HIGGSBOUNDS\textsuperscript{a} \textbf{: CONFRONTING ARBITRARY HIGGS SECTORS WITH EXCLUSION BOUNDS FROM LEP AND TEVATRON}\textsuperscript{b}

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HiggsBounds is a computer code which tests the Higgs sectors of new models against the current exclusion bounds from the Higgs searches at LEP and the Tevatron. As input, it requires a selection of model predictions, such as Higgs masses, branching ratios, effective couplings and total decay widths. HiggsBounds then uses the expected and observed topological cross section limits from the Higgs searches to determine which points in the parameter space have already been excluded at 95\% CL. HiggsBounds will be updated to include new results as they become available.

1 Introduction

The search for Higgs bosons is a major cornerstone of the physics programmes of past, present and future high energy colliders. The LEP and Tevatron experiments, in particular, have been able to turn the non-observation of Higgs bosons into constraints on the Higgs sector, which can be very useful in reducing the available parameter space of particle physics models. Such constraints will continue to be important far into the LHC era as they will need to be taken into account in the interpretation of any new physics.

These analyses usually take one of two forms. Dedicated analyses have been carried out in order to constrain some of the most popular models, such as the SM\textsuperscript{[1] and various benchmark scenarios in the MSSM\textsuperscript{[2]}. In addition, model-independent limits on the cross sections of individual signal topologies (such as $e^+e^- \rightarrow h_iZ \rightarrow bbZ$) have been published. The former type of analyses include detailed knowledge of the overlap between the individual experimental searches, and therefore have a high sensitivity, whereas the latter can be used to test a wide class of models.

There are certain issues involved with the application of these experimental constraints. The data is distributed over many different publications and the limits are given with a variety of normalisations. In the case of the Tevatron, the results are also frequently updated. Furthermore, care must be taken when using more than one experimental analysis to ensure that the resulting exclusion bound has the same confidence level (CL) as each individual analysis.

The fortran code HiggsBounds\textsuperscript{[11] has been designed to facilitate the task of comparing Higgs

\textsuperscript{a}Online version and code download available at: \url{http://www.ippp.dur.ac.uk/HiggsBounds}
\textsuperscript{b}Talk presented by K. E. Williams at “Rencontres de Moriond – QCD and High Energy Interactions 2009”
sector predictions with existing exclusion limits, thus allowing the user to quickly and conveniently check a wide variety of models against the state-of-the-art results from Higgs searches.

2 Outline of the program

The user provides the Higgs sector predictions of the model under consideration. For each neutral Higgs boson $h_i$ ($i = 1, \ldots, n_{\text{Higgs}}$) in the model, this will usually include the mass, total decay width, branching ratios and Higgs production cross sections:

$$M_{h_i}, \Gamma_{\text{tot}}(h_i), \text{BR}_{\text{model}}(h_i \rightarrow \ldots), \frac{\sigma_{\text{model}}(P)}{\sigma_{\text{SM}}(P)}.$$  \hspace{1cm} (1)

Where it exists, $\sigma_{\text{SM}}(P)$ is used as the reference cross section. Variations on this input format are offered, as described in detail in the HiggsBounds manual\cite{HiggsBoundsManual}. The HiggsBounds package includes sample programs which demonstrate how HiggsBounds can be used in conjunction with the widely used MSSM Higgs sector programs FeynHiggs\cite{FeynHiggs} and CPsuperH\cite{CPsuperH}.

A list of the experimental analyses currently included in HiggsBounds is given in Table 1. These include results from both LEP and the Tevatron and consist of tables of expected (based on Monte Carlo simulations with no signal) and observed 95% CL cross section limits, with a variety of normalisations. The list mainly consists of analyses for which model-independent limits were published. However, we also include some dedicated analyses carried out for the case of the SM. These analyses are only considered if the Higgs boson in question would appear sufficiently ‘SM-like’ to this analysis. Roughly speaking, this requires that the ratios of all involved couplings to the SM Higgs are approximately equal\cite{HiggsBoundsManual}.

For each Higgs process $X$ (here, we treat each combination of Higgs bosons in each experimental analysis as a separate $X$), HiggsBounds uses the input to calculate the quantity $Q_{\text{model}}(X)$, which, up to a normalisation factor, is the predicted cross section for $X$.

The normalisation is carried out using SM predictions for Higgs boson production cross sections and decay branching ratios from HDECAY\cite{HDECAY}, 3.303, the TEV4LHC Higgs Working Group\cite{TEV4LHC}, VFB@NLO\cite{VFB@NLO}, HJET\cite{HJET} 1.1 and dedicated calculations of our own\cite{HiggsBoundsManual}.

In order to ensure the correct statistical interpretation of the results, it is crucial to only consider the experimentally observed limit for one particular $X$. Therefore, HiggsBounds must first determine $X_0$, which is defined as the process $X$ with the highest statistical sensitivity for the model point under consideration. In order to do this, the program uses the tables of expected experimental limits to obtain a quantity $Q_{\text{expec}}$ corresponding to each $X$. The process with the largest value of $Q_{\text{model}}/Q_{\text{expec}}$ is chosen as $X_0$. 

Table 1: LEP and Tevatron analyses used by HiggsBounds. $l$ or $l'$ indicates an electron or a muon, and $\dagger$ indicates analyses which combine processes using SM assumptions. In this notation, $m_{h_k} > m_{h_i}$. 

\begin{center}
\begin{tabular}{|l|}
\hline
$e^+e^- \rightarrow (h_k)Z \rightarrow (bb)Z$ & $pp \rightarrow ZH \rightarrow t^+t^-bb$ (CDF,DØ) \\
$e^+e^- \rightarrow (h_k)Z \rightarrow (\tau^+\tau^-)Z$ & $pp \rightarrow WH \rightarrow l\nu bb \ (CDF,DØ)$ \\
$e^+e^- \rightarrow (h_k \rightarrow h_1h_1)Z \rightarrow (b\bar{b}b\bar{b})Z$ & $pp \rightarrow WH \rightarrow l\nu bb$ (CDF,DØ) \\
$e^+e^- \rightarrow (h_k \rightarrow h_1h_1)Z \rightarrow (\tau^+\tau^-)Z$ & $pp \rightarrow H \rightarrow W^+W^- \rightarrow l^+l^-$ (CDF,DØ) \\
$e^+e^- \rightarrow (h_k \rightarrow h_1h_1) \rightarrow (b\bar{b}b\bar{b})$ & $pp \rightarrow H \rightarrow \gamma\gamma$ (CDF,DØ) \\
$e^+e^- \rightarrow (h_k \rightarrow h_1h_1) \rightarrow (\tau^+\tau^-\tau^+\tau^-)$ & $pp \rightarrow H \rightarrow \tau^+\tau^-$ (CDF,DØ) \\
$e^+e^- \rightarrow (h_k \rightarrow h_1h_1)h_i \rightarrow b\bar{b}b\bar{b}$ & $pp \rightarrow bH, H \rightarrow b\bar{b}$ (CDF,DØ) \\
$e^+e^- \rightarrow (h_k \rightarrow h_1h_1)h_i \rightarrow \tau^+\tau^-\tau^+\tau^-$ & $pp \rightarrow WH/ZH \rightarrow bb + E_{\text{miss}}$ (CDF,DØ) $\dagger$ \\
$e^+e^- \rightarrow (h_k \rightarrow h_1h_1)Z \rightarrow (b\bar{b}r^+\tau^-)Z$ & $pp \rightarrow HW/HZ/H \ via\, \text{VBF}$, \\
$e^+e^- \rightarrow (h_k \rightarrow b\bar{b})(h_i \rightarrow \tau^+\tau^-)$ & $H \rightarrow \tau^+\tau^-$ (CDF) $\dagger$ \\
$e^+e^- \rightarrow (h_k \rightarrow \tau^+\tau^-)(h_i \rightarrow b\bar{b})$ & combined Tevatron analyses for the SM Higgs$\dagger$  \\
\hline
\end{tabular}
\end{center}
Figure 1: Coverage of the LEP Higgs searches in the $M_{H_1}$–$\tan \beta$ plane of the CPX scenario, where $M_{H_1}$ is the lightest neutral Higgs boson and $\tan \beta$ is the ratio of vacuum expectation values. Left: the LEP processes predicted to have the highest statistical sensitivity at each parameter point. Right: the parameter regions excluded at the 95% CL (green (dark grey) = excluded, white = unexcluded, light grey = theoretically inaccessible).

Key to processes (left-hand graph):
- red (■) = $(h_1Z) \rightarrow (b\bar{b}Z)$
- blue (■) = $(h_2Z) \rightarrow (b\bar{b}Z)$
- white (□) = $(h_2Z) \rightarrow (h_1h_1Z) \rightarrow (b\bar{b}b\bar{b}Z)$
- cyan (■) = $(h_2h_1) \rightarrow (b\bar{b}b\bar{b})$
- yellow (■) = $(h_2h_1) \rightarrow (h_1h_1h_1) \rightarrow (b\bar{b}b\bar{b}b\bar{b})$
- purple (■) = other

\textbf{HiggsBounds} then derives a value for $Q_{\text{obs}}$ for this process $X_0$, using the appropriate table of experimentally observed limits. If

$$\frac{Q_{\text{model}}(X_0)}{Q_{\text{obs}}(X_0)} > 1,$$

\textbf{HiggsBounds} concludes that this particular parameter point is excluded at 95% CL.

In order to use \textbf{HiggsBounds}, the narrow-width approximation must be valid for each Higgs boson described in the input. This is because the experimental exclusions bounds currently utilised within \textbf{HiggsBounds} have all been obtained under this approximation. We intend to include width-dependent limits into \textbf{HiggsBounds} in the future, where they are provided by experimental collaborations in a model-independent format (such as those provided in Ref. 4).

3 Numerical example: the CPX scenario

We will illustrate some of the main features of \textbf{HiggsBounds} using an example from Ref. 12 (with the modifications described in Ref. 11). The CPX scenario was one of the MSSM scenarios which were investigated in detail by the LEP Higgs Working Group 2. It is phenomenologically interesting because it introduces large CP-violating phases, which induce mixing in the neutral Higgs sector, resulting in weaker exclusions than those obtained for the real MSSM. However, since this original analysis, there have been relevant theoretical advances 13, 12 which can have a large numerical effect on the Higgs sector of the CP-violating MSSM. Therefore, \textbf{HiggsBounds} was employed to investigate the effect of these new results on the amount of CPX parameter space which can be excluded by current Higgs search data.

From Fig. 1(right), it can be seen that, although substantial regions of CPX parameter space can be excluded (green), there are significant regions which remain unexcluded (white), including an unexcluded region (the ‘CPX hole’) at a lightest Higgs mass $M_{h_1} \sim 45$ GeV, qualitatively confirming the result of the original analysis 2. In addition, the use of \textbf{HiggsBounds} allows a greater understanding of the theoretical influences on the exclusions. For example, it can be seen from Fig. 1(right) that the process $e^+e^- \rightarrow (h_1Z) \rightarrow (b\bar{b}Z)$ (red), which is usually the most effective at excluding areas of MSSM parameter space, has the highest statistical sensitivity only in regions with low $\tan \beta$ and/or high $M_{h_1}$. This is because the coupling of the lightest Higgs to two $Z$ bosons is suppressed in the other regions, therefore reducing the $h_1$ Higgsstrahlung production cross section. It is also interesting to note that, near to the CPX...
hole, the processes with the highest statistical sensitivity all directly involve the decay of the second heaviest neutral Higgs $h_2$. Therefore, it can be inferred that variations in the partial decay widths of the dominant decay modes (in this case, the Higgs cascade decay $h_2 \rightarrow h_1 h_1$ and the decay to b-quarks $h_2 \rightarrow b\bar{b}$) will affect the size and position of the CPX hole, as is indeed the case.\textsuperscript{12}

In conclusion, the program HiggsBounds provides a convenient way to compare theoretical Higgs sector predictions with the current exclusion bounds from LEP and the Tevatron, in a way that maintains the statistical interpretation of the exclusion limit and gives extra insight into phenomenological influences on the result.

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