HiggsBounds - using results from the Higgs searches at LEP and the Tevatron to constrain extensions to the Standard Model

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Tools 2010

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

The Higgs Boson

The Standard Model

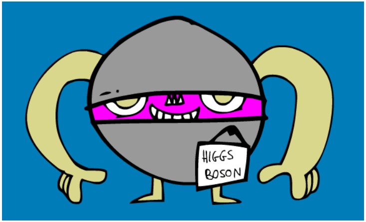
- The Standard Model of particle physics uses the Higgs Mechanism to generate particle masses $\longrightarrow$ predicts the existence of a neutral, scalar particle, called the Higgs Boson.

Beyond the Standard Model

- Many people believe that the Standard Model is incomplete and so study possible extensions e.g. Supersymmetry
- Extensions to the Standard Model can predict more exciting Higgs sectors.
- E.g. the Minimal Supersymmetric Standard Model requires 3 neutral Higgs bosons and one charged Higgs boson.

Higgs Searches

- Searches at past and present colliders have not yet discovered a Higgs boson.
- This puts restrictions on models.



Higgs Searches

Searches at past and present colliders have not yet discovered a Higgs boson. This puts restrictions on models. The results from the experiments are presented in 2 forms:

Model-dependent limits

The analysis has been carried out in the context of a particular model

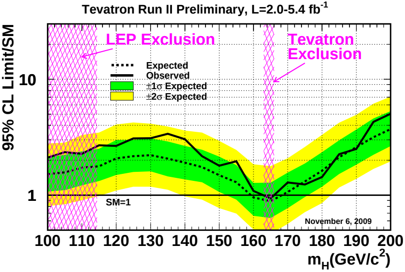
- E.g. Standard Model analysis $\rightarrow$ limits on the Higgs mass in the SM, certain benchmark MSSM scenarios ($m_h^{\max}$, no-mixing, large-μ, gluophobic, small α_{eff}, CPX, ...) $\rightarrow$ limits on the parameter space of these scenarios
- uses lots of search topologies, applies to one model only

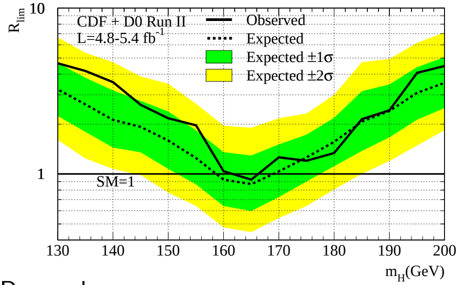
Model-independent limits

Limits on the cross sections of a particular topology which can be used to constrain a wide variety of different models

- E.g. $e^+e^- \rightarrow (h_i)Z \rightarrow (b\bar{b})Z$
- uses one search topology only, applies to lots of models

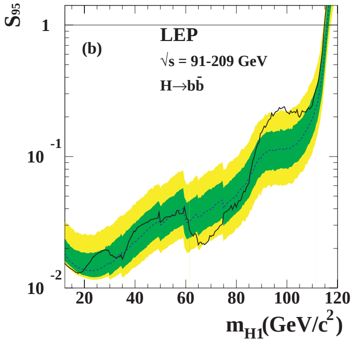
Example of model-dependent limits: Standard Model



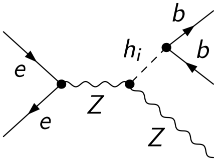


- $M_H < 114.4\ \mathrm{GeV}$ is excluded by LEP searches [Phys.Lett.B565:61-75,2003]
- $162 < M_H < 166\ \mathrm{GeV}$ is excluded by Tevatron searches [arXiv:1001.4162]
- These results combine the results from searches in many different channels.

Example of a model-independent cross-section limit



[Eur.Phys.J.C47:547-587,2006]

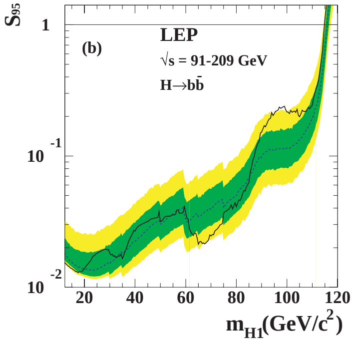


S_{95} is the maximum cross section compatible with the data at 95% CL, normalised to the LEP SM Higgsstrahlung cross section.

Solid line: observed limit

Dashed line: expected limit (based on simulations with no signal)

Example of a model-independent cross-section limit



[Eur.Phys.J.C47:547-587,2006]

To use these limits:

1. For each neutral Higgs h_i for a parameter point in a model, need to compare

$$S_{95}^{\rm theo} = \sigma^{\rm norm}(e^- e^+ \to h_i Z){\rm Br}(h_i \to b\bar{b})$$

with the observed S_{95} value for this mass.

[For example, at tree level in the MSSM, $\sigma^{\rm norm}(e^- e^+ \to h^0 Z) = \sin^2(\beta - \alpha)$]

2. If $S_{95}^{\rm theo} > S_{95}^{\rm obs}$, then this parameter point is excluded at 95% CL.

Using more than one model-independent limit

When using more than one model-independent limit, care needs to be taken to ensure that the exclusions are still at 95 % CL.

One possible method:

1. Calculate S_{95}^{theo} for each search channel.
2. Determine which search channel has the highest statistical sensitivity i.e. which search channel has the largest $S_{95}^{\mathrm{theo}}/S_{95}^{\mathrm{exp}}$, using the expected limits based on simulations with no signal.
3. Look at $S_{95}^{\mathrm{theo}}/S_{95}^{\mathrm{obs}}$ for this channel only. If $S_{95}^{\mathrm{theo}}/S_{95}^{\mathrm{obs}} > 1$, then parameter point is excluded at 95 % CL.

HiggsBounds

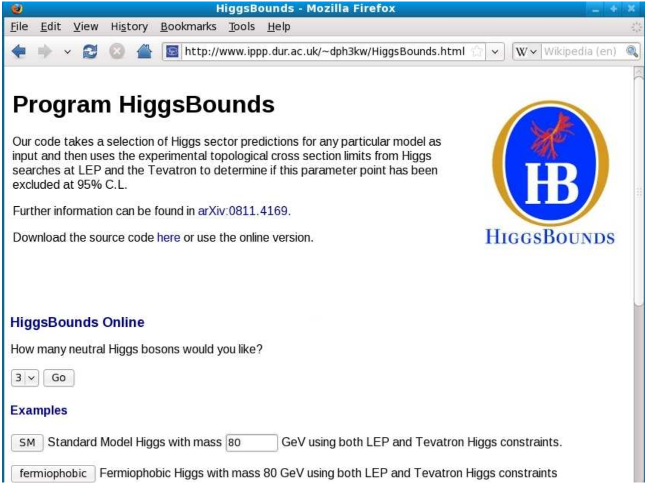
HiggsBounds

is a Fortran program which takes input from the user for a parameter point in a particular model and determines whether this parameter point has been excluded at 95% CL by Higgs searches at LEP and the Tevatron.

- Current release (1.2.0) contains neutral Higgs search results. It can be applied to models containing between 1 and 9 neutral Higgs bosons.
- Next release (2.0.0) will include charged Higgs searches.
- The user can either use
  - the web version
  - the command line version
  - the library of subroutines.

The *HiggsBounds* Website

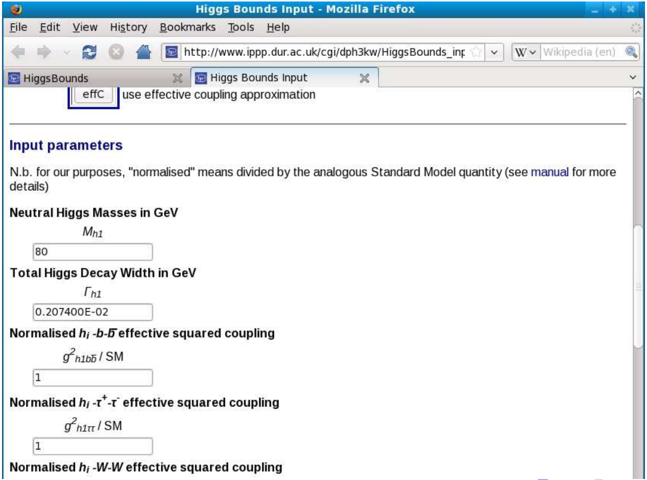
http://www.ippp.dur.ac.uk/HiggsBounds



The *HiggsBounds* Website

The simplest input mode requires

- Higgs masses, total decay widths, normalised effective couplings squared, $\mathrm{BR}(h_j \to h_i h_i)$



The *HiggsBounds* Website

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parameter point is EXCLUDED at 95 per cent C.L.
using the process with highest statistical sensitivity:
 (ee)->(h1)Z->(b b-bar)Z   (hep-ex/0602042, table 14b (LEP))
which has a theoretical rate vs. limit of
  20.526829268292683

********************************************************
```

Input HiggsBounds requires from the user

Input:

- Higgs masses, total decay widths, normalised effective couplings squared, $\mathrm{BR}(h_j \to h_i h_i)$

or

- Higgs masses, total decay widths, normalised LEP cross sections, some normalised partonic Tevatron cross sections, some normalised hadronic Tevatron cross sections, branching ratios

or

- Higgs masses, total decay widths, normalised LEP cross sections, normalised hadronic Tevatron cross sections, branching ratios

or

- Only for real MSSM: SLHA file with extra block HiggsBoundsInputRealMSSMCouplings

  - 'Normalised' means divided by the SM equivalent, where it exists (see documentation for more details).
  - Narrow width approximation must be applicable.
  - t-quark branching ratios are also needed when using the Tevatron charged Higgs searches

Input to *HiggsBounds*: new SLHA block

```
Block HiggsBoundsInputRealMSSMCouplings
# NormEffCoupSq should be given even when zero.
# For exact definitions of NormEffCoupSq see HiggsBounds manual
# Order of particles does not matter, but use the positive PDG code
# (i.e. specify the particle rather than the antiparticle)
#    NormEffCoupSq  NP  IP1  IP2  IP3 # Normalised Effective Coupling Squared
     1.0000001E+00   3   25    5    5 # h0-b-b effective coupling^2, normalised to SM
     1.0000002E+00   3   35    5    5 # HH-b-b effective coupling^2, normalised to SM
     1.0000003E+00   3   36    5    5 # A0-b-b effective coupling^2, normalised to SM
#
     1.0000004E+00   3   25    6    6 # h0-top-top effective coupling^2, normalised to SM
     1.0000005E+00   3   35    6    6 # HH-top-top effective coupling^2, normalised to SM
     1.0000006E+00   3   36    6    6 # A0-top-top effective coupling^2, normalised to SM
#
     1.0000007E+00   3   25   15   15 # h0-tau-tau effective coupling^2, normalised to SM
     1.0000008E+00   3   35   15   15 # HH-tau-tau effective coupling^2, normalised to SM
     1.0000009E+00   3   36   15   15 # A0-tau-tau effective coupling^2, normalised to SM
#
     1.0000010E+00   3   25   24   24 # h0-W-W effective coupling^2, normalised to SM
     1.0000011E+00   3   35   24   24 # HH-W-W effective coupling^2, normalised to SM
     1.0000012E+00   3   36   24   24 # A0-W-W effective coupling^2, normalised to SM
#
     1.0000013E+00   3   25   23   23 # h0-Z-Z effective coupling^2, normalised to SM
     1.0000014E+00   3   35   23   23 # HH-Z-Z effective coupling^2, normalised to SM
     1.0000015E+00   3   36   23   23 # A0-Z-Z effective coupling^2, normalised to SM
#
     1.0000016E+00   3   25   21   21 # h0-gluon-gluon effective coupling^2, normalised to SM
     1.0000017E+00   3   35   21   21 # HH-gluon-gluon effective coupling^2, normalised to SM
     1.0000018E+00   3   36   21   21 # A0-gluon-gluon effective coupling^2, normalised to SM
```

Input to *HiggsBounds*: some publicly available programs

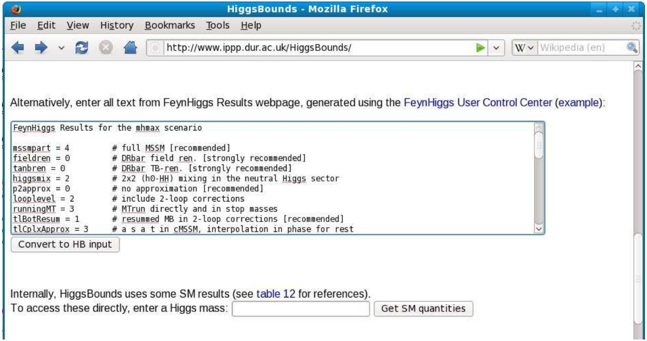
There are many public programs which can be used to calculate the *HiggsBounds* input in the more common models e.g.

- *FeynHiggs** (T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein) for the MSSM
- *CPsuperH** (J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. Ellis, and C. Wagner) for the complex MSSM
- *2HDMC*† (D. Eriksson, J. Rathsman, O. Stål) for the Two-Higgs-Doublet Model

$*$ interface included in *HiggsBounds* packages
$\dagger$ interface included in *2HDMC* package (vs. 1.0.2 and higher)

Input to *HiggsBounds*: using *FeynHiggs* User Control Center

The *FeynHiggs* User Control Center can be used to get MSSM parameters online. The FHUCC results page can then be copy-and-pasted into a box on the *HiggsBounds* website (v. 2.0.0):



HiggsBounds and *DarkSUSY*

DarkSUSY (P. Gondolo, J. Edsjö, P. Ullio, L. Bergstöm, M. Schelke and E.A. Baltz) is a program for supersymmetric dark matter calculations, such as relic density of the neutralinos in the Universe, and the direct and indirect detection rates.

HiggsBounds is included in the *DarkSUSY* package.

DarkSUSY has a web interface at `http://www.physto.se/~edsjo/darksusy/` for mSUGRAm and MSSM-7+ scenarios.

Standard Model results used within *HiggsBounds*

Internally, *HiggsBounds* uses

- SM Higgs branching ratios and total decay width from *HDecay* (A. Djouadi, J. Kalinowski and M. Spira)
- SM Higgs production cross sections (S. Catani et al 2003, O. Brein et al 2003, M. L. Ciccolini et al 2003, R. Harlander et al 2003, J. M. Campbell et al 1999, U. Aglietti et al 2006, K.A.Assamagan et al 2004, W. Beenakker et al 2001, L. Reina et al 2001, S. Dawson et al 2002)
- The SM ratio $\sigma(p\bar{p} \to H \,\mathrm{via}\, WW \,\mathrm{fusion})/\sigma(p\bar{p} \to H \,\mathrm{via}\, ZZ \,\mathrm{fusion})$ using *VBF@NLO* (T.Figy et al 2003)
- ratios of SM hadronic cross sections $\sigma(p\bar{p} \to nm \to H + \ldots)/\sigma(p\bar{p} \to H + \ldots)$, where nm are particular partons provided by O. Brein

to convert between different types of input and to ensure correct normalisation of experimental limits.

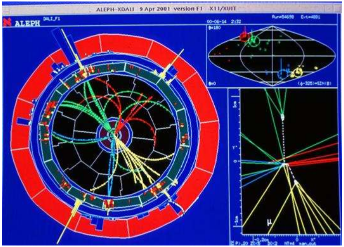
Topological Cross section limits from LEP Higgs searches currently included in *HiggsBounds*

Topologies considered: Higgsstrahlung

1. $e^+e^- \rightarrow (h_k)Z \rightarrow (b\bar{b})Z$
2. $e^+e^- \rightarrow (h_k)Z \rightarrow (\tau^+\tau^-)Z$
3. $e^+e^- \rightarrow (h_k \rightarrow h_i h_i)Z \rightarrow (b\bar{b}b\bar{b})Z$
4. $e^+e^- \rightarrow (h_k \rightarrow h_i h_i)Z \rightarrow (\tau^+\tau^-\tau^+\tau^-)Z$
5. $e^+e^- \rightarrow (h_k \rightarrow h_i h_i)Z \rightarrow (b\bar{b})(\tau^+\tau^-)Z$
6. $e^+e^- \rightarrow (h_k)Z \rightarrow (\ldots)Z$
7. $e^+e^- \rightarrow (h_k)Z \rightarrow (\gamma\gamma)Z$

and Higgs pair production

1. $e^+e^- \rightarrow (h_k h_i) \rightarrow (b\bar{b}b\bar{b})$
2. $e^+e^- \rightarrow (h_k h_i) \rightarrow (\tau^+\tau^-\tau^+\tau^-)$
3. $e^+e^- \rightarrow (h_k \rightarrow h_i h_i)h_i \rightarrow (b\bar{b}b\bar{b})b\bar{b}$
4. $e^+e^- \rightarrow (h_k \rightarrow h_i h_i)h_i \rightarrow (\tau^+\tau^-\tau^+\tau^-)\tau^+\tau^-$
5. $e^+e^- \rightarrow (h_k \rightarrow b\bar{b})(h_i \rightarrow \tau^+\tau^-)$
6. $e^+e^- \rightarrow (h_k \rightarrow \tau^+\tau^-)(h_i \rightarrow b\bar{b})$



A selection of the Tevatron search topologies currently included in *HiggsBounds*

- $p\bar{p} \to Wh_i \to l\nu b\bar{b}$
- $p\bar{p} \to Wh_i \to W^+W^-W^\pm$
- $p\bar{p} \to Zh_i \to l^+l^- b\bar{b}$
- $p\bar{p} \to Zh_i \to \nu\bar{\nu}b\bar{b}$
- $p\bar{p} \to Wh_i/Zh_i \to b\bar{b} + E_T^{\text{miss.}}$ (SM)
- $p\bar{p} \to h_i \to W^+W^- \to l^+l'^-\nu\nu$
- $p\bar{p} \to h_i/h_iW, h_i \to W^+W^-$(SM)
- $p\bar{p} \to (b/\bar{b})h_i, h_i \to b\bar{b}$
- $p\bar{p} \to h_i \to \tau^+\tau^-$
- $p\bar{p} \to h_i/h_iW/h_iZ/h_i$ via VBF, $h_i \to \tau^+\tau^-$ (SM)
- $p\bar{p} \to h_i/h_iW/h_iZ/h_i$ via VBF, $h_i \to \gamma\gamma$
- combined Higgs production and decay (SM)

(+ hadronic remainders)

New Analyses in *HiggsBounds* 2.0.0

HiggsBounds 2.0.0 will be released shortly and will contain results from

- more neutral Higgs searches at LEP
  - $e^+e^- \to (h_k)Z \to (\mathrm{invisible})Z$
  - $e^+e^- \to (h_k)Z \to (\text{ 2 jets })Z$
  - $e^+e^- \to b\bar{b}h_k \to b\bar{b}b\bar{b}$ (h_k is a CP-eigenstate)
  - $e^+e^- \to b\bar{b}h_k \to b\bar{b}\tau^+\tau^-$ (h_k is a CP-eigenstate)
  - $e^+e^- \to \tau^+\tau^-h_k \to \tau^+\tau^-\tau^+\tau^-$ (h_k is a CP-eigenstate)
- more neutral Higgs searches at the Tevatron
  - $p\bar{p} \to t\bar{t}h \to t\bar{t}b\bar{b}$ (h_k is CP-even)
  - $p\bar{p} \to (h_k) + \ldots \to (Z\gamma) + \ldots$ (for $M_{h_k} <$320 GeV)
- charged Higgs searches at LEP and the Tevatron
  - $e^+e^- \to H_k^+H_k^- \to \tau^+\nu\tau^-\nu$
  - $e^+e^- \to H_k^+H_k^- \to q_i\bar{q}_jq_l\bar{q}_m$
  - $e^+e^- \to H_k^+H_k^- \to q_i\bar{q}_j\tau^\pm\nu$
  - $t \to H_k^+b \to \tau^+\nu b$
  - $t \to H_k^+b \to q_i\bar{q}_jb$

Why use *HiggsBounds*?

- Not all of the results are immediately available from the literature, so we had to contact some of the authors. E.g. expected topological LEP cross section limits. Some results have to read from plots.

- There are some additional complications, which *HiggsBounds* takes care internally, e.g.,
  - The tables of limits come with a variety of normalisations.
  - Some limits can only be used for Higgs bosons which fulfil certain conditions (SM-like, particular CP).
  - The possibility of combining cross section predictions for Higgs bosons with similar masses. E.g. useful for the real MSSM at high TB.

- *HiggsBounds* will be continuously updated in order to include the latest results. So far during the development of the code, we have included 138 tables, of which 49 are included in the current release (1.2.0).

Model likeness test

Some of the analyses have been performed under the assumption that model to be tested is similar to the Standard Model.

Therefore we only apply these analyses to parameter points which pass a Standard-Model likeness test:

We check that none of the normalised production cross sections s_i or normalised branching ratios b_i considered by the analysis

$$s_i = \frac{\sigma_{\rm model}(P_i(h))}{\sigma_{\rm SM}(P_i(H))}$$

$$b_k = \frac{{\rm BR}_{\rm model}(h \rightarrow F_k)}{{\rm BR}_{\rm SM}(H \rightarrow F_k)}$$

differ much from the average normalised production cross section $\bar{s}$ or normalised branching ratio $\bar{b}$.

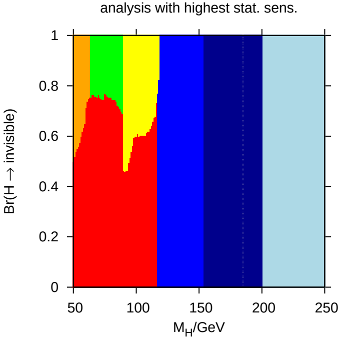
Some of the analyses assume a particular CP-state for the Higgs bosons. For some of the others, it is necessary to check that production or decay channels which are not considered by the analyses are negligible.

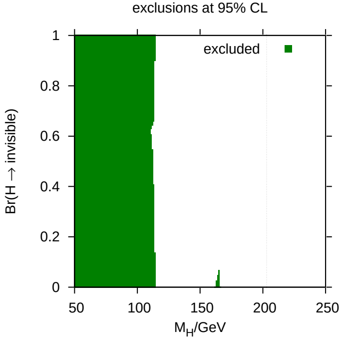
HiggsBounds Example 1: Invisible Higgs decays

There are lots of models which predict a Higgs boson decaying into invisible particles. (e.g. decays to neutralinos, Majorans, neutrinos, hidden sector scalars)

Toy model: Standard-Model like, but with varying $\text{Br}(h_i \to \text{invisible})$

HiggsBounds Example 1: Invisible Higgs decays

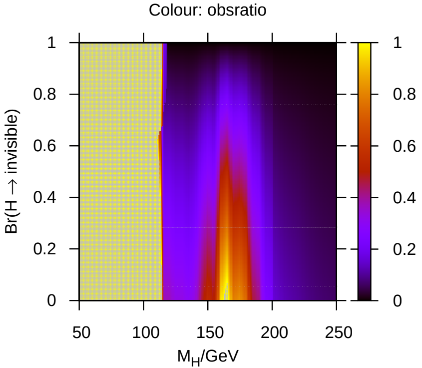


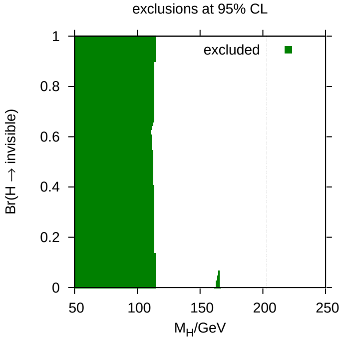


Key to analysis colours:

- $= e^- e^+ \to HZ \to b\bar{b}Z$, hep-ex/0602042 (LEP)
- $= e^- e^+ \to HZ \to (\text{invisible})Z$, arXiv:0707.0373 (OPAL)
- $= e^- e^+ \to HZ \to (\text{invisible})Z$, hep-ex/0501033 (L3)
- $= e^- e^+ \to HZ \to (\text{invisible})Z$, arXiv:0107032v1 (LEP)
- $= p\bar{p} \to H \to W^+W^-$, CDF Note 10101, D0 Note 6039
- $= p\bar{p} \to H + \ldots \to \ldots$ where H is SM-like, arXiv:0911.3930 (TEVNPHWG)
- $= p\bar{p} \to (H \to W^+W^-) + \ldots$ where H is SM-like, arXiv:1001.4162 (TEVNPHWG)

HiggsBounds Example 1: Invisible Higgs decays





$$\text{obsratio} = \frac{\text{the theoretical cross section}}{\text{the observed cross section limit at 95 \% CL}} \quad (1)$$

$\text{obsratio} > 1$ means the parameter point is excluded at 95 % CL (grey)

HiggsBounds Example 2: CPX scenario

The CPX scenario is a benchmark scenario for the MSSM with complex phases (M.S.Carena, J.R.Ellis, A.Pilaftsis, C.E.M.Wagner 2000).

The LEP Higgs Working Group and LEP Collaborations did a dedicated analysis for this scenario [EP JC 46(2006)547] and found an unexcluded region at $M_{h_1} \sim 45\ \mathrm{GeV}$, $\tan\beta \sim 8$.

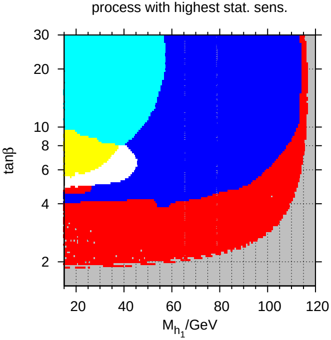
Since this analysis, new results have been obtained in the Feynman-diagrammatic approach, in particular:

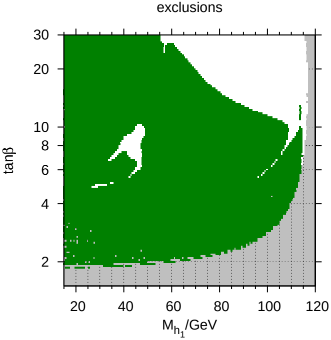
- phase dependent $\mathcal{O}(\alpha_s \alpha_t)$ corrections to the Higgs self-energies (S.Heinemeyer, W.Hollik, H.Rzehak, G.Weiglein 2007)
- phase dependent 1-loop corrections to the Higgs decay $h_2 \to h_1 h_1$ (K.W., G.Weiglein 2008)

We can use *HiggsBounds* to look at the effect of these new corrections.

HiggsBounds Example 2: CPX scenario

HiggsBounds 1.2.0 results, for the CPX scenario*





Channel with the highest statistical sensitivity

- ■ (red) $= e^- e^+ \to h_1 Z \to b\bar{b}Z$
- ■ (blue) $= e^- e^+ \to h_2 Z \to b\bar{b}Z$
- □ $= e^- e^+ \to h_2 Z \to h_1 h_1 Z \to b\bar{b}b\bar{b}Z$
- ■ (cyan) $= e^- e^+ \to h_2 h_1 \to b\bar{b}b\bar{b}$
- ■ (yellow) $= e^- e^+ \to h_2 h_1 \to h_1 h_1 h_1 \to b\bar{b}b\bar{b}b\bar{b}$

Exclusion region at 95 % CL

green = excluded
white = unexcluded

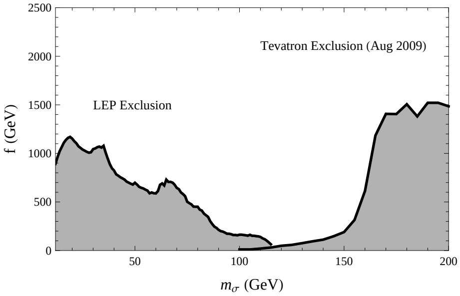
(* as defined in KW, G.Weiglein 2008,
except $m_t = 173.1$ GeV)

HiggsBounds Example 4: Dilaton-assisted Dark Matter

arXiv:0909.1319 (Y. Bai, M. Carena and J. Lykken)

- A dilaton could be the dominant messenger between the SM fields and dark matter.
- The dilaton can have an enhanced coupling to the gluons compared to a Higgs.

The authors of arXiv:0909.1319 used *HiggsBounds* to obtain the exclusions from LEP and Tevatron Higgs searches:



m_σ = dilaton mass

f = energy scale of the spontaneous symmetry breaking

HiggsBounds + *SUSYBounds* extension

We are starting to include some limits from sparticle searches.

So far: OPAL limits on chargino and neutralino production cross sections
[hep-ex/0401026]

HiggsBounds + *SUSYBounds* extension example: Light Neutralino scenario

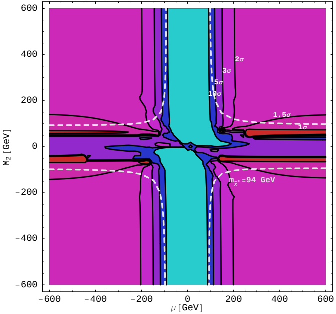
arXiv:0901.3485 (H.Dreiner, S.Heinemeyer, O.Kittel, U.Langenfeld, A.Weber, G.Weiglein) considers the restrictions on MSSM scenarios with a very light neutralino. Includes limits from

- neutralino production, chargino mass limits from LEP
- electroweak precision observables (W boson mass, effective leptonic weak mixing angle, invisible Z width)
- rare meson decays
- neutralino production in supernovae
- cosmological bounds on the neutralino mass (WMAP, structure formation, Ω_{CDM})

HiggsBounds can be used to further constrain the parameter space of this model.

HiggsBounds + *SUSYBounds* extension example: Light Neutralino scenario

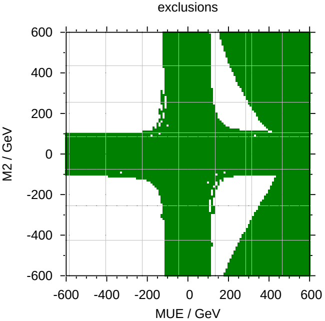
Fig 6 from [arXiv:0901.3485]



Colour: Difference of experimental value and theory prediction for invisible Z width

Dotted line: $M_{\chi_1^+} = 94$ GeV

Exclusions found using HiggsBounds 2.0.0

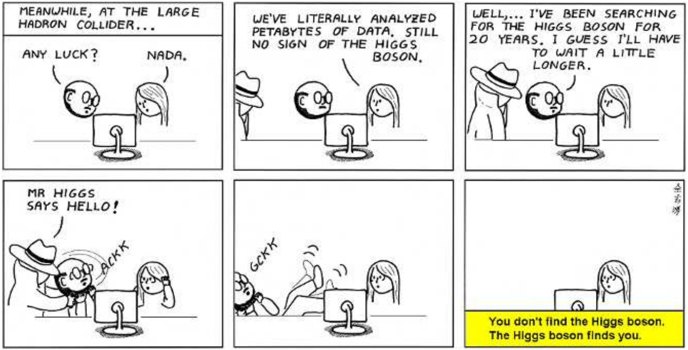


green = exclusions at 95% CL (but with $M_{\chi_1^+} < 75$ GeV excluded, e.g. hep-ex/0311039 (Delphi))

$$\tan\beta = 10, M_{SUSY} = A_\tau = A_t = A_b = m_{\tilde{g}} = M_A = 600 \text{ GeV}, M_{\tilde{\chi}_1^0} = 0$$

The LHC era

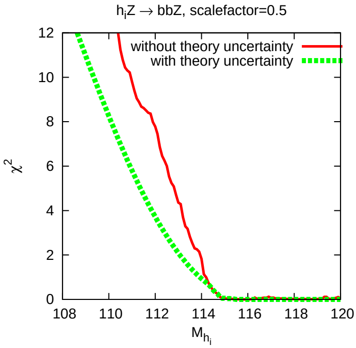
Limits from the Higgs searches at LEP and the Tevatron will need to to be taken into account in the interpretation of any new physics seen at the LHC.



http://abstrusegoose.com/

HiggsBounds + Chi-squared extension

For the LEP Higgs search channels, *HiggsBounds* can also output a chi-squared value, with and without a gaussian theory uncertainty.



This information will then be used by the programs

- Fittino P. Bechtle, K. Desch, P. Wienemann
- MasterCode O. Buchmueller, R. Cavanaugh, A. de Roeck, J. Ellis, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. Weiglein,

which extract SUSY Langrangian parameters from experimental data.

Summary

- Discussed the importance of the results from Higgs searches at LEP and the Tevatron for constraining the Standard Model and its extensions.
- Introduced the program *HiggsBounds*, which provides a very quick and convenient way for theorists to compare their Higgs sector predictions with a wide variety of experimental limits from Higgs searches at LEP and the Tevatron.
- The on-line version and downloadable versions of the program are available at http://www.ippp.dur.ac.uk/HiggsBounds

Future Plans

- Finite width approximations
- Expected LHC limits

The End