strong use of the work of Dührssen and the Heidelberg group [45,46]. The results are shown in Fig. 3. Klute *et al.* [47] have done a similar study and have reached similar conclusions. My analysis is less sophisticated but, I hope, more transparent in terms of the assumptions used. Neither study makes use of the improved knowledge of the ATLAS and CMS detector capabilities that has been obtained through actual data-taking and analysis. I hope

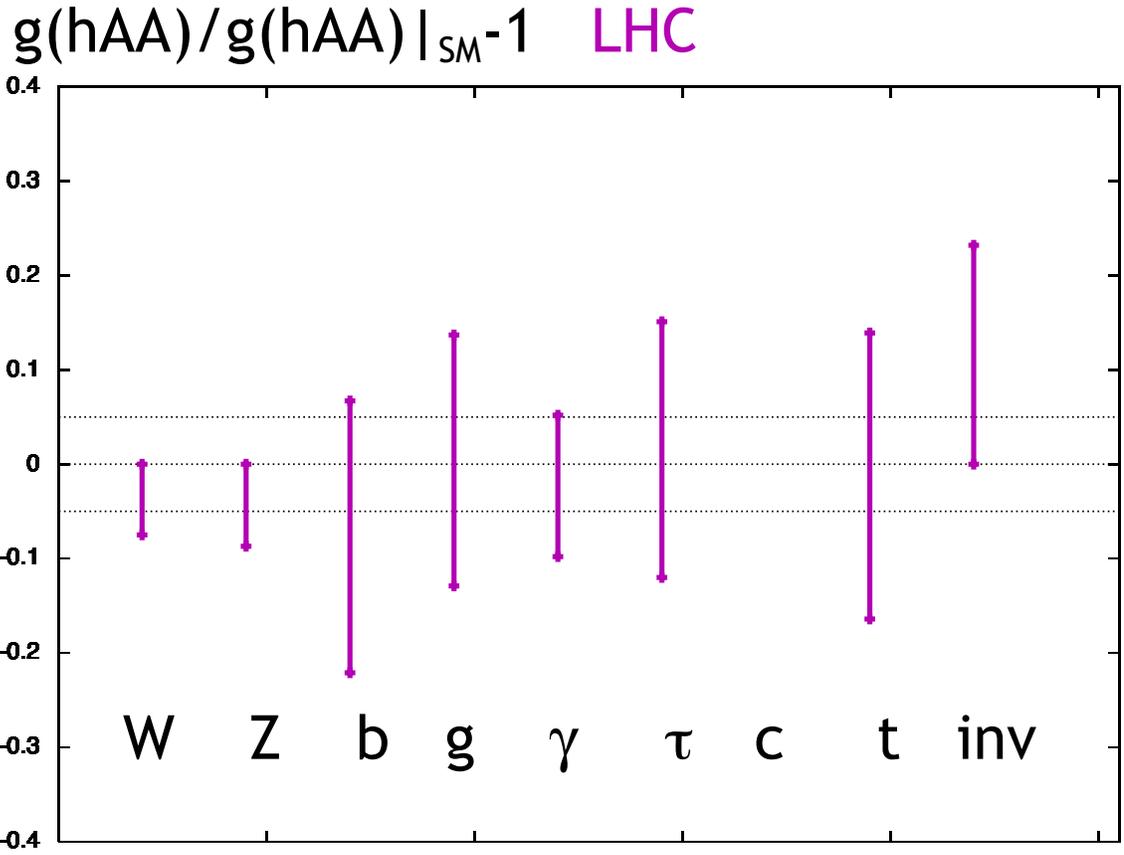


Figure 3: Estimates of the accuracy that can be achieved in Higgs coupling measurements using a model-independent fit to LHC measurements with a  $300 \text{ fb}^{-1}$  data set, from [43]. The estimates are given as a fraction of the predicted Standard Model value for the Higgs coupling constants. The indicated horizontal lines represent 5% deviations. For the invisible Higgs decay, the quantity plotted is the square root of the branching fraction.

that the ATLAS and CMS collaborations will soon study this question and report improved estimates of their prospects for Higgs boson measurements.

The results are quite striking. The analysis sets a high standard by which to measure the LHC capabilities. The conclusion is that the LHC experiments are capable of being evaluated by this standard, and that these experiments—with large data sets of about  $300 \text{ fb}^{-1}$ —will give accurate assessments of the individual Higgs boson couplings, with errors at the level of 10–20% within a model-independent analysis. This will settle the question of whether or not the newly discovered boson has properties close to those of the Standard Model Higgs boson.

And, yet, this level of accuracy is not good enough.

### 3.4 Are there small deviations from the Standard Model?

Must we care about Higgs boson coupling measurements below the 10% level? In fact, measurements of even higher accuracy are likely to provide an essential part of the Higgs boson story.

There are two important points to be made here.

First, although the Higgs boson may turn out to look Standard Model-like by the standards just described, and although it is possible that no new particles will be discovered at the LHC in its first sample of a few hundred  $\text{fb}^{-1}$ , we cannot give up on the idea that there is new physics beyond the Standard Model at the TeV energy scale. It may turn out that the precision study of the Higgs boson is our best route to uncovering evidence of that new physics.

Much has been said about the incompleteness of the Standard Model and its inadequacy as a model of electroweak symmetry breaking. I have little to add on this point except to put the issue bluntly. In the Standard Model, the *complete explanation* for the spontaneous breaking of the  $SU(2) \times U(1)$  electroweak gauge symmetry is the following: The theory has a parameters  $\mu^2$ . Electroweak symmetry is broken if

$$\mu^2(\text{TeV}) < 0 . \tag{8}$$

That's it. Since  $\mu^2$  is additively renormalized, there is no natural distinction between positive and negative values of  $\mu^2$ . As physicists, we should be ashamed of ourselves if we are satisfied with this.

The second point is less widely recognized. Many classes of models of electroweak symmetry breaking contain a light Higgs boson similar to the Higgs boson of the Standard Model. Examples include supersymmetry, Little Higgs models, and Randall-Sundrum extra-dimensional models. After July 4, any model that does not predict a light Higgs that is the major source of electroweak symmetry breaking is at a severe

disadvantage. At the moment, is it still true that certain models without a light Higgs are not excluded [48,49], but they will be in deep trouble if the measurements described in Section 3.2, and available this year, meet the Standard Model expectations.

In Section 3.3, I made reference to many models that predicted order 1 deviations of the Higgs boson couplings from the Standard Model predictions. Most of these models have a common feature of requiring new particles with masses of the order of 200 GeV or below. Those models that modify the Higgs boson couplings through strong interaction effects in the electroweak sector require large perturbations not only in the Higgs couplings but also in the top quark and  $W$  boson couplings. If these particles or effects are not found, what then?

The more typical prediction of new physics models is that the new physics effects on Higgs boson couplings are quite small. In the 1990's, Howard Haber discussed this conclusion in very general terms in [50]. Haber defined the ‘‘Decoupling Limit’’ of a new physics model in which the Higgs boson is light but other new particles are heavy, at masses of 1 TeV or above. In this situation, the fields associated with the new particles can be integrated out of the effective Hamiltonian describing Higgs physics. The effects of these particles is then present only in higher-dimension operators whose coefficients are of the order of

$$m_h^2/M^2 \quad \text{or} \quad m_t^2/M^2, \quad (9)$$

where  $M$  is the mass of the new particles.

Here are some examples of corrections to the Higgs couplings in specific models of new physics. More examples, and further discussion of the Decoupling Limit, can be found in the recent paper of Gupta, Rzehak, and Wells [51].

In supersymmetric models, it is necessary that there are at least two Higgs doublet fields. This gives rise to corrections to the Higgs couplings at tree level. The typical size of the corrections to the  $h\tau\tau$  coupling is [52]

$$g(\tau)/SM = 1 + 10\% \left( \frac{400 \text{ GeV}}{m_A} \right)^2, \quad (10)$$

where  $m_A$  is the mass of the heavy  $A^0$  Higgs boson. In models with large  $\tan\beta$ , the  $hb\bar{b}$  coupling receives additional corrections from loop diagrams, estimated as [53]

$$g(b)/SM = g(\tau)/SM + (1 - 3)\%. \quad (11)$$

In Composite Higgs models, the Higgs bosons are effective Goldstone boson fields. The Higgs couplings receive corrections sized by the scale of the Goldstone boson decay constant  $f$ , which typically is a factor of  $4\pi$  smaller than the scale of the new

strong interactions. An estimate for the corrections to the  $hf\bar{f}$  couplings is [54]

$$g(f)/SM = 1 + (3 - 9)\% \cdot \left(\frac{1 \text{ TeV}}{f}\right)^2. \quad (12)$$

In Little Higgs models, the Higgs boson couplings to  $\gamma\gamma$  and  $gg$  are modified by new contributions to the loop diagrams from the partners of the top quark and the  $W$  and  $Z$  bosons. These particles have masses in the few-TeV range. An estimate of the corrections is [55]

$$\begin{aligned} g(g)/SM &= 1 + (5 - 9)\% \\ g(\gamma)/SM &= 1 + (5 - 6)\% \end{aligned} \quad (13)$$

These results also illustrate the point made already in the previous section that new physics corrections to the Higgs couplings can tweak any individual coupling independently of the others, so that a general, model-independent analysis of the couplings is needed.

After July 4, the issue of the precise values of the Higgs couplings has vaulted to the top of the list of the most important problems in high energy physics. I have just argued that the level of precision needed to address this problem is very high. Can we get there?

## 4 Poised

During all of those years of waiting and hoping for the discovery of the Higgs boson, many theorists and experimenters studied the prospects for new facilities that would dramatically improve our understanding of this particle. We are poised to build them now.

### 4.1 For the High Luminosity LHC

Beyond the LHC at 14 TeV and  $10^{34}$  luminosity, there is the High Luminosity LHC. This planned upgrade of the LHC would begin its experimental data-taking in 2022. The design gives a luminosity greater than  $10^{35}/\text{cm}^2/\text{sec}$ , but also very challenging experimental conditions with 200 pileup events per bunch crossing. This upgrade will enable additional new particle searches, pushing the reach of the LHC for gluinos and other strongly coupled new particles above 4 TeV [56].

The HL-LHC initiative will produce huge statistics for Higgs analyses, a billion Higgs bosons over 5 years. But it will be very difficult to interpret these Higgs events, or even to trigger on them. Many important channels of Higgs decay, especially the decays to  $WW^*$  and  $ZZ^*$ , contain soft leptons. For these channels, it is already a challenge to maintain the trigger thresholds low enough to capture the events. The study of Higgs decay to  $b\bar{b}$  relies on excellent 2-jet mass resolution, which will be compromised by pileup. The study of Higgs decay to  $\tau^+\tau^-$  and invisible modes relies on selection of Vector Boson Fusion event using forward tagging jets. The efficiency for this selection will be compromised by large activity in the forward region  $\eta > 2.5$ .

Thus, it is not obvious that there is any advantage for the study of Higgs couplings in increasing the ATLAS and CMS data samples from  $300 \text{ fb}^{-1}$  to  $3000 \text{ fb}^{-1}$ .

However, there is a tremendous opportunity to be seized here. The ATLAS and CMS collaborations are now studying ambitious detector modifications for the high luminosity era. These include possible pre-triggering or track-based triggering to improve the intelligence of Level 1 event selection and new strategies to maintain performance in the presence of pileup. It must still be demonstrated that ATLAS and CMS have useful capability for Higgs studies in the high-luminosity era. But I hope that the members of the collaborations will consider this a challenge that can be met.

## 4.2 For an $e^+e^-$ Higgs factory

For the  $Z$  and  $W$  bosons, the discovery at hadron colliders was followed by detailed precision study at the  $e^+e^-$  colliders SLC and LEP. The study of these particles in  $e^+e^-$  annihilation led to many incisive experimental probes of the weak interactions, including precision mass measurements and measurements of branching ratios and polarization asymmetries. These experiments provide the foundation that we have today for our understanding of the weak interactions.

There are equally good reasons to construct an  $e^+e^-$  collider to study the Higgs boson. In  $e^+e^-$  annihilation, Higgs boson production is 1% of the total rate, rather than  $10^{-10}$  as it is at hadron colliders. This means that the various Higgs decay modes can all be studied with minimum prejudice. Decays of Higgs bosons to quarks, and Higgs decays with hadronic decays of  $W$  and  $Z$ , can be identified and used in analyses. This permits complete, unambiguous spin analysis of the Higgs boson couplings. Decays of the Higgs to  $c\bar{c}$  and  $gg$  can be identified and distinguished from one another.

Most importantly, the process  $e^+e^- \rightarrow Zh$  allows the Higgs to be tagged by the presence of a recoiling  $Z$  boson at the correct energy in the center of mass system. Using this technique, it is possible to measure the absolute branching fractions of Higgs decays. Tagging of the Higgs also makes it possible to identify invisible Higgs

decays, and also other possible exotic decay channels of the Higgs such as decay to long-lived particles.

Several technological solutions are now being proposed for the design of lepton-collider Higgs factories, including synchrotrons [57], linear colliders with design energies up to 3 TeV [58], and muon colliders with similar energy reach [59]. However, among these solutions, the most compelling is the International Linear Collider. The ILC has been extensively engineered over the past decade. The ILC Technical Design Report is now in preparation and should be completed before the end of the year. This is the one Higgs factory that can be proposed on the correct time scale—immediately [60].

The capabilities of the ILC for precision Higgs boson studies are very impressive. The current estimates are supported by full simulation detector studies with realistic inclusion of the machine environment [61–63]. The improvements anticipated for the ILC over the estimates given earlier for the LHC are shown in Fig. 4 [43]. These estimates correspond to a nominal ILC program of  $250 \text{ fb}^{-1}$  at 250 GeV, followed by  $500 \text{ fb}^{-1}$  at 500 GeV, followed by  $1000 \text{ fb}^{-1}$  at 1 TeV. The errors on statistics-limited modes such as  $\tau^+\tau^-$  and  $\gamma\gamma$  would improve with longer running. These estimates imply that the ILC can meet the goals of a precision Higgs program, with errors on individual couplings at the few-percent level in a model-independent analysis.

The expected precision of the test at the ILC of the proportionality of Higgs couplings and mass is shown in Fig. 5 [63].

Over the years, much scorn has been poured on the ILC because its design energy is “only” 500 GeV, extendable in a later stage to 1 TeV. In the new era, though, those arguments have turned around completely. The first phase of LHC running has led to a discovery—the Higgs boson. The precision study of this particle could well be our only route to uncover new physics beyond the Standard Model.

The ATLAS and CMS experiments have discovered no other new particles. At the moment, there is no case for new particles at masses up to 1.5 TeV, calling for lepton collider experiments at 3 TeV. The LHC has eliminated many scenarios for physics beyond the Standard Model that seemed promising a few years ago. Remarkably, many of the scenarios for new physics that survive the current LHC exclusions imply important experiments to be done in  $e^+e^-$  at 500 GeV. These include “Natural Supersymmetry” models in which the lightest superparticles are Higgsinos with masses near 200 GeV [64] and composite Higgs models that call for a program of precision measurements on the top quark [65,66]. This confirms the message that the new knowledge we have gained from the LHC points to the importance of the ILC.

Whatever might be added from LHC discoveries later in this decade, the Higgs is there. The ILC capabilities are perfectly matched to the needs of an experimental program of precision measurements on the 125 GeV Higgs boson. It is the right time,

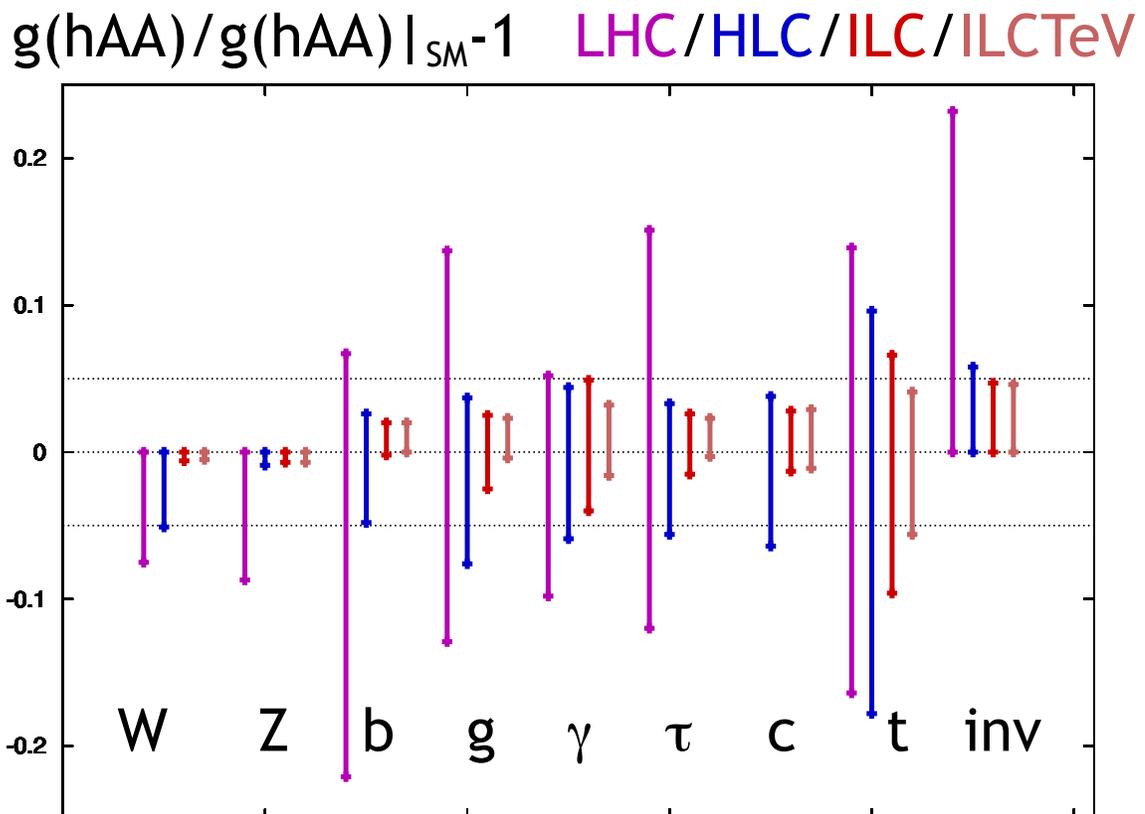


Figure 4: Estimates of the accuracy that can be achieved in Higgs coupling measurements using a model-independent fit to LHC and ILC measurements, from [43]. The estimates are shown as a fraction of the predicted Standard Model value for the Higgs coupling constants. The indicated horizontal lines represent 5% deviations. For the invisible Higgs decay, the quantity plotted is the square root of the branching fraction. The programs shown include (left to right for each entry) LHC at 14 TeV and  $300 \text{ fb}^{-1}$ , ILC at 250 GeV and  $250 \text{ fb}^{-1}$ , ILC at 500 GeV and  $500 \text{ fb}^{-1}$ , ILC at 1000 GeV and  $1000 \text{ fb}^{-1}$ .

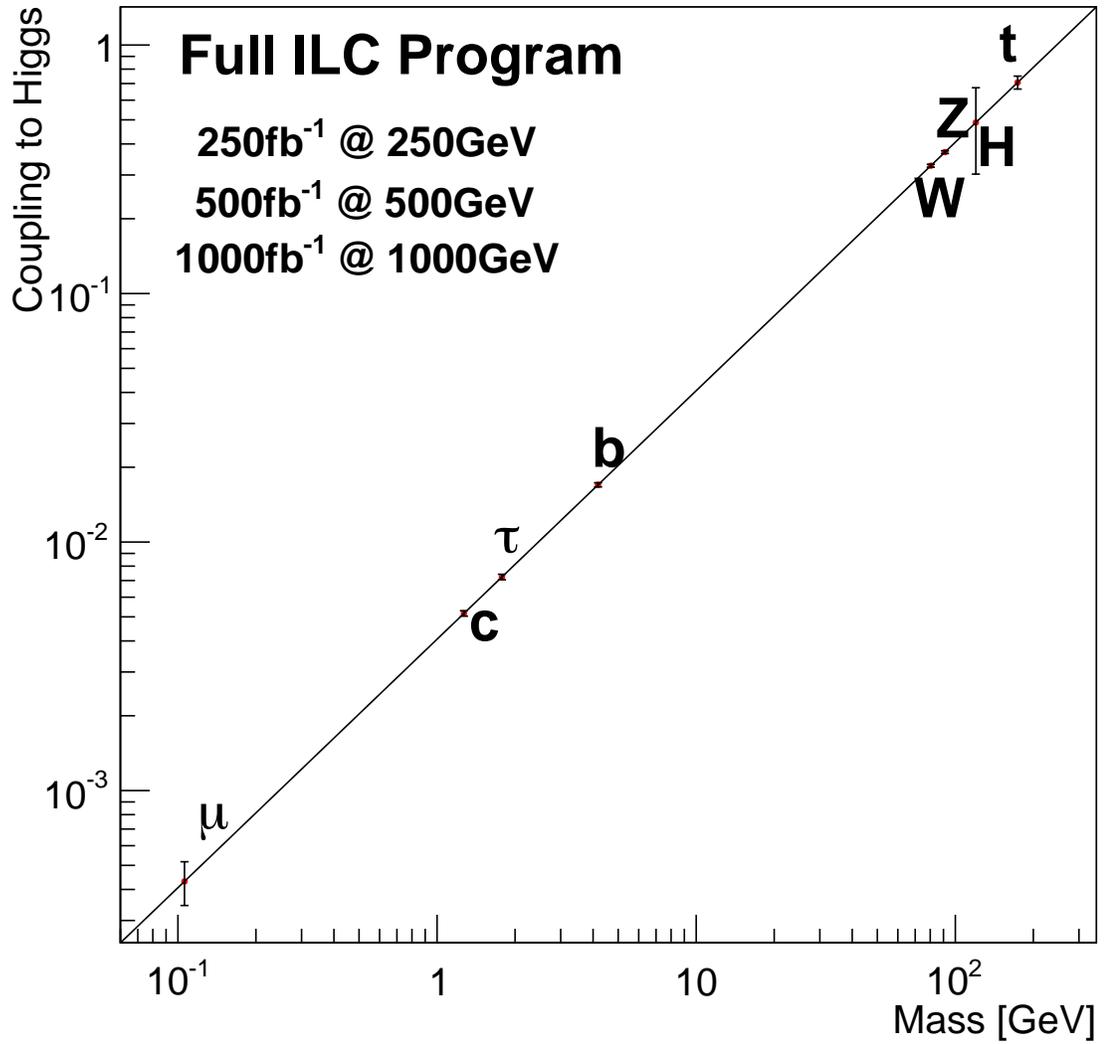


Figure 5: Expected precision from the full ILC program of tests of the Standard Model relation that the Higgs couplings to each particle are proportional to its mass, from [63]. The measurements of the Higgs couplings to  $\mu$  and  $t$  and the Higgs self-coupling require high energies; the other measurements depend mainly on total integrated luminosity.

in direct response to the discovery, to call for the construction of this machine.

## 5 Conclusions

The discovery of the Higgs boson implies an exciting and program of beautiful observations to uncover the secrets that this particle holds. This program will be a major theme of high energy physics experimentation over the next ten years. It is likely to be full of mystery and surprises.

A new era of high energy physics, the Higgs era, has begun. I am awestruck at what has been accomplished in the first chapter of the Higgs story, and I am impatient to see what the Higgs future may bring. We are ready to move forward to make these discoveries.

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## References

- [1] Slides and video from the meeting can be found at: <http://indico2.lal.in2p3.fr/indico/conferenceDisplay.py?confId=1747>.
- [2] <http://indico.cern.ch/conferenceDisplay.py?confId=197461>.
- [3] S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967).
- [4] A. Salam, in *Elementary Particle Theory: 8th Nobel Symposium*, N. Svartholm, ed. (Almqvist and Wiksell, 1968).
- [5] J. R. Ellis, M. K. Gaillard and D. V. Nanopoulos, Nucl. Phys. B **106**, 292 (1976).

- [6] B. L. Ioffe and V. A. Khoze, *Sov. J. Part. Nucl.* **9**, 50 (1978) [*Fiz. Elem. Chast. Atom. Yadra* **9**, 118 (1978)].
- [7] J. D. Bjorken, in *Proceedings of the 4th SLAC Summer Institute on Particle Physics*, M. C. Zipf, ed. SLAC-R-198 (1976).
- [8] L. B. Okun, in *Proceedings of the 1981 International Symposium on Lepton and Photon Interactions at High Energy*, W. Pfeil, ed. (Univ. Bonn, 1981).
- [9] *Elementary Particle Physics and Future Facilities (Snowmass 82)*, R. Donaldson, R. Gustafson, and F. Paige, eds. (AIP, 1983).
- [10] *ECFA-CERN Workshop on a Large Hadron Collider in the LEP Tunnel*, M. Jacob, ed. CERN-84-10-V-1, ECFA-84-85, CERN-YELLOW-84-10-V-1 (1984).
- [11] J. F. Gunion, G. L. Kane and J. Wudka, *Nucl. Phys. B* **299**, 231 (1988).
- [12] P. B. Renton, in LP95: International Symposium on Lepton Photon Interactions, Z. P. Zheng and H. S. Chen eds. (World Scientific, 1996).
- [13] LEP Higgs Working Group for Higgs boson searches and OPAL and ALEPH and DELPHI and L3 Collaborations, in *20th International Symposium on Lepton and Photon Interactions at High Energies*, J. Lee-Franzini, P. Franzini, and F. Bossi, eds. (World Scientific, 2002) [arXiv:hep-ex/0107029].
- [14] <http://www.nytimes.com/2012/07/11/opinion/100-75-50-years-ago.html>.
- [15] D. Denegri, in [1].
- [16] R. Harlander, in [1].
- [17] M. Grazzini, *EPJ Web Conf.* **28**, 07001 (2012) [arXiv:1202.3927 [hep-ph]].
- [18] L. D. Landau, *Dokl. Akad. Nauk USSR Ser. Fiz.* **60**, 207 (1948).
- [19] C.-N. Yang, *Phys. Rev.* **77**, 242 (1950).
- [20] Y. Gao, A. V. Gritsan, Z. Guo, K. Melnikov, M. Schulze and N. V. Tran, *Phys. Rev. D* **81**, 075022 (2010) [arXiv:1001.3396 [hep-ph]].
- [21] A. De Rujula, J. Lykken, M. Pierini, C. Rogan and M. Spiropulu, *Phys. Rev. D* **82**, 013003 (2010) [arXiv:1001.5300 [hep-ph]].
- [22] S. Baffioni, in [1].
- [23] B. Mele, in [1].
- [24] A. Djouadi, *Phys. Rept.* **457**, 1 (2008) [hep-ph/0503172].

- [25] G. Aad *et al.* [ATLAS Collaboration], [arXiv:1207.7214 [hep-ex]].
- [26] S. Chatrchyan *et al.* [CMS Collaboration], [arXiv:1207.7235 [hep-ex]].
- [27] T. Aaltonen *et al.* [CDF and D0 Collaborations], arXiv:1207.6436 [hep-ex].
- [28] CMS Collaboration, Physics Analysis Summary CMS-PAS-HIG-12-019 (2012).
- [29] J. Haley, in [1].
- [30] M. Carena, I. Low and C. E. M. Wagner, JHEP **1208**, 060 (2012) [arXiv:1206.1082 [hep-ph]].
- [31] U. Ellwanger, JHEP **1203**, 044 (2012) [arXiv:1112.3548 [hep-ph]].
- [32] J. F. Gunion, Y. Jiang and S. Kraml, arXiv:1207.1545 [hep-ph], arXiv:1208.1817 [hep-ph].
- [33] M. Carena, S. Gori, N. R. Shah and C. E. M. Wagner, JHEP **1203**, 014 (2012) [arXiv:1112.3336 [hep-ph]].
- [34] Z. Kang, T. Li, J. Li and Y. Liu, arXiv:1208.2673 [hep-ph].
- [35] J. R. Espinosa, C. Grojean and M. Muhlleitner, EPJ Web Conf. **28**, 08004 (2012) [arXiv:1202.1286 [hep-ph]].
- [36] F. Goertz, U. Haisch and M. Neubert, Phys. Lett. B **713**, 23 (2012) [arXiv:1112.5099 [hep-ph]].
- [37] M. Carena, in [1].
- [38] J. Espinosa, in [1].
- [39] J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam, Phys. Rev. Lett. **100**, 242001 (2008) [arXiv:0802.2470 [hep-ph]].
- [40] T. Plehn, G. P. Salam and M. Spannowsky, Phys. Rev. Lett. **104**, 111801 (2010) [arXiv:0910.5472 [hep-ph]].
- [41] A. Abdesselam, E. B. Kuutmann, U. Bitenc, G. Brooijmans, J. Butterworth, P. Bruckman de Renstrom, D. Buarque Franzosi and R. Buckingham *et al.*, Eur. Phys. J. C **71**, 1661 (2011) [arXiv:1012.5412 [hep-ph]].
- [42] G. Salam, in [1].
- [43] M. E. Peskin, arXiv:1207.2516 [hep-ph].
- [44] J. F. Gunion, H. E. Haber and J. Wudka, Phys. Rev. D **43**, 904 (1991).

- [45] M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein and D. Zepfenfeld, Phys. Rev. D **70**, 113009 (2004) [hep-ph/0406323], hep-ph/0407190.
- [46] M. Dührssen, ATLAS report ATL-PHYS-2003-030 (2003).
- [47] M. Klute, R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, arXiv:1205.2699 [hep-ph].
- [48] S. Matsuzaki and K. Yamawaki, arXiv:1207.5911 [hep-ph].
- [49] D. Elander and M. Piai, arXiv:1208.0546 [hep-ph].
- [50] H. E. Haber, in *From the Planck Scale to the Weak Scale (SUSY 94)*, P. Nath, T. Taylor, and S. Pokorski, eds. (World Scientific, 1995) [hep-ph/9501320].
- [51] R. S. Gupta, H. Rzehak and J. D. Wells, arXiv:1206.3560 [hep-ph].
- [52] M. S. Carena, H. E. Haber, H. E. Logan and S. Mrenna, Phys. Rev. D **65**, 055005 (2002) [Erratum-ibid. D **65**, 099902 (2002)] [hep-ph/0106116].
- [53] H. E. Haber, H. E. Logan, S. Penaranda and D. Temes, Nucl. Phys. Proc. Suppl. **157**, 162 (2006) [hep-ph/0601237].
- [54] J. R. Espinosa, C. Grojean and M. Muhlleitner, JHEP **1005**, 065 (2010) [arXiv:1003.3251 [hep-ph]].
- [55] T. Han, H. E. Logan, B. McElrath and L. -T. Wang, Phys. Lett. B **563**, 191 (2003) [Erratum-ibid. B **603**, 257 (2004)] [hep-ph/0302188].
- [56] F. Gianotti, M. L. Mangano, T. Virdee, S. Abdullin, G. Azuelos, A. Ball, D. Barberis and A. Belyaev *et al.*, Eur. Phys. J. C **39**, 293 (2005) [hep-ph/0204087].
- [57] A. Blondel, M. Koratzinos, R. W. Assmann, A. Butterworth, P. Janot, J. M. Jimenez, C. Grojean and A. Milanese *et al.*, arXiv:1208.0504 [physics.acc-ph]; P. Azzi, C. Bernet, C. Botta, P. Janot, M. Klute, P. Lenzi, L. Malgeri and M. Zanetti, arXiv:1208.1662 [hep-ex].
- [58] L. Linssen, A. Miyamoto, M. Stanitzki and H. Weerts, arXiv:1202.5940 [physics.ins-det].
- [59] R. Lipton, arXiv:1204.3538 [physics.acc-ph].
- [60] B. Foster *et al.*, submission to the European Strategy Study, <http://indico.cern.ch/contributionDisplay.py?contribId=72&confId=175067>.
- [61] H. Aihara, (Ed.), P. Burrows, (Ed.), M. Oreglia, (Ed.), E. L. Berger, V. Guarino, J. Repond, H. Weerts and L. Xia *et al.*, arXiv:0911.0006 [physics.ins-det].

- [62] T. Abe *et al.* [ILD Concept Group - Linear Collider Collaboration], arXiv:1006.3396 [hep-ex].
- [63] ILC Detailed Baseline Design Report, in preparation. A draft of the Physics Chapter is available at: <http://lcsim.org/papers/DBDPhysics.pdf>.
- [64] H. Baer, V. Barger, P. Huang and X. Tata, JHEP **1205**, 109 (2012) [arXiv:1203.5539 [hep-ph]].
- [65] C. F. Berger, M. Perelstein and F. Petriello, hep-ph/0512053.
- [66] R. Contino, T. Kramer, M. Son and R. Sundrum, JHEP **0705**, 074 (2007) [hep-ph/0612180].