2005 International Linear Collider Workshop - Stanford, U.S.A.

Higgs Physics and Electroweak Symmetry Breaking Summary

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We discuss new developments in Higgs-sector physics at the ILC with particular emphasis on the studies presented at LCWS 2005.

1. INTRODUCTION

The physics of electroweak symmetry breaking (EWSB) has been the subject of theoretical and experimental studies since a $SU(2) \times U(1)$ gauge theory was first proposed as the underlying structure of electromagnetic and weak interactions. The carriers of the electroweak force, the W and Z gauge bosons, have been found, and their properties have been studied in detail. However, so far no data could be collected that clearly point to one of the possible explanations of EWSB.

Traditionally, models of EWSB fall in one of two classes. If the huge hierarchy between the electroweak and the Planck scales is to be explained as a renormalization-group effect analogous to scale generation in QCD, one expects the scattering amplitudes of electroweak gauge bosons to exhibit strong-interaction behavior at TeV energies. Beyond this threshold, a new underlying gauge theory would emerge. This idea would provide an elegant solution to the problem of EWSB. However, attempts to implement the complex pattern of flavor physics and to satisfy the LEP constraints result in models that are rather contrived [1].

For these reasons, the alternative ansatz of a weakly interacting model has become increasingly popular. The simplest setup is the Standard Model (SM) that adds a single Higgs scalar to the spectrum. So far, all searches for the SM Higgs have been unsuccessful, and the mass window for this particle has been narrowed down to the range between 115 GeV (the LEP limit for direct detection) and a few 100 GeV, where the SM ceases to be a weakly-interacting model. Incidentally, the SM with a Higgs boson in this range is in reasonable agreement with all known electroweak precision data [2].

The SM is a renormalizable field theory and can thus safely be extrapolated up to very high energies. This feature is shared by many other weakly interacting models (SM extensions) that include multiple Higgs states, extra gauge groups, or supersymmetric (SUSY) partners. Weakly interacting models do not allow for a straightforward explanation of the electroweak hierarchy. However, in SUSY models, there is the possibility of dynamical scale generation in a hidden sector that is transmitted to the visible sector by gravitational or extra gauge interactions. In this case, EWSB has to be embedded in the context of SUSY breaking.

Recently, new models of EWSB have been proposed that weaken this distinction between strong and weak interactions. Little-Higgs models [3] contain Higgs bosons and thus are weakly interacting at low energies. These Higgs bosons are part of a multiplet of Goldstone bosons that appear due to the breaking of some enlarged global symmetry with a characteristic scale of a few TeV. Similar to QCD, such global symmetry breaking could be the consequence of strong interactions that do not leave significant low-energy traces. Moreover, such models emerge in a particular realization of (deconstructed) extra dimensions. Extra-dimension models, on the other hand, allow for gauge boson resonances that unitarize gauge-boson scattering amplitudes and thus replace a Higgs boson [4].

In practical terms, these new roads of model-building force us to reconsider the physics of EWSB. It no longer suffices to detect one or more (or no) Higgs bosons; in order to really uncover the underlying principle, all aspects of their interactions have to be determined as precise as possible. This is the only way of separating distinct

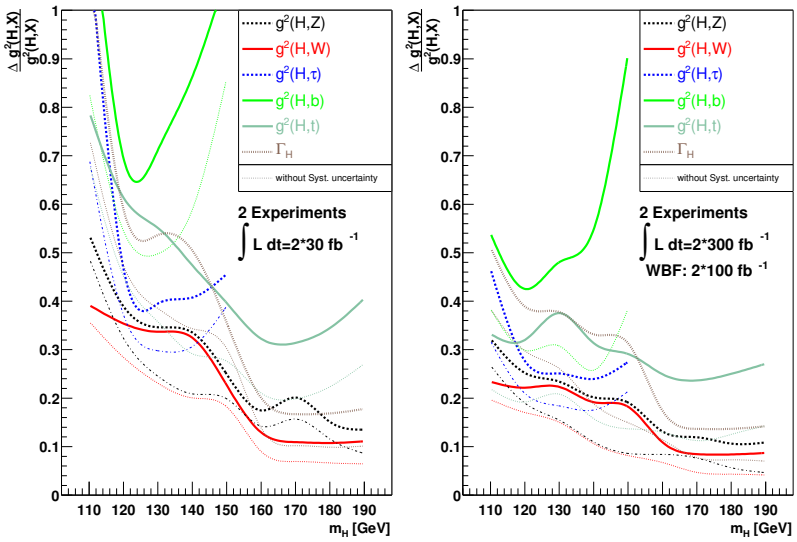

Figure 1: Expected uncertainty in Higgs coupling measurements at the LHC [7]. Left: low-luminosity run, right: high-luminosity run. The assumptions that go into these results are discussed in the text.

scenarios that end up in the same low-energy effective theory. The measurable shifts in observables will be generically proportional to v^2/Λ^2, where $v = 246$ GeV is the electroweak scale, and the new-physics scale Λ is expected to be a few TeV. This implies percent-level precision for Higgs observables, that is achievable at the ILC [6].

2. HIGGS PHYSICS AT THE LHC AND THE IMPORTANCE OF THE ILC

The prospects for Higgs coupling measurements at the LHC have recently been analyzed in detail in Ref. [7]. Under certain conditions, from LHC data alone some couplings of the Higgs boson can be determined to a precision of better than 10 %.

However, rather strong theoretical assumptions are involved in this statement. First of all, in weakly interacting models with Higgs singlets and doublets only, there is a sum rule that limits the Higgs couplings to weak gauge bosons [8]. This sum rule is assumed to hold with a margin of 5 %. However, in view of the variety of models of EWSB discussed above, the Higgs sector need not be weakly interacting, there may be Higgs triplets or higher multiplets, and corrections of less than 5 % are certainly relevant.

In order to bound the Higgs couplings from below, to obtain Fig. 1 one has to assume that the observed rates agree with the SM. If it turns out that the actual rates are significantly lower, the uncertainties in absolute coupling measurements weaken accordingly. (Higher rates would violate the previous assumption.) To conclude, while ratios of Higgs couplings can be measured at the LHC with a precision of several percent, limited mainly by systematics, absolute measurements are meaningful only if the SM is assumed to approximately hold, which need not be the case in reality.

Higgs-sector measurements at the ILC will remove these ambiguities. The inclusive Higgs production rate in $e^+e^- \to ZH$ serves as a *standard meter* against which all other measurements can be gauged. The errors in this measurement have to be completely under control, so a full simulation of the process and the detector [9] is necessary in order to get a precise error estimate. In addition, the precision in many other Higgs coupling measurements can be considerably improved. The price to pay is the increased complexity not just in the experimental analysis, but also in the theoretical prediction that has to match this accuracy. Next-to-leading order corrections are generically necessary.

3. NEW DEVELOPMENTS IN STANDARD HIGGS PHYSICS

The improvements in ILC studies compared to the previous LCWS follow the pattern described above. On the theory side, additional loop corrections have been calculated that make predictions in the Higgs sector more precise. On the experimental side, improved studies enhance the reliability of previous sensitivity estimates. Standard processes as benchmarks help to adapt the detector design to the actual physics needs [10].

For a SM Higgs, the $H\gamma\gamma$ coupling is of particular interest since it occurs via a one-loop diagram at leading order. Moreover, in a certain Higgs mass range there is a cancellation between top and W contributions that make this coupling particularly sensitive to new-physics effects. At the ILC, this coupling can be measured to a good precision in the $\gamma\gamma$ mode [6].

In Ref. [11], the SM prediction for the $H\gamma\gamma$ coupling has been improved by the calculation of two-loop contributions that are enhanced by powers of the top mass. It turns out that these corrections partially compensate the two-loop QCD contribution. The experimental aspects of the $\gamma\gamma \to H$ process have been reconsidered in Ref. [12].

In the MSSM, the Higgs spectrum is determined beyond tree-level by the complete set of soft SUSY-breaking parameters. If the MSSM Higgs bosons can be observed at the LHC and the ILC, a precise mass measurement thus contributes significantly to the determination of Lagrangian parameters that is necessary for drawing conclusions on the SUSY-breaking mechanism. The current knowledge of the loop corrections that go into this relation is coded in the FeynHiggs package that is regularly updated. The current status of this effort is reviewed in Ref. [13].

4. NEW HIGGS MODELS AT THE ILC

Among the variety of EWSB models that have been proposed as alternatives to the SM/SUSY paradigm, the Little-Higgs models are comparatively predictive. At the ILC, the new TeV-scale states that are expected in these scenarios manifest themselves as anomalous couplings in the gauge and Higgs sectors that can be detected. The possible effects have been discussed in Refs. [14–16].

Apart from that, by construction Little-Higgs models contain extended Higgs sectors. Among the extra states, CP-odd singlet scalars play a special role since they are a necessary consequence of the enlarged broken symmetry in these models, unless this symmetry is gauged and the model therefore contains Z' bosons. These particles are difficult to detect, but depending on the model parameters, at the LHC and at the ILC in the e^+e^- and $\gamma\gamma$ modes their observation is possible [17].

CP-odd singlet scalars are not just a characteristic feature of Little-Higgs models, but they also occur in extensions of the MSSM. Due to the addition of an extra singlet, the NMSSM allows for a fit of electroweak observables that implies less fine-tuning than the unmodified MSSM. The key to this observation is the possibility that the Higgs boson decays into light pseudoscalar pairs which could have evaded detection at LEP [18].

The existence of these models demonstrates the importance of verifying the CP quantum numbers of the Higgs boson. Since a pseudoscalar particle can couple to fermion and vector boson pairs (although the latter coupling is typically suppressed), the detection of a scalar resonance in gg, $t\bar{t}$, or weak boson fusion is not an unambiguous proof of the weakly-interacting Higgs mechanism. A possible measurement that distinguishes CP-even and CP-odd states uses angular correlations in $H \to \tau^+\tau^-$ decays [19].

Acknowledgments

W.K. is supported in part by the German Helmholtz-Gemeinschaft, Contract No. VH–NG–005.

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