Recent Refinements in Higgs Physics

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Abstract

Recent refinements of the phenomenology of Higgs bosons in the Standard Model and the Minimal Supersymmetric Standard Model are reviewed.

Invited Talk at the
1995 International Europhysics Conference on High Energy Physics,
Brussels, Belgium, 27 July–2 August, 1995
1 Introduction

In this brief review, I will summarize a few of the advances in Higgs phenomenology during 1995. Space limitations allow me to present only a bare outline of the talk presented at the EPS meeting in Brussels, along with the attendant references. As a result, this review is necessarily incomplete, and I apologize in advance to authors of relevant work that has been omitted.

2 The Standard Model Higgs Boson is a Contradiction in Terms

Phenomenologists and experimentalists who plan the Higgs searches at future colliders spend much effort in designing a search for the Standard Model Higgs boson. However, the Standard Model Higgs boson is a meaningless term unless additional information is provided. This is because the Standard Model itself cannot be a fundamental theory of particle interactions. It must break down once the energy is raised beyond some critical scale $\Lambda$. What is the value of $\Lambda$? Of course, this is unknown at present. $\Lambda$ can lie anywhere between a few hundred GeV and the Planck scale ($M_{PL}$).

Theorists who discuss the phenomenology of the Standard Model usually do not need to know the value of $\Lambda$. At energy scales below $\Lambda$, the physics beyond the Standard Model generally decouples, leaving a low-energy effective theory which looks almost exactly like the Standard Model. However, the Higgs boson presents a potential opportunity to probe $\Lambda$. The stability of the Higgs potential places non-trivial constraints on the Higgs mass, due to the large value of the top quark mass. (More refined limits require only a metastable potential with a lifetime that is long compared to the age of the universe.) Recent computations of Refs. 1 and 2 show for example that if $\Lambda = M_{PL}$, then for $m_t = 175$ GeV the Higgs mass must be larger than about 120 GeV.

Does this mean that if a Higgs boson mass of 100 GeV is discovered then the Standard Model Higgs boson is ruled out? The answer is yes, only if the phrase “the Standard Model Higgs boson” implies that $\Lambda = M_{PL}$. For me, this is too narrow a definition. I would prefer to say that if a 100 GeV Higgs boson were discovered, then new physics beyond the Standard Model must enter at or below an energy scale of $\Lambda \approx 1000$ TeV (based on the graphs presented in Ref. 2). Of course, in this case, if all the new physics were confined to lie in the vicinity of 1000 TeV, then LHC phenomenology would find no deviations from the Standard Model. Thus, physicists who plan searches for the Standard Model Higgs boson are not wasting their time. In particular, even if $\Lambda$ is rather close to the TeV scale, one would expect the lightest Higgs boson to retain all the properties of the so-called Standard Model Higgs boson.

To reiterate, the Standard Model Higgs boson is a sensible concept only if you specify the value of the energy scale $\Lambda$ at which the Standard Model breaks down. Now that we can all agree on the meaning of “the Standard Model Higgs boson”, consider recent refinements in its phenomenology. Here, I would like to refer to two interesting directions.

First, if one assumes the validity of the Standard Model for low-energy physics (below the TeV scale), then one can test this theory by confronting it with the precision electroweak data. In addition to testing the Standard Model, one has the possibility of constraining the value of the Higgs mass, which enters through the radiative corrections to the $Z$ and $W$ boson self-energies. Combining the most recent LEP and SLC electroweak results with the recent top-quark mass measurement at the Tevatron, a weak preference is found for a light Higgs boson mass of order $m_Z$. One must take this result with a large grain of salt, since the overall chi-square of the Standard Model fit is not good (of order 2 per degree of freedom). Nevertheless, it does suggest the potential of future precision measurements for placing interesting constraints on the Standard Model Higgs mass.

Second, a number of two-loop computations of Higgs boson processes have recently been completed. Among them are an $O(\alpha^3_\text{em})$ calculation of $h^0 \to gg$ and $O(\alpha^2_\text{em}, \alpha_s G_F m_t^2, G^2_F m_t^2)$ terms in $h^0 \to bb$. See Ref. 6 for details. Together with the recent computation of “$K$” factors in $pp \to h^0 + X$, one now has both improved pro-
duction cross-section and branching ratio calculations, leading to more accurate Higgs boson phenomenology at both the LHC and future $e^+e^-$ colliders.

3 The Radiatively-Corrected MSSM Higgs Mass

If the minimal supersymmetric extension of the Standard Model (MSSM) is correct, then we should identify the scale $\Lambda$ at which the Standard Model breaks down as the scale of low-energy supersymmetry breaking. In models of low-energy supersymmetry, $\Lambda$ is presumed to lie between $m_Z$ and about 1 TeV. The mass of the light CP-even neutral Higgs boson, $h^0$, in the MSSM can be calculated to arbitrary accuracy in terms of two parameters of the Higgs sector, $m_{A^0}$ and $\tan \beta$, and other MSSM soft-supersymmetry-breaking parameters that affect the Higgs mass through virtual loops. If the scale of supersymmetry breaking is much larger than $m_Z$, then large logarithmic terms arise in the perturbation expansion. These large logarithms can be resummed using renormalization group (RG) methods.

The formula for the full one-loop radiative corrected Higgs mass is very complicated. Moreover, the computation of the RG-improved one-loop corrections requires numerical integration of a coupled set of RG equations. The dominant two-loop next-to-leading logarithmic results are also known. Although this program has been carried out in the literature, the procedure is unwieldy and not easily amenable to large-scale Monte-Carlo analyses. Below, we summarize a very simple procedure for accurately approximating $m_{h^0}$. The method can be easily implemented, and incorporates both the leading one-loop and two-loop effects and the RG-improvement. Although the method is conceptually simple, complications arise when supersymmetric thresholds are fully taken into account. The details can be found in Ref. 13, along with other references to the original literature. Complementary work can be found in Ref. 14. In the limited space allotted here, only the simplest version of our method is outlined.

The dominant radiative corrections to $m_{h^0}$ arise from an incomplete cancelation of the virtual top-quark and top-squark loops. The two top-squark masses ($M_{\tilde{t}_1}$ and $M_{\tilde{t}_2}$) are obtained by diagonalizing a $2 \times 2$ top-squark squared-mass matrix; the off-diagonal elements of this matrix are denoted by $m_{\tilde{t}_1}\tilde{X}_t$ (where $X_t \equiv A_t - \mu \cot \beta$). We also assume that $M_{\tilde{t}_1}^2 > M_{\tilde{t}_2}^2 > m_{A^0} > m_Z$. This case is particularly useful since the upper bound for $m_{h^0}$ (at fixed $\tan \beta$) arises precisely in this limit. The leading terms in the one-loop approximation to $m_{h^0}^2$ are given by

$$m_{h^0}^2 = m_Z^2 \cos^2 2\beta + (\Delta m_{h^0}^2)_{1LL}(m_t) + (\Delta m_{h^0}^2)_{\text{mix}}(m_t),$$

where

$$(\Delta m_{h^0}^2)_{1LL} = \frac{3g_2^2m_t^4}{8\pi^2m_W^2} \ln \left( \frac{M_{\tilde{t}_1}M_{\tilde{t}_2}}{m_t^2} \right) \left[ 1 + O \left( \frac{m_W^2}{m_t^2} \right) \right],$$

and

$$(\Delta m_{h^0}^2)_{\text{mix}} = \frac{3g_2^2m_t^4X_t^2}{16\pi^2m_W^2} \left[ 2h(M_{\tilde{t}_1}^2, M_{\tilde{t}_2}^2) ight. + X_t^2g(M_{\tilde{t}_1}^2, M_{\tilde{t}_2}^2) \left. \right] \left[ 1 + O \left( \frac{m_W^2}{m_t^2} \right) \right].$$

In eq. (2), the functions $g$ and $h$ are given by:

$$g(a, b) = \frac{1}{(a-b)^2} \left[ \frac{a+b}{a-b} \ln \left( \frac{a}{b} \right) \right],$$

$$h(a, b) = \frac{1}{a-b} \ln \left( \frac{a}{b} \right).$$

The notation used in eq. (1) emphasizes the dependence of $(\Delta m_{h^0}^2)_{1LL}$ and $(\Delta m_{h^0}^2)_{\text{mix}}$ on $m_t$. Subdominant terms not shown explicitly in eqs. (2) and (3) by replacing $m_t$ in the formulae above by running top quark mass evaluated at $m_t$. Explicitly, $m_t(m_t)$ is given in terms of the pole mass $m_t^\text{pole}$ by

$$m_t(m_t) = m_t^\text{pole} \left( 1 - \frac{4\alpha_t}{3\pi} + \frac{\alpha_s}{2\pi} \right) \approx 0.966 m_t^\text{pole},$$

where $\alpha_t \equiv h_t^2/4\pi$ and the Higgs-top quark Yukawa coupling is $h_t = g m_t/\sqrt{2} m_W$. Since by assumption $m_{A^0} \approx m_Z$, one should identify $h_t$ as the Yukawa coupling of the low-energy effective one-doublet Higgs sector.

For details appropriate to the case of $m_{A^0} \sim O(m_Z)$, see Ref. 13.) Due to the leading $m_t^2$ behavior of the one-loop corrections, the replacement of $m_t \rightarrow m_t^\text{pole}$ in eqs. (2) and (3) by $m_t(m_t)$ is numerically important, leading to a significant reduction in the predicted value of $m_{h^0}$.

We now proceed to sum the leading logarithmic terms to all orders in perturbation theory via RG-improvement. As noted above, this requires extensive numerical analysis. Nevertheless, we have found a remarkably simple analytic formula that incorporates the dominant effects of the RG-improvement. We already noted that replacing the pole mass $m_t^\text{pole}$ with the running mass $m_t(m_t)$ has the effect of including the dominant part of the $O(m_t^2 \alpha_t^2)$ and $O(m_t^2 \alpha_s \alpha_t)$ next-to-leading logarithmic contributions to $m_{h^0}^2$. We find that the two-loop leading logarithmic contributions to $m_{h^0}^2$ can be incorporated by replacing the running top quark mass with $m_t$ evaluated at an appropriately chosen scale. For $M_{\tilde{t}_1} \approx M_{\tilde{t}_2} \equiv M_t$, our result is:

$$m_{h^0}^2 = m_Z^2 \cos^2 2\beta + (\Delta m_{h^0}^2)_{1LL}(m_t(m_t)) + (\Delta m_{h^0}^2)_{\text{mix}}(m_t(M_t)),$$

where

$$m_{h^0}^2 = m_Z^2 \cos^2 2\beta + (\Delta m_{h^0}^2)_{1LL}(m_t(m_t)) + (\Delta m_{h^0}^2)_{\text{mix}}(m_t(M_t)),$$

and

$$m_{h^0}^2 = m_Z^2 \cos^2 2\beta + (\Delta m_{h^0}^2)_{1LL}(m_t(M_t)) + (\Delta m_{h^0}^2)_{\text{mix}}(m_t(M_t)),$$
The radiatively corrected light CP-even Higgs mass is plotted as a function of $A_t/M_S$ for $\tan\beta = 20$. The one-loop leading logarithmic computation is compared with the RG-improved result which was obtained by numerical analysis and by using the simple analytic result given in eq. (7). $M_S$ characterizes the scale of supersymmetry breaking and can be regarded (approximately) as a common supersymmetric scalar mass.

where $\mu_t \equiv \sqrt{m_t M_T}$, and the running top-quark mass is given by

$$m_t(\mu_t) = m_t(m_t) \left[ 1 - \left( \frac{\alpha_s}{\pi} - \frac{3\alpha_t}{16\pi} \right) \ln \left( \frac{\mu_t^2}{m_t^2} \right) \right]. \quad (8)$$

All couplings on the right hand side of eq. (8) are evaluated at $m_t$. In our numerical work, we have verified that this prescription reproduces the full RG-improved Higgs mass to within 2 GeV for top-squark masses of 2 TeV or below. Figures 1 and 2 exhibit two graphs to support this claim. Further details can be found in Ref. 13.

4 Higgs Searches at Future Colliders

1995 was a year of re-assessment. In the United States, the Division of Particles and Fields published a Long Range Planning Study to assess the future of the US particle physics program in light of the demise of the SSC. One working group of this study focused on electroweak symmetry breaking and physics at the TeV scale. One of the tasks of this working group was to provide an in depth survey of Higgs searches at future collider facilities. Their work can be found in Ref. 15. In Europe, 1995 was the year of the LEP-200 Study. The Higgs Boson Working group played a major role in making the case for upgrading the LEP collider to the highest possible energy. It now appears that LEP will be upgraded to a center-of-mass energy of 192 GeV during the next few years. This will permit the discovery of a Higgs boson up to around 95 GeV. This is very exciting for proponents of the MSSM if $\tan\beta$ is small [see Figure 2]. The LEP-200 Higgs Working group considered in detail the discovery reach of the upgraded LEP collider for the Standard Model Higgs boson and the MSSM Higgs boson (a few non-minimal approaches were also surveyed). The results of this work can be found in Ref. 16.

5 Conclusions

This past year has seen a number of theoretical and phenomenological refinements of Higgs boson properties. The most comprehensive assessments of the Higgs searches at future colliders have been presented. Meanwhile, we await for experiments at LEP-2 and/or the LHC to shed light on the origin of the dynamics that is responsible for electroweak symmetry breaking.

Acknowledgments

The work of Section 3 is based on a collaboration with Andre Hoang and Ralf Hempfling. This work was supported in part by the U.S. Department of Energy.

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