

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

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# Higgs Searches

Searches at past and present colliders have not yet discovered a Higgs boson. However, the results from these searches can be used to restrict theoretical models. These results are presented in 2 forms:

## Model-dependent limits

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

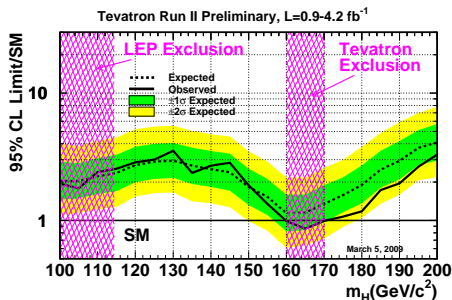
- E.g. **Standard Model** analysis  $\rightarrow$  limits on the Higgs mass in the SM, certain benchmark **MSSM** scenarios ( $m_h^{\max}$ , no-mixing, large- $\mu$ , gluophobic, small  $\alpha_{\text{eff}}$ , CPX, ...)  $\rightarrow$  limits on the parameter space of these scenarios
- uses lots of search 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

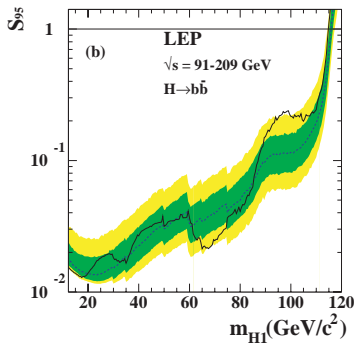
- E.g.  $e^+e^- \rightarrow (h_i)Z \rightarrow (b\bar{b})Z$
- uses one search topology only, applies to lots of models

# Example of model-dependent limits: Standard Model

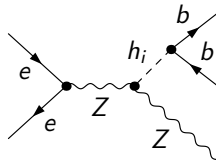


- $M_H < 114.4 \text{ GeV}$  is excluded by LEP searches [[Phys.Lett.B565:61-75,2003](#)]
- $160 \text{ GeV} < M_H < 170 \text{ GeV}$  is excluded by Tevatron searches [[arXiv:0903.4001](#)]
- These results combine the results from searches in many different channels.

# Example of a model-independent cross-section limit



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

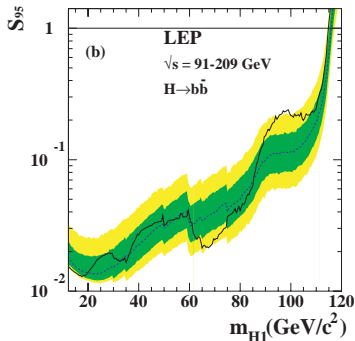


$S_{95}$  is the maximum cross section compatible with the data at 95% CL, normalised to the LEP SM Higgsstrahlung cross section.

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

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

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

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

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

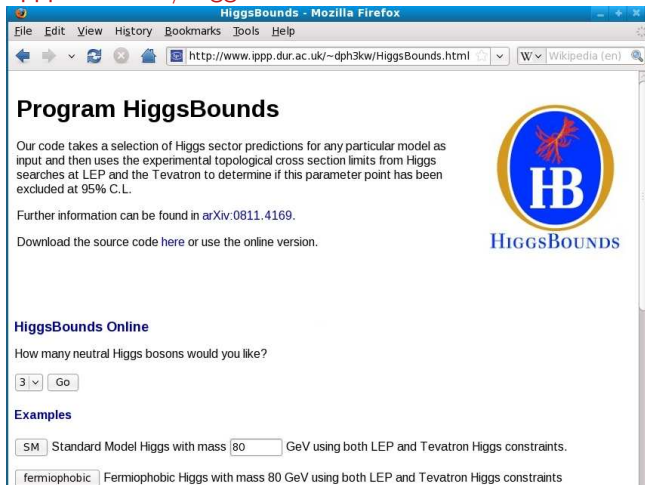
## HiggsBounds

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 screenshot shows a Mozilla Firefox browser window titled "HiggsBounds - Mozilla Firefox". The address bar contains the URL "http://www.ippp.dur.ac.uk/~dph3kw/HiggsBounds.html". The page content includes:

## Program HiggsBounds

Our code takes a selection of Higgs sector predictions for any particular model as input and then uses the experimental topological cross section limits from Higgs searches at LEP and the Tevatron to determine if this parameter point has been excluded at 95% C.L.

Further information can be found in arXiv:0811.4169.

Download the source code [here](#) or use the online version.



### HiggsBounds Online

How many neutral Higgs bosons would you like?

### Examples

Standard Model Higgs with mass  GeV using both LEP and Tevatron Higgs constraints.

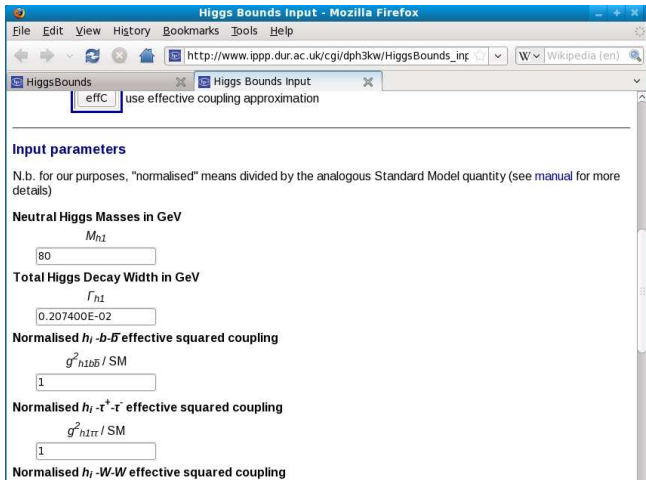
Fermiophobic Higgs with mass 80 GeV using both LEP and Tevatron Higgs constraints



# The *HiggsBounds* Website

The simplest input mode requires

- Higgs masses, total decay widths, normalised effective couplings squared,  $BR(h_j \rightarrow h_i h_i)$



The screenshot shows a Mozilla Firefox browser window titled "Higgs Bounds Input - Mozilla Firefox". The address bar contains the URL "http://www.ippp.dur.ac.uk/cgi/dph3kw/HiggsBounds\_inp". The browser tabs show "HiggsBounds" and "Higgs Bounds Input". A search bar contains the text "effC use effective coupling approximation".

**Input parameters**

N.b. for our purposes, "normalised" means divided by the analogous Standard Model quantity (see manual for more details)

**Neutral Higgs Masses in GeV**

$M_{h1}$

80

**Total Higgs Decay Width in GeV**

$\Gamma_{h1}$

0.207400E-02

**Normalised  $h_i$ - $b\bar{b}$  effective squared coupling**

$g^2_{h1b\bar{b}} / SM$

1

**Normalised  $h_i$ - $\tau^+\tau^-$  effective squared coupling**

$g^2_{h1\tau\tau} / SM$

1

**Normalised  $h_i$ - $W$ - $W$  effective squared coupling**

\*\*\*\*\*

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

\*\*\*\*\*

# HiggsBounds and other codes

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

† interface included in *2HDMC* package (vs. 1.0.2 and higher)

*HiggsBounds* is included in the *DarkSUSY* (P. Gondolo, J. Edsjö, P. Ullio, L. Bergstöm, M. Schelke and E.A. Baltz) package. (See their web interface at <http://www.physto.se/~edsjo/darksusy/>)

# HiggsBounds and other codes

Alternatively, enter all text from FeynHiggs Results webpage, generated using the FeynHiggs User Control Center (example):

```
FeynHiggs Results for the mhmax scenario
mssmparam = 4      # full MSSM [recommended]
fieldren = 0       # DRbar field ren. [strongly recommended]
tanbren = 0        # DRbar TB-ren. [strongly recommended]
higgsmix = 2       # 2x2 (h0-HH) mixing in the neutral Higgs sector
p2approx = 0       # no approximation [recommended]
looplevel = 2      # include 2-loop corrections
runningMT = 3      # MTrun directly and in stop masses
t1BotResum = 1     # resummed MB in 2-loop corrections [recommended]
t1ColxApprox = 3   # a s a t in cMSSM, interpolation in phase for rest
```

Convert to HB input

Internally, HiggsBounds uses some SM results (see [table 12](#) for references).  
To access these directly, enter a Higgs mass:

(new interface for *HiggsBounds* 2.0.0)

# 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 at the Tevatron (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  $\sigma(p\bar{p} \rightarrow H \text{ via } WW \text{ fusion})/\sigma(p\bar{p} \rightarrow H \text{ via } ZZ \text{ fusion})$  using *VBF@NLO* (T.Figy et al 2003)
- ratios of SM hadronic cross sections  $\sigma(p\bar{p} \rightarrow nm \rightarrow H + \dots)/\sigma(p\bar{p} \rightarrow H + \dots)$ , where *nm* are particular partons provided by O. Brein

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

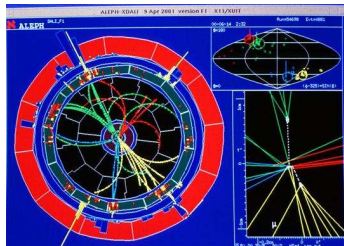
# Topological Cross section limits from LEP Higgs searches currently included in *HiggsBounds*

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  $e^+e^- \rightarrow (h_k)Z \rightarrow (\dots)Z$
- 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*

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

- ▶  $e^+e^- \rightarrow (h_k)Z \rightarrow (\text{invisible})Z$
- ▶  $e^+e^- \rightarrow (h_k)Z \rightarrow (2 \text{ jets})Z$
- ▶  $e^+e^- \rightarrow b\bar{b}h_k \rightarrow b\bar{b}b\bar{b}$  ( $h_k$  is a CP-eigenstate)
- ▶  $e^+e^- \rightarrow b\bar{b}h_k \rightarrow b\bar{b}\tau^+\tau^-$  ( $h_k$  is a CP-eigenstate)
- ▶  $e^+e^- \rightarrow \tau^+\tau^-h_k \rightarrow \tau^+\tau^-\tau^+\tau^-$  ( $h_k$  is a CP-eigenstate)

- more neutral Higgs searches at the Tevatron

- ▶  $p\bar{p} \rightarrow t\bar{t}h \rightarrow t\bar{t}b\bar{b}$  ( $h_k$  is CP-even)
- ▶  $p\bar{p} \rightarrow (h_k) + \dots \rightarrow (Z\gamma) + \dots$  (for  $M_{h_k} < 320$  GeV)

- charged Higgs searches at LEP and the Tevatron

- ▶  $e^+e^- \rightarrow H_k^+H_k^- \rightarrow \tau^+\nu\tau^-\nu$
- ▶  $e^+e^- \rightarrow H_k^+H_k^- \rightarrow q_i\bar{q}_j q_l\bar{q}_m$
- ▶  $e^+e^- \rightarrow H_k^+H_k^- \rightarrow q_i\bar{q}_j\tau^\pm\nu$
- ▶  $t \rightarrow H_k^+b \rightarrow \tau^+\nu b$
- ▶  $t \rightarrow H_k^+b \rightarrow q_i\bar{q}_j b$



# 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.
- 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).
  - ▶ Combining cross section predictions for Higgs bosons with similar masses.
- *HiggsBounds* will be continuously updated in order to include the latest results. So far during the development of the code, we have included 90 tables, of which 49 are still included in the current release (1.2.0).

# Example 1: 4th Generation Model

The 4th generation model extends the SM by a fourth generation of fermions which are much heavier than the mass of the top quark.

The gluon fusion Higgs production cross section  $\sigma$  can be found using

$$\sigma_{4\text{thGen}}(gg \rightarrow H) = 9\sigma_{\text{SM}}(gg \rightarrow H)$$

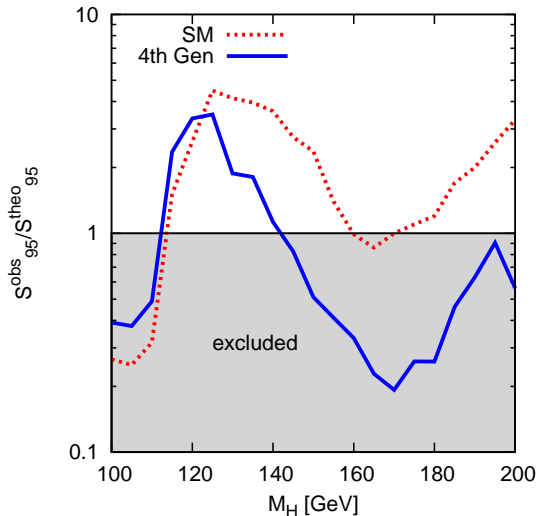
and the decay width  $\Gamma$  of  $H \rightarrow gg$  can be found using

$$\Gamma_{4\text{thGen}}(H \rightarrow gg) = 9\Gamma_{\text{SM}}(H \rightarrow gg)$$

(e.g. G. Kribs, T. Plehn, M. Spannowsky, T. Tait 2007). All other relevant couplings are the same as in the Standard Model.

# Example 1: 4th Generation Model

*HiggsBounds* 1.2.0 results



## 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  $M_{h_1} \sim 45 \text{ GeV}$ ,  $\tan \beta \sim 8$ .

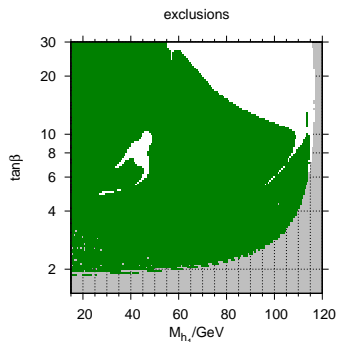
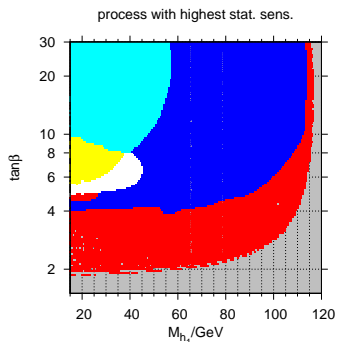
Since this analysis, new results have been obtained in the Feynman-diagrammatic approach, in particular:

- 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  $h_2 \rightarrow h_1 h_1$  (K.W., G.Weiglein 2008)

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

## Example 2: CPX scenario

*HiggsBounds 1.2.0* results, for the CPX scenario\*



Channel with the highest statistical sensitivity

- =  $e^-e^+ \rightarrow h_1Z \rightarrow b\bar{b}Z$
- =  $e^-e^+ \rightarrow h_2Z \rightarrow b\bar{b}Z$
- =  $e^-e^+ \rightarrow h_2Z \rightarrow h_1h_1Z \rightarrow b\bar{b}b\bar{b}Z$
- =  $e^-e^+ \rightarrow h_2h_1 \rightarrow b\bar{b}b\bar{b}$
- =  $e^-e^+ \rightarrow h_2h_1 \rightarrow h_1h_1h_1 \rightarrow b\bar{b}b\bar{b}b\bar{b}$

Exclusion region at 95 % CL

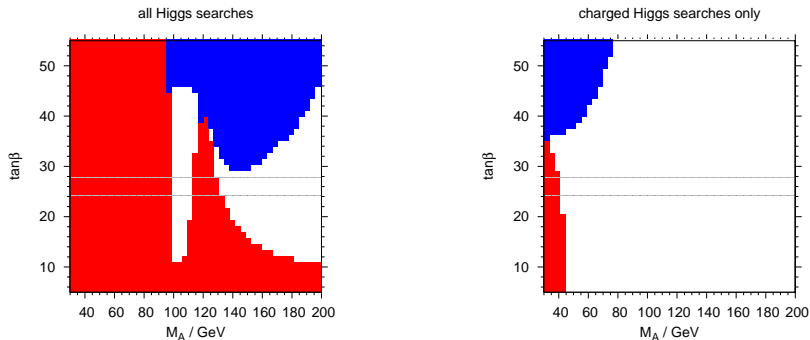
- green = excluded
- white = unexcluded

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

## Example 3: Gluophobic Higgs

The gluophobic Higgs is one of the real MSSM scenarios considered in the LEP Higgs Working Group analysis.

Using *HiggsBounds* 2.0.0beta:



- = exclusions from LEP
- = exclusions from Tevatron

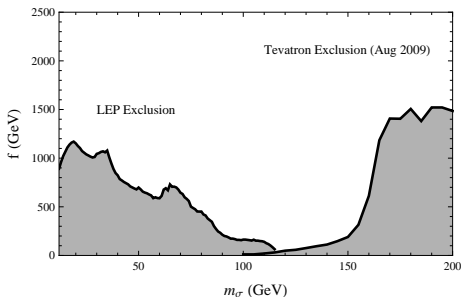
$$M_{SUSY} = 350 \text{ GeV}, M_2 = 300 \text{ GeV}, \mu = 300 \text{ GeV}, m_{\tilde{g}} = 500 \text{ GeV}, X_t = -750 \text{ GeV}$$

## 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:



$m_\sigma$  = dilaton mass

$f$  = energy scale of the spontaneous symmetry breaking

# Future plans

We are currently in the process of incorporating tables of  $CL_{s+b}$  from LEP Higgs searches. This information will then be used by the programs

- **Fittino** P. Bechtle, K. Desch, P. Wienemann



- **MasterCode** O. Buchmller, R. Cavanaugh, A. de Roeck, J. Ellis, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. Weiglein,

which extract SUSY Lagrangian 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>

The End



HIGGSBOUNDS